COPERNICUS SENTINEL-1 SATELLITE AND C-SAR INSTRUMENT

Aniceto Panetti (1), **Friedhelm Rostan** (2), **Michelangelo L'Abbate**(1), **Claudio Bruno**(1), **Antonio Bauleo** (1),
Toni Catalano(1), **Marco Cotogni** (1), **Luigi Galvagni**(1), **Andrea Pietropaolo**(1), **Giacomo Taini**(1),
Paolo Venditti(1), **Markus Huchler**(2), **Ramon Torres**(3), **Svein Lokas**(3), **David Bibby**(3)

(1) *Thales Alenia Space Italia - Via Saccomuro 24, 00131 Rome, Italy, Email:*

Aniceto.Panetti@Thalesaleniaspace.Com, Michelangelo.LAbbate@Thalesaleniaspace.Com,
Claudio.Bruno@Thalesaleniaspace.Com, Antonio.Bauleo@Thalesaleniaspace.Com,
Toni.Catalano@Thalesaleniaspace.Com, Marco.Cotogni@Thalesaleniaspace.Com,
Luigi.Galvagni@Thalesaleniaspace.Com, Andrea.Pietropaolo@Thalesaleniaspace.Com,
Giacomo.Taini@Thalesaleniaspace.Com, Paolo.Venditti@Thalesaleniaspace.Com

(2) *EADS Astrium GmbH, D-88039 Friedrichshafen, Germany, Email:*

Friedhelm.Rostan@astrium.eads.net, Markus.Huchler@astrium.eads.net

(3) *ESA/ESTEC – Keplerlaan 1 Postbus 299 AG 2200 Noordwijk, The Netherlands, Email:*

Ramon.Torres@esa.int , Svein.Lokas@esa.int, David.Bibby@esa.int

ABSTRACT

The Copernicus Sentinel-1 Earth Radar Observatory, a mission funded by the European Union and developed by ESA, is a constellation of two C-band radar satellites. The satellites have been conceived to be a continuous and reliable source of C-band SAR imagery for operational applications such as mapping of global landmasses, coastal zones and monitoring of shipping routes. The Sentinel-1 satellites are built by an industrial consortium led by Thales Alenia Space Italia as Prime Contractor and with Astrium GmbH as SAR Instrument Contractor.

The paper describes the general satellite architecture, the spacecraft subsystems, AIT flow and the satellite key performances. It provides also an overview on the C-SAR Instrument, its development status and pre-launch SAR performance prediction.

1. SATELLITE ARCHITECTURE

The Satellite mechanical configuration is based on the Thales Alenia Space Italia PRIMA multipurpose platform concept, also used for the 4 satellites of the COSMO-SkyMed constellation (ASI) and in Radarsat-2 (CSA). The PRIMA platform comprises three main modules, which are structurally and functionally decoupled to allow for a parallel module integration and testing up to the satellite final integration.

The modules are:

- Service Module (SVM), carrying all the bus units apart from the propulsion ones;
- Propulsion Module (PPM), carrying all the propulsion items connected by tubing and connectors;
- Payload Module (PLM), carrying all the payload equipment including the SAR Instrument antenna.

Figure 1. Artist's View of Sentinel-1 with Deployed Solar Arrays and SAR Antenna

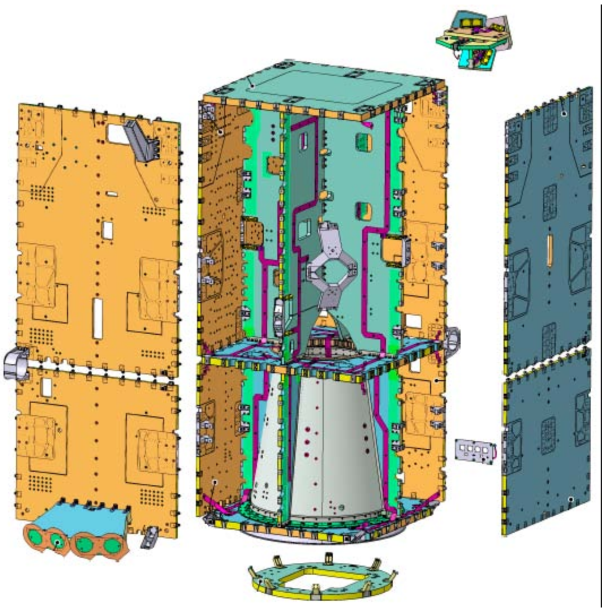

Figure 2. Sentinel-1 Platform: 3D Exploded View

Proc. 'ESA Living Planet Symposium 2013', Edinburgh, UK
9–13 September 2013 (ESA SP-722, December 2013)

Most of the PPM is enclosed in the SVM, being integrated into the cone section interfacing the Spacecraft to Launcher Adapter, while the PLM is mounted onto the SVM allowing the payload units/appendages allocation through four lateral panels and the upper platform. Fig 1 & 2 show some views of the overall satellite and the platform design.

