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The NEMO HD attitude determination and control system: Experimental mode

S. Blažič*, D. Matko, M. Bošnak**,G. Klančar*, G. Mušič***

**University of Ljubljana, Faculty of Electrical engineering, Tržaška 25, SI-1000 Ljubljana, Slovenia*
(Tel: +386-1-4768-763; e-mail: saso.blazic@ fe.uni-lj.si).
***SPACE-SI, Aškerčeva 12, SI-1000, Ljubljana, Slovenia*
(e-mail: drago.matko@space.si)

Abstract: The paper describes the experimental ADCS mode of the NEMO-HD satellite, built in the co-operation between SPACE-SI and Space Flight Laboratory, University of Toronto. In the experimental ADCS mode several imaging modes will be implemented such as fixed target observation, path tracking target observation, area sweep mode and spread area sweep mode. A Matlab-Simulink based simulator was designed, which accurately incorporates the astrodynamics and the kinematics of the satellite in real time. It also provides the images of the observed target by means of the Active-X connection to the Google Earth. The results of simulations demonstrate the applicability of the proposed imaging modes to be implemented on the NEMO-HD satellite, which is planned to be launched in 2015.

1. INTRODUCTION

The NEMO-HD satellite is being built in the co-operation between SPACE-SI and Space Flight Laboratory, University of Toronto (Pranajaya, 2012). The primary objective of the mission is to provide high resolution multispectral imagery and high definition video. Besides standard modes of the Attitude Determination and Control System (ADCS), such as safe, passive, detumble, Sun pointing, data download (nadir-tracking), remote imaging, and real-time imaging, that cover all expected operational cases, also an experimental mode is foreseen. In this mode, the operation team selects the desired Earth-observation target(s) manually and defines the reference for the control algorithm shortly before the over-flight of the satellite. The experimental ADCS mode will be able to perform several imaging modes, which will be described in the paper. Some of the imaging modes discussed in the paper have been introduced in Cutter et. al. (2007) and Cawthorne et al. (2008). An optimization of consecutive imaging was presented in Somov et al. (2013). However, in the cited works only the reference trajectories were derived. The novelty in our approach is the introduction of the feed-back algorithm which considers also disturbances and limited dynamic behaviour to be present in real applications. The paper is organized as follows: In Section 2 the mission objectives are briefly summarized, Section 3 presents the essentials of the experimental mode while the simulated results are given in Section 4.

2. THE MISSION OBJECTIVES

SPACE-SI has an interest in small satellite technologies that enable precise manoeuvring of a spacecraft in high-resolution interactive remote sensing flights. For this purpose a 70 kg class microsatellite for Earth monitoring and observation is being developed in collaboration with the Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies. The satellite, shown in Fig.1, will have a Ground Sampling Distance (GSD) of 2.8 m from a design altitude of 600 km. It will carry two optical instruments: a narrow-field instrument as well as a wide-field instrument. The narrow-field instrument will achieve 2.8 m GSD in panchromatic and 5.8 m in four spectral bands corresponding to Landsat-1, 2, 3, and 4 spectral bands (450-520 nm, 520-600 nm, 630-690 nm, and 760-900 nm). The wide-field instrument will have a 40 m GSD. Both instruments are capable of recording High-Definition video at 1920 by 1080 pixels. The spacecraft will be capable of performing global imaging and real-time video streaming over Slovenia and other regions where it will be in view of a properly sized and equipped ground control station.

