Hyperfield - Hyperspectral small satellites for improving life on Earth

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Abstract—**Over the past few decades, Earth observation technology has provided highly useful information for global climate change research, particularly in providing biological, physical, and chemical parameters on a global scale. Nevertheless, the low revisit rate and spectral resolution, as well as the expensive operational capacities of current spaceborne missions, make it difficult to gain rapid and accurate insights into degrading ecosystems or dissect faltering food security or carbon sinks.**

The Hyperfield constellation that will be launched in 2023 consists of 100 CubeSats with hyperspectral imagers operating in the visible-to-near-infrared (VIS-NIR, 450-1100 nm) and Visible-to-shortwave infrared (VIS-SWIR, 450-2500 nm) ranges and provides two to three times daily images from any location on Earth. The hyperspectral is based on a Piezo-actuated Fabry-Perot interferometer (PFPI) and a tailored camera with innovative modes of acquisition. A novel artificial intelligence (AI) processing platform will be used to provide stakeholders with high-quality, affordable data, analytical services and forecasts on a daily basis, enabling them to make informed decisions that lead to a more sustainable environment, carbon sequestration, food security, and a reduction in climate change impacts.

This paper presents the first and second generations of the Hyperfield satellites. It reviews their innovative platform and detector technology, the optical modes, planned mission operations, processing architecture and services.

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1. INTRODUCTION

A spaceborne hyperspectral imaging system provides detailed, non-destructive, and fast chemical and spatial information analysis of the Earth's surfaces using a series of contiguous and spectrally narrow image bands. Despite the technological advances and wide range of applications, hyperspectral satellites are still underrepresented in spaceborne missions compared to multispectral ones, even with some anticipated launches in the near future [1]. This results in poor temporal resolution, where images are taken about a month apart. In many applications, such as precision agriculture, maritime surveillance and air quality, that frequency is too low to fully utilise the benefits of the technology.

Over the last decade, CubeSats have grown in popularity as a platform for low-cost activity in space by industry, government, academia, and the military. As of August 1st, 2022, 77 countries are currently developing CubeSats, and 1897 CubeSats have been launched [2]. The most popular CubeSat configuration is 3U (about 53%), followed by 1U (18%), and 6U platforms account for 11%. The main sector in which CubeSats are being used is Earth Observation (EO), which represents about 45% of all applications [3]. At a time when a rigorous investigation of changing climate is one of the biggest challenges facing the world, the ability to capture environmental and socio-economic data over a range of spatial, spectral and temporal resolutions is an asset. Since CubeSats can be used to develop a constellation of satellites that scan the same location on a daily basis, they offer a tool to combat climate change, a game-changing opportunity for hyperspectral remote sensing and a plethora of commercial applications.

Kuva Space (formerly Reaktor Space Lab) is a young space-tech company based in Espoo, Finland developing and operating nanosatellites. The company's main mission is to improve life on Earth through daily, space-borne hyperspectral imaging and advanced Artificial Intelligence (AI)-based services. As of today, Kuva Space has launched three satellites to support ESA's Earth Observation,

