NEMO-HD IN-ORBIT RESULTS FOR AGILE SCANNING OF CITIES, RIVER BASINS AND 3D OBJECTS BY SATELLITE VIDEO AND MULTISPECTRAL CAMERAS

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ABSTRACT

This paper presents in-orbit test results for agile video and multispectral scanning of cities, river basins and 3D objects by NEMO-HD microsatellite. The satellite successfully launched on the Vega vv16 SSMS flight on September 2, 2020. It explores new Earth observation concepts by combining video and multispectral imaging with GNC capable of executing advanced multi-payload EO scenarios including very accurate and stable ground point target tracking for video observations of traffic in cities, ports, airports, open mines and other areas with intensive economic activities as well as ground tracking of rivers, coasts, motorways, powerlines, etc. Furthermore, agile observations of 3D objects such as clouds, waste dumps, landslides and open mines from different angles provide rich data streams for 3D object reconstructions not only for classical stereographic techniques but also for advanced Structure from Motion methods, which can be processed onboard to provide information made in space that can be efficiently transferred to ground stations and delivered to end-users by low latency and real-time services.

1 INTRODUCTION

In this paper we describe the performance of the complete Space-SI Earth Observation system including the NEMO-HD microsatellite, the transportable ground station system STREAM, and the data processing chain STORM with respect to the pointing accuracy and data latency for river basin scanning and 3D object shape determination. In particular, we disclose in-orbit test results of the NEMO-HD ground tracking capabilities for the Sava and Neretva river paths, which represent real-life challenges at different complexity levels with respect to the combinations of along- and cross-track pointing from the Low Earth Sun Synchronous polar orbit. Prospects for fast delivery of on-board processed information and interactive navigation of the NEMO-HD spacecraft in real-time satellite video applications are discussed.

2 EARTH OBSERVATION SYSTEM

2.1 NEMO-HD Microsatellite

NEMO-HD is the first Slovenian microsatellite. The satellite is operated by the Slovenian Centre of Excellence for Space Sciences and Technologies SPACE-SI and was developed in collaboration with the Space Flight Laboratory from University of Toronto Institute for Aerospace Studies. NEMO-HD is a compact spacecraft with an octagonal platform and a mass of 60 kg. The spacecraft is designed around the payload optical bench, which comprises approximately one half of the spacecraft mass.

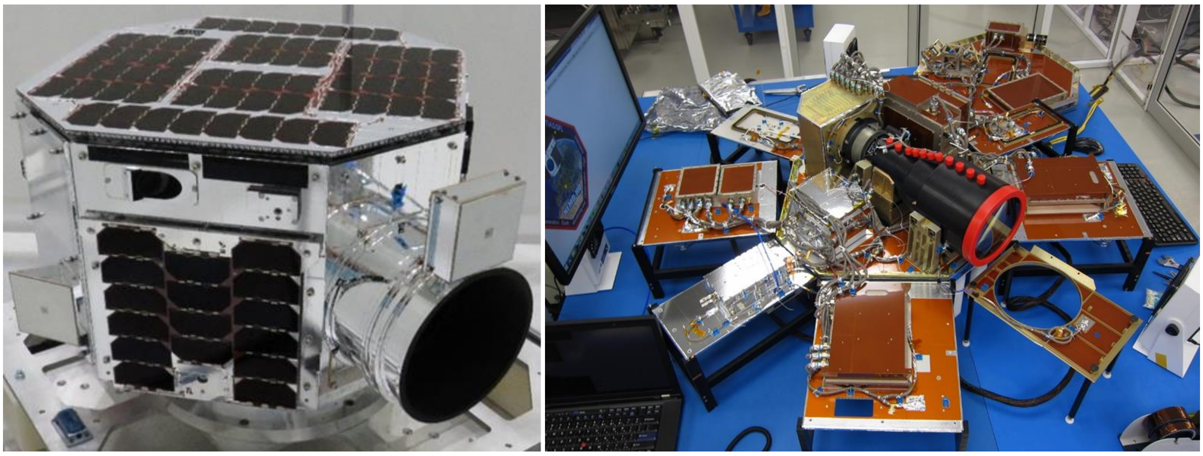


Figure 1. NEMO-HD microsatellite

The primary mission of NEMO-HD is to explore a new Earth observation concept by combining video and multispectral imaging for interactive real time and low latency remote sensing services enabling delivery of pan sharpened multispectral images and high-definition video products. The primary optical imager provides still imagery with a 10 km swath using a panchromatic (PAN) channel at 2.8 m ground sample distance (GSD) and four multi-spectral channels (R, G, B, NIR) which have 5.6 m GSD. In addition, there are two high-definition video channels each with 1920x1080 resolution, one with 2.8 m GSD (5 km swath) and another with 40 m GSD (75 km swath). The four multi-spectral (MS) channels are completely overlaid with one another, while the smaller PAN and HD channels overlap with portions of the MS channels. The PAN channel spans almost the entirety of the MS channels perpendicular to the flight direction (east/west of the ground track), allowing for pan sharpening of the entire MS field of view when operating in swath imaging mode.