2. SATELLITE SUBSYSTEM

The Satellite platform provides the following functional subsystems:

a) Structure Subsystem (STR)
The STR provides the accommodation for all platform and payload units. A box type structure has been adopted using external aluminium sandwich material, with a central structure in CFRP. A modular approach has been taken whereby the payload is mounted to a dedicated part of the structure, allowing separate integration & test of the payload before integration to the main part of the structure carrying the platform units. This has many advantages for the overall AIT process.

b) Thermal Control Subsystem (TCS)
The TCS provides control of the thermal characteristics and environment of the Satellite units throughout all phases of the mission. In general the TCS is passive, with the control provided by means of standard techniques such as heat pipes, radiators and MLI. Survival heaters are provided to prevent units becoming too cold during non-operative phases.

c) Avionics Subsystem (AVS)
The AVS performs both Data Handling & Attitude/Orbit Control functions. This is realized through the concept of an integrated control system that performs the control of the platform and payload. The AVS performs all data management & storage functions for the Satellite, including TM/TC reception and generation, subsystem & unit monitoring, autonomous switching actions and synchronization. The AVS includes the AOCS processing and the interfaces to the AOCS sensors Star trackers, fine sun sensors, and fine gyroscope and actuators, 4 reaction wheels, 3 torquerods, 14 thrusters and 2 solar array drive mechanisms. Telecommand data will be received from the TT&C subsystem and will be decoded and deformatted in the AVS. The AOCS comprises all means to perform transfer and on-orbit control maneuvers and to control all necessary Satellite attitude and antenna pointing states during all mission phases, starting at separation from the launcher until de-orbiting of the Satellite at end of life. This includes the attitude steering of the LEO Satellite to provide both yaw and roll steering capability. At present, a dedicated precise orbit predictor is implemented within the AOCS, in addition to making use of the data uploaded to the payload by the GPS constellation. The AOCS is supported by a very reliable FDIR scheme.

d) Propulsion Subsystem (PRP)
The PRP based on 14 RCT located in 4 different sides of the spacecraft, provides the means to make orbit corrections to maintain the requested tight orbit control throughout the mission. Initially, corrections are required to reach the final orbit position after separation from the launcher. During the mission, some infrequent corrections to the orbit are necessary to maintain the requirements upon the relative and absolute positioning of individual Satellite. The thrusters located on the –Z side of the satellite are specifically dedicated to Attitude control during the Safe Mode.

e) Power Subsystem (EPS)
The EPS is responsible for management of the power distribution, including power generation (via solar array), power storage (via battery) and power distribution to individual subsystems & units. A power control and distribution unit (PCDU) and a C-SAR Antenna Power Supply unit (CAPS) are foreseen to handle these functions. The PCDU is designed to provide adequate grounding, bonding & protection for the overall electrical system (e.g. by use of fuses) and must also be integrated into the Satellite FDIR concept to ensure that adequate power resources and management are available in the event of onboard failures. Li-Ion battery technology has been selected for the batteries in view of the large benefits offered in terms of mass and energy efficiency.

f) Telemetry, Tracking & Control (TT&C)
The TT&C subsystem operating in S-band, receives the up-linked data from the TT&C stations as well as down-linking the TM data from the Satellite. Two antennas are required to provide the full coverage, one for nominal (earth pointing) operations, one for use in non-nominal cases (zenith pointing).

h) Optical Communication Payload (OCP)
The OCP will be embarked on S-1A and S1-B spacecrafts, to provide Data Relay connection towards GEO Satellite by means of Laser Communication Terminal. The OCP is an ESA Customer Furnished Item and it will be operated in addition to the baseline PDHT system.

g) Payload Data Handling and Transmission (PDHT)

Data generated by the Sentinel-1 satellite payload (C-SAR) will be stored, formatted and transmitted to the ground stations by the PDHT subsystem. The PDHT includes all the necessary functions to interface different sources at different data rate, for the data acquisition, storage, formatting, and RF transmission (X-Band communication equipment) to Ground Stations. The PDHT interfaces also the OCP for data transmission to GEO satellite. During downlink operations, stored data are formatted according to the CCSDS standard (AOS

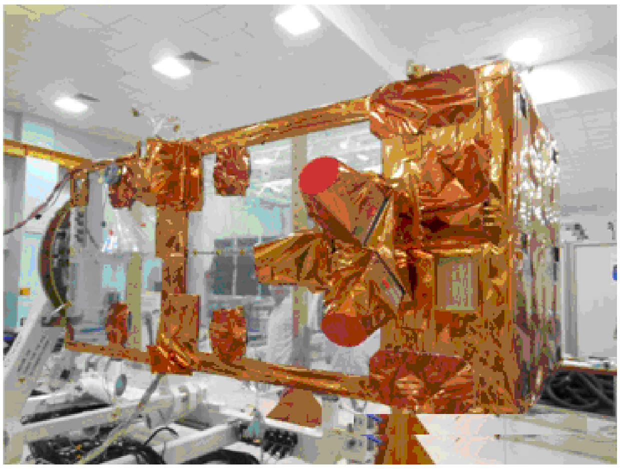

Figure 3. Sentinel-1 Satellite Stowed View (+Y Side)