2023 IEEE Aerospace Conference | 978-1-6654-9032-0/23/$31.00 ©2023 IEEE | DOI: 10.1109/AERO55745.2023.10115806

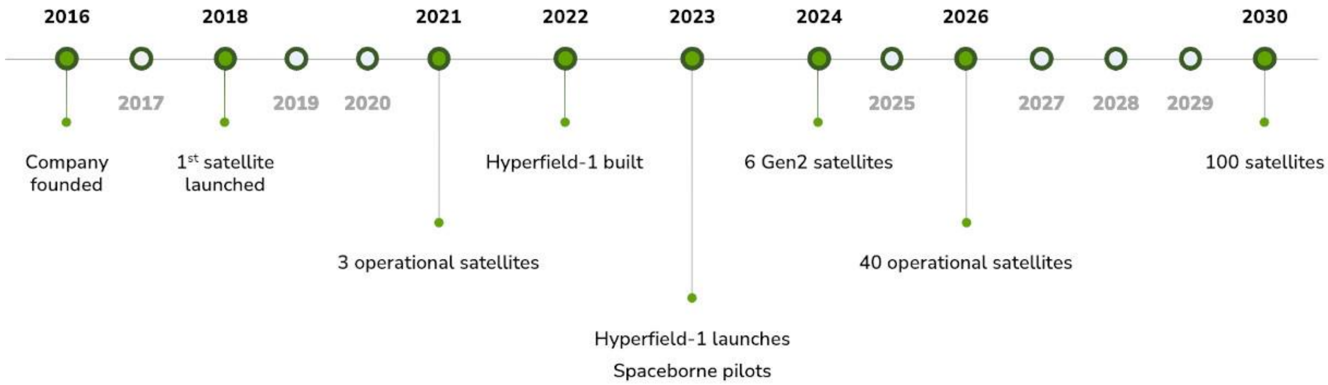

Figure 1: Hyperfield constellation timeline

telecommunication, and space weather missions with hundred percent success rates. This includes Reaktor Hello World, launched in 2018, the first and the smallest (less than 500 g) infrared hyperspectral imager that has ever flown on a nanosatellite [4]. The low earth orbit (LEO) mission, which is still operational, operates in the infrared wavelength range (900-1400 nm) on a 2U platform weighing 2.4 kg and measuring 10 x 10 x 22.7 cm^3.

This paper presents the Hyperfield, a constellation of a new generation of hyperspectral CubeSats currently being developed by Kuva Space. It describes the technical specifications of Generation-1 and Generation-2 of the constellation, payload, ground segment, and processing chain, along with a description of the hyperspectral data service architecture and its current development status.

2. The Hyperfield constellation

The Hyperfield constellation of polar sun-synchronous nanosatellites will extend current Earth Observation capabilities. The first mission, scheduled for launch by SpaceX in Q2/2023, will carry the Hyperfield-1a, a high-resolution hyperspectral camera operating at the visible spectrum to near-infrared wavelengths (450-1000 nm) from an altitude of 550 km. A second satellite Hyperfield-1b will also be launched with a tentative launch date in Q4/2023, with a similar design but for short-wave-infrared (SWIR). The second generation of three satellites will be launched in Q1/2024 into low-earth orbit at an altitude of approximately 350 km. Their platforms will use 12U CubeSats to expand the use of Hyperfield's imaging system to short-wave infrared (450-2500 nm).

The timeline in Figure 1 shows that the constellation is expected to reach 40 units by 2027, providing a global near-daily revisit time. By 2030, a fleet of 100 CubeSats will provide between one- and three- times daily images of the Earth.

3. Platform

The Hyperfield-1 platform is presented in Figure 2. The mission development and launch are co-funded by ESA's InCubed program. Structure and solar panels are custom-made in a 12 x 24 x 36 cm bus with a mass of about 12 kg and a power output of about 15 W. The on-board computer is a failure-tolerant dual-redundant design based on a microcontroller for safety-critical applications. The hyperspectral image acquisition, storage, and processing are handled by a dedicated high-performance data processing unit. The satellite attitude determination and control system combines high-performance sensors and torquers with an integrated Global Navigation Satellite System (GNSS) receiver for accurate orbit determination.

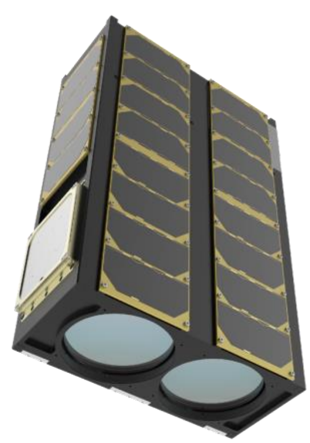

Figure 2: Artistic model of the Hyperfield-1 satellite

The second generation of Hyperfield is built on a 12U bus and acquires data in the visible to the SWIR wavelengths (450 to 2500 nm). As they will be launched into an orbit of about 350 km, the platform will have to include propulsion capability for station-keeping and orbit maintenance.

