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Key Points:

- Current users' needs for hyperspectral earth observation data suggest future investment in improving spatial and temporal resolution
- Coordination between missions can fill this gap especially improving temporal revisit
- Shared community and resources can facilitate the improvement of products from these missions and their use across different sectors

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Maximizing Societal Benefit Across Multiple Hyperspectral Earth Observation Missions: A User Needs Approach

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Abstract Imaging spectroscopy is a powerful tool used to support diverse Earth science and applications objectives, ranging from understanding and mitigating widespread impacts of climate change to management of water at farm-scale. Community studies, such as those deployed by NASA's Surface Biology and Geology and ESA's Copernicus Hyperspectral Imaging Mission for the Environment, have offered new and tangible insights into user needs that are then incorporated into overall mission planning and design. These technologies and tools will be key to develop and consolidate downstream services for users and resource management, given the current pressures on the environment posed by climate change and population growth. This process has highlighted the degree to which planned mission capabilities are responsive to community needs. In this study, we analyze user requirements belonging to the Italian Copernicus User Forum and to the user pool of NASA's Surface Biology and Geology community for the synergic use of hyperspectral imaging technology, providing a reference for the development of earth observation services and the consolidation of existing ones. In addition, potential cross-mission coordination is analyzed to highlight key benefits—(a) addressing shared community needs around products requiring more frequent temporal revisit and (b) shared resources and community expertise around algorithm development. This paper discusses the critical role of early engagement with users to establish a community of practice ready to work with high spatial resolution imaging spectroscopy data sets. The main outcome is a guide for the synergetic use of hyperspectral mission and data together with the identification of the main gaps between user needs and satellite capabilities influencing the development of key national and trans-national downstream services.

Plain Language Summary In this research we have analyzed needs of users to understand how to develop and improve earth observation downstream services. Hyperspectral imaging provides information across the electromagnetic spectrum in more detail than multispectral imaging, allowing more specific analysis and accurate identification of materials and substances. The users in this study belong to the Italian Copernicus User Forum and to the NASA Surface Biology and Geology community which provided requirements respectively for ESA's Copernicus Hyperspectral Imaging Mission for the Environment and NASA's Surface Biology and Geology. This work identifies common users and examines the advantages of potential synergy between these hyperspectral satellites for responding to their needs. This analysis shows that the synergy would bring significant advantages in terms of improved revisit time and represents an opportunity to address shared community needs around product and algorithm development.

1. Introduction

Advances in remote sensing and geographic information technologies have fostered the development of hyperspectral sensors (Transon et al., 2018). Also known as imaging spectroscopy, hyperspectral remote sensing is a technology often employed for the monitoring and detection of minerals (Peyghambari & Zhang, 2021), terrestrial vegetation (Zhang et al., 2021), and man-made materials and backgrounds (Kuras et al., 2021). The data produced by imaging spectrometers is different from that of multispectral instruments owing to contiguous spectral coverage and the large number of wavebands recorded which enables the detection of subtle features in the spectrum at unprecedented spectral resolution (Bioucas-Dias et al., 2013). These can be used

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to separate many mineral and vegetation classes and enable a more comprehensive understanding of surface mechanisms, such as canopy nitrogen content. Given these advantages, imaging spectroscopy has been applied to several domains such as mineral targeting and mapping; detection of soil properties including moisture, organic content, and salinity; identification of species; study of plant canopy chemistry; detection of vegetation stress (Cawse-Nicholson et al., 2021; Shukla & Kot, 2016). Hyperspectral technology may afford to the challenges facing our society, including risks to the world economy and environment posed by climate change. The need to assess environmental changes and the transition to a carbon-neutral society is facilitated by the use of precise data and high-resolution data sets, including hyperspectral images and real-time analysis to aid decision-making through dynamic environmental mapping and monitoring (Stuart et al., 2019). Global initiatives such as the 2030 Sustainable Development Agenda, the Paris Agreement, the Marrakesh Partnership for Global Climate Action, the Global Covenant of Mayors for Climate & Energy, as well as the United States of America (USA) Inflation Reduction Act of 2022, all promote the development of technological innovations. Recent events such as the COVID-19 pandemic, the war in Ukraine and the consequent strain on the global food supplies, the economy and security for our society, have fostered significant investment in the National Plan for Recovery and Resilience (NPRR) implemented by Italy part of the European Recovery and Resilience Facility (European Commission, 2022). These initiatives focus on the improvement of current technologies and the development of new earth observing (EO) missions. Airborne and spaceborne hyperspectral sensors have been developed such as Hyperion (EO-1), PRISMA and its follow-on PRISMA-SG, EnMAP, Copernicus Hyperspectral Imaging Mission for The Environment (CHIME) and LSTM: Copernicus Land Surface Temperature. In addition, NASA has been developing a hyperspectral satellite mission: Surface Biology and Geology (SBG), recommended in the 2018 National Academies' Decadal Survey (NASEM, 2018). In 2022, SBG officially became a mission after completing its architecture study considering all of the Decadal Survey science objectives, system concepts from the Hyperspectral Infrared Imager (HyspIRI) precursor study from the 2007 Decadal Survey, as well as new advanced instrument technologies (NASEM, 2018). Meanwhile, under the investments of the NPRR, the Italian government has planned the development of a constellation of small and medium-size satellites named IRIDE (https://www.asi.it/2022/12/iride-firmati-i-contratti/). IRIDE will be made up of a set of sub-constellations of low Earth orbit satellites (Upstream Segment), the operational infrastructure on the ground (downstream segment) and the services intended for the Italian Public Administration (service segment). Being based on a number of different instruments and detection technologies, the IRIDE constellation will be one of a kind; ranging from microwave imaging (via Synthetic Aperture Radar, SAR), to optical imaging at various spatial resolutions (from high to medium resolution) and in different frequency ranges, from panchromatic, to multispectral, to hyperspectral, to infrared bands.

Data produced by all of these satellites and their potential synergetic use offer great promise of fulfilling the needs and requirements related to the legal commitments of the community of users. The application of this hyperspectral technology can be maximized by providing a clear guide for its development for user needs. Increasing investment in the EO sector calls for a paradigm change. Historically, technological improvement has driven the development of EO missions, leading to subsequent discoveries by the scientific research community, rather than being based upon user needs and market demand. Here, we develop a complementary methodology based on the elicitation of users' operational needs and technical requirements while planning new missions and potential synergies between them. Collecting information on user needs provides the background for the development of crucial services for institutional and private users throughout a wide range of applications. Concurrently, these services can be complemented by the development of big data, new analytics, and high-performance computing (HPC) technologies facilitating the processing and integration of huge amounts of data, such as onboard image processing systems for a hyperspectral sensor, coming from heterogeneous platforms to maximize the development and consolidation of key innovative services.

Understanding user requirements is critical to inform policy development toward climate change adaptation and sustainable development (Buontempo et al., 2020; Herold et al., 2011; National Academies of Sciences, 2018). User-centric design can increase productivity, enhance quality of work, reduce support and training costs and improve user satisfaction (Maguire & Bevan, 2002). To make future satellite missions sustainable and identify a portfolio of new products supporting the regulatory commitments undertaken by the European Union (EU), the European Commission (EC) has identified the Copernicus National User Forum (CUF), established in each Member State of the EU, as the set of user communities in charge of expressing the needs for the Copernicus program [REGULATION (EU) N.377/2014] (European Commission, 2019). In this context, the European Space

