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ARCTIC SEA ICE: USING AIRBORNE TOPOGRAPHIC MAPPER MEASURMENTS (ATM) TO DETERMINE SEA ICE THICKNESS

by

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14. ABSTRACT
As the earth warms, signs of climate change range from subtle to significant, with the most dramatic alterations occurring in the Arctic. Because the concept of a new, navigable ocean to the north signals complications, The United States Navy is particularly interested in studying the Arctic region so as to project those changes and become better prepared for future operations in this emerging maritime environment. However, a key step in understanding sea ice fluctuation within the Arctic is being able to determine sea ice thickness over a vast area. Thus, obtaining an accurate sea ice thickness measurement for the entire expanse makes tracking further variations and predicting possible changes much easier. As such, this paper aims to look at the steps necessary in determining sea ice thickness based off laser altimetry data gathered during NASA?s Operation IceBridge. Using the Airborne Topographic Mapper (ATM), sea ice elevation can be measured from an aircraft flying overhead. From this elevation data, an approximate freeboard is calculated in relation to the earth?s geoid model. By determining locations of leads in the ice, further calculations may be performed to get a sea ice freeboard measurement. Then, through the use of the hydrostatic equation, sea ice thickness may be inferred for the region between successive leads. Therefore, flying over a lead in the ice is very important for determining the exact sea surface elevation. This paper outlines the process, approximations and adjustments necessary to determine sea ice thickness by using laser altimetry measurements of sea ice elevation.

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ABSTRACT

As the earth warms, signs of climate change range from subtle to significant, with the most dramatic alterations occurring in the Arctic. Because the concept of a new, navigable ocean to the north signals complications, The United States Navy is particularly interested in studying the Arctic region so as to project those changes and become better prepared for future operations in this emerging maritime environment. However, a key step in understanding sea ice fluctuation within the Arctic is being able to determine sea ice thickness over a vast area. Thus, obtaining an accurate sea ice thickness measurement for the entire expanse makes tracking further variations and predicting possible changes much easier. As such, this paper aims to look at the steps necessary in determining sea ice thickness based off laser altimetry data gathered during NASA's Operation IceBridge. Using the Airborne Topographic Mapper (ATM), sea ice elevation can be measured from an aircraft flying overhead. From this elevation data, an approximate freeboard is calculated in relation to the earth's geoid model. By determining locations of leads in the ice, further calculations may be performed to get a sea ice freeboard measurement. Then, through the use of the hydrostatic equation, sea ice thickness may be inferred for the region between successive leads. Therefore, flying over a lead in the ice is very important for determining the exact sea surface elevation. This paper outlines the process, approximations and adjustments necessary to determine sea ice thickness by using laser altimetry measurements of sea ice elevation.

INTRODUCTION

With the Arctic climate changing faster than any place on earth, ice-diminishment is cause for immediate concern. Although projections vary, scientists agree that the Arctic is headed toward ice-free summers, which in turn poses numerous challenges for the United States Navy. An open ocean in the near future may increase water traffic, create boundary disputes, and raise questions over sea sovereignty, calling upon American diligence in defending its borders and keeping Arctic sea lanes free and safe. Interest in this northernmost maritime environment is already on the rise and many countries are beginning to acquire territories intended for economic exploration due to the discovery of more and more natural resources. Thus, because of the growing national security implications, it is important to study the altering Arctic environment in greater detail now so that the U.S. Navy is better prepared to operate there in the future.

Because environmental assessment and prediction are essential to guiding future policy and strategy in the region, it is imperative for the U.S. Navy to understand the primary causes for sea ice decline in order to accurately forecast ice-free periods. Rear Admiral Titley, the Oceanographer of the U.S. Navy, believes the best way to promote a secure Arctic is to identify a timeline for "ice-free summers" (Titley, 2010). Therefore, understanding the correlation between sea ice fluctuations and rising air and sea temperatures will likely give insight into when this phenomenon may occur. Obtaining accurate data is vital to prediction capabilities because, through sound scientific information, the U.S. Navy can further revise the Arctic Roadmap and be better prepared for future operations in the Arctic environment.

To do this effectively, an elaborate Arctic sea ice observation system must be fully integrated and thoroughly utilized. This observing network is made up of the combination of insitiu buoys, satellite observations and aerial reconnaissance and observations. Synthesizing these different data sets will allow scientists to obtain a more accurate picture of the recent sea ice decline. Overall, through the various perspectives offered by the observation network, scientists will gain an in-depth understanding of what drives both ice diminishment and re-growth cycles, yielding precise predictions for “ice free summers.”

The general consensus of all data sources is that climate change is affecting the Arctic environment in a noticeable manner; in fact more dramatically than any other region of the globe. Satellites first began observing sea ice coverage in the Arctic 30 years ago in 1978 (IPCC, 2007). During this era, the three lowest satellite recordings of minimum summer sea ice extent results occurred during the consecutive summers of 2007, 2008, and 2009. Although sea ice coverage during the summer of 2009 was more than that in 2007 and 2008, it was still 25% below the average for 1979-2000 (NOAA, 2011). Despite the substantial decrease in this trio of years, a gradual decline has been occurring since satellite observations began.

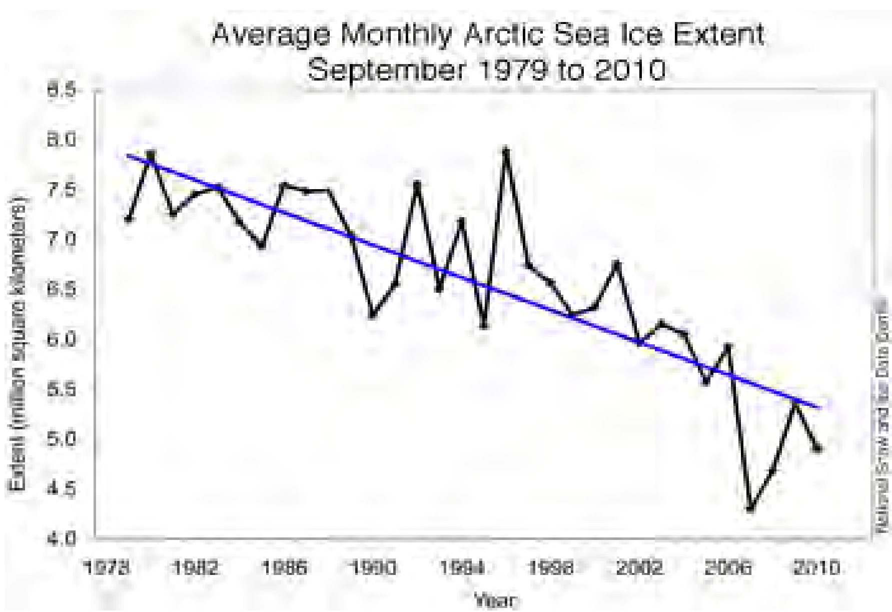

Figure 1: Average Monthly Arctic Sea Ice Extent September 1979 to 2010 <http://nsidc.org/images/arcticseaicenews/20110202_Figure3.png>

Figure 1 shows the downward trend from 1979 until 2007 in the sea ice extent in the Arctic. There are yearly fluctuations in coverage, but the overall pattern (blue line) clearly descends up to 2007 when, as the graph shows, a radical drop in the extent of sea ice occurs, putting that year in record books.

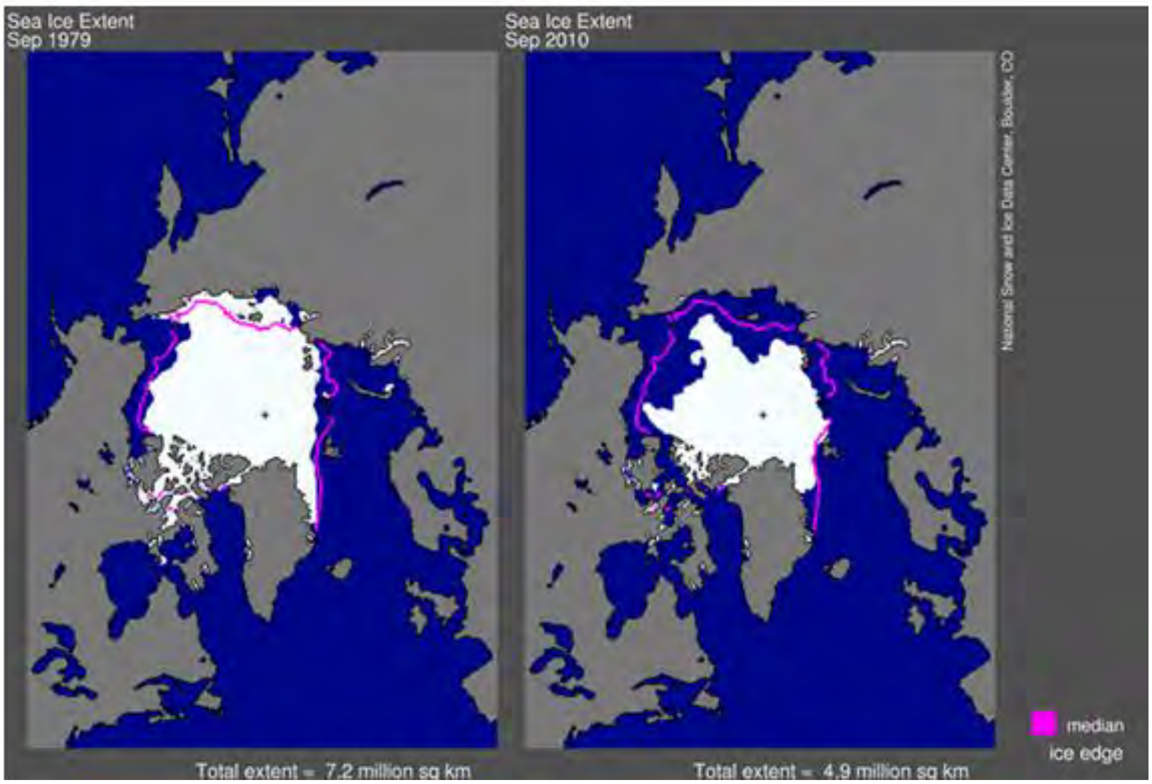

Figure 1: Sea Ice Extent Comparison September 1979 to September 2010.
(ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/Sep/)

Figure 2 indicates the sea ice decline by comparing the National Snow and Ice Data Center (NSIDC) sea ice index images from September 1979 to September 2010. The total coverage in September 1979 spanned 7.2 million square miles whereas in September 2010, ice extended only 4.9 million square miles. (ftp://sidads.colorado.edu/DATASETS/NOAA/G02135/Sep/). This appreciable diminishment in sea ice extent raises a valid question; why is the Arctic changing so rapidly compared to the rest of the world?

The answer can be attributed to a number of factors, but one prominent belief centers around the ice albedo effect. The Arctic has a rapid response to global warming because, when the atmosphere warms, this leads to melting of high-albedo sea ice, land ice and snow, replacing the light-colored frozen landscape with darker low-albedo open oceans. The ice free, darker surface, in-turn, allows more solar energy to be absorbed by the ocean and ground, contributing to more rapid rates of warming for both the air and sea surface temperatures.

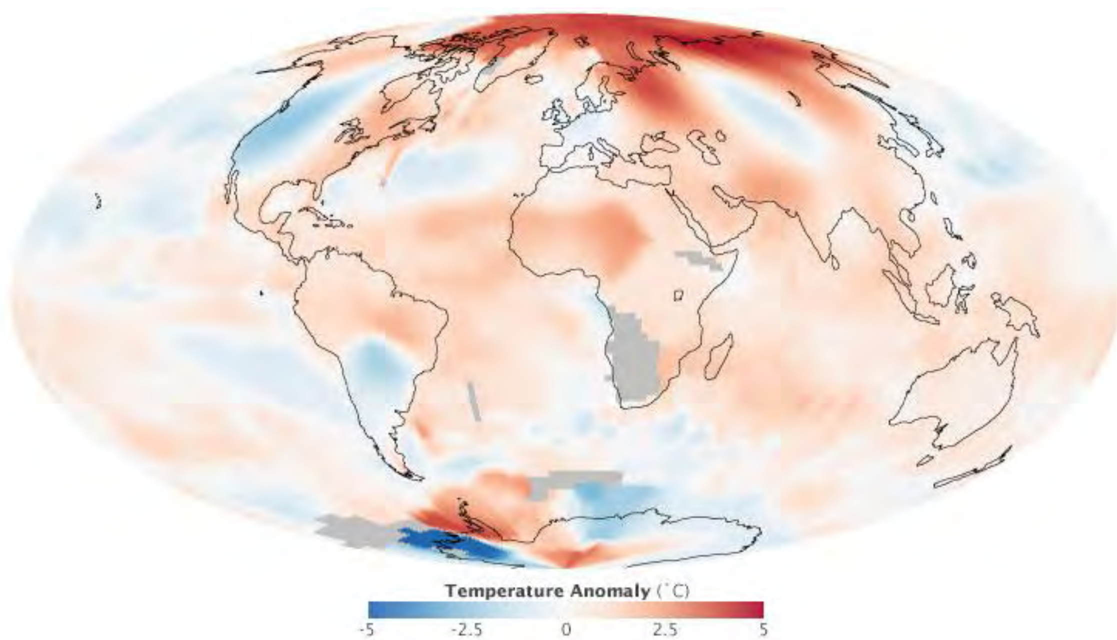

Figure 2: The NASA Goddard Institute for Space Studies (GISS) image showing the global temperature anomalies for May 2010, compared to surface temperature anomalies for May temperatures from 1951 to 1980. (http://earthobservatory.nasa.gov/IOTD/view.php?id=44416)

Figure 3 shows the temperature anomalies around the world for May 2010. The Arctic has risen up to 5 degrees Celsius over the past 30 years, which is more than any other place on earth. A major reason for this drastic temperature increase is the ice albedo effect.

