MINIATURE TT&C MODULE FOR SMALL SATELLITES IN LOW EARTH ORBITS

G. Roeper[1], R. Goldsmith[1], I. Hatziathanasiou[1], C. McLaren[1], P.Maguire[2]

[1]*Com Dev Europe Ltd., United Kingdom, sales@comdev.co.uk*

[2] Zelinda Ltd., Ireland, *p.maguire@zelinda.com*

I.   INTRODUCTION

COM DEV EUROPE has developed a low-cost and lightweight S-Band TT&C transponder, for Low Earth Orbit (LEO) missions. The design is based on Commercial Off-The-Shelf (COTS) components and targets earth observation missions with short mission durations of 3-5 years. To enable the customer to access low cost launch vehicles, the STC-MS01 has been designed free of any components that have US ITAR restrictions. The TT&C transponder is based on a Software-Defined–Radio (SDR) architecture. This makes the unit very flexible and easily adaptable to new mission requirements.

Receiver				Transmitter		
Rx Frequency Range	2025 … 2120	MHz		Tx Frequency Range	2200 … 2300	MHz
Dynamic Range	-135 … -40	dBm		Dynamic Range	+27 … +33	dBm
Noise Figure	2	dB		Carrier Frequency Stability	initial ±1	ppm
Modulation Formats	1) PCM/PSK/PM 8kHz SC				aging ±5	ppm
	2) PCM/PSK/PM16kHz SC			Modulation Formats	1) PCM (NRZ-L)/BPSK	
	3) PCM/BPSK				2) PCM (NRZ-L)/(O)QPSK	
Data Rates	1) 0.5 / 1 / 2	kbps		Data Rates	1) 64 … 1024	kbps
	2) 1 / 2 / 4	kbps			2) 1 … 6.25	Mbps
	3) 64 … 1024	kbps		Error Vector Magnitude	<10	%
Carrier Acquisition Threshold	-120	dBm		Tx Power Consumption	14	W
Carrier Tracking Threshold (35kHz/s)	-125	dBm		Supply Voltage	22 … 34	V
Carrier Tracking Range	±150	kHz		Mass	0.78	kg
Carrier Acquisition Sweep Rate	35	kHz/s		Volume	145 x 110 x 50	mm^3
BER Threshold ($1x10^{-6}$)[4kbps/16kHz SC]	-117	dBm		Operating Temperature Range	-20 … +60	^{o}C
Rx Power Consumption	4	W		Radiation Tolerance	10	kRad

Table 1   Performance Characteristics of the STC-MS01 TT&C transponder
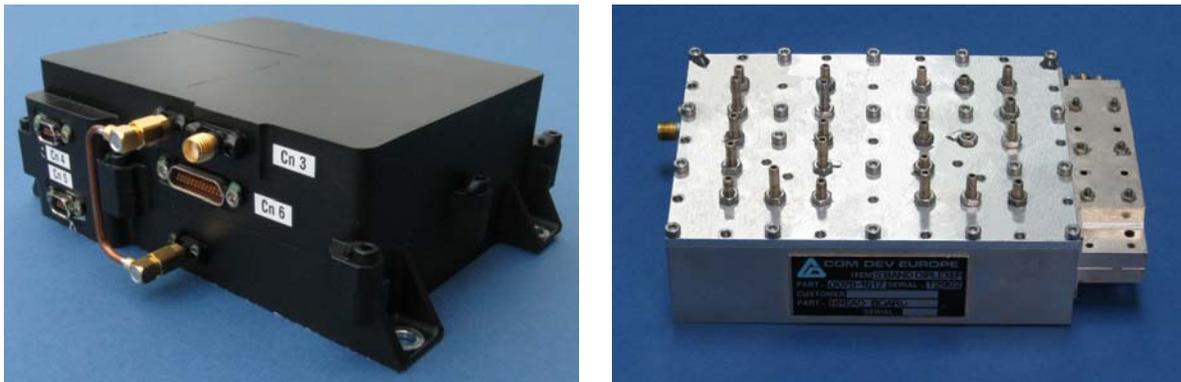
Figure 1   Photograph of the STC-MS01 TT&C transponder and an S-Band diplexer

