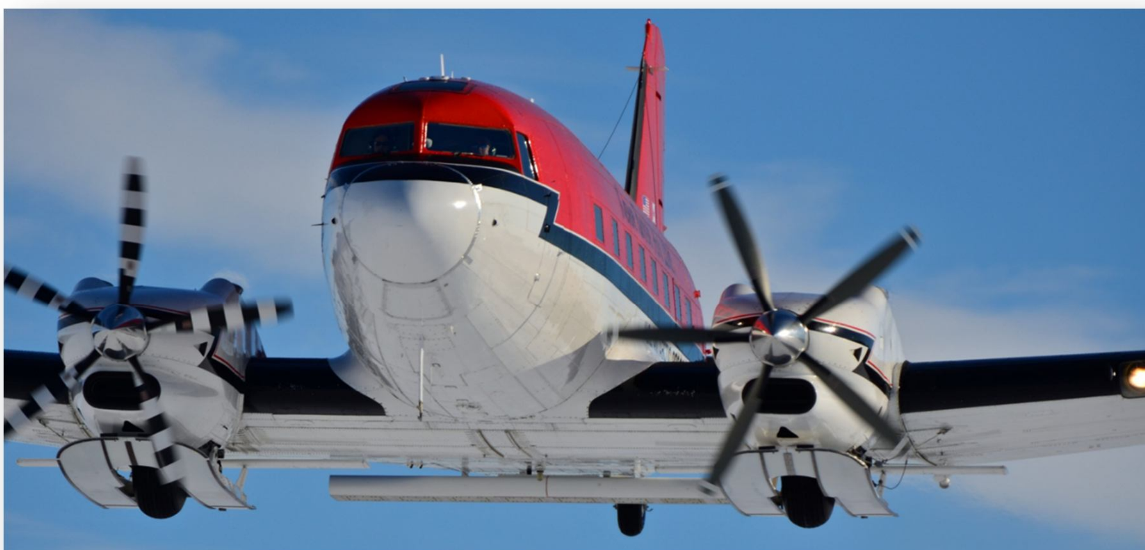
CReSIS

Center for Remote Sensing of Ice Sheets



Science & Technology Center Accomplishments 2005-2014

Introduction

The Center developed key technologies for polar research—high-sensitivity radars coupled with advanced signal processing techniques to sound fast-flowing glaciers and image the ice-bed interface. The Center also developed complex antenna structures for operating these radars on both short-range and long-range aircraft. The Center performed extensive radar measurements over the Greenland and Antarctic ice sheets and has processed these data to generate data products that are now used widely by the Center's science team as well as by the broader science community. Furthermore, the Center documented selected regions of the ice sheets undergoing rapid changes both in time and space. Finally, the Center also made significant progress in designing and manufacturing unmanned aircraft systems (UASs) optimized to accommodate antenna arrays and radars for collecting fine-resolution data over fast-flowing glaciers and imaging the ice-bed.

The Center made excellent progress educating and training a diverse group of students in science and engineering, as well as developing undergraduate and graduate courses. About 60% of these graduates are working in industry today. The Center has also been very active in K-12 activities, including developing a highly successful series of inquiry-based classroom activities called *Ice, Ice, Baby!* for integrating science and math into the classroom. They include 27 activities online, all mapped into the Common Core Standards. CReSIS K-12 Educational Outreach has also developed web-based interactive games and is continuously updating the website with activities and resources for educators, students, and the general public. Finally, the CReSIS education team sponsored a two-week summer program every year for middle school students to learn about polar regions, remote sensing and satellite imagery.

The Center has been very active in knowledge transfer activities, including participation in major conferences and meetings, the organization of an International Glaciological Society (IGS) meeting on radio glaciology, distribution of data sets and products, publication of results in archival journals, and providing professional development opportunities for staff and students. 80% of the radar data used to generate the new bed map for Greenland were generated by CReSIS [Bamber et al., 2013]. In addition, over the past five years, CReSIS has been featured on the cover of nine major archival journals, with one more expected. The sea level rise maps developed by CReSIS are used widely worldwide.

In this document we provide a brief overview of a few selected accomplishments in research, education and diversity, and knowledge transfer. In addition to our annual progress reports, which provide a more complete discussion of the Center's activities, we developed a second yearly report that documents our performance as it relates to our major goals and objectives, as laid out in the original Strategic and Implementation Plan. This is referred to as the "What We Said" document.

Research – Sensors and Platforms

Sensors

CReSIS successfully developed a custom suite of radars optimized for polar research from airborne platforms. Our radars were built specifically for sounding and imaging ice sheet topography and bed conditions, including margins and fast-flowing glaciers, mapping near-surface and deep internal layers, measuring the thickness of snow over sea ice, and determining the bottom melt rates of ice shelves. CReSIS radar instrumentation operate at frequencies as low as 14 MHz in the High-frequency (HF) region to as high as 18 GHz in the microwave region of the electromagnetic spectrum. Our instrumentation consists of radar depth-sounders/imagers (140-210 MHz), the Accumulation radar (600-900 MHz), the Snow radar (2-8 GHz), and the Ku-band radar altimeter (12-18 GHz), each of which has been used widely on both long-range and short-range aircraft over

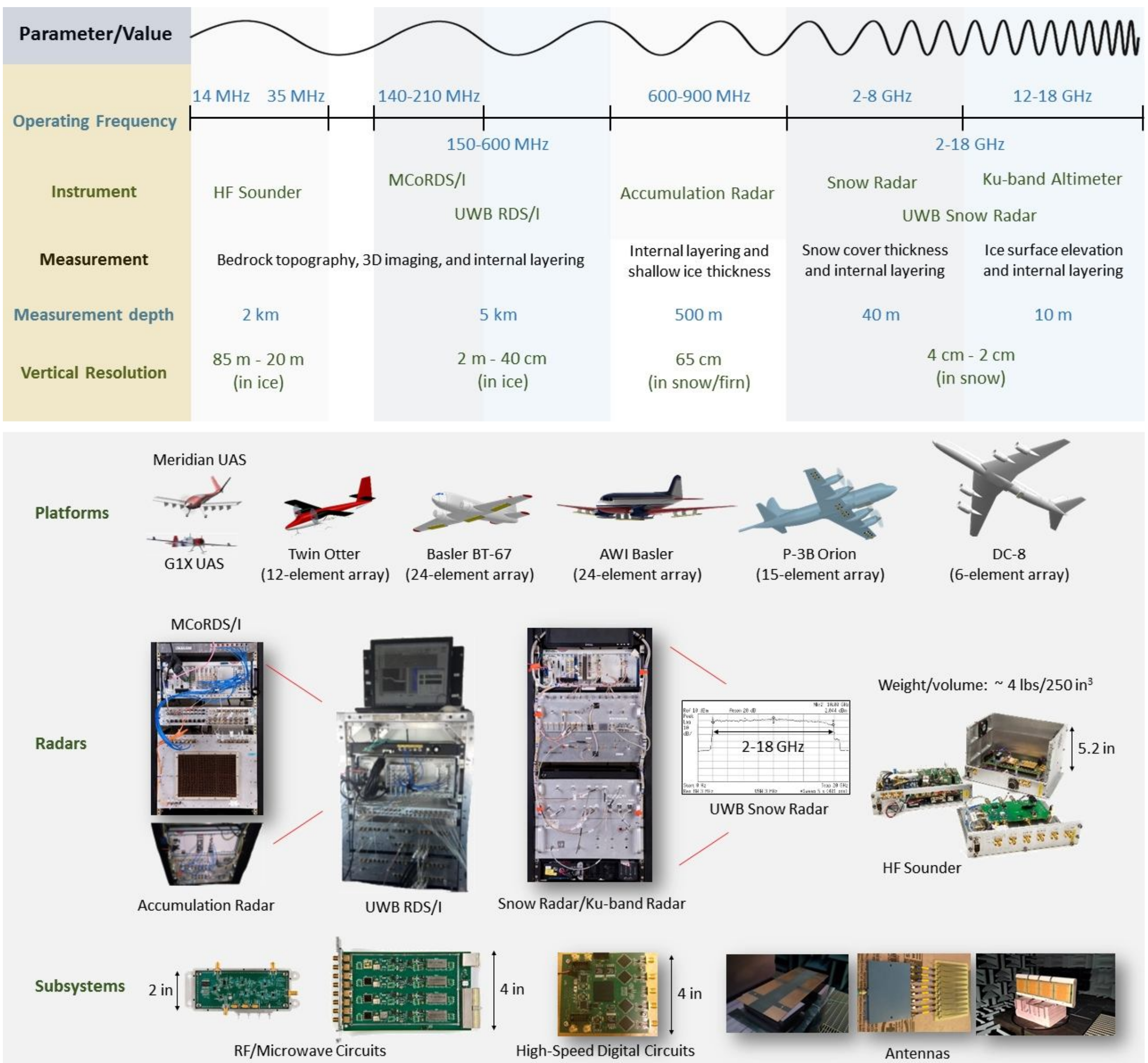
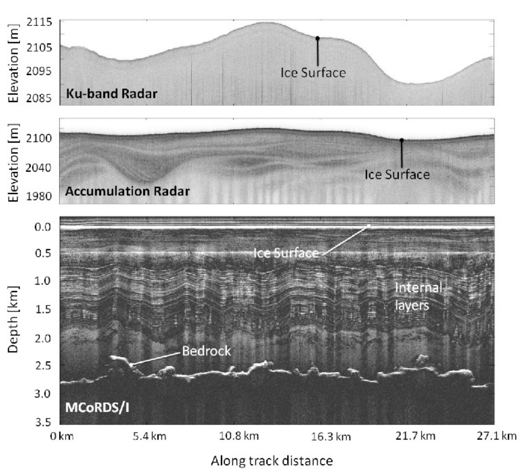


