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Special Section:
The Earth in living color: spectroscopic and thermal imaging of the Earth: NASA's Decadal Survey Surface Biology and Geology Designated Observable

Designing an Observing System to Study the Surface Biology and Geology (SBG) of the Earth in the 2020s

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Key Points:

- Spectroscopic and thermal observations will provide unprecedented information of the Earth's Surface Biology and Geology
- As part of the NASA Earth System Observatory, these observations will transform Earth science and environmental management
- This study informed mission design constraints to provide observations of value for science and decision-making applications

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Abstract Observations of planet Earth from space are a critical resource for science and society. Satellite measurements represent very large investments and United States (US) agencies organize their effort to maximize the return on that investment. The US National Research Council conducts a survey of Earth science and applications to prioritize observations for the coming decade. The most recent survey prioritized a visible to shortwave infrared imaging spectrometer and a multispectral thermal infrared imager to meet a range of needs for studying Surface Biology and Geology (SBG). SBG will be the premier integrated observatory for observing the emerging impacts of climate change by characterizing the diversity of plant life and resolving chemical and physiological signatures. It will address wildfire risk, behavior, and recovery as well as responses to hazards such as oil spills, toxic minerals in minelands, harmful algal blooms, landslides, and other geological hazards. The SBG team analyzed needed instrument characteristics (spatial, temporal, and spectral resolutions, measurement uncertainty) and assessed the cost, mass, power, volume, and risk of different architectures. We present an overview of the Research and Applications trade-study analysis of algorithms, calibration and validation needs, and societal applications with specifics of substudies detailed in other articles in this special collection. We provide a value framework to converge from hundreds down to three candidate architectures recommended for development. The analysis identified valuable opportunities for international collaboration to increase the revisit frequency, adding value for all partners, leading to a clear measurement strategy for an observing system architecture.

Plain Language Summary We present the observing system science, applications, and measurement objectives for studying the Earth's Surface Biology and Geology with a global visible to shortwave infrared imaging spectrometer and a multispectral thermal infrared imager as part of the NASA Earth System Observatory slated for launch in the late 2020s. This mission will enable interdisciplinary science relevant to studying the biology and geology of the Earth's surface unlike any other mission before. Measurements are relevant for studying snow and ice, mineralogy, volcanology, biology, ecology, and components of radiative forcing from the surface such as greenhouse gas emissions. The observations not only have scientific value in studying feedbacks and interactions of surface processes (e.g., wildfire) but also are invaluable to supporting real-world decision making such as water conservation, agriculture crop classification, forest health, and many others. The work presented here outlines the study conducted over 3 years that informed an architecture study to design a satellite observing system to provide the most value for science and applications as possible.

1. Introduction

Remote sensing is a critical technology for understanding spatial and temporal processes in the Earth system. The global fleet of Earth-observing satellites is continually being enhanced by more and more advanced measurements. The United States (US) National Aeronautics and Space Agency (NASA) is currently formulating the next major set of Earth-observing missions, based on a recent National Research Council (NRC) report (National

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Academies of Sciences [NAS], 2018). In this paper, we describe the early formulation of one of these missions, aimed at understanding the Earth's Surface Biology and Geology (SBG) including terrestrial and aquatic surface ecosystems, hydrology, and geology, and how they affect weather and climate. This paper will present the guidance given to NASA to frame this mission, and not the final measurements or design agreed to by the agency. It illustrates how the NRC guidance, subsequent analysis, and community input were used to identify the science and applications community's needs for advanced surface observations.

Climate change and human activities are causing rapid changes in almost all surface processes, many or most of which, directly affect humanity. The world is amidst a biodiversity crisis, with species and ecosystems endangered by a range of stressors, including the changing climate (Ruckelshaus et al., 2020). Warming and changes to hydrological regimes cause climate zones to move, with evidence showing that the *velocity of climate change* may exceed the ability of the biota to adapt, move, and so force the formation of no-analog systems as species move independently of one another (Loarie et al., 2009). Shifts, like the incursion of shrubs into the Arctic tundra or shifts in ecosystem composition and structure following tropical seasonality changes, require observations that can distinguish subtle changes to vegetation, which may not be fully captured by traditional greenness indices (Stavros et al., 2017).

Climate change greatly affects the terrestrial water cycle, through both supply (precipitation and snow melt) and demand (evapotranspiration—"ET"), both "most important" SBG science questions (Box 1). Changes to snow cover (Bormann et al., 2018) affect both snow-covered areas directly (Winchell et al., 2016) and runoff regions (Painter et al., 2010). Changes in snow dynamics affect ecosystems locally and downstream and have attendant large impacts on agriculture and food security (Simpkins, 2018). Snow responds to changes in precipitation, but equally to changes in temperature and albedo which in turn affect melt rates. On the other side of the equation,

Box 1. The Decadal Survey Science and Applications Objectives Related to SBG

The Decadal Survey (NAS, 2018, Table B) identified driving questions, measurement targets, and in many cases, geophysical observables relevant for SBG as they relate to Hydrology (H), Weather (W), Ecosystems (E), Climate, and Solid Earth (S). Key words and phrases constraining responsive architectures are indicated in bold for each of the "most" and "very important" science objectives as written by the Decadal Survey:

1. 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?
2. 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?
3. W-3 How do spatial variations in surface characteristics **(influencing ocean and atmospheric** dynamics, thermal inertia, and water) modify **transfer between domains** (air, ocean, land, and cryosphere) and thereby influence weather and air quality?
4. E-1 What are the **structure, function, and biodiversity of Earth's ecosystems**, and how and why are they **changing in time and space**?
5. E-2 What are the fluxes (of carbon, water, nutrients, and energy) **between ecosystems** and the atmosphere, the ocean, and the solid Earth, and how and why are they changing?
6. E-3 What are the fluxes (of carbon, water, nutrients, and energy) **within ecosystems**, and how and why are they changing?
7. C-3 How large are **the variations in the global carbon cycle** and what are the associated climate and ecosystem impacts in the context of past and projected anthropogenic carbon emissions?
8. S-1 How can **large-scale geological hazards be accurately forecast** in a socially relevant time frame?
9. S-2 How do geological disasters **directly impact the Earth system** and society following an event?

climate affects demand for water from the land surface (Fisher et al., 2017), and ET is one of the largest water fluxes in the climate system responding to both climate and ecosystem state (Worden et al., 2021).

The interaction between the land surface and vegetation with soils, surface, and groundwater is captured by the *critical zone* concept, the zone of the Earth's surface (Amundson et al., 2007) where climate, the solid Earth, the water cycle, and life interact strongly. SBG will observe changes to the critical zone by monitoring changes in interactions between all these components and coupled processes at regional scales. Changes to ET, water supply, water temperature, and adjacent terrestrial dynamics then affect both flows of water and water quality (Heino et al., 2021) and link terrestrial, aquatic, and marine systems.

The Earth surface forces the climate system as well as responds to climate changes. For example, ecosystem state affects temperature directly as land use changes land cover (Alkama & Cescatti, 2016) and modifies latent energy fluxes (e.g., ET) and albedo via clouds (Duveillere et al., 2021). Changes to snow albedo affect surface temperature directly in snow-covered regions, particularly in polluted regions. The land surface affects radiative forcing indirectly by changes to carbon storage on land (Sellers et al., 2018), aquatic "blue carbon" ecosystems (Lovelock & Duarte, 2019), and soil and biomass storage (Schimel et al., 2015). Direct emissions of greenhouse gases (i.e., CO_2, CH_4, and N_2O) also occur at the surface, and spectroscopic observations can detect and quantify point-source emissions adding a fundamental new ability to observe the radiative forcing to the climate system from methane leakage from oil and gas activities (Cusworth et al., 2021). Natural processes such as volcanic activity affect society directly, and indirectly through the climate system (Buongiorno et al., 2013; Friberg et al., 2018). Thus, observing thermal and geochemical change is crucial to forecasting volcanic events, as are direct observations of volcanic gases and particulates. On the other end of the spectrum, human-caused events such as oil spills interact with the Earth system through transport, chemical processing (Joye, 2015), and its impacts on coastal ecosystems (Ainsworth et al., 2018). Also, wildfire is an important example, where climate and vegetation state affect hazard and fire weather that affects active burning (Coen et al., 2018). It also affects the solid Earth and the water cycle affect landslides and postfire water quality (Sankey et al., 2017) and require an integrated observing approach (Veraverbeke et al., 2018).

