Supporting International Capacity Building with the Future NSF Geophysical Facility

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With this letter we advocate for the support of international capacity and cooperation building activities by the NSF Future Geophysical Facility (FGF). The community workshop report *Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences* specifically notes that “[i]nternational training efforts in data collection and distribution catalyze unique professional networks that span from students through senior international network management and staff.” In general, collaboration with international partners plays a vital role in advancing scientific objectives of the U.S. geoscience research community and contributes to an improved understanding of global geohazards (i.e., characterizing the processes which contribute to damaging earthquakes, volcanic eruptions, landslides, tsunamis, and induced seismicity), while also providing crucial observations of varying near-surface dynamics. These include assessments of climate change through observations of permafrost active layer variability, changes in surface and subsurface ice/mass water flows and storage, and near-surface interactions with the lithosphere. These processes cause short and long-term changes at the land-water interface, affecting sea level and environmental hazards during and in the wake of hurricanes or other extreme weather events. The present SAGE and GAGE awards facilitate extensive research beyond the borders of the United States, with U.S.-based Principal Investigators (PIs) working with international collaborators to operate permanent or temporary geophysical observatories on every continent. Furthermore, data from dozens of countries are archived with the UNAVCO and IRIS data centers. International capacity building and cooperation efforts provide both short-term and long-term benefits: they build and sustain international collaborations, improve data quality, promote open data access, broaden participation, and advance science for the benefit of society. A committee focused on international capacity building activities (the International Development Seismology Committee, or IDSC) is part of the IRIS governance structure and includes U.S.-based members from both the IRIS and UNAVCO science communities, along with international members.

The current facilities operated by UNAVCO and IRIS have a successful track record of international capacity building and cooperation, using modest core budgets and small supplemental awards that leverage existing programs and infrastructure. These activities have improved the delivery of key geophysical data from a wide range of international contributors and in some cases facilitated the transformation of the geophysical monitoring capabilities of entire regions (e.g., COCONET in the Carribean basin) or countries (e.g., TLALOCNet in Mexico, GRO-Chile). Over the last decade, IRIS has organized over a dozen workshops and meetings, mostly in international locations in different regions of the developing world (Central and South America, the Caribbean, Africa, the Middle East, and Southeast Asia), which focused on standards for accurate metadata creation and training for network operators. Similarly, UNAVCO routinely hosts short courses on GNSS, strainmeter, LiDAR, and InSAR processing with regular attendance from international (and early career) participants. These events promote high data quality standards among network operators and encourage open data sharing and regional networking for local and international scientists, as well as observatory and other key personnel who are in positions of leadership in foreign earthquake and volcanic hazard mitigation programs. In turn, these efforts have greatly expanded and improved the international seismic and geodetic data available to PIs. Some of these workshops have engaged other sponsors in Europe or been conducted with the International Centre for Theoretical Physics (ICTP in Trieste, Italy).

In recent years, IRIS in particular has leveraged its current programs as well as special funding sources to organize capacity building activities on a trial basis. In late 2015-2016, four Spanish-language webinars focused on seismological topics and analyses were well-attended, with a viewership that was similar to, or higher than, English-language webinars held during the same time period. In 2018-2019, IRIS funded (via the Simpson Fund for Innovation) four internships for international undergraduates and integrated these students with the yearly cohort of U.S.-based IRIS interns. The program has proven popular, with a large number of U.S.-based PIs applying to host interns. The international undergraduates carried out successful summer projects at host institutions in the U.S., and already one has begun graduate school in the U.S. These kinds of capacity building activities could be formalized or expanded with appropriate funding structures within the FGF, and expanded to cover the full range of disciplines supported by the FGF. Partnerships with other international groups (e.g., COMET in UK, GFZ in Germany, ICTP in Trieste) could enable broader participation, and enable sharing that leads to a new, improved 'best practice' in training.

Both the current GAGE and SAGE facilities support the community in response to significant earthquakes, volcanic eruptions, or other geohazards events, often supported through NSF RAPID proposals, for Rapid Array Mobilization Program (RAMP) deployments (a term used by the SAGE facility). SAGE is working to establish a modern, dedicated pool of instruments for RAMP deployments, while GAGE usually uses instruments from its general pool available for short-term equipment loans (for long-term deployments the RAPID proposal may include funds for additional instruments). The history of RAMP-style deployments shows that most are located in regions outside the U.S., often in countries that do not have significant resources to conduct these efforts on their own. Initiation of RAMP-style deployments requires more than just a quick response from the facility. There are many “best practices” for RAMP-type activities that vary by event, environment, country, and scale of the activity. Information about in-country logistics and contacts is often PI specific, and thus not broadly known. This has the potential to diminish the overall effectiveness and responsiveness of the community during these critical events. The FGF is a natural forum to develop a formal process to create best-practices for the international component of RAMP-style deployments, on a level of detail at region or country, including the proactive establishment of a network of in-country contacts and regional partners to maximize the efficiency and thus potential science return of RAMP-style deployments. The FGF would also be able to coordinate with other international teams responding to events to minimize duplication of effort, which undermines the capacity building, and to promote data sharing.

There is a significant benefit to working with international geophysical network operators to either archive data with the FGF or to facilitate the adoption of a federated model to share their data holdings. These activities can drive collaborations by opening data pathways and provide access to data quality assessment tools, metrics, standards, and archiving best practices. We propose renewing and expanding the support for periodic workshops that provide advice and training on the best practices for equipment selection, testing, and installation, real-time network operations, metadata and data handling, and archiving, as well as preservation of legacy data. These activities will increase the capacity for hazard monitoring and basic science and provide a viable foundation for productive, collaborative partnerships with international PIs. Strong international collaborative foundations will be particularly essential as the community pursues ambitious, multi-faceted earth science initiatives such as SZ4D (sz4d.org). For SZ4D and other similar programs, there are scientific goals that cannot be achieved solely with U.S.-focused field studies but can be accomplished abroad through international collaborations. Crucial SZ4D science goals include detailed subduction zone imaging and sampling studies that develop an understanding of earthquake and related processes through the seismic cycle, as well as magmatism and volcanism. New knowledge of geologic processes and associated hazards gleaned from detailed, internationally collaborative studies targeting individual subduction zones can be applied to understand such behavior and their impact within the U.S.

Given the natural synergies with PI-driven research activities in international settings that are supported by the GAGE and SAGE facilities, the successful track record of IRIS and UNAVCO in carrying out capacity building activities, the enthusiasm for such activities in the IRIS and UNAVCO science communities, and upcoming opportunities for international engagement with initiatives such as SZ4D, we urge NSF to consider ways in which international capacity building and trans-national partnerships can be incorporated into plans for the FGF.

An Early Career Investigator Community Vision for the Future NSF Geophysical Facility: Data Services Needs

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Citation: Ford, H.A., M. Floyd, D.S. Stamps, M. Mendoza, E. Bozdag, D. Bowden, J. Byrnes, W. Fan, H. Kehoe, E. Chaussard, N. J. Lindsey, S. Wei, G. Barcheck, T. S. de Smet, H. Janiszewski, E. Lindsey, J. K. MacCarthy, K. Materna, S. Naif, D. Portner, D. Trugman, I. Wang (2020). An Early Career Investigator Community Vision for the Future NSF Geophysical Facility: Data Services Needs. White Paper, 3 p., 10.6084/m9.figshare.12398321.

1.0 Introduction

This white paper has been developed based on a compilation of input from ~45 Early Career Investigators (ECIs) from various institutions who participated in the "*Early Career Investigator Virtual Workshop on a Community Vision for the Future Geophysical Facility*" held April 23-24, 2020 and 59 respondents to a follow-up survey for ECIs distributed via IRIS and UNAVCO list-servs. Our aim is to identify the critical Data Services that need to be within the scope of the future NSF Geophysical Facility such that scientific objectives determined by today's ECIs can be met.

2.0 Data and Data Products Archiving

ECI's scientific advances rely heavily on the availability of both raw data that require specialized processing (e.g. continuous seismic waveforms, magnetotelluric time series, raw GNSS data sets, SAR, meteorological data, real-time data streams), which are fundamental to the function of any Facility, and data products produced by PIs and facilities (e.g. seismic velocity models, magnetotelluric transfer functions and resistivity models, GNSS velocity solutions and time-series, interferograms and time series, synthetic databases of Green's functions) through IRIS and UNAVCO. Both IRIS and UNAVCO host data and data products generated through NSF- and non-NSF-funded projects, including ingestion of international data. We highly recommend the future Geophysical Facility (FGF) ***continue to archive non-NSF funded geophysical datasets*** as requested by PIs.

We suggest the development of ***a single data archiving portal for geophysical data and data products*** that international and domestic scientists could use for archiving at the new FGF. A new single portal for uploads should accommodate standardized file formats, historical data, and updatable metadata that describes the data or data products, as well as any associated information from the originator. A corroborating necessity is the creation of Digital Object Identifiers (DOIs), by the FGF or by the originator, so that the data, data products and related resources are discoverable and citable (following the example of UNAVCO's WInSAR). The service of providing DOIs for data and data products assists in abiding by FAIR data principles and the FORCE11 data citation principles, which are being widely adopted by publishers and is therefore requested by the ECI community. We note that training would be necessary for users of the portal.

ECIs are highly ***supportive of community standards*** as they evolve, such as alignment with the International Federation of Digital Seismograph Networks, SINEX formatted combined velocity solutions, seismic velocity models and magnetotelluric data in HDF5, NetCDF, and ascii formats, and the use of other upcoming standards like GeoCSV and GeodesyML/TimeSeriesML. We suggest that the FGF play a leading role, in cooperation with researchers, in determining, developing, and promoting the most useful standardized data formats that conform to Open Geospatial Consortium and modern High Performance Computing standards.

A centralized repository for diverse derived data products is also of great importance to ECIs. As publishers increasingly require access to these products in FAIR-aligned repositories, a common location provided by the FGF would ensure that the products remain permanently accessible and discoverable by other researchers. Storing published or otherwise unavailable processed solutions are highly recommended for rapid responses to geophysical events.

We envision that the scientific questions addressed by ECIs will increasingly require ***storage of large-volume datasets*** as emerging instrumentation technologies mature (e.g., three component nodal arrays, distributed acoustic sensing, real-time GNSS data, and InSAR time series). Therefore, the FGF will need the capacity to store large datasets and the single archiving portal to upload them. If the costs of storing the large datasets is an issue, additional funding and technical support for storage should be requested by PIs, with consultation with the FGF, when submitting grants to allow the data to be stored in perpetuity.

3.0 Data Distribution

Stable, reliable, and free data retrieval is crucial for geophysical research. ECIs envision the FGF with an intuitive, single-access data portal that will encourage the use of diverse datasets and data products. We suggest that the FGF maintain (or develop) the ability to quickly visualize data and data products with online tools, as well as the capability to access these resources remotely via existing standards (e.g., DaaS, OPeNDAP, HTTP) to minimize disruption in current workflows. We request the FGF to ***offer data retrieval services that cater to various demands***. For example, the FGF would need to be capable of efficiently and securely distributing or providing in-situ access to large volume (multi-TB) continuous data, like the entire TA legacy records. Also, the ability to download portions of larger datasets (e.g., a spatial component of time series data, a subset of stations of a larger network, stations within geographic coordinates), rather than full data archives, is crucial to eliminating unnecessary data requests. We specifically encourage efforts towards efficiency of both storage and tailored *ad hoc* data requests by developing a back-end system alongside an optimized internal database to derive the requested data or product output at a resolution and in a format specified by the user through the front-end. Data storage and requests could then be made more efficient by providing such capability to translate, decimate, or other basic on-the-fly data manipulations as part of distribution, including provision of real-time streams if available.

Due to the inherent diversity of geophysical data sources, the necessity of both raw data and derived data products (see Section 2), and the importance of data quality, we suggest that provenance and attribution be explicitly documented and accessible. For example, when a dataset or data product is accessed the citation and any prior data manipulation should be clear.

We envision that the FGF will continue to develop a variety of tools to assist with the download of data via non-interactive command line calls in several languages used in this community (such as MATLAB, Python, and Julia) as well as interactive GUIs. This may also serve as a single-access front end to facilitate downloads no matter where the data are physically archived (in some instances, this could be on a PI's server that is set-up with external access through cyberinfrastructure such as Hyrax), which in turn may ease the transition to handling large data sets.

4.0 Software Resources and Support

We recommend that the FGF serve as a public face for the data stored and distributed through it. Ideally, there will be simple browsing interfaces (e.g. IRIS Wilber 3, the UNAVCO Data Archive Interface) with interactive tools such as time-series (and, for GNSS and InSAR, velocity) plotters and visualizers. ECIs consider centrally hosted software and some facility-supported software (i.e. translators, portals) to be an asset of the FGF. Examples of desirable software resources include: (1) tools that aid the user in accessing (meta)data archives; (2) tools for appraising data quality; (3) tools that allow flexibility for the user to interact with data, e.g. email, query form, API's, near/real-time monitoring; and (4) a dedicated webpage containing links to externally- and facility-supported software that are commonly used in the geophysical community for education and research. We note that software built to handle data (e.g. Obspy, Antelope, teqc) and collect it (e.g. data loggers, GNSS receivers, clocks) require continuous updates and a degree of understanding in order to utilize properly, therefore ***software support services will be essential at the FGF.*** We also request the FGF continue making standard configuration template files for common equipment in pools and stations that are part of regional/global networks open to the community. We find that it will be useful for the FGF to maintain support for ECIs by way of online documentation/references and technicians/engineers who are contactable via email, phone, or in-person.

5.0 Community Governance:

It is essential that the FGF be responsive to the changing data services needs of its users. We support a ***community governance model*** that pairs facility guidance with community input via an oversight-empowered standing committee made of community member stake-holders, including ECIs. This system ensures detailed, two-way feedback between the FGF and the community, assists the FGF in responding more nimbly to changes or expansions in community science emphases, and enhances community investment in (and usage of) FGF services.

6.0 Preparing for Future Science:

As collaboration amongst geophysics researchers becomes increasingly more common through support from the FGF, ECIs would like to see centralized and standardized methods of hosting, requesting, and downloading data. ECIs are in agreement that, as the volume of geophysical datasets being stored and downloaded inevitably increases, from current to emerging technologies (e.g., distributed acoustic sensing, large-*N* nodal arrays), continued support of existing online services and expansion into efficient data storage and cloud computing tools will both be essential. Transfer and processing of ever-increasing volumes of data is rapidly becoming impractical without community ***access to computing power adjacent to data storage*** and a central repository of benchmarked, open-source code for data-intensive processes, including the potential to provide access to community-developed software on such systems. ECIs agree that a transition to cloud-based storage is a viable option to accommodate fast access to large data volumes and effectively addresses (near-)real time processes and big data projects. While ECIs are excited by the additional possibilities associated with cloud-based storage and computing, there is concern regarding the pricing model of commercially available storage solutions and the long-term autonomy provided by any given operator. ECIs prefer to see cloud-based storage allocated via NSF-supported resources, such as XSEDE, with contingent means to interoperate with other cloud storage and HPC providers.

Managing a diverse range of data types and products will require careful planning in regards to data formats and request tools. We suggest the FGF stay at the ***forefront of data formatting standards***, such as those needed to conform to HPC standards or the cloud. For example, the ASDF standard for seismic data is built on HDF5 containers and has gained traction in recent years, in large part due to its flexibility and scalability on HPC systems. Adapting to new data formats implies that software support to convert back to other formats will be important for many existing software packages.

Comments on the Dear Colleague Letter (DCL) on the "*Competition of Operations of an NSF-supported Geophysical Facility to Succeed the GAGE and SAGE Facilities*" issued by NSF (https://www.nsf.gov/pubs/2020/nsf20037/nsf20037.jsp).

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The Dear Colleague Letter (DCL) on the "*Competition of Operations of an NSF-supported Geophysical Facility to Succeed the GAGE and SAGE Facilities*" issued by NSF invites comments from interested stakeholders. I respectfully submit the following comments as a leader in the Geoscience education community, specifically one of the organizers of the Next Generation Science Standards-Earth and Space Science Working Group core team, past-president of the National Association of Geoscience Teachers, Fellow of the Geological Society of America, 2017 Einstein Distinguished Educator Fellow at the U.S. Department of Energy, and 30 year veteran high school geoscience teacher and department chair.

My comments focus on the innovative contributions to geoscience education, teaching resources, seismological data, and capabilities provided by (SAGE) Incorporated Research Institutions for Seismology (IRIS) that together are an authoritative and important resource for the geoscience education community, especially for grades K-12.

I'd like to frame the importance of IRIS (the SAGE facility) to K-12 science teachers and those who prepare K-12 teachers and provide professional development for in-service teachers in this way: The Framework for K-12 Science Education and Next Generation Science Standards, NGSS, suggest that we ask if modern seismology, such as the resources provided by IRIS, fits within the NGSS, and if so, how? The answer is readily found within each dimension of the three-dimensional standards as framed by the Framework for K-12 Science Education. Within the Disciplinary Core Ideas, DCIs, topics such as Earth's structure, seismic events associated with volcanic activity, earthquakes associated with plate motion, icequakes, bedload in fluvial systems, extreme storms, and the location of natural resources are all present. IRIS lessons such as "Determining and measuring Earth's layered interior," "What's shaking in Greenland," and "Can humans cause earthquakes?" provide exemplary, classroom-ready, easy to access (searchable by topic, level, type), NGSS-aligned teaching materials to teachers.

Furthermore, the lessons make use of seismology as a way to enrich lessons with deeper integration of the NGSS Science and Engineering Practices, SEPs and Crosscutting Concepts, CCCs. For example, providing evidence and data for argumentation, computational thinking, designing solutions to problems and challenges in modern and/or urban society, developing and using models, patterns, and cause and effect relationships. Through this three-dimensional approach the science comes to life in a way that is relevant to students. Importantly, the work of expert curriculum developers from IRIS who have faithfully aligned lessons to the NGSS serves to both provide excellent student-ready lessons and to guide teachers in aligning their curricula to the NGSS.

In my experience it is not only teachers seeking classroom-ready lessons who benefit from the resource collection made available by IRIS. In fact, throughout my years in the classroom I used IRIS materials, animations, videos, "teachable moments," and visualizations to deepen my own content knowledge. I know I am not alone in that. I have also had students use the IRIS resources to help them learn across a variety of levels from the basics to more advanced. Importantly, the resources are also used by both pre-service and in-service teacher professional development providers such as in short courses, workshops, research experiences, and webinars. Examples of high-quality webinars provided by experts from the IRIS (SAGE) facility include the mini-series of webinars presented by M. Hubenthal for the NGSS-ESS Implementation community in early 2020 (Beyond Earthquake Locations: Modern Seismology in the NGSS Classroom and Beyond Earthquake Locations: (MORE) Modern Seismology in the NGSS Classroom?). IRIS also supports teachers and others engaged in geoscience education in discovering their materials through their strong social media presence. In short, it is critical to these audiences to have long-term continuity of access to these important and well-vetted teaching materials and resources.

Looking to the future, it should be a high-priority that the current IRIS (SAGE) resources and capabilities be included in the future combined geophysics facility that the geoscience education community can count on to provide a high level of expertise, particularly for grades K-12. The demand for expert support and resources, such as those currently being provided, is likely to grow in the next few years as school districts continue to shift to more online learning. IRIS animations, visualizations, videos, and lessons provide important keys to deepening student engagement with science. In fact, Android Central estimates that in January 2018 there were 25 million students using Chromebooks at school. That means 25 million students who can access the IRIS resources! Additionally, more schools, and states through updated teacher recertification requirements, are working to encourage teachers to engage in professional development opportunities that will lead to a shift resulting in better curricular alignment with the Framework for K-12 Science Education and three-dimensional teaching and learning (NGSS) as they strive to improve student learning.

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June 1, 2020

Response to Dear Colleague Letter: Competition of Operations and Management of an NSF-supported Geophysical Facility to Succeed the GAGE and SAGE Facilities

Topic: Education and Outreach resources, initiatives, and partnerships of the next Geophysical Facility

SCEC's Communication, Education, and Outreach program has collaborated on education, outreach, and workforce development initiatives with both GAGE/UNAVCO and SAGE/IRIS since the 1990s. These partnerships have leveraged our mutual strengths and our distinct activities, such that we can achieve broader impacts in workforce development, science education, and societal resilience to natural hazards.

SCEC's Office of *Experiential Learning and Career Advancement* (ELCA), led by Dr. Gabriela Noriega, coordinates many of its efforts with the geophysical facilities. For two decades, SCEC and IRIS have partnered to provide transformative research experiences for undergraduate students, to encourage and sustain careers in STEM fields, and to support a diverse and inclusive geoscience pipeline. Joint SCEC/IRIS internships have been provided, and applications have been shared to help well-qualified students find internships. Through this partnership, SCEC has been able to expand the reach and impact of its summer internship program and provide additional year-round research opportunities for undergraduate students.

ELCA also coordinates the SCEC Transitions program to support the development and growth of early career earthquake scientists (geophysicists, geodesists, and seismologists). These activities have benefited greatly by our collaborations with the facilities. In 2018 and 2019, SCEC, IRIS, and UNAVCO co-coordinated the AGU Tectonophysics, Seismology & Geodesy Sections Joint Early Career/Student Networking Luncheon. Through this event, we have been able to connect over 190 early career and senior scientists to exchange knowledge and advice in navigating their career pathways.

SCEC CEO's *Public Education and Preparedness* activities have also benefited from strong partnerships with the facilities. SCEC's Jason Ballmann leads the *GeoHazards Messaging Collaboratory (GMC)* with partners at IRIS (Wendy Bohon), UNAVCO (Beth Bartel), USGS (Lisa Wald) and NOAA (Cindi Preller) to present webinars for media and scientists, coordinate special outreach campaigns, and lead conference workshops, all focused on the value of messaging consistency and resource leveraging. Post-earthquake messaging has been an active aspect of the GMC, allowing each organization to share or amplify key findings or messaging in order to reach more people. These activities and partnerships provide the foundation of our pilot education campaign.

Now that Earthquake Early Warning is online in California (and soon in Oregon and Washington), SCEC CEO will be partnering with state emergency managers, the USGS, universities, IRIS E&O, and others involved to educate the public about how it works, including its limitations. CEO will include EEW messaging across all its messaging channels and activities, which provides another channel for disseminating results of this project via the pilot

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campaign. IRIS is a leader in developing educational videos and other resources about EEW, how earthquakes are measured, and instrumentation; these resources are very useful in SCEC's regular public outreach activities such as presentations to businesses, government agencies, community groups, and youth.

For schools this includes support by SCEC, IRIS, and the USGS ShakeAlert Project science education initiative for installing Quake Catcher Network (QCN) seismometers in educational institutions in states currently (or soon to be) served by ShakeAlert. This includes more than 100 schools in each West Coast state and Alaska, all being served by newly upgraded QCN servers located at USC. Several Coachella Valley school districts are now part of a "tectonic" partnership with schools in Anchorage in partnership with EarthScope's Alaska Native Geoscience Learning Experience (ANGLE) program. Sensors have also been installed in 14 schools in the Central U.S. (in partnership with the Central U.S. Earthquake Consortium) as a regional earthquake science education network.

These resources and partnerships are also central to educational messaging distributed via the SCEC-coordinate "Great ShakeOut Earthquake Drills" that now span all US states and territories, as well as other countries. ShakeOut is now a global infrastructure for providing earthquake information to the public and involving them in community resilience. This includes understanding global earthquake hazards and basic earthquake science concepts, which again we are able to partner with IRIS to share with participants (via monthly ShakeOut newsletters and social media). Millions more learn about ShakeOut via broad news media coverage that encourages dialogue about earthquake preparedness. ShakeOut will also now be utilized for educating West Coast residents about Earthquake Early Warning.