II.   ARCHITECTURE

The TT&C transponder as a functional assembly consists of two physically separate modules, the electronics module, commonly referred to as the TT&C transponder and the diplexer. The here-described diplexer is a generic S-Band diplexer, which would be tailored to meet the specific mission needs. The TT&C transponder consists of two sub-modules, the receiver and the transmitter. Both sub-modules are independently powered; the nominal supply voltage is 28V±6V. The receiver hosts all functions that are shared between the receiver and transmitter; shared functions are the clock generator, the RS422 interfaces, as well as the central FPGA. [02]

The receiver consists of a two stage super-heterodyne architecture, the first stage is implemented in electronics, while the second stage is a logical implementation in firmware. A Low Noise Amplifier (LNA) with a noise figure of better than 2dB forms the input stage of the receiver. The amplified signal than passes through the first frequency converter stage, which is followed by the image reject and channel select filter. The channel select filter is wide enough to support ranging up to a bandwidth of 800 kHz. The channel select filter is followed by the IF-Amplifier chain, which consists of two functional blocks, a linear operating amplifier stage, followed by a limiting amplifier stage. The amplified IF signal is then fed forward into a one-bit sampler that performs the analog to digital conversion. The digital first-IF signal is finally further processed by firmware in the FPGA.

The transmitter architecture is based on a direct modulator. The firmware in the FPGA generates the I/Q signals, which are fed into a dual Digital to Analog Converter (DAC). The DAC is followed by a signal reconstruct and image reject filter. The filtered signal feeds the vector modulator, in which the modulated RF signal is generated. The RF signal is then fed forward into the SSPA, which is designed around a GaN RF power transistor. The power amplifier can generate signal levels up to +37dBm, or +33dBm depending on the applied bias conditions. The SSPA efficiency reaches 49% in the +37dBm mode or 35% in 33dBm mode. Com Dev Europe is currently formally qualifying the GaN transistor for space flight application within the framework of an ESA program.

All amplifier stages in the receiver and transmitter are actively biased to stabilise the devices over the operating temperature range and achieve excellent noise rejection at the device power supply lines. All clock frequencies in the transponder are derived from one common master reference oscillator. The required local oscillator frequencies are generated through PLL frequency synthesizers.
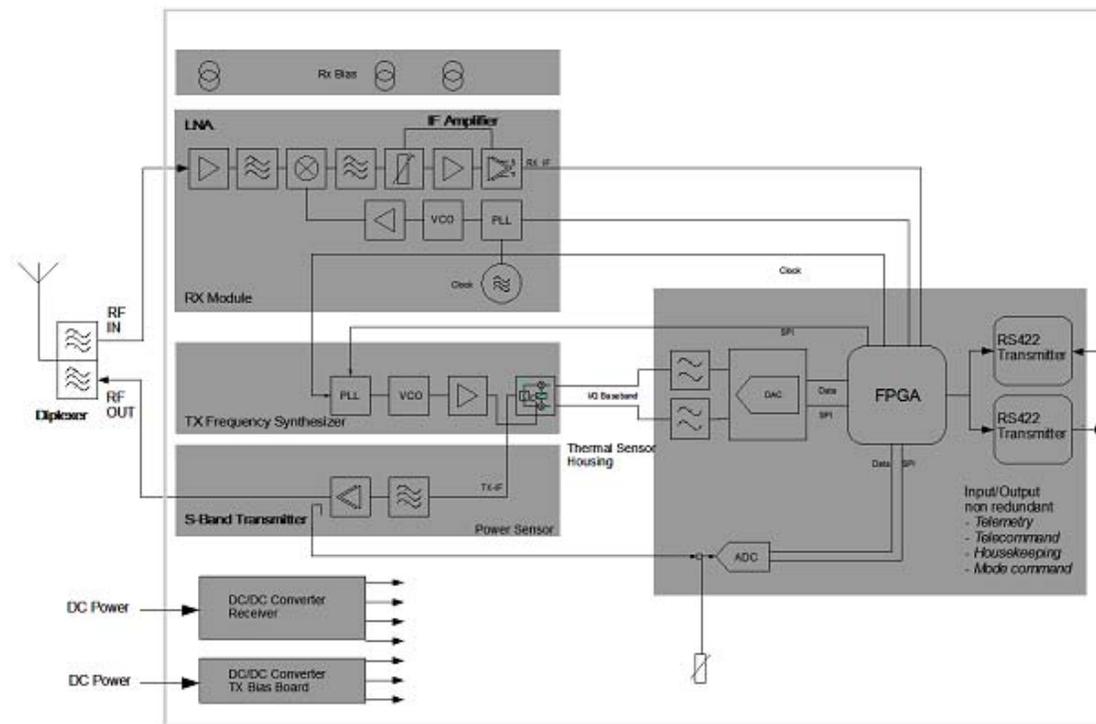

