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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

Key Points:

- The Surface Biology and Geology study has shown that science and applications can be considered synergistically, at the start of the satellite mission life cycle
- Applications and science integration produced a more representative and tailored set of measurement needs driving mission architecture
- Applications conferred unique technical needs, particularly around latency, that were carried through the architecture study

Supporting Information:

Supporting Information may be found in the online version of this article.

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Systematic Integration of Applications into the Surface Biology and Geology (SBG) Earth Mission Architecture Study

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Abstract The Surface Biology and Geology (SBG) concept is the first National Aeronautics and Space Administration (NASA) Earth mission to develop and implement systematic integration of science application needs at the architecture study stage. Prior NASA mission concept and planning activities presumed that science measurement needs would encompasss application measurement needs and so did not explicitly evaluate and include applications at this stage. However, the effort presented here identified, documented and integrated application needs that would not have been included by considering research science needs only. First, a low latency of no greater than 24 hr was identified as the optimal target to enable the maximum number of applications and was then carried through into all SBG candidate architectures. Second, many applications expressed needs around improved spatial and temporal resolution. While increased spatial resolution would not be possible under current cost and technology considerations, the need for improved resolution for temporal sampling helped drive and bolster discussions with international partners such as the European Space Agency, Italian Space Agency, and Centre National D'Etudes Spatiales. Lastly, we found that the applications and science were synergistic with one another; for example, mission concept decisions to consider additional measurement features were driven by both high relevance application and science priorities, and in particular, evapotranspiration for agriculture and high temperature features for fires and geologic hazards. This paper discusses the process and key contributions originating from the SBG Applications Working Group and how they shaped SBG at the architecture study stage. This stage in the mission planning considers the trade space of spacecraft instruments and architectures, and evaluates which formulations are suitable candidates for SBG. The approach described here may be utilized as a framework for applications and science to inform future NASA satellite mission studies.

Plain Language Summary This is the first instance of integration from the perspective of science applications into mission design, and at the architecture study phase. Mission architectures have traditionally been underpinned by science needs only. This effort demonstrates that not only does the applications community confer unique technical and measurement needs that are feasible to integrate into architecture considerations, but also that the overall process for defining mission requirements is enhanced through science and applications synergy and cohesion. Furthermore, applications feed into other aspects of the mission design process at early stages, such as bolstering discussions with international partners and reinforcing the benefits and need of harmonized data products and mission coordination.

1. Introduction

Satellite data from Earth orbiting missions have had direct and profound impacts on society, beyond those that advance our state of knowledge and understanding of the Earth as a system. These impacts often manifest through applied sciences efforts that translate Earth systems knowledge to actionable information for decision support. Several studies have quantified intrinsic and socioeconomic value to society from Earth observations (Bernknopf et al., 2021; Field et al., 1995; Jewiss et al., 2020; Le Traon et al., 2019; Schiavon et al., 2021; Stroming et al., 2020).

To expand this potential, National Aeronautics and Space Administration (NASA) Earth science mission application efforts have included a number of early adopter programs (Brown et al., 2016; Doorn et al., 2016; Escobar et al., 2016; Lee, 2020; Moran et al., 2015; Nastan, 2019; Stavros et al., 2018; Yuen, 2018). Early adopter

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programs are designed to engage stakeholders pre-launch of a mission and help establish the capacity, and inform tools and services provided by NASA, to use data once available. The first formally initiated early adopters effort was in 2010 by the Soil Moisture Active Passive mission Applications Working Group (Brown et al., 2013; Escobar et al., 2016; Moran et al., 2015). In all 10 instances of stakeholder early engagement programs across NASA Earth Science missions (collectively known as "Early Adopters, Early Engagers, Future Adopters") and user needs assessments conducted through the Landsat program (Wu et al., 2019), mission requirements and other architecture features were largely determined beforehand. The NASA-Indian Space Research Organization Synthetic Aperture Radar (NISAR) mission included an applications-focused requirement to their mission to include a portion of data downlink and processing for low latency data products supporting disaster response (Stavros et al., 2018). Other innovations in early adoption efforts include linking user needs to cloud architecture (Stavros et al., 2020), hackathons (Hossain et al., 2022; Srinivasan et al., 2021) and user-focused workshops, all of which will also be critical for infusion of applications into the Surface Biology and Geology (SBG) mission life cycle and development as envisioned by the Project Applications Directive (Freilich, 2016), which serves as a guide to NASA mission application teams in developing and implementing programs to build the respective mission's community of practice. An assessment of NASA mission early adopter programs is also available (Sylak-Glassman & Sheth, 2020).

In general, these efforts are not explicitly or systematically integrated into NASA Earth orbiting mission pre-formulation or architecture studies. While it is widely acknowledged that Earth science data can address knowledge gaps by providing geospatial information about a particular region or resource of interest, science needs have been the primary driver of mission requirements, and applications are expected to use what becomes available. The European Space Agency (ESA), however, has long utilized applications value as a driver for defining capability needs for new Earth orbiting missions (Matevosyan et al., 2017; Schiavon et al., 2021; Taramelli et al., 2020).

Building off the above NASA Earth science mission application efforts, the SBG mission concept considers applications at the onset of planning, at the architecture study stage. The SBG mission concept includes a global imaging spectrometer spanning the visible to shortwave infrared (VSWIR) and a multi-spectral thermal infrared (TIR) radiometer. This mission concept was proposed as a high-priority observing system by the US National Research Council in the 2017 Earth Science Decadal Survey (National Academies of Sciences and Medicine, 2018), hereafter referred to as the "Decadal Survey." Because of precursor missions like the pre-HyspIRI airborne campaign in California (Lee et al., 2015), the Arctic Boreal Vulnerability Experiment (ABoVE) campaign (Fisher et al., 2018; C. E. Miller et al., 2019), COral ReefAirborne Laboratory (Hochberg & Gierach, 2021), and the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (Fisher et al., 2020; Hulley et al., 2017), there has not only been demonstrated added value of additional spectral information (e.g.,Veraverbeke et al., 2014) from these data over the existing program of record (which refers to Earth mission data records from previous and current operating missions), but also a continued and augmented ability to contribute to the long-term multispectral Landsat record (Seidel et al., 2018). Recent work (Culver et al., 2020) conducted through a user-centered design approach articulated the potential value of SBG data through interviews and surveys with the applications community using past missions to help demonstrate the value-add. The Landsat community has also documented the value of the Landsat record to the applied user community (Wu et al., 2019).