The NEMO-HD primary optical payload features a 360 mm f/2.3 lens, employing a wideband beam-splitter followed by a focal plane image splitter to accommodate simultaneous capture of 6 sensors in total, 2 CMOS and 4 CCD. The lenses have also been designed to have high angular resolution, which allows for the short focal length while still meeting the GSD requirement. The payload electronics consists of five payload onboard computers (OBCs), one for each still sensor as its high-speed data recorder, connected to a high-speed X-band downlink. In addition, two video cameras provide H.264 encoded live video streams, with one camera attached to the primary optics and another to a wide-angle secondary optics.

In addition to the two optical payloads, the satellite is equipped with a three-axis attitude determination and control system, body mounted solar panels with maximum power of 55 W and 300

Wh Lithium-Ion battery pack. For command and telemetry, an UHF receiver and S-band transmitter are used, while the payload data will be downloaded by 50 Mbps X-band transmitter.

With NEMO-HD in the orbit, SPACE-SI has achieved a very innovative and cost-effective remote sensing system that combines the agile microsatellite with the novel transportable ground station system STREAM and advanced data processing chain STORM. The main applications are aimed at monitoring smart cities, river basins and maritime as well as for enhanced EO applications for forests, agriculture, droughts, floods, and invasive plants. NEMO-HD mission parameter overview is presented in Table 1.

Table 1: Mission parameter overview

	MS	PAN	HR-HD	LR-HD
Orbit	517 km, SSO, 10:30 LTDN			
Swath width	10 km	9 km	5 km	75 km
Spatial resolution	5.6 m	2.8 m	2.8 m	40 m
Repeat cycle	6 – 13 days (depending on the observation angle)			
Spatial coverage	Data can be collected globally			
Temporal coverage	NEMO-HD is operating since launch on 2.9.2020. Expected operational lifetime is 3-5 years.			
Ground velocity	7.7 km/s			

2.2 Ground Station System

NEMO-HD has separate communication frequency bands for Tracking, Telemetry and Commanding (TT&C) and for data download. A UHF receiver, an S-band transmitter and an X-band transmitter are used for command uplink, telemetry downlink and data downlink respectively. The main function of NEMO-HD TT&C is to provide reliable communication between the spacecraft and the ground. Uplink is in UHF frequency band, while S-band is for downlink. The UHF uplink forms the method with which commands and software are sent to the spacecraft for all mission functions. On-board UHF communication subsystem must be active at all times when power is applied by the spacecraft power system.

The S-band downlink is the method with which telemetry and housekeeping data are received from the spacecraft for all mission functions. The transmitter is a high-performance, configurable transmitter design to take advantage of the flexibility and performance offered by modern wireless circuitry, designed to operate in a demanding orbital environment on power-limited spacecraft. The on-board transmitter design allows on-the-fly selection of the data transmission rate, transmission modulation format and automatic, active, RF output power regulation allowing controlled operation over a very wide range of temperatures and link conditions. It requires active UHF uplink to operate in a closed-loop regime with S-band downlink.

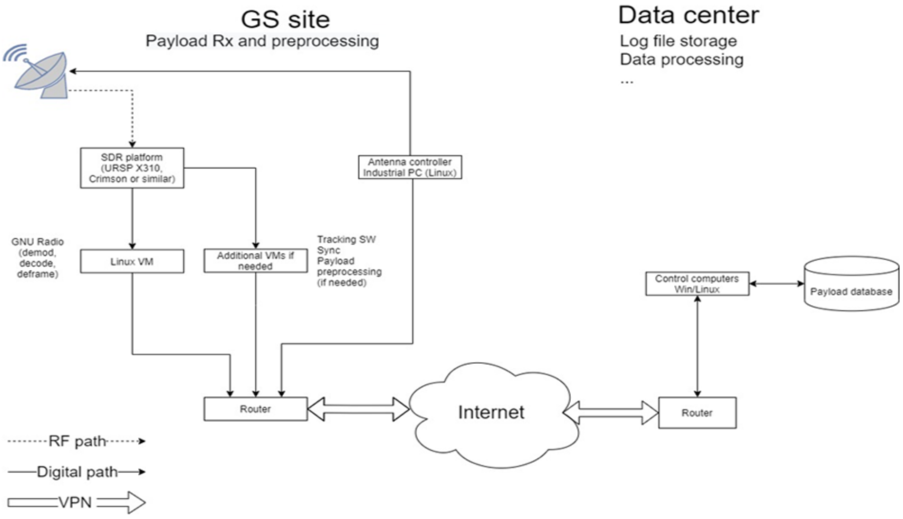


Figure 2. Logical diagram of the ground station system for receiving data.