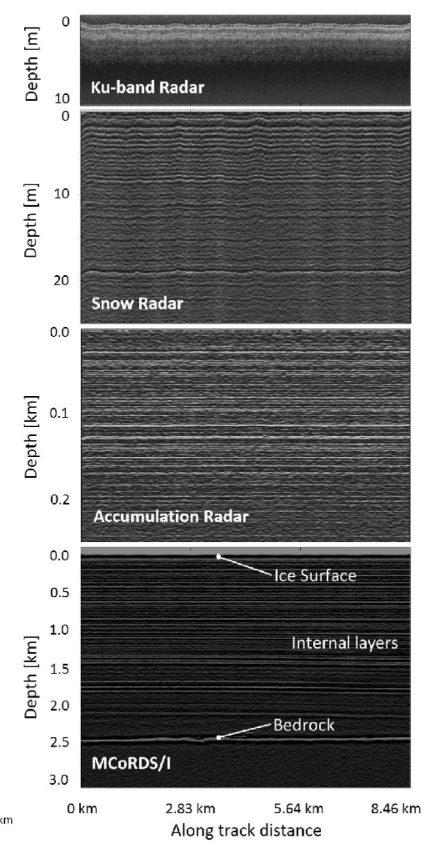
Figure 1: Summary of the radar instruments developed under CReSIS and their capabilities.

the past several years [Rodriguez-Morales et al., 2013]. More recent CReSIS-developed instruments include a compact and light weight (approx. 4 lbs) dual-frequency HF/VHF sounder radar that operates at 14 and 35 MHz for operation on a small UAS, an ultra-wideband radar depth sounder/imager (150-600 MHz), and an ultra-wideband Snow Radar (2-18 GHz) [Leuschen et al., 2014; Gogineni et al., 2014]. These new systems represent major research developments in integrating antenna and aircraft design and will be incorporated on several airborne platforms. Systems developed by CReSIS are being used for extensive data collection on the Greenland and Antarctic ice sheets, as well as on Arctic and Antarctic sea ice. Both undergraduate and graduate students were extensively involved in all aspects of radars development and use, as well as in processing and analyzing the data. 13 of our student assistants in radar development completed an M.S. degree, and four are now pursuing a Ph.D. Two students graduated with a Ph.D., and 10 completed an undergraduate degree while engaged in CReSIS research. Most of these graduates are employed in industry, as shown in Table 3.

Figure 2 provides two examples of data collected with the CReSIS radar instrumentation, one with radars operated on a Twin-otter aircraft over the Byrd glacier catchment area and the other with the package operated on the NASA P-3 aircraft. The results show that we can map internal layers all the way from the surface to ice bed to determine annual, decadal, and century-scale accumulation as well as determine ice thickness and basal conditions [Medley et al., 2013; Dahl-Jensen et al., 2013]. The Ku-band and Snow radars can map near-surface internal layers with fine range resolution of about 5 cm in the top 5-50 m of firn and ice, and the Accumulation radar can map internal layers to a depth of about 250 m or more in dry snow zones. The Snow and Accumulation radars have been shown to provide excellent information on snow accumulation over large areas. Medley et al. [2013 and 2014] successfully estimated the snow accumulation over Pine Island and Thwaites glaciers catchment areas from data collected with these radars.

*Figure 2: **(bottom)** Data collected over Byrd glacier catchment area with three radars on a Twin Otter aircraft; **(right)** data collected over the Greenland ice sheet with four radars on the NASA P-3 aircraft.*





Platforms

Figure 3: The Meridian UAS on takeoff in flight tests at Pegasus ice runway, McMurdo, December, 2011.

CReSIS developed two new unmanned aircraft systems (UASs) designed to support radar measurements over the ice sheets in Antarctica and Greenland: the Meridian and the G1X. The Meridian weighs 1,100 lbs with a 26-foot wingspan. It has a range of 950 nm at the full 120-lb payload capacity [Donovan et al., 2006, 2007, and 2008; Sweeten et al., 2009; Hale et al., 2009; Royer et al., 2010; and Lan et al., 2012]. Figure 3 shows the aircraft on the runway at McMurdo. The vehicle is designed to accommodate an 8-element array for ice-penetrating radar sounder/imager. However, it can also be used to operate additional payloads and sensors. The G1X weighs 85 lbs with a 17-foot wingspan. Its range is approximately 60 nm per gallon of fuel [Leuschen et al., 2014]. The primary payload for this aircraft is a dual-frequency HF/VHF radar for sounding ice in fast-flowing glaciers. We developed the small UAS to synthesize a large 2-D aperture by flying on grid lines spaced as close as 5 m in the cross-track direction. Figure 4 shows the results of data collected

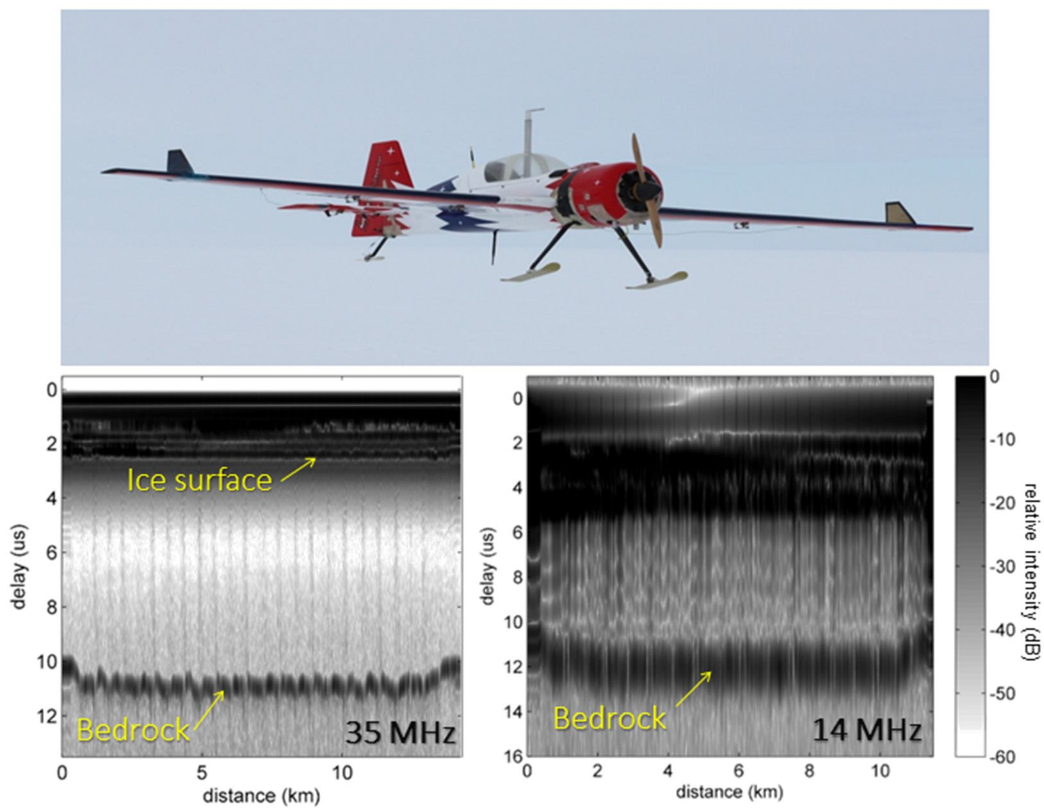


Figure 4: The G1X UAS in flight over the Whillans Lake in West Antarctica and radar depth sounder data at 35 and 14 MHz during that flight. The echograms include multiple lines to test the concept of 2-D aperture synthesis.

over the ice near Lake Whillans in Antarctica. Each echogram consists of results obtained by flying multiple lines (12) to synthesize a 2-D aperture.