The solid Earth also forms a crucial part of the Earth system. Volcanos affect the atmosphere, air quality, aviation, and climate, as well as posing natural hazards to adjacent communities. The surface minerals exposed in soils and outcroppings provide information about edaphic processes, economic resources, and natural hazards such as landslides. The composition of the solid Earth interacts with the biosphere, the atmosphere, the climate system through the transport of minerals in the atmosphere and hydrosphere, affecting ecosystems and climate near and far from source regions.

Thermal and visible to shortwave spectroscopic observations enable quantification, directly and through improved models, of these land surface changes in forcing as well as responding to climate change (Stavros et al., 2017). As such, these measurements of planet Earth from space are a critical resource for Earth science and yield important benefits to society and to sustaining a habitable planet. Satellite measurements, however, represent very large investments of time, effort from skilled professionals, and funding. To do this, US agencies organize and coordinate this effort for the maximum return to science and society. Most recently, NASA announced a new major investment, the Earth System Observatory (ESO; Margetta, 2021) that will integrate observations of the Earth's surface, critical atmospheric processes, and the global water cycle, with a focus on the climate system and Earth system dynamics.

The ESO evolved from recommendations of the 2017 US NRC Earth Science and Applications Decadal Survey (NAS, 2018). The 2017 survey recommended five new NASA "Designated" program elements to address a set of high-value targeted Earth observations during the next decade. One of the elements is the SBG designated observable, which will provide a spectral fingerprint of the Earth's terrestrial, freshwater- and coastal-aquatic surfaces (e.g., Asner & Martin, 2009; Barducci et al., 2015; Gillespie et al., 1998; Johnson et al., 2011; Singh et al., 2015; Wang et al., 2020), and atmospheric trace gases (Brodrick, Thompson et al., 2021; Thompson et al., 2019; Thorpe et al., 2017). SBG will provide visible to shortwave infrared (VSWIR) imaging spectroscopy and thermal infrared (TIR) observations. SBG science, applications, and technology would build on over a decade of experience and planning for such a mission based on the previous Hyperspectral Infrared Imager (HyspIRI) mission study (JPL, 2018; Lee et al., 2015). We conducted and present the findings from a 3-year study to provide a cost-effective observing system architecture that provides value across a range of SBG science and applications.

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Within NASA's ESO, SBG focuses on climate impacts *at* the Earth's surface, as well as components of radiative forcing *from* the surface (Figure 1). SBG will be a premier integrated system for observing the emerging impacts of climate change on ecosystems, the water cycle, the solid Earth, and the critical zone of the Earth's surface (Amundson et al., 2007). As part of the NASA ESO, SBG will have a unique role in characterizing the diversity of life directly due to its ability to resolve chemical and physiological signatures of land and aquatic plants (Jetz ert al., 2016). It will address the increasing challenges posed by wildfire, and directly inform societal responses to natural and anthropogenic hazards and disasters, guiding responses to a wide range of events.

SBG will be launched in the ESO era—the late 2020s (Margetta, 2021)—when other missions will provide complementary observations (Figure 2). Mass change (an analogue to the GRACE missions; Kornfeld et al., 2019; Tapley et al., 2004) will provide measurements of the Earth's gravitational field constraining total water storage, synergistic with SBG's observations of two other parts of the water cycle: ET and snow. NISAR (Amelunng et al., 2019) will map Earth surface changes including changes in surface elevation, moisture, and structure, which can provide information about disturbances and constrain vegetation biomass estimates. ATmOS will observe precipitation, clouds, and aerosols and other boundary layer properties that determine the surface water and energy balance. SWOT (Biancamaria et al., 2016) will constrain river flow, synergistic with SBG measurements of sediment and organic matter to quantify transport from land through rivers to the sea. PACE (Werdell et al., 2019) and GLIMR (Salisbury & Mannino, 2020) both focus on the oceans; GLIMR regionally and diurnally and PACE globally to allow comprehensive studies of interactions from the mountains to the sea, and for the first time, enable the global land–water continuum to be studied as a whole. Taken together, the ESO and

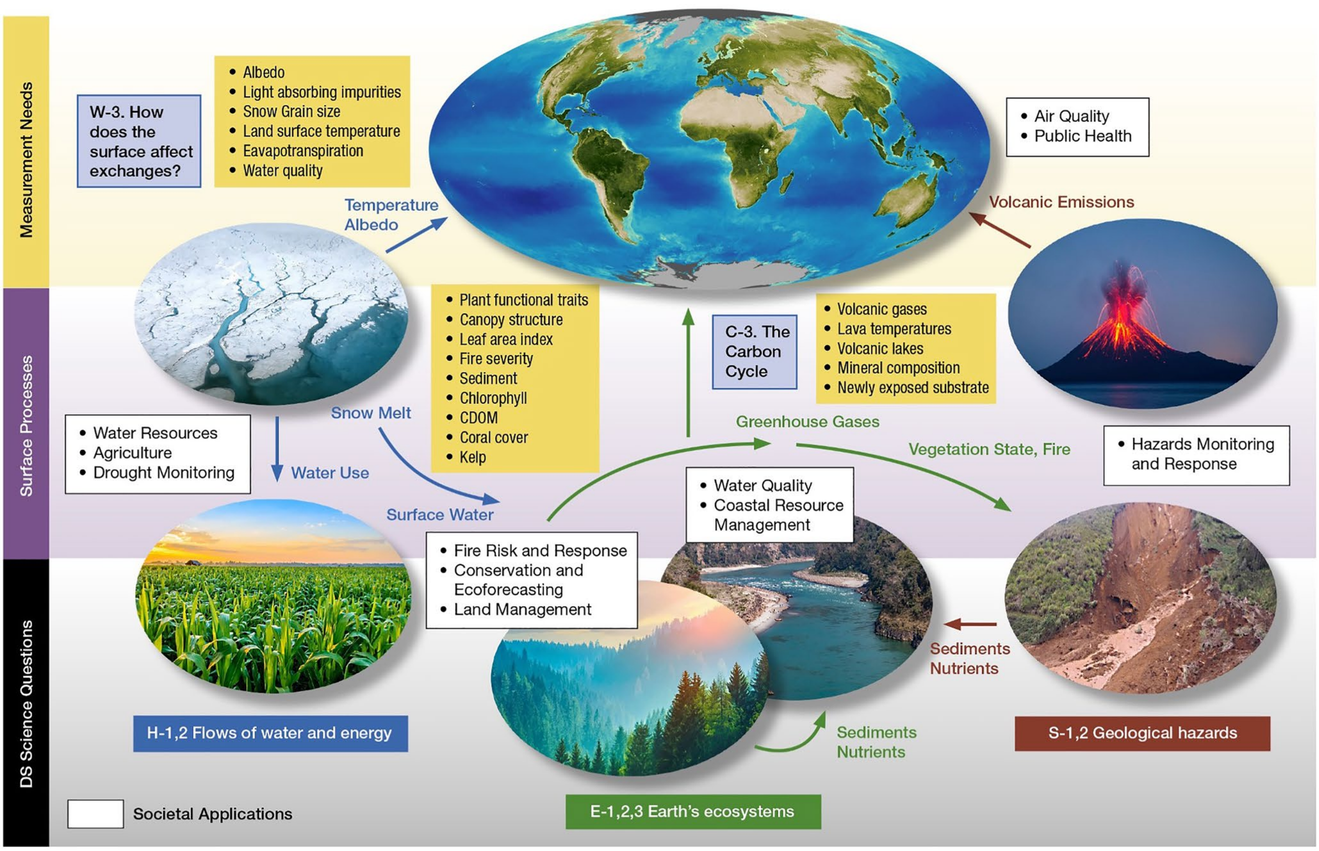

Figure 1. Surface Biology and Geology (SBG) addresses global land surface processes that quantify critical aspects of the land surface, responding to Decadal Survey priorities, which then interact with the Earth's climate system. The observing system has a defined set of critical observables that equally inform environmental management and policy and a host of societal benefit areas. The SBG science and Applications objectives are described in Box 1. The text in the orange boxes represents many, but not all, potential SBG geophysical observations.