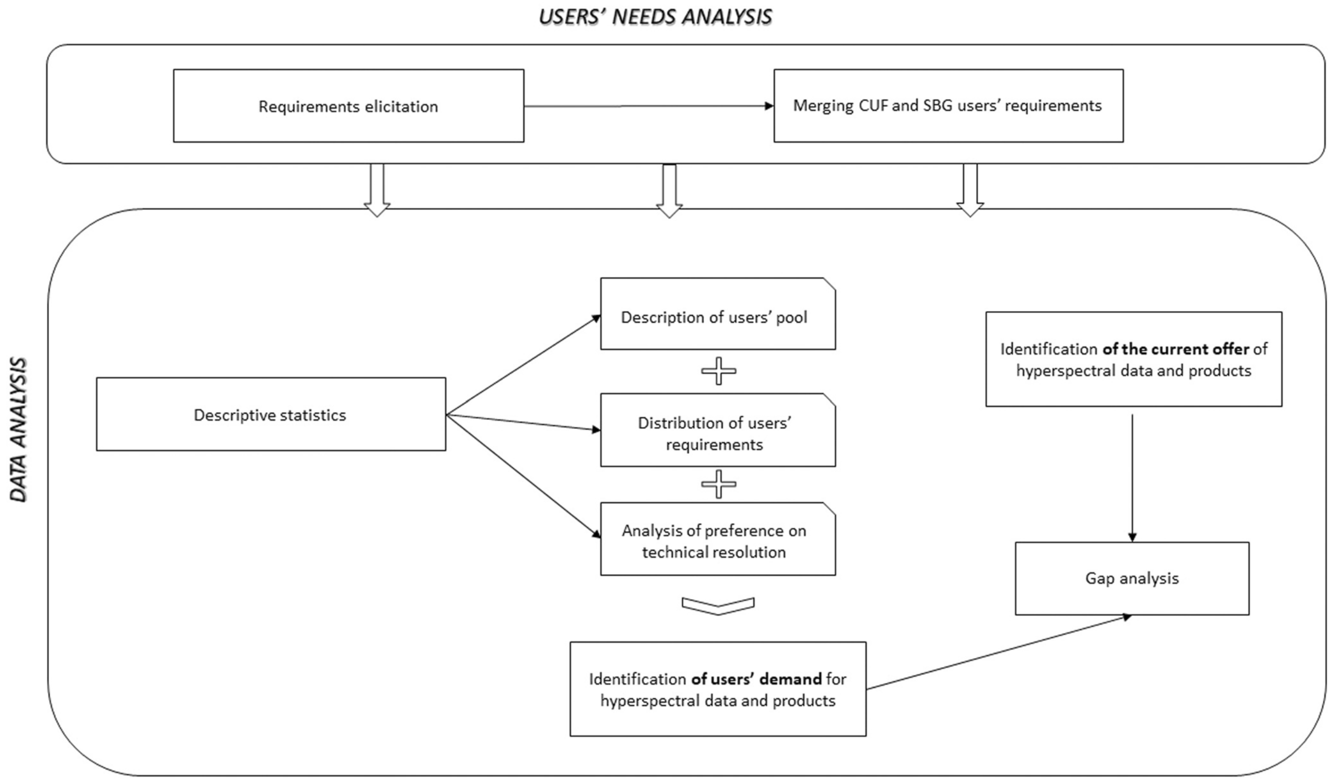


Figure 1. Diagram summarizing the methodological steps of the analysis.

Agency (ESA) commissioned Italy to study user needs, operational requirements as a first study, and the value proposition of CHIME, based upon the unique experience of Italy in the development of both downstream and upstream services in Europe, recognizing the relevance of the CUF in the definition of both national downstream services and upstream EO missions such as the PRISMA mission, HyperSpectral Precursor of the Application Mission (https://www.asi.it/scienze-della-terra/prisma/) (Taramelli et al., 2020). This work started with the "Hyperspectral Imaging Mission Concepts" tender of 2016 and continued in 2018, 2020, and 2021.

In this paper we follow the process of user requirements generation and validation utilizing the method developed by Taramelli et al. (2020), in which the authors employ the Copernicus National User Forum as the user pool to demonstrate the potential benefit of a future Copernicus hyperspectral mission, including missions such as CHIME. A separate specific users' needs analysis has been also carried out for the development of an operational coastal services always with the support of the Italian Copernicus User Forum (Geraldini et al., 2021). That study provides an overview of the coastal user requirements, highlighting the need for integrated information for the management of the coastal areas, and represents the basis for defining a national coastal service (Ibid) also based on upstream user requirements.

Here we provide an analysis of users' needs for different application domains based on surveys of the Italian Copernicus User Forum (CUF) and SBG science and applications communities. Our study is limited to these two communities since they are the only ones who provided a thorough and systematic inventory of requirements in terms of operational and technical needs we believe to be the first study of this sort performed prior to mission launch. Our aim is to identify and analyze users' needs and technical requirements to provide a baseline for the investment in services development. This framework can be exploited for the planning of new EO missions and potential synergies between existing ones.

2. Materials and Methods

This section explains the methodological phases included in the analysis for this study, as summarized in the workflow of Figure 1. It includes first a description of how users' needs were collected and merged into a common data set and a second section of how data were analyzed for the purpose of the gap analyses. All sections mentioned in the framework of the data analysis can be found for reference in the results section.

The requirements analyzed in this paper pertain to the use of hyperspectral EO technology and were collected in two different contexts:

Starting in 2016, the Italian CUF elicited users' needs involving different typologies of users across several applications domains. The aim of the elicitation process was to assess the potential utility of a Copernicus hyperspectral mission and later extended to several other missions such as the Copernicus High Priority Missions. An ad hoc interaction matrix was circulated among several user communities to gather preferences about hyperspectral-based products and services.

In 2018, NASA initiated an architecture study for the Surface Biology and Geology (SBG) Designated Observable, identified in the 2018 National Academies' Decadal Survey entitled, "Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space." (Herold et al., 2011). The SBG architecture study had three objectives: (a) Identify and characterize a diverse set of high value SBG observing architectures; (b) Assess the performance and cost effectiveness of architectures against SBG research and applications objectives; (c) Perform sufficient in-depth design of one or more candidate architectures to enable near-term science return (Poulter et al., 2023; Stavros et al., 2023).

2.1. User Elicitation Approach

CUF Hyperspectral user needs were collected following the methodology developed in Taramelli et al. (2020). Specifically, the interaction methodology includes three phases.

1. Involvement of users through the Italian Copernicus User Forum, specifically considering the different Copernicus application domains;
2. A pre-processing phase in which users' feedbacks on EU policy, thematic areas of interest, requirements, and technical parameters were collected by means of an interaction matrix;
3. A post-processing phase in which the assessment of results was used to match the spatial resolutions and temporal frequency required by the user communities with hyperspectral-based products and services (hyperspectral-derived algorithms, hereinafter referred to as "hyperspectral products"). An extensive review of the scientific literature about hyperspectral-derived algorithms was hence conducted to detect suitable layers for the identified user requirements. Moreover, this association highlighted the number of times a particular spectral range was present in those products and services achieving user needs.

Users' requirements for the SBG mission were collected using a user-centered design framework to define the primary work streams for the study (Culver et al., 2020). This design framework uses a four-phase methodology.

1. Application area selection for detailed investigation was based upon mission science priorities as well as the potential for a broad range of end-users with duties to be fulfilled.
2. Targeted expert interviews were conducted using visual guides to demonstrate future SBG capabilities and capture insights on key user communities, their current use of satellite products, valuation indicators, and future SBG adoption potential.
3. Survey collected feedback from a larger set of users, primarily from the traditional research community, to gather more quantitative data on needs and desired SBG capabilities.
4. Valuation based upon operational requirements where there is low satisfaction with current information and improvement is needed, creating an opportunity for SBG to add value to the user.

The users involved in the study were researchers and practitioners as well as intermediary product developers and service providers, with both specific technical insights and knowledge of their respective application domains. The research was limited to a select set of SBG-relevant primary application areas in order to provide a detailed investigation of these sectors. Focusing on the functional needs of both research and operational communities, the study included representative applications sectors: fire ecology and risk, algal blooms and water quality, agriculture and water resources, and mineral resources (Culver et al., 2020).

The information obtained from the SBG User Needs and Valuation Studies were included in the SBG Community Assessment Report (CAR). The SBG CAR serves as an ongoing record for tracking the preparation, assessment, studies, and analyses during this novel integrated process, and represents the progressive culmination of the SBG Applications Working Group (AppsWG) and user communities' activities, to benefit the development of a new NASA project. A key motivation of the assessment and the CAR is to expand the breadth and types of non-research uses and users beyond traditional, known, or assumed ones. The assessment spans both the technical aspects and organizational characteristics of user communities. The CAR captures information on application opportunities and is intended to help a flight project team become aware of a mission's potential applications value and key "desirements" (a term for unfunded requirements coined by the late ESD Director Michael Freilich) for user communities that need to realize that value. The CAR is intended to inform system architecture options, design considerations, trade-off decisions, and the overall mission concept (Lee et al., 2022; Luvall et al., 2022) details the first instance of a NASA mission's integration from the perspective of science applications into mission design at the architecture study phase.

