

NEMO-HD: HIGH-RESOLUTION MICROSATELLITE FOR EARTH MONITORING AND OBSERVATION

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ABSTRACT

The Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies, in collaboration with the Slovenian Centre of Excellence for Space Sciences and Technologies (SPACE-SI), is developing a 40 kg microsatellite for earth monitoring and observation that is capable of resolving a Ground Sampling Distance (GSD) of 2.8 m from a design altitude of 600 km. NEMO-HD (Nanosatellite for Earth Monitoring and Observation - High Definition) is the second spacecraft that is based on SFL's high-performance NEMO bus and builds upon the heritage of SFL's flight-proven Generic Nanosatellite Bus (GNB). NEMO-HD will carry two optical instruments: a narrow-field instrument as well as a wide-field instrument. The narrow-field instrument will be capable of resolving 2.8 m GSD in four channels corresponding to Landsat-1, 2, 3, and 4 spectral channels (450-520 nm, 520-600 nm, 630-690 nm, and 760-900 nm). The wide-field instrument will be capable of resolving 75 m GSD or better. 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 the ground station. In addition, the spacecraft will also be capable of performing remote observations. NEMO-HD will include the standard complement of subsystems, sensors and actuators that make up a three-axis stabilized NEMO bus. NEMO-HD will be enhanced to include a 50 Mbps X-band downlink, 128 GB of on-board storage, a high-performance instrument computer, and a power system generating 31 W at end-of-life with a 130 W-h Li-ion battery. The paper provides an overview of the NEMO-HD system design.

INTRODUCTION

NEMO-HD (Nanosatellite for Earth Monitoring and Observation – High Definition) is a spacecraft under development at the Space Flight Laboratory (SFL) at the University of Toronto Institute for Aerospace Studies. The 40 kg spacecraft is based on SFL NEMO bus technology and is equipped with a high-resolution, 7-channel optical payload. This development program is being undertaken by SFL in collaboration with the Slovenian Centre of Excellence for Space Sciences and Technologies (SPACE-SI).

Primary Mission Requirements

The primary mission requirements for NEMO-HD can be summarized as follows¹: The spacecraft is to capture still images at 2.8 m Ground Sampling Distance (GSD) with a swath of 10 km from the reference orbit. The still images are to be captured at four spectral bands: 450-520 nm, 520-600 nm, 630-690 nm, and 760-900 nm. These images are to be captured with a

minimum Signal to Noise Ratio (SNR) of 75, assuming a 30% target reflectivity. The optical system is required to have a minimum Modulation Transfer Function (MTF) of 0.10.

The reference orbit is 600 km Sun synchronous orbit with 10:30 local time of ascending node (LTAN). The reference orbit results in an average of three passes during day time and three passes during night time over Slovenia.

In addition to the high-resolution still image capture capability, the spacecraft is to capture color HD (1080p) movie at two resolutions: high resolution at 2.8 m GSD and low-resolution at 75 m (or better) GSD. Both resolutions shall include H.264 compression.

The captured still images and movies are to be downloaded via X-band up to speeds of 50 Mbps. The required data rates for command uplink and telemetry downlink are 4000 bps and 8000 bps, respectively.

The required mission lifetime is one year in the reference orbit.

INSTRUMENT DESIGN

In order to meet the challenging imaging requirements, NEMO-HD will implement two instruments: primary and secondary. The primary instrument will be responsible for capturing the narrow-field, high-resolution images and movies. The secondary instrument will be responsible for capturing the wide-field, low-resolution movies.

Primary Instrument Characteristics

The primary instrument will implement six channels:

- High-Resolution High-Definition (HR-HD), 400-900 nm
- High-Resolution Still Panchromatic (HRS-PAN), 400-900 nm
- High-Resolution Still Multi-Spectral 1 (HRS-MS1), 450-520 nm
- High-Resolution Still Multi-Spectral 2 (HRS-MS2), 520-600 nm
- High-Resolution Still Multi-Spectral 3 (HRS-MS3), 630-690 nm
- High-Resolution Still Multi-Spectral 4 (HRS-MS4), 760-900 nm

HR-HD will capture an HD 1080p movie at 2.8 m GSD with an RGB detector. HRS-PAN will capture a high-resolution panchromatic channel (400-900 nm). Dichroic filters are used to perform the spectral separation of the incoming light into the four required separate bands. Each of the four spectral bands (450-520 nm, 520-600 nm, 630-690 nm, and 760-900 nm) has been designed with a 5.7 m GSD. The panchromatic channel will be used to sharpen the multispectral image to the required 2.8 m GSD.