These activities are strong and emphasize the value of multi-organizational partnerships in the geosciences that leverage each other's strengths to achieve broader goals. Therefore, the next geophysical facility should continue to provide initiatives and develop partnerships that:

- Provide experiential learning opportunities to students who would otherwise not be exposed to geoscience education
- Provide opportunities for early career scientists to exchange ideas and experiences to successfully navigate the geoscience career pathway
- Develop partnerships with academics and industry professionals that lead to initiatives and opportunities that support a STEM educated diverse workforce
- Coordinate public education via shared messaging resources and strategies that benefit many partners

Sincerely,

Mark Benthien, Director, SCEC Communication, Education, and Outreach
Dr. Gabriela Noriega, Program Manager, Experiential Learning and Career Advancement

The Critical Role of Digital Teaching Resources and Online Education support produced by a future integrated NSF Geophysics Facility

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1.0 Introduction

The role of NSF facilities in providing critical digital teaching and learning resources to support online resources has never been more critical. The global COVID-19 pandemic has likely permanently changed the way we teach across the geosciences, reaching across all content areas explored in the recent (CORES) Decadal Survey undertaken by the National Academies on behalf of NSF in 2020. Where online education in the geosciences was seen as something of an emerging art pioneered and researched by the brave few, suddenly the entire global enterprise of geoscience education has been forced to adapt to this unprecedented environment. The massive and sudden shift to online education and a future with frequently hybrid and “flipped classrooms” will likely become the norm, at least in the short term. However, this current moment in time is driving educational innovation that is likely to be permanent, especially as assessment of learning outcomes and impact on academic and career trajectories becomes clear. These permanent changes in the way we teach and how we ask students to learn will likely benefit us all in the long run and help us teach students more effectively, translate research results into practice more readily, and attract a broader array of students to our disciplines.

Fortunately, because of the activities of the SAGE and GAGE facilities and communities, the geophysics education community was well positioned to respond to the current crisis. Over the last decade at least, community members and colleagues organized through scientific societies such as NAGT (and the Science Education Resource Center - SERC) and AGU have steadily produced what is now a vast array of teaching resources that have been carefully developed, assessed and curated. These resources include those created by IRIS and UNAVCO, and most of these have been cross-referenced and made available publicly through the Teach the Earth portal and many other related portals at the Science Education Resource Center. These openly available resources form a collection of a size and scope that is relatively rare across the science education landscape. Our willingness to openly share our educational innovations distinguishes us as a scientific community and leverages the best characteristics of seismological and geodetic geophysical data. The geophysical community has helped show the way forward for many other geoscientists as they seek to build online resources, and the facilities of SAGE and GAGE serve a key transformative role in helping us meet our collective challenges and play a major role in serving the needs of our community.

2.0 Value to the geoscience education community

The Dear College Letter which solicited these white papers asked for the desired capabilities and roles of an integrated geophysics facility, accompanied by the rationale for why a facility should deliver these capabilities. In this section, we explore two main capability areas using a number of examples from the current SAGE/GAGE structure and products. There are vastly more examples and specific educational applications that could be explored here, so we have chosen to focus on areas which we feel best argue in favor of a facility structure to support this research and education community.

Why is a facility the best structure for this community? Stability is the primary reason. SAGE and GAGE both are built as distributed, multi-user facilities where individual contributions should be managed, curated and developed. Individual contributors are distributed across the nation, and the research community served and data sets produced are ultimately global - even interplanetary with addition of

Mars data. A broad, distributed and active research community is best organized by a facility to maximize shared resources. Educational resources are particularly important in this regard. The facility provides consistent standards for quality, depth and breadth, uniform assessment and assignment of educational levels and applications of resources, and full curating and indexing in a manner that within the geosciences has only been equalled by the various efforts based at SERC (also in most cases with NSF support). The facility structure maximizes the impact of the NSF investments in this area, synergy between NSF-supported projects, and minimizes redundancy and loss of developed teaching resources to lack of updating and tracking of material that would accompany a more decoupled model. The SAGE/GAGE facility structure is ideal to maximize the long-term impact and reach of educational products generated from supported research. The capabilities and products highlighted in the sections that follow argue this point, and illustrate the efficacy of a facility structure in a distributed, multi-user environment.

2.1 Online Teaching and teaching resources in the modern era

The demand for online education has grown tremendously in recent years. Both 2-year and 4- year colleges and universities are rolling out fully online degree programs to keep up with increasing demand. Recent trend shows online introductory geoscience science courses tend to reach capacity enrollment much faster than traditional face-to-face (F2F) courses. With the increase in demand for online courses, the need to access reliable ready-to-go online resources also increases. College professors as well as K-12 educators consistently seek high-quality accessible online resources that will advance their teaching goals and provide the cutting-edge geoscience education to students.

IRIS and UNAVCO-managed SAGE and GAGE facilities provide a wide range of high-quality educational resources that can be readily incorporated into online courses and is accessible to all. The IRIS/UNAVCO websites host a repository of lessons, lectures, videos and public displays that can be added as a weblink to an online course. IRIS learning resources include useful animations, posters, animated GIFs, fact sheets, webtools, lesson demonstrations and educational software. The UNAVCO educational resources also includes useful educator packets, data for educators, tutorials, handouts, hands-on demonstrations, short course materials and various activity modules sorted by learning levels from secondary 6-12 through majors-level undergraduate.

Specific desired capabilities an integrated geophysics facility should offer in terms of educational resources should at the very least maintain the current qualities of the vast collections now available through SAGE and GAGE. These include:

- Content curated and mapped to educational levels and settings as well as key teaching objectives. Many resources in the collection are further mapped to educational standards and are integral to many curricular modules and collections in locations like GETSI (housed at SERC) and other secondary projects. The current IRIS/UNAVCO efforts to manage the indexing of these products should be used as a model for capabilities moving forward.
- Educational visualizations for dynamic and spatially and temporally extended phenomena - a distinguishing feature of IRIS and UNAVCO products is an emphasis on interactivity, visualizations and educational products built to make hidden or very long time scale processes visible and accessible to students from grade 6 through majors. The attention paid to advances in modern curriculum and instruction best practices is exemplary, and should set a standard for the services and products provided by any integrated facility moving forward.
- Online and digital content for use in flipped classrooms and asynchronous distance education - the current structure of making resources modular and scalable maximizes the utility and usability of

these research materials back to the community in their role as educators because of the attention to level, scope and scale. Facility staff has placed a high priority on usability and access that needs to be maintained as a priority in capabilities in an integrated facility

2.2 *Resources for Lone Geophysics Faculty*

It is common for geoscience departments in small and mid-sized colleges to hire a single faculty member to teach all geophysics related courses. This faculty may have conducted research and is specialized in a single area of geophysics, such as Ground Penetrating Radar (GPR), geoelectrical methods etc. Being the lone geophysics faculty member on campus often means they are required to instruct students in all areas of geophysics (ex. earthquake seismology, geodetics studies etc.) and provide geophysics related public service.

Compiling and delivering advanced lectures and labs that are not within a faculty member's immediate area of specialty, can be laborious and time consuming; especially since there is no opportunity for oncampus collaboration. Often, the lone faculty member was afforded an inadequate amount of startup funds, limiting their ability to purchase equipment necessary for lab, lecture, and research use. IRIS's effort to develop introductory urban and environmental geophysics modules, IGUANA (Introducing Geophysics for Urban and Near-surface Applications) is especially convenient to the lone geophysics faculty, as it augments the faculty's ability to helps engage students interested in addressing geophysical issues.

The lone geophysics faculty member tasked with conducting research and teaching benefits tremendously from teaching materials available on the IRIS and UNAVCO websites. We encourage these organizations to continue to provide this invaluable service geophysics faculty members who depend on these resources.

3.0 Digital resources support diverse communities, student success, and workforce development

An important role of the facility structure and the investment of facility funds on education, workforce and outreach is broad support for diversity, equity and inclusion, and in supporting workforce development. Digital resources and online curricula facilitate these efforts across the community, due both to the fundamentally digital nature of most SAGE/GAGE research products but also because of the distributed nature of the scientific community served.

While the integrated facility being conceived now will come into existence hopefully long after the current public health emergency has passed, this current crisis has shown the value of the current SAGE and GAGE facilities in providing products which have enabled this community to educate a broad, diverse, and distributed group of students. With universities and school districts becoming all-virtual, these digital products enabled continued high quality instruction.

Students are able to access these resources freely and on their own schedules, which improves access and student success. Flexible access to high quality materials from IRIS and UNAVCO have put geophysical data and instruction in reach for more students than ever. These resources also support other SAGE/GAGE activities, supporting remote REUs, faculty professional development, and public outreach even in times of crisis. These programs have shown results in enhancing diversity in the geophysical community, and quality digital teaching and learning resources synergistically enhance these investments. It is clear from the current lessons learned that any integrated geophysical facility moving forward must continue to have robust programs in workforce development, education and public outreach, supported and enabled by a high quality, curated collection of research-based digital educational resources.

Education & Outreach as an Essential Element of an NSF Geophysical Facility: Supporting Undergraduate Education of Non-Geoscientists, Novice Geoscientists, and Their Teachers

Author: Vincent Cronin 31 May 2020

An obvious place to develop, maintain, and distribute geophysics education-and-outreach (E&O) resources is within the new NSF geophysical facility that will be created to support the needs of the seismology and geodesy communities. This facility will be a hub where established and emerging researchers, data, and instrumental resources could combine with geoscience E&O specialists and the geoscience-education community to develop and share information. Coordinated research and education efforts within the new NSF geophysical facility will enable coherent, integrated development of E&O products that can be offered for free and open access across a broad range of media platforms. The new NSF geophysical facility can provide a stable and predictable portal for all who seek access to reliable information developed through US Federal Government funding of geophysical research.

Lessons from Past Practice. The extraordinary E&O staffs of IRIS and UNAVCO have produced or facilitated the development of a rich set of educational resources that have been made freely available to educators, students, and the public. They have communicated our science through Twitter, Facebook, podcasts, YouTube videos, websites hosted by IRIS and UNAVCO, and in-person presentations. They have created resources that have enhanced learning in traditional face-to-face classroom teaching, in online teaching/learning, through displays for museums and other public spaces, and in self-guided discovery. These resources have included "teachable moment" products created as natural events are unfolding, animations, visualizations of data, PowerPoint slide sets, educational modules in the GETSI and InTeGrate collections, short courses, webinars, and videos of public lectures. And they have supported students and teachers as they seek to gain new knowledge of emerging science that has not yet reached textbooks. These capabilities should be included in the new NSF geophysical facility.

The coherent set of existing animations, data visualizations, web apps, and short lecture videos that were easily accessible on the IRIS website were an absolute course-saver for my undergraduate students and me as my university closed for face-to-face instruction in March due to the COVID crisis. My graduate course on active faulting was able to utilize online resources embedded in the GETSI resources developed at UNAVCO. Past investments and exceptional human resources at IRIS and UNAVCO made a big difference in continuing high-quality geoscience education during this health crisis.

The expert research community associated with the new NSF geophysical facility, along with the facility's E&O staff, should continue the practice of offering training to enhance the utility of the facility and to expand the community of users. Researchers, applied geophysicists, post-docs, teachers, and students who need training to use the instruments, software applications, data, and other scientific/technical assets of the new NSF geophysical facility might not have access to this expert guidance at their home institutions. Training opportunities offered through the E&O resources of the IRIS and UNAVCO facilities have served to broaden access to groups of people who are under-represented in the geosciences, and have enhanced diversity and inclusion within an evolving geophysics community.

Geophysical Education of Undergraduate Non-Geoscientists. I assert that every undergraduate student needs to know at least some basic information about earthquakes. As natural hazards, earthquakes can have a significant negative impact on affected communities, on society as a whole, and on individual lives. Undergraduates should also be exposed to some of the more interesting characteristics of Earth's surface that we are discovering through the use of GPS networks and high-resolution surface mapping based on LiDAR, SfM, SAR, and other emerging technologies. GPS is ubiquitous in society through modern technology, so GPS geodesy is a natural topic for general science education. Our knowledge of present-day plate tectonics is largely based on GPS and seismic data, providing another obvious pathway for non-geoscientists to learn about geophysics.

The informational needs of non-geoscience students are broadly similar to the needs of the general public, as might be addressed beyond the university through various methods of adult continuing education (science-related journalism, video programming like NOVA on PBS or YouTube programming like TED talks, audio programming in podcasts and NPR shows like Science Friday). Non-geoscience undergraduate students emerge from higher education to become K-12 teachers, journalists, community leaders, investors, builders and developers, engineers, and voters -- all of whom can utilize good geoscience information. The facilitators of geoscience education for non-geoscientists act as liaisons between the active geoscience research community and the general public, and those facilitators need access to the best available information. The transfer of high-quality geophysical information, transmitted in a way that it can be understood by the general public, can happen efficiently within the new NSF geophysical facility.

Geophysical Education of Undergraduate Geoscientists (and Their Teachers).
Undergraduate students who will become geoscientists often find themselves in the position of trying to build their airplane while flying it. Geophysics in particular is based on prerequisite knowledge of relevant geology (mineralogy, petrology, stratigraphy, structure), mathematics, physics, and engineering concepts related to mechanics, thermodynamics, rheology, and so on. All of that was true decades ago as it is today. The difference is that, today, geoscience students also need a functional set of computer skills to work with the large and complex digital datasets that are increasingly available, thanks to wise open-data policies implemented by NSF throughout the current century. As the new NSF geophysical facility will be a portal to high-quality geophysical data, it must also be a portal to the basic and advanced educational resources needed for novice and early-career geoscientists to understand and utilize those data.

Many participants in short-courses and workshops offered by IRIS and UNAVCO are current faculty members who need training in emerging content areas. Teaching teachers is an essential method for spreading our best current understanding of the Earth. For example, the ability to estimate crustal strain from GPS velocity data was once a capability limited to a few research labs, but now it is a standard component of undergraduate geoscience education because of GETSI -- a collaboration between geoscience researchers, educators, and E&O specialists that has resulted in useful and free/open educational products. The growth of young investigators in seismology and geodesy is related in part to expanded exposure of students to these fields of geoscience in their pre-graduate-school years. Creation of educational resources that are not hidden behind commercial/publisher pay walls should be an important element of the new NSF geophysical facility.

I was privileged to receive an education at exceptional colleges and universities. However, my education as a geologist included only the most basic concepts in seismology and did not cover geodesy at all. (Indeed, the NAVSTAR constellation was not operational until years after I earned my doctorate.) Even though I lacked formal training in these fields of geophysics, seismology and GPS geodesy became fundamental to my career as a geoscientist: in research, in teaching, in developing educational resources for others to use, and in applying science to address societal needs. My post-graduate education in seismology and geodesy was made possible through my voluntary association with the research communities of IRIS and UNAVCO, and was largely enabled by E&O opportunities hosted by these consortia through their NSF facilities.

A National Geophysical and Educational Asset. Designing a geophysical facility that is truly a national scientific asset involves more than just researchers, instruments, and databases. By incorporating an education-and-outreach mission in this facility and providing stable and adequate funding for that mission, we have the opportunity to lower the barriers to entry for the full range of future geoscience students, teachers, researchers, and applied geoscientists who want or need to develop their knowledge of earthquakes and geodesy. When access to high-quality information is open to all who are curious, and when expertise is shared across a community of interest as has been evident in the IRIS and UNAVCO consortia, we greatly expand the potential for unanticipated benefits to science and society through discovery.

The national investment in the NSF geophysical facility needs to include investment in education support by that facility, to impart current knowledge to geoscience educators as well as to support student learning at all levels. This is what the E&O groups at both IRIS and UNAVCO have done so well for many years, and what we should incorporate by design in the new NSF geophysical facility.

Importance of education, public outreach, and workforce development activities to the future geophysical facility

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01 June 2020

Overview

We write this document in response to the recent Dear Colleague letter *(DCL NSF 20-037),* soliciting feedback on the desired capabilities of a future geophysical facility. We write as current or former members of the IRIS Education and Public Outreach (EPO) Standing Committee and as members of the IRIS/UNAVCO scientific community who are strongly committed to education and outreach activities. In this white paper we stress the importance of a future geophysical facility that includes a dedicated team of innovative and visionary education, workforce and outreach (EWO) specialists. These EWO specialists will be essential to the facility and tasked with developing geoscience resources to support best practices in STEM teaching and learning, outreach, support career preparation of future geoscientists; furthermore, their understanding of diversity, equity and inclusion will inform all facility activities. We stress the importance of ear-marking sufficient funds within the facility to adequately support EWO activities.

In particular, we suggest the geoscience facility RFP include these three areas of need: (1) Geoscience resources and outreach for students, formal and informal educators and the public; (2) Support for K-12 educators, students and college-level faculty who prepare preservice science teachers; and 3) Activities aimed at the development of a diverse geoscience workforce. When funding runs short these areas are often the first on the chopping block, but we view them as a crucial part of the proposed future geophysical facility. We discuss each topic in brief below along with suggestions about the programmatic structure of the new geoscience facility.

Geoscience resources & outreach

In these times of conflicting and often inaccurate information about science presented by news outlets and social media, it is particularly essential that correct science be imparted by skilled scientists presenting information based on peer-reviewed vetted work. The current SAGE and GAGE facilities have an exceptional track record of effective public outreach programs, demonstrating the effectiveness of foregrounding EWO activities as crucial components of geophysical facilities. Here we highlight a few examples of successful activities on the IRIS side. UNAVCO similarly runs a world-class education program that is advised by an Education and Community Engagement Advisory Committee made up of members of the UNAVCO science community. For more than 20 years IRIS' Education and Public Outreach program has supported Geoscience education at all levels through the creation of a wide variety of educational resources. Important in these efforts is the ability to change with the times. For example, the IRIS Active Earth Kiosks and other museum displays that were popular in the early 2000s and were viewed by up to a few million visitors per year, are now being augmented/ replaced by social media posts that can provide information in real-time about specific earthquakes and other geoscience phenomena (i.e., volcanoes, landslides etc.), with a recent reach of over 1 million impressions per month. A similar revamping of the IRIS/SSA Distinguished Lectureship Program series is underway. In the past, two scientists skilled in effectively communicating were selected to present non-technical talks on seismology-related topics to general audiences across the US. These lectures were presented at science museums, universities or similar settings. With the surge in information that can be found on YouTube and other similar platforms, large lecture-type venues are not as popular as they were a decade ago. Recognizing this, even before the COVID-19 pandemic, IRIS was transitioning to alternative venues that required the speakers to travel less, engage with smaller audiences in informal settings such as coffee houses, yet at the same time engage with a similar, if not greater, number of people (>500 people/year). These shifts also increase the number of participants from diverse backgrounds who were not necessarily reached by more traditional programming, serving the goals of diversity, equity and inclusion. The documented past successes of proposers in reaching the public through and growth of their social media as a means of public engagement will be important for sustaining the achievements made by IRIS.

We suggest the NSF consider the quantitative measures of the proposers past successes in the area of public education and outreach, including social media activities. Plans for EWO activities in the future facility should also allow program modifications that are agile enough to change with changing times.

Support for K-12 educators and students

A hallmark of the successful EWO programs of the current GAGE and SAGE facilities is the highly successful support provided for K-12 students and educators, and we view the continuation and expansion of this support as a crucial part of the future facility. Again, to highlight some specific examples on the SAGE side, IRIS' Education and Public Outreach group has played a leading role in community-based collaborations designed to promote an understanding of geoscience education. These collaborations have produced documents, including the Earth Science Literacy Principles, which have guided the development of the Next Generation Science Standards (NGSS). Forty-four states have adopted the NGSS or have developed standards influenced by the *Framework for K-12 Science Education,* creating the need for vetted, standards-aligned teaching resources and teacher preparation. IRIS has been providing vetted teaching products and materials for over two decades and making them available online, as well as through webinars, teacher workshops and presentations at local, regional and national conferences such as the National Association of Science Teachers. IRIS's ongoing engagement with the K-12 science education community has resulted in positive branding and recognition of IRIS as a credible provider of high-quality educational materials and standards-aligned lessons. UNAVCO has a similarly strong track record of engagement with the K-12 teacher and student community. Development of these resources has often occurred in collaboration with members of the geophysical community who serve as the content experts, exposing them to new evidence-based practices and pedagogies that they can incorporate into their own teaching practice, and geoscience education experts external to the facility.

We recommend (a) ongoing updating of the best existing resources and the development of new on-line vetted materials that can be used by K-12 educators and students, with an explanation of how the materials will align with the NGSS, will undergo validation, and will be organized and distributed so that they are accessible and easy to navigate; (b) a plan for the involvement of content experts and education researchers in the development and dissemination of teaching resources; (c) an explanation of how these products will optimize learning among students with different backgrounds and levels of preparation; and (d) provide support for college-level faculty who teach courses that include or are designed for future teachers. Many two and four-year colleges and universities are invested in K-12 teacher education. Faculty who prepare K-12 teachers are often overlooked and yet they are essential to the task of preparing competent Earth Science teachers.

The EWO component of the facility should maintain and provide information that is not only factual and based on vetted, peer-reviewed science, but is also sustainable and useful. One way to gauge what materials and resources are needed can be derived from in-coming requests and the popularity (i.e., web-hits) of existing materials and/ or their inclusion in Earth Science teaching collections (e.g., NAGT's Teach the Earth) or in the curriculum of increasingly popular dual enrollment (high school - college) courses. An explanation of how the EWO will gauge the usefulness of materials and products, and how non-useful products and activities will be swiftly depreciated will be needed. Beyond the collection of metrics that track outputs, determining the outcomes (impact and value) of EWO resources and activities will require more detailed investigation via evaluation.

Workforce development efforts

In our view, the future geophysical facility has a crucial role to play in the development of a diverse geophysics workforce. The importance of diversity to the geoscience workforce of the future was recently forcefully articulated in the recent CORES decadal survey report for NSF-EAR. This report emphasized the need to enhance diversity (along many dimensions) in the geoscience workforce, which currently lags behind other physical science fields. True diversity is essential to reach all of the talent potentially available and to ensure that our workforce is capable of meeting the enormous research and societal challenges that we will face over the next decade and beyond. **The development of a diverse and agile workforce to meet the needs not only of the geoscience research community but also society at large must be included as an integral activity of the future facility and as a key component of its education, workforce, and outreach activities.**

Programmatic structure of a designated geophysical facility

How EWO is included, implemented and integrated within the future geophysical facility will be crucial to the EWO success. A detailed explanation of how outreach programs will be conducted and how their success and value will be determined must be integrated into EWO plans from the outset. The implementation plan should be well thought out and specific, and not stove-piped into non-intersecting parallel tracks. For example, it might include, but is not limited to (a) outlining how science experts will provide timely information that can be used for social media posts following large earthquakes; (b) plans to vet 5- and 10-year goals that leverage known changes in education standards and requirements and expected technology changes; (c) a process for tracking metrics to evaluate diversity, equity and inclusion in all aspects of the facility; and (d) an explanation of how duplication of effort will be avoided. We also view robust community involvement and governance as a key component of a successful EWO program. The EWO programs included in the future geophysical facility cannot be viewed as a standalone effort that is removed from the scientific efforts of the geophysics community. Rather, the scientific community must be heavily involved with, and invested in, the EWO program of the future facility.

An Early Career Investigator Community Vision for the Future NSF Geophysical Facility: Education, Workforce, and Outreach Needs

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Citation: Evans, E.L., A. Nikulin, H.A. Ford, D.S. Stamps, N. Creasy, J.L. Swiatlowski, E. Chaussard, D. Trugman, N.J. Lindsey, S. Naif, C. Rollins, K. Materna (2020). An Early Career Investigator Community Vision for the Future NSF Geophysical Facility: Education, Workforce, and Outreach Needs. White Paper, 3 p., 10.6084/m9.figshare.12398372.