SPACE-SI ground station system consists of three antennas where UHF and STREAM are located in Ljubljana as presented in Figure 3 while AXYOM is installed in Pomjan near Koper.

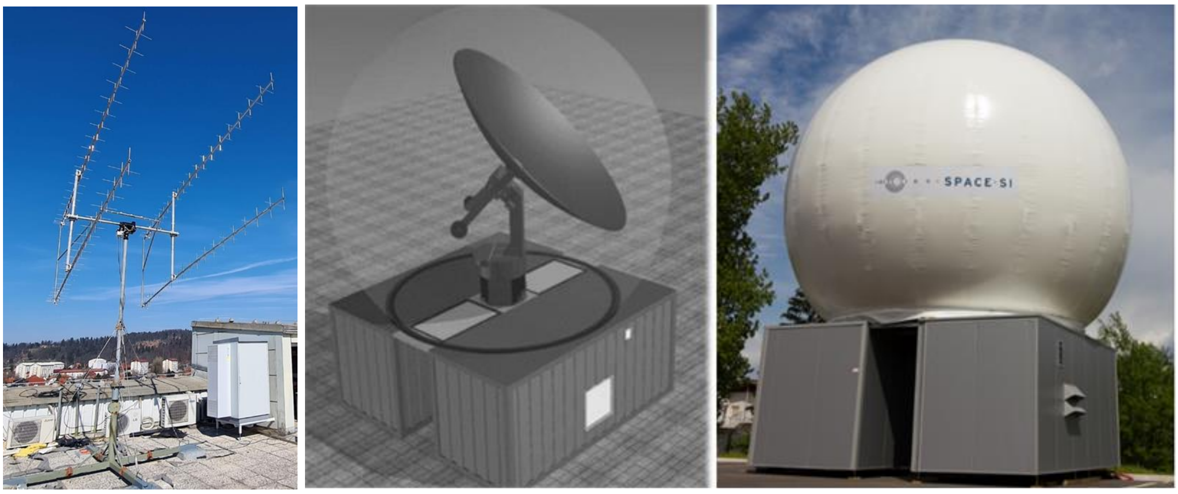


Figure 3. UHF and STREAM antennas located in Ljubljana

SPACE-SI has developed STREAM transportable ground station system for high precision, 3-axis tracking of LEO satellites that can accommodate reflectors of roughly 2.4 m up to 9 m. It employs a new type of positioner with unique geometry developed specifically to maintain the highest degree of tracking accuracies over all possible LEO satellite subtracts.

To enable the high degree of tracking accuracies needed for higher data rate transmissions under all weather conditions, this system is designed to run within a radome, immune from wind loadings and other environmental concerns. By doing so, we can not only provide the best pointing accuracies but also protect the sensitive electronic equipment from rough weather and other environmental conditions like dust, salt etc.

The unique geometry of the system separates this positioner from all others. It is of a three axis X/Y over Azimuth design, but the X axis is slanted at a 45 degree angle to the tangent plane of the earth. The reason for doing this is to move the X axis keyhole away from any operational angle for the Y axis, thus reducing the maximum velocities and accelerations needed by any of the axes. In this system, the Azimuth axis is used to programmatically minimize the Y axis angle displacement from zero. Thus, the X and Y axis are kept as orthogonal as possible, improving auto tracking applications.

The second major innovation is the drive system for each axis. This is a single motor per axis system with almost zero backlash. This is accomplished by cascading two gear reduction systems into each other.

The motors used are another piece of high technology which this system uses to reduce electronics and cost while maintaining the upmost accuracy. The motors are ruggedized, highly integrated servo motors which receive commands over a serial bus and run internal servo loops to maintain pointing accuracies. With integrated encoders and switching logic, they eliminate the need for external electronic hardware. The Antenna Control Unit (ACU) just needs to issue servo commands and monitor feedback from the motors to monitor the positioner. No other control interfaces or hardware is needed.

The Antenna Control Unit (ACU) Software, which enables the positioner to work, can run on just about any modern platform that runs a Red Hat derivative of LINUX.

The ACU is a separate COTS product and isn’t restricted to be used only with a SPACE-SI positioner. It can also be adapted to work on other platforms because of its modular design. By replacing the hardware control module in the software, it can be made to interface with almost any conceivable antenna hardware environment.

