Recommendations for Enabling Earth Science Through NSF's Geophysical Facility – A Portfolio Review of EAR Seismology and Geodesy Instrumentation

Recommendations for Enabling Earth Science Through NSF's Geophysical Facility – A Portfolio Review of EAR Seismology and Geodesy Instrumentation

FINAL | Accepted and publicly released by the NSF Advisory Committee for Geosciences

April 19, 2021

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This document was prepared at the request of the US National Science Foundation to the Advisory Committee for Geosciences (https://www.nsf.gov/geo/advisory.jsp).

Acknowledgements:
Thank you to UNAVCO President Rebecca Bendick and Director of Geodetic Infrastructure Glen Mattioli as well as IRIS President Robert Woodward and Portable Programs Manager Kent Anderson for their rapid and thorough responses to the committee queries. Christopher Crosby (UNAVCO) provided input on geodetic imaging. Jonathan Ajo-Franklin (Rice University), Kent Anderson (IRIS), Jnaneshwar Das (Arizona State University), Rob Evans (WHOI), W. Steven Holbrook (Virginia Tech), and Glen S. Mattioli (UNAVCO) kindly made themselves available for interviews with the committee. We are grateful to Lindsay M. Martin who supported the committee very ably as science assistant from the National Science Foundation. Finally, many thanks to Margaret Benoit (National Science Foundation Program Director) for her careful guidance.

Preferred citation:
Arrowsmith, J R., Brodsky, E. E., Cooper, C. M., Elliott, J. L., Fee, D., Fischer, K.M., Hammond, W. C., La Femina, P., Lekic, V., Wang, H., and Worthington, L. L., Recommendations for Enabling Earth Science Through NSF's Geophysical Facility – A Portfolio Review of EAR Seismology and Geodesy Instrumentation, Report to the US National Science Foundation, April 2021.

Cover image shows the northern end of the Warm Springs Valley (Nevada/California border area). Cover design and photo by Bill Hammond.

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Executive Summary

Overview

Geoscience becomes increasingly relevant as global change affects nearly all aspects of the Earth system. Society continues to expand its exposure to hazardous Earth processes. Now more than ever, science needs to seek to better understand the connections between Earth system components so we can be best equipped to meet these challenges.

Seismic and geodetic instrumentation are essential infrastructure for the study of Earth's surface, interior, dynamics, history and hazards. They are used to elucidate the interactions between the geosphere, hydrosphere, cryosphere and atmosphere. Observations must be sensitive to displacements over orders of magnitude of spatial range (micrometer to global) and time spans (milliseconds to decades).

The National Science Foundation will support a single unified geophysical facility to operate national geophysical networks on behalf of the US scientific community. This review was undertaken to prioritize the instrumentation and sensor network operation capabilities for the new geophysical facility to enable progress on critical scientific questions in the areas of seismology, geodesy, and related fields over the next decade. The review was motivated by the NSF Division of Earth Science's desire to better enable the research community to address scientific grand challenges articulated in the National Academy of Science report "A Vision for NSF Earth Sciences 2020-2030: Earth in Time" and other recent community consensus documents.

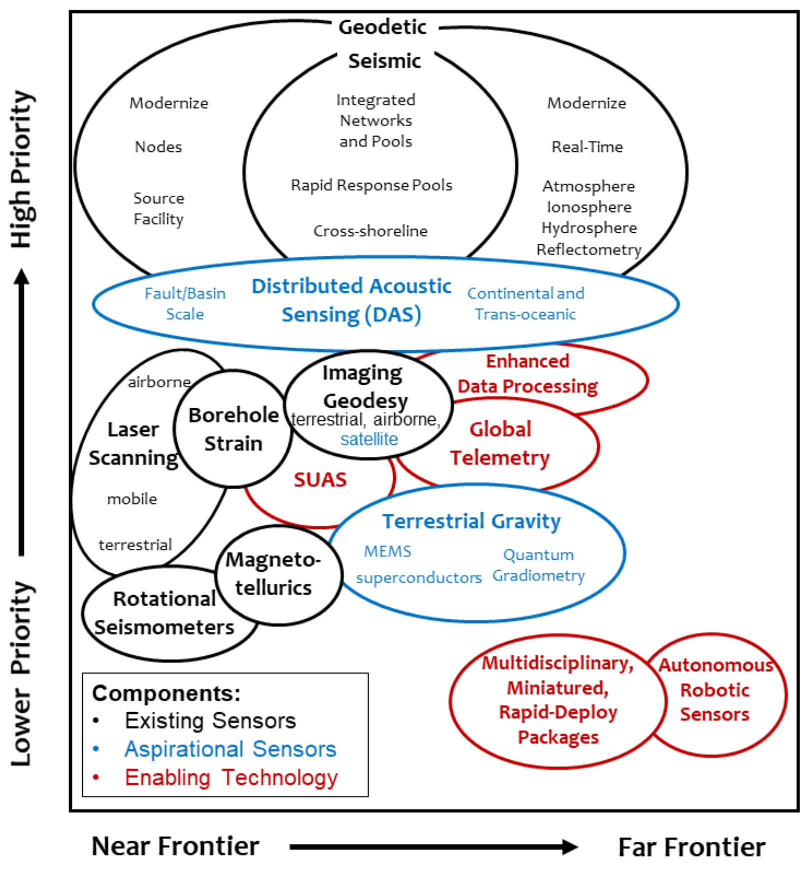


Figure 1. Geophysical sensors by frontier stage and priority for inclusion in a future geophysical facility. Existing sensors, aspirational sensors, and enabling technologies are highlighted. These sensors and networks span a range of spatial and temporal scales.

The goals presented in the Earth in Time report specifically require continued NSF support of geodetic and seismic infrastructure. That support is a very high priority to maintain the US position of strength in the research community. The committee set priorities for facility capabilities enabling investigation of a broad swath of science topics of interest to the community while balancing support of existing and aspirational systems (Figure 1).

Primary Recommendations

1. Expand resources to create large-scale, dense multi-disciplinary, multi-instrument seismic and geodetic networks that sample ground motion at a range of temporal and spatial scales and stimulate the research community to apply new and cutting-edge approaches to achieve the Earth in Time report science goals. This includes maintaining and strategically expanding the Global Seismic Network (GSN) and Network of the Americas (NOTA) geodetic network.

2. Develop, maintain and support deployment of multidisciplinary rapid-deploy sensor packages for collecting critical data during geophysical events, especially those that are hazardous to people.

3. Invest in the exploration of emerging and supporting technologies to enable discovery. These include prioritizing fiber-optic sensor networks (Distributed Acoustic Sensing), terrestrial gravimetry, low-cost, easy-to-access satellite telemetry for geophysical networks, next-generation power systems, advanced robotic systems, and autonomous, multi-sensor, miniaturized rapid-deploy packages.

4. Recapitalize and modernize the beyond end-of life broadband seismometer and GPS-GNSS equipment pools. Adhere to a clear instrumentation recapitalization scheme to maintain stability and forward progress of facility functions.

5. Push for recognition and base support for seismology and geodesy instrumentation and networks as *U.S. National Infrastructure*.

6. Support integration and interoperability of the geophysical data archives as well as frontier technologies that enhance data access, exploration, utility, citability and curation, as these are essential components of scientific infrastructure.

7. The future geophysical facility should develop a structure to embed anti-racist, non-discriminatory policy, practices, and goals, including attention to hidden biases, throughout its operations. The facility should ensure that it be equally accessible by all NSF-funded projects regardless of institutional resources, location, and demographics. We recommend the facility and NSF continue efforts to integrate Justice, Equity, Diversity, and Inclusion activity and enhance the community governance structures to address inequity, and ensure safe and inclusive field experiences for all participants.

8. Maintain a strong and vibrant system of community governance of the facility to set high level science and instrumentation priorities and serve as a focal point, hub and springboard for community interaction, outreach, education, and collaboration.

9. Support and train dedicated professional facility staff who are knowledgeable about data streams, instrumentation, and processes for obtaining research and development funding.

10. Adapt programs to ease the deployment of geophysical networks that cross the shoreline.

11. Coordinate with other federal, state and local agencies, as well as commercial entities, to broaden the base of support for multidisciplinary geophysical instrumentation through co-funding, joint management, joint data processing and transfer of ownership.

More detailed recommendations, including numbers and types of seismic and geodetic instrumentation are presented in Chapter 1: Recommendations of the main report.

Chapter 1: Recommendations

1.1 Overview

This review prioritizes the instrumentation and sensor network operation capabilities for a new geophysical facility to enable progress on critical scientific questions in the areas of seismology, geodesy, and other related fields over the next decade (Figure 1.1). The review was motivated by the U. S. National Science Foundation Division of Earth Science's desire to better enable the research community to address scientific grand challenges in seismology and geodesy in the context of the current challenging outlook for the federal budget.

The primary goals of this review by the Instrumentation Portfolio Review Committee (IPRC) were to examine the portfolio of capabilities provided by SAGE (Seismological Facility for the Advancement of Geoscience) and GAGE (Geodetic Facility for the Advancement of Geoscience), as well as recent advances in seismic and geodetic instrumentation that are not currently provided by SAGE and GAGE, and to recommend a prioritized set of capabilities that should be provided by a future geophysical facility to maximize progress on compelling science. SAGE is operated by the Incorporated Research Institutions for Seismology (IRIS), and GAGE is operated by UNAVCO, Inc.

This report is divided into nine chapters. This first chapter provides an overview of the committee's activity, but most importantly, it presents the IPRC recommendations. The committee's deliberations were guided by a series of principles previously used in other portfolio reviews by the National Science Foundation (see Chapter 2). See Chapter 3 for more information about the committee charge, process, and boundary conditions. The science motivators and challenges for seismology and geodesy are reviewed in Chapter 4 (See Figures 1.1 and 1.2). Chapter 5 and 6 present the current and potential future instrumentation and related technologies (Figure 1.3). Three short highlights include distributed acoustic systems (DAS), seismogeodesy opportunities and gaps, and robotic systems for geophysical sensing. Chapter 7 captures additional cross-cutting recommendations with respect to geophysical infrastructure and facility operations. Chapter 8 presents the bibliography and Chapter 9 provides supplemental information including a glossary of acronyms.

The IPRC was asked to: 1) Recommend the critical instrumentation and sensor network operation capabilities needed over the period from 2023-2033 that would enable progress on the science priorities articulated in "A Vision for NSF Earth Sciences 2020-2030: Earth in Time" (National Academies of Sciences, Engineering, 2020), also known as "the CORES report", and recent community consensus documents. And, 2) Recommend the balance of investments in new and in existing, but evolved, instrumentation and sensor network operation capabilities within the constraints of each of the provided budgetary scenarios.

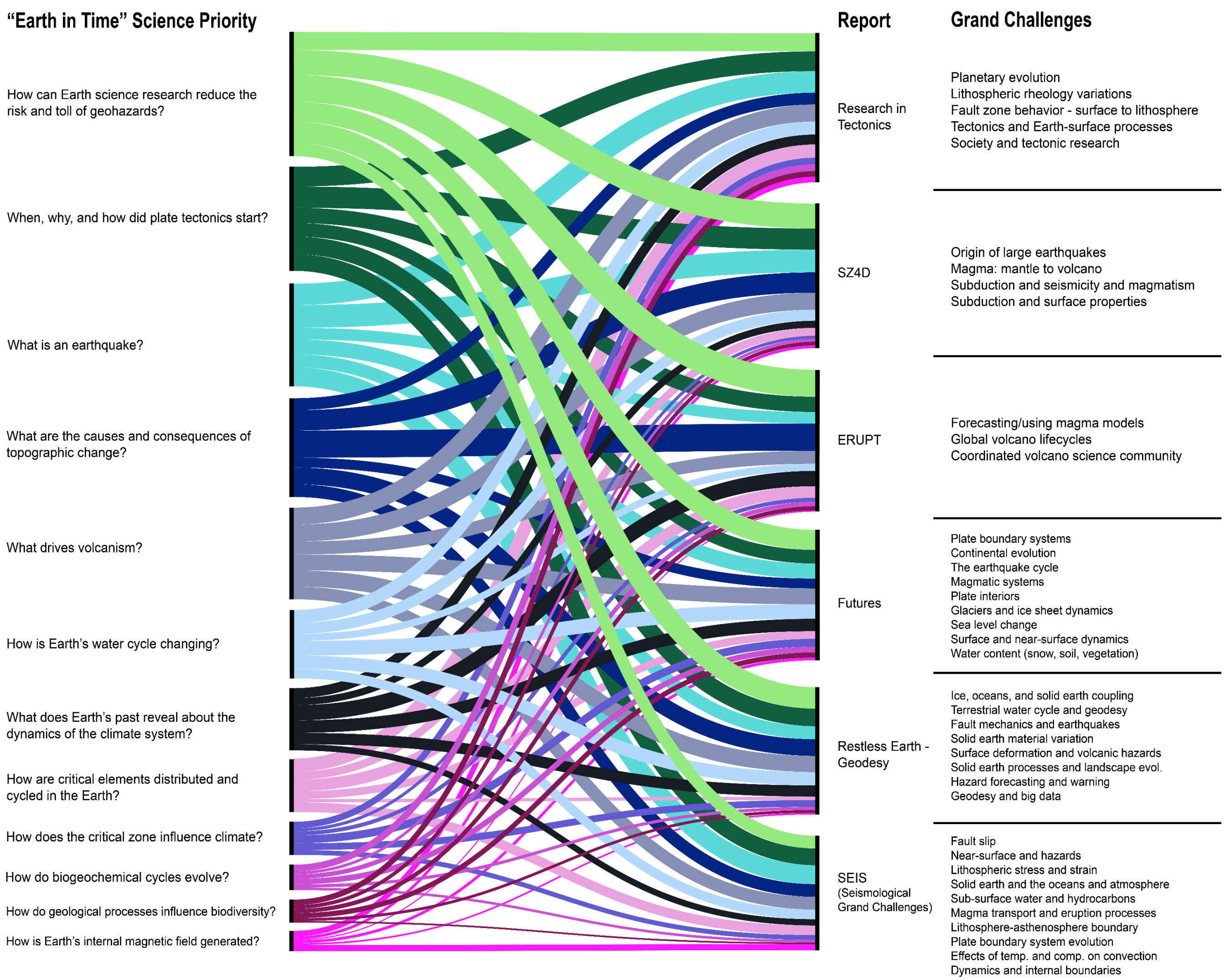


Figure 1.1. Integration of Earth in Time report science questions (left side) with challenges identified in community reports for geodesy and seismology (right side). This figure shows the strength of connection by the thickness of the ribbons, as determined by the IPRC, indicating the community reports and science priorities most relevant to the committee's work and recommendations. Figure by L. Martin.

1.2 Science Challenges

The National Academy of Science prepared the Earth in Time report (National Academies of Sciences, Engineering, 2020). This top-level decadal survey for the Earth sciences provides a framework for prioritization of research and science applications. The Earth in Time report covers a great breadth of contemporary Earth science research and articulates 12 overarching science questions. These questions align variably with those of interest to the broadly defined geodesy and seismology communities (Figure 1.1). We divided them into three classes (Table 1.1). We also recognize the substantial sustained effort by the geodesy and seismology communities to refine and update science motivators through the development of community studies. The level of detail in the community studies is finer than the Earth in Time report. As such, we drew from the reports to integrate with the Earth in Time questions and highlight targets motivating observations (Figure 1.1) and consequent technologies (Figure 1.2). These exercises guided the committee's prioritization process, but also demonstrated the far reaching impact that a strong commitment to geodesy and seismology instrumentation has on the outstanding questions within Earth science.

Table 1.1. Earth in Time science questions aligned with community defined science motivators.

Alignment	Earth in Time questions
Strongly aligned with many connections to themes, challenges, other more granular questions	How can Earth science research reduce the risk and toll of geohazards? When, why, and how did plate tectonics start? What is an earthquake? What are the causes and consequences of topographic change? What drives volcanism?
Strongly aligned with a smaller number of themes, challenges, questions, but in key ways	How is Earth's water cycle changing? What does Earth's past reveal about the dynamics of the climate system? How are critical elements distributed and cycled in the Earth? How does the critical zone influence climate? How is Earth's internal magnetic field generated?
Weakly aligned with themes, challenges, questions, but in ways that represent emerging areas of importance	How do biogeochemical cycles evolve? How do geological processes influence biodiversity?

The science motivators identified by the Earth Science community as discussed above determine the suitability of instrumentation needed to make necessary observations. Therefore, clear connections must be drawn between instrumentation types and the broad questions articulated in the Earth in Time report via observation classes and through the role of investigator-driven research questions. The idea behind this set of connections is illustrated in Figure 1.2. Instrumentation for geodesy and seismology (and related sensing) are further organized by type, cost, ease of use, mode of deployment, and historical organizational decisions by the communities and funding agencies, as discussed more thoroughly in following chapters. Creating new knowledge and applications from these scientific workflows requires more than just capable instrumentation. It requires data management, including high quality telemetry, and, most importantly, a well-supported professional technical staff and an engaged community.

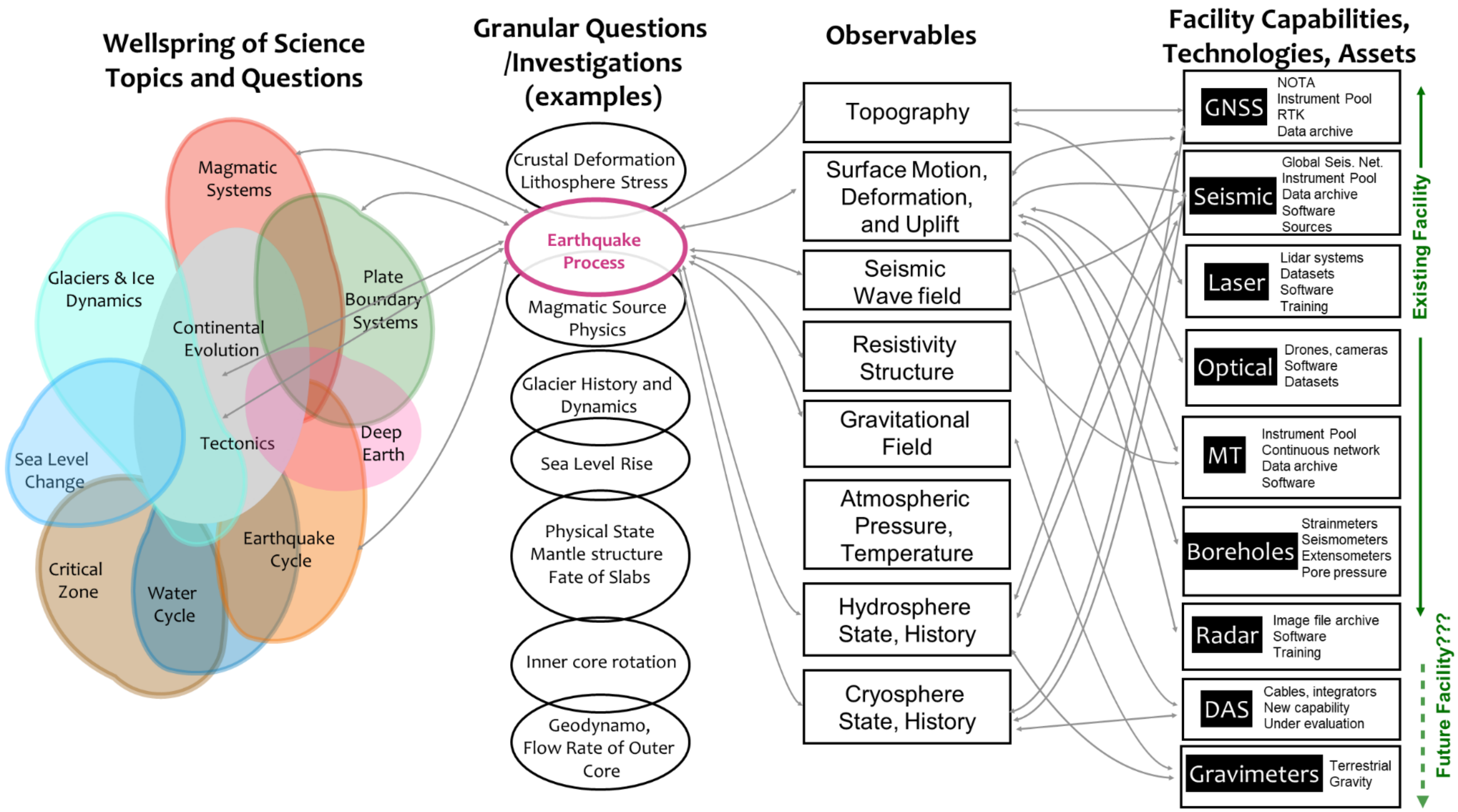


Figure 1.2. One example of science and instrumentation connections. Gray arrows indicate connections between major science topics articulated in community reports (left) to a single example class of scientific questions related to: the earthquake process (magenta ellipse left of center). Arrows to the right of the science question illustrate connections to required geophysical observables (rectangles right of center) and subsequently to specific facility capabilities designed to measure them (right). For clarity, figure does not show all possible connections, observables, and technologies, but instead picks the earthquake process as a representative example to illustrate connections. See Figure 9.1 for an illustration of how the science topics and questions map to process space and time scales. Original version by Bill Hammond.

1.3 Instrumentation and Enabling Technology

Given the scientific priorities and goals highlighted in the Earth in Time and community reports, the IPRC recognizes the necessity for a balance between enabling continued success of current (summarized in Chapter 5) and potential future (Chapter 6) instrumentation and related technologies. Figure 1.3 provides a conceptual view of the committee's prioritization of existing and aspirational sensor as well as enabling technology. It also suggests their relative feasibility. In the next section, we present our recommendations and reasoning. Figure 1.3 demonstrates the committee's recognition of the need to maintain and modernize the current SAGE and GAGE footprint as well as preparing to capitalize on advancements in technology (e.g., DAS).

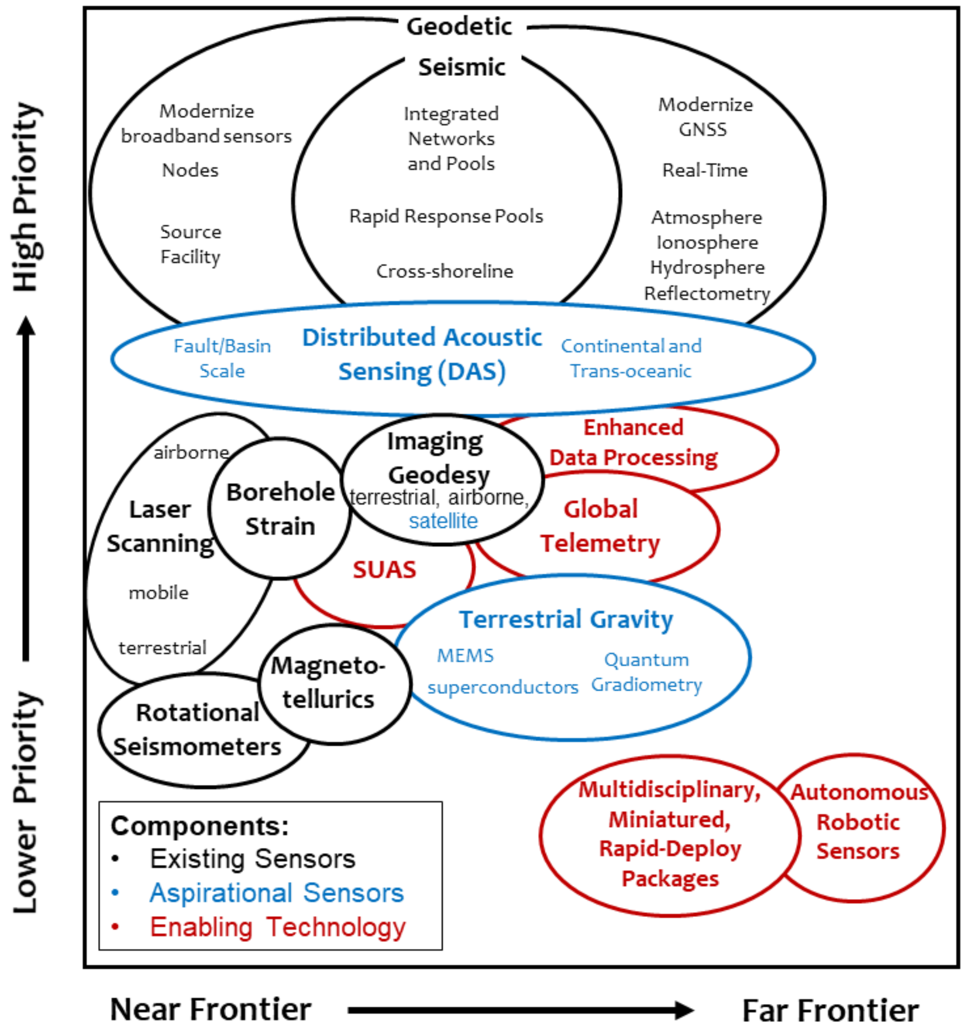


Figure 1.3. Spectrum of priorities and frontiers for instrumentation, sensor networks, and the enabling technology. These sensors and networks span a range of spatial and temporal scales. Near frontier and high priority systems include some existing geodetic and seismological systems. The existing systems are discussed in Chapter 5. Aspirational systems including DAS, terrestrial gravity, and satellite-based geodetic imaging are discussed in Chapter 6. Enabling technologies are important parts of geophysical systems. Improvements in telemetry, data processing, and platforms will make the systems more robust.

1.4 Recommendations

The IPRC found that continued NSF support of geodetic and seismic infrastructure is a very high priority in order to enable geophysical research, maintain the position of the US as a top research community, and achieve the goals presented in the Earth in Time report. The committee set priorities for facility capabilities that support a broad swath of science topics of interest to the community (Figure 1.3). NSF should continue to value the community-driven science goals and technology prioritizations that are highlighted in several guiding reports (Lay, 2009; Aster and Simons, 2015; McGuire and Plank, 2017; National Academies of Sciences, Engineering, 2017, 2020; Huntington and Klepeis, 2018; Freymueller et al., 2019)

The deliberations of the IPRC are summarized by the following recommendations which are supported and amplified by the rest of the report.

1. Expand resources to create large-scale, dense multi-disciplinary, multi-instrument seismic and geodetic networks that sample ground motion at a range of temporal and spatial scales and stimulate the research community to apply new and cutting-edge approaches to achieve the Earth in Time report science goals. This includes maintaining and strategically expanding the Global Seismic Network (GSN) and Network of the Americas (NOTA) geodetic network. See Facility Recommendations on the next page.
    a. Geodesy Specific Recommendations – see Summary, Table 1.3, and notes.
    b. Seismology Specific Recommendations – see Summary, Table 1.4, and notes.
2. Develop, maintain and support deployment of multidisciplinary rapid-deploy sensor packages for collecting critical data during geophysical events, especially those that are hazardous to people.
3. Invest in the exploration of emerging and supporting technologies to enable discovery. These include prioritizing fiber-optic sensor networks (Distributed Acoustic Sensing), terrestrial gravimetry, low-cost, easy-to-access satellite telemetry for geophysical networks, next-generation power systems, advanced robotic systems, and autonomous, multi-sensor, miniaturized rapid-deploy packages (Figure 1.3 and Chapter 6).
4. Recapitalize and modernize the beyond end-of life broadband seismometer and GPS-GNSS equipment pools. Adhere to a clear instrumentation recapitalization scheme to maintain stability and forward progress of facility functions.
5. Push for recognition and base support for seismology and geodesy instrumentation and networks as *U.S. National Infrastructure* – see Chapter 7 of this report.
6. Continue to support integration and interoperability of the geophysical data archives, and press the frontier of technologies that enhance data access, exploration, utility and curation, as these are essential components of our scientific infrastructure. FAIR (Findability, Accessibility, Interoperability, and Reuse) data principles should be prioritized. The committee warns that under a reduced budget environment, data accessibility and discovery tools will likely be impacted. The net effect could discourage their broader use in environmental, cryosphere, oceanographic and other non-solid Earth problems because significant seismological or geodetic expertise would be required to find and utilize the data.

Budget reductions should not be implemented by reducing the type and quality of data products made available by the facility.

7. The future geophysical facility should develop a structure to embed anti-racist, non-discriminatory policy, practices, and goals, including attention to hidden biases, throughout its operations. The facility should ensure that it be equally accessible by all NSF-funded projects regardless of institutional resources, location, and demographics. We recommend the facility and NSF continue efforts to integrate Justice, Equity, Diversity, and Inclusion activity and enhance the community governance structures to address inequity, and ensure safe and inclusive field experiences for all participants.

8. Maintain a strong and vibrant system of community governance of the facility to set high level science and instrumentation priorities and serve as a focal point, hub and springboard for community interaction, outreach, education, and collaboration.

9. Continue to support and grow dedicated professional staff at facilities, knowledgeable about the instrumentation and data streams, and funding for research and development.

10. Adapt programs to ease the deployment of geophysical networks that cross the shoreline.

11. Coordinate with other federal, state and local agencies, as well as commercial entities, to broaden the base of support for multidisciplinary geophysical instrumentation through co-funding, joint management, joint data processing and transfer of ownership.

Facility Recommendations

Summary: The IPRC recommends that the NSF support a state-of-the-art, community driven geophysical facility, that provides open data, data products and data discovery tools, and opportunities for the development of cutting-edge Earth science research utilizing satellite, airborne and terrestrial geodetic methods and a broad range of seismic sensing systems. The facility should capitalize on and maximize the synergies between seismic and geodetic technologies in order to gain efficiencies, improve performance of the observational systems, and advance scientific discovery. As a practical matter related to current differences in instrumentation technologies and pool configurations, and to establish relative priorities independently, the geodetic and seismic instrumentation priorities are in separate tables below. However, the IPRC recognizes synergies between instrument types and that some are difficult to classify as exclusively seismic or geodetic. For example, the recommendation below to develop multi-sensor packages for rapid response to geophysical events has been placed in both tables to emphasize its cross-cutting nature.

