

A HISTORY OF SPATIAL SCIENCES ON THE AMERY ICE SHELF, EAST ANTARCTICA

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ABSTRACT

The Antarctic climate system involves many complex interactions between the atmosphere, oceans and ice and is sensitive to variations in these components. Ice shelves represent the ice-ocean-atmosphere interface of the Antarctic continent and are therefore very important indicators of climate change in the region. The Amery Ice Shelf is the largest ice shelf in East Antarctica and has been the focus of many scientific research projects over the past 50 years. In this paper we present a history of the use of spatial science techniques from basic survey equipment to satellite systems in Australian research projects based on the Amery Ice Shelf (and surrounding glaciers) since 1955. The application of these spatial data to projects primarily based in the fields of geodesy, glaciology, climatology, and oceanography has allowed the measurement and monitoring of the physical, dynamic and environmental characteristics of this large and remote region. This new information provides scientists with a better understanding of the ice shelf/ocean/atmosphere system allowing future monitoring to observe the effects of global climate change.

BIOGRAPHY OF PRESENTER

Dr Volker Janssen graduated with a Dipl.-Ing. (Surveying) from the University of Bonn, Germany, in 1997 and received a PhD from The University of New South Wales (UNSW) in 2003. He worked as an assistant lecturer at UNSW in 2003 and as a graduate surveyor in Sydney in 2004. Volker joined the Centre for Spatial Information Science (CenSIS) at the University of Tasmania as a lecturer in 2004. His research interests lie in the areas of GPS for (volcano) deformation monitoring and the investigation of the dynamics of ice shelves.

INTRODUCTION

The Antarctic continent stores approximately 60% of the freshwater and approximately 90% of the ice on the Earth's surface (Meier 1993) and is therefore an extremely important component of the Earth's climate system. Ice in Antarctica can be classified into three types, grounded ice (ice streams and ice sheets), ice shelves and sea ice. One way of observing the effects of climate change in this region is to monitor the amount and distribution of ice in each of these categories.

Ice shelves are the floating extension of a grounded glacier or ice sheet over the ocean (Thomas 1979) (see Fig. 1). They are important environmental change indicators as they are the primary means of mass loss from the continent via either iceberg calving¹ or basal melt² and as such it is important to understand their processes and monitor changes (e.g. Jacobs *et al.* 1992, Williams *et al.* 2002).

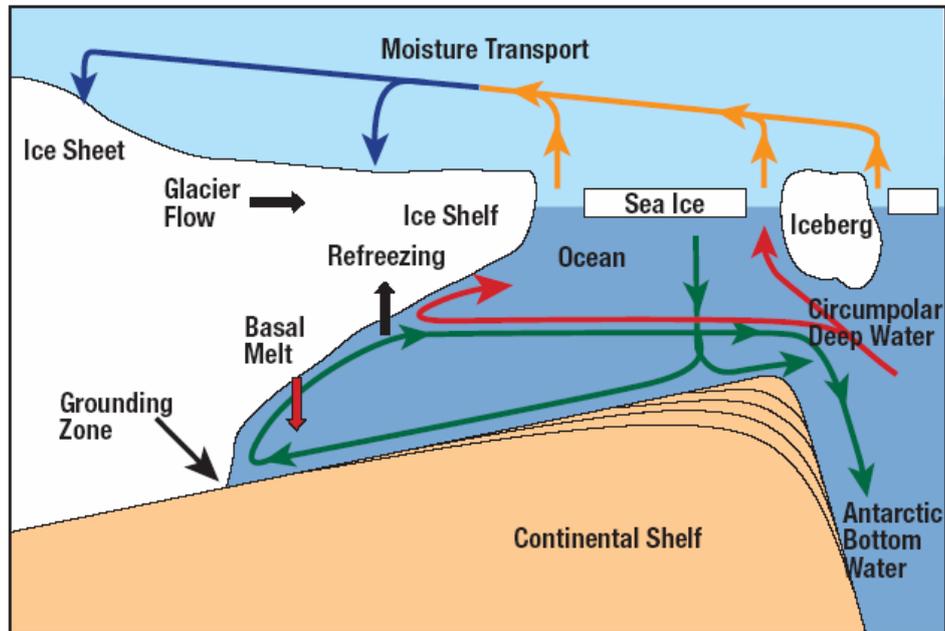


Fig. 1: Schematic representation of an ice shelf and its interactions with the ocean and atmosphere. Source: Allison (2001).

This paper focuses on spatial science projects that were designed to understand the characteristics of the Amery Ice Shelf (AIS) and the glaciers that feed it. Geographically the AIS is located at ($\sim 71^{\circ}\text{S}$, $\sim 70^{\circ}\text{E}$) in East Antarctica between the Australian bases of Davis and Mawson. The AIS is the outlet of the Lambert Glacier Drainage Basin (LGB) which drains continental ice from an area of more than one million square kilometres (Allison 1991) through a section of coastline that represents approximately 1.7% of the total continental circumference (Budd *et al.* 1967) and is therefore a very dynamic system. The ice in the AIS flows with velocities of up to approximately 1350 m/yr (at the ice shelf front) (Young & Hyland 2002) and, as it is floating, is affected by ocean tides and has constant vertical motion at all points north of the grounding zone.

Since their foundation in 1947, the Australian National Antarctic Research Expeditions (ANARE) have played a major role in improving scientific knowledge of the Antarctic continent, and the AIS and LGB have been one of the primary areas of field research during this time. This paper outlines how Australian survey projects on the AIS have evolved from using instruments such as barometers, compasses, optical theodolites and levels in the 1960s to GPS equipment and satellite data in recent times. These projects have provided vital spatial information for scientists in many other disciplines including geodesy, glaciology, climatology, oceanography and remote sensing and allowed them

¹ production of icebergs due to break-off from the ice shelf

² melting of ice at the bottom of the ice shelf due to warmer ocean temperatures or increased pressure

to monitor and develop a better understanding of the physical and environmental characteristics of such a large, remote and climatologically sensitive region.

FIELD SURVEYS (1955-1974)

During this period, fieldwork was restricted by logistical and instrumental constraints and therefore mostly concentrated on the northern part of the AIS. In terms of equipment, the projects undertaken prior to the 1980s initially used compass, tape, wheels and barometers, moving on to traditional terrestrial surveying theodolites, levels and EDMs as well as aerial photography and airborne radio echo sounding. The following summarises the survey projects undertaken on the AIS during this time.

