This synopsis describes the proposals selected in response to the NASA Research Announcement *IceBridge Research* which is subelement A.13 of NASA ROSES 2014. These studies are critical to understanding the changes in thickness occurring in the world’s major ice sheets, especially for characterizing the thinning of the Arctic sea ice cover, and for understanding the current and future contributions to sea level rise from the continental ice sheets in Greenland and Antarctica and the glaciers of Alaska. The IceBridge Mission is designed to fill the gap in altimetry observations left by the demise of ICESat in the latter part of 2009 until the launch of ICESat-2 in 2017. Observations are made using various aircraft in the Arctic and Antarctic. While the program does not have nearly the coverage of satellite, it does allow for monitoring of key areas. Lidar measurements of ice height are the main focus, but the program also collects ancillary data critical to understanding changes occurring in the ice with radar, gravimeters, and magnetometers.

This solicitation called for proposals to use the data collected under the IceBridge mission to understand the mechanisms of change in the polar regions and their implications for global climate, sea level, and the polar environment. Proposed studies must be based on the IceBridge data archived at http://nsidc.org/data/icebridge/, and link to appropriate space-based and other remote sensing data, especially altimetry from NASA’s now completed ICESat mission and the European Space Agency’s CryoSat 2.

The program’s specific goals as listed in the announcement are as follows:

1. Improve understanding of the mechanisms controlling mass balance and dynamics of the ice sheets of Greenland and Antarctica; including studies aimed at improving fundamental understanding of ice flow; ice shelves; grounding lines; bed; melt water formation and role; and connections to the ocean, sea ice cover, and atmosphere;

2. Evaluate and improve predictive models of the contribution of land-based ice to sea level change, especially in the coming century;

3. Improve understanding of the mechanisms controlling sea ice cover, including quantification of the connections between sea ice and the ocean and atmosphere;

4. Evaluate and improve predictive models of changes in sea ice cover, especially in the coming century, and the implications of these changes to the ocean, atmosphere, surrounding land areas, and global system;

5. Improve the utility of IceBridge data to estimate snow accumulation on sea- and land-based ice; and

6. Improve understanding of the mechanisms controlling mass balance and dynamics of Alaskan glaciers and small Arctic ice caps.

Selected projects included altimetry measurements over the Arctic sea ice, Greenland, and Antarctica; radar mapping; and interpretation of video images. The results are critical to models of future sea level rise and understanding changes in Arctic sea ice cover. All
of these projects will occur over the next 3 years. The results will be published in scientific journals and presented at international meetings, and the data will be made available as soon as possible via the NASA DAAC at the National Snow and Ice Data Center.

Out of 23 submitted proposals, 9 will be recommended for awards. The total funding is approximately $3.4 million, spread evenly over three years. The Principal Investigator, institution, and investigation title are listed below.

Joseph MacGregor/University of Texas, Austin  
Accumulation and Flow of the Greenland Ice Sheet During the Late Holocene

The Greenland Ice Sheet (GrIS) is out of balance with the present climate. It is losing mass and is very likely to continue doing so for the foreseeable future. This mass loss is due to both decreasing surface mass balance and increasing flow of marginal outlet glaciers, which are related to changing atmospheric and oceanic forcings, respectively. Disentangling the competing effects of these mass-loss mechanisms and improving understanding of their root causes are areas of active glaciological research.

The internal radiostratigraphy of an ice sheet records and integrates its dynamic response to atmospheric, oceanic and subglacial forcings at annual to millennial time scales, depending on the ages of the observed reflectors. Operation IceBridge (OIB) surveys of the GrIS from 2011 onwards include accumulation-radar observations of the upper few hundred meters of the ice sheet at fine vertical resolution (<50 cm in ice). This radar system has detected dozens of distinct internal reflectors that originate mostly from the last thousand years. These shallow reflectors are not well resolved using deep radar sounders designed to measure ice thickness, and their glaciological significance has received comparatively little attention.