At the time of this writing, the preliminary design of the primary instrument has been completed, and the effort to manufacture the first breadboard prototype is ongoing. The first imaging results from the breadboard prototype instrument are expected to be available in mid-summer 2012. The instrument will have a focal length of 360 mm. The primary instrument has been designed to achieve a GSD of 2.8 m and a swath width of 10.8 km from the reference orbit. Optical simulations of the breadboard prototype instrument shows an MTF value that is better than 0.20 at the required resolution.

Primary Instrument Signal to Noise Ratio

Table 1 below outlines the SNR performance of the primary instrument. The SNR calculation assumes a

184 micro-second exposure time, a minimum overall optical system transmissivity of 65%, and 30% target reflectivity. The SNR requirement is 75.

Table 1: Signal-to-Noise Performance

Channel	Spectral Band	SNR
HRS-PAN	400-900 nm	75.3
HRS-MS1	450-520 nm	89.5
HRS-MS2	520-600 nm	105.5
HRS-MS3	630-690 nm	85.4
HRS-MS4	760-900 nm	76.0

Secondary Instrument Characteristics

The secondary instrument will be implemented to capture the Low-Resolution High-Definition (LR-HD) movie at 1080p format using an RGB detector. A telescope with a focal length of 50 mm has been baselined for the secondary instrument. This optical setup will result in a GSD of 39 m from the reference orbit. Additional optimization of the secondary instrument may be performed during the detailed design phase.

Instrument Electronics

The primary instrument and the secondary instrument on NEMO-HD will have a total of seven channels. The output from these seven detectors will be connected into a high-speed flash-based data recorder. It is expected that the data recorded will have a storage capacity of 128 GB.

SYSTEM DESIGN

Operations Concept and Operations Modes

NEMO-HD will have the following nominal operations modes: Real Time Imaging, Remote Imaging, and Data Downlink Modes.

Real Time Imaging Mode (RTIM) requires that the spacecraft is in view of a ground station. In this mode, the operations team can directly control the spacecraft operations in real time, and the image data will be downloaded in real time. This mode includes the real time streaming video from the primary or secondary 1080p HD cameras.

The spacecraft can also operate in *Remote Imaging Mode (RIM)* when it is not in view of any ground station. This requires that the coordinates of the targets be previously identified and uploaded to the spacecraft. Time-tagged commands will be uploaded to the spacecraft, and the spacecraft will then automatically plan for all of the observations.

The spacecraft can enter *Data Downlink Mode (DM)* whenever it is in view of a ground station and is not imaging. For example, the spacecraft can enter DM during an evening pass over a ground station.

The *Real Time Imaging Mode (RTIM)* can involve the following steps:

- **Step 1:** Wide Area Target selection
The coordinate of the Wide-Area Target (WAT) is uploaded to the spacecraft prior to observation. This can be achieved during the previous pass or at the beginning of the pass. The spacecraft automatically plans its maneuver based on its orbital path and the coordinate of the target.
- **Step 2:** Wide area target observation
Once the WAT is in view of the Secondary Imaging Instrument, the spacecraft will initiate the operation of the Secondary Imaging Instrument to capture and download the Low-Resolution High-Definition video (LR-HD) in real time to the ground station that is in view.
- **Step 3:** High resolution target identification
A High Resolution Target (HRT) may be identified and the coordinate of the HRT. The coordinate of the HRT can then be uploaded prior to observation. As with the WAT, the spacecraft will automatically adjust its attitude and prepare to acquire the HRT with the Primary Imaging Instrument.
- **Step 4:** High resolution target observation
Once the HRT is in view of the Primary Imaging Instrument, the spacecraft will then activate the Primary Imaging Instrument and begin the capture of high-resolution still imagery at four spectral bands or the high-resolution high-definition (HR-HD) video of the target.

Additional modes of operations include the Safe Hold, Detumble, and Sun Pointing Mode. The *Safe Hold Mode* is a passive, safe state in which the spacecraft can remain indefinitely. *Detumble Mode* is an attitude control mode for reducing the rotation rates of the spacecraft. The *Sun Pointing Mode* maximizes the power generation from the solar arrays when the spacecraft is not imaging.

System Architecture

NEMO-HD is based on an evolved NEMO bus architecture. The NEMO bus is first used in NEMO-AM (Aerosol Monitoring) spacecraft for the Indian Space Research Organization (ISRO)². The NEMO platform makes use of essentially the same avionics as SFL's Generic Nanosatellite Bus (GNB) missions³.