1955-1965

The Amery Ice Shelf was first sighted by air on 11 February 1931 by Sir Douglas Mawson (Corry 1986a). In January 1955 the ice shelf front was charted by ship, marking the first ANARE activity in the region (Law 1967). Following aerial photography of the Amery Ice Shelf during several seasons in the late 1950s, the first surface observations on the AIS by ANARE started in 1962 (Law 1967) with strain measurements made during a reconnaissance survey. The ice shelf front was again mapped by ship and an astrofix carried out to determine the rate of forward motion since a Russian expedition in 1957 (Budd *et al.* 1967).

In the summers of 1963/64 and 1964/65 the first major field-based survey program on the AIS was commenced. This project was designed to collect a large amount of snow accumulation and ice velocity/strain rate data via the positioning and re-measurement of an extensive network of stakes (see Fig. 2). In 1963/64 stakes were placed 3.2 km apart, in a line stretching longitudinally for a distance of over 200 km down the centre of the ice shelf and in two lateral lines at either end of the traverse route (Corry 1986a). Strain grids were also established at three points along the central flow-line (G1, G2, G3 – see Fig. 2) to measure longitudinal and transverse strain rates with sun observations carried out to provide orientation information (Budd 1965). For this traverse, strain grid distances were measured by tape, other distances were observed using a sledge-wheel, directions were taken by compass and heights determined by precise barometer (Corry 1986a, 1996).

In 1964/65 the previous season's traverse and strain grids were re-surveyed and extended to new sites at T4 and T5 (see Fig. 2). The 1963/64 astrofixes were repeated, and resection observations to rock features were also made to provide a check on the absolute velocity results of the astrofixes (Budd 1965). A relative surface elevation profile over the traverse route was measured using digital barometers with slopes being checked by theodolite at numerous points (Budd 1965), providing the first extensive surface elevation information on the AIS. Also in 1965, the front of the AIS was mapped by radar, to determine the amount of ice lost in iceberg calving since previous measurements.

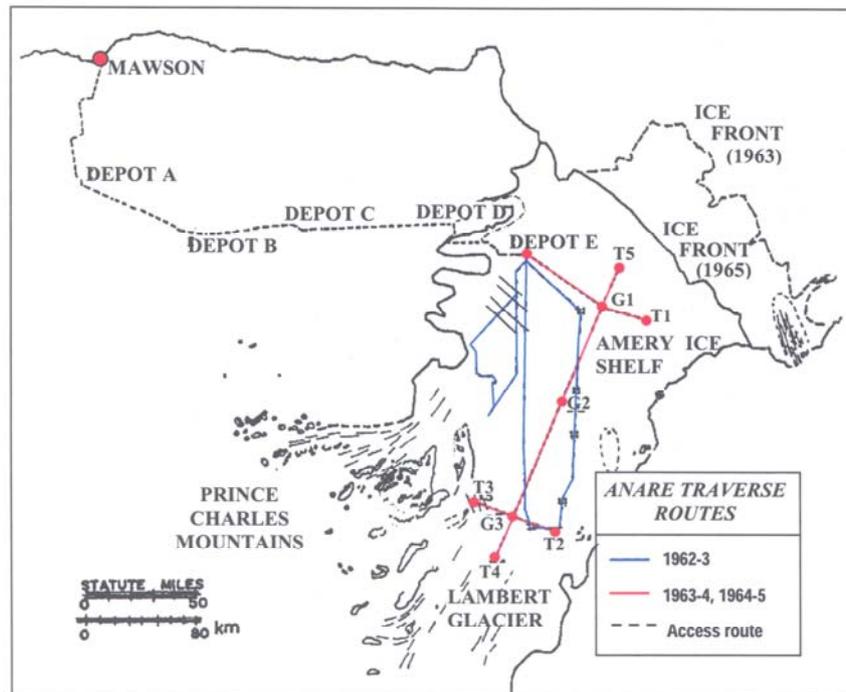


Fig. 2: Location of the Amery Ice Shelf ANARE traverse routes 1962-65.
Source: Phillips (1999), based on the original from Budd *et al.* (1967).

1968-1970

The Amery Ice Shelf Project involved a team spending the winter of 1968 living on the AIS and then completing a summer field program of survey observations to provide a set of extensive glaciological observations for the ice shelf (Corry 1986b). This project was designed to use much higher-level survey equipment than the previous programs on the AIS and as such was completed using a MRA-3 tellurometer, Wild T3 theodolite and an automatic optical level.

The first task was to complete an optical levelling run from G1 to G3, and then extend the line south to T4, east to T2, and west to T3 at the Jetty Peninsula (see Fig. 2). Barometric levelling was then carried out at Jetty Peninsula to provide height information for the surface of Beaver Lake and a levelling run from G1 to Sandefjord Bay was also completed, connecting the traverse to the ocean surface (Corry 1986b).

After the levelling was completed, the tellurometer/theodolite survey commenced. In this traverse, the 1964/65 wooden marker canes were replaced using 9m (or 6m at the southern points) steel poles extending 6m (or 4m) above the snow surface (Corry 1996). These were later referred to as 'Corry' poles, named after the surveyor in charge of placing them. The traverse route extended from T3 to G3, north to G1 and from G1 west towards depot E and north to T5 (Corry 1986b) (see Fig. 2). In January 1969 the traverse was extended north of T5 to within metres of the ice shelf front (Corry 1987). Several observations to surrounding rock sites connected the survey to fixed points and concluded the 1968/69 campaign, the network now consisting of 88 steel pole markers covering about 500 km (Corry 1996). The height of the 'Corry' poles prevented the survey equipment from being set up over the mark and therefore, for the distance measurements, the tellurometer was set up as close to the pole as possible and elevated

by 3m to reduce ground reflection errors (see Fig. 3) while the direction measurements were observed close to the pole and connected to the traverse station via eccentric observations (Linton-Smith 1991).



Fig. 3: Tellurometer set-up at a 'Corry' pole in 1970. The sledge-wheel is visible on the left. Photographs by Max Corry (left) and Norman Linton-Smith (right), Australian Government Antarctic Division © Commonwealth of Australia.

It was initially planned to re-observe the entire traverse during the 1968/69 field season in order to determine the ice movement at each 'Corry' pole and to measure snow accumulation. However, due to adverse weather conditions throughout autumn and winter, this could not be achieved. The Amery Ice Shelf Project was therefore extended into the following 1969/70 summer season, when the network was remeasured using tellurometer and theodolite and the levelling route extended southwards for another 30-50 km (Budd *et al.* 1982, Corry 1987). During this survey, observations were again made between the same traverse and rock sites providing a connection to the 1968/69 survey (Corry 1987). Also in this season, a newly designed ground-based radio echo sounder (RES) was used to provide ice thickness measurements along the traverse route (Budd *et al.* 1982).

