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 30 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 39 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 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.

1 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 30 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).

1.1 Primary Mission Requirements

The primary mission requirements for NEMO-HD can be summarized as follows [1]: 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 colour 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.

2 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.

2.1 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 on-going. 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.

2.2 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.

Table 1. Signal to Noise Performance

Channel	Spectral Band	SNR	Requirement
HRS-PAN	400-900 nm	75.3	75
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	

2.3 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.

2.4 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.

3 SYSTEM DESIGN

3.1 Operations Concept and Operations Modes

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

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 Download 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 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.

3.2 System Architecture

NEMO-HD is based on an evolved NEMO bus architecture, first used for the ongoing development of the NEMO-AM spacecraft for ISRO. The NEMO platform makes use of essentially the same avionics as SFL's Generic Nanosatellite Bus (GNB) missions. 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 shows a block diagram of the NEMO-HD architecture showing the interconnectivity described above.

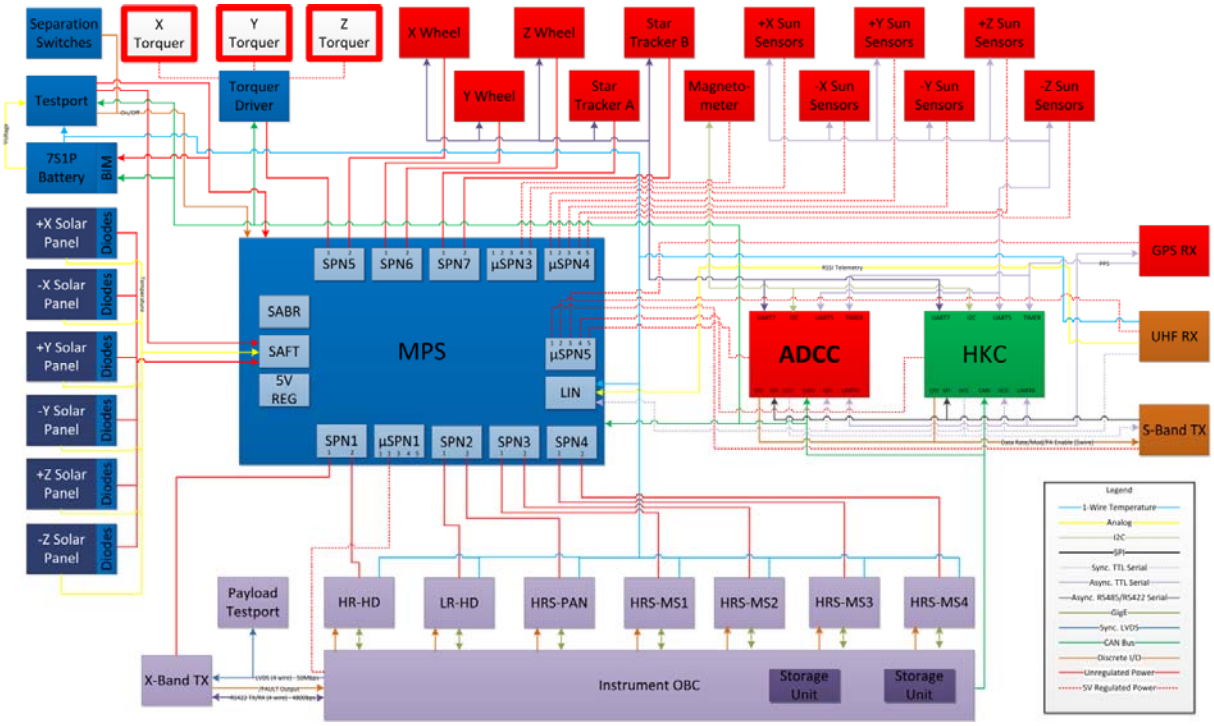

Figure 1. NEMO-HD Architecture Diagram

Figure 2 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 430 mm by 264 mm by 640 mm. The overall launch mass (spacecraft and separation system) is expected to be approximately 30 kg.