The Decadal Survey summarizes and recommends key priority science and application questions and potential measurement strategies to underpin future Earth science missions, with the 2017 Decadal Survey being the second Earth-focused document of this kind. NASA has, thus far, utilized this document as a guide to inform exploration of new Earth mission concepts which are later considered as candidates for fully funded missions. For SBG, the mission concept study team was structured as four working groups which included, Applications, Algorithms (Cawse-Nicholson et al., 2021), Modeling, and Calibration/Validation. Each of these working groups (WG) gathered information from their broader communities of practice, conducted trade studies, and informed the overall mission concept study, and specifically potential SBG architectures. Additional information on the interaction of these groups and their contributions to the architecture study can be found in (Stavros et al., 2022). It should be noted that the organization of mission study teams is determined on a case-by-case basis, with early team members customizing the structure to best suit the needs of the mission concept study.

The dedicated SBG Applications working group (AppsWG) focuses on infusing applications community capability needs into a larger architecture study (i.e., a study to evaluate what kind of sensors and measurement capabilities are needed to address Decadal Survey science and application targets linked to SBG). The AppsWG collected and synthesized the applications community needs in the context of the Decadal Survey (National Academies of Sciences and Medicine, 2018) recommendations.

There were four main activities over the course of the architecture study that resulted in integration of applications considerations into SBG architectures: first, the AppsWG developed a table that documented SBG-enabled applications, along with their associated measurement needs, and their driving science objectives. Second, the AppsWG expanded the Science Traceability Matrix to include applications. The Science Traceability Matrix (STM) is a tool used by mission study teams to show traceability from Decadal Survey priorities, the requisite geophysical parameters needed to address those priorities, and the capabilities necessary to produce the geophysical parameters (Weiss et al., 2005). As a result, the AppsWG helped produce the SBG Science Applications Traceability Matrix (SATM) that identifies feasible applications within the context of science objectives and demonstrates traceability from the Decadal Survey to applications. Third, the AppsWG analyzed trades across disciplines and application domains for different capabilities and needs to assess impacts of different mission architecture design decisions. Finally, the Apps WG assessed the applications value as intrinsically important context that can help improve partnerships within the external community as well as internationally for mission planning—more detail on this effort can be found in (Culver et al., 2020).

This manuscript provides detail on the process developed for integrating science applications in SBG's mission architecture study. Specifically, we detail how the AppsWG collected and incorporated application community needs into the SATM, and how this information ultimately translated to a convergence of a set of recommendations for the SBG architecture study, as well as how the integration of applications perspectives within the Research and Analysis team allowed for more robust understanding of measurement needs and instrument features. For instance, spatial resolution and latency, together, can provide a basis for understanding this convergence of recommendations. Science and applications can have measurement targets that will ultimately be used for deriving geophysical parameters that are used in both. Further, complementary science and applications may both need finer spatial resolution (shared measurement target) but only one of them needs lower latency (not shared). Part of the responsibility of the AppsWG was to help these targets converge to tractable recommendations in the architecture study—that is, recommending both the shared measurement and not shared measurement targets for engineering design sessions.

It is also important to note that SBG is one of four mission concepts under consideration from the recent Decadal Survey, and is part of an envisioning of the NASA Earth System Observatory which embodies a holistic approach to conducting Earth systems research and quantifying climate change and its impacts. The Earth System Observatory in essence considers each mission as one component of a larger observing system, designed with complementary measurements and targets to advance broader science and applications goals. More information about this construct is available here: https://science.nasa.gov/earth-science/earth-system-observatory.

2. Methods

Community Engagement. Beginning in 2018, the AppsWG established an open process for participation and membership upon request and maintains open membership (either by contacting sbg@jpl.nasa.gov or visiting http://tinyurl.com/sbgapplicationswg). Members of the AppsWG received information via an email list regarding announcements and news updates, special discussion topics related to the mission, and seminars about SBG and applications. As of the writing of this manuscript, the AppsWG has 178 members spanning public and private sectors, universities, non-profits, non-governmental and governmental organizations (US/non-US, federal, state, regional, and local). These members do not receive any direct funds from SBG and participate on a voluntary basis. The AppsWG group continues to be active and open to participants. AppsWG meetings were one of the primary mediums through which the SBG team discussed applications needs with the community and then iterated and integrated them into the architecture study. Additional information regarding the other working group structures are available in Stavros et al. (2022). It is expected that the working groups will continue to serve an important and active role in engaging with the broader science and applications community. The primary goal of the AppsWG during the mission study phase was to provide community input regarding architecture-related needs necessary to support applications. This input was captured in the Applications Traceability Matrix (ATM) and other analysis, described in the following subsections.

Table 1

The Surface Biology and Geology Applications Traceability Matrix was Formatted to Show Traceability From Decadal Survey Questions Through Applications Concept and Decision Context

SBG Applications Traceability Matrix Categories												
SATM		**New Category, ATM Specific**			**SATM**			**New Category, ATM Specific**				
Decadal Survey Question	Focused Science Topic	Apps Focus Group	Apps Concept	Decision Context	L2+ VSWIR L2+ TIR geophysical parameters	Spatial	Temporal	Latency*	Other Design Factors	End Users	Ancillary Data	Notes

Note. Latency information was also documented.

