# COMPACT SAR AND MICRO SATELLITE SOLUTIONS FOR EARTH OBSERVATION

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## ABSTRACT

Requirements for near and short term mission applications (Observation and Reconnaissance, SIGINT, Early Warning, Meteorology,..) are increasingly calling for system and spacecraft operational responsiveness, flexibility in configuration, lower cost satellite constellations and flying formations, to improve both the temporal performance of observation systems (revisit, response time) and the remote sensing techniques (distributed sensors, arrays, cooperative sensors). In answer to these users' needs, leading actors in Space Systems for EO are involved in development of Small and Microsatellites solutions. Thales Alenia Space started the Compact SAR small satellite project, with the key objectives of low cost and reduced launch mass, while providing high resolution and image quality performance.

Compact SAR will embark a X-band SAR based on a new technology for the Antenna: deployable reflector antenna fed by an active phased array feed. This concept allows high performance to be achieved, providing some capability of electronic beam steering, in both azimuth and elevation planes, to improve operational performance offered by a mechanically steered SAR system on small platforms. The instrument can provide both STRIPMAP and SPOTLIGHT imaging modes, and thanks to very high gain antenna, can also provide a real maritime surveillance mode based on a TAS patented Low PRF radar operation mode.

Further developments are in progress considering missions based on Microsatellites technology, which can provide effective solutions for different user needs, such as Operational responsiveness, low cost constellations, distributed observation concept, flying formations, and can be conceived for applications in the field of Observation, Atmosphere sensing, Intelligence, Surveillance, Reconnaissance (ISR), Signal Intelligence. To satisfy these requirements, flexibility of small platforms is a key driver and especially new miniaturization technologies able to optimize the performance. An overview of most promising mission concepts is provided, such as passive SAR for bi/multi-static imaging and tandem, Space Debris monitoring, Maritime Surveillance, Atmosphere sensing.

## COMPACT SAR

Compact SAR will provide high flexibility and configurability to answer different users' needs: it is designed to operate in LEO with a reference orbit altitude in the range of 500 – 700 km, in both Dawn-dusk Sun-synchronous orbits (global scale access observation) and inclined non Sun-Synchronous orbits (regional access or specific areas of interest). SAR instrument design is the result of a multi-year experience in developing space borne SAR, which have been proven with in flight high quality images since 2007 : very high resolution, wide areas and wide access region, simultaneous dual polarization, advanced internal calibration. It can be operated in both STRIPMAP and SPOTLIGHT modes, and thanks to the high gain of the large reflector antenna, the system can also provide a maritime surveillance mode based on the TAS patented Low-PRF mode [1].

Advantages in using the COMPACT-SAR solution can be summarized as reduction of antenna dimensions, lightweight, high flexibility, SAR Image quality performance in line with the ones achievable by SAR' systems based on large phased array antenna solution.

***Compact SAR Performance and Mission capabilities***

Extensive analysis of user needs were performed to establish Compact SAR performance targets, considering: imaging modes performances, orbit constraints in terms of user specification and requirement of time performances on area of interest, time performances, images per day requirements, acquisition agility, area coverage requirements, ground station configuration and acquisition scenario, system operative utilization.

The main drivers considered for ***orbit selection analysis*** are Sun-synchronicity (constant local time) and Satellite altitude as compromise between SAR radiometric performances (e.g. Signal To Noise Ratio, SNR), the area of interest (range of latitudes) and Time to revisit (considering the Compact SAR access area).

Compact SAR design allows operations as function of the Mission requirements, allowing to optimize mission performance with Global access capability or over specific Areas of Interest (AOI), considering (see Figure 1) :

- ***Sun-Synchronous Orbits (SSO),*** with Global scale accessibility also at high latitude regions. These orbits have small frequency and duration of the eclipse period, 3 months/year for maximum 20% of the orbit. The uniform sun illumination allow optimal usage of satellite energy resources and thermal control.
- ***Inclined orbits,*** with Optimal access to narrow belt of latitudes, improving revisit time over specific Areas of Interest. Variable sun illumination requires specific energy management and thermal control.