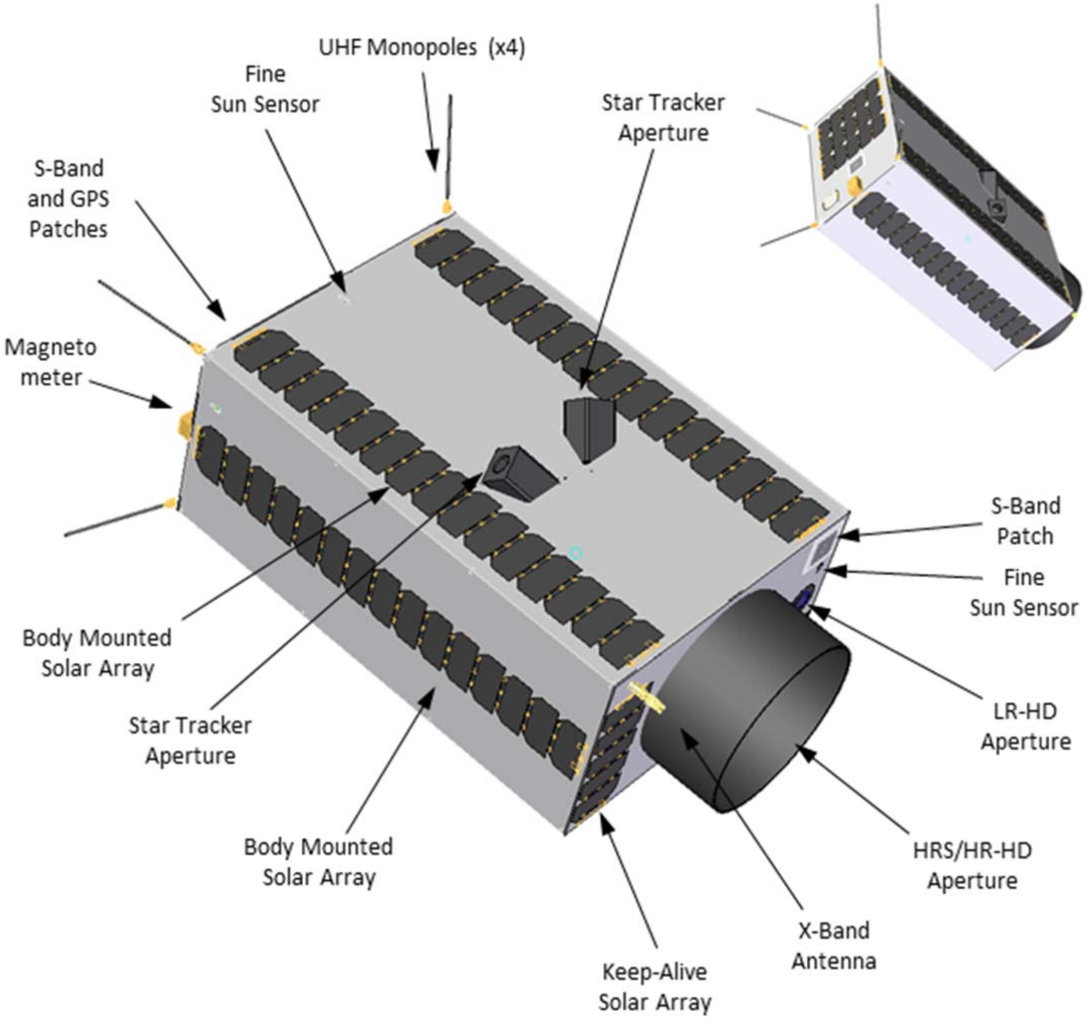

Figure 2. Preliminary Spacecraft Layout

3.3 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.

3.4 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 2 below summarizes the various power consumers on the spacecraft and outlines the power balance. Table 3 below summarizes the energy balance during nominal operations.

Table 2. Power Budget

Loads	Qty	Unit Power (W)	Duty Cycle				Orbit Average (W)			
			Safe hold	House keeping	RTIM	DM	Safe hold	House keeping	RTIM	DM
HKC	1	0.500	100%	100%	100%	100%	0.55	0.55	0.55	0.55
ADCC	1	0.500	100%	100%	100%	100%	0.55	0.55	0.55	0.55
Magnetometer	1	0.045	0%	100%	100%	100%	0.00	0.05	0.05	0.05
Magnetorquers	3	0.500	0%	100%	100%	100%	0.00	1.53	1.53	1.53
Sun Sensors	6	0.150	0%	100%	100%	100%	0.00	0.99	0.99	0.99
Star Tracker	2	0.500	0%	20%	100%	100%	0.00	0.20	1.02	1.02
GPS RX	1	1.100	0%	100%	100%	100%	0.00	1.87	1.87	1.87
S-Band TX	1	5.000	0%	0%	100%	100%	0.00	0.00	5.64	5.64
UHF RX	1	0.125	100%	100%	100%	100%	0.14	0.14	0.14	0.14
RW	3	0.420	0%	100%	0%	0%	0.00	1.29	0.00	0.00
RW Target Tracking	3	1.000	0%	0%	100%	100%	0.00	0.00	3.06	3.06
Pwr Sys Quiescent	1	2.600	100%	100%	100%	100%	2.65	2.65	2.65	2.65
X-Band TX	1	55.00	0%	0%	100%	100%	0.00	0.00	56.72	56.72
POBC	1	1.000	0%	100%	100%	100%	0.00	1.10	1.10	1.10
Storage Device	1	1.000	0%	0%	100%	100%	0.00	0.00	1.10	1.10
Payload	1	10.00	0%	0%	100%	0%	0.00	0.00	10.22	0.00
Distribution Losses (W)							0.16	0.44	3.49	3.08
Total Consumed (W)							**4.04**	**11.36**	**90.67**	**80.04**

