NASA Science Mission Directorate
Research Opportunities in Space and Earth Sciences
NNH16ZDA001N-ICEBST
IceBridge Science Team

This synopsis describes the proposals selected in response to the NASA Research Announcement *IceBridge Science Team* which is sub-element A.49 of NASA ROSES 2016.

IceBridge (http://www.nasa.gov/mission_pages/icebridge/index.html) is a NASA airborne mission to bridge the gap between NASA's ICESat (2003-2009) and ICESat-2 satellite missions that use laser altimetry to characterize the Earth's polar ice sheets. Data collected by IceBridge has improved our knowledge of the contribution of the world's major land-based ice sheets and glaciers in Greenland, Antarctica, and Alaska to sea level rise, while making fundamental contributions to understanding changes occurring in the extent and thickness of the polar sea ice.

The IceBridge mission began in 2009 and will continue for at least one year past the launch of ICESat-2, currently planned for launch in late-2018. In addition to laser altimetery, IceBridge employs radar and other methods to monitor and characterize the polar ice. All data collected by IceBridge are available at https://nsidc.org/data/icebridge.

This solicitation supports participation in the IceBridge Science Team (IST) during the third and final phase of IceBridge data collection during Fiscal Year (FY) 2017–2019 to provide advice to the IceBridge project office on flight planning. For this final phase, the mission focuses on ensuring that its observations are set to build a bridge of altimetry measurements from the ICESat to ICESat-2 satellites to develop a multidecadal time series.

The IceBridge mission will consist of two major airborne data collection campaigns per year; with one in the Antarctic—including the Antarctic ice sheet and Southern Ocean sea ice—and another in the Arctic—including the Greenland ice sheet, Arctic sea ice, and Alaskan mountain glaciers—in their respective spring seasons. One smaller campaign may also occur over the Arctic sea ice and parts of Greenland in the northern hemisphere fall.

The specific measurements and science goals are summarized as follows:

- Make airborne altimetry measurements over the ice sheets and sea ice to extend the record of observations begun by ICESat.
- Link the measurements made by ICESat, ICESat-2, and where possible, CryoSat-2, to allow accurate comparison and production of a long-term, ice altimetry record.
- Use airborne altimetry to monitor key, rapidly changing areas of ice in the Arctic and Antarctic to maintain a long term observation record, improve understanding of glacial dynamics, and improve predictive models of sea level rise and sea ice cover.
- In conjunction with altimetry measurements, collect other remotely sensed data to improve predictive models of sea level rise and changes in sea ice cover.

To support these goals, proposals were required to address the role of the PI as a member of the IST, and to outline a small research program based on IceBridge altimetry measurements that supports mission planning and bridging ICESat and ICESat-2.

Selected proposals emphasized the need to create multi-sensor, multi-decadal time series of ice sheet elevation change, and to develop accurate methods for estimating sea ice thickness from freeboard measurements. Out of 16 submitted proposals, 6 will be recommended for awards. The total funding for the program is approximately $1 million per year for three years. The Principal Investigator, institution, and investigation title are listed below.

Beata Csatho/University at Buffalo
Investigating Greenland and Antarctic Ice Dynamics Using Long-Term Elevation Change Record: A Proposal for IceBridge Science Team Membership
16-ICEBST16-0011

Ice-sheet elevation changes are sensitive indicators of ice-sheet mass balance changes and provide invaluable insight into surface processes and changing ice dynamics. NASA's IceBridge mission is dedicated to collecting airborne laser altimetry data to bridge the ICESat and ICESat-2 satellite laser altimetry missions. Other critical observations characterizing ice sheet surface processes, ice thickness, internal structure as well as subglacial geology are also acquired by the mission.