The Amery Ice Shelf Project resulted in several scientific firsts as described by Corry (1987) among which were:

- The first accurate axis optical levelling profile of any ice shelf extending from the seaward edge to the presumed grounding line, along with two transverse elevation profiles, one at the front and one towards the middle of the ice shelf. Coupled with the ice radar (RES) data, this work made a significant contribution to the understanding of the mass balance of the AIS.
- The first accurate survey of the movement and strain along a very dynamic ice shelf, referenced to rock sites at both ends of the survey.

The 1968-70 traverses have been reanalysed by King (2002) after he discovered several inconsistencies in the original computation concerning error propagation, a large

misclose, and the traverse being reduced to a different ellipsoid than that of the control coordinates. Correction of these errors resulted in the shift of some station coordinates by up to 3-4 km. The resulting set of station coordinates by King is the most accurate, reliable and consistent data set that forms the basis for long-term studies of the Amery Ice Shelf (King 2002).

1971-1974

The following series of field surveys focussed on collecting information on the ice flowing into the AIS and so, in the Antarctic summer of 1971/72, eleven sites were established between the 1500m and 2000m elevation contours around the southern end of the Lambert Glacier Drainage Basin (LGB) (Allison 1979). These markers were positioned through a tellurometer/theodolite traverse that was closed at a rock site on the southern end of the Mawson Escarpment. Small (100m) strain grids were also measured at each site. Elevations at the markers were determined to 2nd order accuracy by reciprocal vertical angles to stations on surrounding mountains, and gravity measurements were also made at the sites (Allison 1979). Two years later, in 1973/74, the survey was repeated in order to determine ice velocities at the traverse sites (Allison 1979). During both seasons, aerial RES data were collected using a 100 MHz echo sounder and covering an area of 200,000 km² with estimated positioning errors for the flight lines of up to ~5km (Morgan & Budd 1975).

During the next few years no spatial science fieldwork took place on the Amery Ice Shelf since the large amount of data collected provided a good first understanding of the AIS and activities concentrated on other areas in Antarctica. However, the arrival of the GPS technology opened up new possibilities and shifted the focus back to the AIS in the late 1980s.

GPS SURVEYS (1988 – PRESENT)

The 1980s saw the advent of GPS technology, which allowed new projects to be attempted at far more remote regions of the AIS than were previously feasible. This technological advance plus improvements in logistical capabilities (e.g. helicopter and skidoo transport) allowed a much greater number of locations to be sampled and a larger amount of data to be collected and analysed at varying levels of precision. These GPS surveys can be split into two eras:

- (i) Pre 1993/94: The GPS equipment used and the GPS system in place was at such a level that only low precision observations could be made during limited observation windows.
- (ii) Post 1993/94: From 1993/94 to the present, GPS surveys have been carried out over extended time periods and to high levels of precision, due to major improvements in the GPS system, field equipment and processing techniques.

The field techniques and scientific purpose for each of the major GPS surveys in the AIS/LGB region were different in each season, however, most were undertaken to provide ice velocity/strain information or ground truthing for remote sensing projects. The following discussion illustrates the advancement of GPS technology over the last 20 years via its implementation in the AIS region. Figure 4 shows the location of the major GPS field surveys conducted.

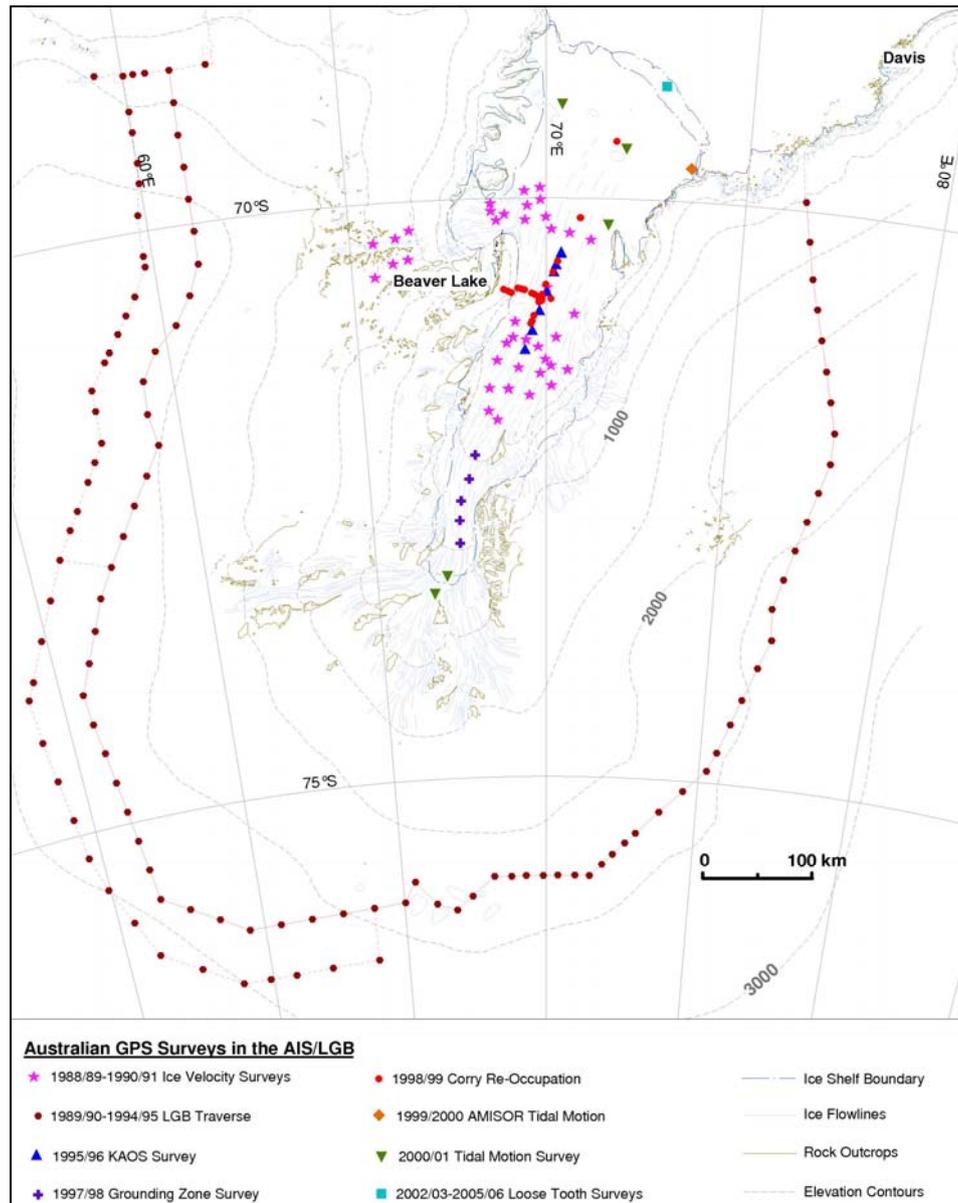


Fig. 4: Locations of major Australian GPS surveys in the AIS/LGB region.