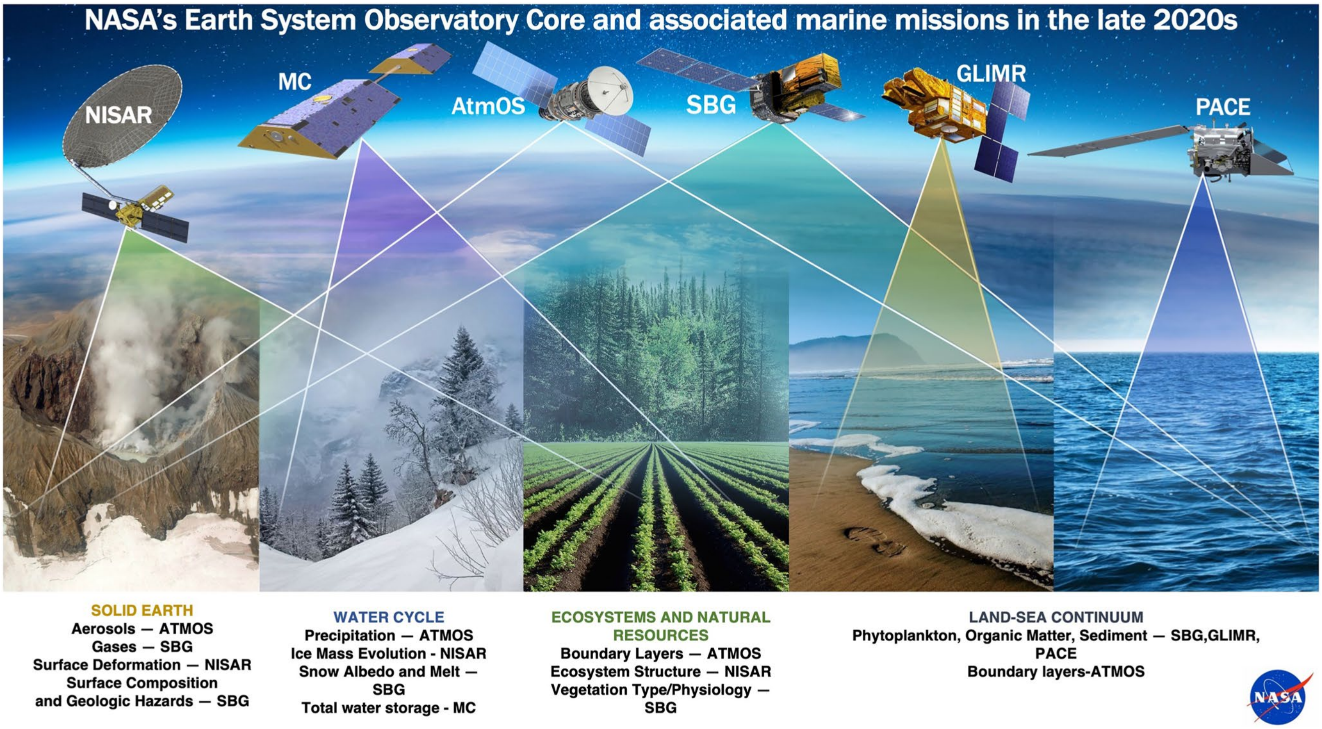

Figure 2. Synergies envisioned between the Earth System Observatory (ESO) and contemporaneous missions, enabling integrated geological, watershed, ecosystem, and food security and land–sea continuum research. Note that names for the ESO missions are provisional.

aligned missions will provide a next-generation-integrated perspective on the Earth's changing climate, impacts, and interactions and Earth system dynamics (Figure 2).

In response to the 2017 Decadal Survey, NASA's Earth Science Division initiated an SBG Architecture Study. This study included scoping science and applications needs with respect to measurement targets such as spatial and temporal resolution and spectral range and sensitivity as well as assessing instrument capabilities and potential mission observing system architectures with respect to risk and cost. *This study aimed to assess hundreds potential architectures for meeting the SBG-specific observational needs as prioritized by the Decadal Survey. The overarching objective was to provide candidate architectures to NASA HQ for programmatic evaluation and selection to advance to mission formulation including requirements definition and a point design.* This study was conducted across NASA centers including the Jet Propulsion Laboratory, Goddard Space Flight Center, Marshall Research Center, Ames Research Center, and the Langley Research Center. The study included many other participating university and federal agency scientists. The SBG Study objectives were to (a) identify and characterize a diverse set of SBG observing architectures, (b) assess the performance and cost effectiveness of each candidate architecture against SBG research and applications objectives, and (c) recommend potential architectures to NASA for consideration to advance to mission formulation with detailed requirements definition and point design. This manuscript represents an overview of the architecture study with references to detailed supporting substudies referenced as other manuscripts in this special collection.

The SBG Study team evaluated the national and international programs of record to assess observing system gaps and potential synergies. In the anticipated SBG time frame, there are several planned and current missions pioneering TIR and VSWIR relevant observations, though with more limited data acquisition and access. It is expected that there will be multiple space-based sensors (e.g., CHIME, LSTM, and Thermal infraRed Imaging Satellite for High resolution Natural resource Assessment [TRISHNA]) with which SBG can establish virtual constellations to minimize revisit times and produce harmonized spectral imaging data products. This program of record provides valuable data that can serve as a testbed for SBG algorithm testing and maturation. Missions with relevant VSWIR and TIR observations include ECOSTRESS (Alonso et al., 2019; Fisher et al., 2020;

Hook et al., 2020; Loizzo et al., 2018), HISUI (Iwasaki & Yamamoto, 2013; Matsunaga et al., 2016), EMIT (Green et al., 2020), EnMAP (Guanter et al., 2015), PACE (Werdell et al., 2019), and GLIMR (Salisbury & Mannino, 2020). SBG could also provide harmony with other optical and thermal missions like Landsat and Sentinel-2, which would increase revisit for these missions (Seidel et al., 2018), but would not increase revisit for SBG observations of imaging spectroscopy.

To assess the science and applications value of different architectures, the SBG Study team adopted an open and transparent approach that encouraged community participation through technical working groups and frequent information exchange via open study workshops and webinars. This included participation by hundreds of science and applications stakeholders in government (NASA and non-NASA), academia, industry, and the international community. The study included stakeholders interested in basic science, algorithm development, decision-support applications, measurement calibration and validation, and mission formulation.