SPACE-SI has developed a innovative carbon composite reflector which is much lighter and stiffer than others on the market. With the diameter of 5,4 m it has curvature accuracy below 0,5 mm, making it precise enough to be very efficient up to Ka-band. With only 120 kg weight we believe it to be the lightest dish of this size on the market. It is designed to support prime focus or Cassegrain configurations. The f/D of the dish is 0,4 which is typical for satellite communication applications.

A new radome design developed by Space-SI in cooperation with Slovenian company DUOL brings an ultimate protection to satellite tracking antennas. Its novel design assures minimal signal loss and truly wideband operation. It can operate on frequencies up to 40 GHz without any tuning to a specific band. The technology used to develop this radome has been field proven in other applications and is operating all over the world in the harshest of environments from tropical to arctic. The radome structure is air supported and can withstand the winds of up to 200 km/h (with gusts up to 250 km/h). This is achieved with automatic control of internal air pressure depending on the measured wind speed.

Main technical parameters of the station are:

Dish diameter:	5,4 m
Bands (Rx)	S & X
Radome loss:	< 0.2 dB
Pointing accuracy:	< 0.01 degree
Power (antenna system):	< 1kW
Axial velocity:	
Typical:	0.6 deg/s
Max:	5.0 deg/s
Axial acceleration :	
Typical:	0.05 deg/s^2
Max.:	3 deg/s^2

(a) construction (b) feed

(c) radome

Figure 4. AXYOM antenna located in Pomjan near Koper

2.3 STORM Data Processing Chain

Satellite data processing is performed in the Space-SI mission control centre. Data processing workflow is described below.

- **Parsing and preparation of metadata:** Metadata comes in a binary file with different information about the state of the satellite during image acquisition. An additional XML file is given for each image with basic image information. A parser was constructed that extracts data about the sensor, image properties, and initial values of exterior orientation parameters. The extracted metadata values are date and time of acquisition, rotation of the platform and position of the platform. The extracted metadata is an input for the next steps. However, before it can be used in the geometric model, the initial values of the exterior orientation parameters must be transformed in the coordinate system of the model, which is also the final system of the orthoimage. The initial rotations and positions of the platform enter the model as approximate values of the exterior orientation parameters, which are finally determined in the geometric model. All prepared data and other useful information extracted from the metadata file are stored and passed to the orthorectification step.

- **Convert images to TIFF:** Images comes in a binary format. Before they enter processing, the images are transformed to the TIFF format.

- **Radiometric correction:** The satellite is calibrated and validated, which allows the traceability of satellite sensor data to physical standards.

- **Stacking:** The approach used to improve the SNR is image stacking. To perform image stacking, the payload captures a number of images in rapid succession. When considering the relative velocity between the spacecraft and the earth, only a portion of any two successive exposures overlaps. The rate of capture is calculated such that any given ground area of interest is captured in a sufficient number of exposures, known as the stack depth. The individual exposures are then spatially aligned, or co-registered, by an algorithm which uses the cross-correlation of two images to find an optimum transformation. Values of corresponding pixels are co-added to produce a result with an SNR higher than any of the original images. Because of the differences in optical configuration for the PAN and MS channels, they require different stack depths to achieve the required SNR and thus operate at different frame rates.

- **Prepare multispectral (MS) and panchromatic (PAN) image:** PAN and MS channels require that each channel is co-added independently before orthorectification or pansharpening can take place. In this step two images are generated: MS (composed by 4 (B, G, R, NIR) co-registered bands) and PAN.

- **Orthorectification** is composed by 5 steps:

    - *Ancillary data preparation* – The module deals with the automatic download and preparation of ancillary data. It is basically composed of three distinct parts where each part focuses on a specific product: DTM, roads or reference image.

    - *Road detection* – The road detection algorithm uses the morphological image filtering using the “top-hat” operator of a predefined size, which detects bright road-line candidate segments. It generates a binary mask of road candidates.

    - *Image matching* – The automatic GCP extraction algorithm performs matching of roads detected on satellite image onto rasterized digital vector road data. The main GCP extraction works in three steps: coarse, fine and superfine matching. The output of this step are GCPs equipped with pairs of image pixel coordinates and reference system coordinates, and with attributes describing their quality.

    - *Geometric modelling* – For the geometric modelling a physical sensor model is utilized. The model is solved with a least squares adjustment (LSA) utilizing automatically extracted GCPs. The geometric model computes the exterior orientation parameters. The algorithm also uses two gross error detection procedures.

    - *Orthorectification* – Because of quality and speed, the orthorectification of images is performed with the indirect method. Relief displacement is corrected pixel by pixel, by computing correct pixel’s position within the orthoimage utilizing a DTM and the estimated parameters computed during geometric modelling. The grey value of the pixel is obtained with the bilinear resampling of the neighbouring pixels on the input image.

