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Collaborative Research: Subglacial Water Intrusion in Greenland

Gordon K. Oswald
Principal Investigator; University of Maine, Orono, gordon.oswald@maine.edu

Preview of Award 0909431 - Final Project Report

Cover

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Accomplishments

* What are the major goals of the project?

The project's goals are:

To analyse radio echo sounding data acquired over the Greenland Ice Sheet by the University of Kansas / CReSIS team with the objective of discriminating between frozen and thawed conditions at the bed of the ice sheet.

To provide maps of the bed state, with the aim of making them available via the National Snow and Ice Data Centre.

To support ice sheet modelling activities by providing information on the bed state, thus related to the temperature at the bed and the rheological conditions at the bed.

To make available to educational establishments information on the relevance and significance of the state of the major ice sheets and the Greenland Ice Sheet in particular

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:

An investigation has been completed into the occurrence of subglacial water beneath the Greenland ice sheet. This is based on archived radio-echo sounding (RES) data. It is possible because liquid water exhibits a higher dielectric permittivity than any bedrock material and can be detected through the ice by means of radar. It is needed because previous analyses have found the variability of basal RES signals to be too great to yield a reliable measure of the bed state, due to the unknown rate of radio absorption through the ice.

This investigation has shown that, based on correct interpretation of the radar reflection intensity, and subject to appropriate assumptions about the range of materials that form the ice sheet bed, it is possible to infer the bed state. Data from RES flights throughout the great majority of the Greenland Ice Sheet have been analysed, and the presence of subglacial water has been determined and mapped over this region.

Data were supplied for the project by collaborators at the University of Kansas for the years 1998, 1999, 2001, 2002 and 2003. The data collection was begun under the Program for Arctic Regional Climate Assessment, and the early results were reported in 2001 in the Journal for Geophysical Research.

The data for 2001 were found difficult to use due to amplitude compression of the signal; however the remaining 4 years provide broad coverage of the ice sheet. Data from 2005 have been inspected, and an intensive search for the bed of Jakobshavns Isbrae completed successfully; however this result assumes the presence of basal water and does not contribute to the quantitative analysis of subglacial water across the ice sheet.

Analytical tools were further developed for the project, based on previously published work. These can be classified as data preparation and visualization, preliminary analysis, thaw discrimination, thaw interpolation, flight and statistical visualization and bed state mapping. All of the tools and processes were developed in the Matlab language, which is accessible to most researchers.

The RES data sets varied considerably in settings and content, and required detailed inspection and preparation. We have modified the file naming conventions for serial analysis, and have made allowance for different attenuation, different sampling pitch, different range window lengths, etc.. In the case of 1999, no flight path information was included with the data. Flight positions were successfully recovered by accurately fitting the depth profiles to the published low-resolution profiles. It was essential for the analysis to use high-resolution radar profiles. Data were collected in short sections of up to 45km along the flight path. Data for 2003 were stored differently; segments have been acquired and then divided in a different way, yielding longer segments of about 100km. The sections have each been processed using common values for attenuation and dielectric absorption rate.

The radar bed returns were then analysed in terms of intensity and of the shape of the signal envelope. A key distinction between this procedure and prior analysis was the use of the integrated signal intensity received from the bed, as opposed to the 'first return' amplitude, which has been relied on in most previous studies. This provides a much more robust measure, related to the material rather than to the shape of the interface, when summed over depth and averaged over short distances. The geometry of the bed affects the shape of the return signal, specifically its sharpness, or 'acuity' and is subsequently used as part of the discrimination of basal thaw.

Visualisation tools were developed so that the intensity and acuity of the bed return can be compared with the depth profile, and with the radio echo profile, both in the published grey-scale form, in a coloured image and also in 'A-scope' plots.

The results of this analysis are a set of files for each flight section containing total intensity and acuity of the reflection as functions of position along the flight path. These files are being made available as secondary outputs of our process.

Once the presence of basal water was determined, a process of along-track interpolation and across-track extrapolation was used to assign the bed state other than directly beneath the flight lines. The measurement itself samples only a width of about 100 metres across the flight paths, whereas the flight paths themselves are of the order of 50km apart. To fully sample the ice sheet bed would be prohibitively expensive.