Quantifying ice sheet thickness changes, imperative for improving ice sheet models and sea level predictions, remain a challenging problem. To address this issue we have developed the Surface Elevation Reconstruction And Change detection (SERAC) approach. SERAC was initially limited to ICESat laser altimetry data. Later on, we extended SERAC to include airborne laser altimetry observations and DEMs derived from repeat stereoscopic imagery. The SERAC method is rapidly gaining popularity for glaciological change detection. It is also the primary motivator for similar change detection approaches for the upcoming ICESat-2 mission. We have extensively used SERAC to study changes of the Greenland and Antarctic ice sheet at scales from individual outlet glaciers to the entire ice sheet.
I propose to use Surface Elevation Reconstruction And Change (SERAC) detection approach to develop multi-decadal time series of elevation and mass balance changes of the Greenland and Antarctic ice sheets (GrIS and AIS) by combining historical laser altimetry data sets with IceBridge laser altimetry observations and CryoSat-2 radar altimetry data. I also propose to extend the capabilities of SERAC to incorporate ICESat-2 photon counting laser altimetry data and to automatically detect surface patches for time series extraction.
The proposed research will generate annually updated long-term ice sheet elevation, thickness and mass balance time series from laser and radar altimetry data to bridge NASA’s ICESat and ICESat-2 missions. It will assist flight planning during the last and final stage of the IceBridge mission and provide accurate reconstruction of ice sheet elevation, thickness and mass balance changes at scales from individual outlet glaciers to entire ice sheets. By incorporating ICESat-2 observations into the elevation change time series it will enable the estimation of ice sheet elevation changes at an early stage of the ICESat-2 mission and will assist the calibration and validation of ICESat-2 measurements. Finally, by revealing the complexity of ice sheet changes,

the results will serve as a guide for future modeling efforts and provide a critically needed comprehensive elevation data set for improving ice sheet balance projections through data assimilation.

Helen Amanda Fricker/Scripps Institution of Oceanography
Quantifying the Error Distribution of Operation IceBridge Swath Altimetry to Generate Robust, Long-Duration Time Series of Height-Changes over Dynamic Features in Antarctica
16-ICEBST16-0006

The primary goal of Operation IceBridge (OIB) is to extend the altimetry record of ICESat (2003-2009) until the launch of ICESat-2 (2017), with the ultimate goal of generating multi-decadal, continuous height-change time series over key regions of the ice sheets and sea ice. OIB's ATM swath laser altimeter will be a dataset key for ground truthing initial ICESat-2 observations and cross-calibrating ICESat, ICESat-2, and other satellite altimetry time series. Initial work from our group analyzing ATM swath altimetry in East Antarctica revealed a bias between forward- and reverse- looking elevation retrievals over a fast-flowing outlet glacier. Instrumental errors of this magnitude will impact the ability of OIB to meet its primary objective; therefore, we propose to identify and quantify any limitations of ATM swath altimetry across Antarctica, as well as design an OIB survey of the salar de Uyuni salt flatin Bolivia in order to provide a common reference for intermission comparisons. After developing and executing methods for quantifying errors in ATM data across Antarctica, we will use ATM swath observations to cross-calibrate multiple satellite altimetry missions (i.e., ICESat, ICESat-2, and, where appropriate, CryoSat-2) and generate internally consistent, long-duration time series over dynamic features such as ice-shelf channels, grounding zones, and subglacial lakes. The main benefit of focusing on dynamic features is that we can measure a range of height-change signals over a short time period in order to quickly evaluate ICESat-2 on-orbit capabilities; this will provide rapid validation of ICESat-2 observations and demonstrate the ability to link satellite altimetry missions through robust methods.

Ronald Kwok/Jet Propulsion Laboratory
IceBridge Snow Depth Retrievals and Sea Ice Thickness: Data Quality and Preparation for ICESat-2
16-ICEBST16-0016

This is a proposal to participate as a member of the IceBridge Science Team and to address the use of IceBridge data in preparation for ICESat-2 and for understanding changes in the Arctic and Antarctic sea ice covers. The IceBridge mission (OIB) began in 2009 and will continue for at least one year past the launch of ICESat-2, currently planned for launch in late-2017. By the completion of OIB, the airborne operations will have acquired over a decade of snow and ice data over the Arctic and Southern Oceans, and the processed data set will be uniquely useful for informing decadal changes of the polar sea ice cover as well as for improving sea ice thickness retrieval approaches for ICESat-2. Thus, in addition to the responsibilities of science team membership (support of data collection strategies and product generation, etc.), I propose to

address topics pertaining to OIB data quality for inferring inter-annual variability and decadal trends, and the use of OIB snow and ice retrievals in preparation for the ICESat-2 mission. These topics include: 1) Evaluation of the quality of snow depth, freeboard, and thickness estimates; 2) Approaches for using OIB snow depth estimates to inform ICESat-2 thickness retrievals; and, 3) Use of OIB retrievals for assessment of ICESat-2 data products. The proposed work is of value and benefit to the US and international science community because the results will address cross-validation of airborne and satellite sea ice data sets and establishes the confidence of these data sets for assessing long-term changes in the Arctic and Southern Oceans.

