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Strategic ship routing with satellite altimeter-based dynamic ocean current information: Impacts of temporal coverage

Lee, Young-Kyun, Ph.D.
The Ohio State University, 1994
STRATEGIC SHIP ROUTING WITH SATELLITE
ALTIMETER-BASED DYNAMIC OCEAN CURRENT
INFORMATION: IMPACTS OF TEMPORAL COVERAGE

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Young-Kyun Lee, B.E., M.E., M.S.

* * * * *

The Ohio State University

1994

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To my parents
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CHAPTER I

Introduction

1.1 Motivation

It has been known for a long time that the guiding of ships through environmental factors, e.g., currents, waves and weather, would be beneficial. By using coarsely gridded ocean current data, Lo et al. (1990) estimated that optimal ocean current routing can save fuel consumption by more than $10 million (1986 dollars and fuel price) annually for the U.S. shipping industry.

Researchers had been developing systematic procedures of incorporating environmental factors, mostly waves and weather, into marine navigation in the 1960s and the 1970s (James, 1957; Zoppoli, 1972; Chen, 1978). However, due to the lack of dynamic current estimates, previous researchers had seldom considered using ocean currents explicitly as a parameter in selecting routes. Here, the term dynamic means that the location and perhaps velocities of ocean currents, e.g., the Gulf Stream, change in time. McCord and Lo (1989) indicated that currents are changing temporally much more than was previously assumed; the Gulf Stream reaches about 75% of their six-month variability in 17 days.

With the remote sensing technology presently available (Cheney et al., 1987) and scheduled for introduction in the future (Born et al., 1987), and the increased activity in
ocean current modeling and forecasting (Robinson and Walstad, 1987), real-time dynamic current estimates are technically feasible. We have demonstrated that we can produce dynamic current estimates from the satellite altimeter measurements in a "near" real time fashion at The Ohio State University (McCord and Berliner, 1990; McCord and Berliner, 1991).

Recently, Lo (1991) developed algorithms to exploit dynamic current information for routing and investigated various routing strategies. He did not consider temporal coverage impacts of an orbiting satellite in his study. Instead he used the daily synoptic ocean current information produced by the Harvard University model. We shall call this ocean current pattern data "Harvard data," for simplicity. We describe it later. Harvard data provided daily current estimates not only along the ground tracks, but also between them. Here, the ground tracks are the projection of the orbiting satellite on the earth's surface; thus they indicate the satellite's location.

In a real-life situation with exact repeat period (ERP) satellites, however, we need to accumulate daily information to produce such synoptic ocean current data because we have only limited spatial coverage in a single day due to the field of view of the orbiting satellite. Also, we have ocean current information along the ground tracks only. Thus, to fully utilize satellite altimeter-based ocean current information for routing purposes, we need to consider the impact of temporal coverage.

We can compute dynamic current velocity estimates from the satellite altimeter measurements. For our approach, it is necessary that the satellite orbits the Earth with the exact repeat ground tracks. This type of a satellite is called an ERP satellite, and we describe it
later. In general, however, a satellite does not necessarily have to orbit in an exact repeat period (Yan et al., 1994).

Consider the ground tracks shown in Figure 1. These ground tracks correspond to complete spatial coverage of a 17-day ERP satellite after 17 days. If currents do not change in time, and we have enough spatial coverage for the purpose of ship routing, we may not need to worry about the temporal coverage impact. On a certain day, however, we have only limited amount of spatial coverage. Figure 2 shows the spatial coverage in three consecutive days. Currents do change in time. McCord and Lo (1989) showed that currents reach about 75% of a six-month variability in 17 days.

The ground tracks, depending on the specific ERP satellite, repeat their entire coverage every $N$ days, with only $1/N$ of the ground tracks being covered in a single day. Therefore, we need to accumulate or combine several days of information to have enough spatial coverage. However, as we accumulate daily information, it gets old.

Then, we ask: What is the temporal coverage impact on ocean current routing as information gets old? Does the strategy for accumulation of daily current estimates along the ground tracks really matter for the purpose of ship routing? If it does, how many days of ground track information should we accumulate to obtain the greatest fuel savings?

Given that it is likely to have a GEOSAT follow-on (17-day ERP) satellite with GEOSAT ground tracks, while the TOPEX (10-day ERP) satellite is still in operation, we raise another interesting question: What is the increased magnitude of fuel savings due to having two different ERP satellites simultaneously instead of having only one ERP satellite for ship routing purposes? It seems obvious that having two different ERP satellites simultaneously
Figure 1: All Ground Tracks of a 17-day ERP Satellite in the Study Region.

Figure 2: The 17-day ERP Ground Tracks for Three Consecutive Days in the Study Region.
would result in more fuel savings, since this would provide more temporally recent data and more spatial coverage than having only one ERP satellite. We, however, do not know the size of the increase in fuel savings yet. Thus, it seems worthwhile to investigate the magnitude of the fuel savings increase. We have reported preliminary results elsewhere under similar settings, and the results were encouraging (Lee, 1994).

Another relevant question is: Which routes or origin-destination (O-D) pairs are most advantageous for satellite altimeter-based ocean current routing? If we could identify O-D pairs which result in more relative fuel savings than others, the routing industry might concentrate on those specific O-D pairs for strategic ship routing purposes when we utilize the satellite altimeter-based current information.

Finally, we are interested in providing research directions for improved ocean routing. Several factors, e.g., time lag and accurate geoid information, affect the performance of ship routing with current information. Therefore, we try to identify which factors are more important than others. More specifically, we ask whether timely delivery of ERP satellite altimeter measurements is more important than having an accurate geoid model or development of an accurate interpolation model.

In summary, we address the following questions in this study. (1) How many days of ground track information should we accumulate to obtain the greatest fuel savings in routing ships when we accumulate daily current information along the ground tracks? (2) What is the increased magnitude of fuel savings due to having two different ERP satellites instead of having only one ERP satellite for ship routing purposes? (3) Which routes or origin-destination (O-D) pairs are most advantageous for ocean current routing? (4)
Where should we concentrate future research efforts to achieve improved ocean routing with satellite altimeter-based ocean currents?

1.2 Background

As mentioned before, when we compute dynamic current velocity estimates from satellite altimeter measurements, a satellite with the altimeter must orbit the Earth with exact repeat ground tracks for our approach – a modified hydrographic approach. A modified hydrographic approach is described later. It does not necessarily have to do so in general, however. This combination of altimeter and exact repeat ground tracks is essential to a modified hydrographic approach in developing dynamic ocean current estimates, thus encouraging the use of satellite altimetry for ocean routing.

Satellite missions are typically exact repeat missions (Robinson, 1985). Also, exact repeat missions allow us to ignore the geoid as described later. Thus, we briefly review the satellite exact repeat mission and how we estimate dynamic ocean current velocity from the altimeter measurements.

1.2.1 Exact Repeat Mission

An exact repeat period (ERP) satellite allows the direct computation of sea level variability by examining data from one track to the next repeat of that particular track. An exact repeat orbit is highly desirable for observing mesoscale oceanographic features (Born et al., 1987).

Figure 3 shows a schematic diagram of an ERP satellite altimeter measurement. As an N-day ERP satellite orbits around the Earth, the altimeter measures the distance between the satellite and the Earth’s surface. The radar altimeter onboard the satellite transmits
pulses toward the Earth. The return time of the pulse after reflection at the Earth's surface is measured. Multiplying one half of this return time by the velocity of the pulse yields the height of the satellite with respect to the Earth's surface. The sea surface height profile is determined with the altimeter measurement and the orbit height of a satellite (McCord and Berliner, 1990; McCord and Berliner, 1991; Lo, 1991). An orbit of a satellite with respect to the reference ellipsoid is determined by the independent satellite tracking stations. Once we have the sea surface height profile, we compute the dynamic height profile by subtracting the reference geoid profile from the sea surface height profile. Here, the geoid is an equipotential surface (Robinson, 1985).

A reference geoid is necessary to compute the dynamic sea surface height profile in non-exact repeating ground tracks. Since the reference geoid is common to the exact repeating ground tracks, however, we do not need a reference geoid to compute sea level variability with exact repeat ground tracks (McCord and Smith, 1989; McCord and Lo, 1989).

Mitchell (1983) suggested that sampling frequencies of about 20 days and with an equatorial ground track separation of approximately 140 km were good enough for quasi-synoptic sampling of the oceanic mesoscale features with typical spatial scales of 100 km and a time scale of at least 30 days. He identified a particular choice of a 17-day exact repeat orbit of GEOSAT. Later, Kindle (1986) showed that an equatorial ground track separation of 100 km is sufficient to determine the height field of stationary eddies very accurately. However, we should note that commercial ship routing was not a factor in determining GEOSAT's exact repeat period of 17-day ground tracks.
Figure 3: A schematic Diagram of an ERP Satellite Altimeter Measurement.
1.2.2 Dynamic Ocean Currents from Satellite Altimeter

Ocean current dynamics can be described by the actions of the following forces: the pressure gradient force, the Coriolis force, the gravitational force, the frictional force and the centrifugal force (Bishop, 1984). Among these forces, the balance between the Coriolis force and the pressure gradient force dominates the horizontal motion of large scale oceanic features (Stommel, 1965). These two forces form the geostrophic balance, in which the pressure gradient force driving the flow is balanced predominantly by the Coriolis force (Robinson, 1985).

At the sea surface, the horizontal pressure is proportional to the sea surface height profile measured relative to the geoid, often called the dynamic height profile. The dynamic height profile with the geostrophic balance equations allows us to estimate ocean currents from the sea surface profile measured from the satellite altimeter. Redefining the horizontal axis as the coordinate system axis along the direction of the satellite’s ground track progression, current velocities that are perpendicular to the satellite’s ground tracks can be estimated (Lo, 1991). Thus, to obtain dynamic ocean currents information from the altimeter sea surface height measurements, it is necessary to know the surface height and slope relative to the geoid.

There are two elements that affect the accuracy of determining the dynamic height profile, and thus the derived current velocity: measurement errors associated with the altimeter and the accuracy of the underlying geoid profile. Measurement errors associated with the altimeter can be classified into three groups: altimeter, media, and orbit errors (Lo, 1991). Altimeter errors are related to the physical collection of the data. Media errors
are related to propagation of the radar through the atmosphere. Orbit errors are related to the orbit determination by independent tracking stations. Lo (1991) summarized the error specifications associated with measuring ocean topography. His summary provides a general idea about the order of magnitude of the different errors. Chase (1988) completed a preliminary study that simulated the effects of measurement errors. Her preliminary conclusion was that the effects of measurement errors in estimating current velocities were insignificant when using design specifications. Even though the effects of measurement errors need more detailed analysis, we assume there is no altimeter measurement related errors in this study.

As mentioned before, the exact repeat ground tracks help to determine temporal changes in sea surface profiles over time without knowing the geoid, since the underlying geoid is time invariant. This fact is very useful for our approach—a modified hydrographic approach (Lo, 1991)—and a synthetic geoid approach (Glenn et al., 1991) to compute dynamic ocean current velocities from altimeter sea surface height measurements. These approaches are used to mitigate the present difficulty of not having an accurate underlying geoid profile. However, it is necessary to know the geoid for a gravimetric approach (Rapp and Wang, 1993) to compute dynamic ocean current velocities from altimeter measurements. Here, we briefly review a modified hydrographic approach. A more detailed explanation for other approaches can be found in Lo (1991).

The idea of a modified hydrographic approach (Lo, 1991) is derived from the fact that the dynamic height profile at time $t$ consists of two parts: the long term mean dynamic height profile and a dynamic height difference at time $t$. If the long term mean dynamic height
profile is small, the dynamic height profile at time $t$ can be approximated by the dynamic height difference profile by ignoring the long term mean dynamic height profile. The advantage of a modified hydrographic approach is that the dynamic height difference profile is directly available from a series of altimeter measurements. A modified hydrographic approach also provides global coverage at fine spatial resolution. However, there are two disadvantages of a modified hydrographic approach. The first one is that this approach is only applicable in areas in which the long term dynamic mean height profiles are small. The Gulf Stream is such an example. The other disadvantage is that we need to accumulate enough altimeter measurements over time to get the mean dynamic height profile. Thus, for a new ERP satellite, this approach will take time to generate reliable mean dynamic height profiles.

### 1.3 Methodology

The questions to be answered in this study are: (1) How many days of ground track information should we accumulate to obtain the greatest fuel savings in routing ships when we accumulate daily current information along the ground tracks? (2) What is the increased magnitude of fuel savings due to having two different ERP satellites instead of having only one ERP satellite for ship routing purposes? (3) Which routes or origin-destination (O-D) pairs are most advantageous for ocean current routing? (4) Where should we concentrate future research efforts to achieve improved ocean routing with satellite altimeter-based ocean currents?

To answer these questions, we use data on ocean current patterns covering a limited area in the North Atlantic Gulf Stream region. The data was produced by the Harvard
University model (Robinson et al., 1989; Robinson and Walstad, 1987). We describe it later. In this study, we aggregate the Harvard data into grid cells of 0.1° latitude by 0.5° longitude with a single current vector in each cell and assume that the vector in the grid cell represents the “true” current patterns everywhere in the grid cell. We use this 0.1° by 0.5° spatial resolution in this study.

With this “true” current data, we address specific scenarios under different information schemes described in Chapter II. We simulate the cases with access to data computed with samples from a 10-day ERP satellite. We also simulate the cases with access to data computed with samples from a 17-day ERP satellite. Also, we simulate the cases with access to data computed with samples from 10- and 17-day ERP satellites simultaneously. Ground tracks of TOPEX/POSEIDON (Vincent, 1990) and GEOSAT (Cheney et al., 1987) were adopted to represent those of 10-day ERP and 17-day ERP, respectively.

We simulate the voyage of a ship on eastbound and westbound routes. In this Gulf Stream region, eastbound means the ship voyages with currents, while westbound means she voyages against currents. We use 16 knots for the ship velocity value. This velocity is representative of tankers, the class of ships that offer the most potential fuel savings from routing with current information (Lo et al., 1991).

1.3.1 Performance Model

Dynamic programming is arguably the most popular approach for optimal ship routing (Chen, 1978; Zoppoli, 1972). Dynamic programming provides a functional recursive relationship to solve the ship routing problem formulated as a discrete optimization problem (Lo, 1991). The solution to the dynamic programming approach is guaranteed to be the
global optimum to the formulated discrete problem. Dynamic programming can also handle constraints easily and directly. Navigational limitations and environmental hazardous areas, for example, can be excluded from the feasible region.

Lo and McCord (1993) and Lo (1991) investigated optimization heuristics based on variations of dynamic programming that would utilize high quality data capturing the dynamics of ocean currents. The goal was to select the ship's headings and power settings so as to minimize fuel consumption. Their results showed that heading was what really mattered, and that power routing was of secondary concern for analysis of strategic routing through currents. Specifically, optimizing for heading and power decreased fuel consumption by less than 0.1% on average, compared to optimizing for heading only. Therefore, we only use heading optimization in this study.

We compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information. In both cases, we consider a ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We call $V_w$ and $V_{wn}$ the constant ship velocities with current information and without current information, respectively. The constant velocity policy is optimal in the absence of current information (Lo et al., 1991). Also, it is practiced in the routing industry (Lo, 1991). By fixing the arrival time $T$ to be the same on the two routes, we do not need to make any assumptions about the tradeoff between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route.
given that the ship is to travel at constant velocity relative to the water $V_w$ plus current velocity $V_c$. With $V_w$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. This path is also the minimum fuel consumption route because power setting is not considered.

The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information. We are interested in the marginal impact of currents which can be added to the effects of weather and/or waves as a first approximation as in Lo et al. (1991). We can ignore other environmental factors unless there are reasons to believe that they are highly correlated with the current pattern. After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_w$ to arrive at the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991).

To find these two routes, we discretize the routing problem into $N$ stages and solve by dynamic programming. We select longitudinal progression and latitude as the stage variable and the state variable, respectively. The direction of the route for the stage transition can be defined by arriving at any stage with different latitude. We obtain the optimal path from any stage onward to the destination by implementing the backward recursive relationship of dynamic programming, and trace the minimum time route when the backward evaluation has reached the ship's origin.

Let $FC_w$ represent the fuel consumed on a specific passage when using ("with") current information to choose the route, i.e., the shortest time route. Let $FC_w$ represent the fuel consumed on a specific passage when not using ("without") current information to choose
the route, i.e., the great circle route. The relative fuel savings, \( FS \), on a specific passage can be expressed as:

\[
FS = 1 - \frac{FC_w}{FC_{wo}}. \tag{1.1}
\]

For a fixed velocity through the water, the fuel consumption on a specific passage can be expressed by the relation (Lee and McCord, 1993; Jansson and Shneerson, 1987):

\[
FC_w = K \times T \times V_w^3 \tag{1.2}
\]

\[
FC_{wo} = K \times T \times V_{wo}^3 \tag{1.3}
\]

where \( K \) is a ship dependent constant, \( T \) is the fixed travel time, and \( V_w, V_{wo} \) are the constant ship velocities with current information (on the minimum time route) and without current information (on the minimum distance route), respectively. Since the ship specific constant \( K \) is the same in both with and without current information cases - i.e., the ship considered is the same - \( K \) cancels out when substituting Equation (1.2) and Equation (1.3) in Equation (1.1). Thus, choosing the percentage fuel savings as the performance measure allows us to evaluate performances without the need to consider specific characteristics of the ships. The fixed travel time \( T \) also cancels out, and the relative fuel savings in percent can be expressed as follows:

\[
FS = (1 - \left( \frac{V_w}{V_{wo}} \right)^3) \times 100 \tag{1.4}
\]
1.3.2 Ocean Current Data

Harvard University collaborated with the U.S. Navy over a period of years to develop a four-dimensional oceanographic current model (Robinson et al., 1989; Robinson and Walstad, 1987) for an area of the Gulf Stream bordered by north latitude and west longitude coordinates of (39°, 74°), (32°, 72°), (38°, 50°), and (46°, 55°). They used a physical oceanographic model to produce a series of daily forecasts of the Gulf Stream and its rings in this region. The model was driven by data obtained from the GEOSAT altimeter, infrared observations and in-situ measurements, and updated on a weekly basis.

We were granted access to a subset of this data and obtained surface current data on a 15 km by 15 km grid for each day in two five-week periods. This spatial resolution is extremely fine for strategic routing purposes, where the ocean circulation features have a spatial scale of approximately 100 km. We aggregated the 15 km by 15 km gridded Harvard data into grid cells of 0.1° latitude by 0.5° longitude with a single current vector in each cell, and used them in this study as our underlying “true” current patterns. A sample output of a “true” current pattern is shown in Figure 4.

Satellite altimeters produce velocity estimates perpendicular to the satellites’ ground tracks through the geostrophic balance equation (Stommel, 1965; Bishop, 1984; Robinson, 1985). Thus, to simulate current information from satellite altimeter measurements, we sampled the Harvard data along the ground tracks and computed their velocity components perpendicular to the ground tracks at individual locations which would be measured by the satellite. We averaged these perpendicular components into grid cells of 0.1° latitude by 0.5° longitude to form a single current vector in each cell. This aggregated data is what
we used as "estimated" currents as opposed to the "true" data that represented full (not perpendicular to ground track) components of the current resolution everywhere (not just along ground tracks) in the region.

1.3.3 Simulation Framework

An orbiting satellite, such as GEOSAT or TOPEX/POSEIDON, collects repeated information over time. One of the questions we are investigating is how many days of information \( X \) should be used to balance the spatial and temporal coverage for routing purposes. Given a temporal progression of current patterns over \( X \) days (a model of which could be \( X \) successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning...
of the $X$ days of analysis. Thus, there are many possible combinations of accumulating daily information for $X$ days.

Let us call the "starting date" the day when the ship leaves its origin in our simulation framework. Let $C_{SD}$ represent the current information on starting date $SD$. It seems reasonable to use only the most recent information available (Lee and McCord, 1993). Therefore, if we were to combine three days of information, for example, we would use $C_{SD}$, $C_{SD-1}$, and $C_{SD-2}$ as a three-day accumulation. In other words, if today is the starting date, we accumulate current information on today, yesterday and the day before yesterday as three days of current information. But, depending on where the satellite sampled the area on day $SD-2$, there could be several sets of sequentially ordered ground tracks that would lead to $C_{SD-2}$, $C_{SD-1}$, and $C_{SD}$ estimates. For an $N$-day ERP, the satellite could have been any repetition of $N$ possible ways of accumulation of current information. Specifically, there are 10 possible accumulation cases for a 10-day ERP satellite and 17 possible accumulation cases for a 17-day ERP satellite. And there are 170 ($= 10 \times 17$) possible accumulation cases for 10- and 17-day ERP satellites. For a 10- or a 17-day ERP satellite, we used all the combinations of accumulation cases for each accumulation scheme $X$. Also, we used 30 out of 170 cases for 10- and 17-day ERP satellites for each $X$.

We sampled current information on a daily basis along 10- and 17-day ERP ground tracks from Harvard data. As explained earlier, for an $N$-day ERP satellite, only $1/N$ of the ground tracks are covered in a single day, and there are $N$ possible ways of accumulation of current information. For example, for a 10-day ERP satellite, we sampled the "true" current pattern ten different ways, each with $1/10$ of the ground tracks in a single day. These
sampled currents estimated along the ground tracks simulate dynamic current information derived from the satellite altimeters. The procedure for data preparation and running the optimization program, then, can be summarized as follows:

Step 0. Choose the starting date, \(SD\).

Step 1. Select the corresponding "true" current patterns from the Harvard data for this day and the preceding \(X - 1\) days.

Step 2. Extract necessary ground tracks in the study area for 10-day and 17-day ERP satellites.

Step 3. Extract velocities depending on the information schemes (see Section 2.1) adopted from the Harvard Data along the satellite ground tracks from Step 2 on the current patterns in Step 1.

Step 4. Aggregate the data from Step 3 to produce a single "snap-shot" of 0.1° latitude by 0.5° longitude gridded current vectors for input to the optimization program. We call this "snap-shot" the "estimated" gridded currents.

Step 5. Run the optimization with the "estimated" gridded currents in Step 4 as input to find estimated minimum fuel consumption/time route.

Step 6. Use the "true" currents pattern from Step 1 to get travel time \(T\) on this minimum time route.

Step 7. Use the "true" currents pattern from Step 1 to get \(V_{\text{v0}}\) on the great circle route to arrive at \(T\) from Step 6.

Step 8. Compute the relative fuel savings with Equation (1.4).
1.4 Overview

In Chapter II, we define and describe the notation for the variables used in this study. We describe the detailed procedures used to select the origin-destination (O-D) pairs and starting dates. The starting dates are defined as the day a ship leaves the origin.

There are two reasons that we want to group fuel savings (FS) based on O-D pairs. First, we want to describe FS relative to the O-D characteristics systematically to investigate if any characteristics lead to better or worse performance. Second, we want to make this study manageable.

We initially select 5 (9) origins and 9 (5) destinations for eastbound (westbound) voyages to form a total of 45 O-D pairs for each direction of voyage. In this study region, eastbound means that the ship will be primarily travelling with the currents, while westbound means that the ship will primarily be travelling against the currents.

We then compute the relative fuel savings for each O-D pair on each selected starting date. We run the performance model described in Section 1.3 to calculate a relative fuel savings for each of the voyages. Then, we compute the mean relative fuel savings (MFS) across the starting dates. We classify the relative fuel savings into nine groups depending on each O-D pair’s physical location relative to the Gulf Stream, i.e., “above” (A), “in” (I) and “below” (B) the Gulf Stream current pattern for origins and destinations. Finally, we cluster the O-D pairs relative to the MFS into 4 groups for eastbound and 3 groups for westbound voyages. In this preliminary selection of O-D pairs we use the ideal information scheme in which we can predict the full current velocity in advance for all time periods of interest.
We summarize the clustering results and the selected O-D pairs used for the rest of the study. For eastbound voyages, RT₁ represents the fuel savings category exclusive to (A-A) cases. RT₂ (A-B) represents the medium fuel savings category, RT₃ (I-I) represents the high fuel savings category, and RT₄ (B-B) represents the low fuel savings category. For westbound voyages, RT₅ (I-I) represents the high fuel savings category, RT₆ (B-B) represents the low fuel savings category, and RT₇ (B-A) represents the medium fuel savings category.

Also, we need to limit the number of starting dates to keep the study manageable. We use four starting dates in the preliminary analysis to determine the number of O-D pairs. We want to consider more starting dates in the more detailed analysis, however, to give some more generality.

We then compute the relative fuel savings for each selected O-D pair on each starting date. In this selection of starting dates we use the ideal information scheme in which we can predict the full current velocity in advance for all time periods of interest. We run the performance model described in Section 1.3 to calculate a relative fuel savings for each of the voyages. Then, we compute the mean relative fuel savings (MFS) across the O-D pairs. Based on these MFS's, we select one starting date from each week, resulting in a total of six starting dates. A total of 6 starting dates are used for the rest of the study.

In Chapter III, we investigate the impact of the accumulation of daily current information along the satellite ground tracks on ship routing performance. The results of this investigation can serve as a guideline to the routing industry to incorporate satellite altimeter-based dynamic ocean current information for strategic routing purposes. Also,
we can simplify the studies in the following chapters by identifying the effect of daily
information accumulation.

If currents did not change in time, we would not worry about the temporal coverage
impact when we have enough spatial coverage for the purpose of ship routing. But they
do change in time (McCord and Lo, 1989). Also, on a certain day, we have only limited
spatial coverage due to the field of view of the orbiting satellite.

In Chapter III, we ask: What is the temporal coverage impact on ocean current routing
as information gets old? Does the strategy for accumulation of daily current estimates
along the ground tracks really matter for the purpose of ship routing? If it does, how many
days of ground track information should we accumulate to obtain the greatest fuel savings
in routing ships when we accumulate daily current information along the ground tracks?

We again measure the performance according to the relative fuel savings on the routes
resulting from optimizing fuel consumption compared to the great circle routes. Also, we
identify the desirable “ground track accumulation scheme” of daily current information to
maximize the FS for 10- and 17-day ERP satellites each.

We consider three information schemes for both eastbound and westbound voyages with
real-time information for each ERP satellite, while we consider two information schemes
for both directions of voyage with “near” real-time information for each ERP satellite. All
3 information schemes considered in this chapter provide daily current information along
the ground tracks.

Results show that the accumulation of daily current information does matter in ship
routing performance for both eastbound and westbound voyages. Specifically, for a 10-day
ERP satellite, we maximize the overall mean relative fuel savings (MFS) when we accumulate up to 10 days of daily current information along the ground tracks with real- and "near" real-time information for both directions of voyage. For a 17-day ERP satellite, we maximize the MFS when we accumulate between 8 and 14 days of daily current information, depending on the information schemes along the ground tracks for both directions of voyage. However, there are some instances in which it would be better not to utilize current information for routing purposes and instead to follow the great circle route. Specifically, westbound voyages with "near" real-time information with a modified hydrographic approach lead to negative relative fuel savings.

Our recommendations of daily current information accumulation schemes for the greatest mean relative fuel savings for 10- and 17-day ERP satellites should be considered with caution. We identified the accumulation schemes under each of the information schemes which provide the greatest overall mean relative fuel savings taken across the O-D pairs and starting dates. As we take the overall mean relative fuel savings across the O-D pairs and starting dates to compare "ground track accumulation schemes," there are wide variations in fuel savings with respect to the O-D pairs and starting dates. Nevertheless, we can make more informed decisions with the help of fuel savings differences.

In Chapter IV, we investigate the increased magnitude of fuel savings due to having two different exact repeat period (ERP) satellites simultaneously compared to having only one ERP satellite. It seems obvious that having two different ERP satellites simultaneously would result in more fuel savings, since this would provide more temporally recent data and more spatial coverage than having only one ERP satellite. We, however, do not know the
size of the fuel savings increase yet. Thus, it seems interesting to investigate the magnitude of the FS increase, given that it is likely to have a GEOSAT-follow-on satellite (17-day ERP) with GEOSAT ground tracks while TOPEX (10-day ERP) is still in operation. In Chapter IV, we ask: What is the increased magnitude of fuel savings due to having two different ERP satellites simultaneously compared to having only one ERP satellite?

We again measure the performance according to the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. First, we investigate the desirable combinations of accumulation of daily current information when we have 10- and 17-day ERP satellites simultaneously. Then, we compare the greatest mean relative fuel savings of each ERP satellite obtained in Chapter II to that of the combination of two ERP satellites.

The results show that, for eastbound routes, we maximize the relative mean fuel savings when we accumulate up to 10 days of daily information from a 10-day ERP satellite with up to 8 days of daily information from a 17-day ERP satellite simultaneously. For westbound routes, we maximize the relative fuel savings when we accumulate up to 10 days of daily information from a 10-day ERP satellite with up to 11 days of daily information from a 17-day ERP satellite simultaneously.

Then, we compare the maximum mean relative fuel savings resulting from having two ERP satellites simultaneously to those resulting from having only one ERP satellite under the case of real time information with the current velocity component profile perpendicular to the ground tracks. Having two different ERP satellites simultaneously performs better than having only one ERP satellite each for both eastbound and westbound voyages. Specifically,
for eastbound voyages, having two different ERP satellites simultaneously results in 0.93% more mean relative fuel savings compared to having a 10-day ERP satellite, and 0.80% more mean relative fuel savings compared to having a 17-day ERP satellite. For westbound voyages, having two different ERP satellites simultaneously results in 0.54% more mean relative fuel savings compared to having a 10-day ERP satellite, and 1.00% more mean relative fuel savings compared to having a 17-day ERP satellite.

In Chapter V, we investigate which O-D pairs are the most advantageous for strategic ship routing purposes when we utilize the ocean current information derived from the satellite altimeter measurements for each of the 10- and 17-day ERP satellites under all information schemes for both directions of voyages. We present the mean relative fuel savings (MFS's) plots disaggregated with respect to the O-D pairs used in Chapters III and IV, to show the influence when we compare the MFS’s to determine the desirable accumulation schemes under different conditions. We notice that wide variations in relative fuel savings among O-D pairs exist.

We compare the O-D pairs based on the mean relative fuel savings taken across the starting dates. We use accumulation schemes which result in the greatest mean relative fuel savings in Chapter III for each of the 10- and 17-day ERP satellites, and in Chapter IV for the combination of two ERP satellites. Also, we compare the ranks of the mean relative fuel savings of the O-D pairs for each starting date under different information conditions.

The results show that, for eastbound voyages, O-D pairs (A-A) and (I-I) whose origins and destinations are “above” and “in” the Gulf Stream, respectively, are the two most advantageous routes, resulting in greater MFS's under all information schemes for each of
the 10- and 17-day ERP satellites. For westbound voyages, an O-D pair (I-J) whose origin and destination are "in" the Gulf Stream is the most advantageous, resulting in greater MFS's under all information schemes for each of the 10- and 17-day ERP satellites, except for three instances. Specifically, when we have real- and "near" real-time ocean current information estimated with a modified hydrographic approach for a 17-day ERP satellite, and when we have "near" real-time ocean current information estimated with a modified hydrographic approach for a 10-day ERP satellite, the result is negative MFS's. Negative mean relative fuel savings mean that we consume more fuel when we utilize altimeter-based dynamic ocean current information. Thus, we are better off to ignore the current information. In these cases, we would have done better to follow the great circle routes.

In Chapter VI, we compare information schemes for the most advantageous O-D pairs identified in Chapter V based on the mean relative fuel savings. The results of the comparison provide research directions for improved ocean routing. In other words, the results provide insight where we should concentrate our efforts to achieve improved ocean routing with satellite altimeter-based ocean current information.

In Chapter VI, we ask: Where should we concentrate our research efforts for better routing performance when we utilize the satellite altimeter-based ocean current information? To answer this question, we raise the following specific questions: 1) What is the effect of not having the forecasting capability? 2) What is the effect of not being able to spatially interpolate among ground tracks? 3) What is the effect of not knowing the full velocity component? 4) What is the effect of not having an accurate geoid model? 5) What is the effect of a time lag in data delivery? 6) What is the effect of having additional satellite
supply?

First, we answer those specific questions to quantify each effect in routing performance. Then, we compare each effect to identify research directions for better routing performance when we utilize the satellite altimeter-based ocean current information.

We compare the information schemes based on the mean relative fuel savings differences taken across the starting dates for the most advantageous O-D pairs for strategic ship routing. Again, we use accumulation schemes which result in the greatest mean relative fuel savings in Chapter III for each of the 10- and 17-day ERP satellites, and in Chapter IV for the combination of two ERP satellites under different information conditions.

