Mission Description - GNSS Reflectometry on TDS-1 with the SGR-ReSI

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1 INTRODUCTION

1.1 SCOPE

This technical note provides a description of the GNSS-R payload on the TechDemoSat-1 Mission. It describes the satellite mission and the GNSS-R receiver payload.

1.2 REFERENCE DOCUMENTS

Documents referenced in the following text, are identified by RD-n, where “n” indicates the actual document, from the following list:

RD#	Title	Issued by:	Doc #	Revision	Date
RD-1	TechDemoSat Mission Web Page *http://www.sstl.co.uk/Missions/TechDemoSat-1-Launched-2014*	SSTL			
RD-2	MERRByS Product Manual - GNSS Reflectometry on TDS-1 with the SGR-ReSI	SSTL	#0248366	1	

1.3 ACRONYMS AND ABBREVIATIONS

The following abbreviations are used within this document:

Acronym	Definition
ADCS	Attitude Determination and Control System
AGC	Automatic Gain Control
APM	Antenna Pointing Mechanism
BW	Bandwidth
CAN	Controller Area Network
CSW	OGC Catalogue Service for Web
DDM	Delay Doppler Map
DF	Dual Frequency
DM	Delayed Mode
DMC	Disaster Monitoring Constellation
DR	Data Recorder
DRT	Data Recorder Track
EM	Engineering Model
EO	Earth Observation
ESA	European Space Agency
EV-2	Earth Venture 2
FD	Fast Delivery
FM	Flight Model
FMMU	Flash Mass Memory Unit
FPGA	Field Programmable Gate Array
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
ICD	Interface Control Document
IGS	International GNSS Service
LHCP	Left Hand Circularly Polarised
LNA	Low Noise Amplifier
LO	Local Oscillator
LTAN	Local Time of Ascending Node
LV	Launch Vehicle
LVDS	Low Voltage Differential Signal
MMIC	Monolithic Microwave Integrated Circuit
MRP	Material Requirements Planning
MSS	Mean Square Slope
NF	Noise Figure
NOC	National Oceanography Centre
NWP	Numerical Weather Prediction
OBDH	On-board Data Handling
OGC	Open Geospatial Consortium
PD	Product Development
PPS	Pulse Per Second
PRN	Pseudo Random Noise (GPS Satellite Code)
PVT	Position Velocity Time
RAAN	Right Ascension of Ascending Node
RF FE	RF Front End
RSS	Really Simple Syndicate (Internet News Feed)
SBAS	Space Based Augmentation System
SBPP	SGR Binary Packet Protocol
SGR-ReSI	Space GNSS Receiver – Remote Sensing Instrument
SMA	Semi-Major Axis
SNR	Signal to Noise Ratio

SF	Single Frequency
SP	Specular Point
SRAM	Static Read Only Memory
SSP	Sea State Payload
SSTL	Surrey Satellite Technology Ltd
SW	Software
TBC / TBD	To be Confirmed / Determined
TDS-1	TechDemoSat-1
VHDL	Very High Level Design Level
ZTC	Zoom Transform Correlator (On-board processing algorithm)

2 INTRODUCTION

This document contains background and reference material for the TDS-1 GNSS-R mission.

3 TECHDEMOSAT-1 GNSS-R EXPERIMENT

Investments in GNSS-R by the UK and the European Space Agency over the past few years have made it possible for Surrey Satellite Technology Ltd to launch a new GNSS-R payload onboard the TechDemoSat-1 (TDS-1; see Figure 3-1) satellite in July 2014. On TDS-1, this GNSS-R payload is part of the Sea State Payload suite (SSP) that also includes a demonstration altimeter. Furthermore the same GNSS-R instrument has been selected to fly on the NASA EV-2 CYGNSS satellite constellation to measure hurricanes.

3.1 THE SGR-RESI

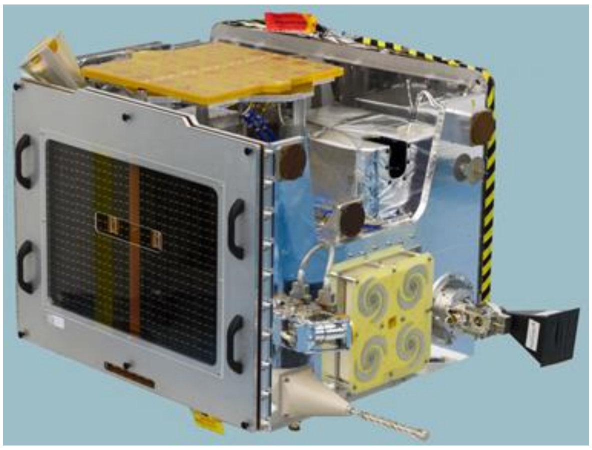


Figure 3-1 TechDemoSat-1 and GNSS-R Unit (part of SSP)

The TDS-1 satellite carries SSTL's prototype GNSS-R Instrument, the SGR-ReSI, similar to the payloads to be flown on CYGNSS. A diagram of the instrument architecture is shown in Figure 3-2.

The GNSS core is implemented on a flash-based FPGA (ProASIC-3), while the signal processing capability is provided by a second FPGA co-processor which is controlled and configured from the ProASIC FPGA. The coprocessor FPGA allows the upload of new algorithms even once the SGR is in orbit. It enables special processing for reflected or occulted signals used allowing the equivalent of thousands of correlators to map the distorted signals. Raw and processed data can be collected into the onboard mass storage.

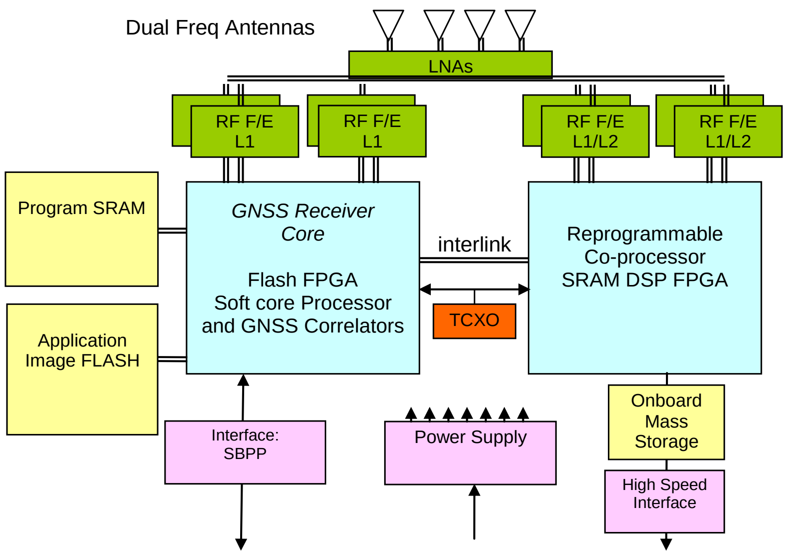


Figure 3-2 SGR-ReSI Instrument architecture

The receiver supports the GPS L1 frequency band, but also carries reprogrammable front-ends that can be set up at any of the navigation bands. Limitations are imposed by the choice of antennas and LNA filtering. Initially GPS signals are supported, but in future Galileo and Glonass are expected to be implemented in the VHDL and software.

The instrument supports multiple interfaces (CAN, RS422, USB, SpaceWire) so it could be accommodated by a variety of different satellite missions. The unit is around 1 kg in mass, consumes approximately 10 watts, and fits within half of an SSTL standard satellite micro-tray (approx 300x 160 x 30 mm).

The instrument is principally designed for GNSS-R, using the ground-reflected GNSS signals to remotely sense the Earth's surface. On TDS-1 there is a high gain (~13 dBi) L1 antenna pointing downwards – which also has the bandwidth to receive L2C signals. Reflected GPS L1 signals are processed into Delay Doppler Maps (DDMs), as shown in Figure 3-3 and Figure 3-4, either or on-board using the co-processor, or alternatively on the ground if the raw data is downloaded.

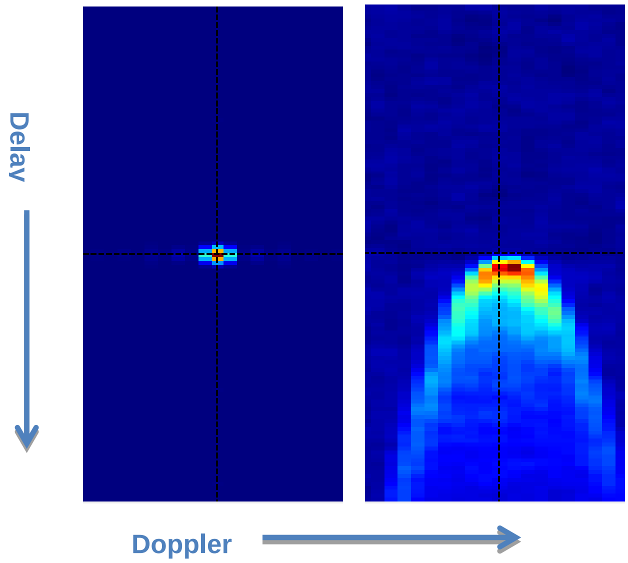


Figure 3-3 GPS L1 signal DDMs. Direct (Left) and Reflected from the ocean (Right). (Shown to the same scale)

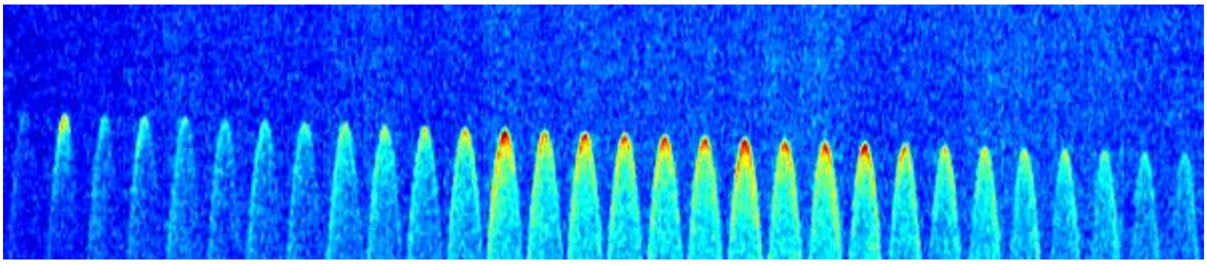


Figure 3-4 A sample of a DDM track of ocean reflections processed by the SGR-ReSI on TDS-1

SSTL's SGR-ReSI collects the signals from GPS and other navigation satellites after they have been reflected off the ocean surface and processes them into DDMs. These are sent down to the ground segment and from these DDMs, ocean roughness and wind speed measurements at the sea surface can be interpreted.