The CReSIS UAS team has supported over 200 piloted flight tests in the USA, Greenland, and Antarctica. UAS models flown include the Meridian UAS (1,100 lbs) and the G1X UAS (85 lbs) discussed above, as well as the smaller 40% scale Yak-54 UAS (55 lbs) and 33% scale Yak-54 UAS (27 lbs), which were used for training our flight crews and exploring research in increasingly autonomous control [Keshmiri et al., 2008; Leong et al., 2008 and 2009; Sweeten et al., 2009; Royer et al., 2010; Jones et al., 2010 and 2011; and Lykins et al., 2010 and 2011]. Over 100 autonomous UAS flight tests were performed, including multiple over-the-horizon flight tests. We completed the first ice-penetrating radar-instrumented UAS flight tests in Greenland and Antarctica, and the G1X achieved the first-ever successful sounding of glacial ice with a UAS-based radar.

In addition to the development of UAS platforms for polar remote sensing, the CReSIS UAS team has contributed to fundamental research in flight dynamics and control, including:

1. Development of complex mathematical algorithms for real-time parameter identification of aircraft's nonlinear and unsteady aerodynamics using adaptive artificial neural networks [Garcia et al., 2012 and Stastny et al., 2013].
2. Identification of a nonlinear aerodynamic behavior known as wing rock in a large UAS using a model identification method called Fuzzy Logic Modeling (FLM) with results reported for the first time in open literature [Lan et al., 2012].
3. Development of an online trajectory modification ensuring collision and obstacle avoidance for multiple collaborative and non-collaborative fixed-wing UASs. The trajectory uses artificial potential field navigation methods and adaptive "morphing" potential formulations. The approach considers not only proximity, but also relative agent velocities and other aircraft dynamic characteristics to reduce conflicts between vehicles with high speed and high inertia [Stastny et al., 2014].
4. Design of tractable resilience and robustness algorithms to reduce the impact of parameter shifting, uncertainty, and component failures in nonlinear model predictive control (NMPC) for the next generation of Earth and Science UASs [Garcia et al., 2010, 2011, and 2014].
5. Development of a technique to eliminate undesirable cross-coupling between UAS control and guidance modules by unification of NMPC's inner and outer loops into a single loop [Garcia et al., 2012 and 2014].
6. Development of an in-house automatic flight system (KU AFS) and advanced ground station for RF and satellite communications, health monitoring, and command and control of UASs in the line of sight and over the horizon [Esposito et al., 2010].

The design, construction, and flight testing of UASs at the University of Kansas contributed to the education and training of 74 undergraduate and 14 graduate students. 12 of 14 graduate students completed their M.S. degrees, and two earned a Ph.D. in Aerospace Engineering.

Research – Data Products and Satellite Observations

Data Products

The Center generated a number of data products for the CReSIS science team and broader science community. These include ice thickness, bed topographies, InSAR-derived surface velocities, and in-situ information. Radar data products span the frequency range from about 150 MHz to 18 GHz over the Greenland ice sheet, eastern Canada, Arctic sea ice, and large parts of the Antarctic. The products are made available online (http://data.cresis.ku.edu/) for the international science community in an organized way with a variety of standard formats to facilitate easy access and use. For the new bedmap of Greenland, CReSIS data contributed 80% of the incorporated flightlines, as shown in Figure 5. CReSIS also created the Open Polar Server (OPS) (web portal at http://ops.cresis.ku.edu/) and made it an open source on Github. The OPS is the geospatial database, map server, and web service that form the backbone of our image analysis. Multi-frequency data products generated by CReSIS led to a number of discoveries, including: (1) mapping of a water-saturated firn layer over much of Greenland's southern margins, as reported in Forster et al. [2013]; (2) the discovery of over-wintering lakes in the margins all over Greenland that have since been mapped and reported in Koenig et al., [2014]; and (3) the discovery of a deep canyon in Greenland, as reported by Bamber et al. [2013] Figure 6 shows a buried lake

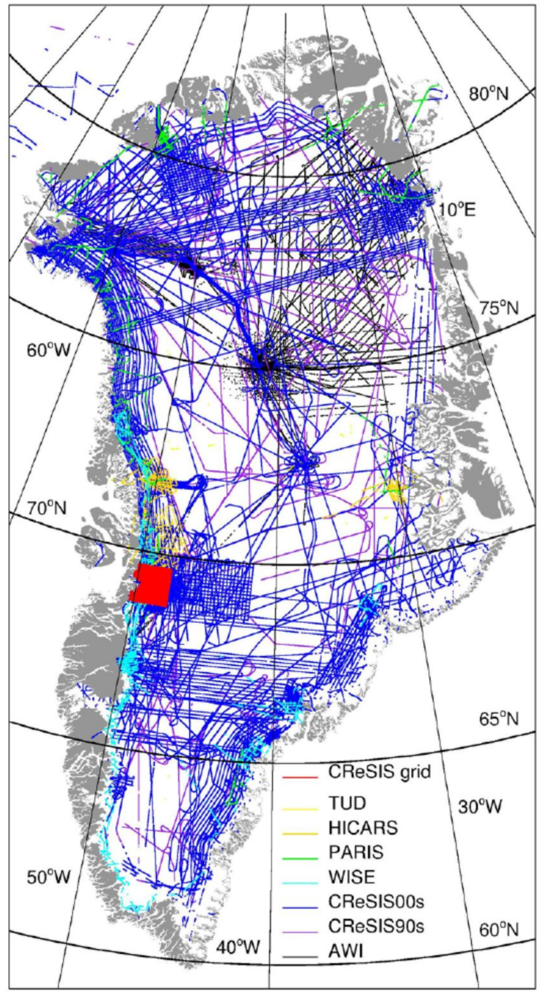


Figure 5: Data sources for the most recent ice bottom DEM of Greenland. CReSIS data constituted 80+% of the data used in generating the DEM. Map reproduced from Bamber et al. [2013].

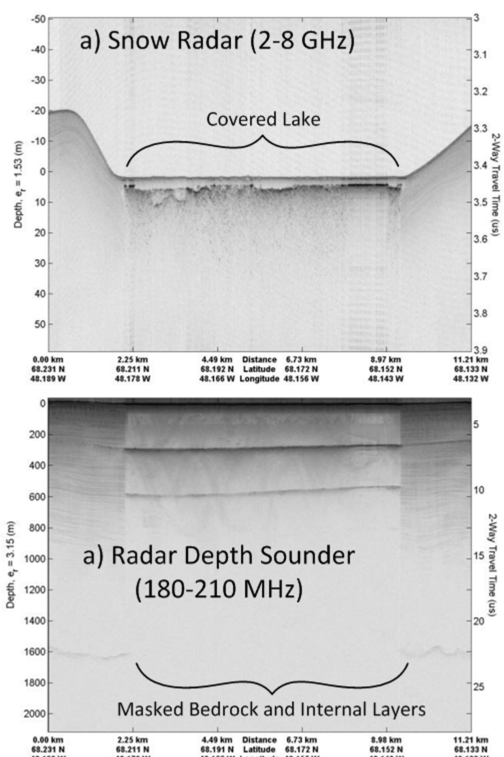


Figure 6: Multi-frequency data showing a buried lake in Greenland.

mapped with fine resolution by the Snow radar; large attenuation caused by the liquid water in the buried lake masked radar-depth-sounder layers and ice-bed returns.

CReSIS also generated digital elevation models (DEMs) for a number of outlet glaciers. An example 3-D rendering of the Jakobshavn Glacier DEM is shown in Figure 7. Jakobshavn drains about 7% of the ice out of Greenland and is the fastest flowing glacier on Earth. Its speed has nearly tripled since the early 1990s [Joughin et al., 2014]. Tributaries of this glacier run to the ice divide, and in places, Jakobshavn Glacier is up to 2700 m thick [Gogineni et al., 2014].

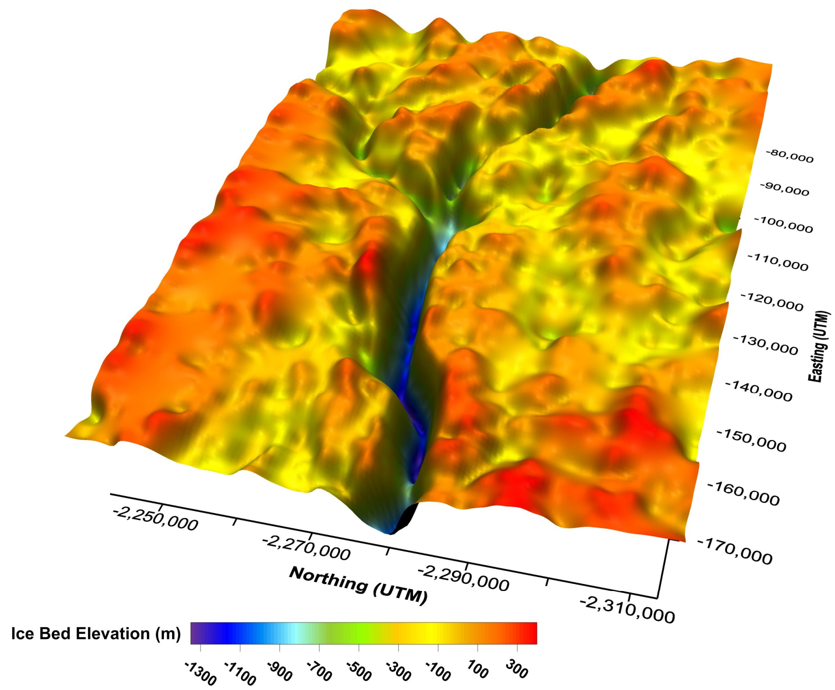


Figure 7: Jakobshavn Glacier, Greenland ice bottom DEM.