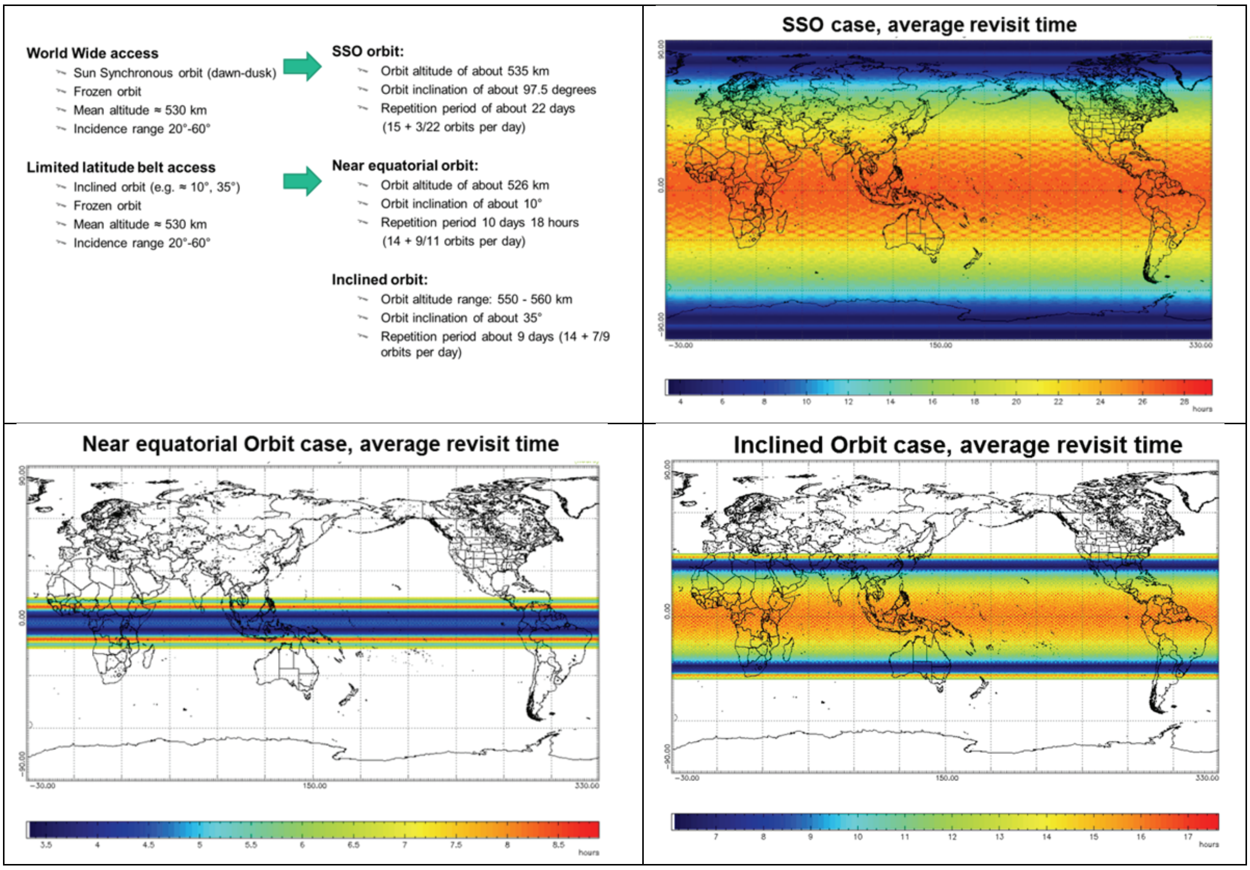



**Figure 1:** Compact SAR orbit design example and achievable Revisit Time performance

Revisit Time is strictly dependent on the site location, the number of satellites (and related orbits) when considering a constellation, the access area of the Compact SAR, nominally in [20°-60°] incidence angle range.

From examples reported in the above figure, ***Average and maximum revisit time*** main figures of merit are estimated point by point, and can be summarized as follows:

- ***SSO case*** : average revisit ≈ 29h near equator, ≈ 20h for latitudes equivalent to Mediterranean Area;
- ***Near equatorial orbit case*** : average revisit ≈ 4.5 h near equator, ≈ 3.5 h at 4° latitude;
- ***Inclined orbit case*** : average revisit ≈ 16 h near equator (<17 h), ≈ 8 h at medium latitudes (30°).

The ***operational capability*** of Compact SAR, in terms of number of images acquired per day and per orbit are driven by system resources: energy balance, driven by sun illumination, on board storage and contact time for data downlink especially in case of single station. On board resources are optimized by mission planning tool.

Compact SAR design has been conceived to provide energy capability similar to higher classes of SAR Satellites based on PRIMA platform, who has huge capability from heritage. The High Agile platform with CMG and the performing power system, allow Compact SAR minimize transient time among different operations along the orbit, and maximize the time slots devoted to battery charging, data downlink and imaging operations.

These features allow Compact SAR to produce ***tens of Images per orbit (hundreds images per day)***, both when operating in SSO or Inclined Orbits.

In terms of ***Imaging Performance*** Compact SAR provides unique capabilities of land cover classification, mapping of areas and monitoring the temporal evolution of geophysical parameters, thanks to the ***very high resolution*** capability and to ***image quality performance*** summarized in Tab.1.

| MEASUREMENT MODE | RESOLUTION | | SWATH | | ACCESS | | SENSITIVITY | POL |
|---|---|---|---|---|---|---|---|---|
| | Ground Rg Res [m] | Az Res [m] | Range [km] | Azimuth [km] | Access Region [deg] | Look Side | NESZ [dBm2/m2] | Polarization |
| SPOT FP | 0.7 | 0.7 | 5 | 5 | 20-60 | RL-LL | -23 | Full |
| SPOT HR | 1.0 | 1.0 | 10 | 10 | 20-60 | RL-LL | -22 | SP/DP |
| SPOT HR WIDE | 1.5 | 1.5 | 15 | 15 | 20-60 | RL-LL | -20 | SP/DP |
| SPOT VHR | 0.5 | 0.5 | 5 | 5 | 26-60 | RL-LL | -27 | SP/DP |
| SPOT VHR WIDE | 0.5 | 0.5 | 10 | 10 | 26-60 | RL-LL | -19 | SP/DP |
| STRIP | 3.0 | 3.0 | 30 | 50 | 20-60 | RL-LL | -18 | SP/DP |
| STRIP-20 | 2.5 | 2.5 | 20 | 50 | 20-60 | RL-LL | -20 | SP/DP |

SP : Single Polarization; DP: Dual Polarization; FP: Full Polarization

**Table 1:** Compact SAR Measurement modes and performance.

Compact SAR will also provide a ***Maritime Surveillance*** operating mode. This innovative concept conceived by TAS uses “low PRF” (50...100Hz) to achieve huge swath (> 1000km) with no range ambiguity. Azimuth ambiguity operation is foreseen, to allow de-correlation of the sea clutter and improve the non-coherent integration gain.