Space Data Link Protocol) and transmitted towards the X-Band transmission assembly, where 4D-TCM 2.5 bit/s/Hz coding, 8-PSK modulation, up-conversion to X-Band, power amplification and RF filtering are executed. In order to provide flexibility in the downlink operation, the PDHT is designed with two X-Band independent links. The PDHT provides an overall input/output throughput of about 1950 Mbps, with a payload input data rate of 2*640 Mbps (multi-polarization acquisition) or 1*1280Mbps (single-polarization acquisition) and a transmitted symbol rate of 2*112 MSps. The data storage capacity is higher than 1410 Gbits EoL. The antenna isoflux coverage zone provided is about ±64 deg with respect to the nadir to allow link establishment with ground starting from the ground antenna elevation angle of 5 deg above the horizon.

h) Harness Subsystem (DPH)

Sentinel-1 Harness Subsystem provides the electrical interconnections necessary to allow the distribution of power and signals. It is composed of the following main components:

- DC Harness for Unit & Heater power supply
- TM / TC signals distribution (thermistors acquisition, status telemetries, discrete commands, serial digital, broadcast pulses, etc.)
- RF Harness including Waveguides, coaxial cables and RF miscellaneous
- NEA / Thermal Knife Harness for deployment activation of SAR antenna, Solar Panels appendages
- 1553 Data BUS Harness for data exchange between Bus Controller (BC) resident in SMU and Remote Terminals (RT)
- Launch Vehicle Umbilical Connector Harness for on-ground Spacecraft to launch vehicle interconnection

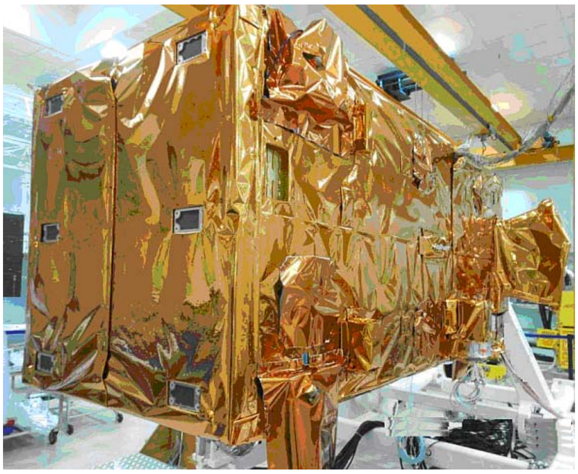

Figure 4. Sentinel-1 Satellite Stowed Views (+Z and –Y Sides)

3. AIT ACTIVITIES AND FLOW

The spacecraft level AIT activities concern all the operations related to the build-up and testing of the PFM spacecraft. The spacecraft tests involve :

a) Spacecraft Mechanical Tests

- Static Load (during sine test),
- Sine Vibration and Acoustic Vibration,
- Fit Check & Separation Shock (with the launcher interface adaptor),
- Appendages Deployments (namely SAR antenna and Solar Arrays),
- Alignments (of all alignment critical elements),
- Mass Properties measurements (namely centre of mass and inertia moments),

b) Spacecraft Propulsion Tests

- Latching Valves Activation (TM-TC)
- Thrusters Activation and Flow Rate (TM-TC)
- Pressure Transducer Calibration Check (TM-TC)
- Thrusters' Valves Leak Test
- Latching Valves Leak Test, overall Leak Test.

Figure 5. Sentinel-1 Satellite entering the Thermal Vacuum Chamber

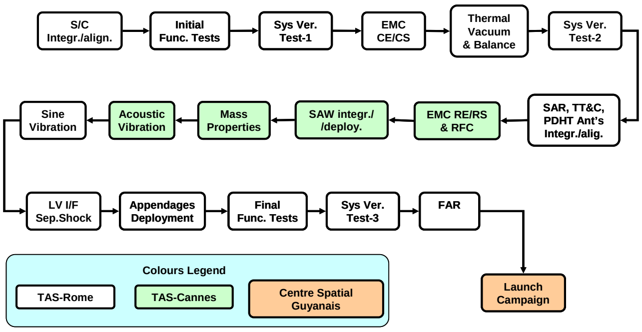

Figure 6. Sentinel-1 AIT Flow and Organisation of Activities

c) Spacecraft Thermal Tests

- Thermal Balance Test (TBT) (for thermal mathematical model correlation),
- Thermal Vacuum Test (TVT),

d) EMC Tests

- Conducted Emission (CE),
- Conducted Susceptibility (CS),
- Radiated Emission (RE),
- Radiated Susceptibility (RS),

e) RF Compatibility (RFC)

- Antenna Coupling, (Antenna Farm Mock-up).
- Radiated Auto-Compatibility.

f) Electrical Verification

- Integration Tests,
- Integrated Subsystem Tests (ISST),
- SES – PDHT Interface Tests,
- Integrated System Tests (IST),
- Spacecraft Health Tests (SHT),
- Power Budget,
- Polarity verification (of all sensors and actuators).