The results show that the spatial coverage effect (having current information not only along ground tracks only, but also between ground tracks), and having an accurate geoid model are most important in overall mean fuel savings performance. The next most important effect is that of the time lag. Thus, we need to concentrate our research efforts on those three areas for better routing performance when we utilize the satellite altimeter-based ocean current information.

Finally, Chapter VII summarizes findings and recommendations obtained throughout this study, and discusses further research directions.
CHAPTER II

Selection of O-D pairs and Starting Dates

In this chapter, we define the notation used for this study and describe the procedures used to select the origin-destination (O-D) pairs and starting dates. The starting dates are defined as the day a ship leaves the origin. Section 2.1 describes the notation which accounts for the variables used in this study. Section 2.2 describes the detailed procedure of selecting the O-D pairs for this study. Section 2.3 summarizes the details of how starting dates are selected.

2.1 Notation

We describe the relative fuel savings (FS) in percent resulting from strategic ship routing with current information as a function of several variables. Specifically, we consider:

\[ FS = f (DIR, RT, LAG, INFO, SD, SAT, ACC, TRK), \]

where DIR represents the direction of voyage; RT represents the origin-destination pair for the routing; LAG represents the time lag of acquiring the current information; INFO represents the information scheme for estimating the current profile; SD represents the starting date; SAT represents the supply of the satellites; ACC represents the accumulation.
of daily information; and TRK represents the number of ground track and the sequence in which they are combined.

We consider 2 directions of voyage:

$$\text{DIR} \in \{E, W\}. \quad (2.2)$$

$\text{DIR} = E$ represents eastbound voyages, and $\text{DIR} = W$ represents westbound voyages. In this study region, eastbound means that the ship will be primarily travelling with the currents, while westbound means that the ship will primarily be travelling against the currents.

We consider 4 origin-destination (O-D) pairs or routes (RT) for eastbound voyages, and 3 O-D pairs for westbound voyages. The procedure for selecting these O-D pairs is described in section 2.2 in detail. Here, we simply denote our notation as:

$$\text{RT} \in \{\text{RT}_1 (= A - A), \text{RT}_2 (= A - B), \text{RT}_3 (= I - I), \text{RT}_4 (= B - B)\} \quad (2.3)$$

for eastbound voyages and

$$\text{RT} \in \{\text{RT}_5 (= I - I), \text{RT}_6 (= B - B), \text{RT}_7 (= B - A)\} \quad (2.4)$$

for westbound voyages. In this notation $A$ represents a location “above” the Gulf Stream current pattern, $I$ represents a location “in” the Gulf Stream, and $B$ represents a location “below” the Gulf Stream. Above and below the current pattern mean north and south, respectively. For example, $A - B$ means that the origin is north of (above) the Gulf Stream and the destination is south of (below) the Gulf Stream.

We consider 2 time lag scenarios:

$$\text{LAG} \in \{0, 7\}. \quad (2.5)$$
Time lag represents the time delay between the altimeter measurements and the delivery of them to the user community. The time lag may be due to various reasons. $\text{LAG} = 0$ represents a real-time information supply, and $\text{LAG} = 7$ represents information supply corresponding to a 7-day time lag. That is, we assume that the information available is that which was sampled 7 days previously. We call this "near" real-time, and consider it because there will usually be a time delay in delivering the data to the general public due to security and institutional reasons (Lo, 1991).

We consider five cases for the information scheme:

\[ \text{INFO} \in \{M, P, F, Nt, Ft\}. \]  \hspace{1cm} (2.6)

INFO = M represents that we do not know the geoid information accurately enough for routing purposes. We model this scenario to simulate a modified hydrographic approach developed by Lo (1991). It is one of several methods to mitigate the problem of not having an accurate geoid model.

This information scheme represents currently available technology. To simulate this approach, we sample ocean current information obtained from the Harvard data along the satellite ground tracks and subtract off the annual mean velocity. We have the velocity component profile of the ocean currents only perpendicular to the ground tracks, and they are available on a daily basis for those sampled on that day. INFO = P represents a scenario when we know geoid information perfectly for routing purposes. This case represents a more advanced information scheme than INFO = M. As in the INFO = M case, in the INFO = P case we have the velocity component profile of the ocean current along the satellite ground tracks only perpendicular to the ground tracks, and these components are available
on a daily basis for those sampled on that day. INFO = F represents a more advanced information scheme than INFO = P. It is the same as INFO = P, except that we have the full velocity profile of the ocean currents along the satellite ground tracks rather than the velocity component profile only perpendicular to the ground tracks.

INFO = Nt represents having full velocity profiles of ocean current with nowcast capability. That is, we have current information each day of the voyage. This case represents a more advanced information scheme than INFO = F. This scheme provides a full velocity profile of the ocean current information as in INFO = F, but it provides current information for the whole study region rather than along the ground tracks only. In other words, INFO = Nt provides full velocity profile not only along the ground tracks but also between the ground tracks. INFO = Ft represents having full velocity profiles of ocean currents with forecast capability. That is, in this scenario we have the perfect full velocity profile of the current information in advance. This information scheme represents the most advanced for routing purposes, and is an ideal case. We need to have perfect geoid information, an interpolation model, and a forecasting model for this information scheme.

We consider 6 starting dates, 3 starting dates in 1987 and 3 starting dates in 1988. Specifically, we consider:

\[ SD \in \{ SD_1 (= 11/15/87), SD_2 (= 11/22/87), SD_3 (= 11/28/87), SD_4 (= 5/6/88), SD_5 (= 5/11/88), SD_6 (= 5/21/88) \}. \] (2.7)

We use only 3 starting dates in each year because we have access to only 5 weeks of Harvard data for each year, and because we need to accumulate daily information up to 17 days sequentially. Also, the Harvard data is likely to be correlated within the same week.
We describe the starting date selection process in section 2.3.

For the satellite supply, we use:

\[ \text{SAT} \in \{T, G, C\}. \]

(S.8)

SAT = T represents having a 10-day exact repeat period (ERP) satellite only, SAT = G represents having a 17-day ERP satellite only, and SAT = C represents having 10-day and 17-day ERP satellites simultaneously. We use TOPEX ground tracks (Vincent, 1990) for the 10-day ERP satellite and GEOSAT ground tracks (Cheney et al., 1987) for the 17-day ERP one.

We consider different accumulation schemes of daily information for the different satellites. Specifically, we consider:

\[ \text{ACC} \in \{5, 8, 11, 14, 17\} \]

(2.9)

for SAT = G. That is, for SAT = G we consider accumulating daily information up to 5, 8, 11, 14 and 17 days. We consider:

\[ \text{ACC} \in \{4, 7, 10\} \]

(2.10)

for SAT = T. That is, for SAT = T we consider accumulating daily information up to 4, 7 and 10 days. We consider:

\[ \text{ACC} \in \{T_4G_5, T_4G_8, \ldots , T_{10}G_{14}, T_{10}G_{17}\} \]

(2.11)

for SAT = C. That is, for SAT = C we consider all 15 combinations of ACC for SAT = T and SAT = G. For example, \(T_4G_5\) represents accumulating daily information up to 4 days for SAT = T and up to 5 days for SAT = G simultaneously.
We consider ground track sequences, TRK:

\[ \text{TRK} \in \{1, 2, \ldots, 9, 10\} \]  \hspace{0.5cm} (2.12)

for SAT = T only,

\[ \text{TRK} \in \{1, 2, \ldots, 16, 17\} \]  \hspace{0.5cm} (2.13)

for SAT = G only, and

\[ \text{TRK} \in \{1, 2, \ldots, 29, 30\} \]  \hspace{0.5cm} (2.14)

for SAT = C. Since the exact repeat periods of 10- and 17-day ERP satellites are 10 and 17 days, respectively, there are 10 possible sequential accumulation of daily information for the 10-day ERP satellite, and 17 possibilities for the 17-day ERP satellite. Therefore, when we have 2 satellites simultaneously, there are 170 possibilities. Among these 170 possible combinations, we select 30 randomly. To do this, we adopted the random number generator code in Press et al. (1986).

2.2 Selection of Origin-Destination Pairs

There are two reasons that we want to group fuel savings (FS) based on origin-destination (O-D) pairs. First, we want to describe FS relative to the O-D characteristics systematically to investigate if any characteristics lead to better or worse performance. Second, we want to make this study manageable.

As defined in Equation (2.1), we describe the FS resulting from strategic ship routing with current information as a function of several variables. For a 10-day ERP satellite, we consider 5 different information schemes, 3 different accumulation schemes of daily
information and 10 different ground track sequence combinations, in addition to O-D pairs and starting dates. Among five different information schemes, two information schemes – INFO = Ft and Nt – do not require any daily information accumulation or any ground track sequence combination. Thus, there is only one case for an O-D pair in a single starting date for each of INFO = Ft and Nt. Accordingly, the number of cases for INFO = Ft and Nt is 2 (= 2 INFO's) multiplied by the number of O-D pairs multiplied by the number of starting dates, i.e., 2 × RT’s × SD’s. Three information schemes – INFO = M, P, and F – require daily information accumulation and ground track sequence combinations. Thus, there are 30 cases (= 3 ACC’s × 10 TRK’s) for an O-D pair in a single starting date for each of the INFO = M, P, and F. Accordingly, the number of cases for INFO = M, P, and F is 90 (= 3 INFO’s × 3 ACC’s × 10 TRK’s) multiplied by the number of O-D pairs multiplied by the number of starting dates, i.e., 90 × RT’s × SD’s. Then, the total number of cases for a 10-day ERP satellite eastbound voyages is 92 × RT’s × SD’s (= 90 × RT’s × SD’s + 2 × RT’s × SD’s).

Considering that one computer run of the performance algorithm for a single O-D pair takes about 30 CPU seconds on an IBM 3081D mainframe computer, the computational requirement for a 10-day ERP satellite is 2,760 (= 30 × 92) CPU seconds multiplied by the number of O-D pairs multiplied by the number of starting dates. In addition to the 10-day ERP satellite, we will have 17-day ERP satellite combination. Thus, we need to limit the number of O-D pairs and starting dates to make this study manageable. We summarize in section 2.3 the details of how the starting dates are selected. Here, we explain how we selected O-D pairs.

To reduce the number of simulations, we initially select 5 (9) origins and 9 (5) destina-
tions for eastbound (westbound) voyages to form a total of 45 O-D pairs for each direction of voyage. We then compute FS for each O-D pair on each selected starting date. Then, we compute the mean relative fuel savings (MFS) across the starting dates and classify the MFS into 9 groups depending on the O-D pair's physical location. Finally, we cluster the O-D pairs relative to the MFS into 4 groups for eastbound and 3 groups for westbound voyages.

First, we compute FS for different combinations of O-D pairs for specific starting dates. The 4 starting dates used to determine O-D pairs are:

\[ \text{SD} \in \{ \text{SD}_1 (= 11/13/87), \text{SD}_2 (= 11/28/87), \text{SD}_3 (= 5/6/88), \text{SD}_4 (= 5/21/88) \} \].

(2.15)

Note that we selected 2 dates from each of 1987 and 1988 - the two years in which we had data. The specific starting dates selected in each year are 2 weeks apart to increase the independence among the current patterns (McCord and Lo, 1989). In this preliminary selection of O-D pairs we use INFO = Ft, i.e., the ideal information scheme, in which we can predict the full current velocity in advance for all time periods of interest.

We define an O-D pair as geodetic coordinates, i.e., \((\lambda_1, \phi_1)\) for the western point and \((\lambda_2, \phi_2)\) for the eastern point, where \(\lambda\) is west longitude and \(\phi\) is north latitude. Whether \((\lambda_1, \phi_1)\) or \((\lambda_2, \phi_2)\) serves as the origin or destination depends on the direction of travel. Specifically, \((\lambda_1, \phi_1)\) is the origin for eastbound voyages and the destination for westbound voyages and vice versa for \((\lambda_2, \phi_2)\). We select the original 45 O-D pairs by changing \(\phi\)'s along two fixed \(\lambda\)'s. Selected \(\lambda\)'s are 53°W and 73°W. They represent the edges of the study area as shown in Figure 5.
Figure 5: Origins and Destinations Forming Initial 45 O-D Pairs in the Study Region.

For eastbound voyages, 5 origins are selected from 34°N to 38°N separated by 1° for φ's along the λ of 73°W, and 9 destinations are chosen from 36°N to 44°N separated by 1° for φ's along the λ of 53°W. For westbound voyages, the 5 origins in DIR = E are used as destinations, and the 9 destinations in DIR = E are used as origins.

For each direction then we have 45 (= 5 × 9) O-D pairs for a starting date. Therefore, we have 180 (= 4 × 45 O-D pairs) voyages when considering the four different starting dates of Equation (2.15). We ran the performance model described in Chapter I to calculate a relative fuel savings for each of the 180 voyages. Calling FS(ODi, Ft, SDj) the relative fuel savings for O-D pair i (i = 1, . . . , 45) and starting date SDj (j = 1, . . . , 4) with INFO = Ft, we formed the mean relative fuel savings (MFS) of each of the O-D pairs ODi for each
direction as:

\[
MFS(DIR, OD_i, INFO_{Ft}) = \frac{1}{4} \sum_{j=1}^{4} FS(DIR, OD_i, INFO = Ft, SD_j)
\]  \tag{2.16}

for each of the 45 O-D pairs. The 45 MFS's for eastbound voyages are shown in Figure 6. Figure 7 shows the 45 MFS's for westbound voyages.

We classify the relative fuel savings into 9 groups depending on each O-D pair's physical location relative to the Gulf Stream, i.e., "above", "in" and "below" the Gulf Stream current pattern. Specifically, we consider an origin to be "above", "in" or "below" the Gulf Stream and a destination to be "above", "in" or "below" the Gulf Stream and take the 9 combinations. To determine whether an origin or destination is "above", "in" and "below" the Gulf Stream, we overlay Figure 5 over the Harvard data for each starting date. The MFS's for each group of the O-D pairs are summarized in Table 1 for eastbound and in Table 2 for westbound voyages.

Initially, we are interested in clustering these MFS's into 3 groups, namely, high, medium, and low fuel savings for each direction. However, we want to separate the effect of rings above the Gulf Stream for eastbound voyages. Accordingly, we cluster the fuel savings into 4 groups for eastbound and 3 groups for westbound voyages, respectively.

To group the FS's, we use the quick cluster procedure in the SPSS package (SPSS Inc., 1986), since it allows clustering cases into a requested number of groups. The quick cluster algorithm selects well-separated values based on the requested number of groups as initial cluster centers. Then, it updates the values of the initial cluster centers to derive the classification cluster centers by assigning each case to the nearest cluster center measured by squared Euclidean distance. As each case is assigned, it updates the center to a mean
Figure 6: Eastbound MFS's of Each O-D Pair.

Figure 7: Westbound MFS's of Each O-D Pair.
for the cases in the cluster. Finally, it reassigns each case to the nearest of the updated classification centers.

We summarize the clustering results in Table 3 and these O-D pairs are used for the rest of the study. For eastbound voyages, the RT₁ represents the fuel savings category exclusive to A-A cases. This is where ring effects occur. The RT₂ represents the medium fuel savings category, the RT₃ represents the high fuel savings category, and the RT₄ represents the low fuel savings category. For westbound voyages, the RT₅ represents the high fuel savings category, the RT₆ represents the low fuel savings category, and the RT₇ represents the medium fuel savings category. For example, when we mention the RT₃, it means that the origin and destination are “in” the Gulf Stream, and it is used as the representative fuel savings of I-I, I-A, A-I O-D pairs for eastbound voyages. Also, RT₃ represents the high fuel savings category.

For each of the starting dates, we choose the center of the Gulf Stream current pattern along the fixed longitudes (73°W and 53°W) as an origin and a destination, which belong to “in” the Gulf Stream. To determine an origin or a destination belonging to “above” the Gulf Stream, we add 1.5° of latitude from the center of the Gulf Stream. To determine an origin or a destination belonging to “below” the Gulf Stream, we subtract 1.5° of latitude from the center of the Gulf Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to approximately 150 km.

2.3 Selection of Starting Dates

As discussed in section 2.2, we need to reduce the simulation size to keep the study manageable. Accordingly, we need to limit the number of starting dates. We used 4 starting
### Table 1: Eastbound MFS’s (%).

<table>
<thead>
<tr>
<th>Origin \ Destination</th>
<th>Above</th>
<th>In</th>
<th>Below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above</td>
<td>8.94</td>
<td>13.02</td>
<td>8.64</td>
</tr>
<tr>
<td>In</td>
<td>10.32</td>
<td>10.46</td>
<td>7.78</td>
</tr>
<tr>
<td>Below</td>
<td>7.38</td>
<td>9.14</td>
<td>3.74</td>
</tr>
</tbody>
</table>

### Table 2: Westbound MFS’s (%).

<table>
<thead>
<tr>
<th>Origin \ Destination</th>
<th>Above</th>
<th>In</th>
<th>Below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above</td>
<td>3.21</td>
<td>7.54</td>
<td>6.35</td>
</tr>
<tr>
<td>In</td>
<td>5.52</td>
<td>9.85</td>
<td>4.56</td>
</tr>
<tr>
<td>Below</td>
<td>4.80</td>
<td>5.82</td>
<td>2.65</td>
</tr>
</tbody>
</table>

### Table 3: Clustering of the O-D Pairs.

<table>
<thead>
<tr>
<th>DIR</th>
<th>RT</th>
<th>Representative O-D</th>
<th>O-D Pairs</th>
<th>FS Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>RT₁</td>
<td>A–A</td>
<td>A–A</td>
<td>special</td>
</tr>
<tr>
<td></td>
<td>RT₂</td>
<td>A–B</td>
<td>A–B, I–B, B–A, B–I</td>
<td>medium</td>
</tr>
<tr>
<td></td>
<td>RT₃</td>
<td>I–I</td>
<td>I–I, I–A, A–I</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>RT₄</td>
<td>B–B</td>
<td>B–B</td>
<td>low</td>
</tr>
<tr>
<td>W</td>
<td>RT₅</td>
<td>I–I</td>
<td>I–I</td>
<td>high</td>
</tr>
<tr>
<td></td>
<td>RT₆</td>
<td>B–B</td>
<td>B–B, A–A</td>
<td>low</td>
</tr>
</tbody>
</table>
dates in the preliminary analysis of the previous section to determine the number of O-D pairs. The 4 starting dates consisted of 2 per year, with those within the year separated by 2 weeks. We wanted to consider more starting dates in the more detailed analysis, however, to give some more generality.

As discussed in Chapter I, we have 5 weeks of the Harvard data in each of 2 years. Any of these 70 (= 2 years × 5 weeks/year × 7 days/week) days could serve as a starting date. For a 17-day exact repeat period satellite, however, we need to accumulate daily information up to 17 days. We would not be able to accumulate 17 days of information for the first 16 days of each year's data. Thus, we eliminate the first 16 days in each year's worth of data, reducing the number of possible starting dates to 38 (= 70 - 2 × 16). Also, depending on the O-D pair, the voyages take up to 4 days in this study region for a 16 knot ship. Therefore, we eliminate the last 3 days of each year's worth of data, further reducing the number of possible starting dates to 32 (= 38 - 2 × 3). Accordingly, 16 possible candidates are remaining for the starting dates for each year.

Among those 16 days we need to select starting dates. To select plausible starting dates, we computed the mean relative fuel savings (MFS) for each of the 32 (16 in each year) starting dates for each direction of voyage with respect to the O-D pairs selected in section 2.2. The MFS of each starting date SDj is defined as:

\[
MFS(DIR, INFO_{FI}, SDj) = \frac{1}{n_i - n_u + 1} \sum_{i=n_i}^{n_u} FS(DIR, RT_i, INFO = FI, SDj)
\]

where \( n_i = 1 \) and \( n_u = 4 \) for \( DIR = E \), and \( n_i = 5 \) and \( n_u = 7 \) for \( DIR = W \).

Here, we use \( INFO = FI \), i.e., the ideal information scheme as in the O-D pairing process. The results are summarized in Figures 8 and 9. The MFS plots show similar fuel savings
Figure 8: MFS of Possible Starting Dates in 1987.

Figure 9: MFS of Possible Starting Dates in 1988.
patterns. They seem to be correlated within each week. For example, we can notice similar relative mean fuel savings between 5/11/88 and 5/17/88 (one week) in Figure 9. This also reflects the nature of the Harvard data. As described in Chapter I, they were calibrated on a weekly basis. Based on these MFS's, we select 1 starting date from each week, resulting in a total of 6 starting dates. Among those 6 starting dates, 3 starting dates, namely 11/28/87, 5/6/88, and 5/21/88, were also used in the O-D selection. A total of 6 starting dates, as defined in Equation (2.7), are used for the rest of the study, namely:

\[
SD \in \{SD_1 (= 11/15/87), SD_2 (= 11/22/87), SD_3 (= 11/28/87), SD_4 (= 5/6/88), SD_5 (= 5/11/88), SD_6 (= 5/21/88)\}. \tag{2.18}
\]
CHAPTER III

Effect of Satellite Ground Track Accumulation

In this chapter, we investigate the impact of accumulating daily current information along the satellite ground tracks on ship routing performance. The results of this investigation can serve as a guideline to the routing industry to accommodate satellite altimeter-based dynamic ocean current information for strategic routing purposes. Also, we can simplify the studies in the following chapters by identifying the effect of daily information accumulation.

If currents did not change in time, we would not worry about the temporal coverage impact when we have enough spatial coverage for the purpose of ship routing. But they do change in time (McCord and Lo, 1989). Also, on a certain day, we have only limited spatial coverage due to the field of view of the orbiting satellite.

In an exact repeat period (ERP) satellite the ground tracks repeat their entire coverage every $N$ days. The value of $N$ depends on the orbital parameters of the specific satellite. Only $1/N$ of the ground tracks are covered in a single day. Therefore, we need to accumulate several days of information to have enough spatial coverage. However, as we accumulate daily information, it gets old.

Therefore, one might ask: What is the temporal coverage impact on ocean current routing as information gets old? Does the strategy for accumulation of daily current estimates along the ground tracks really matter for the purpose of ship routing? If it does,
how many days of ground track information should we accumulate to obtain the greatest fuel savings in routing ships?

We again measure the performance according to the relative fuel savings (FS) on the routes resulting from optimizing fuel consumption compared to the great circle routes. Also, we identify the desirable “ground track accumulation scheme” of daily current information to maximize the FS for 10- and 17-day ERP satellites each.

We consider 3 information schemes for both eastbound and westbound voyages with real-time information for each ERP satellite, while we consider 2 information schemes for both directions of voyage with “near” real-time information for each ERP satellite. Specifically, for LAG = 0 cases, we consider DIR = E and W with INFO = M, P, and F for SAT = T and G. For LAG = 7 cases, we consider DIR = E and W with INFO = M and P for SAT = T and G. Note that we do not consider INFO = F when we have “near” real-time information simply because the performance difference between INFO = F and INFO = P is negligible considering the effect of 7-day time lag.

DIR represents the direction of voyage: DIR = E represents eastbound voyages, and DIR = W represents westbound voyages. In this study region, eastbound means that the ship will be primarily travelling with the currents, while westbound means that the ship will primarily be travelling against the currents.

As defined in Chapter II, all 3 information schemes (INFO) considered in this chapter provide daily current information along the ground tracks. INFO = M represents a modified hydrographic approach (Lo, 1991) – a technique presently available to mitigate the problem of not having an accurate geoid model for routing purposes. We have the velocity component
profile of the ocean current along the ground tracks only perpendicular to the ground tracks. INFO = P represents a more advanced scheme than INFO = M by assuming we have a perfect geoid model for routing purposes. In the INFO = P cases, we have the velocity component profile of the ocean current along the ground tracks only perpendicular to the ground tracks. INFO = F represents a more advanced information scheme than INFO = P. It is the same as INFO = P, except that we have the full velocity profile of the ocean current along the ground tracks rather than only perpendicular to the ground tracks.

LAG represents the time lag – the time delay between the altimeter measurements and the delivery of them to the user community due to various reasons. LAG = 0 represents a real-time information supply, and LAG = 7 represents information supply corresponding to a 7-day time lag.

SAT represents the supply of the satellites. SAT = T represents having a 10-day ERP satellite only, while SAT = G represents having a 17-day ERP satellite only. For a 10-day ERP satellite, we consider 3 different daily information accumulation schemes (ACC) of daily current information for both eastbound and westbound voyages. Specifically, we consider ACC = 4, 7, and 10, regardless of time lag. For a 17-day ERP satellite, we consider 5 different ACC’s of real-time daily current information and 4 different ACC’s of “near” real-time information. Specifically, for both eastbound and westbound voyages, we consider ACC = 5, 8, 11, 14, and 17 for LAG = 0, and ACC = 5, 8, 11, and 14 for LAG = 7.

Results show that the accumulation of daily current information does matter in ship routing performance for both eastbound and westbound voyages. Specifically, for a 10-day ERP satellite, we maximize the mean relative fuel savings (MFS) when we accumulate
up to 10 days of daily current information along the ground tracks with real- and “near” real-time information for both directions of voyage.

For a 17-day ERP satellite, we maximize the MFS when we accumulate between 8 and 14 days of daily current information, depending on the information schemes, along the ground tracks for both directions of voyage. However, there are some instances in which it would be better not to utilize current information for routing purposes and follow the great circle route. Specifically, westbound voyages with “near” real-time information with a modified hydrographic approach lead to negative relative fuel savings.

Our recommendations of daily current information accumulation schemes for the greatest mean relative fuel savings for 10- and 17-day ERP satellites should be considered with caution. We identified the “ground track accumulation schemes” under each of the information schemes which provide the greatest overall mean relative fuel savings taken across the O-D pairs and starting dates. As we take the overall mean relative fuel savings across the O-D pairs and starting dates to compare “ground track accumulation schemes,” there are wide variations in fuel savings with respect to the O-D pairs and starting dates. Nevertheless, we can make more informed decisions with the help of fuel savings differences.

Section 3.1 describes eastbound voyages with real-time information for a 10-day ERP satellite under different information schemes (DIR = E, LAG = 0, INFO = M, P, F, SAT = T). Section 3.2 describes westbound voyages with real-time information for a 10-day ERP satellite under different information schemes (DIR = W, LAG = 0, INFO = M, P, F, SAT = T). Section 3.3 describes eastbound voyages with “near” real-time information for a 10-day ERP satellite under different information schemes (DIR = E, LAG = 7, INFO = M,
Section 3.4 describes westbound voyages with "near" real-time information for a 10-day ERP satellite under different information schemes (DIR = W, LAG = 7, INFO = M, P, SAT = T).

Section 3.5 describes eastbound voyages with real-time information for a 17-day ERP satellite under different information schemes (DIR = E, LAG = 0, INFO = M, P, F, SAT = G). Section 3.6 describes westbound voyages with real-time information for a 17-day ERP satellite under different information schemes (DIR = W, LAG = 0, INFO = M, P, F, SAT = G). Section 3.7 describes eastbound voyages with "near" real-time information for a 17-day ERP satellite under different information schemes (DIR = E, LAG = 7, INFO = M, P, SAT = G). Section 3.8 describes westbound voyages with "near" real-time information for a 17-day ERP satellite under different information schemes (DIR = W, LAG = 7, INFO = M, P, SAT = G). Finally, section 3.9 summarizes our findings and recommendations.

3.1 10-day ERP Satellite: Eastbound Voyages with Real-time Information

In this section, we investigate the impact of accumulating daily current information on the eastbound ship routing performance for 3 different information schemes – INFO = M, P, and F with real-time information for a 10-day ERP satellite. We compare the mean relative fuel savings (MFS) of daily information accumulation schemes (ACC) for each information scheme (INFO) to determine how many days of current information should be accumulated to maximize relative fuel savings for routing purposes.

For each of the O-D pairs, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the
absence of current information. In both cases, we consider a ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We call $V_w$ and $V_{w0}$ the constant ship velocities with current information and without current information, respectively. By fixing the arrival time $T$ to be the same on the two routes, we do not need to make any assumptions about the tradeoff between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at a constant velocity relative to the water $V_w$ plus current velocity $V_c$. With $V_w$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. We use 16 knots for $V_w$. This path is also the minimum fuel consumption route because the power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_{w0}$ to arrive at the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_w$ and $V_{w0}$, we compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information scheme $\text{MFS(DIR = E, LAG = 0, INFO} \in \{M, P, F\}, \text{SAT} = T)$ defined as:

$$\text{MFS(DIR = E, LAG = 0, INFO} = M, \text{SAT} = T) = \frac{1}{4 \times 6 \times 10} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{10} \text{FS(DIR = E, RT}_i, \text{LAG} = 0, \text{INFO} = M, \text{SD}_l, \text{SAT} = T, \text{ACC}_k, \text{TRK}_l)$$

(3.1)
50
for INFO = M,
MFS(DIR = E, LAG = 0, INFO = P, SAT - T) 4

X

6

10

to E E E FS(DIR=
i=i j= i

,

E . RTi, LAG = 0 INFO - P, SDj,

(3.2)

1=1

SAT = T,ACCic,TRKi)
for INFO = P, and
MFS(DIR = E, LAG = 0, INFO = F, SAT = T) =
4

4 x 6 ] x lQ E

6

10

EE

i=l j= l

FS(DIR = E- RT i,LAG = (),INFO = F, SDj,

(3.3)

1=1

SAT — T, ACCk,T R K |)
for INFO = F. RT represents the origin-destination (O-D) pair, and we consider the 4
different O-D pairs specified in Chapter II. As described in Section 2,2, we select the center
of the G ulf Stream current pattern along the fixed longitudes (73°W and 53°W) as an origin
and a destination “in” the Gulf Stream. For an origin and a destination “above" the Gulf
Stream, we add 1.5° of latitude from the center of the Gulf Stream, while we subtract 1.5° of
latitude from the center of the Gulf Stream for an origin and a destination “below” the Gulf
Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to
approximately 150 km. SD represents the starting date - the day ship leaves the origin and we consider the 6 different starting dates specified in Section 2.3.
TRK represents the number of ground track sequence combinations. Given a temporal
progression of current patterns over X days (a model of which could be X successive days
of Harvard data), a satellite with a fixed orbit specification could sample these patterns
in several ways, depending on where the satellite was in its orbit at the beginning of the
X days o f analysis. Thus, there are many possible combinations of accumulating daily
information for X days. We consider 10 cases because there are 10 possible combinations


for a 10-day ERP satellite: \( TRK = \{1, 2, \ldots, 9, 10\} \). Also, we present the MFS for each ACC disaggregated for each RT and SD, respectively.

3.1.1 INFO = M

Each bar in Figures 10 and 11 represents the mean relative fuel savings (MFS) of 240 cases (=4 RT's x 6 SD's x 10 TRK's) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 10 represents an MFS for each RT taken across 60 cases (=6 SD's x 10 TRK's), and each marker in Figure 11 represents an MFS for each SD taken across 40 cases (=4 RT's x 10 TRK's).

We compute the MFS(DIR = E, LAG = 0, INFO = M) of each ACC as defined in Equation (3.1). We use ACC* to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: 2.36% for ACC4, 2.76% for ACC7, and 2.98% for ACC10. The MFS's with standard deviations are shown in Figure 71, and the relative fuel savings frequency distributions of each ACC are shown in Figure 72 in the Appendix.

Negative relative fuel savings for starting dates SD1 and SD3 and ACC4, ACC7, and ACC10 in Figure 11 mean that we would consume more fuel if we utilized altimeter-based dynamic ocean current information than if we followed the great circle route. Thus, we should ignore the current information and instead to follow the great circle routes.

To examine the data at a more disaggregate level, we compute the fuel savings difference
Figure 10: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 11: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
for different variables keeping all other variables the same. Specifically, we form:

\[
\Delta FS(ACC_{x-y}) = \\
FS(DIR = E, RT_j, LAG = 0, INFO = M, SD_j, SAT = T, ACC_x, TRK_k) - FS(DIR = E, RT_j, LAG = 0, INFO = M, SD_j, SAT = T, ACC_y, TRK_k)
\]  

(3.4)

for \( i = 1, \ldots, 4, \ j = 1, \ldots, 6, \) and \( k = 1, \ldots, 10. \) Here, subscripts \( x, y \) represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when \( ACC_x \) outperforms \( ACC_y. \)

As defined in Equation (3.4), we look into the fuel savings differences out of 240 cases. For \( ACC_{10} - ACC_4, \) 124 cases are greater than 0, 22 cases are 0, and 94 cases are less than 0. For \( ACC_{10} - ACC_7, \) 99 cases are greater than 0, 42 cases are 0, and 99 cases are less than 0. The frequency distributions of \( \Delta FS(ACC_{x-y}) \) are shown in Figure 73 in the Appendix.

For eastbound voyages with real-time information from a 10-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 10 days of daily current information with a mean relative fuel savings of 2.98%.