On the following pages, we present recommendations for the geodetic and seismological components of the future geophysical facility. The IPRC was instructed as a part of their charge to consider scenarios that included 1) slightly reduced to flat funding, which we view as the bare minimum to address science goals, 2) modest growth, or 3) substantial increased growth under "blue sky" funding. The austere model was developed reluctantly, as a flat budget will not permit critical recapitalization of existing equipment nor sufficient investment in new technologies, resulting in substantial losses in scientific advancements. In many cases for the austere scenario, we recommend retention of existing equipment with no new recapitalization or maintenance (RENRM). The specific numbers of instruments presented should be reasonably accurate as they are derived from 2020-2021 reports and consultation with current GAGE and SAGE facility operators. However, perhaps more valuable than the specific numbers are the thought processes presented throughout this report which may serve as a play book for future decisions that need to adhere to the coming funding scenarios.

Tables 1.3 and 1.4 presented below provide specific numbers for coping with the broad categories of future funding scenarios, but those funding levels are at this time unknown. Therefore, the actual impact of budgets on instrumentation capabilities is difficult to estimate. Furthermore, it is even more difficult to precisely predict the impact of those changes on the quantity and quality of future scientific discoveries. However, the committee felt it was necessary to qualitatively express the impact of the budget scenarios on science challenges outlined in Chapter 4. Here we attempt to summarize those impacts relative to current facility capabilities.

The impacts of the loss of capabilities can be divided into several categories. For example, fewer observation stations result in reduced capability to observe phenomena near the locations where stations are lost. However, owing to the nature of seismic and geodetic data analysis (e.g., tomography and geodetic imaging) the location where resolution is lost may not be near the station. Thus, lost stations also result in degradation of imaging capability where 'pixels' in our geophysical 'camera' are lost resulting in an unfocused picture. A further separate category of loss occurs when an entire class of observation technology is cut from the facility, resulting in a qualitative loss of capability. We highlight specific capabilities gained or loss in Table 1.2 that are relevant to particular scientific themes as identified in the Earth in Time report.

Table 1.2. Examples of impacts of funding scenarios compared to current state described in Tables 1.3 and 1.4 on each of the scientific focus areas identified by the Earth in Time report (middle column graphics).

Lost under slightly reduced to flat funding	*Earth in Time report question*	*Gained with optimistic funding*
Loss of ability to image resistivity structure of the Earth which influences the magnetic field, due to loss of MT pool.	Magnetic Field	Ability to image state of outer core and related structures in the solid interior through expanded very broadband GSN and portable seismic broadband pool.
Targeted lithospheric plate-scale imaging of structure and deformation lost due to reduced portable pools of seismic and geodetic instrumentation. Resolution of fluids at base of tectonic plates reduced due to loss of MT capability.	Plate Tectonics	Measurement of plate motion and deformation (including transient deformation) with increased uniformity both on boundaries and interiors through a 50% increase in permanent GNSS stations. Improved resolution of crust and mantle structure with enhanced portable seismic instruments and GSN.
Seismic exploration for deep structure associated with critical elements lost due to reduced source facility operations.	Critical Elements	Ability to explore multiple sites for deep structure associated with critical elements through the expanded source facility and seismic sensors.
Probable loss of portions of the earthquake cycle due to lack of maintenance on borehole strainmeters. Loss of ability to measure small, human-induced, earthquakes due to loss of short-period capability. Reduced ability to characterize coseismic and postseismic motion due to limited portable instrument pools.	Earthquakes	Ability to capture multiple earthquakes simultaneously through multi-sensor rapid response kits. Ability to respond to and analyze the small earthquakes commonly associated with induced seismicity through the expanded portable pool of nodes, broadband seismometers and DAS. Ability to cross the shoreline with DAS interrogators. Enhanced integrated seismogeodetic imaging of fault slip through GNS and GNSS expansion. Better measurement of very large earthquake sources with expanded very broadband GSN stations.
Lack of 3D deformation data due to lack of maintainence of UAS and TLS systems and the limited portable GNSS pools. Lack of ability to close seismogeodesy band gap due to decreased size of broadband seismometer pool.	Volcanoes	Ability to resolve volcanic structure and deformation sources controlling eruptions through nodes, broadband seismometers and geodesy. Ability to capture multiple volcanic eruptions simultaneously through rapid response kits. Ability to measure lava and ash during an eruption through expanded UAS capability.
Eventual probable loss of sub-meter scale topographic scanning capability due to lack of maintence on UAS and TLS systems.	Topographic Change	Ability to measure sub-centimeter scale topography and its evolution over time through expanded UAS and laser scanning capability.

Elimination of capability to measure the critical zone with radar due to the elimination of GPR.	Critical Zone	Ability to image the critical zone through complementary techniques sensitive to moisture, mineralogy, and structure through new nodes, DAS, resistivity, gravimetry, MT, and NMR equipment.
Probable loss of some sea level records due to lack of tide gauge station maintenance.	Climate System	Capability of capturing atmospheric structure, effect of droughts, and the impact of vertical land motion on relative sea level changes through expanded GNSS coverage. Capability of resolving mechanisms and impact of rapid ice-sheet movement through expanded broadband seismometer and GNSS pools.
Probable loss of data on groundwater storage due to lack of maintenance of strainmeters.	Water Cycle	Capability of capturing hydrosphere changes through borehole strainmeters and expanded GNSS coverage. Enhance ability to sense troposphere through expanded GNSS coverage. Ability to monitor groundwater table through new nodes and DAS.
No major impact.	Biogeochemical cycles Biodiversity	No major impact
Decreased response capability to earthquakes, volcanoes, and landslides due to decreased broadband pool, lack of UAS and TLS maintainence, and limited portable GNSS pool.	Hazards	Tsunami and earthquake early warning through expanded GSN, DAS and GNSS coverage. Order of magnitude increase in accuracy of volcanic eruption forecasting (Winson et al., 2014) due to availability of nodes, increased broadband seismometer pool, and multisensor rapid response packages. Ability to evaluate time-dependent coastal hazards due to increased UAS pool.

The IPRC recommends that the future *geodetic* component of the facility should:

- Maintain a modern high-precision continuous GNSS network with state-of-the-art instrumentation and very high level of completeness in data return to complement other international, USGS, and regional GNSS networks.
- Maintain a modern (i.e., GNSS) pool of loaner equipment for NSF PI use, including for RAPID-funded deployments. The facility should also explore and develop capabilities for deployment of multi-instrument (i.e., geodetic and seismic) equipment kits, including small Uncrewed Aerial Systems (sUAS).
- Reduce costs through a) divesting stations to federal, state and local agencies with commitment to maintaining existing infrastructure and open data standards, b) looking for low-cost telemetry opportunities, and c) expanding the scientific impact of geodetic networks through increased data analysis of existing non-NOTA stations.
- Maintain the borehole strainmeter networks and expertise in installation and data analysis. New borehole strainmeter installations moving forward should be through individual PI-funded or community projects.
- Continue to explore technologies that close the seismogeodesy bandgap (see box in Chapter 4).
- Nurture state-of-the-art geodetic imaging capabilities, including mobile and airborne laser scanning, photogrammetry for 3D models and change detection, and multi- to hyperspectral imaging, and explore expanding small sUAS capabilities based on community needs.
- In a "bare minimum" funding scenario:
    - Prioritize the NOTA and the portable loaner pool of GNSS instruments over all other aspects of the current GAGE facility.
    - If direct resources for recapitalization are not available, decrease the number of portable loaner GNSS systems to no fewer than 20.
    - Support for tide gauges, TLS, borehole strainmeters, and UAS systems should retain existing equipment but not include recapitalization or maintenance (abbreviated RENRM in Table 1.2), and should minimize operational costs to the greatest possible extent.
    - Divestment of some continuous GNSS stations would free up funding for other critical NSF-EAR needs. However, such decisions should only be made following community input and careful identification and selection of partners.

Table 1.3. Prioritized recommendations for NSF-EAR Instrumentation Portfolio in Geodesy. Italics indicate new instruments not part of the current GAGE instrumentation. See accompanying footnotes for details on recommendations. Highest priority instrumentation is at the top of the table. RENRM = retain existing equipment, no recapitalization or maintenance.

Existing GAGE Instrumentation	Bare minimum to begin addressing science goals under slightly diminished to flat funding	Modest growth to approach science goals	Optimistic scenario: large-scale networks under "blue sky" funding scenarios
1137 Network of the Americas (NOTA) GPS/GNSS stations.	1137 [1, 2, 4]	1137 + *200* GNSS stations[1, 3, 4]	1137 +*500* GNSS stations [1, 3, 4]
Loaner pool of 20 GPS/GNSS receivers and campaign systems [5]	20	20	20
Multi-sensor rapid response packages with seismic and geodetic capability [6]	0	*20*	*40*
74 NOTA Borehole strainmeters (BSM) and seismometers [7]	74 RENRM	74	74
6 UAS systems for geodetic imaging[8]	6 RENRM	6+*6*	6+*18*
2 Tide gauge stations with multiple GNSS antennas, sea surface radar recorder and pressure sensor.[9]	<2 RENRM	2	2
8 Terrestrial Laser Scanning Instruments (TLS) for geodetic imaging[10]	0 RENRM	8	8

Table 1.3: Geodesy prioritized recommendations notes

1) A network of continuous GNSS stations provides key constraints for research in active Earth processes. With their ability to record broadband ground motion signals, these stations have irreplaceable value for studies of tectonics, the earthquake cycle, including earthquake sources and other modes of fault slip, magmatic source deformation, tsunami generation, and surface loading to name a few. The multi-decade lifetimes of these stations provide a unique ability to sample ground deformation related to changes in the solid Earth and separate background noise from transient signals including those owing to droughts and global climate change. The volume of high-quality data has driven innovation in new analysis methods and also provides a critical benchmark against which to assess data from other GNSS stations, both permanent and temporary networks. NOTA stands as the 'gold standard' in national geodetic networks. Through the network, NSF contributes to the missions of other US national and state agencies and to national interests more broadly, given the use of NOTA data for applications ranging from earthquake and tsunami hazard reduction to weather forecasting and navigation. Open data from NOTA stations are also utilized by national networks run by other countries. The committee recommends maintaining the full complement of 1137 NSF-supported NOTA stations, with strategic expansion in growth funding scenarios. Addition of 200 new stations under modest funding increase scenarios would allow the network to fill gaps in the original design of the EarthScope plate boundary observatory including the areas with lower deformation rates and interiors of microplates, reducing the magnitude detection threshold for earthquakes in those locations and allowing more focus on areas where previously unappreciated vertical land motion have now been detected. Addition of 500 new stations would allow a more uniform coverage of the US and cast a wider net to address new science goals such as better understanding mobile and transient surface loading from climate-related and/or anthropogenic activity and their effects on earthquakes, volcanos, and other solid earth processes. Addition of new stations could be efficiently achieved by upgrading existing regional campaign and semi-continuous stations supported by other programs to observatory-grade continuous status, increasing their capabilities.

2) The committee recommends that decisions to decommission or divest NOTA stations from full NSF support be guided by input from the NSF science community. This can include the decommission of stations that are poorly performing, have high noise levels, or are excessively expensive to operate and maintain. Seeking other operators for stations would be preferable if there is a reasonable expectation that they will maintain high instrumentation and data completeness standards, and an open data policy. The geophysical facility should continue to process data and distribute products for divested stations. In all cases, explore options to reduce telemetry costs. Reduction in the number of NOTA stations will require an analysis of the impact of the reduced station number on all specific science applications. An example study of the real time detectability of earthquakes and its impact on early warning is given by Hodgkinson et al. (2020) but other studies would be needed to assess impacts on other science drivers.

3) The committee recommends that all NOTA receivers be eventually upgraded to full-GNSS capability. Currently 657 of the 1137 NOTA stations have full GNSS capabilities. The number upgraded is expected to increase by 140 by the end of the current GAGE award year 5, leaving ~340 receivers to be upgraded. However, by the time upgrades to GNSS are completed, some of the oldest GNSS capable receivers installed in the network will be End of Service (EOS), so the 340 represents only the number needed to bring the network to full GNSS, not the total number of upgrades that will be needed 2023-2032.

[4] The committee recommends that the future facility process multi-constellation GNSS data and provide data products, and increase the number of stations analyzed by including NSF-funded non-NOTA GNSS stations and other high-quality network stations. Processing multi-constellation GNSS has been tested by the GAGE processing center. Achieving full capability requires that stations are upgraded to GNSS-capable receivers, that those receivers are configured to collect and record GNSS observations, and that those observations are processed along with data from the U.S. GPS constellation. The processing in this mode cannot be done operationally until GNSS multi-constellation products are made available by the Jet Propulsion Laboratory, which has plans to do this in the near future.

Currently 2548 stations are present in GAGE time series products. This includes the 1137 NOTA stations and ~1411 non-NOTA stations, however this number has varied over time as divestments are ongoing. The committee recommends that the facility maintain these analyses under 'bare minimum' conditions, but increase this number to 4000 and 9000 under modest and optimistic growth scenarios, respectively.

[5] Portable GNSS instrumentation is key to addressing a multitude of science questions that involve geophysical events that exhibit ground deformation in locations where fixed NOTA GNSS stations may be sparse or unavailable. The committee recommends that a set of portable and rapidly deployable instruments remain a capability of a future facility. The number listed as bare minimum (20) represents instrument kits preserved in ready state for near-immediate deployment of GPS/GNSS and is only the number expected to be needed for a single project deployment. Accommodating needs for multiple projects, or single projects with greater than average requirements, will require more receivers (20-40). GAGE has been committed to meeting PI requests for receivers, and can assemble systems relatively quickly if need for a greater number of system arises, subject to supplies available in house. In recent years, no PI request has gone unfulfilled.

[6] The committee recommends that the future facility develop multi-parameter equipment pools and integrated instruments where co-location and/or logistics allow for better achievement of science goals. Close collocation of geodetic and seismic instruments can improve formal integration of data streams into very broadband seismogeodetic time series and improve research outcomes by better resolving geophysical parameters (see Seismogeodesy Box in section 4). Adequately capturing geophysical data before, during, and after geohazards will enable key scientific discoveries and help mitigate associated hazards. A dedicated pool of multi-sensor geophysical stations ("kits") are needed to obtain these data. At increased funding levels, the committee recommends maintaining a loaner pool of 20 multi-instrument equipment kits. Under "blue sky" funding conditions, this number should be increased to 40 multi-instrument (i.e., geodetic + seismic) equipment kits. This row appears in both the geodetic and seismic table but represents a single set of instruments. Real-time data transmission for these kits should also be prioritized.

[7] Existing borehole strainmeters (BSMs) fill an observational gap between seismic and GNSS systems (see Seismogeodesy Box in Chapter 4). The committee recommends that the facility maintain the existing 74 BSM networks installed as part of EarthScope, and the expertise in installation, maintenance and data analysis. New BSMs should be installed only under new funding regimes and PI projects.

8) The committee recommends that the facility develop sUAS (Small Unpiloted Aircraft Systems) capabilities through collaborations with the community. The facility should supply sUAS that are at the higher cost and larger pay-load end of the spectrum. These should have capabilities to carry interchangeable payloads (some also provided by the future facility), including optical and multi-spectral imaging systems, IR, SWIR, hyperspectral and thermal imaging, and high pulse rate multi return laser scanning with INS. Swarm-based approaches for sUAS imaging should be explored. New commercial off-the-shelf low-cost sUAS with integrated INS and laser scanners are expected to become available in 2021. Under 'Modest' and 'blue sky' funding scenarios, the facility should seek to double sUAS and capabilities.

9) Tide gauge stations are in Mexico and Jamaica. While an extensive tide gauge network is operated by NOAA, the committee recognizes the value of special attention to tide gauge deployments with two GNSS receivers installed in the very near field. These instruments support research in the relationship between relative sea level, geocentric sea level and vertical land motion. Nonetheless, the committee recommends no increase in the number of tide gauge stations under modest growth or 'blue sky' funding scenarios. Under austere budget scenarios, the facility should divest stations or seek other means to support them, possibly among the set of agencies and entities involved in COCONet and TLALOCNet, because these stations support the national interests of Mexico and Jamaica.

10) The committee recommends that the facility maintain existing terrestrial laser scanning capabilities, but not expand the current equipment pool, unless demand for these capabilities increases. New phase-based TLS systems have short range Earth Science applications and are relatively low cost. However, under reduced to flat funding scenarios eliminating this capability will free resources to maintain other facility components.

The IPRC recommends that the future *seismology* component of the facility should:

- Maintain the multi-instrument NSF/USGS Global Seismic Network (GSN) with a national and global reach and its critical very broadband capabilities that complement other international, USGS, and regional seismic networks.
- Maintain a modern pool of broadband seismometers and dataloggers and a modern pool of "nodes" (autonomous sensors + digitizers) for NSF PI use.
- Explore and develop capabilities for deployment of multi-instrument (i.e., geodetic and seismic) equipment kits.
- Add equipment and facilitate DAS data collection for the NSF-EAR community. The scientific potential of DAS is very high, but requires specialized equipment, deployment techniques, and data storage and processing that differs from typical seismic deployments.
- Maintain technical and proposal support and auxiliary equipment provided by the seismic source facility for controlled-source seismic experiments and explore alternate funding routes for individual experiment costs.
- Expand availability of rapid response kits devoted specifically to geohazard response, including portable broadband, nodal, and infrasound instrumentation.
- Promote sharing support of a limited number of GSN stations with federal, state and local agencies with commitment to maintaining very broadband sensors (including periods of 100's to 1000's of seconds), open data, and highest data quality standards, and by looking for low-cost telemetry opportunities.
- In "bare minimum" funding scenario:
    - Prioritize the GSN and the portable pool of broadband and nodal instruments over all other aspects of the current SAGE facility.
    - If direct resources for recapitalization are not available, decrease the number of portable broadband systems to no fewer than 600 through attrition and divestment to enable steady long-term sensor and related technology updates.
    - Support for GPR and multichannel systems and magnetotelluric instrumentation, should retain existing equipment but not include recapitalization or maintenance (abbreviated RENRM in table), and should minimize operational costs to the greatest possible extent.

Table 1.4. Prioritized recommendations for NSF-EAR Instrumentation Portfolio in Seismology. Italics indicate new instruments not part of the current SAGE instrumentation. See accompanying footnotes for details on recommendations. RENRM = retain existing equipment, no recapitalization or maintenance.

Existing SAGE Instrumentation	**Bare minimum to begin addressing science goals under slightly diminished to flat funding**	**Modest growth to approach science goals**	**Optimistic scenario: large-scale networks under "blue sky" funding scenarios**
Global Seismic Network (GSN)[1]: 152 stations, 40 NSF-supported through SAGE[1]	40	40+*5*	40+*40*
Portable Broadband Seismometers and Dataloggers[2]: 1014 (includes intermediate period sensors)	600	600+*400*	600+*1400*
Nodes[3] (5 Hz, 3-component autonomous sensors + digitizers): 2400	2400	2400+*1600*	2400+*7600*
Rapid response kits[4]; including multi-sensor rapid response packages with seismic and geodetic capability: 20 BB, 20 SP/compact BB, 200 nodes, 10 infrasound, 10 strong motion	40 BB, 200 nodes, 10 infrasound, 10 strong motion; 0 seismic and geodetic	40+*20* BB, 200+*200* nodes, 10+*10* infrasound, 10 strong motion; *20 seismic and geodetic*	40+*40* BB, 200+*800* nodes, 10+*30* infrasound, 10+*10* strong motion; *40 seismic and geodetic*
DAS[5]: 0	0	*~10*	*~20*
Seismic Source Facility[6]	Minimize operational support	Increased operational and proposal support and auxiliary systems	Increased operational and proposal support and auxiliary systems
Magnetotelluric (MT)[7]: 100	RENRM	100	100
Short Period Seismometers[8]: 200	RENRM	200	200
GPR and Multichannel[9]:	RENRM	Maintain for EPO purposes	Expand to include resistivity, gravimetry, and nuclear magnetic resonance equipment
Texans[10] (obsolete, single-channel instruments): 2700	--	--	--

Table 1.4: Seismology Prioritized recommendations notes

1) The committee recommends maintaining the full complement of 40 NSF-supported GSN stations, with strategic expansion in growth funding scenarios. GSN stations are key to NSF-EAR science goals and to NSF contributions to other US national and state agencies and to national interests more broadly, given the use of GSN data for applications ranging from earthquake and tsunami hazard reduction to nuclear test ban treaty verification. Data from some GSN stations are also employed by national networks run by other countries. With their ability to record very broadband ground motion signals, including periods of hundreds to thousands of seconds, these stations have irreplaceable value for studies of earthquake sources and other modes of fault slip, tsunami generation and the Earth's interior. In addition, the multi-decade lifetimes of most of these stations provide a unique ability to sample ground motion from earthquakes and other processes in exactly the same location with a similar frequency response. This capability results in researchers repeatedly returning to the GSN data archive as they develop new methods and identify new areas of inquiry. The high-quality of the data from these stations also provide a critical benchmark against which to assess data from other seismic stations, both permanent and temporary arrays. The multiple instruments at each GSN station also provide essential data for multidisciplinary research key to advancing scientific priorities. Five additional GSN stations would enable modest expansion of GSN capabilities in more sparsely sampled regions of the globe. Forty additional GSN stations would provide a high-performance global benchmark for the program of large-scale multi-disciplinary arrays presented in the "blue sky" section of this report. For example, additional GSN stations would provide key data and a permanent anchor to subduction zone studies as articulated in the SZ4D initiative. The expansion of high-quality very broadband ground motion recording to new global locations has potential to discover new processes, for example those related to shifts in cryosphere dynamics in warming polar regions.

Reduction of support for the GSN in the bare-bones funding scenario should only be done by carefully seeking partners in the US and internationally who could share support for specific GSN stations rather than terminating stations, given the unique value of these long-term very broadband data streams. We recommend that decisions to move a station from full NSF support to shared support be guided by input from the NSF science community regarding their priorities for the spatial distribution of GSN stations, by data on individual station performance (including noise levels), and by the likelihood that the partner sharing support would be committed and able to maintain a research-grade very broadband station with open data flow.

2) The committee recommends prioritizing investment in a robust pool of portable broadband instruments. Portable broadband instrumentation is key to addressing a multitude of scientific questions, and these instruments should remain a critical capability of a future facility. The vast majority of the existing broadband and short-period sensors and associated dataloggers at SAGE are beyond end-of-service and in need of recapitalization. The committee foresees some of these existing instruments still being used in future years, although we note many of these instruments were not designed for campaign usage. New sensors and dataloggers exist that are smaller, lighter, lower power, easier to deploy, and have improved performance. Recapitalization of these sensors and associated dataloggers should be a high priority. Given current community utilization through NSF-funded and university projects, 600 is the bare minimum of systems needed; this value represents utilization (~520 instruments per year over the last five years) plus 15% to account for maintenance and transitions between experiments. Under this bare minimum

funding scenario, the current pool of >1000 instruments would be significantly scaled back. Growth and recapitalization of the portable broadband pool would result in notable scientific advances. A pool of ~2000 portable broadband instruments represents the equivalent of three EarthScope Transportable Array footprints. This would enable two to three temporary large-scale broadband arrays that would approach the vision articulated in the "blue sky" section of this document, for example in service of the community science goals captured by the SZ4D initiative. At the same time, this pool would support rapid deployments in response to earthquakes, volcanic unrest, and other hazards and rapidly evolving events.

3) The committee recommends expanding the pool of portable nodal systems for NSF PI use. The existing pool of nodes is in constant use and the level of requests is beyond current inventory. The nodes are routinely scheduled 1-2 years in advance and PIs regularly do not get the number of nodes required by experimental goals. Each node is currently used for ~4-5 experiments/year. Under SAGE-II, the facility plans to increase the number of nodal instruments to 2400 by the end of 2021. Given the phasing out of the Texan instruments, the nodes will see increased demand for use in large, controlled-source experiments (which regularly employ 2000+ instruments) in addition to continued and increased demand for dense-array natural-source projects. In 2019, the node pool of 832 instruments translated to 3544 total instruments used (~4 times the number of instruments). Given continuous demand and similar utilization, a pool of ~4000 nodes would facilitate ~16,000-20,000 individual instrument deployments per year. If individual projects utilize ~2000 instruments, this number of instruments would support 8-10 projects per year while potentially enabling a 2-4 fold increase in instruments available per project. A pool of ~10,000 nodes would greatly increase the number of nodes available per experiment, further facilitating our ability to image the full seismic wavefield in both controlled-source and natural-source modes. Deep reflection imaging of the crust and high-resolution P- and S- wave velocity information would be available in both 2 and 3 dimensions. Repeated experiments near active volcanic centers, waste-water injection sites, impacted water tables and fault zones would provide high-fidelity information in 4 dimensions. This number would also increase the pool available for rapid response deployments to aftershock areas following major earthquakes and active volcanic centers.

4) The committee recommends that the future facility develop multi-parameter equipment pools and integrated instruments where co-location and/or logistics allow for better achievement of science goals. Close collocation of geodetic and seismic instruments can improve formal integration of data streams into very broadband seismogeodetic time series and improve research outcomes by better resolving geophysical parameters (see Seismogeodesy Box in section 4). Adequately capturing geophysical data before, during, and after geohazards will enable key scientific discoveries and help mitigate associated hazards. A dedicated pool of multi-sensor geophysical stations ("kits") are needed to obtain these data. Specifically, the integration of broadband seismometers, nodes, and infrasound sensors will allow dense, broadband collection of the full seismo-acoustic wavefield from volcanic eruptions, earthquakes, the cryosphere, and more. In 2021, based on extensive community feedback, IRIS/SAGE is building up a dedicated pool of ~40 broadband seismic, 200 nodes, and 10 infrasound sensors with associated dataloggers in a quick-deploy kit for the NSF-EAR community to use in response to geohazards. At modestly increased funding levels, the committee recommends maintaining a loaner pool of 20 multi-instrument equipment kits. Under "blue sky" funding conditions, this number should be increased to 40 multi-instrument (i.e., geodetic + seismic) equipment kits. This row appears in

both the geodetic and seismic tables but represents a single set of instruments. Real-time data transmission for these kits should also be prioritized.

5) The committee advocates for a significant investment in DAS technology and associated data management. DAS is one of the most promising emerging technologies for addressing key Earth science questions reviewed by this committee (see DAS Box in Chapter 6). Rapid development and application are occurring within the community, despite little to no current equipment support from NSF-EAR, which has arguably placed the US scientific community behind international teams. Interest from the US and international community in DAS is extremely high. Costs for DAS interrogators (both leasing and purchasing) are decreasing and this equipment is becoming more widely available. Deployments can still be time-consuming and expensive, and training and adherence to best-practices are key. Parallel developments in utilization of dark fiber for seismological applications opens potential for networks spanning tens-to-hundreds of kilometers with meter-scale sampling, including the off-shore environment. Acquisition of hundreds of terabytes of DAS data have prompted IRIS and its French and German counterparts to contemplate data storage, format, transmission, and computing needs (Quinteros et al., 2021). The committee does not envision DAS equipment purchases that meet community needs will be possible under a limited or "flat" budget.

6) The committee recommends continued centralized facilitation of sources and technical expertise for controlled-source seismic experiments in the academic community. Controlled-source experiments require technical expertise for experiment design, training, permitting, contracting, operation, engineering, and firing of sources that are typically beyond the reach of individual PIs. The facility should support experiments across a range of target depths and spatial resolutions: shallow, near surface (<1 km depth), high-resolution to crustal- and lithospheric-scale. The facility should either acquire and operate these sources or facilitate rental contracts through private companies or other institutions. Importantly, the facility should cover the liability of operating sources, relieving individual PIs and academic institutions of this responsibility. The facility should foster and maintain relationships with other NSF-funded facilities, e.g., NHERI at University of Texas, to build capacity and expand the user base. Under a flat or reduced budget scenario, operational costs should be minimized and no additional investment in auxiliary equipment or additional capabilities be pursued.

Through the current facility, all field and deployment costs for controlled-source experiments are covered within individual experimental budgets. Facility personnel are either included as co-PIs on experiments or as a contractor/consultant, with indirect costs assessed at university overhead rates. The committee encourages the facility to explore routing experimental support through facilities via a supplemental budget for individual experiments, similar to Polar/OBSIC mechanisms.

7) The committee recommends that the facility should retain the ~100 MT instruments that are currently being purchased by the SAGE facility, but commit no additional recapitalization or maintenance resources. Because of the very limited usage of the SAGE MT instrument pool and the ongoing recapitalization of these instruments, the MT instrument pool should be re-analyzed in a few years to determine the usage levels by the community and the science goals that can be addressed. Clear scientific potential exists through MT research, but has not been realized over the last five years through NSF-funded PI-driven experiments with the existing MT instrument pool. Under a flat or reduced funding scenario, budget support for operation of MT instruments

is a lower priority until demand for these instruments is demonstrated by the NSF research community.

8) The committee recommends keeping the current SAGE short period sensors (~200 Sercel L-22 Short Period sensors) but phasing them out over time following the RENRM model. We recognize that many of the systems are at end of service. At the same time, we note recent (summer 2021) scheduled deployments of 150 systems. Accounting for spares and other potential scheduled needs is consistent with 200. This technology has been eclipsed by compact broadband sensors that have similar deployment characteristics but have improved responses and are more widely adaptable. This equipment is a lower priority, and its continued operation should occur under a flat or reduced funding scenario only if it results in no additional cost in the facility budget.

9) The committee supports retaining Ground Penetrating Radar (GPR) and multichannel seismic reflection systems primarily for outreach and education purposes. This instrumentation enables high-resolution, near-surface experiments. It is portable, simple commercial software packages are available, data recovery is near immediate and students can produce initial views of the subsurface quickly. Near-surface geophysical methods and associated skills such as surveying and experiment planning are directly applicable to private industry in the environmental or resource extraction sectors. The current instrumentation is rugged and the longevity outlook is good. These systems are relatively inexpensive to replace if needed and are simple to maintain. However, this equipment is a lower priority, and its continued operation should occur under a flat or reduced funding scenario only if it results in no additional cost in the facility budget.

10) The committee supports the decision of the SAGE facility to phase out the 'Texan' instruments. These small, quick-deploy 1-component digitizers normally equipped with 4.5 Hz geophones are most commonly used in controlled-source experiments. These instruments have reached end of life, are no longer supported by the manufacturer, and replacement parts are not available.

1.5 Conclusion

Geodesy and seismology provide valuable fundamental understanding of Earth processes and useful knowledge for anticipating and observing natural and anthropogenic hazards and our changing environment. Instrumentation and sensor network infrastructure (including support for critical technical personnel) should remain a high priority for the NSF. The geodesy and seismology communities have a successful history of high impact, large scale geoscience including the EarthScope project—an examination of the structure and evolution of the North American continent and the processes that cause earthquakes and volcanic eruptions. A major reason for past successes and future potential is the pervasive community leadership identifying science targets and applications, coordinating management of instrumentation facilities, training the next generation of scientists, and engaging and educating the public.