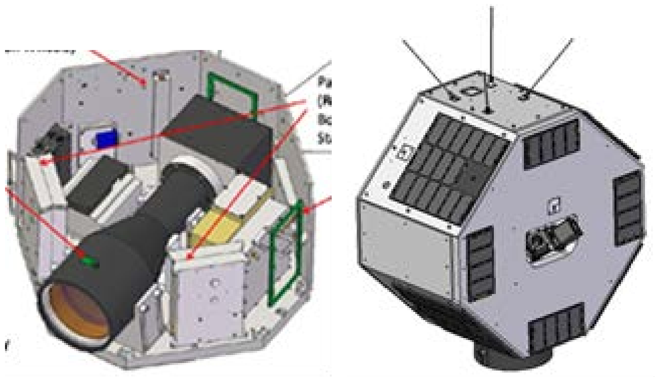

Fig. 1. The NEMO HD Satellite

In addition, the spacecraft will also be capable of performing remote global observations constrained only by on board storage management. The microsatellite will include the standard complement of subsystems, sensors and actuators that make up a three-axis stabilized bus with a 50 Mbps X-band downlink, 128 GB of on-board storage, a high-performance instrument computer, and a power system generating nearly 90 W at end-of-life with a 100 Wh Li-ion battery. The spacecraft is equipped with a variety of sensors providing both coarse and fine attitude determination accuracy throughout the operational phases of the mission. The coarse sensors are: a three axis magnetometer, six fine sun sensors, and a three-axis rate sensor. Two star trackers provide the precise attitude information. The coarse sensors have the attitude determination accuracy (1-σ) of roughly 2.8 degrees, while the two star trackers enable the accuracy of 15 arc seconds. One three-axis MEMS rate sensor with a nominal accuracy of about 0.1 degrees/sec is also provided. Three reaction wheels with a maximum torque output of about 5 mNm are used to actuate the spacecraft (Pranajaya, 2012).

3. THE ADCS EXPERIMENTAL MODE

The experimental ADCS mode is an extension of the remote and the real-time imaging modes, which are two standard modes of the NEMO HD. In the standard modes, the satellite has a fixed orientation in the inertial frame. In the experimental ADCS imaging modes, the orientation of the satellite is adjusted to the desired surveillance targets, which represents a challenging task to the satellite attitude control.

There will be two ways of the ADCS experimental mode application:

- off-line, where there will be no direct contact between the ground station and the satellite, and
- on line real-time, where the contact between the ground station and the satellite will be established.

In the off-line ADCS mode, the scenario will be uploaded within the latest contact of the satellite and the ground station; the images will be recorded and downloaded during contacts to follow. The possibility of store-and-forward videos is under investigation with respect to computer power limitations. In the on-line real time ADCS mode the desired scenario will be uploaded right after the satellite to ground station contact will be established; the video and the imaging sequence follows immediately and the recorded data is downloaded in real time. This mode is an interactive mode, which means that the on-ground target can be adjusted during the imaging. However the duration of the recording is limited by the duration of the satellite-ground station contact.

3.1 The imaging modes

The imaging modes to be implemented in both modes are:

- Fixed target observation – the satellite is oriented towards a fixed point on ground.
- Path tracking target observation – the satellite's orientation follows a predefined path on ground.
- Area sweep mode – the satellite's view of sight is sweeping a predefined area on ground.
- Spread area sweep mode – the satellite's orientation is sweeping several predefined areas on ground, which, however, cannot be wide apart.

In the real-time on-line mode the fixed target can be modified by the operator according to the surveillance demands. The path tracking and the area sweep modes can be interrupted interactively – the mode is then switched to the fixed target one.

3.2 Mono and Stereo modes

All modes can be executed either in a standard (mono) or in a stereo technique. In the stereo technique the same target is observed twice during the same over-flight (along-track): firstly while the satellite is approaching the target, and secondly during its retreat. The optimal imaging angle of stereo-pair acquisition is ±20 degree in the flight direction, which corresponds to the baseline to height ratio (B/H) of approx. 0.75.

4. THE SIMULATOR AND RESULTS OF THE SIMULATIONS

A Matlab-Simulink based simulator was designed, which accurately incorporates the astrodynamics and the kinematics of the satellite in real time. It also provides the images of the observed target by means of the Active-X connection to the Google Earth. Figure 2 represents the simulator set-up.