The bed reflections along each path provide us with a means to estimate the length of continuity of thaw or freeze, and the decision is extrapolated across the path in a circular region, yielding expectation values between the flight lines. Each flight that contains subglacial water yields a number of circular 'areas of inferred liquid or solid state, described by a centre and a diameter obtained from the flight segment for which the inferred state was continuous.

Subsequently, for any point on a grid over the ice sheet, its state is determined by finding the radii of thawed or frozen regions that include that point, and weighting the result toward shorter radii. This method is simple and reasonable, but could be improved by a detailed study of the surrounding topographical features also measured during the survey, and by incorporating knowledge of the direction and rate of ice flow relative to the flight path. However this is beyond the scope of this study.

Preliminary results for 1999 were published in TGARS in September 2011.

A key project workshop was held in Castine, ME, in May 2011, including project participants and specialists in glaciology, numerical modeling, radio-echo sounding and geology. The value of reliable basal water maps was discussed and agreed, and the results of preliminary analysis of 1998/9 data were presented. Maps of results to that date were circulated to the participants. The workshop was reported in Eos, in November 2011.

Data acquired in 1998, 1999, 2002 and 2003 were assembled in 2012. The full dataset has been analysed, and a preliminary set of maps generated to illustrate the sensitivity to varying assumptions. These showed that the method generated internally consistent results, and that these were also consistent with results measured from the GRIP, GISP-2, N-GRIP, NEEM and DYE-3 cores. They suggested that a very simple model of radio absorption could be used to compensate for its effects and isolate the variable reflection coefficient at the bed.

However, a 1966 report of basal temperature at the core site at Camp Century (NW Greenland) was identified and provided by collaborators in Kansas. This was in disagreement with the preliminary radar result at Camp Century. This single report, being one of only six points of ground truth, forced a revision of the simple model used to account for radio absorption. The correlation between received signal intensity and depth has been re-assessed for every flight segment, and it is clear that much-improved compensation can be achieved by means of a new model allowing for locally-variable absorption rates. Using this model, agreement is obtained at Camp Century. This activity and achievement illustrate the benefits of multidisciplinary collaboration.

As a result of this revision we now obtain intensity distributions for steady bed conditions that are significantly narrower than in the preliminary assessment.

The revision has been completed, and new maps have been generated.

Specific Objectives:

To achieve coverage over a large proportion of the Greenland Ice Sheet's area.

The flight paths generate results that sample a width across track of 100-200 metres. However to be affordable, flights were planned for separations on average of ~50km. Thus there is a risk of undersampling the overall area by a factor in excess of 100.

However, we have found that measurements can be seen as continuous over significant distances, frequently on the scale of 10s of kilometres or more, and this means that the undoubted undersampling is not so serious. As a result of an appropriate interpolation procedure, and based on the widely-distributed flight paths, we have been able to use these data to obtain coverage of approximately 80% of the ice sheet.

The interpolation process is statistical and subject to geographical error in detail; however, the density of flights and along-track samples allows us to derive a map that is detailed at the scale of a few times the ice thickness.

To determine the presence or absence of subglacial water at each point of the radio-echo survey

The key calculation for identifying subglacial water is a process in which radar signal values are adjusted according to the depth of the ice (affecting both geometrical losses and dielectric losses), to isolate the effect of varying reflection coefficient at the bed.

The presence of basal water results in an increase of the bed reflectivity of 6-12dB. Given the residual variance of the intensity due to absorption (examples shown in Figure 2), this has allowed a determination of the bed state, which is then available for the purpose of providing boundary conditions for numerical ice sheet models.

A threshold is applied at which the reflectivity is taken to indicate the presence or absence of basal water.

To evaluate the consistency of results and to update the relevant models to

obtain a refined description of the distribution of basal thaw:

We find a high level of agreement between the assessments where more than one inference is available.