CReSIS radar soundings of Byrd glacier contributed to the discovery of the deepest subglacial trench currently known. This trench is situated in the top portion of the Byrd Glacier channel in Antarctica and the ice thickness reaches 3700 m [Gogineni et al., 2014]. CReSIS data were also used to discover folding in the deep basal layers near the NEEM ice core [Dahl-Jensen et al., 2013].

The radar depth sounder/imager collects multichannel data (up to 24 channels in the newest system being prepared for deployment). Using advanced array processing, the channels are combined employing data adaptive algorithms that work on the pixel level to optimally suppress

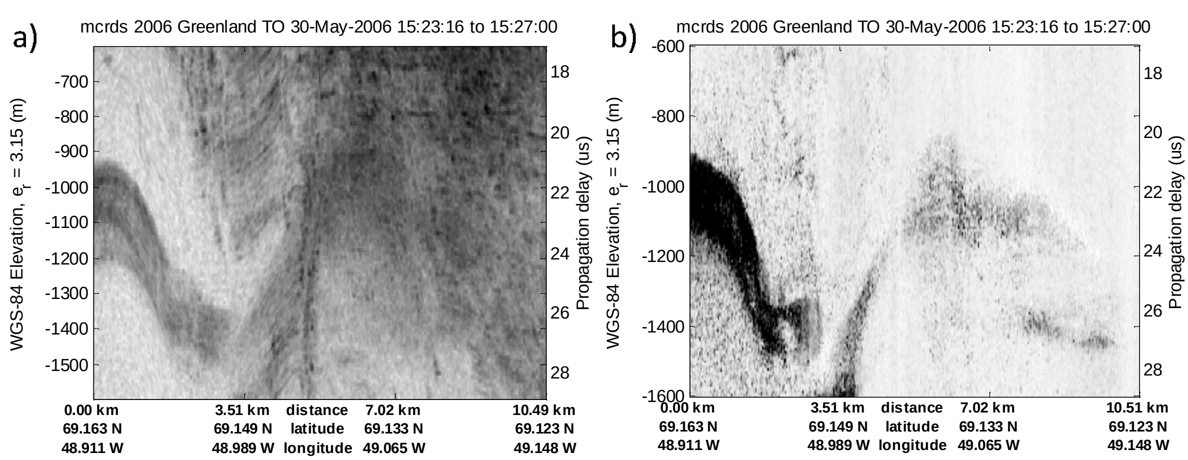


*Figure 8: Radar echogram from Jakobshavn channel using **a)** standard and **b)** adaptive processing.*

image clutter. An example of the image processing capabilities is shown in Figure 8, where standard array processing is compared to adaptive processing. The array data are also used to produce 3D images of the ice bed (e.g. Paden et al., 2010 and Jezek et al., 2013). The combination of a radar with a large cross-track array and advanced signal processing techniques will enable fine-resolution mapping of the ice-bed interface that can support a wide range of scientific investigations in the future.

Satellite Observations

The Center continues to document spatial and temporal variations of key glaciers in Greenland and Antarctica. This activity is heavily leveraged by projects funded by NASA to generate ice surface velocities from InSAR and other data sets.

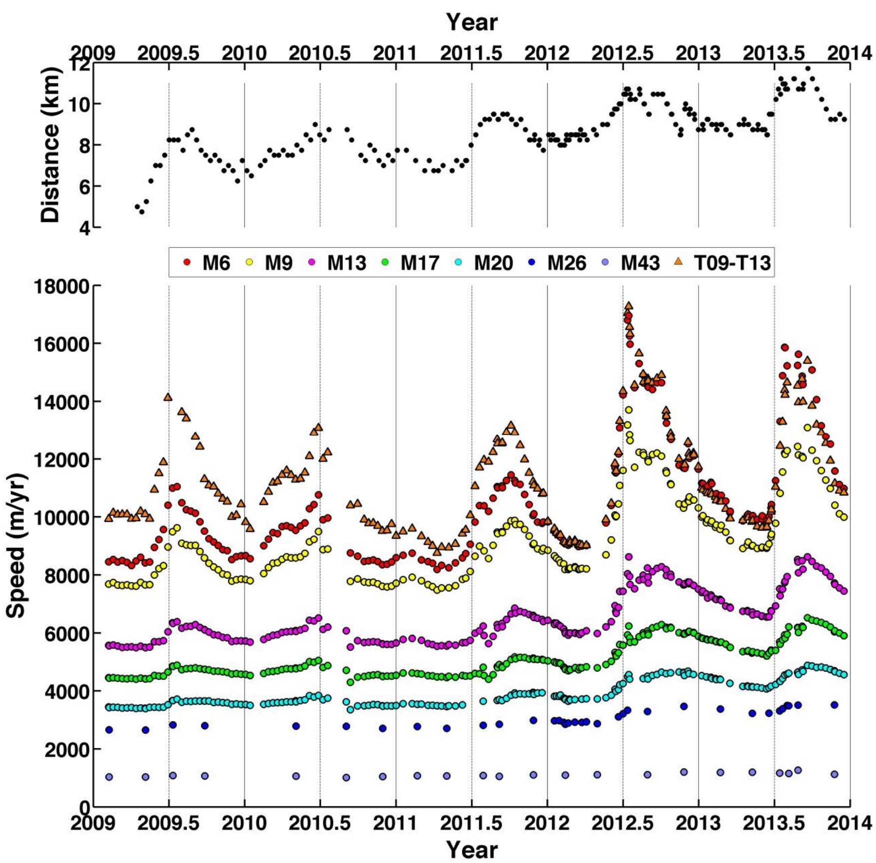


Figure 9: Plots of ***(top)*** *terminus position and* ***(bottom)*** *speed through time for Jakobshavn Isbræ determined from TerraSAR-X data collected from 2009 to 2013. The color circles (M6-M43) show the speed at several points along the glacier's main trunk. Each point's numerical designation (e.g., M6) gives the approximate distance in kilometres from glacier terminus in late summer 2003 and these points are used for consistency with earlier records. Additional markers, T09-T13 (orange triangles), are each situated 1-km upstream of the terminus at its position of maximum retreat for the years 2009-2013. Each year, speeds are plotted for the corresponding point (T09-T13).*

Over the past ten years, the Center analyzed the speeds of nearly all of Greenland's major outlet glaciers. This on-going activity involved University of Washington graduate student Twila Moon, who published a comprehensive analysis of glacier flow variability in Greenland [Moon et al., 2012]. Additionally, work in Greenland has focused on some of the more dramatically changing glaciers in Greenland. For example, during the summer of 2012 there was remarkable transient speedup on Jakobshavn Isbrae (Figure 9), with speeds well in excess of previous summer (17 km/yr near the terminus) [Joughin et al., 2014].

In Antarctica, velocity measurements were on the fast moving Pine Island and Thwaites Glaciers, which were used largely to support modeling efforts, as well as to continue the long-term monitoring of these glaciers [Joughin et al., 2014].

Research – Modeling and Analysis

CReSIS modeling and analysis efforts are designed to ensure that sensor and data product developments are optimized to address critical science questions that can lead to more accurate predictions of sea level rise. Modeling accomplishments have included the assessment of factors that control glacier stability, ice sheet mass balance, surface velocity, and observed transient behavior of the ice sheets. Enabled by CReSIS data products, both theoretical process studies and numerical ice sheet modeling have been conducted on spatial scales ranging from drainage basin scales up to a continental scale ice sheet. Theoretical process studies include force balance calculations along rapidly changing outlet glaciers, the impact of overdeepened beds on basal conditions and ice dynamics, processes at the grounding line that could lead to destabilization, and water at the ice-bed interface. Numerical ice sheet modeling within CReSIS ranges from 1-D flowband models up to 3-D full-Stokes models. Furthermore, significant accomplishments have been made in developing techniques to couple ice sheet models into earth system models. This is key to obtaining accurate sea level rise predictions from coupled earth system models.

Key accomplishments have been achieved in basin-scale through continental scale ice sheet modeling, subglacial hydrology modeling, and assessment of model sensitivity to initial conditions.