The NEMO HD satellite is equipped with two camera payloads: a primary with 10.8 km swath for the panchromatic and multispectral channels and a secondary with a swath of 40km. Both payloads are HD video capable. As for the primary video only a section of the corresponding size is taken, the swath of the primary video is 5.35 km. All optical payloads and their modes are simulated in the simulator.

It should be noted that precise geodetic maps (enabling precise definition of targets to be observed) are implemented only for Slovenia. The results of the simulation for different imaging modes will be given next.

4.1 Fixed target observation

Fig. 3 shows the simulated secondary payload image of the Tokyo area as the fixed target. The satellite trajectory is depicted on the left side of the picture; the image (in the simulation obtained by Google Earth) can be seen on the right. More detailed snapshots are obtained with the primary payload camera, especially in its video mode. In Fig. 4 the Tokyo area as seen by the simulated primary video payload is depicted.

However due to changing perspective, the surveillance area is changing its shape, as depicted in Figures 5, 6, 7, 8, and 9. In Figs. 5 and 6, the case is shown where the target (Ljubljana in this case) lies close to nadir. In Fig. 5 the satellite path over

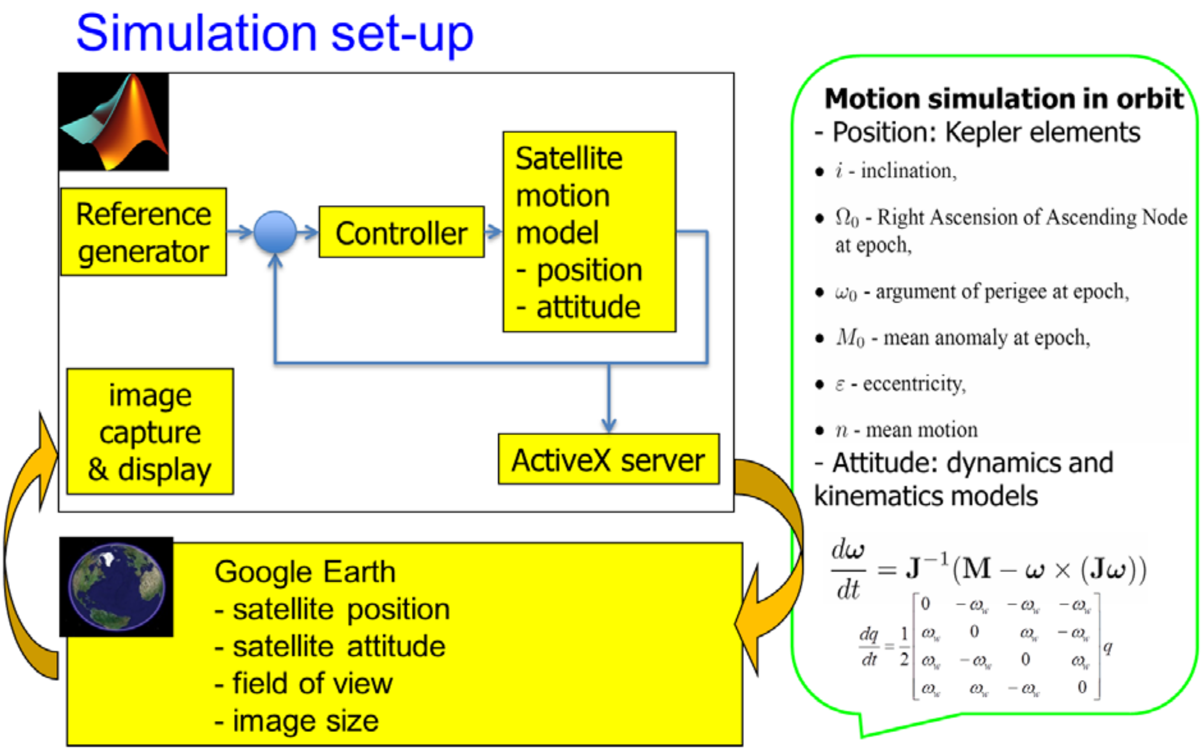

Fig. 2. SPACE-SI Earth Observation Experimental Mode Simulator: Simulation set up

Fig. 3. Tokyo area as seen by the secondary payload

Fig. 4. Tokyo area as seen by the primary video payload

Europe is presented while Fig. 6 depicts the corresponding observation areas for this case. For clarity reasons only one frame within 15 seconds is shown.

