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Key Points

1. Spectroscopic and thermal observations will provide unprecedented information of the Earth's surface biology and geology.
2. As part of the NASA Earth System Observatory, these observations will transform earth science and environmental management.
3. This study informed mission design to provide observations of value across scientific disciplines and applications for decision-making.

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 multi-spectral thermal infrared imager to meet a range of needs. First, and perhaps, foremost, it will be the premier integrated observatory for observing the emerging impacts of climate change. It will characterize the diversity of plant

life by resolving chemical and physiological signatures. It will address wildfire, observing pre-fire risk, fire behavior and post-fire recovery. It will inform responses to hazards and disasters guiding responses to a wide range of events, including 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 resolution, measurement uncertainty) and assessed the cost, mass, power, volume, and risk of different architectures. The Research and Applications team examined available algorithms, calibration and validation and societal applications and used end-to-end modeling to assess uncertainty. The team also identified valuable opportunities for international collaboration to increase the frequency of revisit through data sharing, adding value for all partners. Analysis of the science, applications, architecture and partnerships led to a clear measurement strategy and a well-defined observing system architecture.

Plain Language Summary

We present the observing system measurement targets 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 ground breaking interdisciplinary science relevant to studying the biology and geology of the Earth's surface. Measurements are relevant for studying snow and ice, mineralogy, volcanology, biology, ecology, and components of radiative forcing from the surface such as green house 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 three years that informed an architecture study to design a satellite observing system to provide the most value to as many science and applications as possible.

Introduction

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 represent very large investments of time, effort from skilled professionals, and funding. To do this, United States (US) agencies need to 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 United States National Research Council (NRC) Earth Science and Applications Decadal Survey (NRC, 2019). 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 Surface Biology and Geology (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 et al., 2021; Thompson et al., 2019; Thorpe et al., 2017). SBG science, applications and technology 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; C. M. Lee et al., 2015), and three years of work by the SBG team, leading to the work reported here. 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).

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 in the midst of 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, 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. Ecosystem state affects temperature directly as land use changes land cover (Alkama & Cescatti, 2016) and modifies latent energy fluxes via ET. 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., CO₂, CH₄, N₂O) 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). Thermal and spectroscopic observations thus provide a diverse range of new modes of quantifying, directly and through improved models, the role of the land surface in forcing as well as responding to climate change.

Climate and the solid and living earth interact in multiple ways. 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 and chemical processing (Joye, 2015). SBG observables allow tracking both the distribution of oil (Kokaly et al., 2013) and its impacts on coastal ecosystems (Ainsworth et al., 2018). Other Earth surface dynamics can also require both enhanced scientific monitoring and timely observations that reflect these interactions of the earth system. Wildfire is an important example, where climate and vegetation state affect hazard, weather affects active burning (Coen et al., 2018) and the solid Earth and the water cycle affect landslides and post-fire water quality (Sankey et al., 2017) and require an integrated observing approach (Veraverbeke et al., 2018).

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 Earth System Observatory (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 et 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. 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: evapotranspiration and snow. NISAR (Amelung 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 allow comprehensive studies of interactions from the mountains to the sea, and for the first time, allow the global land-water continuum to be studied as a whole. Taken together, the ESO and aligned missions will provide a next-generation integrated perspective on the Earth’s changing climate, climate impacts and interactions and Earth System dynamics (Figure 2).

SBG AT A GLANCE

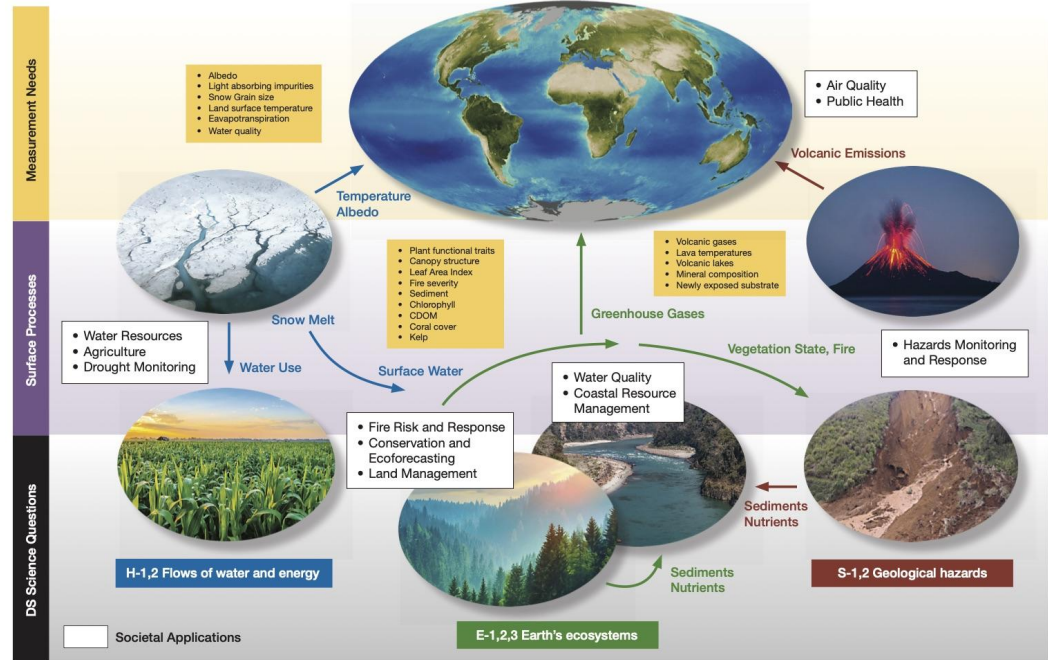


Figure 1. SBG addresses global land surface processes that quantify critical aspects of the land surface, responding to Decadal Survey priorities, which then interact with the Earth's climate system. The observing system has a defined set of critical observables that equally inform environmental management and policy and a host of societal benefit areas. The SBG Science and Applications Objectives are described in Box 1.