### 3.1.2 INFO = P

Each bar in Figures 12 and 13 represents the mean relative fuel savings (MFS) of 240 cases (= \( 4 \times 6 \times 10 \)) for each accumulation scheme (ACC) when estimating currents with a partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 12 represents an MFS for each RT taken across 60 cases (= 6 \times 10 \), and each marker in Figure 13 represents an MFS for each SD taken across 40 cases (= 4 \times 10 \).
Figure 12: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 13: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
We compute the MFS(DIR = E, LAG = 0, INFO = P) of each ACC as defined in Equation (3.2). We use ACCx to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: 3.10% for ACC4, 4.11% for ACC7, and 4.51% for ACC10. The MFS’s with standard deviations are shown in Figure 74, and the relative fuel savings frequency distributions of each ACC are shown in Figure 75 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

\[ \Delta FS(ACC_{x-y}) = FS(DIR = E, RT_i, LAG = 0, INFO = P, SD_j, SAT = T, ACC_x, TRK_k) \]
\[ -FS(DIR = E, RT_i, LAG = 0, INFO = P, SD_j, SAT = T, ACC_y, TRK_k) \]  

for \( i = 1, \ldots, 4 \), \( j = 1, \ldots, 6 \), and \( k = 1, \ldots, 10 \). Here, subscripts \( x, y \) represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when \( ACC_x \) outperforms \( ACC_y \).

As defined in Equation (3.5), we look into the fuel savings differences out of 240 cases. For \( ACC_{10} - ACC_4 \), 137 cases are greater than 0, 21 cases are 0, and 82 cases are less than 0. For \( ACC_{10} - ACC_7 \), 112 cases are greater than 0, 37 cases are 0, and 91 cases are less than 0. The frequency distributions of \( \Delta FS(ACC_{x-y}) \) are shown in Figure 76 in the Appendix.

For eastbound voyages with real-time information from a 10-day ERP satellite with partial current velocity component profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 10 days of daily current information with a mean relative fuel savings of 4.51%.
3.1.3  INFO = F

Each bar in Figures 14 and 15 represents the mean relative fuel savings (MFS) of 240 cases ($=4\ RT's \times 6\ SD's \times 10\ TRK's$) for each accumulation scheme (ACC) when estimating currents with full velocity component perpendicular to the ground tracks (INFO = F). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 14 represents an MFS for each RT taken across 60 cases ($=6\ SD's \times 10\ TRK's$), and each marker in Figure 15 represents an MFS for each SD taken across 40 cases ($=4\ RT's \times 10\ TRK's$).

We compute the MFS(DIR = E, LAG = 0, INFO = F) of each ACC as defined in Equation (3.3). We use ACC$_x$ to denote when we accumulate up to $x$ days, where $x = 4, 7,$ and 10 days. The mean fuel savings are: 3.37% for ACC$_4$, 4.07% for ACC$_7$, and 4.48% for ACC$_{10}$. The MFS’s with standard deviations are shown in Figure 77, and the relative fuel savings frequency distributions of each ACC are shown in Figure 78 in the Appendix.

As in the INFO = M and P cases, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

$$\Delta FS(ACC_{x-y}) = \begin{align*}
FS(DIR = E, RT_i, LAG = 0, INFO = F, SD_j, SAT = T, ACC_x, TRK_k) \\
FS(DIR = E, RT_i, LAG = 0, INFO = F, SD_j, SAT = T, ACC_y, TRK_k)
\end{align*}$$

for $i = 1, \ldots, 4, j = 1, \ldots, 6, \text{and } k = 1, \ldots, 10$. Here, subscripts $x, y$ represent different ACC schemes. Then, we count the number of cases in which $\Delta FS(ACC_{x-y})$ is: greater than 0, equal to 0, and less than 0, indicating when ACC$_x$ outperforms ACC$_y$.

As defined in Equation (3.6), we look into the fuel savings differences out of 240 cases.
Figure 14: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 15: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
For $\text{ACC}_{10} - \text{ACC}_4$, 135 cases are greater than 0, 13 cases are 0, and 92 cases are less than 0. For $\text{ACC}_{10} - \text{ACC}_7$, 112 cases are greater than 0, 19 cases are 0, and 109 cases are less than 0. The frequency distributions of $\Delta \text{FS}(\text{ACC}_{x-y})$ are shown in Figure 79 in the Appendix.

For eastbound voyages with real-time information from a 10-day ERP satellite with full current velocity profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 10 days of daily current information with a mean relative fuel savings of 4.48%.

3.2 10-day ERP Satellite: Westbound Voyages with Real-time Information

In this section, we investigate the impact of accumulation of daily current information on westbound ship routing performance for 3 different information schemes – INFO = M, P, and F with real-time information for a 10-day ERP satellite. We compare the mean relative fuel savings (MFS) of daily information accumulation schemes (ACC) for each information scheme (INFO) to determine how many days of current information should be accumulated to maximize relative fuel savings for routing purposes.

As in the previous section, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information for each of the O-D pairs. In both cases, we consider a ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We call $V_w$ and $V_{w0}$ the constant ship velocities with current information and without current information, respectively. By fixing the arrival time $T$ to be the same on
the two routes, we do not need to make any assumptions about the trade off between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at constant velocity relative to the water $V_w$ plus current velocity $V_c$. With $V_w$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. We use 16 knots for $V_w$. This path is also the minimum fuel consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_{wo}$ to arrive the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_w$ and $V_{wo}$, we compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information scheme $\text{MFS(DIR = W, LAG = 0, INFO \in \{M, P, F\}, SAT = T)}$ defined as:

$$
\text{MFS(DIR = W, LAG = 0, INFO = M, SAT = T)} =
\frac{1}{3 \times 6 \times 10} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{10} \text{FS(DIR = W, RTi, LAG = 0, INFO = M, SDj, SAT = T, ACCk, TRKl)}
$$

(3.7)

for $\text{INFO = M},$

$$
\text{MFS(DIR = W, LAG = 0, INFO = P, SAT = T)} =
\frac{1}{3 \times 6 \times 10} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{10} \text{FS(DIR = W, RTi, LAG = 0, INFO = P, SDj, SAT = T, ACCk, TRKl)}
$$

(3.8)
for $INFO = P$,

$$MFS(DIR = W, LAG = 0, INFO = F, SAT = T) = \frac{1}{3 \times 6 \times 10} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{10} FS(DIR = W, RT_i, LAG = 0, INFO = F, SD_j, SAT = T, ACC_k, TRK_l)$$

for $INFO = F$. $RT$ represents the origin-destination (O-D) pair, and we consider the 3 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes (73°W and 53°W) as an origin and a destination which belong to "in" the Gulf Stream. For an origin and a destination belong to "above" the Gulf Stream, we add 1.5° of latitude from the center of the Gulf Stream, while we subtract 1.5° of latitude from the center of the Gulf Stream for an origin and a destination belong to "below" the Gulf Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to approximately 150 km. $SD$ represents the starting date – the day ship leaves the origin – and we consider the 6 different starting dates specified in Section 2.3.

TRK represents the number of ground track sequence combination. Given a temporal progression of current patterns over $X$ days (model of which could be $X$ successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the $X$ days of analysis. Thus, there are many possible combinations of accumulating daily information for $X$ days. We consider 10 cases because there are 10 possible combinations for a 10-day ERP satellite: $TRK = \{1, 2, \ldots, 9, 10\}$. Also, we present the MFS for each ACC disaggregated for each $RT$ and $SD$, respectively.
3.2.1 INFO = M

Each bar in Figures 16 and 17 represents the mean relative fuel savings (MFS) of 180 cases (=3 RT's x 6 SD's x 10 TRK's) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 16 represents an MFS for each RT taken across 60 cases (=6 SD's x 10 TRK's), and each marker in Figure 17 represents an MFS for each SD taken across 30 cases (=3 RT's x 10 TRK's).

We compute the MFS(DIR = W, LAG = 0, INFO = M) of each ACC as defined in Equation (3.7). We use ACC\_x to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: 0.43% for ACC\_4, 0.83% for ACC\_7, and 0.97% for ACC\_10. The MFS's with standard deviations are shown in Figure 80, and the relative fuel savings frequency distributions of each ACC are shown in Figure 81 in the Appendix.

To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables keeping all other variables the same as in the previous sections. Specifically, we form:

\[
\Delta \text{FS}(\text{ACC}_{x-y}) = \\
\text{FS} (\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = M, \text{SD}_j, \text{SAT} = T, \text{ACC}_x, \text{TRK}_k) \\
- \text{FS} (\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = M, \text{SD}_j, \text{SAT} = T, \text{ACC}_y, \text{TRK}_k)
\]

(3.10)

for i = 5, 6, 7, j = 1, \ldots, 6, and k = 1, \ldots, 10. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which \(\Delta \text{FS}(\text{ACC}_{x-y})\) is: greater than 0, equal to 0, and less than 0, indicating when ACC\_x outperforms ACC\_y.

As defined in Equation (3.10), we look into the fuel savings differences out of 180 cases.
Figure 16: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 17: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
For ACC\textsubscript{0} – ACC\textsubscript{4}, 97 cases are greater than 0, 21 cases are 0, and 62 cases are less than 0. For ACC\textsubscript{0} – ACC\textsubscript{7}, 85 cases are greater than 0, 29 cases are 0, and 66 cases are less than 0. The frequency distributions of $\Delta$FS(ACC\textsubscript{1}–y) are shown in Figure 82 in the Appendix.

For westbound voyages with real-time information from a 10-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 10 days of daily current information with a mean relative fuel savings of 0.97%.

### 3.2.2 INFO = P

Each bar in Figures 18 and 19 represents the mean relative fuel savings (MFS) of 180 cases (=3 RT's x 6 SD's x 10 TRK's) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 18 represents an MFS for each RT taken across 60 cases (=6 SD's x 10 TRK's), and each marker in Figure 19 represents an MFS for each SD taken across 30 cases (=3 RT's x 10 TRK's).

We compute the MFS(DIR = W, LAG = 0, INFO = P) of each ACC as defined in Equation (3.8). We use ACC\textsubscript{x} to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: 0.86% for ACC\textsubscript{4}, 1.73% for ACC\textsubscript{7}, and 2.40% for ACC\textsubscript{10}. The MFS's with standard deviations are shown in Figure 83, and the relative fuel savings frequency distributions of each ACC are shown in Figure 84 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level.
Figure 18: Mean Fuel Savings with DIR = W, RT = {RT5, RT6, RT7}, LAG = 0, INFO = P, SD = {1, ..., 6}, SAT = T, and Disaggregated for Each RT.

Figure 19: Mean Fuel Savings with DIR = W, RT = {RT5, RT6, RT7}, LAG = 0, INFO = P, SD = {1, ..., 6}, SAT = T, and Disaggregated for Each SD.
Specifically, we form:

\[
\Delta FS(ACC_{x-y}) = \\
FS(DIR = W, RT_i, LAG = 0, INFO = P, SD_j, SAT = T, ACC_x, TRK_k) \\
- FS(DIR = W, RT_i, LAG = 0, INFO = P, SD_j, SAT = T, ACC_y, TRK_k)
\]  

(3.11)

for \(i = 5, 6, 7, j = 1, \ldots, 6, \) and \(k = 1, \ldots, 10\). Here, subscripts \(x, y\) represent different ACC schemes. Then, we count the number of cases in which \(\Delta FS(ACC_{x-y})\) is: greater than 0, equal to 0, and less than 0, indicating when \(ACC_x\) outperforms \(ACC_y\).

As defined in Equation (3.11), we look into the fuel savings differences out of 180 cases. For \(ACC_{10} - ACC_4\), 108 cases are greater than 0, 31 cases are 0, and 41 cases are less than 0. For \(ACC_{10} - ACC_7\), 78 cases are greater than 0, 46 cases are 0, and 56 cases are less than 0. The frequency distributions of \(\Delta FS(ACC_{x-y})\) are shown in Figure 85 in the Appendix.

For westbound voyages with real-time information from a 10-day ERP satellite with partial current velocity component profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 10 days of daily current information with a mean relative fuel savings of 2.40%.

### 3.2.3 INFO = F

Each bar in Figures 20 and 21 represents the mean relative fuel savings (MFS) of 180 cases \((= 3 \text{ RT's } \times 6 \text{ SD's } \times 10 \text{ TRK's})\) for each accumulation scheme (ACC) when estimating currents with full velocity component perpendicular to the ground tracks (INFO = F). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 20 represents an MFS for each RT taken across 60 cases \((= 6 \text{ SD's } \times 10 \text{ TRK's})\), and each marker in Figure 21 represents an MFS for each
SD taken across 30 cases (=3 RT's \times 10 TRK's).

We compute the MFS(DIR = W, LAG = 0, INFO = F) of each ACC as defined in Equation (3.9). We use ACC_x to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: 1.16% for ACC_4, 2.04% for ACC_7, and 2.41% for ACC_10. The MFS's with standard deviations are shown in Figure 86, and the relative fuel savings frequency distributions of each ACC are shown in Figure 87 in the Appendix.

As in the INFO = M and P cases, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

\[ \Delta FS(ACC_{x-y}) = \\
FS(DIR = W, RT_i, LAG = 0, INFO = F, SD_j, SAT = T, ACC_x, TRK_k) - FS(DIR = W, RT_i, LAG = 0, INFO = F, SD_j, SAT = T, ACC_y, TRK_k) \]  

for i = 5, 6, and 7, j = 1, ..., 6, and k = 1, ..., 10. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when ACC_x outperforms ACC_y.

As defined in Equation (3.12), we look into the fuel savings differences out of 180 cases. For ACC_10 - ACC_4, 112 cases are greater than 0, 20 cases are 0, and 48 cases are less than 0. For ACC_10 - ACC_7, 87 cases are greater than 0, 29 cases are 0, and 64 cases are less than 0. The frequency distributions of \( \Delta FS(ACC_{x-y}) \) are shown in Figure 88 in the Appendix.

For westbound voyages with real-time information from a 10-day ERP satellite with full current velocity profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 10 days of daily current information with a mean relative fuel savings of 2.41%.
Figure 20: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 21: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
3.3 10-day ERP Satellite: Eastbound Voyages with “Near” Real-time Information

In this section, we investigate the impact of accumulation of daily current information on eastbound ship routing performance for 2 different information schemes – INFO = M and P with “near” real-time information for a 10-day ERP satellite. Here, we consider 7-day time lag as defined in Chapter II. As in the previous sections, we compare the mean relative fuel savings (MFS) of daily information accumulation schemes (ACC) for each information scheme (INFO) to determine how many days of current information should be accumulated to maximize relative fuel savings for routing purposes.

As in the previous sections, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information for each of the O-D pairs. In both cases, we consider a ship traveling at constant velocities and arriving at its destination \( T \) hours after departing its origin. We call \( V_w \) and \( V_{wu} \) the constant ship velocities with current information and without current information, respectively. By fixing the arrival time \( T \) to be the same on the two routes, we do not need to make any assumptions about the trade off between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at constant velocity relative to the water \( V_w \) plus current velocity \( V_r \). With \( V_w \), which is constant along the voyage, and \( V_r \), which varies in space, we compute travel time \( T \). We use 16 knots for \( V_w \). This path is also the minimum fuel
consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_\text{wu}$ to arrive the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_\text{w}$ and $V_\text{wu}$, we compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information scheme $MFS(\text{DIR} = E, \text{LAG} = 7, \text{INFO} \in \{M, P\}, \text{SAT} = T)$ defined as:

$$MFS(\text{DIR} = E, \text{LAG} = 7, \text{INFO} = M, \text{SAT} = T) = \frac{1}{4 \times 6 \times 10} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{10} FS(\text{DIR} = E, RT_i, \text{LAG} = 7, \text{INFO} = M, SD_j, \text{SAT} = T, ACC_k, TRK_l)$$

(3.13)

for $\text{INFO} = M$ and

$$MFS(\text{DIR} = E, \text{LAG} = 7, \text{INFO} = P, \text{SAT} = T) = \frac{1}{4 \times 6 \times 10} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{10} FS(\text{DIR} = E, RT_i, \text{LAG} = 7, \text{INFO} = P, SD_j, \text{SAT} = T, ACC_k, TRK_l)$$

(3.14)

for $\text{INFO} = P$. $RT$ represents the origin-destination (O-D) pair, and we consider the 4 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes ($73^\circ W$ and $53^\circ W$) as an origin and a destination which belong to "in" the Gulf Stream. For an origin and a destination belong to "above" the Gulf Stream, we add $1.5^\circ$ of latitude from the center of the Gulf Stream, while we subtract $1.5^\circ$ of latitude from the center of the Gulf Stream for an origin and a destination belong to "below" the Gulf Stream. Here, $1.5^\circ$ of latitude along the fixed
longitude in this study region corresponds to approximately 150 km. SD represents the starting date – the day ship leaves the origin – and we consider the 6 different starting dates specified in Section 2.3.

TRK represents the number of ground track sequence combination. Given a temporal progression of current patterns over $X$ days (model of which could be $X$ successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the $X$ days of analysis. Thus, there are many possible combinations of accumulating daily information for $X$ days. We consider 10 cases because there are 10 possible combinations for a 10-day ERP satellite: TRK = \{1, 2, \ldots, 9, 10\}. Also, we present the MFS for each ACC disaggregated for each RT and SD, respectively.

### 3.3.1 INFO = M

Each bar in Figures 22 and 23 represents the mean relative fuel savings (MFS) of 240 cases (=4 RT's $\times$ 6 SD's $\times$ 10 TRK's) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 22 represents an MFS for each RT taken across 60 cases (=6 SD's $\times$ 10 TRK's), and each marker in Figure 23 represents an MFS for each SD taken across 40 cases (=4 RT's $\times$ 10 TRK's).

We compute the MFS(DIR = E, LAG = 7, INFO = M) of each ACC as defined in Equation (3.13). We use ACC_x to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: 0.68% for ACC_4, 0.83% for ACC_7, and 0.76%
Figure 22: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 23: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
for ACC₁₀. The MFS’s with standard deviations are shown in Figure 89, and the relative fuel savings frequency distributions of each ACC are shown in Figure 90 in the Appendix.

To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables keeping all other variables the same. Specifically, we form:

\[
\Delta FS(ACC_{x-y}) = \\
FS(\text{DIR} = E, \text{RT}_i, \text{LAG} = 7, \text{INFO} = M, SD_j, SAT = T, ACC_x, TRK_k) \\
- FS(\text{DIR} = E, \text{RT}_i, \text{LAG} = 7, \text{INFO} = M, SD_j, SAT = T, ACC_y, TRK_k)
\]  

(3.15)

for \( i = 1, \ldots, 4, \ j = 1, \ldots, 6, \text{ and } k = 1, \ldots, 10 \). Here, subscripts \( x, y \) represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when \( ACC_x \) outperforms \( ACC_y \).

As defined in Equation (3.15), we look into the fuel savings differences out of 240 cases. For \( ACC_{10} - ACC_4 \), 103 cases are greater than 0, 31 cases are 0, and 106 cases are less than 0. For \( ACC_{10} - ACC_7 \), 88 cases are greater than 0, 47 cases are 0, and 105 cases are less than 0. The frequency distributions of \( \Delta FS(ACC_{x-y}) \) are shown in Figure 91 in the Appendix.

For eastbound voyages with “near” real-time information from a 10-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 7 days of daily current information with a mean relative fuel savings of 0.83%.

### 3.3.2 \( \text{INFO} = P \)

Each bar in Figures 24 and 25 represents the mean relative fuel savings (MFS) of 240 cases (\( \approx 4 \text{ RT}'s \times 6 \text{ SD}'s \times 10 \text{ TRK}'s \)) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (\( \text{INFO} = P \)).
We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 24 represents an MFS for each RT taken across 60 cases (=6 SD's x 10 TRK's), and each marker in Figure 25 represents an MFS for each SD taken across 40 cases (=4 RT's x 10 TRK's).

We compute the MFS(DIR = E, LAG = 7, INFO = P) of each ACC as defined in Equation (3.14). We use ACC\(_x\) to denote when we accumulate up to \(x\) days, where \(x = 4, 7, \) and \(10\) days. The mean fuel savings are: 1.65\% for ACC\(_4\), 2.44\% for ACC\(_7\), and 2.59\% for ACC\(_{10}\). The MFS's with standard deviations are shown in Figure 92, and the relative fuel savings frequency distributions of each ACC are shown in Figure 93 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

\[
\Delta FS(ACC_{x-y}) = \frac{FS(DIR = E, RT_i, LAG = 7, INFO = P, SD_j, SAT = T, ACC_x, TRK_k)}{FS(DIR = E, RT_i, LAG = 7, INFO = P, SD_j, SAT = T, ACC_y, TRK_k)} \quad (3.16)
\]

for \(i = 1, \ldots, 4, \ j = 1, \ldots, 6, \) and \(k = 1, \ldots, 10\). Here, subscripts \(x, y\) represent different ACC schemes. Then, we count the number of cases in which \(\Delta FS(ACC_{x-y})\) is: greater than 0, equal to 0, and less than 0, indicating when ACC\(_x\) outperforms ACC\(_y\).

As defined in Equation (3.16), we look into the fuel savings differences out of 240 cases. For ACC\(_{10} - ACC_4\), 115 cases are greater than 0, 18 cases are 0, and 107 cases are less than 0. For ACC\(_{10} - ACC_7\), 90 cases are greater than 0, 41 cases are 0, and 109 cases are less than 0. The frequency distributions of \(\Delta FS(ACC_{x-y})\) are shown in Figure 94 in the Appendix.

For eastbound voyages with “near” real-time information from a 10-day ERP satellite
Figure 24: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 25: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
with partial velocity component profile perpendicular to the ground tracks, we get the overall
greatest mean relative fuel savings by accumulating 10 days of daily current information
with a mean relative fuel savings of 2.59%.

3.4 10-day ERP Satellite: Westbound Voyages with “Near” Real-time Information

In this section, we investigate the impact of accumulation of daily current information on
westbound ship routing performance for 2 different information schemes – INFO = M and
P with “near” real-time information for a 10-day ERP satellite. Again, we consider 7-day
time lag as defined in Chapter II. As in the previous sections, we compare the mean relative
fuel savings (MFS) of daily information accumulation schemes (ACC) for each information
scheme (INFO) to determine how many days of current information should be accumulated
to maximize relative fuel savings for routing purposes.

As in the previous sections, we compare two routes - one to minimize fuel consumption
in the presence of current information, and the other to minimize fuel consumption in the
absence of current information for each of the O-D pairs. In both cases, we consider a
ship traveling at constant velocities and arriving at its destination $T$ hours after departing
its origin. We call $V_w$ and $V_w^*$ the constant ship velocities with current information and
without current information, respectively. By fixing the arrival time $T$ to be the same on
the two routes, we do not need to make any assumptions about the trade off between the
value of travel time and fuel consumption, and we can compare two routes under the same
conditions.

The route to be followed in the presence of currents would be the shortest time route,
given that the ship is to travel at constant velocity relative to the water $V_w$ plus current velocity $V_c$. With $V_w$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. We use 16 knots for $V_w$. This path is also the minimum fuel consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_{sw}$ to arrive the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_w$ and $V_{sw}$, we compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information scheme $\text{MFS(DIR = W, LAG = 7, INFO} \in \{M, P\}, \text{SAT} = T)$ defined as:

$$
\text{MFS(DIR = W, LAG = 7, INFO} = M, \text{SAT} = T) = \frac{1}{3 \times 6 \times 10} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{10} \text{FS(DIR = W, RT}_i, \text{LAG = 7, INFO} = M, SD_j, SAT = T, ACC_k, TRK_l)}
$$

(3.17)

for $\text{INFO} = M$ and

$$
\text{MFS(DIR = W, LAG = 7, INFO} = P, \text{SAT} = T) = \frac{1}{3 \times 6 \times 10} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{10} \text{FS(DIR = W, RT}_i, \text{LAG = 7, INFO} = P, SD_j, SAT = T, ACC_k, TRK_l)}
$$

(3.18)

for $\text{INFO} = P$. RT represents the origin-destination (O-D) pair, and we consider the 3 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes ($73^\circ W$ and $53^\circ W$) as an origin and a destination which belong to “in” the Gulf Stream. For an origin and a destination
belong to "above" the Gulf Stream, we add $1.5^\circ$ of latitude from the center of the Gulf Stream, while we subtract $1.5^\circ$ of latitude from the center of the Gulf Stream for an origin and a destination belong to "below" the Gulf Stream. Here, $1.5^\circ$ of latitude along the fixed longitude in this study region corresponds to approximately 150 km. SD represents the starting date – the day ship leaves the origin – and we consider the 6 different starting dates specified in Section 2.3.

TRK represents the number of ground track sequence combination. Given a temporal progression of current patterns over $X$ days (model of which could be $X$ successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the $X$ days of analysis. Thus, there are many possible combinations of accumulating daily information for $X$ days. We consider 10 cases because there are 10 possible combinations for a 10-day ERP satellite: TRK = \{1, 2, \ldots, 9, 10\}. Also, we present the MFS for each ACC disaggregated for each RT and SD, respectively.

3.4.1 INFO = M

Each bar in Figures 26 and 27 represents the mean relative fuel savings (MFS) of 180 cases ($=3$ RT's $\times$ 6 SD's $\times$ 10 TRK's) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 26 represents an MFS for each RT taken across 60 cases ($=6$ SD's $\times$ 10 TRK's), and each marker in Figure 27 represents an MFS for each SD taken across 30 cases ($=3$ RT's $\times$ 10 TRK's).
Figure 26: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each RT.

Figure 27: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, SAT = T, and Disaggregated for Each SD.
We compute the MFS(DIR = W, LAG = 7, INFO = M) of each ACC as defined in Equation (3.17). We use ACC
 to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: -0.66% for ACC4, -0.11% for ACC7, and -0.22% for ACC10. The MFS's with standard deviations are shown in Figure 95, and the relative fuel savings frequency distributions of each ACC are shown in Figure 96 in the Appendix.

To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables keeping all other variables the same. Specifically, we form:

\[ \Delta FS(ACC_{x-y}) = FS(DIR = W, RT_i, LAG = 7, INFO = M, SD_j, SAT = T, ACC_x, TRK_k) - FS(DIR = W, RT_i, LAG = 7, INFO = M, SD_j, SAT = T, ACC_y, TRK_k) \] (3.19)

for \( i = 5, 6, 7, j = 1, \ldots, 6, \) and \( k = 1, \ldots, 10 \). Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when ACCx outperforms ACCy.

As defined in Equation (3.19), we look into the fuel savings differences out of 180 cases. For ACC10 — ACC4, 87 cases are greater than 0, 36 cases are 0, and 57 cases are less than 0. For ACC10 — ACC7, 62 cases are greater than 0, 42 cases are 0, and 76 cases are less than 0. The frequency distributions of \( \Delta FS(ACC_{x-y}) \) are shown in Figure 97 in the Appendix.

For westbound voyages with "near" real-time information from a 10-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 7 days of daily current information with a mean relative fuel savings of -0.11%. Under this scenario, however, we had better ignore the current information. Thus, follow the great circle routes.
3.4.2 INFO = P

Each bar in Figures 28 and 29 represents the mean relative fuel savings (MFS) of 180 cases (=3 RT's x 6 SD's x 10 TRK's) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 28 represents an MFS for each RT taken across 60 cases (=6 SD's x 10 TRK's), and each marker in Figure 29 represents an MFS for each SD taken across 30 cases (=3 RT's x 10 TRK's).

We compute the MFS(DIR = W, LAG = 7, INFO = P) of each ACC as defined in Equation (3.18). We use ACC* to denote when we accumulate up to x days, where x = 4, 7, and 10 days. The mean fuel savings are: 0.63% for ACC4, 1.29% for ACC7, and 1.57% for ACC10. The MFS's with standard deviations are shown in Figure 98, and the relative fuel savings frequency distributions of each ACC are shown in Figure 99 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to look at the data at a more disaggregate level. Specifically, we form:

\[
\Delta FS(ACC_{x-y}) = FS(DIR = W, RT_i, LAG = 7, INFO = P, SD_j, SAT = T, ACC_x, TRK_k) - FS(DIR = W, RT_i, LAG = 7, INFO = P, SD_j, SAT = T, ACC_y, TRK_k)
\] (3.20)

for i = 5, 6, 7, j = 1, ..., 6, and k = 1, ..., 10. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which \(\Delta FS(ACC_{x-y})\) is: greater than 0, equal to 0, and less than 0, indicating when ACCx outperforms ACCy.

As defined in Equation (3.20), we look into the fuel savings differences out of 180 cases.
Figure 28: Mean Fuel Savings with \( \text{DIR} = W \), \( \text{RT} = \{\text{RT}_5, \text{RT}_6, \text{RT}_7\} \), \( \text{LAG} = 7 \), \( \text{INFO} = P \), \( \text{SD} = \{1, \ldots, 6\} \), \( \text{SAT} = T \), and Disaggregated for Each RT.

Figure 29: Mean Fuel Savings with \( \text{DIR} = W \), \( \text{RT} = \{\text{RT}_5, \text{RT}_6, \text{RT}_7\} \), \( \text{LAG} = 7 \), \( \text{INFO} = P \), \( \text{SD} = \{1, \ldots, 6\} \), \( \text{SAT} = T \), and Disaggregated for Each SD.
For $\text{ACC}_{10} - \text{ACC}_4$, 99 cases are greater than 0, 23 cases are 0, and 58 cases are less than 0. For $\text{ACC}_{10} - \text{ACC}_7$, 70 cases are greater than 0, 37 cases are 0, and 73 cases are less than 0. The frequency distributions of $\Delta \text{FS}(\text{ACC}_{x-y})$ are shown in Figure 100 in the Appendix.

For westbound voyages with “near” real-time information from a 10-day ERP satellite with partial velocity component profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 10 days of daily current information with a mean relative fuel savings of 1.57%.

### 3.5 17-day ERP Satellite: Eastbound Voyages with Real-time Information

In the previous sections we investigated the impact of accumulation of daily current information on ship routing performance for a 10-day exact repeat period (ERP) satellite. A 10-day ERP satellite provides temporally more updated coverage than a 17-day ERP satellite. A 17-day ERP satellite, however, provides spatially more dense coverage than a 10-day ERP satellite. For a 17-day ERP satellite, we consider the 5 different daily information accumulation schemes (ACC) and the 17 different ground track sequence combinations (TRK), while we considered the 3 different ACC’s and the 10 different TRK’s for a 10-day ERP satellite.

In this section, we investigate the impact of accumulation of daily current information on eastbound ship routing performance for 3 different information schemes – INFO = M, P, and F with real-time information for a 17-day ERP satellite. We compare the mean relative fuel savings (MFS) of daily information accumulation schemes for each information scheme (INFO) to determine how many days of current information should be accumulated
to maximize relative fuel savings for routing purposes.

For each of the O-D pairs, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information. In both cases, we consider a ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We call $V_w$ and $V_{wo}$ the constant ship velocities with current information and without current information, respectively. By fixing the arrival time $T$ to be the same on the two routes, we do not need to make any assumptions about the trade off between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at constant velocity relative to the water $V_u$ plus current velocity $V_c$. With $V_u$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. We use 16 knots for $V_u$. This path is also the minimum fuel consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_{wu}$ to arrive the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_u$ and $V_{wu}$, we compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information
scheme \( MFS(\text{DIR} = E, \text{LAG} = 0, \text{INFO} \in \{M, P, F\}, \text{SAT} = G) \) defined as:

\[
MFS(\text{DIR} = E, \text{LAG} = 0, \text{INFO} = M, \text{SAT} = G) = \\
\frac{1}{4 \times 6 \times 17} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{17} FS(\text{DIR} = E, RT_i, \text{LAG} = 0, \text{INFO} = M, SD_j, \text{SAT} = G, ACC_k, \text{TRK}_l)
\]

for \( \text{INFO} = M \),

\[
MFS(\text{DIR} = E, \text{LAG} = 0, \text{INFO} = P, \text{SAT} = G) = \\
\frac{1}{4 \times 6 \times 17} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{17} FS(\text{DIR} = E, RT_i, \text{LAG} = 0, \text{INFO} = P, SD_j, \text{SAT} = G, ACC_k, \text{TRK}_l)
\]

for \( \text{INFO} = P \), and

\[
MFS(\text{DIR} = E, \text{LAG} = 0, \text{INFO} = F, \text{SAT} = G) = \\
\frac{1}{4 \times 6 \times 17} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{17} FS(\text{DIR} = E, RT_i, \text{LAG} = 0, \text{INFO} = F, SD_j, \text{SAT} = G, ACC_k, \text{TRK}_l)
\]

for \( \text{INFO} = F \).