A model of dielectric absorption is used to compensate the signal intensity. In preliminary assessments a very simple model was used. This was found adequate in view of 5 of the 6 points of comparison with ground truth. However,the 6th point of ground truth, a core temperature from Camp Century, was incompatible with this model. This resulted in the use of a more fine-grained model in which absorption conditions were evaluated ona scale of 10s of kilometres.

This has resulted in markedly narrower distributions of reflection intensity, and therefore in significantly greater confidence in the results. The major subglacial water features remain similar; however there is a significant reduction in the determination of subglacial water in the far North of Greenland.

To provide maps and statistics that can be used by ice sheet modelers as boundary conditions

The project has generated various data products that can be used by modelers. These include:

- The positions along the flights lines at which we determined that subglacial water is present
- The centres and radii of interpolated areas of subglacial freeze and thaw, and
- 1-km interval grid maps of the bed state beneath the ice sheet.

Significant Results:

Radar

The process used here for radar reflection analysis is found to reduce the inherent variance of radar reflection intensity by a factor of more than 10000, or from 50dB to less than 5dB.

This degree of improvement allows us to detect the increase of 6-12dB that is typically associated with a change from a frozen to a thawed or liquid interface.

Glaciology

During this investigation, we have found that more consistent determinations of freeze or thaw have been made near the central and thicker areas of the ice sheet, while close to the coast and outflow glaciers, and where the bed topography shows steep relief, the evaluation of absorption rates are less satisfactory. No actual limit has been chosen, but in general we have made fewer determinations where the ice thickness is less than about 1000 metres. Below this ice thickness the variance of reflecting power increases, and we would place more reliance on a glaciological interpretation of the bed conditions, based on surface elevation, bed topography and surface motion as it evolves in time.

Figure 1 illustrates results for the case where continuity is interpolated up to distances equal to the ice thickness, (and conditions are assumed to be substantially consistent only over such a distance), and the minimum continuity radius dominates. In Figure 2, overlapping interpolation circles are shown where different flights cross neighboring areas, illustrating the degree of agreement obtained between separate flights and different years' survey work.

In the most restrictive case, in which continuity is interpolated over less than half the local ice thickness, and only the shortest melt radius is taken to dominate the state decision, the most prominent thaw feature is an area about 120km in extent, centred at 42deg W, 74.6deg N. This is an area whose basal return intensity is clearly enhanced over that of surrounding areas. The intensity for a flight crossing this area is illustrated in Figure 3, and the basis for discrimination is demonstrated in the histogram in Figure 4.

It is notable that this area comes very close to the point of apparent onset of the North East Greenland Ice Stream, and we will refer to it below as Lake NEGIS. It may be directly linked to the NEGIS onset. Basal water is detected at many points along the flight paths directed along the apparent route of the Ice Stream, and while it is not possible to see the course of the ice stream bed continuously, we suggest that the rheology and thermodynamics arising from the presence of basal water are directly coupled to the ice stream. An increase or decrease in the rate of production of basal water may be coupled to the state of this Ice Stream.

The NEGIS itself is recognizable as an interrupted sequence of areas of thaw running towards the north-east from its point of departure from Lake NEGIS. It does not appear to be continuous, but it is not known whether this is due to an actual discontinuity or a departure between the flight path and the actual historical flow path or the ice stream, which must be expected to diverge substantially from any planned flight path.

There is a further substantial area containing extended thaw and centred, with a radius of about 200km, but without the continuity or overlaps of Lake NEGIS, around the position 35deg W, 71deg N. This is not clearly associated by the measurements with any specific outflow channel; however it suggests a topographical investigation with respect to connections to Kangerdlugsuac and Daugaard Jensen glaciers.

There is an area containing a significant incidence of smaller melt features between the NEGIS/Lake NEGIS area and the northern outflow glaciers, where once again there are some more extensive features. Basal water north of the NEGIS may be related to the onsets of the Northern outflow glaciers; Humboldt, Petermann and Ryder. This suggests the need for a topographical investigation, in which the bed state is considered in detail in relation to the surface and subglacial topography, that is beyond the scope of this study.

There is a further area containing small but potentially connected melt features to the east of Disko Bay.