Users from the CUF expressed needs across all the Copernicus domains which include the following domains: land cover and land use: Agriculture/Food Security, Coast and marine monitoring, Emergency services, Ground motion, Hydro-meteorology climate service, Inland and coastal water, Security, Air quality. The SBG community focused on six specific applications: Terrestrial Ecosystems, Hydrology/Terrestrial, Aquatic Ecosystems, Terrestrial/Weather, Active Surface Geology, General Applications (Culver et al., 2020). The study targeted a diverse and representative set of user types across the value chain for each of the application areas. For each application area, requirements included a general assessment of users' most desired EO spectral imaging capabilities, SBG fit with needs, user community adoption maturity, and the areas where future SBG data could provide the most improvement to the sector, that is, its most promising uses (Lee et al., 2022).

2.2. Challenges of the Comparative Analysis

Because the two studies were independent one from another, the data needed to be normalized to make the comparison and analysis possible. While similar information was reported by both user communities, the two sets of data were divergent in many aspects and therefore homogenization and association between requirements was required before the analysis could be performed.

The main issue has been to identify the thematic area to which users' needs belong. In fact, the two different surveys did not adopt the same semantics. The SBG User Needs and Valuation Study, hereinafter SBG users' study, are organized as answers to Data Scientist interview Questions, according to Focus Science Topics (i.e., Ecosystem traits and biodiversity - terrestrial) that are included in Application Focus Group (i.e., Agriculture). The feedback by the CUF institutional user communities, have been collected as users' needs based on Application Domains (i.e., Agriculture/Food security) identified by EU environmental legislation and regulation framework (Taramelli et al., 2020).

After identifying analogous thematic areas (i.e., Agriculture = Agriculture/Food security), users' needs, expressed by each community were matched, combining the application concept and the decision approach. To facilitate the association between needs, it was essential to recognize the parameters that the communities want to detected and be measured by the hyperspectral sensor. Each users' need has an identification code, one type for the CUF study and another for the SBG study, as reported in the example in Table 2.

2.3. Descriptive Statistics and Comparative Analysis

Once CUF and US surveys were matched, requirements were elaborated under a common data set with the same taxonomy featuring information on.

1. Application domain: this entry identifies the theme under which each domain is classified. It allows to provide conclusions and elaborating results for a specific sector and selection on users. The domains included in this study are: Agriculture/Food Security, Coast and marine monitoring, Emergency services, Ground motion, Hydro-meteorology climate service, Ecosystem structure/composition (Biodiversity), Air Quality, Security, Water resources: Inland/coastal water and environment. It should be noted that the SBG users study did not strictly classify requirements under the categories of "Security" management, intended as national security, border protection and surveillance, maritime surveillance, and "Ground Motion." Although vertical land motion is a priority application for the synthetic aperture radar mission (https://science.nasa.gov/earth-sci-

ence/decadal-sdc) (NASEM, 2018) most requirement that are also relevant for the sector of Ground Motion were classified under the "Disasters" application domain as most were relevant in the context of landslides and volcanic eruptions.
2. Requirement description: a brief description of the requirement identified by different users.
3. Thematic area: within each domain a further specification of the application for each requirement. For example, the domain of agriculture comprises several different areas of application such as the monitoring of water quality, soil quality or the heterogeneity of the landscape.
4. Parameters/variables: the geophysical parameters, derived to a unit of measure, with which each requirement is monitored.
5. Available layer: hyperspectral layer or algorithm available according to the needs of users and their requirements in terms of the different spectral bands.
6. Spectral range: spectral range identified as useful to fulfill the requirements.
7. National and international legislation: laws, regulations or directives that are fulfilled by the requirement expressed by users.
8. Number of users interested in the requirement: sum of all the users that express interest in a particular requirement.
9. User class/type: classification of users according to their nature, such as academic users, Small and Medium Enterprises (SMEs), environmental protection agencies, etc.
10. Expected spatial resolution and expected revisit time: the technical resolutions (spatial resolution and temporal frequency) desired by users to monitor the requirements that they identified in previous cells.

Table 2 Exemplifies how the user requirements are organized for the elaboration of data in the study and each table entry is an example of the variables described above. Specifically, the example shows that for characterizing crop status and phenology ("requirement description"), which is a requirement of the Habitat and Birds Directive ("National and international regulations") users need active Radiation (FAPAR) and chlorophyll a + b (Cab) indexes extraction ("Parameters/variables") which are currently available through three specific products ("Available layer") using the visible and near-infrared range of the spectrum ("Spectral range"). Users for this requirement need a spatial resolution of 1–4 m with an expected revisit time of 1 month. This requirement is needed by five users classified as State and local government authorities.

First descriptive statistics were performed across all the domains in order to understand patterns among the data and provide a description of the needs of the two communities. The statistics performed include the distribution of requirements for both countries, in particular the analysis was divided into three sections concerning users, requirements and technical specifications. Users' distribution was calculated according to each domain and by community type on a percentage base. In addition, users were divided according to their typologies: this taxonomy included a wide range of users, from private companies to public authorities to academic users and universities. Descriptive statistics for the users' requirements also allow to show similarities and differences for the two community of users.

Finally, technical resolutions were mapped according to users' preferences in terms of spatial resolution, temporal frequency and spectral resolution. Since the matrix did not provide a predetermined range of choices, each user identified the preferred resolution, and therefore, the data set has a great variability. Variables were thus normalized according to qualitative ranges reported in Table 3 and derived from the official classification of Copernicus EO missions; the adopted legend for the geometry resolution is based on the requirements for Copernicus Contributing Mission data, which are classified primarily by sensor type (SAR or Optical) but also by geometry resolution, as well as reported in the Technical note "Copernicus Space Component Data Access Portfolio: Data Warehouse 2023" prepared by ESA (ESA, 2023) and regularly used for dissemination to user communities with less in-depth technical knowledge (Tapete & Cigna, 2018). First preferences about spectral resolution were mapped for each application domain, further we assessed cumulative users' preference for spatial resolution and revisit time in order to understand if the improvement in resolution justifies investment according to users' needs. Further, users' preferences concerning spatial resolution and temporal frequency were combined to assess if any current mission is able to fulfill the required need.

2.4. Gap Analysis: Assessment of Users' Needs Versus Hyperspectral Technical Requirements

Finally, users' requirements were assessed against the existing hyperspectral technology, including all present and planned hyperspectral missions as detailed in Table 1 and potential gaps were highlighted. Gaps have been

Table 1
Status of Current Hyperspectral Missions and Their Technical Specification

Hyperspectral missions	Status	Spatial resolution	Revisit time	Spectral bands
PRISMA, HyperSpectral Precursor of the Application Mission, preoperational	Operational, launched in 22 March 2019	30 m	7 days	400–1,010 nm, and a 171 channel NIR/SWIR band with a spectral interval of 920–2,505 nm
EnMAP	Commissioning, launched in April 2022	30 m	4 days	Spectral range of 430–2,450 nm
EMIT	Operational on International Space Station (ISS) July 2022	60 m	Targeted areas for the current and potential future arid land dust source regions	380–2,500 nm Spectral Sampling 7.4 nm 285 bands
DESIS	Operational on International Space Station (ISS) June 2018	30 m	On demand	402–1,000 nm 235 bands
Hyperion (EO-1)	Decommissioned in March 2017	30 m	16 days	VNIR bands 426.82–925.41 nm SWIR bands 912.45–2395.50 nm
CHIME, Copernicus Hyperspectral Imaging Mission for the Environment	Planning, due to launch in 2028	20–30 m	12 or 15 days	400–2,500 nm in the Visible (VIS), Near Infrared (NIR), and Short-Wave Infrared (SWIR)
SBG, Surface Biology and Geology	Planning, due to launch in 2027–2028	30 m 60 m	16 days 3 days	VSWIR: 380–2,500 nm TIR, multi-spectral with two channels in the 3–5 μm range and six channels in the 8–12 μm range
LSTM: Copernicus Land Surface Temperature Monitoring, Multispectral	Planning, due to launch in 2028	50 m	3 days	TIR: 8–12.5 μm VNIR-SWIR: 400–2,500 nm
IRIDE, Hyperspectral constellation	Planning, due to launch in 2025/2026	5 m PAN 21 m SPOTLIGHT 31 m STRIPMAP	1 day	400–2,500 nm in the Visible (VIS), Near Infrared (NIR), and Short-Wave Infrared (SWIR)

identified taking into consideration the association of technical requirements expressed by users, namely spectral resolution, spatial resolution and temporal frequency. Thus, when users' needs concerning the association between these three variables are not met by the current EO offer, a gap is identified. In order to prioritize investment, technical requirements are classified according to the frequency with which they are selected by users through a traffic light approach, consequently, priority for development is suggested. The gap analysis provides a baseline for the development of future synergies between mission or direction for the development of new satellites.

