MELT: Monitoring iceberg calving using Synthetic Aperture Radar

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***Abstract*—The movement of glaciers in remote regions of Greenland and Antarctica have been tracked using images captured by the European Space Agency (ESA) Sentinel-1 mission. The mission is composed of two satellites equipped with C-band (4-8 GHz) synthetic-aperture radar instruments that allow for the collection of high-resolution images and data in all weather conditions. Using imaging provided by the Centre for Polar Observation and Modelling (CPOM), and in collaboration with the Institute for Research in Schools (IRIS), the movement of two key outlet glaciers on the Antarctic and Greenland ice sheets (Pine Island and Petermann glaciers, respectively) has been monitored in near real time. In addition to this, key glaciological features, such as ice speed and supra-glacial lakes have been observed and monitored.**

Keywords—Greenland; Antarctic; glaceology; glaciers; calving; climate change

I. Introduction

The continental glaciers of Greenland and Antarctica provide one of the key outlets for the mass of water accumulated on these landmasses during winter months. Glaciers are formed by the steady accumulation of snow which, over time, is compacted to form ice and begins to flow outwards and downwards under the pressure of its own weight [1]. A major part of the life cycle of a glacier is iceberg break-off, or “calving”. Calving, along with melting and surface evaporation, is the main sources of glacial ablation and gives a strong indication of the health and stability of the glacier [2]. Studies of glaciers and the relationship between global temperature, glacial melting and rising sea levels give indication of how strong and long-lasting any effects of climate change might be [3].

The icebergs that are calved from glaciers are an important source of fresh water in salty seas [4], can provide a valuable habitat to marine life [5-6] and pose a significant threat to shipping [7]. As such, it is important that the location and timing of iceberg calving, as well as the movement of icebergs away from calving fronts is monitored.

Historically, the tracking of glaciers was achieved by comparison of optical images obtained from satellites. However, the acquisition of optical images was limited by the necessity for daylight and favourable weather conditions [8]. More recently, the use of synthetic aperture radar (SAR) images has become standard. The launch by The European Space Agency (ESA) of the Sentinel 1-a and 1-b satellites, in April 2014 and April 2016, respectively, allow many key ice margin areas to be systematically monitored every 6 to 12 days. This novel dataset allows the periodic movement of glaciers as well as movement over short timescales to be monitored. Here, we present a comparison of the movements of the Petermann Glacier in Greenland and the Pine Island Glacier in Antartica between 2015-2018, made using the Sentinel SAR archive.

II. Sentinel-1 Near Real Time Ice Velocity

All data for this project has been accessed via the Centre for Polar Observation and Modelling (CPOM) outlet glacier velocity service [9]. Images were recorded by Sentinel-1, a two-satellite constellation which carries an advanced all-weather imaging radar. Sentinel-1a was the first satellite to be launched as part of Europe’s Copernicus programme, and has delivered a wealth of data and imagery since it was launched in April 2014. During its first year of operations, the short 12-day imaging repeat period and large spatial coverage delivered an invaluable new resource which revolutionized the ability to monitor change in speed of the ice streams on the Greenland and Antarctic Ice Sheets. Europe’s satellite monitoring capability continued to be improved even further with the launch of Sentinel-1b in 2016, and combined, both satellites provide the capability to image the earth every 6 days.

A. Study Areas

Antarctica is surrounded by ice shelves and the floating ice tongues of glaciers. With a total area of more than 1.5 million square kilometers, this floating ice represents an area of approximately equal size to the entire Greenland Ice Sheet [10]. The main mechanism for mass loss has historically been iceberg calving but warming oceans have meant that melting is becoming increasingly significant [10]. However, the in-land ice of the Greenland ice sheet contains the equivalent of 7.2m of sea level rise making the future of the mammoth sheet one of the largest and most complicated issues facing environmental policy in the coming years [10-11].

In order to compare northern and southern hemisphere glaciers, one glacier was chosen for study from each of the three glaciers on Greenland and Antarctica for which data are provided on the CPOM server.