In Fig. 7 the case of two observation windows (also for Ljubljana) is shown. As it can be seen in Figs. 8 and 9, the corresponding surveillance areas are stretched due to high tilt. In the on-line fixed target observation mode the operator is capable to redefine the centre of the observation area by clicking the desired point on the screen. In this way some inaccuracy in the two line elements of the satellite path can be corrected.

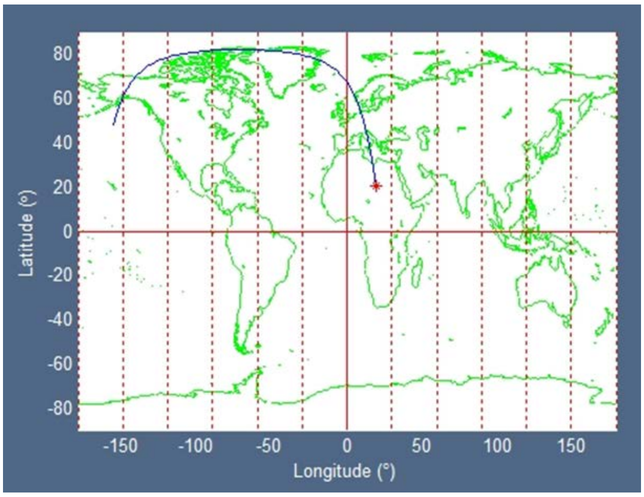

Fig. 5. The satellite path over Europe with Ljubljana close to nadir

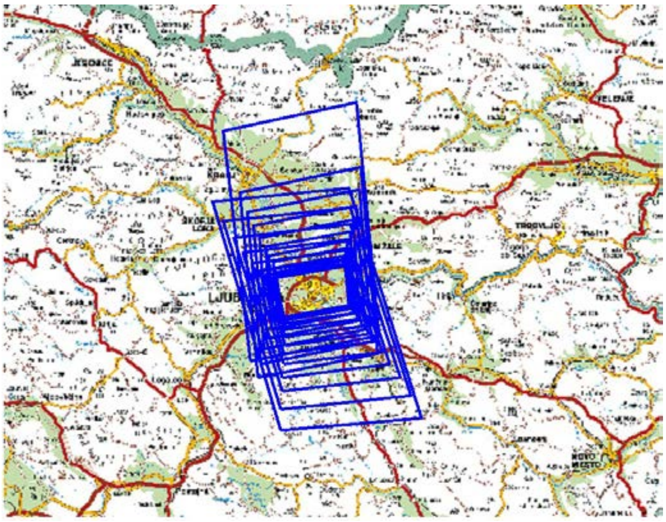

Fig. 6. Surveillance areas due to changing perspective for the case of the target (Ljubljana) close to nadir

