

# The Beauty and Complexity of the Brunt Ice Shelf from MOA and ICESat

ANGELIKA HUMBERT<sup>1</sup>, CHRISTOPHER A. SHUMAN<sup>2</sup>

<sup>1</sup>*Institute of Mechanics,*

*Darmstadt University of Technology,*

*Hochschulstraße 1,*

*D-64289 Darmstadt, Germany*

<sup>2</sup>*NASA Goddard Space Flight Center,*

*Cryospheric Sciences Branch - Code 614.1*

*NASA Goddard Space Flight Center*

*Greenbelt, MD 20771 - USA*

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Correspondence address:

Dr. Angelika Humbert  
Department of Mechanics  
Darmstadt University of Technology  
Hochschulstraße 1  
D-64289 Darmstadt  
Germany

Phone: +49-6151-16-6682

Fax: +49-6151-16-4120

E-mail: [humbert@mechanik.tu-darmstadt.de](mailto:humbert@mechanik.tu-darmstadt.de)

## **Abstract**

Beginning in February 2003, NASA's Ice, Cloud, and land Elevation Satellite (ICESat) has determined surface elevations from  $\sim 86^{\circ}\text{N}$  to  $86^{\circ}\text{S}$  latitude. To date, altimetry data have been acquired in a series of observation periods in repeated track patterns using all three Geoscience Laser Altimeter System (GLAS) lasers. This paper will focus on ice shelf elevation data that were obtained in 2003 across the Brunt Ice Shelf and the Stancomb-Wills Ice Tongue. Integrating the altimetry with the recently available MODIS Mosaic of Antarctica (MOA), quantifies the relative accuracy and precision of the resulting ice shelf elevations. Furthermore, the elevation data was processed onto an elevation grid, by regional interpolation across the area's complex glacial features only. Ice thickness estimation from the altimetry of the floating ice is discussed. ICESat operates at 40 Hz and its elevation data is obtained every 172 m along track. These elevations have a relative accuracy of about 14 cm based on the standard deviation of low-slope crossover differences and a precision of close to 2 cm for the Laser 2a, Release 21, GLA12 data used here.

Keywords: Brunt Ice Shelf; Stancomb-Wills Ice Tongue, remote sensing, ice surface elevation, ice thickness, ice shelf dynamics

## Introduction

The combination of two types of NASA remote sensing data allows a new 3 dimensional mapping of complex ice features such as the Brunt Ice Shelf and the Stancomb-Wills Ice Tongue. The Ice, Cloud, and land Elevation Satellite (ICESat) carries a single remote sensing instrument, the Geoscience Laser Altimeter System (GLAS). ICESat uses GLAS laser to enable precise determination of the elevation of the surface of the Earth. ICESat's primary objective is to provide improved ice sheet elevation data for mass balance assessments and change detection over the mission lifetime (Zwally and others, 2005). Throughout this paper, the phrase "ICESat surface elevation data", or similar wording, will mean the elevations derived from the mission's basic data and processing algorithms. The newly available MODIS Mosaic of Antarctica (MOA) allows the ICESat elevation information to be placed in its spatial context relative to even complex ice topography. This paper will illustrate the beauty of the Brunt ice shelf area using these two types of remote sensing data. Further, these data enable an extensive 3 dimensional model of the area to be developed that can be used for modeling studies.

### ICESat Operations 2003-2005

The polar elevation data from ICESat's operations are described in Shuman et al. (2005). ICESat began operating with Laser 1 in an 8-day repeat orbit in February 2003, that provided  $\sim 5$  passes along each track during a  $\sim 38$  day period. This track pattern was continued in late September 2003 for  $\sim 10$  days initially in the Laser 2a period. In early October through the middle of November, a 91-day repeat pattern was utilized and the longer operation period enabled spatially denser coverage. All

available Laser 2a was used in this study after cloud filtering based on gain number. The latter 33 days of the Laser 2a coverage were specified as the 'standard 33-day subcycle' that have been repeated in the subsequent 2b, 2c, 3a, 3b, and 3c periods. Comparison of these repeated elevation measurements is how ICESat will pursue its goal of change detection and ice sheet mass balance assessments (Smith et al., 2005). The MOA (T. Scambos, pers. comm., 2005) provides an imagery base for examination of the ICESat data; this is especially important across the relatively complex ice features of the Brunt area. Note, much of the MODIS imagery was acquired at nearly the same time as the ICESat data; this fortuitous coincidence enabled a minimum time separation between these data.