4. SATELLITE KEY PERFORMANCES

Sentinel-1 Satellite key performances and characteristics are summarised in the following list.

- Max Mass at Launch: 2172kg (propel.: 154kg)
- SAR Antenna dimensions: 12.30 x 1.02 m (LxW)
- Generated Power: 6140W(BOL)-5900W(EOL)
- Main Body Dimensions: 3.4 x 1.3 x 1.3 m
- Satellite Envelope Dimensions: 3.9 x 2.6 x 2.5 (incl. stowed appendages)
- Deployed solar arrays dimension: 21 m
- Orbit: SSO LEO orbit @ 692 km altitude
- Orbital Period: 98.6 min (max eclipse 19 min)
- Lifetime:7years (12 for battery and propellant)
- S/L BUS&P/L Reliability:0.860&0.888@7y.
- Satellite Availability over lifetime: 0.975
- Avionics: Integrated data handling, control & AOCS system

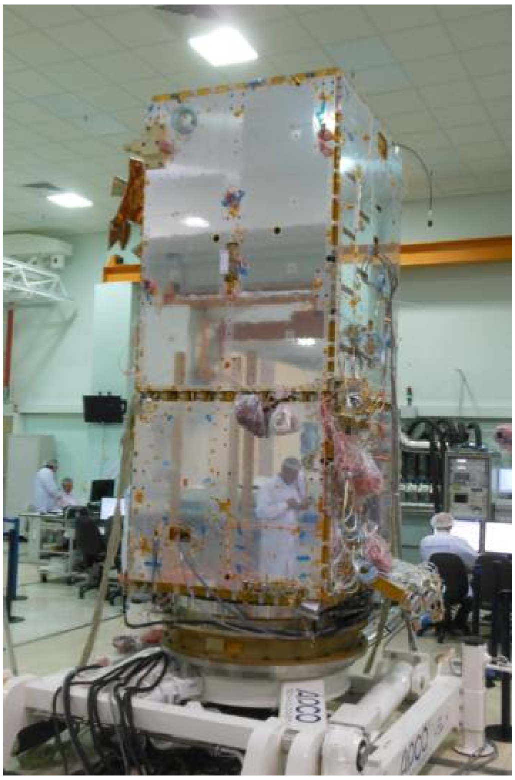

Figure 7. Sentinel-1 Spacecraft during Initial Functional Tests

- Navigation & Ref. time: GPS constellation, dual frequency receiver
- Operative autonomy: 96 h
- Attitude stabilization: 3 axes, Gyro stellar
- Attitude Profile:, Geo-Centric, Sun-Pointing, Yaw and Roll Steering capability
- Nominal Flight Attitude: Right Looking
- Attitude accuracy: < 0.01° each axis
- Attitude Knowledge: < 0.003° each axis
- Satellite Orbit Knowledge: with GPS: better than 10 m (3 sigma) in each axis accuracy on real-time processed data vectors and 5 cm in post-processing
- Propulsion: Mono-propellant (Hydrazine), 14 thrusters, 6 (orbit control)+8 (attitude)
- Structure: Box of aluminium sandwich panels + CFRP central structure
- Thermal Control: Mainly passive, standard techniques
- Power Bus Regulated Voltage: 28 V
- Power Bus Unregulated Voltage range: 46 V to 65 V
- Battery: 240 Ah @65 V, Li-Ion battery
- Solar Array cell type: GaAs
- TT&C: S-Band, zenith/nadir antennas
- TT&C antenna orientation: Zenith/Nadir
- Launcher: Soyouz ST (from Kourou).

5. C-SAR INSTRUMENT

The C-SAR instrument for the Sentinel-1 mission is composed of two major subsystems:

- the SAR Electronic Subsystem (SES)
- the SAR Antenna Subsystem (SAS)

The radar signal is generated at baseband by the digital chirp generator and up-converted to C-band within the SES. This signal is distributed to the High Power Amplifiers inside the EFE Transmit/Receive Modules via the beam forming network of the SAS. Signal radiation and echo reception is realized via the same antenna using slotted waveguide radiators. In receive, the echo signal is amplified by the low noise amplifiers inside the EFE Transmit/Receive Modules and summed up using the same network as for transmit signal distribution. After filtering and down conversion to baseband inside the SES, the echo signal is digitized, formatted and compressed for recording.

a) SAR Electronic Subsystem (SES)

The fully redundant SAR Electronics Subsystem (SES) provides all radar control, IF/RF signal generation and receive data handling functions. It comprises three basic elements, the Integrated Control Electronics (ICE), the Transmit Gain Unit (TGU) and the Mission Dependent Filter Equipment (MDFE). It hosts the SAR Instrument Software and is responsible for control and timing of the whole SAR instrument as well as for the communication with the platform. Apart from this it provides TX signal generation and up-conversion as well as filtering, down-conversion, compression and formatting of the SAR echo data. A block diagram of the SES can be seen in Fig.8.