RT represents the origin-destination (O-D) pair, and we consider the 4 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes \( (73^\circ \text{W} \text{ and } 53^\circ \text{W}) \) as an origin and a destination which belong to "in" the Gulf Stream. For an origin and a destination belong to "above" the Gulf Stream, we add 1.5° of latitude from the center of the Gulf Stream, while we subtract 1.5° of latitude from the center of the Gulf Stream for an origin and a destination belong to "below" the Gulf Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to approximately 150 km. SD represents the starting date – the day ship leaves the origin – and we consider the 6 different starting dates specified in Section 2.3.
TRK represents the number of ground track sequence combination. Given a temporal progression of current patterns over \( X \) days (model of which could be \( X \) successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the \( X \) days of analysis. Thus, there are many possible combinations of accumulating daily information for \( X \) days. We consider 17 cases because there are 17 possible combinations for a 17-day ERP satellite: \( \text{TRK} = \{1, 2, \ldots, 16, 17\} \). Also, we present the MFS for each ACC disaggregated for each RT and SD, respectively.

### 3.5.1 INFO = M

Each bar in Figures 30 and 31 represents the mean relative fuel savings (MFS) of 408 cases (\( = 4 \text{ RT's} \times 6 \text{ SD's} \times 17 \text{ TRK's} \)) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 30 represents an MFS for each RT taken across 102 cases (\( = 6 \text{ SD's} \times 17 \text{ TRK's} \)), and each marker in Figure 31 represents an MFS for each SD taken across 68 cases (\( = 4 \text{ RT's} \times 17 \text{ TRK's} \)).

We compute the MFS(DIR = E, LAG = 0, INFO = M) of each ACC as defined in Equation (3.21). We use ACC\(_x\) to denote when we accumulate up to \( x \) days, where \( x = 5, 8, 11, 14, \) and 17 days. The mean fuel savings are: 2.41% for ACC\(_5\), 2.72% for ACC\(_8\), 2.63% for ACC\(_{11}\), 2.52% for ACC\(_{14}\), and 2.15% for ACC\(_{17}\). The MFS's with standard deviations are shown in Figure 101, and the relative fuel savings frequency distributions of each ACC are shown in Figure 102 in the Appendix.
Figure 30: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 31: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each SD.
To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables keeping all other variables the same. Specifically, we form:

$$\Delta FS(ACC_{x-y}) = \left[ FS(DIR = E, RT_i, LAG = 0, INFO = M, SD_j, SAT = G, ACC_x, TRK_k) - FS(DIR = E, RT_i, LAG = 0, INFO = M, SD_j, SAT = G, ACC_y, TRK_k) \right]$$

for \( i = 1, \ldots, 4 \), \( j = 1, \ldots, 6 \), and \( k = 1, \ldots, 17 \). Here, subscripts \( x, y \) represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when ACC\textsubscript{x} outperforms ACC\textsubscript{y}.

As defined in equation 3.24, we look into the fuel savings differences out of 408 cases. For ACC\textsubscript{8} — ACC\textsubscript{5}, 172 cases are greater than 0, 54 cases are 0, and 182 cases are less than 0. For ACC\textsubscript{8} — ACC\textsubscript{11}, 187 cases are greater than 0, 53 cases are 0, and 168 cases are less than 0. For ACC\textsubscript{8} — ACC\textsubscript{14}, 220 cases are greater than 0, 28 cases are 0, and 160 cases are less than 0. For ACC\textsubscript{8} — ACC\textsubscript{17}, 237 cases are greater than 0, 14 cases are 0, and 157 cases are less than 0. The frequency distributions of \( \Delta FS(ACC_{x-y}) \) are shown in Figure 103 in the Appendix.

For eastbound voyages with real-time information from a 17-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 8 days of daily current information with a mean relative fuel savings of 2.72%.

### 3.5.2 INFO = P

Each bar in Figures 32 and 33 represents the mean relative fuel savings (MFS) of 408 cases (=4 RT's × 6 SD's × 17 TRK's) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (INFO = P).
We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 32 represents an MFS for each RT taken across 102 cases (=6 SD's x 17 TRK's), and each marker in Figure 33 represents an MFS for each SD taken across 68 cases (=4 RT's x 17 TRK's).

We compute the MFS(DIR = E, LAG= 0, INFO = P) of each ACC as defined in Equation (3.22). We use ACC\_x to denote when we accumulate up to x days, where x = 5, 8, 11, 14, and 17 days. The mean fuel savings are: 3.64% for ACC\_5, 4.21% for ACC\_8, 4.51% for ACC\_11, 4.64% for ACC\_14, and 4.23% for ACC\_17. The MFS's with standard deviations are shown in Figure 104, and the relative fuel savings frequency distributions of each ACC are shown in Figure 105 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

$$\Delta FS(ACC_{x-y}) =$$

$$FS(DIR = E, RT_i, LAG = 0, INFO = P, SD_j, SAT = G, ACC_x, TRK_k) - FS(DIR = E, RT_i, LAG = 0, INFO = P, SD_j, SAT = G, ACC_y, TRK_k)$$

(3.25)

for i = 1, . . . , 4, j = 1, . . . , 6, and k = 1, . . . , 17. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which $\Delta FS(ACC_{x-y})$ is: greater than 0, equal to 0, and less than 0, indicating when ACC\_x outperforms ACC\_y.

As defined in Equation (3.25), we look into the fuel savings differences out of 408 cases. For ACC\_14 — ACC\_5, 226 cases are greater than 0, 3 cases are 0, and 179 cases are less than 0. For ACC\_14 — ACC\_8, 201 cases are greater than 0, 9 cases are 0, and 198 cases are less than 0. For ACC\_14 — ACC\_11, 179 cases are greater than 0, 42 cases are 0, and 187 cases are less than 0. For ACC\_14 — ACC\_17, 221 cases are greater than 0, 44 cases are 0, and 143
Figure 32: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 33: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each SD.
cases are less than 0. The frequency distributions of $\Delta FS(\text{ACC}_{x-y})$ are shown in Figure 106 in the Appendix.

For eastbound voyages with real-time information from a 17-day ERP satellite with partial current velocity component profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 14 days of daily current information with a mean relative fuel savings of 4.64%.

### 3.5.3 INFO = F

Each bar in Figures 34 and 35 represents the mean relative fuel savings (MFS) of 408 cases (=4 RT's $\times$ 6 SD's $\times$ 17 TRK's) for each accumulation scheme (ACC) when estimating currents with full velocity component perpendicular to the ground tracks (INFO = F). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 34 represents an MFS for each RT taken across 102 cases (=6 SD's $\times$ 17 TRK's), and each marker in Figure 35 represents an MFS for each SD taken across 68 cases (=4 RT's $\times$ 17 TRK's).

We compute the MFS(DIR = E, LAG = 0, INFO = F) of each ACC as defined in Equation (3.23). We use ACC$_x$ to denote when we accumulate up to $x$ days, where $x$ = 5, 8, 11, 14, and 17 days. The mean fuel savings are: 3.95% for ACC$_5$, 4.61% for ACC$_8$, 4.99% for ACC$_{11}$, 4.70% for ACC$_{14}$, and 4.18% for ACC$_{17}$. The MFS's with standard deviations are shown in Figure 107, and the relative fuel savings frequency distributions of each ACC are shown in Figure 108 in the Appendix.

As in the INFO = M and P cases, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate.
Figure 34: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 35: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each SD.
level. Specifically, we form:

\[
\Delta FS(ACC_{x-y}) = 
FS(DIR = E, RT_i, LAG = 0, INFO = F, SD_j, SAT = G, ACC_x, TRK_k) 
- FS(DIR = E, RT_i, LAG = 0, INFO = F, SD_j, SAT = G, ACC_y, TRK_k) 
\]  \tag{3.26}

for \( i = 1, \ldots , 4, \ j = 1, \ldots , 6, \) and \( k = 1, \ldots , 17. \) Here, subscripts \( x, y \) represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when ACC\(_x\) outperforms ACC\(_y\).

As defined in Equation (3.26), we look into the fuel savings differences out of 408 cases. For ACC\(_{11} -\) ACC\(_5\), 212 cases are greater than 0, 15 cases are 0, and 181 cases are less than 0. For ACC\(_{11} -\) ACC\(_8\), 183 cases are greater than 0, 40 cases are 0, and 185 cases are less than 0. For ACC\(_{11} -\) ACC\(_{14}\), 216 cases are greater than 0, 30 cases are 0, and 162 cases are less than 0. For ACC\(_{11} -\) ACC\(_{17}\), 238 cases are greater than 0, 19 cases are 0, and 151 cases are less than 0. The frequency distributions of \( \Delta FS(ACC_{x-y}) \) are shown in Figure 109 in the Appendix.

For eastbound voyages with real-time information from a 17-day ERP satellite with full current velocity profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 11 days of daily current information with a mean relative fuel savings of 4.99\%.

3.6 17-day ERP Satellite: Westbound Voyages with Real-time Information

In this section, we investigate the impact of accumulation of daily current information on westbound ship routing performance for 3 different information schemes – INFO = M, P, and F with real-time information for a 17-day ERP satellite. We compare the mean relative
fuel savings (MFS) of daily information accumulation schemes (ACC) for each information scheme (INFO) to determine how many days of current information should be accumulated to maximize relative fuel savings for routing purposes.

As in the previous section, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information for each of the O-D pairs. In both cases, we consider a ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We call $V_w$ and $V_{w0}$ the constant ship velocities with current information and without current information, respectively. By fixing the arrival time $T$ to be the same on the two routes, we do not need to make any assumptions about the trade off between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at constant velocity relative to the water $V_w$ plus current velocity $V_c$. With $V_w$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. We use 16 knots for $V_w$. This path is also the minimum fuel consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_{w0}$ to arrive the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_w$ and $V_{w0}$, we compute the relative fuel
savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information scheme $MFS(\text{DIR} = W, \text{LAG} = 0, \text{INFO} \in \{M, P, F\}, \text{SAT} = G)$ defined as:

$$MFS(\text{DIR} = W, \text{LAG} = 0, \text{INFO} = M, \text{SAT} = G) = \frac{1}{3 \times 6 \times 17} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{17} FS(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = M, \text{SD}_l, \text{SAT} = G, \text{ACC}_k, \text{TRK}_l)$$

for $\text{INFO} = M$,

$$MFS(\text{DIR} = W, \text{LAG} = 0, \text{INFO} = P, \text{SAT} = G) = \frac{1}{3 \times 6 \times 17} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{17} FS(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_l, \text{SAT} = G, \text{ACC}_k, \text{TRK}_l)$$

for $\text{INFO} = P$, and

$$MFS(\text{DIR} = W, \text{LAG} = 0, \text{INFO} = F, \text{SAT} = G) = \frac{1}{3 \times 6 \times 17} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{17} FS(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = F, \text{SD}_l, \text{SAT} = G, \text{ACC}_k, \text{TRK}_l)$$

for $\text{INFO} = F$.

$RT$ represents the origin-destination (O-D) pair, and we consider the 3 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes ($73^\circ W$ and $53^\circ W$) as an origin and a destination which belong to “in” the Gulf Stream. For an origin and a destination belong to “above” the Gulf Stream, we add $1.5^\circ$ of latitude from the center of the Gulf Stream, while we subtract $1.5^\circ$ of latitude from the center of the Gulf Stream for an origin and a destination belong to “below” the Gulf Stream. Here, $1.5^\circ$ of latitude along the fixed longitude in this study region corresponds to approximately 150 km. $SD$ represents the
starting date – the day ship leaves the origin – and we consider the 6 different starting dates specified in Section 2.3.

TRK represents the number of ground track sequence combination. Given a temporal progression of current patterns over X days (model of which could be X successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the X days of analysis. Thus, there are many possible combinations of accumulating daily information for X days. We consider 17 cases because there are 17 possible combinations for a 17-day ERP satellite: TRK = {1, 2, …, 16, 17}. Also, we present the MFS for each ACC disaggregated for each RT and SD, respectively.

3.6.1 INFO = M

Each bar in Figures 36 and 37 represents the mean relative fuel savings (MFS) of 306 cases (=3 RT's × 6 SD's × 17 TRK's) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 36 represents an MFS for each RT taken across 102 cases (=6 SD's × 17 TRK's), and each marker in Figure 37 represents an MFS for each SD taken across 51 cases (=3 RT's × 17 TRK's).

We compute the MFS(DIR = W, LAG = 0, INFO = M) of each ACC as defined in Equation (3.27). We use ACCx to denote when we accumulate up to x days, where x = 5, 8, 11, 14, and 17 days. The mean fuel savings are: -0.15% for ACC5, -0.13% for ACC8, -0.34% for ACC11, -0.15% for ACC14, and -0.29% for ACC17. The MFS’s with standard
Figure 36: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 37: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each SD.
deviations are shown in Figure 110, and the relative fuel savings frequency distributions of each ACC are shown in Figure 111 in the Appendix.

To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables keeping all other variables the same as in the previous sections. Specifically, we form:

$$\Delta FS(ACC_{x-y}) = \frac{FS(DIR = W, RT_j, LAG = 0, INFO = M, SD_j, SAT = G, ACC_x, TRK_k)}{FS(DIR = W, RT_j, LAG = 0, INFO = M, SD_j, SAT = G, ACC_y, TRK_k)}$$

(3.30)

for \(i = 5, 6, 7, j = 1, \ldots, 6, \) and \(k = 1, \ldots, 17.\) Here, subscripts \(x, y\) represent different ACC schemes. Then, we count the number of cases in which \(\Delta FS(ACC_{x-y})\) is: greater than 0, equal to 0, and less than 0, indicating when \(ACC_x\) outperforms \(ACC_y\).

As defined in Equation (3.30), we look into the fuel savings differences out of 306 cases. For \(ACC_8 - ACC_5\), 139 cases are greater than 0, 49 cases are 0, and 118 cases are less than 0. For \(ACC_8 - ACC_{11}\), 133 cases are greater than 0, 44 cases are 0, and 129 cases are less than 0. For \(ACC_8 - ACC_{14}\), 142 cases are greater than 0, 22 cases are 0, and 142 cases are less than 0. For \(ACC_8 - ACC_{17}\), 163 cases are greater than 0, 13 cases are 0, and 130 cases are less than 0. The frequency distributions of \(\Delta FS(ACC_{x-y})\) are shown in Figure 112 in the Appendix.

For westbound voyages with real-time information from a 17-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 8 days of daily current information with a mean relative fuel savings of -0.13%. Under this scenario, however, we had better ignore the current information. Thus, we are better off to follow the great circle routes.
3.6.2 INFO = P

Each bar in Figures 38 and 39 represents the mean relative fuel savings (MFS) of 306 cases (=3 RT's × 6 SD's × 17 TRK's) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 38 represents an MFS for each RT taken across 102 cases (=6 SD's × 17 TRK's), and each marker in Figure 39 represents an MFS for each SD taken across 51 cases (=3 RT's × 17 TRK's).

We compute the MFS(DIR = W, LAG = 0, INFO = P) of each ACC as defined in Equation (3.28). We use ACC* to denote when we accumulate up to x days, where x = 5, 8, 11, 14, and 17 days. The mean fuel savings are: 0.45% for ACC₅, 1.21% for ACC₈, 1.83% for ACC₁₁, 1.94% for ACC₁₄, and 1.83% for ACC₁₇. The MFS’s with standard deviations are shown in Figure 113, and the relative fuel savings frequency distributions of each ACC are shown in Figure 114 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

\[ \Delta FS(ACC_{x-y}) = \]
\[ FS(DIR = W, RT_i, LAG = 0, INFO = P, SD_j, SAT = G, ACC_x, TRK_k) - FS(DIR = W, RT_i, LAG = 0, INFO = P, SD_j, SAT = G, ACC_y, TRK_k) \]  
(3.31)

for i = 5, 6, 7, j = 1, … , 6, and k = 1, … , 17. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when ACCₓ outperforms ACCᵧ.
Figure 38: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 39: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each SD.
As defined in Equation (3.31), we look into the fuel savings differences out of 306 cases. For $\text{ACC}_5 \rightarrow \text{ACC}_3$, 179 cases are greater than 0, 31 cases are 0, and 96 cases are less than 0. For $\text{ACC}_{14} \rightarrow \text{ACC}_8$, 160 cases are greater than 0, 34 cases are 0, and 112 cases are less than 0. For $\text{ACC}_{14} \rightarrow \text{ACC}_{11}$, 131 cases are greater than 0, 62 cases are 0, and 113 cases are less than 0. For $\text{ACC}_{14} \rightarrow \text{ACC}_{17}$, 137 cases are greater than 0, 57 cases are 0, and 112 cases are less than 0. The frequency distributions of $\Delta FS(\text{ACC}_{x \rightarrow y})$ are shown in Figure 115 in the Appendix.

For westbound voyages with real-time information from a 17-day ERP satellite with partial current velocity component profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 14 days of daily current information with a mean relative fuel savings of 1.94%.

### 3.6.3 INFO = F

Each bar in Figures 40 and 41 represents the mean relative fuel savings (MFS) of 306 cases (9 RT's x 6 SD's x 17 TRK's) for each accumulation scheme (ACC) when estimating currents with full velocity component perpendicular to the ground tracks (INFO = F). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 40 represents an MFS for each RT taken across 102 cases (6 SD's x 17 TRK's), and each marker in Figure 41 represents an MFS for each SD taken across 51 cases (3 RT's x 17 TRK's).

We compute the MFS(DIR = W, LAG = 0, INFO = F) of each ACC as defined in Equation (3.29). We use $\text{ACC}_x$ to denote when we accumulate up to $x$ days, where $x = 5, 8, 11, 14, \text{and 17 days. The mean fuel savings are: 0.72\% for ACC}_5, 1.29\% for ACC_8, 2.04\%
Figure 40: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 41: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, SAT = G, and Disaggregated for Each SD.
for ACC11, 2.47% for ACC14, and 2.11% for ACC17. The MFS's with standard deviations are shown in Figure 116, and the relative fuel savings frequency distributions of each ACC are shown in Figure 117 in the Appendix.

As in the INFO = M and P cases, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

$$\Delta FS(ACC_{x-y}) = FS(DIR = W, RT, LAG = 0, INFO = F, SD, SAT = G, ACC_x, TRK_k) - FS(DIR = W, RT, LAG = 0, INFO = F, SD, SAT = G, ACC_y, TRK_k)$$  \hspace{1cm} (3.32)

for i = 5, 6, 7, j = 1, . . . , 6, and k = 1, . . . , 17. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which $\Delta FS(ACC_{x-y})$ is: greater than 0, equal to 0, and less than 0, indicating when ACCx outperforms ACCy.

As defined in Equation (3.32), we look into the fuel savings differences out of 306 cases. For ACC11 – ACC5, 179 cases are greater than 0, 28 cases are 0, and 99 cases are less than 0. For ACC11 – ACC6, 145 cases are greater than 0, 57 cases are 0, and 104 cases are less than 0. For ACC11 – ACC14, 126 cases are greater than 0, 43 cases are 0, and 137 cases are less than 0. For ACC11 – ACC17, 146 cases are greater than 0, 13 cases are 0, and 147 cases are less than 0. The frequency distributions of $\Delta FS(ACC_{x-y})$ are shown in Figure 118 in the Appendix.

For westbound voyages with real-time information from a 17-day ERP satellite with full current velocity profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 14 days of daily current information with a mean relative fuel savings of 2.47%.
3.7 17-day ERP Satellite: Eastbound Voyages with “Near” Real-time Information

In this section, we investigate the impact of accumulation of daily current information on eastbound ship routing performance for 2 different information schemes – INFO = M and P with “near” real-time information for a 17-day ERP satellite. Here, we consider 7-day time lag as defined in Chapter II. As in the previous sections, we compare the mean relative fuel savings (MFS) of daily information accumulation schemes (ACC) for each information scheme (INFO) to determine how many days of current information should be accumulated to maximize relative fuel savings for routing purposes.

As in the previous sections, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information for each of the O-D pairs. In both cases, we consider a ship traveling at constant velocities and arriving at its destination \( T \) hours after departing its origin. We call \( V_w \) and \( V_{wo} \) the constant ship velocities with current information and without current information, respectively. By fixing the arrival time \( T \) to be the same on the two routes, we do not need to make any assumptions about the trade off between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at constant velocity relative to the water \( V_w \) plus current velocity \( V_c \). With \( V_w \), which is constant along the voyage, and \( V_c \), which varies in space, we compute travel time \( T \). We use 16 knots for \( V_w \). This path is also the minimum fuel
consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity \( V_w \) to arrive the destination with fixed travel time \( T \) computed under the presence of current information (Lo, 1991). With \( V_w \) and \( V_{w'} \), we compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information scheme \( MFS(\text{DIR} = E, \text{LAG} = 7, \text{INFO} \in \{M, P\}, \text{SAT} = G) \) defined as:

\[
MFS(\text{DIR} = E, \text{LAG} = 7, \text{INFO} = M, \text{SAT} = G) = \\
\frac{1}{4 \times 4 \times 17} \sum_{i=1}^{4} \sum_{j=2}^{3} \sum_{k=5}^{6} \sum_{l=1}^{17} FS(\text{DIR} = E, \text{RT}_i, \text{LAG} = 7, \text{INFO} = M, \text{SD}_j, \text{SAT} = G, \text{ACC}_k, \text{TRK}_l) 
\]

(3.33)

for \( \text{INFO} = M \) and

\[
MFS(\text{DIR} = E, \text{LAG} = 7, \text{INFO} = P, \text{SAT} = G) = \\
\frac{1}{4 \times 4 \times 17} \sum_{i=1}^{4} \sum_{j=2}^{3} \sum_{k=5}^{6} \sum_{l=1}^{17} FS(\text{DIR} = E, \text{RT}_i, \text{LAG} = 7, \text{INFO} = P, \text{SD}_j, \text{SAT} = G, \text{ACC}_k, \text{TRK}_l) 
\]

(3.34)

for \( \text{INFO} = P \).

RT represents the origin-destination (O-D) pair, and we consider the 4 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes (73°W and 53°W) as an origin and a destination which belong to “in” the Gulf Stream. For an origin and a destination belong to “above” the Gulf Stream, we add 1.5° of latitude from the center of the Gulf Stream, while we subtract 1.5° of latitude from the center of the Gulf Stream for an origin and a destination
belong to "below" the Gulf Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to approximately 150 km. SD represents the starting date – the day ship leaves the origin – and we consider the 4 different starting dates out of 6 specified in Section 2.3. Specifically, we consider SD = SD₂, SD₃, SD₅, and SD₆ because we cannot accumulate daily current information even up to 14 days for SD₁ and SD₄.

TRK represents the number of ground track sequence combination. Given a temporal progression of current patterns over X days (model of which could be X successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the X days of analysis. Thus, there are many possible combinations of accumulating daily information for X days. We consider 17 cases because there are 17 possible combinations for a 17-day ERP satellite: TRK = {1, 2, . . . , 16, 17}. Also, we present the MFS for each ACC disaggregated for each RT and SD, respectively.

3.7.1 INFO = M

Each bar in Figures 42 and 43 represents the mean relative fuel savings (MFS) of 272 cases (=4 RT’s × 4 SD’s × 17 TRK’s) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 42 represents an MFS for each RT taken across 68 cases (=4 SD’s × 17 TRK’s), and each marker in Figure 43 represents an MFS for each SD taken across 68 cases (=4 RT’s × 17 TRK’s).

We compute the MFS(DIR = E, LAG = 7, INFO = M) of each ACC as defined in
Figure 42: Mean Fuel Savings with \( \text{DIR} = \text{E}, \ RT = \{\text{RT}_1, \text{RT}_2, \text{RT}_3, \text{RT}_4\}, \ LAG = 7, \INFO = \text{M}, \ SD = \{2, 3, 5, 6\}, \ SAT = \text{G}, \) and Disaggregated for Each RT.

Figure 43: Mean Fuel Savings with \( \text{DIR} = \text{E}, \ RT = \{\text{RT}_1, \text{RT}_2, \text{RT}_3, \text{RT}_4\}, \ LAG = 7, \INFO = \text{M}, \ SD = \{2, 3, 5, 6\}, \ SAT = \text{G}, \) and Disaggregated for Each SD.
Equation (3.33). We use $\text{ACC}_x$ to denote when we accumulate up to $x$ days, where $x = 5, 8, 11,$ and $14$ days. The mean fuel savings are: $1.67\%$ for $\text{ACC}_5$, $1.85\%$ for $\text{ACC}_8$, $1.59\%$ for $\text{ACC}_{11}$, $1.50\%$ for $\text{ACC}_{14}$. The MFS's with standard deviations are shown in Figure 119, and the relative fuel savings frequency distributions of each ACC are shown in Figure 120 in the Appendix.

To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables keeping all other variables the same. Specifically, we form:

$$
\Delta \text{FS}(\text{ACC}_{x-y}) = \text{FS}(\text{DIR} = E, \text{RT}_i, \text{LAG} = 7, \text{INFO} = M, \text{SD}_j, \text{SAT} = G, \text{ACC}_x, \text{TRK}_k) - \text{FS}(\text{DIR} = E, \text{RT}_i, \text{LAG} = 7, \text{INFO} = M, \text{SD}_j, \text{SAT} = G, \text{ACC}_y, \text{TRK}_k)
$$

for $i = 1, \ldots, 4$, $j = 2, 3, 5, 6$, and $k = 1, \ldots, 17$. Here, subscripts $x, y$ represent different ACC schemes. Then, we count the number of cases in which $\Delta \text{FS}(\text{ACC}_{x-y})$ is: greater than 0, equal to 0, and less than 0, indicating when $\text{ACC}_x$ outperforms $\text{ACC}_y$.

As defined in Equation (3.35), we look into the fuel savings differences out of 272 cases. For $\text{ACC}_8 - \text{ACC}_3$, 106 cases are greater than 0, 39 cases are 0, and 127 cases are less than 0. For $\text{ACC}_8 - \text{ACC}_{11}$, 152 cases are greater than 0, 24 cases are 0, and 96 cases are less than 0. For $\text{ACC}_8 - \text{ACC}_{14}$, 155 cases are greater than 0, 16 cases are 0, and 101 cases are less than 0. The frequency distributions of $\Delta \text{FS}(\text{ACC}_{x-y})$ are shown in Figure 121 in the Appendix.

For eastbound voyages with "near" real-time information from a 17-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 8 days of daily current information with a mean relative fuel savings of $1.85\%$. 
3.7.2 INFO = P

Each bar in Figures 44 and 45 represents the mean relative fuel savings (MFS) of 272 cases (=4 RT's × 4 SD's × 17 TRK's) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 44 represents an MFS for each RT taken across 68 cases (=4 SD's × 17 TRK's), and each marker in Figure 45 represents an MFS for each SD taken across 68 cases (=4 RT's × 17 TRK's).

We compute the MFS(DIR = E, LAG = 7, INFO = P) of each ACC as defined in Equation (3.34). We use ACC to denote when we accumulate up to x days, where x = 5, 8, 11, and 14 days. The mean fuel savings are: 2.79% for ACC_5, 3.00% for ACC_8, 3.22% for ACC_11, 2.74% for ACC_14. The MFS’s with standard deviations are shown in Figure 122, and the relative fuel savings frequency distributions of each ACC are shown in Figure 123 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

\[ \Delta FS(ACC_{x-y}) = \]
\[ FS(DIR = E, RT_{i}, LAG = 7, INFO = P, SD_{j}, SAT = G, ACC_{x}, TRK_{k}) \]
\[ - FS(DIR = E, RT_{i}, LAG = 7, INFO = P, SD_{j}, SAT = G, ACC_{y}, TRK_{k}) \]

for i = 1, …, 4, j = 2, 3, 5, 6, and k = 1, …, 17. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which \( \Delta FS(ACC_{x-y}) \) is: greater than 0, equal to 0, and less than 0, indicating when ACC_x outperforms ACC_y.
Figure 44: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 7, INFO = P, SD = \{2, 3, 5, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 45: Mean Fuel Savings with DIR = E, RT = \{RT_1, RT_2, RT_3, RT_4\}, LAG = 7, INFO = P, SD = \{2, 3, 5, 6\}, SAT = G, and Disaggregated for Each SD.
As defined in Equation (3.36), we look into the fuel savings differences out of 272 cases. For $\text{ACC}_{11} - \text{ACC}_5$, 125 cases are greater than 0, 13 cases are 0, and 134 cases are less than 0. For $\text{ACC}_{11} - \text{ACC}_8$, 127 cases are greater than 0, 30 cases are 0, and 115 cases are less than 0. For $\text{ACC}_{11} - \text{ACC}_{14}$, 132 cases are greater than 0, 34 cases are 0, and 106 cases are less than 0. The frequency distributions of $\Delta \text{FS}(\text{ACC}_{x-y})$ are shown in Figure 124 in the Appendix.

For eastbound voyages with "near" real-time information from a 17-day ERP satellite with partial velocity component profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 11 days of daily current information with a mean relative fuel savings of 3.22%.

### 3.8 17-day ERP Satellite: Westbound Voyages with “Near” Real-time Information

In this section, we investigate the impact of accumulation of daily current information on westbound ship routing performance for 2 different information schemes – INFO = M and P with "near" real-time information for a 17-day ERP satellite. Again, we consider 7-day time lag as defined in Chapter II. As in the previous sections, we compare the mean relative fuel savings (MFS) of daily information accumulation schemes (ACC) for each information scheme (INFO) to determine how many days of current information should be accumulated to maximize relative fuel savings for routing purposes.

As in the previous sections, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information for each of the O-D pairs. In both cases, we consider a
ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We call $V_w$ and $V_{w0}$ the constant ship velocities with current information and without current information, respectively. By fixing the arrival time $T$ to be the same on the two routes, we do not need to make any assumptions about the trade off between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at constant velocity relative to the water $V_w$ plus current velocity $V_c$. With $V_w$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. We use 16 knots for $V_w$. This path is also the minimum fuel consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_{w0}$ to arrive the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_w$ and $V_{w0}$, we compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings for each information scheme $\text{MFS} (\text{DIR} = W, \text{LAG} = 7, \text{INFO} = \in \{M, P\}, \text{SAT} = G)$ defined as:

$$\text{MFS} (\text{DIR} = W, \text{LAG} = 7, \text{INFO} = M, \text{SAT} = G) =$$

$$\frac{1}{3 \times 4 \times 17} \sum_{i=5}^{7} \sum_{j=2}^{3} \sum_{k=5}^{6} \sum_{l=1}^{17} \text{FS}(\text{DIR} = W, \text{RT}_i, \text{LAG} = 7, \text{INFO} = M, \text{SD}_j, \text{SAT} = G, \text{ACC}_k, \text{TRK}_l)$$

(3.37)
for \( \text{INFO} = \text{M} \) and

\[
\text{MFS}(\text{DIR} = \text{W}, \text{LAG} = 7, \text{INFO} = \text{P}, \text{SAT} = \text{G}) = \\
\frac{1}{3 \times 4 \times 17} \sum_{i=5}^{7} \sum_{j=2}^{3} \sum_{k=5}^{6} \sum_{l=1}^{17} \text{FS}(\text{DIR} = \text{W}, \text{RT}_i, \text{LAG} = 7, \text{INFO} = \text{P}, \text{SD}_j, \text{SAT} = \text{G}, \text{ACC}_k, \text{TRK}_l)
\]  

for \( \text{INFO} = \text{P} \).

\text{RT} \text{ represents the origin-destination (O-D) pair, and we consider the 3 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes (73°W and 53°W) as an origin and a destination which belong to "in" the Gulf Stream. For an origin and a destination belong to "above" the Gulf Stream, we add 1.5° of latitude from the center of the Gulf Stream, while we subtract 1.5° of latitude from the center of the Gulf Stream for an origin and a destination belong to "below" the Gulf Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to approximately 150 km. SD represents the starting date – the day ship leaves the origin – and we consider the 4 different starting dates out of 6 specified in Section 2.3. Specifically, we consider \( \text{SD} = \text{SD}_2, \text{SD}_3, \text{SD}_5, \text{and SD}_6 \) because we cannot accumulate daily current information even up to 14 days for \( \text{SD}_1 \) and \( \text{SD}_4 \).

\text{TRK} \text{ represents the number of ground track sequence combination. Given a temporal progression of current patterns over } X \text{ days (model of which could be } X \text{ successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the } X \text{ days of analysis. Thus, there are many possible combinations of accumulating daily information for } X \text{ days. We consider 17 cases because there are 17 possible combinations for a 17-day ERP satellite: } \text{TRK} = \{1, 2, \ldots, 16, 17\}. \text{ Also, we present the MFS for each ACC disaggregated}
for each RT and SD, respectively.