Applications Traceability Matrix. The leads and members of the SBG AppsWG co-produced the Application Traceability Matrix (ATM), which expands upon the format of the traditional Science Traceability Matrix (Weiss et al., 2005), a table that illustrates what instrument capabilities are needed to produce the necessary measurements and data products to address critical Decadal Survey questions, to show traceability to applications of NASA data within the decision context. Table 1 summarizes the categories of information collected for the ATM. The columns highlighted in blue correspond with categories in a traditional STM; those highlighted in yellow correspond with categories added to the ATM. Inputs into the ATM were provided by community members; in some cases, the AppsWG organized working meetings to ensure inputs were acquired for targeted application areas and to ensure community concurrence on how needs were being captured and reflected in the ATM (Table S1).

Application Traceability Matrix Integration Into the SATM. To integrate applications into the SATM, ATM entries were mapped to Decadal Survey priority objectives. This enabled a crosswalk between the two matrices (ATM, SATM). Applications with an associated Decadal Survey objective, were summarized, labeled "Enabled Applications," and captured through unique identifiers (EA1-EA46) tagged to each Decadal Survey objective in the SATM as an extra column in the matrix. The number of Decadal Survey relevant applications was later updated to 49, though the SATM version was finalized at 46. Therefore, 49 applications were considered in subsequent analyses. The SATM also labeled Enabled Applications with low latency need in initial reviews, defined notionally as 48 hr, and which was later investigated in more detail to support engineering design sessions. At this stage "low latency" applications were defined as the time from acquisition to user access, and generally included those that were often responding to a natural or anthropogenic hazard or event, which would also benefit from higher revisit or acquisition soon after event occurrence.

Latency Analysis. While the SATM flags applications with low latency needs (initially <48 hr), the optimal latency period was not identified until the more focused Latency Analysis. Latency is defined in the SBG study as the time between data acquisition and data access by users. Each applications entry includes a maximum latency for enabling decision-support. These values were reviewed by the AppsWG community and existing studies for additional reference were also used. For the applications associated with the Decadal Survey, information from the latency category was aggregated and visualized in a cumulative probability plot, with latency categories ranging from no latency requirement to 6 hr within acquisition. Latency categories include 6, 12, 24, and 48 hr, 5 days, 7 days, and 16days, and >1 month or none. This latency analysis was then used as part of a guiding document informing the architecture engineering design sessions that evaluated candidate architectures for SBG. Some core architecture considerations affected by latency include the number of ground stations needed, temporal revisit and subsequently the required number of platforms, ability to point and maneuver, and on-board processing and storage capabilities. The Latency Analysis also included a separate assessment of whether the capability set (Stavros et al., 2022) being proposed for SBG would meet needs for a given application. This analysis initially considered a weekly revisit for the VSWIR instrument (based on the Decadal Survey), and was later updated to biweekly. This change affected the maximum number of applications that could be classified as enabled.

Temporal Analysis. For this analysis, temporal resolution dependencies, defined as revisit frequency, were considered in conjunction with sensor needs for SBG applications that were relevant to the Decadal Survey. We examined applications associated with the spectral ranges needed; these categories included visible to near infrared (VNIR), VSWIR, and TIR, and further combined with temporal needs. First, applications were aggregated into categories based on sensor needs; this was done by reviewing the geophysical products needed to support a particular application, and what combination of sensors would be needed to generate that collection of products. Thus, each application was categorized into sensor combinations: (a) VSWIR only; (b) VSWIR and TIR; (c) TIR only and TIR with a VNIR camera; and (d) VSWIR and TIR with a VNIR camera. The fourth category was considered the most inclusive sensor set. Within each of these four categories, we then reviewed the temporal revisit needs for each application, and binned them into the following categories: <1-day, 1-day, 3-day, 7-day, 14-day, 30-day, 90-day, 180+day. The associated Decadal Survey category was also preserved in this analysis, which was ultimately represented as another cumulative probability plot for each sensor combination.

Application Value Metrics for SBG Candidate Architectures. The AppsWG leadership provided design targets that were considered in the engineering design sessions (Schimel & Poulter, 2020), which assessed potential architectures and weighed their technical feasibility to meet SATM measurement and cost targets. Each of the candidate architectures were evaluated against three application value metrics to confirm the integration of the community needs and maximize value of data for applications:

1. Low latency: candidates were scored “A” if they met the <24 hr latency target and “B” if they did not.
2. Data downlink: candidates scored an “A” if they considered cost for data priority downlink capabilities and “B” if they did not.
3. Hazard response: candidates scored an “A” if they were able to be responsive to hazard applications that required even lower latency than 24 hr, “B” if they did not.

The <24 hr latency target and subsequent “A” score emerged due to findings from the Latency Analysis (see Section 3). The third metric, “hazard responsiveness,” did not explicitly define how an architecture would be responsive to hazard applications but could be notionally envisioned as being able to acquire data upon request, separately from the routine acquisition, and could involve spaceborne, airborne, or other types of modes. The VSWIR and TIR platforms were scored separately as well. The design targets provided to the engineering sessions were as follows for VSWIR and TIR components, respectively: AA (low latency)/BB (data downlink)/BB (hazard response). Unique to this mission concept study is that the AppsWG provided input that influenced the engineering design targets and was included as a co-equal contributor to the engineering design process, alongside the algorithms-, calibration/validation-, and modeling-specific input.