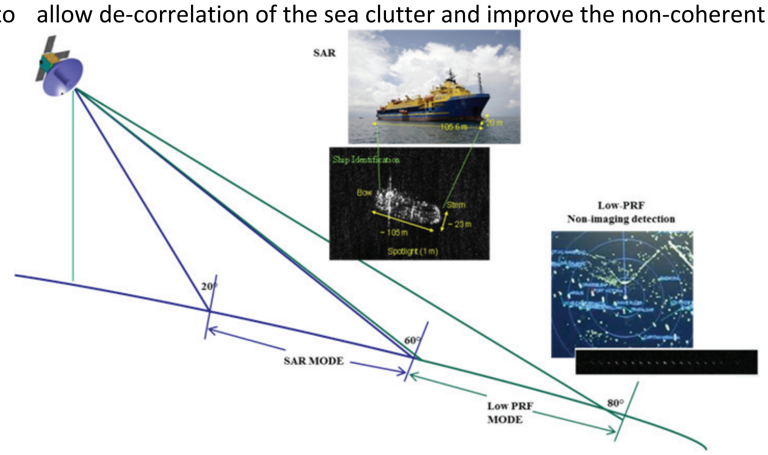



**Figure 2:** Maritime Surveillance : SAR imaging and Non Imaging Wide Swath detection

***Access capability of the Compact SAR*** are greatly improved by the Satellite agility, providing flexibility to acquire scenes with very small gaps, with minimal distance between two consecutive acquisitions, both for Spotlight and Strip-map modes, with different radar look angles, and left and right looking satellite attitude. This allow very wide area coverage, considering ascending and descending passes, distinct views and different geometric configurations on the same targets. Two operational strategies can be adopted by user:

- Acquisition scheme on theater without constraints on inter-image gap.
- Individual programming of each acquisition

Several scheme for Acquisition on Theatre are possible, exploiting the fully agile capability of the platform and the electronic steering capability of the antenna :

- ***Sequential Spotlight images***, however placed across and along track, without spacing and gaps
- ***Pairs of Spotlight images***, at same across track position on opposite sides of sub-satellite track.

- ***Mosaic of Spotlight images***, allowing also 23x23 Km imaging in high resolution.
- ***Sequence of Strip-map images***, with zero spacing along track among images at same elevation angle.

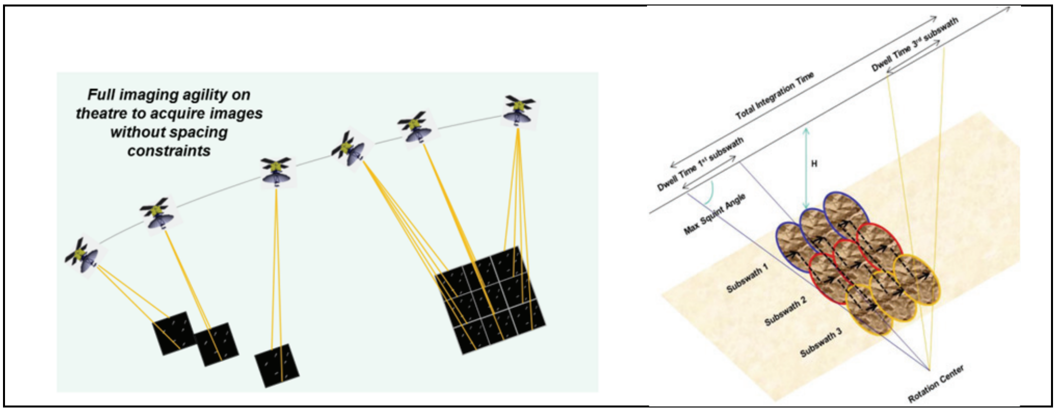



**Figure 3:** Compact SAR image acquisition capability over theater

Thales Alenia Space Italy have also defined a ***Compact SAR instrument in L-Band***. The key objectives for Compact SAR-L will be the maximum synergy and reuse of the developments on-going for the Compact SAR X-Band instrument and Satellite. Is shall be also considered that Thales Alenia Space Italy masters the technologies for active T/R modules over a wide frequency of heritage: X-Band (COSMO), C-Band (Sentinel-1), L-Band (SAOCOM/SIASGE), S-Band (Iridium Next).

Compact SAR-L will operate within ITU allocated frequency bands, in the range 1215 – 1300Mhz with a maximum transmitted bandwidth of 85MHz, with nominal center frequency set to 1257.5 MHz. However the SAR design need to provide flexibility for center frequency and pulse bandwidth, to manage potential interference into RNSS (Radio Navigation Satellite Service).

The proposed concept will be strongly oriented to an "application-oriented" operational system. Due to the image quality performance and operational capability the proposed system can provide, it is dedicated to thematic mapping purposes for topography, vegetation and deforestation, geology, hydrology, etc.

It will be also the natural complement to the X-Band Compact SAR that, due to the very high resolution capability and agility in acquiring images over a small theatre, can provide the optimal solution for any surveillance and security application. Compact SAR-L performance are summarized in Table 2.

| | | SPOTLIGHT | STRIPMAP-3 | STRIPMAP-6 | STRIPMAP-12 |
|---|---|---|---|---|---|
| Access region | deg | 20°-45° | | | |
| Swath | km | 25x25 | 25 | 40 | 40 |
| Range resolution | m | 3-5 | 3-5 | 6 | 12 |
| Azimuth resolution | m | 3 | 3 | 6 | 12 |
| NESZ | dB | -19…-27 | -19…-27 | -18…-26 | -22…-30 |
| AAR | dB | -17…-25 | -20…-27 | -20…-27 | -20…-27 |
| RAR | dB | -22…-50 | -25…-50 | -24…-57 | -24…-57 |
| Looks | - | 6 | 1 | 2 | 4 |

**Table 2 :** Compact SAR-L imaging performance

***The Compact SAR Spacecraft***

The Compact SAR Spacecraft (Fig.4) is a 3-axis stabilized satellite, relying on flight proven PRIMA platform. It represents the state of art technology and is based on a modular architecture whose main features are:

- SAR Instrument, based on a reflector antenna and an active feed array, with full-polarization capabilities. The Instrument access both right and left of flight direction with a 20°- 60° access area.
- Data Link System (DLS) comprising all the functions necessary for the real-time acquisition, storage and handling of SAR data generated by the Payload, and for their transmission to the ground station;
- 3 axis stabilization Platform (PRIMA-S), capable to provide all the functionalities in support to the Satellite Operations (Attitude Control, Orbit Control, Navigation, Communication with Ground capabilities, besides providing Power supply, Thermal control and necessary strength, Stiffness and dimensional stability).