We propose to comprehensively map the shallow radiostratigraphy of the GrIS from OIB accumulation-radar data and to interpret this radiostratigraphy using multiple ice-flow models. We will test two driving hypotheses: 1. The patterns of accumulation and ice flow of the GrIS during the late Holocene (the last 500 years) differ significantly from those inferred from models and observations of the past few decades. 2. Ocean-driven melting of ice fronts and ice shelves is the dominant forcing of GrIS dynamics during the late Holocene. Testing these hypotheses will provide centennial-scale context for recent changes in ice flow that is not easily recoverable from other types of observations. We will compare our results with those of the SeaRISE project, which evaluated the sensitivity of large-scale ice-sheet models to prescribed forcings, to quantitatively attribute the accumulation-radar observed patterns to such forcings using optimal detection. We will also force new runs of Ice Sheet System Model (ISSM) with AR observations to gain confidence in this attribution. This analysis will also identify the regions of the GrIS beyond outlet glaciers that are most sensitive to centennial-scale forcings.

This proposal is focused on the state of the GrIS over the past several centuries, a period comparable in length to that for which predictions of the sea-level rise contribution from
the GrIS are urgently needed. This proposal leverages the tools and expertise developed during a previous IceBridge Research award to comprehensively map the deep radiostratigraphy of the GrIS from NASA-funded archival and OIB data. That award enabled the advances in tracing, dating and modeling of radar reflectors that render feasible this proposal to map and interpret all existing and future OIB GrIS accumulation-radar data. An identified Ph.D.-level graduate student will be trained in geophysics and glaciology. Mapped accumulation-radar reflectors will be developed into L2, L3 and L4 products and suitably archived. This proposal does not require additional fieldwork.

Waleed Abdalati/University of Colorado, Boulder

Quantifying Firn Compaction and its Implications for Altimetry-Based Mass Balance Estimates of the Greenland Ice Sheet

Firn compaction models have uncertainties too large to accurately convert volume change into mass change while satisfying the accuracy requirements of current and future altimetry missions. The baseline science requirements of ICESat-2 propose to measure elevation change within $\pm 0.4$ cm/yr across the world's ice sheets. The most widely cited compaction model used during ICESat-1 estimates that the rate of firn compaction changed by as much as $\pm 2.5$-13.5 cm/yr across the majority of Greenland’s accumulation zone in the six years spanning 2002-07. A bias of as little as $\pm 10\%$ in these modeled estimates adds an uncertainty more than double ICESat-2's first-order measurements. Given the rate at which melt and percolation are increasing in Greenland, quantifying firn compaction is an unavoidable challenge for altimetry missions. Field measurements coincident with IceBridge and ICESat-2 are clearly needed to more accurately constrain firn compaction rates across Greenland. The University of Colorado will team with the University of Washington, who under current funding has developed a Community Firn Model (CFM) that codifies the physics from known published firn compaction models into a single software system. Individual components of each model may be mixed to simulate each physical stage of densification, providing the opportunity to cross-validate existing firn compaction models against each other and against measured strain rates of Greenland’s firn. Although the current CFM is built to simulate dry-snow compaction, we will expand the model to include percolation, grain weakening, and latent heat release that accompany phase changes in percolated firn. The CFM code base will be publicly available, allowing the scientific community to download, run and add to the models to best fit measurements from theoretical or in situ data sets. This community model approach allows data users to leverage the substantial historical work already undertaken to model physical firn processes, without being tied solely to the assumptions and biases of any single published model. To accurately validate the CFM models across Greenland, CU will maintain and expand its current array of firn compaction stations in Greenland. The Firn Compaction Validation Network (FirnCVN) is an array of stations across Greenland’s accumulation zone that transmit real-time high-resolution measurements of firn compaction processes. Prototype CVN stations developed at CU currently transmit from three separate locations in southwest Greenland in three separate melt regimes of Greenland's percolation zone. Vertical strain is measured with a demonstrated accuracy of $\pm 0.2$ cm/yr at depths beneath 1 meter and $\pm 0.8$ cm/yr from the surface. These measurement errors are an order of magnitude
lower than the stated uncertainties of firn compaction models. The instruments and towers, which also record firn temperature, air temperature and new accumulation, are designed to maintain stability and sustain accurate daily measurements even in extreme summer melt events. To quantify the substantial indirect effects that increased melt and refreezing have across Greenland's percolation zones—measured at up to 25% or more of current uncertainties—CU will use IceBridge accumulation and snow radars to map massive subsurface ice lenses that may block partially stall compaction, as well as block percolation and cause additional runoff in regions that are technically above the equilibrium line and runoff is currently assumed not to occur. The CFM and FirnCVN project directly addresses Operation IceBridge's most critical goals of accurately measuring mass change on the world's ice sheets with lidar altimetry, and will be ICESat-2's best hope to achieve its overarching goal of generating the world’s most accurate and spatially-resolved estimates of mass change on the Greenland ice sheet.