3. Results

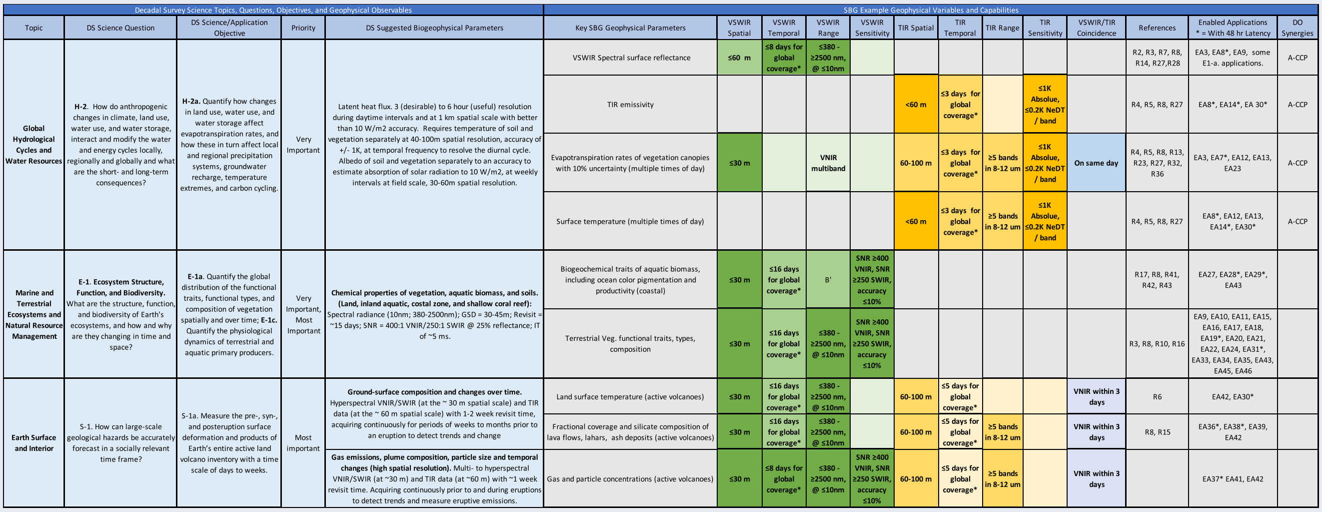
Applications in the SATM. We initially cross-referenced 46 applications into the SBG SATM across the Decadal Survey categories. Of the 46 applications included in the SBG SATM, Terrestrial Ecosystems represented 42% of the identified applications, Aquatic Ecosystems (15%), Solid Earth (15%), Hydrology and Cryosphere (15%) and Weather and Climate (13%). The full breadth of applications continue to be documented in the ATM, a living document that evolves as new use cases are identified.

Table 2 provides a subset of the SATM to illustrate how applications were integrated. Each “EA” code corresponds with a brief summary of what the enabled application is, including a linkage to a potential decision context. EA7* and EA28* correspond with two low latency applications: “Improve consumptive water use (evapotranspiration, ET) estimates to inform in agricultural use, for example, Apply improved ET products in estimates of water demand/crop consumptive use to support advances in irrigation scheduling and on-farm water use efficiency” and “Mitigating harmful algal blooms, for example, Use of chlorophyll, phycocyanin, and other pigment information to characterize extent and location of harmful algal blooms; use this to inform site closures, shutdown water intakes, prevent exposure/illness,” respectively. Other examples span geologic hazard applications, such as EA37* and EA38*, which correspond to mitigating volcanic hazards (plumes and lava flows). A full list of EAs is provided as part of the SBG SATM document (https://sbg.jpl.nasa.gov/satm) and in Supplemental Information.

Latency Analysis (Figure 2). While 46 enabled applications were in the SATM, we discovered an additional three additional applications that were relevant to the Decadal Survey, and used 49 for all further analysis. When the initial SBG capability set updated VSWIR temporal revisit from approximately weekly to biweekly, several application products no longer demonstrated traceability to the proposed capability set (Stavros et al., 2022), which is demonstrated by linking products to capabilities to Decadal Survey priorities. For simplicity, we opted to assess latency as a binary (enabled or not enabled), though in actuality benefits of low latency will be more nuanced.

Table 2

A Subset of the Surface Biology and Geology Science and Applications Traceability Matrix was Formatted to Show Traceability From Questions From the Decadal Survey to Measurement Specifications for Visible to Shortwave Infrared and Thermal Infrared Instruments