The spacecraft design is based on the PRIMA platform concept; deriving from an adaptation of the PRIMA's payload module, it integrates on a single main module (Service Module –SVM-) all the bus units, the propulsion subsystem and the payload equipment, including the pertinent appendages. PRIMA platform family has an extensive heritage in already flown programs, with 6 Satellites already fully operational (Radarsat-2,COSMO-SkyMed FM1 to FM4 and Sentinel-1A, with a total of more than 303,000 flight hours), in which it has successfully demonstrated the flexibility of use, low management costs and the ability to adapt to changing operational conditions.

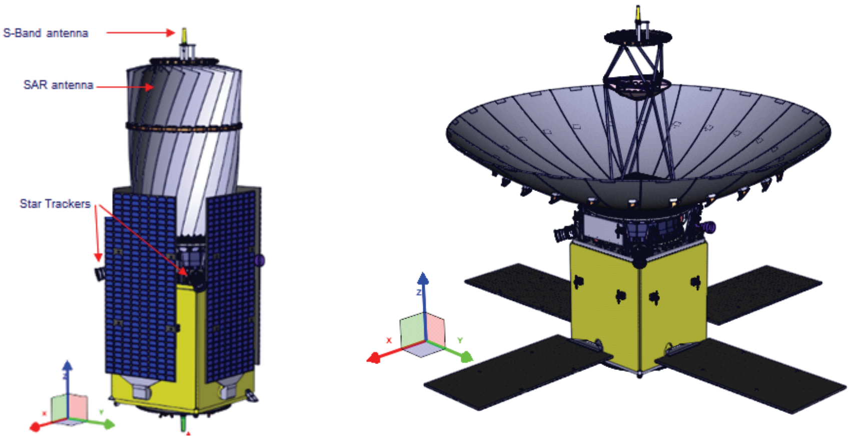



**Figure 4** : Compact SAR Spacecraft, Stowed (left) and Deployed (Right) configuration

Extensive assessment was performed to establish compatibility with a wider range of Launch Vehicle and launch sites, taking into account the selected orbits (ranging from SSO to near equatorial at 10° inclination). Launcher compatibility is shown in the following Figure 5, summarizing also the main Satellite performance.

| Parameter | Performance |
|---|---|
| Operational lifetime | 7 years, goal 10 years |
| Operational type | SSO and inclined |
| Stabilization | 3 axes |
| Navigation and Time Reference | GPS |
| Real time Orbit Determination | < 10 m, Velocity error < 0.01m/s |
| Power generation | ~ 2.2 kW EOL @39 V, UR 47-65 V and 28V |
| Battery | 252 Ah (BOL) |
| Propulsion S/S | Mono propellant, Liquid Hydrazine (N2H4) |
| Launch Mass | 700-900 Kg, mission depending |
| TT&C | S-Band, TC 8 kbps, TM 16-1024 Kbps |
| Downlink | X-Band, 2 x 330 Mbps data rate |
| Mass Memory Area | 512 Gbits EOL (minimum) |

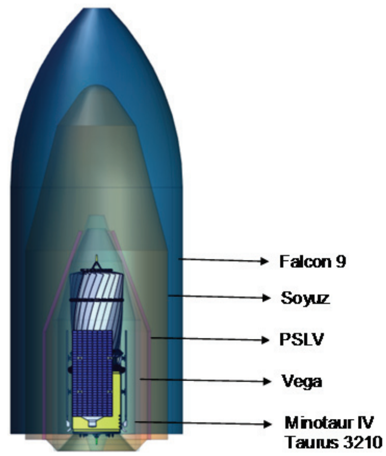



**Figure 5 :** Satellite Performance Summary (left) and launcher compatibility (right)

To fulfill its functions, Compact SAR Spacecraft Platform is organized in the following Subsystems:

- **Structure (STR),** sized to adequately permit equipment accommodation, providing stiffness and resistance towards loads acting on satellite, and guarantee performances for pointing and thermo-elastic distortion.
- **Thermal Control Subsystem (TCS),** providing control of on-board equipment temperature ranges it is actuated both in passive and in active way, with real time temperature measurement.
- **Electrical Power Subsystem (EPS)**, power generation and conditioning system sized to guarantee the imaging and communication functions. Power is provided by solar arrays in sunlight and battery in eclipse. The subsystem also foresees opportune protections against short circuits or anomalous power absorption.

- **Propulsion Subsystem (PRP)**, capable of producing forces and torque for the orbit and attitude maintenance. Composed by a tank with the propellant necessary for supporting all the mission and reaction control thrusters adequate for the generation of forces and torque in the main directions.
- **Avionic Subsystem (AVS)**, integrating the Attitude and Orbit Control functions, based on fully flight proven logics implemented in software monitored from ground via TM TC, with the Data Handling and Failure detection functions (FDIR) as necessary to manage on board functions in autonomy. In emergency case the AVS will bring the satellite in a safe condition without ground intervention.