The newly acquired warmth of the surrounding environment only serves to magnify the ice diminishing process. As the surface ocean temperatures increase, the sea ice thickness decreases; allowing for a greater heat flux to and from the ocean. The oceans continue to warm and contribute to melting from beneath the sea ice (Wahdams, 2000). There is greater absorption of solar energy during the summers since there is less sea ice in the ocean. Therefore, the multi-year sea ice that has been built up over many winters has begun to melt and is being replaced with thinner more fragile first year ice. This ocean warming causes a thinner volume of ice in the Arctic that is more susceptible to future decline. (NOAA, 2011).

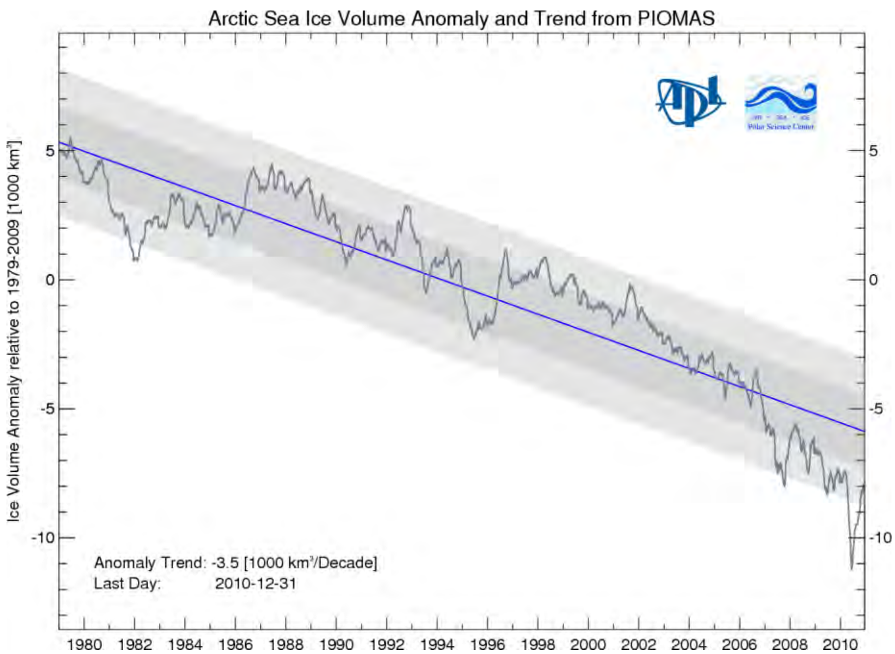

Figure 3: Arctic Sea Ice Volume Anomaly and Trend (University of Washington Applied Physics Laboratory). (http://psc.apl.washington.edu/ArcticSeaiceVolume/IceVolume.php)

Figure 4 shows the volumetric decline of Arctic sea ice. The less multi-year ice, the more solar energy the ocean absorbs adding to this feedback loop which is causing this sea ice to further decline in the Arctic. This data also reflects that Arctic summer sea ice volume in the last decade reached a record minimum in 2010. Submarine measurements of ice draft have indicated a similar finding of a declining thickness of the ice pack.

New laser altimeter measurements from satellites and aircraft are providing details and data to determine sea ice thickness calculations in the Arctic Ocean (S.L Farrell et al, 2011). Having a way to determine sea ice thickness over a large area of the Arctic Ocean is very important in order to track further variations and predict possible change. This paper looks at the steps, process and approximations behind determining sea ice thickness given raw sea ice elevation data collected from the Airborne Topographic Mapper (ATM), a laser altimeter that took measurements during NASA's IceBridge campaign in 2009 and continues to be the primary laser altimeter used in IceBridge today.

MATERIALS AND METHODS

IceBridge is a six-year NASA airborne mission which is aimed at surveying both poles of the earth. IceBridge comprises a series of aerial studies of the cryosphere in areas of interest to scientists. The main goal of the annual IceBridge campaign is to provide the airborne data necessary for a three-dimensional view of Arctic and Antarctic ice sheets, ice shelves and sea ice. While October and November are dedicated to Antarctica, The IceBridge team spends March through May in the Arctic. During this longer spring campaign, IceBridge's mission is to make two major overarching contributions to Arctic science. First, these operational flights are intended to provide annual surface elevation data, focusing on parts of the Arctic that are undergoing rapid changes. Because of the time variability and non-linear changes in the region, repeated monitoring is required to revise existing models. IceBridge's second objective is to expand upon the satellite mission by providing more detailed and precise measurements over the Arctic. Serving as a temporary replacement, IceBridge is intended to "bridge" the gap between ICESat, NASA's ice, cloud, and land elevation satellite, which stopped gathering data in 2009, and ICESat-2 which is scheduled to go into orbit in 2016. The aptly named IceBridge is not only significant to ensuring a continual series of readings during the NASA satellite void, but also for testing new equipment that will help shape the ultimate design of future satellite laser altimetry missions like ICESat-2. Once operational, ICESat-2 will allow the seasonal and inter-annual changes in the Arctic sea ice thickness to be estimated ((S.L Farrell et al, 2011).

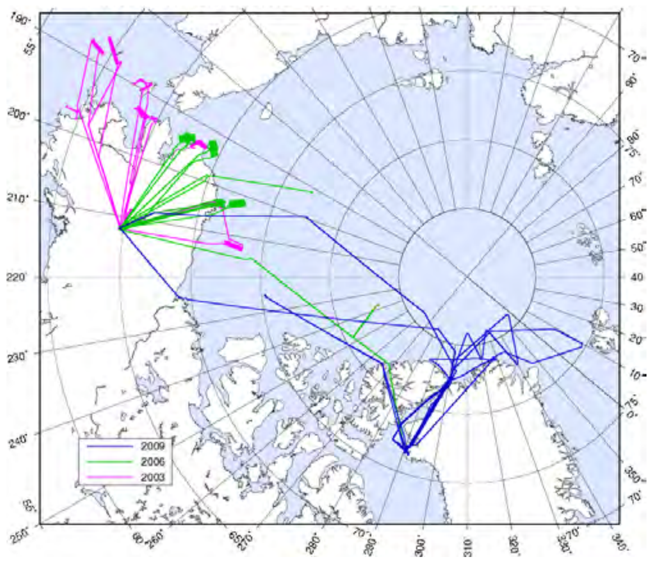

Figure 4: NASA Arctic Sea Ice Missions 2003-2009.
(http://www.espo.nasa.gov/oib/docs/presentations/2010/SEA_ICE_2010-plans.pdf)

Figure 5 shows the aerial flights over the sea ice in the Arctic flown by NASA's aircraft from 2003 to 2009 in support of the original ICESat. Although each flight covered a much smaller area than a satellite would, these complementary measurements served to validate space estimates. Data collected from an airborne platform has proven critical to improving ice sheet models. The current IceBridge flights are able to measure things such as bed topography, grounding line position, and ice and snow thickness. These are some of the parameters that cannot be measured using just a satellite. Satellites actually are not effective over ridges or locations with snow cover and consequently, cause large errors in current models (NASA, 2011).

A major component of the IceBridge operation is to use both laser altimeter mapping of sea ice elevation and then radar measurements to determine snow thickness in order to respectively derive sea ice freeboard and the thickness of the winter-time ice pack (S.L Farrell et al.). This will provide data to construct a continuous sea ice thickness time series over the course of 6 years (S.L Farrell et al, 2011).

The aircraft flown for the Arctic IceBridge flights is a P-3B NASA aircraft which is tasked with conducting airborne remote sensing surveys.

Figure 5: NASA's P-3B Aircraft landing in Thule, Greenland 14 March 2011 for the IceBridge campaign. (Photo taken by LCDR John Woods, USN)

The P-3B aircraft, which is capable of flying long missions and covering great distances. IceBridge flights over the Arctic region are out of Thule Air Force Base, Greenland. NASA uses this P-3B aircraft seen above, which is a four-engine turboprop plane. This specific aircraft is used because it can log eight to twelve hour flights and can carry a variety of instruments as its large payload. The P-3B is a specialized aircraft that operates as an airborne "platform" in support of NASA's "Science Mission Directorate." The plane's endurance and size make it ideally equipped for surveying the Arctic (NASA, 2011).

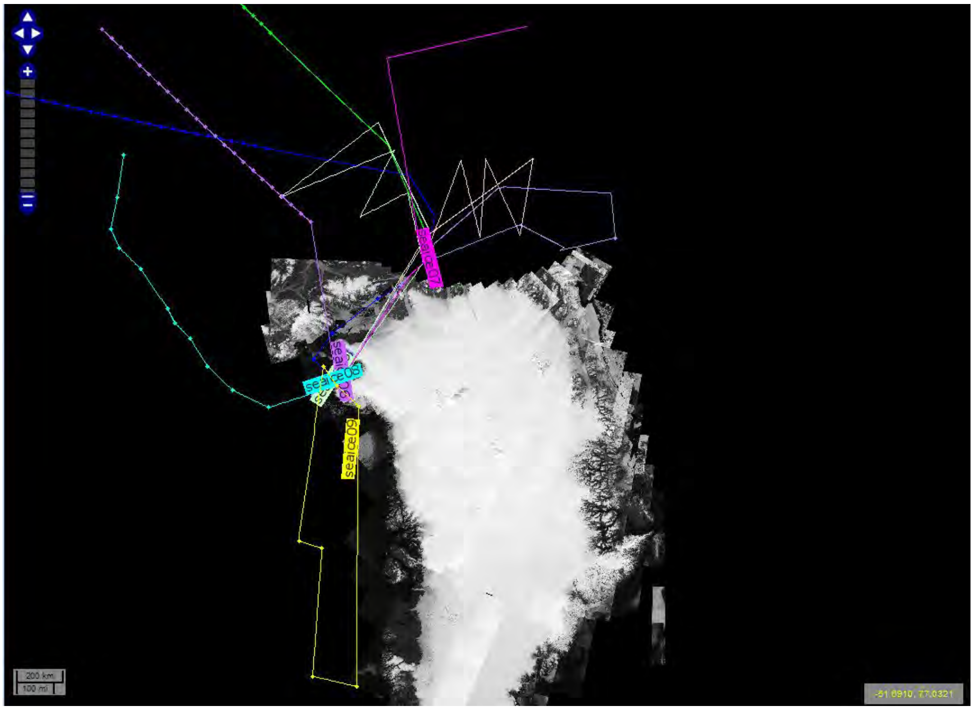

Figure 7: Proposed sea ice P-3B flights for IceBridge operation 2011. (http://erde.sr.unh.edu/icebridge/grn/)

Figure 7 shows the proposed P-3B sea ice flights for the IceBridge operations in 2011. The flight path for the sea ice missions out of Thule, Greenland on any given day is chosen based upon, not only the weather conditions, but the priority of the flight as well. These sea ice flights use the ATM equipment along with other measuring tools in order to accurately map out the elevation of the sea ice in order to determine sea ice thickness.

Throughout the 2011 IceBridge campaign, a variety of data gathering equipment is used so that, collectively, scientists can paint the most accurate picture possible of the Arctic. The onboard equipment consists of a gravimeter, a few airborne topographic mappers (ATM), cameras for the digital mapping system (DMS), a ku-band radar, a snow radar, a multichannel coherent radar depth sounder (MCoRDS) radar and a magnetometer. The gravimeter's role is to map the topographic and bathymetric features of the sea floor and earth's surface by measuring gravity potential. This gives better insight into the geological components of the glaciers and ice sheets (Tinto, 2011). The radars are used more predominantly for land ice thickness measurements to the bedrock below an ice sheet or glacier; however the snow radar is used to determine the snow cover on top of land or sea ice (Yungel, 2011). Finally the magnetometer is used to detect the magnetic anomalies and is used for similar purposes as the gravimeter (Burton, 2011).