Table 3-1 gives a comparison of the capabilities of the SGR-ReSI instrument against specific configuration on TDS-1 and CYGNSS missions.

Table 3-1. GNSS-R Instrument Characteristics

	Capability	TDS-1 if different	CYGNSS if different
Frequency capability	4x L1, 4xprogrammable (L2, E5, E6)	L1 and L2C	L1 only
GNSS	24 channels L1, L2C Glonass Galileo Potential	24 channels GPS L1 and L2C, Galileo E1	12 or 24 channels GPS L1
Antenna ports	8 single or 4 dual frequency	1 nadir antenna (DF), 3 zenith antennas (1 x DF, 2 x SF)	2 nadir antennas (SF) (increased coverage) 1 zenith antenna (SF)
Zenith Antenna		Dual freq, 3 dBi gain (Antcomm)	Single Freq, 4 dBi gain (SSTL)
Nadir Antenna Gain	(UK DMC was 11.8 dBi)	13 dBi	14.6 dBic (TBC)
Nadir Offpointing	(UK DMC was 10 deg)	6 degree in –X axis (L1)	No offpointing in antenna Panels off-pointing from nadir by 28°
LNA Noise Figure		2.7 dB dual freq	~2.5 dB single freq
Sampling Rate	16.367 MHz up to 65.5 MHz I / I&Q	16.367 MHz I / I&Q	16.0362 MHz, I only[1] (32.0724MHz / 2)
DDM Format	Block Floating Point	16 or 32 bit depth	32 bit depth
Default Pixels	Can be reconfigured	128 Delay (250ns ea) 20 Doppler (500Hz ea)	128 Delay (250ns ea) 20 Doppler (500Hz ea)
Co-Processor	Xilinx Virtex 4	V4-SX30	V4-LX60 (same family and pin-out but better match of resources to application)
Number of Reflections	4	4 (though limited by antenna pattern)	4 (dual antennas means >4 reflections are usually available)
Data logging	1 Gbyte	Same	Same
GPS Performance	Approx. 5 m, 10 cm/s	Same	Same
Size, Mass	300 x 200 x 50 mm, 1 kg	Same (in ½ microtray)	Same (in box)
Power	5 W in GNSS mode 10 W in processing mode	Same	Same

Note 1: Master crystal frequency altered for two reasons – firstly a doubling of clock from ~16 to ~32 MHz bypassed the PLL circuitry within the ProASIC FPGA, which is understood to be less tolerant to environment, and secondly, a new frequency was carefully selected to minimise self-interference products in all GNSS bands.

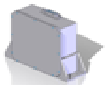
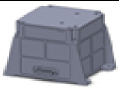
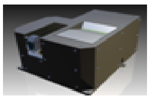
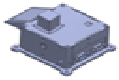
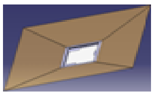
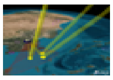
3.2 TECHDEMOSAT-1, SGR-RESI ANTENNA CONFIGURATION & ORBIT

3.2.1 Payloads on TDS-1

An overview of the satellite is given on the Web in RD-1. The satellite carries 8 payloads from different UK space organisations, one of which is the SSTL's Sea State Payload. This comprises of a demonstration altimeter (which also tests components of the SSTL NovaSAR Synthetic Aperture Radar payload), and the SGR-ReSI.

A list of these 8 payloads is given below:

Table 3-2 Payloads on TDS-1

Payload	Supplier	Description	Illustration
MuREM	University of Surrey (Surrey Space Centre)	The Micro (µ) Radiation Environment Monitor (MuREM) is a miniature radiation environment and effects monitoring payload.	
ChaPS	Mullard Space Science Laboratory (MSSL)	The Charged Particle Spectrometer (ChaPS) is designed to measure electron and ion populations in the orbit of the host spacecraft.	
LUCID	Langton Star Centre	The Langton Ultimate Cosmic ray Intensity Detector (LUCID) allows characterisation of the energy, type, intensity and directionality of high energy particles.	
CMS	University of Oxford / RAL	The Compact Modular Sounder (CMS) is a set of compatible optical, detector, cooling and electronic sub-systems which can be used to implement miniature infrared remote sensing spectrometers or radiometers.	
HMRM	Rutherford Appleton Laboratory	The Highly Miniaturised Radiation Monitor (HMRM) is a an ultra-compact, low power radiation monitor developed for re-use on future ESA missions.	
CubeSAT ACS	Satellite Services Ltd	The CubeSAT ACS payload is a complete 3-axes attitude determination and control subsystem for Cubesats.	
DOS	Cranfield University	The De-Orbit Sail (DOS) is intended to demonstrate a novel means for de-orbiting a satellite at the end of its mission lifetime through deploying a sail to increase aerodynamic drag.	
Sea State Payload	Surrey Satellite Technology Limited (SSTL)	Passively monitors ocean roughness via detecting reflected GPS signals and provides orbit determination via dual-band GPS (SGR-RESI).	

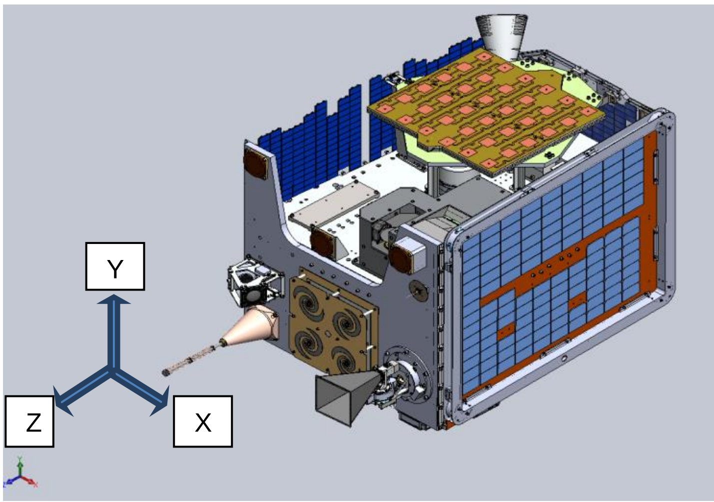
In addition to the payloads, a number of platform technologies are being tested on TechDemoSat-1 to give experience and heritage to new SSTL hardware. The “Product Development” equipment on TDS-1 includes:

- Power: DC/DC converter, charge module, solar cells.
- OBDH: Flash Mass Memory Unit, OBC750, CAN-SU2 protocol
- ADCS: Sun sensors, star sensor, oil-lubricated wheels, radiation monitor, inspection camera,
- RF: FlexRx FPGA-based S-Band receiver, and X-Band Transmitter, X-band horn with Antenna Pointing Mechnism (APM)
- Propulsion: Hollow cathode thruster, resistojet
- Mechanical: Microvibration experiment

See Section 4 for the mission operations timeline.

3.2.2 TDS-1 Axes and GNSS Antenna Locations

Figure 3-5 shows the body-defined coordinate system used in the design of TDS-1. Once in orbit, the +x-axis points towards the velocity direction of the satellite, and the +z-axis points towards the Earth. In Figure 3-5b) the small blue circle indicates the co-ordinate origin, which is in line with the outside edge of the zenith facet.



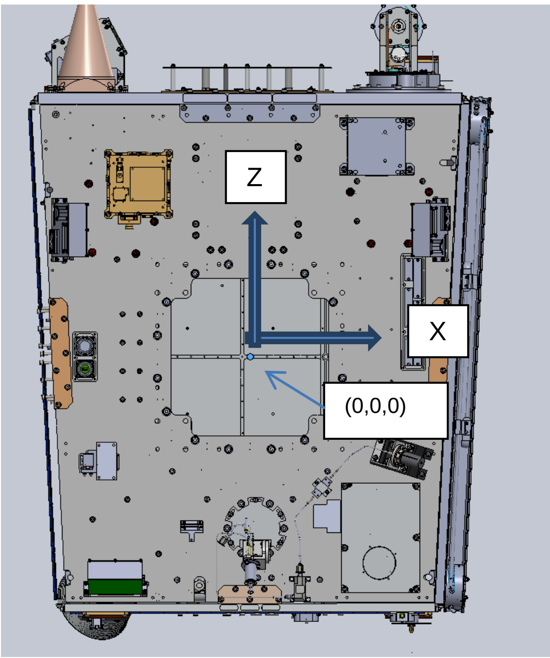
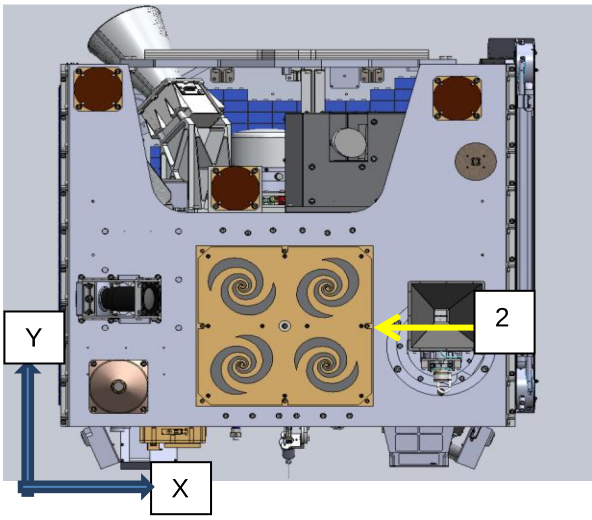


Figure 3-5 a) TechDemoSat-1 and Coordinates, b) Origin on spacecraft (blue point) located centrally on the separation panel, external face

More precisely, when the satellite's +z-axis is aligned with the vector to the centre of the Earth, and the y-axis is normal to the orbit plane, the satellite's attitude is (0,0,0)° roll, pitch, yaw.