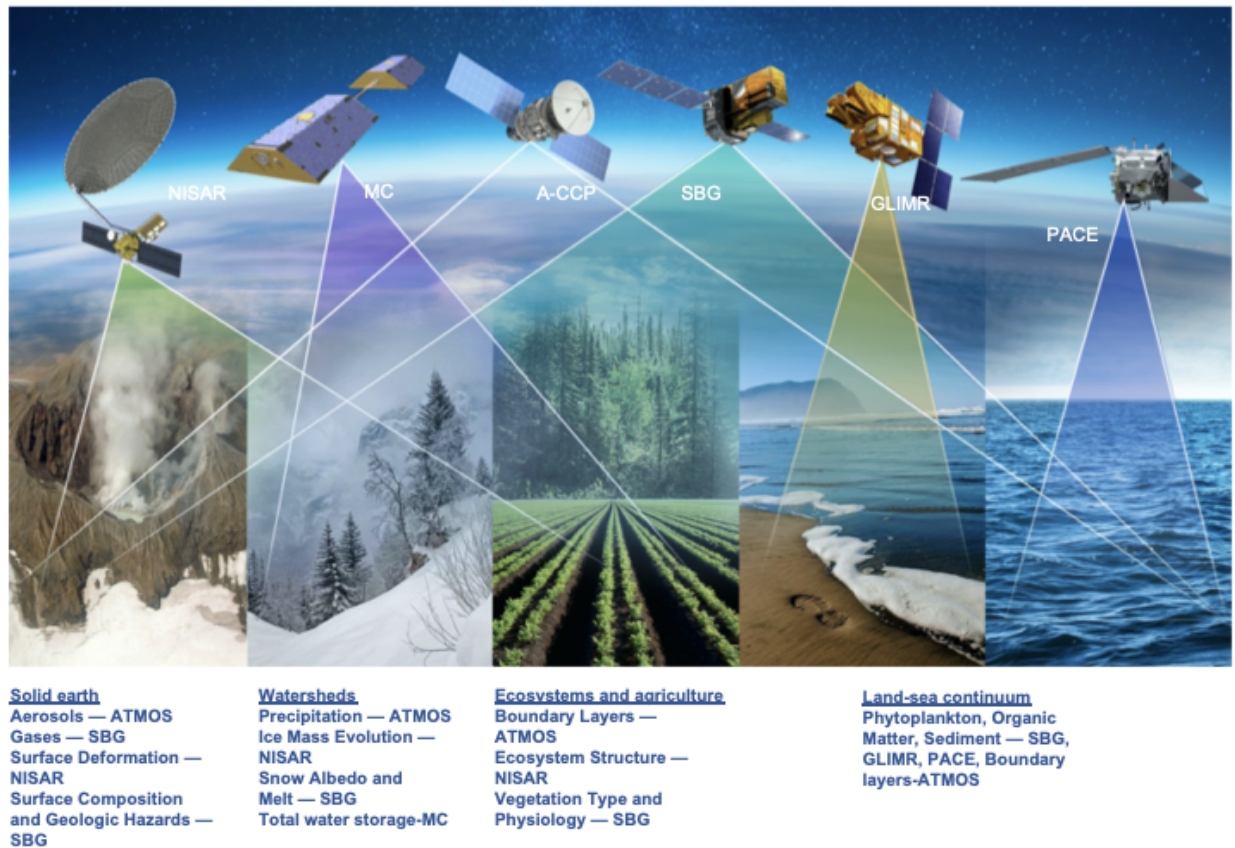


Figure 2. Synergies envisioned between the ESO and contemporaneous missions, enabling integrated geological, watershed, ecosystem and food security and land-sea continuum research.

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

The Decadal Survey Table B (NRC, 2019) identified driving questions, measurement targets and in many cases, geophysical observables relevant for SBG. Key words and phrases constraining responsive architectures are indicated in bold for each of the driving science objectives:

- 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-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?
- 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, cryosphere) and thereby influence weather and air quality?
- E-1 What are the **structure, function, and biodiversity of Earth's ecosystems**, and how and why are they **changing in time and space**?
- 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?
- E-3 What are the fluxes (of carbon, water, nutrients, and energy) **within ecosystems**, and how and why are they changing?
- 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?
- S-1 How can **large-scale geological hazards be accurately forecast** in a socially relevant time frame?
- S-2 How do geological disasters **directly impact the Earth system** and society following an event?

In response to the 2017 Decadal Survey, NASA's Earth Science Division initiated an SBG Architecture Study that included phases where scoping of science, applications, instrument capabilities, mission observing system architecture, risk, and costing were carried out. This study was conducted across NASA centers including the Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), Marshall Research Center (MRC), Ames Research Center, and the Langley Research Center (LaRC) with many other participating university and federal agency scientists. The SBG Study objectives were to: 1) identify and characterize a diverse set of high value SBG observing architectures; 2) assess the performance and cost effectiveness of each candidate architecture against SBG research and applications objectives for all SBG Designated Observables; and 3) recommend potential architectures for NASA to consider for full point-design and mission formulation.

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, it is expected that there will be multiple space-based sensors (eg CHIME, LSTM, TRISHNA) with which SBG can establish virtual constellations to minimize revisit times and produce harmonized spectral imaging data products. There are a number of planned and current missions pioneering TIR and VSWIR relevant observations, though with more limited data acquisition and access. 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 (Fisher et al., 2020; Hook et al., 2020), (Loizzo et al., 2018), (Alonso et al., 2019), 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).

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.

Methods

The SBG Designated Observable Study met the above objectives using *systems engineering* approaches through an *architecture study* (Box 2) conducted in several phases. 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 evaluated 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 already-determined performance targets. Finally, the highest-value options were studied in more detail and a report made to NASA.

Box 2. Systems Engineering Approaches used in the SBG Study

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

What is systems engineering? “Systems engineering” is defined as a methodical, multi-disciplinary 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 as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected. It is a way of looking at the “big picture” when making technical decisions. System engineering is a way of achieving stakeholder functional, physical, and operational performance requirements in the intended use environment over the planned life of the system within cost, schedule, and other constraints. It is a methodology that supports the containment of the life cycle cost of a system.

What is a Science Traceability Matrix? A 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, measurement requirements, instrument requirements and spacecraft and system requirements.

