Developing a Method for Estimating Accumulation Rates using CReSIS airborne Snow Radar

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***Abstract*— Accumulation rates for West Antarctica, specifically Pine Island and Thwaites Glaciers, are poorly characterized. Using the Center for Remote Sensing of Ice Sheets airborne Snow Radar, which is capable of imaging near surface layers in the uppermost part of the ice sheet at a very fine vertical resolution, estimates of very recent firn accumulation rates over the Thwaites Glacier along the Amundsen Coast of West Antarctica were calculated using data from Flight One, Segment 02 of the 10/18/2009 National Aeronautics and Space Administration Operation IceBridge flight.**

The "short" segment layer (130 km) mean accumulation (temporal variation) rate was 0.4 m/y and the "long" segment layer (297 km) was 0.44 m/y. The standard deviation (how much the accumulation rate varies in space) for the "short" segment layer was 0.052 m and 0.068 m for the "long" segment layer. The derived dataset estimates are within range of previous estimates; however, the continent-wide published estimates do not correspond well with each other or the specific dataset for the Thwaites Glacier.

Keywords- accumulation rates, firn, mass balance, snow, West Antarctica

I. Introduction

For more than 50 years, scientists have retrieved ice cores from the world's ice sheets to study ice dynamics, as well as past and present climatic and atmospheric conditions, such as the accumulation rate. The ice-sheet accumulation rate is not only an important climate indicator, but also a significant component of ice-sheet mass-balance, which is the total mass gained or lost over a prescribed period of time [1].

Many recent studies have concentrated on the surface mass-balance (SMB) and mass changes of the Antarctic ice sheet [2]. For an enhanced understanding of Earth's climate changes, as well as the polar regions, which are capable of contributing significantly to global sea-level change [3], these studies are of vital importance [2] [3] [4] [5].

West Antarctica, in particular, is seriously lacking in point based measurements of the accumulation rate, whether through snow pit or ice core analysis [4]. Due to the sparse data points in the region, the fast thinning and speeding up of the Thwaites Glacial region [4], it is imperative to gather more data on the area.

As concern over sea-level change and ice-sheet stability increase, more accurate and spatially complete estimates of the accumulation rate are required [6]. Therefore, the sparse point estimates of the accumulation rate (i.e., ice cores) no longer give sufficient data for regional mass-balance estimates because of their limited spatial coverage. However, these estimates remain important paleo-climate records due to their exceptional temporal resolution.

Previously assessed using compilations of widely spaced point measurements and low-resolution (~25 km) passive microwave data, accumulation rates in Antarctica are not well characterized [5]. Climate models show that the region along the Amundsen Coast receives snowfall amounts unprecedented across most of the continent; yet these models lack any ground-truthing and are limited in their spatial resolution [4] [7]. Due to many models lacking in ground-truthing and data, any estimates of mass balance over this region are ill-constrained and are in need of much better estimates of the snow accumulation rate [4].

In the past, ground penetrating radar (GPR) has been successfully used to follow isochronous firn layers providing detailed information about the SMB variability across Antarctica [2] and connect snow pits and firn-core drilling sites [3]. Furthermore, new techniques, e.g. radar altimetry, have made it possible to study continent-wide elevation changes with high accuracy [2].

In 2009, Operation IceBridge, a six-year National Aeronautics and Space Administration (NASA) mission dedicated to the airborne survey of Earth's polar ice, flew its first mission over the polar regions (Greenland and Antarctica) [8]. IceBridge focuses on providing unprecedented three-dimensional view through the use of radars, such as the Center for Remote Sensing of Ice Sheets (CReSIS) developed Snow Radar and Accumulation Radar, to characterize the behavior of the

NSF REU ANT-0944255: CReSIS - NSF FY 2005-108CM1

rapidly changing features of the Greenland and Antarctic ice [8].