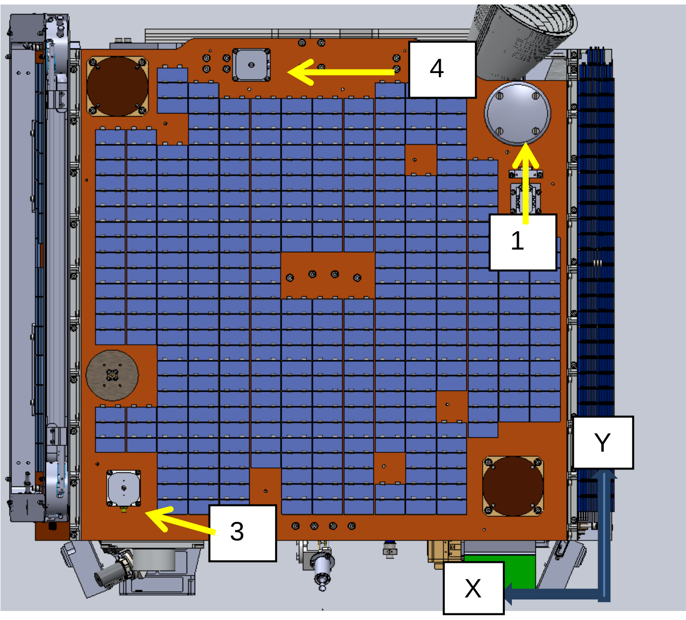


Figure 3-6 TechDemoSat-1 Location and Identification of GPS Antennas a)Nadir, b) Zenith

Figure 3-6a) shows location and identifies nadir antenna as Ant-2. Figure 3-6b) shows the zenith facet and identifies the three zenith antennas. Ant-1 is the dual frequency antenna while the other two are L1 only.

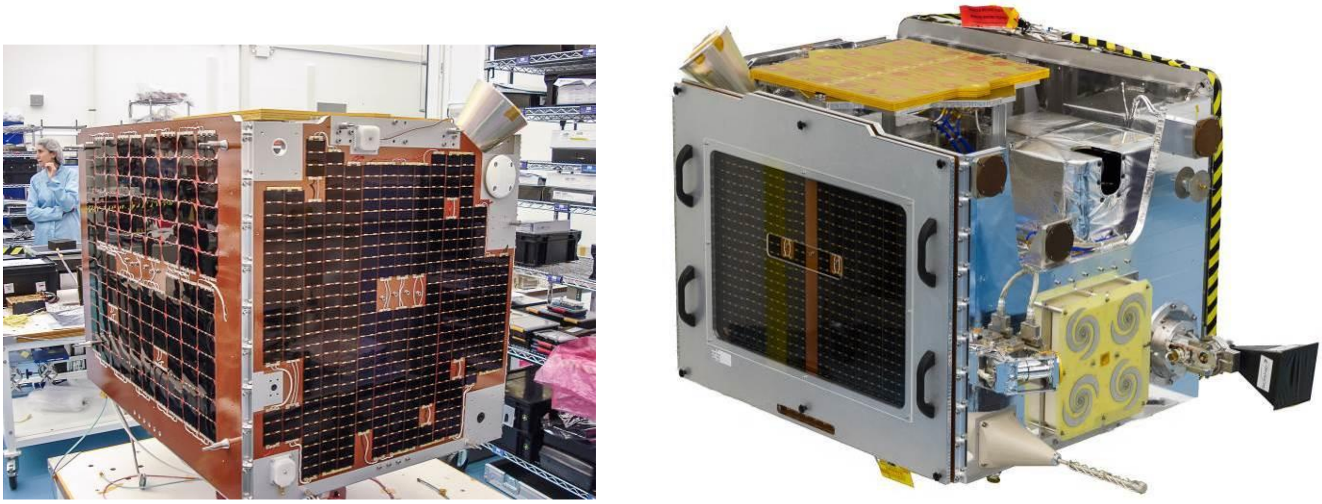


Figure 3-7 TechDemoSat-1 Photos a) Zenith facet during integration (Sep 2012), b) Nadir facet at flight readiness (Feb 2013)

Table 3-3. Body Coordinates: GNSS Antenna and Centre of Mass Locations wrt Origin

Antenna ID	X (mm)	Y(mm)	Z(mm)
1	-259.1	561.6	-447.4
2	5	162.5	463.4
3	267	47	-447.4
4	-96.5	628.5	-447.4
CoM Full Tank	12	237	10
CoM Empty Tank	12	238	14

Table 3-3 gives the location of each GNSS antenna with respect to the co-ordinate origin shown in Figure 3-5b). Each antenna's origin is defined at its internal centre, i.e. the part that is mounted flat to the panel. The table also gives the estimated Centre of Mass locations with full propellant tank and with empty propellant tank.

3.2.3 TDS-1 Launch and Orbit

The TDS-1 satellite was launched on the 8th July 2014 from Baikonor launch site using a Soyuz–2-1b Launch Vehicle, carrying a Fregat upper stage. The primary payload was the Meteor-M №2 weather remote sensing satellite, which was placed into an 825 km 98.8° inclination circular orbit. The launcher upper stage then manoeuvred firstly into an elliptical transfer orbit with a 195 km lower perigee, where it dropped off MKA-FI (PN 2) Russian secondary payload and the support structure. Then the upper stage manoeuvred into a circular orbit at 635 km, with a 98.4 degrees inclination.

There were 6 other non-Russian secondary payloads that are also carried on the launcher: TDS-1, SkySat-2, M3MSat, DX-1, AISSat-2 and UKube-1. All the objects separated in one orbit. Due to separation impulses of different values and directions they were put in close, but nevertheless, different orbits. After separation of all the objects the Fregat US was transferred into its re-entry orbit.

TDS-1 was placed into its orbit about 150 minutes after lift-off with the following osculating elements predicted before launch.

Table 3-4 TDS-1 Orbit (Osculating elements) of Epoch: 01 March 2015 02:58:04 UTC

Perigee height:	623 km
Apogee height:	630 km
Eccentricity:	0.0004868
Inclination:	98.3625°
Right ascension of ascending node:	127.1529°

Perigee argument:	244.7269°
Mean anomaly at epoch:	115.3440°
RAAN rate of change LTAN Drift	1.046°/Day 2145 ° / year 1.42 hour per year

The TDS-1 orbit has a mean semi-major axis a=7005 km and is not absolutely sun synchronous because its LTAN will increase with a rate of about 1.4 hours per year. This can be calculated using equation below:

Nodal Precession: $$\frac{d\Omega}{dt} = -9.95 \frac{\left(\frac{R_{eq}}{a}\right)^{3.5}}{(1-e^2)^2} \cos(i) \quad \text{[deg/day]}$$

Where R_{eq} is the Earth's equatorial radius.

Since launch the propulsion system has been fired a number of times for collision avoidance. The mission payloads are insensitive to LTAN so there has been no propulsion firing to reduce the LTAN drift rate.

The orbital elements are available from NORAD Celestrak with identifier "TDS 1" 40076, or using the navigation solutions of the SGR-ReSI.

3.2.4 Orbit Changing with Propulsion Systems

TDS-1 carries two propulsion units, but neither should significantly alter the orbit.

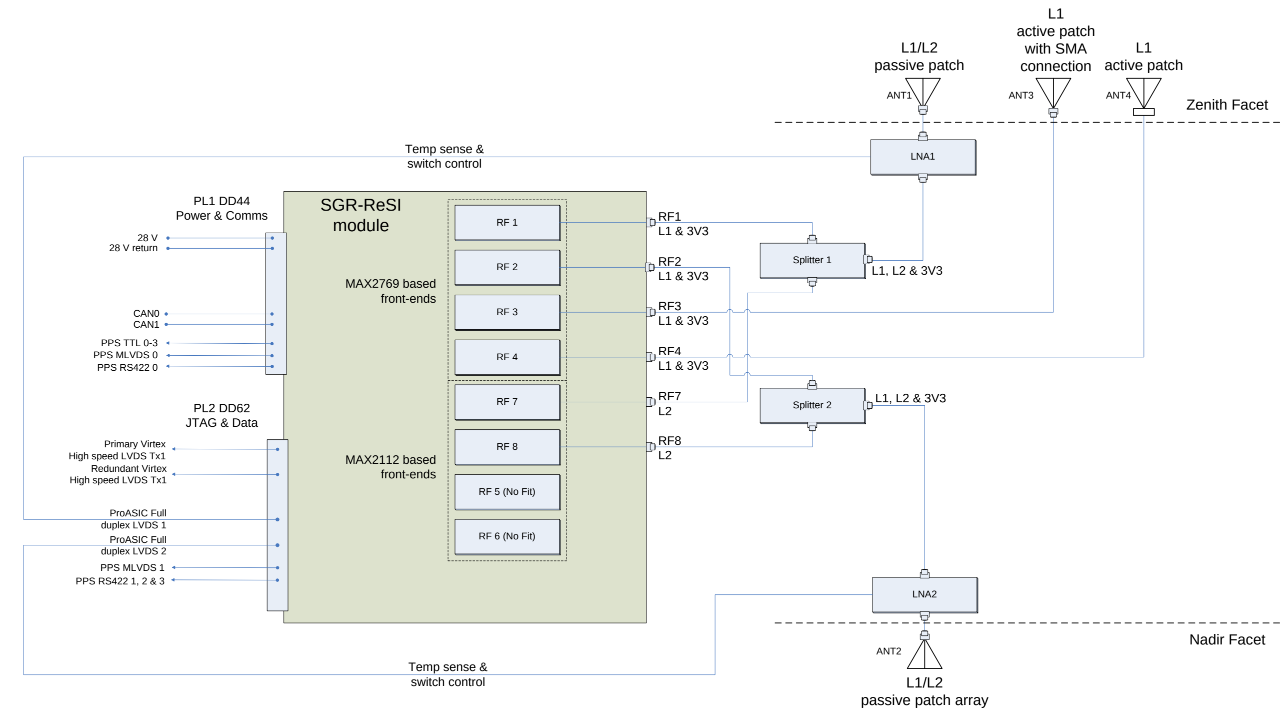
The **Hollow Cathode Thruster** is an experimental 1 millinewton thrust electric propulsion system using xenon propellant provided by the Surrey Space Centre. The nozzle is mounted at an angle in order that any thrust is translated into a torque which will rotate the spacecraft and provide insignificant orbit adjustment. This will be operated in some cases on the 7th or 8th day of the 8 day operational cycle (in spite of xenon ionisation, it is not expected that this thruster will charge the satellite). This will not be indicated in the GNSS-R data, as it is not anticipated to be operated during GNSS-R operations.