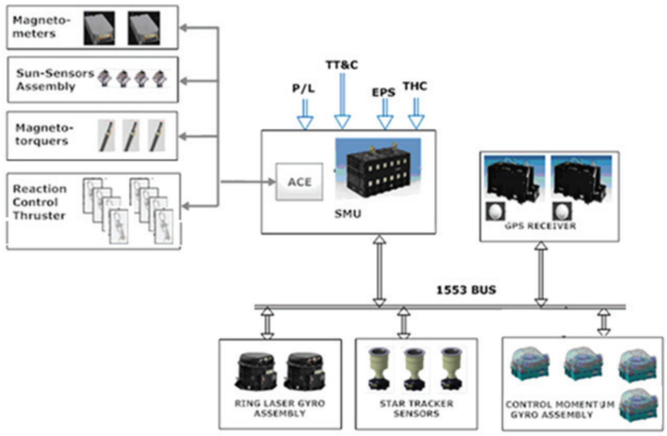



**Figure 6 :** Avionics subsystem architecture

- **Tracking, Telemetry and Command (TT&C)**, providing capability to receive Telecommand from ground control and to transmit Telemetry according to the CCSDS standards. Telecommand function also implements an authentication security algorithm for validation of commands sent to the satellite.

**The Data Link System (DLS),** based on TAS-I fully flight proven heritage and whose modularity and scalability allows to provide solution sized according to the specific mission performances in terms of operative profiles and SAR acquisition data rates. The DLS manages the acquisition, storage, formatting and transmission to ground of the data flow generated by the SAR instrument; SAR data are supplied by the payload in the form of CCSDS Source Packets. A functional diagram of DLS is reported in the following figure, where the DLS is composed by the following major elements:

- Data Storage and Handling Assembly (DSHA);
- X-Band Transmission Assembly (TXA);
- X-Band Antenna Assembly (XBAA).

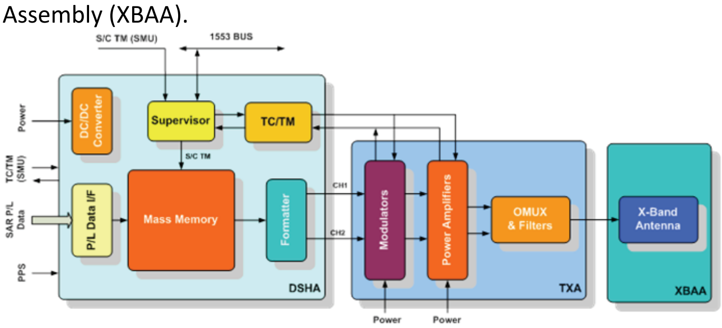



**Figure 7 :** DLS Functional Architecture

***The Compact SAR Instrument***

The design of the Compact SAR sensor [2] is the result of a multi-year experience in developing space-borne SAR instruments, COSMO-SkyMed, KOMPSAT-5, COSMO 2nd Generation, which have been providing high quality images since 2007. The mentioned heritage assures the capability of embracing within one Satellite both the functionalities required to manage acquisitions of high resolution images and those necessary to observe wide areas on the Earth; moreover, this sensor includes additional novel features, such as simultaneous dual polarization on receive, and advanced internal calibration provisions which are definitely the state of the art for space-borne SAR instruments. The main distinctive design aspects of the SAR are:

- SAR Antenna consisting of:
    - Large unfurlable reflector, which provides very high antenna directivity
    - Feed array, which allows controlling the shape and width of the patterns and which implements limited electronic beam steering in azimuth and elevation planes
    - Single channel transmit and receive modules (T/R) to assure the capability of acquiring images at either single, dual, or full polarization
    - True-time Delay Lines (TDL) to avoid pointing dispersion effects during electronic scanning.
- Programmable digital chirp generator based on Direct Digital Synthesis (DDS) in order to guarantee the best trade-off between hardware complexity and performance
- High stability frequency generator to guarantee coherency and astounding spectral purity of the reference signals of the SAR
- Sub-metric Spotlight (0.5m) is implemented with a signal bandwidth of 600 MHz, compliant to current ITU regulations. Technological readiness allow Thales Alenia Space to upgrade to state of the art VHR-UHR resolution (0.8 GHz up to 1.2 GHz bandwidth) as soon as ITU regulations would be updated.
- Double RX chain within the internal electronics of the radar to assure the capability of acquiring images at either single, or dual, or full polarization
- Selectable "deramp-on-receive" receiver to optimize data handling for the high resolution modes
- Selectable digital filters and decimation factors to allow efficient usage of on board storage resources versus range resolution dependence on incidence angle
- Digital I&Q demodulator, for best demodulation performance of amplitude and phase imbalances
- Block Adaptive Quantization (BAQ) to compress without loss of information the SAR data to be down-linked Cold redundancy of SAR electronics equipment to provide high reliability figure and graceful degradation of the performance thanks to the large number of T/R modules of the Feed Array

Fig.8 outlines the functional diagram of the SAR architecture, sketching a high level perspective of its own key functionalities and of their allocation within the two main subsystems of the sensor, which are SAR Sensor Electronics (SSE) and SAR Antenna Subsystem (SAS).

The proposed architecture provides all the hardware and software resources to optimize the achievable performance; at this aim, together with its "measurement modes", the SAR implements also additional "support modes" which allow a detailed characterization of the behavior of the hardware both in-flight and on-ground.

The two fundamental SAR acquisition techniques (i.e. Strip map and Spotlight) are translated into different operative modes in order to assure the required performance. In addition new measurement modes are proposed, which allow introducing novel techniques that can be considered at the state of the art. Eventually, it is worth noticing that the flexibility of the proposed sensor is such to allow implementing possible new future observation techniques by updating the on board software, even in flight.