AIS Velocity Survey (1988/89, 1989/90 and 1990/91)

The first GPS surveys by ANARE on the AIS were undertaken as part of the Lambert-Amery Regional Glaciology Experiment (LARGE) to observe ice dynamics, mass flux and grounding zone characteristics of the AIS and lower Lambert Glacier³ (Allison 1991). Equipment used were single-frequency Wild Magnavox WM101 (1988/89) and dual-frequency WM102 (1989/90 and 1990/91) GPS receivers. In this project, marker poles were placed in ‘gate’ formations across specific areas of ice flowing into the ice shelf and were observed/re-observed with GPS over the three field seasons (Allison 1991). During this work, two of the 1968-70 ‘Corry’ poles were also discovered and positioned with GPS. Initial position results were highly degraded (1-10m precision)

³ now known to actually have been the southern AIS (Fricker *et al.* 2002a)

due to the single-frequency receivers, very long baselines, low satellite numbers, short observation windows (0.5-2 hours), high latitude, high levels of ionospheric disturbances (sunspot maximum) and bad weather limiting the number of possible reoccupations in 1989/90 (Allison 1991). Gravity, barometric levelling and airborne radio-echo sounding (RES) measurements were also collected across the northern AIS during this time to provide further information on the structure of the ice shelf (Allison 1991).

LGB Traverse (1989/90, 1990/91 and 1992/93)

As part of the LARGE experiment, a series of five traverses was completed that placed and positioned a network of permanent ice marker poles (at 30km spacing) to observe ice dynamics and surface slope approximately along the 2500m contour of the LGB between Mawson and Law Base (Kiernan 2001). The GPS equipment used for the first three of these traverses were dual-frequency WM102 instruments (Kiernan 2001). Again, the long baselines (up to 700km), low numbers of satellites, short observation windows, high latitude and high levels of ionospheric disturbances affected these surveys and caused initial results to be of a low precision (~1-10m) (Manson *et al.* 2000, Kiernan 2001).

LGB Traverse (1993/94 and 1994/95)

The final two LGB traverses completed the traverse route from Mawson to Law Base during the Antarctic summers of 1993/94 and 1994/95. In these surveys, 72 ice marker poles were located/relocated using new Leica SR299 dual-frequency receivers (Kiernan 2001). Also, at this time, the GPS satellite constellation had reached its Initial Operational Capability⁴ and ionospheric activity had eased. These improvements in equipment, number of satellites and ionospheric conditions in conjunction with modern data processing techniques allowed the final ice velocities for the LGB traverse sites to be determined with precisions of 1-10 cm/yr (Hurd 2002).

KAOS (1995/96)

The KAOS (Kinematic Amery Over-Snow) survey was undertaken to i) provide ground truthing data for validation of a new elevation model of the AIS created from ERS satellite altimeter data, ii) remeasure surface height and velocity along a section of the 1968-70 optical traverse line, and iii) observe the tidal motion of the ice shelf (Phillips 1999). This survey used three Leica SR299 dual-frequency receivers: one as a base station at a fixed rock site approximately 60 km from the ice shelf survey, the second as a series of local base stations on the ice shelf and the third mounted on a skidoo to collect kinematic GPS surface profiles (Phillips 1999). The kinematic profiles were collected in a grid formation, so that the GPS data could be used to create a new digital elevation model of the area that coincided with several cross-over points of the ERS altimeters (Phillips *et al.* 1998). Whilst collecting the kinematic data, the surveyors also discovered a number of the original 1968 'Corry' poles, which were reoccupied to provide a long-term velocity estimate for these sites (Allison 1995).

⁴ IOC declared 8/12/1993 when 24 (Block I and Block II/IIA) satellites were in orbit (<http://tycho.usno.navy.mil/gpsinfo.html>).

Grounding Zone Survey (1997/98)

Phillips *et al.* (1996) redefined the AIS grounding zone position to be around 73°S, approximately 200 km south of previous estimates. To confirm the southern extent of the floating ice shelf, six Leica SR9500 dual-frequency GPS stations were deployed and ran continuously for up to 4 days to collect vertical and horizontal motion data and therefore indicate the range of tidal motion in this region (King 2002).

Corry/KAOS Re-occupation Survey (1998/99)

To strengthen knowledge of velocity and strain on the ice shelf and obtain a 30-year time-span of observations, a GPS survey was undertaken with the aim of re-observing all available 1968-70 'Corry' poles using GPS (King 2002). In this survey, 22 'Corry' poles, 4 KAOS poles and the 1968 G1, G2 and G3 strain grids were able to be located and surveyed with dual-frequency (Leica SR9500 and Ashtech Z12) GPS equipment (King 2002). For the duration of the survey (11 days), a local GPS base station was installed near G3 providing important information on the tidal motion in this region of the AIS (King *et al.* 2000).

Tidal Motion Surveys (1999/2000 and 2000/01)

The commencement of the Amery Ice Shelf Ocean Research (AMISOR) hot water drilling project in 1999/2000 provided the location and personnel to run a continuous GPS site (Leica CRS1000) to measure tidal motion at the front of the AIS for 31 days (Craven *et al.* 2000). In this same season, the 1997/98 grounding zone sites were also re-observed for a short period with GPS to provide multi-year velocity data at these sites.

The success of the previous seasons' GPS data in providing new and important tidal information lead to the development of a project dedicated to observing tidal motion at specific points along the length of the AIS (King 2002). This information was required for calibrating ocean circulation models and further understanding the ice shelf/ocean dynamics (King 2002). In the summer of 2000/01, six autonomous Leica CRS1000 receivers were deployed powered by batteries and solar panels to allow continuous data collection at widely spaced locations over the summer. Kinematic runs were also completed on skidoos (using Leica SR9500 equipment) when possible during this time to provide surface profile information for ERS altimeter validation.