With advances in radar vertical resolution, the CReSIS Snow Radar has given scientist the ability to examine recent snow accumulation (<50 years) at an unprecendented level [9]. Whereas, the CReSIS developed Accumulation Radar has given researchers the ability to exaimne firn layers in the recent past (<500 years) at an unprecendented level [10]. During NASA's Operation IceBridge, data collected from both radars have the potential to attribute to more accurate estimates of Antarctic accumulation rates and SMB.

In this study, the CReSIS developed Snow Radar was used to image the interior of the ice sheet over parts of Thwaites Glacier and create a high-resolution map of accumulation rates during the (NASA) Operation IceBridge (2009). In utilizing this data, we hope to significantly improve our knowledge of Thwaites Glacier accumulation rates.

II. METHODOLOGY

During the months of October and November of 2009, several of NASA's Operation IceBridge missions flew the CReSIS developed Snow Radar over West Antarctica (Figure 1) [11]; however, we selected one as our flight of interest. We then used radar collected during that flight to map internal layers in the ice sheet, which we converted to accumulation rates with knowledge of the layer ages and the firn density profile. To calculate the accumulation rate, the total mass of snow above a layer was divided by the age the layer was deposited.

A. Selecting the Flight of Interest

Flight paths were compared to determine which radar data were the most useful in estimating snow accumulation for Thwaites Glacier, West Antarctica. The flight paths were evaluated on the following criteria: 1) whether the flight path intersected a dated ITASE 01-2 core site necessary for determining firn layer age, 2) whether the flight path covered the glacier interior, 3) whether the flight has continuous spatial coverage, 4) whether the flight path intersected a preexisting CReSIS accumulation radar flight path from 2009-2010. Based on the criteria, Flight 1 (Figure 2), collected on 10/18/2009 was chosen. The flight segment intersected a dated ITASE 01-2 core site, which served as a reference to accurately date the annual firn layers, vast spatial coverage of the interior, and several hundred kilometers of continuous data collection.

B. Snow Radar Data Processing

Flight 1 dataset was downloaded from the National Snow and Ice Data Center (NSIDC) using the ISNOBR-1B Reader [12], which converts binary data files into MATrix LABoratory (MATLAB®) files. The data for this flight were broken into several hundred files in order to make downloading feasible. Data processing included: 1) merging the hundreds of MATLAB® files to make one continuous image, 2) deleting extraneous data, such as rows of data that were too deep for the radar to return a quality signal, 3) flattening the surface to ease layer mapping as the ice surface topography varied ,causing the surface radar reflection to vary as well, 4)

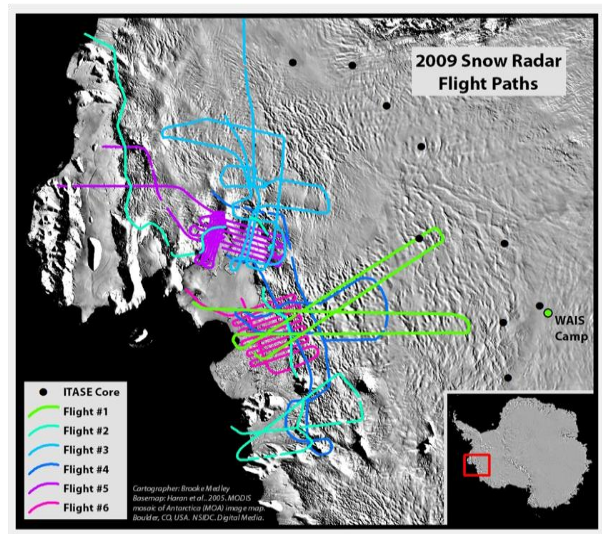


Figure 1: An aerial map depicting the sixth flight paths using the CReSIS developed snow radar over West Antarctica, and the ITASE core site, during the months of October and November of 2009 during NASA's Operation IceBridge Missions [11].