The ATM is the main piece of equipment employed during Operation IceBridge due to its highly accurate and effective laser measurements. It is an airborne laser that measures changes in the surface elevation over sea ice or land ice. The ATM provides highly precise elevation data with ten centimeters accuracy. The current 2011 mission contains two ATM's onboard, one with a 5 degree full angle scan and one with a 30 degree full angle scan. It is a nutating laser which means it rotates in an elliptical orbit, giving seemingly circular data points when they are plotted. The 30 degree scan ATM provides a wide swath, while the 5 degree scan ATM provides a narrow swath but with higher precision because there are more reflected photons that return to the aircraft. With the ability to reflect from the ground back to the aircraft, these scanning lasers can be converted into elevation maps (Yungel, 2011).

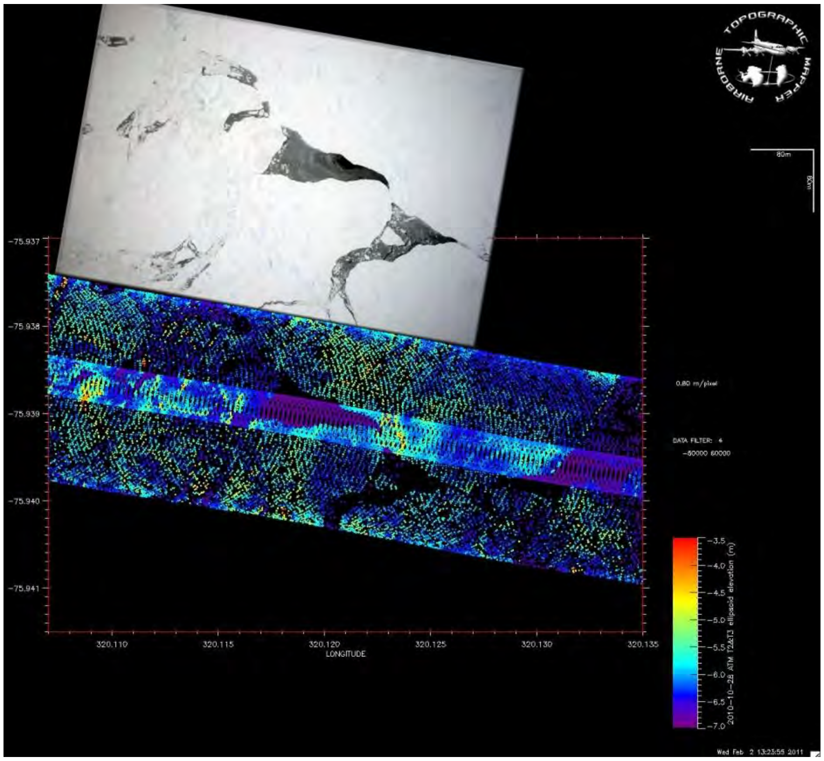

Figure 8: Elevation map created by the ATM flying over leads in the ice (Yungel, 2011).

Figure 8 shows an elevation map created using both the 5 degree full angle scan and the 30 degree full angle scan. As the map indicates, the 5 degree angle scan is much more precise in picking up leads, or breaks in the ice, while the 30 degree angle scan is able to cover a larger diameter. Using both on top of each other in conjunction with camera imagery allows scientists to acquire very precise elevation readings to be used in determining sea ice thickness (Yungel, 2011).

The ATM operates most effectively if the aircraft flies at an altitude of 1500 to 3000 feet above the surface. By flying this ATM over the same surfaces as satellites, or in-situ buoys, clear-cut elevation changes can be measured.

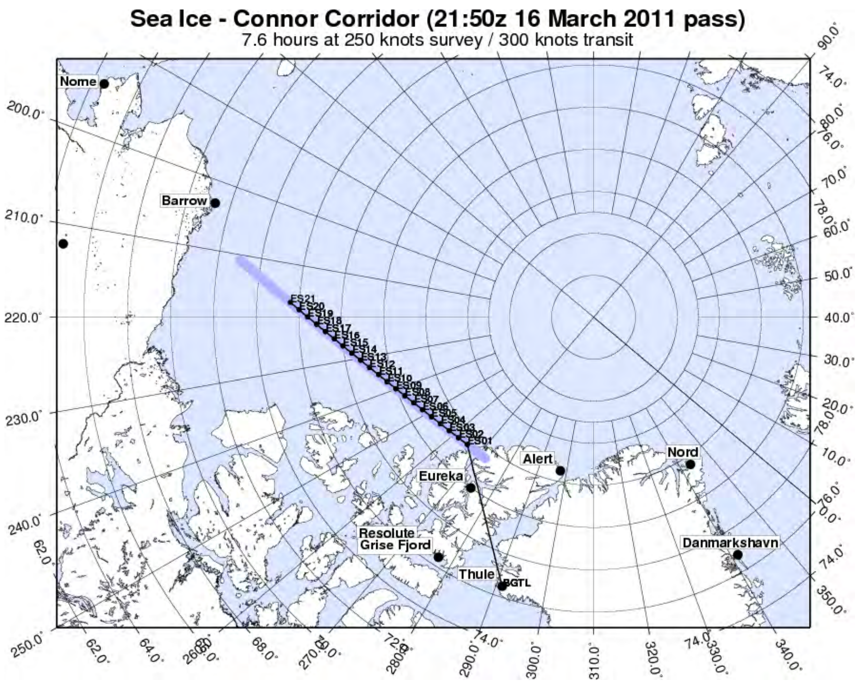

Figure 9: Connor corridor track for first flight in the 2011 IceBridge campaign.

Figure 9 shows the first flight of the 2011 IceBridge campaign known as "Connor Corridor." Although Operation IceBridge is still ongoing at the time of this paper, the opening flight was completed on 16 March 2011. This particular flight track was selected for that date because the European Space Agency (ESA) ENVISAT satellite was scheduled to follow the same path later that day. Once processed and sent to scientists, both the aircraft and satellite measurements will be compared to one another and used together to create more precise models.

I was fortunate to be a part of Operation IceBridge 2011 for eight days in mid March, I gained a profound appreciation for the mission at hand. In the effort to reduce uncertainty about future climate change, the team is committed to collecting data needed to significantly improve ice-sheet models. Prediction of the future state of the Earth's cryosphere is reliant upon the measurements gathered from IceBridge's airborne platform. Thus, this research project is designed to analyze the sea ice thickness in the Arctic region using the findings from Operation

IceBridge flights.

Because the time between gathering data and interpolating data can be extensive, this paper uses data from the flight tracks flown in the 2009 Arctic IceBridge missions.

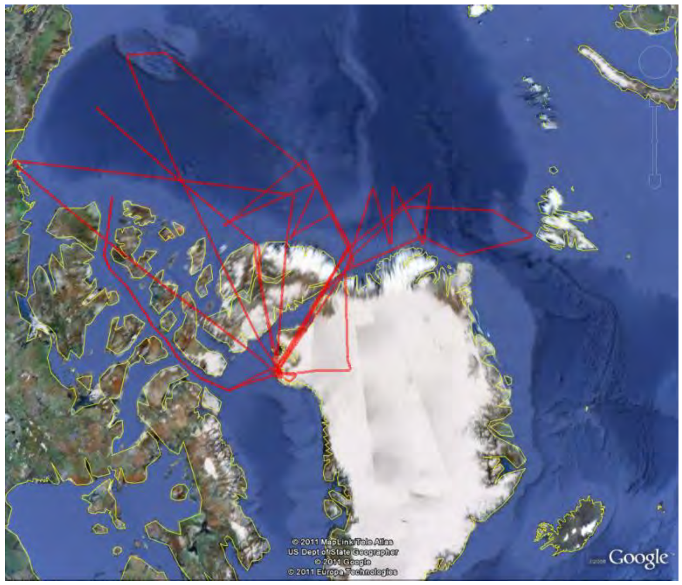

Figure 10: Flight Paths for the 2009 flights using ATM to look at sea ice extent. (GPS data from NSIDC)

Figure 10 shows the flight tracks for the 2009 campaign. This was an important time to look at sea ice, because just two years earlier, in 2007, the Arctic hit the minimum sea ice extent on record.

Due to its accuracy, this project focuses primarily on the sea ice elevation measurements from the ATM onboard the P-3B. The ATM is extremely effective because the waveform reveals the distribution of surfaces above the terrain. This laser altimeter is able to measure various regions that are changing quickly like the sea ice in the Arctic. During the initial minutes of the first flight of the 2011 campaign for example, the ATM collected about two million data points. The laser's massive collection of data can then be adjusted by real time software to create a 3-D map showing the topography that was flown over (Yungel, 2011). This gives scientists more precise sea ice surface properties of the Arctic without having to be physically on the ice.

RESULTS

In order to calculate sea ice thickness, the first step is to get the elevation measurements from the ATM. The elevation data from the ATM that this project focuses on are from sea ice measurements and the elevation is reported with respect to the WGS-84 ellipsoid.

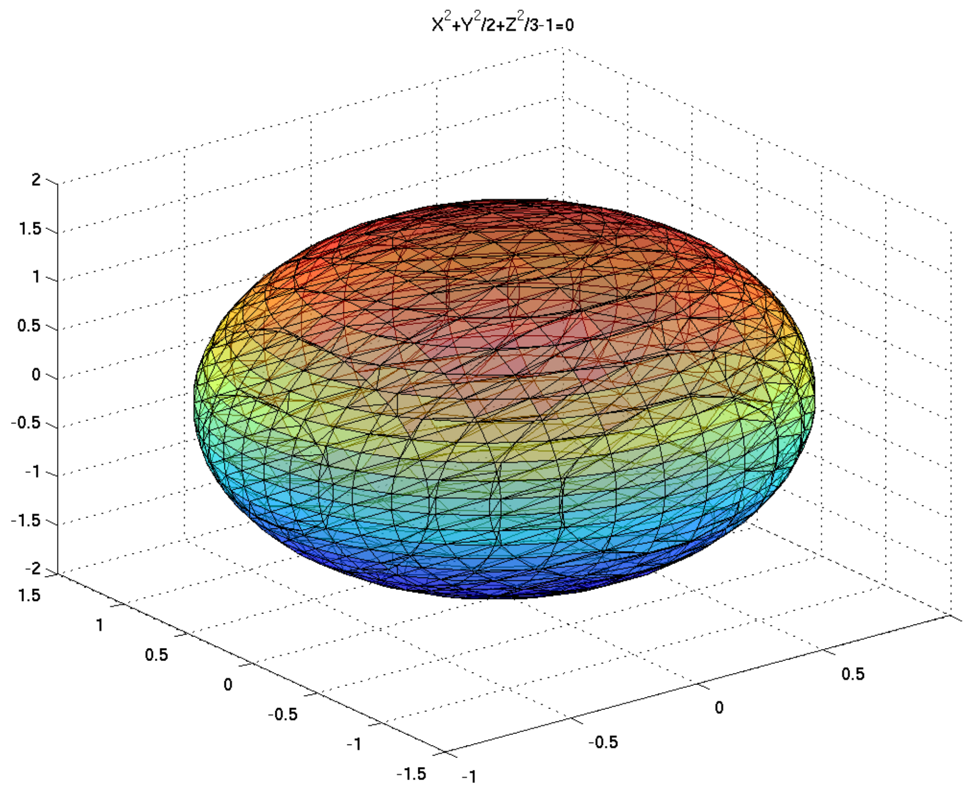

Figure 11: WGS84 Ellipsoid.

Figure 10 shows a three dimensional representation of the WGS84 ellipsoid. The ellipsoid is the mathematical approximation used to represent the earth's ellipsoidal shape and surface. When the ATM measures the elevation of the sea ice surface, it is referenced to the WGS84 ellipsoid, as used by global positioning systems. This is very good for giving accurate elevations, but in order to get measurements with respect to sea level, the data needs to be referenced to a geoid model. In this paper the 1996 model or EGM-96 geoid model is used.

