Final Site Visit Report
October 7 & 8, 2014
NSF Award Number 0424589

1. Introduction

The Science and Technology Center for Remote Sensing of Ice Sheets (CReSIS) is in its tenth and final year. Consequently, a ninth and final review of the center was held on 7-8 October 2014 at the National Science Foundation (NSF). Organized as a "reverse site visit", with CReSIS faculty, staff and students travelling to NSF, the purpose was to: (1) evaluate the STC Center's accomplishments over the lifetime of the Center; (2) to evaluate the added value in all areas of the Center's activities; and (3) to evaluate the legacy of the Center as it begins to "sunset".

The members of the review panel were:

- Dr. Martin Jeffries, Arctic Science Advisor & Program Officer for Arctic and Global Prediction, Office of Naval Research.
- Dr. Tamara Ledley, Senior Scientist and chair of the Center for Science Teaching and Learning at TERC.
- Dr. James Momoh, Professor of Electrical and Computer Engineering, Howard University.
- Dr. Claire Todd, Associate Professor of Geosciences, Pacific Lutheran University.

The NSF members of the site visit team were:

- Dr. Dragana Brzakovic, Senior Staff Associate, Office of International and Integrative Activities.

- Dr. Joyce Evans, Program Director for Undergraduate Education, Directorate for Education and Human Resources.
- Dr. Hedy Edmonds, Program Director for Arctic Natural Sciences, Division of Polar Programs.
- Dr. Julie Palais, Program Director for Antarctic Glaciology, Division of Polar Programs.

2. Overview of the Center

2.1 Center's accomplishments to date. Impact of these accomplishments.

CReSIS has transformed the scientific community's understanding of the role of ice sheets in sea level rise. This understanding has improved projections of future sea level rise, and thus improved the ability of densely-populated coastal areas to respond to the social and economic challenges associated with rising seas.

The Center's chief accomplishments toward these projections include (a) identifying the driving processes behind ice sheet mass loss, (b) developing state-of-the-art sensors and platforms required to study these processes, (c) collecting high resolution data required to quantify those processes, and (d) producing high-quality data products for use by the scientific community. The impact of this work is far-reaching, as CReSIS data has supported numerous high-level publications by scientists at the Center and elsewhere. The use of CReSIS data to refine sea level projections published in the 2014 IPCC report exemplifies the significant role of the Center in the global scientific community.

The Center's commitment to educating the next generation of scientists, with a focus on reaching and supporting underrepresented communities, is evident through the widespread and meaningful involvement of undergraduate and graduate students. Students have participated through curricular activities and independent research projects. Close mentorship of student participants has produced student publications, conference presentations, and awards. Placement of students in jobs in industry, academia, and other sectors suggests a long-lasting legacy of student involvement in CReSIS accomplishments.

Outreach activities in communities surrounding CReSIS institutions have promoted an understanding of the scientific method and fundamental glacial processes. These activities have reached thousands of community members ranging from kindergarteners to high school students, and in some instances the students' families.

Significant attention to diversity is paid at all levels of the CReSIS effort. Evidence can be seen in the percentages of underrepresented populations in

CReSIS faculty, staff, and student participants. Particularly notable is the increase in these percentages over the duration of the Center's activities.

CReSIS has also set a high standard for effective management of a Science and Technology Center. Strategies that led to the Center's success include frequent meetings of the core management team, periodic revision of a strategic plan, and a clear focus on the central goal of the Center.

2.2 Potential legacy and demonstrated programs/activities towards the legacy

CReSIS leaves a legacy in a number of areas. These include the sensors and platforms that they developed to improve the quality and coverage of the geophysical measurements that they collected; the archived data products and satellite observations of the Greenland and Antarctic ice sheets that have led to a more complete understanding of those ice sheets and how they are changing; the modeling and analysis efforts that have contributed to an understanding of the physical processes that shape how ice sheets evolve and how changes in the ice sheets contribute to sea level rise; a large group of undergraduate and graduate students who have gone on to industry and academic careers in the field; and K-12 programs involving students and teachers to engage students in pursuing geoscience careers and becoming science literate citizens.

The accomplishments on the technical side (technologies and platforms, data products, and modeling efforts) will continue to be used in future research programs that will be funded through other avenues. The legacy of the graduate and undergraduate students that have gone through the CReSIS programs will provide a rich research community to carry on the work. The legacy of the K-12 and outreach activities are harder to predict, however, it is hoped through those activities future geoscientists, scientists, technologists and informed professionals and citizens will emerge. It is unclear how the public websites and K-12 curriculum materials will be maintained and updated after the CReSIS funding has ended. We provide suggestions in section 4 of this report.