B. Data and Methodology

Ice velocity was mapped using single look complex (SLC) synthetic aperture radar images acquired in the interferometric wide swath (IW) mode from the Sentinel-1a and Sentinel-1b

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satellites. Each satellite has a repeat cycle of 12 days and 180 degrees orbital phasing difference, resulting in a revisit time of 6 days over the same area after the Sentinel-1b launch. The Sentinel SAR instruments operate at c-band, with a centre frequency of 5.405 GHz, corresponding to a wavelength of 5.55 cm. The IW mode has a 250 km swath and spatial resolution of 5 m in ground range and 20 m in azimuth. It has burst synchronization for interferometry and acquires data in three sub-swaths, each containing a series of bursts, which are acquired using the Terrain Observation with Progressive Scans SAR (TOPSAR) imaging technique [12].

Images were processed using QGIS 2.4.0-Chugiak software. The software was used to generate shapefiles that could include annotations of images as well as positional information on key features, such as calving fronts. Comparisons of images taken on different days allowed for the rate and change position of calving fronts to be monitored (Figure 1).

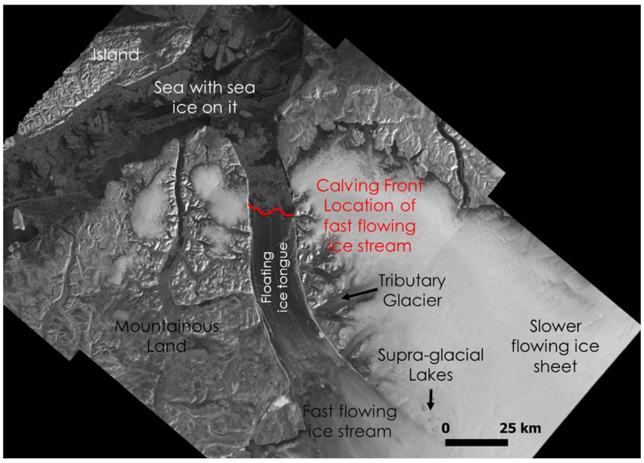

Figure 1: An example image of the Petermann Glacier, with key features labelled. Image Credit: A.E. Hogg, CPOM, Uni. Leeds, ESA and S. Pengelly, CSMS.

III. Results and Discussion

C. *Petermann Glacier (PG), Greenland*

Petermann Glacier (PG) is one of the major outlet glaciers in northern Greenland and drains roughly 4% of the Greenland ice sheet [13]. It has the second largest floating ice tongue in Greenland and so loses most of its mass (80%) by bottom melting [14]. However, significant calving events in 2010 and 2012 produced tabular icebergs of 253 km^2 and 147 km^2 respectively, reducing the extent of the floating ice tongue by approximately a third. Both calving events have been correlated to increased flow rates of the glacier [15].

Initially, the calving front location for PG was tracked between December 2016 and December 2017. In the ~4 months between 6th January and 31st March, the calving front had advanced by an average of 462m, approximately 7.5m per day. It was noteworthy that different sections of the calving front moved at different rates, the western extreme having moved 379m further that the eastern edge. Using the average speed of the calving front from the first four months of the year, an approximate calving front position for December 2017 was predicted. Correlation between calculated and actual positions was reasonable for the western and central parts of PG but the eastern edge showed a significant loss of ice (Figure 2). This could not be contributed to a single calving event but was the result of a more gradual ablation of the calving front.

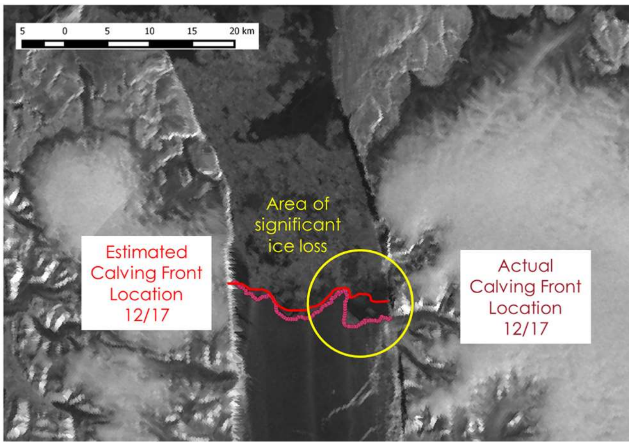

Figure 2: Difference in the calculated calving front (red) and actual calving front (maroon) for December 2017, showing an area of significant ice loss at the eastern edge of Petermann Glacier. Image Credit: A.E. Hogg, CPOM, Uni. Leeds, ESA and S. Pengelly, CSMS.