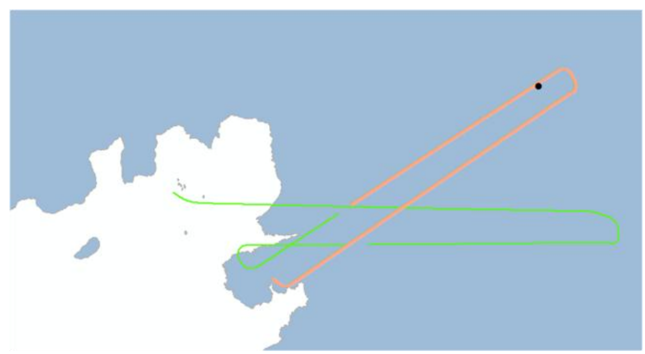


Figure 2: Flight 1 of the 10/18/2009 Operation IceBridge Mission shown in ArcMap® intersecting the ITASE 01-2 core site and geospatially covering the interior glacial region of the Thwaites Glacier.

averaging over 10 columns of data which reduced data noise 5) filtering the final image using a contrast enhancing Sobel filter, 6) exporting the data into geotiff format for further analysis in ArcGIS®.

C. Digitizing Firn Layers in ArcGIS®

In order to begin digitizing firn layers in ArcGIS®, an initial survey of the dataset was performed. This initial survey consisted of finding layers that were bright (easily digitized), laterally continuous, and could be digitized from the ITASE-01-2 core site, as shown in Figure 3.

While surveying the dataset, we found information "gaps", as shown by Figure 4. Additionally, there were areas in the dataset that had poor layer quality, as shown by Figure 5. The poor quality in the radar echogram is sometimes related to the airplane turning whereas the gaps in the data are potentially related to radar operation issues. Therefore, the firn layer's pattern were also examined to determine if we can trace layers across areas of poor layer quality in the data.

After the initial survey, the digitizing of firn layers began. Thirteen polyline shapefiles (or firn layers) were created in ArcMap®. Several layers were digitized beginning at the dated ITASE-01 core site (Figure 6).

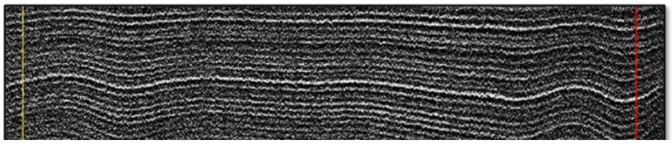


Figure 3: Several "bright" firn layers intersect the ITASE 01-2 core site (red line) and the CReSIS accumulation radar (yellow line). *Note: Image without geospatial reference due to begin in **ArcGIS®**

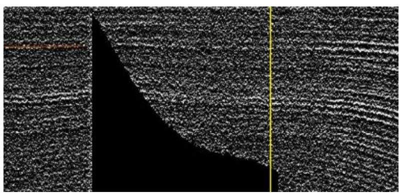


Figure 4: Potentially due to radar operation issues, there are information gaps. These information gaps can omit temporal and geospatial data ranging from shallow layers to deeper layers, as well as spanning meters to several kilometers of data when exported to ArcMap® and geospatially (latitude and longitude) referenced.

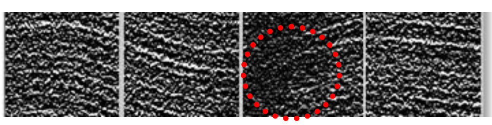


Figure 5: Bright firn layers are spatially shown; however, there is a place of poor spatial and temporal quality (as encompassed by the red oval) in the radar echogram.

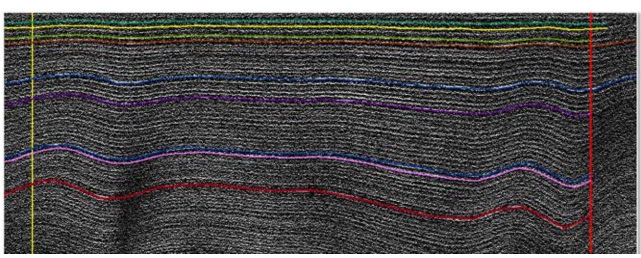


Figure 6: Several digitized firn layers beginning at the ITASE 01-2 core site which were used in estimating the accumulation rates for the Thwaites Glacier.