- **Pansharpening** is a pixel-level fusion technique that increases the spatial resolution of low-resolution MS satellite imagery using high resolution PAN imagery. This is currently the final step of NEMO-HD image processing.

3 NEMO-HD ATTITUDE MODES AND IN-ORBIT RESULTS

We have tested observations in different satellite attitude modes – inertial, target pointing, trajectory tracking and area scanning. All the modes have proven to be very useful as the platform is very stable. Despite its high orbital speed of 7.5 km/s, NEMO-HD enables very precise and stable pointing of the optical payload to the Earth's surface even when observing static targets like airports or mines or when imaging along the coastline or riverbed.

3.1 Inertial Pointing

The inertial pointing mode controls the spacecraft to a fixed inertial orientation, as specified via ground commanded quaternion. Inertial mode is the nominal imaging attitude of the spacecraft. This mode provides the highest stability of the platform as in [1] and allows image stacking which boosts the amount of collected light and improves the SNR. To perform image stacking, the payload captures a number of images in rapid succession. When considering the relative velocity between the spacecraft and the earth, only a portion of any two successive exposures will overlap. The rate of capture is calculated such that any given ground area of interest is captured in a sufficient number of exposures, known as the stack depth. The individual exposures are then spatially aligned, or co-registered, by an algorithm which uses the cross-correlation of two images to find an optimum transformation. Values of corresponding pixels are co-added to produce a result with an SNR higher than any of the original images. This process is illustrated in Figure 5.

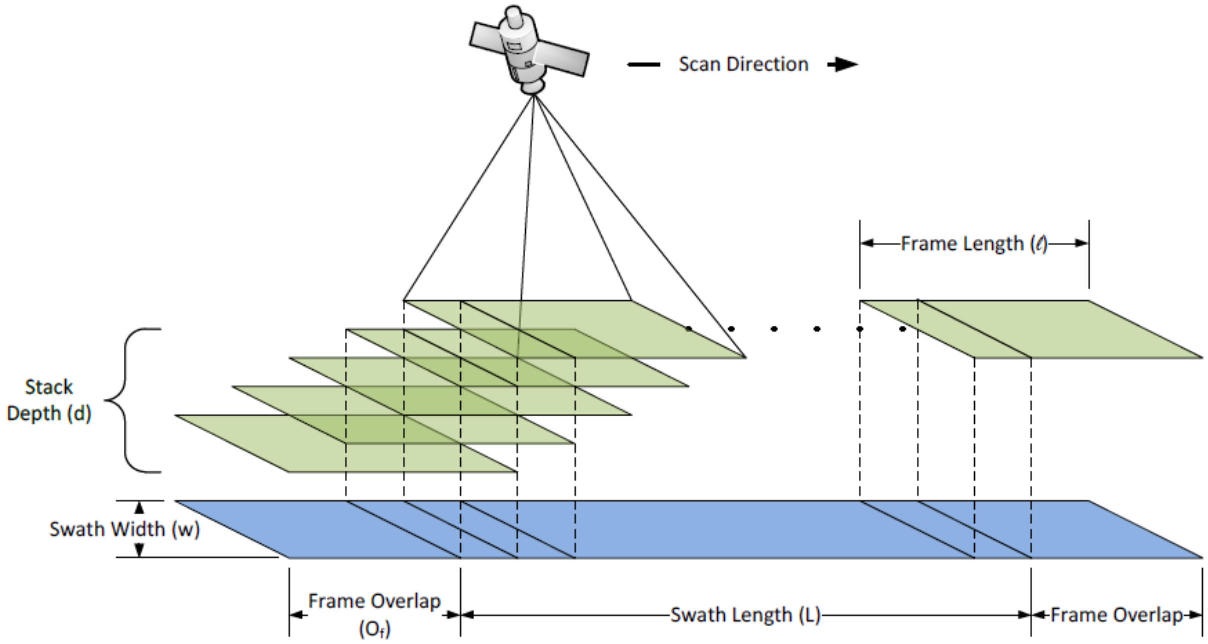


Figure 5. Observation sequence for image stacking

Radiometric analysis shows that an SNR around 75 can be achieved with a stack depth of 5 on the HRS-PAN channel, and 12 on the HRS-MS channels. Instrument is capable of single frame observations, as well as for the stack depths mentioned above.

Figure 6. Stacked NEMO-HD RGB image of Salon de Provence in France captured in inertial attitude mode.

3.2 Ground Point Targeting

In the target pointing attitude the satellite is imaging the same point on the earth up to a few minutes during the flyover. This method is especially useful when shooting high resolution video, as we can monitor various activities on land, at sea, in ports, airports etc. Tests have shown that the satellite can easily record the same point on the earth for 5 minutes, but during such long observations the observation angle changes a lot. With an off-nadir observation angle the image resolution is decreasing. For viewing angles lower than 30° the GSD reduction is up to 30% and target tracking observation shall not be longer than 80 seconds.