This includes the House Keeping Computer (HKC), Attitude Determination and Control Computer (ADCC), UHF Receiver (UHF RX), S-Band Transmitter (S-Band TX), GPS Receiver, Fine Sun Sensors, Magnetometer, Star Tracker, and Magnetorquer. The NEMO platform makes use of larger reaction wheels due to the larger spacecraft inertia of the NEMO platform compared with the GNB platform.

In addition, the NEMO platform has been specifically enhanced to include a high-output power system and a higher capacity battery. The main solar arrays use 15-cell strings, while a keep-alive solar array uses 7-cell strings. 28% Triple Junction solar cells are used on all arrays. The main solar arrays operate between 30 V to 45 V. The battery pack comprises 7-cell Li-ion in 7s1p configuration, providing 130 W-h of energy storage with voltage range of 25 V to 28 V. Power to high-energy devices such as the instrument and the X-band transmitter are distributed through a high-voltage bus that operates between 25 V to 28V. Power to the lower-voltage avionics are distributed through a 5 V regulated bus. Communications between the various avionics modules are performed via I2C, SPI, asynchronous TTL serial, asynchronous RS-485/422 serial and CAN buses. Discrete input/output lines as well as analog telemetry lines are also used. High speed data lines between the detector modules and the data recorder uses GigE, while the high-speed data transmission line to the X-band transmitter uses synchronous low-voltage differential signal (LVDS).

The instrument optics and the detector system will be new development, while the storage unit will be based on a commercial-off the shelf (COTS) module that has been designed for space. The X-band transmitter is based on a flight design.

Figure 1 below shows a block diagram of the NEMO-HD architecture showing the interconnectivity described above.

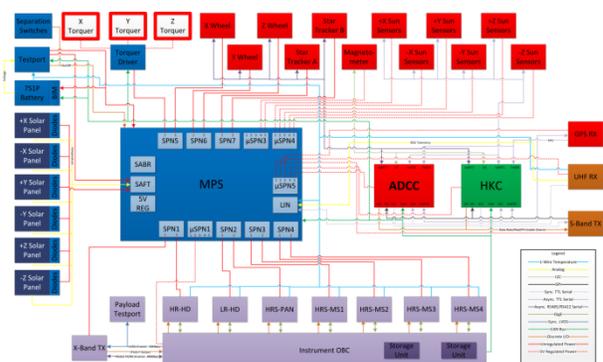


Figure 1: NEMO-HD System Architecture

Figure 2 below shows the preliminary spacecraft layout. The layout of the spacecraft will be revisited during the detailed design phase, taking into account the final optical design of the instrument. The spacecraft has a main bus that measures 43 cm by 29 cm by 65 cm. The overall launch mass (spacecraft and separation system) is expected to be 40 kg.

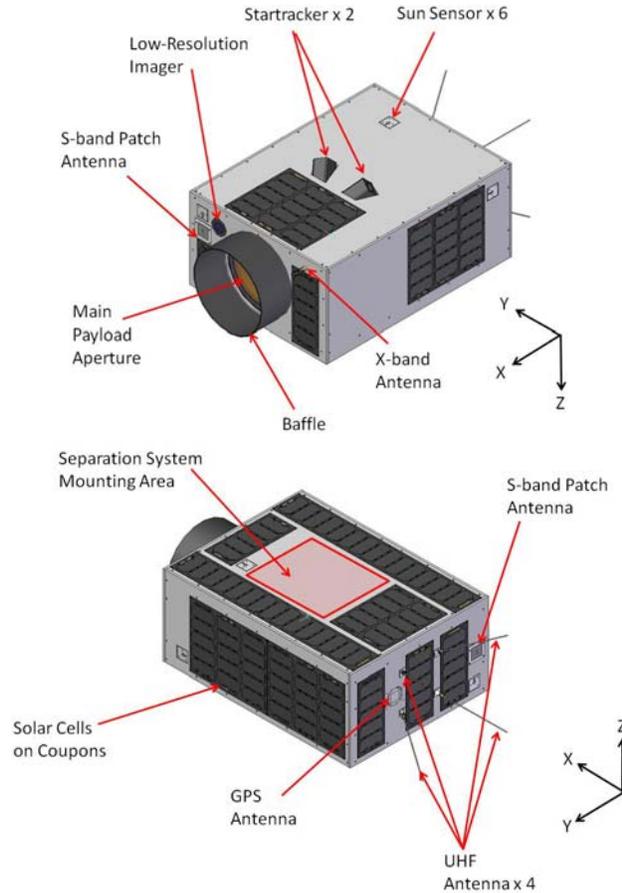


Figure 2: Preliminary Spacecraft Layout

Attitude Control Strategy

NEMO-HD will be stabilized in three-axis. This implementation builds upon the know-how from missions such as BRITE and NEMO-AM. NEMO-HD will add a second star-tracker in order to improve the pointing accuracy and to minimize the impact of the sun exclusion zone on the imaging operations.