Figure 2   Block diagram of the TT&C transponder

III. FIRMWARE

The Digital Signal Processing (DSP) of the receiver and transmitter is designed to fit into a single FPGA of modest size. The chosen architecture does not require hardware multipliers. Various DSP techniques are used to minimize gate count and power consumption. These include:

- One bit sampling with over-sampling
- Frequency plan optimized to move quantizing noise out of the signal bandwidth
- Different word width for I and Q signals;
- Varying word widths through the signal path;
- Extensive use of decimated sampling rates;
- Use of serial arithmetic
- Use of Look up Tables (LUTs) for trigonometrical functions.

The IF signal is sampled with an LVDS input gate of the FPGA using a 50 MHz sampling clock. As the SAW filter in the RF chain limits the bandwidth to less than 5MHz, the result is an approximately 4 fold over sampled signal. This spreads the quantisation noise out of the signal bandwidth. The sampled image is at a frequency around –10 MHz, which is around 1/5, the sampling clock. Having the sampling clock at 5 times the image frequency, rather than the more common 4 times the image frequency, ensures that the low-order spurious harmonics generated by the 1-bit quantisation do not alias back into the signal band. The "price" of a sampling ratio of 5 rather than 4 is that the coarse heterodyne and decimate often used at the front end of demodulators cannot use the simple 0, -1, 0, 1 local oscillator downmix sequence. Instead taking advantage of the fact the sample are represented with only one bit, a 2048 x 4 LUT (Look Up Table) based complex heterodyne and decimate function is used to:

- Buffers up 10 samples in shift registers;
- Phase rotates the 10 real samples to complex baseband,
- FIR low pass filter the 10 baseband samples,
- Decimate by a factor of 2
- Remodulate samples on to a carrier at 1/10 the input sampling rate
- Discard the imaginary ("Q-Channel") Samples
- Multiply by a gain and re-quantise the real ("I channel") samples into 4 bits.