1.0 Introduction

This white paper has been developed based on a compilation of input from ~45 Early Career Investigators (ECIs) from various institutions who participated in the "*Early Career Investigator Virtual Workshop on a Community Vision for the Future Geophysical Facility*" held April 23-24, 2020 and 59 respondents to a follow-up survey for ECIs distributed via IRIS and UNAVCO list-servs. Our aim is to identify the critical Education, Workforce, and Outreach (EWO) services that need to be positioned within the scope of the NSF Future Geophysical Facility (FGF) to help advance scientific objectives determined by current ECIs.

2.0. Professional Development

Both ***in-person and web-based training*** are essential for the professional development of ECIs and are needed to advance scientific goals. Most workshop and survey participants (~85%) have benefited from professional development opportunities made available through IRIS and UNAVCO. IRIS and UNAVCO provide support for PIs to conduct domestic and international professional development workshops. Workshop materials, such as videos and digital presentations, are readily available on the IRIS and UNAVCO websites after the conclusion of the workshops. In the last three years, UNAVCO held over 60 in-person short courses, and those materials are publicly accessible. Similarly, IRIS organized 83 webinars that are archived for public access. These courses and materials are valuable resources for ECIs. We encourage the continuation of the above services with a focus on leveraging professional development workshops, short courses, and webinars by the FGF. Critically, many of the existing workshops are made possible through volunteering by current members. As demand grows for online activities, more workshop instructors are required, as is greater logistical support.

Much of the ECI professional development training has focused on data processing and analysis, often at the introductory level. We suggest that the FGF ***expand its professional development repertoire*** and include advanced training. ECIs have identified needs for training in high-performance computing, cloud computing, new FGF technologies (i.e. single access portal), as well as, expanded software training with "Hackathons" where appropriate. Training on the design, use, and application of geophysical instruments could be linked to training on data access, motivating specific data quality analysis procedures and common pitfalls. This should be seen as distinct from instrument training geared toward data acquisition, field operations, and data archiving procedures. In addition to training geared toward teaching and research, ECIs greatly value ***professional development training in career management and navigation***, including preparation for careers outside of academia.

ECIs have also benefited from science-oriented workshops and webinars, especially the biennial science workshops now hosted jointly by the current SAGE and GAGE facilities. These workshops introduce ECIs to cutting-edge research in a number of geophysical disciplines while also providing them with opportunities to promote their own research and develop new collaborations. Therefore, we request that the FGF continue to provide ***significant travel and lodging support for ECIs*** to participate in such activities.

3.0 Internships

Undergraduate and graduate ***student internship programs*** are critical components of EWO, in particular the USIP, RESESS, and Geo-Launchpad programs at UNAVCO and the IRIS internship program. Specifics of these programs vary, but the essential components include a research immersion experience, presentation at a professional meeting, and development of a cohort/network of geophysics students. ECIs with experience either as research advisors or as past interns themselves were clear about the positive impact of these internships. The value of the internships extends well beyond their direct term***;*** for example, based on a recent report of the IRIS internship program (1998-2018), 89.8% of alumni described the program as influential in shaping their education or career trajectory (internship data provided by Michael Hubenthal of IRIS).

Crucially, IRIS and UNAVCO internships provide a key mechanism for ***advancing underrepresented student participation across geoscience disciplines.*** The UNAVCO RESESS internship, in particular, is dedicated to increasing the diversity of geoscience students (not limited to geodesy), and is a model we recommend is continued and expanded. In parallel, IRIS has put an emphasis on increasing the diversity of its student cohorts; on average, 50% of all IRIS interns have been women and the number of underrepresented minority interns continues to grow each year and reached 30% in 2020. Additionally, from 1998 to 2018, 106 out of the 229 (46.3%) IRIS alumni have come from non-IRIS institutions (e.g. voting members), where they may have had limited exposure to seismology and lacked access to research opportunities in geophysics. In all, the ECI community was in agreement that the IRIS and UNAVCO internship programs are necessary vehicles for introducing, recruiting, and retaining students in the geosciences.

We urge the FGF to ***continue to strengthen these internship programs***, integrate them across disciplines, expand them beyond seismology and geodesy (e.g., magnetotellurics), and streamline the application process with a single application. We also propose that these programs incorporate a time-frame for interns from all of the internship programs to interact and learn about a range of geophysical disciplines beyond their specific programs.

4.0 Teaching Materials

ECIs value and benefit from ***instructional materials*** designed for undergraduate courses. In our survey, 85% of respondents have used teaching materials provided by IRIS and UNAVCO (~50% consider these essential), from short explanatory videos and earthquake teachable moments available from IRIS, to full lesson plans and multi-lesson modules (e.g., GETSI from UNAVCO).

We encourage the FGF to establish a presence in primary education by ***developing and promoting teaching modules*** that can be easily distributed to educators in collaboration with existing sources of K-12 science lessons (e.g., mysteryscience.com). In addition to ensuring that lessons are consistent with the state-of-the-science, this will introduce students and teachers to the FGF and foster the next generation of geoscientists.

5.0 Public Outreach

ECIs agree that public outreach for geophysics is vital to expanding knowledge of geohazards and natural resources that may impact people's lives. For example, ShakeAlert, the earthquake early-warning system for the Western US, has a successful outreach initiative that educates the public about earthquake hazards. Both IRIS and UNAVCO maintain an active social media presence, a critical component of public outreach and a key element of engaging the geophysics community. IRIS also sponsors community lectures and interactive displays for museums and public outreach. We encourage ***continued support for social media engagement, creation of informational graphics and posters, and development of teaching materials*** that may be used by the ECI community for public outreach and K-12 lectures (such as interactive displays and physical analog models). Ideally, resources should be available in multiple languages, including Spanish. We also envision a ***speaker series***, similar to the IRIS/SSA Distinguished Lectureship (a seismology speaker series intended for general audiences), that supports a broad and diverse set of geophysicists presenting locally (e.g., at their local science museum).

6.0 Broader Impacts Support

Numerous ECIs have taken advantage of support services for developing Broader Impacts and Educational components of proposals through IRIS and UNAVCO. For example, ECIs have funded IRIS and UNAVCO internship participants, hosted educational workshops that were supported via IRIS and UNAVCO, and engaged in public outreach in countries where they are pursuing their research projects. We expect the need for ***Broader Impacts and Educational support for proposals*** to continue and request that these services remain a part of the FGF.

7.0 Geophysical Resources Hub

A FGF will ideally serve as a hub for geophysical resources, including both EWO materials and geophysical data. Making this hub easily accessible and navigable will help advance the scientific goals of the FGF and improve accessibility for researchers, students, and the public. This hub would consist of ***high quality metadata, a well-designed user-friendly website, and support for digital tools***. We encourage the FGF to invest in the database and web development efforts necessary to achieve a robust, lightweight, and streamlined user experience on both desktop and mobile devices. This should include organization of all teaching materials categorized into types of materials (e.g., informational posters, presentations, and handouts), as well as, by appropriate experience level (i.e., grade school, high school, college, advanced). The FGF would incorporate these old and new resources into one well-organized web platform that is easily accessible to all.

8.0 Community Governance

It is essential that the FGF be responsive to the changing EWO needs of its users. We support a ***community governance model*** that pairs facility guidance with community input via an oversight-empowered standing committee made of community member stake-holders, including ECIs. This system ensures detailed, two-way feedback between the FGF and the community, assists the FGF in responding more nimbly to changes or expansions in community science emphases, and enhances community investment in (and usage of) FGF services.

9.0 Preparing for Future Science

The professional development and public outreach opportunities afforded to ECIs will play a critical role in driving scientific progress. We encourage the FGF to remain invested in EWO activities, alongside infrastructure, such as data services and geophysical instrumentation. We recommend that these investments be made in a way that further improves the diversity of backgrounds represented in the geophysical sciences.

Increasing the Diversity and Perceived Societal Relevance of Geophysics

John Louie, Professor of Geophysics, University of Nevada, Reno
Former Chair, IRIS PASSCAL Standing Committee, 2003
Former Chair, IRIS Education and Public Outreach Standing Committee, 2018

Problems, and a Transformative Opportunity for a Future Geophysics Facility

The discipline of earth science is currently being shocked by the COVID-19 crisis in two ways: 1) plummeting oil and gas prices have destroyed the careers of many industrial earth scientists and geoengineers (Slav, 2020); and 2) falling enrollments in four-year colleges, together with state- and private-university budget crises have sharply curtailed opportunities for academically oriented earth scientists (Flaherty, 2020).

Where will there be opportunities for early-career earth scientists and geoengineers? The Nation, and the World, are currently in the midst of a new fourth industrial revolution drawing increasing investment away from fossil energy, toward renewable energy. As one indicator, electricity generated within the state of California during 2019 was more than 48% renewable (most of that hydropower and photovoltaic solar), amounting to nearly 100 terawatt-hours over the year (CEC, 2020).

Transportation is moving toward electrification, with advances being made toward even electric airplanes (Trigg, 2017). The renewable-based electrification of the Nation's energy system requires a thorough rebuilding of US energy infrastructure: from wind towers and solar pedestals; through battery farms and a re-engineered, multi-directional smart electrical grid; to higher-wattage connections to everyone's home plus commuters' parking places, accompanied by high data-rate communications.

The US transportation infrastructure transformed from canal boats to railroads in only 20 years, from 1840 to 1860, spawning an unprecedented economic boom (NGS, 2019). The Nation's current transformation to distributed-source renewable energy will require a similar magnitude of investment and could yield similarly unprecedented economic growth, over an even shorter period. It is in the construction of all this new infrastructure where I expect geophysicists will find their careers over the next 20 years.

I predict that most geophysicists will soon work in the shallow subsurface, and in their own cities, within teams including geotechnical and civil engineers. Most utility and communications infrastructure connections are currently laid using shallow (2 m deep) horizontal drilling, rather than trenching, subject to great added expense if there are unexpected obstacles. The millions of new solar pedestals and wind towers are very sensitive to soft soils. These factors necessitate extensive, densely spaced, multidisciplinary geophysical studies in advance of every drill flight, and every single foundation. The National Academies draft *Earth Through Time* report (NASEM, 2020) supports this perspective, calling for an NSF-funded shallow geophysical survey facility.

Advanced geophysical technologies developed in academia and by the oil industry have already been transferred to the construction and engineering industries. Examples include earth resistivity tomography (ERT), prestack depth migration (PSDM), seismic stratigraphy, multichannel analysis of surface waves (MASW), and refraction microtremor (ReMi). As the fourth industrial revolution unfolds, increasing construction volumes will require further development of related geophysical applications; and more, and more qualified, practicing geophysicists to plan, survey, and interpret increasing volumes of geophysical data. This is the transformative opportunity for our field of study, and for our graduates.

Characteristics of the New Geophysicist

During this fourth industrial revolution the field of geophysics, and geophysicists, will transform greatly. Both *must* change, to allow our field to grow and thrive. Some characteristics of the new generation of geophysicists will be:

- Most geophysicists will have industrial and/or engineering certifications in geophysical technologies, and perhaps a two-year Associate's degree. They may have completed an apprenticeship. A few geophysicists will have BS or MS degrees, and fewer still PhD degrees. Most practicing geophysicists will have been instructed by community college faculty holding MS degrees.

- Most PhD geophysicists will make their fortunes starting their own applied technology companies. Some will do research at National Laboratories, or large international engineering companies. Relatively few will teach at research universities, with Federal research grants.
- Most geophysicists will work most of the time in their own cities and neighborhoods, assisting construction projects near their homes. They will have been educated and trained locally. They will be employed by local or regional engineering and construction companies, or they will have their own freelance practice. They will mentor, hire, and promote local talent. They will be local experts, heavily relied upon by local and regional governments as a fulcrum for local economic development.

If we can realize this transformative vision of the new geophysicist, then the new geophysicist will be much more diverse than geophysicists are currently. The "old boys clubs" of academia and the oil industry will not dominate advancement opportunities in the field. There will be a plethora of ways to become a geophysicist; and fewer barriers. Currently, it is nearly impossible to train a geophysicist who happens to be blind, or unable to walk over rough terrain, or even one unable to afford a four-year degree. In the transformative concept of a geophysicist it is possible to imagine many, who were once shut out, now leading the field.

How NSF Instrumentation Centers Can Promote the New Geophysicist

Below are factors in the development and operation of National geophysical instrumentation facilities such as SAGE+GAGE, which will promote the transformative development of a new, larger, and more diverse geophysics workforce. With the collapse of oil exploration and the contraction of academia, geophysics as a field is teetering. NSF now has the opportunity to leverage exactly the strategies that made the SAGE and GAGE facilities so successful, to create opportunities for tens of thousands of new geophysicists. The changes needed from the facilities are not fundamental; they are simply emphasizing the factors that lead to greater workforce diversity.

1. ***Balance emphasis on personnel versus equipment***– NASEM (2020) points out that operating a transformative instrumentation facility ("center") requires much more than instruments; it requires greater than an incidental investment in software, cyberinfrastructure, and expertise. These are personnel investments in large part. The SAGE/IRIS Data Management System (DMS) is largely a personnel investment. One can argue that the DMS is a principal reason for the success of IRIS in the long term. The Computational Infrastructure for Geodynamics (CIG) is another example of a crucial, and very successful "non-instrumental" center. The IRIS and UNAVCO staff and communities know best, but an instrumentation center may be most successful if just 50% of the funding goes to equipment.
2. ***More geophysical equipment for teaching***– The shallow geophysical instrumentation sets maintained at PASSCAL by SAGE are already some of the most-used and widely used sets. Instructors at tertiary institutions are the heaviest users of the shallow geophysical instrumentation, for class instruction and for student research. It is crucial to maintain, grow by a large factor, and diversify the pool of geophysical equipment made available expressly for teaching. The Urban Geophysics course SAGE is currently developing will provide a model and a curriculum that can be adopted by more geophysics, engineering, and earth science instructors. Having many more sets of equipment available to instructors will lead to a greater number and diversity of students getting training and exposure to geophysics. In addition, centers should promote their services and curricula to community colleges.
3. ***Provide geophysical software for teaching***– Simply having more students acquiring geophysical data will not transform our field. We must teach the students to process and interpret their results, and how to apply them in industry-standard ways to problems in

their communities. Substantial efforts need to be funded to develop, purchase, and especially to maintain geophysical software for instructional purposes. The instrumentation center can then effectively provide that software to tertiary instructors at all levels.

4. ***Developing open-source software***– It will be necessary for the centers to incentivize and comprehensively support the development of open-source software. Developing software that meets accessibility standards, especially, is not a hobby but requires concerted effort.
5. ***Maintaining both commercial and open-source software***– A center must dedicate substantial resources not just to the development or acquisition of software, but also to the annual (at least) maintenance and update of software. In many cases the annual cost of maintenance will equal the initial acquisition cost. There will be cases where it is most cost-effective to leverage the large investments that commercial software makers have already made, and for a center to purchase proprietary software, annual maintenance, and training. A universal but non-geophysical example is Microsoft Office.
6. ***Training for undergrad instructors***– A center should dedicate much personnel time to developing training programs and providing training in geophysical surveying and interpretation to instructors. Instructors and researchers from research universities may not need training, but their students will. Community college instructors will need extensive training, plus travel and stipend support to attend training sessions.
7. ***Undergrad internship support***– The IRIS Internships have been for decades a very high-impact program for high achievers. In addition, a center should develop field-based paid internship programs for many more students, from all levels of tertiary institutions.
8. ***Connectivity standards for all instruments, smartphone apps***– Past underinvestment has left geophysical instrumentation in academia and even industry behind the curve for connectivity. All portable instruments in the SAGE and GAGE facilities, for instance, currently require making a physical connection to the device for programing, monitoring, or to download data. A simple bathroom scale now offers much better connectivity. Any geophysical instrumentation center should establish connectivity standards that allow all these necessary actions to take place at a distance in the field of at least 10 m, from a smartphone app. Any instrumentation purchased would have to meet these standards. With such connectivity, field deployment crews could include a member with mobility impairment, who could complete deployment and pickup tasks from inside a vehicle. Less need to kneel on the ground to check an instrument would also promote crew safety. A center needs to be prepared to pay for smartphone app development and maintenance. For current instruments, a center can support the development of self-powered WiFi or Bluetooth dongles, and the needed smartphone apps.

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Desired Capabilities and the associated rationale for the future SAGE/GAGE successor facility.

Cathy Manduca, SERC, Carleton College

One of the strongest aspects of the current IRIS and UNAVCO facilities has been the development of very robust interactions with the scientific communities using the facilities. In fact, I believe it is more accurate to say that these communities and facilities have co-evolved to a place where they are very effective at supporting one another through a combination of formal and informal programming and feedbacks. The strength of these scientific ecosystems comes through in the NASEM report Management Models for Future Seismological and Geodetic Facilities and Capabilities: Proceedings of a Workshop in statements coming from workshop participants about the smooth functioning and strong support from the facilities, and the strong community participation in facility guidance, lack of perception of conflict of interest, and strong use and support for the facilities. The deep engagement of the community in governance of the facilities for more than a decade reflects strong, high functioning leadership and management of the facilities, the responsiveness of the facilities to their communities, and the robust work by both the facilities and the communities to nurture and develop new leadership. This is a major accomplishment. New facilities models and models for their governance and activities should be VERY careful not to disrupt these highly successful ecosystems. Such damage would result in loss of scientific capacity as well as current and future human capital and would take decades to repair.

IRIS and UNVACO play two critical roles in the realm of education and outreach. The first is inward looking –supporting the professional growth and education of current and future members of their own scientific communities. The second is outward facing – improving wider understanding and use of their science. The importance of both functions is discussed in the NASEM report as it was in the previous 2015 workshop. However, the 2019 workshop participant list indicates that the facility directors in these areas were not included in the workshop, nor was their participation or testimony from experts in these areas. Thus, the management models that would simultaneously maximize both scientific and education/outreach capacity have not been fully explored. To better understand this intersection and inform the new solicitation, I would encourage NSF to further investigate models that are successful for their impact on education and outreach as well as those that are lauded for their success in maximizing both scientific impact and education and outreach. Further, I would encourage NSF to seek out input or testimony from experts in geoscience education who can provide the needed missing expertise. Below I provide several comments drawn from my work with UNAVCO and IRIS over the past decade plus, as well as insights from my work in geoscience education, in developing of functioning educational communities, and collaborations with other facilities including NASA and NOAA.

Professional Growth and Education of Current and Future Members of their Own Scientific Communities. UNAVCO and IRIS receive high marks from their user communities for their work in this area. Particularly visible to the scientific community are the activities that support state-of-the-art use of the scientific data through training workshops and meetings that promote exchange of ideas. These are valued by scientists not only for their utility but also for the role that they play in graduate education providing an efficient way to bring graduate students up to speed on needed technical skills. UNAVCO and IRIS also run important and well regarded activities for undergraduates that introduce them to seismological and geodetic research and that serve as important mechanisms for recruiting young students into the field. The leadership of both groups have worked hard to ensure that participating students are diverse – drawn from across the country, from all genders, and from a wide variety of ethnic, racial, and economic backgrounds – and that students of all types are supported to success in these programs. UNAVCO in particular is noted for its innovation in this area. These programs are an important part of diversifying (or 'democratizing' as it is called in the NASEM report) geophysics. UNAVCO and IRIS also develop curricular resources aimed at supporting strong geophysical education for undergraduates both to interest them in the field and to provide needed preparation for future geoscientists. The bulk of this programming, as pointed out in the report has very little overlap in focus because seismology and geodesy have unique, non overlapping technical needs. At the same time, coordination and collaboration across the education offerings by the current education managers at UNAVCO and IRIS is outstanding. Thus, obtaining increased integration and efficiency should be viewed as ongoing evolution of current practice.

Less visible, but I would argue equally important to the professional growth of current and future seismologists and geodesists, are the informal mentoring networks that have developed through the work of the facilities. This mentoring supports students and scientists in finding nearest scientific neighbors to interact with technically, professionals of all ages to find and interact with role models including those who are only a little bit further along than they are; young scientists to be mentored professionally and supported into leadership positions by senior scientists; and students to find guidance from mentors beyond their institution including those who share goals or histories most similar to their own. These networks should not be overlooked in planning for the education and outreach components of the new facilities.

In my experience, obtaining strong distributed mentoring systems of the type currently in place in both communities is not easy and is influenced by both scale and culture. In my own work, significant overlap of participants at meetings over time created a culture of sharing and support in a community of several hundred participants. The number of opportunities, the size of the overlap in participants, and a common set of expectations for what would happen at the events appears to have been important over time in both creating and sustaining this supportive culture. Thus combining communities, changing the number or size of events/courses, or changing their underpinning culture may disrupt this productive professional growth network. This is like gardening, I would hesitate to rip up a productive bed in order to improve the soil.

Increasing public understanding and use of geophysics. UNAVCO and IRIS both run programs aimed at integrating the science produced by their communities into K-12, undergraduate, and informal education and making it directly visible to the public. This includes the development of curricular materials and museum displays; collaboration with partners on outreach activities;

and maintaining an online and social media presence. In all of this work, the strength that the facilities bring is their ability to engage deeply with their scientific communities. This ensures that the science is correct; is the most exciting; is the best matched to the educational need; and provides the opportunity to connect the scientific findings to the research process and to the people who do that. This capacity is a HUGE asset. I collaborate as much as I can with groups who can provide this connection into the middle of the scientific research community because it is so powerful.

When I am seeking collaborators with access to science and scientists as part of a larger educational need, it is critical to have points of contact that give me access to significant sectors of the scientific community. In my experience, it is the ability of the education manager to know exactly what science and which scientists are exactly best matched to an educational need or request that is most critical. UNAVCO and IRIS operate on a scale that is small enough for the education managers to know the science and to know or quickly find the right people, but large enough to have an exciting range of science and expertise. If a single facility emerges from the next solicitation, I would have one fewer person to check with – this is of course always good. But if that person wasn't fluent with the science - both foundational and cutting edge, or couldn't reach deep into both the geodesy and seismology communities, it would be a big loss. So whatever the structure, I encourage you to keep this need at the front of your mind. NASA in particular has much experience with different management models for their educational offerings. Of particular interest might be the recent NASEM review of the SciAct program. This integrated program run by the Science Mission Directorate replaced the distributed efforts run by each mission. The report discusses the strengths and challenges of this integrated approach which focuses primarily on outreach and engagement as opposed to professional preparation of future scientists. The ability to engage with the scientists across the breadth of the science appears to have been weakened in the new structure.

Several comments in the NASEM report speak to the pluses and minuses of one facility from a direct user point of view: e.g. with one facility we would have one website and one point of contact so it would be easier to find things; with a distributed site there are more opportunities for people to engage with the facility. I am not sure that this is the most impactful way to think about this balance. The E&O activities of both groups are budget limited and use different models for highest impact based in part on the different needs for professional growth within the community; in part of the specific affordances of the science for broader education and outreach; and in part on connections and the strengths of staff. Going forward, it will be critical to balance and optimize programming to provide the needed internal education and workforce development and the outward showcasing and use of the science for both geodesy and seismology. The opportunity will be to use the planning process to find not only balance but to create new synergistic outcomes that make use of the human capital across the new organization. A planning process that is perceived as fair and balanced by both communities while also being effective in producing optimized programming is critical. My impression from the 2015 workshop is that the members of both communities care deeply about the development of their future workforce and the role that each facility plays in their own scientific growth. A new model that is not perceived as fully supporting both communities could erode support for the new facility.