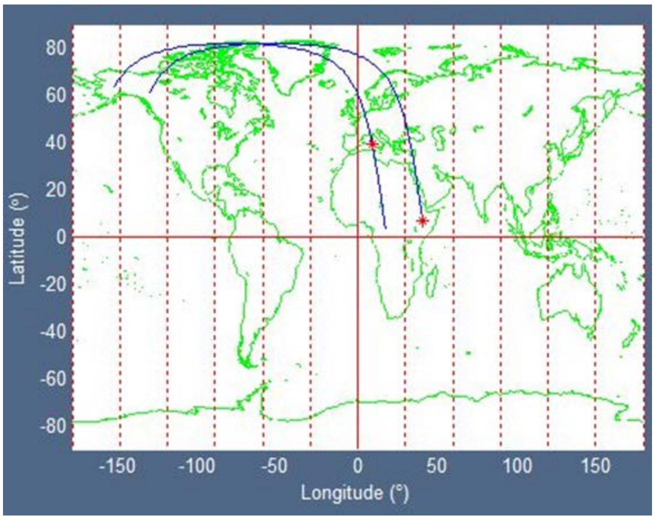

Fig. 7. The satellite path over Europe with two observation windows for Ljubljana (high tilt)

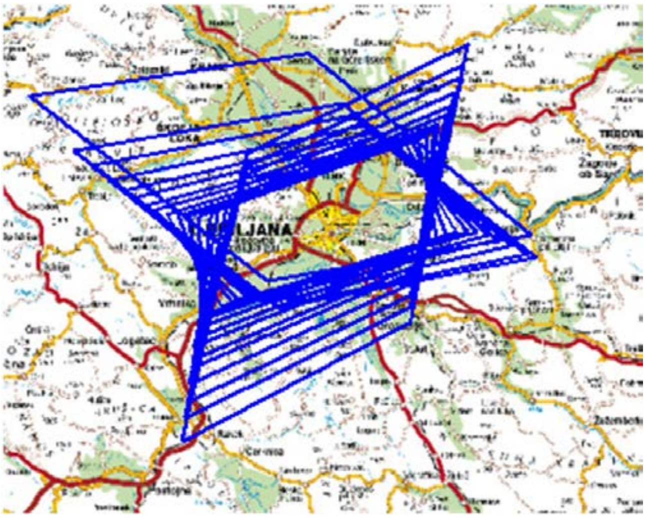

Fig. 8. Surveillance areas due to changing perspective for the high tilt case of the target (Ljubljana) – first observation window

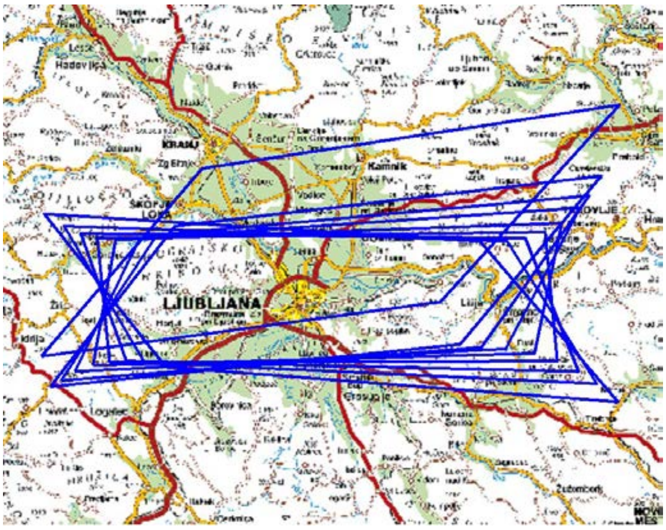

Fig. 9. Surveillance areas due to changing perspective for the high tilt case of the target (Ljubljana) – second observation window

The operator is also capable to switch the source of video imaging between primary and secondary payload optics as well as trigger the high resolution still (multispectral and panchromatic) images. It should be pointed out that the simulator simulates the satellite feedback control algorithm and that the displayed surveillance areas are determined by the actual orientation of the satellite rather than the desired ones, which are obtained during the mission design phase.

4.2 Path tracking target observation

In this mode the satellite tracks a predefined path on Earth, which is determined by clicking the points on the map during the path design phase. The velocity of the observation point movement on ground is determined by the duration of the observation window and by the density of path defining points: the time intervals between consecutive points are equal. In this way the movement of the observation point can be made slower by entering more points on the desired segment of the observation path. The operator is capable of stopping the path tracking and switching to the fixed target mode if something interesting is caught in his sight. In Fig. 10 a path (historical railway Ljubljana-Trieste) is shown together with corresponding observation areas which are changing due to changing perspective due to the satellite motion.

