Report of the SDC First Research *and* Applications Workshop

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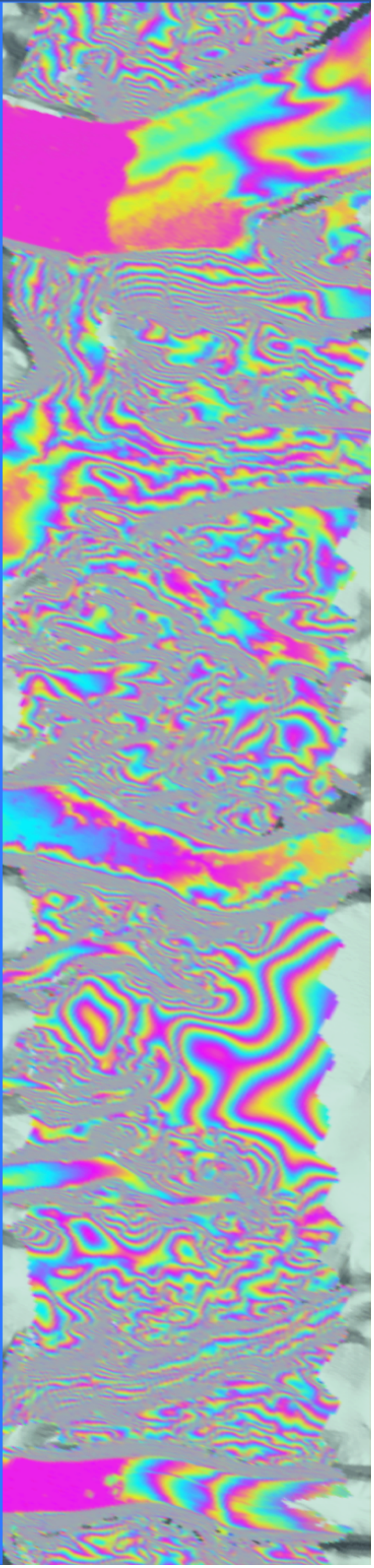

SDC First Research and Applications Workshop
Report of Outcomes and Recommendations

Summary

The first Research and Applications workshop of the Surface Deformation and Change (SDC) study was held between April 29 and May 1, 2019 at Caltech in Pasadena, CA.

The main aims of the workshop were to review the Decadal Survey science and application objectives for clarity and completeness, to prioritize SDC measurements needed to advance those science and application objectives, and to refine their measurement parameters.

The 65 participants were divided into 4 focus areas: Cryosphere, Solid Earth, Geohazards and Ecosystems. Most of the work to realize workshop aims was done during breakout sessions for each of the focus areas.

Common recommendations emerged across the focus areas. There was a shared emphasis on the need to sustain the continuity of measurements to extend existing time series. Regarding geodetic measurement parameters, the most sought attribute was for high temporal sampling of daily or better, which is currently unfulfilled by the existing sensors. An often-cited spatial resolution for finer-scale measurements was 10 m, which is comparable with that of NISAR and Sentinel-1. The desired vertical accuracies of surface deformation measurements varied widely depending on the target and the duration over which change is assessed, and was as small as 1 mm/yr. There was a repeated preference for L-band to maintain signal coherence between passes. Preliminary architecture concepts were proposed, all revolving around the concept of a constellation of satellites, driven by the desire for higher temporal sampling frequency.

Focus areas also had certain desired measurement capabilities that were divergent, while not necessarily incompatible. Geohazards and Ecosystems both described several applications that need amplitude-based measurements. On the other hand, while single polarization would be sufficient for most Geohazards, Solid Earth and Cryosphere science objectives, Ecosystems identified several desired polarization configurations. Short data latency of 1 to 3 hours was of interest particularly to Geohazards. That focus area was also most concerned with local coverage and targeted acquisitions, while the other focus areas aimed for global coverage with consistent repeat sampling.

The focus groups identified areas of research and applications that were not well represented during this first workshop and recommended engaging these communities in future workshops and seeking their input through focused telecons and related community meetings. These areas are key hydrological, sea ice and permafrost science and applications objectives.

Participants furthermore proposed the creation of a navigable electronic SATM that would accommodate the many detailed comments and suggestions made during the discussions, which would be helpful in the process of evaluating alternative observational architectures as the SDC study progresses.

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First SDC Research and Applications Workshop

Report of Outcomes and Recommendations

1. Background and Aims

Dates, Location and Participants

The First Research and Applications Workshop as part of the Surface Deformation and Change study was organized by the SDC study "Research and Applications Team" (R&A Team) and held April 29 to May 1, 2019, at Caltech (Hameetman Auditorium) in Pasadena. The agenda of the meeting is shown in Appendix 3.1. There were 60 to 70 participants mostly from NASA Headquarters, several NASA centers, USGS and academia. The list of participants is shown in Appendix 3.2. Participants were divided among four science and applications focus areas based on the SDC-related disciplines in the 2017 Decadal Survey: Solid Earth, Geohazards, Cryosphere and Ecosystems; as shown in Appendix 3.3.

Aims of the Workshop

The list below shows the main aims of the workshop. Most of the work to realize those was done during the breakout sessions. There were 7 hours of breakouts, divided over 4 sessions starting on Monday afternoon and occupying most of the workshop time on Tuesday (see meeting agenda in Appendix 3.1). The discussion topics during the breakout sessions were listed in descending order of priority, which also suggested to the participants the rough chronology of tackling them. Future SDC R&A workshops would be opportunities to build on the findings of this first workshop, and to further discuss the issues that the focus groups did have the chance to address.

The main aims of the workshop were to:

- Review the Decadal Survey science and application objectives for clarity and completeness, and prioritize.
- Refine the measurement parameters for the science and application objectives, and identify measurement parameters as minimum or target capabilities.

The discussion topics of the workshop breakouts were:

- Identify key observational characteristics that are needed to **advance** the science and applications of in each focus area.
  Approach:
  - Identify observations made by the Program of Record, especially NISAR, that are key to **continue** over the next 5-10 years.
  - Identify what characteristics of those observations are highest priority to improve or change (e.g., temporal sampling, shorter data latency, higher spatial resolution).

- Review the Decadal Survey science and application objectives related to each focus area in the SATM (or the preliminary Ecosystem and amplitude-based SATM) for clarity and completeness.
  Approach:
    - Identify science and application objectives that need to be simplified, expanded or modified for clarity. Are there community documents that support these modifications?
    - Some science and application objectives have two or more corresponding geophysical observables. Prioritize those geophysical observables.
- Refine the measurement parameters related to each focus area as given in the SATM, and identify measurement parameters as minimum or target capabilities.
  Approach:
    - Identify and modify measurement parameters that need to be more specific or changed in other ways for clarity. For example, would observations at higher spatial resolutions be needed everywhere?
    - Identify measurements parameters that need to be modified to advance the science of each focus area either through continuity or improved observations. Indicate whether these are minimum or desirable capabilities to advance the science.
- Prioritize the SDC science and applications objectives based on the criteria applied by the Decadal Survey, and other relevant criteria.
- Identify or propose tools and procedures that can be used to assess the enhanced science to be achieved by the different architectures that will be considered at a later stage in the SDC study. Consider both the scientific advances and added societal benefits that a certain architecture would allow.
- As SDC objectives could be met with a heterogeneous constellation of public and private satellites, existing and planned, identify the potential research and applications benefits of combining and coordinating the observations of these systems.
- Begin to define notionally the attributes of candidate observing systems (e.g., frequencies; polarization; …). Other aspects to consider are data latency and the rapidity of their flow to high-level data products, geolocation accuracy, etc.

Science and Applications Traceability Matrix (SATM)

The starting point of the work of the focus groups was the SATM (Appendix 3.4), which was extracted from the 2017 Decadal Survey (DS). There was a total of 23 science and application objectives related to SDC initially identified in the DS. Following NASA direction, the SDC study will include some observation architecture options that support research and applications measurements of additional Ecosystems-related observables such as biomass, soil moisture, vegetation structure, vegetation disturbance, agriculture, wetlands, coastal and ocean processes, sea ice hazards, and others, including a balance between optimization for phase-based geodetic performance and support for amplitude-based radiometry. To complement the science and societal questions, goals, applications, and related geophysical parameters, the SATM components shown in Appendix 3.5 were included in addition to Decadal Survey

objectives as a starting point for workshop discussions, based on NISAR efforts and community engagement.
We aggregated SATM science and societal benefit questions into the 4 focus areas listed below. Our aggregation and inclusion of Ecosystems led to the following science and applications focus areas for breakout discussions:

We distributed the SDC-related science and applications objectives identified in the 2017 Decadal Survey, and the Ecosystems topics, among the four focus areas as such:

- Cryospheric Sciences:
    Ice sheets, glaciers, sea ice, permafrost
- Solid Earth:
    Landscape changes produced by abrupt events or by continuous reshaping of Earth's surface due to surface processes, tectonics, and human activity
- Geohazard and disaster applications:
    Detection of volcanic eruption precursors; earthquake, volcano and tsunami response; detection of flood water and debris flows extent; land subsidence including of coastal regions; transportation and utility infrastructure monitoring; iceberg and sea-ice monitoring for sea-lane accessibility)
- Ecosystems and other amplitude-based radiometry observables:
    Biomass, soil moisture, vegetation structure, agricultural monitoring, wetlands processes, and related topics

For each of the Earth Science/Application Objectives in the Decadal Survey SATM, shown here in Appendix 3.4, we identified the associated focus area (shown in green in the table) used for organizing breakouts and discussion periods during the workshop.