June 1, 2020

Dear Dr. Benoit,

We are writing in response to the Dear Colleague Letter issued by NSF regarding a single, unified geophysical facility as the successor to SAGE and GAGE. We wish to express our very strong support for the Global Seismographic Network (GSN) as part of this facility. In this white paper we describe aspects of the GSN that are essential to basic research in the geosciences, drawing upon a handful of the scientific advances that the GSN has made possible.

- *A permanent network of globally distributed stations.* The long-term deployment of the current GSN stations has illuminated time-dependent processes within the Earth's interior, such as the rotation of the inner core, and at the surface, such as changes in groundwater level following hurricanes. Long-term recordings allow low-level signals to be enhanced and utilized through stacking, which has revealed the existence of abrupt impedance contrasts within the lithosphere of continental cratons, shedding new light on the processes that form and destroy continents. Permanent and continuous recording around the globe is needed for an exhaustive analysis of global seismicity, to characterize rare but exceptional events, like great earthquakes, and for the comparative analysis of historic and present-day seismic events. It has also made possible unexpected discoveries like seismic events created by calving glaciers in Greenland and the use of seismic noise for imaging interior Earth properties. The global distribution of stations has enabled the development of global tomographic models, providing a snapshot of mantle convection at ever increasing resolution.

  An important but underappreciated aspect is that GSN stations form the backbone of many PI-driven local/regional seismic deployments. In particular, early-career PIs, who do not have local connections in remote study regions, usually rely on GSN stations for pilot studies that may lead to larger-scale NSF-funded projects. Finally, the GSN serves as a critically important augmentation to the International Monitoring System, which contributes to global and national security through monitoring for potential underground nuclear explosions.

- *Very broadband and well calibrated installations with high dynamic range.* The GSN is widely regarded as the gold standard for data quality, especially at low frequencies. These qualities are essential for analysis of the largest earthquakes, for example the M_W>9 events in Sumatra in 2004 and Japan in 2011. These qualities are also critical for measurements of normal modes and for studies of Earth's frequency-dependent anelastic properties, which rely on sensitive amplitude data at low frequencies and help to constrain mantle viscosity and separate the effects of temperature and composition inside the Earth. The very broadband nature of GSN stations is a natural bridge between high-frequency seismology and geodetic techniques focused on longer timescales, thus extending the applications beyond earthquake and seismological studies to deformation in response to, for example, tidal forcings and ice-sheet collapse.

- *Openly and freely available data that is telemetered in real time.* One of the most remarkable aspects of the GSN is that its data can be freely obtained from the IRIS Data Management Center (DMC) by anyone with a computer and an interest in seismology. This aspect of the GSN allows scientific progress even in the absence of external funding to individual PIs. The real-time telemetry of high-quality GSN data is central to rapid earthquake characterization, allowing for improved earthquake impact estimation, tsunami warning, and the generation of scientific observations of broad interest to first responders, educational institutions, and the public.

The management and governance structure of the GSN is unique: IRIS and the USGS share network operations, and the GSN Standing Committee advises both the IRIS Board of Directors and the USGS. We stress that *the dual-operator model works well* and affords the necessary flexibility to install and maintain GSN stations across the globe, sometimes in locations that are politically and geographically challenging. Indeed, the success of the GSN can be at least partly attributed to its shared operation by the USGS and IRIS and the integration of the objectives of the research and monitoring communities. A goal of this white paper is to underscore *the value of the GSN for basic geoscience research* and to convey the important role that NSF plays in the GSN. One measure of this value is that the GSN data set is by far the most requested of the data held in the DMC archive.

Finally, although the GSN in its current configuration has facilitated many scientific advances, we see opportunities to do much more. Uniform global coverage has not yet been achieved, and critical gaps exist in the oceans and southern hemisphere. Exciting scientific potential exists for long-term (>2-5 years) arrays of broadband stations that are either sited with an existing GSN station or used to improve global coverage. Furthermore, GSN stations, with their existing infrastructure, local hosts, and transmission capabilities, are ideal locations for the deployment of other geophysical sensors including geodetic instruments and promising new technology such as rotational seismometers.

In summary, a global network of high-quality, very-broadband seismometers with real-time telemetry and openly accessible data should be a central part of the future geophysical facility.

Sincerely,

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Charlotte Rowe, Research Seismologist, Los Alamos National Laboratory
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The importance of permanent, very broadband, global seismic network capabilities for modern seismology

Summary

Seismology and geodesy have revealed a great deal about the structure of Earth's interior, the relative motion of the lithospheric plates and the ways in which these motions are accommodated through seismic and aseismic processes. The properties of the crust, mantle, outer core and inner core have been assessed at different length-scales using a variety of different seismic techniques, many of which rely upon seismic networks which can record both high- and low-frequency seismic signals, and which are in place for extended periods of time. Earth's internal properties and seismicity are geographically variable, and seismic monitoring must take place across the planet, including from the oceans. A useful seismic network should therefore be permanent, record over a wide range of frequencies (be very broadband) and span as much of the globe as possible. The Global Seismic Network currently fulfills these criteria. The retention of these capabilities is essential as the NSF considers what should be required of a future "NSF-supported Geophysical Facility to Succeed the GAGE and SAGE Facilities".

Very broadband recording

In order to maintain the world-leading capabilities to investigate the properties of Earth's interior, a very-broadband (capable of faithfully recording very long period signals, including frequencies below 1 mHz, and short period signals of order ~ 10 Hz) global network is needed. The current Global Seismic Network (GSN), comprised of the II (IDA, Scripps) and IU (Albuquerque Seismological Laboratory, USGS) networks, and augmented by affiliate stations meets this need. The presence of sensors which can record long-period, mHz signals means that the seismic data they gather can be used to measure the frequencies and amplitudes of Earth's free oscillations or normal modes. Normal modes are excited by large earthquakes, and the modes can be observed for tens to hundreds of hours following the (eg He and Tromp, 1996; Park et al., 2005). The modes are especially sensitive to the large-scale properties of Earth's interior, and are therefore unaffected by the presence of small scale scatters which could affect high frequency observations. Their properties are also sensitive to the distribution of density in the Earth, unlike the seismic waves used in traditional transmission tomography.

Normal mode studies have shed light on the presence of the structure of the mantle (e.g. Moulik and Ekström, 2016), the properties of the lowermost mantle and outer core (e.g. Ishii and Dziewonksi, 2005; Koelemeijer et al., 2017) and the properties of Earth's inner core (e.g. Deuss et al., 2010; Robson and Romanowicz, 2019). Scientists have tried to detect the normal modes of the Moon and Mars using data from the Apollo mission and InSight mission respectively, but the former mission's noise levels were shown to be too high at low frequencies (Gagnepain-Beyneix et al., 2006) and the latter mission is ongoing (Banerdt et al., 2020). Earth remains the only planet whose normal modes have been observed with on-the-ground seismology, and it is important that this capacity is sustained.

Unchanging station locations

Another important attribute for a global seismic network is the presence of stations in exactly the same location for several decades. This is useful for a wide range of applications where seismic waveforms from different records can be stacked, or combined, to enhance desired signals and reduce the levels of unwanted noise, but there are several areas of research for which the presence of unchanged stations for tens (and hopefully hundreds!) of years are vital.

The first I highlight is in the detection of unexpected temporal variations in the properties of our planet. One example of these temporally changing signals is those thought to be due to changes in the core. This is often ascribed to the relative rotation of the inner core (e.g. Song and Richards, 1996), though it is sometimes thought to be related to temporal changes at the inner core boundary (Yao et al., 2015). This work requires seismic stations which have been recording for as long as possible, and indeed sometimes scientists digitize analog records for this purpose. The long-standing GSN provides records which can be used for monitoring temporal changes in the inner core (for example in Tkalčić et al., 2013) which were unknown when the stations used were installed.

Secondly, longstanding stations and networks are useful for the assessment of doublet or multiplet earthquakes, which occur in the same place some time apart. These can shed light on both the mechanisms and locations of rupture, sometimes hundreds of kilometers below Earth's surface (e.g. Myhill et al., 2011). Multiplet earthquakes also be used to highlight temporal variations in the Earth, as described above.

The third reason for keeping stations in the same location is for the assessment of explosions as part of monitoring compliance with the Comprehensive Test Ban Treaty. While the variations in seismic attenuation are not perfectly mapped, having stations whose locations are known to be unchanged removes an extra source of uncertainty in assessing the magnitude of explosive events. GSN data have long been used for this approach (e.g. Murphy et al., 2013), which can be readily compared to the detection and comparison of naturally-occurring seismic multiplets.

Expanding into the oceans

While the current Global Seismic Network has good coverage on multiple continents, there are substantial areas of Earth which are not well-monitored by permanent seismic instruments. While the deployment of further novel 'Mermaid' floating seismometers (e.g. Nolet et al., 2019) is likely to help with this effort (and should be seriously considered as part of the new facility), in order to better understand our planet some permanent, or at least long-lived stations should be placed on the seafloor to augment the current land-based permanent networks. As one author of the "Plan for a Long-Term, Automated, Broadband Seismic Monitoring Network on the Global Seafloor" (Kohler et al., 2020) I support the implementation of this proposal by the GSN's Working Group on Long Term Seafloor Seismology.

Conclusions

The Global Seismic Network has been vitally important for a range of scientific work. It has also freely provided seismic data for my research, and regardless of whether I was working in the US or elsewhere in the world. It has enabled my, and my collaborators' and students' research into Earth's mantle and core, and allowed us to make discoveries about our planet. I recommend that the competition for a new "NSF-supported Geophysical Facility to Succeed the GAGE and SAGE Facilities" require the continued provision for the Global seismic network.

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12 May 2020

Dr. Margaret Benoit
Program Director, SAGE and GAGE
National Science Foundation

Dear Dr. Benoit,

I am writing to express my strong support for the Global Seismograph Network (GSN) as part of the facility that will follow SAGE and GAGE. For over 30 years, my research has relied heavily on records from high-quality global seismic stations, the data from which has been freely distributed to the community. This work has included studies of Earth structure at depths from the crust to the core and analyses of the rupture properties of large damaging earthquakes. I could not do what I do without the GSN!

Seismology and the broader geoscience community depend upon having a reliable global network. Whole fields of study would not be possible without the worldwide coverage of the GSN. Just a few highlights:

- Global tomographic inversions provide the primary evidence for the nature of mantle convection, including the fate of subducting slabs and the compositionally distinct regions just above the core-mantle boundary.

- Finite-slip inversions and back-projection using teleseismic records reveal the complicated rupture dynamics of large earthquakes.

- Waveform cross-correlation relocation projects, which rely on the long duration of GSN installations, have provided detailed images of the fine-scale structure of fault systems.

- Shear-wave splitting studies have mapped asthenospheric mantle flow in subduction zones and other tectonically active areas.

- Receiver function and other mantle discontinuity phases have mapped the topography of the 410- and 660-km discontinuities, placing key constraints on mantle temperature and geodynamic models.

Sustaining a high-quality GSN should be a top priority of any new NSF facility in seismology. It provides an invaluable backbone for global geoscience.

Sincerely,

Peter Shearer

Peter Shearer
Professor of Geophysics
pshearer@ucsd.edu

Characteristics of a Geophysical Facility to Support Research in the Earth Sciences

The integration of the NSF-funded geodetic and seismic facilities, and their associated user communities, has three measurable positive impacts. First, both facilities and communities are more resilient in combination than alone, ensuring that their members have access to a wide range of critical resources needed to support their research. Second, this arrangement advances interdisciplinarity research by facilitating the connection of diverse interests and disparate researchers. Finally, a facility that is wholly a part of a large and diverse geophysical community is able to innovate because, as ideas and expertise are shared, facility staff can anticipate emerging needs. All three of these impacts will combine to support transformative geophysical research.

We can use this broad context to inform the specific critical characteristics of a new geophysical facility. It must be:

- Governed and advised by the community it serves,
- Committed to building social capital through education, workforce development, early career mentoring, and interdisciplinary research,
- Staffed by leaders in the field with both deep and forward-looking domain expertise and technical knowledge,
- Committed to the free and open data exchange of data and multi-data access to support interdisciplinary science,
- Agile enough to evolve the capabilities of the facility to support the changing needs of the geophysical community with both new, state-of the-art capabilities and support for legacy data and instrumentation,
- Able to support the broad range of research currently done by the geophysical community, and
- Committed to public-private partnerships that support its organizational mission.

Community governance: Both IRIS and UNAVCO, the organizations that operate SAGE and GAGE respectively, grew from collaborative groups of scientists and academic institutions. These groups recognized that, by pooling their resources and expertise, more ambitious and innovative scientific efforts could be realized. In addition, the existence of shared infrastructure and institutional support makes science more equitable by allowing researchers from many different kinds of institutions to have access to the same facilities. The bylaws of each organization are natural extensions of these foundational principles, guaranteeing representation of stakeholders, especially academic researchers, through Boards of Directors and diverse formal and informal advisory bodies. Annual workshops, meetings, training programs, internships, and mentoring activities ensure strong ties between the organizations and the communities they serve, and offer many different pathways for engagement from citizen science to advanced data products. This rich network of activities has ensured that the geophysical facilities have never wavered in their service to their community. We believe that the future combined geophysics facility should retain the same strong culture of community engagement and governance as the present facilities while building new cross-disciplinary connections.

Social capital: The merged geophysical facility must not only support today's scientific community; it must also build for the future. Vital communities are always changing as new ideas arise and new technologies are developed, enabling new discoveries. One of the most critical roles for a future geophysical facility is to keep the geophysics community strong and resilient as it changes and evolves. This must be done through both formal and informal mechanisms, for stakeholders at many experience levels and over a wide range of interests. Maintaining the social capital that supports geophysics includes producing world-class educational and outreach materials that share our discoveries outside of the research domain. It also requires investments in workforce development and academic pipelines through internship programs, mentoring, dynamic career pathways, and assertive support for underrepresented groups in physical sciences. It requires innovative mechanisms for supporting early career faculty and faculty and non-research-intensive institutions. Finally, it requires creating and fostering opportunities for scientific collaboration and innovative interdisciplinary research by bringing all different kinds of scientists together in many different ways.

Domain expertise: Some aspects of operational support for geophysical facilities are generalized, such as electronics engineering, field logistics, and project management. These tasks dominate day-to-day operations. However, they function within a broader framework that demands a deep understanding of the scientific context in which these facilities are used joined with specialized domain-specific technical expertise. Only an organization staffed, run, and governed by domain experts can anticipate which scientific questions, which emerging technologies, and which creative approaches are likely to lead to transformative findings. For example, in geodesy, a generalized team of engineers and technicians could run a regional GNSS network, but only engineers and technicians who understand the physics of solid Earth response to surface mass load changes could recognize the potential for that network to measure hydrologic loading instead of tectonic velocities, and seamlessly add that capability. In seismology, the successful operation of a pool of portable instruments or a permanent seismic network requires not just a background in electronics and project management, but a fundamental understanding of how sound propagates through the Earth, the temporal and spatial variability of Earth processes, and the capability of different sensors to image the seismic wavefield. This deep knowledge of the context and the purpose of a geophysical facility makes its operation much more agile and creative, enabling not only basic capabilities but also the conceptual leaps that are vanguards of scientific discovery.

Open data and innovative cyberinfrastructure: A future geophysical facility must be committed to making the data it collects freely and openly available to any scientific user. This requires the development and use of standardized data formats and protocols to facilitate the exchange of data, and innovations in cyberinfrastructure to provide state-of-the-art tools for efficient data discovery, metadata handling and data distribution. A policy commitment to nominally open data without the means of implementing it is hollow. For example, raw sensor observations may be "open" by policy, but if researchers cannot easily find files from a location or epoch of interest, or if they are complicated or expensive to download, translate, or use, then their value for discovery is discounted. The geophysical facility will need to develop and integrate a suite of cyber tools to facilitate the use of many different kinds of sensor data streams for many different uses. This likely means not only search and query, but also automation of many different kinds of data products, since the more interdisciplinary the research, the less likely the researchers will have the capacity to handle all the different kinds of low-order data they need. The need for open data and data handling aligns closely with the domain expertise characteristic above; facility staff must understand the diverse data they handle, and the many different ways in which these data are used, in order to create useful data products and understand the kinds of metadata and data quality standards required for research applications.

Support for frontier research and legacy activities: Geophysical technology is constantly evolving, with major advances in sensors and instrumentation, power systems, autonomous vehicles, cellular and satellite data communications, and satellite capabilities. Driven in part by these advances, and by changing research priorities, the needs of the research community are constantly evolving. For example, seismologists are now not satisfied with deploying portable arrays with a few dozen sensors, but want to deploy hundreds or even thousands of sensors to enable full imaging of the seismic wavefield. It is essential that this geophysical facility be agile enough to evolve its capabilities to support the changing needs of the geophysical community.

While serving the frontiers of geophysics, an effective geophysical facility must also continue to support legacy sensors and data types. Because geophysical phenomena occur over a range of time scales, some of the most valuable time series are the longest, requiring handling of legacy data formats and maintenance of old instrumentation. For example, although the forefront of geodesy is with new full-constellation GNSS and high-resolution laser surface scanning, the very long records of VLBI and SLR positioning are critical to defining reference frames and decadal-scale time-dependence. Some of the older sensors and data streams require highly specialized knowledge to maintain and use, and this expertise is neither highly portable nor commercially monetized.

Support for the broad range of research done by the geophysical community: Earth systems processes encompass an incredibly wide range of spatial and temporal scales, from microscopic grain boundaries critical for understanding why faults slip to a scale of thousands of kilometers on which mantle convection operates, and from fractions of seconds to billions of years. Seismic, geodetic and other geophysical observations are powerful tools for studying these diverse Earth system processes from the Earth's inner core to the upper reaches of the ionosphere. It is essential that this geophysical facility support this broad range of research. While geodesists and seismologists share many common research interests (e.g. fault rupture and mechanics, volcanic processes and glacier dynamics), there are many areas where their interests do not overlap. For example, geodesists study tropospheric dynamics, sea level change and space weather – problems not generally addressable by seismology. Conversely, many seismologists study mantle structure and dynamics or the nature of the core-mantle boundary that geodesy cannot address. It will be a significant challenge for a single facility to provide the range of domain expertise and facility capabilities required to support this extremely broad range of science applications, especially if budgets are reduced, without some users feeling underserved. It is essential, in our opinion, that the new integrated facility continue to support the broad and growing range of research that the current GAGE and SAGE facilities support.

Partnerships: Finally, the future geophysical facility should formalize its role as the nexus of a rich community by supporting diverse and rich partnerships. Working together with public, private, government, and academic institutions to further the goal of science advances will help the facility realize economies of scale and leverage a wide portfolio of resources. UNAVCO's and IRIS's existing partnership with SERC at Carleton College enables the delivery of educational resources far beyond what the facility could support itself. UNAVCO's partnership with the IGS enables distribution of foundational reference frame and orbital products while IRIS's partnership with USGS, and dozens of countries around the world, has supported the maintenance and operation of the GSN for over 30 years. These partnerships depend upon partners' assurance that the facilities operate with a deep commitment to mission and community service with the highest standards of accountability and transparency. The future facility must maintain the system of effective partnerships already developed by IRIS and UNAVCO as well as build new ones responsive to future challenges, drawing on a long history of community trust.

To summarize, we believe that an integrated geophysical facility should be built on the foundation provided by the existing two geophysical facilities. This vision incorporates all of the strengths of the current organizations and augments them so that the result is much greater than the sum of the parts. We believe that the core values of the existing organizations will serve a new facility well, renewing the mission of support for scientific discovery in transformative new ways.

Rebecca Bendick, UNAVCO President
Robert Detrick, IRIS President

1 June 2020

Dr. Margaret Benoit
Division of Earth Sciences, Geosciences Directorate
National Science Foundation

Dear Maggie,

I am writing in response to NSF 20-037, requesting community feedback regarding a next-generation Geophysical Facility. I am responding independently as a research-active academic scientist: I currently hold no leadership or advisory roles within EAR-supported community facilities, or community activities such as the SZ4D RCNs. I do serve as chair of a UNOLS "special committee" providing guidance on for OCE's Ocean-Bottom Seismology Instrument Center (OBSIC), but I am taking at face value that this request for input is limited to EAR facilities provided by SAGE and GAGE. I am focusing my comments accordingly (with one caveat below).

Over the past three decades, solid-earth geophysics has become absolutely central to our evolving understanding of the global Earth system. Imaging of both volumetric structure and deformation processes on faults extends our observational capabilities deep into the subsurface, effectively integrating geology and geochemistry's surficial sampling to global scales in three dimensions. In my initial read, NAS's Earth in Time re-emphasizes a highly integrative view of the Earth system, and effective tools for quantitatively probing subsurface dynamic processes will remain central to EAR's mission for the coming decade and beyond.

My perspective on the dominant community needs in geophysics is informed by my evolving experience, with two points of emphasis: my 15+ year experience leading a graduate-student research program at a private, research-focused university (Lamont), and my current role building a student-based research program within a traditional geology department at a major public university. In short, the success of my program at Lamont was entirely enabled by the highly integrated, community-based seismological facilities provided by SAGE. First, direct community involvement (including my own) in SAGE decision-making and leadership ensured that the facility was deeply engaged with the community, and vice versa. This significantly enabled my own ability to introduce my students to emerging technology, initiatives, and science opportunities. Equally important, through workshops and common facilities, SAGE embeds my students within a truly national and international science community, providing learning opportunities that extend far beyond what they can achieve at their home institution or through large, more generic entities such as AGU. Finally, by providing an integrated set of services spanning instrumentation, data collection, data archiving and distribution, and education and outreach tools, students and researchers develop a depth of technical understanding that is not likely attainable though a more discrete model for providing specific services. A key point is that by being so tightly integrated within a community-driven framework, these services and capabilities are highly accessible, and are equally easy to exploit at an emerging education-focused university such as NAU, as they were at a research-central place like Lamont. Central to this notion is having a highly engaged, open, and sharing community. Such communities exist in SAGE and GAGE, and the most critical attribute of a new Geophysics Facility is that it be retain or even further enable community engagement and participation.

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Beyond the community-driven framework, the details are secondary. I fully expect that other groups will emphasize how the key components of SAGE and GAGE (global networks, field facilities for community use, innovated data archive and distribution, education and outreach activities) are critical in their own right; to me, it is self-evident that the science goals in Earth in Time absolutely require continued investment in these activities. I will weigh in that maintaining very high-fidelity, wide-band seismic instrumentation (i.e. "fully broad-band") is critical, both for observatories and for portable experiments. New, highly flexible narrow-band technologies are exciting, but it is clear that the earth's deformation spectrum is very large, and we must continue to develop and deploy instruments capable of capturing unforeseen phenomena across that full spectrum. I also expect that NSF is getting strong, clear guidance on the critical differences between SAGE and GAGE activities at a technical level. I sincerely hope that NSF hears and provides mechanisms for addressing those challenges, such that key capabilities are not lost, but overall I am enthused by the potential of a national Geophysics Facility for building a broader, more integrated geophysics community in the US.

Finally, I can't miss the opportunity to offer a few thoughts on additional NSF facilities for Geophysics that are funded outside of EAR. Through much of my career, I've been fortunate to receive strong support for my science from programs within EAR (Geophysics, Continental Dynamics, EIS), OCE (MGG), and some combination (MARGINS, GeoPRISMS). At a program level, I've never felt that the administrative division between EAR and OCE hinders my science in any way. However, my long experience working both in the oceans and on land (as a user, as an instrument provider, and in a community leadership roles) has lead me to the conclusion that the strict line delineating EAR and OCE facility funding hinders the science community. The ocean shoreline is irrelevant to much of solid-earth research, something the individual programs recognized long ago. However, the fact that a facility like SAGE is only supported and managed by EAR, or (more problematically) that the US Marine Seismic facility (aka R/V Marcus G. Langseth) and OBSIC are only supported and managed by OCE, potentially puts those facilities at risk if their scientific impact across the broader community is not fully taken into account. In my view, these are very clearly GEO-level facilities. I look forward to a day when the true impact of these facilities is accounted for, and their funding is stabilized such that they are no longer at risk.