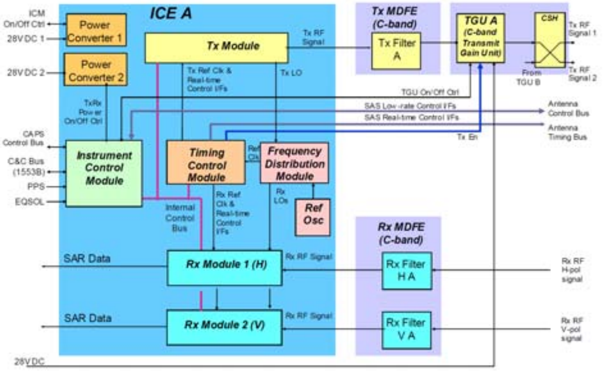

Figure 8. SAR Electronic Subsystem (SES): Functional Block Diagram (only one redundancy chain shown)

The Protoflight Model (PFM) of the fully integrated SES can be seen in Fig. 9. One can clearly distinguish the two large and black ICE boxes as well as the flat TGU mounted on the SES Flight Panel in Aluminium sandwich technology.

The SES PFM has completed its performance and environmental test campaign and has been delivered for integration into the SAR Instrument PFM in the first weeks of January 2013.

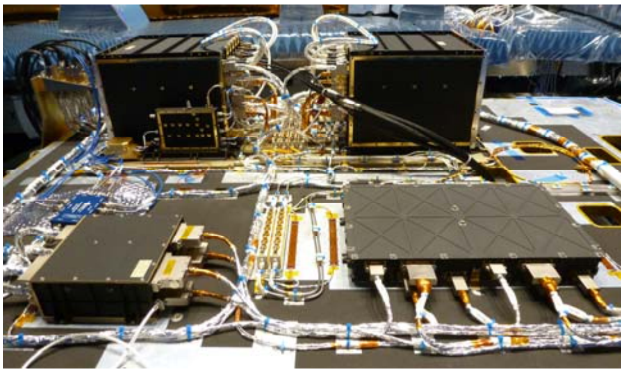

Figure 9. SES Protoflight Model (PFM) Mounted on SAR Instrument Panel

b) SAR Antenna Subsystem (SAS)

The SAS Protoflight Model is a is a deployable planar phased array antenna carrying 280 phase centres, which are organized in 14 SAS Tiles with 20 dual polarized phase centres each. The antenna comprises three elements, i.e. the SAS Centre Panel, which carries two SAS Tiles and which is mounted on the top of the spacecraft and two foldable SAS Wings carrying 6 SAS Tiles each. During launch the two SAS Wings are stowed on the two adjacent sides of the spacecraft and held by 6 Hold-Down and Release Mechanisms (HRMs) each.

A SAS Tile forms the smallest entity of the SAR Antenna Subsystem and contains all the basic functionality of the whole antenna. An electrical block diagram of a SAS Tile is given in Fig.10.

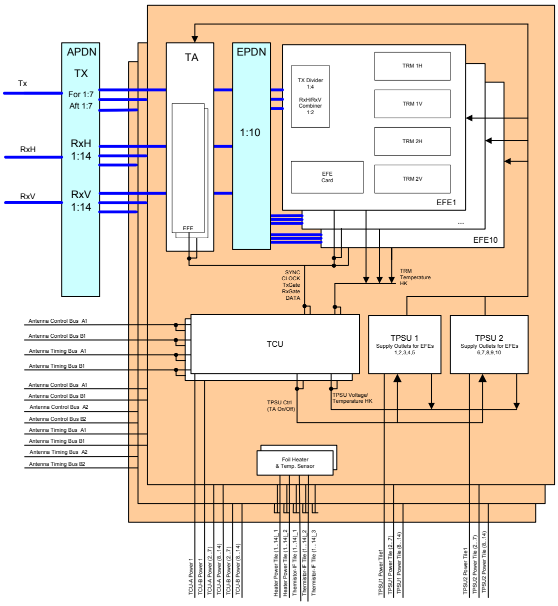

Figure 10. SAR Antenna Subsystem (SAS): Functional Block Diagram of a SAS Tile

The signal received from the SES is distributed by the Azimuth Plane Distribution Network (APDN) to the 14 Tiles. There it is amplified by a cold-redundant Tile Amplifier and distributed to the Transmit/Receive Modules in the so-called EFEs via the Elevation Plane

Distribution Network (EPDN). Each of the 10 pairs of dual polarised low-loss slotted waveguide radiators of each SAS Tile is fed by one EFE, which consists internally out of 4 single polarized Transmit/Receive Modules. The EFEs on each Tile are controlled by a cold redundant Tile Control Unit (TCU) and supplied by two Tile Power Supply Units (TPSU).

Due to the large size of the SAR antenna, the antenna environmental qualification had to be performed at different integration levels, i.e. at SAS Tile level, SAS Centre Panel as well as on SAS Wing level.