Note: The DS describes the entries in the SATM regarding geophysical observable, measurement parameters and examples of measurement approaches as non-comprehensive suggestions, rather than recommendations or definitive guidance.

2. Outcomes and Recommendations

2.1 Cryospheric Science and Applications

Observational Characteristics Needed to Advance Science and Applications

General Remark on the Priority of Cryospheric Research and Applications

SAR satellite measurements of ice sheets, glaciers, sea ice, snow and permafrost have been identified in the DS as *most important* and therefore should be given appropriate priority when balancing with SAR observations desired by other disciplines.

Cryosphere SATM

Addressing Question C-1, the Cryosphere focus group ranked the priority of *geophysical observables* with a color code: Most Important, Very Important and Important.

Societal or Science Question/Goal	**Earth Science/Application Objective**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches**	
				Method	**PoR**
QUESTION C-1. How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	**C-1c.** Determine the changes in total ice sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come	Ice velocity (ice sheets):		InSAR (except geometry and mélange)	PoR-12
		Fast flowing outlet glaciers, grounded and floating (>50 m/yr)	Daily (targeted) to weekly (all), 1-5 m/yr horizontal accuracy, 100 m horizontal resolution		
		Slow flowing ice-sheet interiors (>50 m/yr)	Once yearly, 0.1 m/yr horizontal accuracy, 1 km horizontal resolution		
		Ice velocity (mountain glaciers): Arctic, Alaska, Patagonia, Himalayas**)**	Monthly, 1 m/yr horizontal accuracy, 50 m horizontal resolution		
		Shear margins (grounded and floating)	Daily to weekly, 1 m/yr horizontal accuracy, 10-25 m horizontal resolution		
		Fracture and calving:			
		Strain rates	Daily to weekly, 1 m/yr horizontal accuracy, 10-25 m horizontal resolution		
		Geometry and mélange	Amplitude-based imagery, Daily to weekly, 10-25 m horizontal resolution		
		Grounding lines (+/- 50 km of current locations)	Weekly to monthly, 30 mm vertical accuracy between acquisitions, 100 m horizontal resolution		

		Interior subglacial lakes (lake drainage)	2-4 times per year, 100 m horizontal resolution, 1 m/yr accuracy		

Sea Level Rise (Questions C-1 and S-3)

- The subject of ice sheet change and sea level rise corresponded to the strength of the group and comprised the majority of our discussion.

- Regarding the cryosphere component of sea level change, SAR is well-suited to support efforts needed to make meaningful projections of sea level change. Specifically, SAR observations can contribute to studies of ice sheet dynamics (flow), processes and attribution; and to constraining numerical models. SAR complements measurements of net mass balance of the ice sheets (gravity and altimetry).

- On centennial timescales, changes in the cryosphere will dictate changes in global mean sea level (GMSL).

- Uncertainty in projections GMSL is dominated by uncertainties in the dynamic (flow) response of outlet glacier and ice streams to changes in melt rates, ice shelf thickness, calving rates and friction at the ice-bed interface.

- Question C-1 is addressed in detail here (see SATM above) as GMSL will in turn drive changes on centennial timescales in local/regional sea level rise, which is the subject of Question S-3. Answering Questions C-1 and S-3 necessitates high-priority SAR measurements of the ice sheets.

- The need for high temporal and high spatial resolution acquisitions of outlet glacier and ice stream velocities was identified as a key necessity for advancing the understanding of glacier mechanics and improving ice sheet projections. Ice sheets are subject to large diurnal and fortnightly tidal forcing and weekly to seasonal changes in basal hydrology.

Sea Ice

While the initial SATM included the science and applications objectives that the Decadal Survey deemed to be relevant to SDC (see the table in Appendix C of the DS), the Cryosphere focus group felt that potentially other geophysical observables could benefit from SAR, and recommended examining Table B.2 of the DS for such observables. In particular, topics related to sea ice were not present in the initial SATM. Questions in Table B.2 that contain sea ice observables are listed below with a brief description of measurement parameters:

C-6 (concentration, thickness; 1 to few km, 1-10 days)
C-7 (extent, thickness; 0.5° lon/lat, daily)

C-8 (concentration, extent, type, motion/deformation, thickness, snow thickness; 0.1-10 km, 20 cm vertical for sea ice and snow thicknesses, 1-3 days)
W-2 (concentration, thickness; 10 km, 50 cm for thickness, daily)
W-3 (concentration, motion, thickness; 5-25 km, 3 km/day for motion, 50 cm for thickness, daily)

The focus group recommended the following observables with regards to sea ice (and icebergs) without attempting to prioritize them at this stage:

- Sea ice type (stages of growth)
  - Frequency dependent, polarization diversity are necessary
  - Twice weekly distant form margins
  - Daily at the margins
  - 50 m (size of small ice flow)

- Sea ice motion & leads
  - Daily to fill gaps in PoR
  - 50 m

- Sea ice polynyas
  - Spatial resolution 50 m
  - Daily to weekly

- Icebergs
  - Need to sample hourly
  - Targeted to shipping lanes
  - Need 5 m resolution within 3hr for shipping lanes
  - Sub-weekly repeat

Snow Water Equivalent (Question H-1)

Can SAR be used to answer this question? We request that the SDC study team assess the feasibility/maturity of using SAR (time delay or topography) of any frequency to measure snow water equivalent (SWE) within 10% accuracy. Daily L-Band might work. Consider the European CoRe-H20 project proposal. Given the uncertainty of the applicability of SAR to this problem, the focus group decided not to include this question in its analysis of capabilities.

Permafrost (Question C-8)

Other than sea level rise, the group did not feel qualified to provide meaningful desired capabilities for this important science question. Seeking further input is recommended.

Key Program of Record Observations to Continue

The PoR should continue indefinitely. A long (30+ years) record of surface deformation (ice flow, grounding lines, ice fronts) is required to resolve climate trends relevant to projections. Observation frequency, resolution and accuracy should increase with time to improve processes understanding.

Tools and Procedures to Assess Enhanced Science

- Expanding the NISAR performance tool to include probability of grounding line detection.

- Ice sheet model (e.g., ISSM) data assimilation and performance tool for improved physics provided by SAR observations.

- Include DEM error in analysis (how often does DEM need to be updated for interferometry requirements for non-zero baseline)

Coordination of Observing Constellations

Coordination is taking place through the Polar Space Task Group.

Suggestions of Observing Systems

The sampling frequency and spatial resolution needs of the most important ice sheet observables may be best served by a flock of satellites (likely high-frequency, e.g., X-band, due to per-unit cost) with targeted acquisitions. The need for higher sampling frequency and spatial resolution was discussed at length, but the specifics of the observing system that could satisfy such requirements were not.

Recommendations for Next Steps

- Expand involvement of the snow, sea ice and permafrost communities to help identify capabilities specific to those sub-disciplines. Aspects to explore include:

Snow
- Snow Water Equivalent (SWE) from SAR
- Freeze-thaw cycles
- Snow covered area

Sea ice
- Sea ice type
- Sea ice area
- Sea ice concentration
- Sea ice deformation
- Sea ice drift

Permafrost
- Active layer depth
- Freeze-thaw cycles

- There was discussion of the utility of InSAR for measuring changes in ice sheet and glacier topography but it was unclear if InSAR alone could meet the stringent requirements needed for mass change science. It is recommended the SDC solicit a review of InSAR capabilities for measuring changes in ice sheet surface topography.

2.2 Solid Earth Science and Applications

Observational Characteristics Needed to Advance Science and Applications

As noted in the 2017 Decadal Survey summary of the designated Targeted Observable (TO-19, Appendix C) Surface Deformation and Change is cited by nearly all of the Earth Surface and Interior science and applications objectives including 6 of the Most Important, 5 Very Important and 5 Important (Chapter 10 of the Decadal Survey). As discussed earlier in this report, we chose to break these science objectives into "Solid Earth" and "Geohazards" subsections and some of the hydrological objectives were included in these panels for the workshop. This subsection summarizes the findings of the Solid Earth focus group, and the next those of Geohazards.

A simplified version of the reviewed SATM is included below that highlights the importance of the SDC capabilities to the specific geophysical variables related to Solid Earth science objectives.