A number of issues remain that can impact the use of ICESat data for glaciologic studies. Cloud distribution and detector saturation impact varies in time and space and can subtly influence the accuracy and precision of ice sheet elevation data or totally block their acquisition. Cloud impacts were minimized by excluding elevations with gain  $>100$  (Smith et al., 2005). Remaining uncertainties in ICESat pointing knowledge (Schutz et al., 2005) impact elevation data, especially time-varying differences between operational periods (Luthcke et al., 2005). ICESat's precision and accuracy (Shuman et al., 2005) however suggests extraordinary potential to define even complex topographic features. The summary is that ICESat has sufficient spatial sampling as well as accuracy and precision to provide excellent input data for a study such as this.

# The Brunt Ice Shelf - Stancomb Wills Ice Tongue System

The Brunt Ice Shelf is characterized as a thin unbounded ice shelf. It is attached to the Caird Coast, Coats Land, East Antarctica, along the Weddell Sea. The geographical position is from 23.02 to 27.50°W and from 75.06 to 76.04°S. The Brunt Ice Shelf differs in its constitution from other ice shelves by the fact that it is a heterogeneous mass of discontinuous ice blocks with a melange of sea ice, smaller ice blocks, and accumulated snow between them.

In the north-eastern part the Stancomb-Wills Ice Stream enters the ice shelf from the Caird Coast with a velocity of approximately  $1200 \text{ m a}^{-1}$  Gray and Short (2001). This ice stream forms a floating ice tongue which is in connection with the Riiser-Larsen Ice Shelf on the eastern side, separated at the ice front by Lyddan Island, a substantial ice rise. This ice tongue consists of relatively thick, fast flowing ice.

The south-western part which terminates at Precious Bay, forms a thin and slow moving ice shelf, called the Brunt Ice Shelf, at which a chain of ice rises of small size occurs, the McDonald Ice Rumples. Despite the curious name, these ice rumples are just very small ice rises. The evolution of the ice front between 1973 and 1985, described by Simmons (1986), shows that the McDonald Ice Rumples act as a pinning point of the ice front. Doake (2000) showed that the interaction between the ice rumples and the ice shelf is complex. Investigation of the crack propagation near the western end of the ice rumples showed that the local and regional strain rates vary strongly across the area.

The middle part is a shear zone between the fast, thick ice on the north-eastern

side and the thin, slow ice on the south-western side. Calving of large icebergs occurs at the grounding line region of this ice stream. These are subsequently frozen together with a mix of sea ice, small bergs, and snow as time goes. The ice shelf in this region is therefore formed of thick meteoric ice that is effectively interspersed with areas of a thinner mixture that is largely sea ice. This can be seen in Fig. 1. Elevations in the sea ice areas can reach about 50 m because of the combination of high accretion rates at the ice shelf - sea ice interface as well as wind-enhanced snow deposition (C.S.M. Doake, pers. comm.).

The Brunt Ice Shelf has recently undergone considerable changes (Simmons and Rouse, 1984a,b; Gray and Short, 2001) that suggest a complex reaction to climate and dynamic forcings and is therefore of interest for modelers. In general, the ice flow of ice shelves is found to be very sensitive to the ice thickness (Humbert et al., 2004; Humbert, 2005); thus it is crucial to know the ice thickness as precisely as possible. Fortunately, the floatation of ice shelves or the relationship of ice thickness to the ice surface elevation above sea level (the freeboard) is fairly well known (Bamber and Bentley, 1994). We will use their analysis to estimate an ice thickness grid from the available ICESat ice surface elevations.

## **Ice surface elevation data**

Fig. 1 shows the MOA 125 m map of the area of the Brunt Ice Shelf and the Stancomb-Wills Ice Tongue. The resolution is sufficiently high (125 m pixels) that the heterogeneity of the ice shelf area is very visible. Superposed are the ICESat Laser data with a color contouring applied to the geoid-corrected Laser 2a GLA12 Release 21

elevation data.