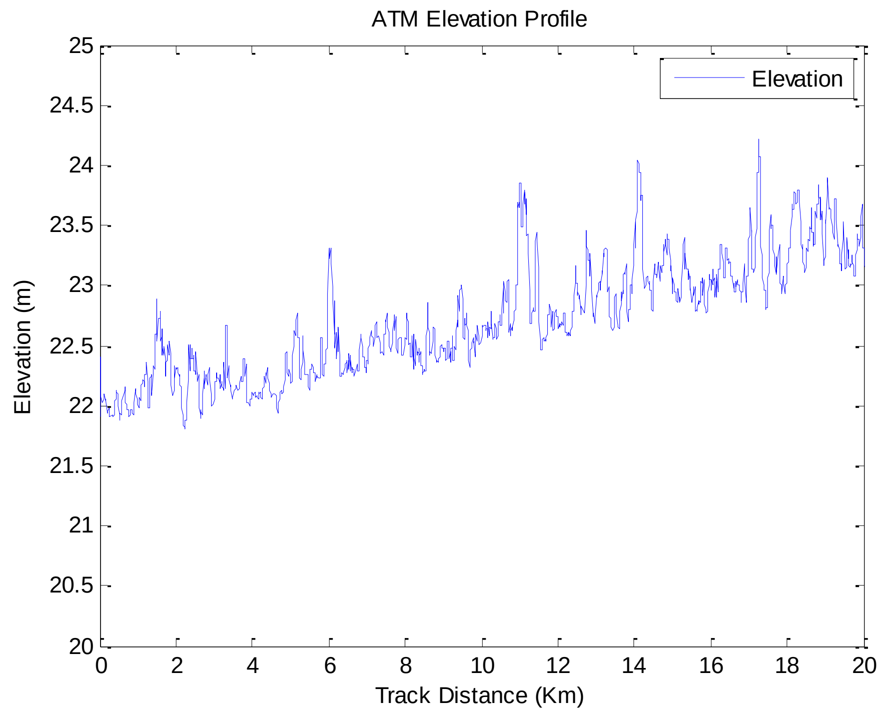

Figure 12: ATM's elevation data over flight track in relation to ellipsoid.

Figure 12 shows the elevation data collected from a 2009 IceBridge flight north of Greenland. As the graph indicates, the elevations are 21 to 24 meters above the surface. These measurements are actually referenced to the ellipsoid (theoretical ellipsoidal earth surface), which is why they are so high. It is extremely important to find this elevation in relation to the geoid because this eliminates that dominant component of the elevation signal (20 to 30 meter elevations) leaving behind small-scale sea level anomaly (-3 to 3 meter elevations). This allows for a more detailed examination of the freeboard. (L.N. Connor et al., 2008)

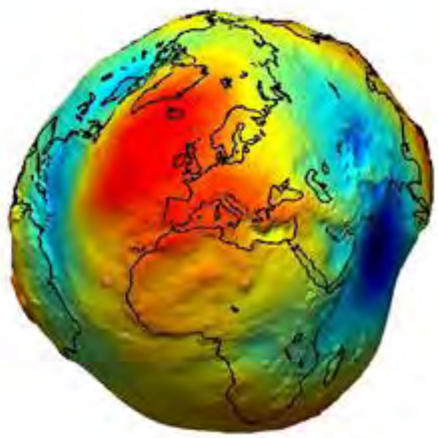

Figure 13: Geoid shape of earth's equipotential surface, which is a mathematical representation of how the sea surface would appear if it was in equilibrium and the earth was not rotating. (ipy.arcticportal.org).

Figure 13 indicates what the EGM-96 geoid looks like. The geoid is another mathematical representation and is how the sea surface would appear if it was in equilibrium. As the figure shows, the geoid varies all over the earth, therefore, this discrepancy is important to consider when taking measurements over great distances such as a flight track. The next step is to adjust the elevation measurements with reference to the geoid instead of the ellipsoid.

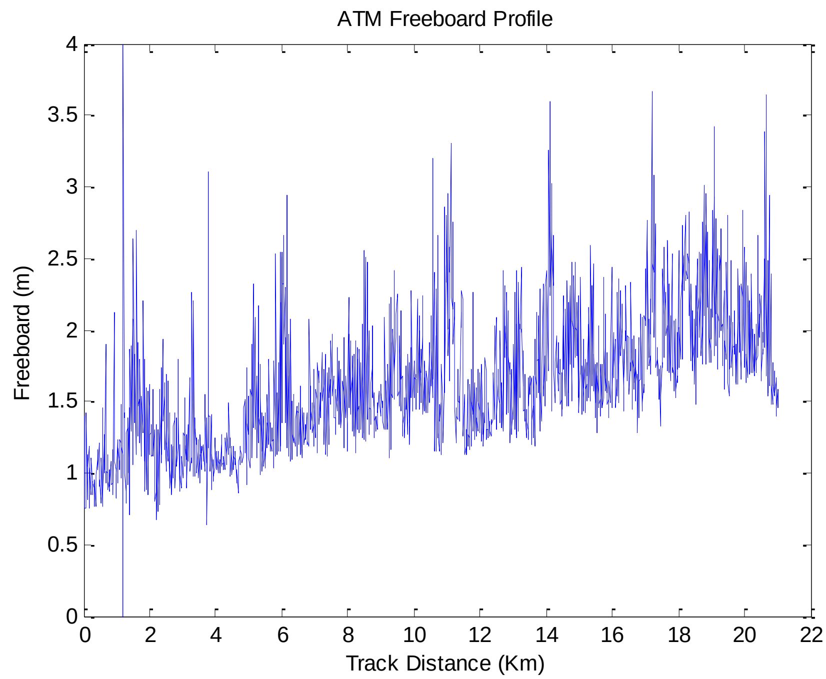

Figure 14: Graph of the Freeboard vs. flight path distance with only using the geoid approximation at 9the first point.

Figure 14 shows the adjusted elevation heights along the flight path now referenced to the geoid height at the beginning of the flight track, instead of the ellipsoid. Notice that the elevations are now between .5 and 3.5 meters instead of 20 to 24 meters. The elevations referenced to the geoid are now known as freeboard heights. Freeboard is how high the sea ice sits on top of the sea surface. Knowing the freeboard of the sea ice is critical when determining the sea ice thickness because it is an important component to the calculation used to infer thickness.

Notice in figure 13 that the freeboard height seems to rise along the flight path. This is misleading because freeboard is relative to the geoid which is not constant at every point on earth. Instead, the geoid, or earth's equapotential sea surface, varies at every location on earth (refer back to figure 13). The following figure shows the freeboard referenced to the geoid at each point along the flight track.

In order to get the proper freeboard data it is necessary to calculate the height above the geoid (water level) instead of the ellipsoid which is the height above the theoretical earth's surface. The geoid varies quite a bit from location to location so there are many factors that go into calculating the height above the geoid.

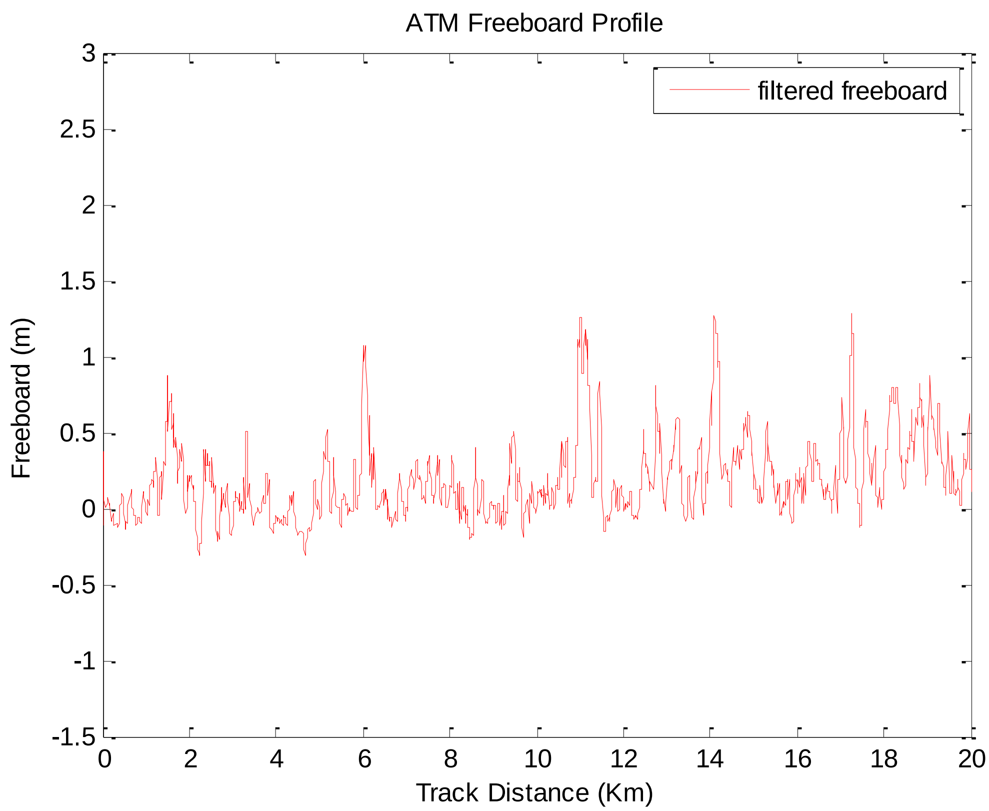

Figure 15: A 20 Km segment track of sea ice freeboard along flight path referenced to geoid.

Figure 15 shows the approximate freeboard in relation to the geoid model at 50 points along the 20 kilometer flight track. This could be a potential source of error because the geoid varies at every single point on the earth's surface and the corrections were only applied at 50 points along the flight track. Notice how the freeboard varies with distance but does not have the upward trend that the graph with only one geoid correction possesses. This is because of the geoid corrections for numerous points along the flight track.

Once the data set is corrected and referenced to the geoid at every point along the flight track, analysis is conducted to look for where there are leads, or separations in the ice. It is very important to find these breaks in the ice because referencing freeboard just to the geoid is still very much an approximation and therefore the sea ice elevation is not referenced to the actual sea surface; just a theoretical one.

DISCUSSION

The ATM does a very good job of finding elevation in relation to the ellipsoid or elliptical sea surface. From this elevation data, an approximate freeboard is calculated in relation to the geoid. The geoid is the sea surface of equal gravity potential. As mentioned before, this is just an approximation though. Therefore, flying over a lead in the ice is very important for determining the exact sea surface elevation. Once this is found, adjustments are made to the approximate freeboard data recorded from the ATM measurements. Freeboard is the first and most necessary component of data when calculating sea ice thickness from overhead measurements.

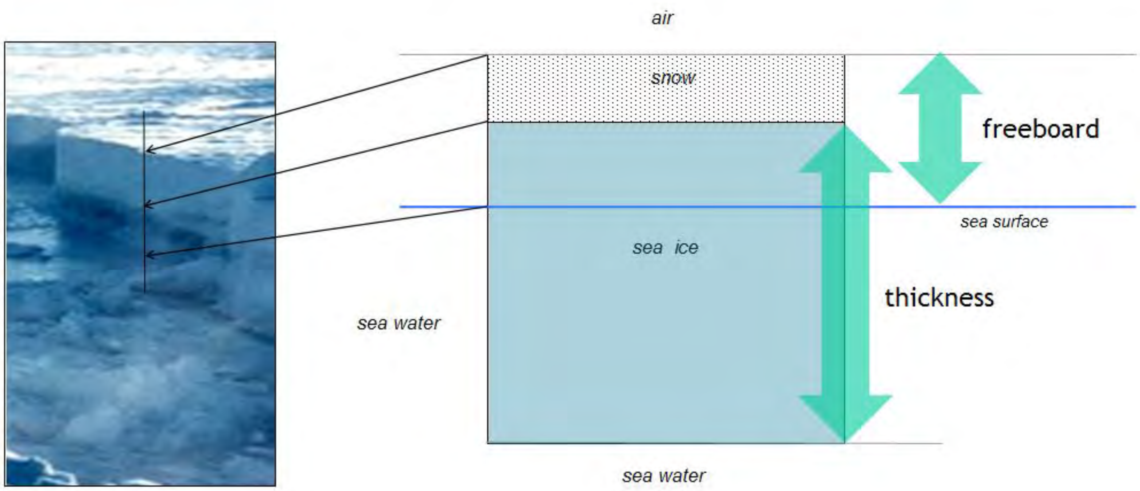

Figure 16: This figure shows a lead in the ice and the components associated with the lead. It is a very good visual representation of sea ice freeboard.
Ron Kwok, NASA/JPL http://rkwok.jpl.nasa.gov/publications/Kwok.2010.Ocean.pdf

Figure 16 is a good visual representation of a lead and how it is essential to finding the exact sea surface and then determining the actual freeboard and sea ice thickness sequentially after that. The figure shows that the freeboard is the height of the sea ice and snow above the actual sea surface, while the thickness is both the freeboard above the water and how far below the water the sea ice sits.

Figure 16 displays another important factor to consider. Laser altimeters will measure elevations of snow accumulated on sea ice while radar altimeters are able to measure elevations at the snow/sea ice interface. This means that, in order to get an accurate ice thickness measurement, both a snow penetrating radar and a laser altimeter need to be used in conjunction with one another (L.N. Connor et al, 2008). This is why the laser elevations tend to be higher than the radar elevations over snow-covered sea ice (L.N. Connor et al, 2008).