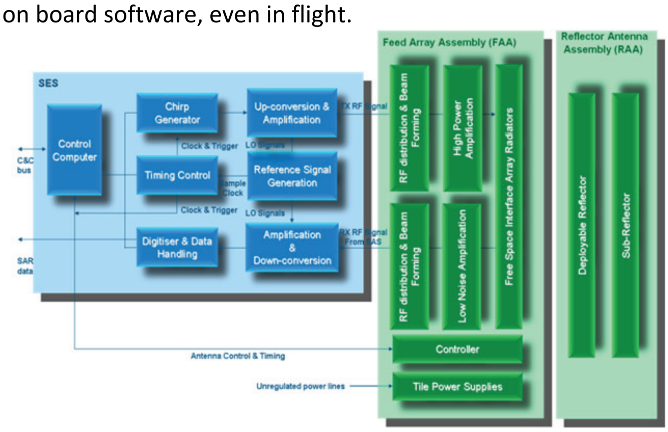



**Figure 8:** Compact SAR functional architecture.

The functions implemented by the SSE are allocated within Digital Electronics Equipment (DEE) and Radio Frequency Equipment (RFE).

- The DEE is charged of generating chirp pulses, receiving and processing echo signals, and generating timing signals. Furthermore the DEE controls the whole sensor, communicating with the Spacecraft through the 1553 Data Bus, handling commands and control protocol, performing telemetry acquisition and commands propagation, generating and dispatching antenna parameters to SAS.
- The RFE provides the functions of up-conversion and amplification of the TX signals, and amplification and down-conversion of the received echoes. In addition, the RFE is also devoted to generate all the internal reference signals of the radar, deriving this frequency signals from an ultra-stable oscillator at 10 MHz.

The SAR Antenna Subsystem (SAS) consists of two major assemblies:

- Large Unfurlable Reflector Assembly (LURA): it consists of a center-fed dual reflector. The reflector is made of foldable solid petals and is designed to be interfaced to the Spacecraft by means of the central hub interface (I/F). The LURA stowed envelope mounted on the Spacecraft top floor is compatible with small launcher's fairings. The reflector assembly includes a sub-reflector, and its central hub is conceived to accommodate the RF radiating sub-system [3].
- Feed Array Assembly (FAA): the antenna feed is based on an active phased array populated by 256x2 T/R modules, the basic elements (i.e. T/R modules, TTDL, TPSU, TCU and EFE) are derived from the larger active phased array based instruments [4].

The SAS is characterized by the following key features:

- Dual linear polarization through independent control of 2 x 256 T/R modules
- RF TX peak power: >1.8 kW , DC power consumption: <3.6 kW
- High flexibility in secondary beams (different swaths along elevation plane in different look angles)
- Electronic steering in azimuth and elevation, with graceful degradation vs potential failures of T/R
- Negligible backscattered field towards the large active feed array, despite centered geometry.

A 3D view of the SAS concept is shown in Fig.9, with both stowed and deployed configurations. The FAA, sketched in the Fig.10, includes and electronics equipment sub-assembly, including dual polarization radiating boards and T/R modules, thermal radiator, and interfaces to the platform top floor.

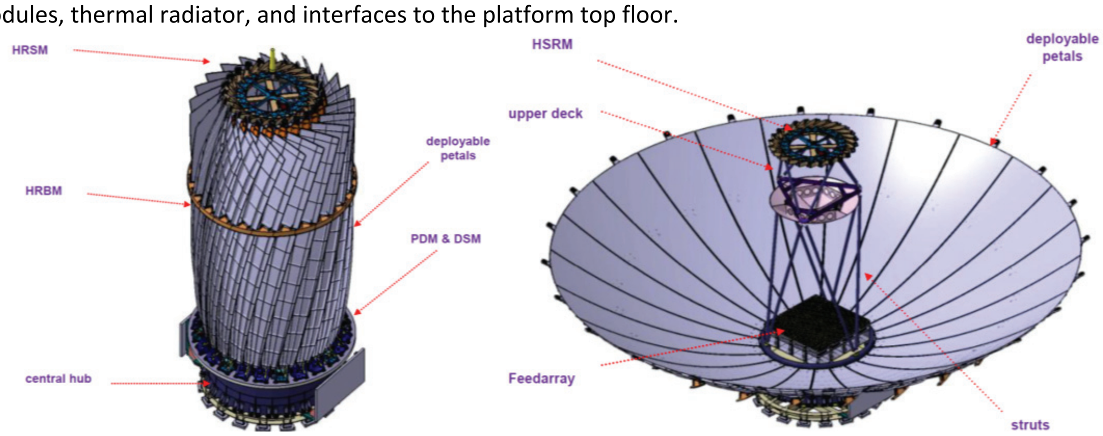



**Figure 9:** SAS in stowed (left) and deployed (right) configuration.

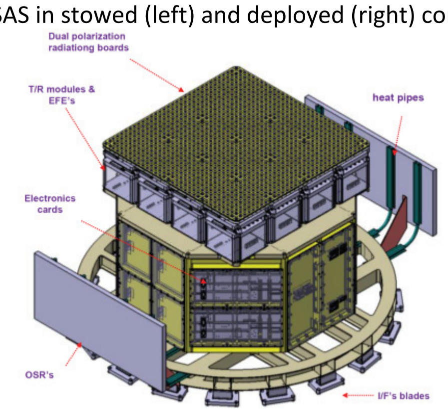



**Figure 10:** Feed Array Assembly.

## MICRO-SATELLITES DESIGN AND APPLICATIONS

Compact SAR satellite described above is aimed to provide a compact satellite solution with high performance as single satellite or as constellation: high resolution, image quality parameters, agility over a theater.

*Micro-Satellites* in the class of 120-150 Kg are today under development as they *represent a key asset to answer specific user needs for* ***Operational Responsive missions*** *and to implement l**ower cost and easily deployable constellations and flying formations**,* allowing distributed and cooperative sensors architectures, increased revisit time and mission access capability, improved coverage for near continuous observation.