Decadal Survey Science Topics, Questions, Objectives, and Geophysical Observables					SBG Example Geophysical Variables and Capabilities												
Topic	DS Science Question	DS Science/Application Objective	Priority	DS Suggested Biogeophysical Parameters	Key SBG Geophysical Parameters	VSWIR Spatial	VSWIR Temporal	VSWIR Range	VSWIR Sensitivity	TIR Spatial	TIR Temporal	TIR Range	TIR Sensitivity	VSWIR/TIR Coincidence	References	Enabled Applications * = With 48 hr Latency	DO Synergies
Global Hydrological Cycles and Water Resources	**H-2**. How do anthropogenic changes in climate, land use, water use, and water storage, interact and modify the water and energy cycles locally, regionally and globally and what are the short- and long-term consequences?	**H-2a.** Quantify how changes in land use, water use, and water storage affect evapotranspiration rates, and how these in turn affect local and regional precipitation systems, groundwater recharge, temperature extremes, and carbon cycling.	Very Important	Latent heat flux. 3 (desirable) to 6 hour (useful) resolution during daytime intervals and at 1 km spatial scale with better than 10 W/m2 accuracy. Requires temperature of soil and vegetation separately at 40-100m spatial resolution, accuracy of +/- 1K, at temporal frequency to resolve the diurnal cycle. Albedo of soil and vegetation separately to an accuracy to estimate absorption of solar radiation to 10 W/m2, at weekly intervals at field scale, 30-60m spatial resolution.	VSWIR Spectral surface reflectance	**≤60 m**	**≤8 days for global coverage***	**≤380 - ≥2500 nm, @ ≤10nm**							R2, R3, R7, R8, R14, R27,R28	EA3, EA8*, EA9, some E1-a. applications.	A-CCP
					TIR emissivity					**<60 m**	**≤3 days for global coverage***		**≤1K Absolue, ≤0.2K NeDT / band**		R4, R5, R8, R27	EA8*, EA14*, EA 30*	A-CCP
					Evapotranspiration rates of vegetation canopies with 10% uncertainty (multiple times of day)	**≤30 m**		**VNIR multiband**		**60-100 m**	**≤3 days for global coverage***	**≥5 bands in 8-12 um**	**≤1K Absolue, ≤0.2K NeDT / band**	**On same day**	R4, R5, R8, R13, R23, R27, R32, R36	EA3, EA7*, EA12, EA13, EA23	A-CCP
					Surface temperature (multiple times of day)					**<60 m**	**≤3 days for global coverage***	**≥5 bands in 8-12 um**	**≤1K Absolue, ≤0.2K NeDT / band**		R4, R5, R8, R27	EA8*, EA12, EA13, EA14*, EA30*	A-CCP
Marine and Terrestrial Ecosystems and Natural Resource Management	**E-1. Ecosystem Structure, Function, and Biodiversity.** What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?	**E-1a**. Quantify the global distribution of the functional traits, functional types, and composition of vegetation spatially and over time; **E-1c.** Quantify the physiological dynamics of terrestrial and aquatic primary producers.	Very Important, Most Important	**Chemical properties of vegetation, aquatic biomass, and soils. (Land, inland aquatic, costal zone, and shallow coral reef):** Spectral radiance (10nm; 380-2500nm); GSD = 30-45m; Revisit = ~15 days; SNR = 400:1 VNIR/250:1 SWIR @ 25% reflectance; IT of ~5 ms.	Biogeochemical traits of aquatic biomass, including ocean color pigmentation and productivity (coastal)	**≤30 m**	**≤16 days for global coverage***	B'	**SNR ≥400 VNIR, SNR ≥250 SWIR, accuracy ≤10%**						R17, R8, R41, R42, R43	EA27, EA28*, EA29*, EA43	
					Terrestrial Veg. functional traits, types, composition	**≤30 m**	**≤16 days for global coverage***	**≤380 - ≥2500 nm, @ ≤10nm**	**SNR ≥400 VNIR, SNR ≥250 SWIR, accuracy ≤10%**						R3, R8, R10, R16	EA9, EA10, EA11, EA15, EA16, EA17, EA18, EA19*, EA20, EA21, EA22, EA24, EA31*, EA33, EA34, EA35, EA43, EA45, EA46	
Earth Surface and Interior	S-1. How can large-scale geological hazards be accurately forecast in a socially relevant time frame?	S-1a. Measure the pre-, syn-, and posteruption surface deformation and products of Earth's entire active land volcano inventory with a time scale of days to weeks.	Most important	**Ground-surface composition and changes over time.** Hyperspectral VNIR/SWIR (at the ~ 30 m spatial scale) and TIR data (at the ~ 60 m spatial scale) with 1-2 week revisit time, acquiring continuously for periods of weeks to months prior to an eruption to detect trends and change	Land surface temperature (active volcanoes)	**≤30 m**	**≤16 days for global coverage***	**≤380 - ≥2500 nm, @ ≤10nm**		**60-100 m**	**≤5 days for global coverage***			**VNIR within 3 days**	R6	EA42, EA30*	
					Fractional coverage and silicate composition of lava flows, lahars, ash deposits (active volcanoes)	**≤30 m**	**≤16 days for global coverage***	**≤380 - ≥2500 nm, @ ≤10nm**		**60-100 m**	**≤5 days for global coverage***	**≥5 bands in 8-12 um**		**VNIR within 3 days**	R8, R15	EA36*, EA38*, EA39, EA42	
				Gas emissions, plume composition, particle size and temporal changes (high spatial resolution). Multi- to hyperspectral VNIR/SWIR (at ~30 m) and TIR data (at ~60 m) with ~1 week revisit time. Acquiring continuously prior to and during eruptions to detect trends and measure eruptive emissions.	Gas and particle concentrations (active volcanoes)	**≤30 m**	**≤8 days for global coverage***	**≤380 - ≥2500 nm, @ ≤10nm**	**SNR ≥400 VNIR, SNR ≥250 SWIR, accuracy ≤10%**	**60-100 m**	**≤5 days for global coverage***	**≥5 bands in 8-12 um**		**VNIR within 3 days**		EA37* EA41, EA42	

Note. Two additional components were added, including a column to show traceability to enabled applications ("EA" column) and a flag to show which enabled applications may need lower latency (<48 hr from acquisition to access).

As a result, 11 applications were not able to be traced to the new capability set. Based on the remaining 38, the latency analysis indicated that 24 hr latency was a minimum threshold needed to enable the maximum number of possible applications (or 78% of the 49 enabled applications).

Temporal Analysis (Figure 3). A <1 day revisit of both visible to shortwave infrared with thermal infrared, visible to near infrared (TIR/VNIR) satisfied the greatest number (76%) of the 49 enabled applications temporal needs. This was largely driven by the combined need for frequent revisit and sensor combinations that included coincident TIR and VNIR observations for evapotranspiration and cloud filtering (Cawse-Nicholson et al., 2021). TIR and coincident VNIR measurements enable critical applications that involve supporting water resources management and weather forecasting. Geologic and solid earth applications (nonhazard) tended to have greater flexibility with temporal revisit (particularly for mineralogy and resource mining) whereas; solid earth hazards would benefit from more frequent revisit, such as active volcanoes and landslides.

Evaluating SBG Candidate Architectures for Applications Value. The assessment of 10 candidate architectures for applications value showed that the engineering design sessions accounted for low latency targets consistently across the architectures, for all VSWIR and TIR configurations, demonstrating that the integration of the applications perspective within the architecture study was useful at propagating an applications-specific design target through to the architectures. This held true for architecture configurations that planned for separate and combined VSWIR and TIR platforms, as well as small and medium sat constellations. The reduction in value was observed for configurations that could not meet the capability set informed by the Science and Applications Traceability Matrix, but not due to latency. Our assessment, however, did underscore that international partnerships, which would enable improved revisit, could be of large benefit for applications. Additional information about how architectures were downselected is available in Stavros et al. (2022).