The three lower panels display subsets of the MOA image and the ICESat ice surface elevation data. Fig. 1a shows an area between the Brunt Ice Shelf and the Stancomb-Wills Ice Tongue, that is very heterogenous. One large iceberg is clearly visible and even a rift in this iceberg can be seen. The iceberg surface also exhibits flow patterns that suggest the flow history of this ice before it calved. This iceberg is bordered by relatively thin sea ice on the western side. It is likely that this sea ice is younger than the sea ice on the eastern side of the iceberg, which has a higher surface elevation. The sea ice is crossed by rifts and the surface elevation within them is just a few meters suggesting that this material is subject to recent dynamic forces.

Fig. 1b shows the shear margin between the fast flowing Stancomb-Wills Ice Tongue and the slower area of the Riiser-Larsen Ice Shelf. The visible crevasses arise from the stress between the ice flow and the bounding resistance of Lyddan Island. The region with the rough surface in the lower left part of the 1b subset is the flow pattern of the fast ice of the Stancomb-Wills Ice Stream. The elevation is 50-60 m, and is the typical ice surface elevation of an ice shelf. On the other hand, the upper right part of the subset shows very slow moving ice, characterized by a smooth surface, with a similar ice surface elevation. The diagonal zone across the subset shows the decoupling of the slow moving ice from the fast moving ice. This shear zone consists of ice with a smooth surface that is likely not of the melange type. The rifts, visible both in the MOA image and the ice surface elevation profiles, are parallel to the ice stream margin and are perpendicular to the ice flow direction.

The subset Fig. 1c shows an area along and across the grounding line. It has two very



interesting areas: the diagonal rift going from the lower left to the upper right corner of the subset and the lower left area below the rift. The latter area is interesting because it shows so well the high spatial variability of the ice surface elevation along the grounding line that reflects a highly crevassed area. The rift visible in this panel is noticeably different from other rifts and it is almost a straight line. Since to the southeast of the rift (closer to the coast) no iceberg can be detected, we hypothesize that this rift is the initiation point of iceberg calving rather than the grounding line. Since surface elevations across the rift approach zero, the rift likely contains open water sometimes. This is particularly interesting, because the surrounding area contains relatively thick sea ice. Rifts containing open water are known from the Fimbulisen (Orheim et al., 1990a,b; Nøst, 2004) as Jutulgryta, but the location of the rift in that region is at the grounding line and at the margin of a fast ice stream Jutulstraumen draining into the ice shelf, and is thus in a shear zone. It is likely that the Brunt rift is kept open by dynamic processes, and is repeatedly produced anew. However, this rift is not in a shear zone and thus, shearing can't be the mechanism to produce it each time. A high geothermal heat flux is unlikely the reason, too, since the icebergs exhibit a typical high thickness. The only logical alternative is an unusual tide interaction with the ice shelf and the sea floor topography. Study of additional MODIS imagery and ICESat data would help constrain this hypothesis by defining the rift characteristics through time.

## Ice surface elevation grid

The whole area was divided in three general regions: i) the Stancomb-Wills Ice Tongue, ii) the Brunt Ice Shelf and iii) a heterogenous middle part. In areas i) and ii) interpolation of the ICESat altimetry data could be done by usual techniques. In area iii) the interpolation had to be more sophisticated to ensure that large surface elevation changes between the icebergs and sea ice were not blurred. The margins of the features that are visible in the MOA image have been mapped manually. Subsequently, interpolation was performed within the defined area of the feature only. This resulted in single tiles, which were later combined together to form a complete ice surface elevation grid of the entire area. This method of processing the tracks to form an ice surface elevation grid is sketched in Fig. 2.

The resulting grid is shown in Fig. 3 (for comparison, the subsets (a) to (c) show the same areas as in Fig. 1). In the subsets the original ice surface elevation data along the tracks are displayed as dots (only a few arbitrary chosen data points are shown here) with the same colour coding. The colour difference between the dots and the background represents the quality of the interpolation (in other words, the real elevations are shown against the interpolated grid elevations).