2.3 Value added, including specific examples in research, education, and knowledge transfer.

The added value of CReSIS is the bringing together of a multi-disciplinary, multi-institution team of experts in ice sheet geophysics, radar engineering (hardware and software), airborne platforms and cyberinfrastructure to generate open access data products that have transformed the knowledge and understanding of the great ice sheets. The Center has also developed a potentially transformative model for integrating research into education, and providing research opportunities for undergraduate and graduate students, as exemplified by the Aerospace Engineering and the REU program. CReSIS

funding enabled partnerships among research intensive universities, minority-serving institutions and professional organizations that provided a pathway for undergraduates from underrepresented groups to enter graduate education and research, and ultimately pursue STEM careers.

3. Research

3.1 Comments on accomplishments to date, specifically comment on any significant ones that would not have occurred without this Center

3.1a. Sensors and platform development: CReSIS has developed advanced radar technology for data collection over the Greenland and Antarctic ice sheets. They have developed different radars to map internal layers all the way from the surface to ice bed to determine annual, decadal, and century-scale accumulation. CReSIS has also developed a Ku-band radar to map near surface internal layers with fine resolution of about 5 cm in the top of 5-50 m of firn and ice. Accumulation radar data provide excellent information on snow accumulation over large areas. Finally, CReSIS has developed radars for high resolution mapping of the glacier bed.

CReSIS has also designed and built the Meridian unmanned aircraft to support radar and other measurements. The aircraft payload capacity was studied to ensure that the aircraft could operate in different locations with high radar penetration of ice sheets; many successful flight tests were performed. To achieve the design and construction of the Meridian there has been fundamental research in dynamics and control, including real time parameter identification of the aircraft non-linear and unsteady aerodynamics using adaptive artificial neural networks, and identification of non-linear aerodynamic behavior known as wing rock in a large UAS using Fuzzy Logic Modeling (FLM). CReSIS developed an online trajectory modification scheme for collision and obstacle avoidance for multiple collaborative and non-collaborative fixed-wing UASs. The Center has also designed tractable resilience and robustness algorithms to reduce the impact of parameter shifting, uncertainty and component failures in non-linear model predictive control (NMPC) for the next generation of Earth and Science UASs. There has also been 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. Finally, CReSIS has development of an 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.

b. Data analysis and modeling: CReSIS has developed high resolution data products, e.g., radio-echograms of ice thickness and bed topography, and internal layers, which are available to CReSIS researchers and the broader

research community. These products are essential to accurate modeling of ice dynamics and ice sheet contribution to sea level rise. The Center facilitated the close integration of numerical modeling and data collection, which led to significant improvements in understanding ice sheet behavior and projecting future sea level rise.

3.2 Potential impact of the activities planned for the remaining year

CReSIS has a comprehensive program for the final year. This includes continuing work on sensors, signal processing, the SAR processor, adaptive array processing, platforms, and data products and modeling. Much of the proposed activity is aimed at making further technology improvements that will enhance the quality of the data and derived products obtained from the glaciers and ice sheets. The program for the final year is potentially high impact.

3.3 Legacy

CReSIS has identified the driving processes that control the stability of the Greenland and Antarctic ice sheets, and the most valuable locations for quantifying those processes. This effort has focused the broader polar science community on the significant knowledge gaps in our understanding of sea level rise.

The development of high-performance sensors and platforms has dramatically expanded the types and amount of glaciological data that can be collected in polar regions. CReSIS can extend this legacy by clearly outlining how these instruments will be available for use by a broader scientific community in the future.

The collection, processing, and distribution of high-resolution glaciological datasets will enable the investigation of ice sheet processes at temporal and spatial scales previously unavailable to the polar science community. These datasets will provide the foundation for more accurate modeling of ice sheet evolution. To ensure this legacy persists, the Center must plan for the storage, cataloging, discovery and availability of raw and processed data.

4. Education and diversity

4.1 Integration of research and education activities, and value-added aspects

CReSIS has done an excellent job of integrating students – undergraduate and graduate students at the partner institutions, other undergraduate students through the REU program, and K-12 teachers (Research Experience for Teachers) in the research components of their programs; and in integrating

their research into rigorous courses that are available to students across the institutional boundaries.

Undergraduate and graduate students as well as K-12 teachers have been involved in all aspects of the CReSIS research and development programs. This includes sensor and platform development as well as science research programs. The CReSIS project has produced 266 peer-reviewed articles, 288 conference presentations, and 60 reports. Of these, 57 articles, 107 presentations and 47 reports were led by students.