### 3.8.1 INFO = M

Each bar in Figures 46 and 47 represents the mean relative fuel savings (MFS) of 204 cases (=3 RT's \times 4 SD's \times 17 TRK's) for each accumulation scheme (ACC) when estimating currents through a modified hydrographic approach (INFO = M). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 46 represents an MFS for each RT taken across 68 cases (=4 SD's \times 17 TRK's), and each marker in Figure 47 represents an MFS for each SD taken across 51 cases (=3 RT's \times 17 TRK's).

We compute the MFS(DIR = W, LAG = 7, INFO = M) of each ACC as defined in Equation (3.37). We use ACC\(_x\) to denote when we accumulate up to \(x\) days, where \(x = 5, 8, 11, \) and 14 days. The mean fuel savings are: -0.48 \% for ACC\(_5\), -0.58 \% for ACC\(_8\), -0.90 \% for ACC\(_{11}\), -1.02 \% for ACC\(_{14}\). The MFS's with standard deviations are shown in Figure 125, and the relative fuel savings frequency distributions of each ACC are shown in Figure 126 in the Appendix.

To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables keeping all other variables the same. Specifically, we form:

\[
\Delta FS(ACC_{x-y}) = FS(DIR = W, RT_i, LAG = 7, INFO = M, SD_j, SAT = G, ACC_x, TRK_k) - FS(DIR = W, RT_i, LAG = 7, INFO = M, SD_j, SAT = G, ACC_y, TRK_k)
\]

for \(i = 5, 6, 7, j = 2, 3, 5, 6\), and \(k = 1, \ldots, 17\). Here, subscripts \(x, y\) represent different ACC schemes. Then, we count the number of cases in which \(\Delta FS(ACC_{x-y})\) is: greater than 0, equal to 0, and less than 0, indicating when ACC\(_x\) outperforms ACC\(_y\).
Figure 46: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{2, 3, 5, 6\}, SAT = G, and Disaggregated for Each RT.

Figure 47: Mean Fuel Savings with DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{2, 3, 5, 6\}, SAT = G, and Disaggregated for Each SD.
As defined in Equation (3.39), we look into the fuel savings differences out of 204 cases. For ACC_5 – ACC_8, 84 cases are greater than 0, 38 cases are 0, and 82 cases are less than 0. For ACC_5 – ACC_{11}, 101 cases are greater than 0, 14 cases are 0, and 89 cases are less than 0. For ACC_5 – ACC_{14}, 105 cases are greater than 0, 10 cases are 0, and 89 cases are less than 0. The frequency distributions of ΔFS(ACC_{x-y}) are shown in Figure 127 in the Appendix.

For westbound voyages with "near" real-time information from a 17-day ERP satellite with a modified hydrographic approach, we get the overall greatest mean relative fuel savings by accumulating 5 days of daily current information with a mean relative fuel savings of -0.48%. Under this scenario, however, we had better ignore the current information. Thus, follow the great circle routes.

### 3.8.2 INFO = P

Each bar in Figures 48 and 49 represents the mean relative fuel savings (MFS) of 204 cases (=3 RT's × 4 SD's × 17 TRK's) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 48 represents an MFS for each RT taken across 68 cases (=4 SD's × 17 TRK's), and each marker in Figure 49 represents an MFS for each SD taken across 51 cases (=3 RT's × 17 TRK's).

We compute the MFS(DIR = W, LAG = 7, INFO = P) of each ACC as defined in Equation (3.38). We use ACC_x to denote when we accumulate up to x days, where x = 5, 8, 11, and 14 days. The mean fuel savings are: 0.08 % for ACC_5, 0.39 % for ACC_8, 0.36
Figure 48: Mean Fuel Savings with \( \text{DIR} = \text{W} \), \( \text{RT} = \{\text{RT}_5, \text{RT}_6, \text{RT}_7\} \), \( \text{LAG} = 7 \), \( \text{INFO} = \text{P} \), \( \text{SD} = \{2, 3, 5, 6\} \), \( \text{SAT} = \text{G} \), and Disaggregated for Each RT.

Figure 49: Mean Fuel Savings with \( \text{DIR} = \text{W} \), \( \text{RT} = \{\text{RT}_5, \text{RT}_6, \text{RT}_7\} \), \( \text{LAG} = 7 \), \( \text{INFO} = \text{P} \), \( \text{SD} = \{2, 3, 5, 6\} \), \( \text{SAT} = \text{G} \), and Disaggregated for Each SD.
% for ACC\textsubscript{11}, 0.53 % for ACC\textsubscript{14}. The MFS's with standard deviations are shown in Figure 128, and the relative fuel savings frequency distributions of each ACC are shown in Figure 129 in the Appendix.

As in the INFO = M case, we compute the fuel savings difference for different variables keeping all other variables the same to look at the data at a more disaggregate level. Specifically, we form:

\[
\Delta \text{FS}(\text{ACC}_{x-y}) = 
\begin{align*}
&\text{FS}([\text{DIR} = \text{W}, \text{RT}_i, \text{LAG} = 7, \text{INFO} = \text{P}, \text{SD}_j, \text{SAT} = \text{G}, \text{ACC}_x, \text{TRK}_k]) \\
&- \text{FS}([\text{DIR} = \text{W}, \text{RT}_i, \text{LAG} = 7, \text{INFO} = \text{P}, \text{SD}_j, \text{SAT} = \text{G}, \text{ACC}_y, \text{TRK}_k])
\end{align*}
\]  

(3.40)

for i = 5, 6, 7, j = 2, 3, 5, 6, and k = 1, \ldots, 17. Here, subscripts x, y represent different ACC schemes. Then, we count the number of cases in which \(\Delta \text{FS}(\text{ACC}_{x-y})\) is: greater than 0, equal to 0, and less than 0, indicating when ACC\textsubscript{x} outperforms ACC\textsubscript{y}.

As defined in Equation (3.40), we look into the fuel savings differences out of 204 cases. For ACC\textsubscript{14} – ACC\textsubscript{5}, 100 cases are greater than 0, 16 cases are 0, and 88 cases are less than 0. For ACC\textsubscript{14} – ACC\textsubscript{8}, 105 cases are greater than 0, 17 cases are 0, and 82 cases are less than 0. For ACC\textsubscript{14} – ACC\textsubscript{11}, 95 cases are greater than 0, 46 cases are 0, and 63 cases are less than 0. The frequency distributions of \(\Delta \text{FS}(\text{ACC}_{x-y})\) are shown in Figure 130 in the Appendix.

For westbound voyages with "near" real-time information from a 17-day ERP satellite with partial velocity component profile perpendicular to the ground tracks, we get the overall greatest mean relative fuel savings by accumulating 14 days of daily current information with a mean relative fuel savings of 0.53%.
3.9 Summary

In this chapter, we investigated the impact of accumulating daily current information along the satellite ground tracks on ship routing performance. The results of this investigation can serve as a guideline to routing industry to accommodate satellite altimeter-based dynamic ocean current information for strategic routing purposes. Also, we can simplify the studies in the following chapters by identifying the effect of daily information accumulation.

We determined the performance according to the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. Also, we identified the desirable accumulation of daily current information to maximize relative fuel savings for 10- and 17-day exact repeat period (ERP) satellites each. We considered 3 information schemes for both eastbound and westbound voyages with real-time information for each ERP satellite, while we considered 2 information schemes for both eastbound and westbound voyages with "near" real-time information for each ERP satellite. Notationally, for $\text{LAG} = 0$, we consider $\text{DIR} = E$ and $W$ with $\text{INFO} = M$, $P$, and $F$ for $\text{SAT} = T$ and $G$. For $\text{LAG} = 7$, we consider $\text{DIR} = E$ and $W$ with $\text{INFO} = M$ and $P$ for $\text{SAT} = T$ and $G$.

For a 10-day ERP satellite, we considered 3 different daily current information accumulation schemes ($\text{ACC}$) for both eastbound and westbound voyages. Specifically, we considered $\text{ACC} = 4$, 7, and 10 regardless of the time lag. For a 17-day ERP satellite, we considered 5 different ACC's of real-time daily current information and 4 different ACC's when we have "near" real-time information for both eastbound and westbound voyages. Specifically, for both eastbound and westbound voyages, we considered $\text{ACC} = 5$, 8, 11, 14, and 17 for $\text{LAG} = 0$, and $\text{ACC} = 5$, 8, 11, and 14 for $\text{LAG} = 7$. 
Table 4: Mean Relative Fuel Savings (%) for a 10-day ERP Satellite with Real- and “Near” Real-time Information.

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<tr>
<th>DIR</th>
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<th>INFO</th>
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<th>MFS</th>
<th>Std. Dev.</th>
<th>Number of Cases</th>
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<td>M</td>
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<tr>
<td></td>
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<td>7</td>
<td>2.76</td>
<td>4.94</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>2.98</td>
<td>5.19</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>4</td>
<td>3.10</td>
<td>4.44</td>
<td>240</td>
<td></td>
</tr>
<tr>
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<td>7</td>
<td>4.11</td>
<td>5.19</td>
<td>240</td>
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<td></td>
</tr>
<tr>
<td></td>
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<td>4.51</td>
<td>5.64</td>
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<td>F</td>
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<td>240</td>
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Table 5: Relative Fuel Savings Differences for a 10-day ERP Satellite with Real- and “Near” Real-time Information.

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<th>INFO</th>
<th>ACC&lt;sub&gt;io&lt;/sub&gt; - ACC&lt;sub&gt;y&lt;/sub&gt;</th>
<th>Number of Cases</th>
<th>ΔFS &gt; 0</th>
<th>ΔFS = 0</th>
<th>ΔFS &lt; 0</th>
<th>Total</th>
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<tr>
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<td>M</td>
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Table 6: ACC for the Greatest MFS's with a 10-day ERP Satellite.

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<th>MFS (%)</th>
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<td></td>
<td>P</td>
<td>1.57</td>
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</table>

For a 10-day ERP satellite, we summarize the overall mean relative fuel savings and corresponding standard deviations with real- and “near” real-time information in Table 4. In Table 5 we summarize the number of cases in which the relative fuel savings difference is greater than 0, equal to 0, and less than 0. Finally, we summarize our recommendations to the routing industry in Table 6 to accommodate satellite altimeter-based dynamic ocean current information for strategic ship routing purposes when a 10-day ERP satellite information is available.

For a 17-day ERP satellite, we summarize the overall mean relative fuel savings and corresponding standard deviations with real-time information in Table 7 and with “near” real-time information in Table 8. We summarize the number of cases in which the relative fuel savings difference is greater than 0, equal to 0, and less than 0 in Table 9 for real-time information and in Table 10 for “near” real-time information. Finally, we summarize our
recommendations to the routing industry in Table 11 to accommodate satellite altimeter-based dynamic ocean current information for strategic ship routing purposes when a 17-day ERP satellite information is available.

For a 10-day ERP satellite, results show that the accumulation of daily current information does matter in ship routing performance for both eastbound and westbound voyages. Specifically, for a 10-day ERP satellite, we maximized the mean relative fuel savings (MFS) by accumulating up to 10 days of daily current information along the ground tracks when we have real-time information (LAG = 0) for both eastbound and westbound voyages. This result did not depend on the INFO scheme.

For “near” real-time information with time lag of 7 days (LAG = 7) for both directions of voyages, we maximized the MFS by accumulating up to 7 days of daily current information along the ground tracks when we use a modified hydrographic approach (INFO = M), while we maximized the MFS by accumulating up to 10 days of daily current information along the ground tracks when we only have a current velocity component profile perpendicular to the ground tracks (INFO = P). However, there is an instance where we should not utilize current information for routing purposes. Specifically, westbound voyages with “near” real-time information with a modified hydrographic approach lead to negative relative fuel savings. Negative MFS’s in Tables 4 and 6 mean that we consume more fuel when we utilize altimeter-based dynamic ocean current information. Thus, we are better off to ignore the current information. In these cases, we would have done better to follow the great circle routes.

For a 17-day ERP satellite, we maximized the mean relative fuel savings (MFS) when we
Table 7: Mean Relative Fuel Savings (%) for a 17-day ERP Satellite with Real-time Information.

<table>
<thead>
<tr>
<th>DIR</th>
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<th>Std. Dev.</th>
<th>Number of Cases</th>
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Table 8: Mean Relative Fuel Savings (%) for a 17-day ERP Satellite with “Near” Real-time Information.

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Table 9: Relative Fuel Savings Differences for a 17-day ERP Satellite with Real-time Information.

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125
Table 10: Relative Fuel Savings Differences for a 17-day ERP Satellite with “Near” Real-time Information.

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<th>Number of Cases</th>
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<th>(\Delta FS = 0)</th>
<th>(\Delta FS &lt; 0)</th>
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Table 11: ACC for the Greatest MFS’s with a 17-day ERP Satellite.

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<td>W</td>
<td>7</td>
<td>M</td>
<td></td>
<td>-0.48</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>P</td>
<td></td>
<td></td>
<td>0.53</td>
<td>14</td>
</tr>
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</table>
accumulate between 8 and 14 days of daily current information, depending on the information schemes, along the ground tracks regardless of the direction of voyages. Specifically, we maximized the MFS by accumulating up to 8 days of daily current information along the ground tracks for eastbound voyages when we use a modified hydrographic approach (INFO = M) regardless of time lag. Westbound voyages with a modified hydrographic approach lead to negative mean relative fuel savings regardless of time lag. Negative MFS’s in Tables 7 and 8 mean that we consume more fuel when we utilize altimeter-based dynamic ocean current information. Thus, we are better off to ignore the current information. In these cases, we would be better off to follow the great circle routes.

We maximized the MFS by accumulating up to 14 days of daily current information along the ground tracks of a 17-day ERP satellite when we have only current velocity component profile perpendicular to the ground tracks (INFO = P) for both eastbound and westbound voyages with real-time information and westbound voyages with “near” real-time information, while we maximized the MFS by accumulating up to 11 days of daily current information along the ground tracks for eastbound voyages with “near” real-time information.

We maximized the MFS by accumulating up to 11 days of daily current information along the ground tracks of a 17-day ERP satellite when we have full current velocity profile along the ground tracks (INFO = F) for eastbound voyages with real-time information, while we maximized the MFS by accumulating up to 14 days of daily current information along the ground tracks for westbound voyages with real-time information.

Our recommendations of daily current information accumulation schemes for the great-
est mean relative fuel savings for 10- and 17-day ERP satellites summarized in Tables 6 and 11 should be considered with caution. We compared the overall mean relative fuel savings (MFS) taken across the O-D pairs and starting dates. Then, we identified the accumulation schemes which provide the greatest MFS’s. The overall MFS’s, however, tend to mask the details, and may not be always applicable without further knowledge. Thus, we computed the relative fuel savings differences to look into the data at a more disaggregated level.

For example, when we look into the overall MFS’s for each daily accumulation scheme (ACC) for eastbound voyages for a 10-day ERP satellite estimating currents with a modified hydrographic approach with real-time information (DIR = E, LAG = 0, INFO = M, SAT = T), the MFS’s of each of the ACC’s are: 2.36% for ACC4, 2.76% for ACC7, and 2.98% for ACC10. The standard deviations are 4.22%, 4.94%, and 5.19% for ACC4, ACC7, and ACC10, respectively. ACC10 performed little better than ACC7 with 0.22% more overall mean relative fuel savings. The disaggregated mean relative fuel savings with respect to the O-D pairs and starting dates presented in Figures 11 and 11 show that ACC10 performed similar to ACC7, except SD1. In SD1, ACC10 performed worse than ACC7. Also, relative fuel savings differences ΔFS(ACC10 − ACC7) counts summarized in Table 4 show that ACC10 performed similar to ACC7. The number of positive and negative ΔFS(ACC10 − ACC7) are 99 out of 240 cases each, with 42 cases being 0. In this case, we would recommend to accumulate up to 10 days of information to maximize overall mean relative fuel savings. Our recommendation, however, may be different when we need to present a desirable accumulation scheme under specific conditions, e.g., a specific O-D pair under a specific starting date.
Wide variations in Table 4 for a 10-day ERP satellite and Tables 7 and 8 for a 17-day ERP satellite can be explained when we look into the disaggregated plots presented throughout this chapter with respect to the O-D pairs and starting dates. We can easily notice that the wide variations in relative fuel savings among O-D pairs and starting dates exist. Specifically, an O-D pair whose origin and destination belong to “in” the Gulf Stream (I - I), and an O-D pair whose origin and destination belong to “above” the Gulf Stream (A - A) tend to outperform the other O-D pairs. If specific O-D pairs consistently outperform other O-D pairs, we would do better to identify them, and concentrate on those O-D pairs for the strategic ship routing purposes to materialize more benefits. Chapter V will address this issue in more detail.

Also, we notice that seasonal variations may exist considering the plots of disaggregated MFS’s with respect to the starting dates. Categorizing desirable accumulation schemes based on the seasonal variation would provide more insight in utilizing altimeter-based current information for the strategic ship routing purposes. However, it is beyond the scope of this study.

The results show that the benefit of choosing one accumulation scheme over another depends on O-D pairs and starting dates. We, however, need to fix an accumulation scheme for the rest of this study. Thus, we choose the accumulation schemes (ACC) which provide the greatest overall mean relative fuel savings as summarized in Table 6 for a 10-day ERP satellite, and in Table 11 for a 17-day ERP satellite.
CHAPTER IV

Effect of Satellite Supply

In this chapter, we investigate the increased magnitude of fuel savings due to having two different exact repeat period (ERP) satellites simultaneously compared to having only one ERP satellite. It seems obvious that having two different ERP satellites simultaneously would result in more fuel savings, since this would provide more temporally recent data and more spatial coverage than having only one ERP satellite. We, however, do not know the size of the fuel savings increase yet. Thus, it seems worthwhile to investigate the magnitude of the FS increase, given that it is likely to have a GEOSAT-follow-on satellite (17-day ERP) with GEOSAT ground tracks while TOPEX (10-day ERP) is still in operation.

We again measure the performance according to the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. First, we investigate the desirable combinations of accumulating daily current information when we have 10- and 17-day ERP satellites simultaneously. Then, we compare the maximum mean relative fuel savings (MFS) of each ERP satellite obtained in Chapter II to that of the combination of two ERP satellites. We use the same data on ocean current pattern for each satellite supply. We sample ocean current pattern along the ground tracks of both 10- and 17-day ERP satellites. Then, we aggregate sampled data into grid cells of 0.1° latitude by 0.5° longitude to form a single current vector in each cell.
We compare 15 different combinations of accumulation schemes for daily current information. Specifically, as defined in Chapter II, we consider the combinations of 3 ACC’s (ACC = 4, 7, and 10) for SAT = T – a 10-day ERP satellite – and 5 different ACC’s (ACC = 5, 8, 11, 14, and 17) for SAT = G – a 17-day ERP satellite. The set of resulting 15 combinations for SAT = C, having 2 ERP satellites simultaneously, is denoted:

\[ \{T_4G_5, \ldots, T_4G_{17}, T_7G_5, \ldots, T_7G_{17}, \ldots, T_{10}G_5, \ldots, T_{10}G_{17}\}. \tag{4.1} \]

The results of Sections 4.1 and 4.2 show that, for eastbound routes, we maximize the relative fuel savings when we accumulate up to 10 days of daily information from a 10-day ERP satellite with up to 8 days of daily information from a 17-day ERP satellite simultaneously. The maximum mean relative fuel savings is 5.44%. For westbound routes, we maximize the relative fuel savings when we accumulate up to 10 days of daily information from a 10-day ERP satellite with up to 11 days of daily information from a 17-day ERP satellite simultaneously. The maximum mean relative fuel savings is 2.94%.

The results in Sections 4.1 and 4.2 show that the benefit of choosing one accumulation scheme over another depends on O-D pairs and starting dates. We, however, need to fix an accumulation scheme for the rest of this study. Thus, we choose the accumulation schemes (ACC) which provide the greatest overall mean relative fuel savings as summarized in Table 6 for a 10-day ERP satellite and in Table 11 for a 17-day ERP satellite. For 10- and 17-day ERP satellites case, we choose the accumulation schemes (ACC) which provide the greatest overall mean relative fuel savings as summarized in Table 12 for eastbound voyages and in Table 14 for westbound voyages.

In Section 4.3, we compare the maximum mean relative fuel savings (MFS) resulting
from having two ERP satellites simultaneously to those resulting from having only one ERP satellite (either SAT = T or G) for eastbound voyages under the case of real time information with the current velocity component profile perpendicular to the ground tracks. Having two different ERP satellites simultaneously performs better than having only one ERP satellite each for eastbound voyages. Specifically, having 10- and 17-day ERP satellites simultaneously results in 0.93% more MFS's compared to having a 10-day ERP satellite, and 0.80% more MFS's compared to having a 17-day ERP satellite.

In Section 4.4, we compare the maximum MFS's for westbound voyages in the same way as in Section 4.3. Having two different ERP satellites simultaneously performs better than having only one ERP satellite each for westbound voyages. Specifically, having 10- and 17-day ERP satellites simultaneously results in 0.54% more MFS's compared to having a 10-day ERP satellite and 1.00% more MFS's compared to having a 17-day ERP satellite. These increases in overall mean relative fuel savings represent an increase of between 17 and 50% of those that would be obtained with a single ERP satellite. In Section 4.5, we summarize our findings.

4.1 Determination of Daily Accumulation for Eastbound Voyages with 2 ERP Satellites

In this section, we investigate the impact of accumulating daily current information on eastbound ship routing performance with real-time information for 10 and 17-day ERP satellites under a specific information scheme – INFO = P. We choose this information scheme rather than INFO = M – a currently available technology – to avoid geoid model related errors, since we assume that we have a perfect geoid model under INFO = P. We
compare the mean relative fuel savings (MFS) of daily information accumulation schemes (ACC) to determine how many days of current information should be accumulated to maximize relative mean fuel savings for routing purposes.

For each of the O-D pairs, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information. In both cases, we consider a ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We call $V_w$ and $V_{w0}$ the constant ship velocities with current information and without current information, respectively. By fixing the arrival time $T$ to be the same on the two routes, we do not need to make any assumptions about the tradeoff between the value of travel time and fuel consumption, and we can compare two routes under the same conditions.

The route to be followed in the presence of currents would be the shortest time route, given that the ship is to travel at constant velocity relative to the water $V_w$ plus current velocity $V_c$. With $V_w$, which is constant along the voyage, and $V_c$, which varies in space, we compute travel time $T$. We use 16 knots for $V_w$. This path is also the minimum fuel consumption route because power setting of the ship is not considered. The route to be followed in the absence of currents would be the shortest distance route. There is no reason to travel longer than the shortest path without current information (Lo et al., 1991). After the great circle route, which is the shortest distance route, is chosen, we compute constant ship velocity $V_{w0}$ to arrive the destination with fixed travel time $T$ computed under the presence of current information (Lo, 1991). With $V_w$ and $V_{w0}$, we compute the relative fuel savings as defined in Equation (1.4).
We summarize the results in the mean of the relative fuel savings $MFS(DIR_E, LAG_0, INFO_P, SAT_C, ACC_k)$ for each $ACC_k$ defined as:

$$MFS(DIR = E, LAG = 0, INFO = P, SAT = C) = \frac{1}{4 \times 6 \times 30} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{30} FS(DIR = E, RT_i, LAG = 0, INFO = P, SD_j, SAT = C, ACC_k, TRK_l)$$

where $ACC_k$ is $T_4G_5, \ldots, T_{10}G_{17}$ as defined in Equation (4.1). $RT$ represents the origin-destination (O-D) pair, and we consider the 3 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes (73°W and 53°W) as an origin and a destination which belong to "in" the Gulf Stream. For an origin and a destination belong to "above" the Gulf Stream, we add 1.5° of latitude from the center of the Gulf Stream, while we subtract 1.5° of latitude from the center of the Gulf Stream for an origin and a destination belong to "below" the Gulf Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to approximately 150 km. $SD$ represents the starting date – the day ship leaves the origin – and we consider the 6 different starting dates specified in Section 2.3.

$TRK$ represents the number of ground track sequence combination. Given a temporal progression of current patterns over $X$ days (model of which could be $X$ successive days of Harvard data), a satellite with fixed orbit specification could sample these patterns in several ways, depending on where the satellite was in its orbit at the beginning of the $X$ days of analysis. Thus, there are many possible combinations of accumulating daily information for $X$ days. As described in Chapter II, we consider randomly selected 30 cases out of 170 possible combinations for 10- and 17-day ERP satellites: $TRK = \{1, 2, \ldots, 29, 30\}$. Also, we present the MFS for each $ACC$ disaggregated for each $RT$ and $SD$, respectively.
Each bar in Figures 50 and 51 represents the mean relative fuel savings (MFS) of 720 cases (=4 RT's x 6 SD's x 30 TRK's) for each accumulation scheme (ACC) when estimating currents with partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 50 represents an MFS for each RT taken across 180 cases (=6 SD's x 30 TRK's), and each marker in Figure 51 represents an MFS for each SD taken across 120 cases (=4 RT's x 30 TRK's). Disaggregated M FS's plot show wide variations in fuel savings performance with respect to O-D pairs and starting dates.

The MFS's of eastbound voyages with LAG = 0 and INFO = P are: 5.05% for T4G5, 5.29% for T4G8, 5.32% for T4G11, 5.11% for T4G14, 5.07% for T4G17, 5.05% for T7G5, 5.25% for T7G8, 5.08% for T7G11, 5.04% for T7G14, 4.92% for T7G17, 5.18% for T10G5, 5.44% for T10G8, 5.32% for T10G11, 5.09% for T10G14, and 4.94% for T10G17. These results are summarized in Table 12 with standard deviations and the number of fuel savings cases.

To examine the data at a more disaggregate level, we compute the fuel savings difference for different variables, keeping all other variables the same. Specifically, we form:

$$\Delta \text{FS}(\text{ACC}_{x-y}) = \text{FS}(\text{DIR} = E, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j, \text{SAT} = C, \text{ACC}_x, \text{TRK}_k) - \text{FS}(\text{DIR} = E, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j, \text{SAT} = C, \text{ACC}_y, \text{TRK}_k)$$

(4.3)

for $i = 1, \ldots, 4$, $j = 1, \ldots, 6$, and $k = 1, \ldots, 30$. Here, subscripts $x, y$ represent different ACC schemes. Then, we count the number of cases in which $\Delta \text{FS}(\text{ACC}_{x-y})$ is greater than 0, equal to 0, and less than 0, indicating when ACC$_x$ outperforms ACC$_y$. The results are summarized in Table 13. Fuel savings differences counts show that fuel savings performance of each of the accumulation schemes is similar.

The results show that the benefit of choosing one accumulation scheme over another
Figure 50: Eastbound MFS's of Each ACC under LAG = 0, INFO = P for SAT = C, and Disaggregated for Each RT. Subscripts Represent ACC for Each SAT.

Figure 51: Eastbound MFS's of Each ACC under LAG = 0, INFO = P for SAT = C, and Disaggregated for Each SD. Subscripts Represent ACC for Each SAT.
Table 12: Eastbound MFS's(%) with 10- and 17-day ERP Satellites Simultaneously with Real-time Information.

<table>
<thead>
<tr>
<th>DIR</th>
<th>LAG</th>
<th>INFO</th>
<th>ACC</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
<td>P</td>
<td>T₄G₅</td>
<td>5.05</td>
<td>4.96</td>
<td>720</td>
</tr>
<tr>
<td></td>
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<td>5.11</td>
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<td></td>
<td>T₄G₁₁</td>
<td>5.32</td>
<td>5.15</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T₄G₁₄</td>
<td>5.11</td>
<td>4.74</td>
<td>720</td>
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<td></td>
<td>T₄G₁₇</td>
<td>5.07</td>
<td>5.00</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T₇G₅</td>
<td>5.05</td>
<td>5.04</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T₇G₈</td>
<td>5.25</td>
<td>5.24</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T₇G₁₁</td>
<td>5.08</td>
<td>5.17</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T₇G₁₄</td>
<td>5.04</td>
<td>4.77</td>
<td>720</td>
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<td></td>
<td></td>
<td></td>
<td>T₇G₁₇</td>
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<td>5.03</td>
<td>720</td>
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<td></td>
<td>T₁₀G₅</td>
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<td>5.59</td>
<td>720</td>
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<td></td>
<td></td>
<td>T₁₀G₈</td>
<td>5.44</td>
<td>5.53</td>
<td>720</td>
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<td>T₁₀G₁₁</td>
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<td>5.38</td>
<td>720</td>
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<td></td>
<td></td>
<td></td>
<td>T₁₀G₁₄</td>
<td>5.09</td>
<td>5.22</td>
<td>720</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T₁₀G₁₇</td>
<td>4.94</td>
<td>5.12</td>
<td>720</td>
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</tbody>
</table>
Table 13: Eastbound Relative Fuel Savings Differences for 10- and 17-day ERP Satellites Simultaneously with Real-time Information.

<table>
<thead>
<tr>
<th>ACC&lt;sub&gt;x&lt;/sub&gt; − ACC&lt;sub&gt;y&lt;/sub&gt;</th>
<th>ΔFS &gt; 0</th>
<th>ΔFS = 0</th>
<th>ΔFS &lt; 0</th>
<th>Total</th>
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</thead>
<tbody>
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<td>ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;5&lt;/sub&gt;</td>
<td>339</td>
<td>18</td>
<td>363</td>
<td>720</td>
</tr>
<tr>
<td>ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt;</td>
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<td>38</td>
<td>370</td>
<td>720</td>
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<td>ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;11&lt;/sub&gt;</td>
<td>333</td>
<td>24</td>
<td>363</td>
<td>720</td>
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<td>ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;10&lt;/sub&gt;G&lt;sub&gt;14&lt;/sub&gt;</td>
<td>374</td>
<td>15</td>
<td>331</td>
<td>720</td>
</tr>
<tr>
<td>ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;11&lt;/sub&gt;</td>
<td>382</td>
<td>9</td>
<td>329</td>
<td>720</td>
</tr>
<tr>
<td>ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;17&lt;/sub&gt;</td>
<td>377</td>
<td>10</td>
<td>333</td>
<td>720</td>
</tr>
<tr>
<td>ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt;</td>
<td>260</td>
<td>72</td>
<td>388</td>
<td>720</td>
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<td>ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;11&lt;/sub&gt;</td>
<td>354</td>
<td>28</td>
<td>338</td>
<td>720</td>
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<td>ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;14&lt;/sub&gt;</td>
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<td>380</td>
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<td>720</td>
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<td>109</td>
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<td>720</td>
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<tr>
<td>ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;14&lt;/sub&gt;</td>
<td>366</td>
<td>22</td>
<td>332</td>
<td>720</td>
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<td>ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;8&lt;/sub&gt; − ACC&lt;sub&gt;T&lt;sub&gt;11&lt;/sub&gt;G&lt;sub&gt;17&lt;/sub&gt;</td>
<td>395</td>
<td>14</td>
<td>311</td>
<td>720</td>
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</table>
depends on O-D pairs and starting dates. We, however, need to fix an accumulation scheme for the rest of this study. Thus, we choose the accumulation scheme which provides the greatest overall mean relative fuel savings.

For eastbound routes, we maximize the overall mean relative fuel savings by accumulating up to 10 days of daily current information along the ground tracks of a 10-day ERP satellite with up to 8 days of daily current information along the ground tracks of a 17-day ERP satellite simultaneously. The maximum mean relative fuel savings is 5.44%.

4.2 Determination of Daily Accumulation for Westbound Voyages with 2 ERP Satellites

In this section, we investigate the impact of accumulating daily current information on westbound ship routing performance with real-time information for 10 and 17-day ERP satellites under a specific information scheme – INFO = P. Again, we choose this information scheme rather than INFO = M – a currently available technology – to avoid geoid model related errors. We compare the mean relative fuel savings (MFS) of daily information accumulation schemes (ACC) to determine how many days of current information should be accumulated to maximize relative mean fuel savings for routing purposes.

As in Section 4.1, for each of the O-D pairs, we compare two routes - one to minimize fuel consumption in the presence of current information, and the other to minimize fuel consumption in the absence of current information. In both cases, we consider a ship traveling at constant velocities and arriving at its destination $T$ hours after departing its origin. We compute the relative fuel savings as defined in Equation (1.4).