Science Question/Goal	Objective	Importance in DS	Importance of SDC
Solid Earth Q1: How can large-scale geological hazards be accurately forecast in a societally relevant timeframe?	**1a: Volcanic Eruptions**	**Most**	**Most**
	1b: Earthquake Cycle	Most	Most
	1c: Landslides	Very	Most
Solid Earth Q3: How will local sea level change along coastlines around the world in the next decade to century?	3b: Vertical motion of land along coastlines	Most	Most
Solid Earth Q6: How much water is traveling deep underground and how does it affect geological processes and water supplies?	6a: Fluid pressures, storage, and flow in confined aquifers	Very	Most
	6d: Determine the impact of water-related human activities and natural water flow on earthquakes	Important	Very
Solid Earth Q4: What processes and interactions determine the rates of landscape change?	4a: Landscape change due to surface processes, tectonics, societal activities	Most	Very
Hydrology Q2: How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally, and globally, and what are the short- and long-term consequences?	2c: Quantify how changes in land use, land cover and water user elated to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies.	Most	Very

Solid Earth Q5: How does energy flow from the core to the Earth's surface?	5a: Interaction between mantle convection and plate motions	Very	Important
Solid Earth Q7: How do we improve discovery and management of energy, mineral, and soil resources?	7a: Mapping for management of energy, mineral, agricultural, and natural resources	Important	Important

Unlike some of the other Decadal Survey chapters, the Earth Surface and Interior Land Surface Deformation requirements for different science objectives were very specific. When we reviewed Table 10.3 (below) we made only minor modifications and they are given in green:

Adopted from Decadal Survey Table 10.3 and amended by Solid Earth breakout (green text), note that from the Decadal, requirements for Decadal Survey's "Most Important" objectives are presented in bold. Solid Earth breakout contributors added a requested number of deformation components for some objectives.

Objective	Spatial Resolution	Precision	Frequency	Duration
S-1a	**10 m**	**10 mm**	~~**Event dependent**~~ **Daily**	**10+ years (3 deformation comp.)**
S-1b	**10 m**	**10 mm**	~~**12 days**~~ **Daily**	**10+ years (3 deformation comp.)**
S-1c	~~50 m~~ 10 m	1 mm/yr	~~< Seasonal~~ Daily	**10+ years (3 deformation comp.)**
S-2a	**10 m**	**10 mm**	**Event dependent**	
S-2b	10 m	1 mm/yr	Event dependent	
S-2c	100 m	1 mm/yr	Event dependent	5+ years
S-3a	**100 m**	**10 mm/yr**	**< Seasonal**	
S-3b	**< 50 m**	**5-10 mm**	**Weekly**	**10+ years**
S-4a	**< 5 m**	**5-10 mm**	**Weekly**	**10+ years**
S-5a	100 m	10 mm		
S-6a	~~5 m~~ 10 m	10 mm	Weekly	**10+ years (3 deformation comp.)**
S-6b	5 m	3 mm/yr	Weekly	
S-7a	5 m	10 mm	Weekly	

Extended periods of time in the break-out groups were devoted to a discussion of the top priorities for the SDC observation capabilities needed to advance the Solid Earth science and applications objectives. These included:

- *Higher temporal sampling than the current InSAR PoR that includes the ESA Sentinel series and NISAR.* This was the highest observation priority especially for earthquake and volcano processes. This was also important for maintaining signal coherence for the deformation time series.

- *A desired capability discussed extensively was to measure 3 components of deformation* (beyond the line of sight displacements such as that obtained from ascending and descending passes). 3-D deformation is desired to disentangle tectonic/volcanic/hydrologic processes occurring simultaneously in many regions. In the future, this may provide an important capability for enabling continuity and it would promote use of all available SAR mission data in the same model.

- *Better corrections for the atmospheric delay when measuring surface deformation.* Forward/backward squint and synergy with A-CCP measurements may enable more reliable corrections.

- *Long-term time series are needed to understand processes that occur on decadal and greater time scales.*

In anticipation of the evaluation of different observing capabilities, important discriminators that could drive Architecture Priorities were highlighted for Solid Earth needs:

- *Global land coverage* with free and open data.
- *No strong need for polarization data.* Higher spatial or temporal resolution was a higher priority than polarization.
- *Data latency was not a strong need for the Solid Earth group*.
  Data latency is the time between the sensor observation and data products being available for a science or applications user in their analysis. The Solid Earth group focused on science needs, with the that most of the related applications were being discussed in Geohazards breakout.
- Preference for L-band to ensure coherence continuity between passes especially in vegetated regions.

Tools and Procedures to Assess Enhanced Science

The Solid Earth group recommended doing analysis on scenario based synthetic and recovery assessments. These assessments should build on some existing studies, e.g., those using UAVSAR and GPS. An example of an assessment study would be one where we look at the measurement needs to separate coseismic and postseismic processes. The group also recommended adding some simple modeling components to the performance tool to relate it to various geophysical scenarios. This effort could start with Most Important Science Objectives and could be applied to evaluating the problem of disentangling multiple processes – e.g., postseismic deformation + groundwater deformation. Enhancements to the performance tool to evaluate how various qualities of atmospheric correction affect our ability to resolve deformation were also recommended.

Recommendations for Next Steps

- *Refinement/editing of the complete solid Earth SATM* and combine with other SATM suggestions and contributions into a navigable, electronic format to share with the community for further input. During the review of the SATM many comments and suggestions were placed in the notes column. These need to be culled and refined for inclusion in the final SATM in some way. This work can be accomplished by telecons that include Jeanne Sauber (SDC R&A Team), Solid

Earth breakout chair Susan Owen, and others that participated in the SE breakout at the workshop.

- To enable better representation of the Hydrology science and applications we need to expand our SDC team to include at least several members of this community. A separate Hydrology breakout group should start from our SATM and then through telecons take ownership.

2.3 Geohazards Science and Applications

Observational Characteristics Needed to Advance Science and Applications

The 2017 Decadal Survey summarized Targeted Observables to include Surface Deformation and Change (SDC) for several societal or science questions and goals that the workshop gathered for representation as a breakout on "Geohazards" with several participants who are actively engaged in the use of synthetic aperture radar measurements inclusive of both phase and backscatter. Of the questions proposed by the 2017 Decadal Survey, we include here a high-level summary description of the geohazard aspect of the longer "societal or science question" in the 2017 Decadal along with the degree of importance:

Science Question/Goal	Objective	Importance in DS	Priority for SDC
H-4: How does the water cycle interact with other Earth System processes to change the predictability and impacts of hazardous events and hazard-chains, and how do we improve preparedness?	4a: Hazard Response	Most Important	4
S-1: How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?	1a: Volcanic Eruptions	Most Important	5
	1b: Earthquake Cycle	Most Important	2
	1c: Landslides	Very Important	3
S-2: How do geological disasters directly impact the earth system and society following an event?	2a: Transient Processes	Most Important	6
	2b: Surface Deformation	Most Important	6
	2c: Earthquakes	Most Important	6
S-3: How will local sea level change along coastlines around the world in the next decade to century?	3b: Coastal Subsidence	Most Important	1

Following the guidance offered to the breakout session leads, the geohazards team focused on summarizing responses in general categories to describe the characteristics of observations necessary to meet the goals of the 2017 Decadal regarding SDC as a targeted observation. To advance the science and applications of the Geohazards area, it is expected that Program of Record (PoR) continuity includes the current state into the next 5-10 years: ongoing programs of value to the Geohazards community include routine C-band collections from Sentinel-1 and the upcoming NISAR mission, along with non-SDC measurements complimentary to radar-based observations such as higher spatial resolution optical imaging from the Landsat series, Sentinel-2, and a growing constellation of commercial optical imaging currently available through NASA's Commercial Data Buy Pilot Program.

When asked to identify the most important characteristics of future missions benefitting Geohazards through observations of surface deformation and change, priorities were:

- more frequent temporal sampling,
- combined higher resolution with a longer radar wavelength to mitigate issues in deep vegetation canopies.

Breakout participants were asked to review science and applications areas specific to Geohazards, and to refine measurement parameters related to these areas by reporting out desired minimums. Participants chose to consider various categories of geohazards aligned with the 2017 Decadal science objectives in order to give clarity to the needs of each hazard topic, and where necessary, parsed out varying needs as they relate to different aspects of each hazard type:

Volcanoes, Earthquakes, and Landslides

	Wavelength	Sampling Frequency	Resolution	Desired Accuracy
Monitoring	L-band	<= 6 days	10 m	1-5 mm/yr 1-5 cm for consecutive acquisitions
+Crisis Response	L-band	<= 24 hours	10 m ++3 m	1-5 cm for consecutive acquisitions
Post-Event	L-band	<= 3 days	10 m	1-5 cm for consecutive acquisitions

+In all "crisis response" scenarios, it is assumed that data latency (the time between satellite-acquired observation and data in-hand for analysis) needs to be minimized, desired as 3 hours or less.

++During the breakout discussions, some contributors noted that even higher spatial resolution imaging for crisis response would advance key science and applications areas of damage mapping, a specific scientific and societal question asked by the Decadal Survey's S-2c.

- For *monitoring*, L-band with 6-day repeat cycle was sufficient, and measurement accuracy permitting long-term surface deformation rates of 1-5 mm/y and changes between consecutive acquisitions of 1-5 cm over the precursor image.
- For *crisis response*, most events begin with onset of the hazard, though for landslides the monitoring of precipitation, slope, and other geological considerations can provide some prediction. As these events unfold, imaging is requested with less than 10 m spatial resolution (3 m or less is believed to help advance some science and applications areas), with sampling frequency of better than daily, latency (defined here as data delivered for analysis) of less than 3 hours, and an accuracy of 1-5 cm between consecutive acquisitions.
- For *post-event*, timing is to include the weeks following the event with characteristics equal to "crisis response", but with reduced sampling to less than three days and latency of 12-24 hours.

Coastal Subsidence

	Wavelength	Sampling Frequency	Resolution	Desired Accuracy
Monitoring	L-band	<= 6 days	<= 50 m	1 mm/y over 5-10 yrs of measurement 5-10 cm/yr over a period of 1-2 yrs

- Advancing science and applications in this topical area requires a good measurement of subsidence in low-elevation coastal areas to determine the subsidence component relative to surrounding sea level rise: 1 mm/y over 5-10 years of measurements and 5-10 cm/yr over a period of 1-2 years of measurements.