Basin Scale Ice Sheet Modeling

Basin scale modeling has been focused on the West Antarctic Ice Sheet due to recent observations of thinning, acceleration, and grounding-line retreat of the Pine Island and Thwaites Glaciers (PIG/THW). The PSU 3-D hybrid ice sheet-shelf model has been adapted to run on a nested domain centered on PIG/THW at 5 km resolution, driven at the boundaries by the results of prior

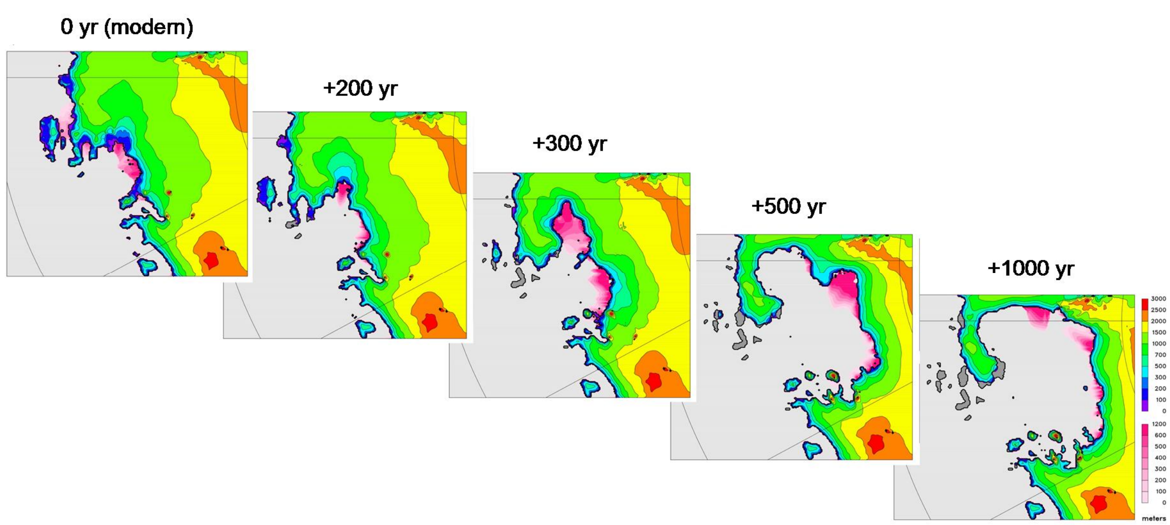


Figure 10: PSU 3-D hybrid ice sheet-shelf model results for future PIG/THW grounding zone retreat.

continental-scale simulations. Past and future climates are parameterized, and past ocean temperatures are obtained from published coupled general circulation model results.

Time-continuous simulations are being run through the last approx. 15,000 years and are then extended into the future with various climate scenarios. Preliminary projections based on future warming show dramatic grounding-line retreat into the interior of West Antarctica within approx. 2000 years, contributing at least 2 to 3 m to global sea-level rise.

Continental Scale Ice Sheet Modeling & Sea-Level Rise Projections

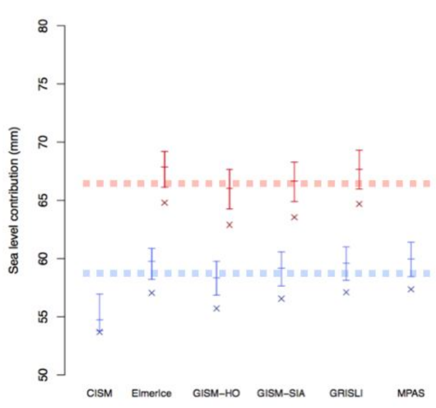
Participation in two international ice sheet modeling exercises, *SeaRISE* (U.S.-led) and *Ice2Sea* (E.U.-led) by LANL has contributed new assessments of future sea-level rise from ice sheets to the most recent Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5). Both modeling exercises used new and improved, high-resolution CReSIS datasets of ice sheet geometry. A total of 6 publications from this work include LANL co-authors Hoffman, Lipscomb, and Price [Bindscalder et al., 2013; Nowicki et al., 2013a; 2013b; Shannon et al., 2013; Edwards et al., 2014a; 2014b].

Subglacial Hydrology Modeling

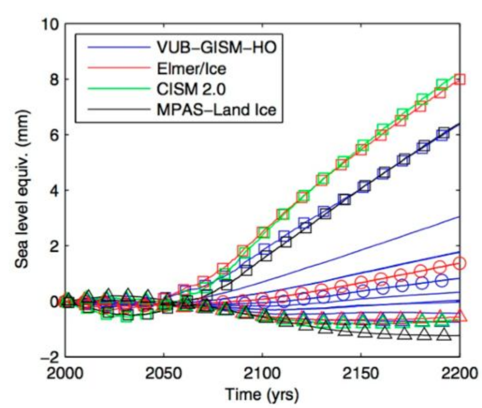
CReSIS-supported LANL postdoc M. Hoffman developed and applied a new, evolutionary subglacial hydrology model within the Community Ice Sheet Model (CISM). Simulations explored the evolution of a combined distributed and channelized subglacial water system and its coupling to a dynamic, higher-order, ice flow model using a realistic, effective-pressure-dependent sliding law. This work, described in detail in Hoffman and Price [2014], identified and explained several previously unexplored *negative* feedbacks between subglacial hydrology and ice sheet dynamics. Importantly, these feedbacks are only apparent when there is full, two-way coupling between the hydrology and ice-dynamics models.

Optimal Ice Sheet Model Initial Conditions

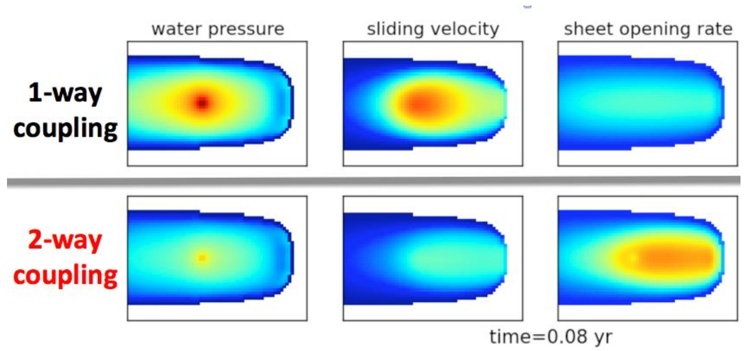
Development and demonstration of an improved ice sheet model optimization approach is a major accomplishment that provides both a good match to observed velocity fields (e.g., Satellite Observations section) and new high-resolution datasets of ice sheet geometry (e.g., Data Products section), while also providing smooth coupling to forcing from a climate model [Perego et al.,



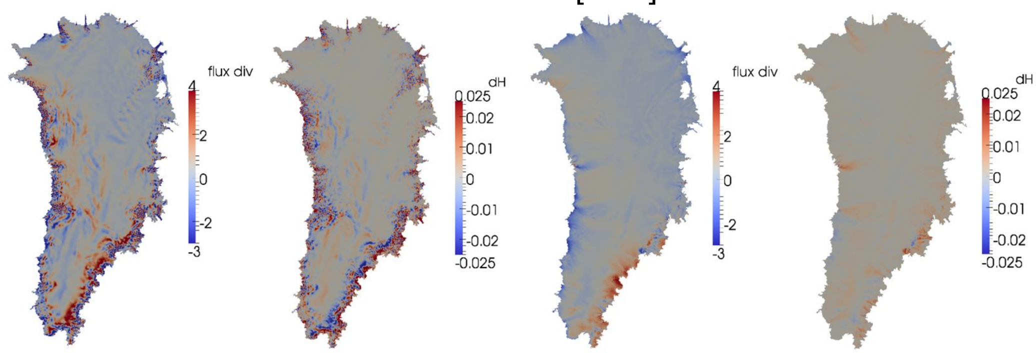
Edwards et al. (*The Cryos.*, 2014a; 2014b)



Shannon et al. (*PNAS*, 2013)



Hoffman et al. [2014]



Perego et al. [2014]

Figure 11: ***(top left)*** *Estimated sea-level rise from Greenland at 2100 from a range of ice sheet models under the A1B emissions scenario and for two different climate models (red vs. blue). The range (vertical bars) quantifies the importance of the ice sheet elevation vs. surface mass balance feedback, with slightly higher rates of sea-level rise when the feedback is included.* ***(top right)*** *Additional sea-level rise from coupling between surface melting and basal lubrication, for a range of sensitivities supported by observations. At 2100, the additional sea-level rise is <5% relative to the case of no feedback (MPAS and CISM contributions in upper figures from LANL).* ***(middle)*** *Idealized ice-dynamics and subglacial hydrology test case demonstrating negative feedbacks between sliding and hydrology with one- vs. two-way coupling.* ***(bottom)*** *Modeled flux divergence (m/yr; left panel) and change in ice thickness (km; center-left panel) after 5 yrs of forward model integration when model optimization targets observed velocities only. Modeled flux divergence (m/yr; center-right panel) and change in ice thickness (km; right panel) after 5 yrs of forward model integration when model optimization also targets climate model forcing and uncertainties in ice thickness. In the latter case, the flux divergence is nearly in equilibrium with climate model forcing (surface mass balance), resulting in a much smaller initialization shock.*

2014]. The new method reduces highly problematic “shocks” upon coupling to climate forcing, which result from a model initial condition that is in disequilibrium with climate model forcing. Importantly, the new method allows the ice thickness field to vary within reported uncertainties, providing a necessary additional degree of freedom. This new method shows great promise for addressing a long standing modeling problem that, to date, has severely limited the use of high-resolution ice sheet geometry data in both coupled and stand-alone ice sheet evolution experiments.