Beata Csatho/State University of New York, Buffalo
Understanding Dynamic Outlet Glacier Behavior in Greenland: Synthesizing Altimetry Record and Numerical Modeling

Although satellite and airborne missions have been delivering observations at an ever-increasing rate during the last few decades, there is a lack of suitable methods capable to combine these observations and incorporate into ice sheet models. Thus, modeling studies investigating the dynamic responses of Greenland outlet glaciers to climate forcings were limited to studying four rapidly changing glaciers (Jakobshavn Isbrae, Helheim, Petermann, and Kangerlussuaq glaciers) with exceptionally detailed elevation and velocity change records. To estimate the future contribution of the entire Greenland Ice Sheet to sea level rise, the predicted responses of these four glaciers were scaled to the entire ice sheet but this extrapolation has limitations given the observed variability among Greenland’s outlet glaciers. Our reconstruction of elevation changes from laser altimetry spanning the period 1993 to 2012 shows that outlet glacier behavior exhibits large spatial and temporal variability, and response of individual outlet glaciers to external forcings is highly modulated by local conditions such that neighboring glaciers can exhibit very different patterns of elevation change. The motivation for this proposal is to use the improved SERAC method that allows fusing altimetry data with stereoscopic DEMs to develop accurate time-series of reconstructed elevation changes over the entire fast flowing region of the ice sheet, even in areas where no stable control surfaces exist. On the one hand, DEMs derived from stereoscopic satellite imagery have elevation errors that are at least one order of magnitude larger than laser altimetry. On the other hand, they cover an area almost continuously while laser altimetry observations are usually confined to a narrow swath-width with large gaps in between different swaths. We have demonstrated the unique feature of SERAC to fuse these disparate data sets in a recent publication and we propose to use this novel methodology in this research. We will address two major questions regarding dynamic evolution of the GrIS over the next 100-200 years: (1) how representative are the four glaciers that have been studied in detail for other outlet glaciers? (2) what physical processes are the most likely cause for observed glacier changes in Greenland? We propose a systematic and quantitative investigation of glacier changes from 1993 to the present. Rather than investigating each of the 122 outlet
glaciers for which detailed elevation change records are available, we will select glaciers exhibiting distinctly different behaviors based on a classification that we developed using the laser altimetry record. We will reconstruct a detailed record of elevation, flow velocity and calving front history for each selected glacier and investigate commonalities of glacier geometry and temporal evolution for each group of our classification. For a quantitative analysis we will use a suite of modeling approaches, ranging from semi-analytical perturbation analysis to flow band modeling.