D. *Converting ArcGIS® files to ArcMap®*

The digitized firn layers were converted from polyline to point shapefiles, based on the polyline vertices. Next the x-coordinate (column number) and y-coordinate (row number) were added to the each layer's attribute table. Each coordinate was truncated to an integer to correspond to a specific row/column number. Each radar column relates to a geographic location (i.e., latitude and longitude) and each row relates to a depth (based on the speed of a radar wave through firn). Additionally, the total mass of snow above a given depth cumulative mass) was needed to estimate the accumulation rate.

Based on the density profile at the ITASE 01-2 core site, a depth to cumulative mass (total mass of snow above a given depth) relationship was developed by integrating the density profile with depth. This permitted each mapped layer point to have associated latitude and longitude (based on the column number) and a cumulative mass (based on the row number).

To date each firn layer, the depth at the point that intersects the ITASE 01-2 core was recorded and converted to an age based on the depth-age scale developed by Steig *et al.* (2005**)** [13]. Accumulation rates for all layers were then calculated by dividing the cumulative mass for each point in the layer by its age. Based on the latitude and longitude of each point, accumulation rates were derived and compared with those of pre-existing datasets.

III. Results and Discussion

Two radar segments were mapped, which are referred to as the "short" segment (130 km) and the "long" segment (297 km) (Figure 7). Two measurements, the variation in mean and the standard deviation, were examined. The variation in mean is a measurement of the temporal variation in the accumulation rate, or how much the accumulation rate changes with time. Thus, it was important to map very recent firn deposits, past firn deposits, and document the age of each layer. The standard deviation is a measure of spatial variation, or how much the accumulation rate varies in space, along the flight path. Mathematically, if the standard deviation is low, the accumulation rate is consistent and does not change much. However, if it is high, accumulation rates vary along the flight path significantly. Figure 8 shows the average variation in mean and the standard deviation for the "short" and "long" segment.

A. *Short Segment Accumulation Rates*

Digitized firn layers for the "short" segment were mapped from very recent firn accumulation to previous firn deposits. The digitized firn layers range from depths that correspond to 0.805 m or 1.80 yrs to past firn layers that corresponding to 36.12 m or 48.28 yrs. In addition to the age and variation in mean and standard deviation of each firn layer, minimum and maximum accumulation rates for each layer were documented. The minimum and maximum accumulation rates for each layer are indicators for the amount of snow fall received along the flight path.

The "short" segment temporally covered ~ 35m or ~ 47 years, according to the depth to density ratio.

B. Long Layers Accumulation Rates

Digitized firn layers for the "long" segment were mapped from very recent firn accumulation to more previous firn deposits. The digitized firn layers range from depths corresponding to 0.311 m or 0.80 yrs to more past firn layers corresponding to 52.24 m or 70.07 yrs. In addition to the age and variation in mean and standard deviation of each firn layer, minimum and maximum accumulation rates for each layer were documented.

The digitized "long" segment temporally spanned ~ 51 m or ~ 70 yrs.

C. Comparison of Published Accumulation Rates

Three published continent-wide accumulation rate datasets [14][15][16], as shown in Table I, provided a credible basis for the derived estimates of accumulation rates using data from the snow radar. The pre-existing published datasets do not agree very well. This can be attributed to various reasons such as the variation in pixel resolution [2], data sparse regions of West Antarctica [4], as well as various non-negible zero accumulation sites (so called glazed area) in the interior of the East Antarctica plateau (EAP) that are often not taken into account by mass-balance estimates [2].