Chapter 2: Statement of Principles

Recommendations are needed to balance investments in new and existing geophysical instrumentation for a future integrated geophysical facility to deliver the needed seismic and geodetic capabilities within the constraints of each of the budgetary scenarios provided by EAR. Following approaches developed in other portfolio reviews (ASPRC, 2012), we have adopted a set of principles as a framework and context for the recommendations of the Instrumentation Portfolio Review Committee (IPRC). There is an inevitable tension between science aspirations and budget realities, and between investments in resources and in people. We must balance the need to support new domains of scientific discovery with the need to protect essential existing infrastructure. The health of the U.S. geodesy and seismology community depends not only on the NSF, but also on other federal agencies and non-federally-funded facilities.

To the degree permitted by this process, which was subject to the Federal Advisory Committee Act (FACA), the IPRC consulted with the community.

This Portfolio Review was designed to be forward-looking, leaving the research community in a healthy state a decade from now.

To accomplish this, the IPRC aimed to construct instrumentation portfolios that:

Maintain U.S. research leadership in seismological and geodetic sciences. U.S. geodesy and seismology are highly successful research communities, as recently indicated by the NSF EarthScope program and the vigorous community activities that are building on EarthScope's success and moving forward in new directions. There are major demands for the application of fundamental observations and science to address societal needs. The goal is to maintain and advance the U.S. track record of scientific excellence and technological innovation in all fields of geodesy and seismology, while also promoting international collaboration and data sharing which are key to scientific progress.

Set priorities according to science goals. The research communities of geodesy and seismology are propelled by community prioritization of science challenges in open processes that have led to several guiding reports (Lay et al., 2009; Aster and Simons, 2015; McGuire and Plank, 2017; National Academies of Sciences, Engineering, 2017; Huntington and Klepeis, 2018; Freymueller et al., 2019). Those consensus priorities were not revisited or altered in this exercise. However, the IPRC did synthesize them into a single set of goals broadly relevant for geodesy and seismology under the framework of National Academies of Sciences, Engineering, and Medicine decadal survey report *A Vision for NSF Earth Sciences 2020-2030: Earth in Time*. This Portfolio Review aims to maximize scientific return according to these summary scientific goals and priorities, while acknowledging fiscal constraints defined by EAR. One of the aims is to fulfill a mission to support basic research and push the frontiers of Earth science. This process may lead to prioritization that recommends the divestment of some existing instrumentation and infrastructure when they are not key for addressing major science goals over the next decade.

Maintain a reliable system of core capabilities. The U.S. needs to maintain the long-term viability, accessibility, and advanced quality of core geodetic and seismological infrastructure, and specialized engineering and design capabilities that enable us to respond to science opportunities. Many science discoveries have relied on continuous long term data collection, and we need to be mindful of preserving essential data streams for future science innovation.

We also recognize the key role of large geodetic and seismological facilities in various agency and international commitments, and in the education of the geodesy and seismology workforce. On the other hand, we need to guard against unhelpful inertia and provide room for new capabilities.

Maintain a flexible system of capabilities to support innovative research by single or small groups of investigators, in addition to larger group efforts. One function of geophysical facilities is to host instrumentation that is too demanding or expensive for individual investigators to manage cost effectively. These instruments are available to investigators upon request and may not be used continuously. Their management is most cost effective when done so centrally. We recognize the value of supporting individual and small groups of investigators, but also that group science with large scale shared resources advances understanding.

Explore alternative modes of facility support, including partnerships with commercial groups and public agencies. Within a fixed funding envelope some facilities might have to be reduced or eliminated, or adopt new financial or partnership models, to allow new capabilities to be added. Commercial technology may eclipse long-relied-upon observational systems. Other agencies may have vested interests in supporting networks.

Value the importance of investigator-driven and competitively selected scientific priorities and community governance of instrumentation and facilities. In addition to the guidance provided by the community studies, development of facility capabilities should respond to scientific questions and research directions that emerge through the highly competitive NSF individual-investigator grants programs. Peer review and open competition should guide priorities in funding instrumentation and facilities. This principle should be honored by systems of management, operation and governance. Community-driven governance, prioritization, and decision-making has been effective for systems for both GAGE and SAGE and should continue to be a central value going forward.

Value openness in the availability of data. Geodesy and seismology have an admirable tradition of open access to data that is now integrated into facility functions and governance. This obligation is particularly strong when federal funds are involved. Openness should extend to the sharing of technology (including software), and access to competed resources such as funding and instrumentation. In an international context, this openness should reasonably include an expectation of reciprocity. Such openness should be based on the FAIR principles-- Findability, Accessibility, Interoperability, and Reusability (Wilkinson et al., 2016).

Chapter 3: Charge, boundary conditions (financial and domains), major committee activities

3.1 Context for the Instrumentation Portfolio Review Committee (IPRC) from the National Science Foundation (NSF)

This review was designed to prioritize the instrumentation and sensor network operation capabilities that a new geophysical facility would enable to advance critical scientific priorities in the areas of seismology, geodesy, and other related fields over the next decade. The review was motivated by the Division of Earth Science's desire to better enable the research community to make advances in addressing scientific grand challenges in seismology and geodesy in the context of the current challenging outlook for the federal budget.

The primary goal of this review was to examine the portfolio of capabilities provided by SAGE (Seismological Facility for the Advancement of Geoscience) and GAGE (Geodetic Facility for the Advancement of Geoscience), as well as recent advances in seismic and geodetic instrumentation that are not currently provided by SAGE and GAGE, and recommend a prioritized set of capabilities that should be provided by a future geophysical facility to maximize progress on compelling science.

3.2 The Charge

The Instrumentation Portfolio Review Committee (IPRC) was asked to construct its recommendations in a two-stage process:

1. Recommend the critical capabilities needed over the period from 2023-2033 that would enable progress on the science priorities articulated in the NASEM Earth in Time decadal survey report and recent community consensus documents. These recommendations should be focused on instrumentation and sensor network operation capabilities.

2. Recommend the *balance of investments* in new and in existing, but evolved, instrumentation and sensor network operation capabilities within the constraints of each of the provided budgetary scenarios. These recommendations may include divestment of sensor networks as well as termination of programs and other activities. The elements of the recommended portfolio should be prioritized in sufficient detail to enable EAR to make subsequent adjustments in response to variations in Federal and non-Federal funding. The recommended portfolio and any changes should be viable and lead to a vigorous and sustainable future.

The IPRC was a sub-committee of the Directorate for Geosciences Advisory Committee (AC-GEO). The committee was asked to provide its recommendations by First Quarter of Calendar Year 2021 for presentation to the AC-GEO, so NSF could consider them in formulating solicitations.

3.3 Boundary Conditions

The following boundary conditions were adopted for the review (as specified by the NSF):

1. The review should emphasize the science priorities outlined in the National Academies of Science, Engineering and Medicine (NASEM) Earth in Time, also known as the CORES (*"Catalyzing Opportunities for Research in the Earth Sciences")* consensus study.
2. The review should also take into account science priorities articulated in recent community consensus documents, including but not limited to the 2015 *Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences* (Aster and Simons, 2015); *The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D (*McGuire and Plank, 2017*);* and *Future Directions in Tectonics* (Huntington and Klepeis, 2018).
3. The review should also take into consideration NSF-selected information contained in white papers submitted to NSF in association with DCL 20-037 regarding instrumentation and sensor network operations.
4. The review should assume different budget scenarios, to be provided by EAR to encompass the period between 2023-2033 and consider the costs of (i) delivering the existing capabilities, as well as of (ii) cost estimates of new capabilities.
5. The committee's deliberations should take into consideration the national and international geophysical landscape and consequences of its recommendations for domestic and international partnerships.

Additional constraints on the committee's deliberations included an emphasis on EAR – supported instrumentation. That meant that the committee did not address Polar-related activity and instrumentation, even though it is generally managed by the same facilities and there are economies of scale and sharing of personnel, expertise, and even instruments. While the Education and Public Outreach (EPO) of the facilities are laudable and have certainly broadened the impact of EAR's investments in instrumentation, we also did not examine EPO activity. The committee also struggled to limit our consideration to terrestrial deployments, in spite of community enthusiasm for seafloor geodesy and ocean bottom seismometry. We pushed back with the need to have broad aperture networks (spanning or including seafloor deployments) given the significance of some science questions.

Finally, as a constituted subcommittee of the AC-GEO, the Instrumentation Portfolio Review Committee is subject to Federal Advisory Committee Act (FACA; www.gsa.gov/faca) oversight. This helps to protect the process of decision-making by the NSF and to avoid any special influence on the committee recommendations. The committee struggled early with a lack of familiarity with the FACA and a desire to seek community input as has been the general custom and experience. The committee's charge and membership were public, but we were not to share other information and the committee deliberations were confidential. The committee was chosen to be unconflicted and to have sufficient knowledge to do its work. We were able to interview specific colleagues who had expertise or knowledge that was not otherwise available to us.

3.4 Committee activities and time frame

The committee was constituted by the NSF as soon as possible after the public release of the Earth in Time report and had its first meeting in July 2020. The committee met regularly with at least one 3 hour meeting and one 1 hour meeting each month through January 2021. Weekly one hour meetings completed the committee deliberations through March 2021 (>50 hours of meetings). The report was drafted during January through March 2021. An initial complete draft was circulated to NSF colleagues and the AC-GEO at the end of March 2021. Following FACA guidance, the committee was unable to have community review of the document prior to its completion. Review suggestions were considered. The final draft was completed in early April 2021 and officially accepted by the AC-GEO at its mid April 2021 meeting. The committee's work was accomplished during unprecedented socio-political crises and the Coronavirus pandemic.

Chapter 4. Science challenges and drivers addressed by geodetic and seismic instrumentation

4.1 Introduction

The National Academy of Science prepared the report "A Vision for NSF Earth Sciences 2020-2030: Earth in Time" (National Academies of Sciences, Engineering, 2020), also known as "the CORES report". This top-level decadal survey for the Earth sciences provides a framework for prioritization of research and science applications. We recognize the substantial sustained effort by the seismology and geodesy communities to refine and update science motivators through the development of community studies (Table 4.1). The level of detail in the community studies is finer than the Earth in Time report. We drew from the reports to integrate with the Earth in Time report questions and highlight targets motivating observations and consequent technologies.

This chapter serves two functions, one is to focus on the scope of the Earth in Time report that is relevant to geodesy and seismology, and also to coalesce questions in the Earth in Time report with the scientific themes developed in the other community reports. While briefly summarized here, this activity consumed a substantial portion of the IPRC's deliberative resources, as it forms the foundational set of questions from which facility functions will support.

In an effort to manage our scope, we do not provide exhaustive citations (which are provided in the individual reports), but instead highlight either specifically appropriate or some generally appropriate references. Figures are drawn from some highly relevant examples as well as synthetic ones developed by the committee.

Table 4.1. Summary of the community studies used by the IPRC to identity geodesy and seismology science priorities (short name for report and citation with title underlined)

SEIS (Lay, T. editor, 2009, <u>Seismological Grand Challenges in Understanding Earth's Dynamic Systems</u>: Report to the National Science Foundation, IRIS Consortium, 76 pp.)
FUTURES (Aster, R., and Simons, M., 2015, <u>Future Geophysical Facilities Required to Address Grand Challenges in the Earth Sciences</u>: Report to the National Science Foundation, 52 pp.)
SZ4D (McGuire, J.J., and Plank, T., 2017, <u>The SZ4D Initiative: Understanding the Processes that Underlie Subduction Zone Hazards in 4D</u>. Vision Document Submitted to the National Science Foundation, 72 pp.)
ERUPT (National Academies of Sciences, Engineering, and M., 2017, <u>Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing</u>: Washington, DC, National Academies Press, 161 pp.)
Tectonics (Huntington, K.W., and Klepeis, K.., 2018, <u>Challenges and opportunities for research in tectonics: Understanding deformation and the processes that link Earth systems, from geologic time to human time</u>. A community vision document submitted to the U.S. National Science Foundation: University of Washington, 84 p., doi:10.6069/H52R3PQ5.)
Restless Earth <u>(Freymueller, J.T., Bendick, R., Borsa, A., Newman, A., Brooks, B.A., Fu, Y., Kinsman, N., Larson, K., Plag, H.-P., and van Dam, T., 2019, Measuring the Restless Earth - Grand Challenges in Geodesy</u>, 59 pp.)

4.2. Questions from the Earth in Time report: Alignment with Geodesy and Seismology

The Earth in Time report covers a great breadth of contemporary Earth science research and articulates 12 overarching science questions. These questions align variably with those of interest to the broadly defined geodesy and seismology communities (Table 4.1). We divided them into three classes: 1) strongly aligned with many connections to themes, challenges, other more granular questions; 2) strongly aligned with a smaller number of themes, challenges, questions, but in key ways; and 3) weakly aligned with themes, challenges, questions, but in ways that represent emerging areas of importance.

In order to determine which of the Earth in Time report questions are most closely aligned with seismology and geodesy research themes, we developed a scoring process by which the science questions could be semi-objectively ranked in terms of the degree of connection to the community reports (Figure 1.1). This exercise coalesces the goals of the community supported by the SAGE/GAGE facility with the overarching directive questions described in the Earth in Time report. The twelve questions are listed below sorted into sections based on their respective degree of alignment.

Below, we detail the connections between the overarching Earth in Time report questions and more granular science questions from the other community reports. These connections form one link in the traceability between facility components and the overarching Earth in Time report topics and are represented by arrows between the first and second columns of Figure 1.2. Again, we follow the order of general alignment as illustrated in Figure 1.1. For each overarching Earth in Time report question below we cite specific sections of the other reports that discuss their scientific relevance.

Strong alignment with many themes, challenges, and questions in geodesy and seismology (Earth in Time report icons)

Earth in Time: How can Earth science research reduce the risk and toll of geohazards? Understanding geohazards is a very strong application of geodesy and seismology. Common themes here include understanding the fundamental processes that create the hazards from earthquakes, volcanoes, landslides, and sea level rise in an effort to improve forecasting and warning. This theme also aligns with other process-related ones (earthquakes, volcanoes, surface processes, climate system).

SEIS: In particular Grand Challenge (GC) 2. How does the near-surface environment affect natural hazards and resources? But also other passages on faulting, magmatic processes, and earthquake rapid warning systems, (Lay, 2009).

FUTURES: 3.2 Faults and earthquakes and 3.3 Magmatic systems, 3.4 Plate interiors, 4.1.1 The complexities of fault rupture dynamics and the subsequent propagation of seismic waves through the highly heterogeneous near-surface environment causes great variability in strong ground motion that can be anticipated by seismological and geological characterization, by rapid inversions for slip history, and through the development of high-resolution crustal models in populated areas in advance of earthquakes, 4.1.2 Improving our understanding of conditions by which a small percentage of injection wells induce appreciable basement seismicity is crucial for implementing optimal strategies for mitigation of this anthropogenic hazard; 4.1.3 Volcano monitoring provides basis for predicting eruptions (and their cessation) as well as other hazards such as lava dome collapse, lahar potential, modeling lava flows, etc., 4.2.1 Tracking soil moisture, vegetation, surface and ground-water, snowpack, and their fluxes across spatial and temporal scales is needed to forecast flood vulnerability, wildfire risk, drought severity, and coastal flooding due to subsidence, and inform mitigation efforts. (Aster and Simons, 2015).

SZ4D: 2.1 When and where do large earthquakes happen? 2.4 How do surface processes link to subduction? (McGuire and Plank, 2017).

ERUPT: GC 1. Forecasting using magma models; GC 2. Global volcano lifecycles, GC 3. Coordinated volcano science community (National Academies of Sciences, Engineering, 2017).

Tectonics: GC 3. Understanding fault zone behavior from Earth's surface to the base of the lithosphere, GC 4. Understanding the dynamic interactions among Earth-surface processes and tectonics, GC 5. Synergies between meeting societal needs and advancing tectonics research (Huntington and Klepeis, 2018).

Restless Earth: 1.2 How will future sea level rise and its impacts be distributed around the globe? 2.1 How can geodesy help track the movement of water through the Earth system in response to climate change and human activity? 3.1. What are the mechanisms that drive the nucleation, propagation, and cessation of all forms of fault slip behavior? 3.2. What controls whether slip will remain slow, or accelerate to seismic speeds? 3.3. What can Geodesy inform about the location, timing, and magnitude of future earthquakes? 5.3. Can we forecast the occurrence, type, and duration of large, globally disruptive volcanic events on human relevant timescales? 7.1. How can ubiquitous real-time data flow and processing enable science and early warning in the geodetic realm? 7.3. How do geodetic data inform forecasting, warning, rapid response, recovery, and long-term consequences of natural hazards? (Freymueller et al., 2019).

Earth in Time: When, why, and how did plate tectonics start? This question has strong resonance with the community reports. The reports cite common themes of, for example: geological evolution of Earth's surface and landscapes; stress and strain in the lithosphere and mantle; temperature, flow, dynamics, rheology, Earth structure, and related processes in the crust, mantle, core, and magnetic field; and seismicity, magmatism and volcanism. Sections and/or Grand Challenges (GC) are cited by section number in those reports.

SEIS: GC 3. What is the relationship between stress and strain in the lithosphere? What is the lithosphere-asthenosphere boundary? GC 8. How do plate boundary systems evolve? GC 9. How do temperature and composition variations control mantle and core convection? (Lay, 2009).

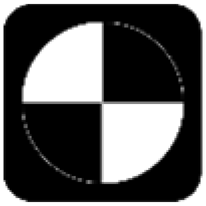
FUTURES: 3.1 Earth structure and evolution: "Quantifying complex mantle and core dynamical systems is essential to understanding Earth's thermo-chemical evolution. It is also critical to understanding the ongoing circulation systems that generate the magnetic field and drive plate tectonics... " 3.1.1 Plate Boundary systems and 3.1.2 Evolution of the continents (Aster and Simons, 2015).

SZ4D: 2.3 How do spatial variations in subduction inputs affect seismicity and magmatism? (McGuire and Plank, 2017).

ERUPT: GC 2. Global volcano lifecycles, (National Academies of Sciences, Engineering, 2017).

Tectonics: 1.2 The unexplored frontier of Earth's lithosphere and lower mantle, 1.4 Exploring the evolution of plate tectonics and a habitable planet, 1.5 Exploring the tectonics of other worlds, 1.6 Exploring the timing and tempo of tectonic processes, 2.5 Linking deep and shallow parts of tectonic systems, 3.6 Integrating fault zone behavior through the full thickness of the lithosphere, (Huntington and Klepeis, 2018).

Restless Earth: 4.1. What do geodetic observations reveal about Earth's material heterogeneity in space and time? What are the time constants for different mechanical approximations? 4.2. How can we combine geodetic data with other information to improve our knowledge of Earth's mechanical behavior, and what are the fundamental limitations of this knowledge? 4.3. How do complexities in material properties limit our understanding of Earth processes and dynamics? (Freymueller et al., 2019).



Earth in Time: What is an earthquake? Earthquake processes are of central concern in geodesy and seismology. Common themes here include the stress, strain, fluid pressures, rheology of Earth materials, source and effects of friction in faults, relationship to earthquake recurrence and hazards.

SEIS: GC 1. How do faults slip? GC 3. What is the relationship between stress and strain in the lithosphere? (Lay, 2009).

FUTURES: 3.2 Fault zones and the earthquake cycle, 3.1.2 Developing a theoretical structure for tying earthquake behavior to changes in fluid/gas pressure, spatio-temporal heterogeneity of material properties, hydrologic conditions, triggering sensitivities, frictional behavior. 3.1.2 Elucidating complex time-variable behavior of slip, which requires observations spanning time and space, 3.4 What is the relationship between stress and strain in the lithosphere, and resulting earthquake potential, particularly in stable interiors? (Aster and Simons, 2015).

SZ4D: 2.1 When and where do large earthquakes happen? (McGuire and Plank, 2017).

ERUPT: GC 1. Forecasting eruption, GC 3. Coordinated volcano science community (National Academies of Sciences, Engineering, 2017).

Tectonics: GC 1. Understanding planetary evolution in four dimensions, GC 2. Understanding variations in rheology throughout the lithosphere, GC 3. Understanding fault zone behavior from Earth's surface to the base of the lithosphere, GC 4. Understanding the dynamic interactions among Earth-surface processes and tectonics, GC 5. Synergies between meeting societal needs and advancing tectonics research (Huntington and Klepeis, 2018).

Restless Earth: 2.2. How do changes in terrestrial water storage modulate displacement, strain, stress, and stress transfer in the solid Earth? 3.1. What are the mechanisms that drive the nucleation, propagation, and cessation of all forms of fault slip behavior? 3.2. How can geodesy inform the behavior of the solid Earth during the entire earthquake cycle, and how do patterns of slip change within and between cycles? What controls whether slip will remain slow, or accelerates to seismic speeds? 3.3. What can geodesy inform about the location, timing, and magnitude of future earthquakes? 4.3. How do complexities in material properties limit our understanding of Earth processes and dynamics? (Freymueller et al., 2019).

Earth in Time: What are the causes and consequences of topographic change? Long term interactions between the surface and interior, volcanic, surface and tectonic process interactions, and direct displacements of the Earth surface were broadly resonant. Common themes here included the connection between the Earth's mantle and surface, and how do processes collude across widely varying spatio-temporal scales to create landscapes.

FUTURES: 3.1.1 Effects of mantle convection on the long-term uplift and subsidence within plate interiors; 3.4 Plate interiors, 3.6 Understanding the contributing factors, spatial patterns, and temporal variability of sea level changes are essential for climate change mitigation efforts, 3.6 Seismic, mineral physics, and geodynamic constraints on lateral variations in lithospheric thickness and mantle viscosity must be integrated (Aster and Simons, 2015).

SZ4D: 2.4 How do Surface Processes Link to Subduction? (McGuire and Plank, 2017).

ERUPT: GC3: Volcano lifecycles (National Academies of Sciences, Engineering, 2017).

Tectonics: GC 1. Understanding planetary evolution in four dimensions, GC 2. Understanding variations in rheology throughout the lithosphere, GC 3. Understanding fault zone behavior from Earth’s surface to the base of the lithosphere, GC 4. Understanding the dynamic interactions among Earth-surface processes and tectonics, GC 5. synergies between meeting societal needs and advancing tectonics research (Huntington and Klepeis, 2018).

Restless Earth: 1.3. How will changes in ice and oceans interact with the solid Earth to change its elevation and coastlines, and with what consequences? 6.1. How does land surface morphology express the interaction between tectonic, hydrological, and gravitational processes? 6.2. How does topography evolve towards steady state, at steady state, and during/after extreme forcing events? What is the relative importance of timescales and processes in topographic evolution? 6.3. What causes landscape evolution to change state from quiescent, to steady, to catastrophic? (Freymueller et al., 2019).

Earth in Time: What drives volcanism? Volcanic and magmatic processes are of central concern in geodesy and seismology. Common themes here include the processes and pathways at work in the crust and mantle, their magma and volatiles.

SEIS: GC 6. How do magmas ascend and erupt? (Lay, 2009).

FUTURES: 3.1 Seismic imaging of mantle plumes, 3.3. The relationship among deformation, seismicity, intrusions, eruptions and normal vs. transient behavior, 3.3 How much magma is present and where is it stored and how much is eruptible, 3.3. Submarine volcanism, nature of horizontal flow, creation of interconnected porous channels, role of water, 3.3 Intraplate volcanism, depth distribution of magmas and volume of magma trapped in the crust, (Aster and Simons, 2015).

SZ4D: 2.2 How is mantle magma production connected through the crust to volcanoes? (McGuire and Plank, 2017).

ERUPT: GC1. Forecasting using observations integrated into magma models; GC 2. Global volcano lifecycles; GC 3. Coordinated volcano science community, (National Academies of Sciences, Engineering, 2017).

Tectonics: GC 1. Understanding planetary evolution in four dimensions, GC 2. Understanding variations in rheology throughout the lithosphere, GC 5. Synergies between meeting societal needs and advancing tectonics research, (Huntington and Klepeis, 2018).

Restless Earth: 5.1. What processes, over what timescales, can trigger volcanic eruptions, and how do volcanoes interact with nearby tectonic and magmatic systems? 5.2. What are the sizes, depths, and connections between deep and shallow magma reservoirs, and what fraction of magma intruded into the shallow crust is ultimately erupted? 5.3. Can we forecast the occurrence, type, and duration of large, globally disruptive volcanic events on human relevant timescales? (Freymueller et al., 2019).

<u>Strong alignment with a *smaller* number of themes, challenges, questions in geodesy and seismology, but in key ways (Earth in Time icons)</u>

Earth in Time: How is Earth's water cycle changing? Common themes include measurement and understanding of the effects that water's movement has on the Earth, its shape, deformation, and processes.

SEIS: GC 2. How does the near-surface environment affect natural hazards and resources? GC 5. Where are water and hydrocarbons hidden beneath the surface? (Lay, 2009).

FUTURES: 3.6 Sea level changes, 3.8 Soil Moisture; 4.2.1 Groundwater depletion and related subsidence; changes in ground- and surface waters can affect flood and drought potential; Vignette 7 Water in the West, (Aster and Simons, 2015).

Restless Earth: 1.1. How much water is being transferred from Earth's ice reservoirs into the oceans? 1.2. How will future sea level rise and its impacts be distributed around the globe? 1.3. How will changes in ice and oceans interact with the solid Earth to change its elevation and coastlines, and with what consequences? 2.1. How can geodesy help track the movement of water through the Earth system in response to climate change and human activity? 2.2. How do changes in terrestrial water storage modulate displacement, strain, stress, and stress transfer in the solid Earth? 2.3. Can geodesy provide information about the water cycle at the water management scale? (Freymueller et al., 2019).

Earth in Time: What does Earth's past reveal about the dynamics of the climate system? Common themes include links between solid Earth, ocean and cryogenic processes and their connection to the climate that are detectible today but whose processes may be relevant over longer periods of geologic history.

SZ4D: 2.4 How do surface processes link to subduction? (McGuire and Plank, 2017).

ERUPT: GC 2. Global volcano lifecycles (National Academies of Sciences, Engineering, 2017).

Tectonics: 4.4 Evaluating predicted feedbacks between climate, erosion, and tectonics, (Huntington and Klepeis, 2018).

Restless Earth: 1.3. How will changes in ice and oceans interact with the solid Earth to change its elevation and coastlines, and with what consequences? 4.1. What do geodetic observations reveal about Earth's material heterogeneity in space and time? What are the time constants for different mechanical approximations? (Freymueller et al., 2019).

Earth in Time: How are critical elements distributed and cycled in the Earth? This topic is applied to petroleum, water, and economic minerals and was represented in all of the studies. Common themes here included, for example, the roles of water, volatiles, reservoirs, fluid and gas pressures in evolving the distribution of elements in the Earth system, and the transport of geological materials through tectonic processes.

SEIS: GC 5. Where are water and hydrocarbons hidden beneath the surface? (Lay, 2009).

FUTURES: 3.1 - Distribution and circulation of fluids and volatiles in Earth's interior, 3.1.1. Global water budget, the flux of water through the mantle, and influence of volatiles on mantle rheology, 4.2.2 Monitoring and management of energy reservoir production and optimization, the characterization and mitigation of induced seismicity, management of injected fluids including both enhanced recovery and geological CO2 sequestration, depend on imaging subsurface properties and understanding relevant processes, (Aster and Simons, 2015).

SZ4D: 2.3 How do spatial variations in subduction inputs affect seismicity and magmatism? (McGuire and Plank, 2017).

ERUPT: GC 1. Forecasting using observations integrated into magma models, GC 2. Global volcano lifecycles, (National Academies of Sciences, Engineering, 2017).

Tectonics: GC 1. Understanding planetary evolution in four dimensions (Huntington and Klepeis, 2018).

Restless Earth: 2.1. How can geodesy help track the movement of water through the Earth system in response to climate change and human activity? 2.2. How do changes in terrestrial water storage modulate displacement, strain, stress, and stress transfer in the solid Earth? (Freymueller et al., 2019).

Earth in Time: How does the critical zone influence climate? This topic relates to coupling between the lithosphere, hydrosphere and atmosphere. Common themes include surface and subsurface movement of water, interactions between tectonics, erosion, landscape and climate change.

SEIS: GC 4. How do processes in the ocean and atmosphere interact with the Solid Earth?

FUTURES: 3.7 How does subsurface critical zone architecture vary across landscapes, what are the processes that control that variation and its coupling to the land surface? 3.8 Soil moisture, snow and vegetation water content, (Aster and Simons, 2015).

Tectonics: 4.4 Evaluating predicted feedbacks between climate, erosion, and tectonics, 4.6 Dynamic coupling of crustal stresses, fracturing, chemical weathering, and physical erosion (Huntington and Klepeis, 2018).

Restless Earth: 2.1. How can geodesy help track the movement of water through the Earth system in response to climate change and human activity? (Freymueller et al., 2019).

Earth in Time: How is Earth's internal magnetic field generated? This topic ties to global Earth structure and the geodynamo of the outer core. Common themes here include core-mantle interactions, deep Earth composition, conductivity, temperature, physical state, history and role in planetary formation.

SEIS: GC 9. How Do Temperature and Composition Variations Control Mantle and Core Convection? (Lay, 2009).

FUTURES: 3.1 Understanding mantle-core coupling and the influence of lateral mantle variations, (Aster and Simons, 2015).

SZ4D: 2.3 How do spatial variations in subduction inputs affect seismicity and magmatism? (McGuire and Plank, 2017).

Tectonics: 1.2 The unexplored frontier of Earth's lithosphere and lower mantle tectonics, (Huntington and Klepeis, 2018).

Weak alignment with themes, challenges, questions in geodesy and seismology, but in ways that represent emerging areas of importance. These emerging areas of connection are important to Earth sciences but did not reflect strongly the research topics of geodesy and seismology.

Earth in Time: How do biogeochemical cycles evolve?

Tectonics: 1.4 Exploring the evolution of plate tectonics and a habitable planet, (Huntington and Klepeis, 2018).

Earth in Time: How do geological processes influence biodiversity?

FUTURES: 3.8 How is water distributed in the soil and in plants ... is critical for phenology studies, (Aster and Simons, 2015).