2. Methods

The SBG Designated Observable Study met the above objectives using *systems engineering* approaches through an *architecture study* (Box 2) conducted in several phases (Figure 3). In the first phase, the study team evaluated the science and application priorities in the Decadal Survey document and identified measurement targets. In parallel with that, a wide array of technological means that could potentially meet those priorities were identified for subsequent evaluation. In the next phase, the study team used a system engineering approach (Box 2) to evaluate a wide range of technical solutions for their contributions to science and applications, their technological maturity, and their approximate cost. This led to *trade studies* (Box 2) balancing technical performance, cost, and risk. Detailed design studies were done for a number of promising options, and their quantitative performance against the performance targets derived from the NRC Decadal Survey (NAS, 2018). Finally, the highest-value options were studied in more detail and a report made to NASA.

The Study team established four working groups to provide input, verify current understanding, conduct literature reviews, and to support ongoing evaluation of candidate architectures. The working groups addressed: societal benefit applications, algorithms, modeling, and calibration and validation (Cal/Val). Each of these working groups provides supporting substudies documented in this special collection and referenced throughout this manuscript. Participation in the working groups was open to the community, and each group had more than 84 participants (see Acknowledgments). These working groups delivered a series of reports (Figure 3) that informed the architecture study through regular physical and virtual meetings with the broader stakeholder community through the entire study.

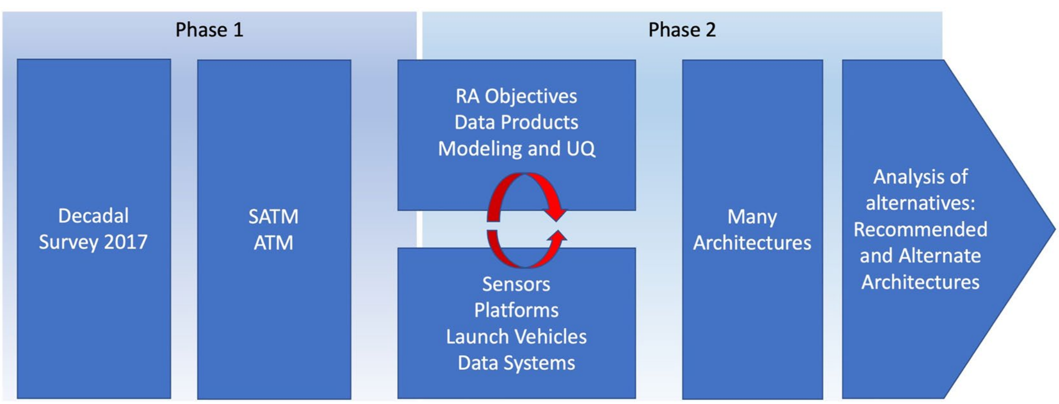

Figure 3. The high-level deliverables for Study Phases 1 and 2 from the study team defining the research and application objectives (RA objectives) and associated tasks for each Research and Applications (R&A) Working Group. Note that this study occurred before traditional NASA formulation phases begin.

Box 2. Systems Engineering Approaches Used in the SBG Study

Unless otherwise stated, text is from the NASA Systems Engineering Handbook (NASA, 2007):

Systems engineering: is a methodical, multidisciplinary approach for the design, realization, technical management, operations, and retirement of a system. A "system" is the combination of elements that function together to produce the capability required to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose; that is, all things required to produce system-level results. The results include system-level qualities, properties, characteristics, functions, behavior, and performance. The value added by the system, beyond that contributed independently by the parts, is primarily created by the relationship among the parts (i.e., how they are interconnected). System engineering is a way of looking at the "big picture" to achieve stakeholder functional, physical, and operational requirements in the intended use environment over the planned life of the system within cost, schedule, and other constraints.

Science traceability matrix (STM; Weiss et al., 2005): provides an overview of what a mission will accomplish to meet high-level objectives. The STM provides a logical flow from the high-level objectives through mission objectives, science objectives, geophysical observables, measurement objectives, as well as measurement, instrument, spacecraft, and system requirements.

Architecture study: leads to defining a comprehensive solution based on principles, concepts, and system properties related to and consistent with each other. The solution's architecture includes hardware, data systems, and operations which satisfy, as far as possible, the science and applications objectives. In the context of the SBG Study, these objectives are traceable to the Decadal Survey and consider alternative configurations of sensors, platforms, and infrastructure as well as other systems (e.g., operations, calibration and validation, and user access). Architectures are implementable through technologies (e.g., mechanics, electronics, software, in situ networks, and procedures).

Trade study: are used to identify the most acceptable solution among a set of proposed solutions. By nature, all decisions are subjective, framed by stakeholder values, and involve risks. Trade studies provide a means for addressing this by documenting the decision-making process to enable traceability and repeatability. Potential solutions of a trade study are judged by their overall satisfaction of a series of desirable characteristics. These characteristics may conflict with one another or even be mutually exclusive. For example, the physics of optical systems mean setting one parameter (e.g., aperture size) influences other characteristics (e.g., detector performance) and programmatics (e.g., cost). Other trades may reflect policy or direction, for example, policies about choice of vendor or supplier.

Analysis of Alternatives (AoA; Ullman & Ast, 2011**):** guides the analytical comparison of multiple alternatives before committing to a project. In an AoA, multiple alternatives are proposed and a multidimensional comparative analysis with some inclusion of risk completed. An AoA ensures that new projects, programs, processes, policies, and organizational changes have a robust, credible, executable business case with quantified risks.

2.1. Defining Science and Applications Measurement Targets

The Decadal Survey recommended SBG provide specific observations and classified them by objective as "Most Important," "Very Important," and "Important." The SBG Study considered the "Most Important" and "Very Important" objectives to derive science measurement targets. The team then assessed the number of "Important" objectives that were enabled by the measurement targets needed for "Most" and "Very Important" objectives. To meet the needs across objectives (Box 1), we converge on priorities and design constraints of the architecture study summarized as follows:

1. The system must provide **global coverage** of terrestrial land between 85 deg N and S) and the coastal zone (within 200 nautical miles of the coast) to address the global scope across science objectives (Box 1).

2. The observing system must have **sufficient mission duration** (3–7 years) to detect changes for addressing dynamics of the Earth system such as interannual variations (e.g., El Niño) and not just local processes. The study should also develop a strategy for continuity of identified key measurements.
3. The system's orbit must allow for **consistent sun-sensor geometry** for consistency in retrievals and for calibration and validation (Queally et al., 2022; Seidel et al., 2018), and provide for global coverage, as above (polar orbit).
4. **VSWIR (380–2,500 nm) imaging spectroscopy and multispectral TIR (4–12 μm) measurements** must be capable of observing "diversity" in ecosystem function, and not merely bulk processes that may be quantified with other types of observation.
5. The observing system must provide **high spatial resolution** with a pixel size defined in the Decadal Survey between 20 and 60 m for VSWIR and 60–100 m for TIR with repeat observations every 3–5 days or >100 m with repeat observations every day. The objectives defined by the Decadal Survey led to tight constraints on pixel size and need for uniform band-to-band coregistration; for example, spatial resolution must be small enough to identify plant communities, landslide tracks, or boundaries of land versus water or snow versus bare ground.
6. The SBG observing system acquisition frequency (henceforth "**temporal resolution**") must be adequate to capture, for thermal synoptic, and, for VSWIR, seasonal (weeks to months) variation given cloud cover assumptions as well as observe rapid or transient changes related to SBG-assigned Earth system events such as fires, landslides, volcanic activity, and anthropogenic impacts (e.g., oil pollution events).
7. Observation **latency**, the time between data acquisition and data access (Davies et al., 2017), must be low enough to support applications. For many applications, such as disaster response or agricultural water management, the data are of no use if not available in a timely manner.

These criteria constrain the potential SBG observing system architecture trade space while still being broad enough to enable hundreds of architectures built from combinations of sensors, platforms, launch vehicles, partnerships, and data purchases. In several cases, these priorities impose diametrically opposed constraints, requiring systems engineering discipline to balance priorities and optimize the performance of the overall system design (Box 2).