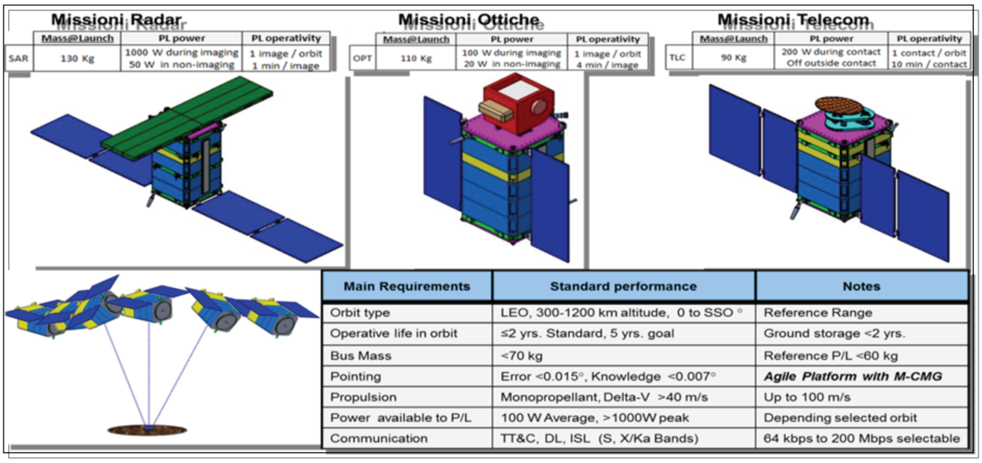
They can accomplish specific missions or cooperate in synergy to complement existing assets capability. Indeed they may support both strategic and tactical needs, to access remote areas not reachable by other means (for example, by UAVs) and provide additional capabilities or temporarily fill gaps or recover from failure. Same assets are also considered for civilian applications (environmental monitoring, border control, disaster monitoring and support humanitarian missions), and thus synergies can be offered by this typically dual use technology.

### *NIMBUS Platform*

Thales Alenia Space Italy started since 2012 the development of platform for LEO micro-satellite, taking into account an extensive set of possible mission scenarios, candidate payloads typologies and different launch strategies: the NIMBUS (New Italian Micro BUS) micro-satellite, for which technological development for miniaturization have been started. The key objective of NIMBUS is to achieve the highest possible performance in the micro-satellite class, to support applications which are typically served with by the higher segment of platforms. Thanks to modular design, NIMBUS will serve different mission applications and operational scenarios with different payload: orbit altitude (300-1200 Km), orbit inclination (quasi-equatorial to SSO), payload type (e.g. telecom, optical, radar), complex operational scenarios (e.g. multiple targets acquisition in tactical theatres) and launch configurations (single/multiple with small launchers, single airborne launch). These requirements drive a new design approach and the selection of new emerging technologies:

- ***Modularity and miniaturization of all main components:*** mechanical structure (smart "plug and play" concept), avionics system, electrical power system (modularity of battery, SAW and use of MPPT).
- ***High agility capabilities for multi-target imaging:*** high angular rates and accelerations achieved by use of a *Mini Control Momentum Gyro (MCMG)*, in lieu of mini reaction wheels as required by mission.
- ***Integrated Power, Attitude control & DH:*** *centralized architecture based on a high performance multi-core processor with fully integrated power, attitude*, data handling control, Power Module control, TT&C, Mass Memory and Reconfiguration Module.
- ***Highly modular and compact structure & thermal system*** : Multi-Modular Function Frame, allowing smart plug and play based on functional trays concept.
- ***Integrated communication and data handling:*** high rate downlink, TT&C, Inter-Satellite Link, memory.
- ***Easier integration and testing :*** high degree of electrical and mechanical testability at tray level, simplified integration through stacking .

The following exhibit report NIMBUS concept, the target performances and key technologies.




| Main Requirements | Standard performance | Notes |
|---|---|---|
| Orbit type | LEO, 300-1200 km altitude, 0 to SSO ° | Reference Range |
| Operative life in orbit | ≤2 yrs. Standard, 5 yrs. goal | Ground storage <2 yrs. |
| Bus Mass | <70 kg | Reference P/L <60 kg |
| Pointing | Error <0.015°, Knowledge <0.007° | ***Agile Platform with M-CMG*** |
| Propulsion | Monopropellant, Delta-V >40 m/s | Up to 100 m/s |
| Power available to P/L | 100 W Average, >1000W peak | Depending selected orbit |
| Communication | TT&C, DL, ISL (S, X/Ka Bands) | 64 kbps to 200 Mbps selectable |

**Figure 11:** NIMBUS Micro-Satellite platform concept and typical performance.

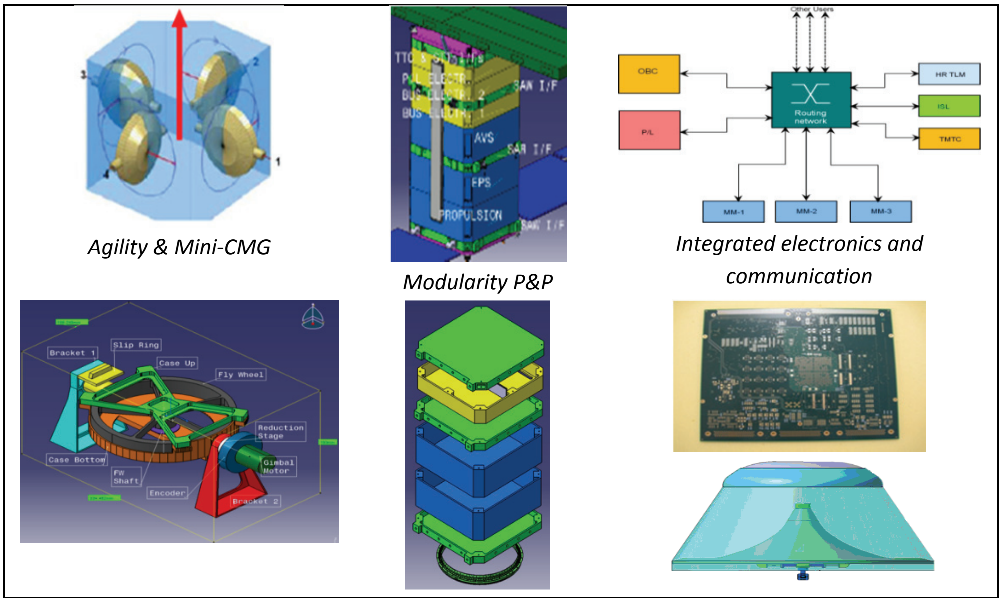



**Figure 12:** NIMBUS Micro-Satellite platform technologies.

***SAR observation with Micro-Satellites***

*Applications*

Micro-Satellites, although their reduced dimension and power, offers the opportunity to perform different SAR applications by adopting, in some cases, different solutions with respect to the conventional SAR missions.