Ted Maksym/Woods Hole Oceanographic Institution

Reconciling Antarctic Sea Ice Thickness and Snow Depth Using IceBridge and ICESat Data

In contrast to the dramatic declines in Arctic sea ice extent, Antarctic sea ice has seen a modest increase in extent over the past 30 years, in stark contrast to model predictions. This overall trend, however, obscures strong regional trends that rival those in the Arctic. The causes and consequences of these changes remain poorly understood. Moreover, while declines in Arctic sea ice age and thickness have been observed over the past decade, we have no comparable information for the Antarctic. Recent model results suggest that changes in ice thickness (due to enhanced deformation) have been greater than changes in extent. The paucity of in situ data has hampered determination of even the climatological mean distribution of ice thickness. Satellite estimates of ice thickness are at present uncertain, owing to the deep snow cover over much of the ice-covered area, requiring an independent estimation of snow depth. The prevailing view of the Antarctic sea ice cover is that it is thin, based on available in situ data. Recent in situ, ICESat and IceBridge freeboard and snow depth data indicate that sea ice thickness in the difficult to access interior regions of the ice pack are significantly thicker, with often deeper snow cover, indicating a significant bias in existing in situ assessments. This thick ice is formed through heavy deformation and deep snow accumulation. While thickness variability in the thinner, outer pack is minimal, like the observed changes in thick multiyear ice in the Arctic, ice thickness changes will be most apparent in the distribution of this thick ice.

We propose to determine a robust assessment of Antarctic snow and ice thickness distribution, focussing on these areas of thicker ice using a novel combination of coincident IceBridge (OIB) snow radar, lidar, and digital imagery, and ICESat laser altimetry. We will examine the following KEY HYPOTHESES: (1) Much of the Antarctic sea ice cover is much thicker than is suggested by in situ observations, particularly by spring, (2) This thicker ice is heavily deformed and/or has deep, complex snow cover. Freeboards and surface roughness can provide reasonable ice thickness estimates and snow depths from laser altimetry alone, and (3) Interannual variability in extent and thickness of this ice is detectable and can be related to interannual variations in seasonal atmospheric forcing. This work will (1) develop an improved snow depth with robust error bounds record over Antarctic sea ice from OIB data, (2) develop the first estimate of ice thickness from OIB data, (3) calculate the extent and thickness of thick Antarctic sea ice for the entire ICESat period of 2003-2009, using an improved algorithm guided by OIB data that avoids the need for assumptions about snow depth, and (4) using reanalysis winds, precipitation and satellite ice drift, examine the
connections between thick ice distribution and atmospheric forcing driving its seasonal evolution in key regions of rapid change around coastal Antarctica.

This analysis will provide an improved record of sea ice thickness and its variability, with robust error bounds, and for the first time, an observational evaluation of the drivers of ice thickness variability in the Antarctic. Through comparison of OIB and ICESat data, we will determine potential spatial and sampling biases in the existing in situ record of Antarctic sea ice thickness. This addresses several key objectives of the NRA, including improving the utility of IceBridge data to estimate snow accumulation on sea ice, and improving the understanding of the mechanisms controlling the sea ice cover including quantification of the connections between sea ice and the ocean and atmosphere. This work will lead to improved algorithms for ICESat-2 and a new sea ice variable with which to evaluate Antarctic ice climate interactions, with the eventual aim to further elucidate the causes and consequences of recent, surprising trends in Antarctic sea ice.

Isabella Velicogna/University of California, Irvine
Reducing Uncertainties in Greenland Surface Mass Balance Using IceBridge Altimetry, GRACE Data and Regional Atmospheric Climate Model Outputs.

The Greenland Ice Sheet is undergoing rapid changes at present, with surface melt increasing and ice discharge increasing.