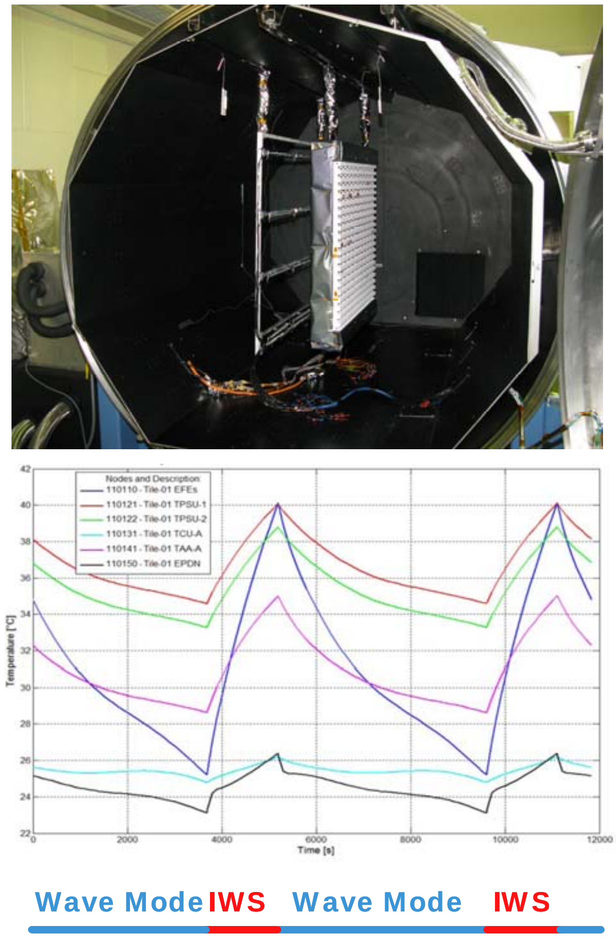

Figure 11. Thermal Vacuum Test: SAS Tile in TV Chamber and Temperatures during Hot Orbit Scenario

Figure 11 shows a SAS Tile in the Thermal Vacuum Chamber for thermal vacuum testing and hot orbit simulation. During hot orbit simulation the SAS Tile has been continuously operated over 8 orbits using the specified operational scenario with 25 minutes in high dissipating Imaging mode, followed by 74 minutes in lower dissipation Wave mode. The test verified that for this worst case hot operational mission scenario a Steady State condition is reached, for which all the Tile units stay within their specified temperature limits.

Fig. 12 and 13 show the set-ups for the environmental tests on the next higher integration level, i.e. SAS Wing level. The photo in Fig. 12 shows the -X-Wing in front of the Thermal Vacuum chamber. The two panels of the SAS -X-Wing are in stowed condition, mounted on the Antenna Panel Frame (APF). Also the Hold-Down and Release Mechanisms (3 HRMs on each edge of the panel) are clearly visible.

Figure 12. Preparation for SAR Antenna Subsystem (SAS) Wing Thermal Vacuum Test

Figure 13. Vibration Test: SAS -X Wing Mounted on Shaker

Fig. 13 shows the -X Wing on the shaker for vibration testing. Both SAS Wings and the SAS Centre Panel have successfully completed thermal vacuum and vibration testing.

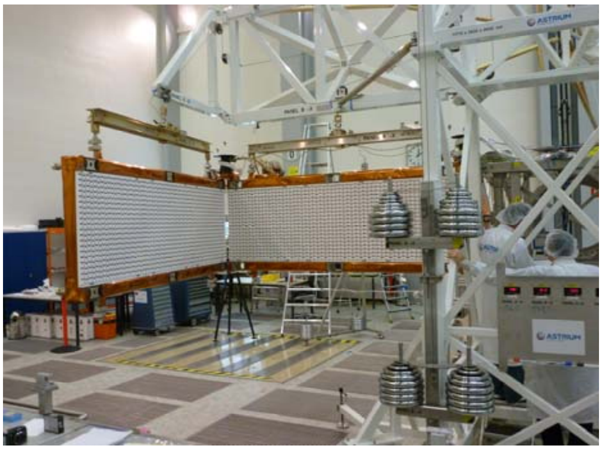

Figure 14. SAS Deployment Test: SAS Mounted on Zero Gravity Instrument Deployment Device (IDD)

After completion of environmental testing on Wing and Centre Panel level the SAS has undergone deployment testing to verify that the antenna will be capable to deploy safely after the stress imposed by the launch. Fig. 15 shows the deployment test in the Astrium clean room facility. The antenna is mounted on a spacecraft dummy. Zero gravity conditions are ensured by the counter balance mass elements of the specially designed Instrument Deployment Device (IDD). The deployment test has been controlled by the PFM of the Deployment Control Unit (DCU).