Table 3. Energy Balance

Nominal Operations Power Budget			
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%**		

3.5 Link Budgets

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 7 dB as shown in Table 4. 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 5.

Table 4. Link Budget for the UHF Command Uplink.

	Input	Calculations	Unit
Frequency	402		MHz
Wavelength	0.7458		m
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 error	5		degrees
Pointing loss		-3.00	dB
EIRP		**70.98**	**dBm**
Satellite orbital altitude (circular orbit)	600		km
Minimum elevation	5		degrees
Maximum distance to satellite	2328.05		km
Free space loss		-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
Antenna Mismatch Loss (VSWR)	3	-1.25	dB
Antenna Interface Loss	1	-1.00	dB
Power Splitter Loss	0.8	-0.80	dB
Feed harness loss	0.5	-0.50	dB
Preamplifier Noise Figure	2.5		dB
Preamplifier Gain	15		dB
Receiver Noise Figure	10		dB
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
Information Data Rate	4000		bps
Coding Rate	1.00		dB
Channel Data Rate	4000		bps
Modulation Index	1		Hz/Hz
Occupied Bandwidth (98% Power BW)	8000		Hz
Implementational Losses	5.4	5.40	dB
Baseband S/N		**21.34**	**dB**
Required S/N for 10E-5 BT=0.5 GFSK	12	12.00	dB
Coding Gain	0	0.00	dB
Coded Required S/N for 10E-5 BT = 0.5 GFSK		12.00	dB
Uplink Margin		**9.34**	**dB**
C/N at Detector Input		19.58	dB
FM Threshold C/N (discriminator detector)		12.00	dB
FM Threshold Margin		**7.58**	**dB**

Table 5. Link Budget for the S-Band Telemetry Downlink.

	Inputs	Calculations	Units
Frequency	2200		MHz
Wavelength	0.1363		m
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 (circular orbit)	600		km
Minimum elevation	5		degrees
Maximum distance to satellite	2328.05		km
Free space loss		-166.63	dB
Polarization mismatch loss	1		dB
Atmospheric loss	1		dB
Total propagation loss		-168.63	dB
Isotropic signal power at Antenna Input		**-150.69**	**dBm**
Antenna size	5.0		m
Antenna efficiency	70		%
Antenna gain		39.69	dBic
Antenna beamwidth (half power)	1.91		degrees
Pointing error	0.3		degrees
Pointing loss		-0.3	dB
Filter loss	0	0.00	dB
Feed harness loss	0.5	-0.50	dB
Receiver LNA Noise Figure	2.8		dB
LNA Gain	30		dB
Receiver Noise Figure	10		dB
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
Information Data Rate	32000		bps
Coding Rate	0.50	-3.01	dB
Channel Data Rate	64000		bps
Receive Bandwidth	64000	48.06	dBHz
C/N		13.52	dB
Implementational Losses	1	1.00	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 Required 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 6 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 6. Link Budget for the X-Band Data Downlink.

	Inputs	Calculations	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 (circular orbit)	600		km
Minimum elevation	5		degrees
Maximum distance to satellite	2328.05		km
Free space loss		-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
Antenna beamwidth (half power)	0.51		degrees
Pointing error	0.3		degrees
Pointing loss		-4.2	dB
Filter loss	0	0.00	dB
Feed harness loss	0.5	-0.50	dB
Receiver LNA Noise Figure	2.8		dB
LNA Gain	30		dB
Receiver Noise Figure	10		dB
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
Information Data Rate	50E+6		Bps
Coding Rate	0.50	-3.01	dB
Channel Data Rate	100000000		Bps
Receive Bandwidth	100000000	80.00	dBHz
C/N		9.28	dB
Implementational Losses	1	1.00	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**

3.6 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), Rockot (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 Rockot, Cosmos-3M (no longer available), and PSLV [3]. Currently SFL has manifested eleven additional spacecraft for launch in five upcoming cluster launches on board PSLV and Dnepr.

4 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.

5 ACKNOWLEDGMENT

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