The "real" output from the complex Heterodyne and decimate, centered on an IF of 5 MHz, is fed to the two independent carrier demodulators: the BPSK demodulator; and the PM demodulator and the ranging channel. The receiver firmware architecture is illustrated in Figure 3 below. [01]
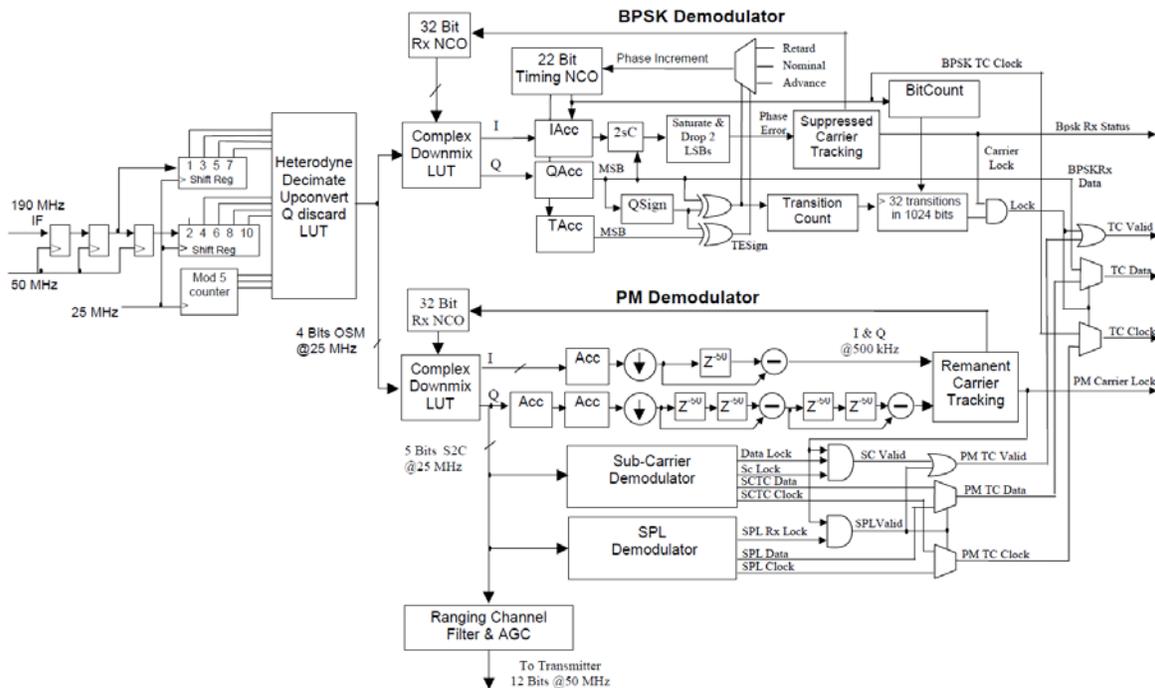

Figure 3   Block diagram of the receiver firmware

The transmitter can be operated in one of the following modes:
- Generate unmodulated return carrier;
- Phase Modulate the return carrier with the ranging channel;
- SPL phase modulate the carrier with or without ranging phase modulation; (optional)
- BPSK modulate the return carrier.
- SRRC SQPSK modulate the return carrier.

The modulator uses a cordic transform to upconvert from complex baseband to a complex first transmit IF. The frequency of this first IF is typically between –2MHz and +2 MHz (plus any Doppler when in coherent mode) depending on the exact transmit and receive frequencies. The transmit carrier NCO is responsible for generating the LO phase for this first IF, and is programmed with a fixed phase increment when in non-coherent mode, and a phase increment that depends on the receive frequency when coherent.

In BPSK mode the same digitally filtered sample is fed into both the I and Q input of the cordic rotator. Using both inputs ensures a full-scale output from the cordic and eliminates a risk of a carrier component arising. The BPSK filter is also used in SPL mode, but in SPL mode a constant amplitude is supplied to the I input of the Cordic transform, which establishes the remanent carrier power, and the filtered SPL signal applied to the Q input.

Ranging channel phase modulation and PCM/BPSK/PM modulation with subcarrier are done by adding the required modulation phase to the transmit carrier NCO phase prior to passing the phase to the Cordic rotator.

SRRC filtered OQPSK is generated using polyphase interpolating filters in the I and Q channels. These filters use the phase from the transmit data clock NCO (which is phase locked to the incoming data clock) to interpolate between stored samples of an ideally filtered SRRC pulse. Arithmetic logic is then used to sum the filtered response from a 12 bit history. In this way the SRRC frequency response is automatically correctly matched to the data rate for any data rate up to 6.25 Mbps.