Eric Rignot/University of California Irvine
Land Ice Dynamics and Ice Sheet Mass Balance with Operation IceBridge and Other Data
16-ICEBST16-0007

Measurements of ice thickness, velocity, elevation and bed topography are critical to observe and understand the evolution of coastal sectors of the ice sheets in Greenland and Antarctica, which in turn have a major influence on global sea level rise now and in the future. Here, we will provide scientific guidance to NASA's Operation IceBridge (OIB) Mission, as Science Team (ST) Member, to study coastal ice dynamics and ice sheet mass balance in Antarctica and Greenland based on our experience studying changes in ice dynamics, ice-ocean interaction, and ice sheet/ice shelf mass balance using satellite, airborne and other data. We will adopt appropriate measurement strategies to build up time series of laser altimetry data bridging ICESat-1 and ICESat-2, document volume changes over the past decades, and prepare for cal/val activities with ICESat-2. We will generate 2 sets of advanced products: 1) ice thinning corrections for ice discharge in Greenland; and 2) Antarctic ice shelf bathymetry from gravity. For (1), we will generate OIB time series of laser altimetry on outlet glaciers to quantify glacier thinning at flux gates around Greenland, correct the discharge estimates, and improve the precision of mass balance estimates. For (2), we will use a new 3-D inversion constrained by a mass conservation algorithm (MC) inland and multibeam echo sounding (MBES) data off shore to infer ice shelf bathymetry for Getz Ice Shelf and George VI Ice Shelf, Antarctica. The products will be of high interest to ice-ocean interaction studies, especially in relation to the transport of subsurface ocean heat toward the glaciers and the estimation of melt rates. In addition, we will collaborate with other researchers on 2 ongoing studies: 1) evaluation of surface mass balance models (SMB) from laser altimetry time series; and 2) reconstruction of bed topography or BedMachine from depth sounding data. For (1), we will analyze pre-OIB/OIB and spring to fall campaigns in the ablation zone of Greenland to evaluate SMB models (RACMO, MAR, GEOS5) and quantify their errors in runoff; this will improve the determination of ice mass balance and help understand the limitations of ICESat-2. For (2), we will use depth radar sounding combined with InSAR-derived ice motion vectors to improve BedMachine Greenland, fill data gaps, and extend BedMachine Antarctica in select sectors. In Greenland, we will combine OIB results with MBES surveys of the coastline from NASA's EVS'2 Ocean Melting Greenland (OMG) mission to provide seamless topography across the ice front regions. These products are of high importance for ice sheet and ocean modeling studies. We will provide continuous feedback to the ST and OIB Project on the product generation to guide mission planning. As ST member, we will guide mission planning, optimize the measurement strategy, provide feedback on data quality, contribute to higher-order product

generation, ensure that OIB meets its science objectives, and help assemble the final report of the OIB mission. Lessons learned from phases 1 and 2 of OIB will help improve the observation strategy, quality control, advocacy of OIB in the community and data usage, and reporting of the mission progress towards its stated science goals to management and NASA. We will continue advocacy of the OIB mission at the national and international levels, publish science results, and take into account feedback, comments, or requests from the community when designing field campaigns. A major goal of phase 3 will remain to support ICESat-2 cal/val activities and wrap up the OIB mission. Overall, our effort will contribute to the success of OIB mission, the timely availability of quality data for the scientific community, and the assessment of OIB contribution to cryosphere science toward the end of the mission. This work will contribute to NASA's Earth Science strategic goals of studying the role of Earth's ice masses on sea level rise.

