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Flexible S-Band TT&C (Telemetry, Tracking, and Command) for Small Spacecraft in LEO

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ABSTRACT

The increasing demand for commercial and institutional missions with smaller spacecraft has been a catalyst in the development of smaller and higher efficiency technologies for space applications. Additional pressure from ever evolving standards and the need to adapt to conditions in-flight (when necessary) has been driving the development of a new generation of small, flexible products able to modify in-flight the operational parameters.

The S-Band TT&C transceiver presented in this paper is based on ECSS class-3 component selection and represents the latest generation of products developed by COM DEV in its Aylesbury facility in Europe. The class-3 philosophy combined with exhaustive testing has been employed to verify the equipment's ability to function in space and achieve the high degree of flexibility required for the type of missions this product range is targeting. Careful component selection is also used to enable a route to miniaturization leading to an S-Band TT&C transceiver with mass of 2.2 lbs, and a volume envelope of 7 x 5.5 x 1.8 in.

The product architecture and characteristics are presented in this paper together with some of the available mission-specific options focused around mission architects needs to evolve and adapt missions after launch.

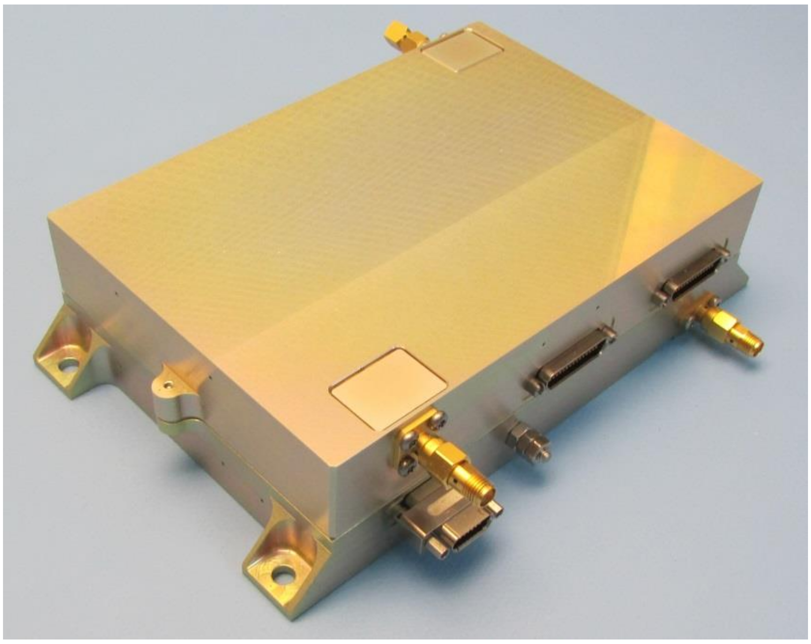

Figure 1: STC-MS03 Transceiver

GENERAL PHILOSOPHY

The space industry is accustomed to following strict guidelines for development and manufacture of equipment that are suited to products with life expectations of 15 years or more. However, when the mission requirements have a reduced scope of life expectancy and orbital altitudes, the traditional processes are not always desirable due to the cost and timescale burden they add to the development of the equipment. Having analyzed the traditional requirements, COM DEV is one of the pioneering companies that has developed equipment designed to withstand those environments without carrying the cost and timescale burden of traditional space developments. The product presented in this paper follows this approach.

SPECIFICATION

Considerable effort was placed at the early stages of the programme in identifying the most appropriate and flexible set of specifications required for the target range of spacecraft platforms. The equipment design have been focused on spacecraft operating in LEO with a mass of 50 Kg or more and with an expected mission lifetime of seven years.
Table 1 presents the general characteristics of the Transceiver.