## Transformation from elevation to thickness

Since ice shelf ice by definition is floating, we can use the equation for the hydrostatic equilibrium

$$h = \frac{\rho_{SW} - \rho_I}{\rho_{SW}} H + \frac{\rho_I}{\rho_{SW}} \left(1 - \frac{\bar{\rho}_I}{\rho_{SW}}\right) H, \quad (1)$$

where  $h$  is the surface elevation above the free ocean surface,  $H$  is the ice thickness,  $\rho_{SW}$  the density of sea water and  $\bar{\rho}_I$  the vertically averaged ice density, to derive the ice thickness. The vertically averaged ice density differs from the pure ice density  $\rho_I$  mainly due to the firn layer and different ice characteristics. Eq. 1 can be used for fitting. This has to be done separately for each ice shelf component in order to account for variations in the density structure and different ice characteristics. For the Ross Ice Shelf Bamber and Bentley (1994) extracted

$$h = (0.104 \pm 0.004)H + 15.5 \pm 2.6, [h, H \text{ in } m], \quad (2)$$

from the RIGGS campaign and radar altimetry data up to 81.5 deg S latitude. This equation is only valid for elevations above 15.5 m. As a first approximation, we assume that this equation is valid for the Brunt Ice Shelf, too. Applying this equation to ICESat Track no. 0344 results in the ice thickness shown in Fig. 4. The magenta line is the surface elevation beginning inland heading towards the ice front. The solid blue line shows an estimate of the bottom of the floating ice mass. The underlying light blue stripe shows the uncertainty arising due to the uncertainty in the accuracy of eq. 2. Where there is no blue line, the surface elevation was below 15.5 m. These thinner areas may be possible to estimate using techniques specific for sea ice studies (Kwok et al., 2004).

Eq. 2 is only valid for ice shelf ice. Therefore, we can't apply the equation to the ice surface elevation grid fully, but to the two large areas of the Brunt Ice Shelf and Stancomb-Wills Ice Tongue and the detected icebergs in the middle area only. Thus, the processing is analogous to the derivation of the ice surface elevation grid. The altimetry data shows that sea ice trapped in between the icebergs has considerable

total thickness and is not first year sea ice. The thickness is due to bottom accretion, snow accumulation from precipitation and from wind blown snow. The sea ice can be as thick as 50 m (C.S.M. Doake, pers. comm., 2002). This is because the vertical structure formed by the combination of icebergs and sea ice, makes these areas 'traps' for high accumulation of wind blown snow. Therefore the snow cover layer thickness is locally much higher than in usual multiyear sea ice. Additionally, we can't even be sure that the sea ice is freely floating and may be mechanically connected to ice shelf or iceberg margins. Therefore the transformation from sea ice surface elevation to an ice thickness is a more problematic estimate but one that must be made to ensure accurate modeling of the entire area.

However, a transformation from ice surface elevation to ice thickness for this sea ice can only be done with making assumptions. We assume, that the sea ice is freely floating and that it is undeformed. According to Ackely et al. (1990); Eicken et al. (1994), the sea ice draft  $d$  is then related to the sea ice freeboard (which equals our ice surface elevation)  $h$  like

$$\rho_{SW}d = \rho_{si}(h + d) + \rho_{snow}H_{snow}, \quad (3)$$

in which  $\rho_{si}$  is the density of sea ice,  $\rho_{snow}$  is the density of snow and  $H_{snow}$  is the snow thickness. We assume here, that the snow thickness is 30 cm.

The sea ice thickness  $H_{si}$  is thus

$$H_{si} = \frac{\rho_{si}h + \rho_{snow}H_{snow}}{\rho_{SW} - \rho_{si}} + h. \quad (4)$$

Figure 5 shows the resulting ice thickness along the ICESat tracks in the left panel. The right panel shows a subset, the western most area of the Brunt Ice Shelf, with the

thickness data we computed and the ice thickness obtained by RES from the British Antarctic Survey in the BRUNT\_9697 campaign. Both datasets are in good agreement in this area. Further north and east, where the ice is moving much faster and the ice is highly crevassed, the two datasets differ. This is due to the time difference in the data acquisition. Ice in this area is moving at a speed of  $750 \text{ m a}^{-1}$ , crosses six pixel per year and thus 36 to 48 pixels since BRUNT\_9697 campaign. According to Heraklit, we examine here not the same bodies of ice and therefore it is not surprising, that the ice thicknesses are not as clearly comparable.