The ice sheet is losing mass to the ocean at a rapid rate and the mass loss is increasing with time. Different techniques have been used to document these changes including radar and laser altimetry surveys from space and airborne platforms, time-variable gravity data from the GRACE satellite mission, and mass budget estimates combining ice discharge along the periphery from airborne-derived ice thickness and satellite-derived ice motion data, with surface mass balance reconstructions from regional atmospheric climate models constrained by global re-analysis data. Considerable progress has been made to reduce the uncertainties of each technique and consolidate the agreement between them via for instance the International IMBIE experiment, so that it is now possible to employ these different tools together to resolve residual uncertainties and address the key physical processes behind the mass balance evolution. In this proposal, we will address one of the largest remaining uncertainties in ice sheet mass balance which is runoff output from the ice sheet due to surface melt; precipitation, the other major component of surface mass balance, is in comparison better constrained by observations and field data, with errors estimated in the range of 5-7% for the best reconstructions. Runoff model outputs are inherently difficult to evaluate due to a lack of in-situ monitoring networks, and the presence of large interannual variations, so that errors in runoff are currently guess-estimated at about 20% by default. Here, we propose to document the uncertainty in runoff and how it varies spatially in Greenland by comparing the runoff products with two other major sets of observations. First, we will compare the surface mass balance outputs with GRACE regional time series calculated using the least-squares mascon approach- corrected for ice discharge - with a particular emphasis on two regions where ice dynamics is less significant than in the rest of Greenland: southwest and north Greenland. The comparison over multiple years will
establish limits in the precision of the surface mass balance outputs versus GRACE and GRACE errors. Second, at the smaller scale, we will use NASA IceBridge surface elevation change products, \( \frac{dh}{dt} \), in the ablation zone of Greenland and compare them with regional climate model outputs to evaluate how well seasonal runoff is modeled over multiple years and how well the results agree with uncertainties highlighted at the regional scale with GRACE. The results will help constrain current uncertainties in surface mass balance and especially runoff. The results will also provide important feedback to climate modelers to help them reduce these errors based on uncertainties in surface melt water retention, surface albedo and other major components of the surface energy budget. This research will support the science goals of NASA IceBridge mission to observe the evolution of the ice sheet mass balance in Greenland and examine and understand the major physical processes behind it. It will finally serve NASA goals in Earth Science to study the evolution of ice sheets and their contribution to sea level.

Britney Schmidt/Georgia Tech Research Corporation

From Order to Disorder: An IceBridge Investigation into the Collapse Phase of Damaged Glaciers

Despite the fact that the waning polar ice sheets are a significant consideration for future sea level rise and the changing climate, factors that control the retreat and advance of the world’s major ice sheets---and more specifically, iceberg calving processes---remain relatively poorly understood. Fracture initiation and propagation is clearly linked to flow dynamics, and occur across a range of environmental and structural conditions in the ice. Major calving events from both glaciers and ice shelves occur following the initiation and propagation of these large fractures in the ice as it flows toward the ocean. But, while previous studies have shed light on these processes that lead up to ice front calving and collapse, the actual transition mechanism from intact, crevassed glacier--possessing a large amount of gravitational potential and fracture energy--to what is essentially a rubble pile in the proglacial fjords below remains something of a mystery. This makes it difficult to validate empirical- or theoretically-derived calving models, and limits our ability to estimate potential changes in calving rates and their effect on mass balance, glacier dynamics and sea level. With this in mind, we ask: can we characterize or parameterize the transition from order to disorder? From fractured to fragmented? The overarching aim of this proposed study seeks to combine fractal analysis and a novel fragmentation physics model to characterize the transition from fractured to fragmented proglacial mélange for Greenland’s ocean-terminating glaciers to develop an understanding of the precursory observables for such a transition and a parameterization of critical fracture density in glaciers prior to collapse. The nature of this study, which is based upon tracing crevasse patterns and measurement of rubble size distributions, requires high-resolution image and altimetry measurements with which to characterize both glacier and mélange topography. These requirements are directly met by data acquired by the IceBridge program, in addition to ICESat altimetry measurements and available supplemental imagery. We will accomplish our goal of finding a characteristic fracture density by: (i) developing a time series of digitally-traced crevasse patterns across the surface of the four glaciers using IceBridge imagery for the Rink, Kangerdlussuaq, Helheim, and Jakobshavn glaciers; (ii) creating a database of mélange fragment size
distribution measurements over time in front of the same glaciers; (iii) determining the change in glacier and mélange topography over time using IceBridge and ICESat altimetry; (iv) using fractal analysis techniques on crevasse pattern maps to back out fracture energy within the glacier; (v) determine the back stress provided by a given arrangement of mélange; (vi) develop a fragmentation model that will take as input calculated energy and measured fragment distributions to determine energy of collapse and a fracture density criterion for failure. We suggest that our application of fragmentation theory to the problem of glacier collapse using IceBridge data will result in the ability to characterize the fundamental transition from fractured to collapse, a phenomenon important to our understanding of both glacial retreat and ice shelf collapse and something that is, as yet, a mystery.