CReSIS developed new courses and enriched pre-existing courses with Center-specific content. This curricular development led to a new masters program at ECSU and a more immersive undergraduate program in the KU Aerospace Engineering department. In addition, using internet-based video conference facilities, students and faculty at the partner institutions were able to participate in and contribute to the implementation of these courses.

A particularly impressive example of the benefits of the integration of research and education is in the Aerospace Engineering Department at the University of Kansas. In that program CReSIS research is integrated throughout the curriculum – in 18 courses at the University of Kansas freshman through senior year. Some of the sensor and platform development became problems that students were assigned in their classes. In addition, two capstone senior design projects were required. One of these was individual and the other was more open where students could choose the topic and could work on teams. Many of the senior design projects were submitted to design competitions and one year all of the CReSIS projects won. These successes can be really engaging for students as they can see that their work has an impact on the field.

In addition to integrating students and teachers into the research and the research into the undergraduate and graduate courses, CReSIS has integrated its science knowledge into a number of avenues for K-12 education and the public. It has been integrated into the *Ice Ice Baby!* curriculum materials, into classroom visits and informal science and engineering activities, a two week summer program for middle school students, and teacher workshops at a number of the partner institutions and in the second phase through online workshops. The Education and Outreach team also published 5 articles in teacher professional publications.

4.2 Involvement of U.S. citizens as undergraduates and graduate students, and postdocs.

CReSIS' education program begins with our youngest students, reaching elementary and high school students through the Center's extensive outreach activities. CReSIS' outreach staff has developed easily-transferrable educational

tools such as lesson plans, and outreach activities for scientists. Over the life of the Center, outreach activities have evolved considerably through careful evaluation. For example, outreach materials available to teachers now align more closely with core curriculum standards. These materials are available online and will reach U.S. elementary and secondary students for years to come.

CReSIS scientists have integrated undergraduate, graduate, and post-doctoral scholars in all aspects of their work. Undergraduate students may have contributed to CReSIS through an REU program or in their classroom, tackling current and challenging problems in STEM fields. Graduate students have been actively involved in field, numerical, remote sensing and laboratory investigations central to CReSIS's goal. This involvement is documented in the long list of student conference presentations and publications. Some of these conferences were of particular value to the Center's diversity goals, as collaborations with ADMI enabled the participation of students in conferences serving minority professional groups.

One of the hallmarks of the CReSIS education program is the aggressive and early recruitment of students from groups underrepresented in STEM fields. This recruitment was facilitated through close collaboration between CReSIS partner institutions, and led to the development of pathways for MSI students who would not have had opportunities to participate in scientific research.

The Center has also engaged and supported undergraduate and graduate students in novel ways. Extracurricular initiatives such as the CReSIS student group and the graduate student mentoring award has extended student involvement to outreach activities and peer-to-peer mentorship. Student involvement with CReSIS education staff has led to professional development for students in education, journalism and graphic design.

4.3 Clarity and focus of education and diversity mission, and potential legacy

CReSIS developed and pursued two major education and diversity goals. The first 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." The second goal was "to inspire and encourage students in K-12 to purse education in STEM fields."

CReSIS pursued these goals partially through the activities described in the "integration of research and education activities" above. In addition, they pursued the clear goal of increasing the number of students, staff, and faculty from underrepresented groups in science and engineering and fostering an interest in science in the minority K-12 community. This is evident through their partnership with a number of minority serving institutions to increase the

number of minority students who participated in the program. The percentage of minority graduate students increased from 7% in year 2 to 29% in year 9. Between 2009 and 2013 Masters or PhD degrees were awarded to 12 minority and 21 female students with 9 minority and 8 female student currently in the program.

The CReSIS REU/RET program has a higher success rate for including minority and female students. Since 2005 minority student participation has increased from 67% and 92% and female participation increased from 33% to 50%. 43% of the CReSIS undergraduate research assistants are from underrepresented populations.

The large number of minority and female students that have participated in the CReSIS program will go a long way to increasing their representation as future leaders in the field – whether in academia or industry. In addition, the new Masters program at ECSU will provide additional students at that minority serving institution the opportunity to pursue a career in the fields of Earth and climate science.

While the impact of the K-12 activities are more difficult to measure, the reach of the program – over 55,387 people – suggests that it has been large and the impact important. There is some concern about how the *Ice Ice Baby!*, the *Climate Change FAQ Book*, *The Icebreaker*, and outreach website will be maintained into the future to insure accuracy and up to date information for those using it now and as a resource for teachers and future students.