We summarize the results in the mean of the relative fuel savings $\text{MFS(}\text{DIR}_w, \text{LAG}_0,$
INFO_p, SAT_c, ACC_k) for each ACC_k defined as:

\[
\text{MFS} (\text{DIR} = W, \text{LAG} = 0, \text{INFO} = P, \text{SAT} = C) = \frac{1}{3 \times 6 \times 30} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{k=1}^{30} \text{FS} (\text{DIR} = W, RT_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j).
\]

\[
\text{SAT} = C, \text{ACC}_k, \text{TRK}_i
\]

where ACC_k is \(T_4G_5, \ldots, T_{10}G_{17}\) as defined in Equation (4.1). RT represents the origin-destination (O-D) pair, and we consider the 3 different O-D pairs specified in Chapter II. As described in Section 2.2, we select the center of the Gulf Stream current pattern along the fixed longitudes (73°W and 53°W) as an origin and a destination which belong to "in" the Gulf Stream. For an origin and a destination "above" the Gulf Stream, we add 1.5° of latitude from the center of the Gulf Stream, while we subtract 1.5° of latitude from the center of the Gulf Stream for an origin and a destination "below" the Gulf Stream. Here, 1.5° of latitude along the fixed longitude in this study region corresponds to approximately 150 km. SD represents the starting date – the day ship leaves the origin – and we consider the 6 different starting dates specified in Section 2.3.

TRK represents the number of ground track sequence combination. As described in Chapter II, we consider randomly selected 30 cases out of 170 possible combinations for 10- and 17-day ERP satellites: TRK = \{1, 2, \ldots, 29, 30\}. Also, we present the MFS for each ACC disaggregated for each RT and SD, respectively.

Each bar in Figures 52 and 53 represents the mean relative fuel savings (MFS) of 540 cases (=3 RT's \times 6 SD's \times 30 TRK's) for each accumulation scheme (ACC) when estimating currents with a partial velocity component perpendicular to the ground tracks (INFO = P). We disaggregate the MFS for each ACC with respect to O-D pair (RT) and starting date (SD) to show the influence. Each marker in Figure 52 represents an MFS for each RT taken
across 180 cases (= 6 SD's x 30 TRK's), and each marker in Figure 53 represents an MFS for each SD taken across 90 cases (= 3 RT's x 30 TRK's). Disaggregated MFS's plot show wide variations in fuel savings performance with respect to O-D pairs and starting dates.

The MFS's of westbound voyages with LAG = 0 and INFO = P are: 2.05% for T_4G_5, 2.21% for T_4G_8, 2.35% for T_4G_11, 2.51% for T_4G_{14}, 2.49% for T_4G_{17}, 2.30% for T_7G_5, 2.49% for T_7G_8, 2.62% for T_7G_{11}, 2.57% for T_7G_{14}, 2.59% for T_7G_{17}, 2.84% for T_{10}G_5, 2.88% for T_{10}G_8, 2.94% for T_{10}G_{11}, 2.67% for T_{10}G_{14}, and 2.54% for T_{10}G_{17}. These results are summarized in Table 14 with standard deviations and the number of fuel savings cases.

As in the eastbound voyages, we compute the fuel savings difference for different variables, keeping all other variables the same to examine the data at a more disaggregate level. Specifically, we form:

\[
\Delta \text{FS}(\text{ACC}_x, y) = \text{FS}(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j, \text{SAT} = C, \text{ACC}_x, \text{TRK}_k) - \text{FS}(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j, \text{SAT} = C, \text{ACC}_y, \text{TRK}_k)
\]

for \( i = 5, 6, 7, \ j = 1, \ldots, 6, \) and \( k = 1, \ldots, 30. \) Here, subscripts \( x, y \) represent different ACC schemes. Then, we count the number of cases in which \( \Delta \text{FS}(\text{ACC}_x, y) \) is greater than 0, equal to 0, and less than 0, indicating when ACC\(_x\) outperforms ACC\(_y\). The results are summarized in Table 15. Fuel savings differences counts show that fuel savings performance of each of the accumulation schemes is similar.

The results show that the benefit of choosing one accumulation scheme over another depends on O-D pairs and starting dates. We, however, need to fix an accumulation scheme for the rest of this study. Thus, we choose the accumulation scheme which provides the greatest overall mean relative fuel savings.

For westbound routes, we maximize the relative fuel savings by accumulating up to 10
Figure 52: Westbound MFS's of Each ACC under LAG = 0, INFO = P for SAT = C, and Disaggregated for Each RT. Subscripts Represent ACC for Each SAT.

Figure 53: Westbound MFS's of Each ACC under LAG = 0, INFO = P for SAT = C, and Disaggregated for Each SD. Subscripts Represent ACC for Each SAT.
Table 14: Westbound MFS's(%) with 10- and 17-day ERP Satellites Simultaneously with Real-time Information.

<table>
<thead>
<tr>
<th>DIR</th>
<th>LAG</th>
<th>INFO</th>
<th>ACC</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Number of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>0</td>
<td>P</td>
<td>T4G5</td>
<td>2.05</td>
<td>3.37</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T4G8</td>
<td>2.21</td>
<td>3.55</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T4G11</td>
<td>2.35</td>
<td>3.79</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T4G14</td>
<td>2.51</td>
<td>3.93</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T4G17</td>
<td>2.49</td>
<td>4.06</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T7G5</td>
<td>2.30</td>
<td>3.55</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T7G8</td>
<td>2.49</td>
<td>3.58</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T7G11</td>
<td>2.62</td>
<td>3.88</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T7G14</td>
<td>2.57</td>
<td>4.02</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T7G17</td>
<td>2.59</td>
<td>3.88</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T10G5</td>
<td>2.84</td>
<td>3.63</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T10G8</td>
<td>2.88</td>
<td>3.74</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T10G11</td>
<td>2.94</td>
<td>3.98</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T10G14</td>
<td>2.67</td>
<td>4.09</td>
<td>540</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T10G17</td>
<td>2.54</td>
<td>4.03</td>
<td>540</td>
</tr>
</tbody>
</table>
Table 15: Westbound Relative Fuel Savings Differences for 10- and 17-day ERP Satellites Simultaneously with Real-time Information.

<table>
<thead>
<tr>
<th>( \text{ACC}_x - \text{ACC}_y )</th>
<th>( \Delta \text{FS} &gt; 0 )</th>
<th>( \Delta \text{FS} = 0 )</th>
<th>( \Delta \text{FS} &lt; 0 )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{4}G_{5}} )</td>
<td>280</td>
<td>18</td>
<td>232</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{4}G_{8}} )</td>
<td>239</td>
<td>38</td>
<td>248</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{5}G_{11}} )</td>
<td>210</td>
<td>24</td>
<td>265</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{4}G_{14}} )</td>
<td>267</td>
<td>15</td>
<td>248</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{4}G_{17}} )</td>
<td>255</td>
<td>9</td>
<td>260</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{5}G_{5}} )</td>
<td>266</td>
<td>10</td>
<td>249</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{4}G_{8}} )</td>
<td>233</td>
<td>72</td>
<td>258</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{5}G_{11}} )</td>
<td>146</td>
<td>28</td>
<td>281</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{5}G_{14}} )</td>
<td>273</td>
<td>11</td>
<td>247</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{5}G_{17}} )</td>
<td>261</td>
<td>13</td>
<td>258</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{5}G_{8}} )</td>
<td>236</td>
<td>37</td>
<td>278</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{10}G_{8}} )</td>
<td>89</td>
<td>109</td>
<td>332</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{10}G_{14}} )</td>
<td>212</td>
<td>22</td>
<td>273</td>
<td>540</td>
</tr>
<tr>
<td>( \text{ACC}<em>{T</em>{10}G_{11}} - \text{ACC}<em>{T</em>{10}G_{17}} )</td>
<td>245</td>
<td>14</td>
<td>264</td>
<td>540</td>
</tr>
</tbody>
</table>
days of daily current information along the ground tracks of a 10-day ERP satellite with up to 11 days of daily current information along the ground tracks of a 17-day ERP satellite simultaneously. The maximum mean relative fuel savings is 2.94%.

4.3 Comparison of the MFS's for Eastbound Voyages

We compare the greatest mean relative fuel savings (MFS) resulting from having two ERP satellites simultaneously to those resulting from having only one ERP satellite (either SAT = T or G) when we have real time information (LAG = 0) with the current velocity component profile perpendicular to the ground tracks (INFO = P). As described in Chapter I, we use the same data on ocean current patterns for each satellite supply. We sample the ocean current pattern along the ground tracks of both 10- and 17-day ERP satellites. Then, we average sampled data into grid cells of 0.1° latitude by 0.5° longitude to form a single current vector in each cell.

A 10-day ERP satellite provides more recent temporal data but spatially sparse coverage, while a 17-day ERP satellite provides more dense spatial coverage, but temporally obsolete data. Thus, 10- and 17-day ERP satellites simultaneously provide more temporally recent data and more spatial coverage than having only one ERP satellite.

For eastbound voyages, the mean relative fuel savings of having 10- and 17-day ERP satellites simultaneously MFS(DIR_E, LAG_0, INFO_P, SAT_C, ACC_k) is defined as:

\[
MFS_c = \frac{1}{4 \times 6 \times 30} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{30} FS(DIR = E, RT_i, LAG = 0, INFO = P, SD_j, SAT = C, ACC_k, TRK_l) \tag{4.6}
\]

For having a 10-day ERP satellite, the MFS(DIR_E, LAG_0, INFO_P, SAT_T, ACC_k) is defined
Figure 54: Comparison of Eastbound MFS's under LAG = 0, INFO = P for each SAT, and Disaggregated for Each RT.

Figure 55: Comparison of Eastbound MFS's under LAG = 0, INFO = P for each SAT, and Disaggregated for Each SD.
as:

\[ MFS_T = \frac{1}{4 \times 6 \times 10} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{10} FS(DIR = E, RT_l, LAG = 0, INFO = P, SD_j, SAT = T, ACC_k, TRK_l) \]  \hspace{1cm} (4.7)

For having a 17-day ERP satellite, the \( MFS(DIR_E, LAG_0, INFO_P, SAT_G, ACC_k) \) is defined as:

\[ MFS_G = \frac{1}{4 \times 6 \times 17} \sum_{i=1}^{4} \sum_{j=1}^{6} \sum_{l=1}^{17} FS(DIR = E, RT_l, LAG = 0, INFO = P, SD_j, SAT = G, ACC_k, TRK_l) \]  \hspace{1cm} (4.8)

Thus, \( MFS_C \) represents the MFS's of 720 (= 4 RT's x 6 SD's x 30 TRK's) cases. \( MFS_T \) represents the MFS's of 240 (= 4 RT's x 6 SD's x 10 TRK's) cases, and \( MFS_G \) represents the MFS's of 408 (= 4 RT's x 6 SD's x 17 TRK's) cases. Each bar in Figures 54 and 55 represents the MFS's of eastbound voyages for each ERP satellite combination. Also, we present the MFS's disaggregated by the O-D pairs and starting dates to show the influence.

The maximum MFS by accumulating 10 days of information of a 10-day ERP satellite with 8 days information of a 17-day ERP satellite is 5.44%. The maximum MFS by accumulating 10 days of information of a 10-day ERP satellite only is 4.51%, while the maximum MFS by accumulating 14 days of information of a 17-day ERP satellite only is 4.64%. The greatest MFS's with standard deviations of each SAT are shown in Figure 131, and the relative fuel savings frequency distributions of each SAT are shown in Figure 132 in the Appendix.

In Figure 54, each symbol which belongs to the same ERP satellite combination disaggregated by the O-D pairs represents the MFS of 180 (= 6 SD's x 30 TRK's) cases for
SAT = C, 60 (= 6 SD's × 10 TRK's) cases for SAT = T, and 102 (= 6 SD's × 17 TRK's) cases for SAT = G, respectively. In Figure 55, each symbol which belongs to the same ERP satellite combination disaggregated by the starting dates represents the MFS of 120 (= 4 RT's × 30 TRK's) cases for SAT = C, 40 (= 4 RT's × 10 TRK's) cases for SAT = T, and 68 (= 4 RT's × 17 TRK's) cases for SAT = G, respectively.

Results show that having two different ERP satellites simultaneously is always best regardless of O-D pair and best for 4 out of 6 stating dates. Those 2 in which it did not do as well as having 17-day ERP satellite had small MFS anyway. Having 10- and 17-day ERP satellites simultaneously results in more mean relative fuel savings by 0.80% compared to having a 17-day ERP satellite only, and by 0.93% compared to having a 10-day ERP satellite only for eastbound voyages.

4.4 Comparison of the MFS's for Westbound Voyages

We compare the maximum mean relative fuel savings (MFS) resulting from having two ERP satellites simultaneously to those resulting from having only one ERP satellite (either SAT = T or G) when we have real time information (LAG = 0) with the current velocity component profile perpendicular to the ground tracks (INFO = P). Each bar in Figures 56 and 57 represents the MFS of eastbound voyages for each ERP satellite combination.

As in Section 4.3, 10-day ERP satellite provides more recent temporal data but spatially sparse coverage, while 17-day ERP satellite provides more dense spatial coverage but temporally obsolete data. Thus, 10- and 17-day ERP satellites simultaneously provide more temporally recent data and more spatial coverage than having only one ERP satellite.

For westbound voyages, the mean relative fuel savings of having 10- and 17-day ERP
Figure 56: Comparison of Westbound MFS's under LAG = 0, INFO = P for each SAT, and Disaggregated for Each RT.

Figure 57: Comparison of Westbound MFS's under LAG = 0, INFO = P for each SAT, and Disaggregated for Each SD.
satellites simultaneously \( \text{MFS}(\text{DIR}_w, \text{LAG}_0, \text{INFO}_p, \text{SAT}_c, \text{ACC}_k) \) is defined as:

\[
\text{MFS}_c = \frac{1}{3 \times 6 \times 30} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{30} \text{FS}(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j, \text{SAT} = C, \text{ACC}_k, \text{TRK}_l)
\]

(4.9)

For having a 10-day ERP satellite, the \( \text{MFS}(\text{DIR}_w, \text{LAG}_0, \text{INFO}_p, \text{SAT}_r, \text{ACC}_k) \) is defined as:

\[
\text{MFS}_r = \frac{1}{3 \times 6 \times 10} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{10} \text{FS}(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j, \text{SAT} = T, \text{ACC}_k, \text{TRK}_l)
\]

(4.10)

For having a 17-day ERP satellite, the \( \text{MFS}(\text{DIR}_w, \text{LAG}_0, \text{INFO}_p, \text{SAT}_g, \text{ACC}_k) \) is defined as:

\[
\text{MFS}_g = \frac{1}{3 \times 6 \times 17} \sum_{i=5}^{7} \sum_{j=1}^{6} \sum_{l=1}^{17} \text{FS}(\text{DIR} = W, \text{RT}_i, \text{LAG} = 0, \text{INFO} = P, \text{SD}_j, \text{SAT} = G, \text{ACC}_k, \text{TRK}_l)
\]

(4.11)

Thus, \( \text{MFS}_c \) represents the MFS's of 540 (\( = 3 \text{ RT}'s \times 6 \text{ SD}'s \times 30 \text{ TRK}'s \)) cases. \( \text{MFS}_r \) represents the MFS's of 180 (\( = 3 \text{ RT}'s \times 6 \text{ SD}'s \times 10 \text{ TRK}'s \)) cases, and \( \text{MFS}_g \) represents the MFS's of 306 (\( = 3 \text{ RT}'s \times 6 \text{ SD}'s \times 17 \text{ TRK}'s \)) cases. We present the MFS's disaggregated by the O-D pairs and starting dates to show the influence.

The maximum MFS's by accumulating 10 days of information of a 10-day ERP satellite with 11 days information of a 17-day ERP satellite is 2.94%. The maximum MFS by accumulating 10 days of information of a 10-day ERP satellite only is 2.40%, while the maximum MFS by accumulating 14 days of information of a 17-day ERP satellite only is 1.94%. The greatest MFS's with standard deviations of each SAT are shown in Figure 133,
and the relative fuel savings frequency distributions of each SAT are shown in Figure 134 in the Appendix.

In Figure 56, each symbol which belongs to the same ERP satellite combination disaggregated by the O-D pairs represents the MFS's of 180 (= 6 SD's x 30 TRK's) cases for SAT = C, 60 (= 6 SD's x 10 TRK's) cases for SAT = T, and 102 (= 6 SD's x 17 TRK's) cases for SAT = G, respectively. In Figure 57, each symbol which belongs to the same ERP satellite combination disaggregated by the starting dates represents the MFS's of 90 (= 3 RT's x 30 TRK's) cases for SAT = C, 30 (= 3 RT's x 10 TRK's) cases for SAT = T, and 51 (= 3 RT's x 17 TRK's) cases for SAT = G, respectively.

Results show that having two different ERP satellites simultaneously is best for 2 out of 3 O-D pairs and best for 5 out of 6 stating dates. Those 2 in which it did not do as well as having 10-day ERP satellite had small MFS anyway. Having 10- and 17-day ERP satellites simultaneously results in more mean relative fuel savings by 1.00% compared to having a 17-day ERP satellite only, and by 0.54% compared to having a 10-day ERP satellite only for westbound voyages.

4.5 Summary

In this chapter, we investigated the increased fuel savings due to having two different exact repeat period (ERP) satellites simultaneously instead of having only one ERP satellite, either SAT = T or G each. We again measured the performance according to the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. First, we investigated desirable combinations for accumulating daily current information when we have 10- and 17-day ERP satellites simultaneously and identified the
corresponding maximum mean relative fuel savings. Then, we compared the maximum mean relative fuel savings (MFS) resulting from having two ERP satellites simultaneously to those resulting from having only one ERP satellite, each under the case of real time information with the current velocity component profile perpendicular to the ground tracks.

For eastbound routes, we maximized the overall mean relative fuel savings by accumulating up to 10 days of daily current information along the ground tracks of a 10-day ERP satellite, along with up to 8 days of accumulation of daily current information along the ground tracks of a 17-day ERP satellite simultaneously. The maximum mean relative fuel savings was 5.44%. For westbound routes, we maximized the overall mean relative fuel savings by accumulating up to 10 days of daily current information along the ground tracks of a 10-day ERP satellite along with up to 11 days of accumulation of daily current information along the ground tracks of a 17-day ERP satellite simultaneously. The maximum mean relative fuel savings was 2.94%.

The results from the comparison of the MFS’s for eastbound voyages show that having two different ERP satellites simultaneously performs better than having only one ERP satellite. Having 10- and 17-day ERP satellites simultaneously results in 0.80% more mean relative fuel savings compared to having a 17-day ERP satellite only, and 0.93% more mean relative fuel savings compared to having a 10-day ERP satellite only for eastbound voyages. The results from the comparison of the MFS’s for westbound voyages show that having two different ERP satellites simultaneously performs better than having only one ERP satellite. Having 10- and 17-day ERP satellites simultaneously results in 1.00% more mean relative fuel savings compared to having a 17-day ERP satellite only and 0.54% more
mean relative fuel savings compared to having a 10-day ERP satellite only for westbound voyages. These increases in overall mean relative fuel savings represent an increase of between 17 and 50% of those that would be obtained with a single ERP satellite.

As in Chapter III, a more disaggregate analysis of the results in Sections 4.1 and 4.2 show that the benefit of choosing one accumulation scheme over another depends on O-D pairs and starting dates. We, however, need to fix an accumulation scheme for the rest of this study. Thus, we choose the accumulation schemes (ACC) which provide the greatest overall mean relative fuel savings. Specifically, for 10- and 17-day ERP satellites case, we choose the accumulation schemes of ACC_{Tin,Gn} for eastbound, and ACC_{Tin,G11} for westbound voyages.
CHAPTER V

Most Advantageous O-D Pairs for Ship Routing

In this chapter, we investigate which O-D pairs are the most advantageous for strategic ship routing purposes when we utilize the ocean current information derived from the satellite altimeter measurements. In Chapter II, we clustered the mean relative fuel savings (MFS) taken across the O-D pairs and starting dates into 4 groups for eastbound and 3 groups for westbound voyages. Specifically, we clustered the MFS’s as: high, medium, low, and special mean fuel savings groups for eastbound, and high, medium, and low mean fuel savings groups for westbound voyages. Special in the eastbound voyages referred to the O-D pair whose origin and destination are “above” the Gulf Stream.

We, however, computed the MFS’s under the ideal conditions in which we can predict the full (not partial component only) current velocity profile. Moreover, we have current information not only along the ground tracks, but also between them in advance for all time periods of interest. If those O-D pairs in high mean fuel savings group perform consistently better than other O-D pairs under various conditions, the routing industry might concentrate on those specific O-D pairs which result in more mean relative fuel savings. Then, the shipping industry could materialize more benefits in terms of mean relative fuel savings.

In Chapter III and Chapter IV, we presented the MFS’s disaggregated with respect to
the O-D pairs and the starting dates to show the influence when we compared the MFS’s to determine the desirable accumulation schemes under different conditions, e.g., different information schemes. The disaggregated MFS’s with respect to the O-D pairs seemed to show systematic patterns for both eastbound and westbound voyages. Specifically, for eastbound voyages, an O-D pair whose origin and destination are “in” the Gulf Stream (I-I) and an O-D pair whose origin and destination are “above” the Gulf Stream (A-A) tended to outperform the other O-D pairs. For westbound voyages, an O-D pair whose origin and destination are “in” the Gulf Stream (I-I) tended to outperform the other O-D pairs.

Here, we ask: What are the most advantageous O-D pairs for strategic ship routing purposes when we utilize the ocean current information? More specifically, do O-D pairs whose origin and destination are “in” the Gulf Stream (I-I), and “above” the Gulf Stream (A-A) result in more mean relative savings than an O-D pair whose origin and destination are “below” the Gulf Stream (B-B) and an O-D pair whose origin is “above” the Gulf Stream and destination is “below” the Gulf Stream (A-B) for eastbound voyages? Does an O-D pair whose origin and destination are “in” the Gulf Stream (I-I) result in more mean relative savings than an O-D pair whose origin and destination are “below” the Gulf Stream (B-B), and an O-D pair whose origin is “below” the Gulf Stream and destination is “above” the Gulf Stream (B-A) for westbound voyages? In other words, we compare O-D pairs (I-I) and (A-A) to O-D pairs (B-B) and (A-B) based on the MFS’s for eastbound voyages. For westbound voyages, we compare an O-D pair (I-I) to O-D pairs (B-B) and (B-A) based on the MFS’s.

We again measure the performance based on the relative fuel savings on the routes.
resulting from optimizing fuel consumption compared to the great circle routes. Then, we compare 8 different scenarios with respect to the MFS's taken across the starting dates for each O-D pair. Specifically, we consider 6 scenarios in which we accumulate daily current information along the ground tracks (INFO = M and P, with and without time lag, INFO = F without time lag, and INFO = P with 2 ERP satellites), and 2 scenarios in which there is no accumulation scheme of daily current information along the ground tracks (INFO = Ft and Nt).

For the 6 scenarios involving daily information accumulation, we choose the accumulation schemes (ACC) which resulted in the greatest mean relative fuel savings from Table 6 for a 10-day ERP satellite and from Table 11 for a 17-day ERP satellite in Chapter III. For the combined 10- and 17-day ERP satellites scenario, we again choose the accumulation schemes (ACC) which resulted in the greatest mean relative fuel savings identified in Chapter IV. We summarize these ACC's in Table 16 for eastbound and in Table 17 for westbound voyages.

We define the MFS's taken across the 6 starting dates (SD) for each O-D pair as follows. For information schemes in which we need to accumulate daily current information along the ground tracks – INFO = M, P, and F – regardless of the time lag we define the MFS for each O-D pair RTi and accumulation scheme ACCk as:

$$MFS(DIR, LAG, RT_i, INFO, SAT_T, ACC_k) =$$

$$\frac{1}{6 \times 10} \sum_{j=1}^{6} \sum_{i=1}^{10} FS(DIR, LAG, RT_i, INFO, SD_j, SAT = T, ACC_k, TRK_i)$$

(5.1)

for a 10-day ERP satellite;

$$MFS(DIR, LAG, RT_i, INFO, SAT_G, ACC_k) =$$

$$\frac{1}{6 \times 17} \sum_{j=1}^{6} \sum_{i=1}^{17} FS(DIR, LAG, RT_i, INFO, SD_j, SAT = G, ACC_k, TRK_i)$$

(5.2)
Table 16: ACC’s for the Greatest MFS’s for Eastbound Voyages.

<table>
<thead>
<tr>
<th>SAT</th>
<th>LAG</th>
<th>INFO</th>
<th>MFS (%)</th>
<th>ACC</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>0</td>
<td>M</td>
<td>2.98</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P</td>
<td>4.51</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F</td>
<td>4.48</td>
<td>10</td>
</tr>
<tr>
<td>G</td>
<td>M</td>
<td>2.72</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>P</td>
<td>4.64</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>4.99</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>P</td>
<td>5.44</td>
<td>T₁₀G₈</td>
<td></td>
</tr>
<tr>
<td>T</td>
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<td>M</td>
<td>0.83</td>
<td>7</td>
</tr>
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<td>G</td>
<td>M</td>
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<tr>
<td></td>
<td>P</td>
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<td>11</td>
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</table>

Table 17: ACC’s for the Greatest MFS’s for Westbound Voyages.

<table>
<thead>
<tr>
<th>SAT</th>
<th>LAG</th>
<th>INFO</th>
<th>MFS (%)</th>
<th>ACC</th>
</tr>
</thead>
<tbody>
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<td>M</td>
<td>0.97</td>
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<td></td>
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<td>G</td>
<td>M</td>
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<td>C</td>
<td>P</td>
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<td>T₁₀G₁₁</td>
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<td>7</td>
<td>M</td>
<td>-0.11</td>
<td>7</td>
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<tr>
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<td>M</td>
<td>-0.48</td>
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<tr>
<td></td>
<td>P</td>
<td>0.53</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>
for a 17-day ERP satellite; and

\[
\text{MFS}(\text{DIR}, \text{LAG}, \text{RT}_i, \text{INFO}, \text{SAT}_C, \text{ACC}_k) = \frac{1}{6} \times 30 \sum_{j=1}^{6} \sum_{l=1}^{30} \text{FS}(\text{DIR}, \text{LAG} = 0, \text{RT}_l, \text{INFO} = \text{P}, \text{SD}_j, \text{SAT} = \text{C}, \text{ACC}_k, \text{TRK}_i)
\]

(5.3)

for 10- and 17-day ERP satellites. We, however, consider 4 starting dates for a 17-day ERP satellite with "near" real-time information (LAG = 7, SAT = G) because we cannot accumulate up to even 14 days of daily current information for the other 2 starting dates. For information schemes in which there is no accumulation of daily current information along the ground tracks – INFO = Ft or Nt – we define the MFS as:

\[
\text{MFS}(\text{DIR}, \text{RT}_i, \text{INFO}) = \frac{1}{6} \sum_{j=1}^{6} \text{FS}(\text{DIR}, \text{RT}_i, \text{INFO}, \text{SD}_j)
\]

(5.4)

The results show that the O-D pairs whose origin and destination are "in" the Gulf Stream (I-I) and "above" the Gulf Stream (A-A) result in more mean relative savings than other O-D pairs for eastbound voyages. For westbound voyages, an O-D pair whose origin and destination are "in" the Gulf Stream (I-I) results in more mean relative savings than other O-D pairs.

5.1 Eastbound Voyages

For eastbound voyages, we summarize the mean relative fuel savings (MFS) taken across the 6 starting dates for each O-D pair in Figure 58 for a 10-day ERP satellite and in Figure 59 for a 17-day ERP satellite, respectively. Each bar for INFO = Ft and Nt in both Figures 58 and 59 represents the MFS computed with Equation (5.4) for each O-D pair. Thus, it is an MFS taken across 6 (=6 SD's) starting dates. Each bar for INFO = F, P, and M in Figure
Figure 58: Eastbound MFS's of Each O-D Pair under Each INFO with LAG = 0 for SAT = T. Subscript C represents SAT = C, and 7 represents LAG = 7.

Figure 59: Eastbound MFS's of Each O-D Pair under Each INFO with LAG = 0 for SAT = G. Subscript C represents SAT = C, and 7 represents LAG = 7.
58 and 59 represents the MFS computed with Equations (5.1) and (5.2) for each O-D pair. Thus, it is an MFS taken across 60 (=6 SD's x 10 TRK's) cases in Figure 58, while each bar in Figure 59 for the same information schemes represents an MFS taken across 102 (=6 SD's x 17 TRK's) cases. For 10- and 17-day ERP satellites case, each bar for INFO = P in Figures 58 and 59 represents the MFS computed with Equations (5.3) for each O-D pair. Thus, it is an MFS taken across 180 (=6 SD's x 30 TRK's) cases.

The MFS's taken across the 6 starting dates for each O-D pair when we have full velocity profiles of the ocean current with forecast capability not only along the ground tracks but also between the ground tracks (INFO = Ft) are: 14.77% for RT1, 10.16% for RT2, 14.66% for RT3, and 7.50% for RT4. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 18. Based on the overall mean relative fuel savings comparison under INFO = Ft, RT1 and RT3 result in more mean relative fuel savings than other O-D pairs. It is interesting to note that RT2 and RT4 still perform well in the INFO = Ft case, however.

The MFS's taken across the 6 starting dates for each O-D pair when we have full velocity profiles of the ocean current with nowcast capability not only along the ground tracks but also between the ground tracks (INFO = Nt) are: 14.36% for RT1, 9.72% for RT2, 13.85% for RT3, and 6.75% for RT4. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 19. Again, based on the overall mean relative fuel savings comparison under INFO = Nt, RT1 and RT3 result in more mean relative fuel savings than other O-D pairs. As in INFO = Ft, RT2 and RT4 still perform well when INFO = Nt.
Table 18: Ranks of MFS's for Each Starting Date with INFO = Ft for Eastbound Voyages.

<table>
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<tr>
<th>LAG</th>
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<th>4</th>
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<tbody>
<tr>
<td>0</td>
<td>Ft</td>
<td>SD₁</td>
<td>RT₁</td>
<td>RT₄</td>
<td>RT₂</td>
<td>RT₃</td>
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<td></td>
<td></td>
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<td>RT₁</td>
<td>RT₃</td>
<td>RT₂</td>
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<td>SD₃</td>
<td>RT₃</td>
<td>RT₁</td>
<td>RT₂</td>
<td>RT₄</td>
</tr>
<tr>
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<td></td>
<td>SD₄</td>
<td>RT₁</td>
<td>RT₃</td>
<td>RT₂</td>
<td>RT₄</td>
</tr>
<tr>
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<td></td>
<td>SD₅</td>
<td>RT₁</td>
<td>RT₃</td>
<td>RT₂</td>
<td>RT₄</td>
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</table>

Table 19: Ranks of MFS's for Each Starting Date with INFO = Nt for Eastbound Voyages.

<table>
<thead>
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<th>LAG</th>
<th>INFO</th>
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<td>RT₃</td>
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<tr>
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<td>SD₃</td>
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<td>RT₁</td>
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</table>
The MFS’s taken across 60 (=6 SD’s × 10 TRK’s) cases for each O-D pair for a 10-day ERP satellite when we have real-time full velocity profile of the ocean current along the ground tracks (LAG = 0, INFO = F, SAT = T) are: 8.72% for RT₁, 1.94% for RT₂, 6.10% for RT₃, and 1.21% for RT₄. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 20. Based on the overall mean relative fuel savings comparison under LAG = 0, INFO = F, and SAT = T, RT₁ and RT₃ result in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 102 (=6 SD’s × 17 TRK’s) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 0, INFO = F) are: 8.25% for RT₁, 2.99% for RT₂, 6.80% for RT₃, and 1.93% for RT₄. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 20. Again, based on the overall mean relative fuel savings comparison under LAG = 0, INFO = F, and SAT = G, RT₁ and RT₃ result in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 60 (=6 SD’s × 10 TRK’s) cases for each O-D pair for a 10-day ERP satellite when we have real-time partial velocity component profile of the ocean current along the ground tracks (LAG = 0, INFO = P, SAT = T) are: 8.03% for RT₁, 2.05% for RT₂, 6.42% for RT₃, and 1.55% for RT₄. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 21. Based on the overall mean relative fuel savings comparison under LAG = 0, INFO = P, and SAT = T, RT₁ and RT₃ result in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 102 (=6 SD’s × 17 TRK’s) cases for each O-D pair for a 17-day
Table 20: Ranks of MFS’s for Each Starting Date with INFO = F, LAG = 0, SAT = T and G for Eastbound Voyages.

<table>
<thead>
<tr>
<th>LAG</th>
<th>INFO</th>
<th>SAT</th>
<th>SD</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<tr>
<td>0</td>
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<td>SD₂</td>
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<td>RT₁</td>
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<td>RT₃</td>
<td>RT₁</td>
<td>RT₂</td>
<td>RT₄</td>
</tr>
</tbody>
</table>

ERP satellite (SAT = G) under the same conditions (LAG = 0, INFO = P) are: 7.86% for RT₁, 3.05% for RT₂, 6.34% for RT₃, and 1.56% for RT₄. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 21. Again, based on the overall mean relative fuel savings comparison under LAG = 0, INFO = P, and SAT = G, RT₁ and RT₃ result in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 180 (=6 SD’s x 30 TRK’s) cases for each O-D pair when we have real-time partial velocity component profile of the ocean current along the ground tracks of 10- and 17-day ERP satellites simultaneously (SAT = C) under the same conditions (LAG = 0, INFO = P) are: 8.68% for RT₁, 3.69% for RT₂, 7.45% for RT₃, and 2.51%
Table 21: Ranks of MFS’s for Each Starting Date with INFO = P, LAG = 0, SAT = T and G for Eastbound Voyages.