4. THE PAYLOAD

The first generation of the hyperspectral payload consists of a VNIR snapshot imager offering a 50x50 km^2 imaging area with two cameras and a wavelength range from 450 to 1000 nm. The second generation that will be launched in 2024 expands this range to 450 to 2500 nm, with two cameras that are currently under development. The system is based on a new Piezo-actuated Fabry-Perot interferometer (PFPI) developed by the Technical Research Centre of Finland (VTT) [5]. The FPI acts as a tunable bandpass filter. It consists of two semi-transparent reflectors separated by a gap. The gap is controlled by three piezo-actuators in a closed control loop. Compared to a traditional piezo-actuated FPI, which consists of two metallic mirrors placed very close to each other, the novel PFPI makes use of three piezo-actuators and is controlled through a closed capacitive feedback loop. The mirror substrates are at least 10 mm thick in order to achieve good flatness and adequate mirror quality. This novel design offers higher optical throughput and greater flexibility in wavelength selection.

The development and integration of the 2D snapshot camera, presented in Figure 3, are done by Kuva Space.

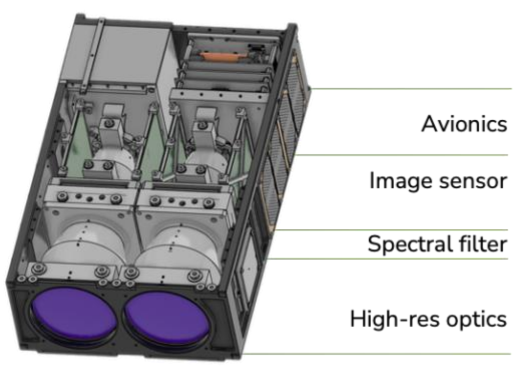

Figure 3: Hyperfield-1 internal configuration

The imager presented in Figure 4 is divided into two channels: VIS and NIR, that operate as individual payloads. The VIS channel operates in the 450 - 675 nm range, and the NIR channel operates in the 675 - 1000 nm range. The implementation is done in this manner to isolate the multiple transmission orders of the FPI.

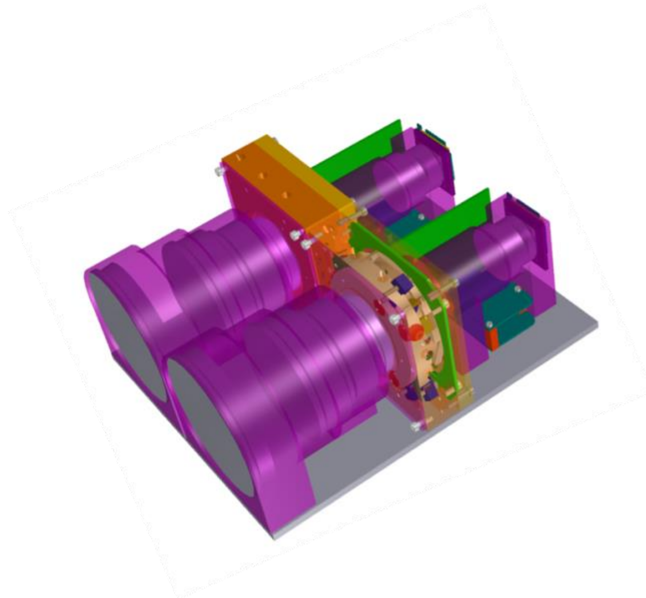

Figure 4: The Hyperfield payload

Figure 5 presents the optical design, consisting of four doublet lenses, two apertures of 88 mm each, an FPI, and two optical filters, reaching a total length of about 235 mm [6].

The sensor is based on CMOSIS CMV [7] technology with an array size of 2048 x 2048 pixels. The spectral sampling of the hypercube image is controlled by software according to the application design and client requirements and can be modified before and during acquisition.