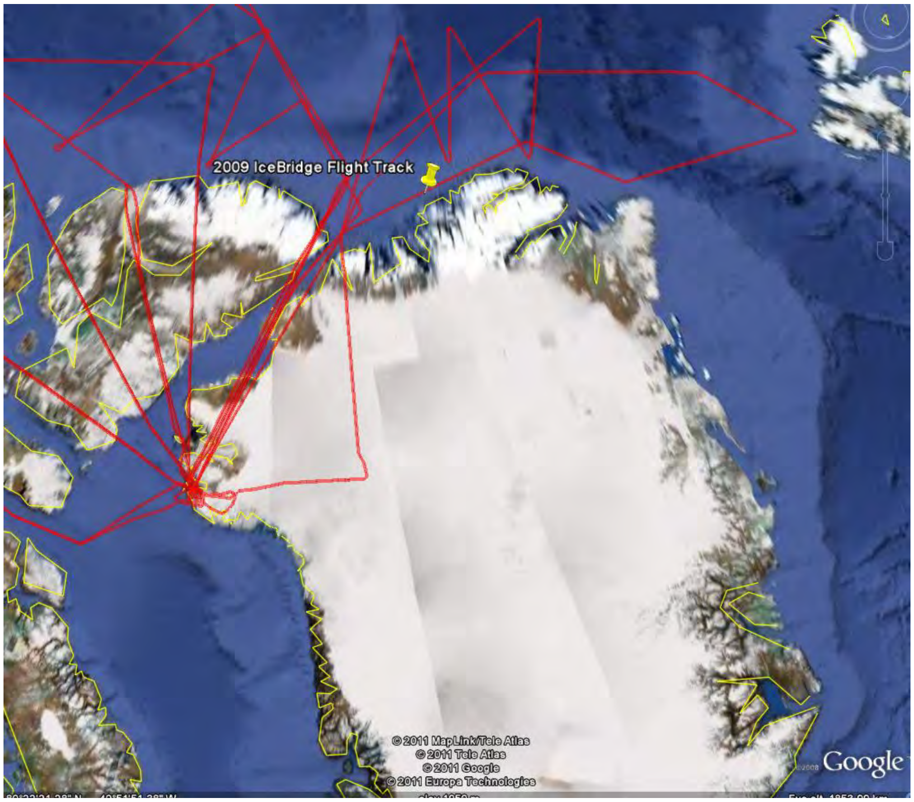

Figure 17: The yellow marker indicates the location of the start of the 20 kilometer flight track analyzed in this paper.

Figure 17 shows a yellow marker for the start of the 20 kilometer flight track that I looked at in my analysis. This portion of the flight was an appropriate region to study because it was right over a portion of earth where there is a large gradient in the geoid surface. As discussed in the "results" section, adjustments were made along the flight track in order to get freeboard heights relative to the geoid. By seeing how precise the geoid approximation is in relation to the actual freeboard, then thickness can be determined for surrounding areas and used in models displaying the sea ice thickness over a region. The ATM is one of the best suited instruments for this task because of its dense, along track sampling (S.L Farrell et al., 2011).

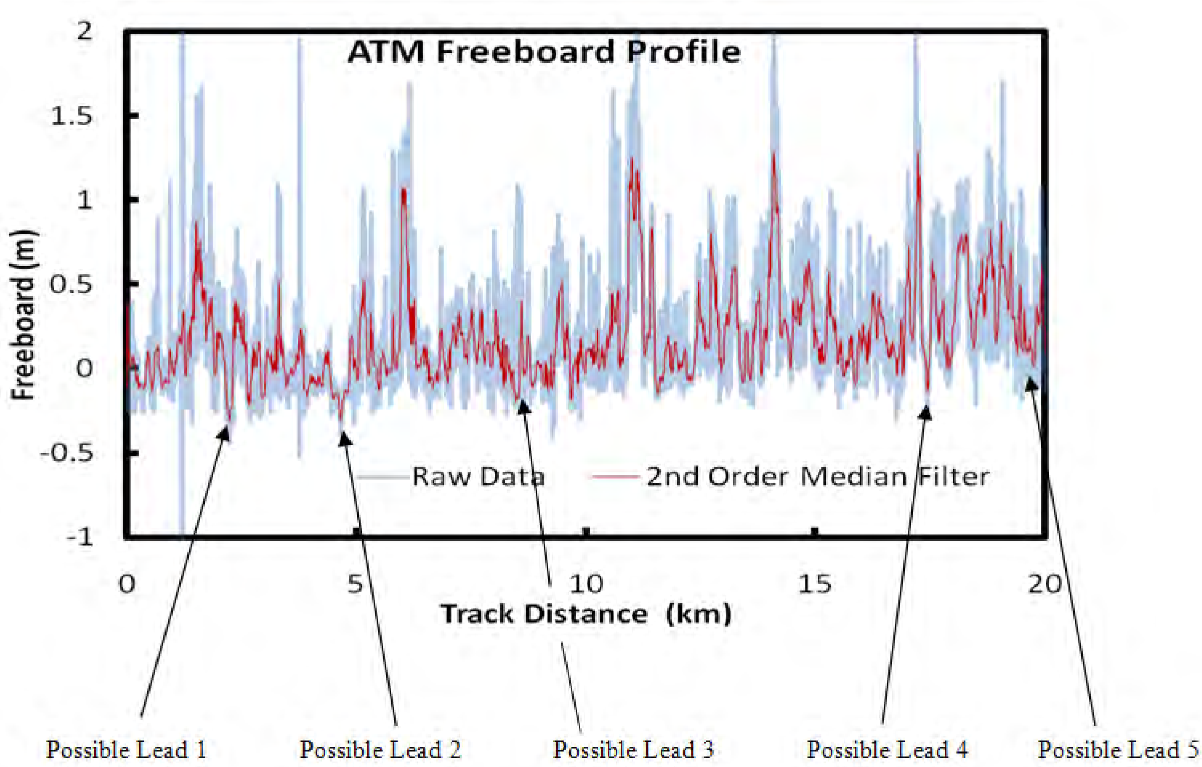

Figure 18: A 20 Km segment of sea ice freeboard (m) showing the raw data and then the filtered data of sea ice freeboard along flight path.

Figure 18 shows both the unfiltered and filtered freeboard heights for the 20 kilometer flight track flown during the 2009 IceBridge campaign. As the graph reveals, there are certain locations on the flight track where minimum points exist. These locations could represent leads or breaks in the ice. A lead is a portion of the ice that separates from another portion leaving open water due to wind forcing and ocean currents moving the sea ice. Imagery from the digital mapping system (DMS) cameras or satellite imagery would be needed to confirm a lead in the ice. Finding leads is critical in order to get the exact sea level and exact freeboard for this portion of the flight track. Therefore, when determining the exact sea ice freeboard and hence, thickness, there needs to be an accurate identification of a lead in order to find the exact sea level. From here, adjustments can be made to the surrounding freeboard data allowing it to be zeroed at sea level.

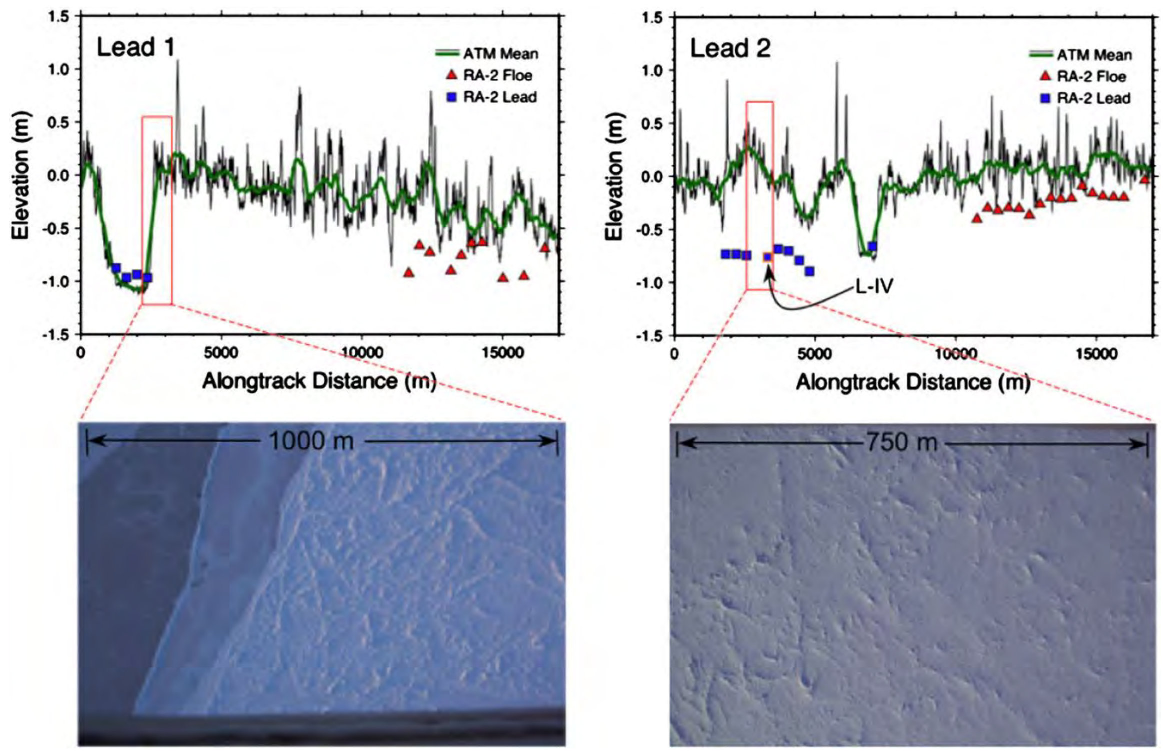

Figure 19: Elevation or freeboard graphs corresponding to leads at the minimum points along the flight track (L.N. Connor et al, 2008).

Figure 19 shows ATM data points along with a radar altimeter's data points looking at two leads within the flight track. This is a good example of using both altimetry elevation data in conjunction with camera imagery to identify leads on a given flight track. It is very important to the sea ice thickness approximations to obtain measurements over leads. Flying over a lead reveals the precise freeboard because the elevation will be in relation to the exact sea surface whereas, in the geoid approximation, it is just that; an approximation to a mathematical sea surface.

As figure 19 shows, the elevation measured over a lead will often be less than zero due to the geoid approximation. This is why it is critical to find exact sea level heights over a lead so that these elevations can be made equal to zero and represent exact freeboard. From here, it is possible to interpolate out to approximate the exact freeboard along the entire flight track in between successive leads.

The data I used for the flight track came from the NSIDC data archives for the 2009 IceBridge Campaign. In order to plot a flight track, I first needed to have its GPS coordinates put into degrees for GIS software to plot it. The GIS software used in this paper is Geosoft, which is used by many geologists and earth scientists on the IceBridge campaign including Kirsty Tinto from Lamant-Doherty's Earth Observatory and Beth Burton from the U.S. Geological Survey. The GPS coordinates were the only reference position available; therefore, using the GIS software, Geosoft, I converted GPS coordinates into a track distance, which came out to be roughly 20 kilometers. The following graph shows the elevation data relative to the ellipsoid for the entire flight track.

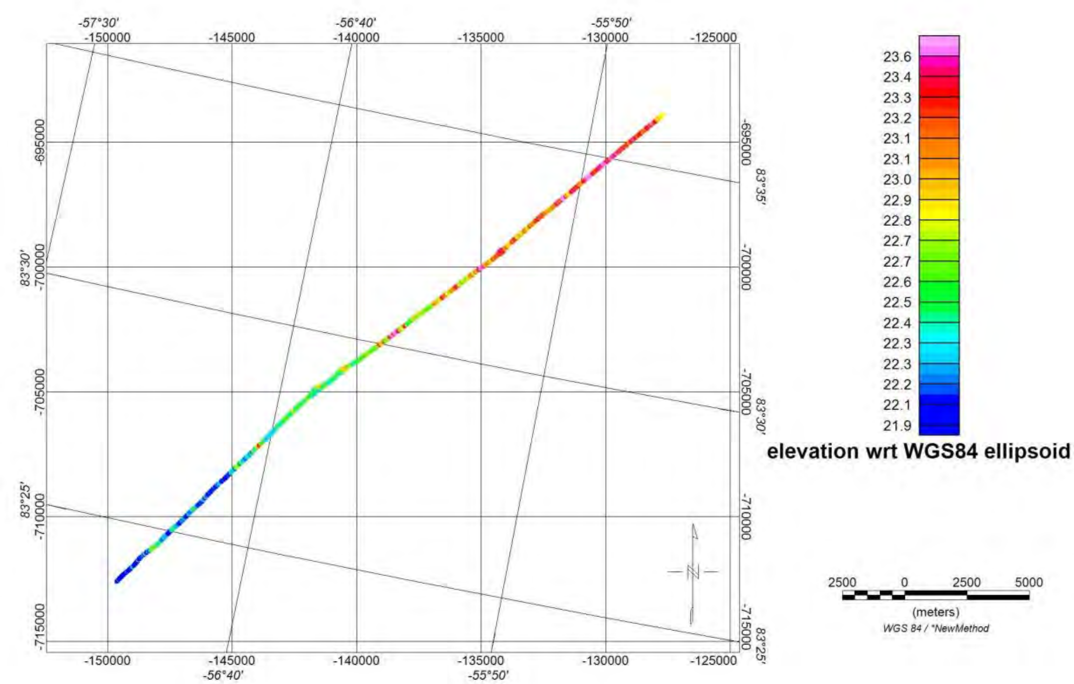

Figure 20: A 20 km flight track elevation data referenced to WGS84 ellipsoid collected from ATM during 2009 IceBridge sea ice flight north of Greenland.