In 2006, Arthern et. al used radar with a 3 km x 3 km resolution [14] to derive an accumulation rate dataset for the continent of Antarctica. With a finer spatial resolution (3 km vs. 25 km of Monaghan [15] and van de Berg [16]), theoretically Arthern et al. was able to derive a more accurate measurement of Antarctica's accumulation rate [2]. However, the snow radar (<100 m resolution) utilized a greater resolution than all previously published datasets to derive the accumulation rates.

Figure 11 provides a comparison of data compiled using the CReSIS developed airborne Snow Radar, covering the Thwaites Glacier region, to pre-existing continent-wide estimates.

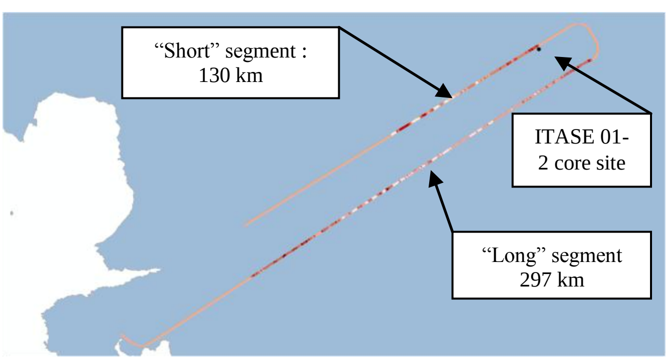


Figure 7: The digitized "short" and "long" segments along the 10/18/2009 Operation IceBridge Flight 1 - Segment 02, as well as the ITASE core site is shown in ArcMap®.

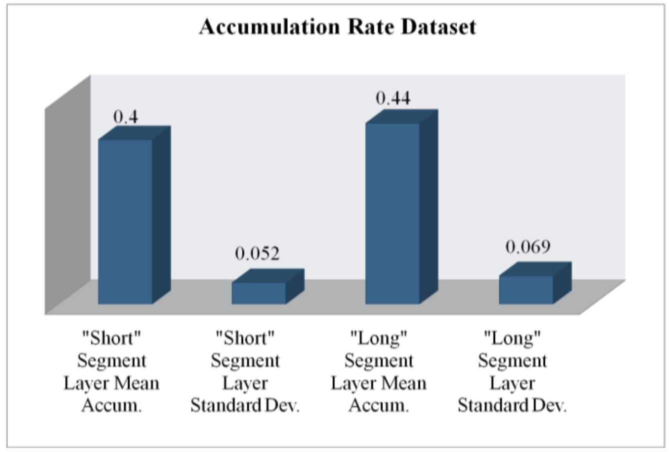
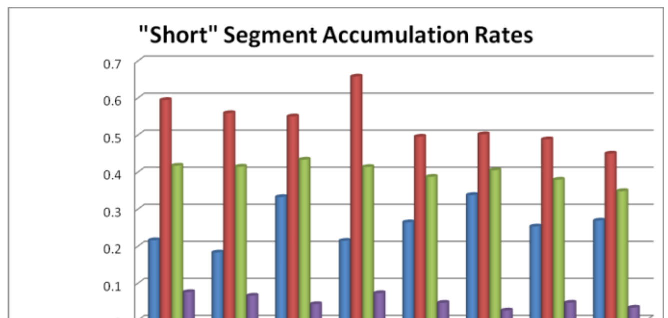
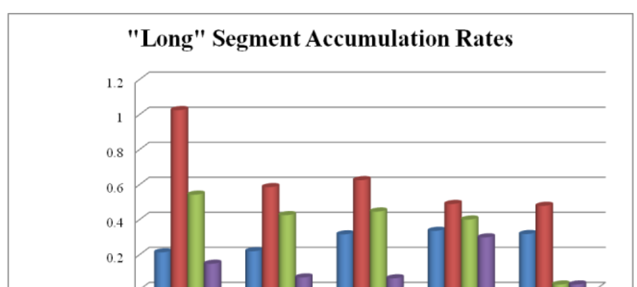


Figure 8: Average measurements of the dataset derived for the Thwaites Glacier region utilizing data collected from the snow radar. The "short segment" has a variation in mean accumulation of 0.40 and a standard deviation of 0.052. The "long" segment is shown to have a variation in mean accumulation of 0.44 and a standard deviation of 0.069.