3. Results

3.1. Description of the User Pool

As a preliminary step the users' pool was characterized to understand who provided input to the study. The following phase focused on the characterization of users, particularly the identification of similarities and differences between the CUF and SBG communities.

According to the users' self-classification (Figures 2 and 3), the SBG community is mainly dominated by users interested in Ecosystem structure/composition and Emergency services (30% and 32%, respectively) (Figure 2). We note that users can express interest and suggest requirements for more than one domain, yet few users expressed interest for the air quality monitoring or hydro-meteorology climate services, both of which are priority applications for the Atmosphere Observing System mission (NASEM, 2018).

Conversely, the users for the CUF community are more evenly distributed across domains, with similar percentages for all the applications proposed in the study (Figure 2); this is partly due to the fact that the Italian survey included two additional domains, namely Ground Motion and Security Monitoring and because of the fact that

Table 2
Example of the Data Available in the Interaction Matrix

Application domains	Requirements description	Thematic area	Parameters/variable	Available layer	Spectral range	National and international regulations that the requirements respond to	Number of users interested in the requirement	User class/type	Expected spatial resolution	Expected revisit time
Monitoring of land cover and use: Agriculture/ Food Security	Characteriztion crop status and phenology	Monitoring habitat heterogeneity and habitat quality	Active Radiation (FAPAR) and chlorophyll a + b (Cab) indexes extraction	AGR-02 AGR-03 FOR-01	VIS VIS VIS-NIR	Habitats Directive (92/43/EEC) and Birds Directive (2009/147/EC)	5	State and local government	1–4 m	Monthly

Note. The data represents users' preferences concerning a specific requirement including information on spectral range, type of variables needed, spatial resolution and revisit time.

CUF users are usually evenly distributed among different areas of expertise. Among this distribution a further analysis has been performed to assess which type of users are interested in the different services. First, it should be noted that most of the SBG users involved in the study are national authorities (Figure 3), specifically, 45%. Among the Italian community the largest user group are regional environmental protection agencies (70%), ARPA (Agenzia Regionale per la Protezione Ambientale—Regional Environmental Protection Agency), that in Italy operate in every region with a specific mandate and relative autonomy. While for the SBG community a great variety of users is involved, the CUF community of hyperspectral users is mainly composed of institutional authorities because of the collection process and the environment pertaining to the Copernicus User Forum, further explained in the next section. Relatively small number of regional authorities and, most importantly, the private sector is only represented in the SBG community in very small percentage of the total users while most of the users' typology are private or public organization, an exception is made for so-called "Experts" present in both users' pools. These users are indeed individuals who have a significant scientific expertise in the field of EO hyperspectral technology, downstream and upstream services. In the context of the CUF, these experts are an integral and official part of the users' board and represent the scientific community in different domains.

3.2. Requirements

The second part of the analysis focused on understanding how the requirements are structured and to unveil patterns among user needs. From the first elaboration reported in Figure 4, it can be also observed that, while requirements collected within the CUF are more evenly distributed across domains, SBG users are more interested in requirements related to water resources, biodiversity monitoring and emergency service. On the other hand, the data set does not present requirements pertaining to the security and ground motion domain from the SBG side. This limitation is mainly due to the type of users involved in the study, since in the SBG users study these two areas were not covered. Despite this partial bias, important considerations can be made on the common requirements. Naturally, given the geography of the area, CUF users present an interest for coastal and marine monitoring and for security issues related in particular to border patrol, where EO data can play a pivotal role.

Despite the differences that characterize each country, 47 requirements expressed by the two communities, or 16% of the data, are common. Most of these requirements apply to applications related to land cover land use monitoring, for agriculture and ecosystem assessment. While also coastal monitoring and emergency services feature several common needs identified by users, hydro-meteorology climate services and water resource monitoring services do not have several requirements in common.

3.3. Technical Resolution

Looking more in detail at the technical requirements expressed by users, it is possible to analyze the preferences concerning the spectral ranges per each domain. In Figure 5 for each requirement, each user has identified the spectral range most useful to develop relevant products and services, and results have been aggregated by each domain.

Looking at the single application domains from Figure 5, it appears that the full spectrum is required particularly for the monitoring of Emergency services, Ground motion, Water resources: inland/coastal water and environment and Monitoring of land cover and use: Agriculture/Food Security. Nevertheless, most requirements would be already fulfilled by the full range of the infrared spectrum (VIS + NIR + SWIR). It should be pointed out that the security domain is not present in this figure since the community has not provided requirements concerning its technical specification: this limitation is caused by the sensitive nature of the information handled by the service and for limitations connected to national security. New missions such as SBG or LSTM can be fulfilled exclusively by the TIR range of the spectrum (although less than 1%), while the combination of TIR with other bands is useful for all domains and accounts for almost 30% of the preferences expressed by users. While TIR has less applications compared to the VSWIR range of the spectrum, current hyperspectral missions do not feature this particular sensor, opening opportunities for future investment in such an instrument.

Similarly, analysis has been performed on the preference regarding spatial resolution and temporal frequency. The cumulative distributions of users' needs reported in Figures 6a and 6b are useful to iden-

Table 3
Classification of Spatial Resolution and Temporal Frequency According to Qualitative Variables

Qualitative spatial resolution classes	Spatial resolution in m	Qualitative temporal frequency classes
VHR1 very high resolution 1	≤1 m	Hour
VHR2 very high resolution 2	>1 m and ≤4 m	Day
HR1 high resolution 1	>4 m and ≤10 m	Week
HR2 high resolution 2	>10 m and ≤30 m	2 Weeks
MR1 medium resolution 1	>30 m and ≤100 m	Month
MR2 medium resolution 2	>100 m and ≤300 m	Trimester
LR low resolution	≥300 m	Semester
		Year

tify thresholds where the degradation of the resolution or revisit time stops meeting users' needs: this representation is useful to understand where investment in technology is valuable given the benefits it would bring to the community. Looking at temporal frequency for example, it is clear that hourly revisit time, besides being very costly and technically extremely challenging, brings only small benefits to the user community. On the other hand, it appears that degrading the resolution to 1 week would bring a loss of almost 30% of users' requirements. Nevertheless, only a new generation of satellites such as IRIDE and Copernicus' new Sentinels (such as the CO_2 mission) will be able to fulfill this need. Similar results however can be reached through a synergetic use of hyperspectral missions such as CHIME and SGB, both having a revisit time of around 2 weeks. The implementation of this synergy would satisfy the needs of those services and applications that require a weekly revisit time, covering almost 80% of the users' requirements expressed by users (including requirements with lower resolutions) and improving the current offer by fulfilling additional 12% of requirements.

Results concerning spatial resolution show significant preference for high to very high spatial resolutions which involves a trade off with the area of interest the satellite can acquire data on. However, existing missions are able to provide a resolution of around 30 m (High resolution 2), satisfying 44% of total users' needs.

3.4. Gap Analysis

Finally, a preliminary gap analysis is performed to assess which are the opportunities for the future development of the upstream sector and where the synergy between hyperspectral missions can bring additional benefits.

Table 4 combines the preferences on spatial resolution and revisit time expressed by users. The frequency of each choice among the user pool is represented by the color of each cell, where the darker colors indicate that users have expressed the preference more often. Because several associations are possible, through this representation it is possible to prioritize the combination of requirements that are most often requested by the users' community.

Although several users' have identified requirements that cannot be provided relying solely on existing missions, 31% of requirements are already fulfilled by the existing offer of hyperspectral products, namely those requirements with a 2 week or lower revisit time and a spatial resolution between 4 and 10 m. In this context the synergetic use of CHIME and SBG missions would add a significant 9% of additional requirements by potentially improving the revisit time to 1 week.