I hope that you find these comments useful. I sincerely thank you for the support that NSF and EAR have provided for geophysics over the past decades; it has been a fabulous community within which build my career, and to help my students start theirs. I look forward to the next generation of NSF support for a Geophysics Facility.

Regards,

James Gaherty
Professor, School of Earth & Sustainability

Desired Capabilities of a Future Geophysical Facility: One Seismologist's View

Maureen D. Long, Yale University

I am writing this letter in response to the call for comments on desired capabilities for a future geophysical facility as a successor to the current SAGE and GAGE facilities. I expect that NSF will receive a large number of letters from the community that focus on a single aspect of such a facility (indeed, I contributed to one such letter on international activities). In this document, I provide my own personal view of critical capabilities for the future facility, in the hope that it is useful for NSF to hear from individual scientists about what facility capabilities are crucial for their own work. This view is, of course, highly specific to my own science and is not even close to being comprehensive; still, I hope that this type of perspective is useful for NSF as it considers future facility needs. For context, I am an observational seismologist who is interested in the structure and dynamics of the deep Earth, from the crust to the core-mantle boundary. My scientific interests include subduction zone dynamics and processes, the structure and evolution of continental lithosphere, and the dynamics of the deep mantle. My research encompasses a substantial field component, and I have been involved in broadband seismic deployments in Cascadia, Peru, the central Appalachian Mountains, New England, and offshore North Carolina.

I view the move towards a single, unified geophysical facility with excitement and with optimism that it will not only provide a more efficient structure for facility management, but will help to bring together the communities of scientists who are currently supported by IRIS and UNAVCO, and thus make our science better. In my view, any future facility needs to be well-run, nimble, and highly responsive to community needs. It must have a robust community governance structure; this is a hallmark of the current facilities managed by IRIS and UNAVCO, and is a crucial piece of their success to date. The new facility must serve a diverse set of stakeholders across the range of scientific disciplines represented by the IRIS and UNAVCO communities, and embrace new communities that have not traditionally been served by the SAGE and GAGE facilities (such as near-surface and urban geophysics). Finally, the new facility has a crucial role to play in the development of a diverse geophysics workforce; the importance of this diversity was forcefully articulated in the recent CORES decadal survey report for NSF-EAR.

In the framework of these general characteristics of the future facility, here I discuss the specific needs and capabilities that underpin my own research.

Archiving and distribution of seismic data: The seamless availability of data from the currently-supported SAGE facility, through the IRIS Data Management Center, is so central to the scientific life of seismologists around the world that it is easy for us to forget how fundamental it is. The DMC archive enables seismologists to access an enormous archive of high-quality seismic data at the click of a button, using an array of user-friendly access tools. The DMC's archiving and distribution of (increasingly large) data sets allows us to carry out our research using data from all over the world, to store and manage the data sets that we collect through our own field projects and to spin up undergraduate research projects quickly. Furthermore, the array of data products that are managed by the DMC not only allow seismologists seamless and friction-free access to the results of others, but also distribute important results, models, and data products to scientists beyond the seismology community. The future geophysical facility must retain the capabilities of the current facility to archive and distribute (via an array of user-friendly tools) seismic data, and associated data products, to scientists around the world.

Permanent, high-quality, globally distributed seismic stations: One of the mainstays of research into deep Earth structure is the availability of data from long-running, high-quality broadband seismic stations that are distributed across the globe. Indeed, it is difficult to overstate the importance of such data for studies of the deep Earth. Seismologists who work on deep Earth problems rely on data from long-running stations that feature (very) broadband data, low noise, and good coverage across the globe. In my own research, I've discovered the value of high-quality data from long-running stations in obtaining strong constraints on deep Earth structure; for example, it's striking how much more information one can get on upper mantle anisotropy beneath a seismic station from SKS splitting measurements using 20 or 30 years' worth of data rather than 2 or 3 year's worth. The Global Seismographic Network is, of course, the gold standard for high-quality, low-noise, real-time global data, and strong support for the GSN must remain as a key component of the future facility.

Facility to support the temporary deployment of seismic instrumentation: As a seismologist who does her own field experiments and collects her own data, the availability of a facility that loans seismic instrumentation and supports PI-driven field experiments has been crucial to my scientific output. I've been fortunate to lead or participate in several PASSCAL-supported experiments, and it is difficult to overstate the importance of the PASSCAL facility to my science. Not only is PASSCAL extraordinarily well run and responsive to the needs of PIs, but the world-class expertise in how to run a seismic deployment that resides in the PASSCAL personnel is an absolute treasure for the seismology community. It is crucial that the future facility provide this type of support to the seismology community in the future. Furthermore, even as the facility supports new and cutting-edge instrumentation (such as those used in large-N, nodal deployments), it is important that it continue to support broadband seismic deployments; there are many scientific questions relating to the structure and dynamics of the Earth's interior that require broadband data to address.

Education and outreach activities, particularly workforce development: One of the most important, if perhaps sometimes underappreciated by the community, category of activities that are carried out by the current SAGE and GAGE facilities is education and public outreach. Both IRIS and UNAVCO carry out world-class EPO programs that include a huge range of activities, including social media, undergraduate internships, the distribution of animations and lesson plans, the development of software, and communication with the public after major earthquakes. Not only do these activities play a crucial role in bringing our science to a wide audience, but the current EPO programs help to facilitate outreach activities by individual PIs; for example, PIs can distribute lesson plans or curricular materials via the IRIS EPO InClass portal. A key aspect of the EPO efforts for the future facility must be a focus on the development of a diverse and agile workforce to meet the needs not only of the geoscience research community but also society at large. The recent CORES report emphasized the need to enhance diversity in the geoscience workforce in order to reach all of the talent potentially available and to ensure that our workforce is capable of meeting the enormous research and societal challenges that we will face over the next decade and beyond. I feel strongly that the future geophysical facility must play a key role in the development of this workforce.

International activities and capacity building: I am the lead author on another whitepaper that articulates the widespread support in the IRIS and UNAVCO science communities for international capacity building activities, and argues for the importance of considering such activities in the vision for the future facility. I will not reiterate all of these arguments here, but I do want to emphasize that I hope that such international activities will be included as part of the future facility. Given the natural synergies with PI-driven research activities in international settings that are supported by the current facilities, the successful track record of IRIS and UNAVCO in carrying out capacity building activities, the enthusiasm for such activities in our science communities, and upcoming opportunities for international engagement with the SZ4D initiative, I urge NSF to consider ways in which international capacity building can be incorporated into plans for the future facility.

In closing, I would like to thank NSF for their solicitation of community feedback on future geophysical facility needs, and for their thoughtful consideration of the feedback received. This is an exciting time for the U.S. geophysics community as we consider how the future facility will enable our scientific discoveries for years to come.

An Early Career Investigator Community Vision for the Future NSF Geophysical Facility: Instrumentation Services Needs

Authors: D.S. Stamps, Z. Eilon, W. Fan, C. Lynner, H. Kehoe, H.A. Ford, S. Wei, C. Rollins, C.G. Barcheck, N.J. Lindsey, M.R. Siegfried, S. Naif

Citation: Stamps, D.S., Z. Eilon, W. Fan, C. Lynner, H. Kehoe, H.A. Ford, S. Wei, C. Rollins, C.G. Barcheck, N.J. Lindsey, M.R. Siegfried, S. Naif (2020). An Early Career Investigator Community Vision for the Future NSF Geophysical Facility: Instrumentation Services Needs. White Paper, 3 p., 10.6084/m9.figshare.12398288.

1.0 Introduction

This white paper has been developed based on a compilation of input from ~45 Early Career Investigators (ECIs) from various institutions who participated in the "*Early Career Investigator Virtual Workshop on a Community Vision for the Future Geophysical Facility*" held April 23-24, 2020 and 59 respondents to a follow-up survey for ECIs distributed via IRIS and UNAVCO list-servs. Our aim is to identify the critical instrumentation services that need to be provided by the future NSF Geophysical Facility in order to best serve today's ECI scientific community.

2.0 Free-use Portable Instrument Pool with a Diverse Set of Geophysical Equipment

It is essential that the Future Geophysical Facility (FGF) provide a ***diverse, community input-driven, pool of geophysical equipment*** to scientists for geophysical fieldwork. It is imperative that this instrumentation be ***free at the point of use***, following the current model of PASSCAL, to ensure equity among institutions and investigators. The practice of prioritizing NSF-funded projects, but also supporting non-NSF projects given capacity, has an established record of success in enabling novel science. The support of non-NSF projects is particularly important for new faculty appointees who often pursue smaller, proof-of-concept deployments that lead to full-scale NSF proposals. We recommend that the FGF provides limited funding distributed through a competition model to support shipping costs for scientists without external grants or internal funds given equipment availability, thereby maximizing utilization. The specific geophysical equipment supported should, at a minimum, support data types (if not precise instrumentation) that IRIS and UNAVCO currently maintain. We would place ***recapitalization priority on modernizing*** the existing, aging instrument core to ensure that the community retains access to modern data collection capabilities through the lifetime of the FGF and beyond.

We advocate a ***balance of breadth and depth***. No other organization can provide the sheer number and variety of instruments required for modern emerging array-based (e.g., ***large***-N) science. The FGF instrument center should be able to support PI requests for large numbers of geophysical instruments and emerging big-data acquisition. We also request that the FGF continues to invest in emerging new technologies and instruments that facilitate cutting-edge research across the growing diversity of geophysical sub-specialities (see also Sections 5, 6, and 7), with prioritization of new capabilities based on community input.

3.0 Support for Permanent Global and Long-term Regional Networks

Current support for the Global Geodetic Network and Global Seismographic Network is highly valued in the ECI community, with nearly every workshop and survey participant having used either GGN or GSN data in their research. Both global and regional networks are crucial for advancing our understanding of broad-scale geophysical processes, and they provide an ***essential framework for targeted PI-driven studies*** using complementary instrumentation to investigate more localized processes. We recommend that the continuation of existing permanent global and long-term regional networks be a priority of the FGF. We also recognize that some advances in our understanding of fundamental Earth processes are only possible through *community-level* experiments involving regional-to-continental multi-scale and dense geophysical arrays. We advocate that the FGF actively support experiments at scales beyond single-PI capacity (e.g. USArray, NOTA, SZ4D, Alaska Aleutians CSE).

The ECI community envisions future expansion of multidisciplinary, division-crossing investigations that include ***simultaneous collection of multiple complementary data types***. ECIs view experiments that ***bridge on-shore and off-shore*** regions, as well as, those encompassing the cryosphere and solid Earth as transformational for Earth Sciences in the next 5-10 years. The FGF is well-suited to take a leading role in facilitating such experiments by coordinating the use of equipment from multiple smaller NSF-funded facilities, e.g., Polar science instruments, OBSIC, the Seismic Source Facility, the new NSF-funded sea-floor geodetic facility. In parallel, building out regional and/or global networks with more co-located geophysical instruments that share common infrastructure will reduce overhead and foster collaboration amongst researchers from multiple disciplines. In particular, shoreline-crossing data acquisition is logistically daunting for individual PIs and can act as a barrier for ECIs entering the field. We would like to see the FGF develop mechanisms for coordinating multi-modal experiments.

4.0 Engineering and Logistical Support

Excellent data relies on resilient instrumentation and robust field procedures. Several components of engineering and logistical support are integral to achieving ECI scientific objectives. IRIS and UNAVCO engineers currently provide ***training*** at the instrument centers and in the field. This training is critical for acquiring high quality data, ensuring responsible (and sustainable) instrument handling and consistency of results particularly for practitioners with limited experience. Both IRIS and UNAVCO currently assist with ***field experiment planning***. As experimental designs become more complex, involving combinations of data and instrument types, multi-scale arrays, and deployments in increasingly challenging environments, the insights from experienced technicians and engineers will maximize the success of instrument deployments. ECIs, in particular, benefit from the experience of IRIS and UNAVCO engineers in experiment design and in engineering equipment for novel, challenging environments. We consider retaining and recruiting expert facility engineers a fundamental component of the FGF. To help facilitate international geophysical investigations and deployments, we suggest that the FGF fosters relationships with skilled technicians that maintain the global networks. Global partnerships bring numerous benefits, including skill- and network-building within international communities, local expertise and resource access, broad involvement of local communities, and support for installation and maintenance of equipment. We suggest the FGF proactively support global science, for example by providing a detailed global contact list of trusted engineers for PIs to seek in-country technical support.

ECIs also rely heavily on the existing ***logistical support*** provided by IRIS and UNAVCO when shipping instruments both domestically and internationally (including polar regions). In addition to maintaining the role of shipping equipment that IRIS and UNAVCO already support, we recommend that the FGF take a more prominent and active role in shipping logistics by providing more information about best practices for shipping procedures (e.g., approved shipping vendors, customs requirements, insurance). New logistical considerations have emerged in recent years that would benefit from centralized administration of the FGF, such as shipping restrictions on items with internal lithium batteries and solar panels requiring certification for some countries. Following our recommendations in Section 3, we also emphasize the importance of logistical assistance with combined onshore and offshore geophysical experiments, which are often complex and time-sensitive.

In-field support has been critical to the success of numerous ECI-led field experiments. IRIS and UNAVCO engineering experience in areas that ECIs often lack (e.g., telemetry systems, power station design, and equipment weatherization) is vital to deploying and maintaining complex networks that may contain real-time data transmission or co-located multi-instrument stations, particularly in extreme environments. The current model that requires the PI to provide only travel support for field engineers is highly valued, and the availability of remote field support through phone, email, or two-way satellite messaging has also proven crucial.

5.0 Facilitating Instrumentation Purchases, Testing, and Repair

ECIs already benefit from ***centrally negotiated vendor rates*** on GNSS/GPS instruments, and from IRIS and UNAVCO-supported testing of novel equipment that comes to market. We advocate expanding this model of central negotiation to the entirety of FGF equipment. Competitive pricing and detailed instrument quality reports are particularly important to ECIs seeking to maximize the impact of their startup funds. Researchers want to take advantage of new technological advancements as they emerge but often do not have the expertise or capital to evaluate instrument quality and resiliency. ***Instrument vetting and testing*** is a vital service provided by existing facilities, and one that needs to be incorporated into the FGF. In addition, ***repair services*** sustain existing equipment pools well beyond their marketed longevity, enhancing return on investment and supporting user specialization. We also advocate for continuation of limited repair services for PI-owned equipment, which substantially mitigates replacement costs that ECIs often cannot bear.

6.0 Community Governance:

It is essential that the FGF be responsive to the changing instrument services needs of its users. We support a ***community governance model*** that pairs facility guidance with community input via an oversight-empowered standing committee made of community member stake-holders, including ECIs. This system ensures detailed, two-way feedback between the FGF and the community, assists the FGF in responding more nimbly to changes or expansions in community science emphases, and enhances community investment in (and usage of) FGF services.

7.0 Preparing for Future Science

The ideal FGF will facilitate collaborations across the subdisciplines of geophysics in pursuit of new scientific discoveries. To ensure this future, we recommend the FGF demonstrate flexibility in its support of new directions in science and technology. For example, as technological advances continue to shape ECI-led research, it is important to maintain robust support for existing infrastructure while simultaneously accommodating future community needs. Access to free-use instruments (Section 2) and related technical support (Section 4) will remain vital. Maintaining state-of-the-art instrumentation and investing in new technologies (e.g., distributed acoustic sensing, sea-floor monitoring instruments) will ensure the impact and quality of future geophysical studies and the sustained growth of geoscience as a discipline. We expect that community-driven, multidisciplinary projects will become more prevalent, leveraging multi-scale and multi-instrument arrays that expand upon existing network infrastructure. Supporting interdisciplinary and innovative community experiments through the FGF is essential to NSF's core values.

Desired Capabilities for the SAGE and GAGE Successor Facility: Recruiting and Training the Next Generation of Geophysicists and Promoting Public Geophysics Literacy through Education and Outreach

One of the benefits of the existing SAGE and GAGE geophysical facilities is the dissemination of geophysical and seismological knowledge to both the public and the educational system from primary school to university undergraduates. Additionally, the support provided by these facilities to early career researchers is invaluable. As such, we would recommend any future facility continue along the path created by UNAVCO Education and Community Engagement (ECE) and IRIS Education and Public Outreach (EPO), to:

- popularize geoscience through public outreach
- generate educational materials for teachers from K-undergraduate
- train undergraduates (such as the IRIS intern program) and early career researchers in geophysical methods and public communication
- build community and expertise among all levels of geophysicists, through training and networking events

We consider these activities by the existing SAGE and GAGE facilities to be highly successful, and see them as a model for similar activities by a future facility. In this white paper, we present the importance of broadening participation and creating an inclusive environment in the geophysics community, suggest new initiatives for improving undergraduate and graduate geophysics education, and discuss strategies for promoting public geophysical literacy.

1. The importance of broadening participation and creating an inclusive environment

We suggest that the education, outreach, and workforce development branches of the successor facility actively work to engage teachers, students, and the public across the U.S., including under-represented groups in the geosciences. The geosciences, addressing complicated and dynamic Earth systems, remains one of the least diverse Science, Technology, Engineering, and Mathematics (STEM) fields (Czujko and Nicholson, 2010; Bernard and Cooperdock, 2019). The majority (86%) of PhDs awarded over the last 40 years were to those who identify as non-Hispanic white, and there has been virtually no change in the percentage of PhDs awarded to minorities over this same period (Bernard and Cooperdock, 2019). Furthermore, the educational environment that minority students and professionals face in the geosciences also continues to be unwelcoming and exclusionary (Velasco and Jaurrieta de Velasco 2010; Dutt, 2020). We hope that the future geophysical facility's educational programming creates an inclusive professional environment for undergraduate and graduate students from all backgrounds. We encourage the successor facility to advertise student opportunities to a wide range of universities including small and large universities, public and private universities, community colleges, and minority-serving institutions. We also recommend that the facility take a leadership role in modeling inclusive practices and potentially offering training or facilitating discussions with the community on these topics at workshops. We note that while the college student body is becoming increasingly diverse, much of this diversity is in two-year institutions and less select four year institutions (e.g. Espinosa et al., 2019). Incorporating faculty and staff from these institutions into major decision making bodies and workshops in the future facility will be essential for improving recruitment and retention of students from groups underrepresented in geosciences.

2. New suggestions for supporting undergraduate and graduate science education through the future geophysical facility

In the interest of further democratizing undergraduate and graduate science education, we suggest the following activities for the new facility to build upon existing programs like intern training:

a) Development and curation of community-based open source courses and activities in geophysics, geodesy, and seismology. This would be a natural complement to the SERC repository, which is a collection of mostly lower-level and individual components. These courses would be produced by community members (perhaps with financial incentives), and would include explanations and derivations, learning goals, activities, labs, and suitable summative and formative assessments. These resources would provide a number of benefits: a) most existing upper level textbooks in geophysics, geodesy, and seismology lack learning goals and exercises that address learning goals; b) the texts would contain complete derivations (that could be skipped) so they can be used at a range of course levels; c) the courses would be useable out-of-the-box, so that early career faculty could spend less time preparing such courses; d) the content could be forked or modified as the fields progress; and e) we believe that high-quality courses in geophysics can reduce some of the "leaky pipeline" issues and help transition students from underrepresented groups from undergraduate to graduate school.

b) A new program to broaden the research tools available to graduate students. In this program, the graduate student would team up with an external geophysicist to use a software tool the external person has developed. The student would work with the external collaborator to prepare data and learn the methods, and then travel to the external collaborator's institution for a short period of time, such as two weeks, where they would focus on significant progress in processing the dataset of interest. The student would return with the software tool, and the external collaborator would be a co-author on any research publications. This would benefit students and faculty at smaller or more teaching-oriented institutions, where the breadth of geophysical research expertise may be limited.

c) Provide funding and support for continuing education, fellowships, and research conferences for early career researchers, especially those at PUI's and non-R1 institutions.

3. Strategies for promoting public geophysics literacy

Geophysics research and awareness impacts a wide range of challenges and issues in our communities including earthquake hazards, volcano hazards, geomorphological hazards such as landslides and slope stability, hydrology/water resources, environmental contaminant tracking and clean-up, energy and mineral resources, climate change, and tectonic activity. Public awareness of geophysics is important for helping people understand and deal with geohazards as well as understand earth resources critical to our lifestyles such as water, energy, and mineral resources. We recommend that the future geophysical facility continue the work of the SAGE and GAGE facilities to communicate geophysics to the public. Current activities that have been successful include:

- educational videos, posters, and fact sheets describing geophysical concepts to the public

- K-12 teacher training for teachers from a broad variety of schools in different geographic areas of the country
- public displays and lectures on seismology and geodesy presented at international meetings and general public spaces like museums
- training workshops for graduate students and professional geophysicists on communicating science
- interactions with the public over social media platforms.

Compared to the existing programs at SAGE and GAGE, we suggest a future facility will likely need extra resources to reach out to partners with updates as the merger progresses. Continued face time and outreach to diverse organizations such as the Society for Advancement of Chicanos and Native Americans in Science (SACNAS), National Association of Black Geoscientists (NABG), Association of Women Geoscientists (AWG), and National Association of Geoscience Teachers (NAGT) will be important for continuing the missions of promoting public geoscience literacy and recruiting the next generation workforce. We know of no group that specifically supports first-generation or students from low income families, but also encourage recognition of these students as a marginalized group.

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Sincerely,

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Early Career Community Vision For Future Magnetotelluric Facility

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1. Introduction

This white paper serves to communicate the need for and value of a magnetotelluric (MT) instrument pool to Early Career Investigators (ECIs) as part of the NSF Future Geophysical Facility (FGF). It was motivated by the "*Early Career Investigator Virtual Workshop on a Community Vision for the Future Geophysical Facility*" held April 23-24, 2020. The views expressed here arise from ECIs with expertise in a variety of disciplines, including MT, controlled-source electromagnetics, seismic imaging, earthquake seismology, geodynamic modeling, cryospheric processes, space physics, numerical simulations, and geophysical inversion. The diversity of expertise represented reflects the growing need for multidisciplinary, multimethod studies to tackle the scientific questions at the forefront of geophysical research; MT is a critical component of this effort. We envision the geophysical community using MT for a wide-range of scientific and engineering applications, including geothermal energy systems, mineral resource exploration, carbon sequestration, permafrost gas hydrates, hydrology, volcano science, cryospheric and climate-change science, deep Earth imaging, geohazards, space physics, subduction zones, and planetary analog research.

MT expertise has experienced a surge in demand from the broader geoscience community, particularly in areas MT has not traditionally been used (e.g., subglacial groundwater hydrology). Yet instrument availability has not kept pace with growing demand, resulting in limited expansion of the novel use of MT among ECIs. To alleviate this barrier to transformative scientific advances using MT methods, we strongly recommend the continuation and expansion of the recently established IRIS MT instrument pool in the FGF. In addition to maintaining instrumentation, we recommend the FGF consolidates and strengthens the MT community through open data requirements, software development, and education and training for the next generation of early career geophysicists.

2. MT as part of a multidisciplinary toolkit

MT provides the community with an observational approach to imaging electrical properties at depth that is uniquely sensitive to conductors, such as aqueous fluids and partial melts. MT methods applied in conjunction with other geophysical methods (e.g., seismic imaging), then can holistically identify spatiotemporal variations in subsurface physical properties of both the rock matrix and any fluids in the pore space that result from geophysical processes, both past and present.