Figure 7. Observation geometry in the middle (upper left) and at the end (bottom left) of 5-minutes long observation with target pointing. On the right side there are NEMO-HD images taken in such satellite positions. Images are of Havana, Cuba.

3.3 Predefined Trajectory Tracking

We have developed an algorithm for tracking and scanning any trajectory on the Earth's surface. The satellite follows a certain sequence of points along the predefined path, so it can capture line objects or systematically scan an area wider than the imaging swath width with several parallel swaths. The path (e.g. river, road, powerline, etc.) that the satellite shall follow is described with the minimum number of points, so that the distance between any part of the object of interest and the conjunction line between two consecutive trajectory points is smaller than half the width of the recording band. When planning observations, we consider the position of the satellite, the viewing angle, the position of the area of interest with respect to the satellite's orbit, and the distances between individual points of the trajectory.

The trajectory tracking algorithm was tested by tracking the rivers Sava and Neretva. Sava flows 990 km almost perpendicular to the satellite orbit. We managed to scan the whole river sequentially in 5 flyovers. Figure 8 shows the Sava River as recorded by NEMO-HD. All five individual sections are stacked together.

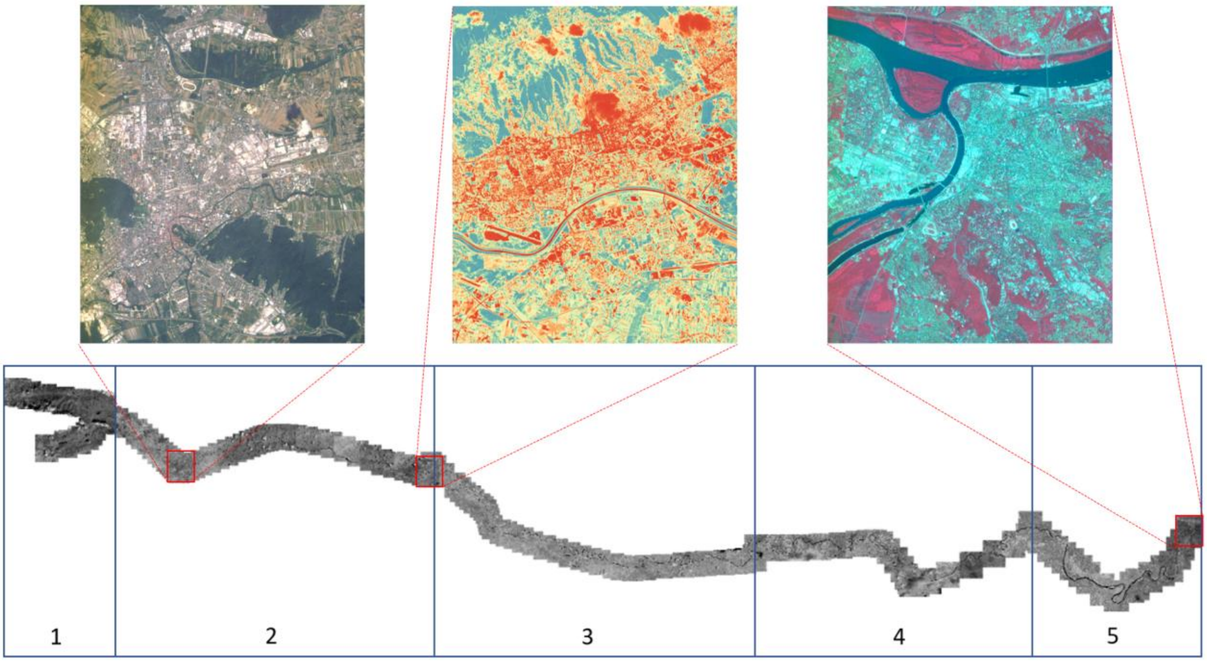


Figure 8. NEMO-HD images of Sava River from its both sources to its confluence with river Danube in Belgrade, Serbia. Marked are five segments of continuous imaging. Emphasised are individual images of Ljubljana (left, true colour), Zagreb (middle, NDVI) and Belgrade (right, false colour).

The entire Neretva River (225 km) from its source to its outflow into the Adriatic Sea was imaged in one orbit, in 70 seconds. While imaging, the satellite followed a 7-point trajectory along the river. The trajectory and the result of the imaging in the NIR channel are shown in Figure 9.