Thirty three percent of the requirement fulfilled by existing missions or potential synergies belongs to the domain of Monitoring of land cover and use (through the domains of Agriculture and Ecosystem structure) and another 23% belongs to the domain of Coastal monitoring. A consistent share of these requirements also includes the

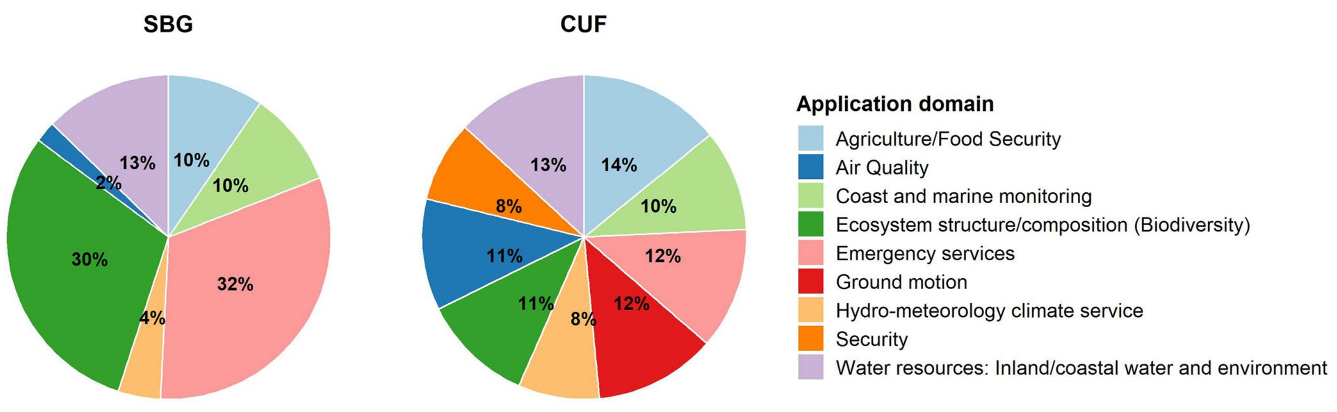


Figure 2. These pie charts represent how users are distributed across different domains for the SBG and CUF communities.

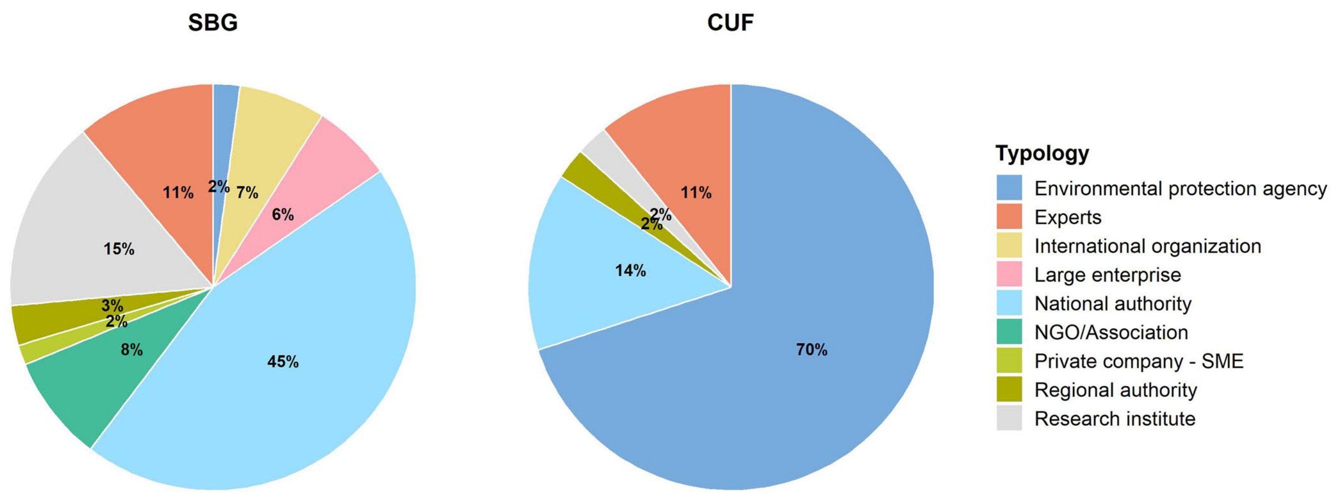


Figure 3. These pie charts represent how users are distributed across different domains for the SBG and CUF communities.

needs of the Water resources (14%). Thus, these services can be considered as the ones with the highest degree of maturity in comparison with the others (Figure 7).

Further analysis will concentrate on a selection of requirements that are considered critical given the approach adopted in Table 4. As a means to prioritize investment in the short term, we consider this first set of requirements for further analysis, however considerations can be made regardless of the frequency with which users require them. In Figure 8, spectral ranges are distributed given users' preferences for each association of spatial and temporal resolution.

Table 1 includes details about the main hyperspectral missions, planned or existing, in global and regional contexts, their foreseen spectral range, spatial resolution, revisit time and coverage. When analyzing the existing offer of EO data and products described in Table 1, several limitations can be highlighted given users' demands. The comparison between the specifications of the desired products and services shows that not all users' needs would be fulfilled by these planned missions, highlighting the main limitations between demand and offer of hyperspectral products.

4. Discussion

The potential of hyperspectral EO technology has proven crucial for several applications and in the future will represent a fundamental resource for tackling some of the most important challenges faced by our modern society. Future and current investment call for the identification and understanding of the market demand for products

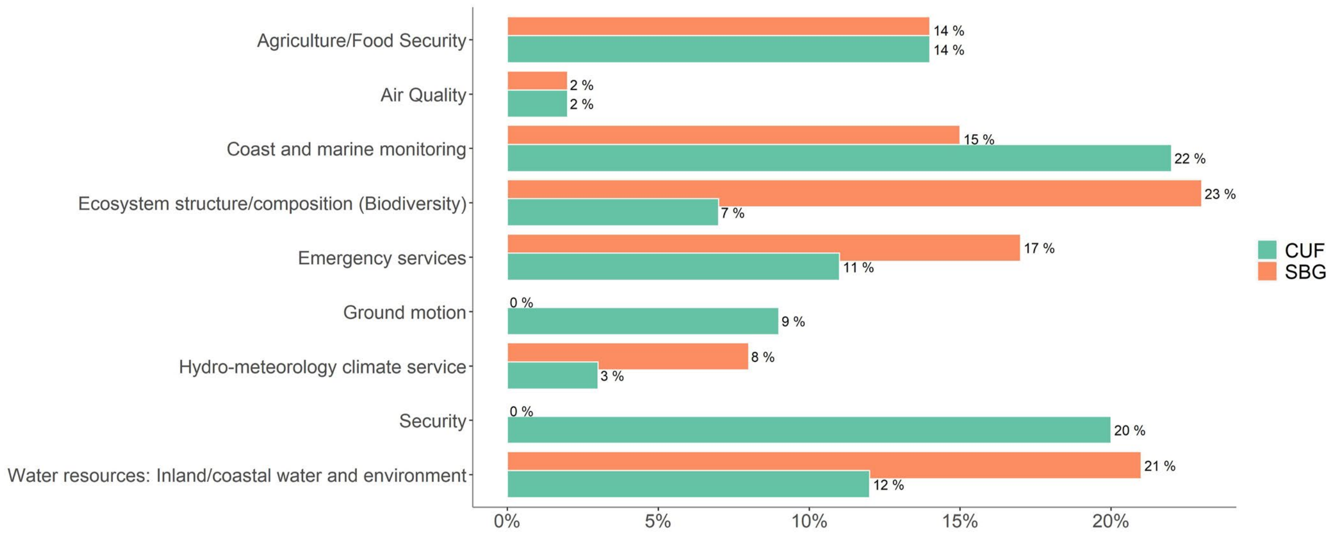


Figure 4. Distribution of requirements by domain according to the different community of users.