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**Eric Larour/Jet Propulsion Laboratory**

**Assimilation of Altimetry Data in North-East Greenland Using ISSM.**

The contribution of polar ice sheets to sea level rise is controlled by the mass transport of ice through the margins of both Greenland and Antarctica. This transport is in turn controlled by the velocity, density and thickness of ice fluxing through these margins, be they grounded or marine. However, such fluxes, even though they are required only at the coastline for sea level rise assessment, cannot be predicted short of knowing the behavior of the entire ice sheet, both in terms of ice dynamics and mass transport. Indeed, the highly non-local nature of ice flow has been recognized early on, which spurred intense efforts to monitor the evolution of both ice velocity (ERS-1,2, RADARSAT-1,2, Sentinel to be followed by NiSAR) and surface heights (ATM in the early 1990s, ICESat-1 starting 2003, CryoSat 2 starting 2010, Operation IceBridge starting 2009 and to be followed by ICESat-2 starting 2018). NASA's efforts have been focused heavily on altimetry in the past two decades, especially starting 2003 with ICESat-1, and now with Operation IceBridge in concert with CryoSat-2. This has led to a wealth of altimetry data for which the main scientific goal has been to understand the mass balance of ice sheets. However, the advent of higher-order ice-flow models starting only in the late 2000's has severely lagged this massive influx of data, and the resulting improvements in predictions of mass balance have not been significant. Several reasons explain this current state of research: 1) models have recently been focused mainly on understanding the boundary conditions at the ice/bed interface, which control ice flow dynamics heavily. This has resulted in major improvements in the mapping of the bedrock (through IceBridge) and in inversions of the state of the friction using inverse control methods and SAR derived surface velocities. 2) models have lacked capabilities in terms of temporal inversions of the coupled "dynamics/mass transport" of ice sheets, which is required to assimilate surface altimetry into reconstructions of ice flow. 3) surface heights evolve according to a complex interplay between mass transport of the underlying ice and firn densification. This complex interplay is not yet fully resolved, and even less so taken into account in ice-flow models. Here, given recent progress in mapping the bedrock of Greenland, and understanding the state of friction at the ice/bed interface, we propose to address the situation raised by reasons 1) and 2). We propose to use the newly developed algorithmic differentiation of ISSM and a coupled ice-flow/firn-densification model to reconstruct the state of the ice between 2003 and present-time, using all the available surface
altimetry data from ICESat-1, IceBridge and CryoSat-2, on the North-East Greenland quadrant. The goals will be to reconstruct surface mass balance, basal friction and ice hardness for the entire altimetry record, understand the contribution of each of these forcing to the observed variability in surface heights and to assess the impact of firm densification in the assimilation of such surface altimetry. The expected significance of this research will be to improve our understanding of which processes can be captured by surface altimetry, improve model spin-ups of ice flow models and their predictive capability, a complete reconstruction of model forcing (or state of the ice) between 2003 and present-time, and a better understanding of the complex interplay between firm densification and ice-flow dynamics.

Ala Khazendar/Jet Propulsion Laboratory
The Dynamic Evolutions of Larsen B Tributary Glaciers and Remnant Ice Shelf Investigated with IceBridge Observations and Numerical Modeling