- There is a need to map at a spatial resolution of 50 m or less because of soil composition, layer depth variability, and shallow compaction.
- Large-scale measurements require improved tropospheric and ionospheric corrections
- There are challenges in maintaining coherence across multiple collections in these regions, therefore a 6-day repeat cycle is needed and at L-band wavelength
- Ancillary data and instruments including GPS/GNSS is required for geodetic tie-points

Flooding, Inundation, and Related Hazards

	Wavelength	Sampling Frequency	Resolution	Desired Accuracy
Monitoring	L-band	[+]<= 6 days	10 m	2 cm
Crisis Response	L-band	[++]3-6 hours	10 m [+++]3 m	2 cm DEMs assist with depth estimations
Post-Event	L-band	<= 3 days	10 m	2 cm

[+] In flood mapping activities, the "monitoring" phase requires sufficient sampling frequency to establish a reliable pre-flood water extent for mapping of changes against a pre-event baseline. Breakout participants mentioned that improved, higher-resolution DEMs are beneficial for supporting flood mapping activities and supporting modeling efforts.

[++] Flood events are rapidly changing due to ongoing precipitation, incoming streamflows, damage to levees and sudden changes caused by flash flooding, and other uncertainty. Crisis response activities benefit from as frequent observations as can reasonably be made, along with minimizing data latency to end users and analysts.

[+++] During the breakout discussions, some contributors noted that even higher spatial resolution imaging for crisis response would advance key science and applications areas of damage mapping, a specific scientific and societal question asked by the Decadal Survey's S-2c.

- Very frequent observations are required during a flood event, at least daily, along with a period of record for baseline pre-flood conditions. Similar to *crisis response* aspects of geological hazards, higher sampling frequency is needed as a flood event unfolds, whereas less sampling frequency is typically needed to establish the normal extent of water bodies such as lakes, rivers, streams, and coastlines.
- Longer wavelength imaging (L-band) with polarization capabilities to discern inundated vegetation areas and standing water that contribute to comprehensive mapping.
- Digital elevation models at high spatial resolution (better than present) are needed to assist with the derivation of water depth from flood maps derived from L-band data.
- Long-term subsidence measures such as those described in *Coastal Subsidence* contribute to understanding of changing risk, particularly in areas with rapid change or where current observations of subsidence rates are not available.
- SDC observations that contribute to measures of soil moisture can be helpful as contributions to flood modeling, especially for neighborhood-scale and other high spatial resolution applications.

When asked to prioritize the SDC science and applications objectives listed by the 2017 Decadal Survey, participants were asked to consider: 1) How well are these topics being addressed by extant and near-future instruments? 2) What is the impact to people and property? and 3) How significantly would an SDC observation improve the current state-of-the-art? Based upon these considerations, priorities ranked by the Geohazards breakout group ranked as following and are included as the right-most column in the table starting this section:

- S-3b: Coastal Subsidence
- S-1b: Earthquakes and Surface Deformation
- S-1c: Landslide Hazards
- H-4a: Floods and Flood Risk
- S-1a: Volcanoes and Surface Deformation
- S-2a, S-2b, and S-2c: Geological Disasters and Impacts

Tools and Procedures to Assess Enhanced Science

Geohazards breakout participants believe that the radar performance simulation tool developed for NISAR will be informative for understanding how a given architecture would benefit addressing of science questions and applications outcomes from a future SDC-focused mission, as would aircraft acquisition of SDC-like data that could be produced in a comparable format, repeat pattern, and temporal resolution (i.e., UAVSAR as it was flown to support NISAR or a comparable future capability).

Suggestions of Observing Systems

When asked to consider the notional attributes of a future observing system architecture, all science and applications areas require InSAR with sub-daily observations for crisis response, though depending upon the specific question these sub-daily repeats may be possible through combination of different constellations. Single polarization imaging is sufficient, and longer wavelengths desirable for phase and backscatter to assist with penetration of vegetation as coherence is an issue for virtually all of the proposed science and applications areas.

Recommendations for Next Steps

Refinement and Editing of SATM: Geohazards breakout team members contributed highly detailed feedback on various aspects of future measurement requirements which will be captured in more detail through inclusion into a revised SATM document.

Collaboration with Hydrology and Ecosystems: Some aspects of Geohazards topics have shared interests with hydrology and ecosystems, such as the mapping of water extent, flood, wetlands, and inundation, generation of higher resolution DEMs, goals for the temporal and spatial resolution of imaging, and other topics. Where relevant, Geohazards breakout session participants, session lead, and/or SDC Study R&A Team member(s) can help to share information and reach consensus in areas with overlapping topic interests.

2.4 Ecosystems Science and Applications

Ecosystems SATM

We constructed an Ecosystems-focused SATM by identifying the science goals that could be achieved if the SDC mission were able to accommodate our preferred capabilities. The ability of SAR to achieve the desired geophysical observables was supported by the strong representation of radar platforms in the PoR.

Societal or Science Question/Goal	**Earth Science/Application Objective**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches**	
				Method	**PoR**
Characterize the spatial distribution of carbon and biodiversity in the ecosystem	Mapping spatial extent of woody vegetation (e.g. forest/non-forest map)	Forest Extent	100 m or better resolution, at 80% of area Desire for higher-resolution (< 100 m) to capture small-scale linear features	Cross-Pol or better Full-Polarimetric SAR Backscatter time series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-12 (P-band BIOMASS) PoR-14 (GEDI)
	Habitat mapping, carbon monitoring	Vegetation structure -> Canopy height and vertical distribution	100 m or better spatial resolution, vertical accuracy 10 m or better.	Single-pol InSAR, or dual-pol PolInSAR or TomoSAR (single or repeat-pass) Coherence and phase Baseline (0 and non-zero)	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)
	Measure above ground vegetation biomass	Biomass	100 m resolution or better where biomass is < 100 Mg/ha, 20 mg/ha over 80% of area	SAR Polarimetric (HV mostly) backscatter	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-12 (BIOMASS)
Understand ecosystem response to disturbance events	Measure changes in above ground woody vegetation biomass annually	Biomass Change	100 m, 80% or better classification accuracy where canopy cover changes by > 50%	SAR Polarimetric Backscatter temporal change	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-12 (BIOMASS)
	Episodic events (e.g. natural and anthropogenic disasters)	Change in landcover due to flooding, wildfire, wind, insects, anthropogenic.	250 m or better resolution, better than 50%	Backscatter temporal change	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)

Quantify the accuracy of mapping wetlands	Measure inland and coastal wetlands areas at a resolution of 1 hectare every 12 days	Inundation	100 m, 80% or better classification accuracy, need to track beginning and end of flooding	HH backscatter Contrast Backscatter time-series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1)
	Measure relative water level changes in wetlands	Relative Water Level Change	100 or better spatial resolution, with 10 cm or better vertical accuracy	HH InSAR Backscatter time-series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-27 (SWOT)
Monitor trends and conditions of agriculture in a timely manner	Measure active crop area at 1 hectare resolution every 3 months with a classification accuracy of 80%	Crop Extent	80% or better classification accuracy	Polarimetric backscatter contrast and temporal change Backscatter time-series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)
	Monitor global soil moisture content	Soil Moisture	1 km or better spatial resolution in low biomass covered areas at 80% accuracy	Full-Polarimetric or Quasi-quad pol Backscatter	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-23 (SMAP)
	Predict and monitor crop yield	Crop Yield	250 m or better, measured per growing period		PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)
	Classification of crop type	Structure and structure changes over growing season Soil Moisture Inundation mapping (rice)	30 m domestic, 1 ha globally, per growing period over given field.	Time series change and backscatter monitoring	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)
	Management practices	crop rotation, tillage, multi-use, plant and harvest time	Field level (1 ha), measured annually	Time series change and backscatter monitoring	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-9 (Landsat) PoR-9 (Sentinel-2) PoR-12 (C-band Sentinel-1)

This SATM is ecosystems specific, but builds upon a wide range of targeted observables in the 2017 Decadal Survey. The focus group felt that SAR was overlooked in the Decadal Survey for a wide range of science goals. From the 2017 Decadal Survey, 23 science and application objectives that relate to SDC were identified, of which 4 (H-2c, C-7b, C-8f, S-4b; Appendix 3.4) were applicable to ecosystems. We were given scope to address this deficiency in the Decadal Survey and evaluate which science and application objectives were achievable with SAR. We identified an additional 31 such science and application objectives. This took much of our focus but was a necessity in order to evaluate the ability of SDC to meet as many of the ecosystems-related science goals of the Decadal Survey as possible. Through this we identified the science and application objectives that needed to be expanded and/or modified for clarity, supported by the NISAR science user's handbook. The additional science and application objectives were:

- Soil Moisture:
    - W-2a, W-3a, H-1a, H-2a, H-2c, H-3b, H-3c, H-4b, H-4c, H-4d, E1-c, E-1d, E-3a, E-5a, C-5a, C-6b, S-4b, S-6b (a total of 17)
- Vegetation cover and vegetation cover change (disturbance):
    - E-1e, E-2a, E-3a, C-3a, C-3c, C-5a (6)
- Vegetation Structure:
    - H-3c, E-1b, E-1e, E-5a, E-5c (5)
- Biomass:
    - E-4a, C-3a (2)
- Inundation:
    - H-4a (1)

Following this we identified the key observational characteristics that were needed to advance the Ecosystems science and applications. These included:

- Cross-Pol and InSAR at L-band
- 10-20 m resolutions
- NISAR-like revisit periods (Soil moisture: 1-3 days)
- Continuity of time-series
- Global coverage over land surfaces

The ecosystems-focused capabilities of SDC can leverage a range of observational characteristics. These can include amplitude, phase and information on polarimetry. For SDC, we identified these key observational characteristics based upon the geophysical observables that can be attained by NISAR. Looking forward to SDC, the ability to continue to achieve these would be beneficial for building a long-term archive of SAR observations. This has important implications for observing phenomena that typically occur over longer time-scales than a single platform.