Benjamin Smith/University of Washington, Seattle
Understanding Changes in Ice Sheet Mass and Optical Properties from Using IceBridge Altimetry
16-ICEBST16-0004

The NASA Operation Ice Bridge (OIB) is designed to provide elevation measurements in Greenland, Alaska, and Antarctica during the nine years between the end of the ICESat (Ice Cloud and land Elevation Satellite) mission and the start of the ICESat-2 mission. Early in the mission, the altimetry missions consisted of annual surveys over each ice sheet. As OIB begins its ninth calendar year of operations in 2017, it will begin provide measurements more and more aimed at extending and adding value to the first ICESat-2 measurements; these include seasonal repeat measurements in Greenland, which will begin to provide baseline data for ICESat-2's year-round measurements, and, soon, two-wavelength laser-altimetry measurements to help calibrate potential biases in the ICESat-2 data. In the proposed project, we will work towards integrating these two new components of the mission into the complete ICESatto ICESat-2 time series. Using the new two-wavelength altimetry measurements, numerical modeling, and remotely sensed surface-reflectance measurements, we will generate a preliminary correction for the subsurface scattering bias in ICESat-2 data. Using the new multi-seasonal altimetry measurements over Greenland, we will document the performance of available firn-thickness models in matching seasonal height changes, and will help design altimetry missions to capture the full range of seasonal behaviors across the ice sheet. Last, we will participate as the ice-sheet altimetry leads in the IMBIE-2 Ice-sheet Mass Balance Intercomparison Exercise, bringing together a variety of ice-sheet mass-change estimates from a variety of sources, which should be a valuable preliminary step towards interpretations of the first ICESat-2 results.

Edward Blanchard Wrigglesworth/University of Washington, Seattle
Assessing the Impact of IceBridge and ICESat-2 Observations on Sea Ice Forecast Skill
16-ICEBST16-0003

The loss of Arctic sea ice over the last few decades has been dramatic, particularly during the summer season, when sea-ice extent has declined by almost half and sea-ice volume by about two-thirds. Ice-free summers by the middle or end of the century are now simulated under

business-as-usual scenarios in most state-of-the-art climate models, illustrating that the Arctic will continue to be a fast-changing environment for the foreseeable future. These climatic changes are having profound impacts on the natural and socio-economic environment in the Arctic and further a field. The loss in sea-ice has contributed to an increase in economic activity in the Arctic ocean, ranging from industrial activities such as resource extraction and shipping to tourism and national defense, while local communities are becoming more exposed to growing hazards such as coastal erosion.

Observing this changing environment is key for improving our understanding of the physical processes at play in the climate system and its simulation in climate models. Better sea ice forecasts are needed to improve both regional and global forecasts that are vital to human activities as well as wildlife protection. Forecast skill depends on the quality of the forecast's initial conditions, which is determined by the quality of both the observations and the methodology used to incorporate the observations into the forecast's initial conditions.

In this proposal we describe the PI's role as an IceBridge Science Team (IST) member and propose a research plan that assesses the impact of IceBridge and future ICESat-2 altimetry observations of ice thickness and snow depth on improving sea ice forecasts. As members of the Science Team, we aim to advise on flight planning that i) optimizes the flight line location in order to maximize the continuity of the ICESat, ICESat-2 and CryoSat-2 satellite observations and ii) plans for future calibration/validation of ICESat-2. As it pertains to sea ice, in order to both help monitor key regions and best construct a complete (2009-2019) IceBridge dataset, we propose making an initial review of flight lines from phases I and II of IceBridge to prioritize past flight lines based on number of times flown and sea ice geography, while we encourage flights extending toward the Eastern Arctic as far as logistics allow. We will provide support in the preparation of analysis, development and reporting, and help produce the final report in 2019.

Our research plan is to quantify the improvement in sea ice forecasts borne by altimetry observations of sea ice thickness and snow depth with the use of observing system simulation experiments (OSSEs) with a state-of-the-art climate model. The experiment design will be to assimilate the IceBridge ice thickness and snow depth, together and separately, into the initial conditions of the forecast using a recently-developed assimilation technique specific to NCAR's Community Earth System Model version 1.5 and the accompanying Data Assimilation Research Testbed (DART). Subsequently we will perform equivalent experiments using future ICESat-2 observations and orbit prediction information to initialize sea ice forecasts.

To successfully conduct the proposed team member work, the PI will draw upon his experience in the use of IceBridge altimetry data, participation in past IST meetings, established strong collaborative network with current IST members and past leadership of international modeling experiments. His standing within the sea-ice community will allow him to play an active ambassadorial role for the IceBridge product. To conduct the proposed research, the PI will draw upon his experience in sea-ice predictability studies using the CESM suite of models, studies of Arctic variability across different dynamical models and use of the IceBridge altimetry observations. This project will help support an early career scientist and a female post-graduate scientist.