NEMO-HD is expected to achieve a pointing accuracy of 1.5 arcminutes. With the instrument pointing towards nadir from the reference orbit, this pointing accuracy translates to approximately 260 m pointing accuracy on the ground.

Mass Budget

Table 2 below summarizes the mass budget for the spacecraft. The preliminary estimate of the launch mass is 50 kg including margins. It is expected that the overall launch mass will be approximately 40 kg.

Table 2: Mass Budget

Subsystem	Mass g	Margin g	Total g	Fraction %
Structural	5447	1362	6809	13.7%
Thermal	100.0	25.0	125	0.3%
ADCS	1793	202	1994	4.0%
Power	4293	711	5004	10.1%
Computer	859	202	1061	2.1%
Communications	1308	95	1404	2.8%
Payloads	25128	6282	31409	63.4%
Integration	399	91	491	1.0%
Separation System	1000	250	1250	2.5%
Total	40327	9220	49547	100%

Power Budget

The current power system design has been sized for imaging operations over Slovenia during the day time passes. Data download will occur during all six passes. The spacecraft will recharge during the remainder of the orbit. In this case, the maximum power generation required will be approximately 31 W, while the peak power consumed is approximately 88 W. Table 3 below summarizes the various power consumers on the spacecraft and outlines the power balance. Table 4 below summarizes the energy balance during nominal operations.

Table 3: Power Budget

Loads	Qty	Unit Power	Orbit Average (W)		
			House Keeping	RTIM	DM
HKC	1	0.500	0.55	0.55	0.55
ADCC	1	0.500	0.55	0.55	0.55
Magnetometer	1	0.045	0.05	0.05	0.05
Magnetorquers	3	0.500	1.53	1.53	1.53
Sun Sensors	6	0.150	0.99	0.99	0.99
Star Tracker	2	0.500	0.20	1.02	1.02
GPS RX	1	1.100	1.87	1.87	1.87
S-Band TX	1	5.000	0.00	5.64	5.64
UHF RX	1	0.125	0.14	0.14	0.14
RW	3	0.420	1.29	0.00	0.00
RW Target Track	3	1.000	0.00	3.06	3.06
Pwr Sys Quiescent	1	2.600	2.65	2.65	2.65
X-Band TX	1	55.00	0.00	56.72	56.72

POBC	1	1.000	1.10	1.10	1.10
Storage Device	1	1.000	0.00	1.10	1.10
Payload	1	10.00	0.00	10.22	0.00
Distribution Losses			0.44	3.49	3.08
Total Consumed			11.36	90.67	80.04

Table 4: Energy Balance

Mode of Operations	House Keeping	RTIM	DM
Daily Mode Duty Cycle	94.7%	2.7%	2.7%
Orbit Average Consumed (W)	15.4		
Daily Energy Consumd (Wh)	368.7		
Orbit Average Produced (W)	19.5		
Daily Energy Produced (Wh)	468.0		
Energy Margin (%)	21.2%		
Average Battery DOD (%)	10.9%		

Link Budget

Command uplink in the UHF band and health and telemetry downlink in the S-Band will implement systems that are similar to what are currently being used on other SFL missions. The UHF uplink at 401-403 MHz Space Operations Band assumes a 23 dB Yagi antenna system on the ground station and maintains a link margin of 9 dB as shown in Table 5. The S-Band downlink at 2200 MHz Space Research Band assumes a 5 m dish on the ground station and maintains a link margin of 11 dB as shown in Table 6.