Table 1: General Characteristics of STC-MS03

General	
Expected life	7 years
Mass	2.2 lbs
Volume	7 x 5.5 x 1.8 in
DC Power Consumption	30 W (Total at 37 dBm out)
Supply Voltage	28V ±6 V
Data Interfaces	Dual RS-422
Operating Temperature Range	-20°C to +60°C
Radiation Tolerance	10 KRad
S-Band Receiver	
Modulation Format / Data Rates	PCM (NRZ-L)/PSK/PM 8kHz (0.5,1,2 Kbps) & 16kHz SC (1,2,4 Kbps), PCM (NRZ-L)/BPSK (64 to 1024 kbps)
Modulation Index TC	0.2 to 1.5 rad
Receiver Power Consumption	4 W
Input Power Range	-135 to -40 dBm
Carrier Acquisition Threshold	-120 dBm
Carrier Acquisition Sweep Rate	±32 kHz/s
Carrier Tracking Range	±150 kHz
S-Band Transmitter	
Tx Power Consumption	26W at 37 dBm RF-out
Output Power Range	0.2 to 5W (23 to 37 dBm)
TM Modulation Formats	QPSK, OQPSK, BPSK
Data Modulation Formats	BPSK, (O)QPSK SRRC filter, NRZ/BPSK/PCM, SP-L
Data Rate	32 to 1024 kbps BPSK 1024 to 6250 kbps
Encoding	Convolutional 1/2, NRZ-M, NRZ-L, PCM

ARCHITECTURE

The product aims to address the needs of smaller satellites with limited power so parameters affecting volume, mass and power have been in the core of the product design. To reduce the space envelope and minimize interconnects, the product is laid out in three modules.

- The RF Receiver and Modem module: Implements the receiver section, the digital processing and control functions. The digital signal processing functionality is realized on an ACTEL FPGA which delivers a high degree of flexibility and reconfiguration.
- The Power Amplifier module: This is based on a high efficiency GaN technology which has excellent characteristics in relation to radiation tolerance.
- The Power supply module: This module contains independent DC/DC converters for the transmit and receive sections of the transceiver as well as EMI filtering to ensure EMC compatibility with the primary power bus.

The Telemetry, Tracking and Command (TT&C) subsystem has two main functions.

- Telecommand-receive function: Receives and demodulates the uplink signal from the ground station and delivers the received telecommands to the spacecraft On Board Computer (OBC)
- Telemetry-transmit function: Processes and modulates the downlink payload telemetry from the OBC for transmission to the ground station.

Dependent upon mission requirements the transceiver may need additional filtering in the form of

- a diplexer - when using a common transmit/receive antenna
- individual transmit and receive filters – when using dedicated transmit and receive antennas

This filtering (which can be effectively supplemented by the antenna to antenna isolation when using dedicated antennas) provides the following functionality

- Reduction in transmitter noise in the receive band to well below the noise floor hence improving sensitivity
- Preventing overdriving of the receiver LNA, either from the transmitter or other mission specific interferers – hence maintaining sensitivity
- Compliance with ITU spectral requirements from the transmitter

Figure 2 shows the STC-MS03 with a mounted diplexer.

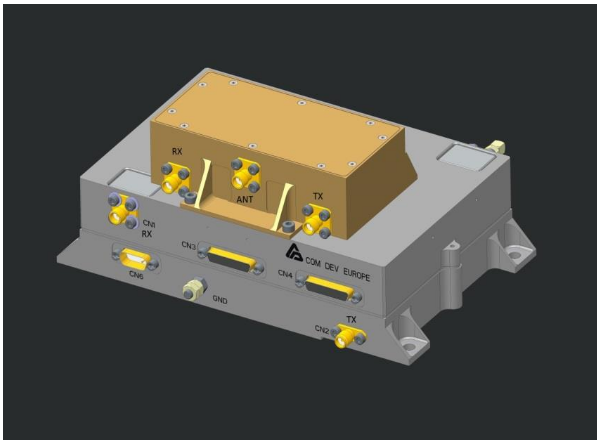

Figure 2: TT&C with mounted diplexer

The transceivers have dual redundant interfaces to allow for cross-strapping in missions aiming to operate in redundant mode. Mission architects have the option of operating the equipment in full cold-redundant mode or a combination of hot redundancy for the receivers and cold redundancy for the transmitters.

Assembly

The TT&C product consists of two trays assembled together to form the complete unit as presented in Figure 3.