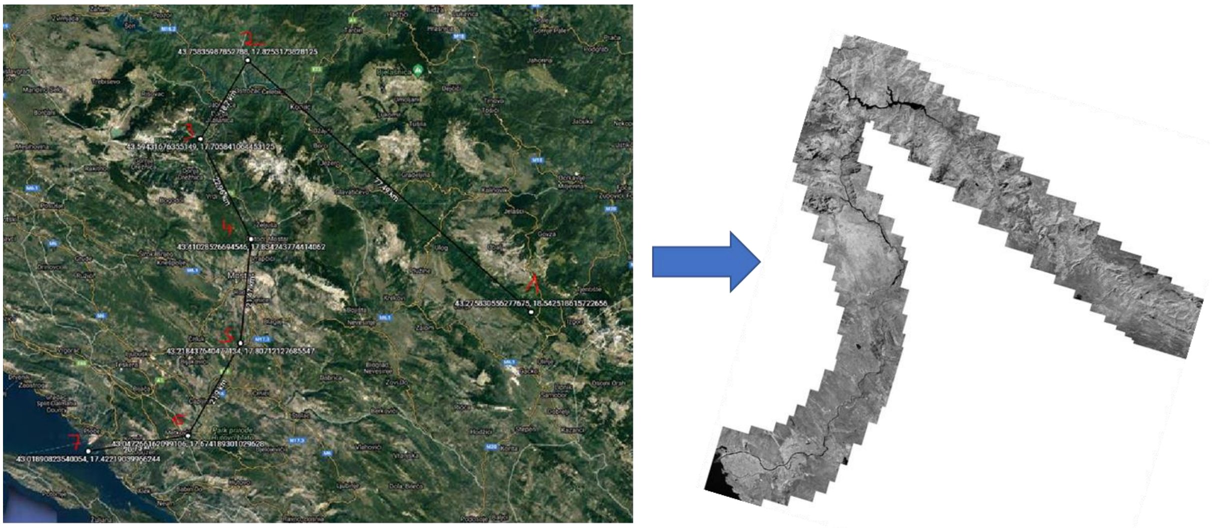
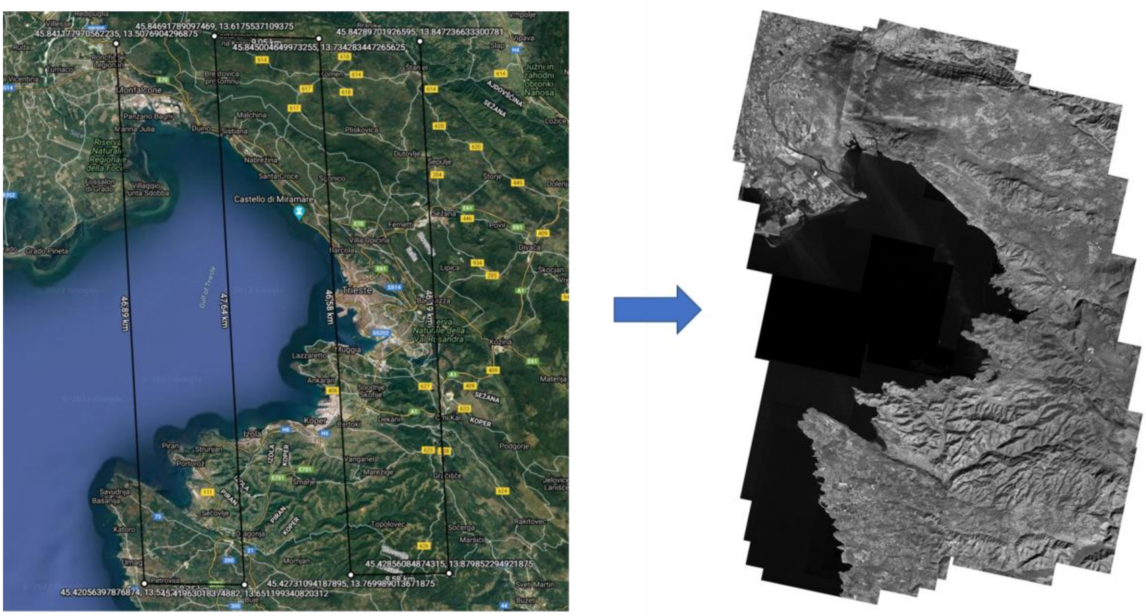


Figure 9. A 7-point trajectory along Neretva River (left) and NEMO-HD images of Neretva River from its source in Dinaric mountains to its outflow in the Adriatic Sea (right). All images were taken within 70-second-long imaging from one orbit.

3.4 Area Scanning

To test the algorithm for area scanning we performed test observations with imaging in several parallel swaths from a single orbit. The principle of area scanning is the same as for the trajectory tracking. The satellite follows the pre-set trajectory of points that are distributed to represent several slightly overlapping parallel swaths. The maximum length of parallel swaths depends on their number and vice versa – the more parallel swaths we want to make within one orbit, the shorter they should be as the observation time is limited to 80 seconds to keep the observation angle smaller than 30°. When scanning areas, the distance between adjacent swaths should be narrower than the recording bandwidth of the selected sensor to ensure that the images overlap and that there are no holes between images. An example of area scanning is presented in Figure 10 for the Primorska region in Slovenia with four parallel swaths.