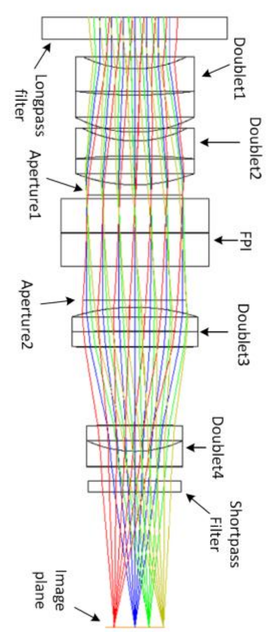

Figure 5: Optics layout of the spectral imager

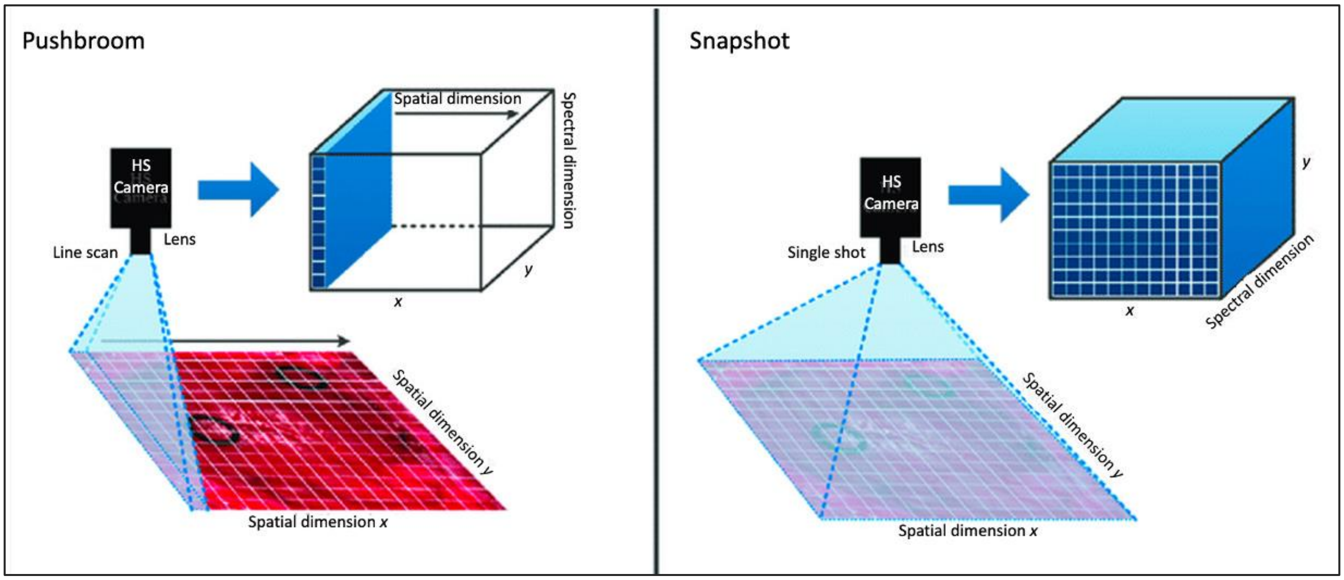

Figure 6: Pushbroom and snapshot scanning modes

5. ACQUISITION MODES

Besides being highly resistant to any jitter or movement and enabling precise subpixel post-alignment of pictures, our imaging platform also enables several imaging modes that to our knowledge, are not available on other hyperspectral imagers. Spectral imaging sensors sample the spectral irradiance of a scene to create a three-dimensional dataset, also known as a datacube. Conventional CMOS sensors are 2D arrays of pixels. In order to capture a high-dimensional dataset, different technological approaches are available. In order to capture more than 100 bands, conventional approaches, such as a Bayer-like filter, rapidly fall short. Figure 6 presents the two most common approaches used in hyperspectral imaging: push-broom cameras, which scan a single line of the scene and break it up into its different wavelengths using an imaging spectrometer, and snapshot systems that take a sequence of images at different wavelengths and then stack them together to produce the final datacube. Kuva Space's snapshot imager makes use of the latter.

In pushbroom systems, a line image is generated and then scanned along the surface of the Earth. The advantage of snapshot solution lies in two technical aspects: 1) the snapshot camera acquires 100 frames per 1.5 second with 1 millisecond integration time, and 2) in-flight software powered by artificial intelligence (AI) determines how many wavelengths to measure and which acquisition mode to use. The operator also guides the system to collect data in one of four acquisition modes (Figure 7): scan, "stare at" a specific spot for a longer period of time, produce super-resolution images via micromovements, or collect stereo images. As a result, the amount of collected data can be greatly reduced, the signal to noise can be significantly improved and the quality of the service can be maintained.