Using images of the glacier at the same time each year, the forward progression of the glacier over longer time periods could be tracked. By comparing the shapefiles generated on images from February 2015 to February 2018 (the tenure of the Sentinel-1 satellite at the time of analysis) the glacier was calculated to be moving at a forward rate of 1.15 kilometers per year (Figure 3).

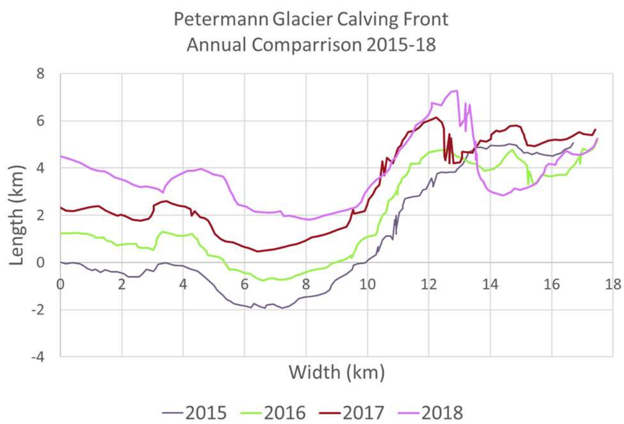

Figure 3: Plot of calving front locations (CFLs) for the month of February 2015-2018. A comparison of locations shows a steady flow equating to an average of 1.15km/y. CFLs clearly show the differing flow rates of the different sections of the glacier; the western extreme flows significantly faster than the eastern edge which in turn is faster than the centre.

As had previously been seen, the western edge of the glacier was found to move at the fastest and at a most constant rate. The central section of the glacier moved at a slower and less regular rate. The glacier moved slowest and with the most erratic rate at the eastern edge, especially in 2018 when a large amount of

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ice was lost from this section. It is speculated that the reason for this discrepancy in movement is the contribution of tributary glaciers which may disrupt the flow and stability of PG's eastern edge [12].

D. Pine Island Glacier (PIG), Antartica

The Pine Island Glacier currently experiences the largest negative mass balance of all Antarctic glaciers and so is the biggest single contributor to modern sea-level rise [16]. Recent evidence of a volcanic geothermal heat source beneath the Pine Island ice shelf and glacier [17] may go some way to explaining the high flow rate of the glacier; since 2008, the ice stream has accelerated and is now responsible for about 25% of Antarctica's ice loss [18].

The first available image of the calving front on PIG came from the 14th June 2017 and showed one feature of particular interest, a crevasse extending approximate 17km across the face of the glacier and approximately 8km behind the calving front (Figure 4).

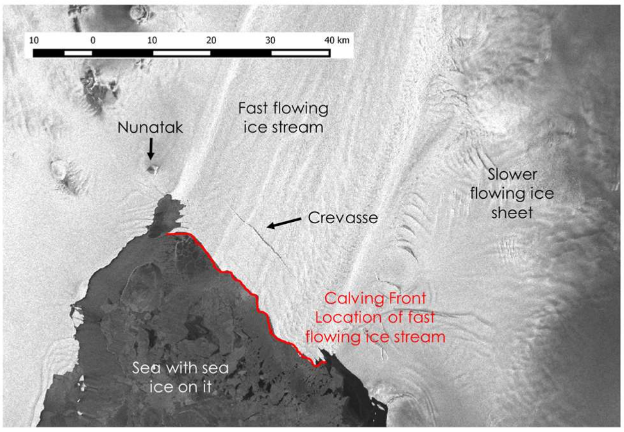


Figure 4: The first available image of the Pine Island CFL showing a crevasse developing approximately 8km behind the CFL. Image Credit: A.E. Hogg, CPOM, Uni. Leeds, ESA and A. Baker, CSMS.