Suggestions of Observing Systems

Based on the Decadal Survey science and applications goals, we identified the following characteristics of SDC to satisfy ecosystems desired capabilities:

- Non-zero baseline InSAR
- Along-track interferometry
- A NISAR companion satellite (passive)

These would aim to provide an increased temporal sampling frequency needed by some geophysical observables and also provide continuity from existing radar platforms that have strong ecosystems requirements (NISAR). Increased temporal sampling frequency could be provided by a heterogeneous constellation of public and private satellites. Alternatively, it is possible that SDC could take the form of a NISAR companion platform (passive), as this would enable NASA to leverage existing assets to achieve the objectives of both missions. This companion platform would remain viable with a NISAR follow-on mission. The attributes of any such candidate observing system would include L-band frequency, cross-pol and multi-baseline InSAR.

Recommendations for Next Steps

- The Ecosystems team will meet, via a teleconference, to discuss and finalize the Ecosystems SATM.
- The Ecosystems team will also assign an importance to the geophysical observables in the Ecosystems SATM. We will evaluate our acquisition preferences to attain these and subsequently categorize them into 'baseline' and 'ideal'.
- We will also meet with the Research and Application leads to convey our results and recommendations from an Ecosystems perspective.

2.5 Synergies with Other Designated Observables and Missions

During the workshop, Batuhan Osmanoglu gave a summary presentation on the synergies between SDC science and applications objectives and the objectives of the other 2017 Decadal Survey (**DS**) Designated Observable (**DO**) studies, i.e., **M**ass **C**hange (MC), **S**urface **B**iology and **G**eology (SBG), and **A**erosol and **C**loud, **C**onvection and **P**recipitation (A-CCP). Appendix 3.6 shows tables that illustrate the Targeted (Geophysical) Observable synergies for each of the 5 **DS** theme areas (Climate, Ecosystems, Hydrology, Solid Earth, and Weather). Also, the tables show added synergies that were not identified by the **DS** such as science and application objectives that SDC mission scenarios could address in the Ecosystems focus area. As part of the SDC study in its first year, the three R & A leads acted as liaison to each of the other DO studies and they attended team meetings. Ala Khazendar was the liaison to A-CCP, Jeanne Sauber to MC, and Andrew Molthan to SBG. Those interactions resulted in the following examples of science and applications objectives that could be jointly addressed by SDC and the other DOs.

<u>A-CCP and SDC Synergy Possibilities</u>

Climate
- Sea ice tracking using A-CCP radar.
- Ice sheet elevation using A-CCP lidar.

Hydrology
- Relationship between snow-fall and snow accumulation.
- Relationship between precipitation and soil moisture.

Weather
- Can A-CCP Cloud Lidar improve the atmospheric phase correction for SDC?
- Perhaps A-CCP modeling can benefit from SDC water vapor time series.

<u>MC and SDC Synergy Possibilities</u>

Climate
- Quantifying the cryosphere contribution to sea-level change: Ice velocities (flux) using InSAR and basin scale Mass Change.
- Sea ice extent and thickness using SAR and geoid changes from GRACE.

Hydrology
- Downscaling MC total water mass change in basins using InSAR.
- Relationship between precipitation and soil moisture.
- Improve drought monitoring to forecast short-term impacts.

Solid Earth
- Radar backscatter and InSAR phase change for high temporal and spatial resolution land surface change with MC providing long-wavelength, global coverage for earthquake cycle processes.
- InSAR based quantification of local/regional coastal land change to complement GRACE-derived sea-level change.

SBG and SDC Synergy Possibilities

Climate

- Sea ice extent and thickness using SAR.
- Radar backscatter and InSAR phase change for land surface change (e.g. freeze/thaw).

Ecosystems

- Radar backscatter and InSAR phase change for vegetation structure, biomass change.

Hydrology

- SDC measurement of high-resolution snow cover and possibly SWE, and soil moisture.
- Drought monitoring at high spatial resolution and sub-weekly sampling.

Solid Earth

- InSAR phase change for surface deformation time series.

Weather

- Radar backscatter for ocean wind vectors.

3. Appendices

3.1 Workshop Agenda

Surface Deformation and Change Study
Research & Applications Workshop
Caltech, Pasadena, CA, April 29, 30, May 1

Agenda

Monday April 29 Morning (Hameetman Auditorium)

8:00am Coffee & Pastries

8:30am (15 min) Welcome and purpose of meeting (Charles Elachi)
8:45am (15 min) Welcome and meeting plan (R&A Team)
9:00am (15 min) Overview of SDC Study (Paul Rosen)
9:15am (30 min) The View from HQ (Gerald Bawden)

9:45am (15 min) Break

Recent Directions in Research and Applications

10:00am (30 min) Geohazards and Disaster Applications (Ken Hudnut, USGS)
10:30am (30 min) Solid Earth (David Sandwell, UCSD)
11:00am (30 min) Cryosphere (Brent Minchew, MIT)
11:30pm (30 min) Hydrology (Jeff Dozier, UCSB)

12:00pm (75 min) Lunch

Monday April 29 Afternoon (Salvatori Seminar Room)

1:15pm (1 hour) Program of Record, Phenomenology, Technology advances (Rosen et al.)

2:15pm (30 min) Discussion of working groups activities and assignments
    Cryosphere (Moderator: Alex Gardner)
    Ecosystems (Moderator: Paul Siqueira)
    Geohazards (Moderator: Cathleen Jones)
    Solid Earth (Moderator: Susan Owen)

2:45pm (15 min) Break

3:00pm (2 hrs) Four working groups parallel meetings
    Gutenberg Library, South Mudd 256

Conference Room, South Mudd 162
Conference Room, South Mudd 176
Salvatori Seminar Room, South Mudd 365

5:00pm End of Day

Tuesday April 30 (Hameetman Auditorium)

8:00am Coffee & Pastries

8:30am (30 min) Community Engagement (Andrew Molthan)
9:00am (30 min) Coordination and Synergies with other DO and Missions (Batu Osmanoglu)
9:30am (30 min) Criteria to Assess Science Values and Science Applications Objectives (Randy Friedl)

10-10:30am Break

10:30am (2 hours) Four working groups parallel meetings
Cryosphere (Moderator: Alex Gardner)
Ecosystems (Moderator: Paul Siqueira)
Geohazards (Moderator: Cathleen Jones)
Solid Earth (Moderator: Susan Owen)

Gutenberg Library, South Mudd 256
Conference Room, South Mudd 176
Conference Room, Keith Spalding 415
Hameetman Auditorium

12:30pm (75 min) Lunch

1:45pm (1.5 hours) Four working groups parallel meetings continue

3:15-3:30pm Break

3:30pm (1.5 hours) Four working groups parallel meetings continue

5:00pm End of Day

Wednesday May 1 (Hameetman Auditorium)

8:00am Coffee & Pastries

8:30-10:30am (4 x 30 min) Presentations by Working Group Moderators
10:30-11:30am Discussion of way forward (R&A Team, Paul, Charles)

11:30am End of Meeting

3.2 Workshop Participants

1. Adrian Borsa (UCSD)
2. Ala Khazendar (JPL)
3. Alex Gardner (JPL)
4. Andrew Molthan (MSFC)
5. Belgacem Jaroux (ARC)
6. Ben Holt (JPL)
7. Bernd Scheuchl (UCI)
8. Bruce Chapman (JPL)
9. Byron D. Tapley (UT Austin)
10. Cathleen Jones (JPL)
11. Charles Webb (NASA HQ)
12. David Bearden (JPL)
13. David Bekaert (JPL)
14. David T. Sandwell (UCSD)
15. Eric Fielding (JPL)
16. Eric Rignot (UCI, JPL)
17. Filippo Cantani (Univ. Florence)
18. Franz Meyer (UAF)
19. Gary Jedlovec (MSFC)
20. George E. Hilley (Stanford)
21. Gerald Bawden (NASA HQ)
22. Heresh Fattahi (JPL)
23. Howard A. Zebker (Stanford)
24. Ian Joughin (UW)
25. Jeanne Sauber (GSFC)
26. Jeff Dozier (UCSB)
27. Jordan Bell (MSFC/UAH)
28. Marc Simard (JPL)
29. Mark Simons (Caltech/JPL)
30. Paul Lundgren (JPL)
31. Paul Rosen (JPL)
32. Paul Siqueira (UMass Amherst)
33. Pietro Milillo (JPL)
34. Piyush Agram (JPL)
35. Randy Friedl (JPL)
36. Sang-Ho Yun (JPL)
37. Scott Hensley (JPL)
38. Shadi Oveisgharan (JPL)
39. Shanti Rao (JPL)
40. Stephen Horst (JPL)
41. Surendra Adhikari (JPL)
42. Susan Owen (JPL)
43. Tom Farr (JPL)
44. Tony Freeman (JPL)
45. Venkatachalam Ramaswamy (NOAA)
46. Zhen Liu (JPL)
47. Zhong Lu (SMU)
48. Fabio Rocca (Milan Polytech.)
49. Alessandro Ferretti (TRE ALTAMIRA)
50. Laura Rogers (LaRC)
51. Esayas Gebremichael (MSFC/UAH)
52. Nathan Thomas (GSFC/UMD)
53. Seungkuk Lee (GSFC)
54. Mike Falkowski (NASA HQ)
55. Andrea Donnellan (JPL)
56. Derek Posselt (JPL)
57. Gareth Funning (UCR)
58. Margaret Glasscoe (JPL)
59. Katia Tymofyeyeva (JPL)
60. Anh Nguyen (ARC)
61. Brent Minchew (MIT)
62. Ken Hudnut (USGS)
63. Helene Seroussi (JPL)
64. Erik Ivins (JPL)
65. Eric Larour (JPL)