The Cordic transformed is operated at 50 Msps and produces I and Q output samples at close to baseband (offset by Doppler and an offset to ensure coherency). Figure 4 displays the block diagram of the transmitter firmware.
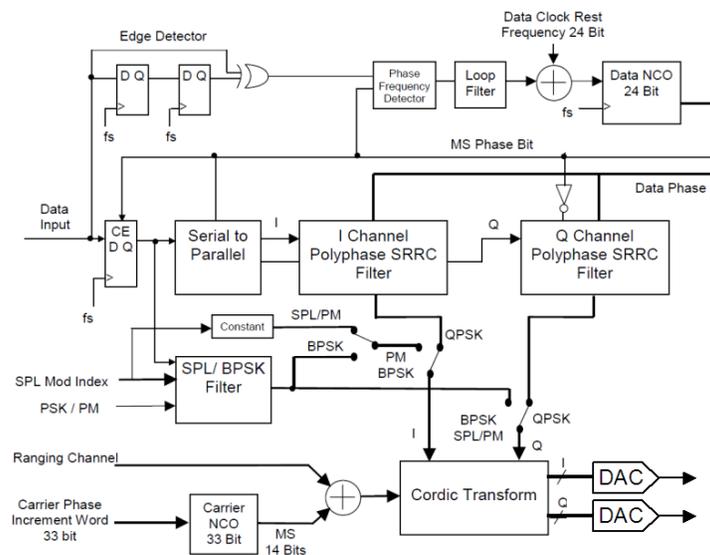

Figure 4   Block diagram of the transmitter firmware

IV.   TEST APPROACH

COM DEV has a core competence in development of flexible test systems using its proprietary CodeOne®
Enterprise solution that has been developed over a number of years. This system allows automated testing
scripts to be rapidly developed using a simple excel front end with drivers for Agilent test equipment that
automatically records calibration status and configures output test data efficiently and rapidly. COM DEV
engages CodeOne® extensively throughout its internal product test operations with over 100 test systems or
stations that use it. COM DEV has significant experience with practical deliveries of Payload Test Systems
(PTS) and TR Module Tester into Canadian, US and European customers. The combination of CodeOne®
software, together with COTS Test Equipment, and custom-designed test equipment (custom interfaces and
signals), results in a highly flexible testing environment. The major benefits to the user are the consistency of
approach, in generating test procedures, making measurements and reporting the performance.

Using CodeOne® offers maintaining calibration and traceability throughout the entire production process, even
up to the launch pad. The test system (top-left picture) is offered as an option together with the TT&C
transponder. The GIOVE-A (bottom-right picture showing GIOVE-A in the clean room in Baikonur) mission is
the most prominent example where the integrated end-to-end test approach has been used from design, through
integration up to the launch pad.

Figure 5   CodeOne® – one consistent test system from component level through to launch

V. PERFORMANCE

The STC-MS01 has been taken forward for an environmental qualification campaign, including shock, vibration, temperature cycling and thermal vacuum testing. Functional performance measurements have been undertaken in addition to the environmental measurements. Selected examples are presented below.

For the receiver, under ambient condition, a carrier acquisition threshold of –120dBm has been measured, where the carrier-tracking threshold for sweep rates of 35kHz/s is –125dBm.

Bit Error Rate (BER) measurements have been performed at the receiver. Figure 6 shows the achieved BER and the associated implementation loss at the example of the BPSK direct modulated carrier with data rates of 256 … 1024kbps, at ambient temperature condition.