	1.803 yrs	2.865 yrs	4.729 yrs	5.9 yrs	14.837 yrs	19.734 yrs	35.566 yrs	48.288 yrs
Min. Accum	0.2162	0.1832	0.3329	0.2147	0.2647	0.3384	0.2533	0.2693
Max. Accum	0.5948	0.5594	0.5504	0.6581	0.4957	0.5022	0.4886	0.4501
Mean Accum	0.417581	0.414928	0.433785	0.414057	0.387564	0.405334	0.379733	0.348854
Standard Dev.	0.076306	0.066579	0.043827	0.073472	0.047351	0.02648	0.047624	0.034316

Figure 9: Depicting the shallowest "short" digitized layer (0. 805 m) and the deepest digitized layer (36.12 m), the chart also included the age of the layer, minimum accumulation rate, maximum accumulation rate, variation in mean, and standard deviation for each digitized firn layer.

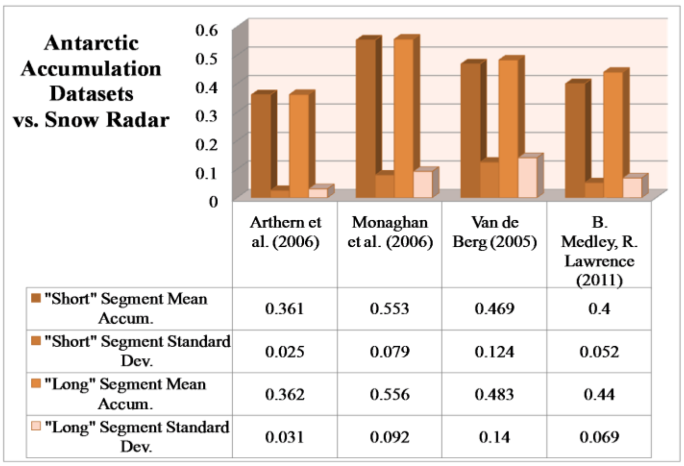


	0.821 yrs	9.355 yrs	15.635 yrs	36.047 yrs	70.070 yrs
Min. Accum	0.2137	0.2198	0.3163	0.3362	0.318
Max. Accum	1.0253	0.5857	0.6256	0.4895	0.4788
Mean Accum	0.542647	0.425694	0.446375	0.400701	0.029872
Standard Dev.	0.148424	0.070199	0.0652281	0.29872	0.029903

Figure 10: Depicting the shallowest "long" digitized layer (0. 311 m) and the deepest digitized layer (52.24 m), the chart also included the age of the layer, minimum accumulation rate, maximum accumulation rate, variation in mean, and standard deviation for each digitized firn layer.

Table I: Listed below are the published accumulation rate datasets for the entire Antarctic continent, specifically detailing the values for 1) variation in mean and 2) standard deviation [14][15] [16].

Published Continent wide Accumulation Rate Datasets				
Author	"Short" segment mean	"Short" segment std. dev.	"Long" segment mean	"Long" segment std. dev.
Arthern et.al (2006)	0.361	0.025	0.362	0.031
Monaghan et.al (2006)	0.553	0.079	0.556	0.092
van der Berg (2005)	0.469	0.124	0.483	0.140



	Arthern et al. (2006)	Monaghan et al. (2006)	Van de Berg (2005)	B. Medley, R. Lawrence (2011)
"Short" Segment Mean Accum.	0.361	0.553	0.469	0.4
"Short" Segment Standard Dev.	0.025	0.079	0.124	0.052
"Long" Segment Mean Accum.	0.362	0.556	0.483	0.44
"Long" Segment Standard Dev.	0.031	0.092	0.14	0.069

Figure 11: Continent wide datasets (specifically measurements of the variation in mean and standard deviations for the "short" and "long" segments) from Arthern et. al (2006), Monaghan et. al (2006) , and van de Berg (2005) were compared to the derived Thwaites Glacier dataset from Ms. Brooke Medley and Mr. Ryan Lawrence.