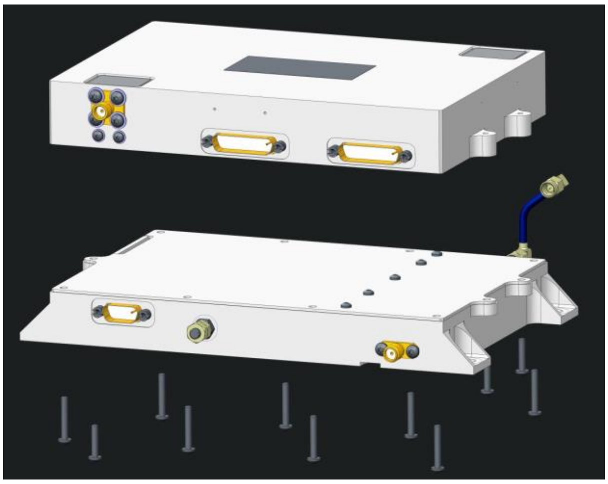

Figure 3: Two tray assembly

The lower tray houses the Power amplifier and power supply including the DC/DC Converters and EMI filters. Those are the parts of the system that are likely to generate heat during operation and as such need direct contact with the spacecraft thermal plate to cool the components appropriately. The lower tray also accommodates the interface connectors for the power supply and RF-transmit output.

The upper tray houses a single board that encompasses the RF receiver and modem elements of the system including the digital processing and data interfaces. The board is carefully partitioned to minimize interference and cross-talk. This is a proven technique widely adopted by COM DEV with very successful results and allows for a mechanically compact board with minimum interconnects. Figure 4 depicts the upper-tray board with the partitioning. The individual sections are fully enclosed with lids during assembly.

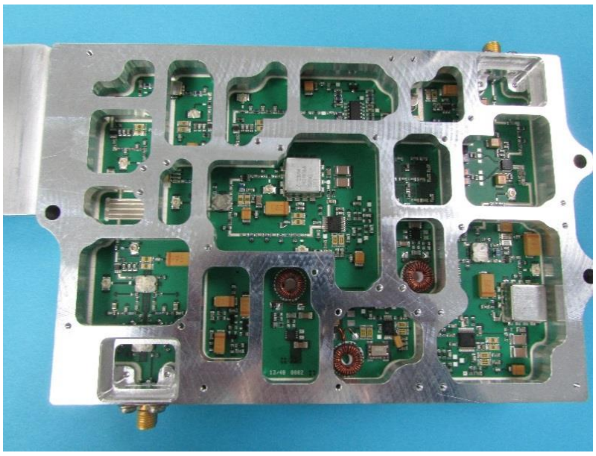

Figure 4: Upper-tray board with RF fencing (lids removed)

Receiver RF Chain

The receiver RF chain performs the following functions:

- Converts the received frequency into an intermediate frequency, filtering interference or harmonics
- Provides the necessary power amplification whilst minimizing the receiver noise figure

The major components of the receiver are a two stage LNA that amplifies the input signal, an image-reject filter and a mixer that down-converts the signal to the IF frequency. Amplifying stages are used to ensure sufficient signal amplification throughout the receive chain. The receiver gain control is achieved via a limiting amplifier and an AGC loop.

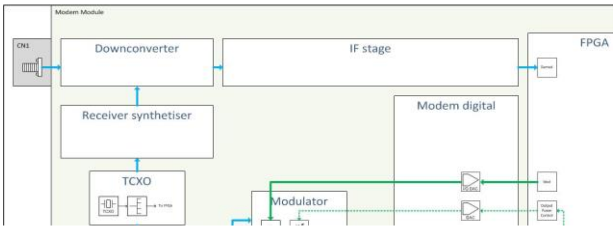

Figure 5: Receiver RF Chain

A TCXO provides the reference frequency for the receive and transmit PLLs and the FPGA. The part chosen has been selected for its excellent performance over temperature and minimal drift. The short term frequency stability has been measured at ≤1.0ppm over -40°C to +85°C and ≤10ppm over seven years aging. Radiation endurance of the TCXO is enhanced by extra shielding provided by the enclosure.

The performance of the receiver chain is presented in Table 2.

Table 2: Performance parameters of receiver (including diplexer)

Parameter	Specification
Frequency	2025MHz to 2110MHz
Input dynamic range	From -120dBm to -35dBm
Carrier acquisition threshold	-124dBm
Carrier acquisition range	±150kHz and ±32kHz/s
Noise Figure	≤ 3 dB
Implementation loss	≤ 2 dB
Long term frequency stability	≤ ±10ppm
Data Rate	From 0.5 kbps to 1024 kbps
PCM encoding	NRZ-M, NRZ-L
Modulation schemes	NRZ/PSK/PM, SP-L, BPSK
BER at Eb/N0=10.6dB	<10-5
DC power consumption	≤ 4 W EOL

Low noise amplification

As the first stage of the receiver dominates the overall noise figure a custom designed Low Noise Amplifier (LNA) is utilized for optimum performance. The LNA typically has a noise figure of 0.9dB and a gain of 14dB.