Loose Tooth Surveys (2002/03 – 2005/06)

Scientists analysing satellite images of the AIS identified a 30km x 30km area at the front of the ice shelf (now known as the 'Loose Tooth') that has a number of dormant and active rift systems (Fricker *et al.* 2002b). In order to understand mechanisms behind iceberg calving, GPS and seismic data have been collected each summer since 2002/03 around the tip of one of the active rifts that will eventually cause the iceberg to calve from the shelf (Bassis *et al.* 2005). The GPS network in each survey consisted of between 6 and 12 sites spanning the area immediately behind, in front and either side of the rift tip (see Fig. 5). The equipment used was a combination of Leica, Ashtech and Trimble dual-frequency receivers powered by solar panels and collecting data for between 2 and 59 days.



Fig. 5: GPS site on the 'Loose Tooth' in 2004/05.

SATELLITE REMOTE SENSING DATA ANALYSIS

Satellite remote sensing data allows extensive and relatively precise mapping of vast and/or remote areas that would otherwise not be possible from land-based surveys. The AIS/LGB is an example of an area for which satellite remote sensing provides scientists with much valuable information that can also be validated using the previously described ground-based observations. There are many types and epochs of satellite data available to scientists in the international community and therefore in recent times there have been many studies carried out which include observations in the AIS region (e.g. Rignot 2002, Liu & Jezek 2004, Raup *et al.* 2005). This section briefly introduces three types of satellite remote sensing data available over the AIS and, as an example, outlines the work of some projects that were/are specifically focussed on improving the understanding of the dynamics and physical attributes of the AIS.

Satellite Imagery

The Landsat program has been running for over 30 years, providing visible and infrared satellite images of the Earth (NASA 2006a). These images provide useful feature identification for glaciological studies, which aid in identifying characteristics of different regions of the ice. For example, Swithinbank (1988) used Landsat images to create a detailed map of the surface features of the AIS/LGB including flow-lines, melt water and crevassed areas while Hambrey & Dowdeswell (1994) used Landsat MSS (Multi Spectral Scanner) images to investigate historic ice flow patterns on the AIS. In combination with other data, Landsat imagery has also been used to track the ice shelf front over many years in order to study iceberg calving (Fricker *et al.* 2002b).

Satellite Altimetry

Satellite altimeters measure the distance between the satellite (of known orbit) and the ground or ocean surface, from which surface elevations can be calculated. The first satellite radar altimeter to provide coverage over the AIS was the Seasat altimeter (operational in 1978), and from these data Brooks *et al.* (1983) and Zwally *et al.* (1987) generated the first detailed surface elevation maps of the AIS.

The second radar altimeter to collect data over the AIS was Geosat, which was operational between 1985 and 1990. The data collected by Geosat were used by both

Herzfeld *et al.* (1993) and Lingle *et al.* (1994) to create new DEMs of the AIS in order to investigate elevation changes between 1978 and the 1980s.

The European Remote-Sensing Satellites ERS-1 (operational 1991-99) and ERS-2 (launched in 1995) carry various instruments including a radar altimeter and synthetic aperture radar (SAR) (ESA 2006). Data from the ERS-1 satellite in particular have been used by many authors (e.g. Ridley *et al.* 1993, Bamber & Gomez-Dans 2005) to derive DEMs of Antarctica as i) it collected data to 82°S, ii) its operation was modified to allow better tracking over areas of ice, and iii) its orbit was varied on two occasions to allow a smaller separation distance of the ground tracks. The most extensive use of ERS-1 altimeter data on the AIS was undertaken by Phillips (1999) in which she and her collaborators generated DEMs of the AIS and the AIS/LGB system (Fricker *et al.* 2000a) and used these DEMs to investigate the mass balance of the system (Fricker *et al.* 2000b) and the distribution of marine ice beneath the AIS (Fricker *et al.* 2001). The ERS altimeter DEMs were also compared with results from the KAOS GPS survey which showed that ERS altimeters can closely reproduce the surface topography of the AIS (to within 1-2m) (Phillips *et al.* 1998).

The most recent advance in remote sensing technology is the Ice, Cloud, and land Elevation Satellite (ICESat), which was launched in January 2003 and is the first laser altimeter operating in a polar orbit (NASA 2006b). It carries three Geoscience Laser Altimeter System (GLAS) altimeters which have been shown to deliver high quality elevation data with a high level of horizontal resolution (~70m footprint and ~170m along-track spacing) and a relative accuracy of $\pm 0.14\text{m}$ (Shuman *et al.* 2006). On the AIS, ICESat data have recently been used to investigate rift topography and rift widening of the 'Loose Tooth' system (Fricker *et al.* 2005a) and will be very important to future research on the ice shelf.

Synthetic Aperture Radar (SAR)

Interferometric synthetic aperture radar (InSAR) is an imaging technique used to map the topography of a surface and its changes over time at a high resolution, based on a pair of radar images acquired over the same area from almost the same satellite position (Rosen *et al.* 2000). Although SAR instruments have been accommodated on several satellites, RADARSAT (launched in 1995) was the first to deliver complete coverage of the Antarctic continent (Jezek 1999), and thus initiated numerous studies. For example, Young & Hyland (2002) used RADARSAT data to generate a dense network of velocity estimates (see Fig. 6) and to determine strain rates over the AIS, while Fricker *et al.* (2002b) investigated the iceberg-calving cycle on the AIS. A combination of SAR data and satellite imagery was used to monitor the propagation of the 'Loose Tooth' rift system (Fricker *et al.* 2005b).

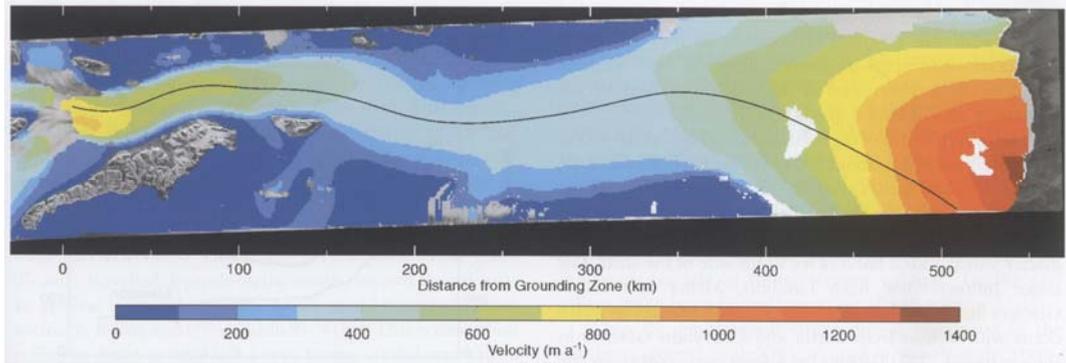


Fig. 6: Distribution of ice velocities over the AIS. Source: Young & Hyland (2002).