The derived thickness data show that the derived sea ice thickness can exceed 50 meters. In addition, the ice thicknesses along the Stancomb-Wills Ice Tongue shows the typical thinning towards the ice front and the lateral shear margin towards Lyddan Island, show steep ice thickness gradients. These results are compatible with field observations and suggest that this complex region can be well represented for modeling studies.

## Conclusions

In conclusion, the combination of the precise ICESat altimetry data and the detailed MOA map enables confident discrimination of the various ice types in the area. We derived a local ice surface elevation grid that reflect these ice types. Dynamic factors that control the location and evolution of these ice types can also be defined. This enables a more complete three-dimensional model of the complex and climatically/dynamically sensitive region to be developed for modeling studies. As the margins of Antarctica are where change is happening most rapidly (Scambos et al., 2000;

Vaughan and Doake, 1996; Vaughan et al., 2001; Thomas et al., 2004), integrated data sets such as these and modeling studies of them will be needed to better assess overall mass loss from the continent.

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## Figure captions

Figure 1: MOA 125m map (polar stereographic projection, 71°S reference latitude, WGS84) of the Brunt Ice Shelf and Stancomb-Wills Ice Tongue with ICESat surface elevation data.

Figure 2: Sketch of the process of transforming the tracks to an elevation grid.

Figure 3: Ice surface elevation grid.

Figure 4: ICESat Laser track No.0344 across the StancombWills Ice Tongue. Surface elevation and ice thickness shown.

Figure 4: Ice thickness derived from the ice surface elevation. The right panel show a subset of the left panel and the ice thickness data from the BRUNT\_9697 campaign (BAS). For details see main text.