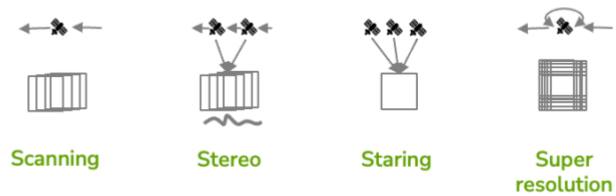

Figure 7: Hyperfield imaging modes

6. CALIBRATION

The Hyperfield's VNIR and SWIR payloads will be subject to the following pre-flight spectroscopic, radiometric, and geometric calibration procedures**:**

Spectroscopic calibration

The goal of the spectroscopic calibration is to determine the spectral properties of the camera over a relevant range of FPI gaps and over the entire field of view (FOV). It consists of a setup described in the work of Pekkala et al. [8], which makes use of a (close to) monochromatic light source and a diffusing element. An ideal Lorentzian function approximates the transmission of the FPI. Nevertheless, the multilayer structure of the interferometer and material dispersion introduce deviations from this assumption. Although these complexities were initially considered during the design phase using simulations based on transfer matrix models, other effects, such as the nonuniformity of the gap in the FPI and smile effect, are difficult to characterize. To overcome these effects and to calibrate for non-linearities in the sensor response, a neutral density filter (NDF) is added to the setup described in [8], and the spectral response of the system is characterized across the wavelength range and pixel array.

To simulate in-orbit conditions, the spectral measurements are conducted in a thermal vacuum chamber before and after vibration testing of the flight model. With the detailed spectral calibration and the map of the FPI gap to wavelength, we can identify (i) the smile effect in each pixel; (ii) the leakage from adjacent FPI modes; (iii) obtain precise information on the shape of the selected FPI mode for the relevant range of gaps, and (iv) estimate the uncertainty of all of the above measurements to better understand the repeatability of the measurements.

Radiometric calibration

The radiometric calibration entails mapping the digital numbers recorded by the complementary metal-oxide-semiconductor detector, at each wavelength, to the radiance at the telescope aperture over the entire FOV, using a calibrated flat broadband light. Upon completion of this calibration procedure, a lookup table associated with each FPI gap and every possible digital number (DN, via interpolation) yield a radiance value in W/(str * um * m^2). This step is essential in order to be able to compare the data collected from our spacecraft with those of other Earth-observing missions and to apply an atmospheric correction.

Internal/Geometric calibration

Every optical instrument is subject to optical aberrations which need to be measured and corrected. Since Hyperfield-1's cameras operate across a wide range of wavelengths, chromatic aberration is also a major concern. Correction is accomplished through geometric calibration (also called internal calibration), where the degree of radial distortion is quantified. Specifically, in this procedure, the linear camera parameters are extracted and the radial distortion up to second order is chareterized using the approach described by [9] and a modulation transfer function (MTF).

Pre-flight calibrations and corrections are followed by in-orbit calibrations to monitor radiometric calibration stability and to perform cross-calibrations across the constellation. The Hyperfeld's spacecraft is equipped with an attitude determination and control system (ADCS) that allows it to point the imager in arbitrary directions and lock its orientation to a given target. This capability will be used by all the satellites in our constellation to take weekly hyperspectral images of the moon, selected star targets, and images of the Pseudo-Invariant Calibration Sites (PICS) listed by the USGS [10] to ensure radiometric calibration stability and corrective measures.

7. DATA TRANSMISSION

After the acquisition, the metadata is recorded to facilitate storage and downstream processing schemes. Among others, it includes satellite identifier, altitude and attitude, exposure time, wavelength, number of detector pixels, position and velocity, instrument status and temperature and start/stop time of acquisition for each frame. In Hyperfield-1, the images are compressed using JPEG-XL after Principal component analysis (PCA) to reduce rate distortion and preserve spectral information [11] and downlinked to ground stations.

Kuva Space will utilise an X-band high data downlink transmitter with a miniaturised COTS antenna to transmit data in the 8025-8400 MHz frequency range at data rates of up to 225 Mbps.

8. GROUND SEGMENT

Kuva Space has its own ground station in Espoo, Finland, but obviously, for providing rapid global services, we use third-party stations located all over the globe. At the ground station, the image is stamped with information about the solar zenith angle. This information, which is provided by a real-time space weather service, is crucial for the atmospheric correction described in section 9. The data is then packaged and transmitted to a cloud storage environment where open-source software such as GeoServer and GeoNode is used to register the data in standard OGC protocols and store it as a '1A product'.