By September 2017, the crevasse had extended across the full width of the advancing glacier, calving a section of ice approximately 300km^2 in area that, over the following weeks, was rapidly broken down into smaller chunks of ice (Figure 5).

The movement of the crevasse gave a useful way of measuring the speed of the glacier, without having to rely on taking measurements from the fragile calving front. Between 14th June and 29th December 2017, the crevasse (which eventually developed into the calving front) progressed an average of 1.56km, a rate of just over 7 meters per day. The rate of movement was relatively constant, showing no significant post-calving acceleration.

IV. Conclusions

All processed images and shapefiles generated as part of this project have been uploaded to the IRIS data server and are available to other scientists through the CPOM network.

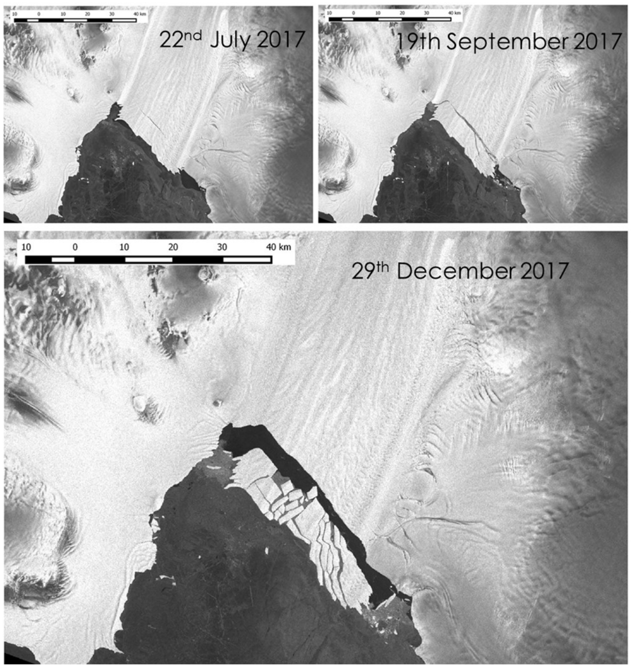
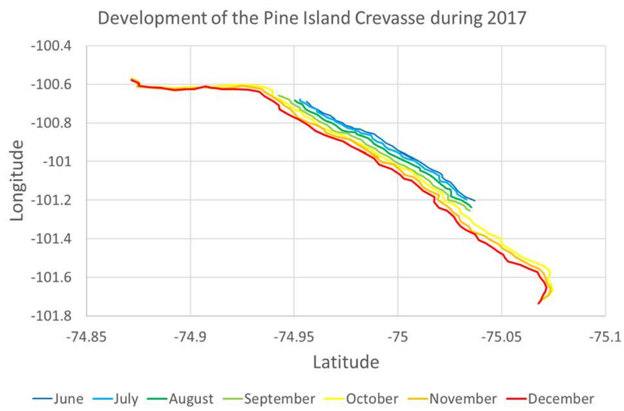


Figure 5: (above) The calving and subsequent breaking up of a ~300km^2 section of PIG between June-December 2017. Image Credit: A.E. Hogg, CPOM, Uni. Leeds, ESA and A. Baker, CSMS. (below) Development of the PIG crevasse; October 2017 represents the first data point post calving and thus the establishment of the new CFL.

SAR images recorded by the Sentinel-1 satellite constellation and distributed by the Centre for Polar



Observation and Monitoring offer a fascinating insight into some of the world's biggest and fastest flowing ice streams. The two glaciers studied here have displayed very different behaviours over the brief duration of this project but are of ongoing interest to glaciologists.

The use of SAR for near-real time study of glaciers is of vital importance to monitoring their behaviours. It is hoped that by better understanding the dynamics of glaciers, calving and glacial melting, scientists may predict how the Earth's delicate icecaps may respond to its rapidly changing climate.

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