<table>
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<tr>
<th>LAG</th>
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<th>SAT</th>
<th>Rank</th>
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<td>SD6</td>
<td>RT3</td>
<td>RT1</td>
<td>RT2</td>
<td>RT4</td>
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</tbody>
</table>

% for RT4. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 22. Again, based on the overall mean relative fuel savings comparison under LAG = 0, INFO = P, and SAT = C, RT1 and RT3 result in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 60 (=6 SD’s x 10 TRK’s) cases for each O-D pair for a 10-day ERP satellite when we have real-time partial velocity component profile of the ocean current estimated with a modified hydrographic approach along the ground tracks (LAG = 0, INFO
= M, SAT = T) are: 5.63% for RT₁, 1.40% for RT₂, 4.33% for RT₃, and 0.56% for RT₄.

The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 22. Based on the overall mean relative fuel savings comparison under LAG = 0, INFO = M, and SAT = T, RT₁ and RT₃ result in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 102 (=6 SD's x 17 TRK's) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 0, INFO = M) are: 3.90% for RT₁, 2.11% for RT₂, 4.37% for RT₃, and 0.89% for RT₄. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 22. Again, based on the overall mean relative fuel savings comparison under LAG = 0, INFO = M, and SAT = G, RT₁ and RT₃ result in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 60 (=6 SD's x 10 TRK's) cases for each O-D pair for a 10-day ERP satellite when we have "near" real-time partial velocity component profile of the ocean current along the ground tracks (LAG = 7, INFO = P, SAT = T) are: 5.96% for RT₁, 0.09% for RT₂, 4.58% for RT₃, and 0.04% for RT₄. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 23. Based on the overall mean relative fuel savings comparison under LAG = 7, INFO = P, and SAT = T, RT₁ and RT₃ result in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 102 (=6 SD's x 17 TRK's) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 7, INFO = P) are: 5.04%
Table 22: Ranks of MFS's for Each Starting Date with INFO = M, LAG = 0, SAT = T and G for Eastbound Voyages.

<table>
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</tr>
</thead>
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<td>T</td>
<td>SD1</td>
<td>RT3, RT1, RT4, RT2, RT3</td>
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<td></td>
<td>SD3</td>
<td>RT3, RT1, RT4, RT2</td>
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<td>SD4</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>SD6</td>
<td>RT3, RT1, RT2, RT4</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td>SD1</td>
<td>RT1, RT4, RT2, RT3</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>SD6</td>
<td>RT1, RT3, RT2, RT4</td>
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</table>

for RT1, 1.79% for RT2, 6.27% for RT3, and 0.17% for RT4. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 23. Again, based on the overall mean relative fuel savings comparison under LAG = 7, INFO = P, and SAT = G, RT1 and RT3 result in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 60 (=6 SD's x 10 TRK's) cases for each O-D pair for a 10-day ERP satellite when we have “near” real-time partial velocity component profile of the ocean current estimated with a modified hydrographic approach along the ground tracks (LAG = 7, INFO = M, SAT = T) are: 2.18% for RT1, -0.43% for RT2, 2.14% for RT3, and 0.06% for RT4. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings...
Table 23: Ranks of MFS’s for Each Starting Date with INFO = P, LAG = 7, SAT = T and G for Eastbound Voyages.

<table>
<thead>
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<td></td>
<td></td>
<td></td>
<td>RT_4</td>
</tr>
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</table>

performance for each starting date are summarized in Table 24. Based on the overall mean relative fuel savings comparison under LAG = 7, INFO = M, and SAT = T, RT_1 and RT_3 result in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 102 (=6 SD's x 17 TRK's) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 7, INFO = M) are: 1.94% for RT_1, 1.09% for RT_2, 4.94% for RT_3, and -0.01% for RT_4. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 24. Based on the overall mean relative fuel savings comparison under LAG = 7, INFO = P, and SAT = G, RT_1 and RT_3 result in more mean relative fuel savings than other O-D pairs.
Table 24: Ranks of MFS's for Each Starting Date with INFO = M, LAG = 7, SAT = T and G for Eastbound Voyages.

<table>
<thead>
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<td>RT1</td>
<td>RT3</td>
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</tbody>
</table>

5.2 Westbound Voyages

For westbound voyages, we summarize the mean relative fuel savings (MFS) taken across the 6 starting dates for each O-D pair in Figure 60 for a 10-day ERP satellite and in Figure 61 for a 17-day ERP satellite. Each bar for INFO = Ft and Nt in both Figures 60 and 61 represents the MFS computed with Equation (5.4) for each O-D pair. Thus, it is an MFS taken across 6 (=6 SD's) starting dates. Each bar for INFO = F, P, and M in Figure 60 and 61 represents the MFS computed with Equations (5.1) and (5.2) for each O-D pair. Thus, it is an MFS taken across 60 (=6 SD's x 10 TRK's) cases in Figure 60, while each bar in Figure 61 for the same information schemes represents an MFS taken across 102 (=6 SD's x 17 TRK's) cases. For 10- and 17-day ERP satellites case, each bar for INFO = P in Figures 60 and 61 represents the MFS computed with Equations (5.3) for each O-D
Figure 60: Westbound MFS's of Each O-D Pair under Each INFO with LAG = 0 for SAT = T. Subscript C represents SAT = C, and 7 represents LAG = 7.

Figure 61: Westbound MFS's of Each O-D Pair under Each INFO with LAG = 0 for SAT = G. Subscript C represents SAT = C, and 7 represents LAG = 7.
pair. Thus, it is an MFS taken across 180 (=6 SD's x 30 TRK's) cases.

The MFS's taken across the 6 starting dates for each O-D pair when we have full velocity profiles of the ocean current with forecast capability not only along the ground tracks but also between the ground tracks (INFO = Ft) are: 9.24% for RT5, 5.23% for RT6, and 6.83% for RT7. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 25. Based on the overall mean relative fuel savings comparison under INFO = Ft, RT5 results in more mean relative fuel savings than other O-D pairs. It is interesting to note that RT6 and RT7 still perform well in the INFO = Ft case.

The MFS's taken across the 6 starting dates for each O-D pair when we have full velocity profiles of the ocean current with nowcast capability not only along the ground tracks but also between the ground tracks (INFO = Nt) are: 8.90% for RT5, 4.80% for RT6, and 6.25% for RT7. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 26. Again, based on the overall mean relative fuel savings comparison under INFO = Nt, RT5 results in more mean relative fuel savings than other O-D pairs. As in INFO = Ft, RT6 and RT7 still perform well in the INFO = Nt case.

The MFS's taken across 60 (=6 SD's x 10 TRK's) cases for each O-D pair for a 10-day ERP satellite when we have real-time full velocity profile of the ocean current along the ground tracks (LAG = 0, INFO = F, SAT = T) are: 4.41% for RT5, 1.37% for RT6, and 1.53% for RT7. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 27. Based on the overall mean
Table 25: Ranks of MFS’s for Each Starting Date with INFO = Ft for Westbound Voyages.

<table>
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Table 26: Ranks of MFS’s for Each Starting Date with INFO = Nt for Westbound Voyages.

<table>
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</table>
Table 27: Ranks of MFS's for Each Starting Date with INFO = F, LAG = 0, SAT = T and G for Westbound Voyages.

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</tr>
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</table>

relative fuel savings comparison under LAG = 0, INFO = F, and SAT = T, RT5 results in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 102 (=6 SD's x 17 TRK's) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 0, INFO = F) are: 4.18% for RT5, 2.03% for RT6, and 1.19% for RT7. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 27. Based on the overall mean relative fuel savings comparison under LAG = 0, INFO = F, and SAT = G, RT5 results in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 60 (=6 SD's x 10 TRK's) cases for each O-D pair for a 10-day ERP satellite when we have real-time partial velocity component profile of the ocean current
along the ground tracks (LAG = 0, INFO = P, SAT = T) are: 4.14% for RT₅, 1.36% for RT₆, and 1.70% for RT₇. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 28. Based on the overall mean relative fuel savings comparison under LAG = 0, INFO = F, and SAT = T, RT₅ results in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 102 (=6 SD's x 17 TRK's) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 0, INFO = P) are: 4.02% for RT₅, 1.56% for RT₆, and 0.65% for RT₇. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 28. Again, based on the overall mean relative fuel savings comparison under LAG = 0, INFO = P, and SAT = G, RT₅ results in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 180 (=6 SD's x 30 TRK's) cases for each O-D pair when we have real-time partial velocity component profile of the ocean current along the ground tracks of 10- and 17-day ERP satellites simultaneously (SAT = C) under the same conditions (LAG = 0, INFO = P) are: 4.79% for RT₅, 2.76% for RT₆, and 1.87% for RT₇. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 28. Again, based on the overall mean relative fuel savings comparison under LAG = 0, INFO = P, and SAT = C, RT₅ results in more mean relative fuel savings than other O-D pairs.

The MFS's taken across 60 (=6 SD's x 10 TRK's) cases for each O-D pair for a 10-day ERP satellite when we have real-time partial velocity component profile of the ocean current estimated with a modified hydrographic approach along the ground tracks (LAG =
Table 28: Ranks of M FS’s for Each Starting Date with INFO = P, LAG = 0, SAT = T and G for Westbound Voyages.

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0, INFO = M, SAT = T) are: 1.21% for RT5, 1.18% for RT6, and 0.80% for RT7. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 29. Based on the overall mean relative fuel savings comparison under LAG = 0, INFO = M, and SAT = T, there is no clearly dominant O-D pair for strategic routing purposes. RT5 and RT6, however, result in more mean relative fuel savings than RT7.

The MFS’s taken across 102 (=6 SD’s × 17 TRK’s) cases for each O-D pair for a 17-day
Table 29: Ranks of MFS’s for Each Starting Date with INFO = M, LAG = 0, SAT = T and G for Westbound Voyages.

<table>
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<td>SD5</td>
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<td>SD6</td>
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</table>

ERP satellite (SAT = G) under the same conditions (LAG = 0, INFO = M) are: -0.78% for RT5, 0.69% for RT6, and 0.38% for RT7. The ranks of the O-D pairs (RT's) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 29. Based on the overall mean relative fuel savings comparison under LAG = 0, INFO = M, and SAT = G, there is no clearly dominant O-D pair for strategic routing purposes. Note that RT5 results in worse mean relative fuel savings than other O-D pairs.

The MFS’s taken across 60 (=6 SD’s × 10 TRK’s) cases for each O-D pair for a 10-day ERP satellite when we have “near” real-time partial velocity component profile of the ocean current along the ground tracks (LAG = 7, INFO = P, SAT = T) are: 3.56% for RT5, 0.24% for RT6, and 1.04% for RT7. The ranks of the O-D pairs (RT’s) corresponding to overall
Table 30: Ranks of MFS’s for Each Starting Date with INFO = P, LAG = 7, SAT = T and G for Westbound Voyages.

<table>
<thead>
<tr>
<th>LAG</th>
<th>INFO</th>
<th>SAT</th>
<th>Rank</th>
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<tbody>
<tr>
<td>7</td>
<td>P</td>
<td>T</td>
<td>SD1</td>
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<td>RT7</td>
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<td>SD5</td>
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<td>RT5</td>
</tr>
<tr>
<td></td>
<td>SD6</td>
<td></td>
<td>RT5</td>
</tr>
</tbody>
</table>

mean fuel savings performance for each starting date are summarized in Table 30. Based on the overall mean relative fuel savings comparison under LAG = 7, INFO = P, and SAT = T, RT5 results in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 102 (=6 SD’s x 17 TRK’s) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 7, INFO = P) are: 1.39% for RT5, 0.96% for RT6, and -0.05% for RT7. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 30. Again, based on the overall mean relative fuel savings comparison under LAG = 7, INFO = P, and SAT = T, RT5 results in more mean relative fuel savings than other O-D pairs.

The MFS’s taken across 60 (=6 SD’s x 10 TRK’s) cases for each O-D pair for a 10-day ERP satellite when we have “near” real-time partial velocity component profile of the ocean
current estimated with a modified hydrographic approach along the ground tracks (LAG = 7, INFO = M, SAT = T) are: -0.19% for RT₅, 0.03% for RT₆, and -0.16% for RT₇. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 31. Based on the overall mean relative fuel savings comparison under LAG = 7, INFO = M, and SAT = T, there is no desirable O-D pair for strategic routing purposes. Note that RT₅ results in worse mean relative fuel savings than other O-D pairs.

The MFS’s taken across 102 (=6 SD’s x 17 TRK’s) cases for each O-D pair for a 17-day ERP satellite (SAT = G) under the same conditions (LAG = 7, INFO = M) are: -1.97% for RT₅, 1.01% for RT₆, and 0.63% for RT₇. The ranks of the O-D pairs (RT’s) corresponding to overall mean fuel savings performance for each starting date are summarized in Table 31. Based on the overall mean relative fuel savings comparison under LAG = 7, INFO = M, and SAT = G, there is no clearly dominant O-D pair for strategic routing purposes. Also, note that RT₅ results in worse mean relative fuel savings than other O-D pairs.

5.3 Summary

In this chapter, we investigated which O-D pairs were the most advantageous for strategic ship routing purposes when we utilize the ocean current information derived from the satellite altimeter measurements. If O-D pairs in the high mean fuel savings group identified in Chapter II would perform consistently better than other O-D pairs under various conditions, the routing industry might concentrate on those specific O-D pairs which would result in more mean relative fuel savings with satellite altimeter-based current information for strategic ship routing purposes. Then, the shipping industry could materialize more
Table 31: Ranks of MFS's for Each Starting Date with INFO = M, LAG = 7, SAT = T and G for Westbound Voyages.

<table>
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<tr>
<th>LAG</th>
<th>INFO</th>
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<th>Rank</th>
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<tr>
<td>7</td>
<td>M</td>
<td>T</td>
<td>SD1</td>
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<td>SD6</td>
<td>RT7</td>
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benefits in terms of mean relative fuel savings.

We raised two questions. Specifically, do RT1 and RT3 result in more relative fuel savings than RT2 and RT4 for eastbound voyages? In other words, do O-D pairs whose origin and destination are “in” the Gulf Stream (I-I) and “above” the Gulf Stream (A-A) result in more mean relative savings than an O-D pair whose origin and destination are “below” the Gulf Stream (B-B) and an O-D pair whose origin is “above” the Gulf Stream and destination is “below” the Gulf Stream (A-B) for eastbound voyages?

Another question was: Does RT5 result in more relative fuel savings than RT6 and RT7 for westbound voyages? In other words, does an O-D pair whose origin and destination are “in” the Gulf Stream (I-I) result in more mean relative savings than an O-D pair whose origin and destination are “below” the Gulf Stream (B-B) and an O-D pair whose origin is
“below” the Gulf Stream and destination is “above” the Gulf Stream (B-A) for westbound voyages?

We measured the performance based on the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. Then, we compared 8 different scenarios with respect to the MFS’s taken across the starting dates for each O-D pair. Specifically, we considered 6 scenarios in which we accumulated daily current information along the ground tracks (INFO = M and P, with and without time lag, INFO = F without time lag, and INFO = P with 2 ERP satellites) and 2 scenarios in which there was no accumulation scheme of daily current information along the ground tracks (INFO = Ft and Nt).

For eastbound voyages, we summarized the mean relative fuel savings taken across the 6 starting dates in Figure 58 for a 10-day ERP satellite and in Figure 59 for a 17-day ERP satellite, respectively. Also, we summarized the rank of the mean fuel savings performance taken across each starting date for each O-D pair in Tables 18 through 24.

Based on the comparison of O-D pairs’ mean fuel savings performance and the rank of the MFS’s, we answer the first question: do O-D pairs whose origin and destination are “in” the Gulf Stream (I-I) and “above” the Gulf Stream (A-A) result in more mean relative savings than other O-D pairs for eastbound voyages?

The answer is yes. The O-D pairs whose origin and destination are “in” the Gulf Stream (I-I) and “above” the Gulf Stream (A-A) consistently resulted in more mean relative savings than other O-D pairs. Also, it is interesting to note that the other O-D pairs still performed well when we had full velocity profiles of the ocean current not only along the ground
tracks, but also between the ground tracks with forecast or nowcast capabilities ($INFO = Ft$ or $Nt$).

For westbound voyages, we summarized the mean relative fuel savings taken across the 6 starting dates in Figure 60 for a 10-day exact repeat period (ERP) satellite and in Figure 61 for a 17-day ERP satellite, respectively. Also, we summarized the rank of the mean fuel savings performance taken across each starting date for each O-D pair in Tables 25 through 31.

Based on the comparison of O-D pairs' mean fuel savings performance and the rank of the MFS's, we answer the second question: does an O-D pair whose origin and destination are "in" the Gulf Stream ($I$-$I$) result in more mean relative savings than other O-D pairs for westbound voyages?

The answer is yes with few exceptions. An O-D pair whose origin and destination are "in" the Gulf Stream ($I$-$I$) consistently resulted in more mean fuel savings than other O-D pairs, except when we had a "near" real-time partial velocity component profile of the ocean current estimated with a modified hydrographic approach along the ground tracks for each of the 10- and 17-day satellites ($LAG = 7, INFO = M, SAT = T$ and $G$), and when we had real-time partial velocity component profile of the ocean current estimated with a modified hydrographic approach along the ground tracks for a 17-day satellite ($LAG = 0, INFO = M, SAT = G$). In these cases, an O-D pair whose origin and destination are "in" the Gulf Stream ($I$-$I$) resulted in the worst mean relative fuel savings, while an O-D pair whose origin and destination are "below" the Gulf Stream performed best. Also, it is interesting to note that other O-D pairs still performed well when we had full velocity profiles of the
ocean current not only along the ground tracks, but also between the ground tracks with forecast or nowcast capabilities (INFO = Ft or Nt).

We identified the most advantageous O-D pairs which resulted in more mean relative fuel savings for strategic ship routing purposes when the ocean current information derived from the satellite altimeter measurements. We use those most advantageous O-D pairs for both direction of voyages in Chapter VI to investigate where we should concentrate future research efforts for better routing performance.
CHAPTER VI

Effect of Information Scheme

In this chapter, we investigate the effect of information scheme with respect to the O-D pairs which resulted in greater mean relative fuel savings for both eastbound and westbound voyages identified in Chapter V. The results of this investigation provide directions for further research for better ocean routing performance by identifying the effect of each different information scheme. We defined each information scheme and time lag in Chapter II. We briefly review the meaning of them here. Then, we raise specific questions to address.

INFO = M represents that we do not know the geoid information accurately enough for routing purposes. We model this scenario to simulate a modified hydrographic approach. It is one of several methods to mitigate the problem of not having an accurate geoid model developed by Lo (1991). This information scheme represents currently available technology. To simulate this approach, we sample ocean current information obtained from the Harvard data along the satellite ground tracks and subtract off the annual mean velocity. We have the velocity component profile of the ocean current only perpendicular to the ground tracks, and they are available on a daily basis for those sampled on that day.

INFO = P represents a scenario when we know geoid information perfectly for routing purposes. This case represents a more advanced information scheme than INFO = M. As
in the INFO = M case, in the INFO = P case we have the velocity component profile of the ocean current along the satellite ground tracks only perpendicular to the ground tracks, and these components are available on a daily basis for those sampled on that day.

INFO = F represents a more advanced information scheme than INFO = P. It is the same as INFO = P, except that we have the a full velocity profile of the ocean currents along the satellite ground tracks rather than the velocity component profile only perpendicular to the ground tracks.

INFO = Nt represents having a full velocity profiles of ocean current with nowcast capability. That is, we have full current information each day of the voyage. This case represents a more advanced information scheme than INFO = F. This scheme provides full velocity profile of the ocean current information as in INFO = F, but it provides current information for the whole study region rather than along the ground tracks only. In other words, INFO = Nt provides a full velocity profile not only along the ground tracks, but also between the ground tracks.

INFO = Ft represents having full velocity profiles of ocean current with forecast capability. That is, in this scenario we have the perfect full velocity profile of the current information in advance. This information scheme represents the most advanced for routing purpose. It is an ideal case. We need to have perfect geoid information, an interpolation model, and a forecasting model for this information scheme.

Time lag represents the time delay between the altimeter measurements and the delivery of them to the user community. The time lag may be due to various reasons. LAG = 0 represents a real-time information supply, and LAG = 7 represents information supply
corresponding to a 7-day time lag. That is, we assume that the information available is that which was sampled 7 days previously. We call this "near" real-time, and consider it because there will usually be a time delay in delivering the data to the general public due to security and institutional reasons (Lo, 1991).

As we review the meaning of each information scheme and time lag, we notice that there are differences among information schemes. We summarize the differences as follows. The only difference between INFO = Ft and INFO = Nt is whether we can predict the current pattern in advance or not. Thus, when we take the fuel savings differences between INFO = Ft and Nt, these differences are due to the effect of forecasting capability. We call \( \Delta \text{MFS}(Ft - Nt) \) the effect of forecasting capability and define it as:

\[
\Delta \text{MFS}(Ft - Nt) = \frac{1}{6} \sum_{j=1}^{6} \left( \text{FS}(\text{DIR}, RT_j, LAG = 0, INFO = Ft, SD_j) - \text{FS}(\text{DIR}, RT_j, LAG = 0, INFO = Nt, SD_j) \right)
\]

for \( i = 1 \) and 3 for \( \text{DIR} = E \), and \( i = 5 \) for \( \text{DIR} = W \).

The only difference between INFO = Nt and INFO = F is whether we have current information everywhere or only along the ground tracks. Thus, when we take the fuel savings differences between INFO = Nt and F, these differences are due to the effect of spatial interpolation. We call \( \Delta \text{MFS}(Nt - F) \) the effect of spatial interpolation and define it as:

\[
\Delta \text{MFS}(Nt - F) = \frac{1}{6 \times n} \sum_{j=1}^{6} \sum_{k=1}^{n} \left( \text{FS}(\text{DIR}, RT_i, LAG = 0, INFO = Nt, SD_j, SAT) - \text{FS}(\text{DIR}, RT_i, LAG = 0, INFO = F, SD_j, SAT, ACC, TRK_k) \right)
\]

for \( i = 1 \) and 3 for \( \text{DIR} = E \), and \( i = 5 \) for \( \text{DIR} = W \).
for $i = 1$ and $3$ for $\text{DIR} = \text{E}$, and $i = 5$ for $\text{DIR} = \text{W}$. For $\text{SAT} = \text{T}$, $n = 10$, and $n = 17$ for $\text{SAT} = \text{G}$. Note how we take the differences between $\text{INFO} = \text{Nt}$ and $\text{F}$. There is no track sequence combination for $\text{INFO} = \text{Nt}$, but we assume the fuel savings for different $\text{TRK}$ within each starting date is the same for $\text{INFO} = \text{Nt}$.

The only difference between $\text{INFO} = \text{F}$ and $\text{INFO} = \text{P}$ is whether we have the full current velocity profile along the ground tracks or a partial current velocity component profile along the ground tracks. Thus, when we take the fuel savings differences between $\text{INFO} = \text{F}$ and $\text{P}$, these differences are due to the effect of the parallel (to the ground tracks) velocity component. We call $\Delta \text{MFS}(\text{F} - \text{P})$ the effect of parallel velocity component and define it as:

$$
\Delta \text{MFS}(\text{F} - \text{P}) = \frac{1}{6 \times n} \sum_{j=1}^{6} \sum_{k=1}^{n} (\text{FS}(\text{DIR}, \text{RT}_i, \text{LAG} = 0, \text{INFO} = \text{F}, \text{SD}_j, \text{SAT, ACC, TRK}_k) - \text{FS}(\text{DIR}, \text{RT}_i, \text{LAG} = 0, \text{INFO} = \text{P}, \text{SD}_j, \text{SAT, ACC, TRK}_k))
$$

(6.3)

for $i = 1$ and $3$ for $\text{DIR} = \text{E}$, and $i = 5$ for $\text{DIR} = \text{W}$. For $\text{SAT} = \text{T}$, $n = 10$, and $n = 17$ for $\text{SAT} = \text{G}$.

The only difference between $\text{INFO} = \text{P}$ and $\text{INFO} = \text{M}$ is whether we have an accurate geoid model or not. Thus, when we take the fuel savings differences between $\text{INFO} = \text{P}$ and $\text{M}$, these differences are due to the effect of geoid model. We call $\Delta \text{MFS}(\text{P} - \text{M})$ the effect of the geoid model and define it as:

$$
\Delta \text{MFS}(\text{P} - \text{M}) = \frac{1}{6 \times n} \sum_{j=1}^{6} \sum_{k=1}^{n} (\text{FS}(\text{DIR}, \text{RT}_i, \text{LAG} = 0, \text{INFO} = \text{P}, \text{SD}_j, \text{SAT, ACC, TRK}_k) - \text{FS}(\text{DIR}, \text{RT}_i, \text{LAG} = 0, \text{INFO} = \text{M}, \text{SD}_j, \text{SAT, ACC, TRK}_k))
$$

(6.4)
for $i = 1$ and $3$ for $\text{DIR} = E$, and $i = 5$ for $\text{DIR} = W$. For $\text{SAT} = T$, $n = 10$, and $n = 17$ for $\text{SAT} = G$.

The only difference between $\text{LAG} = 0$ and $\text{LAG} = 7$ is whether there is a time lag or not when we receive altimeter measurements information. Thus, when we take the fuel savings differences between $\text{LAG} = 0$ and $7$, these differences are due to the effect of time lag. We call $\Delta \text{MFS(LAG)}$ the effect of time lag and define as:

\[
\Delta \text{MFS(LAG)} = \frac{1}{6 \times n} \sum_{j=1}^{6} \sum_{k=1}^{n} \left( \text{FS(\text{DIR}, R1, LAG = 0, INFO, SDj, SAT, ACC, TRK)} - \text{FS(\text{DIR}, R1, LAG = 7, INFO, SDj, SAT, ACC, TRK)} \right)
\]

(6.5)

for $i = 1$ and $3$ for $\text{DIR} = E$, and $i = 5$ for $\text{DIR} = W$. We calculate $\Delta \text{MFS(LAG)}$ for $\text{INFO} = P$ and $M$. For $\text{SAT} = T$, $n = 10$, and $n = 17$ for $\text{SAT} = G$.

Finally, we want to consider effect of satellite supply described in Chapter IV because we want to compare the satellite supply effect to other effects, e.g., the effect of forecasting capability, the effect of spatial coverage, and so on.

\[
\Delta \text{MFS(SAT)} = \frac{1}{6 \times 30} \sum_{j=1}^{6} \sum_{k=1}^{30} \text{FS(\text{DIR}, R1, LAG = 0, INFO = P, SDj, SAT = C, ACC, TRK)} - \frac{1}{6 \times n} \sum_{j=1}^{6} \sum_{k=1}^{n} \text{FS(\text{DIR}, R1, LAG = 0, INFO = P, SDj, SAT, ACC, TRK)}
\]

(6.6)

for $i = 1$ and $3$ for $\text{DIR} = E$, and $i = 5$ for $\text{DIR} = W$. For $\text{SAT} = T$, $n = 10$, and $n = 17$ for $\text{SAT} = G$.

We identify 6 different sources to affect fuel savings performance related to information schemes. These are: the effect of forecasting, the effect of spatial interpolation, the effect
of velocity component, the effect of geoid model, the effect of time lag, and the effect of satellite supply. Now, we raise a question: Which effect is more important than others to achieve better fuel savings performance? In other words, where should we concentrate future research efforts for better fuel savings performance among those 6 sources?

We again measure the performance based on the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. Then, we compare 6 different sources with respect to the MFS's differences taken across the starting dates for each of the O-D pairs identified in Chapter V.

The results show that the effect of spatial interpolation is most important, followed by the effect of the geoid and the effect of time lag for both direction of voyages.

6.1 Eastbound Voyages for an O-D Pair (A-A)

In this section, we investigate the effects of the 6 sources with respect to the O-D pair whose origin and destination are “above” the Gulf Stream for eastbound voyages. We base the effects on the overall mean fuel savings performance taken across the starting dates.

We present the mean relative fuel savings (MFS) for each of the information schemes in Figure 62 for a 10-day ERP satellite and in Figure 63 for a 17-day ERP satellite. We disaggregate the MFS's for each information scheme with respect to the starting dates to show the influence.

Each bar in Figures 62 and 63 for INFO = Ft and Nt represents the mean of 6 starting dates. There are 6 cases since no accumulation of daily information along the ground tracks is involved. The mean relative fuel savings is 14.77% for INFO = Ft and 14.36% for INFO = Nt. Each marker represents the fuel savings for each starting date.
Figure 62: Eastbound MFS's of the O-D Pair RT1 (A - A) under Each INFO scheme with LAG = 0 for SAT = T. Subscript C represents SAT = C, and 7 represents LAG = 7.

Figure 63: Eastbound MFS's of the O-D Pair RT1 (A - A) under Each INFO scheme with LAG = 0 for SAT = G. Subscript C represents SAT = C, and 7 represents LAG = 7.
Each bar in Figure 62 represents the MFS's of 60 (= 6 SD's \times 10 TRK's) cases for \text{INFO} = F, P, and M. The mean relative fuel savings is 8.72\% for \text{INFO} = F, 8.03\% for \text{INFO} = P, and 5.63\% for \text{INFO} = M. Each marker represents the mean of 10 cases of fuel savings of each starting date. Each bar in Figure 63 represents the MFS's of 102 (= 6 SD's \times 17 TRK's) cases for \text{INFO} = F, P, and M. The mean relative fuel savings is 8.25\% for \text{INFO} = F, 7.86\% for \text{INFO} = P, and 3.90\% for \text{INFO} = M. Each marker represents the mean of 17 cases of fuel savings of each starting date.

Each bar in Figures 62 and 63 represents the MFS's of 180 (= 6 SD's \times 30 TRK's) cases for \text{INFO} = P and \text{SAT} = C. The mean relative fuel savings is 8.68\%. Each marker represents the mean of 30 cases of fuel savings of each starting date.

Each bar in Figure 62 represents the MFS's of 60 (= 6 SD's \times 10 TRK's) cases for \text{INFO} = P and M with LAG = 7. The mean relative fuel savings is 5.96\% for \text{INFO} = P, and 2.18\% for \text{INFO} = M. Each marker represents the mean of 10 cases of fuel savings of each starting date. Each bar in Figure 63 represents the MFS's of 68 (= 4 SD's \times 17 TRK's) cases for \text{INFO} = P and M with LAG = 7. The mean relative fuel savings is 5.04\% for \text{INFO} = P, and 1.94\% for \text{INFO} = M. Each marker represents the mean of 17 cases of fuel savings of each starting date.

Disaggregated MFS's for each information scheme with respect to each starting date in Figures 62 and 63 show that the fuel savings performance, as measured by the MFS's, are generally consistent across the starting dates. In other words, we may claim based on the MFS's plot that the effect of starting date is generally consistent for different information schemes.
Figure 64: Eastbound ΔMFS's comparison for an O-D Pair A-A. Subscript C represents SAT = C, and 7 represents LAG = 7.

We compute the ΔMFS's with Equations (6.1) through (6.6) and summarize the results in Figure 64. Note that the effect of forecasting has nothing to do with an ERP satellite. We, however, present this for each ERP satellite for visual effect only. The mean effect of forecasting is 0.41%. The mean effect of spatial interpolation is 5.64% for a 10-day ERP satellite and 6.11% for a 17-day ERP satellite. The effect of velocity component is 0.69% for a 10-day ERP satellite and 0.39% for a 17-day ERP satellite. The mean effect of the geoid model is 2.40% for a 10-day ERP satellite and 3.96% for a 17-day ERP satellite. The mean effect of the time lag is 2.07% (INFO = P) to 3.45% (INFO = M) for a 10-day ERP satellite, and 1.96% (INFO = M) to 2.62% (INFO = P) for a 17-day ERP satellite. Finally, the mean effect of satellite supply is 0.63% for a 10-day ERP satellite and 0.80% for a 17-day ERP satellite.
The order of importance based on the MFS's comparison is the effect of spatial interpolation, followed by the effect of geoid model, the effect of time lag, the effect of satellite supply, the effect of velocity component, and the effect of forecasting. Developing an accurate spatial interpolation model, an accurate geoid model, and the minimization of time lag are the areas which appear to need more attention based on this analysis.