IV. Conclusion

West Antarctica has some of the highest accumulation rates; however, there is a lot of uncertainty in those measurements [4]. In contrast to previous estimates, the Amundsen Sea sector of West Antarctica and the western Antarctic Peninsula, both data sparse regions, are found to receive 80–96% more accumulation than previously assumed [4]. For the Pine Island and Thwaites Glaciers (West Antarctica), which have recently undergone rapid acceleration and thinning, this means a downward adjustment of their contribution to global sea level rise [4].

To further constrain Antarctic mass (im-) balance and associated changes in global sea level, new observations utilizing remote-sensing techniques and satellite-based methods from high-accumulations areas, especially from coastal West Antarctica and the western Antarctic Peninsula, are urgently needed [4].

Pre-existing published continent-wide firn accumulation rates [14] [15] [16] vary significantly. Furthermore, those estimates do not correspond well with the derived firn accumulation rates for Thwaites Glacier region.

In comparison to the aforementioned preexisting continent wide published estimates, the Monaghan et. al (2005) [15] and van de Berg (2005) [16] datasets overestimated the accumulation rates; however, the estimates by Arthern et. al (2006) [14] slightly underestimate the accumulation rates (when specifically compared to Thwaites Glacier dataset).

V. Future Works

Firn accumulation rates need to be completed for the remaining snow radar flights during the 2009 International Polar Year. Furthermore, it is pertinent to include the data and research from Ms. Brooke Medley and the CreSIS developed Accumulation Radar to assist in deriving the depth to age scale for the uppermost firn layers of West Antarctica (Figure 12). Published datasets for Antarctica are to be compared to provide a baseline for the firn estimates, as well as data regarding possible climatic indicators that affect the mass balance. Due to Ms. Medley and I developing MATLAB® that could be easily modifieed and adapted for the downloading and analysis of the remaining NASA Operation IceBridge missions, it is our goal to complete the research for other flights in the area, as well as for the upcoming IceBridge Missions.

Acknowledgment

I would like to thank Dr. Linda B. Hayden, PI of the REU OPMS 2011, for the opportunity to participate in this internship. Furthermore, I greatly appreciate the insight, expertise, and patience of my mentors, Ms. Brooke Medley and Dr. Ian Joughin (UW), and Ms. K. Pointer for her knowledge and assistance with MATLAB®. All of you played an intricate part of this research experience. I am eternally grateful for your time, efforts, and confidence in me. I pray for your continued success.

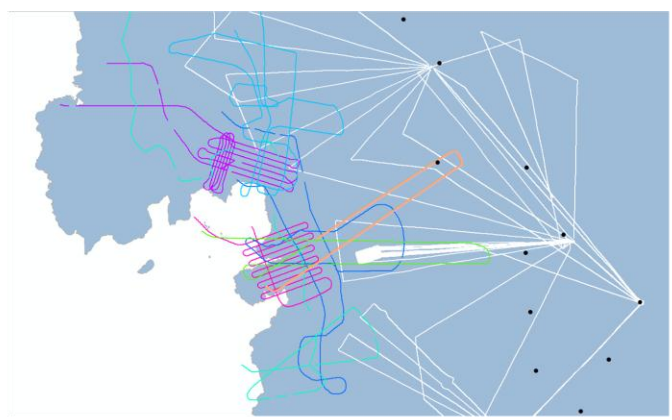


Figure 12: An image in ArcMap® of the 2009 Operation IceBridge flights (represented by the colored lines), the ITASE core sites (represented by the black dots), and the flight path of the CReSIS developed accumulation radar used by Ms. Brooke Medley to derive accumulation rates of Antarctica (2009-2010).

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