The recently released National Academies of Sciences report "A Vision for NSF Earth Sciences 2020-2030: Earth in Time" makes two recommendations to NSF-EAR that are relevant to the MT community: (1) continued support for the community development of the SZ4D initiative, and (2) funding a Near-Surface Geophysics Center. Shore-crossing MT is a crucial component of the SZ4D Initiative; p.57 of the "SZ4D Vision Document" explicitly notes that "conducting large-scale MT experiments […] received considerable support at the [Subduction Zones Observatories] workshop". Therefore, we recommend that the FGF: (1) lead the charge on instrumentation, engineering, logistics, and data services support for any future MT subduction zone experiment; (2) explore options for establishing and/or coordinating community access to seafloor MT instruments. Since audio-MT, radio-MT, and controlled-source AMT are important components of Near-Surface Geophysics (depth investigation <100s of meters with applications including hydrology, geothermal, mineral exploration, seismic hazard, etc.), the FGF should coordinate with any future facility to leverage access to MT and other EM systems.

At subduction zones, the need to understand controls on megathrust slip behavior and the magmatic processes that trigger volcanic eruptions is evident in the destructive nature of these hazards. Here too MT is of great value, particularly in its adeptness at imaging fluids and partial melts, key variables in several outstanding questions linked to forecasting the timing and location of tsunamigenic earthquakes and explosive eruptions. Recent time-lapse studies also highlight the potential for MT in volcanic monitoring applications.

The SZ4D initiative is emblematic of a broader shift in geophysics towards both time-dependent and shore-crossing research. Studies of regional groundwater systems and geothermal groundwater circulation patterns, in both terrestrial and marine environments, will be critical for the development of renewable energy and sustainable water resource management as well as characterizing globally significant nutrient fluxes across coastlines; MT is particularly suited for imaging such systems. MT is of great value to the cryosphere community as well, as subglacial geothermal and groundwater systems likely play key roles in modulating ice behavior.

The complementary nature between passive seismic and MT (and geodesy) can also provide novel insight into active transform plate tectonics. High resolution crustal information on strain, seismic velocities, fault geometry and brittle-ductile behavior relies directly or indirectly on estimates of local seismicity. Some major earthquake-producing faults (e.g. southernmost San Andreas fault) have almost no microseismicity and subsequently their strain and structural properties are poorly constrained. MT, however, does not depend on non-uniform seismicity patterns and therefore provides unique insight into fault zone architecture in regions where there is little seismicity, including the ductile crust, which is crucial for any seismic hazard assessment.

New and consequential applications of MT data have emerged over the past decade. Recently, MT has become invaluable in studies of the geoelectric hazards posed to grounded technological infrastructure by large magnetic disturbances, including research on geomagnetically induced currents (GICs). Both MT transfer functions (TFs) and the three-dimensional electrical conductivity models derived from them provide crucial information for such applications. Additionally, TFs, as well as raw electric and magnetic field time series data, have proven useful in ground-based and integrated satellite-ground studies of near-Earth space phenomena, particularly with respect to how those geospace processes couple with the electrically conductive Earth. By integrating MT instruments, engineering support, and community development into the FGF, these emergent and potentially transformative uses of MT methods will be able to mature and thrive in the coming decade.

3. Instrumentation and Engineering Services

We support the recent IRIS acquisition of 12 long-period (LP) MT instruments. More LP systems will need to be acquired as the demand will quickly overwhelm this initial limited supply. As more experiments are proposed and funded, and as those experiments become longer, larger, and involve time-lapse observations, a pool of >40 LP MT instruments will likely be necessary.

To complement these LP instruments, we envision the FGF acquiring at least 24 ultra-wideband (UWB) instruments; again, this number will likely have to grow as demand for instruments expands, especially for long-term monitoring experiments. Ideally, the instrument pool will support multiple surveys simultaneously as well as high-density surveys that cover large areas. The need for dense coverage is readily apparent in inverse solutions obtained from EarthScope data, where upper-crustal structures are aliased by sparse sampling. Furthermore, the FGF should support rapid-response surveys with instruments that can quickly be mobilized to investigate sudden geologic events, such as the Ridgecrest Earthquake. In this regard, “non-traditional” MT deployments that record only electric field data could be used to add station density. Although magnetic field sensors at every site would be optimal, survey in-fill with electric-field-only stations could quickly and cheaply expand station density when data coverage is important.

We also expect a need for several auxiliary capabilities that may require engineering development. Specialized accessories that make it possible to deploy LP and UWB systems in extreme and/or low-contact-resistance environments, such as deserts, polar regions, and areas of pervasive rock outcrop, should be made available to users. These accessories include ruggedized instruments and cases, high impedance electrodes, preamplifier buffers, and specialized electrode cables. A permanent station in a quiet environment near the FGF would provide a ground truth for testing custom equipment as well as benefit MT research, as this easily serviced station would provide a readily available remote-reference site for data processing purposes while also enabling both deep mantle imaging and long-term studies of the MT source fields. Additional permanent stations, where feasible (e.g., recording electric field time series at geomagnetic observatories), serviced by the FGF would multiply these community benefits. For site deployments lasting more than a few days, we recommend that users have the ability to: (1) remotely monitor and check instrument health to ensure proper operation (e.g., the USGS has such "status-of-health" monitors for MT, similar to UNAVCO and IRIS with GNSS and seismic stations); (2) wirelessly connect to the data logger via bluetooth or wifi to retrieve data; and (3) add full data telemetry to less accessible site locations. Lastly, we support the IRIS plan to hold a field training course for new users, and we encourage continuing to offer in-person field training courses and archiving teaching materials and field procedure guides for public access to foster the next generation of MT-capable researchers.

4. Data and Software services

A critical part of serving and growing the MT community is enabling access to these data and any complementary computational tools. We envision the FGF achieving both by: (1) archiving data, from raw time-series to analysis-ready TFs along with metadata, and making them freely available and accessible to the community, and (2) fostering a community and ecosystem of open-source, interoperable software tools for processing, inverting, and visualizing MT data and models.

We support ongoing IRIS-backed efforts to formulate MT data and metadata formats that are specific to MT. These formats should simultaneously support researchers using High Performance Computing (HPC) resources, which use parallel file storage (e.g. HDF5), as well as Cloud Computing resources, which are most performant with object storage (e.g. Zarr). The choice and design of an appropriate format will be done in consultation with the wider open-source geoscience community in order to promote interoperability with data and software tools from other scientific domains (e.g. seismology). Data, metadata, and data products associated with an MT instrument deployment should be accessible programmatically through an API, as well as interactively through a web-interface, to promote data discovery. Data should be archived with an appropriate license (ideally permissive licensing, but also for cases where data may be restricted to academic use only), and assigned a DOI, which is a permanent link and facilitates citation of those data. In addition to archiving current and newly acquired data, the FGF would also be responsible for improving access to legacy data, including reformatting data to adhere to modern standards.

The development and long-term curation of software for MT data processing and visualization will be a key component for broadening the user base of MT through the FGF. In line with the strategy of successful projects such as ObsPy in seismology and Pangeo in climate science and oceanography, the FGF will seek to promote an ecosystem of open, interoperable software tools (as opposed to the development of a monolithic "toolbox" meant to address all aspects of working with MT data). By prioritizing contributions to existing open-source software projects including MTpy and SimPEG, the FGF will be investing in tools that already have proven their value to the community, and will be well-positioned to facilitate interoperability with widely used software such as ModEM and HexMT. Where there are gaps in the open-source workflow, the FGF should undertake development efforts that might include upgrading legacy software, or the development of open-source analogs that are comparable to widely used legacy software, such as Gary Egbert's EMTF code. Similarly, the FGF should develop and maintain software to assist in planning and managing MT surveys with facility-provided instruments. In conjunction with the data archiving efforts, we envision that the FGF could also archive derived data products such as inversion results following current practices of the IRIS EMC, which could serve the community by disseminating scientific results as well as by providing benchmarks and mechanisms for comparing codes. Finally, the FGF is well-positioned to support and create learning resources for the community on the use of open-source tools for working with MT data, such as by hosting short courses (both in-person and virtual) and webinars.

An NSF-supported Geophysical Facility to Succeed the GAGE and SAGE Facilities Must Include a Fleet of Mobile Earthquake Recorders in Marine Areas

Frederik J. Simons, Princeton University
and The EarthScopeOceans Consortium

June 1, 2020

Abstract

While all of us are sequestered inside, planes are grounded, and ships are berthed, a fleet of forty-seven autonomous earthquake recorders are drifting at 1500 m depth along with the currents in the Pacific, surfacing every 4–7 days to report via satellite a handful of recently recorded seismic records. The target of the ongoing South Pacific Plume Imaging and Modeling project are teleseismic global earthquakes, but MERMAID lends itself equally well to recording local or regional seismicity. In its current commercially available third-generation incarnation one MERMAID costs about $35k to acquire, $100 per month for data recovery, and as little to deploy (and never to recover) as can be had by using ships of opportunity. Closing the oceanic coverage gap should be part of the next-generation Facility. A fleet of autonomous marine instruments is a vital component of a modern-day seismological observing strategy.

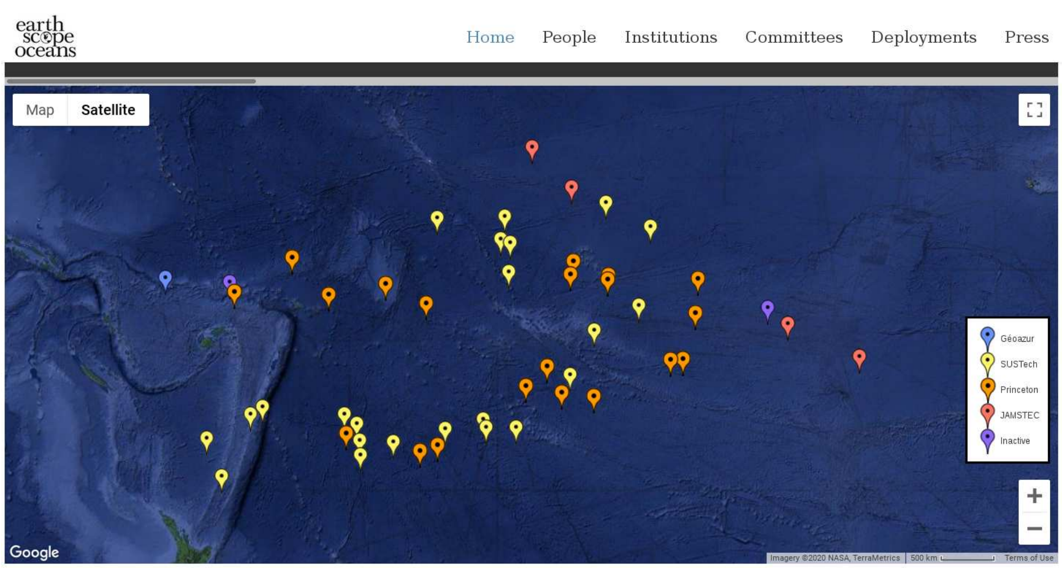

Figure 1: Location of the international MERMAID fleet as of June 1, 2020.

1 Objectives

(a) To understand how the solid Earth drives plate tectonics and maintains its internal temperature, we need a map of its interior. We predict ground motion due to earthquakes numerically, and compare it to instrumental records using tomographic imaging techniques. Because two-thirds of the Earth's surface is covered in water, largely inaccessible to instrumentation, gaping holes in our understanding have persisted for decades. (b) The deep ocean itself is a vast receptacle of heat—a major factor in regulating the evolution of Earth's climate, but virtually no direct observations of the time-evolving temperature of its deep currents exist. We cannot constrain climate models without knowing the heat content of the deep ocean. We *have* the technology—a new type of instrument: MERMAID—to plug the data coverage gap.

2 The MERMAID instrument

The current third-generation MERMAID is an unrecovered freely-drifting diver that combines [1] a hydrophone to record earthquakes while floating at up to 2 km depth, [2] GPS for location and timing, [3] an on-board digitizing and processing unit that uses STA/LTA, and probabilistic wavelet-based detection and discrimination algorithms, and [4] an Iridium satellite unit for near real-time data transfer (triggered *and* buffered) with two-way communication. The easily deployable instrument has a lifetime of up to 5 years, and is manufactured by OSEAN SAS (of Le Pradet, France). With up to 7 kg of sensor payload, additional configurable sensors available today include a SeaBird SBE 41 CTD, and, in the near future, a suite of other instruments with utility in bioacoustics, environmental monitoring, meteorology, bathymetric determination, and chemical and physical oceanography. Equipping the next-generation Facility with a fleet of MERMAID instruments will serve seismology first, while bringing together the variety of scientific communities jointly interested in opening up the oceans for remote observation.

3 MERMAID's tomographic data quality

Figure 2 shows examples of MERMAID seismograms (numbered and color-coded) reported from the Pacific. Grey data are from sparse land stations in the Global Seismographic Network.

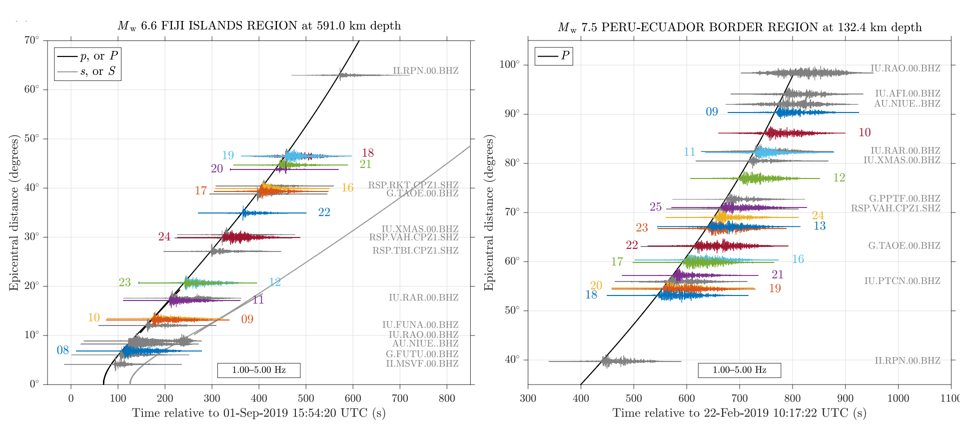

Figure 2: Tomography-quality MERMAID seismograms from the Pacific.

4 A global strategy

Acquiring, deploying, and replenishing an array of MERMAID instruments should become a core component of the new Facility. While no claim is made as to the inherent intrinsic superiority of Ocean Bottom Seismometers (OBS), freely floating devices, reporting seismic waveforms in near-real time will occupy an important niche at a fraction of the cost. A global program to deploy and recover OBS sensors for five years would cost well upwards of half a *billion* dollars. A deployment of several hundred acoustic floats such as envisaged in our strategy, should be feasible for a mere fraction of the cost, with $20 *million* a high-end estimate, based on our current experience with 50 units deployed and reporting live from the Pacific.

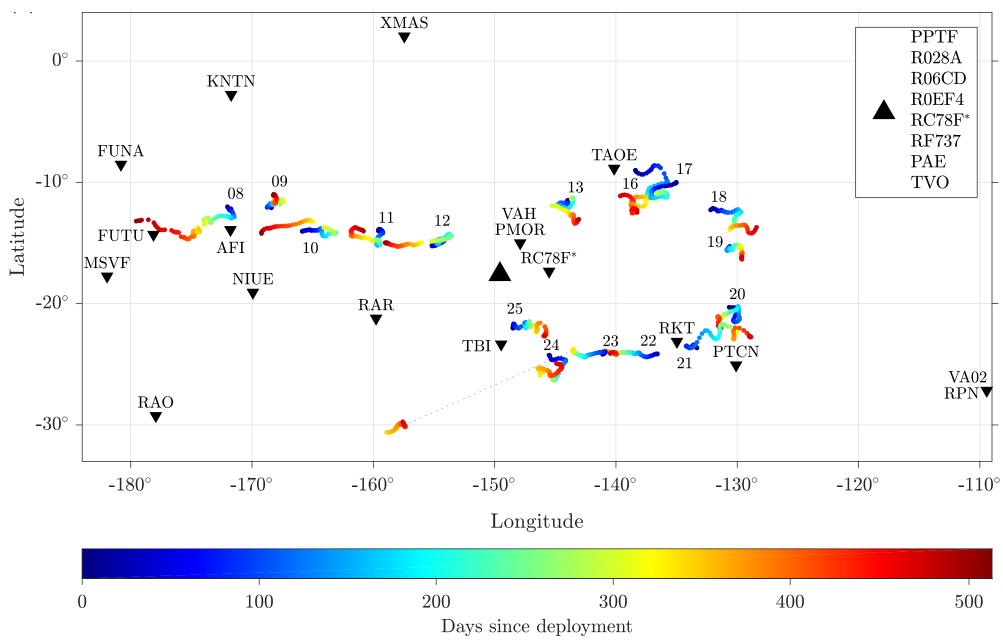

Figure 3: Sixteen months of 18 MERMAID trajectories. Lifetime: 5 years.

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Opportunities for advancing Critical Zone (CZ) Science through a shared-use Near-Surface Geophysics Facility (NSGF)

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1. Introduction and significance:

Defined as the dynamic interface between the atmosphere, biosphere, hydrosphere, and lithosphere (Brantley et al. 2007), the shallow subsurface architecture of Earth's critical zone (CZ) controls the flux of water, solutes, and sediment across and through landscapes, influencing landscape patterns in hydrology, vegetation, weathering, and erosion important for sustaining life. This shallow region (on the order of 100 m depth) is complex due to its heterogenous nature and the fact that physical, chemical, and biological processes occur concurrently.

The importance of the CZ when exploring the Earth system is clear in a recent report from the Division of Earth Sciences (EAR) at the National Science Foundation (NSF) that describes the most urging research questions to be addressed during the next coming decade (NAS 2020), stressing the link between subsurface and surface processes, structure and morphology, and the influence of the CZ on the water-cycle, biogeochemical cycles, biodiversity or climate. Furthermore, the report also highlights the importance of geophysical methods in guiding these CZ-related priority research questions by recommending the creation of a Near-Surface Geophysics Center to "*provide access to instrumentation, technical support, and training required to address several of the science priority questions and enable novel observations that lead to new questions and insights*" (NAS 2020).

For several decades near-surface geophysical methods have proven their value as a tool for imaging CZ processes and helpful in answering CZ science research questions, from the geometry of subsurface structural features, to the evolution of fluxes of water, nutrient and/or gases (Parsekian et al. 2015). However, applicability of these geophysical methods is often limited to equipment availability in different ways. First, researchers are often limited to equipment available at their own institution or other collaborating institutions, or rental pools from service companies. That makes university–owned equipment not available to other non-collaborating institutions that will often remain unused for most of the year. This is particularly difficult for early-career investigators and researchers that are still in early stages of building both ties with collaborating institutions and their own pool of equipment. Secondly, many institutions that have geophysical instrumentation available may lack resources to maintain and service this equipment. Furthermore, many researchers have difficulties supporting maintenance costs of geophysical instrumentation once the active grants used for their purchase expire, resulting in pools of abandoned equipment due to lack of resources. *For all these reasons a shared-use equipment Near-Surface Geophysics Facility (NSGF) that is professionally maintained and serviced, and focuses on state-of-the-art near-surface instrumentation would represent an efficient, cost-effective investment to ensure equipment availability to a wide range of researchers and institutions*. Similar NSF-funded facilities (such as IRIS-operated Seismological Facilities for Advancement of Geoscience, SAGE) have already proven the effectiveness of such a model.

2. Importance of a shared-use NSGF to advance CZ science:

Given the interdisciplinary nature of Near-Surface Geophysics, a NSGF facility can help a broad variety of science areas, but as specifically applied to the CZ community we feel it would benefit researchers and institutions in several ways:

2a. *By supporting true 3D-imaging to better capture the heterogeneous nature of the CZ architecture.*

2b. *By supporting spatial scales of measurement beyond traditional approaches that are relevant to watershed-scale processes.*

2c. *By expanding temporal scales of measurement to better capture CZ processes in real-time.*

2d. *By combining multiple geophysical methods to infer physical properties and generate better constrained geophysical models.*

2e. *By providing training, education and outreach support to the wider CZ community.*

2a. True 3D imaging of the CZ architecture

Given the level of heterogeneity that landscapes exhibit, quantification of the CZ that includes three-dimensional (3D) spatial characterization of surface and subsurface architecture and processes has been a common goal across the network of NSF-funded CZ Observatories in recent years (Chorover et al. 2015). Current efforts to capture spatial variability in 3D within the CZ have focused on determination of subsurface architecture (Befus et al. 2011, Tye et al. 2011, Cheng et al. 2019, DiBiase et al. in review), and hydrological (Flinchum et al. 2018, Guo et al. 2019), or soil properties (Shepard et al. 2018, Song et al. 2019). However, these studies are characterized by: 1) relatively small measurement scales (<1 km^2); and 2) measurements rely on interpolation of scattered 2D transects. Advances in ground-based geophysical methods have resulted in a new generation of instrumentation for acquiring true 3D datasets regardless of terrain conditions. For example, fully 3D resistivity and induced polarization (IP) imaging (**Figure 1**) is now possible utilizing distributed receiver systems (Truffert et al. 2017, Ahmed et al. 2019). However, *new instrumentation is often costly and not readily available for the average CZ researcher, therefore stressing the need for a shared-use NSGF that can regularly update with the latest state-of-the-art instrumentation and make it available to the CZ community.*

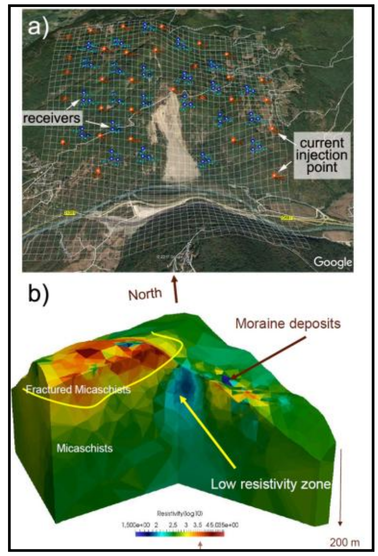

Figure 1: **a**) FullWaver 3D DC resistivity survey showing location of receivers and current injection points at a landslide study site in the French Alps; **b**) 3D inverted profile showing resistivity distribution. Modified from Truffert et al. (2017).

2b. Expansion of spatial scales relevant to watershed-scale processes

Technological advances over the last decade have also improved data collection efficiency for other geophysical methods. For example, ground-penetrating radar (GPR) surveying with rough terrain antennas allows for efficient data collection (i.e. walking pace) over large areas of rugged terrain (Comas et al. 2017, Ceru et al. 2018, Comas et al. 2019, DiBiase et al. in review). Capacitively-coupled resistivity and multi-frequency terrain conductivity have been extensively used for the last two decades (Allred et al. 2006, Oldenborger and LeBlanc 2013, Niu et al. 2014, Saribudak and Hawkins 2019), yet few studies have deployed these methods over larger (km) scales (Comas et al. 2019) that may be more relevant to watershed-scale processes.