What is an architecture study? An 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 this 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, user access). Architectures are implementable through technologies (e.g., mechanics, electronics, software, in situ networks, procedures).

What is a trade study? Trade studies used to identify the most acceptable solution among a set of proposed solutions. By nature, all decisions are subjective and framed by the values the stakeholders bring to the decision 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.

What is an analysis of alternatives₀ (AoA; Ullman & Ast, 2011)? AoA is a process that 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.

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The Study team established four working groups to provide input to the study and to support ongoing evaluation of candidate architectures. The working groups addressed: societal benefit applications, algorithms, modeling, and calibration and validation (Cal/Val). Participation in the working groups was open to the community, and each group had more than 80 participants. 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.

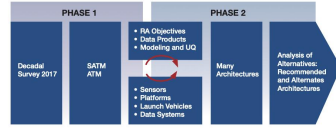


Figure 3. The high-level deliverables for Study phases 1 and 2 from the study team defining the research and application objectives (RA Objectives) and associated tasks for each Research and Applications (R&A) Working Group.

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 required for “Most” and “Very Important” objectives.

These objectives (Box 1) converge on priorities to be addressed in the architecture study:

1. The system must provide **global coverage** to address the global scope of the science.
2. The observing system must have **sufficient mission duration** to observe change (3-7 years), and the study should develop a strategy for continuity of identified key measurements. As such, measurements must be able to

detect **long term changes** for addressing dynamics of the Earth System and not just local processes.

3. The system’s orbit must allow for **consistent sun-sensor geometry** for consistency in retrievals and for calibration and validation, and provide for global coverage, as above (polar orbit).
4. **Visible to Shortwave Infrared (VSWIR; 400-2500 nm) imaging spectroscopy and multi-spectral thermal infrared (TIR; 4 - 12 m) 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 20-60 m for VSWIR and 60-100 m for TIR. The objectives defined by the Decadal Survey led to tight constraints on pixel size; 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 **temporal resolution** must be adequate to capture synoptic and seasonal variation 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., pollution events).
7. Observation **latency**, the time between an event and data access (Davies et al., 2017), must be low enough to support these and other 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 also incorporated 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; <https://sbg.jpl.nasa.gov/satm> accessed 8 February 2021 and Supplemental Online Material) 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 from the Decadal Survey document. We began with the Decadal Survey’s science traceability matrix itself, including all rows referencing the SBG investigation (NRC, 2019). 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 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 (Table 2). These include: snow and ice coverage fraction (cryosphere); snow spectral albedo from visible to thermal (cryosphere); snow surface temperature (cryosphere); VSWIR spectral surface reflectance; evapotranspiration 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); non-photosynthetic vegetation; high-temporal feature delineation (active volcanoes and fires); fractional coverage and silicate composition of lava flows, lahars, ash deposits (active volcanoes); gas and particle concentrations (active volcanoes); surface composition of rock, and soils. Beyond this list, we included additional rows to address instrument needs for 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 are described by Townsend et al. (n.d.).

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 8 parameters per architecture. We also captured the need for temporal coincidence between Visible/Near Infrared (VNIR) images and TIR for specific observables (evapotranspiration).

Not all of the 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, frequent revisit, 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. 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 analogues 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.

Table 1: The 11 Decadal Survey science objectives had associated measurement performance targets listed (NRC, 2019). We analyzed those targets and found them to describe 9 parameters, with typically 3 levels of performance depending on objectives. Performance levels were designated A, B, or C for each of the nine instrument performance categories.

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 Absolute 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 multiple 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

We verified the performance levels needed to derive geophysical observables (Table 2) 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 snow and ice, 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). Several key additional considerations emerged from the analysis of algorithms and their application. First, TIR measurements over “hot” targets such as volcanic events and wildfires were greatly improved by adding non-saturating *middle* infrared (MIR) bands between 3 and 5 μ m. Second, fixed time of day over passes significantly reduce calibration and validation complexity and enable a more consistent time series. Third, the VSWIR and TIR observations have different optimal overpass times: VSWIR benefits most from 1000-1100 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 1300-1400 local solar time overpasses when daily surface temperatures typically reach their daily maximum values. Finally, VSWIR measurements over coastal waters improve significantly if active sunglint avoidance maneuvers are enabled to avoid sun glint conditions.

The SBG Science and Applications Traceability Matrix (SATM) 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). For each of the science objectives and associated geophysical parameters listed, we documented the decision-support applications that could be enabled and marked with an asterisk the 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 objectives. These included measurements related to radiation balance and evapotranspiration 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.

Architecture Trade Space

The SATM 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 HypIRI (C. M. 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 solutions for end-to-end solutions including launch vehicles, instruments, spacecraft/platform, mission/ground/science data systems, and mission design. 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 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 400-2500 nm. An actual instrument might not measure exactly those values; for example, it might go deeper into the UV with channels near 380 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 x pixel size) that reduce coverage or increase acquisition repeat, and lower signal-to-noise (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 revisit. Frequency of revisit is important for several reasons. One is to avoid confounding long-term change (year on year) with shorter timescales, the seasonal cycle, synoptic variations in insolation and temperature, or for coastal regions, the tidal cycle. A second reason is to capture sudden events, wildfires, volcanic activity and disasters, requiring frequent sampling and rapid data availability. Revisit frequency is limited by the available optical and sensor systems defining maximal swath width for any given pixel size. 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 partners with whom to collaborate on cross-calibration to other 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 achieving shorter repeat intervals.

Architecture Value Framework

To inform mission architecture assessment, the team developed and used a framework to characterize the value of each mission architecture defined by its provided science and programmatic benefits 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: 1) clear, traceable, and repeatable analysis; and 2) 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 frequent revisit, and essentially all needed high instrument performance (spectral coverage and resolution, signal-to-noise or its thermal equivalent, noise equivalent to a change in temperature, NeDT). Meeting the more demanding targets usually enabled the less, so we set desired performance at the consensus level where ~70% of specific targets were met.