To further refine and evaluate each potential architecture while working within a transparent process for tracing driving objectives to Earth-observing measurement targets for informing an architecture, we used a modified version of the NASA science traceability matrix (Weiss et al., 2005) that incorporates applications. Applications were defined to include research enabled by the measurement targets (e.g., "Important" decadal survey objectives) and decision-support uses. This resulted in the Science and Applications Traceability Matrix (SATM; Stavros et al., 2022) with driving science (Most and Very Important) objectives to the geophysical parameters needed, the science measurement targets, and the applications enabled. These measurement targets then informed the mission architecture study to converge from hundreds of potential architectures down to three suggested architectures.

We developed a more detailed and complete SATM (Stavros et al., 2022) from the Decadal Survey document. We began with the Decadal Survey's science traceability matrix itself, including all rows referencing the SBG investigation (NAS, 2018). We preserved the Decadal Survey's thematic categorization and the specific text of their science objectives and geophysical observations. Some Decadal Survey matrix rows associated with SBG described measurements available by the program of record (e.g., Landsat) instead of a new VSWIR-TIR architecture. We preserved these rows in the new SATM (Stavros et al., 2022) for completeness, with annotations to indicate that they were not part of the architecture selection process.

We evaluated the Decadal Survey-suggested performance levels (Table 1) and derived a core list of the geophysical parameters that could be delivered by an SBG observing system (SATM in Stavros et al., 2022). These include snow and ice coverage fraction (cryosphere); snow spectral albedo from visible to thermal (cryosphere); snow surface temperature (cryosphere); VSWIR spectral surface reflectance; ET rates of vegetation; land and water surface temperature; biogeochemical traits of aquatic biomass, including ocean color pigmentation and productivity (coastal); phytoplankton functional type (coastal); benthic composition (coastal); chemical properties of canopies; soil properties; terrestrial and aquatic vegetation functional traits, types, composition; terrestrial and aquatic vegetation species (where possible); nonphotosynthetic vegetation; high-temporal feature

Table 1
The 11 Decadal Survey Science Objectives Had Associated Measurement Performance Targets Listed (NAS, 2018)

Performance Level	VSWIR				TIR				VNIR/TIR Coincidence
	Spatial	Temporal	Range	Sensitivity	Spatial	Temporal	Range	Sensitivity	
A	≤30 m	≤8 days for global coverage*	VSWIR, ≤380 - ≥2500 nm, at ≤10nm sampling	SNR ≥400 VNIR, SNR ≥250 SWIR **, ≤10% Absolute radiometric accuracy	<60 m	≤1 day for global coverage*	≥5 bands in 8-12 um, ≥ 1 band in 3 - 4.5 um	≤1K Absolue accuracy, ≤0.2K NeDT per band	Simultaneous within 30 seconds
B	≤60 m	≤16 days for global coverage*	VNIR, ≤380 nm - ≥1000 nm, at ≤10nm sampling	≤10% Absolute radiometric accuracy	60-100 m	≤3 days for global coverage*	≥5 bands in 8-12 um	≤1.5% Uncertainty in absolute emissivity, <1K NeDT per band	On same day
C	Not defined	Not defined	VNIR with mulitple bands (≥3 visible & 1 NIR)	Not defined	>100 m	≤5 days for global coverage*	≥3 bands in 8-12 um	Not defined	VNIR within 3 days

Note. We analyzed those targets and found them to describe nine parameters that could be categorized into three levels of performance. Performance levels were designated A, B, or C for each of the nine instrument performance categories.

delineation (active volcanoes and fires); fractional coverage and silicate composition of lava flows, lahars, ash deposits (active volcanoes); gas and particle concentrations (active volcanoes); and surface composition of rock, and soils. Beyond this list, we included additional rows to address instrument needs for base products needed across geophysical parameters including atmospheric correction and temperature/emissivity separation. While not explicitly called out in the Decadal Survey, these are necessary prerequisites for all Earth surface studies. Intermediate and derived products will be decided later in mission formulation but will draw from the deep literature review of available algorithms (Cawse-Nicholson et al., 2021) and an end-to-end uncertainty assessment using the frameworks develops during this architecture study (Cawse-Nicholson et al., 2022; Raiho et al., in press).

The Decadal Survey recommendations on measurement sensitivity and coverage focused on a few parameters: spectral range, radiometric sensitivity, spatial resolution, and temporal coverage. The VSWIR and TIR capabilities were each defined separately, for an initial total of eight parameters per architecture. We also captured the need for temporal coincidence between Visible/Near Infrared (VNIR) images and TIR for specific observables (ET).

Not all Decadal Survey observables needed the same level of instrument and mission performance. As such, these criteria were categorized into "performance levels" representing the options for trade decisions (Table 1). An "A" represented the most demanding measurement (high spatial resolution, temporal resolution, fine spectral or thermal resolution, and sensitivity); "B" was a slightly less capable measurement sufficient for a subset of the Decadal Survey measurement goals; and a "C" option that was still less demanding. Achieving a performance level A, subsequently includes achieving performance levels B and C. Occasionally, the Decadal Survey did not supply instrument performance standards, but instead described the desired accuracy in terms of a geophysical parameter of interest. In these cases, we used previous studies and analogs in the peer-reviewed literature, documenting the references used. Where the decadal survey did not specify any quantitative capability, we left the corresponding column blank.

We verified the performance levels needed to derive geophysical observables (SATM in Stavros et al., 2022) associated with each Survey objective (Box 1) by conducting an in-depth analysis through the Algorithm Working Group. This analysis examined 125 algorithms of 273 identified for 10 data product suites covering geophysical parameters for snow and ice, the aquatic environment, terrestrial vegetation, geology, and volcanoes. This analysis was the culmination of input from 60 authors from 40 affiliations, from 7 countries (Cawse-Nicholson et al., 2021). The analysis also considered any measurement performance constraints on the algorithms as determined by previous published algorithms in the peer-reviewed literature. For example, did an algorithm require multiple cloud-free scenes? Spatial resolution? Or measurement sensitivity?

The SBG SATM (Stavros et al., 2022) includes two additional columns: Enabled Applications and Synergies with one other Decadal Survey recommended Designated Observable the Aerosol and Cloud, Convection and Precipitation (A-CCP/AtmOS in Figure 2). The Applications Working Group conducted an independent assessment of applications needs, defined as community needs for science beyond the SBG core science objectives (Box 1) and for meeting decision-support needs. This verified measurement targets. For each of the science objectives and associated geophysical parameters listed, we documented the decision-support applications that could be enabled. Two additional measurement targets for latency were identified. Enable applications in the SATM marked with an asterisk represent applications that needed low latency, defined as time between acquisition and data access (Davies et al., 2017). A final column noted any measurements that were synergistic with A-CCP (AtmOS) objectives. These included measurements related to radiation balance and ET which could help constrain surface/atmosphere fluxes of energy and water vapor. Atmospheric correction, which involves estimating the column abundance of aerosols and water vapor, was also strongly synergistic.

2.2. Architecture Trade Space

The SATM (Stavros et al., 2022) and resulting measurement targets were used as design constraints for consideration in the Architecture Study to explore trades in architecture design. The architecture study considered past NASA investments in similar concepts such as HyspIRI (Lee et al., 2015, p. 2; Mouroulis et al., 2016), ECOSTRESS (Fisher et al., 2020; Hook et al., 2020), and EMIT (Green et al., 2020) and explored the latest potential for end-to-end solutions including launch vehicles, instruments, spacecraft/platforms (e.g., constellation vs. single platform), mission/ground/science data systems, and mission design. Architectures were defined as a combination of these components and partnerships with international constellation of future missions. It also considered experience from relevant non-US missions and sensors such as DESIS (Alonso et al., 2019), HISUI (Iwasaki & Yamamoto, 2013; Matsunaga et al., 2016), EnMAP (Guanter et al., 2015), PRISMA (Loizzo et al., 2018), PACE (Werdell et al., 2019), and GLIMR (Salisbury & Mannino, 2020).