The science and engineering departments involved in CReSIS should partner with the education departments and integrate the maintenance and possibly the use of the educational resources and materials into the undergraduate education and science major courses. The partnership will increase education students science content knowledge and the science students understanding of the needs of educators and experience with communicating science to teachers and students. This effort could build on the experience with the integration of the CReSIS research into the KU aerospace engineering courses, which is being institutionalized after CReSIS funding ends.

4.4 Balance between educational and diversity activities that are innovative and unique to the Center and existing activities at the institutions

CReSIS brought a number of unique and innovative educational and diversity activities to the partner institutions. The focus on the recruitment and retention of minority students benefited all of the partners and the future of the field. For example, the path from outreach activities to participation in REU programs, sometimes at multiple partner universities, and then ultimately to graduate programs is increasing diversity in STEM fields. The Research

Experiences for Teachers was an innovative effort to involve K-12 teachers in research and to have them integrate that experience into teaching materials and into their teaching.

CReSIS developed courses that were collaborations between faculty at partner institutions and through the use of internet based video conferencing students at all of these institutions could participate in these courses. CReSIS also enabled the development of a new Masters program at a minority serving institution and the enrichment of degree programs at other partner institutions.

4.5 Accomplishments to date

CReSIS staff and scientists have engaged hundreds of graduate and undergraduate students in their work. This engagement has occurred at all stages of the scientific process; CReSIS students have participated in field and laboratory research, as well as presentation to the scientific community through conferences and publications. The placement of most graduates in STEM fields is further evidence of CReSIS' commitment to education and mentorship. Through internship and REU programs, CReSIS has reached many students at MSIs, creating new paths for underrepresented groups to participate in STEM activities.

The Center's impressive outreach program has led to permanent incorporation of polar science education at lower grade levels and through groups such as the Girl Scouts. The availability of the *Ice Ice Baby!* lesson plans is one example of the legacy of CReSIS' education program. We suggest that the Center submit these for review for inclusion in the Climate Literacy and Energy Awareness Network (CLEAN) Collection (http://cleanet.org) where it will get broader dissemination there and through NOAA's Climate.gov portal.

We suggest that CReSIS develops a partnership with the KU Education department and integrate the maintenance and possibly the use of the educational resources and materials into the undergraduate education and science major courses. The partnership will increase education students' science content knowledge and their understanding of the needs of educators, and experience with communicating science to teachers and students. This effort could build on the experience with the integration of the CReSIS research into the KU aerospace engineering courses, which is being institutionalized after CReSIS funding ends.

The Center's education group has successfully leveraged initial CReSIS funds to maintain these activities throughout the life of the Center. This fundraising will need to continue to maintain these paths in the future. The education group is already preparing for this transition by applying for REU support and

other education-focused funds. Another approach would be for future polar science proposals to take advantage of the considerable education infrastructure in place, and request funds to continue outreach activities and collaborations with MSI institutions.

5. Knowledge transfer

5.1 Clarity of knowledge transfer goals and potential legacy

The knowledge transfer goals and potential legacy are very clear; CReSIS has conducted a very successful and wide-ranging knowledge transfer effort. The overarching goal is to engage in 2-way knowledge transfer that benefits CReSIS, scientific and academic communities, industry and the public. Knowledge transfer also includes commercialization and entrepreneurship, and engagement with policy-makers.

From an academic research perspective, CReSIS success in knowledge transfer is exemplified by the publication of >250 papers in leading peer-reviewed journals, and as many presentations at conferences. The review panel commends CReSIS for enabling students to present the results of their research at many of the conferences. CReSIS research has also been featured on the front cover of a number of leading journals; this recognizes the quality and importance of the research and increasing awareness of the center.

CReSIS also organized an International Glaciological Society Symposium (IGS) on Radioglaciology. The IGS is the premier professional society for glacier and ice sheet scientists; organizing an IGS symposium attests to CReSIS's reputation in the scientific community. Symposium papers will be published in the peer-reviewed Annals of Glaciology.

CReSIS has an exemplary data policy, i.e., it makes available all data products (echograms of glacier and ice sheet thickness, internal layers, bottom topography, etc.) online via a Web site. This open data policy has enhanced the impact of CReSIS by making it possible for non-CReSIS researchers to analyze data and publish the results of their research. The CReSIS sea level rise maps, also available online, are another successful data product that has been downloaded for use by the public and policy-makers.