9. VALIDATION MISSION

Operational tasks for the validation mission will be performed at Kuva Space's ground station in Espoo, Finland. The data will be processed on the ground using a large set of radiometric and geometric ground truthing data to verify the usability of the downlinked hyperspectral data to selected customer and end-user applications.

The eventual satellite constellation will be launched after this validation mission providing up to daily re-visits and data acquisition from areas of interest anywhere on the globe supported by a distributed network of ground stations.

10. PROCESSING CHAIN ARCHITECTURE

Kuva Space's image-processing architecture is presented in Figure 8. It is designed to determine the measured surface reflectance values within each image pixel from the acquired raw data and to create analytic-based services. The fully automated workflow is composed of three processing blocks: i) image acquisition, ii) image correction and rectification, and iii) product/service generation. The first processing block occurs onboard the satellite, and the other two after the data has been downlinked to the ground stations. As explained earlier, the workflow architecture is supported by rapid data transmission from the satellite to the ground segment. Cloud storage also provides a global product catalogue, storage media transparency, and scalability in terms of data transfer and storage capacity. A graphical user interface controls the processing system and serves as a visualisation tool for the data in stock. It is capable of displaying the status of the

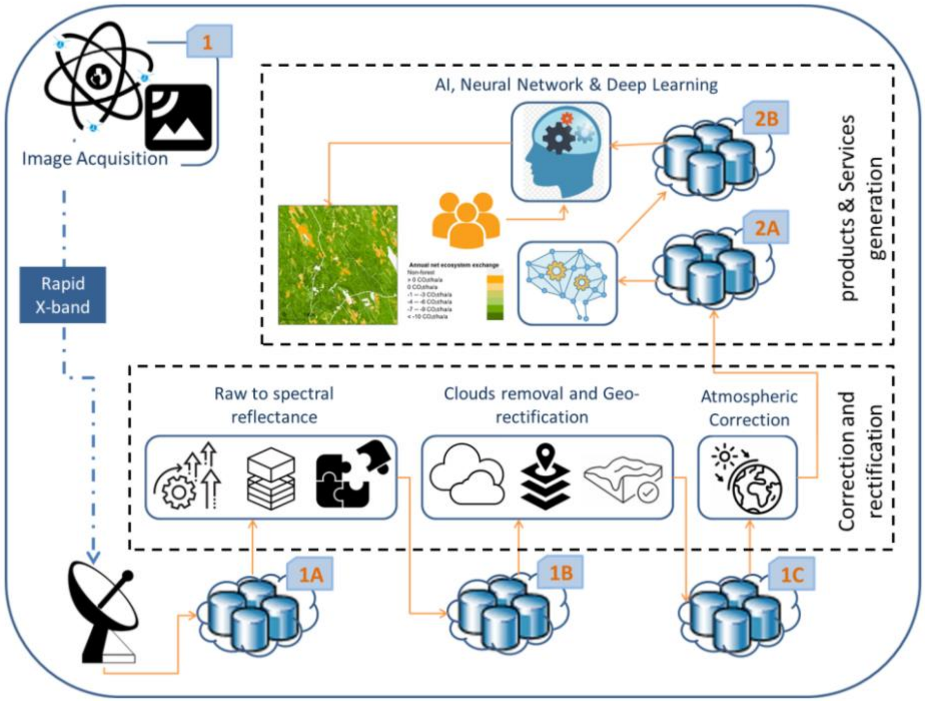

Figure 8: Processing chain architecture

processes requested, accessing data stored in the catalogue and providing search capacity based on geographic location and keyword.

As known, cloud cover prevents optical satellite imaging systems from obtaining useful Earth observation data and negatively impedes the extraction of meaningful information from the image product. Mostly this is a hindrance for applications such as disaster monitoring, where a specific scene must be observed at a specific time. At level 1A of our processing chain, we will follow the lead of other scientific missions (like PRISMA and Sentinel-2) and produce a cloud mask with an estimate of the cloud thickness. By doing so, it is possible to estimate the amount of cloud cover on each image and remove these pixels from downstream analysis when necessary.