Education and Diversity

Education

In 2005, the CReSIS education and diversity programs developed two major long-term goals. One of these was to educate a diverse group of graduate and undergraduate students in multidisciplinary research with an emphasis on topics related to remote sensing, climate change, and ice. To accomplish this goal, we developed a set of courses on topics related to remote sensing of the earth, with a particular focus on ice sheets. We also involved both undergraduate and graduate students in all aspects of the CReSIS research—sensors and platforms, signal processing and analysis, generation of data products, modeling of ice sheets, interpretation of data products, and synthesis of results. We carried out an annual research experience for undergraduates (REU) program that involved approx. 15 students per year since 2006.

The second goal was to inspire and encourage students in K-12 to pursue education in STEM fields. To support this goal, we conducted extensive outreach activities as a part of our K-12 program. We developed a highly successful series of inquiry-based classroom activities called *Ice, Ice, Baby!* to integrate science and math into the classroom. The CReSIS education team also sponsored a two-week summer program every year for middle school students where they received instruction on the polar regions, remote sensing, and satellite imagery. The education team also worked directly with K-12 teachers through teacher training at conferences and workshops.

Graduate and Undergraduate Education

Courses

We developed a number of introductory and advanced graduate courses to teach students topics related to remote sensing of ice. We used web-based learning and collaboration techniques to make a selected set of courses available to students at partner institutions using the Center's internet-based video conference facilities. Students outside the course's host institution enrolled in a directed readings or research course with a faculty member at his/her home institution. This faculty member participated in course lectures, answering students' questions, grading homework and exams, and assigning a final grade. The development of Center-related classes and the inclusion of Center-specific content in previously-existing courses led to a new master's program at ECSU and a more immersive undergraduate curriculum in KU's Aerospace Engineering department.

ECSU now offers a Master of Science Degree in Mathematics with a Concentration in Mathematics Teaching, Applied Mathematics, and Remote Sensing. The program provides a broad base of formal course work and research in mathematics and requires students to complete a thesis or product of learning. The degree requires that the students: (1) complete a minimum of 36 hours of graduate credit applicable to the program; (2) complete a thesis or product of learning; and (3) maintain a minimum GPA of 3.0. Included is a 15-hour core of mathematics courses and 18 hours of remote sensing courses, as listed in Table 1.

Table 1: CReSIS Courses				
Phase 1	**Phase 2**	**Course**	**Instructor**	**Offered**
ECSU	**ECSU**	Topics in Computer Science	L. Hayden (K. Jezek - OSU)	Spring 2006
		Geophysical Remote Sensing	Various	See narrative below
		Geo. Info. Sys. & Geo. Sig. Proc		
		Digital Image Process & Analysis		
		Gen. Analytic Meth. of Remote		
		Geophysical Modeling		
		Microwave Rem. Prin. & App.		
PSU	**PSU**	Principals of Microwave Remote Sensing	S.Anandakrishnan	Fall 2005
		Ice and Climate	R. Alley, S.Anandakrishnan	Fall 2007/ Fall 2008
		Ice Physics	R. Alley	Fall 2011
		MultiChannel Seismic Imaging	S. Anandakrishnan	Fall 2007/Spring 2009/ AY2011-
KU	Electrical Engineering	Introduction to Radar	C.Allen	Fall 2008/Fall 2009
		Principals of Microwave Remote Sensing	C. Allen	Fall 2006/Fall 2008
		Geophysical Signal Processing	C. Leuschen	AY 2007-2008/Fall 2014
		InSAR and Applications	C. Allen	Spring 2007/2009
		Advanced Antennas	A. Harish (visiting Professor)	AY 2007-2008
		Array Signal Processing	P. Sircar (visiting Professor)	Spring 2010
		Electromagnetics II	S. Gogineni	Spring 2010
		Applied FPGA design	C.Leuschen	Spring 2012
		RF Circuit Design	P. Gogineni, F. Morales	Fall 2008
		Electromagnetic Compatibility	S. Seguin	Spring 2010
		Radar Systems	S. Gogineni	AY 2011-12
	Aerospace Engineering	Areospace Computer Graphics	R. Hale	Spring annually since 07
		Aerospace Structures I	M. Ewing	Fall annually since 07
		Aerospace Structures II	R. Hale, M. Ewing	Spring annually since 07
		Fundamental of Airplane Reciprocating Propulsion	R. Taghavi	Spring 07-10
		Fundamental of Jet Propulsion	R. Taghavi, S. Farokhi	Fall 07-10
		Aerospace Instrumentation Laboratory	R. Vos, S. Keshmiri, H. Chao	Spring annually since 08
		Structural Composites	R. Hale	Annually since 07
		Special Projects in Aerospace Engineering	Various	Annually since 07
		Aircraft Design Laboratory I	R. Colgren	Fall 05-09
	Geology Geography	Introduction to Glacier Dynamics	C J Vanderveen	AY 2007-2008
		Glaciology	L. Stearns	Fall 2011
		Graduate Glaciology	L. Stearns	Spring 2010
		Glaciers and Landscape	C J Vanderveen	Fall 2008
		Freshman Honors Tutorial: Glaciers and Climate	L. Stearns	Fall 2009
		Climate System Science	D. Braaten	Fall 2014
		Climate Change in Greenland and Antarctic (IGERT course with field trip to Greenland)	D. Braaten and C. J. Van der Veen	Spring 2010
	Center for Teaching Excellence	Teaching College Level Science and Engineering	D. Bernstein	Fall 2006
		Being an Effective College Instructor (added to the regular curriculum 2007)	D. Bernstein	Continuous
	Business	Business and Financial Issues of Climate Change	S. Mishra	Fall 2007/2008
		Entrepreneurship Workshop	S. Mishra	Summer 2007
		Fuzzy Front End of Product Development & Technology Evaluation	S.Mishra	Spring 2012
	IU	Grid Computing with Applications	G. Fox	Fall 2013
		X-Informatics	G. Fox	AY 2011-12
OSU		Topics in Computer Science	L. Hayden (K. Jezek - OSU)	Spring 2006
Haskell		Introduction to GIS	RJ Rowley/D. McDermott	Fall 2005/2009
		Applications of ArcGIS	D. McDermott	Fall 2005/Spring 2006/Fall 2008/2009
		Advanced GIS and GPS	D. McDermott	Spring 2006/2009/2010
		Principles of Physical Geography	RJ Rowley/ D. Braaten	AY 2006/2007
		Introduction to Physical Geography	D.McDermott	Alternating semesters,annually
UMaine		Holistic Ice-Sheet Modeling, offered as a short course at ECSU	T. Hughes	Summer 2006

Research in sensors and platforms has also been integrated into undergraduate and graduate courses at KU. Figure 12 provides an example of how radar-integrated UAS development is incorporated into AE curriculum at the University of Kansas. The CReSIS-AE faculty effectively embedded immersive research experiences for all undergraduate students in aerospace engineering, with at least 17 courses using Meridian and G1X UAS development as the basis for design projects, homework, and examination content. For instance, composite design, analysis, and fabrication efforts address interdisciplinary design requirements for radar, aerodynamic, aircraft, and structural performance, often requiring trades between physical and mechanical properties inherent in different classes of fiber-reinforced materials. Such experiences have been leveraged by the CReSIS team to design, fabricate, flight test, and field extensive ice and snow radar arrays for NASA Operation Ice Bridge installations on NASA DC-8 and NASA P-3 aircraft as well as other for projects on Basler BT-67 aircraft, none of which would have been feasible without the interdisciplinary team formed within CReSIS.