A further and more substantial area incorporating basal melt is found beneath the South Dome, around 43W, 65N. It is suitably positioned to feed Helheim Gletscher, and initial inspection suggests this is topographically possible.

These are areas where we are confident that the ice sheet bed is largely thawed.

Although early analysis suggested that up to 17% of the bed of the ice sheet might be in the thawed state, recent work using additional ground truth information, a more flexible model of radio absorption in the ice, and covering a greater fraction of the ice sheet has led to a signifiant reduction, closer to 5%. The principal features remain, but the area of detected thaw is significantly reduced in the North.

The figures are attached as .pdf images, but are available as Matlab files that can be used by Matlab-equipped researchers.

All of these areas of basal melt are consistent with measurements of surface topography and net accumulation on the Greenland Ice Sheet; deep ice and slow accumulation tend to lead to warmer basal ice temperatures. As an example, the distribution illustrated by Zwally and Giovinetto in the 2001 report of the Program for Arctic Regional Climate Assessment, shows a large area in the North and East of Greenland in which net accumulation is low, and the ice is relatively thick, according to Bamber and Layberry.

This is also consistent with recent modelling work carried out by researchers at the University of Kansas under a separate project, showing a continuous area of basal thaw towards the North and East (private communication). In this model there is also more sporadic melting towards the far North and the central West coast, as is found here.

Basal water to the East of Jakobshavns Isbrae, also consistent with this area, is in a position to affect its dynamics, allowing sliding at the bed and acceleration of ice flow.

We have not considered the possible source of subglacial water. It has been suggested that this may be strongly linked to the occurrence of surface melting and flow paths between surface and bed. However, we have taken the view that, since the overlying material is ice, since the thermomechanical regime is very variable over the rough interface, and since reasonable models of geothermal flux directly suggest that basal melting occurs, it is most probable that basal thaw occurs naturally where these forcings combine to raise the temperature sufficiently.

Geothermal

The actual locations of basal melt will provide improved estimates of the distribution of geothermal flux beneath the whole extent of the Ice Sheet.

Inspection of the incidence of basal water, and of the ice profiles generated by radio-echo sounding, yield a surprising insight into Greenland's subglacial geophysics. In particular, in addition to large tracts of ice with a relatively steady vertical profile, there are areas of dramatic basal relief and distorted internal layering. In certain cases the presence of water and its distribution as a function of ice depth suggest high rates of basal heating and even volcanic activity.

Climate Change

The occurrence of water at the bed of an ice sheet is naturally dependent on climate. Indeed, while it is not known what causes the perceived rapid climate change events observed in Arctic ice cores, it is possible that the stability of large ice sheets has a part to play in determining their progress.

However, if climate change is a consequence of human activity, it is improbable that these observations have been affected by such activity, or are evidence for such change.

Nevertheless, knowledge of the presence of subglacial thaw and lubrication, especially where it is concentrated in areas whose ice overburden contains substantial gravitational potential, should be taken into account in assessments of climate stability.

Key outcomes or Other achievements:	We consider that there are two key outcomes that should be taken into account in future ice sheet investigations. The first is that the archives of PARCA and CReSIS RES data represent an enormous resource for study of the ice sheets, far beyond what has yet been derived. New surveys would be attractive; however there is a mass of information waiting to be extracted. Secondly, this study has made clear that in analysing radar target data (as these are), the true effects of interface roughness, materials, radar frequency, signal forms, complex wave values, the Doppler effect etc. need to be taken into account. These are what makes the difference between a quantitative analysis of radar surveys and what otherwise risks being superficial. This study has benefited from a close connection between radar engineers, glaciologists, and physicists immersed in the interaction of electromagnetic waves with natural materials. We believe that this has been a fruitful effort.

* What opportunities for training and professional development has the project provided?

The datasets generated by this project provide substantial opportunities for collaboration between the University of Maine, the University of Kansas, the Free University of Brussels, the State University of New York, and Scripps Institute of Oceanography, each of which participated in the Castine Workshop.

These opportunities arise from the massive volume and quality of data contained in the CReSIS radio-echo archive.