Geophysical methods traditionally deployed at plot scales (i.e. 10s-100s m) such as electrical resistivity, can also be expanded by increasing electrode spacing (Galazoulas et al. 2015, Nickschick et al. 2019), however while increasing electrode spacing results in increased depth of investigation, it also causes a decrease in resolution which may be detrimental for many CZ studies. Increasing efficiency is possible by increasing number of channels where voltage is measured. Alternatively, simultaneous arrays of measurements can be deployed. However, this requires having several electrical resistivity systems which is not feasible for most researchers. For those reasons, *a shared-use NSGF would facilitate the ability for researchers to expand arrays and increase efficiency of high resolution measurements at spatial scales of measurement relevant to larger scale CZ processes.*

2c. Expansion of temporal scales relevant to the monitoring of CZ processes

CZ processes varying over time require application of time-lapse measurements that match appropriate temporal scales of measurement. Many studies have shown the ability of geophysical methods to capture the dynamic nature of CZ processes in a variety of settings and scales, including water storage and preferential flow pathways, sediment transport, or soil carbon storage and release (Parsekian et al. 2015). For example, temporal changes in electrical resistivity value can be linked to hyporheic exchange in a mountain watershed, water infiltration and subsurface flow, contanimnant transport and remediation in groundwater (Singha et al. (2015) and references therein). Additionally, the cutting edge of fiber optics instrumentation has demonstrated the advantanges of temperature and acoustic sensing in long-term and low-cost monitoring of hydrosystem, e.g., monitoring the permafrost development using DAS (Ajo-Franklin et al. 2017) and alpine river hyporheic zone using DTS (Busato et al. 2019). The existing scattered distribution of instruments lack the ability and functionality to offer comphrensive mointoring capacities for long-term CZ observations. *A NSGS with next generation of instrumention is crucial for understanding temporal CZ functions over extended periods of time*.

2d. Improving CZ models by combining multiple geophysical methods

A significant gap exists between conceptual models of CZ architecture and the empirical data currently available to test these models. For example, several recent studies have shown the potential of geophysics for understanding propagation of weathering fronts from seismic measurements (Hayes et al. 2019, Holbrook et al. 2019), characterization of subsurface variations in regolith properties associated with changes in climate, vegetation cover and topography (Dal Bo et al. 2019), from GPR, or characterization of the extent of weathering fronts as controlled by geological structures such as faults and veins (Place et al. 2016), or fracturing (Comas et al. 2019), however they also commonly suffer from non-unique interpretation or limited resolution of inferred physical properties and based on application of a single or few geophysical methods.

Therefore, the combination of multiple geophysical methods may provide unique complementary information to derive robust geophysical models. For example, where geophysical properties like acoustic impedance from seismic measurements can be used to infer compressive strength, and better understand physical weathering, simultaneous electrical resistivity and induced polarization measurements could provide information on chargeability and inferred surface area to inform about chemical weathering and therefore potentially allowing discrimination between physical vs. chemical weathering processes. For these reasons, *a shared-use NSGF would facilitate multi-method approaches by providing CZ researchers with an expanded array of geophysical measurements to better constrain geophysical models.*

2e. Training, education and outreach support to the wider CZ community

Increasing student access to near surface instrumentation will benefit student learning by enabling students to construct and conduct their own field investigations, and to analyze and interpret the resultant data. These types of student-driven research projects have the potential to enable learners to construct deeper levels of understanding (Osborn and Karukstis 2009.), communication skills (Bauer and Bennett 2003), critical thinking and problem-solving (Ishiyama 2002), and to increase understanding of the nature of science (Moss et al. 2018).

In addition to these pedagogical benefits, hands on experiences, which can only be made possible with instrument access, also provide affective domain benefits, via a sense of belonging and shared experiences with the larger Earth Science community that are shown to positively impact not only learning (Elkins and Elkins 2007), but also recruitment and retention in STEM fields (Keating et al. In prep). This is particularly important for many minority-serving and other under-represented serving institutions, and for institutions with limited internal resources for Earth science curriculum and activities. *The new infrastructure provided by a NSGF will enhance many undergraduate and graduate courses by providing instrumentation that is not feasible for many institutions and CZ researchers.*

3. Summary

The application of geophysical methods in CZ research is relatively new as the CZ community has only recently begun to be aware of the power of connecting geophysical measurements to hydrogeochemical datasets. This document exemplifies how a shared-use equipment Near-Surface Geophysics Facility (NSGF) would provide unique opportunities to advance process-based CZ models with cross-disciplinary datasets, capable of providing unique 3D imaging at large watershed scales, capturing CZ processes at different temporal scales, or translating geophysical observations into key CZ parameters from multiple methods, while providing unique opportunities for training, education and outreach of the CZ community, and particularly students.

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Community Comment:

Desired capabilities for a future national geophysical facility to support near-surface geophysical instrumentation needs for cryospheric science

Background

The cryosphere – from the Antarctic Ice Sheet to seasonal snow in the western US to permafrost and sea ice in the Arctic – presents some of the most challenging features in which to measure subsurface properties, but are also some of the most important places for science and engineering research due to their susceptibility to rapid environmental and disturbance-induced change and large societal implications (e.g., global sea level rise, water resources, geohazards). Earth's cryosphere forms a critical component of the planet's dynamic near-surface system, and one that is highly amenable to geophysical study. Ground-based near-surface geophysical methods are deployed to observe and monitor targets below the ground or in ice that may be difficult or impossible to measure using conventional direct observations and measurements. At present, the most common near-surface geophysical techniques include ground-penetrating radar, electrical resistivity, electromagnetics, nuclear magnetic resonance, small-diameter borehole logging, and shallow seismic refraction methods.

Near-surface ice – both as ice sheets and glaciers, but also incorporated in permafrost – is highly sensitive to environmental perturbations on time scales ranging from mega-year to human time and participates in critical feedback processes with climate, weather, the solid Earth, oceans, and hydrology. Climate perturbations strongly affect the cryosphere through melt and other wasting processes and have profound implications for the human and natural world, notably including sea-level rise, coastal and alpine glacial instability, and altered water resources. Permafrost, which is perceptible to study and monitoring via near-surface geophysical methods, is thawing across large areas of the Northern Hemisphere, contributing to coastal and inland instability and accelerated release of sequestered carbon to the atmosphere. A wide range of cryosphere science questions are being addressed using near-surface geophysical data, and most are highly relevant to understanding impacts and contributors of climate change. For example: How does liquid water affect snow, glacier, and permafrost dynamics; what controls snowpack distribution and water content; what controls water movement in the active layer above permafrost; what is the distribution and thickness of ice-rich permafrost deposits; and how are sensitive features like Antarctic lakes and ice shelves evolving? In all cases, near-surface geophysical measurements provide parameters vital to understanding the structure and function of these systems, often in 2D or 3D space or through time.

Problem and Solution

There is widespread agreement that cryospheric science questions are amongst the most pressing environmental and earth-system science questions facing society today (e.g., NSF's 10 Big Ideas: Navigating the New Arctic; NSF/NERC International Thwaites Glacier Collaboration), yet major challenges remain in the way of rapid, paradigm-changing advancements. A substantial body of evidence has been developed over the past >70 years showing that near-surface geophysical data can provide unique insights into cryospheric processes, yet access to the required instrumentation by a broad cross-section of researchers is limited. This is in part due to the expense of equipment, as well as the associated knowledge base to appropriately acquire data. It is not uncommon for a single near-surface geophysical instrument to cost between tens-of-thousands of dollars (e.g., ground penetrating radar) to several hundred thousand dollars (e.g., surface nuclear magnetic resonance). In rare cases this may be within the range of what a newly-hired researcher may be able to budget within startup funds, but often the cost is out of reach for individual scientists, particularly early in their career. Similarly, such costs may be included in federal funding proposals, however large equipment costs rapidly deplete research budgets and thus can hinder the potential to actually accomplish the research needed. Commercial instrument rental services are sparsely available, may not have the most cutting-edge instrumentation, carry a high cost, and lack the specific research support and training capacities needed to be used successfully by non-experts. Furthermore, an expensive geophysical instrument may only be used by a given researcher for several weeks per year, and otherwise sits idle – a case that is more likely to happen when used by the more general "broadly defined cryosphere scientist" in comparison with a geophysical specialist. In order to tackle the most pressing research questions, we should strive to empower the broadest range of scientists with these tools, rather than only those who are "instrument specialists."

<u>Rationale for these capacities to be centralized in a national facility</u>

The elements of this problem seem ideally suited for augmentation by a nationally-supported facility that focuses on procurement, maintenance, and training with near-surface geophysical instrumentation. When the SAGE and GAGE facilities are integrated in the near future, we strongly lobby for the inclusion of a near-surface geophysical instrumentation pool as a part of the new facility that would be available for use in the cryosphere sciences. This is a clear opportunity to catalyze new research results and provide greater equity in access to this equipment. By investing resources in this community equipment pool, rather than in isolated individual-grant funded equipment, the return on NSF's investments will be greatly magnified.

Broader Impacts

- A wider range of researchers – particularly students, early-career scientists, and researchers at colleges/universities with more limited resources – will be enabled to incorporate cutting-edge geophysical tools into their projects and greater equity access to this equipment
- Particularly in the Northern Hemisphere, cryosphere science is closely linked with infrastructure and indigenous peoples who experience first-hand many of the problems and processes studied; enhanced understandings of Arctic systems and dynamics will have local direct benefits to these communities
- Change in the cryosphere is happening very rapidly on human timescales, and the effects of warming in cold regions has an outsized impact on the broader population living at mid latitudes. Increased capacity to acquire geophysical measurements of these systems will improve understanding and projections of their influence, and has the potential for substantial policy and management payoffs

Intellectual Merits

Inclusion of near-surface geophysics instrumentation is expected to result in numerous advances in cryosphere research. To name a few:

- Geophysical imaging to improve understanding of subsurface cryosphere processes including freeze/thaw, talik development and thermokarst, firn aquifers and snow dynamics, fluid migration, glacial and ice-sheet calving, crevassing, sliding, and mass balance changes, ground surface deformation, etc.
- Capacity to observe deeper targets and provide more spatially explicit information than can be achieved through portable drilling programs alone and with less surface impact
- Capacity to characterize large areas and depth ranges with adaptable surface methods, resulting in larger data collection at lower costs compared with drilling
- Improved understanding of system science perspective linkages between atmosphere, vegetation, hydrology, biogeochemistry, and the subsurface

Desired capabilities housed in a national near-surface geophysics facility

In order to support a robust cryosphere geophysics instrumentation component for the broadest range of projects, a national-near surface geophysics facility should, at minimum, contain equipment aligned with the range of recent publications in the field. In particular, ground penetrating radar, electrical resistivity, surface nuclear magnetic resonance, slimline borehole nuclear magnetic resonance, time-domain electromagnetics, and shallow seismic refraction. Additionally, such a facility should provide access to relevant accessories needed to utilize these instruments under the unique conditions encountered with cold-regions field work (e.g., custom designed sleds, mounting brackets for snowmobiles, solutions for air transport of batteries, etc.). For example, there is a gap between the support for operating near-surface geophysical instruments that the NSF-contracted polar logistics services team can provide, and the requirements of actually executing geophysical measurements in the field. In comparison to the currently national seismology facility that primarily address a single set of physics with a focused range of analytical software through at least the data QC phase, a near-surface focused facility should maintain a library of software licenses for processing the data acquired. Finally, technical support, training, and field personnel would be highly desirable.

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Educational and community diversity benefits from the creation of a national near-surface geophysics instrumentation facility

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Introduction:

In anticipation of the merger of IRIS and UNAVCO to compete to become the national geophysical instrumentation center, we urge the inclusion of a program to foster research and teaching of near-surface geophysics. The development of a national near-surface geophysical instrumentation pool, along with dedicated teaching materials to bolster non-expert educators, would create opportunities for local, hands-on field research and classroom experiences for students nationwide. While other white papers address critical research needs, here we address critical educational needs that would be met by a near-surface geophysics instrument pool.

A pool of equipment shared across the scientific community would advance geophysics teaching and research efforts of faculty and staff across the spectrum of post-secondary educational institutions. The ongoing reality of higher education budget cuts and reduced enrollment will shrink discretionary spending and impact in-house monies available for faculty to build and support equipment capabilities. This makes a national pool of equipment ever more critical to expanding geophysics research and education opportunities to a broader community. Access to a geophysical equipment pool will increase student learning, facilitate workforce skill development, and enhance diversity and inclusion efforts within geosciences. However, these benefits will not be available without an investment in an equipment pool and a base of experts that can be accessed during implementation.

Implications for Student Learning:

Most introductory geology/geophysics courses are geared toward non-geophysics students, from both STEM and liberal arts fields. For an audience like this, it is important that the instructor can help students develop connections between their existing knowledge and real data, and to build a framework to understand and meaningfully apply these new connections (Ambrose et al., 2010). Hands-on work and group-based discussions grounded in authentic data collection and interpretation offer ideal active and project-based learning opportunities that help to increase student knowledge and critical thinking skills (e.g. Stokes et al., 2011). Therefore, access to equipment improves student learning by enabling students to engage in these activities.

Increasing student access to near surface instrumentation will benefit student learning by enabling students to construct and conduct their own field investigations, and to analyze and interpret the resultant data. These types of student-driven research projects have the potential to enable learners to construct deeper levels of understanding (e.g. Osborn and Karukstis, 2009), communication skills (e.g. Bauer and Bennett, 2003), critical thinking and problem-solving (e.g. Ishiyama, 2002), and to increase understanding of the nature of science (e.g. Moss et al., 2018).

The authors recognize that field-based learning can be exclusionary and note that inquiry-based and hands-on laboratory activities have been shown to foster deeper understanding and promote logical thinking among students (e.g. McConnel et al., 2003). We strongly recommend building hands-on inclusive near surface geophysics activities in the laboratory and on campus as an intentional, well-planned, key component of the facility, but the reasons for this are beyond the facility alone - the reasons are in building a more equitable, inclusive and diverse sub-discipline/user-base.

In addition to these pedagogical benefits, hands on experiences, which can only be made possible with instrument access, also provide affective domain benefits, via a sense of belonging and shared experiences with the larger Earth Science community that are shown to positively impact not only learning (Elkins and Elkins, 2007), but also recruitment and retention in STEM fields (Keating et al., In Prep).

Implications for Recruitment and Retention in the Geosciences:

The pipeline for minority participation in geoscience has problems at the recruiting as well as at the retention stage. Positive experiences in introductory geology courses have led students to enroll as geoscience majors (e.g., Houlton, 2010; Stokes et al., 2011), and classroom research projects have been suggested as a way to increase diversity in the geosciences (Baber et al., 2010). Courses based on locations or problems of interest to minority students have been shown to be effective in attracting and retaining minority students (Hammersley et al., 2012). Clearly, early access to instrumentation could be an effective intervention. IRIS is currently developing a set of geophysics teaching modules (IGUaNA) aimed at introductory students, especially from African American and Hispanic communities, in urban environments.

Students' first encounters with geophysics are typically not via large-scale seismic/geodetic research opportunities, but with local environmental, engineering or experiment demonstrations. Expanding these research and teaching opportunities would allow for geophysics to reach a broader and more diverse population of students. Hands-on experiences can thus help to recruit students and be a valuable tool in promoting diversity. Students who view themselves as contributors to science are more likely to be retained in STEM, and thus in geoscience fields (Findley-Van Nostrand and Pollenz, 2017). This equipment pool will increase access to these experiences for under-represented groups and students attending all post-secondary educational institutions. These research and educational endeavors transcend institutional and disciplinary boundaries to provide more diverse, equitable, and inclusive access to existing and to-be-created resources and opportunities across the Earth Sciences.

Implications for Geoscience Workforce Skill Building:

Ground penetrating radar (GPR) and induced electromagnetic (EM) are the two most widely used near surface geophysical methods. GPR and EM have widespread use in engineering, construction, cultural resource management, law enforcement, archaeology, natural resources/agriculture, and environmental industries. For example: over the past decade the field of subsurface utility engineering (SUE) has grown exponentially, due to the increased number of utilities being placed underground and the disastrous and/or expensive consequences if the service is interrupted. In addition, popular media has spurred an interest in forensics which has drawn more classical criminology, anthropology and biology students into the Earth science fields for exposure to emerging technologies. Other techniques such as seismic refraction, electrical resistivity and nuclear magnetic resonance are starting to appear as solutions yet have not been fully appreciated by the industry. Training and practical usage of these technologies in the classroom will provide students with workforce qualifications that push students ahead of other potential hires. The authors note that student advisees had an edge in getting a job because they had experience with geophysical instrumentation and the critical thinking skills fostered using these technologies.

Integrating a Near-Surface Instrumentation Facility Within the National Geophysical Facility

We believe there are both efficiencies and benefits to having equipment and support structures managed by the national geophysical facility. The management and education and outreach expertise is already in place within IRIS and UNAVCO. The educational products of both institutions are highly valued in the geophysics teaching community. In particular, we feel that the current organizational structures from IRIS and UNAVCO, if carried into the future, would allow for flexible and democratic community input from the varied users of a near-surface instrumentation facility. The Committee on Catalyzing Opportunities for Research in the Earth Sciences (CORES), recommends that NSF-EAR should fund a Near-Surface Geophysics Center. The report states that, "*Geophysical surveys of the near-surface region… of the Earth have become an essential tool in many Earth science fields. A center would provide access to instrumentation, technical support, and training required to address several of the science priority questions and enable novel observations that lead to new questions and insights"* (National Academies Press, 2020). The merger of SAGE and GAGE would provide a substantial amount of the infrastructure needed to serve as the host of this facility.

IRIS already supports field courses, webinars to provide professional training on various data processing and interpretation topics, and a longstanding REU program. This multi-faceted approach to supporting the career paths of students through to early-career faculty has enabled IRIS to take an active role in developing the next generation of geophysics community leaders.

The new infrastructure provided by a near surface geophysical instrumentation facility will enhance many undergraduate and graduate courses by providing instrumentation that is beyond the means of many individual universities to afford on their own. It will enable the types of experiences that grow belonging and build workforce-desirable skills for all students. This is particularly important for many minority-serving and other under-represented serving institutions, and for institutions with limited internal resources for Earth Science curriculum and activities.

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Next generation electrical imaging instrumentation for characterization and monitoring of the near surface Earth

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Geophysical technologies

Geophysical technologies are essential to investigations of the near-surface region of the Earth, which extends from the ground surface to depths of hundreds of meters (National Academies of Sciences, Engineering (NAS), 2020). Geophysical datasets have significantly advanced our understanding of near surface hydrology (Binley *et al.*, 2015), critical zone structure (St. Clair *et al.*, 2015), geohazards (e.g. landslides and volcanic activity (Revil et al., 2010) and permafrost dynamics (Doetsch *et al.*, 2015). They also are transforming agricultural science through soil characterization and decision support in precision agriculture. Electrical imaging is arguably the most versatile near-surface geophysical technology. This versatility in part results from (1) the dependence of the measured electrical properties on a wide range of physical and chemical properties, (2) the scalability and flexibility of implementation, allowing surface, borehole, and water (surface or submerged) configurations, and (3) deployment as monitoring systems for automated tracking of subsurface processes. This versatility has resulted in extensive deployment of electrical imaging within hydrological and critical zone observatories.

The vision for the next decade of Earth Sciences investment in research stated that "EAR should fund a Near-Surface Geophysics Center" (NAS, 2020). The success of such a center for investigating the science priority questions proposed in this vision (e.g., *How does the critical zone influence climate?, How is Earth's water cycle changing?, How can Earth science research reduce the risk and toll of geohazards?*) will critically depend on the investment in instrumentation that is capable of providing the right spatial and temporal datasets needed to address such questions. We argue that next generation electrical imaging instrumentation is needed to capture near surface structure and processes at spatiotemporal scales beyond the capabilities of conventional electrical imaging technologies. First, there is a pressing need to acquire true 3D images of near surface structure over complex 3D terrain. Examples include over a mountain catchment, on the flank of a volcano or across a hillslope experiencing failure. Second, there is an equally pressing need to instrument observation sites with reliable electrical infrastructure designed to monitor near surface processes over a wide range of temporal scales. Examples include monitoring of hillslope hydrology, moisture content on unstable slopes, water and nutrient fluxes and surface-groundwater exchange in streams, permafrost loss, water and nutrient uptake by plants, microbial biomineralization during contaminant sequestration, and soil organic matter biodegradation.

Fully 3D electrical imaging in complex terrain

Conventional electrical imaging instrumentation is woefully inadequate for characterization of 3D structures across complex terrain and therefore is unlikely to be the best investment with respect to addressing science priority questions formulated by NAS (2020). These instruments rely on centralized transmitter and receiver electronics that address a series of electrodes via multicore cables. Practical limitations of deployment across complex terrain typically restrict watershed-scale imaging to 2D profiles, from which complex structures are often inferred. This approach is now so commonplace that the inherent inapplicability of the methodology to studying complex 3D environments is usually entirely overlooked. Two-dimensional electrical images are frequently presented and interpreted without reference to the fact that these models represent a system where structure is not changing in the direction perpendicular to the images, an obvious fallacy when considered complex geological structures inherent in many important near surface settings. Although 2D imaging was a revolutionary improvement on the 1D geophysical modeling of the subsurface that remained the standard until the 1970s, it will be necessary to embrace the potential of fully 3D geophysical imaging if the NAS (2020) vision for the next decade of research in the Earth Sciences is to be achieved.

Next generation distributed 3D electrical imaging systems have recently become available to meet this pressing characterization challenge (Truffert et al., 2019). These systems consist of a transmitter and a set of full-waveform recording devices (Fig. 1). Receivers record the full waveform in response to an applied electric field at specific locations; this voltage waveform is synchronized with the full waveform current recorder via a GPS clock signal. The full waveform recorders eliminate the need to run lengthy wires from a centralized instrument to electrodes and thus dramatically reduce the complexity of 3D surveying in rough terrain. This provides a powerful solution to fully 3D imaging in complex terrain: rather than having to try and place electrodes at specific locations defined by a survey line or a grid, the electrodes are strategically placed where accessibility permits. This commercially available technology has been recently demonstrated for 3D imaging of mineral deposits, characterization of landslides in mountainous regions and for mapping watershed-scale structures supporting intra-basin water flow (Truffert et al., 2019).

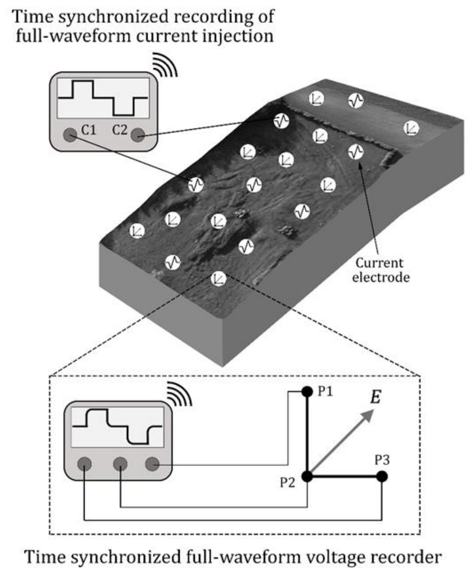

Fig. 1. Concept of 3D resistivity and IP imaging using a fully distributed system.

Dedicated infrastructure for electrical monitoring

Electrical imaging instrumentation is increasingly utilized for monitoring over extended periods of time to capture the evolution of a wide range of hydrogeological and biogeochemical processes (Singha *et al.*, 2014). Conventional instrumentation is generally poorly configured for long-term monitoring in remote areas. Such instrumentation may once again represent poor investment in EAR resources if the intent is to promote long-term geophysical monitoring observations e.g. at critical zone observatories or hydrological observatories Existing instruments may offer some monitoring capabilities, but they tend to have relatively high power requirements and lack valuable functionality (e.g. the ability to self-reboot without loss of connectivity) required in a monitoring system.

Next generation, purpose built electrical monitoring systems constructed from dedicated hardware and software that facilitates autonomous data acquisition in remote places ‘off the grid’ could revolutionize time-lapse geophysical monitoring of near surface processes. One example of a recently developed, commercially available resistivity monitoring system is the Proactive Infrastructure Monitoring and Evaluation (PRIME) system (Fig. 2) developed by the British Geological Survey (Chambers *et al.*, 2015). PRIME is based on a low power (10W) instrument developed around a modular design. It is configured to simultaneously record information on environmental sensors (e.g. rain gauges, moisture probes) that trigger more frequent resistivity data acquisition during times of interest (e.g. during rainfall events). The hardware and software support autonomous data acquisition with pre-configured software for remote transfer of command files and datasets.