Frequency conversion

The receiver frequency conversion converts the received signal to a lower frequency suitable for the demodulator.

The signals involved in the frequency conversion are:

- The RF signal (radiofrequency signal in S-band).
- The LO signal (local oscillator signal).
- The IF signal (intermediate frequency signal output of the mixer).

Figure 6 presents the block diagram of the frequency conversion in the receiver chain.

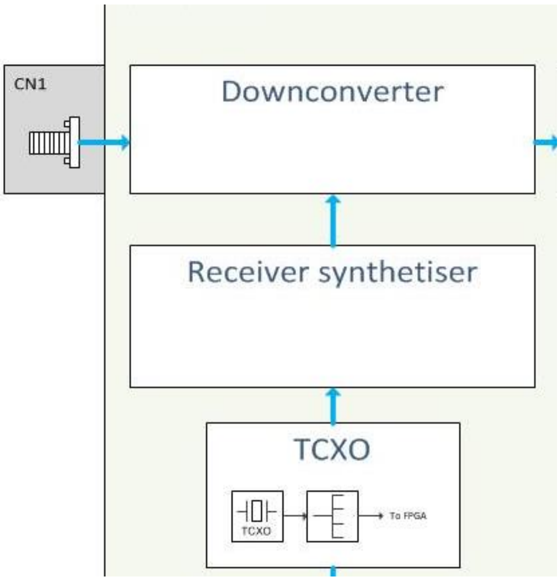

Figure 6: Frequency conversion block diagram

The TCXO provides the reference frequency to the synthesizer in order to generate the LO signal. This is set to 190 MHz below the RF signal frequency to derive a 190MHz IF signal. The synthesizer includes an amplification stage that helps to obtain 13dBm of power at the mixer input.

After the LNA, the RF signal is passed through a standard amplification block and a custom designed Band Pass Filter (BPF) with the characteristics shown in Figure 7.

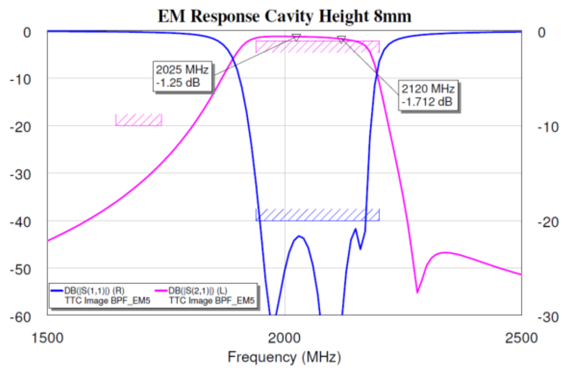

Figure 7: Band-pass filter frequency response

Transmitter RF Chain

The transmitter RF chain is designed to accomplish the following functions:

- To modulate the downlink carrier with the signal to be transmitted.
- To amplify the signal to the requested output power setting.
- To automatically control the output power.

Figure 8 presents a detailed transceiver block diagram. The green continuous path indicates the transmitted signal path. The green dashed line indicates the output power control loop path. Table 3 gives the performance of the transmit chain.

Table 3: Performance parameters of transmitter (including diplexer)

Parameter	Specification
Frequency	2200 MHz - 2290 MHz
Long term frequency stability	≤ ±10ppm
Modulation schemes	PCM/BPSK/PM SP-L, BPSK, QPSK, OQPSK
PCM	NRZ-L and NRZ-M
Subcarrier offset	2 to 300 kHz
Modulation index	0.2 to 1.5 rad
Maximum data rate	6.25 Mbps
QPSK pulse shaping filter	SRRC 0.35 and 0.5
Channel coding	Convolutional 1/2
Variable output power (1dB steps) at diplexer output	+24 dBm to +33 dBm (standard configuration) or +24 dBm to +37 dBm (high-power configuration)
DC power consumption at diplexer when output power is 37dBm	≤ 26 W EOL