ERUPT: GC 2. Global volcano lifecycles (National Academies of Sciences, Engineering, 2017).

Tectonics: 1.4 Exploring the evolution of plate tectonics and a habitable planet, (Huntington and Klepeis, 2018).

Restless Earth: 1.2. How will future sea level rise and its impacts be distributed around the globe? 1.3. How will changes in ice and oceans interact with the solid Earth to change its elevation and coastlines?

4.3 Science and technology traceability overview

The science themes, challenges, and questions identified by the Earth science community as discussed above must indicate the suitability of instrumentation needed to make necessary observations. An ontological problem is to balance a higher level perspective on Earth science knowledge with tractable investigative questions, necessary observables, and the instrumentation-related facilities necessary for the community to address the fundamental topics (Figure 1.2). In many NASA planning activities, a Science and Applications Traceability Matrix (SATM) is often employed (e.g., https://sbg.jpl.nasa.gov/satm). Given the overview perspective of this committee's activity, we decided that the typical fine grained level of detail of a traditional SATM was not necessary or tractable in the time available. Instead, we attempted to schematically (and not exhaustively) connect the science challenges to the suite of foundational and emerging instrumentation and technology that is available for Earth science research. These are discussed in Chapters 5 and 6.

The fundamental topics and investigative questions summarized in Figure 1.2 are developed in the community studies and were summarized earlier. The observables and follow-on facilities for instrumentation are unevenly covered in the community studies though Aster and Simons (2015) identify future geophysical facilities.

Earth science observables include those made using geodetic and seismological instrumentation directly (e.g., position, displacement, and their time derivatives sampled at a range of time scales and variably spatially; and gravity). They also included indirectly sampled properties such as air pressure and its dynamics. Electro-magnetic and temperature observations are highly complementary to those made using geodetic and seismological tools. Finally, additional more generically defined observations regarding the state of the atmosphere, hydrosphere, and cryosphere can be necessary (Figure 1.2). A fundamental problem is that while instrumentation senses signals that have temporal scales from milliseconds to decades, the processes they are intended to measure are ongoing for millennia (see Figures 9.1 and 9.2).

Existing facility capabilities in Earth sciences include permanent (surface and borehole installed) and deployable GNSS and seismic sensors, laser scanners and optical imagers on multiple platforms (which require GNSS positioning usually for georeferenced 3D earth models), magnetotelluric systems, and strainmeters and creepmeters (Figure 4.2). A future facility might more formally include radar systems (the most important being space-based InSAR), distributed fiber-optic sensing, and terrestrial gravimetry (Figure 1.2).

Creating new knowledge and applications from these scientific workflows require more than just capable instrumentation. They require data transfer, including high quality telemetry. They need a well-supported professional technical staff to deploy, maintain, and recover them, understand the inevitable idiosyncrasies, train users, and keep their eye on developing technologies and efficiencies. In addition, managing the incoming data to make it as useable and interpretable as possible and to produce multiple data product levels for different user needs is essential.

Box 4.1: Seismogeodesy

Seismology is the study of Earth motion in seismic waves. Geodesy is the study of the Earth's deformation and shape and is traditionally concerned with long-term effects. The instruments favored by seismologists capitalize on the inertial aspect of seismic waves to measure rapid movement of the ground relative to a stationary reference frame. The instruments favored by geodesists do not utilize inertia and are therefore optimized to measure strain or displacement relative to either an external reference frame, e.g., satellites, or a known point in an instrumental reference frame, e.g., the far end of a taught wire or laser reflector in a strainmeter. As the historic scientific goals of these instruments differed, it made sense to pursue distinct engineering solutions. As a result, the optimal detection capabilities tend to best resolve high or low frequency motion (Figure 4.1.1). An intermediate range of frequencies near hours forms a seismological-geodetic bandgap that is poorly measured by most standard instruments. The few specialized instruments that can fill the gap, such as creepmeters and strainmeters, are valuable point measurements of an otherwise uncharted territory.

Recent observations have increased the urgency of filling the seismo-geodesy bandwidth gap on standard instrumentation. It is now well-established that faults slip both quickly and slowly with a dizzying array of creep events at all observed timescales. However, observations of fault motion at the most human timescales (hours) are lacking. This is precisely the timescale at which interaction between earthquakes and slip events could be most diagnostic. A long-term goal is to fill this gap in observational capability.

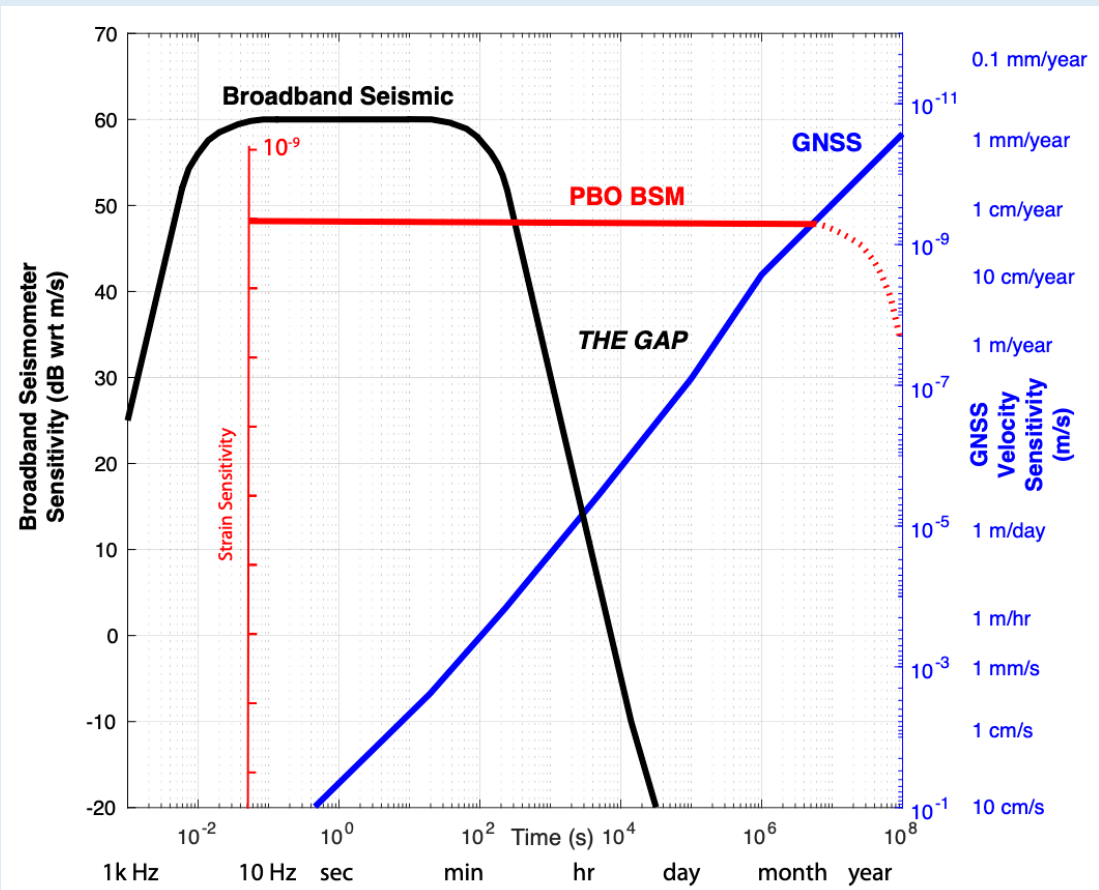


Figure 4.1.1 (previous page). *Borehole strainmeters (BSM) address the seismological-geodetic bandwidth gap. The sensitivity range of broadband seismic systems (black line) drops off at periods above 100 seconds (Ackerly, 2014). The velocity sensitivity of GNSS systems (blue line) picks up with increasing observation time, surpassing 1 mm/yr after a few years. The band from hours to weeks has lesser sensitivity for each technique. The GTSM instruments deployed in PBO per manufacturers' specification have flat response from 20 Hz to DC (Gladwin, 1984), bu compression of the grout and rock around the hole after installation and other noise sources reduces the effective sensitivity in periods longer than ~1 month (red line - dashed where fall off in sensitivity is uncertain). The separate vertical axis for the borehole strainmeters (BSMs) indicates sensitivity better than* 10^{-9}.

The complementarity of seismic and geodetic systems broadens the range of sensitivity for studying geophysical phenomena, but there is a band, with periods near hours to weeks, where GNSS and broadbands have a gap in their sensitivity (Figure 4.1.1). Signals in this band include those from important fault phenomena such as earthquakes and creep events, slow earthquakes, episodic tremor and slip in subduction zones, strain transients. There are also non-earthquake signals that drive stress changes including tides, seiches, magmatic signals, surface pressure changes from hydrological and atmospheric changes. One example of a system that can see in this band is the Gladwin Tensor Strain Meters (GTSM) instruments that are deployed in boreholes of the Plate Boundary Observatory (PBO). For short baseline measurements these borehole strainmeters (BSM) are orders of magnitude more sensitive than GNSS and can detect signals that are difficult to access with broadband seismic networks, filling the gap. Their main disadvantages are that they are expensive and complex to deploy, have complex noise characteristics (Barbour and Agnew, 2011) and are difficult to move, repair or upgrade once placed in the ground.

For the special case of earthquakes, seismic and geodetic data streams can be combined in various ways. They can be formally integrated at the data product level, e.g., by Kalman filtering GNSS solutions together with seismic acceleration(Bock et al., 2011). Alternatively, different aspects of the same event can be measured separately by seismic or geodetic techniques. Seismic recordings of the elastic wave field give information about the main shock location, time, focal mechanism, distribution of foreshocks and aftershocks, structural aspects of the faults that ruptured, the ambient crust and tectonic environment, to name a few. Geodetic networks sense slower aspects of the seismic cycle, including steady interseismic crustal strain rates prior to the event, weeks or months-long slow earthquakes, coseismic displacement, and the days- to decades-long evolution of postseismic after slip and/or mantle flow. In rare cases when the signal is sufficiently large, the different systems resolve separate aspects of the same signals, e.g., the distribution of coseismic slip where geodetic and seismic time series can be simultaneously inverted for rupture propagation, slip evolution, rise time, etc., especially when GNSS resolves the wave field (Figure 4.1.2).

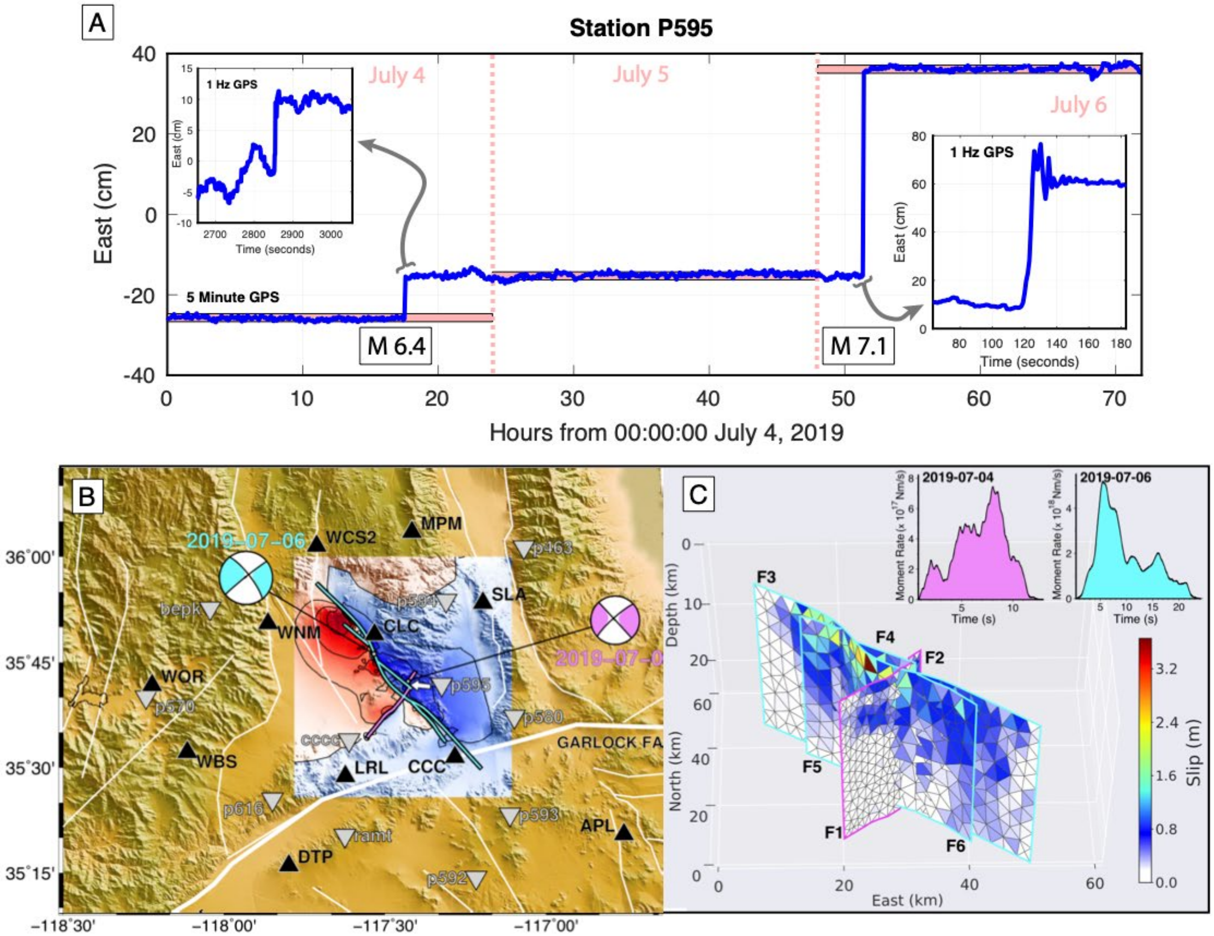


Figure 4.1.2. Seismogeodetic constraints on the M 6.4 and M 7.1 earthquakes near Ridgecrest, CA on July 4 and 6, 2019 used to evaluate timing and distribution of slip, static and dynamic stress changes. A) GNSS position time series for NOTA station P595 that measured coseismic offsets and seismic waves. Pink bands behind the five-minute sample rate time series indicate the 24-hour position solution for each day. Five-minute time series are from the Nevada Geodetic Laboratory (http://geodesy.unr.edu), 1 Hz solutions are from Melbourne et al., 2020. For the M7.1 on July 6 the 1 Hz time series clearly show seismic waves prior to the position settling into its post-event location ~50 cm east of its starting point. B) InSAR constraints for the events and location of strong motion seismic (black triangles) and high rate GNSS (gray triangles) used by (Goldberg et al., 2020) to solve for C) kinematic slip distribution, moment rate functions and other features of the events.

Chapter 5. Existing Instrumentation

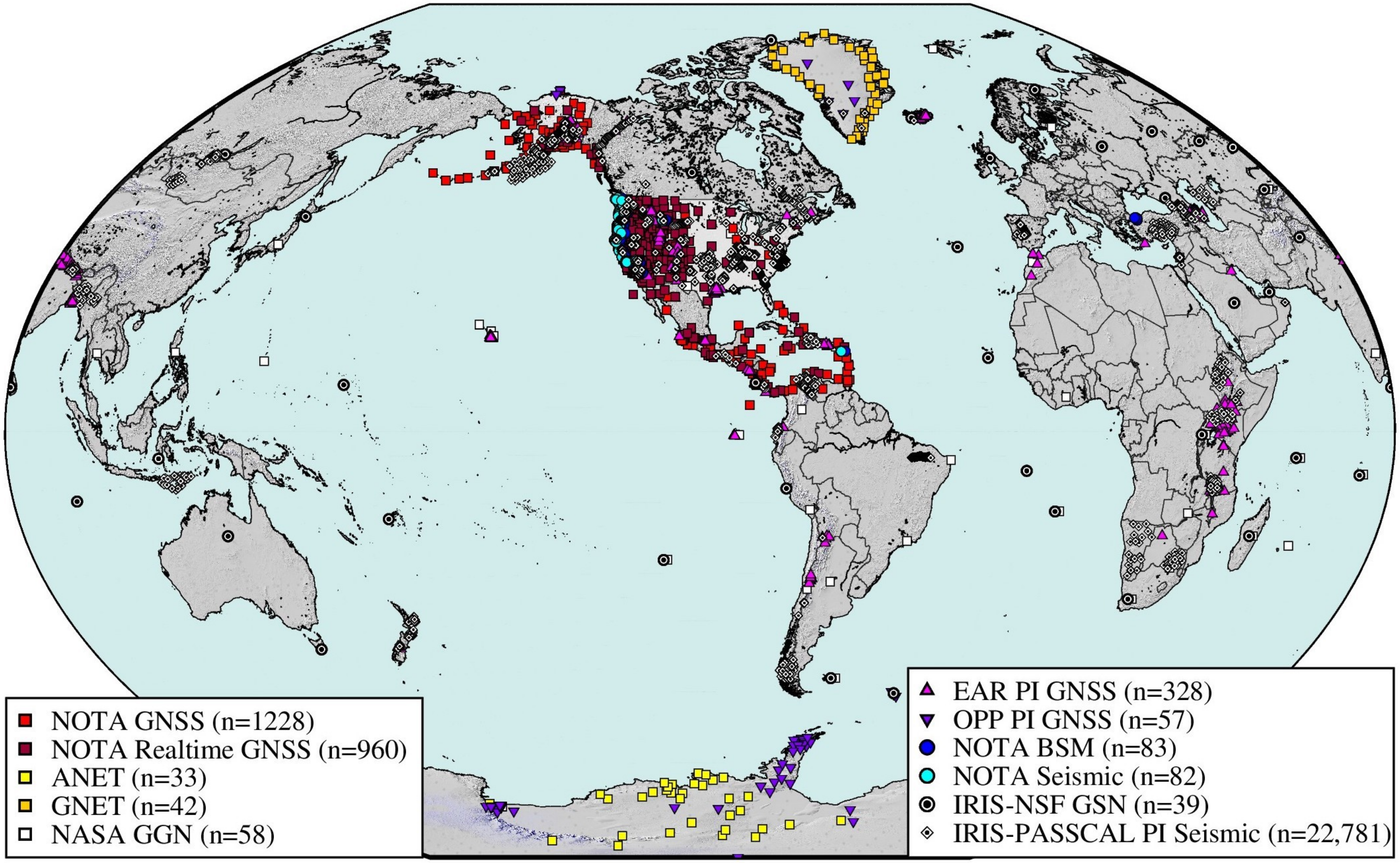
5.1 Introduction

The current state of national seismic and geodetic networks for geophysical science represents the fulfillment of sustained efforts by the US science community and led to the construction of EarthScope (https://www.earthscope.org/) between 2003 to 2020 (official end was 2018). That collaborative vision was to develop geophysical networks in a new mode that emphasized large numbers of high-quality instruments, continental-scale network aperture, open data, strong and stable facility operational support and the benefit of cross-disciplinary investigations. The result was a massive push to understand the structure and dynamics of the geophysical processes that built, and continue to build, North America from crust to core. The project was enabled through the National Science Foundation's Major Research Equipment and Facilities Construction (MREFC) program. In a transformative conceptual leap, the ambitious project had the view that the network of seismic, geodetic, and other types of sensors could be operated and utilized as a single instrument (like a telescope pointing downward) to study the interior workings of the Earth. Building EarthScope as a synoptic mega-network required placing Earth science in the leagues with other large facilities that design and support systems to collect, prepare and distribute data. Parallels can be made to, for example, research vessels for marine studies, large telescopes for astrophysics or particle colliders for nuclear physics.

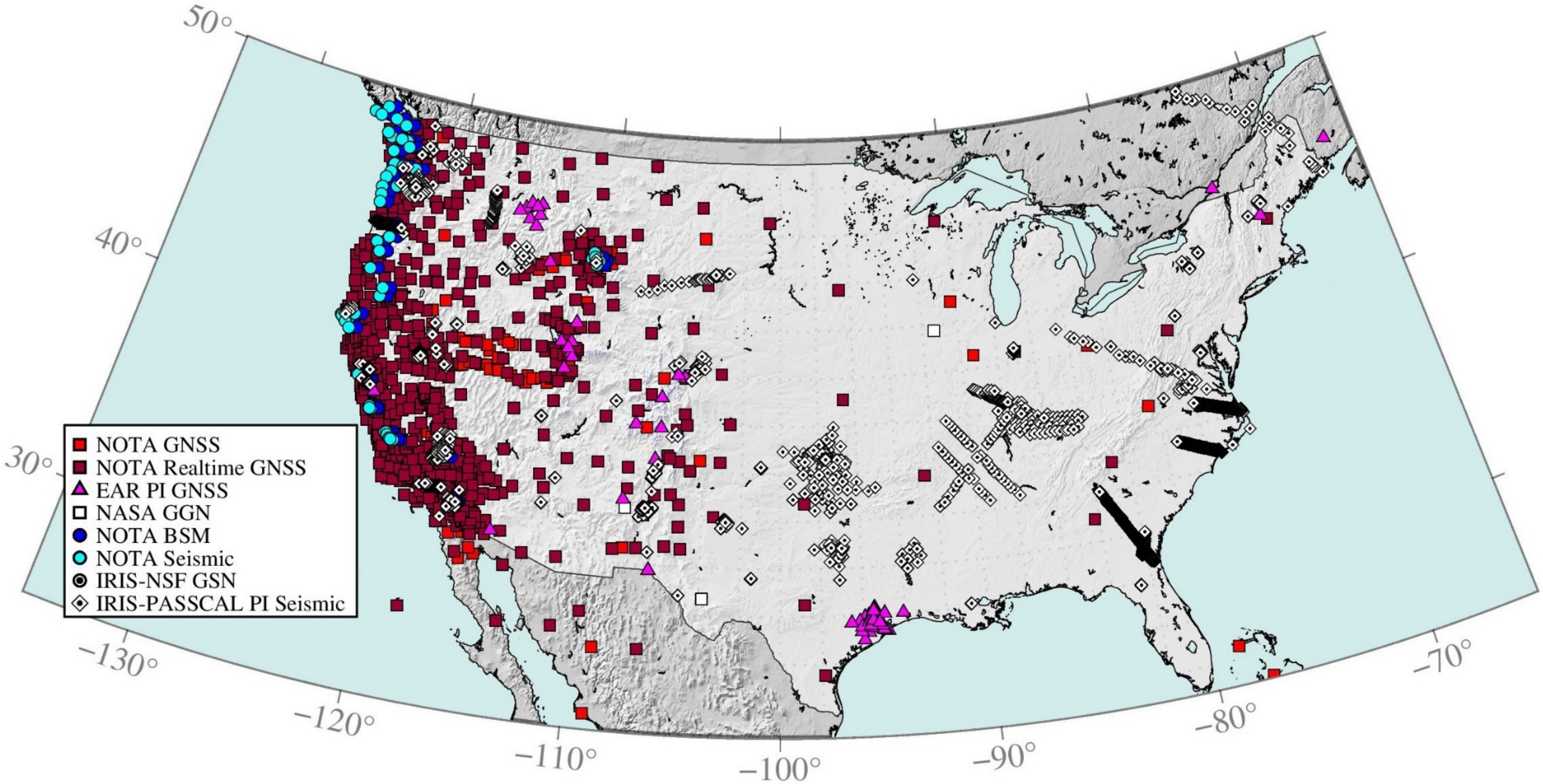
Owing to its continental-scale geographic scope and variety of instrumental features, many types of investigations are possible given the EarthScope facility resources. The blend of seismic and geodetic instruments sought to take advantage of a natural complementarity between the period bands of broadband seismology and velocity sensitivity of geodesy (see Seismogeodesy Box in Chapter 4). While the diversity of instrumentation is a strength that has resulted in a rich set of discoveries, it poses challenges for the operation and optimization of the networks that are distributed over great distances (Figure 5.1). To address these challenges, the facilities have adapted to efficiently manage the instrumentation, logistics and data services needed to satisfy scientific requirements.

In this section, we provide an overview of the existing technology and instrumentation prioritized in the recommendations chapter (Tables 5.1 and 5.3 and Figure 1.3). We generally limit our discussion here to on land systems. We follow the nomenclature and distinction of Aster and Simons (2015) and refer to existing or foundational observational capabilities. They distinguished foundational as existing or emergent capabilities. Existing foundational capabilities are fundamental to present and near-term science directions, including the continuation of currently funded NSF projects. Emergent foundational capabilities incorporate current technologies that would drive significant progress on major science challenges and are high priority for the next five years. Emergent and frontier (nascent, but demonstrate potential) technologies will be discussed in Chapter 6 (Figure 1.3). All of these tools require professional staff support, data management consistent with the FAIR principles (Wilkinson et al., 2016), and computational tools for interpretation.

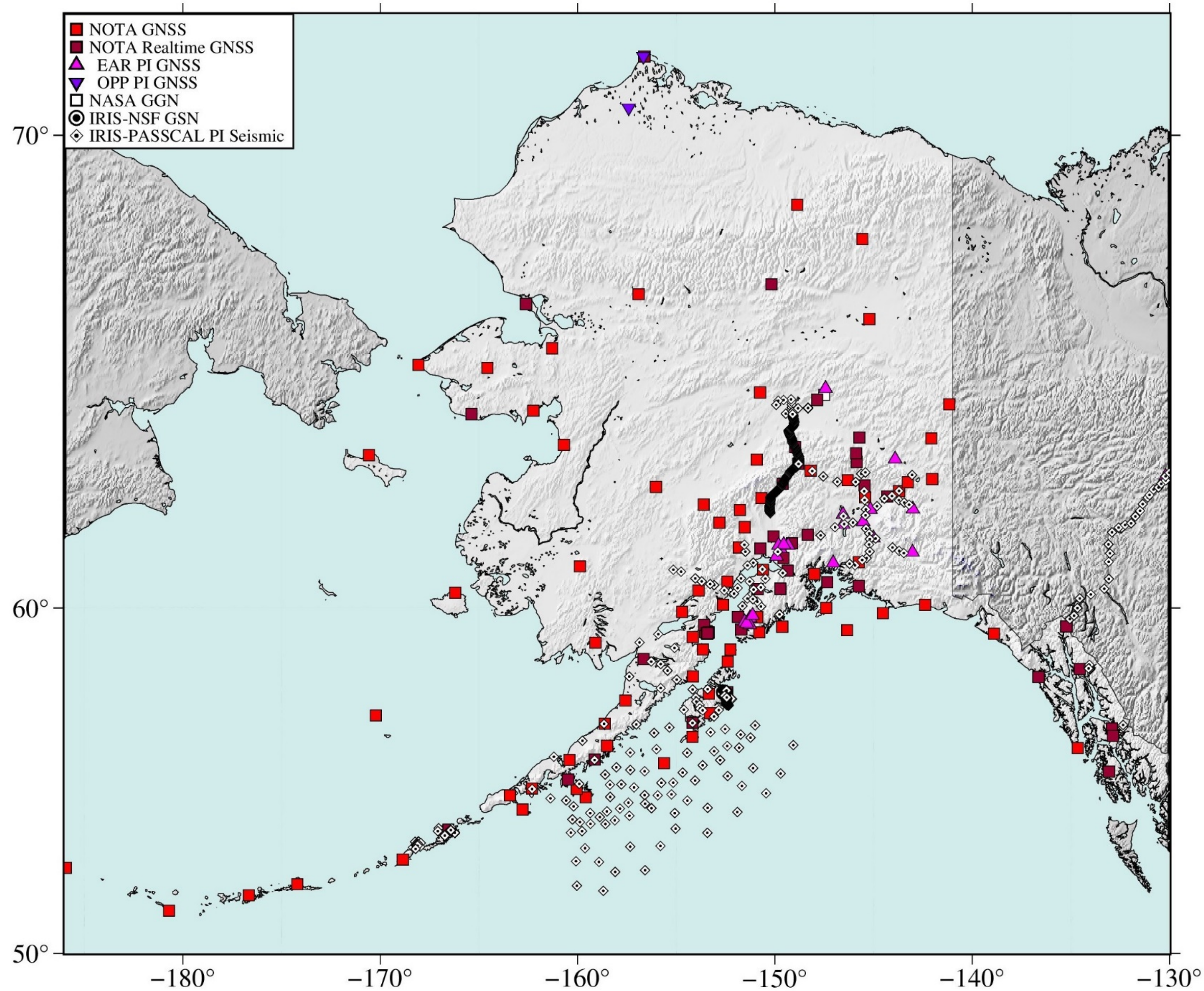
Because our overall focus in this report is on instrumentation, we present relatively little discussion about the specifics of data products that are provided by the facilities to the community. This was done despite the obvious difficulty of separating the value of instruments from the data products they provide, which have a direct impact on the science. The committee deliberated under the impression that review of data products will be undertaken elsewhere.