4. Discussion

Applications Integration Into the SBG Architecture Study. The direct inclusion of the AppsWG as one of four co-equal groups in the SBG study construct allowed for continuous feedback and integration of the end-user community perspective and needs into the architecture study process. Contributions from other working groups and the integration of working group inputs are summarized in another manuscript in this special issue (Stavros et al., 2022). The inclusion of applications input is evidenced by several key products and points of integration: (a) the SBG SATM adopted an explicit applications component, along with latency flags for low latency applications;

(b) the temporal analysis is used within discussions to advance international partnerships; (c) Figure 2 was used to set a latency target for architecture engineering design sessions. The use of this target was also confirmed (see: Section Applications Value Metrics for Candidate Architectures).

A survey of user needs and the value of information (Culver et al., 2020) is also being used to inform future community and partner engagement, where value of information is estimated using industry size and evaluating value of notional SBG products to support decision contexts (full reports are available: sbg.jpl.nasa.gov/doc_links/user-needs-and-valuation-study, https://sbg.jpl.nasa.gov/doc_links/2nd-sbg-user-needs-and-valuation-study). The synthesis of applications community needs and perspectives has also been conducted in concert with science needs, as a cohesive unit, to identify other key measurement needs for an SBG architecture. Two of the most notable updates in science and applications needs in terms of measurements include (a) the need to include VNIR coincident with TIR acquisitions, to ensure high accuracy ET estimates in support of water resources and agriculture management needs and hydrologic and terrestrial ecosystem science as well as (b) the importance of a mid-IR band on the TIR which is critical for science and applications associated with high temperature measurements for tracking fire radiative power and geologic hazards (lava flows).

Latency Analysis. This analysis may underestimate the value of low latency, as a large portion of the enabled applications are terrestrial ecosystem applications, many of which have greater flexibility on data latency (typically operating on seasonal to annual scales). Aquatic ecosystems are often much more dynamic (Turpie et al., 2016) with temporal revisit needs ranging from hours to daily, weekly, and monthly; it may be that as the SBG mission concept is further developed, additional benefits to other application areas will be better defined and articulated. Currently, this dataset only consists of the specified latency targets from the application entries that were comprised primarily of those in the SATM. Other considerations, such as event-driven applications may have latency-relevant technology requirements which should be further explored.

Low latency is largely considered beneficial (Culver et al., 2020; Davies et al., 2017; Moyle et al., 2016; NASA, 2019b) in that data and information needs to be delivered in relevant timescales for decision-makers to find them useful. Culver et al., 2020 found that for agriculture, water quality, and fire-related applications, between 83% and 94% of survey respondents in an SBG applications study indicated that 24 hr latency is optimum to confer benefit. Additional detail is provided for each of the sub-areas, that is, for harmful algal bloom monitoring, decision-makers identify a latency range of 24–48 hr with a temporal revisit of 1–3 days to support their issuance of effective warnings (Culver et al., 2020). Therefore, as an aggregate, <24 hr as a general target for design consideration would be suitable for meeting most latency needs. However, to define and refine detailed requirements associated with latency, it is recommended that further studies evaluate communities' needs within the context of data quality and latency together. It has been shown that there can be considerable changes in uncertainty in the data products processed through a near real time (NRT) system versus a nominal science pipeline (NASA, 2019a). The difference between NRT or low latency products and the standard product pipeline warrants deeper investigation to help inform ground data system architectures.

Another interesting observation emerged from the latency assessment is that low latency applications generally fell into two categories: routine low latency products (such as evapotranspiration and water management) and event-driven low latency products (hazard response). We observed that these bins are expected to have varying low latency requirements (hazards benefit from <6 to 12 hr to data access; routine low latency may have more flexibility ~24 hr). Furthermore, these low latency categories have varying requirements around data volumes and computational requirements, all of which can have an impact on the system architectures. SBG measurements are highly relevant to many hazard applications, including active wildfires and volcanoes, and oil spill detection. This category of applications can benefit from near real time capabilities for SBG data products. Further work is recommended to better characterize specific products and NRT latencies needed for various applications.

SBG Applications and NASA Mission Applications Landscape. Of particular relevance to SBG are four missions whose existing communities are likely future users of SBG data—the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS (ecostress.jpl.nasa.gov)), the Earth Surface Mineral Dust Source Investigation (EMIT (https://earth.jpl.nasa.gov/emit/)), the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE - https://pace.oceansciences.org), and Geostationary Littoral Imaging and Monitoring Radiometer (GLIMR - https://essp.nasa.gov/earth-pathfinder-quests/projects/glimr/). ECOSTRESS is the only one of the four that is in operations as of the writing of this manuscript. Further, ECOSTRESS is a NASA Earth Venture mission that was