4.2 Area sweep mode

Area sweep mode is an efficient way to cover larger areas during one overfly of the satellite. In the standard strip mode only a narrow strip determined by the optical instrument swath can be recorded; the area sweep mode enables several strips to be pasted together and so virtually increase the swath without reducing the ground sampling distance resolution. However the demand on the attitude determination and control equipment is much higher. In the standard strip mode, the satellite is oriented in a constant orientation in the inertial

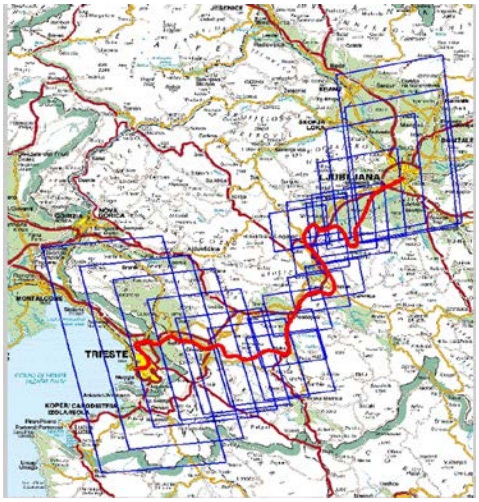

Fig. 10. Path tracking mode: historical railway Ljubljana-Trieste (red line) and corresponding observation areas (blue frames)

system. It is in the steady state, which can be obtained during the settling time of the satellite attitude. In the area sweep mode however there is no steady state; the satellite orientation is changing continuously while the observation areas sweep the ground as shown in Fig. 11. In order to cover entire area, the individual strips have to overlap and as the control algorithm is not perfect (some oscillations appear as shown in Fig. 12 showing three distinguished strips), the overlapping must be sufficient. This effects and changing perspective of the individual shots put very high demand on the post-processing procedures. In Fig. 13 a detail of turning the sweep direction is given. The red and blue frames correspond to the taken and skipped images respectively.

4.3 Spread area sweep mode

The spread area sweep imaging mode is similar to the area sweep mode; the only difference is that in this mode several (smaller) areas may be observed during a single overfly of the satellite. As seen in Fig. 14, the demand on control algorithm in this mode is much higher than in the other modes. Figs. 15 and 16 depict the Euler angles errors for all four (fixed target, path tracking, area sweep and spread area sweep) modes. It can be seen that in the fixed target mode