The **Resisto-jet** again uses xenon propellant and can provide up to 4 m/s delta-v. It is only included in case some small tweaks to the orbit are deemed necessary.

3.3 RF CONFIGURATION ON TECHDEMOSAT-1

Figure 3-8 shows the RF configuration of the SGR-ReSI on TechDemoSat-1. There are 6 front-ends being used – two for the dual frequency nadir antenna, two for the dual frequency zenith antenna, and two for two further zenith single frequency antennas. (On CYGNSS, by contrast, 3 front-ends are being used – two nadir and one zenith single frequency antennas.)

On TDS-1 there is more hardware capability than is initially expected to be used, but permitting flexible extension of the experimentation. The baseline operations support GNSS receiver operation, and L1 GNSS Reflectometry. The extra frequencies, antennas and reprogrammability will permit further experimentation.



<u>**Note:**</u> only the connections and signals relevant to TechDemoSat-1 are shown in this diagram

Figure 3-8 SGR-ReSI Antenna Configuration on TechDemoSat-1

3.3.1 Nadir Antenna (Passive, Cobham)

The nadir antenna was designed by Cobham (formerly European Antennas) to a specification provided by SSTL, to provide > 12 dBi gain on L1, similar gain on L2 LHCP, maximum width beamwidths, and fitting within 300x300 mm footprint. An off-pointing was requested of up to 10 degrees of the main beam from the antenna normal, similar to the antenna on UK-DMC. This off-pointing slightly increases the number of reflected signals available, and allows the potential for simple steering of the antenna footprint by a yaw rotation of the satellite.

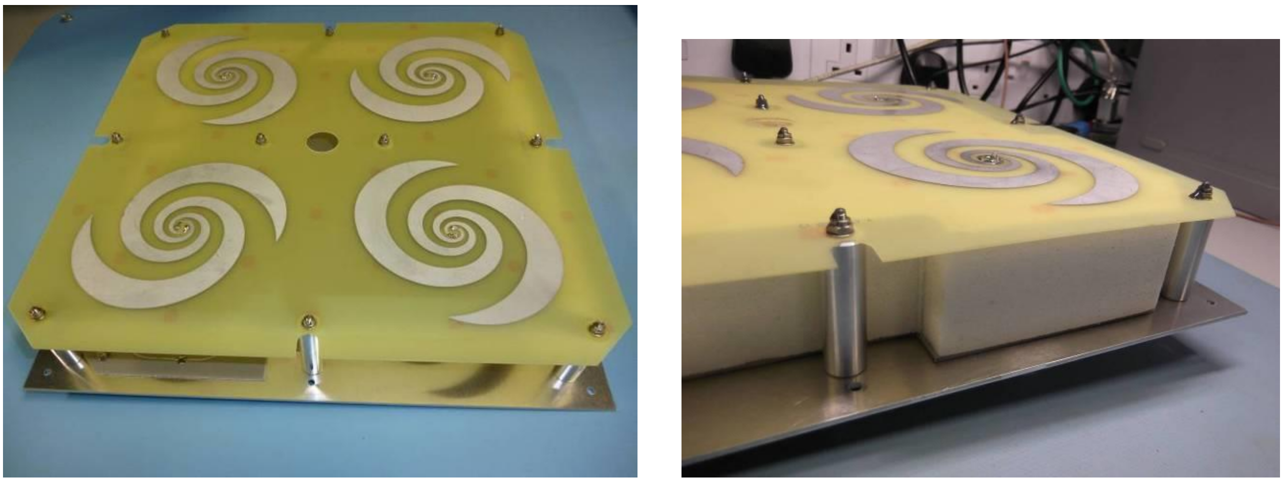


Figure 3-9 a) First FM Antenna, b) Replacement FM Antenna with increased rigidity

Cobham designed an antenna that met the requirements using a fixed array of 4 flared spiral elements. The spiral elements give a wide bandwidth capable of receiving L1 and L2 signals. The figures achieved in Cobham's simulation were 49° x 41° @ L2 with a peak gain of 10.8dBi and 34° x 35° @ L1 with a peak gain of 13.8dBi. Both L1 and L2 beams are off-pointing from nadir by approx. 6 degrees from nadir. In antenna terms, the beam is pointing towards the SMA connector (which is the main asymmetrical feature of the antenna). In TDS-1 terms, this off-pointing is along the –X-axis in the opposite direction to the satellite velocity vector (i.e. pointing behind the satellite as was the case with UK-DMC).

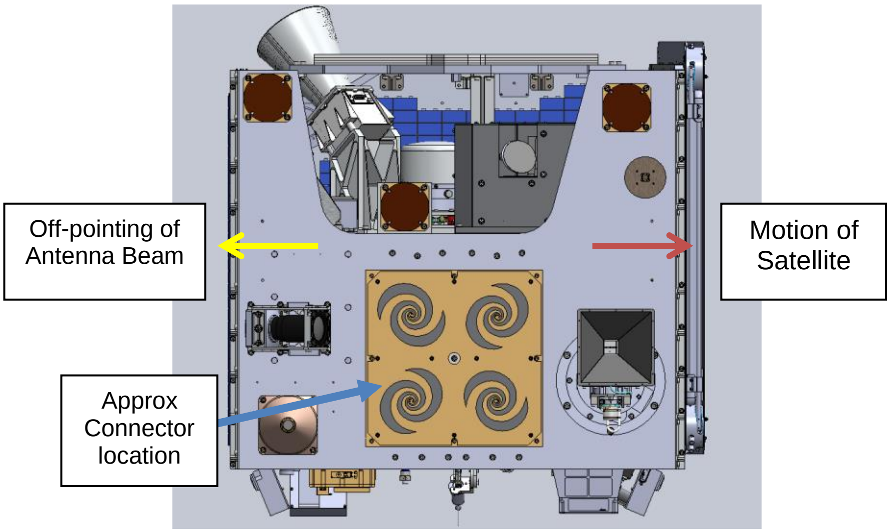


Figure 3-10 –Motion of Satellite and Off-pointing of Antenna Beam

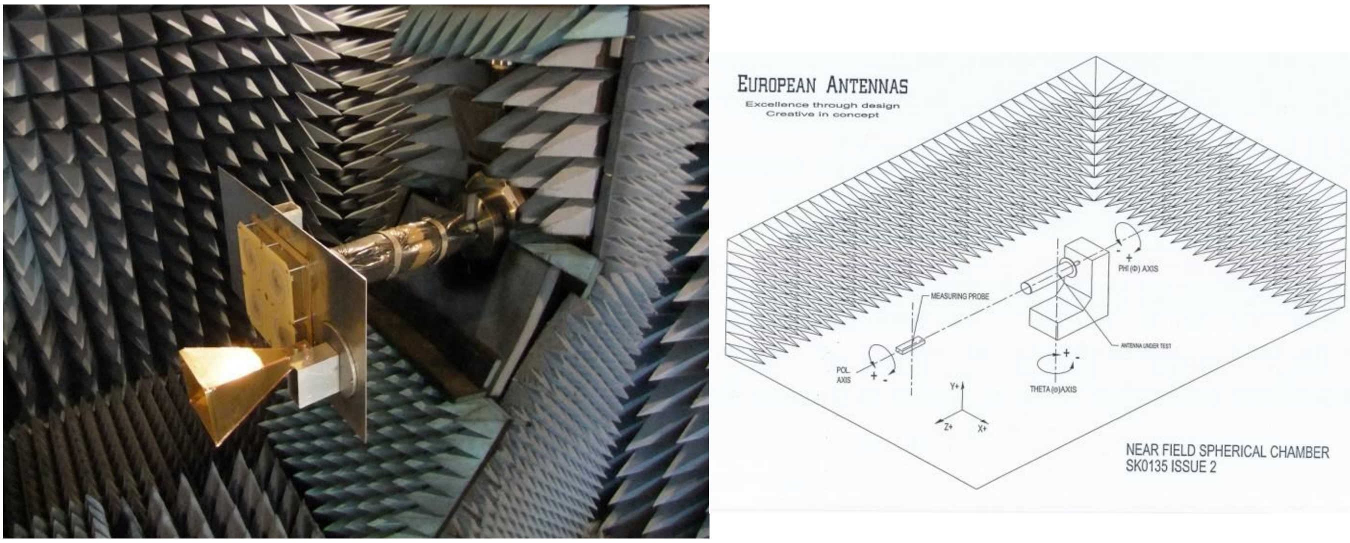


Figure 3-11 Nadir Antenna testing in Anechoic Chamber (at 0° Theta, -90° Phi), plus coordinate system for measurements.