SUMMARY OF MAJOR RESULTS FROM SPATIAL DATA COLLECTED ON THE AIS BY AUSTRALIAN PROGRAMS

The scientists who have collected and analysed the AIS spatial data have produced a wide body of work that defines various aspects of the ice shelf and its surroundings. The spatial data collected over the AIS during the past 50 years both on the ground and from satellites have allowed scientists to progress from an initial, basic understanding of the physical characteristics of the AIS to now fine-tuning their knowledge of the entire glacier/ice-shelf/ocean system. These studies are important as they provide the knowledge required to understand the role of this region in the Antarctic system and to allow future monitoring of the effects of climate change in this sensitive region. The current assessment of the AIS is summarised below:

- It extends 550 km in length from $\sim 73^{\circ}\text{S}$ to $\sim 68.5^{\circ}\text{S}$ (Fricker *et al.* 2002a, Young & Hyland 2002).
- The width of the ice shelf increases from about 40 km at the grounding zone to about 200 km at the front (Young & Hyland 2002).
- The area of the AIS is approximately $71,260 \text{ km}^2$ (Fricker *et al.* 2002a).
- The thickness of the ice shelf varies from 2500m at the grounding zone to 200m at the front (Budd *et al.* 1982, Fricker *et al.* 2002a) with some areas of sea-ice accretion and some areas of melt at the ice/ocean interface (Fricker *et al.* 2001).
- Ice velocities range from 300 m/yr to 1350 m/yr (Young & Hyland 2002).
- The AIS/LGB system is currently thought to be in a state of slightly positive mass balance (Fricker *et al.* 2000b).

The results of the projects described in this paper have been published previously by the researchers involved (refer to reference list for details). The major findings from these studies of the AIS/LGB are (in chronological order):

- 1) Identification of a significant iceberg calving event in late 1963 (Budd 1966).
- 2) Initial definition of the ice shelf extent, topography and dynamics, mainly in the northern half of the ice shelf (Budd 1966, Budd *et al.* 1967, Corry 1986a). Budd *et al.* (1982) presented the results of the 1968-70 surveys which included the identification of a grounding line just south of T4, determination of initial ice velocity values (Fig. 7) and noting that strain rates were the primary cause of ice shelf thinning.

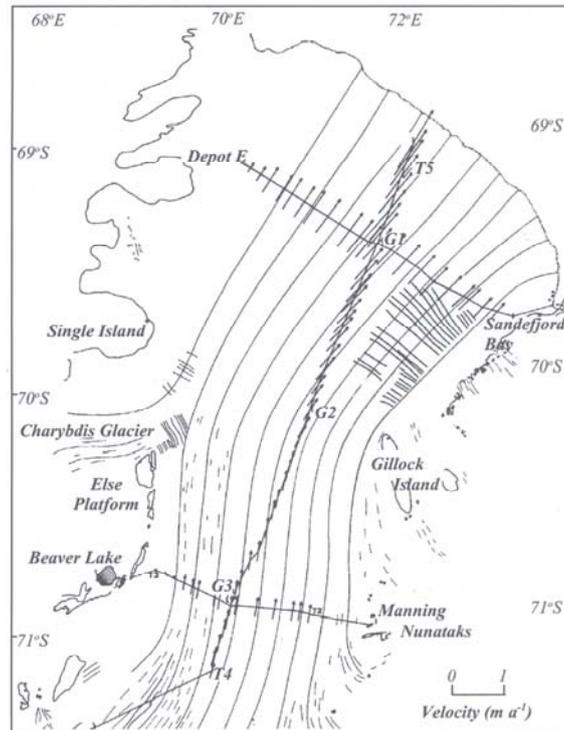


Fig. 7: Surface ice flow velocity vectors on the Amery Ice Shelf determined during the 1968-70 surveys, together with estimated flow-lines from satellite imagery.

Source: Phillips (1999), based on the original from Budd *et al.* (1982).

- 3) The major results of the 1968-70 RES measurements were reported by Morgan & Budd (1975), most importantly mapping the bedrock below the ice, determining ice thickness values in the AIS/LGB region and finding a maximum ice thickness of 2500m.
- 4) Using field survey data from the 1968-74 campaigns, combined with the RES ice thickness data (Morgan & Budd 1975), Allison (1979) estimated a mass budget of the Lambert Glacier Drainage Basin of +12 Gt/yr. This assessment had quite a large error budget due mainly to the lack of available snow accumulation values across the LGB.
- 5) The LGB traverses provided a large amount of glaciological information regarding the ice flowing into the AIS. The main results arising from the GPS data collected during the traverses were ice velocities and identification of the major ice streams, surface elevation and slope and, in combination with other information, mass flux values for balance calculations (Kiernan 2001, Hurd 2002).
- 6) Ice velocities over the ice shelf and the northern LGB glaciers were first discussed in Allison (1991) and later King (2002) provided updated velocity and strain values for many of the ice markers in the centre of the ice shelf including long-term velocities for sites observed in both the 1960s and 1990s.
- 7) ERS satellite altimeter data were used by Phillips (1999) and collaborators to produce the most extensive physical maps of the AIS. From these studies several important findings were made including i) redefinition of the grounding zone to between 73.2°S and 73.3°S, about 240km further upstream than previously proposed by Budd *et al.* (1982), identified in the AIS DEM and the 1997/98 GPS

- data (Fricker *et al.* 2002a), ii) marine ice accretion patterns on the AIS account for about 9% of the ice shelf volume (Fricker *et al.* 2001), iii) AIS/LGB system mass balance recalculation also incorporating information from the LGB traverses (Fricker *et al.* 2000b), and iv) surface elevation maps of the AIS and LGB using GPS data for ground truthing (Phillips *et al.* 1998, Fricker *et al.* 2000a).
- 8) The analysis of quasi-continuous GPS observations on the AIS produced valuable information about its tidal characteristics and the ocean circulation beneath the ice shelf (Phillips *et al.* 1996, King *et al.* 2000, King 2002). These studies revealed tidal signals of 1-2m across the AIS and the GPS data have been used to improve and validate tide models (Padman *et al.* 2002, King *et al.* 2005).
 - 9) Mapping of surface velocities over the entire AIS from InSAR data showed that velocities decreased from around 800 m/yr at the grounding zone to around 300 m/yr, and then increased to a maximum of about 1350 m/yr at the front (see Fig. 6), while strain rates varied systematically across and along the ice shelf (Young & Hyland 2002). Similar velocity values were obtained by Joughin (2002) who employed a different data processing approach.
 - 10) Understanding of rift mechanics and iceberg calving processes around the 'Loose Tooth' using GPS in conjunction with seismic and satellite data. Rift propagation rates of about 4 m/day and evidence of seasonal dependence (rifts propagate faster in summer than in winter) were found by Fricker *et al.* (2005b). Propagation occurs in episodic bursts lasting about four hours, separated by several (10-20) days (Bassis *et al.* 2005) and the collection of ice and snow trapped inside the rift (often called *mélange*) may potentially be an important factor in the rifting process (Fricker *et al.* 2005a).