These offer a virtually unlimited resource for investigation and new insight by researchers in radar, in glaciology, in numerical modelling, and in solid Earth geophysics.

A concerted effort would be justified to connect the subglacial water results with topography and analysis of the internal structure of the ice, also revealed by the radio-echo records.

An outstanding opportunity exists to link the results of this work with other research being carried out by researchers at the University of Copenhagen in collaboration with the University of Kansas. Specifically, a link between interpretation of basal radar reflections, as in this study, and an investigation of the topography of internal annual layers in the context of bed topography could add the great advantage of a quantitative measure not only of the presence of water but of its rate of melting or freezing.

* How have the results been disseminated to communities of interest?

Papers:

A single paper has been published in the IEEE Transactions in Geoscience and Remote Sensing in Septembet 2011. This dealt with the initial results for northern Greenland.

A notice of the Castine workshop has been published in Eos in October, 2011

A final comprehensive paper has been prepared; however it requires revision in view of the changes that have been made in the model of the rate of dielectric absorption, based on additional ground truth information and the clear improvement in the echo intensity statistics. This will be submitted to the Journal of Glaciology as soon as possible.

Workshop:

The Castine workshop has been described. It brought together different glaciological researchers and different disciplines, and provides us with a solid context for evaluating these results.

Following the recent completion of the reanalysis of dielectric absorption, data are being prepared for submission to the National Snow and Ice Data Center.

However, since this is a relatively narrow field, it is intended to supply appropriate data files to a list of the key participants.

These will include teams that were represented at the workshop, and many others including Pennsylvania State University, the University of Texas, the University of Copenhagen, the University of Washington, the University of New Hampshire, Ohio State University and the British Antarctic Survey.

Future on-line publication:

The volume of data generated in this study is larger than can be contained and appropriately described in a journal publication. Maps are also necessarily a shorthand for the total picture. Our preference will be to compile an extended volume of files and detail maps that allows the subglacial water we have discovered to be visualised in its topographical context at a scale corresponding to the granularity of the data itself.

We propose that this should be published on line as an extensive but screen-accessible set of images.

Supporting Files

Filename	Description	Uploaded By	Uploaded On
Figure 1. Subglacial water distribution in Greenland.pdf	The distribution of frozen and thawed subglacial interfaces in Greenland	Gordon Oswald	11/25/2013
Figure 2. Subglacial water interpolation and extrapolation.pdf	The result of in-path interpolation and cross-path extrapolation of frozen and thawed subglacial interfaces in Greenland	Gordon Oswald	11/25/2013
Figure 3. Intensity and acuity profiles 051499.pdf	An ice profile from May 14 1999. The upper blue line represents the ice surface, the green line the ice bed with superposed (blue) water determined. The magenta line represents the radar signal intensity (10dB grid lines), and the lower blue line represen	Gordon Oswald	11/25/2013
Figure 4. Intensity distribution 051499.pdf	A histogram of the intensity profile in Figure 3. The lower lobe represents the frozen population, the upper lobe represents the thawed population.	Gordon Oswald	11/25/2013

Products

Books

Book Chapters

Conference Papers and Presentations

Inventions
Nothing to report.

Journals
G. K. A. Oswald and R. leB. Hooke (2011). Theory and Observations of Subglacial Water. *Eos, Transactions American Geophysical Union*. 92 (41), 352. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Gordon K A Oswald, S P Gogineni (2012). Mapping Basal Melt Under the Northern Greenland Ice Sheet. *IEEE Transaction on Remote Sensing*. 50 (2), 585. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Licenses
Nothing to report.

Other Products
Databases.

Flight maps, continuity maps and grid maps of the state of the bed of the Greenland Ice Sheet are available. They have been updated in the light of recent revision of the model for dielectric absorption in the ice, and will be made available through the Nationa Snow and Ice Data Center, through direct dissemination with glaciology, modeling and radio echo sounding teams, and possibly by direct online publishing.

Other Publications

Patents
Nothing to report.