In late 2011, Cobham tested the antenna in three dimensions on a model of TDS-1 Earth-pointing facet, including the X-band horn (Figure 3-11). The results contain multiple cuts at multiple frequencies, including L1 and L2. In addition to these, Cobham have given 1 degree step measurements, at dual frequencies. Results recorded by Cobham are stored and available on request. The pattern has been translated into a map over azimuth and elevation which is available on the MERRByS website.

The model of the facet was important, as tests of the antenna by itself without the facet gave a reduced gain. The X-band horn antenna was modelled in its normal nadir-pointing parked position, but no tests were done to investigate the sensitivity to the horn when it is moved to other positions. The SGR-ReSI nadir antenna off-pointing points away from the horn antenna, so little interaction is expected. When data is being downloaded to the Guildford ground station, however, the X-band horn will move, and at times may impinge and affect the ReSI nadir antenna pattern. This may be flagged in the GNSS-R metadata (TBC).

The antenna was tested with multiple cuts by Cobham - the principal axis cuts are shown in Figure 3-12 and Figure 3-13. After delivery, SSTL confirmed these results using SSTL's anechoic chamber facility and results agreed to within about 0.5 dB (NB SSTL's chamber is not a calibrated facility).

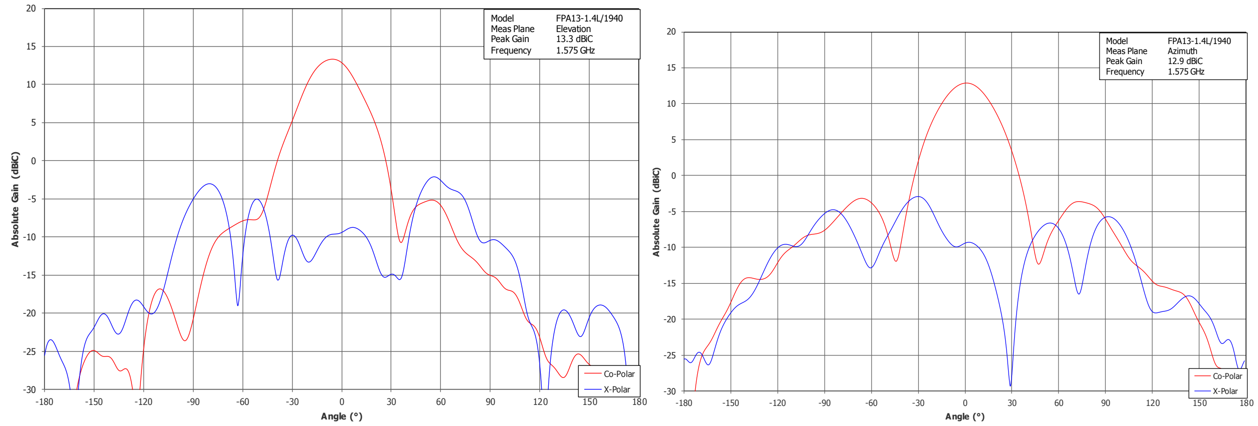


Figure 3-12 First Antenna Plot of pattern at L1 (1.575 GHz)
a) with Elevation (Phi = 0°), and b) With Azimuth (Phi = 90°)

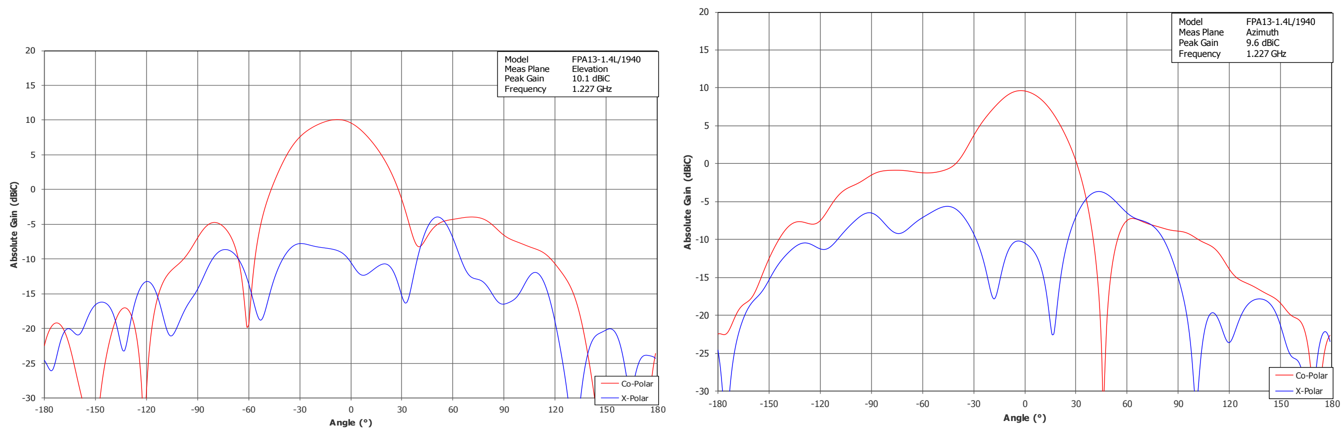


Figure 3-13 First Antenna Plot of pattern at L2 (1.227 GHz)
a) with Elevation (Phi = 0°), and b) With Azimuth (Phi = 90°)

Unfortunately vibration tests with the satellite showed that there was an unacceptable coupling between the antenna and the spacecraft structure, so at a late stage, the antenna was replaced with a rigidised version that included rigid foam between the elements and the base (see Figure 3-9b). Cobham's testing showed no significant change in the test results from the original product, so the test data from the first antenna is being used.

As a short summary, the antenna can be considered to have these characteristics:

Table 3-5 Nadir Antenna Pattern Summary

	GPS L1: 1575 MHz		**L2: 1227 MHz**	
Peak Gain	13.3 dBi		10.069 dBi	
Phi	**0° (i.e. Along track)**	**90° (Cross track)**	**0°**	**90°**
Theta of Peak	6°	1°	8°	-2°
3 dB BW Theta	29° (-8.5°/+20.5°)	32.5°(-15.5°/+17°)	44° (-12°/+32°)	37.5° (-21°/16.5°)
6 dB BW Theta	42° (-15.5°/+26.5°)	46.5°(-22.5°/+24°)	54° (-30°/+24°)	54° (-30°/+24°)

3.3.2 Zenith Antenna (Passive, Antcom)

Part number 3G1215P-XSR-1-S was used. Note this has SMA connector in centre of antenna – another variant has an offset connector.

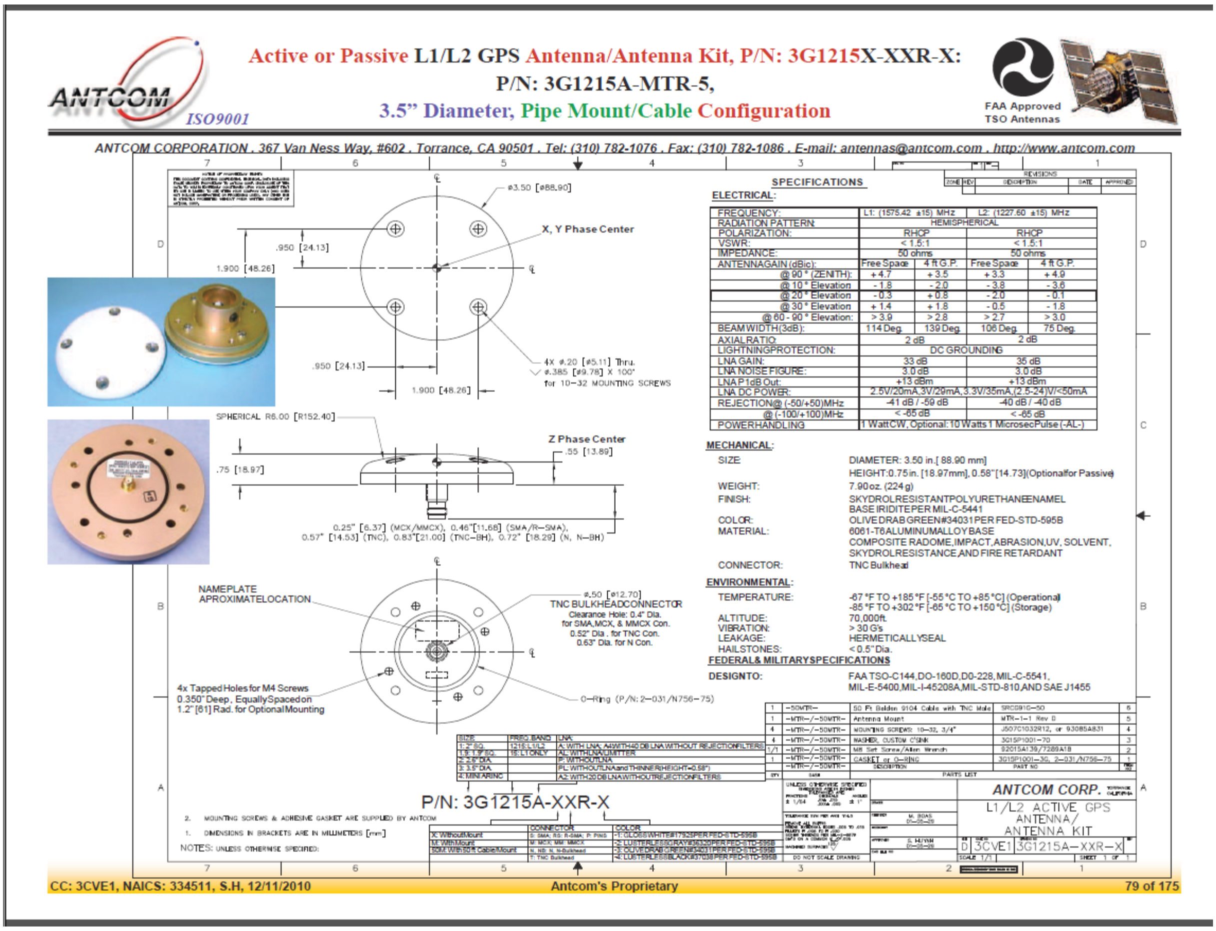


Figure 3-14 –Zenith Antenna Datasheet

The antenna characteristics on datasheet are as follows:

Table 3-6 Zenith Dual Frequency Antenna Pattern Summary

	GPS L1: 1575.42 MHz		GPS L2: 1227.60 MHz	
Gain (dBic)	**Free Space**	**4 ft Ground Plane**	**Free Space**	**4 ft Ground Plane**
90° (zenith)	+4.7	+3.5	+3.3	+4.9
10° Elevation	-1.8	-2.0	-3.8	-3.6
20° Elevation	-0.3	+0.8	-2.0	-0.1
30° Elevation	+1.4	+1.8	-0.5	-1.8
60-90° Elevation	>3.9	>2.8	>2.7	>3.0

It is assumed that the "free space" figures are where the antenna has been tested with no ground plane, while the "4 ft Ground Plane" means that the antenna is tested while mounted on a reflector sized 1.2 x 1.2 metres^2. On TDS-1, the zenith antenna is mounted (see Figure 3-6a) such that on one side of it is the whole reflective facet, but the other side is the edge of the satellite. So it is expected that the antenna gain will be somewhere between the "free space" and "4ft ground plane" figures, with some asymmetries in the pattern.