Figure 20 shows that the elevation of the sea ice increases from southwest to northeast from approximately 21 meters to 23.6 meters. This is due to the fact that the ATM measures height above the ellipsoid and has not been corrected to the geoid yet. In order to do the geoid conversion, I needed to have the longitude and latitude in degrees, minutes and seconds. Therefore, again using Geosoft, I converted the decimal coordinates into degrees, minutes and seconds.

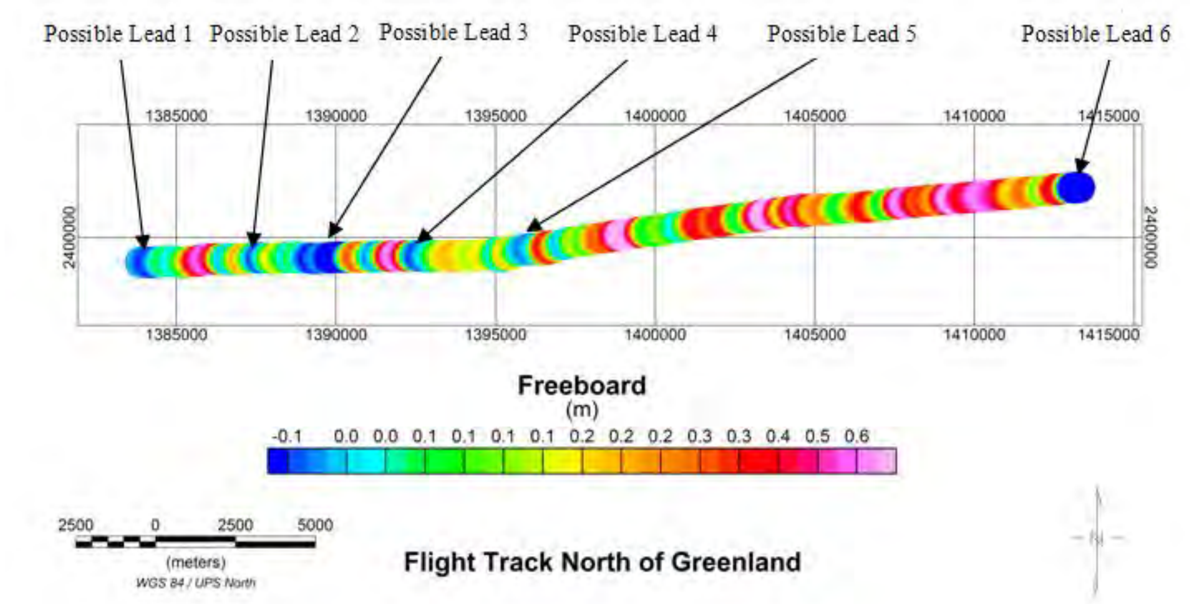

Figure 21: A 20 km flight track of the freeboard elevations in reference to the EGM96 geoid during the 2009 IceBridge campaign.(Beth Burton, 2011).

Figure 21 shows a zoomed in version of the flight track where the adjustments have been made for the difference in the ellipsoid height and geoid surface at multiple points along the track. Because the geoid surface varies at every point on earth, many adjustments were needed along this 20 kilometer flight track. Figure 9 does a very good job showing points along the flight track that could represent leads. The blue portions have a -.1 meter elevation which is the lowest elevation measurement.

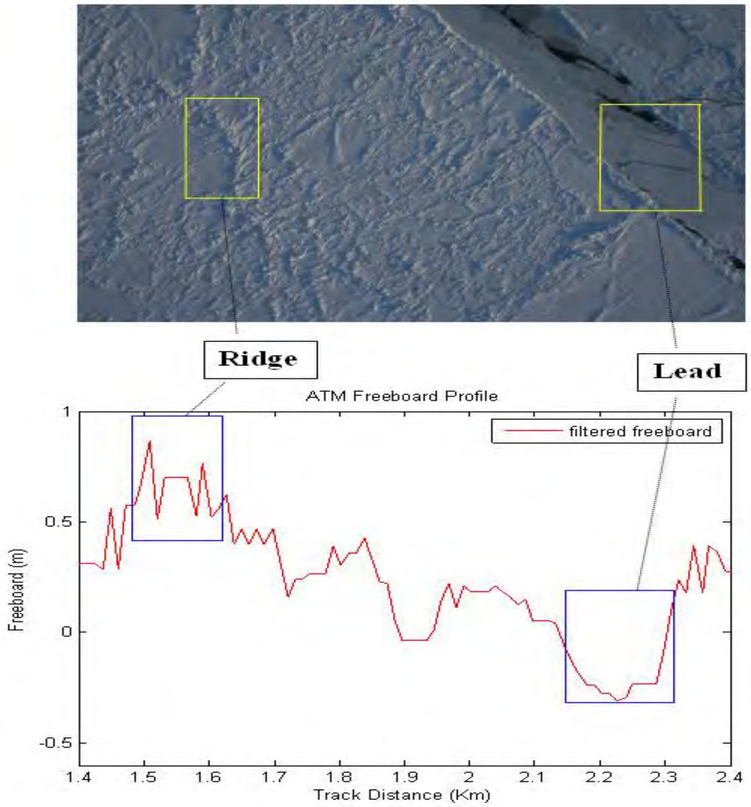

Figure 22: "Cambot" photo imagery corresponding to along track regions enclosed in the boxes. The imagery is used to confirm leads and other areas of interest.

Using "Cambot" photo imagery from the 2009 IceBridge flight I was able to find the portion of the flight track the imagery corresponded to. Focusing in on the portion of flight track the image represented allows for a clear positive identification of the lead. It is very important to the sea ice thickness approximations to obtain measurements over leads. More recent flights use DMS imagery instead of Cambot; however the analysis remains the same. Further investigation would need to be done by looking at Cambot imagery for the entire flight track. By looking at the imagery, I would be able to confirm all of the leads in the ice and make sure there was not an ATM error in measuring elevation. After properly identifying the lead, I could set the blue portions in figure 22 equal to a freeboard of 0 meters (sea surface). By doing this, it would adjust the rest of the flight track to be referenced of the zeroed sea surface.

The next step in determining the thickness of the sea ice is to use density approximations of the ice, snow and sea water to see how deep the ice sits in relation to its freeboard. To do this, the isostatic equilibrium equation is used to determine thickness. (Giles 2008). Sea ice thickness may be estimated using measurements of sea ice freeboard along with a characterization of the vertical density structure of the sea ice ((L.N. Connor et al, 2008). Using the simple concept of Archimedes principle, the thickness of the sea ice is able to be estimated. Snow depth, snow density and ice density have a strong impact on the sea ice buoyancy and freeboard. NASA's operation IceBridge utilizes the ATM laser altimetry team along with Kansas University's radar team, enabling a variety of measurements along the same flight track. The ATM determines the elevation of the surface while the snow penetrating radar is able to determine the snow depth at each point along the track. The higher frequency radars are able to measure snow depth quite well, while the ATM gets very accurate elevation data because so many samples are taken along the track.

(Alexandrov, DATE). In order to determine the sea ice thickness the isostatic equilibrium equation is used. The isostatic equilibrium equation is as follows:

$$H_i = \frac{\rho_w}{(\rho_w - \rho_i)} F_i + \frac{\rho_{sn}}{(\rho_w - \rho_i)} H_{sn} .$$

Where H_i represents ice thickness, ρ_w represents the density of sea water (set at 1025 kg/m^3), ρ_i represents the density of the ice (differs for multi-year and first year ice), F_i represents the freeboard depth of the sea ice, ρ_{sn} represents the density of the snow and H_{sn} represents the depth of the snow on top of the ice (Alexandrov, DATE).

As seen in the isostatic equilibrium equation, there are many factors that need to be considered in order to estimate ice thickness from freeboard data. Snow, ice and water density along with snow depth and freeboard are all are parts of the calculation. It is important to realize that all of these parameters exhibit regional and season variability. Furthermore, the type of sea ice is important to consider. For example, first year ice has a density between 840 and 910 kg/m^3 while multi-year sea ice has a density between 720 and 910 kg/m^3. (Alexandrov, DATE). These uncertainties of ice density, snow density, snow thickness and freeboard are the major sources of error in ice thickness calculation (Giles, 2008).

Even though there are many variables in the isostatic equation, there is a consistent relationship between freeboard and ice thickness. Peter Wadhams, a Professor at the University of Cambridge, found an empirical relationship between the freeboard and ice thickness of multi-year ice off the coast of Northern Greenland, according to the following equation: $Hi = 9.04Fi$, where Hi is sea ice thickness and Fi is freeboard. Therefore, it is apparent from his equation that a linear relationship exists between sea ice freeboard and multi-year sea ice thickness.

SUMMARY AND CONCLUSIONS

With temperatures in the Arctic up 5 degrees Celsius over the course of the last 30 years, many environmental changes are evident. Greenland's glaciers are melting, Arctic sea ice extent is declining and so is the volume of the multi-year sea ice. The Arctic is transforming at a very rapid rate in terms of climactic time scales. This phenomenon makes it more important than ever to monitor, study, and understand the Arctic now, so that scientists can predict the possible changes to come. For the United States Navy in particular, it is crucial to understand this altering environment so that the fleet can keep sea lanes safe and free as more and more maritime activity begins to occur in the Arctic.

NASA has been at the forefront of studying this northernmost maritime environment beginning with the employment of ICESat, an ice, cloud, and land elevation satellite, which gathered data from 2003 until 2009. NASA's next ice, cloud and elevation satellite (ICESat-2) is scheduled to go into orbit in 2016. In the meantime, NASA is utilizing a P-3B aircraft in the Arctic to "bridge" the gap between these two remote sensing satellites. This mission, which takes measurements over both the Arctic and Antarctic for a few months each year, has become known as Operation IceBridge.

Although a variety of equipment is used onboard the P-3B aircraft, the Airborne Topographic Mapper (ATM), in particular, plays a vital role in analyzing the Arctic environment. Not only does the ATM provide very accurate topographic models, but the elevation data that the ATM gathers can be used to infer sea ice thickness. Being able to calculate sea ice thickness over a large area is very important for scientists because this allows them to monitor changes in the thickness for entire regions instead of single points where an ice mass balance buoy is taking insitiu data. However, the process involved in calculating the thickness over a vast area, from just using the ATM's elevation data, is quite complex. There are many steps and adjustments that need to be done in order to infer an accurate sea ice thickness.

This paper aims to look at the steps necessary to determine sea ice thickness based off laser altimetry data gathered during NASA's Operation IceBridge. Using the Airborne Topographic Mapper (ATM) sea ice elevation can be measured from an aircraft flying overhead. Two different ATM's are taking measurements at all times during the flight. One ATM uses a 5 degree full angle scan, while the other uses a 30 degree full angle scan. The reason for the different angles is that, while the 30 degree scan covers a larger area, the photons may scatter and not be received if it measures over surface water. So, if there is a lead or opening in the ice, the 30 degree angle scan is useless. The 5 degree angle scan, however, reflects back very well when flying over leads and is an essential instrument because identifying leads is critical in the sea ice thickness calculation.