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. The value of each of the 9 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 class 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 reduce 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 and likely launch dates. Two international collaborations were considered explicitly as sufficient data on instruments and orbits was available: 1) the European Space Agency (ESA) CHIME mission (Nieke & Rast, 2019) and 2) the French National Centre for Space Studies (CNES)/Indian Space Research Organization (ISRO) Thermal infraRed Imaging Satellite for High resolution Natural resource Assessment (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. Other architecture-specific benefits considered qualitatively included: calibration/validation, optimal overpass time, and visible to near infrared (VNIR) and thermal infrared (TIR) coincidence. 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 TRISHNA (or additionally or alternately, with ESA’s planned LSTM thermal mission; (Koetz et al., 2018)) could reduce 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 the low latency, a combination of frequent overpass and rapid downlink.

Results and Discussion

Analysis of the SBG SATM showed that a majority of 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):

- A for spatial resolution; B for temporal revisit;
- A/B respectively for VSWIR and TIR on sensitivity;
- A for spectral coverage;

- A for simultaneous coverage in the VNIR (full VSWIR not needed) and TIR

In short, ABAA ABBA needs high spatial resolution, relatively frequent revisit and excellent instrument performance (spectral resolution, coverage and sensitivity). The most frequently compromised instrument parameter was revisit, 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 (Table 2). The ABAA ABBA “satisfier” measurement target identified for the Study met >70% of needs. Evaluating the satisfier against the ideal performance (all As) for all criteria scored a science value of 6.7, and that was used later in the study to determine a cut-off value for architectures.

Table 2. Many of the Decadal Survey objectives were met by similar performance levels, leading to performance targets for the 9 key parameters that met about 70% of capabilities outlined in the Decadal Survey (ESAS, 2017). The satisfier shows the most common performance level over the 11 Most and Very Important objectives, used as input to the architecture study.

	VSWIR	TIR	Coincidence						
	Spatial	Temporal	Range	Sensitivity	Spatial	Temporal	Range	Sensitivity	
Satisfier	A	A/B	A	A	A	B	B	A	B
H-1a	A	A	A	-	A	B	B	A	-
H-1c	A	A	A	B	A	B	B	A	-
H-2a	A	A	A	-	A	B	B	A	B
H-4a	A	A	A	B	A	B	B	A	-
W-3a	-	-	-	-	B	A	B	A	-
E-1a	A	B	A	A	-	-	-	-	-
E-1c	A	B	A	A	-	-	-	-	-
E-3a	A	-	A	A	A	B	B	A	-
S-1a	A	A	A	A	A	A	B	A	-
S-1c	A	A	A	A	A	C	B	-	-
S-2b	A	A	A	A	A	A	A	-	-

The verification of optimal capabilities by the Algorithms Working Group (Townsend et al., n.d.) supported most Decadal Survey performance specifications, but also revealed a gap in capabilities (Table 3). Algorithmic needs largely parallel the capabilities in Table 3, with the exception of the TIR range. The volcanic and high-temperature algorithms were identified as requiring additional midwave (~4 m) inset spectral range) bands, which fell under capability code “A”. Certain algorithms for estimating volcanic emissions and high temperature features required measurements in the midwave infrared, with high saturation to capture the expected temperature range of volcanic eruptions, in addition to measurements spanning the thermal IR. In this case, the optimal combination ABAA ABBA did not require a 4 m, so this additional

design constraint was considered. It was noted that high SNR was required for many existing aquatic algorithms in the VSWIR, and for algorithms related to volcanic eruptions and evapotranspiration in the TIR. The full visible to shortwave infrared range was necessary for mineral mapping, tracking high temperatures, determining proportional cover, and functional trait algorithms in the VSWIR. High spatial resolution was necessary for mineral mapping algorithms, proportional cover assessment, and the mapping of functional traits. Phenomena with rapid onset or occurrence, such as snow melt or volcanic eruptions, needed to be monitored at high temporal resolutions in order for the algorithms to capture the appropriate phenomena.

Table 3. The Decadal Survey-identified performance levels were validated by analyzing the performance needs for the ten identified SBG geophysical product suites. Where cells are blank, either the algorithm does not use that (VSWIR or TIR) wavelength range, or the community did not identify that parameter as a limiting factor for the relevant algorithms. 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 multi-temporal data the temporal column is left blank even though the science objective may define a revisit need (Table 2).

Product Suite	VSWIR spatial	VSWIR temporal	VSWIR range	VSWIR sensitivity	TIR
Snow		A			
Water biogeochemistry			B	A	
Water biophysics			B	A	
Aquatic classification			B	A	
Substrate composition	A		A		
Volcanic SO2 and Ash		A			B
High temperature features		A	A		
ET			C		B
Plant functional traits	A	B	A		
Proportional cover	A		A		

Community input provided through the Applications Working Group (C. Lee et al., n.d.) was used to provide 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, priority downlink, etc. would enable 77% of potential applications of SBG data (Figure 4). If latency were extended beyond 24 hours, 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 the majority of applications, low-latency and even-driven capabilities were ultimately considered during the architecture filtering process (C. Lee et al., n.d.).

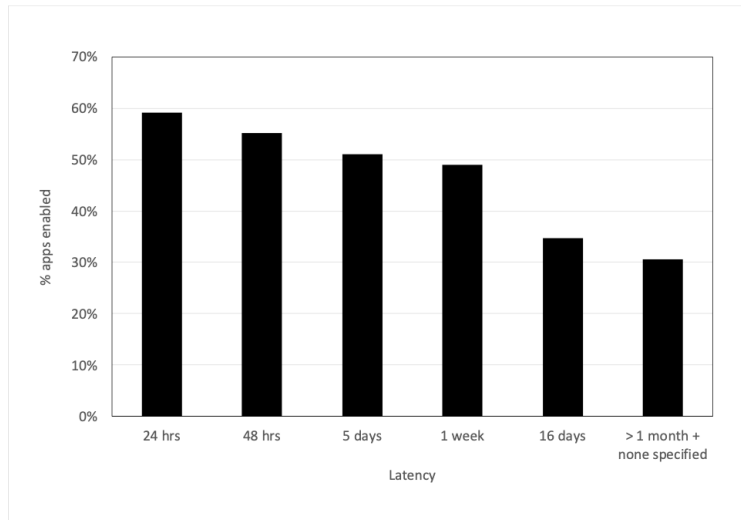


Figure 4. Analysis of applications in the A

Critical to evaluating architectures trades in instrument specifications, number of platforms, orbital altitude, was 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 (Poulter et al., n.d.). The modeling system was based on open-source modeling software, HYPERTRACE (<https://zenodo.org/record/4614338>; Accessed 17 March 2021) for VSWIR and TEUSim for thermal (Hulley et al., 2012). This work resulted in constrained instrument specifications to provide an accuracy at 5% relative uncertainty surface reflectance including dark targets for VSWIR and 1°K absolute uncertainty surface temperature for TIR. The Calibration and Validation Working Group provided strategies as additional design constraints for the architecture team (Turpie et al., n.d.) including: pointing knowledge for subpixel geometric accuracy, and stability for change detection, geolocation and global mosaicking.