SSTL tested the Antcom antenna in its own anechoic facilities with a ground-plane of approx 60 x 30 cm. The peak gains of these antennas were measured by SSTL as 3.66 dBi and 4.02 dBi at 1.575 and 1.227 GHz respectively.

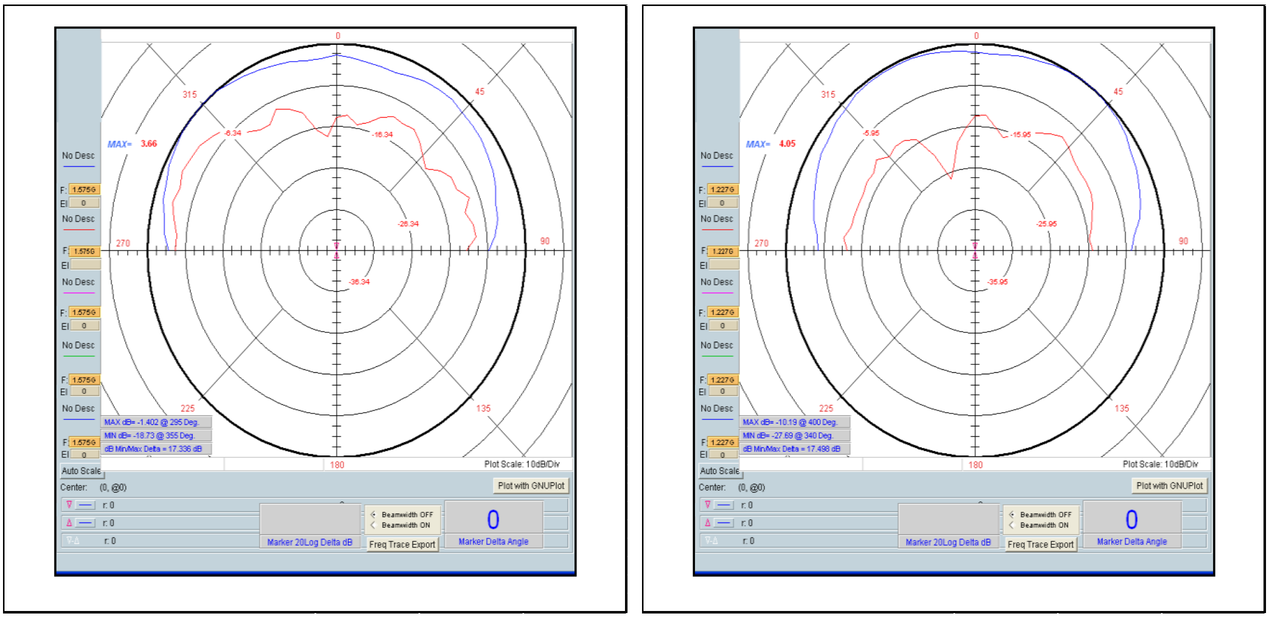


Figure 3-15 –SSTL Tests of Zenith Antenna a) 1.575 GHz, b) 1.227 GHz – Blue trace is co-polar, red trace is cross polar

As no anechoic testing of the antenna was performed on the spacecraft facet, so it is suggested that these assumed symmetrical figures are used, unless one day replaced by measurements from representative hardware, or from space:

Table 3-7 Zenith Single Frequency Antenna Pattern Summary

Gain (dBic)	L1	L2
90° (zenith)	+3.5 dBi	+4.0 dBi
3 dB Beamwidth	125°	90°

3.3.3 Active Antennas

Two extra active antennas have been included to permit experimentation with attitude determination, and to provide a back-up means of navigation should there be problems with the dual frequency passive zenith antenna / LNA combination. Both active antennas use the same single frequency tuned patch element and LNA MMIC, but Antenna 3 is a new cable-less active configuration (cable is a separate assembly) while Antenna 4 is a heritage active cabled antenna. Antenna patterns have been recorded but are not expected to be relevant to reflectometry experiment.

3.3.4 RF Cables

RF cable is routed from each passive antenna to the dual frequency LNA. The cable type is Huber Suhner K02252D (1.1dB/m loss).

Table 3-8 Cable Loss Summary

Cable Lengths	Between antenna and LNA	Assumed Loss	Between LNA and Receiver	Assumed Loss
Nadir Antenna	17 cm	0.2 dB	< 50 cm	<0.6 dB
Zenith Antenna	35 cm	0.4 dB	< 1 m	<1.1 dB

3.3.5 Dual Frequency LNA

Two dual frequency LNAs are used on TDS-1: one for the zenith antenna, and one for the nadir antenna. A third EM LNA (LNA 0) is also listed here as it remains in the laboratory available for further testing. The LNAs target L1 and L2 signals from GPS (1.575 GHz and 1.227 GHz). The initial requirements were for Gain > 20 dB, Noise Figure < 3 dB across temperature.

A wideband dielectric filter is used that covers both L1 and L2. A pair of MAX2659s is used as the main amplifier block, balanced to give a sufficiently wide bandwidth. It is followed by SAW filters that select L1 and L2 bands. (NB for CYGNSS, there is only a requirement for single frequency so a different design is used and, in particular, a cavity filter is used instead of the dielectric filter to give a lower Noise Figure).

A temperature sensor and a switched load were incorporated to allow accurate measurement of noise levels. The LNAs were powered by 3.3V via phantom fed cables.

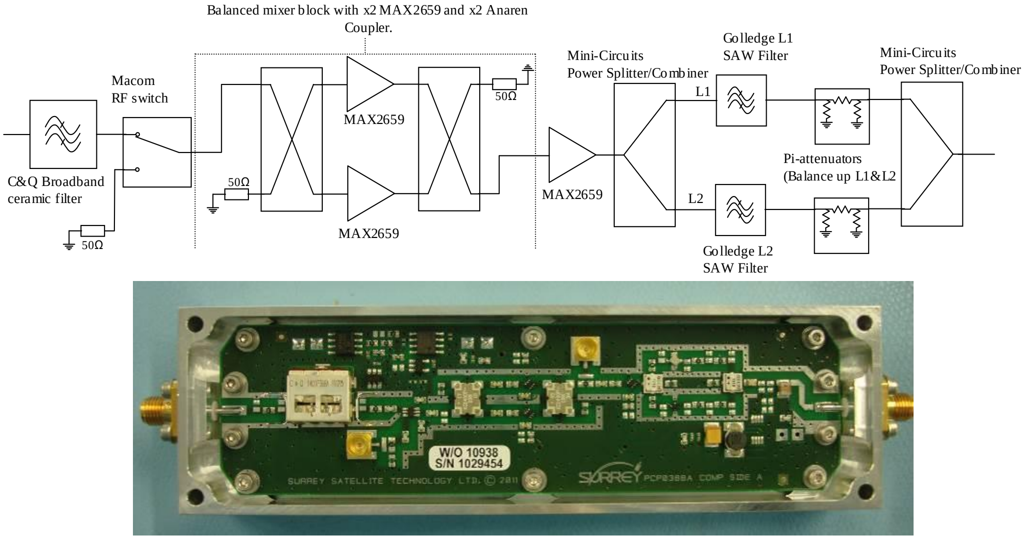


Figure 3-16 Dual Frequency LNA design

Table 3-9. LNA Characteristics - L1 (1.575 GHz)

\ (all in dB)	NF: -20°	NF: +20°	NF: +50°C	S21:-20°	S21:+20°	S21:+50°
LNA 0 (EM)	-	2.48	-	-	27.1	-
LNA 1 (Zenith)	2.23	2.73	2.98	28.6	26.9	26.2
LNA 2 (Nadir)	2.08	2.59	2.91	28.6	27.0	26.2

Table 3-10. LNA Characteristics – L2 (1.227 GHz)

\ (all in dB)	NF: -20°	NF: +20°	NF: +50°C	S21:-20°	S21:+20°	S21:+50°
LNA 0	-	2.48	-	-	24.0	-
LNA 1	2.14	2.65	2.94 dB	25.8	23.9	22.9
LNA 2	2.15	2.64	2.89	25.8	23.7	22.7

Table 3-11. LNA Characteristics (Ambient)

\ (all in dB)	S11 L1	S11 L2	S22 L1	S22 L2
LNA 0	-12.5	-12.2	-7.0	-6.9
LNA 1	-9.5	-11.2	-6.8	-6.8
LNA 2	-10.4	-12.7	-7.1	-6.8

The current drawn is 25.0mA at ambient with the 3.3V power supply (approx. 83 mW power draw).

The temperature sensing within the LNA uses a Maxim sensor, which has been tested against thermocouples, achieving agreement within 2 degrees.