3.3 Participants in Each Focus Group

Cryosphere:

1. Alex Gardner (JPL; Moderator)
2. Ben Holt (JPL)
3. Erik Ivins (JPL)
4. Ian Joughin (UW)
5. Ala Khazendar (JPL)
6. Pietro Milillo (JPL)
7. Brent Minchew (MIT)
8. Shadi Oveisgharan (JPL)
9. Eric Rignot (UCI/JPL)
10. Bernd Scheuchl (UCI)
11. Charles Webb (NASA HQ)

Solid Earth:

1. Piyush Agram (JPL)
2. David Bekaert (JPL)
3. Andrea Donnellan (JPL)
4. Tom Farr (JPL)
5. Eric Fielding (JPL)
6. Zhen Liu (JPL)
7. Zhong Lu (SMU)
8. Paul Lundgren (JPL)
9. George E. Hilley (Stanford)
10. Susan Owen (JPL; Moderator)
11. Paul Rosen (JPL)
12. David T. Sandwell (UCSD)
13. Jeanne Sauber (GSFC)
14. Mark Simons (Caltech/JPL)
15. Ekaterina Tymofyeyeva (JPL)
16. Byron Tapley (UT Austin)
17. SangHo Yun (JPL) Howard
18. Zebker (Stanford)

Geohazards

1. Gerald Bawden (NASA HQ)
2. Alessandro Ferretti (TRE ALTAMIRA)
3. Margaret Glasscoe (JPL)
4. Ken Hudnut (USGS)
5. Cathleen Jones (JPL; Moderator)
6. Andrew Molthan (MSFC)
7. Sang-Ho Yun (JPL)
8. Laura Rogers (LaRC)

Ecosystem

1. Jordan Bell (MSFC)
2. Bruce Chapman (JPL)
3. Mike Falkowski (NASA HQ)
4. Seung Kuk Lee (GSFC)
5. Marc Simard (JPL)
6. Paul Siqueira (UMass Amherst; Moderator)
7. Nathan Thomas (GSFC/UMD)

3.4 SDC-related SATM Derived from the Decadal Survey

Societal or Science Question/Goal	Earth Science/Application Objective	Geophysical Observable	Measurement Parameters	Example Measurement Approaches	
				Method	PoR
QUESTION H-1. How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?	**H-1c.** Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide at scales driven by topographic variability. **Cryospheric Sciences**	Snow water equivalent (SWE).	Global SWE at 1 (desirable) or 4 km (needed) resolution every 3-5 days, to 10 % accuracy for SWE values to 1 m.	Existing passive microwave for global scale okay for SWE values to ~200 mm. Problematic for deep snow in heterogeneous terrain.	PoR-23
			In mountains, SWE at ~100 m resolution suitable for SWE values to 2.5 m.	In mountains, measure depth (Ka band radar or laser altimeter) and density (SAR).	PoR-17 (KaRIN, SWOT)
QUESTION H-2. How do anthropogenic changes in climate, land use, water use, and water storage, interact and modify the water and energy cycles locally, regionally and globally and what are the short- and long-term consequences?	**H-2c.** Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, threatening sustainability of future water supplies. **Solid Earth** **Ecosystems**	Recharge rates (i.e. space-time rates of change in groundwater storage and availability) at 1 (desired) up to 10 km (useful) scale globally at 10-day intervals with accuracy of better than ± 1 mm/day	Land surface deflection to 1 cm accuracy, 100 m spatial resolution.	L-band InSAR. Perhaps combined with airborne lidar.	PoR-12
QUESTION H-4. How does the water cycle interact with other Earth System processes to change the predictability and impacts of hazardous events and hazard-chains (e.g. floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?	**H-4a.** Monitor and understand hazard response in rugged terrain and land-margins to heavy rainfall, temperature and evaporation extremes, and strong winds at multiple temporal and spatial scales. This socioeconomic priority depends on success of addressing H1b and H1c, H2a, and H2c. **Geohazard and disaster applications**	Magnitude and frequency of severe storms. Depth and extent of floods.	Precipitation, snowmelt, water depth, and water flow in soil at time and space scales consistent with events.	For precipitation and snow: Similar to SWOT but at finer spatial resolution.	See H-1b and 1c See H-1b and 1c
				For River Discharge: Similar to SWOT but at finer spatial resolution.	PoR-26 (SWOT)
	H-4b. Quantify key meteorological, glaciological, and solid Earth dynamical and state variables and processes controlling flash floods and rapid hazard chains to improve detection, prediction, and preparedness. (This is a critical socio- economic priority that depends on success of addressing H1b, H1c and H4a). **Geohazard and disaster applications**	Rainfall intensity and volume for storms in the 95th percentile of values specific to areas, especially estimates in mountainous terrain where other measurement sources are not available, soil moisture, SWE, and glacier changes.	Precipitation, snowmelt, and flow in soil and glaciers at time and space scales consistent with events.	See measurement approaches associated with Objective H-2c.	PoR-23
QUESTION S-1. How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?	**S-1a.** Measure the pre-, syn-, and post eruption surface deformation and products of the Earth's entire active land volcano inventory at a time scale of days weeks. **Solid Earth** **Geohazard and disaster Applications**	Land surface deformation	At least 2 components of land surface deformation and strain localization (e.g., surface fracturing) over length scales ranging from 10 m to 1000 km and a precision of 1 mm at a sampling frequency related to the volcanic activity. Regionally-sampled global coverage.	L- or S-band InSAR with Ionospheric correction, [GPS/GNSS]	PoR-12 (NISAR)
	S-1b. Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades. **Geohazard and disaster applications** **Solid Earth**	Land surface deformation	At least 2 components of land surface deformation 10 m to 1000 km resolution and precision of 1-10 mm at a sampling frequency related to seismic/tectonic activity. Ideally, resolution of 1 mm/week. Need more	L- or S-band InSAR with ionospheric correction, [GPS/GNSS].	PoR-12 (NISAR)