Table 5: UHF Uplink Budget

Parameter	Value		Units
Frequency	402		MHz
Transmit power (mWatts)	250000	53.98	dBm
Feed harness loss	3	-3.00	dB
Antenna gain		23.00	dBic
Antenna beamwidth (half power)	10.00		degrees
Pointing loss		-3.00	dB
EIRP		70.98	dBm
Satellite orbital altitude	600		km
Free space loss @5 deg elevation		-151.87	dB
Polarization loss	2		dB
Atmospheric loss	1		dB
Total propagation loss		-154.87	dB
Isotropic signal at Spacecraft		-83.89	dBm
Antenna gain		-8.00	dBic
System Noise temp (K)	598.24	27.77	dBK
G/T		-39.32	dB/K
Receiver Signal Power	-95.44		dBm
Receiver Noise Power	-120.42		dBm
C/No		75.39	dB/Hz
Receive Bandwidth	110000	50.41	dBHz
C/N		24.98	dB

Implementational Losses	5.4	5.40	dB
Baseband S/N		21.34	dB
Req S/N for 10E-5 BT=0.5 GFSK	12	12.00	dB
Uplink Margin		9.34	dB

Table 6: S-Band Telemetry Link Budget

Parameter	Value		Units
Frequency	2200		MHz
Transmit power (mWatts)	350.00	25.44	dBm
Filter loss	0	0.00	dB
Feed harness loss	0.5	-0.50	dB
Antenna gain		-7.00	dBic
EIRP		17.94	dBm
Satellite orbital altitude	600		km
Free space loss @5 deg elevation		-166.63	dB
Polarization mismatch loss	1		dB
Atmospheric loss	1		dB
Total propagation loss		-168.63	dB
Isotropic power at Antenna Input		-150.69	dBm
Antenna size	5.0		m
Antenna efficiency	70		%
Antenna gain		39.69	dBic
System Noise temp (K)	332.38	25.22	dBK
G/T		13.67	dB/K
Receiver Signal Power	-111.80		dBm
Receiver Noise Power	-125.32		dBm
C/No		61.58	dB
Ec/No		12.52	dB
Eb/No		15.53	dB
Required Eb/No for 10E-5 C-BPSK	9.6	9.60	dB
Coding Gain	5.2	5.20	dB
Coded Req. Eb/No for 10E-5 C-BPSK		4.40	dB
Downlink Margin		11.13	dB

For the data download, the spacecraft will implement one X-band antenna with 10 dB of maximum gain. Table 7 below shows the link budget for the X-Band data downlink operating at 50 Mbps. A frequency of 8237.5 MHz, which is the midpoint between 8025 to 8450 MHz, is assumed. The link budget shows a healthy 6.9 dB of link margin at the minimum elevation angle of 5 degrees into a 5 m dish on the ground station.

Table 7: X-Band Data Link Budget

Parameter	Value		Units
Frequency	8237.5		MHz
Transmit power (mWatts)	10000.00	40.00	dBm
Filter loss	0	0.00	dB
Feed harness loss	0.5	-0.50	dB
Antenna gain		10.00	dBic
EIRP		49.50	dBm
Satellite orbital altitude	600		km
Free space loss @5 deg elevation		-178.10	dB
Polarization mismatch loss	1		dB

Atmospheric loss	1		dB
Total propagation loss		-180.10	dB
Isotropic signal power at Antenna Input		-130.60	dBm
Antenna size	5.0		m
Antenna efficiency	70		%
Antenna gain		51.15	dBic
System Noise temp (K)	332.38	25.22	dBK
G/T		21.28	dB/K
Receiver Signal Power		-84.10	dBm
Receiver Noise Power		-93.38	dBm
C/No		89.28	dB
Ec/No		8.28	dB
Eb/No		11.29	dB
Required Eb/No for 10E-5 OQPSK	9.6	9.60	dB
Coding Gain	5.2	5.20	dB
Coded Required Eb/No for 10E-5 OQPSK		4.40	dB
Downlink Margin		6.89	dB

Launch Vehicles

The spacecraft will be designed to be compatible with launch loads of a number of launch vehicles, including the PSLV (India), Dnepr (Russia), Rocket (Russia/Germany), and Cyclone-4 (Ukraine/Brazil). These launch vehicles represent the launch providers that SFL has launched with, will be launching with, or is in discussion with for a potential launch. SFL Nanosatellite Launch Services (NLS) program has successfully launched a total of sixteen spacecraft in six cluster launches on board Rocket, Cosmos-3M (as part of SSETI/Express spacecraft), and PSLV⁴. Currently SFL has manifested eleven additional spacecraft for launch in five upcoming cluster launches on board PSLV and Dnepr.

CONCLUSION

The preliminary system design of the NEMO-HD has been presented. Instruments capable of meeting the requirements have been designed. The breadboard prototype of the primary instrument is currently under construction, and it is expected that the first imaging results will be available by mid-summer 2012. At the systems level, NEMO-HD is largely based on an evolved NEMO architecture with a few enhancements, including a power system capable of delivering higher power and a high-speed X-band transmitter.

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