Table 3-12 Temperature sensing

	SGR-ReSI Measure	Thermocouple
Temp @ Cold (°C)	-19.5	-21
Temp @ Hot (°C)	49	50

When the 50 Ohm load is switched in, there is an isolation from the input antenna of approximately 20 dB. In normal operating situations, this is sufficient to bury the GPS signals (direct or reflected) under thermal noise. Although, if a strong signal is present (e.g. interference, or strong simulated GPS signals), the switched load attenuation can be overcome.

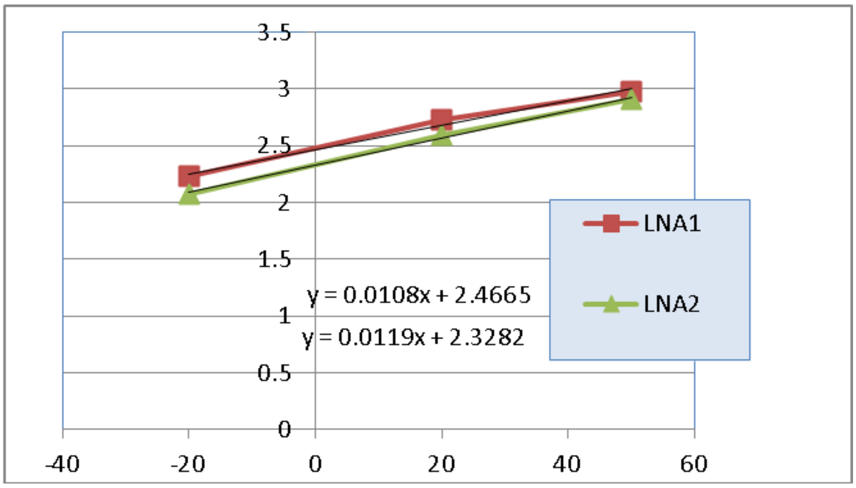


Figure 3-17 LNA Noise Figure Behaviour with Temperature (plus equations)

The relationship of LNA Noise Figure with temperature is shown in Figure 3-17. Where the X-Axis is temperature in degrees Centigrade and the Y-axis is noise figure in dB.

3.3.6 RF Daughterboards - Max2769

The MAX2769 RF front-ends designed specifically for GNSS L1 signals and are the main front-ends used for receiving GPS L1 signals by the SGR-ReSI on all antennas (both on TDS-1 and on CYGNSS). A Gollege prefilter was included in the design of the RF front-end, but was omitted for the RF channels that were fed by the dual frequency LNA (i.e. RF1, 2). This is because the dual frequency LNA design includes a filter after the LNA, which effectively excludes noise in the image frequency zone.

The Max2769 has settings that affect the data that is collected including the most significant:

Table 3-13 RF Front-End Summary

Parameter	Description	Setting on TDS-1
Pre-filter	SAW Filter can be fitted	Not fitted on RF1 & 2 – using filter in LNA
LNA	Two choices – LNA 1 / 2	LNA 1 (18 dB gain, 1.4 dB NF)
Current mode settings	LNA, LO, Mixer	Normal (defaults)
IF	Intermediate frequency of signal	4.188 MHz
Bandwidth Setting	Software-controlled adjustments in front-end	Initial tests with default 2.5 MHz BW. Alternative is 4.2 MHz for flatness & Galileo signal reception. Both BPF. (Codes: 010101 or 001011)
Filter Order Selection	3^{rd} or 5^{th} Order	5^{th} Order (default)
Sample Rate	Data is clocked from A/D	16.367 MHz
Sample Outputs	Different options, e.g. I&Q	I Only, 2 bits (Sign and Mag)

	at baseband can be supported	
Gain Control	AGC and Programmable Gain supported	Initial Tests with AGC enabled (independent I & Q) and unmonitored Later operations with Programmable Gain Control
Low ADC, DC Offset	Control parameters	Both Set (default)

One potential anomaly on RF-4 (L1, fed by heritage antenna), the signal was apparently lost during cold testing of thermal vacuum, but it returned at ambient. Due to the low priority of this antenna and the late stage in the project, this anomaly was not investigated and resolved. One possible cause is the rework on the RF front-end to improve the RF match - an RF cable was soldered directly onto this front-end to bypass the SMA connector (DRs #12099, #12535). This antenna will rarely if ever be used and should not have any relevance to GNSS Reflectometry activities.

3.3.7 RF Daughterboards – Max2112

These second type of front-ends, Max2112, have been included to allow reception of L2C signals, and are connected to antennas 1 and 2 only (not present in CYGNSS configuration). They are intended for dual frequency operation (L2C), but could potentially be repurposed as an alternative way of diagnosing L1 signals, as there is no pre-filter (instead relies on LNA filter).

3.3.8 Link Budget for Main Signals

The System Noise Figure is dominated by the LNA Noise figure and due to the high gain of the module is hardly sensitive to the Noise Figure of subsequent stages at all.

In contrast, the system gain is affected equally by every amplification and attenuation stage from the antenna through to digital quantization (and is also affected by digital signal processing methods), so is not separated or quantified here. The contribution of the feeds and the Noise Figure is shown below.

Table 3-14: TDS-1 System Noise Temp (L1 only)

At L1	**Gain (dB)**	**Noise Fig (dB)**	**Noise Temp (°k)**	**T Contribution**
			Te=To(F-1)	T+T2/G1+T3/G1G2…
Feed1	-0.2	0.2	13.7	13.7
Amplifier	26.9	2.8	262.6	275.0
Feed2	-1.5	1.5	119.6	0.3
Receiver		16.0	11255.1	34.0
Rx System NF (dB)		**3.2**	Rx System Noise Temp (°K)	322.9
(For reflectometry, assume antenna is pointing at Earth at ~ room temperature)			*Antenna Noise Temp (°K)*	*290.0*
System Noise Temp (°K)		**612.9**		

The Noise received by the SGR-ReSI dictates the Automatic Gain Control, and the bit distribution of a manually controlled gain. The desired signal is not visible, but is embedded within the noise, and is only recovered after despreading. Hence the gain settings of the front-end are based upon the voltage level of the noise, and not the reflected signal. This is illustrated in Table 3-15, where it can be seen that the programmable voltage gain has more than adequate dynamic range to deal with minimum and maximum noise levels, and the nominal amplification of the embedded signal is also indicated.

Table 3-15: System Gain Stages (L1)

	Minimum Noise	Nominal Noise	Max Noise	Nominal GNSS Signal	Notes
Output from Antenna[1]	-110.5 dBm	-108 dBm	-106 dBm	-145 dBm	Assume Noise is 2 MHz (K T B = -228+27+63)+30
Feed 1	-0.2	-0.2	-0.2		Change insignificant
Ext LNA	26.2	27.0	28.6		
Feed 2 (est.)	-0.6	-0.6	-0.6		
PCB track to F/E (est.)	-0.2	-0.2	-0.2		
RF F/E LNA 1	18.6	19	19.2		
Gain Sub-tot	43.8	45	46.8	45	
Power Level dBm (50 Ohm)	-66.7	-63	-59.2	-100	
Level in Volts	103 uV -79.7 dBV	158 uV = -76 dBV	245 uV =-72.2 dBV	2.23 uV =-113 dBV	30 dB adj to go to Watts P =V^2/R, still 50 Ohms
Programmable Voltage Gain (No longer assuming 50 Ohm)	36	69	96	69	
Output level in V	-43.7 dBV 0.006 V	-7 dBV **0.45 V**	23.8 dBV *15.5V*	-44 dBV **0.0063 V**	ADC Target 0.4V Saturates above ~1V
Signal Impl. Loss, 2 bit, dB	1.1	1.15	1.35	1.15	NB Does not take into account NF losses

Note 1: Minimum noise is when antenna noise is zero, Max is set as 2 dB > room temperature.

The signal Implementation loss is a function of the 2-bit sampling, but also the gain setting. The gain setting has a resolution of 1 dB steps. If the gain is ideal for the noise level (i.e. magnitude bits are high 33% of the time), the implementation loss is 1.1 dB. If the gain is wrong by nearly a full 1 dB, the implementation loss is 1.35 dB. Most of the time, however, it is likely to be within around 1.15 dB level. If interfering noise is present (e.g. from transmitters on the satellite, or interferers on the ground), the implementation loss may rise to the higher value. In this case, a clue may be present in the measured bit distribution in the front-end readings.

3.4 ON-BOARD CALIBRATION APPROACH

The collection of data, onboard processing, and processing on the ground to recover sea state requires an understanding of the sensitivity of each possible parameter on the outputs of the model inversion. Parameters include transmit properties (GPS satellite power, antenna pattern, attitude), channel (ionospheric and tropospheric effects), and receiving instrument (amplitude, noise figure, antenna pattern, attitude). Sea state retrieval approaches differ; while some depend on absolute radiometric knowledge, others are able to make use of relative amplitudes.

The GPS Reflectometry experiment on UK-DMC had Automatic Gain Control in its front-end, such that the RF front-end amplitude was automatically regulated to keep Gaussian noise evenly spread across the 2 bits of the A/D converter.

The SGR-ReSI can operate in AGC mode, or it can be operated in Programmable Gain Control mode. In this mode the processor controls the front-end gain in 1 dB steps to ensure the correct bit distribution of the 2 bit sampling.

A switched load in the nadir LNA provides a reference ambient temperature black-body source. By switching in the load at regular intervals, the antenna noise can be compared to a known noise reference, and hence estimated, allowing the derivation of the received signal power from the signal to noise measurement.

There is also a switched load in the direct antenna LNA – this allows the estimation of the direct power of the GPS signals, which can be referred against a standard direct power level to adjust the scattering cross-section calculation – or compared to other measurements of the direct power on the ground.

4 OPERATIONS AND ANALYSIS

The TechDemoSat-1 project-funded activities include initial commissioning of platform and limited commissioning of payloads, basic payload scheduling and download of unprocessed data.