NOTA GNSS (n=1228)
NOTA Realtime GNSS (n=960)
ANET (n=33)
GNET (n=42)
NASA GGN (n=58)
EAR PI GNSS (n=328)
OPP PI GNSS (n=57)
NOTA BSM (n=83)
NOTA Seismic (n=82)
IRIS-NSF GSN (n=39)
IRIS-PASSCAL PI Seismic (n=22,781)



NOTA GNSS
NOTA Realtime GNSS
EAR PI GNSS
NASA GGN
NOTA BSM
NOTA Seismic
IRIS-NSF GSN
IRIS-PASSCAL PI Seismic
50°
40°
30°
−130°
−120°
−110°
−100°
−90°
−80°
−70°


NOTA GNSS
NOTA Realtime GNSS
EAR PI GNSS
OPP PI GNSS
NASA GGN
IRIS-NSF GSN
IRIS-PASSCAL PI Seismic
70°
60°
50°
−180°
−170°
−160°
−150°
−140°
−130°

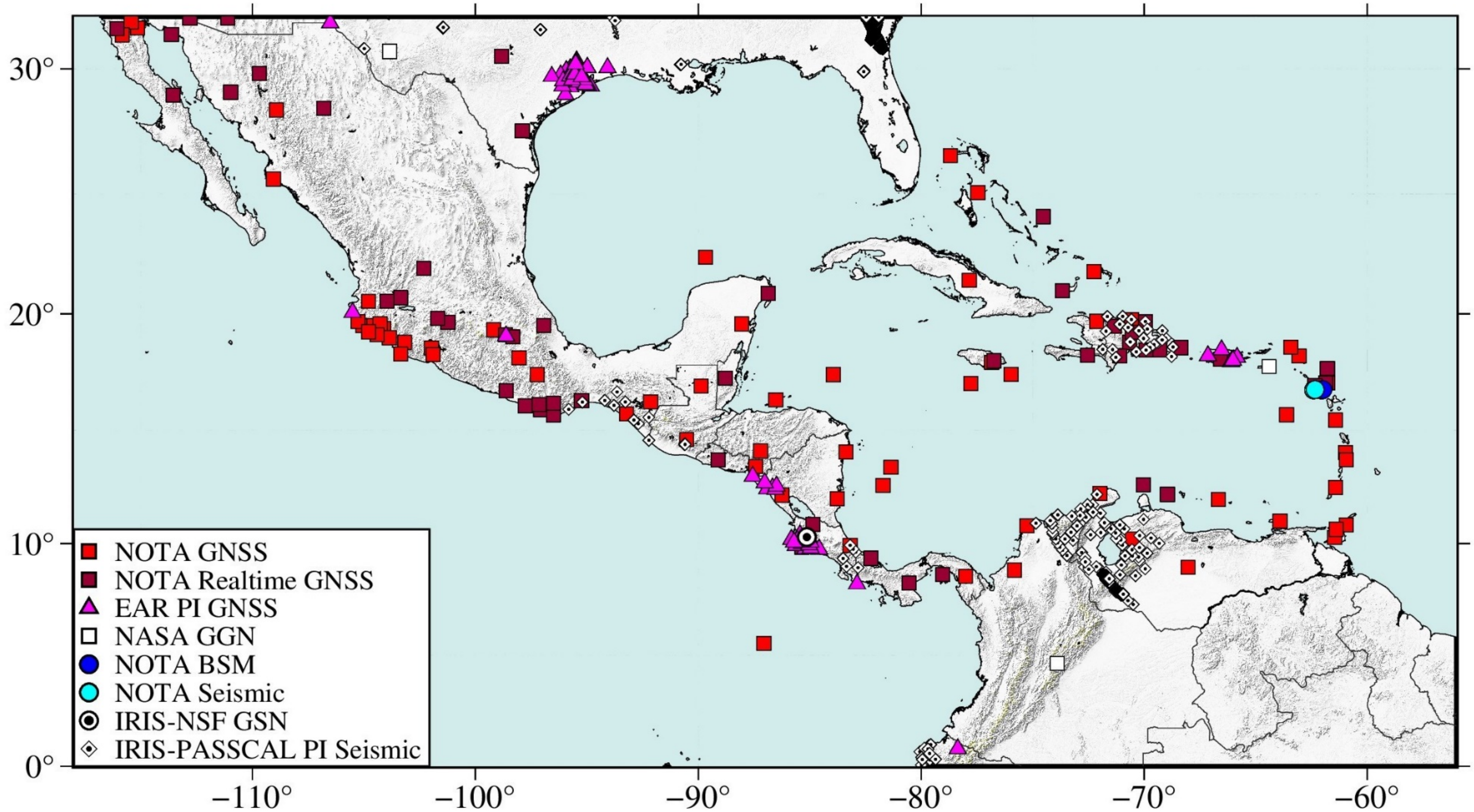

30°
20°
10°
0°
−110°
−100°
−90°
−80°
−70°
−60°
NOTA GNSS
NOTA Realtime GNSS
EAR PI GNSS
NASA GGN
NOTA BSM
NOTA Seismic
IRIS-NSF GSN
IRIS-PASSCAL PI Seismic

Figure 5.1 (prior pages). Geophysical networks globally, Alaska, US lower 48, and Mexico/Central America/Caribbean supported by NSF. Maps show geophysical stations that are or were recently operating continuously and are currently or recently funded by NSF EAR or OPP. The global map includes ~23,000 PI-led seismic station deployment locations (last 5 years) with data in the IRIS DMC. The NASA GGN is a critical component in the GAGE Facility. In some cases, the NASA GGN and NSF-EAR GSN have colocated stations in which power and telecommunications infrastructure are shared. The EAR and OPP PI Networks are not "projects" but are continuously operating GNSS stations whose metadata management, data flow, and archival of raw and processed data are managed by UNAVCO using GAGE resources. These data are freely and openly available in near-real-time to the community, so while they are not part of NOTA, ANET, GNET, or the NASA GGN, and the funding to build them was from individual PIs who obtained awards from EAR or OPP, they reflect continuous geodetic infrastructure.

The Alaska map includes Ocean Bottom Seismometers that were a part of the AACE (Alaska Amphibious Community Experiment) of which PASSCAL instruments were used for the land-based observations. The off shore stations are in the same experiment network code. PASSCAL did not install those stations, but contributed stations on the land side (Kodiak and beyond).

Relevant acronyms include (see also Chapter 9):

ANET=Antarctic (GNSS) Network
DMC= Data Management Center
EAR=Earth Sciences Division, Geoscience Directorate, National Science Foundation
GNET=Greenland (GNSS) Network
GNSS=Global Navigation Satellite System (includes GPS, GLONASS, Galileo, etc.)
IRIS EAR-GSN=IRIS EAR portion of Global Seismic Network
NASA GGN=NASA Global GNSS Network
NOTA=Network of the Americas
OPP=Office of Polar Programs, National Science Foundation
PASSCAL=Portable Array Seismic Studies of the Continental Lithosphere
PI=Principal Investigator

The data used to produce these figures were provided by IRIS and UNAVCO. The figures were made using Generic Mapping Tools (GMT: https://www.generic-mapping-tools.org, Wessel et al., 2019) by C. Puskas, UNAVCO, with data compiled and reviewed by UNAVCO (F. Blume, K. Feaux, M. Gottlieb, K. Hodgkinson, J. Normandeau, and J. Pettit) and IRIS (K. Anderson and K. Hafner); the final figures were reviewed by G. Mattioli (UNAVCO).

5.2 Existing Foundational Capabilities: Seismology

5.2.1. Kinds of measurements and instruments

Seismology is the study of vibrations in the Earth, the sources of these vibrations and the structures they travel through. Through seismology, scientists study earthquake processes, image faults, map the deep Earth's interior and monitor natural hazards. Because seismology can take advantage of any sources that send elastic waves propagating through the Earth, seismological tools have been further expanded to study and monitor a variety of other phenomena, including nuclear and volcanic explosions, glaciers and ice sheets, landslides, and river sediment load transport and debris flow.

5.2.2. Permanent and deployable seismic systems

Both global and regional seismic networks are crucial for advancing understanding of broad-scale geophysical processes. They also provide essential framework for targeted PI-driven studies using complementary instrumentation to investigate more localized processes. Table 5.1 summarizes the sensors and instrumentation currently available at PASSCAL.

The Global Seismographic Network (GSN) is a 152-station global network providing data for basic research in global seismicity and Earth structure, earthquake location and characterization, tsunami warning and nuclear test monitoring (Figure 5.1 and Table 5.1). Through IRIS and the University of California San Diego, NSF-EAR provides operational support for 40 stations. The USGS operates 99 of the GSN stations and the remaining 13 are operated by other entities. These stations provide high-quality, multi-sensor data used by a wide group of scientists. Each site includes Very Broadband (VBB), secondary broadband, and strong motion seismic instruments, with a number of ancillary sensors (microbarograph, infrasound, GPS, geomagnetic, and meteorological packages) also being recorded. These data are all sent in real-time over robust telemetry links and are available to the seismological community through the IRIS DMC. Data quality and reliability are high from these sites, and they have served as monitoring and research backbone for decades. The GSN has recently undergone a notable recapitalization to modernize equipment and ensure high quality data.

NSF-EAR also supports considerable temporary (campaign) seismological and related instrumentation through the IRIS Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) Instrument Center (Table 5.1). PASSCAL has a large pool of broadband (~0.01-25 Hz), intermediate band (~0.025-50 Hz), and short-period (1-100 Hz) seismometers, as well as high-frequency geophones ("Texans", 4.5 Hz and 40 Hz cabled) and accelerometers. PASSCAL also hosts associated dataloggers to digitize the sensor data and power systems and telemetry for campaign deployments. Also of note are the relatively recent acquisition of thousands of "all-in-one" nodal seismometers ("nodes") that contain both sensing and digitizing equipment, along with positioning and power-source in one small, easily deployable package. PASSCAL also performs a number of related activities, such as instrument and deployment training, shipping, and experiment scheduling.

Table 5.1. Existing seismology instrumentation in SAGE. Notes on usage and deprecations culled from facility interviews and reports. Note 1 for the GSN is Ringler et al., 2020.

SAGE Instrumentation	Existing	Notes on Age and Deprecations	Notes on Usage
Global Seismic Network (GSN)	152 stations, 40 NSF-supported through SAGE	Currently, recapitalization of vault sensors in progress; new recapitalization requirements in 10-15 yrs	GSN data usage turnover (percentage of total data holdings shipped annually) was 500% in 2018, highest across all IRIS DMC holdings[1]
Portable Broadband Seismometers and Dataloggers	1014 (includes intermediate period sensors)	Dataloggers need replacing, and are past end of life (up to ~900/1500 units); many sensors (up to ~500/1014) are not designed for portable use, need replacing	Typically fully subscribed
Nodes (5 Hz, 3-component autonomous sensors+digitizers)	2400	Newer instruments (all <5 yrs old); predicted 10 yrs+ lifespan	Fully subscribed up to 2-3 years in advance
Rapid response kits; including multi-sensor rapid response packages with seismic and geodetic capability	20 BB, 20 SP/compact BB, 200 nodes, 10 infrasound, 10 strong motion	Newer instruments (all <5 yrs old); predicted 10 yrs+ lifespan	New equipment. Usage TBD, but likely highly subscribed before/after hazardous events
DAS	0	--	--
Seismic Source Facility	Experiment design and permitting, A200 (P- and S- wave truck-mounted source), small and large explosives	A200 source is new	Supports ~1 large explosive project/year, ~2-3 A200 projects/year, proposal development (5-15 proposals/year), technical consultation and virtual support
Magnetotelluric (MT)	100 new instruments coming online 2021	New instruments; predicted 10-15 yrs+ lifespan	Unknown
Short Period Seismometers	200	Rugged, in good shape and repairable	Used mostly as back up
GPR and Multichannel	1 GPR, 20 Multichannel systems	Rugged, could be used for decades	Predicted increase in GPR use particularly for urban geophysics courses; multichannel systems fully subscribed, mostly in educational purposes
Texans (obsolete, single-channel instruments)	2700	No longer supported, phased out by 2021	No longer supported, phased out by 2021

In the last five years, PASSCAL has taken over the magnetotelluric (MT) facility from the Oregon State University facility that was established under EarthScope. Current MT system use is as semi-continuous campaign deployments, filling in lower-48 state US EarthScope coverage. PASSCAL is in the process of procuring ~100 new instruments in anticipation of the facility evolving to a temporary, PI-based experiment model (Table 5.1). The PASSCAL MT program plans to leverage existing expertise in managing, housing, servicing and shipping instruments and in data quality control, management and archiving through IRIS data management services. The program is nascent and PASSCAL is evaluating long-period and wide-band systems, developing training and instrument specification and protocols for data handling, archiving and processing.

5.2.3 Connections to the science questions and challenges

Seismic instrumentation plays a central role in addressing many of the priority science questions identified in the Earth in Time report (see Table 5.2 for question numbers). The GSN and deployable broadband instruments are the backbone for much of global-scale imaging using tomographic, reflected-wave, or scattered-wave approaches. Very broad band instruments, which benefit from the quiet installations offered by GSN sites, enable observations of free oscillations crucial for mapping large-scale density variations. The resulting constraints on variations in temperature and composition, and the distributions of melt and volatiles inform reconstructions of plate subduction history (2), mantle dynamics (2), critical element cycling (3), upwellings associated with volcanic hotspots (5), lithospheric structure influencing seismicity, deformation, and magma movement (4, 5), as well as conditions in the deep mantle and core intimately tied to geodynamo processes (1). Crucially, they also inform inferences of rheologic properties of the upper mantle and dynamic topography due to mantle flow, which are crucial for estimating ice-loss resulting from global warming (8) and understanding topographic changes (6). Deployable short-, intermediate-, and broad-band seismometers, enable rapid data acquisition in wake of significant earthquakes, seismic swarms, and heightened volcanic activity (4, 5), and for monitoring fluvial bed-load transport and turbulence (9). They also enable high-resolution imaging of crustal structure, mapping potentially seismogenic faults (4), volcanic plumbing systems (5), and quantifying amplification of ground shaking by basin structures (12). Short-period instruments and geophone multichannel acquisition systems are particularly well-suited for probing structure at smaller scales, such as across the critical zone (7). Some of the clearest images at these scales come from methods utilizing active source approaches, facilitated by the active source facility.

Together with geodetic networks, seismic networks are indispensable for geohazards science. They are used to monitor temporal changes in subsurface properties related to the hydrologic cycle and groundwater depletion/recharge (9). Volcano monitoring seismic networks establish baseline conditions and map out seismic activity accompanying both pre-, syn-, and post-eruptive processes, and are a key ingredient in eruption forecasting (12). Permanent high-quality networks such as the GSN, provide real-time data crucial for detecting and characterizing damaging earthquakes – with strong motion instruments enabling accurate recording strong ground shaking – and identifying tsunamigenic potential (12).

Table 5.2. Numbers of key science questions articulated in the National Academy of Science report "A Vision for NSF Earth Sciences 2020-2030: Earth in Time" by the Committee on Catalyzing Opportunities for Research in the Earth Sciences (Earth in Time Report). See sections 5.2.3 and 5.3.3.

1	How is Earth's internal magnetic field generated?
2	When, why, and how did plate tectonics start?
3	How are critical elements distributed and cycled in the Earth?
4	What is an earthquake?
5	What drives volcanism?
6	What are the causes and consequences of topographic change?
7	How does the critical zone influence climate?
8	What does Earth's past reveal about the dynamics of the climate system?
9	How is Earth's water cycle changing?
10	How do biogeochemical cycles evolve?
11	How do geological processes influence biodiversity?
12	How can Earth science research reduce the risk and toll of geohazards?

5.2.4 Technology evolution: where are we now, what are new developments to be expected in this area in the next decade?

The aforementioned seismological instrumentation is able to sense elastic waves over a broad range of periods and scales, and related processing of these data permit detailed insight into the seismic sources, earth structure, and response at the site where they are sensed. Very broadband sensors are able to accurately record signals with periods out to hundreds of seconds and measure Earth's free oscillations as well as the tides. Broadband and intermediate period sensors have been the backbone of a wide variety of seismological studies: from determining Earth structure through teleseismic and local earthquakes studies, characterizing aftershocks, imagining volcanic plumbing systems, investigating earthquake source properties, and a multitude of other applications. Relatively quick, posthole installations of these instruments have reduced deployment time while still providing high-quality data. Broadband sensors are becoming smaller, more portable, easier to deploy, and use less power. These trends are expected to continue in the next decade. Rotational seismometers have been utilized in the past 10 years and provide a unique view of the seismic wavefield not captured by traditional sensors.

The proliferation and advancement of nodal seismometer capabilities has permitted numerous "Large-N" deployments that provide very dense sampling of the seismic wavefield not attainable with traditional seismic deployments. These instruments are now rugged and can operate unvisited for weeks, and many are now 3-components with an improving low frequency response. It is expected that nodal systems will continue to improve in the coming decade. Lower frequency response, longer battery life, and real-time telemetry are all in development. Deployment of nodes via UAS is also being explored and may allow deployments to previously inaccessible regions. Subsequent processing of nodal seismometer datasets has given detailed views into earth structure and seismicity previously unavailable, and this is expected to continue in the future.

Distributed Acoustic Sensing (DAS) instruments have provided tantalizing views into recording the seismic wavefield and studying seismic sources. A single fiber-optic cable can provide Large-N-style capabilities similar to those from nodal deployments, but with an improved frequency response and sensitivity. The transformative potential of DAS applies to a wide range of sources and environments (including off-shore), and the seismic community is making rapid advances on how to utilize these instruments. The extremely large DAS datasets present a considerable challenge, as do issues of calibrations, repeatability, and deployment feasibility. DAS also only records a single chain of strain, so polarization-based analysis commonly applied to 3 component data will be limited. See the DAS box and Chapter 6 for more.

5.2.5 Complementary or relied upon systems

NSF-EAR currently supports the Seismic Source Facility (SSF), operated by IRIS through a subaward to the University of Texas at El Paso. The SSF provides specialized support for explosive and other controlled-source seismic experiments for investigating Earth structure from the near surface to the deep crust and uppermost mantle. The supported controlled-sources currently include small, near-surface imaging devices (seis-gun, pneumatic hammer, small explosives, recently acquired P- and S-wave truck-mounted source). Funding for large, crustal imaging explosives and technician time during the experiment is currently provided through individual research grants. The SSF provides logistical and engineering support for experiment design and permitting for all source types.

NSF-EAR (through IRIS-Education and Public Outreach) also maintains near-surface geophysical equipment for ground-penetrating radar and high-resolution, shallow seismic studies. These include one GPR set up and 20 multichannel seismic recording systems (Geodes). These instruments are highly subscribed in support of college and university courses and for other educational and outreach purposes. The multi-channel seismic equipment also supports near-surface seismic imaging research.

5.2.6. Facility-related issues including status/age of existing NSF-supported systems

Notably, the majority of the sensors and dataloggers in the PASSCAL instrument pool were purchased at least 10 years ago, and some of them almost 30 years ago (Table 5.1). The associated dataloggers used with these instruments have a similar age. These sensors and dataloggers are no longer sold or supported by the manufacturers, and are maintained and repaired by PASSCAL technicians using spare parts. A critical need exists for recapitalization of these systems. The nodal systems are a notable exception as they have all been purchased in the past four years; their 10 year expected lifespan projects to a need for recapitalization in the 5-10 year timeframe. Community interest in the nodal systems has also been very high, and this portion of the pool is currently oversubscribed. This creates delays in deployments and, at times, loss of critical data collection. The high-frequency Texan geophones are being removed from the PASSCAL pool and will be “replaced” with the nodal systems.

5.2.7. Connections to other programs and agencies

NSF-EAR supported data are used by a variety of other programs and agencies. First and foremost, all NSF-EAR supported data are to be uploaded to the IRIS DMC where they are freely available to the community for use. The IRIS DMC estimates roughly 40-50% of the data downloads are from .edu domains, which can be viewed as a minimum as some academic users may use a non-.edu domain. Approximately 20-30% of the NSF-EAR data usage comes from commercial domains, and 5-10% are from US government domains. This demonstrates clear interest in and usage of NSF-EAR data by those funded via other means. Of particular note in its non-EAR use is the jointly-operated GSN. This network is critical for earthquake, tsunami, and nuclear explosion monitoring, from regional to global scales. Multiple U.S. (e.g. USGS, NOAA) and international (e.g. CTBTO) agencies rely on these data to meet their hazard monitoring missions. While the U.S. government usage is aligned with their hazard and research missions, the commercial usage is not clearly understood and tracked at this point. International usage of these NSF-EAR resources is also common, and likely represents a mix of academic, government, and, and commercial interests.

5.3 Existing Foundational Capabilities: Geodesy

5.3.1 Kind of measurements and instruments

Geodesy is an ancient study that addresses the shape of Earth, its size, rotation, geometry, and gravitational field and how these properties change over time owing to active physical processes. In some ways geodesy is similar to seismology, but the discipline has traditionally tended to focus on the much slower or permanent deformations, such as those impacting the large parts of the planet; for example, tides, moment of inertia, tectonic plate movement, loading from glaciers or mantle flow. Over shorter temporal scales, similar to seismic instrumentation, geodetic techniques can provide actionable information on geohazards such as earthquakes, landslides, ground subsidence, volcanos, and even atmospheric or ionospheric phenomena. New earthquake and tsunami early warning systems incorporate Global Navigation Satellite Systems (GNSS), providing a more rapid solution of earthquake magnitude and location than seismic sensors.

In recent decades, the field has been revolutionized through the advent and proliferation of space geodetic systems including GNSS which provides ubiquitous precise positioning capability for users everywhere on Earth, as well as radar interferometry and more recently geodetic imaging. GNSS systems have the advantage of providing three-component locations in a global frame of reference making it possible to meaningfully compare measurements from stations separated by thousands of kilometers. Unlike seismic instruments, GNSS geodesy measures displacement directly and so can access the infinite period band where permanent, static displacements or slow steady motion can be readily detected and analyzed. As the techniques and technologies have improved, GNSS geodesy has become more intertwined with seismology and can even measure displacements caused by seismic waves from large earthquakes at 1 Hz sampling. The complementarity and overlap between seismic and geodetic techniques from an instrumentation and science perspective are discussed explicitly in Chapter 6 (see the box on Seismogeodesy).

The national and global proliferation of GNSS sensors; for example, the Plate Boundary Observatory (now Network Of The Americas (NOTA)), has greatly expanded the utility of these observations to studies of the atmosphere, hydrosphere and cryosphere. Previously noise for geodetic studies of active tectonic and magmatic processes, researchers are now using multipath signals (i.e., signals reflected off surfaces before being observed) to quantify soil moisture, snow depth, and vegetation or measure the elevation of the sea surface. GNSS signals must travel through the earth's troposphere, which is laden with moisture and slows the signals. Again, this is a source of noise for solid Earth studies, but important observations for weather and climate scientists. The COCONet (now part of NOTA) network was partially designed to improve the forecasting of hurricanes by estimating wet tropospheric path delays.

Owing to the balance of current assets in the geodesy instrumentation portfolio owned by NSF EAR, the relatively high utilization of these assets, and the recommendations made in this report, the technology discussed in this section is strongly biased toward GNSS systems and networks. There are however other geodetic technologies owned and operated by GAGE, and others that are utilized by the NSF EAR community. These include borehole strainmeters that are part of the former PBO network, and geodetic imaging in the form of terrestrial laser scanning and small uncrewed aerial systems (sUAS). The facility provides SAR data through the WInSAR consortium. We provide some discussion of these instrumentation assets below, while some other technologies which are not currently supported but are within the realm of EAR scientific concern are discussed in Chapter 6.

Table 5.3 Existing instrumentation in GAGE. Notes on age and deprecation are derived from facility interviews and reports.

GAGE Instrumentation	Existing	Notes on Age and Deprecations	Notes on Usage
Network of the Americas (NOTA)	1241 (number will be reduced to 1137 by end of GAGE2)	67% of receivers are > 5 years old; 72% will be at End-of-Service (EOS) or End-of-Life (EOL) by end of GAGE2	132,000 users (unique IP addresses) over past five years
Portable GNSS Pool	20	Most are non-GNSS	Number represents kits ready to deploy. Additional systems can be assembled quickly if needed and no PI request has gone unfulfilled in recent years.
Borehole Stations[1]	74		
Tiltmeter	15 with data available 13 reported by facility 8 have up-to-date time series + 6 spares	Functioning	2497 users over past five years
Strainmeter	4	EOS	4496 users over past five years
Seismometer	88 installed or planned; 12 spares	EOS	6394 users over past five years
Tide gauge stations (including multiple GNSS antennas, sea surface radar recorder and pressure sensor)	2	See NOTA for GNSS component	Data shared via UNESCO-IOC tide gauge archive. Download statistics unavailable.
UAS	6	Modern Instruments	50% usage during first quarter 2020
TLS instruments	8	7 are modern instruments; 1 is ready to be deprecated	62.5% usage during first quarter 2020

[1] Borehole stations also contain other components including Q330 and Q330S+ seismic digitizers, Marmot data loggers, and Basalt digitizer/data loggers. All but one of these instruments are at end-of-service.

5.3.2 Permanent and temporary deployments of GNSS equipment

GNSS equipment is deployed through both permanent (continuous) and temporary (campaign or episodic) station installations. The continuous networks include the Network of the Americas (NOTA), currently funded through GAGE, and PI-funded sites (Table 5.3 and Figure 5.1). The continuous and campaign networks are complimentary, with the continuous sites providing more detailed information on time-varying processes and serving as a backbone of deformation data and the campaign sites providing spatially dense data in focus areas. The key components of these systems are the GNSS receivers and antennas, but both continuous and campaign stations also depend on a variety of auxiliary equipment. Continuous stations include an antenna mount that is attached to bedrock or driven/drilled into the ground, an electronics enclosure, a power system usually consisting of a battery bank and solar panels, and usually, but not always, a communications system (see below). The stations can and are sometimes augmented with accelerometers for EEW research and weather stations. Campaign systems include a portable antenna mount, a portable power system usually consisting of a battery and sometimes a small solar panel, and a case that holds the receiver during deployment and transports both the receiver and antenna. Besides a permanently installed benchmark, campaign stations have little infrastructure. Equipment is generally deployed over a period of days to weeks or months.

GNSS systems are usually deployed in networks with multiple stations recording data (raw data are recorded typically at 1 Hz and 30 s) simultaneously so that differences in station motion over time can be tracked and used to infer properties of active processes. Network design is a key element of GNSS station deployment that is driven by scientific targets. For example, configurations will differ for studies of processes related to fault slip rates, earthquakes, magmatic systems, landslide tracking, continental tectonics, glacial or hydrological loading. In some cases, the primary science targets require information on horizontal crustal strain while others are primarily concerned with vertical ground motion. A typical deployment for a single PI-driven project to study a fault, earthquake or volcano could use ~20 instruments, but as little as one can be useful because the results can be aligned to the global reference frame determined by the global network of continuous stations.

5.3.3. Synthetic Aperture Radar (SAR)

Satellite-based SAR data provides blanket coverage of large swaths of Earth surface and are especially valuable for parts of Earth where GPS networks are sparse or non-existent. The SAR data contain both amplitude and phase images. Amplitude images provide information about properties and features of the Earth's surface and, when two images are compared, surface deformation. Synthetic Aperture Radar Interferometry (InSAR) is a technique where pairs of radar phase images are processed together to measure displacement of the ground from landslides, earthquakes, volcanic deformation, subsidence and aquifer deformation, and other solid Earth processes. While SAR data is not directly collected by NSF geophysical facilities, EAR-supported science benefits from these data and has led the GAGE facility operator UNAVCO to host and support activities of a consortium of InSAR users. This group, the Western North America InSAR Consortium (WinSAR) coordinates data distribution, software and data services training courses, and promotes utilization of the data for scientific discovery. With NASA's NISAR mission scheduled to launch in 2022 (https://nisar.jpl.nasa.gov) there will be a new stream of data with free and open access that will benefit EAR science goals. The future will see technique improvements including better coping with error sources and more systematic integration of InSAR analysis with GNSS data.

5.3.4. Borehole strainmeters

Borehole strainmeters (BSMs) are extremely sensitive devices that are emplaced in deep (~100-250 meters below the surface) and quiet environments. These instruments have sufficient sensitivity and coupling to the surrounding rock that they respond to changes in hole dimensions that result from geophysical processes. Phenomena that can be detected include passing seismic waves, but also strains occurring over longer period ranges (days to months) from changes in nearby volcanic and hydrological features, surface load changes from the atmosphere and hydrosphere, and aseismic and transient fault slip. While they are classified as geodetic technology because they directly sense changes in Earth shape over time at high sampling rates, they could be more accurately described as a hybrid between seismic and geodetic systems that extends the sensitivity band to address a gap in the observation spectrum left by other instruments (See Box on Seismogeodesy in Chapter 4). The borehole instrumentation installed as part of the Plate Boundary Observatory has fewer users than GNSS (Table 5.3), but is still valuable because it provides an independent and much more sensitive observational constraint that cannot be obtained any other way.

During the original installation phase of the NSF EarthScope Plate Boundary Observatory, a network of BSMs was installed along the Pacific-North American plate boundary. The boreholes are grouped into arrays that target tectonic and magmatic processes in Cascadia, Yellowstone, Mount St. Helens, the Mendocino triple junction, and San Andreas fault system. The BSMs installed were four-component Gladwin Tensor Strainmeter (GTSM). Many of the PBO installations included barometers, a three-component short-period seismometer; some also include pore-pressure transducers, accelerometers, and tiltmeters. Of the original complement there are 87 BSMs still operating at over 90% up time. The instruments have not changed specification since installation. Many of these down-hole instruments are past end-of-service and are approaching end-of-life but are not designed to be recovered or replaced. Based on community prioritization, these instruments are maintained, mostly by maintaining data communications. Interruptions to data flow are commonly due to communications problems, even while the instruments continue to record useful data, which often may be recovered later.

5.3.5 Laser scanning and photogrammetry-based geodetic imaging

Geodetic imaging uses electromagnetic waves at radar and optical laser frequencies and photogrammetry to quantify meter to centimeter-scale positions and motions at the Earth's surface from less than a square meter to hundreds of square kilometers. The SAR section above (5.3.3) addressed spaced-based radar contributions to geodetic imaging. Other technologies that have been part of a revolution in Earth imaging are laser scanning and photogrammetry. These systems provide truly 3D measurements of the Earth surface and the overlying vegetation and built environment. Laser scanning (Light Detection And Ranging - lidar) is used most often as time of flight ranging, but some short range interferometric based approaches can be employed. Photogrammetry and its recent incarnation as "Structure from Motion" use matched features in many photographs taken from different positions as the basis of the computation of scene structure. Satellite, airborne, and mobile and fixed terrestrial platforms are employed (see some review of the robotic platforms in the Robotics box of chapter 6). The fundamental data products are 3-dimensional point clouds that include attributes such as laser return intensity or RGB color.

Their spatial sampling can be from less than one to 1000s of points or more per square meter. Derived products include digital elevation models and orthoimagery in 2D and 3D meshes, sometimes with texture. When combined with GNSS absolute positioning and inertial navigation, the resulting dense point clouds may have cm- to dm- global accuracy.

Geodetic imaging is fundamental for mapping and feature identification; landscape reconstruction; surface process interactions with tectonic, volcanic, cryospheric, ecological processes; and differencing of repeat surveys, which directly measure 3D displacements. These tools are essential parts of the geodetic toolkit and enable scientific investigations emphasizing surficial processes highlighted in the questions of Table 5.2. The high spatial sampling and accuracy provide powerful direct measures of object positions as well as a base on which many other observations and samples can be located. The potential for point cloud classification in particular of actively sensed lidar derived data enables virtual removal of vegetation and production of Digital Terrain Models which form the basis of many surficial geology and process maps. It is often possible to reconstruct landscapes deformed by tectonic, volcanic, cryospheric, and landslide processes as well as those altered by erosion and sedimentation at the appropriate fine spatial scale of the operational processes using topographic data. Topography (especially its derivatives—slope and curvature as well as watershed properties) is a fundamental driver of surface processes and so it is an essential ingredient in the establishment of transport laws and advancing understanding of surface process interactions with other phenomena (tectonic, volcanic, cryospheric, ecological). Finally, differencing of repeat surveys is a powerful capability for directly measuring vertical changes due to erosion and sedimentation (as well as vegetation change and anthropogenic changes) and computing 3D displacements, rotations, and strains. These determinations can be made from differencing of derived raster products or direct computations on the point clouds. Going from positions to displacements is critical for understanding many processes (see co-seismic fault displacement image in the Robotics box 6.2).