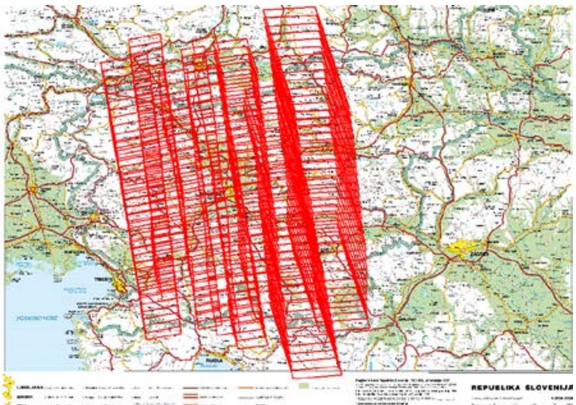

Fig. 11. Area sweep mode consists of parallel overlapping strips

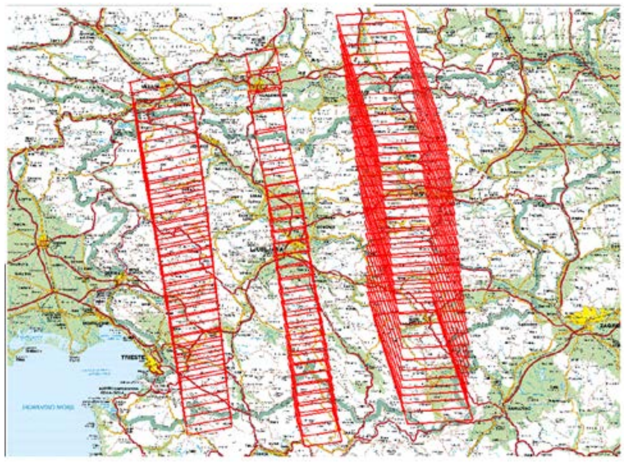

Fig. 12. Area sweep mode: a detail (3 distinguished parallel strips)

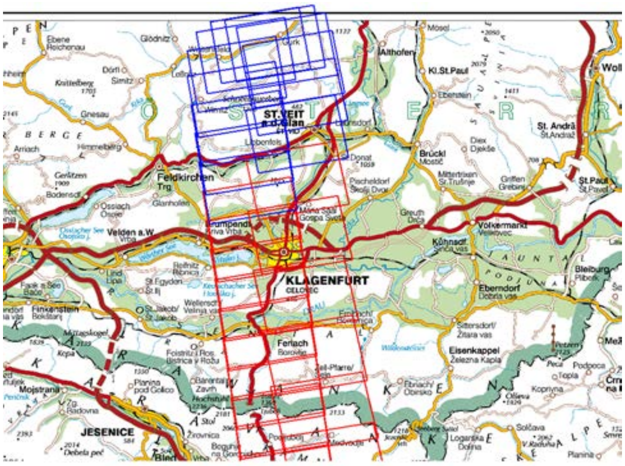

Fig. 13. Area sweep mode: a detail of turning the sweep direction; red frames – images taken; blue frames – no images taken

maximum error is below 10 arc seconds (corresponding to 1.7 km at 600 km altitude), while in the spread area sweep mode becomes 160 arc seconds (corresponding to 28 km at 600 km altitude).

4.3 Stereo mode

All imaging modes can also be performed in stereo mode. In this mode the entire scenario is repeated twice: forward and backward looking. In Fig. 17 the stereo pair of the Tokyo skyscraper area is show.

5. CONCLUSION

In the paper the NEMO HD ADCS experimental imaging modes for interactive surveillance were described. In the fixed target imaging mode the operator has the possibility to change the inspected target interactively. The path tracking mode enables surveillance of targets along a predefined path. Area sweep and spread area sweep modes enable much broader coverage during a single overfly of the satellite. However they also put very high demand on ADCS system and post-processing software.

A Matlab-Simulink based simulator was developed which takes into account real environmental conditions an ADCS has to cope with. The simulator accurately incorporates the astrodynamics and the kinematics of the satellite in real time. It also provides the images of the observed target by means of the Active-X connection to the Google Earth. Results of simulations illustrate the described imaging modes.