The current plan indicates one month for platform commissioning, and two months of payload and PD (SSTL's Product Development hardware) commissioning prior to more extensive operation of the payloads. After approximately 7 months of special payload operations (TBC), TDS-1 will transition to a data collection phase.

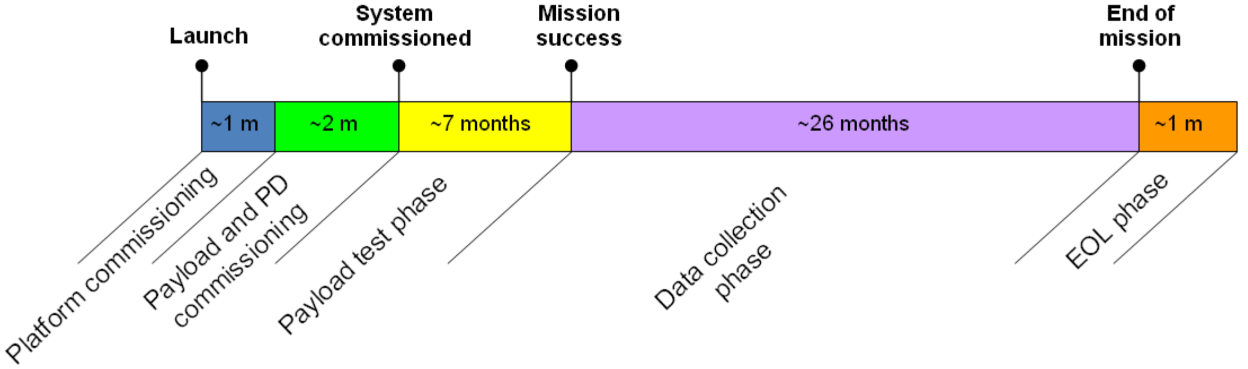


Figure 4-1 Commissioning Plan

4.1 PLATFORM COMMISSIONING

The platform was commissioned during Month 1. This commissioning ensures that the satellite is safe, communications are acceptable and the attitude is controlled. Avionics sub-systems are commissioned one at a time. The SGR-ReSI was briefly tested during this time for its navigation function but not its payload function.

4.2 PAYLOAD AND PD COMMISSIONING

The SGR-ReSI was operated in the second month, though a third month is allocated after launch to allow for some slippage of payload and PD commissioning. After testing the health of the co-processor, the application code and FPGA image will be uploaded to support reflectometry. Then one collection of raw data will be taken (approx. 1 minute), and an operation of processed DDMs will be collected.

4.3 PAYLOAD TEST PHASE - 8 DAY CYCLE

The SGR-ReSI is operated in the first 2 days of the 8 day cycle, and shares its operations with the MSSL ChaPS instrument. This will continue for 7 months to complete the payload test phase.

As of February 2015 the SGR-ReSI is being operated for more time than originally anticipated. It is running for the full 48 hours slot in DDM collection mode, interrupted for 3 lots of 1GB raw collections and for about 10 minutes every 2 orbits to reduce the data loss from any unexpected outages.

4.4 DATA COLLECTION PHASE - LONGER TERM PAYLOAD OPERATIONS

Of the TDS-1 experiments, it is expected that some technologies will be demonstrated adequately with quite short-term tests. Others, such as the SGR-ReSI have longer term data gathering goals. If the power and data budgets permit, a new operating schedule may be envisaged that permits more continuous concurrent operation of these payloads.

4.5 SCHEDULING METHODOLOGY

The mission operation system accepts commands from each of the payload operators into a common scheduling scheme for TechDemoSat-1, and calculates to ensure the safety criteria of the satellite are met by the scheduled operations (thermal, power, attitude, etc.) before issuing “sked-files” to the satellite uplink.

For DDM operations, scheduling provides standard settings as far as possible for the sake of consistency. The collection period is currently spilt into shorter operations periods of two orbits, but could be run continuously.

For raw data operations, a time for collection is required, and the appropriate settings for the SGR-ReSI. SSTL and NOC are able to predict the time of a cross-over of reflections of a particular GPS satellite. This can be fed into the schedule. The schedule must also ensure that the SGR-ReSI will be operated in positioning mode some time prior to the raw data collection to allow the collection of the meta-data. These raw data collections must be scheduled >1 week beforehand (sometimes as long as 2 weeks beforehand) to make use of the standard mission planning system. The normal mode of raw data collection will last for 2 minutes 20 seconds, which corresponds to the SGR-ReSI onboard mass storage of 1GB, for GPS L1 on zenith and nadir antennas.

A special collection to target a hurricane is unlikely to be possible using the normal scheduling system as it may need less than 2 days’ notice. In this situation, there is the potential for bypassing the automated system and using manual scheduling of TDS-1. This is not expected to be possible during the early phases of the mission when days 7 and 8 of the cycle are in high demand for testing the experimental platform subsystems.

4.6 OPERATIONS PLANNING

The Campaign Implementation Plan includes phases for commissioning, calibration, L0-L1 testing, L1-L2 validation and data dissemination.

The L0 to L1 DDM processing on the satellite can be verified by collecting raw data and DDMs at the same time, allowing ground-based processed comparisons. Calibration operations include using the LNA internal reference load to measure the noise environment, and the possibility of receiving a beacon licensed at L1 to be broadcast from the ground.

The L2 validation requires a wide range of data collection over buoys, satellite cross-overs, etc. to ensure that a range of wind speeds are collected, with independent data. The continuous stream of DDMs is valuable for building up an archive of data that can be verified.

4.7 SPECIAL EXPERIMENTATION

In addition to the routine DDMs and raw data collection, special experimentation with the SGR-ReSI will be planned for. This might include variation of integration times (coherent and incoherent), SAR mode processing, off-pointing the antenna, dual frequency raw data collection, and ice and land collections. The hardware architecture allows Galileo signals to be targeted (and some lower frequency Glonass) – both direct and reflected. Potentially the satellite can be configured to stream raw data from the SGR-ReSI directly into the main satellite data recorder. This increases the size of files collected from the SGR-ReSI internal limit of 1 GByte to >100 GByte, i.e. up to 2 hours of continuous raw data collection.

5 GROUND PROCESSING SYSTEM

The TechDemoSat-1 project only provides a basic ground segment that will send schedule commands and store unprocessed data for the payload operators to extract and process themselves.

A separate ground processing facility has been implemented, referred to as MERRByS (Measurement of Reflected Radionavigation-signals By Satellite), This is being developed to allow the dissemination of the data to future users of GNSS-R data. In particular, as highlighted in the recent UK-funded WaveSentry project, the cataloguing of data for scientific validation, and fast delivery capability for exploitation by meteorological users is of importance.

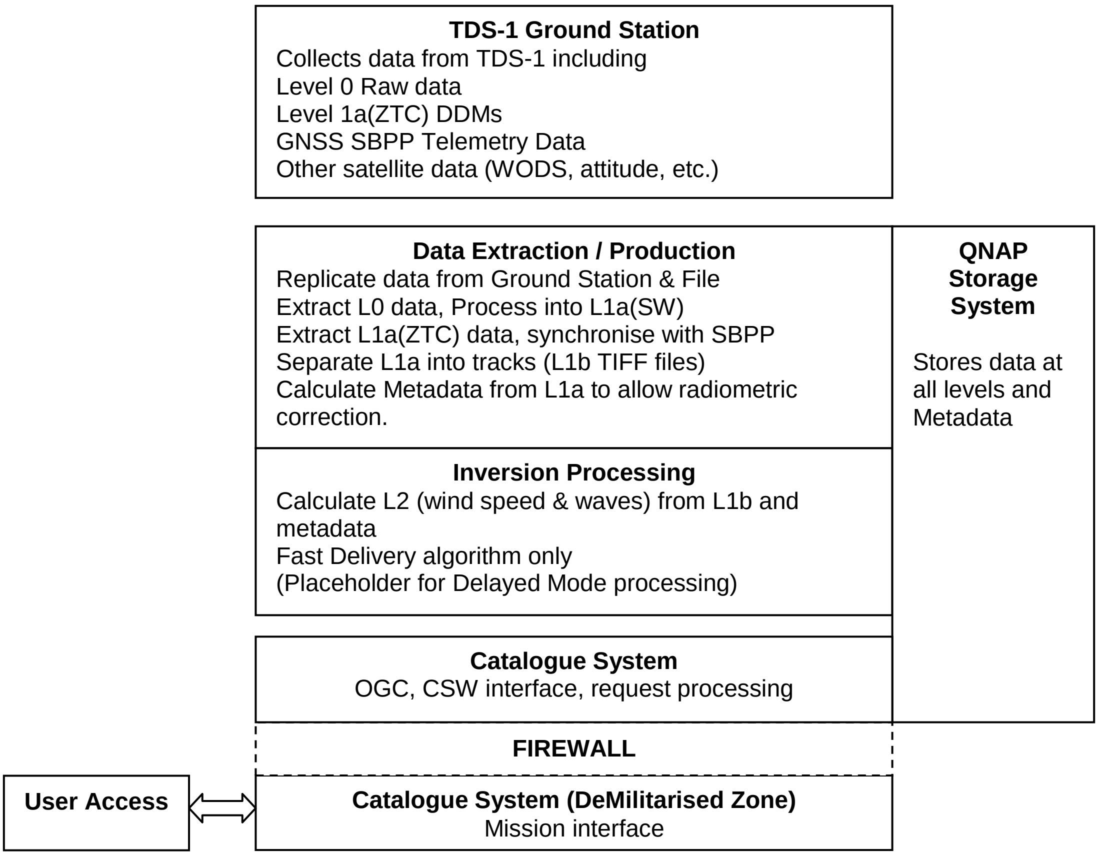


Figure 5-1 GNSS-R Ground Data Processing Architecture

More detail is given in RD-2 “MERRByS Product Manual - GNSS Reflectometry on TDS-1 with the SGR-ReSI”. This contains further information on the processing algorithms and available data.