After the in-depth Architecture study, each architecture was assigned a science value. A number of architectures were considered that exceeded the science value threshold of at least 6.7 (the score of satisfier measurement targets ABAA ABBA). This process led to multiple candidate architectures for more detailed evaluation. The final architectures were evaluated were considering their science value using a methodology called *analysis of alternatives* (AoA: Box 2) commonly employed in systems engineering. Criteria evaluated in the AoA were:

1. **Science and applications value:** Architectures not meeting the minimum quantitative science value were discarded. These architectures, generally scored below 6.7, “fell off the cliff”. For example, narrower-swath instruments that could not meet 16 and 3 day revisit were unable to achieve

adequate sampling of synoptic or seasonal variation and so had not slightly but dramatically reduced science value, more than was apparent from the numerical value. For example, a VSWIR instrument that could achieve a 20 day revisit 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 3-6 scenes per three-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 co-orbiting with ESA’s CHIME and LSTM or the CNES and ISRO TRISHNA mission. This was not considered in scoring but was used in the final integrated assessment.
3. **International collaboration opportunities:** Architectures differed in their compatibility with potential international collaborators, such as CHIME, LSTM and TRISHNA. The ease of cross-collaboration, coordination of overpass time and orbit were evaluated.
4. **Agility:** Agile platforms, those with considerable inherent attitude control, enable a variety of functions. These include turning to point at the moon for calibration, ocean sunglint avoidance maneuvers and pointing to image abrupt events, to lower latency between events and data availability. **Agile solutions were preferred.**
5. **Coincidence:** Temporal overlap (i.e., “coincidence”) between the TIR and Visible-Near infrared (VNIR) measurements is of value for an important geophysical observable, evapotranspiration. 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 revisit 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.**
6. **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.

7. **Cost, risk and schedule:** While outside the scope of this paper, the final analyses were also guided by cost estimates, provided by NASA parametric cost models and an independent cost estimate provided by a contractor, estimates of risk informed by technology readiness level, and schedule or anticipated timeline for design and construction affected the evaluation of alternative architectures.

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. 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.

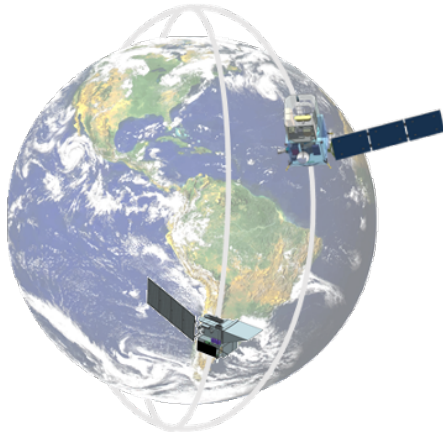


Figure 5. The recommended option for SBG consists of two spacecra

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 and risk advantages, but had several science value challenges (e.g., sub-optimal 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 and 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 considerations above, or had less well-understood risks. As such, they were studied in detail but not ultimately deemed as desirable.

The recommended option was presented to NASA to further develop a *point design*, a design with sufficient detail for implementation. 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, and design leading to one or more program reviews followed by a Key Decision Point, advancing the project into implementation (NASA, 2007).

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

Summary

The SBG observing system will transform the science community’s understanding of terrestrial and marine ecosystems, snow and evapotranspiration 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.

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References

- Ainsworth, C. H., Paris, C. B., Perlin, N., Dornberger, L. N., Patterson, W. F., Chancellor, E., et al. (2018). Impacts of the Deepwater Horizon oil spill evaluated using an end-to-end ecosystem model. *PLoS ONE*, *13*(1). <https://doi.org/10.1371/journal.pone.0190840>
- Alkama, R., & Cescatti, A. (2016). Biophysical climate impacts of recent changes in global forest cover Science. *Science*, *351*(6273), 600–604. <https://doi.org/10.1126/science.aac8083>
- Alonso, K., Bachmann, M., Burch, K., Carmona, E., Cerra, D., de los Reyes, R., et al. (2019). Data Products, Quality and Validation of the DLR Earth Sensing Imaging Spectrometer (DESI). *Sensors*, *19*(20), 4471. <https://doi.org/10.3390/s19204471>
- Amelung, F., Bawden, G., Borsa, A., Buckley, S., Callery, S., Chakraborty, M., et al. (2019). *NASA-ISRO SAR (NISAR) Mission Science Users' Handbook* (No. CL18-1893). NASA Jet Propulsion Laboratory. Retrieved from https://nisar.jpl.nasa.gov/system/documents/files/26_NISAR_FINAL_9-6-19.pdf
- Amundson, R., Richter, D. D., Humphreys, G. S., Jobbágy, E. G., & Gaillardet, J. (2007). Coupling between Biota and Earth Materials in the Critical Zone. *Elements*, *3*(5), 327–332. <https://doi.org/10.2113/gselements.3.5.327>
- Asner, G. P., & Martin, R. E. (2009). Airborne spectranomics: mapping canopy chemical and taxonomic diversity in tropical forests. *Frontiers in Ecology and the Environment*, *7*(5), 269–276. <https://doi.org/10.1890/070152>
- Barducci, A., Guzzi, D., Lastri, C., Marcoionni, P., Nardino, V., & Pippi, I. (2015). Emissivity and Temperature Assessment Using a Maximum Entropy Estimator: Structure and Performance of the MaxEntES Algorithm. *IEEE Transactions on Geoscience and Remote Sensing*, *53*(2), 738–751. <https://doi.org/10.1109/TGRS.2014.2327218>