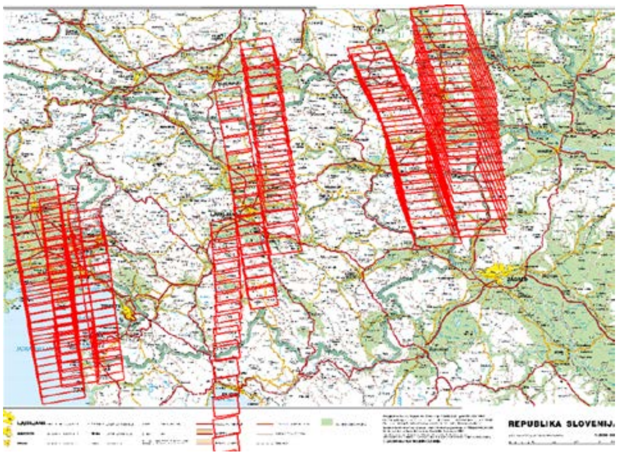

Fig. 14. Spread area sweep mode: demand on control algorithm is high

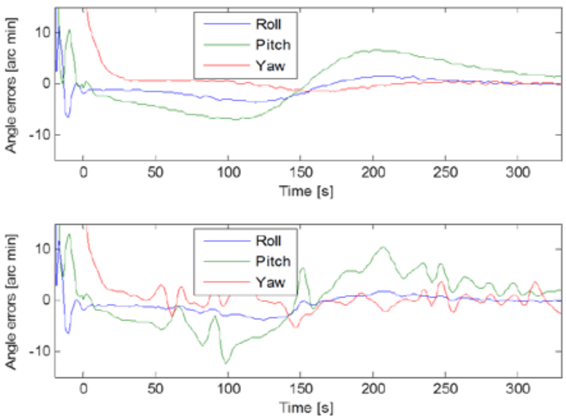

Fig. 15. Euler angle errors: fixed target (upper) and path tracking (lower)

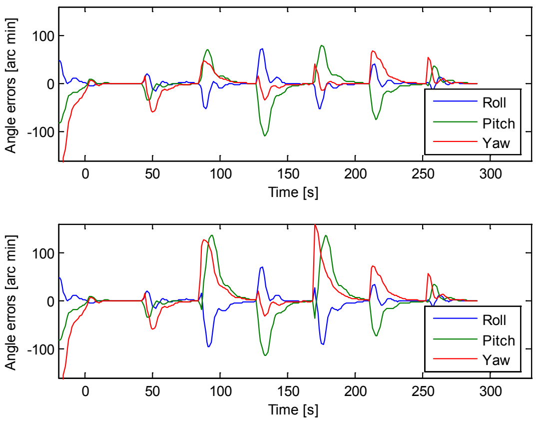

Fig. 16. Euler angle errors: area sweep(upper) and spread area sweep (lower)

NEMO HD is currently in the final assembling stage and is scheduled for launch in 2015. The described simulator will be used for developing the on-board software. We hope that the real experiment will confirm the simulated result and that the on line interactive surveillance will become a daily routine.

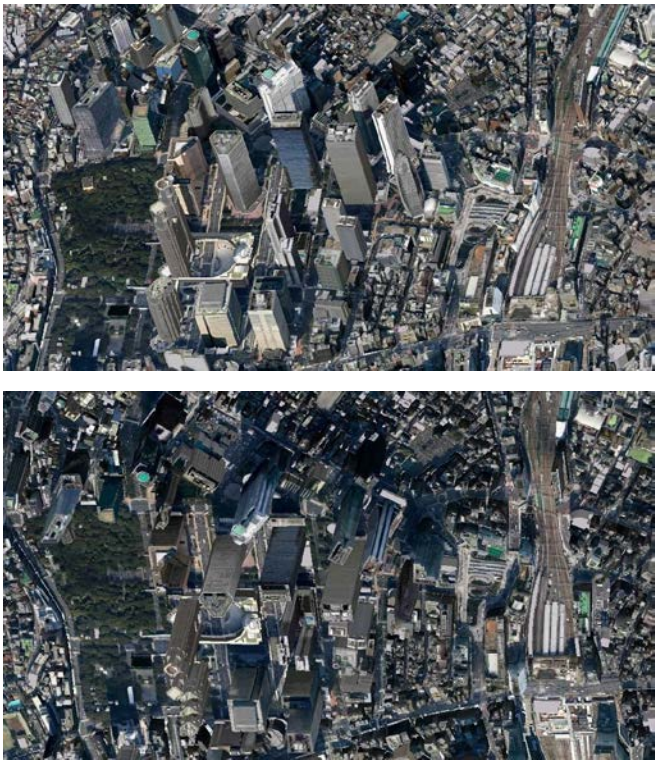

Fig. 17. Along-track stereo-pair (upper: forward looking, lower backward looking) of the Tokyo Shinjuku area

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