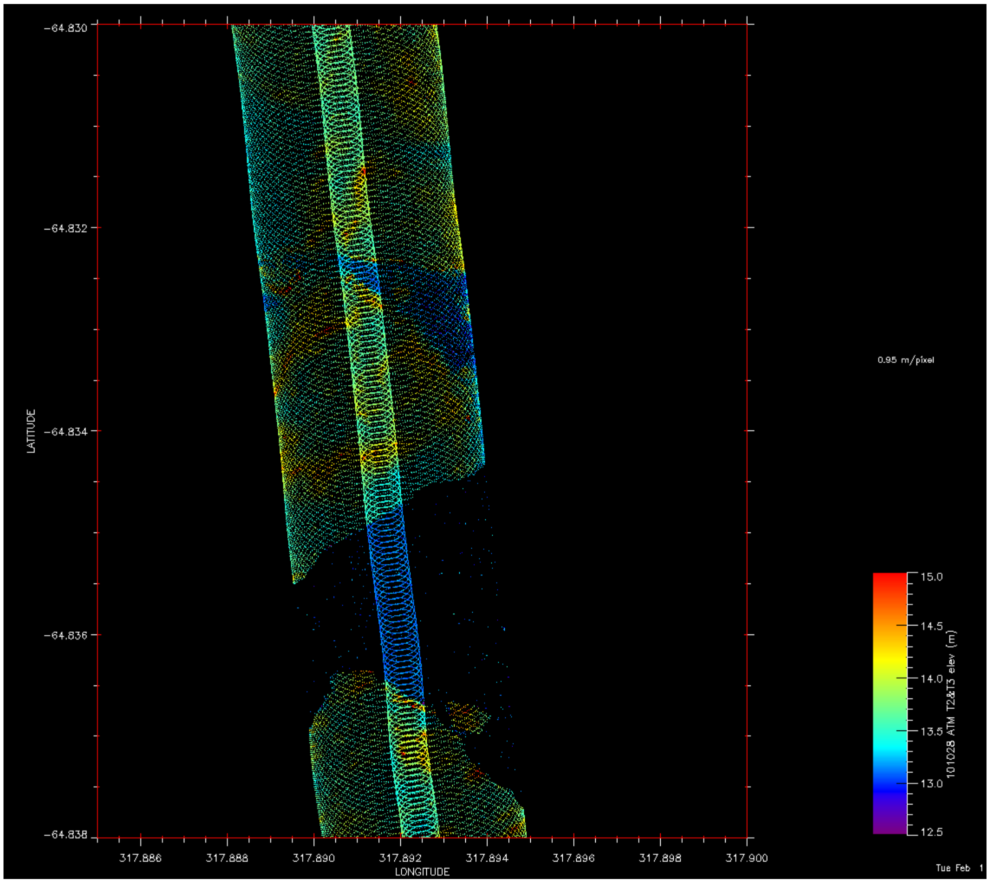

Figure 23: ATM 30 degree and 5 degree swath plot of surface elevation flying over a lead in the sea ice.

Figure 23 shows the 30 degree full angle scan and the 5 degree full angle scan taking elevation measurements while flying over a lead in the ice. As the figure indicates, while the 30 degree scan fails to send elevation measurements back over the lead, the 5 degree scan fills the gap, sending very accurate elevation measurements back that indicate a low point in the ice, which is very likely open ocean.

Once the ATM has gathered its elevation data, an approximate freeboard is calculated in relation to the earth's geoid model. By determining the location of leads in the ice, further calculations may be done to get a sea ice freeboard measurement relative to the exact sea surface. This is why it is so important to locate and positively identify leads in the sea ice. Next, by using the hydrostatic equation and the density approximations associated with it, sea ice thickness may be inferred for the region between successive leads.

Ultimately, the goal of scientists is to perfect this process of calculating sea ice thickness from laser altimetry data by comparing the thickness measurements to insitiu and satellite data. By doing this, scientists will be able to monitor and better understand the changes in sea ice thickness, allowing them to predict the future of the Arctic environment.

ACKNOWLEDGEMENTS

I would like to extend a special thanks to my adviser, LCDR John Woods; his guidance throughout this project and dedication to me has been truly exceptional and gratefully appreciated. He spent countless hours formulating a project where I would actually be able to go to the Arctic and partake in the monitoring of sea ice-thickness firsthand. Thank you for unveiling this unique opportunity; the hands-on Arctic experience was phenomenal. I would also like to express my gratitude to Professor Malek-Madani for providing the generous funding required for traveling to Thule, Greenland and participating in NASA's Operation IceBridge 2011. Thank you to James Yungel of NASA's IceBridge team for explaining the ATM in depth to me and showing me the intricacies of the P-3B aircraft. Thank you to Beth Burton of USGS for your help with Geosoft and for bolstering my understanding of the magnetometer. Lastly, a very special thanks goes to Kirsty Tinto of Lamant-Doherty Earth Observatory for assisting me with the GIS and for letting me be part of the "gravimeter team" at IceBridge 2011. Thank you NASA team and friends for your steadfast support and for the amazing opportunity you afforded me.

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ARCTIC SEA ICE: USING AIRBORNE TOPOGRAPHIC MAPPER MEASURMENTS (ATM) TO DETERMINE SEA ICE THICKNESS

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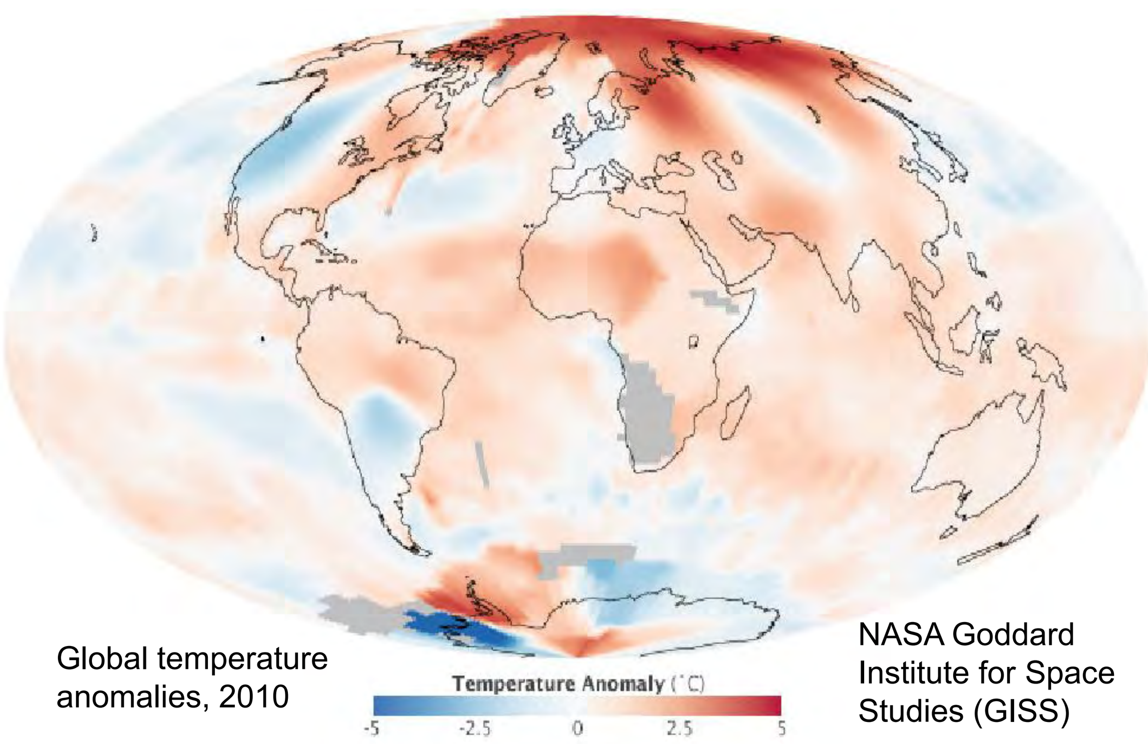
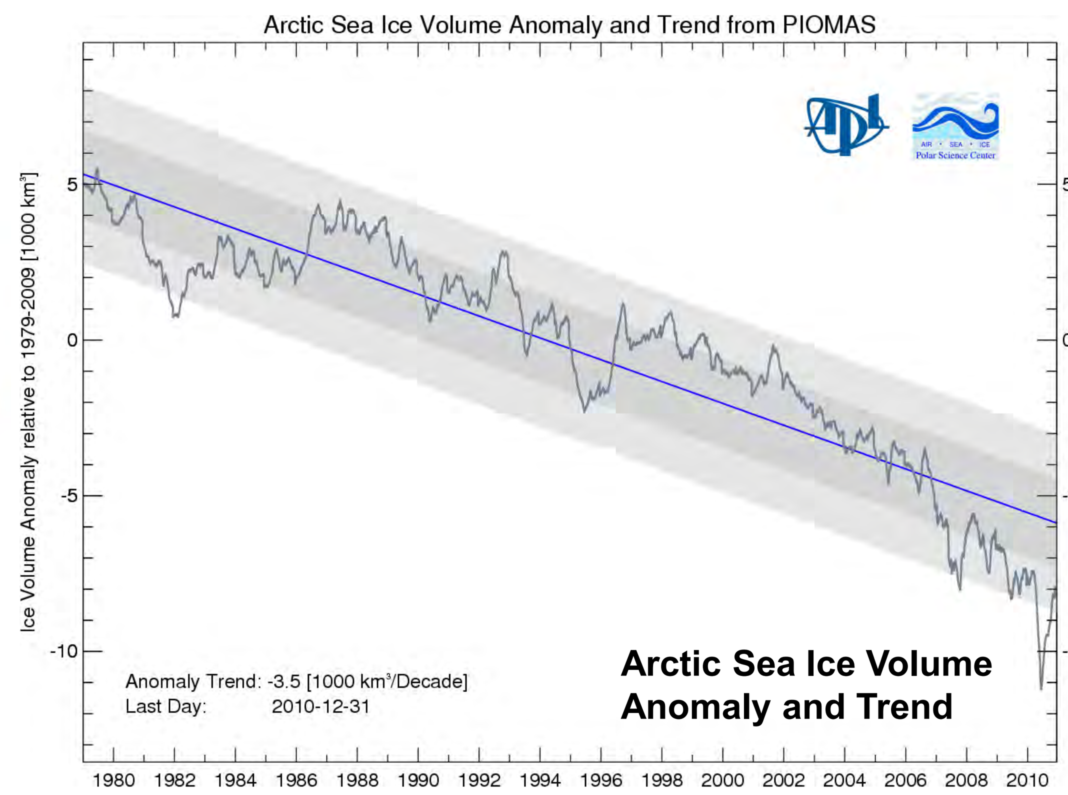
LCDR John Woods, USN, United States Naval Academy



Global temperature anomalies, 2010

NASA Goddard Institute for Space Studies (GISS)



Arctic Sea Ice Volume Anomaly and Trend

Introduction

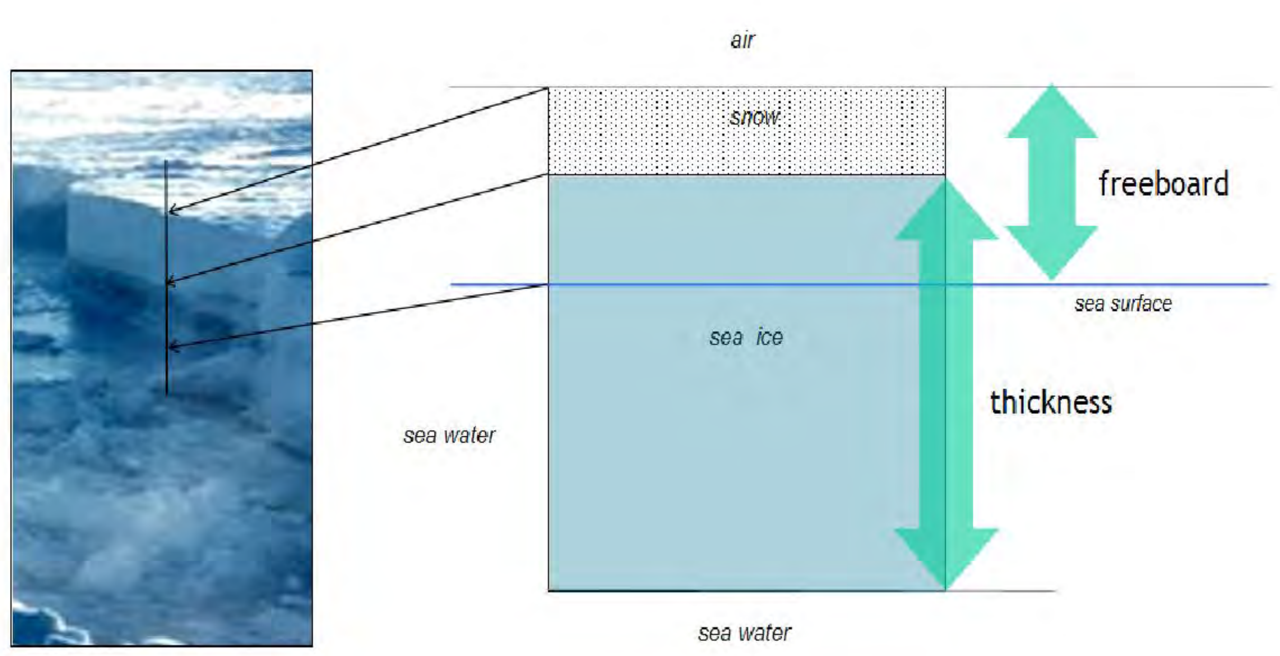
With the Arctic changing faster than any place on earth, ice-diminishment is cause for immediate concern. Although projections vary, scientists agree that the Arctic is headed toward ice-free summers, which in turn poses numerous challenges for the United States Navy. An open ocean in the near future may increase water traffic, create boundary disputes, and raise questions over sea sovereignty, calling upon American diligence in defending its borders and keeping Arctic sea lanes free and safe. Thus, because of the growing national security implications, it is important to study the altering Arctic environment in greater detail now so that the U.S. Navy is better prepared to operate there in the future.