Technologies or Techniques

Dielectric absorption decorrelation. In allowing for the loss of radio energy through dielectric absorption in the ice, it is effective to minimise the correlation between depth and echo intensity over distances of tens of kilometers - long compared with the transitions between thawed and frozen bed, and in most cases not too long compared with the correlation length of overall ice conditions. This is achieved by adjusting the 'effective absorption rate' for each selected record segment, and allows for estimation of the reflection coefficient, provided that a suitable adjustment is also made to account for the integrated effect over the total thickness of ice.

Radio Echo Intensity measurement. Past efforts to measure reflection intensity of radar signals from the bed of ice sheets have focused on the 'first return' - that is, the first signal arrival that is characteristic of the length of the transmitted pulse. However, that approach neglects that interface roughness on the scale of the pulse length can and does result in the spreading od the signal energy over an extended range. The correct calculation integrates the signal energy received over a time that includes all the upper and deeper roughness extents, including those that arrive from oblique facets of the rough interface. This, when averaged over likely fading distances, results in a much steadier and repeatable value for the reflection amplitude.

Thesis/Dissertations

Websites
Nothing to report.

Supporting Files

Filename	Description	Uploaded By	Uploaded On

Subglacial water distribution in Greenland.pdf	The file contains a map illustrating the distribution of subglacial water determined during the project	Gordon Oswald	11/25/2013

Participants/Organizations

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Oswald, Gordon	PD/PI	12

Full details of individuals who have worked on the project:

Gordon K Oswald
Email: gordon.oswald@maine.edu
Most Senior Project Role: PD/PI
Nearest Person Month Worked: 12

Contribution to the Project: Oswald has provided the analytical skills, radar expertise and physics knowledge to support the outcomes of the project.

Funding Support: ARRA 0909431

International Collaboration: No
International Travel: No

What other organizations have been involved as partners?

Name	Type of Partner Organization	Location
Center for Remote Sensing of Ice Sheets	Academic Institution	University of Kansas

Full details of organizations that have been involved as partners:

Center for Remote Sensing of Ice Sheets

Organization Type: Academic Institution
Organization Location: University of Kansas

Partner's Contribution to the Project:
Collaborative Research

More Detail on Partner and Contribution: The CReSIS team have provided extensive radio echo sounding data, access to students' effort in data preparation, and feedback on the consistency of results with ground truth and glaciological interpretation.

What other collaborators or contacts have been involved?

NO

Impacts

What is the impact on the development of the principal discipline(s) of the project?

Radio-echo sounding is a tool for geophysical exploration. It stands between the application of radar technology and the study of the nature and behavior of ice; specifically ice sheets. These are large masses of ice that measure hundreds to thousands of kilometres in extent and kilometres in depth.

Successful application of radio-echo sounding depends on the combination of skills of radar engineers and glaciologists; two very distinct disciplines. The participants tend to focus on, in one case, the design, construction and operation of the hardware and software rather than use of the information generated; in the other, the focus in on derived products of the radar survey rather than the fine detail of how they are generated.

In such studies, there needs to be an interchange of knowledge and practice.

In this case, detailed knowledge on the part of the PI as to how a wide range of radar systems interact with their targets has allowed better exploitation of the information contained in the radar signals. The key measure of the received signal is not the 'first return' as used in many prior studies (because it is easy to measure), but the aggregate return, including oblique reflections from the rough interface, and specifically its average intensity over distances that are related both to the radar wavelength, and to the geometry of the interface and the flight path.

In exchange, evidence that an early, too-simple model of the effect of dielectric absorption of radar signals by the ice was leading to apparently incorrect conclusions in the study has provided the PI with greater understanding of the complexity of the ice as well as the rock interface target. As ice flows under gravity towards the ice edge and into outflow glaciers, its dielectric characteristics (along with its layer structure and temperature distribution) do not vary smoothly at the scale of the radio-echo survey. Measurements show that changes in topography and ice flow have a pronounced effect on the rate of radio absorption with depth and its aggregate over the ice depth. This is so despite the early conclusion that such effects were not seriously degrading the accuracy of results. A single item of ground truth (based on a temperature measurement at the ice sheet bed in 1966) has led to a re-evaluation of the model and a much finer-grained analysis of the effect of radio absorption.