NSF-EAR support for geodetic imaging includes the 6 sUAS systems and 8 terrestrial laser scanning systems managed by UNAVCO in the GAGE Facility (Table 5.3). In addition, the National Center for Airborne Laser Mapping has provided high quality data acquisition for many EAR projects for the community (e.g., B4 and EarthScope, and post-earthquake and fire response), for PI projects, and their laudable student seed projects. These data are distributed openly through the OpenTopography project (also NSF-supported). Numerous polar related geodetic imaging efforts are supported by NSF including several at UNAVCO and satellite photogrammetry through the Polar Geospatial Center. The NSF funded Community Response to Volcanic Eruptions (CONVERSE) RCN has a UAS component. The NSF Rapid Facility at the University of Washington (https://rapid.designsafe-ci.org/equipment-portfolio/) and the Air CTEMPS activity at Oregon State University and University of Nevada Reno (https://ctemps.org/uas) are related activities. Community coordination through American Geophysical Union hosted town halls has also identified broad interest in robotic platforms supporting much science including geodetic imaging. See the Robotics box of chapter 6 for additional forward-looking ideas in enhanced capabilities for geodetic imaging including new sensors, swarms of platforms, and greater reliability and autonomy.

5.3.6 Connections with science questions and challenges

Geodetic instrumentation also directly informs many of the priority science questions identified in the Earth in Time report (see Table 5.2 for question numbers used below). They address the same sets of questions as seismic instrumentation but in different ways. Modern geodetic networks of continuously recording GNSS stations now provide precise positioning (mm precision) and can capture changes in positions with time, providing invaluable insight about a wide variety of active Earth processes. Tracking GNSS station locations has provided maps of the active crustal strain accumulation across plate boundary zones, elucidating the natural processes that underlie the observed geologic, tectonic and seismic hazard framework in unprecedented detail. These constraints lead to understanding of the kinematics and dynamics of continental deformation on scales from slip rates on individual faults to the balance of stresses in the lithosphere from gravitational potential and plate boundary tractions (2, 4, 6, 12). Vertical motion reveals the contemporary signature of strain accumulation and locking in subduction zones and mountain building in uplifting belts. Continuously recorded data has allowed the discovery of previously unknown transient events such as slow slip events along subduction plate interfaces (4, 12) and has allowed detailed analysis of postseismic motion that provide robust estimates of rheological parameters in the lower crust and mantle (2, 4, 12). Continuous networks have also revealed details about how volcanic systems change leading up to, during and after eruptions and offered opportunities to track volcanic ash plumes in the atmosphere (5, 6, 12).

Networks with stations near the coastline are increasingly valuable for constraining vertical land motion from natural and anthropogenic processes which can exacerbate or mitigate the impact of sea level rise (6, 8, 9, 12). Networks have captured the effects of past ice on the solid Earth as well as the impacts of rapid present day ice loss (6, 8, 9). Also related to the water cycle, GNSS networks have revealed patterns and causes of uplift and crustal strain related to large scale drought, aquifer or geothermal reservoir depletion, hydrocarbon extraction, seasonal change of the terrestrial hydrosphere, and time varying signals related to changes in vegetation height, snow level, and soil moisture (7, 9, 11). The networks have been shown to be able to track the influx of moisture in atmospheric rivers (wet troposphere) and are used operationally in hurricane forecasts, surface loading from storms and floods, and even the small surface displacements from atmospheric pressure changes. These data have revealed, and are still revealing through ongoing analyses, the interaction of water fluxes and the cryosphere with many other components of the solid Earth system (9), some of which can influence crustal deformation and seismicity in ways that are still not fully understood (4, 12).

While campaign stations have lower temporal resolution than continuous stations, they provide increased spatial density and in some regions are the only source of data because of the difficulty, expense, or impracticality of installing continuous stations. Networks of campaign stations have provided valuable information about long-term tectonic motion (4, 6, 12), coseismic and postseismic motion (4, 12), glacial isostatic adjustment (2, 6, 8, 9, 12), and volcanic activity (5, 6, 12). Campaign networks are also easily mobilized and deployed during rapid response to events which can, and often do occur in unexpected locations.

5.3.7 Technology evolution: where are we now, what are new developments to be expected in this area in the next decade?

The frontier in geodesy continues to evolve as positioning technology has become increasingly available, sophisticated and precise. GNSS systems have evolved rapidly over the last couple of decades, and today these networks provide daily precision better than 1 mm in a global frame of reference every day, with time series duration of decades potentially. Receivers and antennas have become smaller and use much less power than previous versions. The first commercially available receivers had a single frequency and a handful of channels while today's state of the art equipment boast multiple frequencies and dozens to hundreds of channels. These advances provide greater coverage and increased positioning precision. Over the next decade, the newer GNSS systems will continue to increase the numbers of satellites available to track. Originally limited to one system (GPS), other GNSS systems have been developed by Russia (GLONASS), the European Union (Galileo), and China (BeiDou) and are now operational. Modern antennas and receivers are now able to track the satellites in multiple GNSS constellations, thus improving constraints on positions, especially for higher sample rate applications. A decade ago, a 30-second or 15-second data collection rate was the standard. With the improvements in hardware and communications, real-time (low-latency) and high-rate (1Hz or greater) data collection is now common, enabling new frontiers in research and applications, especially in societally relevant areas such as early warning from natural hazards such as earthquakes, tsunamis, landslides, volcanos and strong storms.

Improved sensor technology coupled with reduced costs have driven proliferation of GNSS networks that follow open data policies, vastly improving their geographic reach and providing a wider aperture for the imaging 'camera' of active solid Earth processes. Other state and municipal agencies operate GNSS networks for various purposes (e.g., survey control), and those data can be assimilated into GAGE facility processing. However, the GAGE-operated network is special in that it has high level instrumentation and monumentation purpose-built for Earth science research, making its results gold-standard, i.e., the most stable, complete and precise available. Furthermore, its network design has a distribution of stations focused on tectonic deformation of the Cordillera and Caribbean (Figure 5.1) which optimizes its function for Earth science like no other network. The future may hold innovations in network design to better optimize the GAGE GNSS network for science targets that were not appreciated during its original design phase. Continued engagement with this community is necessary in order to take advantage of future developments in these products.

5.3.8 Complementary or relied upon systems

The majority of GNSS and BSM sites operated by GAGE employ telemetry, which stream data back to the data center on a regular basis, with latency generally less than 1 s. In many areas these communications systems rely on cell modems, but in other regions satellite based communications such as Iridium or BGAN are required. The cost of these communications vary by type, and can be a substantial part of ongoing operation budgets for the networks overall, but are absolutely necessary to maintain stations in remote locations that satisfy science requirements. The future of global access to telecommunications is currently set to evolve with the introduction of ubiquitous satellite services such as Starlink, however prices will have to continue to fall before they become an all-network solution.

Other relied-upon systems include products that support GNSS data processing and analysis. Currently, for GAGE processing based on the GIPSY software, required analysis products are provided by the Jet Propulsion Laboratory, including files with satellite orbits, clocks, and reference frame transformation files. Other required resources include antenna calibrations, software for data formatting and product generation, and data from non-GAGE networks, all of which are maintained by other (sometimes non-US) academic or government entities. These include the underlying reference frame (International Terrestrial Reference Frame - ITRF) supported by the International Earth Rotation and Reference Systems Service (www.iers.org), with standards, agreements and products. Thus, the continued operation, quality and development of the GNSS data products produced by GAGE are reliant on the GNSS space geodesy community in a number of ways. GAGE personnel should continue to maintain awareness and involvement in the international organizations that support GNSS products.

5.3.9 Facility-related issues including status/age of existing NSF-supported systems

The existing GNSS equipment has not kept up with the technological advances (Table 5.3). Of the currently operating NOTA sites, 45% of the receivers are Trimble NetRS that are more than 10 years old and at end-of-service without manufacturer support. These receivers are not capable of tracking the full GNSS constellation. Roughly 26% of the receivers are Trimble NetR9s, the majority of which are more than 5 years old and already at the end-of-service or will be by the close of the current GAGE facility agreement in 2023. By the end of the current GAGE agreement, after anticipated station decommissioning and upgrades through a USGS ShakeAlert agreement, slightly less than 60% of the NOTA stations will be capable of tracking the full GNSS constellations. Of the 322 receivers currently in the NSF-EAR PI/portable pool, only ~20% are considered modern (less than 5 years old). Thus, a critical need exists for recapitalization of the GNSS receivers in NOTA and the portable pool. The sUAS systems are modern. The TLS systems vary in their age.

5.3.10 Connections to other programs and agencies

Several federal agencies depend on data from the NOTA. The roughly 2000 continuous stations in National Geodetic Survey CORS network overseen by NOAA, relied upon by state and federal agencies, scientists, and the private sector, includes ~500 NOTA stations in the western continental US, Alaska, and the Caribbean. NOAA also depends on NOTA data for atmospheric data products that are either produced in-house or obtained through third-party vendors. The US Geological Survey relies on data from NOTA, especially the real-time GNSS streams, for the ShakeAlert earthquake early warning system and the Volcanic Hazards Program. The USGS is critically dependent on at least 300 NOTA sites for long-term hazard monitoring and mitigation. NASA-JPL routinely accesses data from a large percentage of NOTA sites for use in solid Earth, hydrostatic loading, and other key applications. Many state and location agencies (e.g. DOTs) also rely on data from NOTA stations for surveying applications. GAGE is also involved in monitoring the NASA Global GNSS Network (GGN), a continuous GNSS network that provides data critical to GNSS satellite operations, global reference frame realizations, and the estimation of atmospheric parameters need for GNSS processing. Finally, NASA has recently convened planning activities associated with sUAS, including geodetic imaging. It will benefit EAR research goals to maintain strong connections between NSF-EAR and NASA programs concerned with GNSS, the upcoming NISAR mission, and geodetic imaging using UAS platforms.

5.4 Supporting/Enabling Technologies

The SAGE and GAGE facilities also support a variety of resources for geodetic and seismic data processing. First and foremost are robust data centers at UNAVCO and IRIS. Both organizations have put considerable effort and funding towards data management and access, enabling a broad array of science. Open data and adherence to FAIR data principles has been recognized as key to fostering scientific advances and a healthy scientific community. We note that these data centers are facing increasing challenges as high-rate, Large-N, and new technologies (i.e., DAS) create extremely large datasets that may not adhere with existing standards and formats. Robust data centers are key components of a future facility, and they must be able to handle new technologies and technological advancements. Beyond hosting raw and minimally processed data, these facilities also currently host a number of data processing tools available to the community. These tools range from standard data conversion and archiving, to more advanced scientific processing. They have been produced by both the SAGE and GAGE facilities and the scientific community.

Getting the data from the sensor to the data center remains an important supporting technology via telemetry. Instrument health is also often communicated. Telemetry can be a major fixed cost for many deployments and can require substantial labor for maintenance. High-bandwidth and real-time global telemetry balanced against cost optimization is an area of needed emphasis to support geophysical sensor networks. This may be achieved with new satellite internet systems (e.g., Starlink). Robotic systems may also be developed and deployed for data recovery and sensor health check.

All sensors and their enabling technology require power. Advances in battery technology, solar and other small footprint power generation, and greater efficiency of power consumption are required for light weight, long duration deployment, and low cost sensor networks. The future geophysical facility will need to work closely with instrument vendors and portable power supply innovators to continue to harness commercially driven power supply improvements.

Chapter 6. Seismic and Geodetic Instrumentation Priorities to Achieve "Earth in Time" Science Goals

6.1 Introduction

The IPRC deliberations included time for discussion in a mode that encouraged unconstrained, collegial, and futuristic thinking about the possibilities for an NSF-supported geophysical facility. In this mode, the committee gave itself permission to reflect on potential avenues for facility development that were free from administrative, fiscal or technical readiness limitations (aka "blue sky"). The goal was to identify new technologies, or expanded capabilities of existing technologies, that our community could employ to make transformative progress on the identified science challenges in 2023-2033 (Figure 1.3).

These ideas are not intended to be prescriptive of future facility functions but represent the imaginative musings of a specific set of scientific minds at a specific point in time, representing a diverse set of perspectives. The spirit of these reflections is intended to frame facilities as being in the midst of an evolving capability space where change is the rule, and research directions can be spontaneous. New scientific priorities can emerge and make new demands for instrumentation, and new capabilities in instrumentation can result in serendipitous discoveries.

Ideas captured this way reflect the diverse interests of the committee, which though a small sample of individuals, may reflect the breadth and scope of ambition of the community. These ideas reflect a greater degree of scientific unboundedness than is present in the existing seismic and geodetic facilities and illustrates the frontier of research domains that exist near (or over) the horizon. The diversity of ideas shared here is itself representative of an ongoing widening of the range of science topics and applications that are accessible through seismic and geodetic methods. This pattern of widening diversity of scientific ideas has continued through and beyond the development phase of the EarthScope project. Given this reality it may be impossible to accurately predict the emergence of the next great scientific discoveries. We can, however, forecast that the trend of increasing technique and applications diversity in seismic and geodetic science will continue, much as it has done over the last couple of decades. We ask which novel approaches are now emerging, and which are around the next corner?

Some of these "blue sky" priorities rely on technologies that are reasonably well-understood and at least in part already within the SAGE and GAGE instrument pools; these are designated as "near frontier" (see prior discussion building from Aster and Simons, 2015). "Intermediate frontier" priorities would require further development of existing technologies not yet covered by the SAGE and GAGE facilities. "Far frontier" priorities would require significant new technology development. New technologies bring new data streams. Therefore, we also discuss several "blue sky" data science projects. Finally, there is a need for robust data communications from sensor networks to data analysis and archiving facilities, and the scientific community. Examples of links between the proposed elements of frontier infrastructure and science challenges are provided. However, we stress that these examples cover only the tip of the iceberg of the potential science pay-off of these new technologies.

Previous community reports have emphasized that geophysics is dependent on observations over spatial scales from local-to-global and time scales from milliseconds to decades (see e.g., Figure 9.2 at end of this document). New technologies can improve observational accuracy and/or precision and/or open new lines of inquiries. Current and future instrumentation portfolios must strike a balance between both long-term continuous measurements and targeted short-term deployments, including rapid response to natural hazard events.

6.2 Near Frontier: Expansion of current facility/technology capabilities

6.2.1 Large-scale networks of multi-disciplinary geophysical sensors

Large-scale multi-disciplinary networks are the IPRC's top priority for the future. Continent-scale networks of GNSS, such as COCONet and TLALOCNet projects, now known as the Network of the Americas (NOTA), and seismic sensors installed as part of the GSN and the NSF-supported EarthScope program, revolutionized our ability to study tectonics, Earth's interior structure and dynamics, and earthquake, magmatic/volcanic and climatic processes. These networks also led to unanticipated observations, such as wide-scale uplift caused by drought in the western United States and the ability of GNSS signals to detect environmental factors including soil moisture, snow depth, and vegetation height. EarthScope's seismometers were critical to identifying and responding to the increase of human-induced earthquakes in the early 21st century. In addition, targeted dense, multi-disciplinary networks (i.e., GNSS, seismometers, MT, infrasound, borehole seismic and strain) were deployed along active plate boundaries and magmatic systems, and in enigmatic continental interiors, to investigate processes at higher spatial and temporal density. A whole generation of geoscientists now conceives of science projects with comparably ambitious arrays. Moving forward, there is an opportunity to capitalize on existing infrastructure and data, and further advance science, through strategic installations of enhanced multidisciplinary instrumentation.

The value of real-time data streams from multiple data sources for the study of tectonic and magmatic processes, hazards, and risk reduction has been proven by existing infrastructure. Site locations in the past were understandably influenced by access, power, and other operational issues. This often resulted in sparse distributions in high scientific value areas such as along plate boundaries, volcanic systems, coastal areas and under the oceans. Both instrumentation and power systems have improved significantly since the EarthScope program began and there is now the possibility to have lower power, robust systems that can run more reliably in remote areas.

Developing/enhancing/expanding integrated geophysical observatories that would host borehole observatories, including strainmeters and broadband seismometers, along with co-located high-rate, real-time GNSS stations along active plate boundaries and magmatic systems would greatly increase our ability to investigate processes in these regions, including their temporal variability. Combination with other geophysical, geologic, and geochemical observations would greatly improve our understanding of these systems. These integrated observatories would sit within (often already existing) dense networks of GNSS and broadband seismic stations.

Integrated geophysical observatories could also help bridge the gap between studies of the solid earth, critical zone, hydrosphere and cryosphere, allowing for new understanding of the interactions and influence each system has on one another. For example, coastal observation stations consisting of GNSS set up for reflectometry, a tide gauge, environmental sensors such as a weather stations and soil probes if applicable, and a seismometer would provide an unprecedented view into processes including tectonics, crustal change due to water loading or GIA, sea level changes, soil moisture and precipitation, and sea ice movement (in the Arctic).

The stations could also be utilized for earthquake and tsunami early warning and monitoring atmospheric and ionospheric conditions.

To assess ideal configurations of large multi-disciplinary networks, the requirements for each sensor type must be individually evaluated. Multi-disciplinary networks should not be equated with the idea that every type of sensor is deployed at each location. Networks should be optimized so that cutting-edge analysis methods in the geodetic and seismological domains are enabled, in addition to collecting observations that promote joint modeling and interpretation of multiple data types.

6.2.2 Rapid response instrumentation/mobilization

The capability to rapidly respond to geohazards with dense multi-disciplinary sensor networks will also facilitate marked scientific progress. Transient data during and in the immediate aftermath of eruptions, earthquakes and other catastrophic events plays a key role in unravelling the processes underlying these hazards. A pool of ready-to-install geophysical sensors deployed prior to or immediately after significant geological events (e.g. volcanic eruptions or earthquakes) will supplement permanent geophysical observations and increase spatial and temporal sampling. These dense, multi-disciplinary observations will help provide critical information to improve physical models of the geohazard and improve future forecasting and hazard mitigation. We emphasize that the rapid response equipment datasets should be closely coordinated with relevant monitoring agencies and aimed at maximizing scientific returns, and not replace hazard monitoring.

6.2.3 Broadband seismometers

One key goal is to expand capabilities for deploying large numbers (hundreds) of truly broadband seismometers (i.e., able to record signals out to periods of ~200 s) at spatial scales that enable array-based interpretation and modeling of seismic wavefields. For example, this type of array permits the identification of the backazimuth and slowness of anomalous arrivals (phases such as postcursors, scattered waves, etc.) and dramatically improves our ability to interpret signals in terms of small-scale structure in the mantle (which is crucial for targets such as mantle plumes). The ability to record waveforms at periods of more than 50 s is needed for recording fundamental mode and overtone surface waves, which are in turn crucial for resolving upper mantle and transition zone structure.

Although blanketing the Earth with broadband seismometers at these scales is sadly not feasible, intermediate strategies such as arrays with a temporally translating footprint, such as pioneered by the EarthScope Transportable Array, have been demonstrated to be highly effective. Alternatively, global arrays of broadband arrays could be simultaneously targeted on certain features of Earth structure. Ideally future broadband seismometers would be significantly easier to deploy and less expensive than the broadband instruments that exist at present in the SAGE pool.

This broadband seismometer pool would allow for greater flexibility in large-scale deployments that could record unaliased wavefields and dramatically improve resolution of mantle structure at regional to global scales. Virtually every science challenge that involves processes in Earth's interior, from geodynamo generation in the core to the expression of plate tectonics and mantle dynamics at the surface, would be advanced by this capability.

6.2.4 Cable-free, compact, light-weight seismographs

The last decade has seen rapid development in instrument design with the advent of cable-free, compact, light-weight seismographs (e.g., "nodes") with integrated GPS clock, digitizer and 3-component capabilities. Extended battery life for these portable, easily deployable seismic nodes (~1 month for current generation instruments) would enable longer deployments and more potential for joint imaging using both controlled and natural sources. Studies are increasingly moving toward 3-dimensional experiments and high-spatial density deployments that require large numbers of channels. The demand for these nodal sensors is high and the existing instrumentation available to NSF-EAR funded researchers currently limits scientific advances.

For the NSF-EAR community to fully utilize advances in processing and analysis techniques, expanded access and instrument capabilities are needed. True "large-N" deployments should consist of thousands of instruments and have improved performance metrics such as lower noise floor, broader frequency bands, increased dynamic range and further extended battery life. Wifi-connectivity or telemetry would enable real-time processing. An expanded instrument pool would be utilized across seismology disciplines, benefitting a large proportion of the academic seismic community. The pool would facilitate: 1) increased capacity to image the full seismic wave field, 2) precise detection and location of microseismicity, 3) future controlled source imaging with increased resolution and utilization of 3D acquisition, and 4) hybrid active/passive surveys, a frontier area for innovation and an experiment mode that can leverage complementary industry and academic approaches to research. Integrating other sensors into node packages would also encourage interdisciplinary science and discovery. The current IRIS PASSCAL nodal instrument pool is substantially oversubscribed and insufficient to meet the community's current needs, let alone increased interest.

To address science questions that depend on high-resolution imaging of the shallow subsurface and crust, central facilitation of controlled sources and technical expertise for controlled-source seismic experiments is also essential. Sources should facilitate experiments across a range of target depths and spatial resolutions. To fully take advantage of an expanded pool of of 3-component nodes, both P- and S-wave sources are needed. By allowing scientists to capture the complete 9-component wavefield in a controlled-source mode, these combined capabilities will yield critical discoveries in Earth sciences by addressing questions about fluid migration, fault properties, subsurface characterization and material properties distribution.

Continued investment in nodal instruments will contribute to detailed knowledge of Earth's crustal structure and shallow subsurface, thus addressing questions across a broad spectrum of the Earth sciences, from the origin and evolution of continental crust, to tectonic plate structure, strength and rheology and plate boundary deformation and dynamics. Increased capacity for earthquake detection and microseismic characterization provides important constraints on faulting and magmatic processes and can illuminate actively deforming regions over short observation periods. High resolution characterization of fault zone geometry and magmatic systems is essential to investigating seismic and volcanic hazards. Lithospheric scale controlled-source experiments are a major component of cross-disciplinary research initiatives such as the NSF GeoPRISMS, EarthScope and FRES programs and the nascent SZ4D program. There is also growing demand for shallow (<1 km) studies focused on geohazards, groundwater cycling, neotectonics, landscape evolution, critical zone and the cryosphere. Multiscale imaging facilitated by large-N arrays and controlled-source seismic capabilities would advance most topics highlighted in the recent Earth in Time report.

Looking further into the future, the committee encourages EAR investment in the development of broadband seismometers that capture the ease and flexibility of nodal instruments with high fidelity recording at longer periods, thus bridging the gap between seismometers described in this and the preceding sections.

6.2.5 Improving geodetic precision

The precision of GNSS positioning is strongly dependent on the seamless integration of a large number of frameworks that model the effects on the signal between satellite constellation and the ground receiver (e.g., Blewitt, 2015; Herring et al., 2016 provide overviews). There is a large literature that describes the various aspects, but a short and incomplete list of factors that the analysis must account for includes: the orbits of the GNSS satellites, their satellite atomic clock slips, affects of atmospheric refraction on the satellite to ground signal, dispersion from the ionosphere, antenna and receiver biases, the motion of Earth's surface owing to its tides and its rotation in space, loading from the oceans, tectonic plate movement, atmospheric loading, inherent accuracy of and alignment to the global reference frame. As improvements are made and new generations of models for each of these aspects (and others) are developed, the end positioning products improve. The rate of improvement has continued up to the present day, and the ultimate limit of precision is unknown. However, extrapolating the trend into the near future suggests that greater stability, sensitivity and precision are to come, which will allow better partitioning of the signal sources into the various physical processes that cause position changes. The near frontier will see innovations in all the components, and include multi-constellation GNSS processing (e.g., incorporating data from Galileo, GLONASS, BeiDou). These improvements will propagate into all subsequent product levels and geophysical models that are informed by the data. The facility plays multiple roles in supporting these improvements including (but not limited to) hosting and evaluating data products, coordinating the establishment of and following community standards, maintaining external advisory committees.

A separate and equally important aspect of improvement comes from station proliferation and improvements to GPS network design and application. For the purpose of hazard estimates and warning systems the USGS supports a federation of networks that now covers much of the seismically and volcanically active areas of the United States (Murray et al., 2020), complementing NSF's Network of the Americas (NOTA). These networks each have station numbers, spacing, latency, and observation strategies that are appropriate for their respective natural hazard environments, subject to fiscal constraints. For example, some have dense real time data streaming continuous stations surrounding major plate boundary faults that can enhance early warning systems, while others have many un-telemetered stations occupied part time to maximize geographic coverage. Additionally, the last decade has seen a realization that there is great benefit to science from accessing data from GNSS networks originally constructed for purposes other than academic studies (Blewitt et al., 2018). In the near frontier we can expect further proliferation, innovation and diversity of modes across greater extents of Earth, inside and outside of the US, a trend that will be accelerated by the availability of inexpensive satellite telemetry. A consideration for NSF's future geophysical facility will be how it takes advantage of data from all networks in ways that leverage resources and community expertise appropriately and fruitfully.

6.2.6 Data exploration and curation

Data are only as useful as the science they enable. Increasingly, science is driven by comparing diverse datasets in a geographic region. Such comparisons require: 1) easily interrogable data archives with cross-listing of data from multiple archives and 2) data formats and processing workflows that are amenable to non-specialists utilizing the data. Ultimately, a scientist should be able to draw a box on a map and be informed of all available geophysical data from that region, regardless of data type. Ideally, they should also be able to visualize and utilize the data in a common platform. These tools are essential to making the geophysical data a useful tool for all of Earth sciences and is consistent with the vision set out in the Lay et al. (2009) report and other recent community documents. Geomapapp (http://www.geomapapp.org/) offers a commonly used platform for some of the integration that we envision.

Such interoperability is technically feasible today, as we all experience the search power of Google or Amazon on a daily basis, but implementing it for a scientific platform requires intensive computational and programming resources. Data accessibility is poised to become a growing challenge both because the potential user base of geophysical data has expanded into aligned disciplines and because the datasets themselves are becoming increasingly large. Handling the enormous datasets of nodal and DAS data is a challenge even for specialists. The facility needs to address this challenge with a suite of software tools that utilize modern data handling techniques.

As a vision for the future, imagine that over your morning espresso, you could say "Computer, plot all earthquakes around Mt. St. Helens for the last month on a map of GNSS station velocities, NiSAR SAR interferograms/time series and yesterday's lidar topography. Run Monte Carlo kalman filter analysis integrating geodetic time series and seismicity rate, and provide daily probabilities of eruption for the week using a failure criterion model." All of the components for this type of analysis exist, but they need to be integrated, as stated above.

6.2.7 Global telemetry

Robust near-real-time data produces substantial opportunities for data analysis, scientific discovery, and for ensuring data quality and instrumentation "up-time." EarthScope exemplified this concept by providing high-quality, real-time, multidisciplinary data to scientists around the world. PI driven seismic and geodetic deployments typically do not have real-time telemetry, making it difficult to quickly identify station issues and resulting in loss of data and diminished scientific return.

Experiments that utilized cellular networks (e.g., FACES, Brudzinski and Allen, 2007) were able to more quickly address station issues as they emerged. However, real-time data transmission also poses considerable challenges, both logistically and financially. Data transmission via satellite is beneficial in that it can be applied globally in a uniform manner. However, high cost for equipment and data transfer has traditionally limited its use to permanent, well-funded geophysical networks. The EarthScope TA in Alaska used (in part) InMarSat Broadband Global Area Network (BGAN) satellite telemetry. This provided decent bandwidth, reliability, and latency, but at relatively high expense (Busby and Aderhold, 2020). Recent initiatives present great opportunities for improvements in global data transfer. Satellite internet constellations, such as SpaceX Starlink, will consist of thousands of low-orbit satellites that could provide relatively high-bandwidth, low-latency global internet access. Future geophysical instrumentation should be made compatible with emerging satellite internet constellations.

6.2.8 Other communication models

Dense geophysical networks, exemplified by nodal deployments, can detect and map out aftershock sequences, swarms, and induced seismicity as well as capture full seismic wavefields and enable imaging of subsurface structure at unprecedented resolution. The relative density of such deployments has the potential of transforming the telemetry model, by enabling sensor-to-sensor communication and, with it, the transmission of information across the array. This would eliminate the need for each sensor to have satellite or cellular telemetry. Development of necessary communication protocols and hardware should be encouraged.

Station health of geophysical deployments that lack real-time data telemetry is usually assessed through field campaigns, which are infrequent due to significant personnel and financial costs. Rapid advances in drone technology makes possible a different model for assessing station health. A long-range drone can fly over a geophysical array, communicate with each station at short-range, and then carry the information back to a central location where it can be analyzed or transmitted. This model is akin to the Waveglider (Bingham et al., 2012) concept for ocean-bottom seismology, in which the Waveglider travels near the ocean-bottom seismometers, communicates with them via acoustic modems, and carries the data back.

6.3 Intermediate Frontier: Further development of existing technologies not yet covered by existing facilities

6.3.1 Transoceanic and continent-wide fiber-optic sensor networks

Fiber optic sensing has potential to address both the spatial and temporal scientific needs (see the Distributed Acoustic Sensing Box in this Chapter). As an intrinsically distributed technology, fiber optics could provide the density required for earthquakes, environmental seismology and crustal structure. DAS cables can act as sensors with meter-scale spacing (Zhan, 2019 and references therein). In fact, DAS is arguably the most viable approach for increasing the density of earthquake catalogs to capture the critical small events (Brodsky, 2019). It is probably the preferred technology for fluvial, landslide, and other environmental applications where spatial density is critical due to both the small amplitude of the signals and the strongly attenuating nature of the near-surface environment.