NASA's P-3B Aircraft

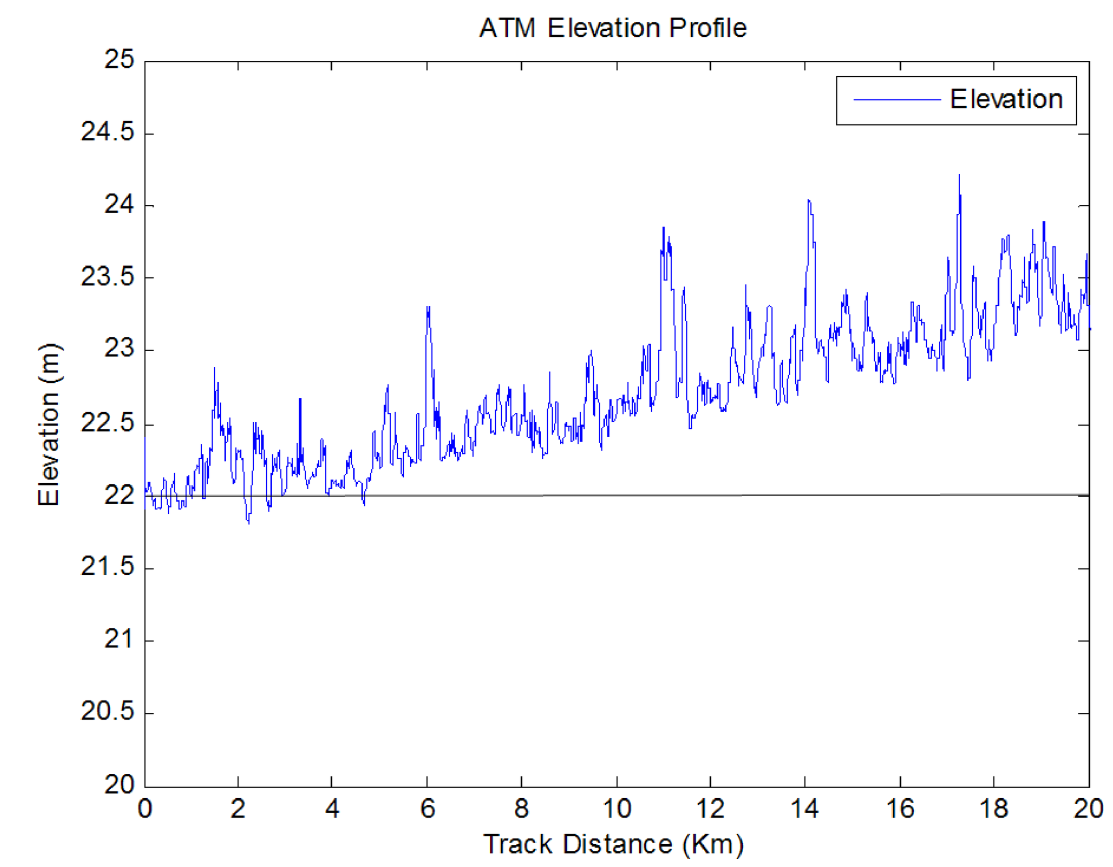
View of sea ice flying1500 feet over Arctic Ocean

Materials

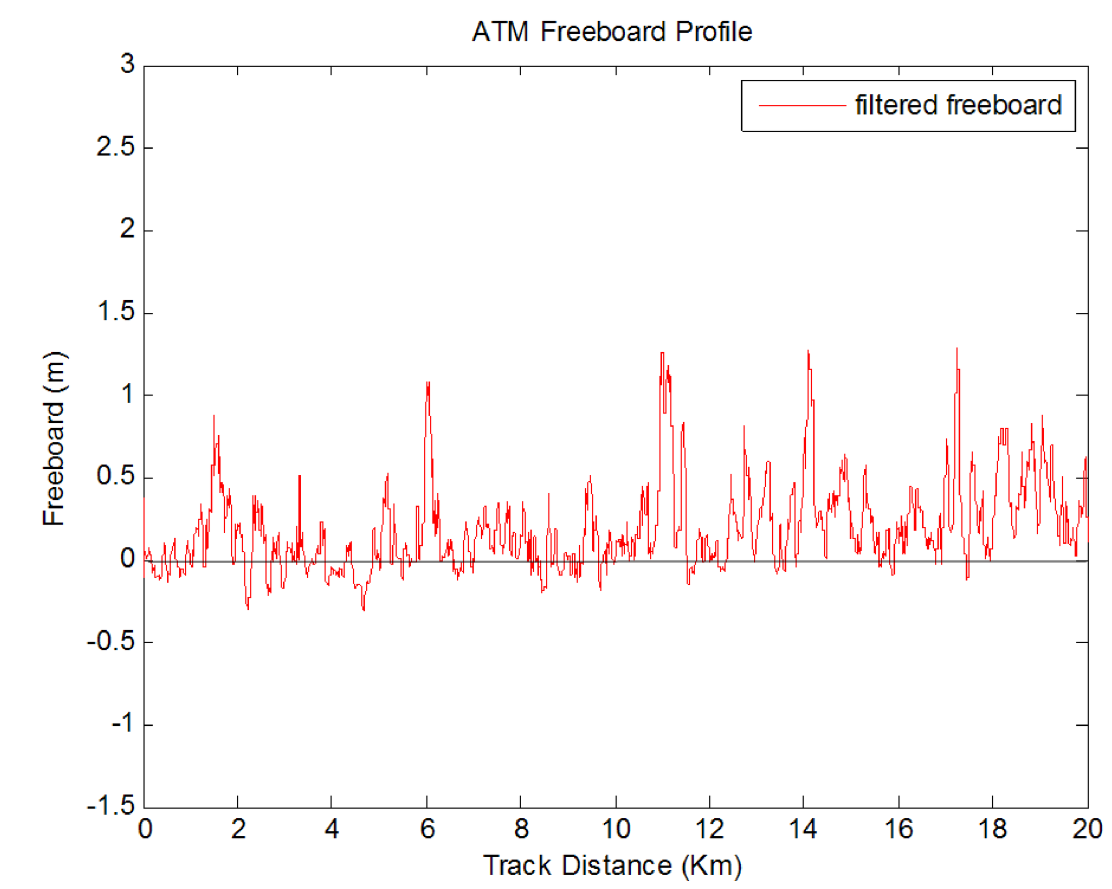
NASA's annual Operation IceBridge will bridge the gap between ICESat and ICESat-2. The airborne measurements will provide the data necessary for a three-dimensional view of Arctic and Antarctic ice sheets, ice shelves and sea ice. This paper looks at the steps, process and approximations behind determining sea ice thickness given raw sea ice elevation data collected from the Airborne Topographic Mapper (ATM), a laser altimeter that took measurements during NASA's IceBridge campaign in 2009 and continues to be the primary laser altimeter used in IceBridge today.



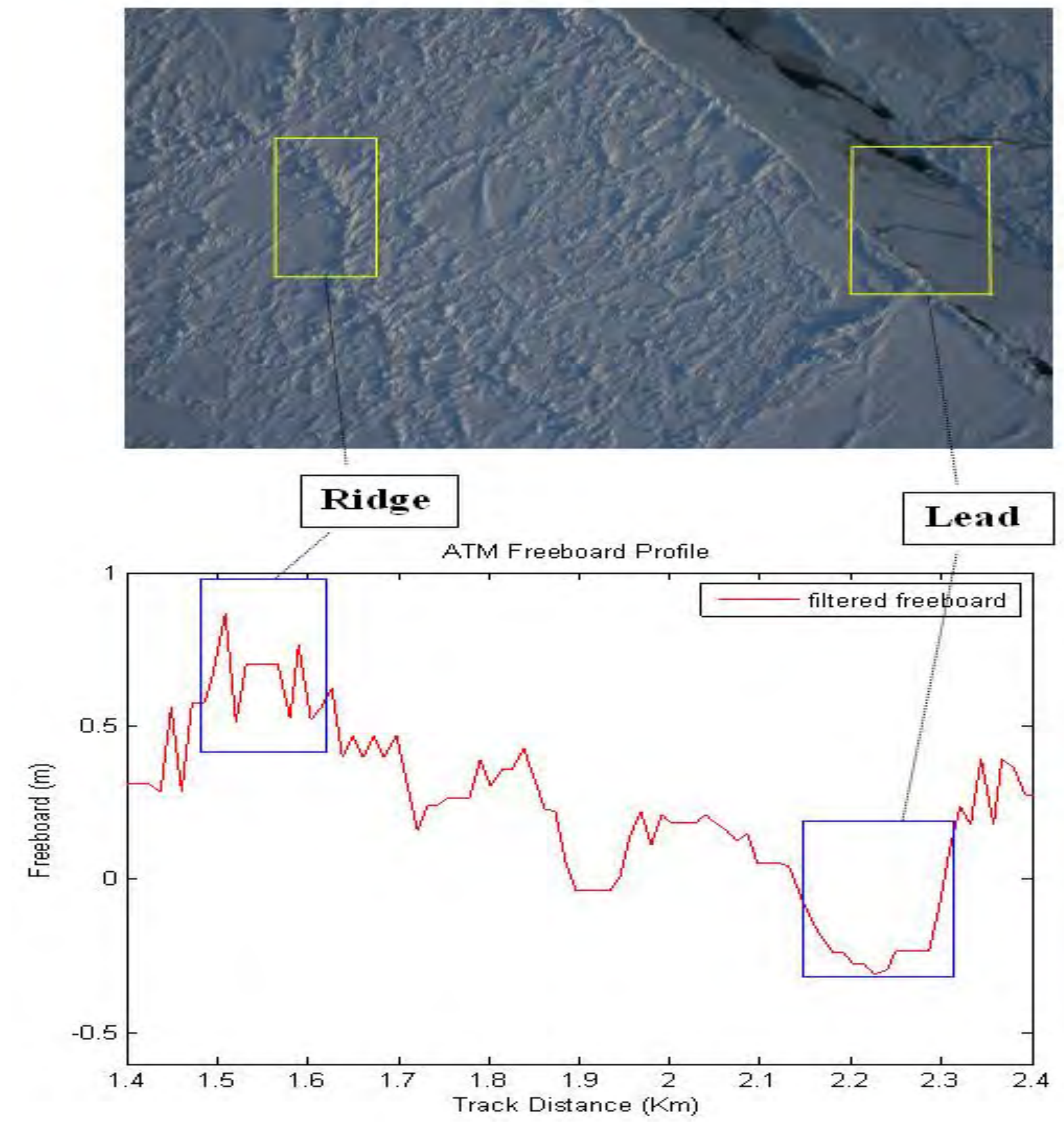
This figure shows a lead in the sea ice and the components associated with the lead. It is a very good visual representation of sea ice freeboard (Kwok, 2010).



Elevation data taken over flight track in relation to WGS-84 ellipsoid



Sea ice freeboard along flight track referenced to EGM-96 geoid



"Cambot" photo imagery corresponding to along track regions enclosed in the boxes. The imagery is used to confirm leads and other areas of interest.

Conclusions

As the earth warms, signs of climate change range from subtle to significant, with the most dramatic alterations occurring in the Arctic. Obtaining accurate sea ice thickness measurements over a large area are needed in order to track any further variations and predict possible changes. Therefore, it is necessary to understand the steps used in determining sea ice thickness based off laser altimetry data gathered during NASA's Operation IceBridge. Using the Airborne Topographic Mapper (ATM), sea ice elevation can be measured from an aircraft flying overhead. From this elevation data, an approximate freeboard is calculated in relation to the earth's geoid model. By determining locations of leads in the ice, further calculations may be performed to get a sea ice freeboard measurement. Then, through the use of the hydrostatic equation, sea ice thickness may be inferred for the region between successive leads. This makes flying over a lead in the ice is very important for determining the exact sea surface elevation. Although summed up in a few steps there are many factors that make this calculation much harder than it appears.

Department of Oceanography