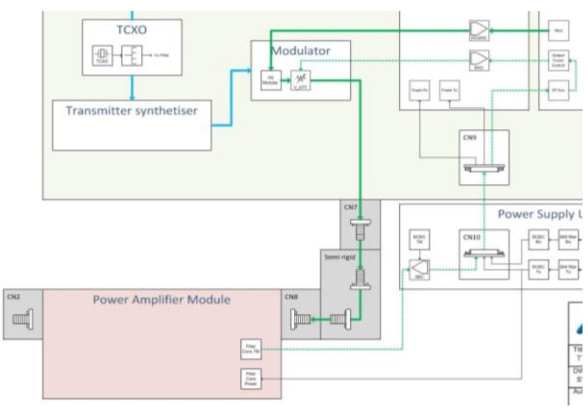

Figure 8: Transmitter RF chain

Modulator and Power Amplifier

The modulator is driven with a 0dBm LO at the transmit frequency. In-phase and Quadrature signals are delivered by a 12 bit DAC. I and Q signals have bias and amplitude level adjusted to obtain an optimum performance at the modulator output. The modulator output power is controlled by a variable attenuator to obtain the desired transmitter output power.

The PA is designed to apply filtering to the carrier signal from the modulator aiming to remove any harmonics in the signal and then achieve the required transmit power level through two initial pre-driver and driver stages (which are based on MMIC technology). Finally a GaN Solid State Power Amplifier amplifies the signal to the required level. At this stage, an isolator is in place to protect the amplifier from any reflected power and a sensor is used as a power detector in a closed loop control circuit to maintain the transmit power at the correct level.

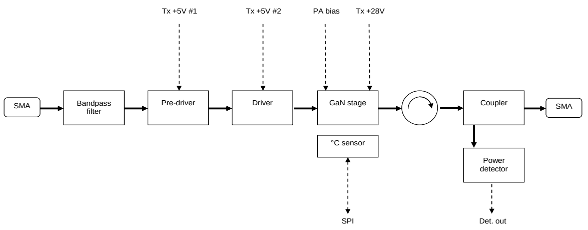

Figure 9: Power Amplifier Block Diagram

The block diagram in Figure 10 is demonstrating the functional blocks of the digital sub-system.

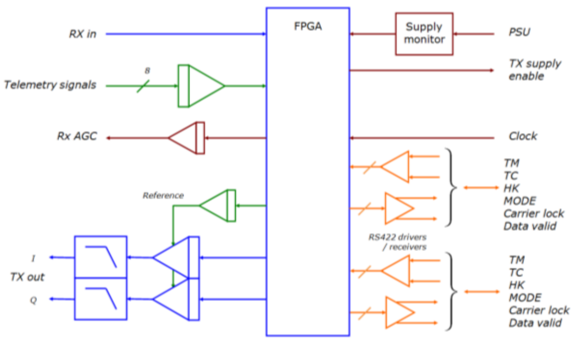

Figure 10: Digital layout

The digital signal processing of the transceiver involves the following functions:

- Receiver baseband conversion and sampling: Frequency down conversion of the IF signal with a one bit sampling. Given the bandwidth of the signal is approximately 5MHz (or less), the sampled signal is highly over-sampled thus spreading the quantization noise out of the signal bandwidth. Moreover, utilizing a one bit sampling scheme results in a BER degradation of less than 1dB. This combined with the demodulator implementation loss results to very low total implementation loss.
- Demodulation: Digital demodulation of the down-converted signal using a complex demodulator to a baseband signal. So the outputs are complex baseband I and Q signals.
- Analogue telemetries monitoring: Two 8-channels ADCs convert the analogue telemetries to digital measurements. The digital telemetries are then reported in the housekeeping data stream. The ADCs also convert the analogue signal from the transmitter output sensor and the received signal strength indicator (RSSI), which is then fed to the output power gain control and the receiver AGC loop respectively.
- Receiver AGC loop-control: The implementation of the receiver AGC, which is used to control the receiver variable attenuator to within a certain target range. If the measured level is within this range there is no change to the DAC. If a signal is outside this range, adjustment steps occur at fixed update rates until the signal is within the target range.
- In-phase and quadrature signal generation: I and Q signals are generated by the FPGA firmware. Baseband filtering is implemented to control the transmitted signal spectral efficiency, I and Q signals from the modulation combiner are fed into a cordic transform and then converted to an analogue form via a dual 12-bit ADC.
- Power-on control: The FPGA provides the ability to control its power-on sequence functions via a power supply rail monitoring circuit, which holds the FPGA in reset until the supply rails are stable.