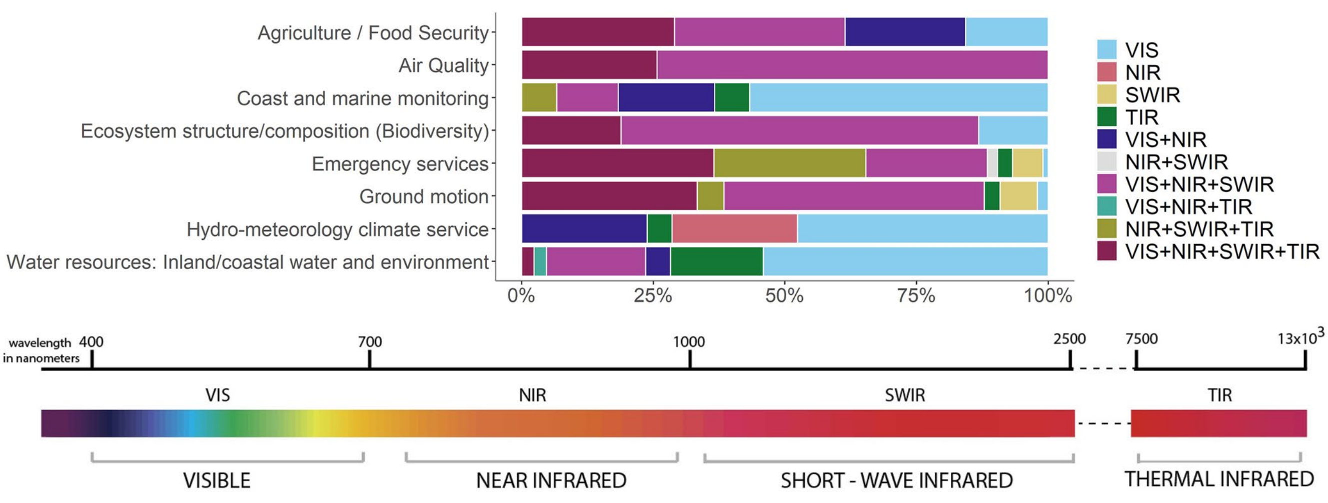


Figure 5. The figure describes the choices of users concerning the spectral ranges preferred for each application domain.

derived from spectral imaging to efficiently orient the development of new satellite missions and for the planning of potential synergies between them. The type of investigation presented here will serve as an input for the development of new technology and also to develop policy in a direction that satisfies users' needs in the long term (European Commission, 2019). In Italy in the framework of the National Recovery and Resilience Plan (PNRR) funding, the user communities' feedback is the base leading design of the candidate constellation architectural and deployment solutions and the development of the concepts for the marketplace, its components, characteristics, and services.

This study has taken into consideration two main user communities: the Italian Copernicus Users Forum and potential users of the NASA Surface Biology and Geology (SBG) mission and elicited their needs for hyperspectral EO products. The goal is to create a solid ground for the determination of the synergetic use of hyperspectral missions and to provide input for investment in the definition of key downstream services according to their current maturity. In this study thus, we indicate which services should be prioritized given both their advancement and potential value to users, and we highlight the potential additional benefits of the synergic use of hyperspectral missions.

An important aspect concerns the type of users for each potential service in order to address them as stakeholders and target groups for developing and improving specific products and components. While the community of Italian users is mainly composed of institutional users because of the structure and governance of the Copernicus National User Forum (European Commission, 2013), namely environmental protection agencies, national authorities and scientific experts, the SBG community includes a variety of new users across all domains in addition to national authorities. Understanding the national and local government is crucial for the development of a governance model for the exploitation of hyperspectral EO data, with the possibility to create anchor tenancies pushing further development and investment in the private sector.

Most of the results in this first section follow traditional applications for hyperspectral technology, in particular, the SBG community has an important interest in services related to Ecosystem structure/composition (Biodiversity) monitoring and Emergency services since 30% and 32% of users respectively operate in this field. These domains features many users as well as many requirements: therefore, it appears that users' needs are very specific to stakeholders and that only few users are interested in a certain service in other words, one requirement satisfies a relatively limited number of users. Similar considerations can also be made for the domains of emergency services for which several users are featured.

The CUF community instead has expressed interest more evenly across domains, It should be noted that the community of CUF users also expressed interest for the domains of Ground motion and Security monitoring which was not included in the study of the SBG community: this additional information does not exclude the importance of this domain for one community but provides input for potential service development.

Nevertheless, the distribution of requirements does not necessarily provide an indication of the importance of one domain compared to another as some requirements could be more important than others for certain users.

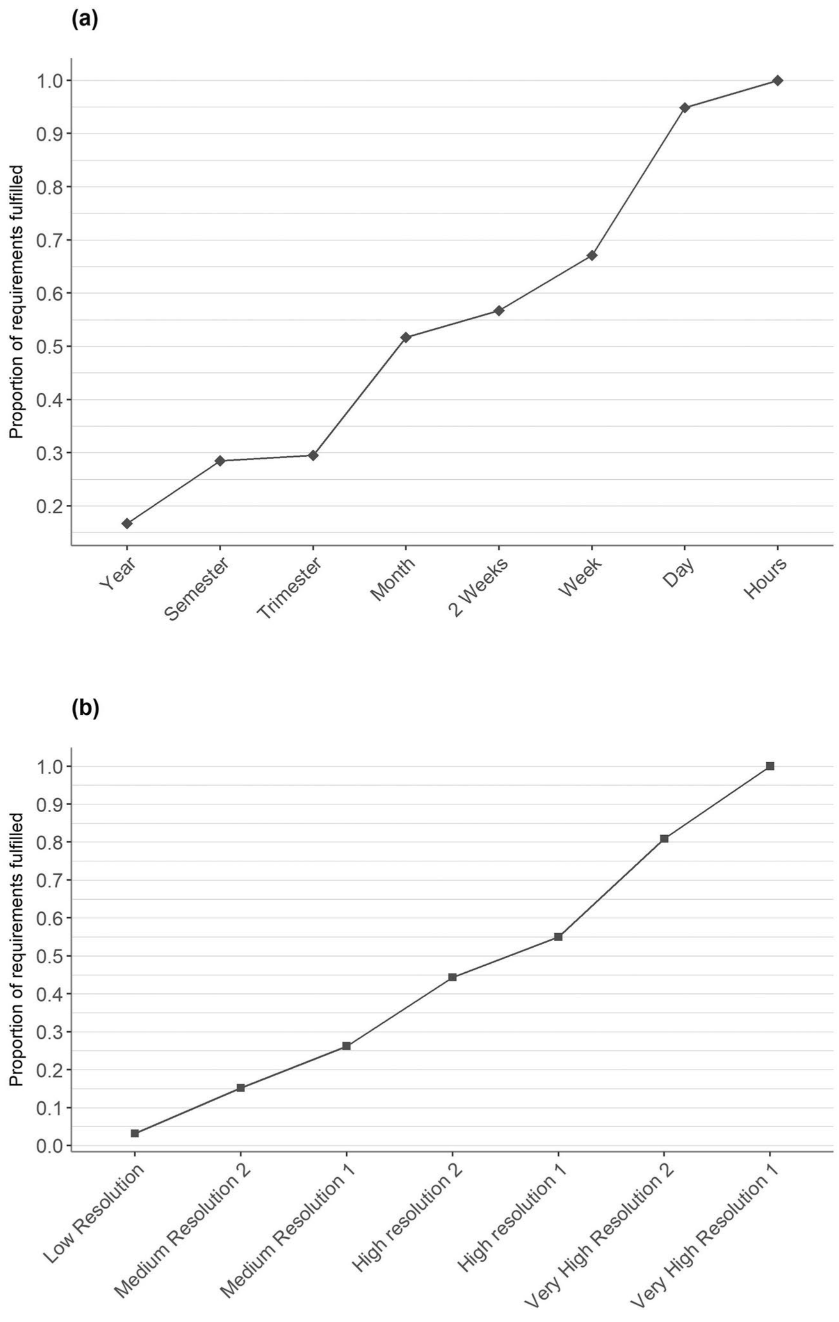


Figure 6. (a, b) The graphs represents the cumulative percentage of users' needs met by each different temporal frequency and the cumulative percentage of users' needs met by each different spatial resolution. Users' requirements are accumulated since higher resolutions cover the needs of lower ones; this representation shows if there are noticeable differences between resolutions to provide a guidance for investment in a specific technology.

Still, this representation provides an understanding of the flexibility and heterogeneity of the technology that is being developed.

The results of the gap analysis, summarized in Tables 4 and 5, show some shortcomings of the current offer of hyperspectral data and some opportunities concerning the development of new missions and potential synergies.