Figure 7 shows the constellation diagram of a 2Mbps OQPSK modulated carrier, with an output power of 34dBm at ambient temperature condition. It can be observed that the eye-diagram is wide open, the constellation pattern is focused, symmetrical and square. The spectral plot shows very moderate spectral re-growth adjacent to the communication channel. No discrete spurii signal can be observed, neither in-band nor adjacent to the modulated signal.
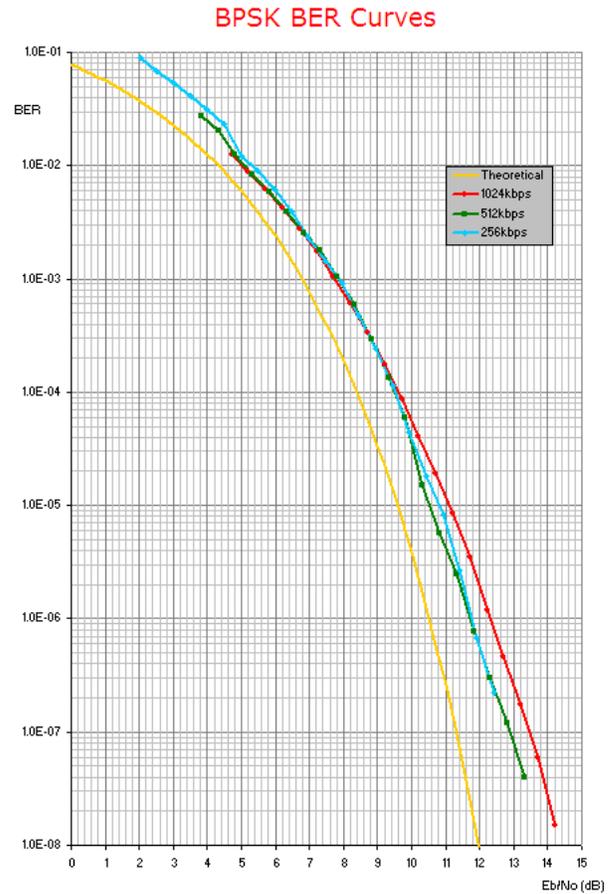

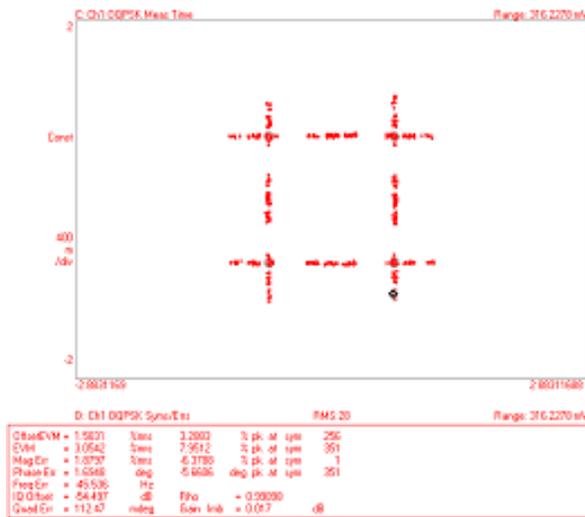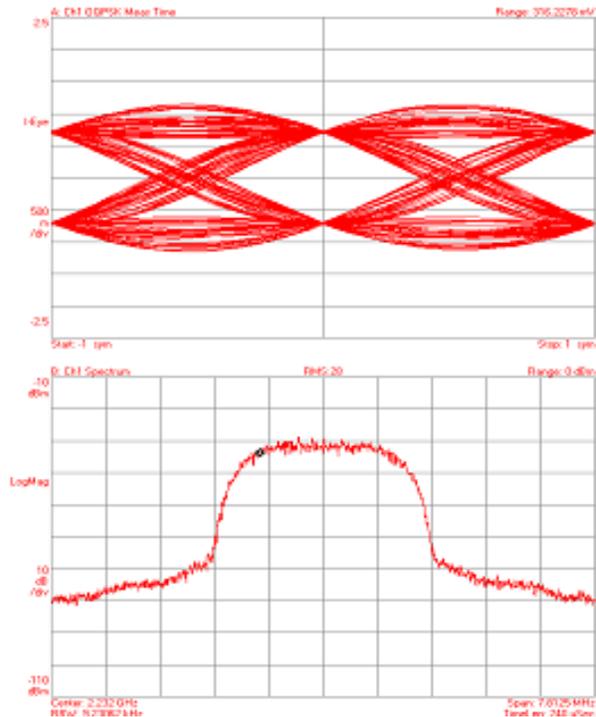**Figure 6   BER performance of the receiver in BPSK direct carrier mode**