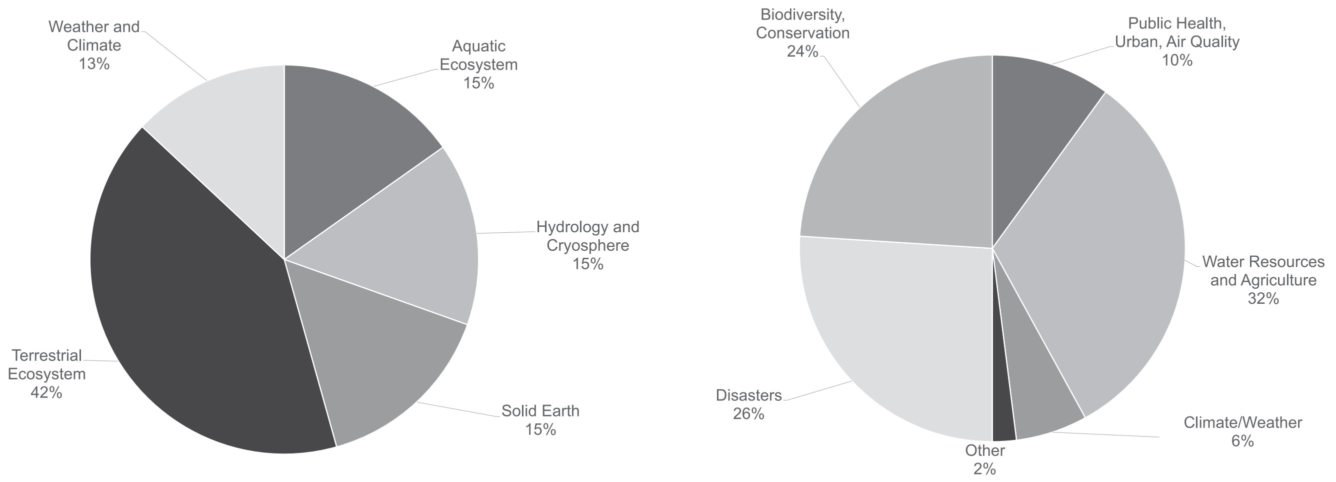


Figure 1. (a) Forty six applications were included in the Science Applications Traceability Matrix, relevant to the Decadal Survey priorities identified for Surface Biology and Geology, and (b) were varied in their application sector.

the first to utilize the Early Adopters program for Class D missions, to function under a more cost-constrained environment. It was under this constraint that ECOSTRESS expanded an Early Adopters program that included the broader community (science to applications) as well as targeted engagement with decision-makers. Under this model, ECOSTRESS had 249 Early Adopters actively testing ECOSTRESS data products and providing feedback to the Land Processes Distributed Active Archive Center (LP DAAC), which led to development of new tools and services to support users after all data were fully released (Lee, 2020). Notably, ECOSTRESS is also being actively utilized in several applied contexts and decision-making, including urban heat island mitigation and environmental justice concerns (Spotts, 2021), irrigation water alerts (Bastiaanssen, 2021), active fire response (L. Miller & Coleman, 2021), and ecosystem management and stewardship (Gustine et al., 2021; Hamberg et al., 2020). ECOSTRESS Early Adopter lessons learned and efforts, and that of other highly synergistic missions mentioned above, such as partnership with the DAAC, community engagement, tutorials, are serving as the initial basis for the SBG applications community of practice.

A clear distinction between prior Early Adopter and mission application programs and the work presented here is that the AppsWG began the systematic integration of applications **at the architecture study phase** through its co-equal status within the SBG Project Research and Applications Team (an analog to the Project Science Team). By further building on the vision of the Early Adopters Program (Sylak-Glassman & Sheth, 2020), SBG Applications has demonstrated that integration of applications into the full mission life cycle can start at the conception of the mission and that the Applications Community confers unique technical needs and perspectives relative to architecture and engineering (Figure 1), in addition to synergistic needs relative to science priorities. That is, SBG Applications and Science, when integrated, represent a more comprehensive and inclusive set of needs that can inform mission architecture. Two key examples of this are the science and applications-informed inclusion of a 4 micron band for improved quantification of active fire and other high temperature features, and inclusion of a VNIR camera with the TIR platform. This configuration of the TIR platform will, in particular, improve applications and science relying on evapotranspiration and consumptive water use.

The other area for high return for systematic integration for applications is international partnership to maximize, in particular, higher frequency temporal revisit. While the AppsWG efforts were able to secure a low latency target for VSWIR and TIR architectures, another applications need is more frequent temporal revisit and was not possible under the cost/budget boundaries put forward in the Decadal Survey. For many applications, a combination of frequent temporal revisit and low latency would add tremendous value to natural hazards and disaster response applications (Culver et al., 2020). Synergy through international partnerships are in progress between SBG and ESA, Italian Space Agency, and Centre National D'Etudes Spatiales.

The ESA Copernicus Program has used an applications-driven approach to inform new Earth missions, and have documented the social and economic benefit to support new programs (Matevosyan et al., 2017), including the Copernicus Hyperspectral Imaging Mission (Schiavon et al., 2021). In particular, latency is a key parameter

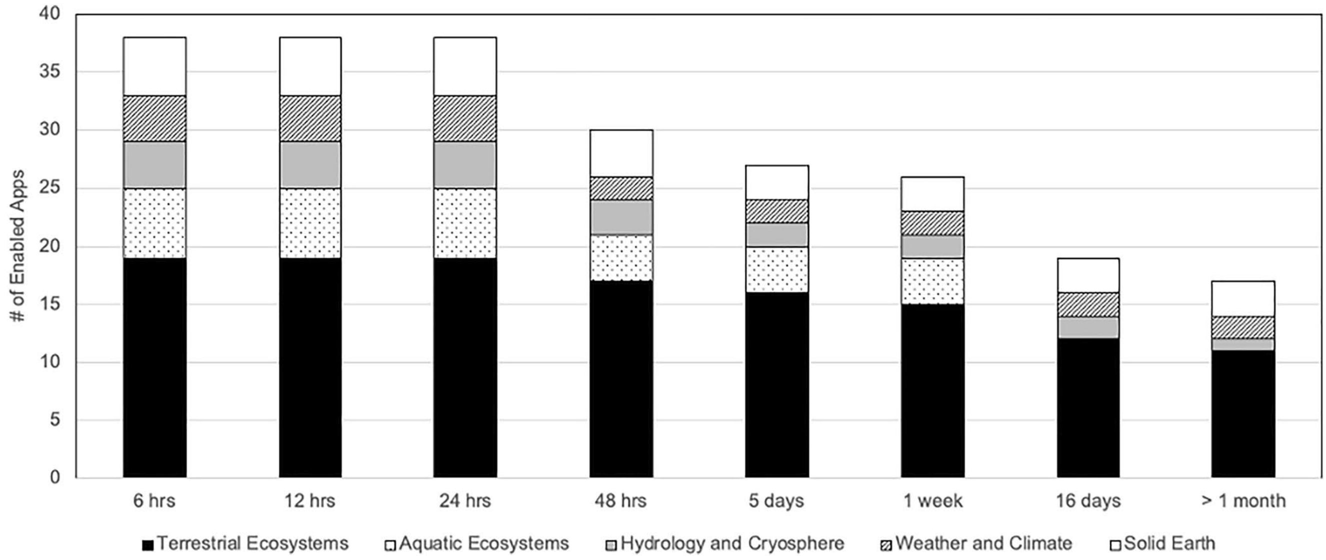


Figure 2. 24 hour latency (acquisition to L2+) would enable 78% of applications possible with the current capability set ((Stavros et al., 2022)), which is the maximum possible in the current configuration.