- Biancamaria, S., Lettenmaier, D. P., & Pavelsky, T. M. (2016). The SWOT Mission and Its Capabilities for Land Hydrology. *Surveys in Geophysics*, 37(2), 307–337. <https://doi.org/10.1007/s10712-015-9346-y>
- Bormann, K. J., Brown, R. D., Derksen, C., & Painter, T. H. (2018). Estimating snow-cover trends from space. *Nature Climate Change*, 8(11), 924–928. <https://doi.org/10.1038/s41558-018-0318-3>
- Brodrick, P. G., Thompson, D. R., Fahlen, J. E., Eastwood, M. L., Sarture, C. M., Lundeen, S. R., et al. (2021). Generalized radiative transfer emulation for imaging spectroscopy reflectance retrievals. *Remote Sensing of Environment*, 261, 112476. <https://doi.org/10.1016/j.rse.2021.112476>
- Buongiorno, M. F., Pieri, D., & Silvestri, M. (2013). Thermal Analysis of Volcanoes Based on 10 Years of ASTER Data on Mt. Etna. In C. Kuenzer & S. Dech (Eds.), *Thermal Infrared Remote Sensing: Sensors, Methods, Applications* (pp. 409–428). Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-6639-6_20
- Cawse-Nicholson, K., Townsend, P. A., Schimel, D., Assiri, A. M., Blake, P. L., Buongiorno, M. F., et al. (2021). NASA’s surface biology and geology designated observable: A perspective on surface imaging algorithms. *Remote Sensing of Environment*, 257, 112349. <https://doi.org/10.1016/j.rse.2021.112349>
- Coen, J. L., Stavros, E. N., & Fites-Kaufman, J. A. (2018). Deconstructing the King megafire. *Ecological Applications*, 28(6), 1565–1580. <https://doi.org/10.1002/eap.1752>
- Cusworth, D. H., Duren, R. M., Thorpe, A. K., Eastwood, M. L., Green, R. O., Dennison, P. E., et al. (2021). Quantifying Global Power Plant Carbon Dioxide Emissions With Imaging Spectroscopy. *AGU Advances*, 2(2), e2020AV000350. <https://doi.org/10.1029/2020AV000350>
- Davies, D. K., Brown, M. E., Murphy, K. J., Michael, K. A., Zavodsky, B. T., Stavros, E. N., & Carroll, M. L. (2017). Workshop on Using NASA Data for Time-Sensitive Applications. *IEEE Geoscience and Remote Sensing Magazine*. <https://doi.org/10.1109/MGRS.2017.2729278>
- Fisher, J. B., Lee, B., Purdy, A. J., Halverson, G. H., Dohlen, M. B., Cawse-Nicholson, K., et al. (2020). ECOSTRESS: NASA’s Next Generation Mission to Measure Evapotranspiration From the International Space Station. *Water Resources Research*, 56(4). <https://doi.org/10.1029/2019WR026058>
- Friberg, J., Martinsson, B. G., Andersson, S. M., & Sandvik, O. S. (2018). Volcanic impact on the climate – the stratospheric aerosol load in the period 2006–2015. *Atmospheric Chemistry and Physics*, 18(15), 11149–11169. <https://doi.org/10.5194/acp-18-11149-2018>
- Gillespie, A., Rokugawa, S., Matsunaga, T., Cothorn, J. S., Hook, S., & Kahle, A. B. (1998). A temperature and emissivity separation algorithm for Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) images.

- IEEE Transactions on Geoscience and Remote Sensing*, 36(4), 1113–1126. <https://doi.org/10.1109/36.700995>
- Green, R. O., Mahowald, N., Ung, C., Thompson, D. R., Bator, L., Bennet, M., et al. (2020). The Earth Surface Mineral Dust Source Investigation: An Earth Science Imaging Spectroscopy Mission. In *2020 IEEE Aerospace Conference* (pp. 1–15). Big Sky, MT, USA: IEEE. <https://doi.org/10.1109/AERO47225.2020.9172731>
- Guanter, L., Kaufmann, H., Segl, K., Foerster, S., Rogass, C., Chabrillat, S., et al. (2015). The EnMAP Spaceborne Imaging Spectroscopy Mission for Earth Observation. *Remote Sensing*, 7(7), 8830–8857. <https://doi.org/10.3390/rs70708830>
- Heino, J., Alahuhta, J., Bini, L. M., Cai, Y., Heiskanen, A.-S., Hellsten, S., et al. (2021). Lakes in the era of global change: moving beyond single-lake thinking in maintaining biodiversity and ecosystem services. *Biological Reviews*, 96(1), 89–106. <https://doi.org/10.1111/brv.12647>
- Hook, S. J., Cawse-Nicholson, K., Barsi, J., Radocinski, R., Hulley, G. C., Johnson, W. R., et al. (2020). In-Flight Validation of the ECOSTRESS, Landsats 7 and 8 Thermal Infrared Spectral Channels Using the Lake Tahoe CA/NV and Salton Sea CA Automated Validation Sites. *IEEE Transactions on Geoscience and Remote Sensing*, 58(2), 1294–1302. <https://doi.org/10.1109/TGRS.2019.2945701>
- Hulley, G. C., Hughes, C. G., & Hook, S. J. (2012). Quantifying uncertainties in land surface temperature and emissivity retrievals from ASTER and MODIS thermal infrared data. *Journal of Geophysical Research: Atmospheres*, 117(D23). <https://doi.org/10.1029/2012JD018506>
- Iwasaki, A., & Yamamoto, H. (2013). Data product of Hyperspectral Imager Suite (HISUI). In *2013 IEEE International Geoscience and Remote Sensing Symposium - IGARSS* (pp. 4407–4410). Melbourne, Australia: IEEE. <https://doi.org/10.1109/IGARSS.2013.6723812>
- Jetz, W., Cavender-Bares, J., Pavlick, R., Schimel, D., Davis, F. W., Asner, G. P., et al. (2016). Monitoring plant functional diversity from space. *Nature Plants*, 2(3), 16024. <https://doi.org/10.1038/nplants.2016.24>
- Johnson, W. R., Hook, S. J., Mouroulis, P., Wilson, D. W., Gunapala, S. D., Realmuto, V., et al. (2011). HyTES: Thermal imaging spectrometer development. In *2011 Aerospace Conference* (pp. 1–8). Big Sky, USA: IEEE. <https://doi.org/10.1109/AERO.2011.5747394>
- Joye, S. B. (2015). Deepwater Horizon, 5 years on. *Science*, 349(6248), 592–593. <https://doi.org/10.1126/science.aab4133>
- JPL. (2018). *HypIRI Final Report - HypIRI Mission Concept Team*. National Aeronautics and Space Administration (NASA).