DAS is being explored in several test beds typically a few kilometers in length. Studies of earthquake wave fields, hydrological processes, urban infrastructure and hazard monitoring, to name a few, are booming. Thus, proof-of-concept is essentially in hand to build continent-wide networks of opportunity based on backbone and metropolitan internet infrastructure. The laying of fiber can further be expanded by requiring all road, rail, and pipeline construction or rehabilitation to include fiber in the foundation at very little marginal cost.

Fiber optic technology can involve multiple modes. Active probing of dedicated fiber for its response to seismic waves is a relatively mature technology over short distance. Utilization as strainmeters is a more exploratory strategy and depends critically on the coupling of the fiber to the ground. Successful reutilization of existing internet fiber infrastructure has been used both on dark fibers and even on active systems (Sladen et al., 2019). The latter approach opens the possibility of dense instrumentation at the scale required to sense the smallest earthquakes and local signals. The near future will likely see a rapid increase of DAS or DAS-like monitoring for commercial applications (e.g., surveillance, infrastructure) and hazard monitoring (e.g., earthquake early warning).

In addition to continent-wide networks, the exploitation of transoceanic fiber is technically within reach. Exploratory studies have shown subsea structure in vivid detail using dark fiber (Lindsey et al., 2019). For active sensing methods, a possible impediment is the need for optical signal amplifiers every couple of hundred kilometers. However, some success has been had with long-baseline measurements (Sladen et al., 2019). Off-shore and transoceanic networks need to be coordinated with the NSF Division of Ocean Sciences based on the "one-Earth" paradigm. Further exploitation of transoceanic fiber using femtosecond stable laser interferometry is considered in the "far frontier" section.

6.3.2 Miniaturized sensors

Miniaturized sensors, in particular MEMS (microelectromechanical systems), have substantially increased data collection efforts in the scientific, commercial, governmental, and public sectors. The NSF-EAR communities have already benefited from these relatively low-cost, low-power sensors, including those integrated into smartphones. For example, the successful Community Seismic Network (CSN) has designed and deployed a low-cost accelerometer network in the Los Angeles region (Clayton et al., 2015) and the MyShake app (Kong et al., 2016) uses a smartphone accelerometer and crowd-sourcing to investigate ground shaking associated with earthquakes. MEMS sensors for infrasound (Nief et al., 2018) and gravity (Middlemiss et al., 2016) have also been developed and in many cases already exist in smartphones (e.g., Asmar et al., 2018). The performance of the MEMS sensors (generally) trails that of traditional sensors, but this gap is decreasing. NEMS (nanoelectromechanical systems) sensors are now being produced on even smaller scales and will likely be important for future data collection.

Single-frequency GPS receivers provide a low-cost option to measure deformation due to a variety of geologic processes including volcanic activity, landslide and glacial studies (Dzurisin et al., 2008; Tu et al., 2013) and can be combined with MEMS sensors. Joint data collection and processing of data from multiple sensors, such as single-frequency GPS and MEMs accelerometers, may improve precision (Tu et al., 2013). Several non-US groups have developed low-power single frequency contained systems that can be deployed in large numbers. In particular, IGN in France has developed what they call Geocubes. Dual-frequency, multi-constellation receiver chips, offer benefits, but it remains to be see whether the price has come down enough to be able to deploy them in similar numbers to the single frequency units and what the power cost of the dual/multi-constellation chips is compared to the single frequency chips. The dual frequency chips still have a higher power draw, which could impact deployment. In comparison, the Geocubes get by with a 10W solar panel. The single frequency systems could be an immediate "blue sky" goal while the dual frequency, multi-constellation systems could be an *Intermediate* to *Far Frontier* "blue sky" goal as they would need more testing and development to look at power issues.

The development of compact packages of sensors has offered new opportunities for deployment of instrumentation in remote or otherwise hazardous areas that may not allow on-the-ground personnel. During recent activity at Mount St. Helens, the Cascades Volcano Observatory packaged single-frequency GPS into lightweight, self-contained platforms called spiders that could be deployed and retrieved via helicopter without the need for landing or personnel on the ground (Dzurisin et al., 2008). Recent versions of the spider integrated GPS, seismic, infrasound, and other sensors, transmitted data in near real-time, and were capable of operating for a year using on-board power systems. Such systems would also have applications to studies of glacier dynamics and landslides where working on the ground would be unsafe.

Substantial scientific advances could be achieved through: 1) integration of numerous high-quality MEMS sensors into a single instrument package; 2) deployment of these packages in Large-N networks; and 3) options for deployment in self-contained platforms that do not require on-the-ground work, or are compact and lightweight enough to be carried into remote areas or deployed by UAS. By combining these small sensors into a single package, including that of a smartphone, cost, power, and data transmission savings can all be achieved. An extensive NSF-EAR supported pool of very portable, multidisciplinary sensors would foster interdisciplinary science and unprecedented resolution of processes in the critical zone, volcanoes, and many other areas. Data management and communications (i.e., telemetry) for this network should be carefully considered, as the different sensor types may require different sample rates, formats, and protocols. Emphasis should be placed on the highest quality data and resolution possible. MEMS seismometers (or gravimeters) that can communicate and share timing information with each other, instead of having each one having its own direct telemetry and GPS-clock, would make the system more robust.

6.3.4 Robotic sensors

Robotics have a key role to play in Earth science. Robotics including small unmanned aerial systems (sUAS or drones) are being increasingly used in Earth science research, from measuring topography and topographic change following natural events to measuring the concentration of gases emitted from volcanoes (see Robotics Box in this Chapter). At the same time, the capabilities of these systems to make more observations or do increasingly complicated tasks is growing every day. Satellite remote sensing has revolutionized our ability to make observations of the Earth's surface and processes and will continue to do so. Nevertheless, for some research problems higher temporal and/or spatial resolution is required, or the observations simply cannot be made with current satellite techniques. In these cases, sUAS could be deployed to collect high spatial and temporal resolution data sets over targeted areas.

The Earth science community would benefit from UAS that can fly autonomously and for extended distances and time periods making high spatial and temporal resolution observations of topography (lidar & SfM), optical, hyperspectral, multispectral, VNIR, and SWIR imaging, potential fields (gravity, magnetics, resistivity), and gas flux and concentration. For volcano targets we should have UAS swarms that can focus on individual volcanoes or arc segments, making daily sorties and/or sitting on existing stations making observations. The technology already exists, but has not been applied. Possibilities include: UAS swarms that can be given individual tasks (e.g., measuring gas flux or topography and imagery); UAS sampling of gas and eruptive products; and drones that are able to deploy and retrieve terrestrial robotics, and geophysical and geochemical monitoring instrumentation (e.g., GNSS, seismic, thermal, infrasound and MEMS sensors).

Although outside our formal charge, the committee notes that rich potential of robotics for marine environments, for example unmanned aquatic vehicles (UAV) that 1) can ping seafloor geodetic monumentation (technology which already exists); 2) install seafloor instrumentation (pressure sensors, ocean bottom seismometers; exists or is in development); and 3) map the seafloor at high-spatial resolution. In all cases, onboard data analysis should occur, and data should be telemetered in real-time.

With the increasing volume of remotely sensed data, including data from drones, new techniques must be developed to analyze and model these data. Current and future data collection initiatives are/will take advantage of artificial intelligence and machine learning methodologies for the detection, analysis, and modeling of remotely sensed data (Das et al., 2020).

6.3.5 Rotational seismometers

Traditional seismometers measure the three-components of particle displacement associated with the passage of seismic waves; however, they do not record rotations associated with the seismic waves, except in the vicinity of large earthquakes where the particle displacement records can be contaminated by rotational motions (Igel et al., 2005). The field of rotational seismology is concerned with recording and analysis of these rotations. Using a single 3-component rotational sensor, collocated with a traditional 3-component particle displacement sensor, one could discern the type, speed, and direction of an incident wave, which can traditionally only be done using arrays of seismometers (Igel et al., 2005; Aldridge and Abbott, 2009). Such co-located 6-component sensors would enable single-station S-wave tomography (e.g., Fichtner and Igel, 2009), aid in seismic source inversions (e.g., Bernauer et al., 2018), seismic engineering and strong-motion seismology (Lee et al., 2009), and have multiple applications in the near-surface exploration context (Li and van der Baan, 2017).

While the ring-laser rotational sensor (MacEk and Davis, 1963), has unrivaled sensitivity and noise performance, and has been successfully used to detect rotational motions from teleseismic earthquakes, their high cost, energy usage, and infrastructure requirements make them unsuitable for use outside an observatory setting (e.g., Jaroszewicz et al., 2016). Fortunately, several alternative technologies currently exist. The closely related fiber-optic gyroscope is already on the market as a low-noise, broadband sensor suitable for structural and source studies (Bernauer et al., 2018). Rotational sensors based on other promising technologies also exist, including MEMS (micro electro-mechanical systems) and MET (molecular electronic transfer) (e.g., Pierson et al., 2016; D'Alessandro et al., 2019), and magnetohydrodynamic sensors (see Ringler et al., 2018). Traditional sensors, such as the three-component magnetometer (Barak et al., 2015; Kappler et al., 2018) and multiple geophones (Brokešová and Málek, 2013), can also be used to estimate rotational motions. Future geophysical facilities should consider currently available and in-development, affordable, low-energy use, easy-to-deploy rotational sensors, for use in both structural inversions, seismic hazard research, and investigations of seismic sources. Capabilities presented by such sensors would complement existing geophysical observations.

6.3.6 Gravimetry

Gravity is one of the fundamental fields of geophysics and is closely associated with geodesy as one of its three "pillars". The gravity field carries an abundance of information about Earth's structure, history, movement and dynamics, on geographic scales that span from basins to the entire planet. The gravity field is ever changing and responding to the interplay between solid Earth deformation from the forces exerted by the moon, sun, internal dynamics and changing surface loads from the fluid atmosphere, oceans, cryosphere, and terrestrial hydrosphere. Time variability of gravity can reveal the underlying patterns of how climate change affects the solid Earth. One example measuring system, the satellite mission known as the Gravity Recovery and

Climate Experiment (GRACE, and its follow-on GRACE-FO) senses and maps the entire Earth's gravity field approximately monthly, revealing the changes in water content on Earth's surface that varies with seasons, drought cycles and climate change (Luthcke et al., 2006; Watkins et al., 2015). Other features of solid Earth change such as mantle flow, glacial isostatic adjustment, tectonics, earthquake cycle, earthquake precursors, mantle and core processes are seen, or potentially seen, in the gravity field (Han et al., 2006; Chen et al., 2007, 2016; Heki and Mitsui, 2013). Trends in gravity when combined with measurements of vertical land motion can be diagnostic of viscous mantle flow versus elastic uplift (Wahr et al., 1995). Gravity data can be used to infer rheological and structure properties (Martens et al., 2016; Chanard et al., 2018), and help understand the impacts of surface mass changes on earthquake occurrence around aquifers (Silverii et al., 2016). However, the pixel size of GRACE is ~300 km and samples ~monthly, so there is opportunity for advances in geophysical research at shorter spatial and temporal scales.

Meanwhile, technological and instrumental advances in terrestrial gravimetry have continued to increase the precision and stability of the measurements. The amazing sensitivity of superconducting gravimeters (sub μ-gal) is well documented. They see, for example, the gravity signal of large earthquakes detected before the arrival of the elastic waves (Imanishi et al., 2004; Montagner et al., 2016), and Earth's subsequent free oscillations (Lei et al., 2011). Their sensitivity allows them to give complementary constraints on the mass and movement of the atmosphere and hydrosphere. However, they can be so sensitive that it makes their use challenging beause they can be strongly affected by local surface hydrology and separating those contributions from other geophysical processes is a major challenge (Van Camp et al., 2017; Rosat and Hinderer, 2018).

While these systems are at this time expensive, they are inexpensive compared to satellites, and could be replaced in the future by less expensive, possibly even radically less expensive, MEMS units (Tang et al., 2019). Quantum gravity gradiometry which is now under development may result in complementary drift-free measurements of the gravity gradient tensor components for 3D mapping of subsurface mass distributions. P-waves disturb the Earth's gravity field at the speed of light (Zhang et al., 2020a), and detecting these perturbations with highly sensitive gravity measurements is within reach (Harms et al., 2015) and could have application for earthquake early warning. New science might develop because the gravity-gradient tensor directly measures mass redistribution and can carry different information about the earthquake source mechanism currently inferred from seismometers. Similar systems are starting to see use in geophysical applications. For example, the Newton-g project (http://www.newton-g.eu/) looks to combine a quantum gravimeter with a network of MEMS gravimeters to study magmatic and volcanic processes at the Etna volcano, Italy.

Thus, if we extrapolate into a future (in "blue sky" thinking mode) where unit costs are lower, sensitivities greater, and knowledge of hydrology improved, then continental scale networks of gravimeters with large numbers of instruments could be deployed across active plate boundaries. While the IPRC sees potential in the future of gravity instrumentation for geophysical science, it recommends a slow approach at this time. Once current trends in instrumentation stabilize it may be appropriate to have a period of evaluation of which instruments and configurations are most valuable and cost effective for investigations into EAR-relevant science topics.

6.4 Far Frontier: Will require investments in new technology

New advances in physics can be the source of new sensors for seismology and geophysics. DAS came out of developments in photonics. Its commercialization was largely by the oil industry. Recently, glimpses of future sensors for seismology and geodesy have come from the disciplines of metrology; for example, atomic clock comparisons using laser interferometry (Marra et al., 2018) and atomic clock frequency changes with elevation (Grotti et al., 2018), and gravitational waves (Zhang et al., 2020b). Transferring these seminal investigations into transformative geophysical instruments involves engineering challenges in sensitivity and transportability. An incentive to encourage partnering between geophysicists with these other communities is needed to support development and bring together the expertise because they are unlikely to become practicalities otherwise. Physicists have long had multi-decadal visions for achieving breakthrough facilities, and geophysicists could benefit from similar long-range thinking. Expert panels could be created to examine in detail the payoff and development costs and needs for these far-frontier technologies.

6.4.1 Transoceanic Earthquake Monitoring

The Marra et al. 2018 paper is a case study of the meteorologist's noise being the geophysicist's signal. Locating sub-seafloor earthquakes can be achieved using femtosecond-stable lasers based on trans-oceanic interferometry. The technology behind the frequency stability is the basis for John Hall's Nobel prize. DOE's NNSA program is sponsoring some research into this area. This blue-sky, far-frontier concept assumes cooperation between EAR and OCE with regard to oceanic seismic sensing networks.

6.4.2 Portable Atomic Clock

It is mostly the case that Newtonian physics underpins geophysics; for example, the Lacoste-Romberg gravimeter. But Einstein's theory of gravity includes a time effect associated with gravitational potential. Therefore, a fractional change in frequency of 10^{-17} is associated with an elevation change of 10 cm of a transportable optical clock. Transportable atomic clocks could potentially allow 1-cm vertical spatial resolution for tracking ice sheets in real time or volcano deformation. This could be achieved using differential GPS on short baselines at potentially lower cost. Tiltmeters could be used to track micro-radian changes in tilt on volcanoes.

Box 6.1 Distributed Acoustic Sensing

DAS (Distributed Acoustic Sensing) records strain in the direction of a fiber-optic cable that is comparable in signal-to-noise ratio to measurements by single-component accelerometers or geophones (Figures 6.1.1, 6.1.2, and 6.1.3). Interferometric analysis of backscattered signal allows the entire cable to be utilized as a string of meter-scale sensors. The technology therefore promises extremely closely spaced measurements potentially spanning kilometer-scale cable. This can be the ideal technology for shallow sources such as volcanic eruptions, ice movement and avalanches, continental and marine landslides, ocean noise, and groundwater hydrology as well as the observation of small earthquakes, including human-induced ones.

DAS and related fiber optic technologies can also be used for measuring the full seismic wavefield. New technologies are being developed that utilize integrated signals on active cables. The advantage here is not in the density of instrumentation but in the locations of the cables. It is possible in principle to reuse commercial cables for DAS which opens up the tantalizing possibility that the seismological infrastructure could be dramatically increased by repurposing currently underutilized dark fiber. The usage of transoceanic cables may address the long-standing lack of instrumentation over the 70% of the Earth's surface covered by water.

The principle of operation of conventional DAS is that outgoing laser pulses are propagated in the near-infrared (1550 nm) where fused silica is optically transparent. Interferometric analysis of the phase difference of local variations of the Rayleigh backscattered signal over a short section of cable from two successive incident pulses generates a dynamic strain recording at a spatial resolution of a few meters. The phase response is linear with the strain induced in the cable. The fiber can be tens of kilometers in length and it can be located in shallowly buried trenches, in boreholes, or in some combination. Its frequency response is affected by cable construction and coupling to the ground. It is generally comparable to geophones in the one-to-100 Hz frequency range.

DAS applications in geosciences are numerous and growing, including opportunities for earthquake seismology. Opportunistic use of dark fiber along internet corridors and ambient noise provides exciting opportunities for seismic monitoring at the urban scale. DAS can complement and supplement conventional seismic sensors and arrays already used across a wide range of disciplines.

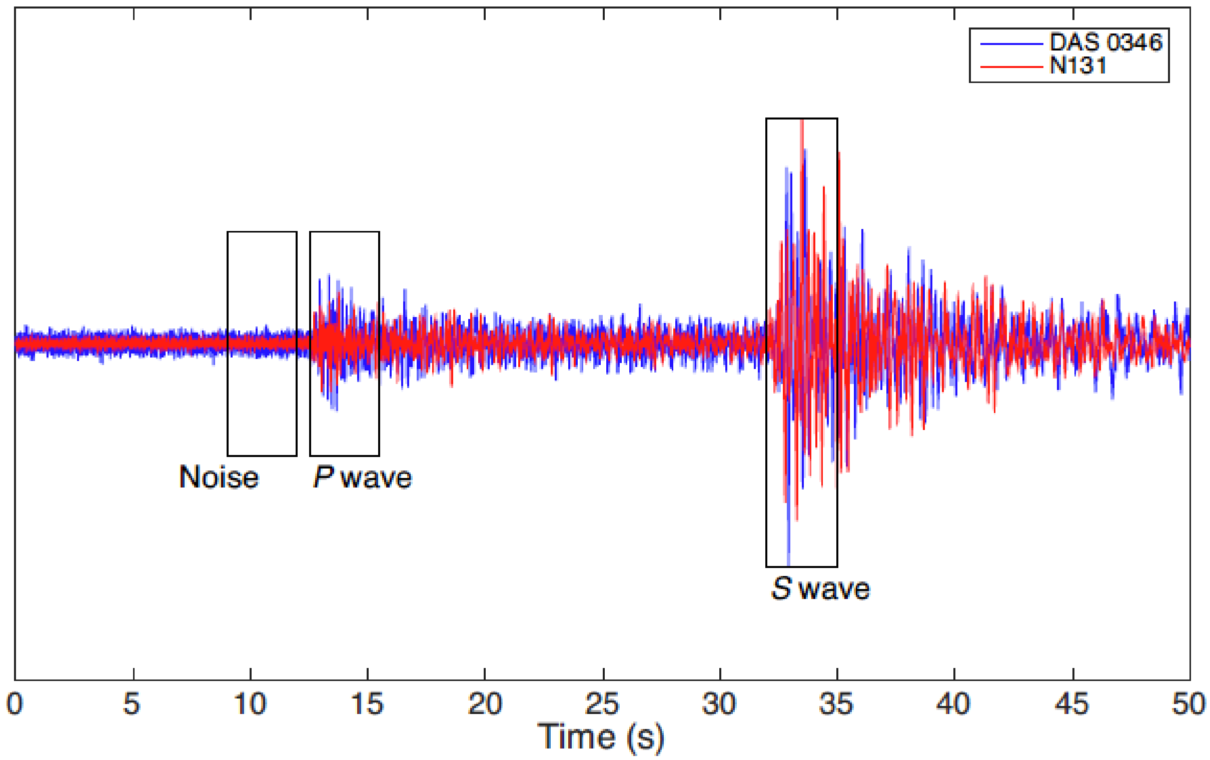


Figure 6.1.1. Example comparison of normalized DAS strain rate (blue) and geophone velocity (red) recorded on 2016 March 21 at Brady Hot Springs, NV due to magnitude 4.3 earthquake 150 km south-southeast .

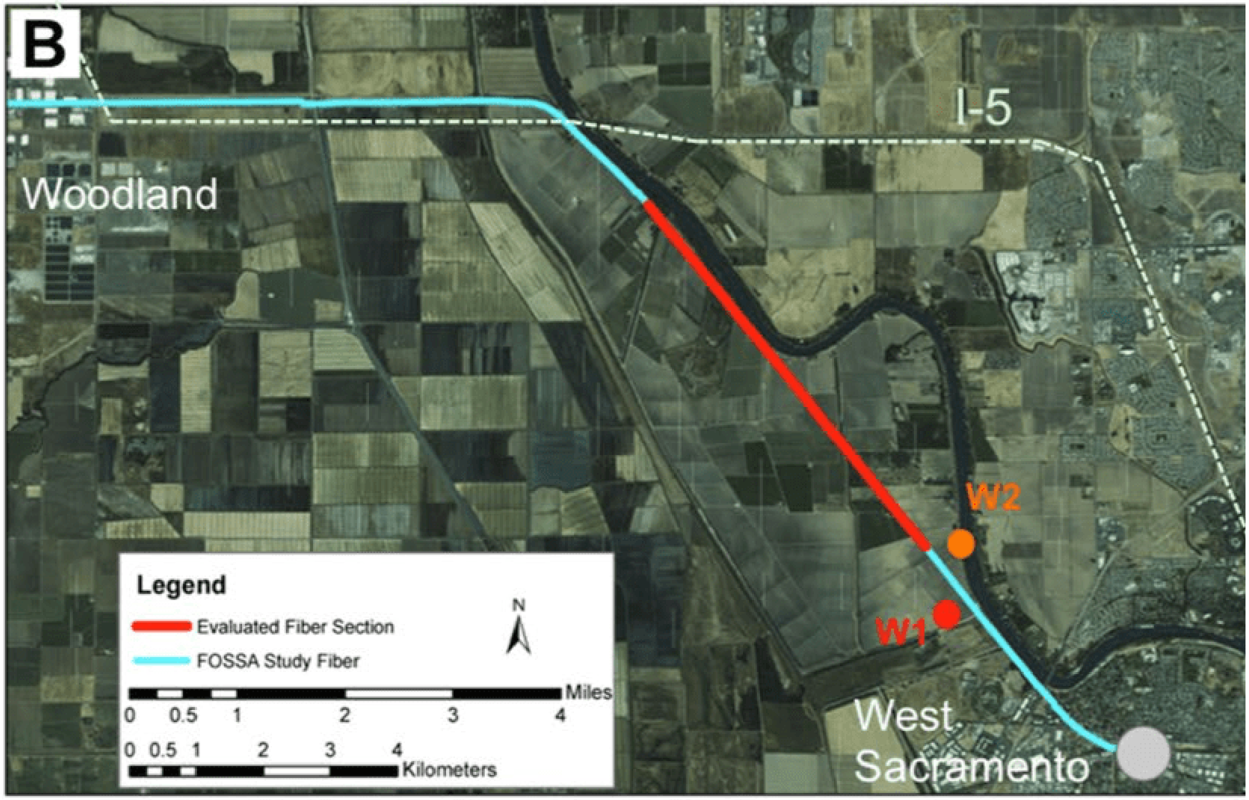


Figure 6.1.2. Map of a subsection of the ESNet Dark Fiber Testbed in West Sacramento, California (Ajo-Franklin et al., 2019).

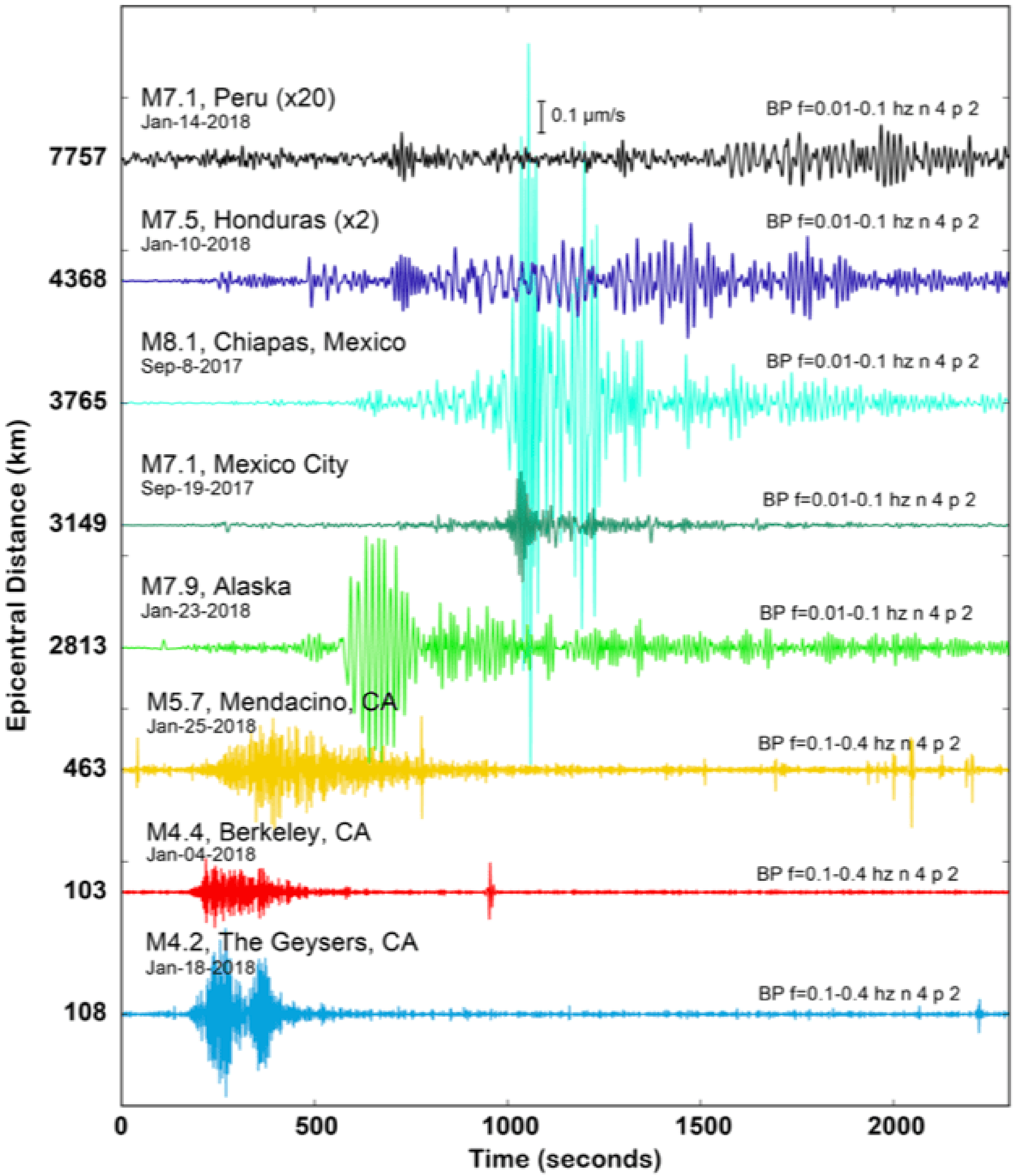


Figure 6.1.3. Example earthquakes recorded by the Sacramento Dark Fiber DAS array, a subset of the ESNet Dark Fiber Testbed (Ajo-Franklin et al., 2019).

Box 6.2: "Dirty, dull, and dangerous"--applications for robotic systems in the Earth sciences

Advances in robotic systems offer important opportunities to enhance observations of geologic and geophysical processes. Applications include 1) (semi)autonomous sensor platforms, 2) sensor deployment and retrieval, and 3) data recovery and sensor health check. The accompanying figure illustrates many of the points below.

Uncrewed and/or autonomous aerial, terrestrial or submarine platforms are used ubiquitously across the Earth sciences, improving our ability to map the continents and oceans and make novel observations of our changing planet. These platforms are routinely used to map and quantify changes in topography, bathymetry and land use at high-spatial and temporal resolution, and other important environmental parameters; for example, the flux and species of gases emitted through volcanoes and ecosystems. Low-cost and ease of use have made small (<23 kg) uncrewed aerial systems (sUAS) available to a wide swath of the geoscience community, spurring development of observational methods. sUAS are now part of the geoscience toolkit.

The GAGE facility currently maintains 6 sUAS and field engineering support for NSF PIs. These systems are most commonly used for visible imaging with position (via GPS/GNSS) and orientation (internally or externally) specified. The resulting images can be used in photogrammetric applications to build maps of topography (digital elevation models) and orthoimagery, as well as 3D point clouds and textured meshes. Measures of change come from differencing repeat models. Heavier and more diverse imaging and sensing payloads may include higher quality camera systems, hyperspectral or thermal imagers, laser scanners, and magnetic or electromagnetic sensors. These capabilities and applications are the tip of the iceberg.