CONCLUDING REMARKS

In this paper we have charted the recent history of spatial information gathering in general by looking at the work carried out in a specific region over the past 50 years. The use of spatial techniques, which have evolved from instruments such as barometers, compasses, optical theodolites and levels in the 1960s to GPS equipment and satellite data in recent times, provided invaluable insight into the structure, dynamics and environmental interactions of the Amery Ice Shelf, allowing new discoveries to be made as technologies improved. Australian activities in the region have made a significant contribution to the advance of scientific knowledge. Future projects will benefit from the next generation of spatial observations and with the current knowledge as a basis will allow scientists to use the AIS region for monitoring the effects of climate change in this region.

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REFERENCES

- Allison, I. 1979. The mass budget of the Lambert Glacier Drainage Basin, Antarctica. *J. Glaciol.*, 22(87), 223-235.
- Allison, I. 1991. The Lambert Glacier/Amery Ice Shelf study: 1988-1991. *Aurora*, 10(4), 22-25.
- Allison, I. 1995. Surveying the Amery Ice Shelf. *ANARE News*, Spring/Summer 1995-96, 12.
- Allison, I. 2001. Peephole through the ice: The AMISOR project. *Australian Antarctic Magazine*, 1, Autumn 2001, 20-21.
- Bamber, J. and Gomez-Dans, J.L. 2005. The accuracy of digital elevation models of the Antarctic continent. *Earth Planet. Sci. Lett.*, 237, 516-523.
- Bassis, J.N., Coleman, R., Fricker, H.A. and Minster, J.B. 2005. Episodic propagation of a rift on the Amery Ice Shelf, East Antarctica. *Geophys. Res. Lett.*, 32(6), L06502, doi:10.1029/2004GL022048.
- Brooks, R.L., Williams, R.S.J., Ferrigno, J.G. and Krabill, W.B. 1983. Amery Ice Shelf topography from satellite radar altimetry. In *Antarctic Earth Science*, Oliver, R.L., James, P.R. and Jago, J.B. (Eds.) (Cambridge: Cambridge University Press), 441-445.
- Budd, W. 1965. Glaciological survey of the Amery Ice Shelf. *Antarctic*, 4(3), 158-159.
- Budd, W. 1966. The dynamics of the Amery Ice Shelf. *J. Glaciol.*, 6(45), 335-358.
- Budd, W., Landon Smith, I. and Wishart, E. 1967. The Amery Ice Shelf. In *The Physics of Snow and Ice, Proc. Int. Conf. on Low Temperature Science*, Hokkaido University, Sapporo, Japan, Oura, H. (Ed.) (Sapporo: Institute of Low Temperature Science), 447-467.
- Budd, W.F., Corry, M.J. and Jacka, T.H. 1982. Results from the Amery Ice Shelf Project. *Ann. Glaciol.*, 3, 36-41.
- Corry, M. 1986a. The Amery Ice Shelf saga: Part 1 - pre 1968. *Aurora*, 6(1), 17-20.
- Corry, M. 1986b. The Amery Ice Shelf saga - Part 2: The Amery Ice Shelf Project 1968. *Aurora*, 6(2), 28-34.
- Corry, M. 1987. The Amery Ice Shelf saga: Part 3 - 1969-70. *Aurora*, 6(3), 25-29.
- Corry, M. 1996. Those Amery Ice Shelf glaciological marker snowpoles. *Aurora*, 15(4), 18-20.
- Craven, M., Brand, R., Elcheikh, A. and Jones, N. 2000. Summer field report for Amery Ice Shelf HWD test season: AMISOR-1. Internal report, Cooperative Research Centre for the Antarctic and Southern Ocean Environment, Hobart, Australia.
- ESA. 2006. <http://earth.esa.int/ers/> (accessed 7 December 2006).
- Fricker, H.A., Hyland, G., Coleman, R. and Young, N.W. 2000a. Digital elevation models for the Lambert Glacier-Amery Ice Shelf system, East Antarctica, from ERS-1 satellite radar altimetry. *J. Glaciol.*, 46(155), 553-560.
- Fricker, H.A., Warner, R.C. and Allison, I. 2000b. Mass balance of the Lambert Glacier-Amery Ice Shelf system, East Antarctica: A comparison of computed balance fluxes and measured fluxes. *J. Glaciol.*, 46(155), 561-570.
- Fricker, H.A., Popov, S., Allison, I. and Young, N. 2001. Distribution of marine ice beneath the Amery Ice Shelf. *Geophys. Res. Lett.*, 28(11), 2241-2244.
- Fricker, H.A., Allison, I., Craven, M., Hyland, G., Ruddell, A., Young, N., Coleman, R., King, M., Krebs, K. and Popov, S. 2002a. Redefinition of the Amery Ice Shelf, East Antarctica, grounding zone. *J. Geophys. Res.*, 107(B5), ECV 1/1-1/9.