Figure 15. SAR Antenna Subsystem (SAS) in Astrium Planar Near Field Scanner (15 m x 7 m x 7 m)

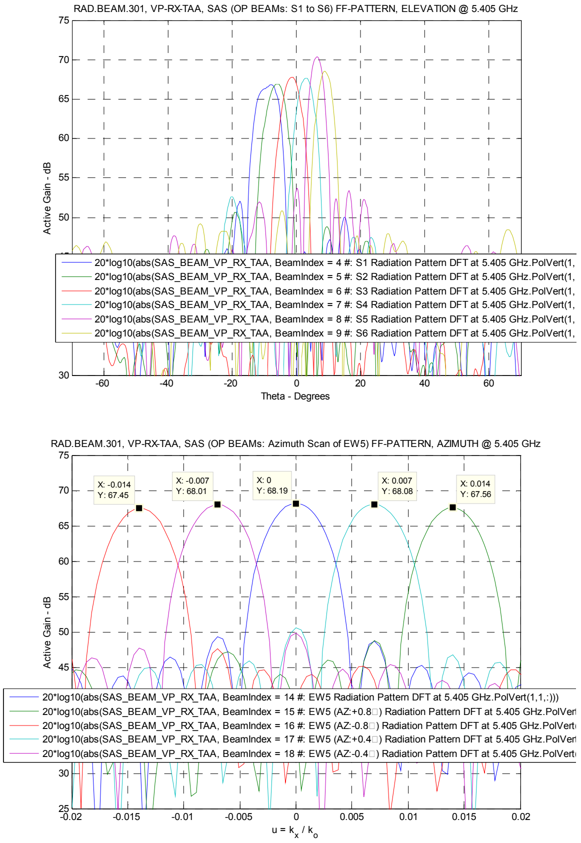

Figure 16. SAS RF Radiation Patterns: a) Elevation (S1 to S6 Beams) b) Azimuth (+/- 0.8° Scan for EW5 TOPS)

Finally, one of the key tests for a SAR Antenna is of course the RF radiation pattern test. Fig. 15 shows the fully deployed and fully integrated 12.30 x 1.02 m SAR Antenna in the new-built Astrium Planar Near Field Scanner (PNFS) in Friedrichshafen during RF Pattern testing and Antenna Model characterization and validation. The near field scanner has a dimension of 15 m x 7 m x 7 m.

An excellent SAR antenna radiation performance has been achieved. Fig. 16 shows the antenna agility in elevation (with the shaped and squinted beams of the SAR Stripmap modes S1 to S6) as well as in azimuth (with different scan positions for the Extra Wideswath Mode EW5 as needed for TOPS operation). The achieved cross-polarization for all SAR modes is better than 40 dB and in most cases close to 50 dB.

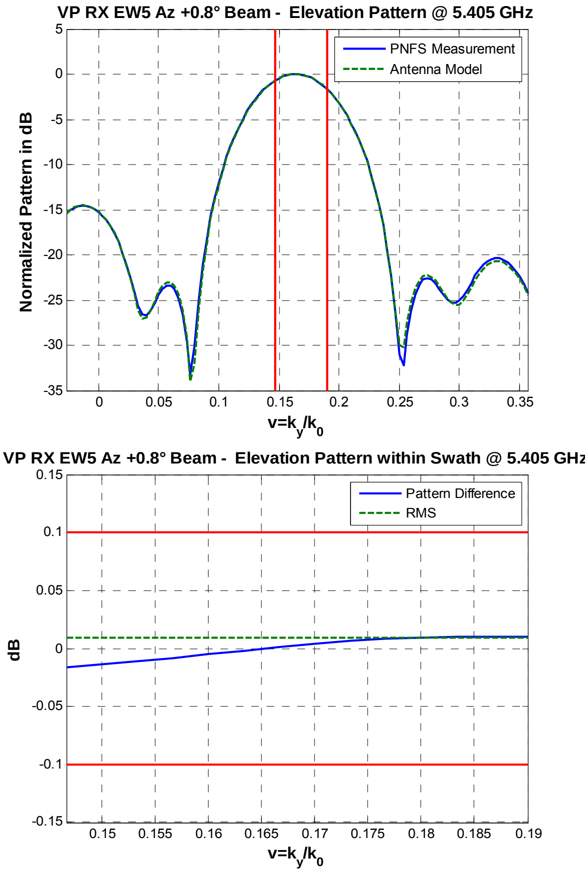

Figure 17. SAS Antenna Model Accuracy (Example for double squinted (az. + el.) EW 5 Beam)

Also the achieved Antenna Model accuracy is excellent. For the population of the antenna model all 280 dual polarized phase centres of the antenna have been individually characterized. Fig. 17 shows the comparison of the resulting antenna model prediction vs. the direct PNFS measurement for the EW5 beam, which has been scanned in both azimuth and elevation at a time. The peak to peak difference within the swath is better than 0.03 dB. The rms difference over the swath is even better than 0.01 dB.

c) C-SAR Instrument

After completion of environmental testing and qualification on both SES and SAS level, both SAR subsystems have been combined to form the C-SAR Instrument.