Figure 7   Constellation diagram of the Tx output with 2Mbps OQPSK P_{OUT}=34dBm

VI.   PA & QUALIFICATION APPROACH

The STC-MS01 is targeting low-cost missions in Low Earth Orbits (LEO) with mission durations of up to three years. COM DEV EUROPE follows the Microspace philosophy of Quality Assurance, although COM DEV EUROPE implements a Product Assurance (PA) program to ensure that the project deliverable items meet the requirements contained in the contractual documents. The Product Assurance Program emphasizes a preventative approach, and ensures that documentary evidence of product quality is available in the form of design documentation and inspection and test results.

COTS components are used for the fabrication of the STC-MS01. The components are purchased in large batches from the same manufacturing lot. This guarantees that all units will have the same component reliability figures. A database for all parts used with reference to application, mission and environment is maintained. The operational success of each satellite is recorded. Any faults identified with the parts performance on mission are also recorded. This database builds up an extensive heritage listing for all parts used.

Wherever possible Com Dev Europe uses automated PCB population in the production process. The PCB population is performed by external partners, which have been vetted for the quality requirements of this production process. For all work that is carried out internally COM DEV EUROPE makes use of its existing operating policies and procedures (OPPE's), which are available at COM DEV for review, as they are deemed appropriate through OPP 4.1.101 'COM DEV Europe Group Quality Manual'. Assembled PCBs shall meet the requirements of IPC-A-610 Class 3 High Performance Electronics

The unit is designed following a single string philosophy, with no unit internal redundancy. All EEE components are de-rated according to ECSS-Q-ST-30-11C. Screening and burn-in is carried out at board- or system-level. Where deemed necessary, TID radiation testing is carried out at board- or system-level.

Like in any other conventional space program, COM DEV EUROPE implements a Configuration Management (CM) program in COTS-grade programs to ensure that documentation controlling and describing hardware, software, firmware and interfaces is initiated, identified, prepared, reviewed, approved, released, controlled and accounted for in a systematic manner, and that any changes are approved, released and controlled so that they are correctly implemented and recorded.
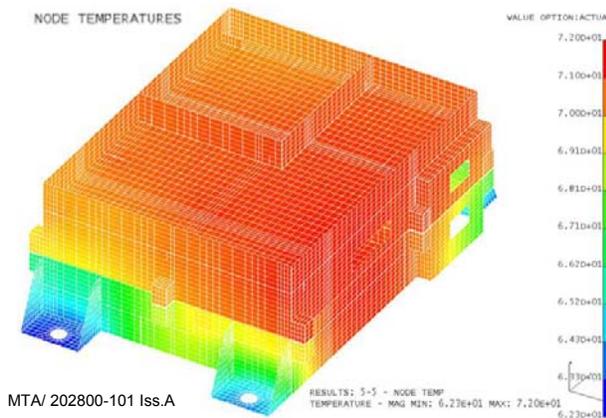

Figure 8   Temperature map of the STC-MS01 with an interface conductance of 4650W/m2 (left side)
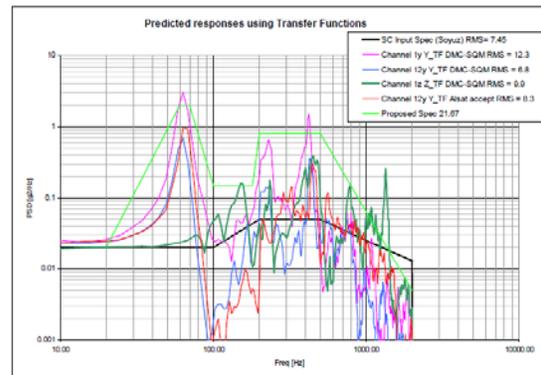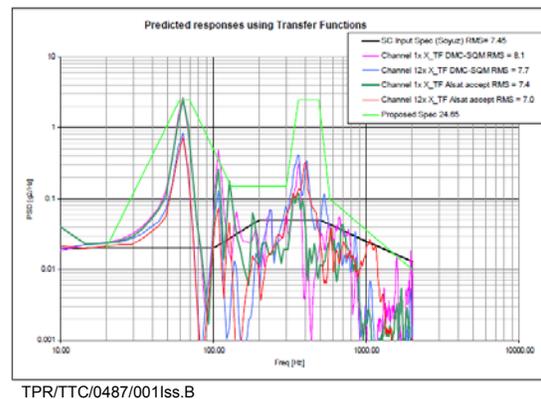
Figure 9 Predicted TTC random vibration input, lateral axis (SC Y and Z axis) (right side), Predicted TTC random vibration input, axial axis (SC X axis) (right bottom)