(a) (b)

Figure 10. Area scanning observation: (a) trajectory and (b) the images in NIR channel taken within 90 second observation following this trajectory.

4 VIDEO FROM SPACE

The GNC capabilities of NEMO-HD have been successfully tested in-orbit also by video acquisitions in ground point and trajectory targeting modes presented in Figures 11 – 14 for which corresponding videos are available on the SPACE-SI web page ([2]).

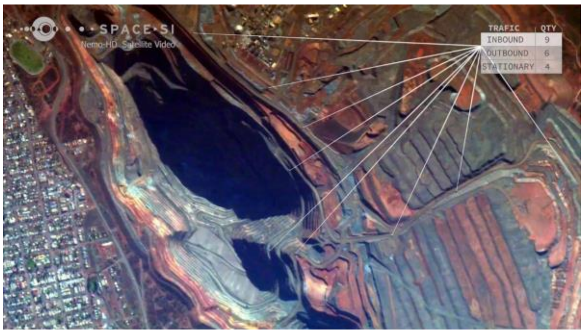


Figure 11. Video analytics of gold mine in Australia - monitoring the economic activities.

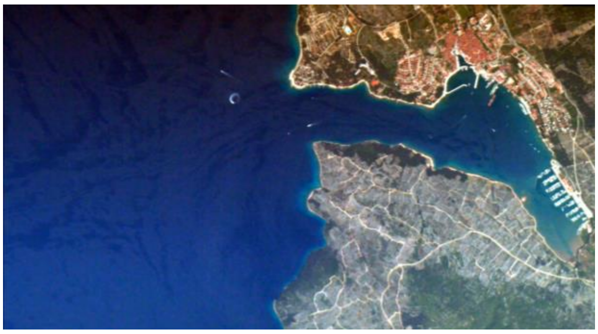


Figure 12. NEMO-HD video from space - maritime traffic in the port of Cres.

Figure 13. NEMO-HD video along the Slovenian coastline.

Figure 14. Monitoring of the Port of Koper in cooperation with Slovenian Maritime Administration.

5 FUTURE PROSPECTS

The in-orbit test results of NEMO-HD microsatellite and SPACE-SI ground segment enable further development of advanced EO applications including low latency and real-time remote sensing services. The concept of transportable ground station system STREAM strongly supports the development of such services and SPACE-SI is in the process of preparing a technology demonstration case in collaboration with Slovenian Maritime Administration.

SPACE-SI is also developing efficient methods for 3D shape determination of clouds where pre-parameterized representative volumes of cloud formations are scanned by agile satellite acquisitions from different angles and then processed on-board to efficiently produce information in space in order to minimise on-board storage as well as data download requirements per observed area. This will enable climatologists to obtain valuable information for more realistic modelling of 3-D cloud-radiative effects in a cost-effective way.

6 CONCLUSIONS

The in-orbit tests results demonstrate that NEMO-HD is a very reliable, agile and precisely guided microsatellite for Earth observation and monitoring by combining multispectral and video sensors. The examples of satellite video show that despite the high orbital speed of the platform, NEMO-HD enables very stable pointing of sensors to observe movements in stationary scenes such as cities, ports, airports, open mines and other areas of interest for video analytics. All videos presented in this paper are without time and geometric corrections, which proves the very high GNC performance of the satellite. In addition to that the remote sensing platform can scan the Earth's surface along trajectories that follow seashores, river basins, roads, railways, powerlines, etc in both along and cross track directions. Since high- and low-resolution video sensors can be turned on in sequence or simultaneously, NEMO-HD enables combined remote sensing at micro and macro levels which improves situational awareness for observed phenomena. A further advantage of the NEMO-HD satellite is that video can also be combined with multispectral imaging in the red, blue, green and near-infrared spectra. All above mentioned satellite features together with transportable ground station performances offer great potentials for developing new multi-purpose remote sensing applications including advanced low latency and real time EO services.

7 REFERENCES

[1] Roth, N., Johnston-Lemke, B., Handojo, N., Grocott, S., Zee, R., Rodič, T., Urbas, A., Bošnak, M. *Flight Results of the Attitude Determination and Control System for the NEMO-HD Earth Observation Microsatellite*, in 35th AIAA/USU Conference on Small Satellites, Logan, Utah, 2021.

[2] http://www.space.si/mikrosatelit/nemo-hd-dosezki-v-prvem-letu-od-izstrelitve/