			than 10 year of observations to measure interseismic deformation		
	S-1c. Forecast and monitor landslides, especially those near population centers. **Geohazard and disaster applications** **Solid Earth**	Land surface deformation	At least 2 components of land surface deformation at <50 m spatial resolution and 1mm/yr at a temporal frequency <seasonal (InSAR and GPS/GNSS)	L- or S-band InSAR, [GPS/GNSS] {Complements ground-based seismic data}	PoR-12 (NISAR)
QUESTION S-2. How do geological disasters directly impact the earth system an society following an event?	**S-2a.** Rapidly capture the transient processes following disasters for improved predictive modeling as well as response and mitigation through optimal retasking and analysis of space data **Geohazard and disaster applications**	Provide rapid deformation map acquisitions and interconnectivity to other sensors	At least 2 components of land surface deformation over 10 m to 1000 km length scales at 10 mm precision and ASAP after the event. Adequate resolution of 1 cm/week for afterslip applications	InSAR	PoR-12 (NISAR)
	S-2b. Assess surface deformation (<10 mm), extent of surface change (<100 m spatial resolution) and atmospheric contamination, and the composition and temperature of volcanic products following a volcanic eruption (hourly to daily temporal sampling) **Geohazard and disaster applications**	Land surface deformation	At least 2 components of land surface deformation and surface fracturing over length scales ranging from 10 m to 1,000 km and temporal resolution of 1 mm yr-1 at a sampling frequency related to the volcanic activity (InSAR and GPS/GNSS). Everywhere.	L- or S-band InSAR with Ionospheric correction, [GPS/GNSS]	PoR-12 (NISAR)
	S-2c. Assess co- and postseismic ground deformation (spatial resolution of 100 m and an accuracy of 10 mm) and damage to infrastructure following an earthquake. **Geohazard and disaster applications**	Land surface deformation	At least 2 components of land surface deformation at 100 m spatial resolution and 1 mm yr-1 at a temporal frequency related to the tectonic activity (InSAR and GPS/GNSS). Need more than 10 years of interseismic observations and 5 years of post seismic observations	L- or S-band InSAR with ionospheric correction, [GPS/GNSS]	PoR-12 (NISAR)
QUESTION S-3. How will local sea level change along coastlines around the world in the next decade to century?	**S-3a**. Quantify the rates of sea level change and its driving processes at global, regional, and local scales, with uncertainty < 0.1 mm yr-1 for global mean sea-level equivalent and <0.5 mm yr-1 sea-level equivalent at resolution of 10 km. **Cryospheric Sciences**	3D surface deformation vectors on ice sheets Ice velocity	Monthly, cm yr^{-1} accuracy, 100 m resolution and better than seasonal sampling Monthly or less, uncertainty <10 cm yr^{-1} over areas of 100 km^2	InSAR InSAR	PoR-12 (NISAR) PoR-12 (NISAR)
	S-3b. Determine vertical motion of land along coastlines at uncertainty <1 mm yr 1. **Solid Earth** **Geohazard and disaster applications**	Land surface deformation	5-10 mm vertical precision, <50 m horizontal, weekly	InSAR	PoR-12 (NISAR)
QUESTION S-4. What processes and interactions determine the rates of landscape change?	**S-4a**. Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface due to surface processes, tectonics, and societal activity. **Solid Earth**	Land surface deformation Reflectance for freeze/thaw spatial and temporal distribution	5-10 mm vertical precision, <50 m horizontal, weekly <50 m horizontal, weekly	L- or S-band InSAR, [UAVSAR], [GNSS]. Radar reflectivity	PoR-12 (NISAR) PoR-9 (Pleiades, RADARSAT-2), PoR-12 (NISAR)
	S-4b. Quantify weather events, surface hydrology, and changes in ice/water content of near surface materials that produce landscape change. **Ecosystems**	Reflectance for freeze/thaw spatial and temporal distribution Reflectance for snow depth / snow water equivalent	< 50 m horizontal, weekly SWE at ~100 m resolution suitable for SWE values to 2.5 m.	Radar reflectivity Ka band radar or laser altimeter (depth) and SAR (density) InSAR	PoR-12 (NISAR) PoR-17 (KaRIN, SWOT) PoR-12 (NISAR)
QUESTION S-5. How does energy flow from the core to the Earth's surface?	**S-5a**. Determine the effects of convection within the Earth's interior, specifically the dynamics of the Earth's core and its changing magnetic field	Determine plate motions and deformation and track the evolution of plate boundaries	SAR interferometry, 10 mm vertical, 100m mm horizontal	L-band InSAR with ionospheric correction	PoR-12 (NISAR)

	and the interaction between mantle convection and plate motions. **Solid Earth**				
QUESTION S-6. How much water is traveling deep underground and how does it affect geological processes and water supplies?	**S-6a**. Determine the fluid pressures, storage, and flow in confined aquifers at spatial resolution of 100 m and pressure of 1 kPa (0.1 m head). **Solid Earth**	Land surface deformation	For seasonal variations: 1 cm/yr measured weekly at 10 m spatial sampling (which allows stacking for sub cm secular trends)	L- or S-band InSAR, [GPS/GNSS]	PoR-12 (NISAR)
	S-6b. Measure all significant fluxes in and out of the groundwater system across the recharge area. **Solid Earth**	Deformation from fluid fluxes (uses several above measurements) Land surface deformation	Spatiotemporal distribution of subsidence/uplift at 3 mm vertical per year, 5 m horizontal, weekly. Coverage over active reservoirs. Spatiotemporal distribution of subsidence/uplift at 1 cm vertical, 5 m horizontal, weekly. Coverage over managed watersheds, other watersheds of interest	L- or S-band InSAR, [GPS/GNSS] L- or S-band InSAR, [GPS/GNSS]	PoR-12 (NISAR) PoR-12 (NISAR)
	S-6c. Determine the transport and storage properties in situ within a factor of 3 for shallow aquifers and an order of magnitude for deeper systems. **Solid Earth**	Deformation from fluid fluxes (uses several above measurements)	Spatiotemporal distribution of subsidence/uplift at 3 mm/yr vertical, 5 m horizontal, weekly. Coverage over active reservoirs.	L- or S-band InSAR, [GPS/GNSS]	PoR-12 (NISAR)
	S-6d. Determine the impact of water-related human activities and natural water flow on earthquakes. **Solid Earth**	Vertical surface deformation	Spatiotemporal distribution of subsidence/uplift at 3 mm/yr vertical, 5 m horizontal, weekly	L- or S-band InSAR, [GPS/GNSS] {seismic data and production/injection data from regulatory agencies}	PoR-12 (NISAR)
QUESTION S-7. How do we improve discovery and management of energy, mineral, and soil resources?	**S-7a**. Map topography, surface mineralogic composition/distribution, thermal properties, soil properties/water content, and solar irradiance for improved development and management of energy, mineral, agricultural, and natural resources. **Solid Earth**	Land surface deformation	Spatiotemporal distribution of subsidence/uplift at 1 cm vertical, 5 m horizontal, weekly	L- or S-band InSAR with ionospheric correction, [GPS/GNSS]	PoR-12 (NISAR)
QUESTION C-1. How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage?	**C-1c.** Determine the changes in total ice sheet mass balance to within 15 Gton/yr over the course of a decade and the changes in surface mass balance and glacier ice discharge with the same accuracy over the entire ice sheets, continuously, for decades to come **Cryospheric Sciences**	Ice sheet velocity	Horizontal resolution/range: 100 m / pole to pole; Temporal sampling: weekly to daily; Precision: 1 m/yr in fast flow areas, 1 cm/yr near ice divides	SAR (e.g., NISAR), Landsat	PoR-12
QUESTION C-7. How are decadal scale global atmospheric and ocean circulation patterns changing, and what are the effects of these changes on seasonal climate processes, extreme events, and longer term environmental change?	**C-7b.** Quantify the linkage between natural (e.g., volcanic) and anthropogenic (greenhouse gases, aerosols, land-use) forcings and oscillations in the climate system (e.g., MJO, NAO, ENSO, QBO). Reduce the uncertainty by a factor of 2. Confidence levels desired: 67% **Ecosystems**	The relevance of this objective to SDC in the DS is rather vague.			
QUESTION C-8. What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes?	**C-8f.** Determine how permafrost-thaw driven land cover changes affect turbulent heat fluxes, above and below ground carbon pools, resulting greenhouse gas fluxes (carbon dioxide, methane) in the Arctic, as well as their impact on Arctic amplification.	Freeze-thaw state Active layer thickness Lake and wetland fraction	Weekly, at 100m horizontal and 5-10 cm vertical resolution Bi-weekly (except in winter, when no measurement is needed) at 100m horizontal and 5 cm vertical resolution	Passive microwave radiometers, scatterometers, SAR; InSAR, C + L-band SAR; Tomographic SAR; Airborne EM; GPR; SMAP AirMOSS (P-band SAR); UAVSAR (L-band InSAR); Airborne-EM; OIB low-frequency radars; ground based (or airborne) GPR	PoR-12 (PALSAR), PoR-12 (Sentinel-1), PoR-23 (SMAP) PoR-12 (L-band PALSAR), POR-12 (NISAR)

	Cryospheric Sciences **Ecosystems** **Geohazard and disaster applications**		Bi-Monthly at 100-250m	Optical instruments (e.g. MODIS, Landsat, SPOT, Sentinel-2), active SAR instruments (C+L bands),	PoR-12 (PALSAR) PoR-12 (Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2) PoR-27 (SWOT) PoR-21 (MODIS)
		Snow water equivalent	Daily at 1km, within 1 cm SWE	Combination of sensors: e.g., laser altimetry, polarimetric imaging radar, microwave imaging radar, radiometers	PoR-23 (AMSR-2) PoR-23 (SMOS)
		Surface elevation	Annually at 50m resolution, within 2 cm uncertainty	Active SAR instruments (Interferometry), LIDAR; US L-band SAR; DLR Tandem-X and Tandem-L; ICESat-ATLAS	PoR-12 (L-band PALSAR) PoR-12 (S-band NISAR) PoR-12 (C-band Sentinel-1) PoR-14 (ICESat-ATLAS)

3.5 Preliminary SATM of objectives related to Ecosystems and Amplitude-Based Measurements

SATM was compiled by N. Thomas, B. Osmanoglu, L. Fatoyinbo, S-K. Lee and J. Sauber on the basis of NISAR and other community documents.