Based on scientific traceability for mission formulation (Weiss et al., 2005) and experience from these past missions, the parameters in Table 1 were identified as being sufficient to estimate instrument size and cost for the architecture study. Specifically, the performance levels for each parameter were not specific to a particular instrument, rather provided aggregate functional groupings that would capture the key choices in the trade study. For instance, the VSWIR spectroscopic range code "A" indicated a measurement spanning 380–2,500 nm. An actual instrument might not measure exactly those values; for example, it might go deeper into the UV with channels near 370 nm. Such minor within-target distinctions might neither preclude nor enable any of the Decadal Survey measurement recommendations. These "within-target" distinctions did not significantly change the projected cost or platform needs so they did not affect scoring for the coarse-grained architecture selection process. However, since they would eventually matter for selecting an instrument, we recorded these desires. In this manner, categorical capability assignments facilitated coarse-grained architectural decision making, while leaving minor distinctions within each measurement target for later study.

The architecture trade study explored trades in making target measurements varying the number of platforms, platform size, orbital altitude, and instruments. As an example, spatial resolution is a critical parameter and drives many architecture trades. Smaller pixels lead to narrower instrument swaths (number of pixels × pixel size) that reduce coverage or increase acquisition repeat and lower signal-to-noise (SNR; fewer photons); all of which affect needed number of platforms, orbital altitude, and instrument specifications. Having selected a spatial resolution, a parameter for which Decadal Survey objectives showed clear consensus, choices for other parameters were constrained. The Research and Applications study team participated in architecture design sessions to account for these considerations as different architectures were evaluated.

The most challenging parameter to meet, for science and applications, was temporal resolution. Temporal resolution is important for several reasons. One is to avoid confounding long-term change (year on year) with shorter timescales such as the seasonal cycle, synoptic variations in insolation and temperature, or the seasonal tidal cycle (e.g., King tide). A second reason is to capture sudden events, wildfires, volcanic activity, and disasters, requiring frequent sampling and rapid data availability. Temporal resolution is limited by the available optical and sensor systems defining maximal swath width for any given pixel size. Any temporal resolution target must make assumptions about cloud cover, causing measurement gaps, as such we assumed global 50% cloud cover and a revisit frequency (i.e., platform/sensor overpass rate) set to achieve synoptic and seasonal targets assuming a subsequent 50% data loss, recognizing some regions would be more and less favorable (Mercury et al., 2012). Current detector arrays are limited in the number of pixels (detector elements) and optics limit how far off to the side a sensor can look to broaden its swath. As such, the SBG Study identified international thermal and imaging spectrometer missions to collaborate with using instruments likely to be deployed in the same era. This provided a means of remaining financially feasible (multiple high-performance instruments being outside cost constraints) and providing the community with shorter repeat acquisition intervals.

2.3. Architecture Value Framework

To inform the mission architecture assessment, the team developed a framework to characterize the value of each mission architecture defined by its provided science and applications benefit relative to its associated cost and risk. All key Study staff participated in the definition of the science value metric to ensure objective and equal representation of SBG objectives across disciplines when assessing architectures' science value. The use of a Value Framework facilitates conversations among stakeholders by highlighting key areas of agreement and disagreement and offers key benefits of (a) clear, traceable, and repeatable analysis and (b) comparison of each architecture against the same criteria.

We first identified the performance levels that met the largest number of Decadal Survey objectives. The Decadal Survey objectives generally targeted high spatial resolution and relatively high-temporal resolution, and essentially all needed high instrument performance (spectral coverage and resolution, SNR or its thermal equivalent, noise equivalent to a change in temperature, NeDT). The SBG team set desired performance at the consensus level to satisfy ≥70% of geophysical observations across objectives in the SATM (Stavros et al., 2022).

The science-value metric was calculated as the summed value of a given architecture's ability to meet the needed capabilities defined by the SATM (Stavros et al., 2022). The value of each of the nine capability criteria (Table 1) was calculated by dividing the "reference" performance by the "actual" performance; where the "actual" was the performance level of a given architecture and the "reference" code was an optimal performance level A for all design criteria (AAAA AAAA). For example, an architecture may only provide a VSWIR temporal repeat of 16 days, but the optimal performance level A is 8 days, so the value of the VSWIR temporal repeat measurement target of that architecture is 0.5. We used a linear score with the A code as maximum (i.e., maximum score of 1 for any measurement target). The values for each measurement target were then added together to give an architecture overall score.

The SBG team also evaluated the value of coordinating with international partners to potentially improve revisits from the adequate but not ideal levels achievable with wide-swath instruments. This revealed architectures that could align with partners, when instruments had sufficiently similar characteristics, matched overpass times (e.g., similar orbits), and likely launch dates. Other architecture-specific benefits considered qualitatively included: calibration/validation, optimal overpass time, and VNIR and TIR coincidence. Two international collaborations were considered explicitly as sufficient data on instruments and orbits were available: (a) the European Space Agency (ESA) CHIME mission (Nieke & Rast, 2019) and (b) the French National Centre for Space Studies (CNES)/Indian Space Research Organization (ISRO) TRISHNA mission (Lagouarde et al., 2019). Other collaborations (e.g., with the commercial sector) were less defined with uncertain funding or timing; as such, their value was noted qualitatively. For the two known international collaborations (CHIME and TRISHNA), the science-value score was modified to include credit for improved temporal repeat. Data sharing with CHIME and TRISHA (or additionally or alternately, with ESA's planned LSTM thermal mission; Koetz et al., 2018) could improve revisit times from 16 and 3 days to weekly and daily, meeting the more demanding needs of some Decadal Survey objectives.

The applications value of each architecture was additionally evaluated based on the ability of an architecture to accommodate low latency, frequent overpass, and rapid downlink.

3. Results and Discussion

Analysis of the SBG SATM (Stavros et al., 2022) showed that most Decadal Survey objectives could be met with a consensus solution, referred to as the "satisfier," in shorthand ABBA ABAA. ABBA ABAA refers to the performance levels of the four design criteria for each VSWIR and TIR measurements (Table 1):

1. A for spatial resolution: B for temporal resolution;
2. A/B respectively, for VSWIR and TIR on sensitivity;

3. A for spectral coverage; and
4. A for simultaneous coverage in the VNIR (full VSWIR not needed) and TIR.

In short, ABAA ABBA needs high spatial resolution, relatively frequent acquisition revisit, and excellent instrument performance (spectral resolution, coverage, and sensitivity). The most frequently compromised instrument parameter was temporal resolution, where the ABAA ABBA solution achieved an acceptable, but not ideal level. In other cases, performance exceeded the acceptable level for some applications by meeting the most demanding need, with cost and trade implications (SATM in Stavros et al., 2022). The ABAA ABBA "satisfier" measurement target identified for the Study met 70% of needs when looking across geophysical parameters needed to meet objectives; that is 31 of the needed 45 observables (including duplicates and base observables) were satisfied by ABAA ABBA. Evaluating the satisfier against the ideal performance (all A) for all criteria scored a science value of 6.7, and that was used later in the study to determine a cutoff value for considering architectures.

The verification of optimal capabilities by the Algorithms Working Group used an in-depth literature review of existing algorithms (Cawse-Nicholson et al., 2021), to verify most Decadal Survey performance specifications; though it revealed some gaps in capability needs to meet retrieval targets of geophysical variables (Table 2). Algorithmic needs largely parallel the Decadal survey capabilities (Table 2), with several additional considerations.