Another benefit is that a historical dataset has been used for a purpose not directly expected when the equipment was built and the survey undertaken. This shows the value of precise recording and effective archiving of data. To obtain these data for the purpose of this study in isolation would have been impractical and unaffordable.

On that subject, as data analysis becomes ever more sophisticated, the radio-echo data archive has been shown to contain a wealth of information that, as our understanding grows, will allow understanding of more obscure but important aspects of the ice; particularly its flow, its bed erosion, its internal 'turbulence' and its response to changing climate.

Secondary benefits, if this experience were incorporated in future radio echo sensor design or campaign design would focus on the stability and standardization of the radar configuration. For example, all adjustments such as attenuator settings, pulse lengths, generated pulse shapes, record file naming, data formats and scales, etc... can be specified and, where adjusted, recorded.

What is the impact on other disciplines?

Our end goal in trying to understand the current state of the world's large ice sheets is to enable the prediction of their future behaviour. For example, foreknowledge of changes in the rate of discharge of fresh water ice into the North Atlantic is an ambition of climate scientists.

The technique available for prediction of ice sheet behavior is numerical modelling, using suitable differential equations and finite element or finite difference methods.

All such techniques rely on (a) starting with suitable boundary conditions (preferably measured data), and (b) having adequate measured data to validate the current output of models and prepare for predictive applications.

The state (temperature and thaw/freeze condition) of the bed of an ice sheet is one of the most important determinants of its behavior. Although it is not possible to make extensive direct measurements of the bed state, the ability of radar signals to penetrate the ice and reflect from the bed provides us with a tool capable of determining the state.

The product of this project is a set of digital maps and files that can be used in either of these modes. Existing models can be run and compared with the findings, and their parameters varied until a match is obtained. Alternatively, and preferably, models capable of importing data that indicate the bed state can now be used in conjunction with these data, and adjusted to match current surface phenomena.

If used correctly in either of these ways, the information developed under this project is capable of enhancing the practice of numerical ice sheet modeling. Without such information there is a risk that such modeling remains an academic activity, but if successfully incorporated in either way, these models can begin to generate predictions relevant to climate change.

The project will also provide data that, in the context of ice sheet modelling, may have significance for geologists studying the distribution of geothermal flux.

What is the impact on the development of human resources?

Students at the University of Kansas have been involved in various aspects of the project. These have primarily been in data preparation and provision, but there have also been activities in data analysis, providing students with a vision of the use to which data generated by the systems they work on will lead to the development of information of wider significance.

What is the impact on physical resources that form infrastructure?

Nothing to report.

What is the impact on institutional resources that form infrastructure?

Nothing to report.

What is the impact on information resources that form infrastructure?

The importance of effective databases, data communications, data standards and archiving has been very clear throughout the project. Some aspects have provided opportunities for improvement; however, this project could have become impractical if good standards of data handling had not been adhered to.

As radar sensors, and particularly multi-beam radars, increase in the rate and scale of the data, results of analysis, and imagery they generate, data archiving and data access will become even more critical. This project has had available the necessary data reources, and will reinforce both institutions' consciousness of the need to handle 'big data' appropriately.

What is the impact on technology transfer?

These results are potentially valuable in the broader study of climate, its change and its stability. The major ice sheets are key contributors to change in sea level and ocean acidity and temperature, and these are themselves key indicators of the state of the Earth's climate.

What is the impact on society beyond science and technology?

Although these results increase knowledge of a significant component of the climate system, they are unlikely to have a distinct, observable impact within timescales that directly affect broader society.

Changes/Problems

Changes in approach and reason for change

There has been a minor change in the way in which the radar data have been analysed. This resulted from the introduction of an item of ground truth that enforced a reassessment of certain details of the method. This necessitated a rapid action in re-processing data; however there has been no impact on time or cost.

Actual or Anticipated problems or delays and actions or plans to resolve them

Nothing to report.

Changes that have a significant impact on expenditures

Nothing to report.

Significant changes in use or care of human subjects

Nothing to report.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use or care of biohazards

Nothing to report.

Special Requirements

Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.

Nothing to report.