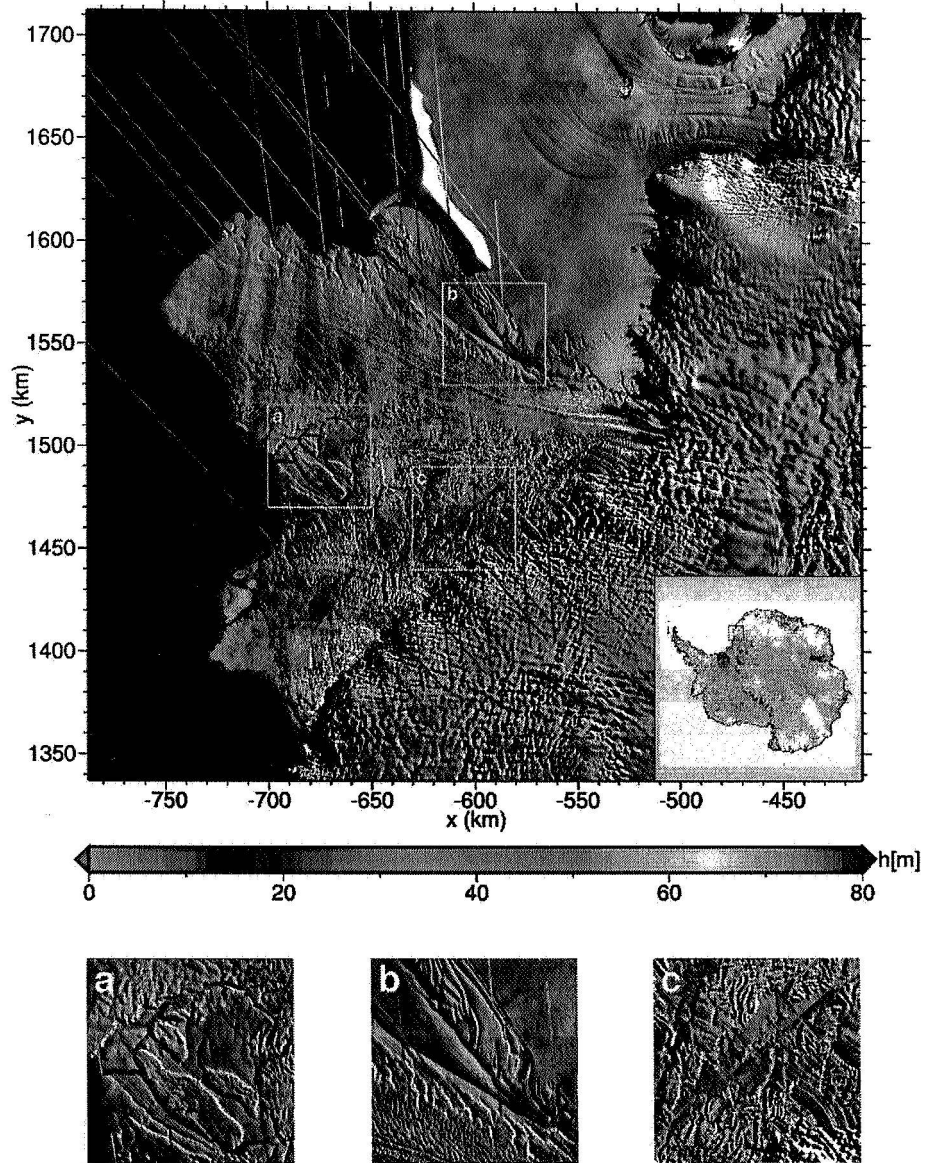


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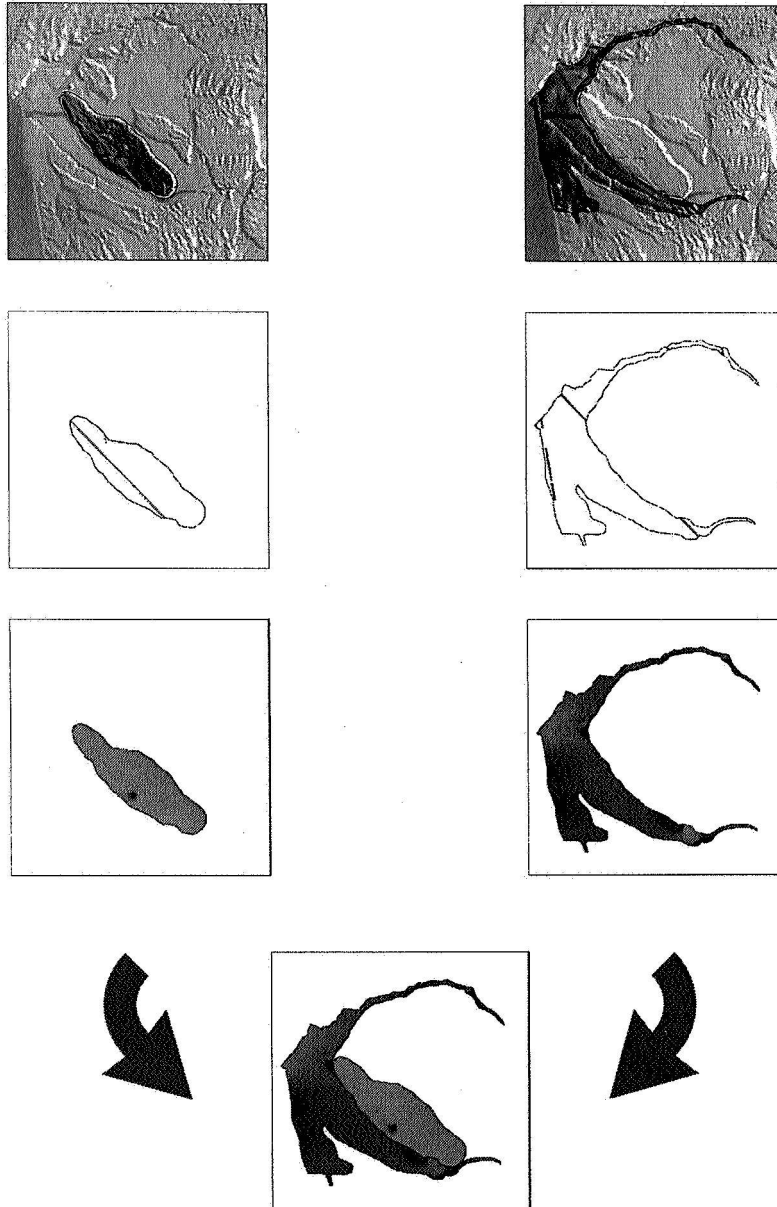


Figure 2: Sketch of the process of transforming the tracks to an elevation grid.