With respect to time of acquisition (temporal resolution), fixed time of day over passes significantly reduce calibration and validation complexity and would enable a more consistent time series. VSWIR and TIR observations have different optimal overpass times: VSWIR benefits most from 10:00 to 11:00 local solar time overpass when daily cloud cover typically reaches its daily minimum to optimize the number of cloud-free scenes while TIR benefits most from 13:00 to 14:00 local solar time overpasses when daily surface temperatures typically reach their daily maximum values. Additionally, VSWIR measurements over coastal waters improve significantly if active sun glint avoidance maneuvers are enabled to avoid sun glint conditions. Finally, phenomena with rapid onset or occurrence, such as snow melt or volcanic eruptions, needed to be monitored at the best temporal resolutions (capability code A) for the algorithms to capture the appropriate phenomena.

With respect to spectral range and sensitivity, the volcanic and high-temperature algorithms were identified as requiring an additional nonsaturating *middle* infrared (MIR) band (~4 μm), which fell under capability code

Table 2
We Verified the Decadal Survey-Identified Measurement Target Performance Levels Needed to Derive Geophysical Parameters by Organizing Them Into Ten Product Suites (Rows)

Product Suite	VSWIR spatial	VSWIR temporal	VSWIR range	VSWIR sensitivity	TIR spatial	TIR temporal	TIR range	TIR sensitivity
Snow		A				A		
Water biogeochemistry			B	A				
Water biophysics			B	A				
Aquatic classification			B	A				
Substrate composition	A		A				B	
Volcanic SO_2 and Ash		A			B	A	A	A
High temperature features		A	A			A	A	A
ET			C		B		B	A
Plant functional traits	A	B	A					
Proportional cover	A		A					

Note. Where blank cells are either algorithms that do not use that (VSWIR or TIR) wavelength range, or the community did not identify that parameter as a limiting factor for the relevant algorithms. Note that the algorithm requirements are distinct from the science requirements. Many, though not all, of the geophysical product suites are produced pixel-wise and are not dependent on revisit, even when that is critical for meeting science or application needs; when the algorithm does not require multitemporal data the temporal column is left blank even though the science objective may define a revisit need (SATM in Stavros et al. [2022]). Product suites assume use of base products: surface reflectance, land surface temperature/emissivity, and landcover class.

"A." Certain algorithms for estimating volcanic emissions and high-temperature features required measurements in the MIR with high saturation to capture the expected temperature range of volcanic eruptions, in addition to measurements spanning the TIR. The satisfier combination ABAA ABBA did not originally require a 4 μm, so this additional design constraint was considered in the architecture evaluation. Also noted, was that high SNR was required for many existing aquatic algorithms in the VSWIR, and for algorithms related to volcanic eruptions and ET in the TIR, verifying the need for performance target A for spectral sensitivity. Spectral sensitivity was inferred from SNR based on an exhaustive literature review, not a formal quantitative analysis (Cawse-Nicholson et al., 2021). Future work should consider a more quantifiable framework for this.

Community input provided through the Applications Working Group (Lee et al., 2022) provides a threshold for defining low latency (Davies et al., 2017). An analysis of the enabled applications showed that architectures with low-latency capabilities such as onboard processing and priority downlink would enable 77% of potential applications of SBG data (Figure 4). If latency were extended beyond 24 hr, SBG data would only enable 60% of potential applications. It is worth noting that enabling 100% of applications (e.g., event-driven) would require more frequent observations than feasible with a single nadir-viewing platform. Because of the strong basis for enabling most applications, low-latency and event-driven capabilities were considered during the architecture filtering process (Lee et al., 2022).

Evaluating architecture trades in instrument specifications, number of platforms, and orbital altitude necessitates an understanding of uncertainty needs and strategies for instrument calibration and validation. The Modeling Working Group verified uncertainty needs and constraints on instrument selection using an end-to-end simulation of the observing system (Raiho et al., in press). The modeling system was based on open-source modeling software, Brodrick, Erickson et al. (2021) (https://zenodo.org/record/4614338; accessed 17 March 2021) for VSWIR and TEUSim for thermal (Hulley et al., 2012). This work provided preliminary analyses to constrain instrument specifications for providing an accuracy at 5% relative uncertainty surface reflectance including dark targets for VSWIR and ≤1°K absolute uncertainty surface temperature for TIR. Using these uncertainty constraints, the Calibration and Validation Working Group provided strategies as additional design constraints based on the ability for instruments to be calibrated: Radiometrically (R), Thermally (T), Spectrally (S), and Geometrically (Turpie et al., 2023). Architecture budgets for mass, power, and volume were then assessed based on their ability to accommodate working group recommended on-orbit calibration infrastructure elements and ability for lunar

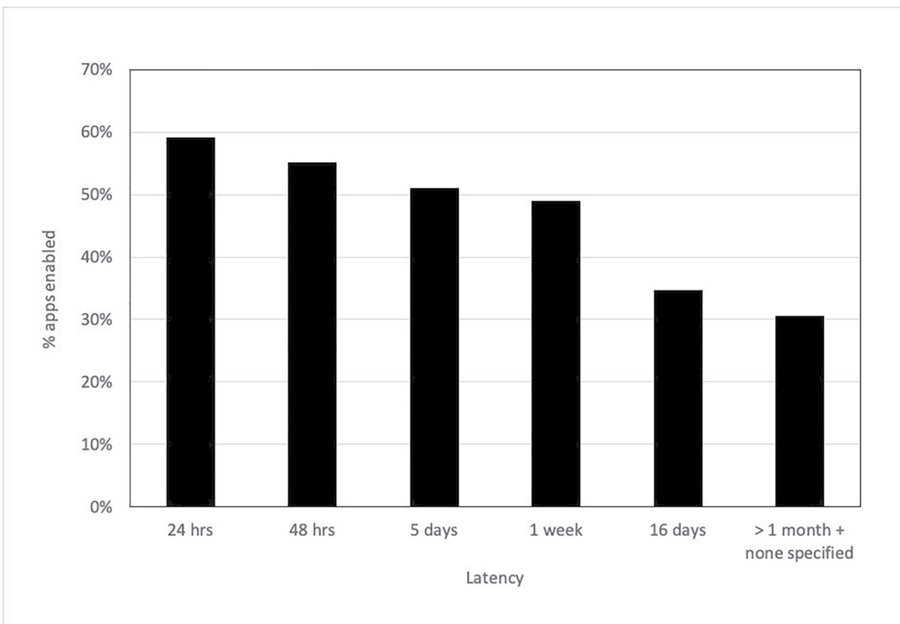

Figure 4. Analysis of applications in the Application Traceability Matrix (Lee et al., 2022) and the resulting justification of additional design criteria for assessing architecture value included low latency defined as the time between data acquisition and data access.

calibration and vicarious calibration. For the high-level architecture trade study, end-to-end uncertainty quantification and assessment was not necessary, but mission formulation to develop a point design would require it to provide detailed calibration infrastructure element selections.