- Koetz, B., Bastiaanssen, W., Berger, M., Defournay, P., Bello, U. D., Drusch, M., et al. (2018). High Spatio- Temporal Resolution Land Surface Temperature Mission - a Copernicus Candidate Mission in Support of Agricultural Monitoring. In *IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium* (pp. 8160–8162). <https://doi.org/10.1109/IGARSS.2018.8517433>
- Kokaly, R. F., Couvillion, B. R., Holloway, J. M., Roberts, D. A., Ustin, S. L., Peterson, S. H., et al. (2013). Spectroscopic remote sensing of the distribution and persistence of oil from the Deepwater Horizon spill in Barataria Bay marshes. *Remote Sensing of Environment*, 129, 210–230. <https://doi.org/10.1016/j.rse.2012.10.028>
- Kornfeld, R. P., Arnold, B. W., Gross, M. A., Dahya, N. T., Klipstein, W. M., Gath, P. F., & Bettadpur, S. (2019). GRACE-FO: The Gravity Recovery and Climate Experiment Follow-On Mission. *Journal of Spacecraft and Rockets*, 56(3), 931–951. <https://doi.org/10.2514/1.A34326>
- Lagouarde, J. P., Bhattacharya, B. K., Crébassol, P., Gamet, P., Adlakha, D., Murthy, C. S., et al. (2019). Indo-French high-resolution thermal infrared space mission for earth natural resources assessment and monitoring - Concept and definition of TRISHNA. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(3/W6), 403–407. <https://doi.org/10.5194/isprs-archives-XLII-3-W6-403-2019>
- Lee, C., Glenn, N. F., Stavros, E. N., Luvall, J., Hain, C., Yuen, K., & Schollaert Uz, S. (n.d.). Integrating Earth Decadal Survey application priorities during mission pre-formulation for Surface Biology and Geology (SBG). *AGU JGR Biogeosciences*.
- Lee, C. M., Cable, M. L., Hook, S. J., Green, R. O., Ustin, S. L., Mandl, D. J., & Middleton, E. M. (2015). An introduction to the NASA Hyperspectral InfraRed Imager (HyspIRI) mission and preparatory activities, 14.
- Loarie, S. R., Duffy, P. B., Hamilton, H., Asner, G. P., Field, C. B., & Ackerly, D. D. (2009). The velocity of climate change. *Nature*, 462(7276), 1052–1055. <https://doi.org/10.1038/nature08649>
- Loizzo, R., Guarini, R., Longo, F., Scopa, T., Formaro, R., Facchinetti, C., & Varacalli, G. (2018). Prisma: The Italian Hyperspectral Mission. In *IGARSS 2018 - 2018 IEEE International Geoscience and Remote Sensing Symposium* (pp. 175–178). Valencia: IEEE. <https://doi.org/10.1109/IGARSS.2018.8518512>
- Lovelock, C. E., & Duarte, C. M. (2019). Dimensions of Blue Carbon and emerging perspectives. *Biology Letters*, 15(3), 20180781. <https://doi.org/10.1098/rsbl.2018.0781>
- Margetta, R. (2021, May 24). New NASA Earth System Observatory to Help Address Climate Change [Text]. Retrieved June 7, 2021, from <http://www.nasa.gov/press-release/new-nasa-earth-system-observatory-to-help-address-mitigate-climate-change>

- Matsunaga, T., Iwasaki, A., Tsuchida, S., Iwao, K., Tanii, J., Kashimura, O., et al. (2016). Current status of Hyperspectral Imager Suite (HISUI) and its deployment plan on International Space Station. In *2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)* (pp. 257–260). Beijing, China: IEEE. <https://doi.org/10.1109/IGARSS.2016.7729058>
- Mouroulis, P., Green, R. O., Van Gorp, B., Moore, L. B., Wilson, D. W., & Bender, H. A. (2016). Landsat swath imaging spectrometer design. *Optical Engineering*, 55(1), 015104. <https://doi.org/10.1117/1.OE.55.1.015104>
- NASA. (2007). NASA Systems Engineering Handbook. *NASA SP-2016-6105*, 297. Retrieved from <https://www.nasa.gov/seh/1-introduction>
- Nieke, J., & Rast, M. (2019). Status: Copernicus Hyperspectral Imaging Mission For The Environment (CHIME). In *IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium* (pp. 4609–4611). <https://doi.org/10.1109/IGARSS.2019.8899807>
- NRC. (2019). *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space: An Overview for Decision Makers and the Public* (p. 25437). Washington, D.C.: National Academies Press. <https://doi.org/10.17226/25437>
- Painter, T. H., Deems, J. S., Belnap, J., Hamlet, A. F., Landry, C. C., & Udall, B. (2010). Response of Colorado River runoff to dust radiative forcing in snow. *Proceedings of the National Academy of Sciences*, 107(40), 17125–17130. <https://doi.org/10.1073/pnas.0913139107>
- Poulter, B., Calle, L., Cawse-Nicholson, K., Serbin, S. P., Shiklomanov, A. N., Schimel, D. S., et al. (n.d.). Simulating Surface Biology and Geology global land-surface reflectances.
- Ruckelshaus, M. H., Jackson, S. T., Mooney, H. A., Jacobs, K. L., Kassam, K.-A. S., Arroyo, M. T. K., et al. (2020). The IPBES Global Assessment: Pathways to Action. *Trends in Ecology & Evolution*, 35(5), 407–414. <https://doi.org/10.1016/j.tree.2020.01.009>
- Salisbury, J., & Mannino, A. (2020). The NASA Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR) requires advanced processing techniques. Presented at the Ocean Sciences Meeting 2020, AGU. Retrieved from <https://agu.confex.com/agu/osm20/meetingapp.cgi/Paper/655253>
- Sankey, J. B., Kreitler, J., Hawbaker, T. J., McVay, J. L., Miller, M. E., Mueller, E. R., et al. (2017). Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds. *Geophysical Research Letters*, 44(17), 8884–8892. <https://doi.org/10.1002/2017GL073979>
- Schimel, D., Pavlick, R., Fisher, J. B., Asner, G. P., Saatchi, S., Townsend, P., et al. (2015). Observing terrestrial ecosystems and the carbon cycle from space. *Global Change Biology*, 21(5), 1762–1776. <https://doi.org/10.1111/gcb.12822>