Spectral resolution: Results on the preferences of users for spectral bands show that 73% of users' needs would be covered by the visible, near infrared and short-wave infrared range of the spectrum according to the cumulative sum of users' preferences shown in Figure 4. 27% of requirements also need the thermal infrared range of

Table 4
The Table Describes Users' Preferences on a Percentage Base Concerning Technical Resolutions, Specifically Spatial Resolution and Revisit Time

	Very high resolution 1	Very high resolution 2	High resolution 1	High resolution 2	Medium resolution 1	Medium resolution 2	Low resolution	NA
Hours	0.0038	0.0009	0.0038	0.016	0.0103	0.0028	0.0009	0.0094
Day	0.0789	0.0291	0.0207	0.0733	0.0179	0.0235	0.0141	0.0028
Week	0	0	0.0038	0.0451	0.031	0.015	0.0009	0.0019
2 Weeks	0	0	0	0.0169	0.0169	0.0132	0	0
Month	0.0197	0.0846	0.0094	0.0714	0.0019	0.0197	0.0028	0
Trimester	0	0	0	0.0056	0.0038	0	0	0
Semester	0.0141	0.0376	0.015	0.0329	0.0019	0.0085	0.0009	0
Year	0.0047	0.0611	0.0169	0.0498	0.0009	0.0207	0.0028	0
NA	0.0385	0.0009	0	0.0085	0.0009	0.0019	0	0.0085

Note. The values highlighted in yellow are the needs that are already fulfilled by the existing or planned hyperspectral missions. The colored dots represent how much a requirement is needed on a comparative basis, red being the lowest lever of preference and green the highest.

the spectrum (TIR), alone or in combination with other bands. Considerations on the TIR range of the spectrum are important since they feature a separate and distinct sensor beyond the ones used to provide hyperspectral data; this naturally induces some considerations concerning potential investments. While TIR has fewer applications compared to optical ranges; it is nevertheless relevant across all domains, but existing missions do not provide this data mainly because a whole different sensor is required. New missions such as SBG or LSTM: Copernicus Land Surface Temperature Monitoring will provide this type of data at a resolution of 50/60 m and a revisit time of 3 days, filling the gap of the current demand.

Spatial resolution: Concerning the needs expressed about the spatial resolution and temporal frequency, it can be noted a specific focus on high to very high resolution. High spatial resolution products and data are increasingly available through the development of radar technology, particularly useful in the context of coastal monitoring

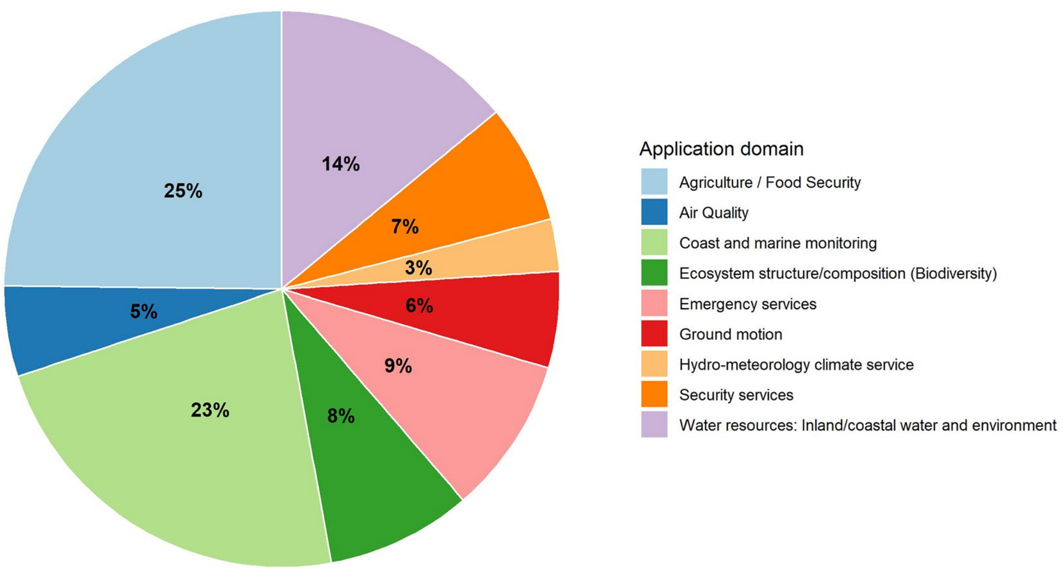


Figure 7. This pie chart shows the distribution of the requirements expressed by users that are fulfilled by existing or planned hyperspectral missions.

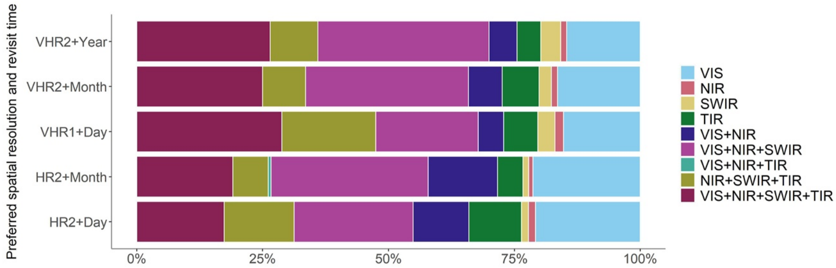


Figure 8. The figure highlights the most frequent technical requirements in terms of spatial resolution, revisit time, and spectral ranges information combined. Five most frequent associations between spatial and temporal resolution are analyzed given the distribution of preferences on spectral ranges.

because of the ability to provide data also in cloudy conditions. The request for sub-daily frequency updates poses more of a challenge because of limited area coverage and because only geostationary satellites at the moment are able to provide such a frequent revisit time but at much lower spatial resolutions. Users nevertheless might benefit from model-based products specifically for coastal emergencies and weather-related events. Concerning the specific requests of users, very high resolutions, under 1 m, cannot be fulfilled given the current specifications of EO products, regardless of the spectral resolution required. In addition, US government optical satellite sensors are limited to 10 m or greater spatial resolution so as not to compete with private sector satellites, nevertheless not all these products are mature (Cheng & Han, 2016).

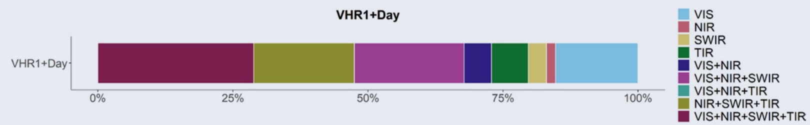
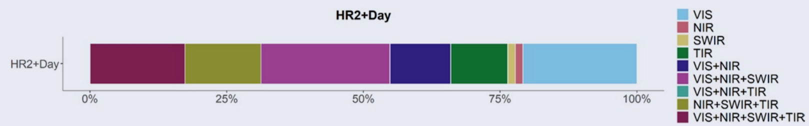
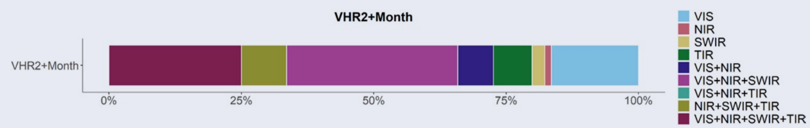
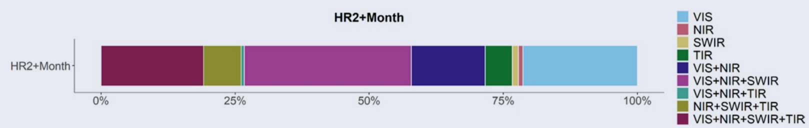
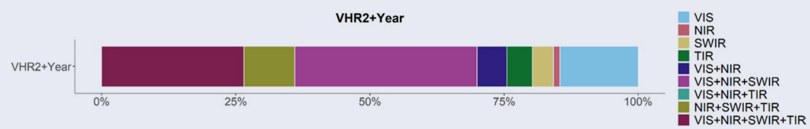
Despite this limitation the current offer of satellite products is already able to satisfy a consistent portion of users' needs, given that most satellites are able to provide a resolution of around 30 m. Given these observations it should be noted that the high resolution will probably be covered by a new set of constellations under development in Italy. Several requests could be satisfied by the new constellation of constellations IRIDE which will feature a Hyperspectral sensor and that will provide high spatial resolutions for the VIS, NIR and SWIR bands of the spectrum. Another consideration should be made on the request for daily revisit time, particularly important for emergency services where this feature will mainly be available for security and emergency related activities targeted for specific institutional users. To improve this limitation, it is crucial to work on missions' synergies in order to prioritize higher temporal frequencies for the data.

Temporal frequency: Preferences on temporal frequency show that, although daily revisit time is the preferred option for users, a synergy between CHIME and SBG could increase revisit time up to 1 week, satisfying10% additional users' requirements compared to the current offer of hyperspectral data (Figure 6a). Daily revisit time will in fact be covered only from the private offer of satellites and from missions that operate on a regional rather than global basis. Although the PRISMA satellite features a weekly time frequency, it is still a demonstrator project, a precursor phase of the future generation hyperspectral missions that is primarily intended for research and development of Earth Observation applications and does not provide data systematically to the user community.