VII   HERITAGE

The transmitter will be flown in the autumn of 2010 in the ADS1b mission closely followed by the M3M mission in 2011. Orders for 6 units have been received.
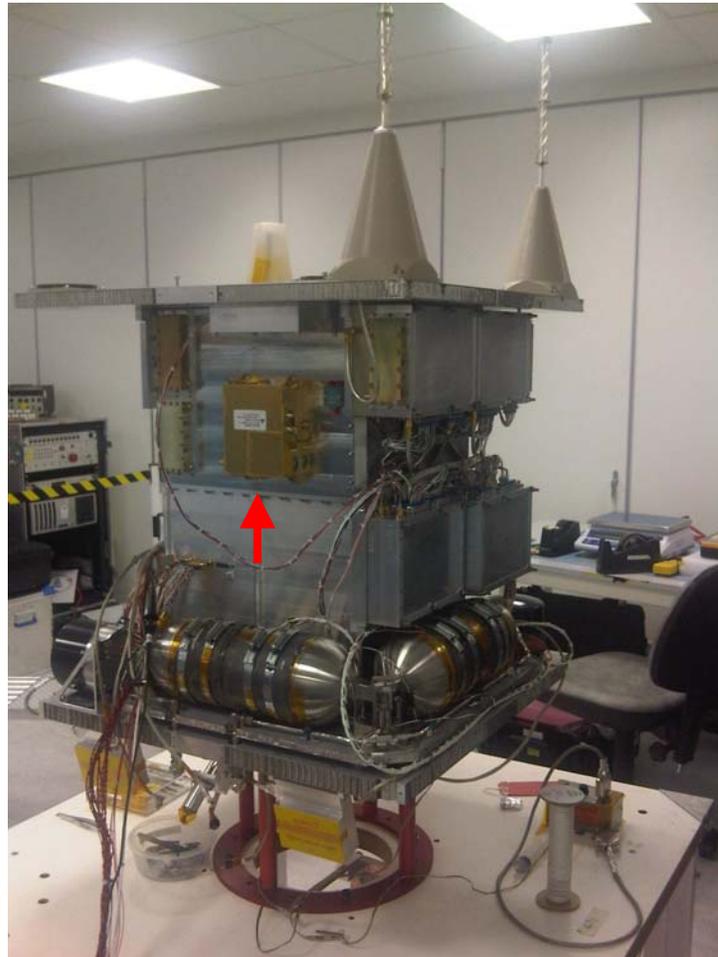

Figure 10   The STC-MS01 TT&C transponder during integration at the ADS-1B spacecraft

REFERENCES

[01]   Roeper G., Maguire P. "DEVELOPMENT OF A FLEXIBLE AND MODULAR TT&C TRANSPONDER", 4th ESA International Workshop on TT&C, 2007

[02]   Hatziathanasiou I., Roeper G., Goldsmith R., McLaren C., Maguire P., " MINIATURE TELEMETRY TELECOMMAND AND CONTROL (TT&C) MODULE FOR SMALL SATELLITES IN LOW EARTH ORBITS (LEO)", Symposium on Small Satellite Systems and Services, 2010