The effect of spatial interpolation, however, includes the effect of a geoid model, since we assume we have perfect geoid information for INFO = Nt and F. Thus, when we exclude the effect of a geoid model from the effect of spatial interpolation, we may call this the net effect of spatial interpolation. For a 10-day ERP satellite, the effect of spatial interpolation is 5.64% and the effect of the geoid model is 2.40%. Thus, the net effect of spatial interpolation model is 3.24%. For a 17-day ERP satellite, the effect of spatial interpolation is 6.11% and the effect of the geoid model is 3.96%. Thus, the net effect of spatial interpolation model is 2.15%.

The net effect of spatial interpolation still provides about 2.15 to 3.24% additional mean relative fuel savings. This savings would come from an accurate spatial interpolation model which provides current information not only along the ground tracks, but also between the ground tracks. For an O-D pair A - A, the net effect of spatial interpolation (3.24% for SAT = T, and 2.15% for SAT = G) is comparable to the effect of a geoid model (2.40% for SAT = T, and 3.96% for SAT = G). Also, it is interesting to note that the forecasting effect is minimal.
6.2 Eastbound Voyages for an O-D Pair (I-I)

In this section, we investigate the effects of the same 6 sources as in Section 6.1 with respect to the O-D pair whose origin and destination are "in" the Gulf Stream for eastbound voyages. Again, we base the effects on the overall mean fuel savings performance taken across the starting dates.

We present the mean relative fuel savings (MFS) for each of the information schemes in Figure 65 for a 10-day ERP satellite and in Figure 66 for a 17-day ERP satellite. We disaggregate the MFS's for each information scheme with respect to the starting dates to show the influence.

Each bar in Figures 65 and 66 for INFO = Ft and Nt represents the mean of 6 starting dates. There are 6 cases since no accumulation of daily information along the ground tracks is involved. The mean relative fuel savings is 14.66% for INFO = Ft and 13.85% for INFO = Nt. Each marker represents the fuel savings for each starting date.

Each bar in Figure 65 represents the MFS's of 60 (= 6 SD's x 10 TRK's) cases for INFO = F, P, and M. The mean relative fuel savings is 6.10% for INFO = F, 6.42% for INFO = P, and 4.33% for INFO = M. Each marker represents the mean of 10 cases of fuel savings of each starting date. Each bar in Figure 66 represents the MFS's of 102 (= 6 SD's x 17 TRK's) cases for INFO = F, P, and M. The mean relative fuel savings is 6.80% for INFO = F, 6.34% for INFO = P, and 4.37% for INFO = M. Each marker represents the mean of 17 cases of fuel savings of each starting date.

Each bar in Figure 65 and Figure 66 represents the MFS's of 180 (= 6 SD's x 30 TRK's) cases for INFO = P and SAT = C. The mean relative fuel savings is 8.68%. Each marker
Figure 65: Eastbound MFS's of the O-D Pair RT, (I - I) under Each INFO scheme with LAG = 0 for SAT = T. Subscript C represents SAT = C, and 7 represents LAG = 7.

Figure 66: Eastbound MFS's of the O-D Pair RT, (I - I) under Each INFO scheme with LAG = 0 for SAT = G. Subscript C represents SAT = C, and 7 represents LAG = 7.
represents the mean of 30 cases of fuel savings of each starting date.

Each bar in Figure 65 represents the MFS’s of 60 (= 6 SD’s x 10 TRK’s) cases for INFO = P and M with LAG = 7. The mean relative fuel savings is 4.58% for INFO = P and 2.14% for INFO = M. Each marker represents the mean of 10 cases of fuel savings of each starting date. Each bar in Figure 66 represents the MFS’s of 68 (= 4 SD’s x 17 TRK’s) cases for INFO = P and M with LAG = 7. The mean relative fuel savings is 6.27% for INFO = P and 4.94% for INFO = M. Each marker represents the mean of 17 cases of fuel savings of each starting date.

Disaggregated MFS’s for each information scheme with respect to each starting date in Figures 65 and 66 show that the fuel savings performance, as measured by the MFS’s, are generally consistent across the starting dates. In other words, we may claim based on the MFS’s plot that the effect of starting date is generally consistent for different information schemes.

Again, we computed the ΔMFS’s with Equations (6.1) through (6.6) and summarize the results in Figure 67. Note that the effect of forecasting has nothing to do with an ERP satellite. We, however, present this for each ERP satellite for visual effect only. The mean effect of forecasting is 0.81%. The mean effect of spatial interpolation is 7.75% for a 10-day ERP satellite and 7.05% for a 17-day ERP satellite. The effect of velocity component is -0.32% for a 10-day ERP satellite and 0.46% for a 17-day ERP satellite. The mean effect of the geoid model is 2.09% for a 10-day ERP satellite and 1.97% for a 17-day ERP satellite. The mean effect of time lag is 2.03% (INFO = P) to 2.19% (INFO = M) for a 10-day ERP satellite, and -0.57% (INFO = M) to 0.07% (INFO = P) for a 17-day ERP satellite. Finally,
the mean effect of satellite supply is 1.03% for a 10-day ERP satellite and 1.11% for a 17-day ERP satellite.

The order of importance based on the MFS's comparison is the effect of spatial interpolation, followed by the effect of a geoid model, the effect of time lag, the effect of satellite supply, the effect of forecasting, and the effect of velocity component. Developing an accurate spatial interpolation model, an accurate geoid model, and the minimization of time lag are the areas which appear to need more attention based on this analysis.

The effect of spatial interpolation, however, includes the effect of a geoid model, since we assume we have perfect geoid information for INFO = Nt and F. Thus, when we exclude the effect of a geoid model from the effect of spatial interpolation, we may call this the net effect of spatial interpolation. For a 10-day ERP satellite, the effect of spatial
interpolation is 7.75% and the effect of the geoid model is 2.09%. Thus, the net effect of spatial interpolation model is 5.66%. For a 17-day ERP satellite, the effect of spatial interpolation is 7.05% and the effect of the geoid model is 1.97%. Thus, the net effect of spatial interpolation model is 5.08%.

The net effect of spatial interpolation still provides about 5.08 to 5.66% additional mean fuel savings with an accurate spatial interpolation model which provides current information not only along the ground tracks, but also between the ground tracks. For an O-D pair I - I, the net effect of spatial interpolation (5.66% for SAT = T, and 5.08% for SAT = G) is much better than the effect of a geoid model (2.09% for SAT = T, and 1.97% for SAT = G). Also, it is interesting to note that the forecasting effect is minimal.

Negative mean fuel savings $\Delta$MFS(F - P) in Figure 67 for a 10-day ERP satellite means that INFO = P performs better than INFO = F. The effect of velocity component is negligible, however, as seen by the small magnitude of the $\Delta$MFS(F - P). Moreover, in Figure 65, we see that the MFS's of INFO = F and MFS's of INFO = P are similar for each starting date.

6.3 Westbound Voyages for an O-D Pair (I-I)

In this section, we investigate the effects of the same 6 sources as in Sections 6.1 and 6.2 with respect to the O-D pair whose origin and destination are "in" the Gulf Stream for westbound voyages. Again, we base the effects on the overall mean fuel savings performance taken across the starting dates.

We present the mean relative fuel savings (MFS) for each of the information schemes in Figure 68 for a 10-day ERP satellite and in Figure 69 for a 17-day ERP satellite. We
Figure 68: Westbound MFS's of the O-D Pair RT₅ (I - I) under Each INFO scheme with LAG = 0 for SAT = T. Subscript C represents SAT = C, and 7 represents LAG = 7.

Figure 69: Westbound MFS's of the O-D Pair RT₅ (I - I) under Each INFO scheme with LAG = 0 for SAT = G. Subscript C represents SAT = C, and 7 represents LAG = 7.
disaggregate the MFS’s for each information scheme with respect to the starting dates to show the influence.

Each bar in Figures 68 and 69 for INFO = Ft and Nt represents the mean of 6 starting dates. There are 6 cases since no accumulation of daily information along the ground tracks is involved. The mean relative fuel savings is 9.24% for INFO = Ft and 8.90% for INFO = Nt. Each marker represents the fuel savings for each starting date.

Each bar in Figure 68 represents the MFS’s of 60 (= 6 SD’s x 10 TRK’s) cases for INFO = F, P, and M. The mean relative fuel savings is 4.41% for INFO = F, 4.14% for INFO = P, and 1.21% for INFO = M. Each marker represents the mean of 10 cases of fuel savings of each starting date. Each bar in Figure 69 represents the MFS’s of 102 (= 6 SD’s x 17 TRK’s) cases for INFO = F, P, and M. The mean relative fuel savings is 4.18% for INFO = F, 4.02% for INFO = P, and -0.78% for INFO = M. Each marker represents the mean of 17 cases of fuel savings of each starting date.

Each bar in Figure 68 and Figure 69 represents the MFS’s of 180 (= 6 SD’s x 30 TRK’s) cases for INFO = P and SAT = C. The mean relative fuel savings is 4.79%. Each marker represents the mean of 30 cases of fuel savings of each starting date.

Each bar in Figure 68 represents the MFS’s of 60 (= 6 SD’s x 10 TRK’s) cases for INFO = P and M with LAG = 7. The mean relative fuel savings is 3.56% for INFO = P and -0.19% for INFO = M. Each marker represents the mean of 10 cases of fuel savings of each starting date. Each bar in Figure 69 represents the MFS’s of 68 (= 4 SD’s x 17 TRK’s) cases for INFO = P and M with LAG = 7. The mean relative fuel savings is 1.39% for INFO = P and -1.97% for INFO = M. Each marker represents the mean of 17 cases of fuel
Figure 70: Westbound ΔMFS’s comparison for an O-D Pair i-j. Subscript C represents SAT = C, and 7 represents LAG = 7.

savings of each starting date.

Disaggregated MFS’s for each information scheme with respect to each starting date in Figures 68 and 69 show that the fuel savings performance, as measured by the MFS’s, are generally consistent across the starting dates. In other words, we may claim based on the MFS’s plot that the effect of starting date is generally consistent for different information schemes.

Again, we computed each ΔMFS’s with Equations (6.1) through (6.6) and summarize the results in Figure 70. Note that the effect of forecasting has nothing to do an with an ERP satellite. We, however, present this for each ERP satellite for visual effect only. The mean effect of forecasting is 0.34%. The mean effect of spatial interpolation is 4.49% for a 10-day ERP satellite and 4.72% for a 17-day ERP satellite. The effect of velocity
component is 0.27% for a 10-day ERP satellite and 0.16% for a 17-day ERP satellite. The mean effect of the geoid model is 2.93% for a 10-day ERP satellite and 4.80% for a 17-day ERP satellite. The mean effect of time lag is 0.58 to 1.40% for a 10-day ERP satellite, and 1.19 to 2.63% for a 17-day ERP satellite. Finally, the mean effect of satellite supply is 0.65% for a 10-day ERP satellite and 0.77% for a 17-day ERP satellite.

The order of importance based on the MFS's comparison is the effect of spatial interpolation, followed by the effect of a geoid model, the effect of time lag, the effect of satellite supply, the effect of velocity component, and the effect of forecasting. Developing an accurate spatial interpolation model, an accurate geoid model, and the minimization of time lag are the areas which appear to need more attention based on this analysis.

The effect of spatial interpolation, however, includes the effect of a geoid model, since we assume we have perfect geoid information for $INFO = N_t$ and $F$. Thus, when we exclude the effect of a geoid model from the effect of spatial interpolation, we may call this the net effect of spatial interpolation. For a 10-day ERP satellite, the effect of spatial interpolation is 4.49% and the effect of the geoid model is 2.93%. Thus, the net effect of spatial interpolation model is 1.56%. For a 17-day ERP satellite, the effect of spatial interpolation is 4.72% and the effect of the geoid model is 4.80%. Thus, the net effect of spatial interpolation model is -0.08%.

The net effect of spatial interpolation still provides about -0.08 to 1.56% additional mean fuel savings with an accurate spatial interpolation model which provides current information not only along the ground tracks, but also between the ground tracks. For an O-D pair $A \rightarrow A$, the net effect of spatial interpolation (1.56% for $SAT = T$, and -0.08% for
SAT = G) is much worse than the effect of geoid model (2.93% for SAT = T, and 4.80% for SAT = G). Negative net effect of spatial interpolation means that we would be better off not to do spatial interpolation for this O-D pair. In other words, the net effect of spatial interpolation is minimal compared to the geoid model effect. Also, it is interesting to note that the forecasting effect is minimal.

6.4 Summary

In this chapter, we investigated the effect of information scheme with respect to the O-D pairs which resulted in greater mean relative fuel savings for both eastbound and westbound voyages identified in Chapter V. The results of this investigation provide directions for further research for better ocean routing performance by identifying the effect of each different information scheme.

We identified 6 different sources to affect fuel savings performance related to information schemes. These were the effect of forecasting, the effect of spatial interpolation, the effect of velocity component, the effect of geoid model, the effect of time lag, and the effect of satellite supply.

We raised a question: Which effect is more important than others to achieve better fuel savings performance? In other words, where should we concentrate future research efforts for better fuel savings performance among those 6 sources?

We again measured the performance based on the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. Then, we compared 6 different sources based on the overall MFS's taken across the starting dates for each of the O-D pairs identified in Chapter V. Specifically, selected O-D pairs were
the O-D pairs whose origin and destination are "above" and "in" the Gulf Stream for eastbound voyages, and an O-D pair whose origin and destination are "in" the Gulf Stream for westbound voyages.

The order of overall MFS's was the effect of spatial interpolation, followed by the effect of a geoid model, the effect of time lag, and the effect of satellite supply. The effect of velocity component and the effect of forecasting were minimal. The effect of spatial interpolation included the effect of a geoid model, since we assumed we have perfect geoid information for INFO = Nt and F. Thus, when we excluded the effect of the geoid model from the effect of spatial interpolation, we called this the net effect of spatial interpolation. The net effect of spatial interpolation still provided additional mean relative fuel savings comparable to or better than the effect of the geoid model for eastbound O-D pairs. The net effect of spatial interpolation was at most minimal for the westbound O-D pair.

The results show that the effect of spatial interpolation is more important than others, followed by the effect of the geoid model and the effect of time for both direction of voyages. Thus, developing an accurate spatial interpolation model, an accurate geoid model, and the minimization of time lag are the areas which need the most attention.

Note that we assumed there is no altimeter measurement related errors in estimating current velocities from the altimeter measurements in this study. The effects of altimeter measurement errors would need a separate analysis to determine the impact on fuel savings performance in strategic ship routing with satellite altimeter-based dynamic ocean current information.
CHAPTER VII

Conclusions

In this study, we considered 4 issues. The first revolved about the following questions: What is the temporal coverage impact on ocean current routing as information gets old? Does the strategy for accumulation of daily current estimates along the ground tracks really matter for the purpose of ship routing? If it does, how many days of ground track information should we accumulate to obtain the greatest fuel savings in routing ships when we accumulate daily current information along the ground tracks?

The second issue was centered on the question: What is the increased magnitude of fuel savings due to having 2 different exact repeat period satellites simultaneously compared to having only 1 ERP satellite?

The third issue involved the questions: Which origin-destination (O-D) pairs are the most advantageous for strategic ship routing purposes when we utilize the ocean current information? More specifically, do the O-D pairs whose origin and destination are “in” the Gulf Stream (I-I) and “above” the Gulf Stream (A-A) result in more mean relative savings than other O-D pairs for eastbound voyages? Does an O-D pair whose origin and destination are “in” the Gulf Stream (I-I) result in more mean relative savings than other O-D pairs for westbound voyages?

The final issue we considered revolved about the following questions: Which effect is
more important than others to achieve better fuel savings performance? In other words, where should we concentrate our research efforts for better routing performance when we utilize the satellite altimeter-based ocean current information? To answer this question, we raise the following specific questions: 1) What is the effect of not having the forecasting capability? 2) What is the effect of not being able to spatially interpolate among ground tracks? 3) What is the effect of not knowing the parallel velocity component? 4) What is the effect of not having an accurate geoid model? 5) What is the effect of a time lag in data delivery? 6) What is the effect of having additional satellite supply?

In Chapter II, we defined and described the notation which accounts for the variables used in this study. Also, we described the detailed procedures used to select the O-D pairs and starting dates. There were two reasons that we wanted to select O-D pairs and starting dates. First, we wanted to describe fuel savings with respect to the O-D characteristics systematically to investigate if any characteristics lead to better or worse performance. Second, we wanted to make this study more manageable.

We clustered the O-D pairs based on the mean relative fuel savings into 4 groups for eastbound and 3 groups for westbound voyages, and selected representative O-D pairs from each group. Starting dates were selected based on the mean relative fuel savings with respect to the selected representative O-D pairs. The selected 4 O-D pairs for eastbound and 3 O-D pairs for westbound voyages were used for the rest of the study.

In Chapter III, we addressed the first issue. The questions involved were: What is the temporal coverage impact on ocean current routing as information gets old? Does the strategy for accumulation of daily current estimates along the ground tracks really matter for
the purpose of ship routing? If it does, how many days of ground track information should we accumulate to obtain the greatest fuel savings in routing ships when we accumulate daily current information along the ground tracks?

We measured the performance according to the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. Also, we identified the desirable “ground track accumulation scheme” of daily current information to maximize the mean relative fuel savings for 10- and 17-day exact repeat period satellites each.

We considered 3 information schemes for both eastbound and westbound voyages with real-time information for each exact repeat period satellite, while we considered 2 of these 3 information schemes for both directions of voyage with “near” real-time information for each exact repeat period satellite. All 3 information schemes considered in that chapter provided daily current information along the ground tracks.

The results showed that the accumulation of daily current information did matter in ship routing performance for both eastbound and westbound voyages. Specifically, for a 10-day exact repeat period satellite, we maximized the overall mean relative fuel savings when we accumulated up to 10 days of daily current information along the ground tracks with real- and “near” real-time information for both directions of voyages. For a 17-day exact repeat period satellite, we maximized the overall mean fuel savings when we accumulated between 8 and 14 days of daily current information, depending on the information schemes, along the ground tracks for both directions of voyages. There were, however, some instances in which it would have been better not to utilize current information for routing purposes but
to follow the great circle routes. Specifically, westbound voyages with "near" real-time information with a modified hydrographic approach lead to negative relative fuel savings.

Our recommendations of daily current information accumulation schemes for the greatest overall mean relative fuel savings for 10- and 17-day exact repeat period satellites should be considered with caution. We identified the "ground track accumulation schemes" under each of the information schemes which provided the greatest overall mean relative fuel savings taken across the O-D pairs and starting dates.

In Chapter IV, we addressed the second issue. The question was: What is the increased magnitude of fuel savings due to having two different exact repeat period satellites simultaneously compared to having only one ERP satellite?

We again measured the performance according to the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. We investigated the desirable combinations of "ground track accumulation scheme" of daily current information when we have 10- and 17-day exact repeat period satellites simultaneously. Then, we compared the greatest mean relative fuel savings of each exact repeat period satellite obtained in Chapter III to that of the combination of two exact repeat period satellites.

The results showed that, for eastbound routes, we maximized the relative mean fuel savings when we accumulated up to 10 days of daily information from a 10-day exact repeat period satellite with up to 8 days of daily information from a 17-day exact repeat period satellite simultaneously. For westbound routes, we maximized the relative fuel savings when we accumulated up to 10 days of daily information from a 10-day exact repeat period
satellite with up to 11 days of daily information from a 17-day exact repeat period satellite simultaneously. Then, we compared the greatest mean relative fuel savings resulting from having two exact repeat period satellites simultaneously instead of having only one exact repeat period satellite.

The results of the comparison showed that having two different exact repeat period satellites simultaneously performed better than having only one exact repeat period satellite each for both eastbound and westbound voyages. Specifically, for eastbound voyages, having two different exact repeat period satellites simultaneously resulted in 0.93% more mean relative fuel savings compared to having a 10-day exact repeat period satellite, and 0.80% more mean relative fuel savings compared to having a 17-day exact repeat period satellite. For westbound voyages, having two different exact repeat period satellites simultaneously resulted in 0.54% more mean relative fuel savings compared to having a 10-day exact repeat period satellite, and 1.00% more mean relative fuel savings compared to having a 17-day exact repeat period satellite.

In Chapter V, we addressed the third issue. The questions were: Which origin-destination (O-D) pairs are the most advantageous for strategic ship routing purposes when we utilize the ocean current information? Specifically, do the O-D pairs whose origins and destinations are “in” the Gulf Stream (I-I) and “above” the Gulf Stream (A-A) result in more mean relative fuel savings than other O-D pairs for eastbound voyages? Does an O-D pair whose origin and destination are “in” the Gulf Stream (I-I) result in more mean relative fuel savings than other O-D pairs for westbound voyages?

We again measured the performance according to the relative fuel savings on the routes
resulting from optimizing fuel consumption compared to the great circle routes. Then, we compared the greatest mean relative fuel savings for each O-D pair taken across the starting dates obtained in Chapters III and IV.

The results showed that, for eastbound voyages, O-D pairs (A-A) and (I-I), whose origins and destinations are "above" and "in" the Gulf Stream, were the two most advantageous O-D pairs. They resulted in greater overall mean fuel savings when we utilized ocean current information for strategic ship routing purposes under all information schemes for each of the 10- and 17-day exact repeat period satellites. For westbound voyages, an O-D pair (I-I), whose origin and destination are "in" the Gulf Stream, was the most advantageous route, resulting in greater MFS's when we utilize ocean current information for strategic ship routing purposes under all information schemes for each of the 10- and 17-day exact repeat period satellites except in 3 instances. Specifically, real- and "near" real-time ocean currents estimated with a modified hydrographic approach along the ground tracks for a 17-day exact repeat period satellite and "near" real-time ocean current estimated with a modified hydrographic approach along the ground tracks for a 10-day exact repeat period satellite resulted in negative mean relative fuel savings. Negative mean relative fuel savings mean that we would consume more fuel when we utilize altimeter-based dynamic ocean current information. Thus, we might be better off to ignore the current information. In these cases, we would have done better to follow the great circle routes.

In Chapter VI, we addressed the fourth issue. The questions were: Which effect is more important than others to achieve better fuel savings performance? In other words, where should we concentrate our research efforts for better routing performance when we
utilize the satellite altimeter-based ocean current information? To answer this question, we raise the following specific questions: 1) What is the effect of not having the forecasting capability? 2) What is the effect of not being able to spatially interpolate among ground tracks? 3) What is the effect of not knowing the parallel velocity component? 4) What is the effect of not having an accurate geoid model? 5) What is the effect of a time lag in data delivery? 6) What is the effect of having additional satellite supply?

We again measured the performance according to the relative fuel savings on the routes resulting from optimizing fuel consumption compared to the great circle routes. Then, we compared the mean relative fuel savings differences between the different information schemes with respect to the O-D pairs which resulted in greater mean relative fuel savings in Chapter V. We identified the magnitude of each effect and ordered them based on the mean relative fuel savings with respect to the selected O-D pairs.

The results showed that spatial coverage effect (having current information not only along the ground tracks, but also between the ground tracks), and an accurate geoid model were most important in overall mean fuel savings performance. These effects were followed by the time lag effect and the satellite supply effect. The effect of the parallel velocity component and the effect of forecasting were minimal. Thus, we need to concentrate future research efforts on developing an accurate spatial interpolation model and an accurate geoid model for better routing performance.

Note that we assumed there is no altimeter measurement related errors in estimating current velocities from the altimeter measurements in this study. The effects of altimeter measurement errors would need a separate analysis to determine the impact on fuel savings
performance in strategic ship routing with satellite altimeter-based dynamic ocean current information.
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Appendix A

Relative Fuel Savings Frequency Distributions Relative to Chapter III
Figure 71: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 72: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 73: Relative Fuel Savings Differences ($\Delta FS(\text{ACC}_{x-y})$) Frequency Distributions when $\text{DIR} = \text{E}$, $\text{RT} = \{\text{RT}_1, \ldots, \text{RT}_4\}$, $\text{LAG} = 0$, $\text{INFO} = \text{M}$, $\text{SD} = \{1, \ldots, 6\}$, $\text{TRK} = \{1, \ldots, 10\}$, $\text{SAT} = \text{T}$.

Figure 74: Mean Fuel Savings with Standard Deviations for Each ACC when $\text{DIR} = \text{E}$, $\text{RT} = \{\text{RT}_1, \ldots, \text{RT}_4\}$, $\text{LAG} = 0$, $\text{INFO} = \text{P}$, $\text{SD} = \{1, \ldots, 6\}$, $\text{TRK} = \{1, \ldots, 10\}$, $\text{SAT} = \text{T}$. 
Figure 75: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 76: Relative Fuel Savings Differences (\Delta FS(ACC_{x-y})) Frequency Distributions when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 77: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 78: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 79: Relative Fuel Savings Differences ($\Delta FS(ACC_{x-y})$) Frequency Distributions when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 80: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 81: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 82: Relative Fuel Savings Differences (\Delta FS(ACC_x-\gamma)) Frequency Distributions when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 83: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = {RT₅, RT₆, RT₇}, LAG = 0, INFO = P, SD = {1, ..., 6}, TRK = {1, ..., 10}, SAT = T.

Figure 84: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = {RT₅, RT₆, RT₇}, LAG = 0, INFO = P, SD = {1, ..., 6}, TRK = {1, ..., 10}, SAT = T.
Figure 85: Relative Fuel Savings Differences ($\Delta F S(ACC_{x,y})$) Frequency Distributions when DIR = W, RT = \{RT\textsubscript{5}, RT\textsubscript{6}, RT\textsubscript{7}\}, LAG = 0, INFO = P, SD = \{1, ..., 6\}, TRK = \{1, ..., 10\}, SAT = T.

Figure 86: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = \{RT\textsubscript{5}, RT\textsubscript{6}, RT\textsubscript{7}\}, LAG = 0, INFO = F, SD = \{1, ..., 6\}, TRK = \{1, ..., 10\}, SAT = T.
Figure 87: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 88: Relative Fuel Savings Differences (AFS(ACC_{x,y})) Frequency Distributions when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 89: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 90: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 91: Relative Fuel Savings Differences ($\Delta FS(ACC_{x-y})$) Frequency Distributions when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 92: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 93: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 94: Relative Fuel Savings Differences ($\Delta$FS(ACC_1-\gamma)) Frequency Distributions when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 95: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 96: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 97: Relative Fuel Savings Differences ($\Delta FS(ACC_{x-y})$) Frequency Distributions when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 98: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 99: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.

Figure 100: Relative Fuel Savings Differences (ΔFS(ACC_{x-y})) Frequency Distributions when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 10\}, SAT = T.
Figure 101: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 102: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 103: Relative Fuel Savings Differences ($\Delta FS(ACC_{x-y})$) Frequency Distributions when DIR = E, RT = $\{RT_1, \ldots, RT_4\}$, LAG = 0, INFO = M, SD = $\{1, \ldots, 6\}$, TRK = $\{1, \ldots, 17\}$, SAT = G.

Figure 104: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = $\{RT_1, \ldots, RT_4\}$, LAG = 0, INFO = P, SD = $\{1, \ldots, 6\}$, TRK = $\{1, \ldots, 17\}$, SAT = G.
Figure 105: Relative Fuel Savings Frequency Distributions of Each ACC when \( \text{DIR} = E \), \( \text{RT} = \{RT_1, \ldots, RT_4\} \), \( \text{LAG} = 0 \), \( \text{INFO} = P \), \( \text{SD} = \{1, \ldots, 6\} \), \( \text{TRK} = \{1, \ldots, 17\} \), \( \text{SAT} = G \).

Figure 106: Relative Fuel Savings Differences (\( \Delta FS(\text{ACC}_x-y) \)) Frequency Distributions when \( \text{DIR} = E \), \( \text{RT} = \{RT_1, \ldots, RT_4\} \), \( \text{LAG} = 0 \), \( \text{INFO} = P \), \( \text{SD} = \{1, \ldots, 6\} \), \( \text{TRK} = \{1, \ldots, 17\} \), \( \text{SAT} = G \).
Figure 107: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 108: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 109: Relative Fuel Savings Differences ($\Delta FS(ACC_{x-y})$) Frequency Distributions when DIR = E, RT = $\{RT_1, \ldots, RT_4\}$, LAG = 0, INFO = F, SD = $\{1, \ldots, 6\}$, TRK = $\{1, \ldots, 17\}$, SAT = G.

Figure 110: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = $\{RT_5, RT_6, RT_7\}$, LAG = 0, INFO = M, SD = $\{1, \ldots, 6\}$, TRK = $\{1, \ldots, 17\}$, SAT = G.
Figure 111: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 112: Relative Fuel Savings Differences (\Delta FS(ACC_{k-1})) Frequency Distributions when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = M, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 113: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 114: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 115: Relative Fuel Savings Differences ($\Delta FS(ACC_{x-y})$) Frequency Distributions when $DIR = W$, $RT = \{RT_5, RT_6, RT_7\}$, $LAG = 0$, $INFO = P$, $SD = \{1, \ldots, 6\}$, $TRK = \{1, \ldots, 17\}$, $SAT = G$.

Figure 116: Mean Fuel Savings with Standard Deviations for Each ACC when $DIR = W$, $RT = \{RT_5, RT_6, RT_7\}$, $LAG = 0$, $INFO = F$, $SD = \{1, \ldots, 6\}$, $TRK = \{1, \ldots, 17\}$, $SAT = G$. 
Figure 117: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 118: Relative Fuel Savings Differences (\Delta FS(ACC_{x,y})) Frequency Distributions when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = F, SD = \{1, \ldots, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 119: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = M, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 120: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 7, INFO = M, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 121: Relative Fuel Savings Differences ($\Delta FS(ACC_x,y)$) Frequency Distributions when $DIR = E$, $RT = \{RT_1, \ldots, RT_4\}$, $LAG = 7$, $INFO = M$, $SD = \{2, 3, 5, 6\}$, $TRK = \{1, \ldots, 17\}$, $SAT = G$.

Figure 122: Mean Fuel Savings with Standard Deviations for Each $ACC$ when $DIR = E$, $RT = \{RT_1, \ldots, RT_4\}$, $LAG = 7$, $INFO = P$, $SD = \{2, 3, 5, 6\}$, $TRK = \{1, \ldots, 17\}$, $SAT = G$. 
Figure 123: Relative Fuel Savings Frequency Distributions of Each ACC when \( \text{DIR} = E, \ RT = \{RT_1, \ldots, RT_4\}, \ \text{LAG} = 7, \ \text{INFO} = P, \ SD = \{2, 3, 5, 6\}, \ TRK = \{1, \ldots, 17\}, \ \text{SAT} = G. \)

Figure 124: Relative Fuel Savings Differences \( (\Delta FS(ACC_{x-y})) \) Frequency Distributions when \( \text{DIR} = E, \ RT = \{RT_1, \ldots, RT_4\}, \ \text{LAG} = 7, \ \text{INFO} = P, \ SD = \{2, 3, 5, 6\}, \ TRK = \{1, \ldots, 17\}, \ \text{SAT} = G. \)
Figure 125: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 126: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = M, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 127: Relative Fuel Savings Differences ($\Delta FS(ACC_{x,y})$) Frequency Distributions when DIR = W, RT = \{RT5, RT6, RT7\}, LAG = 7, INFO = M, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 128: Mean Fuel Savings with Standard Deviations for Each ACC when DIR = W, RT = \{RT5, RT6, RT7\}, LAG = 7, INFO = P, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Figure 129: Relative Fuel Savings Frequency Distributions of Each ACC when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = P, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.

Figure 130: Relative Fuel Savings Differences (\(\Delta FS(ACC_{x-y})\)) Frequency Distributions when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 7, INFO = P, SD = \{2, 3, 5, 6\}, TRK = \{1, \ldots, 17\}, SAT = G.
Appendix B

Relative Fuel Savings Frequency Distributions Relative to Chapter IV
Figure 131: Mean Fuel Savings with Standard Deviations for Each SAT when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}. ACC_{10} for SAT = T, ACC_{14} for SAT = G, and T_{10}G_{8} for SAT = C.

Figure 132: Relative Fuel Savings Frequency Distributions of Each SAT when DIR = E, RT = \{RT_1, \ldots, RT_4\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}. ACC_{10} for SAT = T, ACC_{14} for SAT = G, and T_{10}G_{8} for SAT = C.
Figure 133: Mean Fuel Savings with Standard Deviations for Each SAT when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}. ACC_{10} for SAT = T, ACC_{14} for SAT = G, and T_{10}G_{11} for SAT = C.

Figure 134: Relative Fuel Savings Frequency Distributions of Each SAT when DIR = W, RT = \{RT_5, RT_6, RT_7\}, LAG = 0, INFO = P, SD = \{1, \ldots, 6\}. ACC_{10} for SAT = T, ACC_{14} for SAT = G, and T_{10}G_{11} for SAT = C.