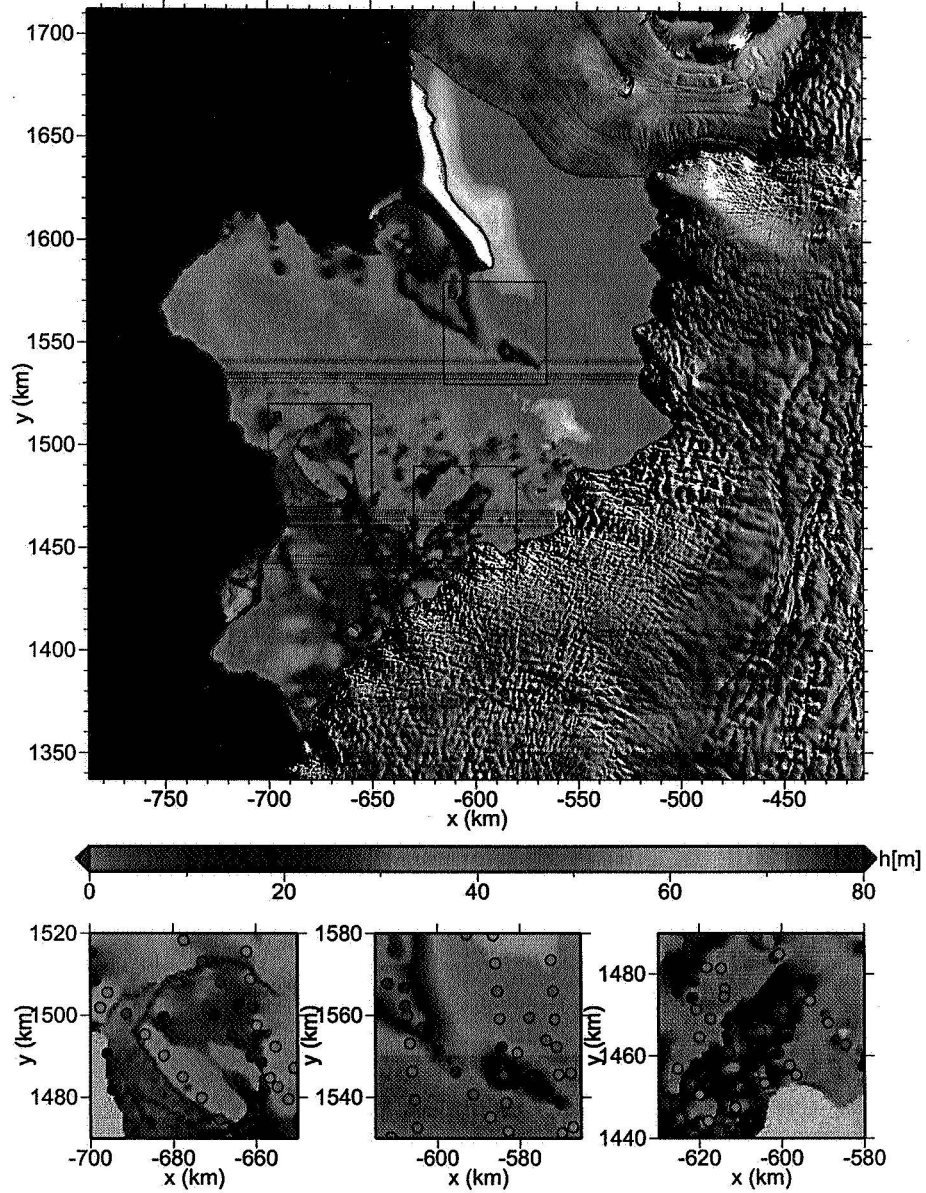


Figure 3: Ice surface elevation grid.