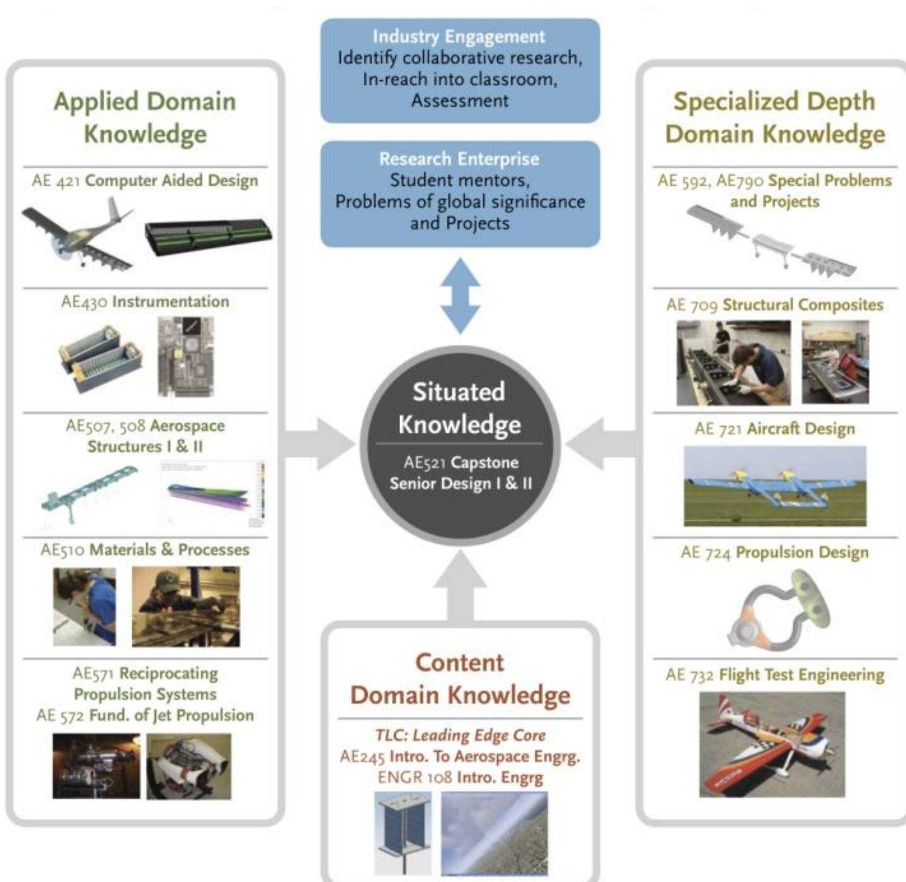


Figure 12: CReSIS vehicle design, build, fly activities have revolutionized immersive, experiential learning across the KU Aerospace curriculum.

Table 2: Undergraduate Students Supported by Polar Research							
	Current Placement						
	TOTAL	Industry	Academia	Government	Current student	Graduate School	Other or Unknown
KU	141	35	6	1	36	17	46
ECSU	50		7		15	18	10
Haskell*	15		1	3	1	5	5
Combined	206	35	14	4	52	40	61

* Phase 1

Table 3: Graduate Students Supported by Polar Research						
	Employment					
	TOTAL	Industry	Academia	Government	Current student	Other or Unknown
OSU*	4	2	1	1	0	
KU	137	62	19	5	31	20
ECSU	9	1	5		3	
Maine*	2		2		0	
Indiana	5				5	
PSU	22	3	12		4	3
Haskell*	1				0	1
ADMI**	1				1	
Washington**	3				3	
Combined	184	68	39	6	47	24

* Phase 1 ** Phase 2

Tables 2 and 3: Total numbers of students supported by Polar Research at KU and CReSIS partners from 1998-2013.

Student Research Assistants

CReSIS employs students as both Undergraduate and Graduate Research Assistants. An average of 41 undergraduate and 46 graduate students work on CReSIS-related research every year. Tables 2 and 3 show the numbers of undergraduate and graduate students supported by polar research. From 1998 to 2013, a total of 390 students have been supported by polar research, 206 students at the undergraduate level and 184 at the graduate level. At the undergraduate level, most students (52) were currently enrolled in courses. An additional 40 students once supported at the undergraduate level moved on to a graduate program. Among the graduate population, the majority of students (68) transition from school to industry.

REU/RET Program

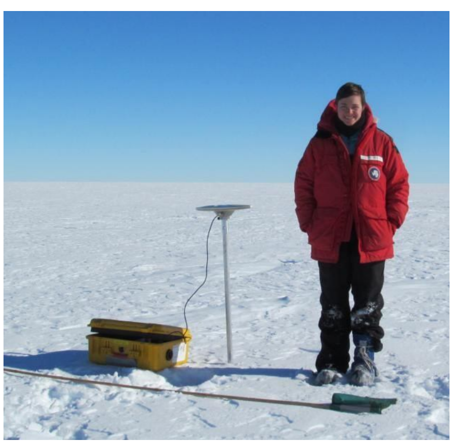


Figure 13: Carolyn Branecky, 2012 KU CReSIS REU student and current PhD student at UC Santa Cruz. Carolyn spent time out on the ice in Antarctica for the 2014 spring field season.

CReSIS involved additional undergraduates in research through the CReSIS Research Experience for Undergraduates (REU) program, which has hosted 170 students since 2006. The CReSIS REU program was recently renewed for an additional 3 years. In 2011, CReSIS added a Research Experience for Teachers (RET) component to the REU summer program that targets pre-service teachers. Initially, RET participants were restricted to secondary math and science majors, but the program has expanded in recent years to include primary teachers. In 2014, the KU CReSIS RET program had one secondary math student from ECSU and two elementary education students from Haskell Indian Nations University. All students who participate in the REU and RET programs are required to develop a poster, give an oral presentation, and either write a paper or, if they are RET students, develop a lesson plan.

REU students have made and continue to make significant contributions CReSIS. During the 2014 REU/RET program, REU student Jacquelynn Vaughan (UCLA senior, physics major) worked with Dr. Fernando Rodriguez-Morales, KU CReSIS faculty researcher and his team to create and develop a new circuit driver, which is expected to provide switching speeds in excess of 500 ns. This new circuit driver outperforms previous, generic drivers used and will be deployed in future radar systems currently in development.

CReSIS faculty and GRAs also provide valuable mentoring opportunities for REU and RET students, assisting them with designing their research projects and answering questions about graduate school. The CReSIS REU program has even expanded to include a professional development component that touches on how to write a CV, careers in STEM, and applying for graduate school.

K-12 Outreach and Publications

Ice, Ice, Baby! is an inquiry-based STEM curriculum developed at CReSIS and available through the CReSIS website. The 27 lessons provide hands-on activities for use in the classroom and at outreach events. The lessons cover a variety of topics, including glaciers, icebergs, the impact of sea level rise, and remote sensing. Seven additional online lessons, focusing on grades 9-12, use real world data for students to manipulate and range from calculating ice thickness to measuring glacier mass balance and solar irradiance. In addition, the CReSIS K-12 Educational Outreach team has developed web-based interactive games and continuously update the website with free activities and resources for educators, students, and the general public. Through classroom visits and informal science and engineering activities, our K-12 outreach team has reached over 55,387 people.

Each year, the education team sponsored a two-week summer program designed for middle school students to learn about Polar Regions, Remote Sensing and Satellite Imagery. The students also take scientific measurements in the fields of atmospheric science and hydrology and analyze the data. Members of the education team engage these students using lessons developed by the team including Ice, Ice Baby lessons.

Figure 14: (left to right) Fourth grade students at Lowman Hill assist K-12 Education Coordinator Cheri Hamilton with Ice Ice Baby!*; CReSIS Education GRA Kuang Cheng demonstrates the "Glacier in Motion" electronic program at the 2014 USA Science and Engineering Expo; CReSIS students work during the NSF Change the World Expo in Dulles, VA.*

CReSIS Teacher Training

From 2005 to now, CReSIS has worked directly with K-12 teachers through teacher workshops at KU, OSU, and PSU as well as through demonstrations at professional conferences and workshops. During the first phase of the Center, CReSIS hosted two-week immersive summer workshops at OSU and PSU. These workshops provided teachers with an understanding of how the scientific community assesses evidence of climate change and an introduction to remote sensing and other methods of studying the Earth's cryosphere. Teachers were provided with lesson plans and materials and spent time developing their own activities. In 2008, materials from these workshops were assembled into a DVD called "Understanding Global Climate Change". Updated in 2011, the DVD and associated materials are available on the OSU Byrd Polar Research center website http://bprc.osu.edu/education/blog/climate_change_dvd/ .

Teacher training activities expanded during the second phase of the Center with online teacher workshops during the school year, demonstrations at teacher conferences, and the development of the RET program. In addition, our K-12 Educational Outreach Team has published several articles in *Science Scope*, *The Science Teacher,* and other appropriate venues.

- Houk, L. and B. Gillette, Modeling the physical properties of glaciers, *The Science Teacher,* 2014.
- Gillette, B., K. Leinmiller-Rennick, and S. Foga, Reading the Ice: Using Remote Sensing to Analyze Radar Data, *The Science Teacher*, 80(02), 2013.
- Gillette, B., Explorations of our Frozen Planet! *Science Scope*, 36(4), 2012.
- Gillette, B. and C. Hamilton, Flooded! An Investigation of Sea-Level Rise in a Changing Climate, *Science Scope*, 34, 2011.
- Gillette, B. and C. Hamilton, Tried and True: Earth's reflection - Albedo, *Science Scope*, 34(6), 2011.