Power supply module

The power supply module contains two separated DC/DC converter chains, one for the receiver and one for the transmitter. This approach allows the DC/DC converters to be optimised to deliver the required secondary voltages and currents, delivering an optimum overall system power performance. Each DC/DC converter provides an unregulated output that is electrically isolated from the primary power bus. The outputs are then individually regulated to provide low-noise supplies for each sub-section of the unit. The transmitter DC/DC converter is switched off entirely during “reception only” mode to minimize the transceiver power consumption. The receiver DC/DC converter has an external reset facility which allows power cycling of the whole sub-system in-flight. This is provided as a method for recovery from potential latch-up situations due to single events upsets.

The DC/DC converters are designed to operate under a non-regulated +28V line with EMI protection at the input and comply with typical spacecraft EMC requirements (conducted emissions and conducted susceptibility).

Interfaces

The S-band transceiver provides the following power and data interfaces:

- Power interface.
- Primary digital interface
- Redundant digital interface

The power interface is based on a single 15-way MDM connector. Transmitter and receiver DC/DC converters use dedicated pins on the connector, thus allowing independent LCLs on the spacecraft power distribution. Power interfaces are protected with EMI filters to ensure Electromagnetic Compatibility with the main power bus.

Interface with the spacecraft On Board Computer (OBC) is done via two 31-way MDM connectors. Digital interfaces contain the following data lines:

- Mode interface
- Housekeeping interface
- Telecommand interface
- Telemetry interface
- Carrier lock line

The dual interface enables system redundancy when each connector is linked to the primary and redundant OBC. Primary and redundant digital interfaces are internally cross-strapped in the transceiver, thus simplifying the spacecraft system design. The mode, housekeeping and telecommand interfaces implement hot redundancy so that both interfaces receive and transmit simultaneously. The telemetry interface implements cold redundancy and the active interface must be selected via command.

Equipment commands and housekeeping telemetry data are provided via the Mode and Housekeeping interfaces, which conform to the RS422 electrical standard and the TTC.B.01 data format standard. Mode commands are fixed 16-bit length and comprise an 8-bit command byte followed by an 8-bit data byte. Housekeeping data is comprised of several words of 16 bits each and provide detailed information concerning key functions of the TT&C transceiver, which can to be monitored periodically by the satellite OBC.

A large set of internal housekeeping information is available, allowing continuous monitoring of the transmitter and receiver. Table 4 provides a non-exhaustive list of the main transceiver telemetries.

Table 4: Available Housekeeping readings

Receiver Housekeeping	Transmitter Housekeeping
Internal temperature	Internal temperature
Receiver DC/DC secondary voltages	Transmitter DCDC secondary voltages
Receiver power consumption	Transmitter power consumption
Input signal strength	Transmitter VCO frequency
AGC setting	
Receiver PLL status	
Receiver VCO frequency	
Received Signal to Noise Ratio	
Carrier lock	

Uplink telecommand data from the ground station are presented on the Telecommand line with an additional output signal indicating whether the data is valid. Downlink telemetry data to the ground station are presented real time to the Telemetry line.

The receive RF input and transmit RF output ports are SMA female connectors. Power supply and data connectors are MDM type.

RADIATION TOLERANCE

The equipment has undergone a full qualification campaign and was tested for Total Dose radiation up to 28 KRad. The equipment survived this radiation level with no deterioration of performance. The equipment also has flight heritage proving its ability to cope with the environment of operation in space.

CONCLUSIONS

The paper presented COM DEV's approach in developing a small, flexible TT&C complying with ECSS Class-3 requirements. This is the first of a new generation of space equipment able to reduce costs whilst maintaining high levels of reliability.

From a technical perspective, the product offers a high performance and high reliability communications link with the ground whilst addressing mission planers requirements for in-flight re-configurability (e.g. modulation, data-rate) by allowing changes that maximize the mission's potential and minimize the risk of losing the spacecraft when unexpected incidents occur.

The TT&C equipment has successful heritage from the ADS1B mission and has been integrated on the M3M spacecraft awaiting launch in July 2014. This will be closely followed by the launch of six spacecraft flying redundant TT&Cs in the FormoSAT-7 constellation mission.

References

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