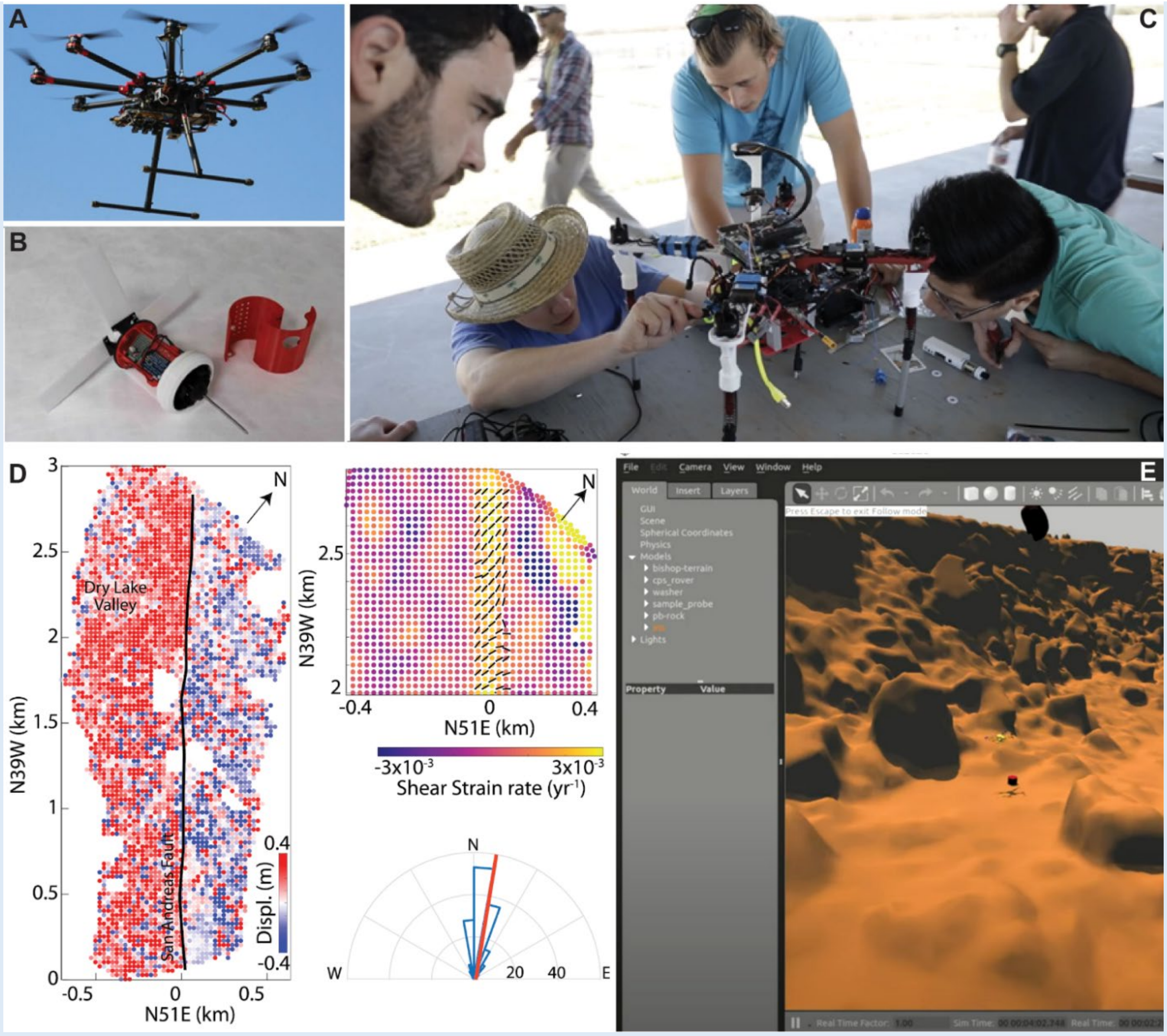
Robotics technology is rapidly evolving to fully-autonomous collaborative systems that can carry sensors to observe and measure important environmental parameters, reducing the 'dull, dirty and dangerous' field operations currently done by humans. Robotic systems are generally challenged by endurance, scene perception, and failure recovery. They need to have the navigational autonomy plus platform awareness to achieve the science that is desired. Along with bespoke low-cost sensor designs and efficient low-cost vehicles, robotic applications have and continue to benefit from algorithm development; for example, terrain relative navigation and trajectory optimization for robust visual servoing. GPS-denied navigation, and multi robot or swarm coordination should be improved. All of the above need end to end hardware and software in the loop simulation for robust software development. Future software development will include efforts to close the perception-action loop to increase the robustness of the systems and maximize science returns.

Robotic systems could be utilized for sensor deployment and retrieval (within weight limits) in challenging and dangerous locations, again reducing the risk to field researchers. Autonomous aerial manipulation may become possible in the next decade. This could include drilling or sampling or sensor interactions. These applications require the development of robust, light-weight low-power sensors. Data telemetry and collection is a challenge for all field deployed sensor systems. Lightweight low power and robust geophysical sensors may not be able to communicate over cellular or satellite networks, reducing their effectiveness for timely decision making. Robotic systems approaching a series of deployed sensors can awaken them if needed, download data rapidly via fast wifi or other links (“data muling”) and check sensor health without otherwise disturbing them.

In the next 5-10 years, we can expect to see multi robot systems deployed for science applications. It should be possible for swarms of 20-100 drones (managed by a single operator), to enable truly large-scale high resolution spatial and temporal mapping and sensor manipulation. Such a capability will enable increases in data quantity (more sensors in more scientifically interesting locations) if not also data quality (better telemetry and sensor health information). Imagine a scenario where a single sUAS or a swarm fly from and return to a docking station located on or near an active volcanic system where its power source is recharged and high-quality data links available. Such a capability would enable repeat optical, thermal and hyperspectral imaging of active craters, gas sensing, sensor manipulation and even measurements. For example, an sUAS could land on a benchmark, perhaps indicated by fiducials, and measure position with GNSS, collect seismic signals or geologic samples, and then move to another location or return to its base station. These integrated capabilities would improve forecasting of volcanic activity and reduce risk to scientists studying the volcanic systems, for example. These tasks involve path planning, safe navigation (i.e., obstacle avoidance), and landing.

The future geophysical facility should explore opportunities to collaborate with the geoscience and aerospace engineering communities to expand the utility of robotic system in Earth science research. This may represent an important opportunity for cross-directorate collaborations between NSF-EAR/GEO and NSF-CISE, including the new National Robotics Initiative 3.0. Finally, robotic systems represent an important STEM gateway for geophysics. The inherent fascination many of us have with robotics is a lure that indicates the need for learning the appropriate math and engineering background to advance robotic systems.

--many thanks to Jnaneshwar Das, Ph.D., Alberto Behar Research Professor, School of Earth and Space Exploration at Arizona State University for his input.



Robotics figure: A) Hexrotor sUAS as sensor platform. B) Specialized lightweight sensor probe. C) Enthusiastic young scientists and engineers working on a robotic system. D) 3D displacements and strains and the maximum horizontal shortening direction (rose diagram) derived from differencing of 2007 EarthScope airborne laser scanning and 2017 structure from motion point clouds (Scott et al., 2020). E) Environment for realistic robotic hardware and software simulation (http://gazebosim.org/ as implemented at Arizona State University (ASU); https://web.asu.edu/jdas). Photographs by J. Das (ASU).

Chapter 7. Other Cross-Cutting Recommendations

Over the nine months of deliberations, the IPRC's discussions surfaced several other issues that were tangential to the charge, yet were perceived to be ***vital to the ability of the future facility to promote scientific discovery.*** We include these further thoughts as a set of cross-cutting recommendations to help guide the course of future geophysical facilities.

7.1 Justice, Equity, Diversity and Inclusion

Sustained work to increase justice, diversity, equity and inclusion (JEDI) in the geoscientific fields is the responsibility of both individual scientists and community institutions (e.g., Bernard and Cooperdock, 2018). The IPRC advocates that the future geophysical facility embed anti-racist policy, practices, and goals throughout its operations. In summer of 2020, both IRIS and UNAVCO released statements on racism in the geosciences. These statements outlined specific plans to address anti-Black and other forms of racism and discrimination. Further, the recent rise in anti-Asian sentiment and violence in the US highlights the continued need to include the Asian and Asian-American community in our anti-racist policies and actions.

The actions and plans (detailed in the linked statements below) include but are not limited to:

- Assessing and increasing transparency in selection governance, internships, speakers, scholarships, and hiring
- Providing training and resources for staff and community members to avoid and intervene to stop anti-Black, anti-Asian, racist, and biased actions and words
- Expanding selection criteria for meeting locations and field trips to include safety for all community members
- Featuring Indigenous knowledge of and contributions to geosciences
- Providing clear timelines for improvement and regular reports for accountability

We support this work and recommend continued efforts, including building in JEDI efforts into the community governance structure to help identify and change institutional structures that contribute to inequality, ensuring safe and inclusive field experiences for all participants (e.g., Clancy et al., 2014; Nelson et al., 2017; Anadu et al., 2020; Olcott and Downen, 2020), and emphasizing FAIR data principles.

The IPRC recognizes the decades-long movement to address racism and JEDI in geosciences, especially work done by Black, Indigenous and other people of color. This legacy should guide our efforts.

Guiding Documents and References

- IRIS Statement on Racisms in Geosciences
- IRIS Efforts on Justice, Equity, Diversity and Inclusion
- UNAVCO Statement on Equity, Inclusion and Racial Justice
- A Call to Action for an Anti-Racist Science Community from Geoscientists of Color: Listen, Act, Lead
- Call for a Robust Anti-Racism Plan for The Geosciences

7.2 Ensuring equity and supporting human infrastructure

It is also important that the facility remain a stand-alone entity distinct from any university. This model has important equity implications. A facility that is equally accessible by all NSF-funded projects helps level the playing field between institutions with diverse resources, geographies and demographics. Access to professional staff and technical support is particularly important for scientists working at universities and colleges with modest internal support.

As the facility branches into novel technologies with significant logistical hurdles to deployment, such as DAS and nodes, it is very important that the staffing is commeasurably built to allow all scientists to effectively use the new tools. Technical staff of the facilities are specially capable in that they combine knowledge of the science drivers with practical awareness of the technologies required to make appropriate observations and produce FAIR data. They often have substantial institutional memory and ample experience observing the phenomena of interest. Their service and guidance is critical and should be valued and appreciated. The current facilities note a challenge of staff turnover due to uncertain funding conditions and limited resources.

IRIS and UNAVCO have consistently provided professional development opportunities to the academic community, including early-career investigators. These opportunities include short courses, workshops and webinars that are archived for public access. The IPRC advocates that the future geophysical facility continue these services for investigators at all levels and maintain the open access and public archiving feature. The facility should be supported to consider the growing needs of the community and to facilitate offerings tailored to introductory data processing and analysis as well as advanced training.

Student training should remain a high priority and the committee recognizes the success of student internship programs facilitated by IRIS and UNAVCO. These internship programs provide immersive research and networking experiences, opportunities for presenting research at a large professional meeting and group training to create a strong cohort of students at similar career stages. Further, the student internship programs provide an important pathway to increase participation of underrepresented communities in the geosciences. The future geophysical facility should continue to facilitate these opportunities and provide internship training across geophysical disciplines (e.g., seismology, geodesy, magnetotellurics).

7.3 Governance

The geophysical facilities have historically had a community governance structure that includes Boards of Directors from consortium member institutions and a robust structure of committees. Through this community governance hundreds of scientists are engaged in inspecting, designing and steering the facility. This structure has worked well and resulted in facilities that continue to adapt to the needs of members and changing scientific needs. The governance structure also has a function in developing the human infrastructure through regular discussion of technological developments and cross-fertilization of ideas across the over 100 institutions represented. Related to governance, convening roughly annual science workshops has been a useful activity that helps to stimulate and improve outcomes of research, capitalize on intersections between domain experts, educate and bring new members into the community. The IPRC strongly endorses the community governance model for the future facility.

7.4 Data management and discovery

The path taken by scientific data does not end with the instrumentation. The importance of data management and discovery tools has been recognized by the NSF and is of particular import to the facilities. One of the largest challenges of the integration of the seismology and geodesy facilities is likely to be integration of the diverse datasets of the underlying disciplines. This problem will likely grow as the recommendations of this report are implemented, and new types of instrumentation introduced. Fiber optic technology in particular will deliver very large datasets that will present challenges to effective collection, storage and sharing.

Thus, it is clear that investments in instruments need to be matched with investments in data management and tools that ease and increase the speed of discovery and use. These investments are especially important if the data is to be useful to allied disciplines where users of the data may not be experts in seismic and/or geodetic technologies. This report and its scientific driving documents articulate uses of seismological and geodetic data for hydrology, oceanography, and atmospheric sciences, but these visions cannot be realized if only highly trained seismologists and geodesists are capable of handling the data. We strongly support the development of software and data management tools that lower the bar to entry to the data.

7.5 Ensuring technological innovation

Supporting a center of excellence in instrumentation for geophysical data collection requires dedicated focus on technological development. New technologies require highly trained personnel devoted to exploring the boundaries of technical capabilities. The IPRC has expressed concern that facility operations in a cost-constrained environment could lead to deemphasis of, or routing of resources away from, technology development in favor of network operations. Support for the highly trained personnel that drive cutting edge technological development may come under budget pressure. We urge the NSF to seriously consider budgetary mechanisms that are sufficiently flexible to ensure that innovation will continue to occur and adequately protect capacity to cutting-edge development.

A related issue is the appropriate interpretation of Figures 1 and 1.3 of this report. The prioritizations undertaken by the IPRC necessarily emphasized well-developed technologies that are ripe for utilization in the near frontier moment as a high priority. This part of the recommendation set does not imply that no far frontier technologies should be explored, supported or considered for eventual integration into facility capabilities. If financial boundaries need to be drawn on the basis of this figure, NSF should consider both axes rather than just one. A threshold could be a curve with a negative slope, and not necessarily straight.

7.6 Underwater instruments

The solid Earth extends under the oceans. The fact that deep water lies over 70% of the planet is both a technical and organizational impediment to geophysical progress. Submerged instrumentation is particularly important to hazards-related research that endeavors to understand earthquakes, tsunamis, mass movement and volcanic events that occur under the sea surface. The division-boundary between OCE and EAR has historically been problematic for our disciplines that cross the shoreline. We encourage the NSF to continue to find organizational solutions to pursuing an integrated vision of solid Earth problems in all environments. Seafloor geodesy and seismology continues to be a central priority for geophysics that is highlighted in multiple community documents that steered our work and yet it does not appear to fall under the purview of the unified geophysical facility that is being considered by NSF. The IPRC therefore did not consider strategies for implementing seafloor geodesy in detail, nor did it deeply discuss ocean bottom seismometry. This lack of consideration is not a reflection of the committee's view of the importance of sea floor observations and the other sciences it supports, but a reflection on the scope of the facility under discussion.

7.7 National Infrastructure

The IPRC views geophysical networks funded by NSF as essential national infrastructure – fundamental structures and facilities needed for modern American society and economy to function. A broad swath of city, county, state and federal agencies and the private sector rely on these networks, and their support and growth are critical national priorities. This essential national infrastructure directly benefits society by providing the critical information required for monitoring geologic hazards (including earthquakes, volcanoes, and landslides), real-time earthquake and tsunami early warning systems, real-time weather forecasting, and national security (including monitoring of space weather that can interfere with power grids). ***We recommend that geophysical instrumentation and sensor networks currently funded by NSF and partner agencies be supported as US National Infrastructure, rather than through ad hoc research funding mechanisms, and be maintained as research grade observational networks to advance fundamental scientific knowledge and essential applications to benefit the nation.***

See Box 7.1 (next pages) for a more complete articulation of this concept.

Box 7.1 Geophysical Sensor Networks as US National Infrastructure

Summary: The Instrumentation Portfolio Review Committee (IPRC - a committee of the NSF Advisory Committee for Geosciences) views geophysical networks funded by NSF as essential national infrastructure – fundamental structures and facilities needed for modern American society and economy to function. A broad swath of city, county, state and federal agencies and the private sector rely on these networks, and their support and growth are critical national priorities. This essential national infrastructure directly benefits society by providing the critical information required for monitoring geologic hazards (including earthquakes, volcanoes, and landslides), real-time earthquake and tsunami early warning systems, real-time weather forecasting, and national security (including monitoring of space weather that can interfere with power grids). ***The IPRC recommends that geophysical instrumentation and sensor networks currently funded by NSF and partner agencies be supported as US National Infrastructure, rather than through ad hoc research funding mechanisms, and be maintained as research grade observational networks to advance fundamental scientific knowledge and essential applications to benefit the nation***.

Current seismic and geodetic networks originated as research tools, but have now transcended their original intent. They have become essential infrastructure that are continuously and reliably present, can be plugged into when needed, and have a low cost threshold for users to access. A sensor network with these properties is analogous to bridges and roads (common examples of national infrastructure). *This proposal is to extend geophysical sensor networks in a way similar to how the NSFnet and other research programs ultimately became the modern internet.* Backbone geophysical networks provide high quality and high accuracy reference data trusted by end-users and which form the basis for many critical applications. Their long duration operation establishes baseline behavior needed to identify changes and calibrate performance. Below we highlight a few of the applications that regularly rely on the infrastructure of geodetic and seismic networks. We close by identifying potential agency partnerships.

Critical Infrastructure Networks

Geodetic: Modern geodetic networks provide near- to real-time positioning and data on changes in Earth's atmosphere and ionosphere. The NSF Network of the Americas (NOTA-operated by UNAVCO) provides critical positioning for modern science seeking to understand and forecast earthquakes, volcanic eruptions, landslides, and aquifer-related subsidence and uplift during droughts. These geodetic networks also support research into the complex phenomena underlying mountain growth, impact from melting glaciers, and how the planet itself responds to climate change. They have also come to serve applications that are critical for numerous other federal agencies, including the USGS' efforts in Earthquake Early Warning (EEW), NGS/NOAA's interest in national geodetic control, tsunami warning, and real-time weather forecasting, NASA's maintenance of a global reference frame, and planetary science, sea level rise and crustal geodynamics programs. The Earth science positioning needs and capabilities dovetail with those of the Departments of Transportation, Agriculture, Commerce, Interior, and Defense, especially those requiring long-term observation (decades) at stable monuments with the most modern instrumentation available.

Seismic: Seismic networks monitor ground vibrations, and were originally intended as a tool to determine Earth structure and measure the properties of earthquakes. Seismic waves are also generated by nuclear explosions, volcanic eruptions, landslides, mining activity, rivers, ocean waves, hurricanes, traffic, and a variety of other transient processes. Seismic networks have found uses in monitoring all of these phenomena, as well as changes in subsurface conditions due to, for example, groundwater levels. They are also essential for recently operational EEW systems that can potentially provide tens of seconds of warning before damaging ground shaking following a major earthquake in the western US. The NSF/USGS Global Seismic Network (GSN - operated by IRIS) of broadband seismometers provides the highest quality data with even coverage over the entire planet. With national and global reach, the GSN is critical for monitoring earthquakes around the globe that have potential to create tsunamis that impact US coastal regions. The GSN thus provides an essential complement to the USGS Advanced National Seismic System, a backbone of seismic stations within the US, and the regional seismic networks that exist in nearly every state. The latter are managed by state or academic entities and provide key information on local earthquakes, including ones induced by human activities in locations such as Oklahoma and Texas.

A transformative opportunity is emerging to deploy seismic sensing networks over distances of tens of kilometers using Distributed Acoustic Sensing (DAS) on existing internet fiber across the U.S. Currently, limited access to existing fiber optic network infrastructure is a barrier to progress that may be overcome with a coordinated national approach. At a spatial resolution of a few meters, DAS networks can monitor engineering infrastructure, vehicular traffic, and natural hazards to the benefit of multiple federal agencies, commercial entities, and research communities with impacts analogous to other major technologies like computing infrastructure.

Agency Partnerships

The NOTA and GSN, designed originally for scientific applications, were established with the highest technical standards of instrumentation and installation, are maintained by full-time professional staff, and have helped propel development in observational technologies. Their utilization crosses directorate boundaries within the NSF, and spans multiple agencies with scientific missions (e.g., NSF, NASA, USGS) and those that support safety from natural hazards (USGS, NOAA), support the economy (NOAA/NGS, DOA, DOT) and national security (DOD, DOE). While applications of the technologies vary, the core systems that support the data streams are consistent and interoperable. The infrastructure also serves private sector aspirations, e.g., flying drones through cities to deliver packages or driving tractors remotely for efficient agriculture, and are helping to track and monitor a rapidly changing climate. Pervasive use of data streams from these systems is growing across domains of the US society and needs robust protection. However, existing equipment is aging and recapitalization, modernization, and extension of the systems are at the forefront of priorities established by the NSF IPRC.

This broad utility is one of the best possible outcomes of NSF's previous research investments. However, it has also created a situation where the need for NSF to support these critical systems has limited the US scientific community's ability to pursue innovations that would ordinarily be driven by evolving scientific goals. We advocate allocation of coordinated federal support for these networks, enabling their continued use by multiple agencies while freeing NSF to support instrumentation priorities at the cutting-edge of scientific discovery.

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Chapter 9. Appendix

9.1 Glossary of Acronyms

ANET	Antarctic (GNSS) Network
BB	Broad Band (seismic sensor)
BSM	Borehole Strainmeter
CONVERSE	Community Network for Volcanic Eruption Response
CORES	Catalyzing Opportunities for Research in the Earth Sciences, aka Earth in Time Report
CTBTO	Comprehensive Nuclear-Test-Ban Treaty Organization
DAS	Distributed Acoustic Sensing
DMC	Data Management Center
DOA	Department of Agriculture
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EAR	Earth Sciences Division, Geoscience Directorate, National Science Foundation
EEW	Earthquake Early Warning
EOS	End of Service is the epoch when the manufacturer no longer supports the device.
EOL	End of Life when there is "no useful" life in the device. EOS usually arrives before EOL.
FACA	Federal Advisory Committee Act
FAIR	Findability, Accessibility, Interoperability, and Reuse
GNET	Greenland (GNSS) Network
GSN	Global Seismographic Network
GAGE	Geodetic Facility for the Advancement of GEoscience
GGN	NASA Global GNSS Network
GLONASS	Russian operated GNSS system
GNSS	Global Navigation Satellite System (includes GPS, GLONASS, Galileo, etc.)
GPR	Ground Penetrating Radar
GTSM	Gladwin Tensor Strain Monitor
INS	Inertial Navigation System

InSAR	Synthetic Aperture Radar Interferometry
IPRC	Instrumentation Portfolio Review Committee
IRIS	Incorporated Research Institutions for Seismology
JPL	Jet Propulsion Laboratory
Lidar	Light Detection and Ranging
MEMS	Micro Electro-Mechanical Systems
MET	Molecular Electronic Transfer
MREFC	Major Research Equipment and Facilities Construction
MT	Magnetotelluric
NASA	National Aeronautics and Space Administration
NASEM	National Academies of Sciences, Engineering, and Medicine
NGS	National Geodetic Survey
NHERI	Natural Hazards Engineering Research Infrastructure Program
NISAR	NASA-ISRO SAR mission
NOAA	National Oceanographic and Atmospheric Administration
NOTA	Network of the Americas
NSF-EAR	National Science Foundation Division of Earth Sciences
OBSIC	Ocean Bottom Seismic Instrument Center
OPP	National Science Foundation Office of Polar Programs
PASSCAL	Portable Array Seismic Studies of the Continental Lithosphere
PBO	Plate Boundary Observatory
PI	Principal Investigator
RCN	Research Coordination Network
RENRM	Retain existing equipment, no recapitalization or maintenance
SAGE	Seismological Facilities for the Advancement of Geoscience
SfM	Structure from Motion
SUAS	(small) Uncrewed Aircraft System
SWIR	Short Wave Infrared
TLS	Terrestrial Laser Scanning or Scanner
USGS	United States Geological Survey
UNAVCO	University NAVSTAR Consortium, now UNAVCO, Inc.

VNIR	Visible Near Infrared
WinSAR	Western North America InSAR Consortium

9.2 Additional figures

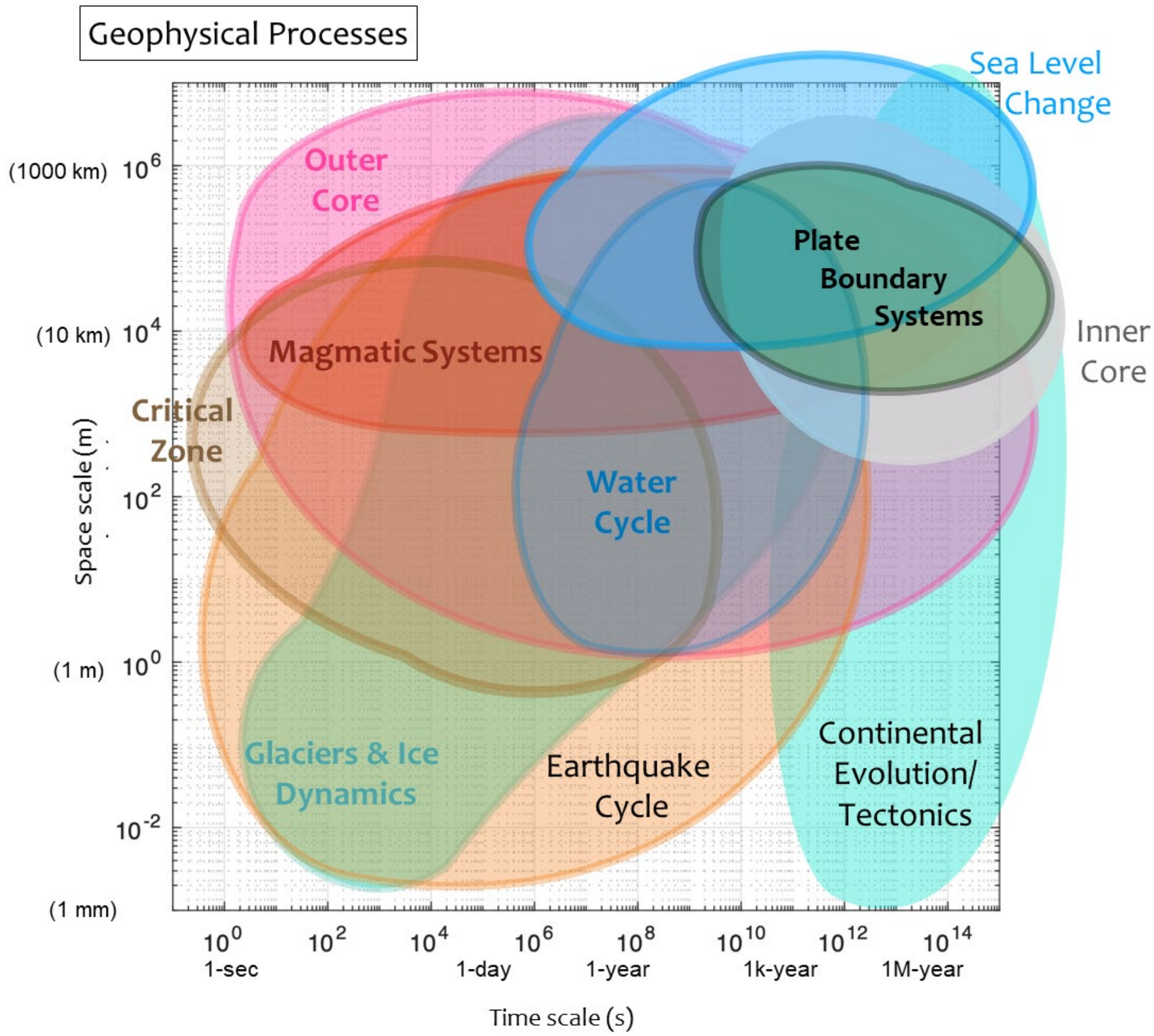

Figure 9.1. Temporal and spatial scale of geophysical processes examined using the tools of geodesy and seismology (Figure 9.2). Figure by Bill Hammond.

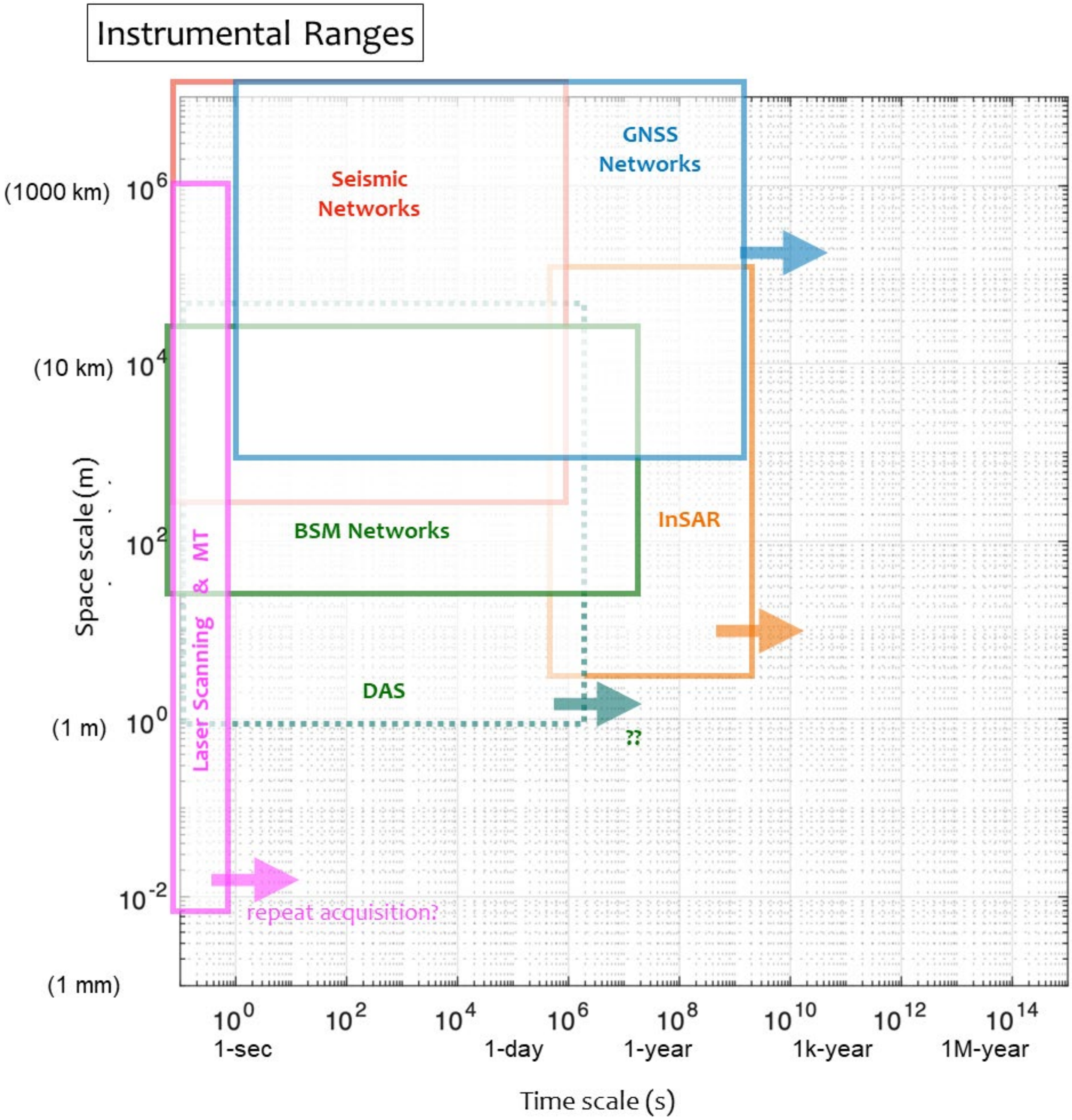

Figure 9.2. Temporal and spatial ranges of geodetic and seismological instrumentation. Figure by Bill Hammond.