Diversity

The diversity goals at CReSIS are to increase the number of students, staff, and faculty from underrepresented groups in science and engineering by fostering an interest in science throughout the K-12 minority community, as well as among women and individuals with disabilities. We also seek to ensure diversity in all aspects of the Center by encouraging and facilitating the involvement of students at our partner and minority serving institutions to pursue graduate education in science or engineering. To achieve these goals, CReSIS has worked with ADMI, ECSU, and Haskell to increase minority students entering graduate school, increased participation of underrepresented groups in the REU programs, and focused K-12 educational outreach at schools with underrepresented populations (average of 72%).

Recruitment and Mentoring of Graduate Students

The Center has experienced significant success in minority graduate student recruitment. Most notably, during Year 9, the percentage of underrepresented minority graduate students increased to 29% compared to 7% in Year 2. The underrepresented minority graduate students include Hispanic, Native American, and African-American student populations. From 2006 to 2013, CReSIS awarded Masters or Ph.D. degrees to 21 females and 12 minority students. Eight female and nine minority students are currently working toward degrees with CReSIS. In addition:

- Six CReSIS students have been awarded NASA fellowships, including two minority students and two females.
- The Kansas University Department of Aerospace Engineering has graduated two female Ph.D. students since 2004—both were supported by CReSIS and each began their research as CReSIS undergraduate research assistants.

Research Opportunities for Undergraduate Students

CReSIS has been successful in placing students from underrepresented groups into the REU/RET program. Since 2005, participation by females increased from 33% to 50% and minority participation increased from 67% to 88%. Nine students who were originally introduced to CReSIS through the REU Program have gone on to pursue graduate work at a CReSIS partner institution. Finally, an average of 43% of our undergraduate research assistants are from underrepresented populations.

Knowledge Transfer

Throughout its lifespan, CReSIS has consistently been active in knowledge transfer activities. The Center-developed sea-level-rise maps are widely used to assess the impact of rising sea on coastal regions. The Center has also provided opportunities for faculty, staff, and students from all areas of the Center to participate in major international and national conferences and workshops, publish results in major archival journals, and openly provide data products to the broader scientific community. These data products have successfully been used in research that led to new scientific findings and discoveries.

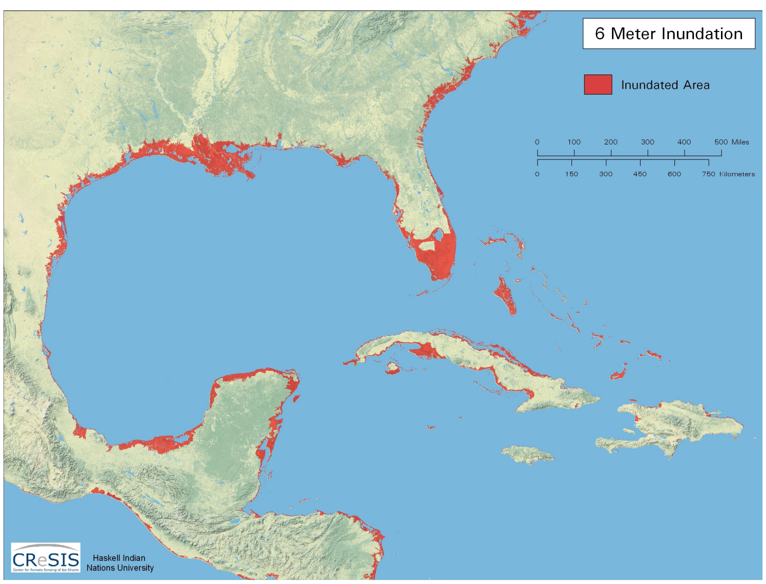


Figure 15: Sea level rise map developed by CReSIS showing the inundation that results from 6 m of sea level rise globally.

Sea Level Rise Maps and Requests for Data

CReSIS developed global sea level rise maps to illustrate the impact rising seas in a warming climate. Geographic Information System (GIS) students at Haskell Indian Nations University developed these maps using a global digital elevation map to show inundation areas from 1-6 m of sea level rise globally [Li et al., 2009; Rowley et al., 2007]. Figure 15 is an inundation map for a 6 m sea level rise illustrating the impact on the coastal U.S. These maps are widely downloaded and used in reports for both the public and policy makers.

Data products produced by CReSIS are hosted on the Center's website at https://data.cresis.ku.edu/ and on a geospatial server at https://ops.cresis.ku.edu/. We host over 7 TB of data products with a monthly average of 269 visitors and 274.4 GB of data downloaded. At the conclusion of a field campaign, data are returned to CReSIS to be post-processed and analyzed; they are posted to our website within a year. Beyond the standard data products, CReSIS also provides custom data products, training, and analysis by request from data users.

IGS International Symposium on Radioglaciology 2013

CReSIS and the International Glaciological Society hosted a conference on radioglaciology at the University of Kansas from September 9-13, 2013. The conference, which was attended by delegates from 15 countries, took a comprehensive look at developments in radar, signal processing, and seismic technologies; previewed the latest results and technical advances; and identified gaps in observations to improve ice-sheet models.

Figure 16: Dr. Gogineni opens the 2013 IGS Symposium on Radioglaciology at the University of Kansas.

Topics for the meeting included:

- Radars and signal processing techniques for sounding and imaging of polar ice sheets.
- Recent radar observations and results over the Greenland and Antarctic ice sheets.
- Using radar observations to improve ice sheet models.
- Quantifying ice physical properties and basal conditions with radar techniques.
- Validating radar measurements with seismic observations and modeling techniques.
- Quantifying the geometry of temperate and debris-covered glaciers.

Photos and presentations from the 2013 International Glaciological Society Symposium on Radioglaciology are available on the CReSIS website at http://www.cresis.ku.edu/ content/news/cresis-meetings/igs-conference-2013.

Cover Pages and Outputs

Over the past five years, CReSIS has been featured on the cover of nine different publications, including *IEEE Aerospace and Electronic Systems Magazine* (2009), the *Journal of Glaciology* (2010), *IEEE Geoscience and Remote Sensing Letters* (2010), *Transactions on Aerospace and Electronic Systems* (2012), *IEEE Transactions on Geoscience and Remote Sensing* (2012 and 2013), *IEEE Geoscience and Remote Sensing Magazine* (2014), *Annals of Glaciology* (2014), and *IEEE Transactions on Geoscience and Remote Sensing* (2014).

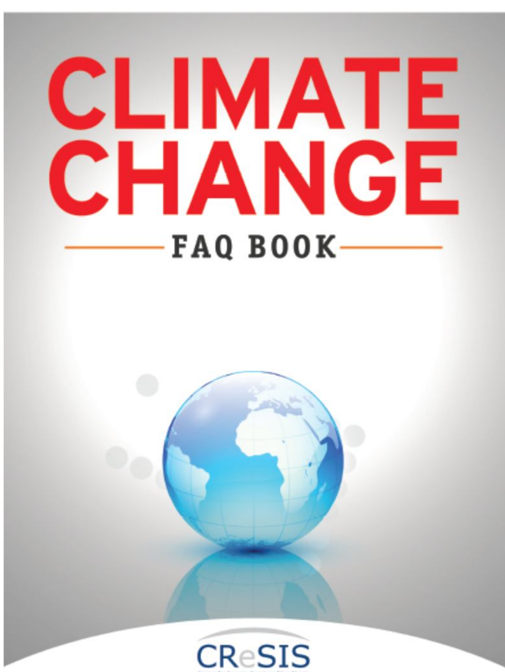
In addition, CReSIS has produced 266 peer-reviewed articles, 288 conferences presentations, and 60 reports. Of these, 57 articles, 107 presentations, and 47 reports were led by students.

Conferences, Symposia and Workshops

From 2005 to now, CReSIS has supported student attendance at a wide variety of conferences and workshops. These include several major IEEE conferences and symposia, AGU meeting in San Francisco, and IGS meetings and workshops on snow and ice. In addition, staff and students have attended short courses on Synthetic Aperture Radar (SAR), seismic data processing and analysis, ice-sheet models, and communicating science to public. CReSIS faculty have also given lectures on radar, signal processing, and ice sheet models in international short courses.

Information Dissemination

CReSIS provides information to the general public in a variety of platforms. The CReSIS website serves as the main external portal, housing features such as the quarterly *Icebreaker* newsletter and the Climate Change FAQ book. These sources are updated and maintained by the Knowledge Transfer team, which includes two student journalists, a student graphic designer, a student website administrator, a staff member, and a faculty sponsor.



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