On SAR Instrument level both Functional and RF Performance tests (incl. internal calibration loops) as well as EMC testing have been performed. Fig. 18 shows the test set-up in the Astrium PNFS. In order to allow a check of the radar transmit and receive characteristics of the full SAR Instrument an RF probe has been mounted on a tower above the antenna. The probe has been used to collect transmit pulses from the SAR or to inject test signals into the SAR instrument receive chain. In addition, a SAR end-to-end test has been performed where an echo simulator has been connected to the RF probe. The echo simulator generates echoes corresponding to a distributed target scenario with several point targets. The received echoes have been processed. Fig. 19 shows an example of such a processed scenario with clearly visible and well focussed point targets.

Figure 18. SAR Instrument Functional and RF Performance Tests: Test Set-up with RF Probe

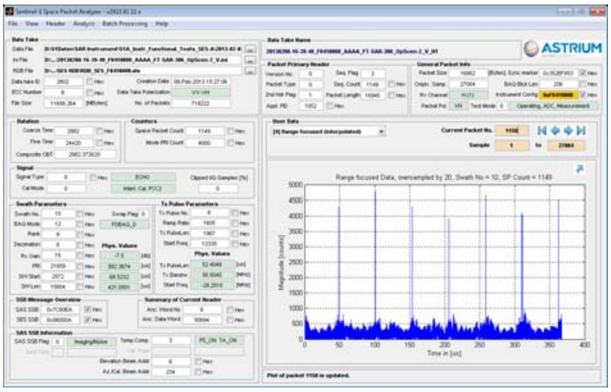

Figure 19. SAR End-to-End Test with Echo Simulator: Processed SAR Data with Several Point Targets

The RF performance data collected during SES, SAS and SAR testing have been introduced into the SAR performance model in order to make a pre-launch prediction of the Sentinel-1 SAR performance.

As an example Figure 20 shows the predicted Noise Equivalent Sigma Zero (NESZ) for the Stripmap and the Interferometric Wideswath Modes at low altitude.

Table 1 provides a summary of the key performance data for all SAR Instrument modes (worst case values).

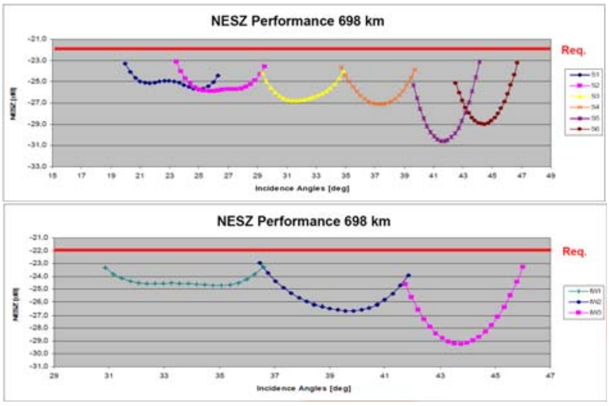

Figure 20. Predicted NESZ vs. Incidence Angle for Stripmap and Interferometric Wideswath Modes

Mode	RG-Resolution [m]	AZ-Resolution [m]	Rad. Acc. [dB]	Rad. Stab. [dB]	2D-DTAR [dB]	NESZ [dB]
S1	4,90	4,90	0,65	0,53	-28,35	-23,10
S2	4,90	4,86	0,65	0,53	-26,17	-23,08
S3	4,89	4,90	0,65	0,53	-25,77	-23,82
S4	4,89	4,85	0,65	0,53	-25,64	-23,76
S5	4,89	4,95	0,65	0,53	-22,18	-22,94
S6	4,89	4,90	0,65	0,53	-23,87	-22,97
IW1	4,90	19,50	0,65	0,53	-22,77	-22,81
IW2	4,90	19,50	0,65	0,53	-23,78	-23,07
IW3	4,90	19,50	0,65	0,53	-23,04	-23,11
EW1	19,42	39,53	0,65	0,53	-25,39	-23,15
EW2	19,42	39,50	0,65	0,53	-23,33	-26,27
EW3	19,38	39,50	0,65	0,53	-24,42	-26,88
EW4	19,46	39,50	0,65	0,53	-23,28	-26,38
EW5	19,35	39,50	0,65	0,53	-26,61	-29,86
WM1	4,90	4,90	0,65	0,53	-28,85	-27,62
WM2	4,89	4,90	0,65	0,53	-26,18	-23,27

Table 1. SAR Pre-launch Performance Prediction (worst case values) based on S1 Test Data

6. CONCLUSION

The Sentinel-1 space segment has successfully passed environmental and performance testing on both Spacecraft Subsystem as well as SAR Instrument Subsystem level. The SAR Electronic Subsystem (SES) has already been delivered to the S1 Prime and participated at Spacecraft Subsystem level tests.

The next milestone will be the delivery of the SAR Antenna Subsystem (SAS) to the Prime contractor and its integration onto the satellite, which will be followed by integrated systems tests verifying the end-to-end functionality and performance of the Sentinel-1 space segment.

7. REFERENCES

R. Torres et. al., “GMES Sentinel-1 Mission”, *Remote Sensing of Environment, Special Issue: The Sentinel-1 Missions - New Opportunities for Science*, May 2012