Supporting effective adoption of next generation electrical imaging instrumentation within a Near-Surface Geophysics Center.

A near-surface geophysics center would need to go beyond purchase of the instrumentation for community use. Although an interdisciplinary group of scientists (including hydrologists, soil scientists, geochemists, microbiologists and geomorphologists) is increasingly aware of the merit of geophysical technologies for understanding the near surface Earth, most will only be familiar with conventional instruments and applications of the technologies. Consequently, the center would need to promote the utility of next generation technologies, provide training and technical support, even to geophysicists that are comfortable with existing technologies.

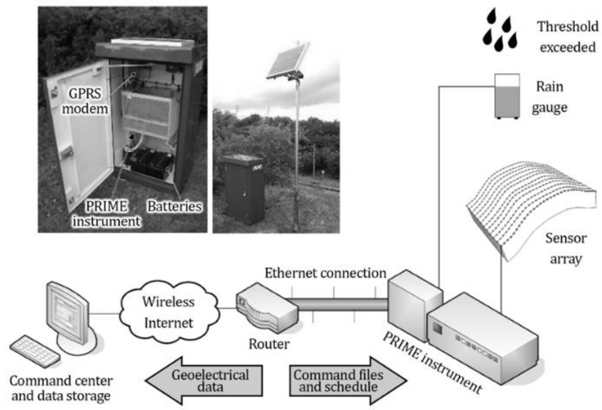

Fig.2 The low power PRIME monitoring system developed by the British Geological Survey (BGS).

The distributed systems are currently expensive (a typical system of 1 transmitter and 10 receivers might be close to $100k) and beyond the budget of most geoscience departments unless purchased on a large research grant. A pool of such instrumentation is the obvious solution to serve the broad EAR community effectively. As with any distributed system that maintains compatibility, there are inherent advantages and economies of scale in a community pool. Whereas one user may only need a small number of receivers (e.g. 10), another user might need 20 for more complex investigation. With a distributed resistivity system, a user could be provided with a system composed of 10 receivers, whilst the additional 10 could be used to create another system. Such advantages are lost on conventional instruments.

Next generation electrical monitoring systems will require technical support from an electrical engineer more than a geophysicist. The system will look less like a geophysical instrument and more like a permanent monitoring unit, similar to the distributed temperature sensing (DTS) equipment offered by the NSF-funded Center for Transformative Environmental Monitoring Programs (CTEMPS). As users will want to install systems at remote fieldsites that they visit infrequently, software engineering support to ensure reliable equipment operation and data transfer will be essential. These systems will generate large amounts of data, which will require support with data storage, processing and inversion. Existing software is incapable of handling such large data streams, so support for new data handling strategies will need to accompany infrastructure investment.

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Requirements for Geophysical Facility to Support Science in Polar and Ice-covered Regions

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Geophysical research in polar and ice-covered regions is guided by interdisciplinary science questions related to the interactions between the solid Earth, oceans, atmosphere, and ice-sheet dynamics. With increasing evidence for strong linkages between polar Earth systems and global climate-change, these questions have direct societal relevance. NSF-supported geophysical facilities have and will continue to play an instrumental role in the success of these endeavors. Below, we have outlined four areas where continued investment is essential for the success of cutting-edge NSF-sponsored polar research.

1) Access to instrumentation suited to meet the rigorous demands of polar fieldwork

The current SAGE and GAGE facilities have played a pivotal role in the success of scientific experiments in the polar regions by providing free access to geophysical instrumentation. **Any future facility must continue to ensure access to a broad range of both seismic and geodetic instrumentation, including short-period and broadband seismometers and geodetic-quality GPS receivers**. Further, the new facility must be able to support additional geophysical approaches. For example, under the current SAGE award, magnetotelluric instrumentation is being made widely available to the scientific community, and under the current GAGE award, support for using unoccupied aerial systems (i.e., drones) for topographic mapping has increased. In consultation with the facility's advisory board, continued re-evaluation of instrument capabilities over time is desirable.

2) Engineering support to achieve success in polar environments

The polar geophysical community must constantly push the boundaries of instrumentation to collect the observations required for transformative science. Much of the geophysical equipment used in polar regions is commercially available hardware that was not initially designed or tested for polar applications but which has been modified for experiments in extreme environments. Environmental challenges are both harsh and varied. Whereas cold temperatures and long polar nights are the most conspicuous challenges of working in polar regions, both extreme moisture and extreme aridity can be challenges in different glacial regions, highlighting the breadth of solutions required for widespread geophysical experiments across the poles. Design must take account of transportability and ease of deployment given limits on polar logistics and the challenges of extreme environmental conditions. Thus, **engineering,design, and testing of enclosures, power systems, and telemetry are critical to successful deployments across this broad range of environments**.. The current facilities have been successful in supporting both relatively small projects, deploying only a handful of instruments for short durations (less than a month), as well as multi-year campaigns that involve dozens of instruments. The associated engineering efforts have typically been most efficient when made with collaboration between the geophysical facilities.

The new facility must be responsive and nimble to support the broad spectrum and scope of NSF-sponsored polar research projects and continue to "push the envelope" to develop polar-specific equipment. Development and vetting of new field capabilities, including sensors, telemetry, and battery technologies, have long timelines relative to the lifetime of a typical grant. In order to provide timely support to polar investigators, engineering efforts must be an ongoing process. Thus, it would be optimal for the polar component of the new facility to have a modest budget to continuously explore evolving opportunities for technological advancements that will aid polar experiments. A key component of these activities will be incorporating community input via facility governance committees and workshops to ensure the alignment of engineering and scientific goals as priorities evolve.

3) Dedicated polar staff

Essential to each of the previous objectives is the hiring and retention of exceptional staff who will maintain the instrument pool and support the engineering efforts. More specifically, **the new facility must employ polar-dedicated staff that understand the environmental and logistical challenges of geophysical deployments in polar regions**. Such understanding and knowledge can only be developed from personal experience and on-the-job training. In recent years, both the SAGE and GAGE facilities have struggled to retain experienced polar staff due to burn-out and fatigue as they attempt to balance frequent and extended field deployments with preparation and engineering development . Thus, dedicated polar staff are not only required for the new facility, but the staffing level must be sufficient that workload expectations are sustainable.

4) Training and Education

The current geophysical facilities provide equipment and software training for project PIs as well as their students. Such activities have been and will continue to be critical to help educate the next generation of polar researchers; therefore, the new facility must also provide such training opportunities. Part of this effort can be provided by enhanced online resources providing detailed information on sensors and system components, reporting selection criteria and testing history, and installation instructions including videos to facilitate remote training. The new facility could also explore collaborations with other NSF-funded education and outreach programs. For instance, the PolarTREC (Polar Teachers and Researchers Exploring and Collaborating) initiative supports U.S. educators to participate in both Arctic and Antarctic research, working side-by-side with polar scientists. Several polar researchers have included PolarTREC teachers in their projects; however, this has not previously included direct interaction with the geophysical facilities. Another example is the Joint Science Education Program (JSEP), operated by Dartmouth College, which is a summer field initiative where students work alongside researchers in Greenland to learn about polar science. Historically, the JSEP has been strongly focused on biology and ecology topics; however, the organizers are interested to develop a solid Earth component for the program. By working with such established organizations, the new geophysical facility could leverage polar-specific training and education opportunities.

<u>On the need for a modernized broadband seismometer pool</u>

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For the past two decades, broadband seismology has featured prominently in science guided by reports from the National Academy of Science (NAS) reports (*Basic Research Opportunities in Earth Scince* (NRC, 2001) and *New Research Opportunities in the Earth Sciences* (NRC, 2012)). Both reports emphasized the importance of supporting PI-driven science, complemented by larger coordinated efforts like EarthScope's Transportable Array, to enable rapid responses to advances that could not have been predicted at the time of their writing. In seismology, PI-driven data collection in the United States is supported by the Incorporated Research Institutions for Seismology - Portable Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL). This pool of seismic equipment, primarily housed and maintained at New Mexico Tech in Socorro, NM, has made possible dramatic advances in our understanding of basic Earth processes by providing ever more detailed and deep glimpses into the interior structure of the Earth.

The new NAS report *"A Vision for NSF Earth Sciences 2020-2030: Earth in Time"* highlights a dozen questions poised for major advances over the next decade and highlights the facilities needed to make these advances. Included among these are "**How are critical elements distributed and cycled in the Earth**", "**What is an earthquake**", "**What drives volcanism**", and "**What are the causes of topographic change**" that are particularly relevant to broadband seismology and in particular, broadband seismic imaging. While new advances in seismic technology are highlighted in the report as critical infrastructure to address some of these questions (i.e. the need for rapidly deployable instruments for volcano and earthquake responses), the need for advanced seismic equipment to enable improved imaging to provide valuable and otherwise unobtainable insights into all four of these questions is not included beyond some vague generalized references. However, the same new technological advances that make possible rapid broadband responses to volcano unrest and earthquake aftershock studies also make possible radical new advances in PI driven seismic imaging that will enable science that is critical to fully answering these questions.

To understand this potential, it is vital to understand the bottleneck that has limited our ability to improve the resolution of our seismic images using the broadband equipment available to us from IRIS-PASSCAL today. Using this type of equipment, the number of stations that can reasonably be deployed for a PI-driven project is typically less than 100, though a small number of projects have exceeded that number slightly. However, improved resolution at depth is gained by increased station density (i.e. reduced distance between individual stations produces overall improved resolution and improved resolution at shallow depths) and by increased array aperture (i.e. arrays covering a larger area can "see" deeper than smaller arrays). The combination of the two means investigators have had to decide between somewhat dense (<10 km station spacing) linear transects that provide 2-D images of the subsurface or broadly spaced (~25 – 75 km spacing) grids of stations that allow for deep 3-D imaging, but at comparatively low resolution. Even the extensive Transportable Array used 70 km station spacing in their goal to gain a continental-aperture imaging network. These limits come from the equipment available, both to PIs (through IRIS-PASSCAL today) and to the Transportable

Array at the time of its inception in the lower 48: Seismic equipment that remains fundamentally unchanged over the past 30 years that is heavy, power hungry, and requires the construction of a waterproof vault in order to safely and reliably collect seismic data.

There is a calculatable cost to using antiquated equipment. Constructing vaults for seismometers dramatically increases the time it takes to deploy (and therefore per diem expenses for installation teams), particularly because most designs involve the pouring and curing of concrete which (depending on the location) often necessitates repeated visits to remote locations for a single installation. The volume of material that has to be transported for a single vault is large, dramatically increasing vehicle and gasoline costs. This increase in driving time, both from repeated trips and because of the additional vehicles needed to transport materials results in increased exposure to driving-related hazards, a concern that is particularly acute in regions with underdeveloped infrastructure. The lack of waterproofness of the equipment results in data loss from flooded vaults that inevitably occur despite best practices. But most critically for the science, it puts a hard limit on the amount of data that can be collected for a given amount of time and money (i.e. by a given program or grant for any one project) which in turn limits the questions we have been able to address with seismic imaging.

The technology exists to remove these barriers and costs, and dramatically change the boundaries of what is possible in PI-driven seismology experiments. Several manufacturers of seismic instruments now produce water- and dirt-proof "direct burial" seismometers, which, together with smaller, lighter, less power-consuming recording devices reduce the number of person-hours required for the installation of a single station by a factor of 5 or more (not including driving time). The smaller size of this equipment, together with the removal of the need for vault construction materials means that drive time to and from equipment storage units is dramatically reduced as well. The smaller footprint and lower power consumption (meaning smaller solar panels) means easier permitting of sites and reduced chances of theft as stations are less conspicuous. It is therefore not unreasonable to assume that an order of magnitude increase in the number of stations that could be deployed *for the same amount of money* with a 21st century broadband seismometer pool is possible.

Seismic imaging at this resolution at depths that span the upper mantle and transition zone has the potential to address many of the fundamental unknowns behind the science questions posed in the NSF report. A good example is the potential improvement in the ability of seismology to investigate the cycling of volatiles (water in particular) through the Earth. This addresses not only the obviously related question "**How are critical elements distributed and cycled in the Earth**", but it plays a central role in helping us to understand "**What drives volcanism**" through the role of water in subduction zones in generating flux melting and associated effects on melt transport and viscosity, "**What are the causes of topographic change**" through the buoyancy effects of hydrated mantle and mantle melting, and even "**What is an earthquake**" as we work to further our understanding of intermediate depth and deep earthquakes that occur predominantly in subducting slabs. The fate of subducted water can be seen seismically in various waves. Hydrated oceanic crust transmits seismic waves at dramatically slower velocities than its dehydrated, metamorphosed reaction product, eclogite. Similarly, mantle hydrous phases are characterized by overall slower seismic wavespeeds, unusual ratios between acoustic and shear-wave speeds (Vp/Vs ratios), and by strong seismic anisotropy. Mantle hydrous phases can be tracked both in the oceanic mantle lithosphere as the plate begins to sink, and in the asthenospheric mantle overlying the slab as the slab dehydrates and releases its water. The release of water from both the slab mantle and crust likely contributes to the generation of intermediate depth seismicity, though substantial debate about the precise mechanisms remains. We know from places like Japan where high seismic station densities exist that it is possible to produce detailed images of slab volatile transport and its relationship to slab seismicity, but the ability to do similar deployment elsewhere is not currently in the hands of U.S. scientists. Dense linear arrays such as the one used by Bostock and Rondenay (Nature, 2002) almost 20 years ago are rarely repeated and are limited to producing two-dimensional glimpses of the complexities of our three-dimensional world.

Looking at the transport of water deeper to greater depths, while geochemists have now found direct evidence of water in the transition zone, we have only begun to attempt to look at the global distribution of water in this layer of the Earth. Again, we have glimpses from receiver function studies that show heterogeneities in the presence of strong low velocity regions directly above and below the transition zone, but increased station density together with increased array apertures would allow us to image these critical structures with a resolution previously unknown.

It is impossible in a single three-page whitepaper to encapsulate all of the potential for a 21st century broadband seismic equipment pool. It is, however, critical to maintain existing infrastructure at least until its replacement is established to meet the community need. Much as the Magellan Telescopes are not being dismantled before the completion of the Giant Magellan Telescope, so too is it important that we maintain our aging broadband seismometer pool at the IRIS-PASSCAL instrument center until we no longer have need for this equipment. There is still significant science to be accomplished with this pool that will move us towards the goals outlined in the 2020 *Earth in Time* NAS report, even if not as expediently or cost-efficiently as it could be with modern equipment. Critically, also, the expertise present at the IRIS-PASSCAL instrument center is truly unique and would be directly applicable to the newer instrumentation – indeed, they have been actively involved in the testing of this technology in close collaboration with the manufacturers as early prototypes are developed. The personnel of the IRIS-PASSCAL instrument center represent precisely the type of resource described in the NAS *Earth in Time* report in its recommendation to "**commit to long-term funding that develops and sustains technical staff capacity, stability, and competitiveness**." The loss of this valuable repository of experience and knowledge in broadband seismology in particular would be incalculable.

I therefore submit that the establishment of a 21st century broadband seismometer pool is vital if we are to fully address the challenges set forth in the 2020 *Earth in Time* NAS report. I also hope that the need for modernization expressed here is not used as justification for the reduction of support for existing broadband facilities until such a time as a new, fully modernized facility is available. To do so would result in irreparable losses to our community, both in terms of the technical expertise and in terms of the support for the community that continues to depend on existing equipment to do their science.

An Early Career Investigator Vision for Shoreline-Crossing Geophysics at the NSF Future Geophysical Facility

Authors: Joseph Byrnes, Helen Janiszewski, Zachary Eilon, Chris Rollins, Colton Lynner, Shawn Wei, Erik Fredrickson, Samer Naif, Brandon Shuck, Noel Bartlow, Miles Bodmer

1. Introduction

We wish to emphasize the importance of shoreline-crossing science to the goals of the National Science Foundation (NSF) Future Geophysical Facility (FGF). Below, we detail necessary support for shoreline-crossing datasets and amphibious geophysical experiments. This whitepaper was motivated by the "Earth Career Investigator Virtual Workshop on a Community Vision for the Future Geophysical Facility" held April 23rd-24th, 2020.

2. Support for Shoreline-Crossing Geophysics

The oceans account for over 70% of Earth's surface. Oceanic plate boundaries host the planet's largest earthquakes and oceanic plates record the history of Earth's evolution. Near-shoreline processes are particularly relevant to society as well as critical to understanding of the Earth as a system. These include megathrust seismicity and coupling, strain at plate boundaries, upper-plate and outer-rise deformation in subduction settings, arc volcanism, slope instability, tsunamigenesis, shallow mantle dynamics, and resource discovery. The integration of offshore experiments with land-based datasets is essential to the interpretation of data gathered in the oceans and to achieve the Earth Science community's goal of a comprehensive, amphibious perspective on tectonics. Recent amphibious community geophysical experiments (e.g., 2010-2015 Cascadia Initiative; 2018-2019 Alaska-Aleutians; 2014-2015 Eastern North American Margin) illustrate the importance of this synthesis between land and marine observations.

As early career investigators with existing and future research based on both marine and land-based data, we strongly recommend that the FGF archive, maintain, and distribute marine and shoreline-crossing geophysical data and derived products in close coordination with the initiatives that provide instrumentation and collection for these data. We emphasize here the inherent complementarity of land-based and marine facility infrastructure: data archival, data and derived product distribution, community engagement, and instrument services are all essential on both sides of the shoreline and must cross it seamlessly. Supporting amphibious research is not only scientifically worthwhile; it is efficient.

While we recognize the FGF as being within the EAR division and distinct from the marine instrumentation centers, we wish for the FGF to coordinate with the marine instrumentation centers (e.g., UNOLS, MSROC, OBSIC) for the proposal of experiments that seamlessly cross the shoreline. Studies originating onshore or offshore stand only to gain from the inclusion of an adjacent dataset made accessible by the efforts of the FGF. Active-source seismic experiments, for example, often involve offshore seismic sources that are recorded by land instruments and vice-versa. Streamlined coordination of land and marine capabilities across many geophysical disciplines should thus be a natural service of the FGF. To this end, the FGF should have personnel with technical expertise in marine instrumentation for both instrumental and data-service needs. This will maintain the ability of the FGF to support amphibious science as the instrumentation, infrastructure, and science evolves.

Support for amphibious deployments should occur at both the PI and community levels. We expect a growing need for experiments that are not neatly described as either land or marine geophysics and request that the FGF aid PIs navigating the divisions at the NSF outside of special programs. The proposal of amphibious science should be accessible to the scientific community. We also envision a significant role for the FGF in any community experiments such as SZ4D. Support can take the form of logistical assistance with deployments, indirect instrument-services by coordination of efforts and technical abilities with the marine instrumentation centers, and community activities such as hosting conferences and promoting the educational opportunities provided by geophysical cruises.

3. Data-service Requirements for Shoreline-Crossing Geophysics

The current DMC at IRIS hosts data from both marine and land seismic experiments, as well as pressure and temperature records from marine instruments. Continuation of this practice and expansion to include marine geodetic, magnetotelluric, and related datasets is critical to maintaining a vibrant community of researchers. A single data archiving portal at the FGF that extends to marine geophysical data is essential for the future of multi-disciplinary amphibious research.

For seismology, close coordination between the FGF and OBSIC regarding data service needs is critical. Raw data from broadband ocean-bottom seismometers (OBS) typically require additional processing steps to become directly comparable to land-based seismic data (e.g., horizontal orientations, tilt/compliance corrections). Assessment and processing are traditionally performed by individual investigators, but as community use of such datasets expands, the FGF could provide the community with data products from open-source processing routines. Alternatively, the FGF could provide web-services to process data according to user specifications. Since there are variations in data-processing techniques in the OBS community, providing processed data-products alongside raw data would facilitate research by both specialized OBS scientists and the broader community. To determine the most suitable approach, close coordination between the FGF, OBSIC, and data-users will be indispensable.

Integration of data across the shoreline is equally essential for seafloor geodesy. For example, geodetic position data are typically placed in a terrestrial reference frame via network- and global-scale algorithms, and so offshore data requires integration with onshore data as a first step. Many widely used techniques in geodesy, such as principal and independent component analysis and the estimation of slip or deformation at depth, are also network-scale and so require that the preceding reference frame estimation be correctly done, that nuisance signals be removed, and that the offshore data be in units relatable to surface displacement. Offshore geodetic data requires different processing from onshore geodetic data, both because the measurement techniques are fundamentally different and because the nuisance signals are different. This processing could be efficiently executed at the facility level. More fundamentally, offshore geodetic data are only useful to researchers when discoverable and accessible. If not centrally published, data discovery often comes down to knowing the right person, which is disproportionately challenging for early career researchers and researchers at less well connected institutions . Therefore, we request that the FGF publish, archive, and maintain seafloor position and acoustic data and all relevant metadata. In particular, the NSF recently awarded funding for the creation of a pool of GNSS-Acoustic sites for seafloor geodesy, but the authors are not aware of a plan for processing or disseminating data generated by this pool. The publication of processed position time series, as is common practice for onshore geodetic data, will increase the use and role of these shoreline-crossing data in research. Centralized publication will also ensure that research products derived from these data are verifiable by other members of the community. Nascent seafloor geodetic datasets from the Cascadia subduction zone, for example, will likely furnish new findings about its locking state that have far-reaching implications for hazard. It is of crucial scientific and practical importance that research products derived from these data are verifiable by other members of the community.

Over the last few decades, significant technological advancements in seafloor electromagnetic (EM) instrumentation have demonstrated the value-added by offshore magnetotelluric studies. The FGF should host these data. Community access for these datasets would be well timed given recent moves towards open-source modeling software (e.g., MARE2DEM, ModEM), in addition to similar advantages seen for other data types. Seafloor EM receivers are remarkably similar to OBSs, meaning facility-support should be efficient in light of existing efforts.

While this document is not exhaustive of the data types we hope the FGF will support, similar dataservice issues are likely to arise with all types of marine datasets. Workflows closely coordinated with the marine instrument centers will ensure that the FGF can provide end-users with properly processed data products and can distribute both instrument- and experiment-specific metadata (e.g., ship reports) that would not traditionally be necessary for land-based datasets. Seafloor instrumentation is generally distinct from the analogous instrumentation used on land, and standardized approaches to providing users full descriptions of the instrumentation should be implemented. As the instrument centers and the instrumentation itself evolves, we expect a centralized center for data-services to remain essential with the capacity to handle the evolving needs of the community.

4. A Long-term Vision of Integrated Science

We expect integrated datasets to play an important role in 21st-century geophysics. The success of initiatives such as GeoPRISMS and the amphibious community experiments of the last decade show how scientifically fruitful these efforts can be. Looking forward, the recently released National Academies of Sciences report, "A Vision for NSF Earth Sciences 2020-2030: Earth in Time", recommends that the NSF fund geoscience research that crosses shorelines and to fund the inherently amphibious SZ4D initiative. Of the 10 Seismological Grand Challenges in Understanding Earth's Dynamic Systems outlined by a 2008 NSF-funded workshop, at least 6 are directly tied to offshore and shoreline-crossing processes, including Challenge #7: "*How do plate boundary systems evolve*"? Of the 8 Grand Challenges in Geodesy identified in 2018, 6 are directly tied to shoreline-crossing science.

As early career scientists, we have a vested interest in the long-term infrastructure supporting geophysical deployments. Greater integration of marine and land instrument services would both efficiently and effectively support the science targets we will pursue in the coming decades. Future community pools that include an expanded set of marine equipment, such as EM instrumentation, along with seismic and geodetic equipment, under integrated management would streamline future experiments and create new scientific opportunities.