Societal or Science Question/Goal	**Earth Science/Application Objective**	**Geophysical Observable**	**Measurement Parameters**	**Example Measurement Approaches**	
				Method	**PoR**
Characterize the spatial distribution of carbon in the biosphere	Mapping spatial extent of vegetation (e.g. forest/non-forest map)	Forest Extent	100 m or better resolution, at 80% of area	Dual-Pol or betterFull-Polarimetric SAR Backscatter time series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-12 (P-band BIOMASS) PoR-14 (GEDI)
	Vegetation structure	Canopy height and vertical distribution	100 m or better spatial resolution, vertical accuracy 10m or better.	Single-pol InSAR, or dual-pol PolInSAR or TomoSAR	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)
	Measure above ground vegetation biomass	Biomass	100 m resolution or better where biomass is < 100 Mg/ha, 20 mg/ha over 80% of area	SAR Polarimetric backscatter	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-12 (BIOMASS)
Understand ecosystem response to disturbance events	Measure changes in above ground woody vegetation biomass annually	Biomass Change	100 m, 80% or better classification accuracy where canopy cover changes by > 50%	SAR Polimetric bBackscatter tempoeral change	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-12 (BIOMASS)
	Episodic events (e.g. natural and anthropogenic disasters)	Change	250 m or better resolution, better than 50%	Backscatter temporal change	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)
Quantify the accuracy of mapping wetlands	Measure inland and costal wetlands areas at a resolution of 1 hectare every 12 days	Inundation	100 m, 80% or better classification accuracy, need to track beginning and end of flooding	Polarimetric backscatter Contrast Backscatter time-series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1)
	Measure relative water level changes in wetlands	Relative Water Level Change	100 or better spatial resolution, with 10 cm or better vertical accuracy	InSAR Backscatter time-series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-27 (SWOT)
Monitor trends and conditions of agriculture in a timely manner	Measure crop area at 1 hectare resolution every 3 months with a classification accuracy of 80%	Crop Extent	80% or better classification accuracy	Polarimetric backscatter contrast and temporal change Backscatter time-series	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-9 (Landsat) PoR-9 (Sentinel-2)
	Monitor global soil moisture content	Soil Moisture	1 km or better spatial resolution in low biomass covered areas at 80% accuracy	Full-Polarimetric Backscatter	PoR-12 (L-band PALSAR) PoR-12 (L-band NISAR) PoR-12 (C-band Sentinel-1) PoR-23 (SMAP)

3.6 Mapping of Targeted Observable Synergies Among Studies

The following tables were prepared by B. Osmanoglu. The tables are for each DS theme areas, which are presented in alphabetical order. Each table has the four DO studies on the left-hand side forming the rows, and all identified targeted observables (TO) creating columns. If a TO can be addressed by a DO study, the intersecting cell is colored red, green or blue based on DS rankings: most important, very important and important, respectively. SDC team identified some other TO that SDC can contribute to, for which the corresponding cells are colored with pink, light green and light blue based on their ranking. If more than one DO can address a single TO, a short summary is listed below the table identifying a synergy.

Climate:

	DS	SDC
Most Important	🟥	🩷
Very Important	🟩	🟢
Important	🟦	🔵

	Climate																																												
	1 a	1 b	1 c	1 d	2 a	2 b	2 c	2 d	2 e	2 f	2 g	2 h	3 a	3 b	3 c	3 d	3 e	3 f	3 g	4 a	4 b	4 c	4 d	5 a	5 b	5 c	5 d	6 a	6 b	6 c	7 a	7 b	7 c	7 d	7 e	8 a	8 b	8 c	8 d	8 e	8 f	8 g	8 h	8 i	9 a
ACCP					🟥						🟩	🟥				🟦		🟦					🟦	🟩	🟦	🟩	🟦				🟩	🟦			🟦							🟦	🟦		🟦
MC	🟥	🟥	🟥	🟩																														🟦	🟦										
SBG													🟩		🟦	🟦													🟦						🟦						🟦				
SDC			🟥	🟢									🟢		🔵														🔵			🟦		🔵	🔵						🟦				

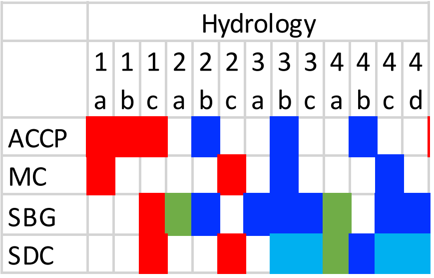
(MC, SDC) 1c. changes in total ice-sheet mass balance
(MC, SDC) 1d. Determine regional sea-level change to 1.5-2.5mm/yr.
(SBG, SDC) 3a. Quantify CO_2 fluxes … year-to-year carbon uptake (in ecosystems)
(SBG, SDC) 3c. carbon loss from large reservoirs (tropical forests, permafrost)
(ACCP, SBG) 3d. carbon uptake by ocean
(SBG, SDC) 6b. quantification land surface states
(SBG, SDC) 7d. Linkage between dynamic … state of the ocean upon atmosphere
(ACCP, MC, SBG, SDC) 7e. large scale…verification of models used for climate projections
(SBG, SDC) 8f. permafrost-thaw-driven land-cover changes affect … carbon pools

Ecosystems:

	Ecosystems														
	1 a	1 b	1 c	1 d	1 e	2 a	2 b	2 c	3 a	3 b	4 a	4 b	5 a	5 b	5 c
ACCP									🟥						
MC															
SBG	🟩		🟥	🟦		🟥			🟥				🟦	🟦	🟦
SDC				🔵							🔵				🔵

(SBG, SDC) 1d. Quantify moisture status of soils
(ACCP, SBG) 3a. Quantify the flow of energy, carbon, water and nutrients
(SDC) 4a. Terrestrial C pools and their rate of turnover.
(SBG, SDC) 5c. Understand ecosystem response to fire events

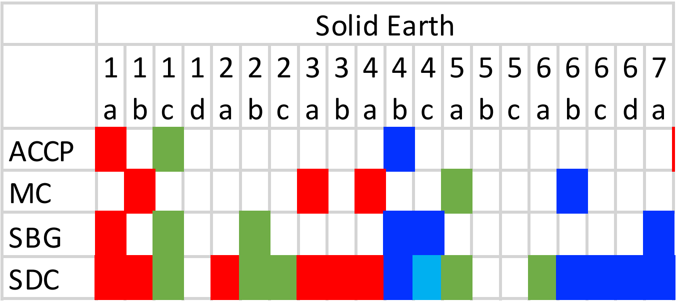
Hydrology:



	Hydrology												
	1 a	1 b	1 c	2 a	2 b	2 c	3 a	3 b	3 c	4 a	4 b	4 c	4 d
ACCP	🟥	🟥	🟥		🟦			🟦			🟦		
MC	🟥					🟥		🟦				🟦	
SBG			🟥	🟩	🟦		🟦	🟦	🟦	🟩		🟦	🟦
SDC			🟥			🟥		🔷	🔷	🟩	🟦	🔷	🔷

(ACCP, MC) 1a. accurately quantify the components of the water and energy cycles
(ACCP, SBG, SDC) 1c. Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation
(ACCP, SBG) 2b. anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt
(MC, SDC) 2c. changes in land use, land cover, and water use related to agricultural activities, food production
(ACCP, MC, SBG, SDC) 3b. changes (in) water quality, fluxes, and storages in and between all reservoirs
(SBG, SDC) 4a. Monitor and understand hazard response in rugged terrain
(ACCP, SDC) 4b. Quantify key meteorological, glaciological, and solid Earth dynamical and state variables
(MC, SBG, SDC) 4c. Improve drought monitoring to forecast short-term impacts
(SBG, SDC) 3c. Determine structure, productivity, and health of plants
(SBG, SDC) 4d. Understand linkages between anthropogenic modification of the land

Solid Earth:

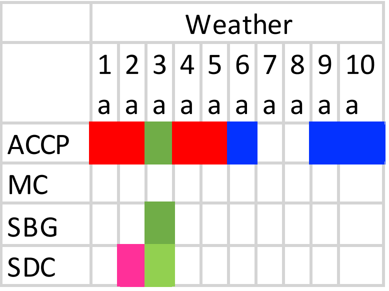


	Solid Earth																			
	1 a	1 b	1 c	1 d	2 a	2 b	2 c	3 a	3 b	4 a	4 b	4 c	5 a	5 b	5 c	6 a	6 b	6 c	6 d	7 a
ACCP	🟥		🟩								🟦									
MC		🟥						🟥		🟥			🟩				🟦			
SBG	🟥		🟩			🟩					🟦	🟦								🟦
SDC	🟥	🟥	🟩		🟥	🟩	🟩	🟥	🟥	🟥	🟦	🔷	🟩			🟩	🟦	🟦	🟦	🟦

(ACCP, MC, SDC) 1a. Measure the pre-, syn-, and post-eruption surface deformation
(MC, SDC) 1b. Measure and forecast interseismic, preseismic, coseismic, and postseismic activity

(ACCP, SBG, SDC)	1c. Forecast and monitor landslides, especially those near population centers.
(SBG, SDC)	2b. Assess surface deformation, extent of surface change, and atmospheric contamination
(MC, SDC)	3a. Quantify the rates of sea-level change and its driving processes
(MC, SDC)	4a. Quantify global, decadal landscape change produced by abrupt events
(ACCP, SBG, SDC)	4b. Quantify weather events, surface hydrology, and changes in ice/water content
(SBG, SDC)	4c. Quantify ecosystem response to and causes of landscape change
(MC, SDC)	5a. Determine the effects of convection within Earth's interior
(MC, SDC)	6b. Measure all significant fluxes in and out of the groundwater system
(SBG, SDC)	7a. Map topography, surface mineralogic composition and distribution, thermal properties, soil properties/water content, and solar irradiance

Weather:



	Weather									
	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a
ACCP	🟥	🟥	🟩	🟥	🟥	🟦			🟦	🟦
MC										
SBG			🟩							
SDC		🟪	🟩							

(ACCP, SDC)	2a. Improve the observed and modeled representation of natural, low-frequency modes of weather/climate variability (e.g., MJO, ENSO)
(ACCP, SBG, SDC)	3a. Determine how spatial variability in surface characteristics modifies regional cycles of energy, water, and momentum (stress)