Despite the fact that some gaps remain, the results show that around 40% of users' requirements are currently fulfilled by existing or planned hyperspectral missions (Table 4) at least in terms of spatial resolution and revisit time. These requirements are mainly pertaining to the domains of land cover and land use for agriculture, water resources and coastal and marine management and monitoring, in fact, hyperspectral sensors have a value added in the above-mentioned services. Given this baseline, it appears that there is room for the development of synergies between different missions specifically for the improvement of the offer on revisit times and spectral ranges: specifically, considerations should be made on the improvement of capacities for the thermal infrared range of the spectrum in terms of spatial resolution and on the potential improvement of temporal frequencies for the other bands.

Given the analysis of users' requirements that was performed, users have a strong interest in higher spatial and temporal resolution across all the spectrum. Limitations however exist in the current offer of hyperspectral EO data, since, fine spatial resolution is not yet available. In addition, trade-offs exist between single missions' revisit time, spatial coverage, and resolution (Ferringer & Spencer, 2012). Nevertheless, mission coordination, especially regarding synchronies between SBG-CHIME satellites would enable a better response to applications and

Table 5
The Table Shows the Gap Between Users' Demand Concerning the Most Frequent Needs (the Green Traffic Lights) and Offer of EO Products According to the EO Missions Included in Table 1

Users' demand on spatial resolution and revisit time	Users' demand on spectral ranges	Availability of EO offer
Less than 1 m and daily revisit time		No current availability in the current or planned offer because of the limitations on spatial resolution
Up to 30 m and daily revisit time		Availability of IRIDE products for VIS + NIR + SWIR, comprising 34% of the requirements asked by users
Up to 4 m and monthly revisit time		Only IRIDE could cover 59% of the requirements on the VIS + NIR + SWIR spectrum given the high spatial resolution provided
Up to 30 m and monthly revisit time		PRISMA, CHIME, SBG and IRIDE cover 68% of the requirements, in particular VIS + NIR + SWIR range of the spectrum
Up to 4 m and yearly revisit time		Only IRIDE could cover 59% of the requirements on the VIS + NIR + SWIR spectrum given the high spatial resolution provided

research that have a revisit sensitivity and would provide access to shared resources and community expertise around algorithm development and evaluation. Scientific and operational needs motivate more spatial coverage and more rapid revisit time than any one agency's observing system can provide. In addition, SBG and CHIME coordination could provide more global coverage spectroscopic observing systems. Nevertheless, this synergy is influenced by the different technical specifications of the two missions such as number and type of ground stations, orbit definition and most importantly coordination around revisit time.

In this context interactions between the SBG and CHIME scientific communities have been carried out during the 6–10 March 2023 workshop hosted in Italy at ESA—ESRIN headquarter. The two teams discussed together the future steps toward harmonization of data products and practices, open science elements, products calibration and validation to provide extended global scale operational Imaging Spectroscopy observations. The workshop aim was to develop a roadmap for joint CHIME-SBG activities to realize instrument agnostic algorithms and data products and to identify together test cases to evaluate Level 2 algorithms performances in common application domains. During the workshop the candidate algorithms and priority products were widely discussed considering different application domains and the technical and operational requirements to have synergies in biophysical and geophysical variables readiness. ESA CHIME hyperspectral performances and synergies with the SBG VSWIR instrument were consolidated also by harmonizing the language for the thematic areas considered a priority for each of the two missions. The two missions are in fact considering a list of products that are partially overlapping and partially complementary, opening a wider portfolio of products and services related to the missions. It is also expected that users will benefit from blended variables coming from multiple sensors and ancillary data. The interaction of the two groups is creating a vision for the engagement and impact on a greater community of users. Coordination on Calibration/Validation and data quality activities is also crucial when data from different satellites are used by users worldwide in a complementary and synergetic manner. The identification of such large community of users will facilitate the cross-calibration and validation goals and improve interoperability and accuracy of products. Future effort by the two groups will harmonize terminology and protocols for measurements, agreeing that calibration and validation measurements should be independent from the bio-geophysical retrieval process to allow independent verification. By joining together, the two communities, more than 500 individual users and 309 organizations have been surveyed who provided more than 270 requirements spanning nine different application domains.

This process will allow for more shared resources and a community around which new products can be evaluated. Given the findings of this work and the future objectives of this research, some key messages are highlighted.

1. New generation of missions may be able to tackle the needs of users especially in terms of high spatial resolution and expansion of the TIR range of the spectrum.
2. Currently gaps can be filled by CHIME-SBG coordination increasing the value of key services and applications by improving temporal revisit and expanding the spectrum to the thermal infrared range.
3. Shared community and resources can facilitate the improvement of products from these missions and their use across different communities: an opportunity exists to double societal benefit through coordination, but this needs to be realized over time and by collaborating on precursor data sets
4. Although new missions could significantly improve the spatial resolution of hyperspectral data and products, tradeoff would limit the geographical coverage of such data.

In this context it should be highlighted the different nature of missions such as CHIME, SBG, and PRISMA and the Low Earth Orbit (LEO) IRIDE constellation. While LEO satellites require the lowest amount of energy for their placement, they also provide high bandwidth and low communication latency. Unlike geosynchronous satellite, satellites in LEO have a small field of view and so can observe and communicate with only a fraction of the Earth at a time and therefore a constellation of satellites is required to provide continuous coverage. Missions like IRIDE, because of their LEO specification will also suffer from fast orbital decay and require either periodic re-boosting to maintain a stable orbit or launching replacement satellites when old ones re-enter (Sebestyen et al., 2018). These elements naturally influence the cost of the mission and their planning.

Thus, it is advocated that these challenges can be met by a multi-mission and multi-Agency synergetic approach, rather than by any single observing system (Boccia et al., 2021).Concerning users' need for TIR acquisitions, infrared imaging spectroscopy radiometers, operating from the International Space Station such as ECOSTRESS (Fisher et al., 2020) will contribute to filling this gap for a wide variety of applications. EMIT (Green et al., 2020), on the other hand will contribute to the needs of users in the in the visible and short-wave infrared spectrum by accurately mapping the composition of areas that produce mineral dust. In this context precursor missions such as PRISMA (Hyperspectral Precursor of the Application Mission) (Sacchetti et al., 2010) will also be critical to build a community of practice in parallel with mission development for users to be ready once mission data become available.

5. Conclusions

This study has engaged diverse communities of users from different domains and geographic regions with the aim to understand the evolution of specific services through the use of hyperspectral EO technology. The results that have been obtained can be used as a baseline not only for the development and improvement of downstream applications and services but also for the definition of potential synergies in the upstream component between existing and planned hyperspectral missions.

Although users' needs vary between geographical regions, it is possible to identify similarities for the development of coherent observation strategies and for the development of user-based services. In particular, the Ecosystem and Agriculture services are crucial both in terms of the interest by the sector and the current gaps that users have highlighted.

While this does not mean that these services are more important than others it provides decision makers with the possibility to prioritize investment over time through the EO chain, in its upstream, midstream and downstream components. While the planned hyperspectral missions featured in this study already promise good coverage for the needs expressed by users, there is indeed an opportunity to improve or adjust the offer of products and services by pushing further technical specifications in the TIR range of the spectrum which is particularly useful for the land cover, ground motion and emergency management services.

While this study does not have the main aim to propose technical solutions for the upstream component nor to give suggestions regarding the architectural design of specific EO missions and their synergetic use, it is worth mentioning the opportunities that could arise from such an investigation. Specifically, we see potential in the synergetic use of hyperspectral sensors to improve the temporal resolution of products and extend the potential of the thermal infrared range of the spectrum.

Finally, this study features some limitations that should be highlighted. First the fact that the two user needs studies were conducted independently posed some challenges when interpreting the results and identifying a common taxonomy that provided ground for comparison. In addition, this study is limited by the lack of data provided by other national communities and future studies would benefit from the inclusion of requirements from other nations through the engagement of National User Fora and other formal collection methods in non-European states. While these data are not currently available, this study represents an incentive for their development. Second, the gap analysis between users' requirements and current offer of EO hyperspectral products takes into consideration only some technical specification which are not exhaustive but only provide a first input that should be supported by further studies.

Data Availability Statement

The users' derived data used for the elicitation of user requirements and needs in the study are available at Zenodo.org through the repository by the title “Maximizing Societal Benefit Across Multiple Hyperspectral Earth Observation Missions: A User Needs Approach—DATA and CODES” via https://doi.org/10.5281/zenodo.8415780 with license CC by 4.0, and Open Access conditions (Schiavon, 2023). To preserve the privacy of stakeholders that took part in this study, the responses to the questionnaire are available only in an anonymous format. Data has been processed using the R Statistical Software (RStudio Team, 2022), the script used for processing the data in this study are also available in the above-mentioned repository.

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