After the Architecture study, each architecture was assigned a science value. Several architectures were considered that exceeded the science-value threshold. This process led to multiple candidate architectures for more detailed qualitative evaluation. The final architectures were evaluated using *Analysis of Alternatives* (AoA: Box 2) commonly employed in systems engineering. The AoA considered both the quantitative science-value score and qualitative assessment of candidate architectures for meeting additional design considerations identified by the Algorithms and Applications Working Groups:

1. **Science and applications value:** Architectures not meeting the minimum quantitative science value were discarded. These architectures scored <6.7, the threshold value for the satisfier ABAA ABBA against optimal measurement targets of AAAA AAAA. For example, narrower-swath instruments that could not meet 16- and 3-day temporal resolution targets for VSWIR and TIR, respectively, were unable to achieve adequate sampling of synoptic or seasonal variation, especially assuming a 50% cloud cover rate, and so had not slightly, but dramatically reduced science value, more than was apparent from the numerical value. For example, a VSWIR that could achieve a 20-day temporal resolution would score 0.4, where an ABAA ABBA instrument would score 0.5, for combined scores of 6.7 versus 6.6. However, this difference changes the sampling relative to the seasonal cycle from 3 to 6 scenes per 3-month season to 1–4, dramatically reducing the ability to capture the seasonal evolution of vegetation or snow cover. **As a result, the ABAA ABBA score was strictly applied.**
2. **Overpass time:** The wavelength ranges (VSWIR and TIR) differ in their optimal overpass time, VSWIR which does not exhibit strong diurnal variability is optimized in the morning by lower cloud probability. TIR is more informative in the afternoon. **Architectures where each instrument was on a separate platform were preferred.** This also allowed more flexibility for international collaboration and data sharing by coorbiting with ESA's CHIME and LSTM or the CNES and ISRO TRISHNA mission. This was not considered in scoring but was used qualitatively in the final integrated assessment.
3. **International collaboration opportunities:** Architectures differed in their compatibility with potential international collaborators, such as CHIME, LSTM, and TRISHNA. We qualitatively considered the ease of creating a consistent record as an assessment of our ability for cross-collaboration on: mission formulation schedules, coordination of overpass time, spectral range and sensitivity, spatial resolution, and orbits. This is especially important not only to improve temporal resolution but also to enable continuation of observations (Seidel et al., 2018).
4. **Coincidence:** Temporal overlap (i.e., "coincidence") between the TIR and VNIR measurements is of value for the geophysical observable ET. Technical solutions resulted in instrument designs for TIR and VSWIR that had differing swaths, 90–185 km for VSWIR and >900 km for TIR. As a result, and counterintuitively, if temporal resolution is prioritized so that swaths are kept as wide as possible, coincidence is not enhanced by a single-platform solution. However, the ET observable does not require the full VSWIR but only limited radiometry. **Solutions adding a simple VNIR imager to the TIR platform were preferred.**
5. **Calibration:** The SBG concept requires well-calibrated and stable measurements to enable quantitative retrievals, trend detection in time series, and seamless maps covering multiple orbits. Calibration is expensive and poses a risk if inadequate. Constellation solutions with multiple small instruments, while technically feasible, require considerable additional calibration and so add risk. **Options with simpler and well-understood calibration requirements, as well as key capabilities (e.g., agility—see 3) were preferred.**
6. **Cost, risk, and schedule:** While a quantitative risk analysis was outside the scope of this study, we performed a qualitative assessment of risk based on the projects ability to take on technological development within cost and schedule constraints. Specifically, estimates of risk were informed by technology readiness level (TRL; NASA, 2021) assuming that architectures reliant on component technologies with low TRL would not be developed within the cost and schedule constraints of the mission assuming a TRL 6 by the end of Formulation Phase B. Note a mission TRL is classified based on the lowest TRL of any component or subsystem. The mission concept targeted a cost of $650M (2018 USD) and a launch date of 2027–2028. As such, we estimated architecture costs using NASA parametric cost models and an independent analysis provided by a contractor. While not a detailed cost estimate, this framework provided a means for evaluating hundreds of architectures, many of which were well outside of the cost constraints for this mission (e.g., simply based on launch vehicle),

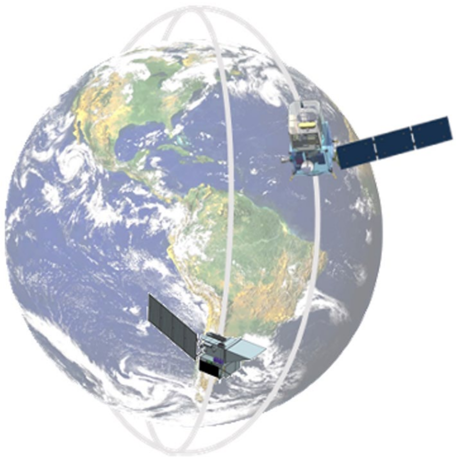

Figure 5. The recommended option for SBG consists of two spacecraft, in separate orbits, with morning overpass for the VSIR element and an afternoon overpass for the thermal infrared (TIR). These orbits could be coordinated with international collaborators to improve temporal resolution, while meeting all essential performance targets on their own.

thus eliminating them from consideration. Programmatic risks such as international agency coordination was determined by NASA Headquarters outside the scope of this study.

The AoA (Box 2) led to a recommended option (Figure 5) consisting of two small platforms, each in a different orbit, with morning and afternoon overpass times (as in point 2 above), each with the widest swath achievable and high-performance VSWIR and TIR instruments. Exact orbits will be determined during a detailed point design. A solution was also found where an international partner could contribute a well-tested VNIR camera for the TIR component and will be studied further as the mission goes through subsequent formulation.

Two other options were chosen for further consideration. One was a conventional solution, using well-understood and larger platform technology, where both instruments were on a single platform. This had technical build and risk advantages but had several science-value challenges (e.g., suboptimal acquisition time for either VSWIR or TIR as a single platform would favor one time over another). A second option had a single TIR instrument but a small constellation of narrow-swath VSWIR instruments, each on its own small spacecraft. This option is technically innovative and could constitute a path forward for a long-term sustainable approach but raised calibration concerns. Also, the ability of instrument providers (NASA centers and industry) to manufacture multiple identical, high-performance instruments has not been demonstrated, raising technology readiness and schedule risk concerns. These solutions could both, in principle, meet the ABAA ABBA performance level, but ranked lower on the additional qualitative considerations above, or had less well-understood risks. As such, they were studied in detail but ultimately not deemed as desirable.

Note that the recommended architecture is not a *point design* but a concept. It does not include specific instrument details, beyond confirming that instruments of the size and specifications (power, data volume, etc.) would fit on the size platforms assumed. The actual design and detailed requirements for those instruments, spacecraft, and supporting infrastructure are to be developed in later phases of the NASA process.

4. Summary

We present the results of a study to assess hundreds of potential architectures for meeting the Earth Science Decadal Survey recommendations for priority observations of global VSWIR imaging spectroscopy and multispectral TIR measurements. The candidate architectures and AoA were presented to NASA for their consideration. The next phase for SBG is referred to as the formulation phase, which establishes a cost-effective program capable of meeting Agency and science mission directorate goals and objectives and will begin in 2021. Formulation follows a standardized procedure, analyses using systems models, and design leading to one or more program reviews followed by a Key Decision Point, advancing the project into implementation (NASA, 2007). This process includes a detailed end-to-end analysis of system design and uncertainty analysis, which will inform requirements definition.

The SBG observing system will transform the science community's understanding of terrestrial and marine ecosystems, snow and ET in the water cycle, the mineralogy and volcanology of the solid Earth, and its evolving landscapes. It will inform a myriad of societal applications spanning agriculture, hydrology, disaster response, human health and urban systems, ecosystem management and conservation, wildfire forecasting and recovery, and many other areas. The science and applications are tightly integrated; much of the science is motivated by the need for improved understanding to inform decisions, and many of the applications motivate scientific and technical advances. The mission lives in Pasteur's Quadrant where fundamental discovery and utility go hand-in-hand. The implementation of the observing system builds on extraordinary technical innovation by NASA and the commercial sector. It will use cutting-edge technology matured over a decade or more of precursor sensor and data system development to facilitate open science (Stavros et al., 2020). The open and publicly available data and derived data products will provide an invaluable resource for science and society globally.

Data Availability Statement

All data pertinent to this manuscript are available in Stavros et al. (2022). Data for subsequent manuscripts in this special issue are responsible for their own data. All data presented in this manuscript are described in the methods and available at: https://doi.org/10.5281/zenodo.6325668.

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