when considering application use cases (Matevosyan et al., 2017) and that latency needs will inform future Copernicus Program data downlink architectures, as well as ground based infrastructure to disseminate necessary products more quickly. Many decision-making processes are time sensitive, particularly within the context of climate change exacerbating natural hazards and variability. While Schiavon et al. (2021) focus on the agriculture sector, their study points out the gap between data availability and useability, for example, needs around improved spatial resolution for agriculture. These are the types of applications-driven needs that we have begun to incorporate to the SBG mission planning efforts, starting at the architecture study. Future work may consider expanding the breadth of applications and further exploring the complexity of needs of the applications associated with tradeoffs between spatial, temporal, spectral resolutions, and other parameters.

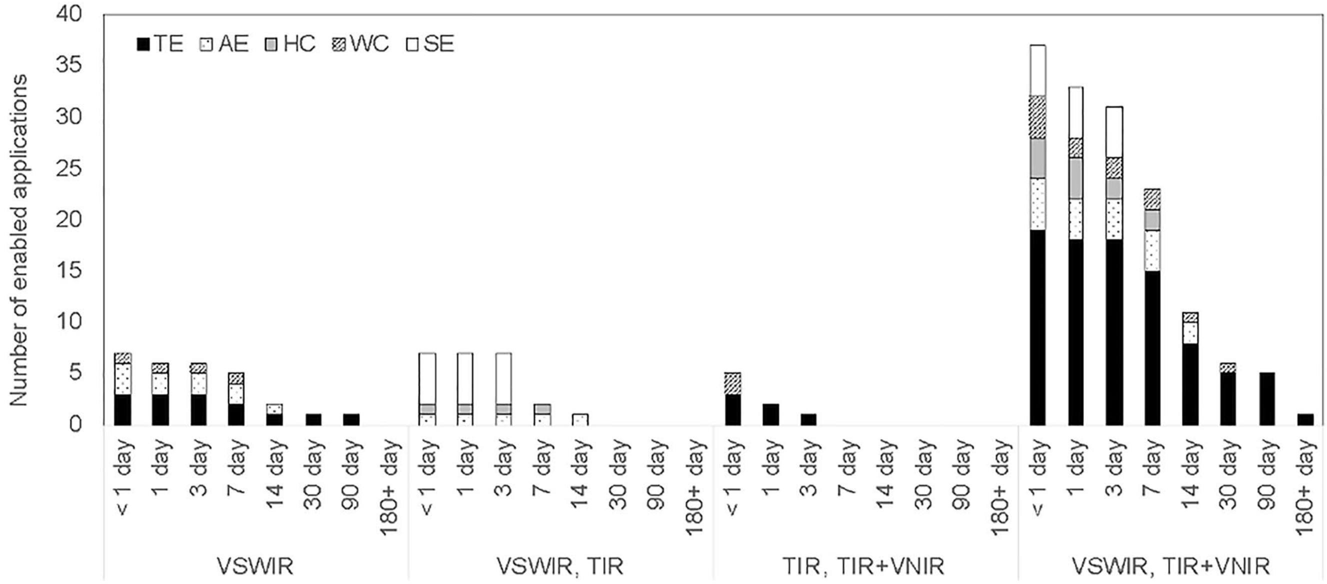


Figure 3. This figure shows the combined needs for applications around visible to shortwave infrared (VSWIR) and thermal infrared, visible to near infrared (TIR/VNIR) sensor targets along with more frequent revisit. The VSWIR; VSWIR, TIR; TIR, TIR + VNIR; and VSWIR, TIR + VNIR groups are intended to show the combination of sensor/temporal revisit targets that would enable the maximum number of applications. TE, Terrestrial Ecosystems; AE, Aquatic Ecosystems; HC, Hydrology and Cryosphere; WC, Weather and Climate; SE, Solid Earth.

5. Conclusion

This work presents impactful outcomes associated with the integration of discovery and applications together in the SBG mission architecture study, illustrating a pathway for collaboration across applications and science to inform NASA satellite mission studies. The development of an ATM which was integrated into the SATM, ultimately resulted in an applications-unique design target for latency which was included into the architecture engineering design sessions. Further, application needs around temporal and spatial resolutions helped advance international partnership discussions with space agencies such as ESA, Italian Space Agency, Centre National D'Etudes Spatiales, and the Indian Space Research Organisation. Lastly, applications and science needs, taken together, resulted in changes in target specifications for the TIR platform including the addition of a VNIR camera and added mid-IR channel. Iterative and inclusive approaches with the SBG Applications community were used to understand needs, translate those needs to measurement targets, and incorporate them in the architecture study for SBG. With this information, the SBG architecture has the potential to lead a robust mission capable of addressing a wide range of applications and science for societal benefit, from post-fire hazards analysis to urban heat island mitigation. Further, by coupling the work presented here with additional proven NASA early adopter efforts including early adopter programs, hackathons, and user-workshops, the potential impact of SBG to the science applications community is high.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in this paper are available in Stavros et al., 2022 and in Supplemental Information.

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