- Sellers, P. J., Schimel, D. S., Moore, B., Liu, J., & Eldering, A. (2018). Observing carbon cycle–climate feedbacks from space. *Proceedings of the National Academy of Sciences*, 115(31), 7860–7868. <https://doi.org/10.1073/pnas.1716613115>
- Simpkins, G. (2018). Snow-related water woes. *Nature Climate Change*, 8(11), 945–945. <https://doi.org/10.1038/s41558-018-0330-7>
- Singh, A., Serbin, S. P., McNeil, B. E., Kingdon, C. C., & Townsend, P. A. (2015). Imaging spectroscopy algorithms for mapping canopy foliar chemical and morphological traits and their uncertainties. *Ecological Applications*, 25(8), 2180–2197. <https://doi.org/10.1890/14-2098.1>
- Stavros, E. N., Schimel, D., Pavlick, R., Serbin, S., Swann, A., Duncanson, L., et al. (2017). ISS observations offer insights into plant function. *Nature Ecology & Evolution*, 1(7), 0194. <https://doi.org/10.1038/s41559-017-0194>
- Stavros, E. N., Townsend, P. A., Chang, G., Hua, H., Huang, T., Malarout, N., et al. (2020). Imaging Spectroscopy Processing Environment on the Cloud (ImgSPEC). Presented at the American Geophysical Union Fall Meeting, Virtual. <https://doi.org/doi.org/10.1002/essoar.10506888.1>
- Tapley, B. D., Bettadpur, S., Ries, J. C., Thompson, P. F., & Watkins, M. M. (2004). GRACE Measurements of Mass Variability in the Earth System. *Science*, 305(5683), 503–505. <https://doi.org/10.1126/science.1099192>
- Thompson, D. R., Babu, K. N., Braverman, A. J., Eastwood, M. L., Green, R. O., Hobbs, J. M., et al. (2019). Optimal estimation of spectral surface reflectance in challenging atmospheres. *Remote Sensing of Environment*, 232, 111258. <https://doi.org/10.1016/j.rse.2019.111258>
- Thorpe, A. K., Frankenberg, Christian, Thompson, David R., Duren, Riley M., Aubrey, Andrew D., Bue, Brian D., et al. (2017). Airborne DOAS retrievals of methane, carbon dioxide, and water vapor concentrations at high spatial resolution: applicaiton to AVIRIS-ng. *Atmospheric Measurement Techniques*, 10, 3833–3850. <https://doi.org/10.5194/amt-10-3833-2017>
- Townsend, P. A., Cawse-Nicholson, K., Chlus, A., Dennison, P. E., Dierssen, H., Dozier, J., et al. (n.d.). Core algorithms and products for Surface Biology and Geology.
- Turpie, K., Kokaly, R., Crawford, C., Guild, L. S., Thome, K., Shrestha, A., et al. (n.d.). Calibration and Validation for the Surface Biology and Geology (SBG) Mission Concept and the Challenges of a Multi-Sensor System for Imaging Spectroscopy and Thermal Imagery.
- Ullman, D. G., & Ast, R. (2011). Analysis of Alternatives (AoA) Based Decisions. *MORS, Phalanx*, 44(3).
- Veraverbeke, S., Dennison, P., Gitas, I., Hulley, G., Kalashnikova, O., Katagis, T., et al. (2018). Hyperspectral remote sensing of fire: State-of-the-art

and future perspectives. *Remote Sensing of Environment*, 216, 105–121. <https://doi.org/10.1016/j.rse.2018.06.020>

Wang, Z., Chlus, A., Geygan, R., Ye, Z., Zheng, T., Singh, A., et al. (2020). Foliar functional traits from imaging spectroscopy across biomes in eastern North America. *New Phytologist*, 228(2), 494–511. <https://doi.org/10.1111/nph.16711>

Weiss, J. R., Smythe, W. D., & Wenwen Lu. (2005). Science traceability. In *2005 IEEE Aerospace Conference* (pp. 292–299). <https://doi.org/10.1109/AERO.2005.1559323>

Werdell, P. J., Behrenfeld, M. J., Bontempi, P. S., Boss, E., Cairns, B., Davis, G. T., et al. (2019). The Plankton, Aerosol, Cloud, Ocean Ecosystem Mission: Status, Science, Advances. *Bulletin of the American Meteorological Society*, 100(9), 1775–1794. <https://doi.org/10.1175/BAMS-D-18-0056.1>

Winchell, T. S., Barnard, D. M., Monson, R. K., Burns, S. P., & Molotch, N. P. (2016). Earlier snowmelt reduces atmospheric carbon uptake in mid-latitude subalpine forests. *Geophysical Research Letters*, 43(15), 8160–8168. <https://doi.org/10.1002/2016GL069769>

Worden, J., Saatchi, S., Keller, M., Bloom, A. A., Liu, J., Parazoo, N., et al. (2021). Satellite Observations of the Tropical Terrestrial Carbon Balance and Interactions With the Water Cycle During the 21st Century. *Reviews of Geophysics*, 59(1), e2020RG000711. <https://doi.org/10.1029/2020RG000711>