CReSIS has created a number of information products for the general public, e.g., the *Icebreaker* newsletter and the *Climate Change FAQ Book*. These publications are maintained and updated by the Knowledge Transfer team that includes students.

The review panel notes that CReSIS has more work to do with respect to commercialization and entrepreneurship. The center continues to develop

cutting edge advanced technology and ought to do more to protect the intellectual property, e.g., via patents. This, in turn, could lead to royalties that could support further research and education activities.

5.2 Involvement of appropriate partners in accomplishing goals

To accomplish its numerous knowledge transfer goals CReSIS has engaged with a number of appropriate partners in the U.S. and overseas. These are primarily academic institutions, but also include U.S. National Laboratories (Los Alamos National Laboratory, Naval Research Laboratory) and leading international polar research centers such as the Alfred-Wegener-Institut in Germany. CReSIS partnership with the private sector has been less than with other sectors, and the review panel recommends that CReSIS do more to engage with the private sector, particularly with respect to commercialization and entrepreneurship.

5.3 Appropriateness of developed (or under development) mechanisms for knowledge transfer

CReSIS uses a variety of appropriate and successful methods for knowledge transfer. These include use of the Web for access to data products and information dissemination to the public; conference presentations and publication in conferences proceedings; publication in leading peer-reviewed journals.

CReSIS also lends its radar systems to other institutions, both in the U.S and overseas, which attests to CReSIS's reputation in remote sensing of ice sheets and enhances international collaboration. International collaboration has also been enhanced by student and faculty exchanges with institutions and organizations in Australia, Chile, Denmark, Germany, India and the U.K.

5.4 Integration of knowledge transfer with other Center activities

Knowledge transfer is well-integrated with other Center activities such as research and education. This is exemplified by the full participation of undergraduate and graduate students in Center research activities, and the many opportunities provided for students to present the results of their research at conferences, and to publish papers in conference proceedings and peer-reviewed journals. Students also play a key role in maintaining and updating the content of the CReSIS web site.

5.5 Accomplishments to date

The knowledge transfer accomplishments to date are many and successful. They include: hundreds of publications in conference proceedings and peer-reviewed journals; CReSIS research featured on journal covers; organizing

conferences and seminars; open access to data products for the entire scientific community; radar system loans to other organizations and institutions; publication awareness efforts via the Web that include a newsletter and book about climate change; international collaboration; and some interaction with industry.

6. Summary and Recommendations

CReSIS has done an amazing job of enabling collaborations among a diversity of institutions and a range of academic disciplines that have resulted in the development of sensors and platforms in the direct service of scientific research that has contributed to improved ice sheet models and understanding of ice sheet mass balance and contributions to sea level rise; a legacy of future scientists and engineers (with significant numbers of minorities and women) in aerospace engineering and polar research and other fields where these skills are needed; and the engagement of K-12 teachers, students, and the public. Enabling and managing these complex partnerships is very difficult and rare.

The review panel offers the following recommendations as CReSIS approaches the conclusion of its ten years of NSF support, and looks ahead to address its future direction and sustainability:

1. CReSIS should consider finding a way, through publication or other approaches, of sharing how to accomplish such productive collaborations and partnerships. This might enable future STCs and other smaller collaborations and partnerships to be more effective. NSF might facilitate sharing lessons learned from the CReSIS partnership and management structure to help other projects and programs be more effective.
2. CReSIS must do all it can to ensure that the vast amount of raw signal data obtained by the radars are archived, with complete metadata profiles and data documentation, and available for future use via a user-friendly Web interface.
3. CReSIS should do more to address the issue of intellectual property (IP). This includes identifying technology that could/should be patented, and potentially earn royalties via commercialization by the private sector. This could include novel applications of the technology in, for example, oil and gas exploration, natural hazards detection and security.
4. CReSIS should give careful consideration to how its sensors and platforms will be made available to the broader research community.
5. CReSIS should do all it can to maintain the partnership among the institutions that has helped to develop pathways for under-represented groups to pursue graduate degrees in STEM.
6. CReSIS should do all it can to maintain and use the extensive and effective outreach infrastructure that has been created.

7. CReSIS should do all it can to continue the integration of research and education in the many courses developed by the partner institutions, and disseminate this experience more broadly to promote adoption elsewhere.

Signatures: STC Site Visitors for CReSIS:

Dr. Martin Jeffries, Chair Date: 10/08/2014

Dr. Clair Todd Date: 10/8/14

Dr. James Momoh Date: 10/8/14

Dr. Tamara Ledley Date: 10/8/14