In ground-based processing procedures, advanced machine learning and neural network algorithms convert raw measurements to spectral reflectance automatically, rapidly and robustly. These algorithms enhance the hypercube images by implementing the following four corrective processes: i) identify and mask out bad pixels, ii) improve bands alignment and stitch the images to produce a continuous strip of hyperspectral data, using advanced feature matching method and iii) improve the georeferenced image using a base map or orthorectified for selected applications using an available digital elevation model (DEM), and iv) retrieve surface reflectance values by removing atmospheric effects from the 1B imaging product using a radiative transfer (RT) model [12]. After atmospheric correction, the 1C product can be used to create true-colour imagery or to detect and classify objects based on their spectral characteristics.

11. Analytical Products and Services

Hyperfield will address a wide range of applications, including monitoring of water, soil, and polar environments, security, and land use changes. Our goal is to improve the available remote sensing services by providing actionable data, insights and forecasts to help growers to improve crop yields and quality, enhance financial planning, prepare for risks, and optimise operations.

Only with high frequency and affordable data like those produced by the Hyperfield constellation, over large periods of time and coverage, it will be possible to produce reliable forecasts of climate change impacts on the land surface, which are vital for decision-making, mitigating consequences, and securing livelihoods. In the wake of anthropogenic climate change and the subsequent increase of air and sea temperatures that result in reduced agricultural yields, polar ice melt, sea level rise, water shortage, extensive deforestation and increased air pollution, spatial-spectral monitoring and forecasting changes are becoming essential to humanity's future.

The Kuva Space mission is not to create or sell EO data but to build a services platform that will provide global, daily insights into every location on Earth. Within an hour, our AI services will convert satellite data, which is difficult to process and interpret, into accurate maps and analytical products. By integrating data from ground sensors, complementary EO missions (like Meteosat, radar, lidar or thermal), and media using advanced deep learning algorithms, it would forecast yield and crop growth accurately for insurance purposes or carbon sequestration rates for carbon credits. Additionally, the platform can also be used to develop high-end defence and security products, including surveillance or monitoring of methane releases from gas pipelines that require near-real-time responses.

12. SUMMARY

The ultimate goal of Kuva Space's services is to provide global and daily insights into the environment and food production on Earth and, by doing so, to enforce green policies, improve sustainable economies, and ensure food production and human health. It is anticipated that the nanosatellite constellation and the automatic processing chain will provide affordable satellite products and global, robust, and timely EO services that are not currently available.

ACKNOWLEDGEMENTS

Hyperfield development is done under ESA Contract No. 4000134368/21/I/MG.

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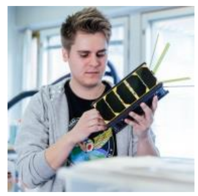
BIOGRAPHY



***Tuomas Tikka** has a M.Sc.(Tech.) in space technology from Aalto University, Finland. During his doctoral studies in Aalto University, he was one of the key persons in building Finland's first satellite launched in 2017 and received Finland's engineer of the year award for it in 2018. In 2016, he co-founded Kuva Space (previously Reaktor Space Lab) to commercialize nanosatellite technology and related services and acted as the CEO for the first 5 years. Since 2021 Tuomas has acted as the CTO of Kuva Space and is responsible for the development of the Hyperfield constellation and services. He is also a member in Kuva Space's board of directors.*

***Jussi Makynen** has a MSc in electrical engineering. Prior joining the Kuva Space as Head of Camera Technology Jussi Mäkynen has co-founded and exited Spectral Engines, a spectral sensor company, selling thousands of NIR spectroscopic solutions with cloud-based analytics for businesses and professionals in pharma and law enforcement among other fields. Before Spectral Engines Jussi was working at VTT's Spectral Sensing team developing hyperspectral imagers and spectral sensors. Among other things Jussi and the team developed the electronics and assembly setup for the Fabry-Perot module, used now at Kuva Space.*

Michal Shimoni *has a PhD and MSc in civil engineering and geosciences. She is an awarded scientific expert in the field of hyperspectral with more than 20 years of experience in implementing spectral imaging and developing machine learning, fusing multi-sensor technologies, building physical modelling, and integrating sensors into airborne and space-borne platforms. She is currently employed as Head of Analytics and Applications at Kuva Space, coordinating the development of products and services. She is also an active senior member of the International Society IEEE within she is an associate editor of the scientific journal IEEE-GRSL and was the technical chair of the IEEE's flagged conference IGARSS in 2021.*