- Fricker, H.A., Young, N.W., Allison, I. and Coleman, R. 2002b. Iceberg calving from the Amery Ice Shelf, East Antarctica. *Ann. Glaciol.*, 34, 241-246.
- Fricker, H.A., Bassis, J.N., Minster, B. and MacAyeal, D.R. 2005a. ICESat's new perspective on ice shelf rifts: The vertical dimension. *Geophys. Res. Lett.*, 32, L23S08, doi:10.1029/2005GL025070.
- Fricker, H.A., Young, N.W., Coleman, R., Bassis, J.N. and Minster, J.B. 2005b. Multi-year monitoring of rift propagation on the Amery Ice Shelf, East Antarctica. *Geophys. Res. Lett.*, 32(2), L02502, doi:10.1029/2004GL021036.
- Hambrey, M.J. and Dowdeswell, J.A. 1994. Flow regime of the Lambert Glacier-Amery Ice Shelf system, Antarctica: Structural evidence from Landsat imagery. *Ann. Glaciol.*, 20, 401-406.
- Herzfeld, U.C., Lingle, C.S. and Lee, L.-H. 1993. Geostatistical evaluation of satellite radar altimetry for high-resolution mapping of Lambert Glacier, Antarctica. *Ann. Glaciol.*, 17, 77-85.
- Hurd, R. 2002. An investigation of glaciological and meteorological parameters in the Lambert Glacier Basin using high precision GPS strategies. PhD thesis, University of Tasmania, Hobart, Australia.
- Jacobs, S.S., Helmer, H.H., Doake, C.S.M., Jenkins, A. and Frolich, R.M. 1992. Melting of ice shelves and the mass balance of Antarctica. *J. Glaciol.*, 38(130), 375-387.
- Jezek, K.C. 1999. Glaciological properties of the Antarctic ice sheet from RADARSAT-1 synthetic aperture radar imagery. *Ann. Glaciol.*, 29, 286-290.
- Joughin, I. 2002. Ice-sheet velocity mapping: A combined interferometric and speckle-tracking approach. *Ann. Glaciol.*, 34, 195-201.
- Kiernan, R. 2001. Ice sheet surface velocities along the Lambert Glacier Basin traverse route. Research Report No. 23, Antarctic Cooperative Research Centre, University of Tasmania, Hobart, Australia, 76 pp.
- King, M. 2002. The dynamics of the Amery Ice Shelf from a combination of terrestrial and space geodetic data. PhD thesis, University of Tasmania, Hobart, Australia.
- King, M., Nguyen, L.N., Coleman, R. and Morgan, P. 2000. Strategies for high precision processing of GPS measurements with application to the Amery Ice Shelf, East Antarctica. *GPS Solutions*, 4(1), 2-12.
- King, M.A., Penna, N.T., Clarke, P.J. and King, E.C. 2005. Validation of ocean tide models around Antarctica using onshore GPS and gravity data. *J. Geophys. Res.*, 110(B8), B08401, doi:10.1029/2004JB003390.
- Law, P. 1967. Movement of the Amery Ice Shelf. *The Polar Record*, 13(85), 439-441.
- Lingle, C.S., Lee, L.-H., Zwally, H.J. and Seiss, T.C. 1994. Recent elevation increase on Lambert Glacier, Antarctica, from orbit crossover analysis of satellite radar altimetry. *Ann. Glaciol.*, 20, 26-32.
- Linton-Smith, N. 1991. Alone on the Amery Ice Shelf, 1969-70. *Aurora*, 10(3), 11-14.
- Liu, H. and Jezek, K.C. 2004. A complete high-resolution coastline of Antarctica extracted from orthorectified Radarsat SAR imagery. *Photogramm. Eng. Rem. Sens.*, 70(5), 605-616.
- Manson, R., Coleman, R., Morgan, P.J., King, M.A. 2000. Ice velocities of the Lambert Glacier from static GPS observations. *Earth Planets and Space*, 52(11), 1031-1036.
- Meier, M.F. 1993. Ice, climate and sea level: Do we know what is happening? In *Ice in the Climate System*, Peltier, W.R. (Ed.) (Berlin: Springer-Verlag), 141-160.

- Morgan, V.I. and Budd, W.F. 1975. Radio-echo sounding of the Lambert Glacier Basin. *J. Glaciol.*, 15(73), 103-111.
- NASA. 2006a. <http://landsat.gsfc.nasa.gov/> (accessed 7 December 2006).
- NASA. 2006b. <http://icesat.gsfc.nasa.gov/> (accessed 7 December 2006).
- Padman, L., Fricker, H.A., Coleman, R., Howard, S. and Erofeeva, L. 2002. A new tide model for the Antarctic ice shelves and seas. *Ann. Glaciol.*, 34, 247-254.
- Phillips, H.A. 1999. Applications of ERS satellite radar altimetry in the Lambert Glacier – Amery Ice Shelf system, East Antarctica. PhD thesis, University of Tasmania, Hobart, Australia.
- Phillips, H.A., Allison, I., Craven, M., Krebs, K. and Morgan, P. 1996. Ice velocities and grounding line location in the Lambert - Amery system, East Antarctica. Pres. at Western Pacific AGU Meeting, 23-27 July, Brisbane, Australia.
- Phillips, H.A., Allison, I., Coleman, R., Hyland, G., Morgan, P.J. and Young, N.W. 1998. Comparison of ERS satellite radar altimeter heights with GPS-derived heights on the Amery Ice Shelf, East Antarctica. *Ann. Glaciol.*, 27, 19-24.
- Raup, B.H., Scambos, T.A. and Haran, T. 2005. Topography of streaklines on an Antarctic ice shelf from photogrammetry applied to a single advanced land imager (ALI) image. *IEEE Trans. Geosci. Remote Sens.*, 43(4), 736-742.
- Ridley, J.K., Laxon, S., Rapley, C.G. and Mantripp, D. 1993. Antarctic ice sheet topography mapped with the ERS-1 radar altimeter. *Int. J. Rem. Sens.*, 14(9), 1649-1650.
- Rignot, E. 2002. Mass balance of East Antarctic glaciers and ice shelves from satellite data. *Ann. Glaciol.*, 34, 217-227.
- Rosen, P.A., Hensley, S., Joughin, I.R., Li, F.K., Madsen, S.N., Rodriguez, E. and Goldstein, R.M. 2000. Synthetic aperture radar interferometry. *Proc. of the IEEE*, 88(3), 333-382.
- Shuman, C.A., Zwally, H.J., Schutz, B.E., Brenner, A.C., DiMarzio, J.P., Suchdeo, V.P. and Fricker, H.A. 2006. ICESat Antarctic elevation data: Preliminary precision and accuracy assessment. *Geophys. Res. Lett.*, 33(7), L07501, doi:10.1029/2005GL025227.
- Swithinbank, C. 1988. Antarctica. In *Satellite Image Atlas of Glaciers of the World*, Williams, R.S.J. and Ferrigno, J.G. (Eds.) (Washington: U.S. Geological Survey).
- Thomas, R.H. 1979. Ice shelves: A review. *J. Glaciol.*, 24(90), 273-286.
- Williams, M.J.M., Warner, R.C. and Budd, W.F. 2002. Sensitivity of the Amery Ice Shelf, Antarctica, to changes in the climate of the Southern Ocean. *J. Climate*, 15, 2740-2757.
- Young, N.W. and Hyland, G. 2002. Velocity and strain rates derived from InSAR analysis over the Amery Ice Shelf, East Antarctica. *Ann. Glaciol.*, 34, 228-234.
- Zwally, H.J., Stephenson, S.N., Bindschadler, R.A. and Thomas, R.H. 1987. Antarctic ice-shelf boundaries and elevations from satellite radar altimetry. *Ann. Glaciol.*, 9, 229-235.