The retreats and disintegrations of ice shelves in the northern Antarctic Peninsula over the past two decades were associated with dissimilar changes in tributary glacier thicknesses and flow speeds. We propose here to examine this large-scale natural experiment to gain insights into outlet glacier dynamic reactions to the weakening or removal of ice-shelf buttressing. We plan to seek these insights by a combination of IceBridge, ICESat-1 and InSAR observations and high-resolution numerical modeling and data assimilation. We therefore intend to analyze IceBridge and pre-IceBridge ATM laser altimetry (2002-present) and depth-sounding radar measurements to find ice elevation changes and bed topography. Across-flow glacier surface profiles will be traced with GLAS/ICESat-1 data. We will find flow velocity changes (1997-present) from InSAR measurements made by RADARSAT-1 and -2, ALOS PALSAR and TanDEM-X. Concurrently, we will apply the numerical modeling with the Ice Sheet System Model (ISSM) to simulate tributary glacier perturbation by loss of buttressing, either completely as following the disintegration of northern and central Larsen B Ice Shelf, or partially as its remnant southern section accelerates and weakens by fracture and front retreat. Comparing model outputs with observed ice surface elevation and flow speed changes should help reveal the impact of different parameters on glacier dynamics and identify processes not represented in the model. We then can apply these insights to simulate possible future scenarios of glacier evolution. Our study region includes the remnant Larsen B Ice Shelf and its tributaries, where ice-shelf buttressing still exists but is probably weakening with time; the tributary glaciers of the central and northern Larsen B embayment, where the loss of ice-shelf buttressing occurred in 2002; and Drygalski Glacier in the Larsen A embayment, where ice-shelf buttressing loss occurred in 1995 hence presenting an experiment with an earlier perturbation date. The main anticipated outcome is a better understanding of processes that contribute to modifying ice-shelf and tributary glacier flow and mass balance. Hence, this study ultimately supports the efforts seeking more reliable predictions of the role of Antarctica in global sea level rise. This work is proposed to be conducted as Fundamental Research.

Mark Fahnestock/University of Alaska, Fairbanks
Dh/Dt Due to Flow: Mapping the Impact of Ice Flow Changes on Surface Elevation Using Detailed Surface Height Histories from Multiple Laser Altimeters Through A Simple Universally-Applicable Differencing Engine Approach

Goal:
Improve our ability to separate ice dynamics from surface mass balance as drivers of surface elevation change around the edges of the Greenland ice sheet by:
1) Deriving surface elevation histories that are as detailed (in both space and time) as possible from laser records (using a differencing tool we have developed).
2) Combining these records with ice flow histories from InSAR and feature tracking to delineate areas where increased strain rates will have contributed to surface elevation change - including deriving limits on detectability of flow changes.
3) Mapping the spatial patterns of surface elevation change that cannot be explained by ice flow changes, to develop an elevation-measurement-based record of the spatial pattern of surface mass balance driven changes.

Products:
1) Detailed surface elevation histories binned as finely as possible (<1 km where data allow - along track for ICESat; along flight for ATM; along and across swath for LVIS; gridded locally for the combination of all three. This will be done in a manner that can be easily updated after each flight season and as new elevation models are derived - the intent is to put this system in the hands of the IceBridge project office, allowing them to place change measured with each new flight period in the context of all previous change as a data product for the community.
2) Maps of changing strain rates and their along-flow integrated impact, which can be compared with dh/dt histories from 1, with consideration for the impacts of along-flow variations in ice thickness.
3) Maps of surface lowering due to changing surface mass balance (verified from areas where ice flow changes have not had an impact).

The combination of these products, derived directly from measurements of change, should enhance the research community’s ability to understand the spatial patterns of mass balance change - e.g. derived patterns and magnitudes of the changes should be useful constraints on surface mass losses predicted with regional climate models; improved ties between ice flow changes and measured surface lowering should help close mass budgets on ice lost to flow acceleration, constrained by mass lost to enhanced melt in nearby but slowly changing ice.

This work directly addresses NASA’s Cryospheric Program goals of understanding the impacts of changing climate on the Earth’s ice cover, and the goals of this IceBridge Science solicitation, as it fuses all of the available NASA laser surface elevation measurement records into a more coherent look at changes in the Greenland Ice Sheet, and in the process sets up an analysis system that is constructed to rapidly take advantage of new laser data and new or improved surface elevation models - allowing a continuously updated record to be produced even after this research effort ends.