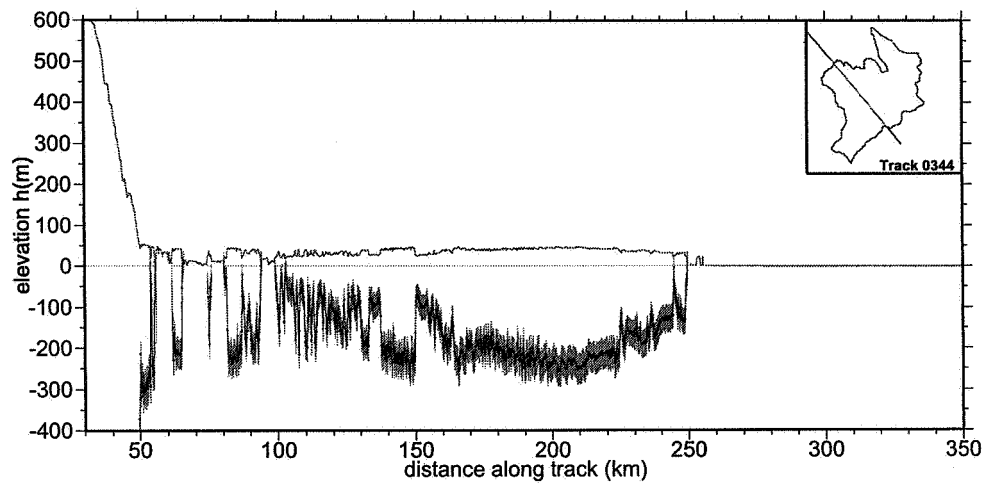


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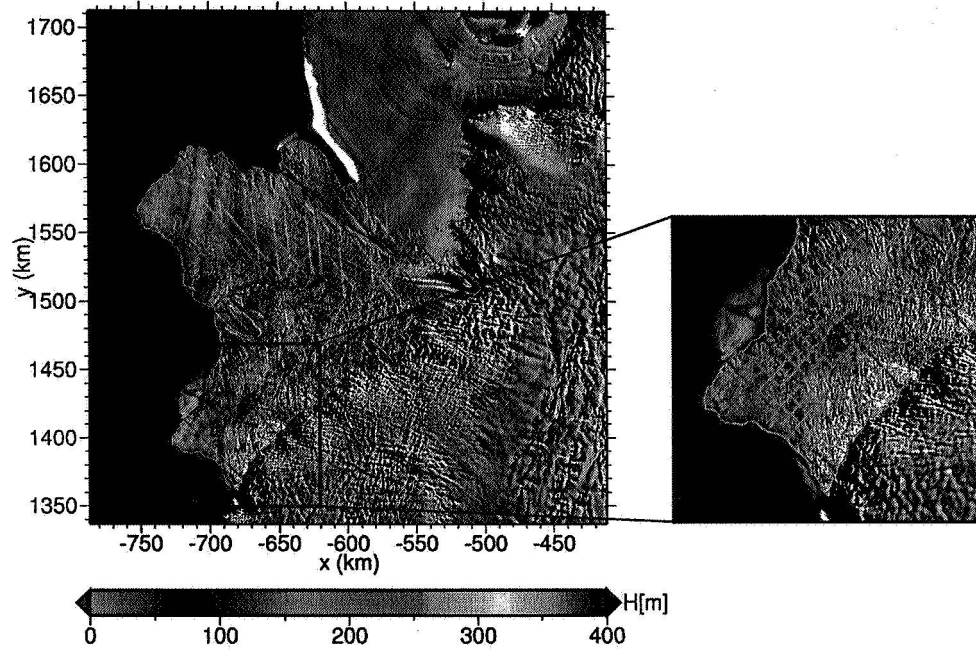


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Angelika Humbert

Christopher A. Shuman

[Christopher.A.Shuman@nasa.gov](mailto:Christopher.A.Shuman@nasa.gov)

### Popular Summary

This paper shows the complex geometry of the Brunt Ice Shelf region on the South Atlantic coast of Antarctica. Elevation data from late 2003 from ICESat's Laser 2a campaign across the Brunt Ice Shelf and the Stancomb-Wills Ice Tongue were integrating with a portion of the recently available MODIS Mosaic of Antarctica (MOA). The comparison of these two remote sensing data sets illustrates the accuracy and precision of the resulting ice shelf elevations because MOA allows the ICESat elevation information to be placed in its spatial context relative to even complex ice topography. The elevation data was then processed onto an elevation grid or 3 dimensional model of the area that can be used for modeling studies of this climatologically- and dynamically-sensitive portion of Antarctica's changing perimeter.

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