SAR applications that can be performed with a constellation of Micro-Satellites includes:

- Very low revisit time land and maritime surveillance with imaging of high or low reflecting scenarios
- Interferometry for Digital Elevation Model (DEM), displacement monitoring or change detection
- Stereogrammetry for 3D reconstruction applications

Micro-Satellites missions are characterized by a reduced cost, hence the possibility to increase the number of sensors is an attractive option. This leads to constellation characterized by a very low revisit time. This peculiarity can be exploited in different monitoring and surveillance applications.

SAR imaging for land and maritime surveillance can be performed either on high or on low reflecting scenarios. This difference regard the amount of reflected power that can be received and processed by the sensor. Scenes with fields and mountains are classically characterized by a low reflecting signal and, to obtain acceptable images, an elevated power is needed. Differently, scenarios with high reflecting targets, such as ships over the sea and building with low reflecting background, can be acquired with lower power (both transmitted and received by a smaller antenna). A representation of high and low reflecting scenarios is reported in Figure 13, where on the left, a simulated image is acquired with an higher power, while on the right, the same area is acquired with a lower power. It can be observed how, on the higher power image (left in figure), even low reflecting targets, such as streets, can  be identified. On the other hand, in the lower power image (right in figure), only the high reflecting targets, such as ships, can be observed.

SAR Micro-Satellites mission can be designed, according to customer needs, either for high reflecting target monitoring or for low reflecting areas surveillance. The design of the mission is strictly linked to the final application, and, as described in the following paragraph, mission configuration will be shaped according to needs.

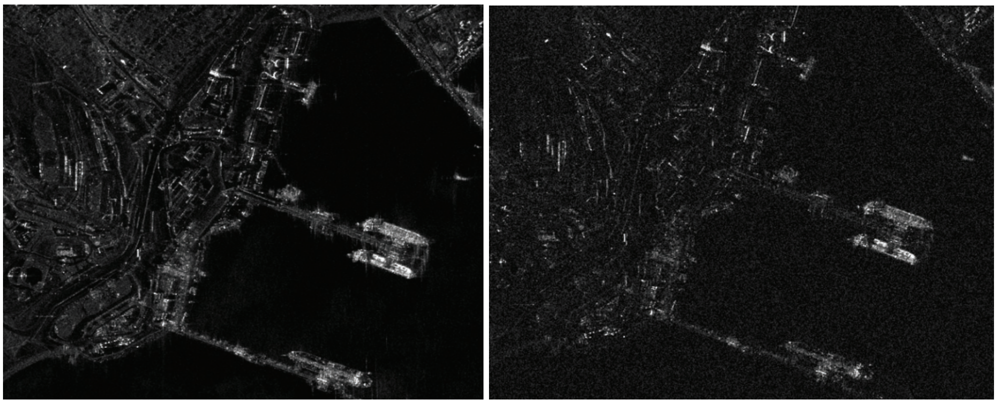


**Figure 13:** Simulation of high (left) and low (right) reflecting scenario application.

Interferometry can be performed, as for the other SAR missions, for DEM generation, displacement monitoring and change detection. In order to perform interferometry, a strong constraint is applied on the mission configuration, in which, the master and slave sensors should be located at a close distance one to the other. The satellite location will affect the Micro-Satellite sensing capabilities, hence a performance evaluation will take into consideration the whole mission configuration. Another application that can be performed with Micro-Satellites is stereogrammetry, which is imaging of the same area with two or more sensors, this permits to acquire the scene from different points. Different algorithms and techniques can use this acquisitions to generate 3D models of the scene by using the amplitude information of the image.

*Mission Configuration*

A SAR Micro-Satellite mission can be classified, by its configuration, in one of the following:

- Monostatic Micro-Satellite SAR mission
- Bi/multistatic mission with existing master SAR satellite and Micro-Satellite SAR slave (passive)

A Micro-Satellite SAR monostatic configuration will be strongly driven by the lower transmitted and received power, hence, in order to obtain acceptable performances (see next paragraph), the satellite altitude is preferred around 300 km from the sea level. Furthermore the possibility to increase the number of SAR sensors leads to constellation designed to decrease the revisit rate on a specific area of interest.

An access area of 20°-40° has been used for a 300 km inclined orbit to obtain information on the revisit time constellation performance. In Figure 14 an average revisit time plot is reported. The reported analysis starts (left in figure) with the focus on the Mediterranean area (in fact the monostatic Micro-Satellite mission is characterized by a low power imaging, good for ships monitoring), obtaining an average revisit time around 5 hours in the whole Mediterranean sea with four satellites (revisit time performances takes into account access area, hence this performance depends on the payload capabilities too). Enlarging the mission objectives on the equatorial area, a constellation of eight satellites is reported in Figure 14 on the right. The location of the eight satellites on orbits with different inclination permits to distribute the revisit time performance with respect to the latitude on the interested regions. In the reported design the performance on the Mediterranean area is kept constant with respect to the previous one, while the performance at the equator is increased to 5 hours.

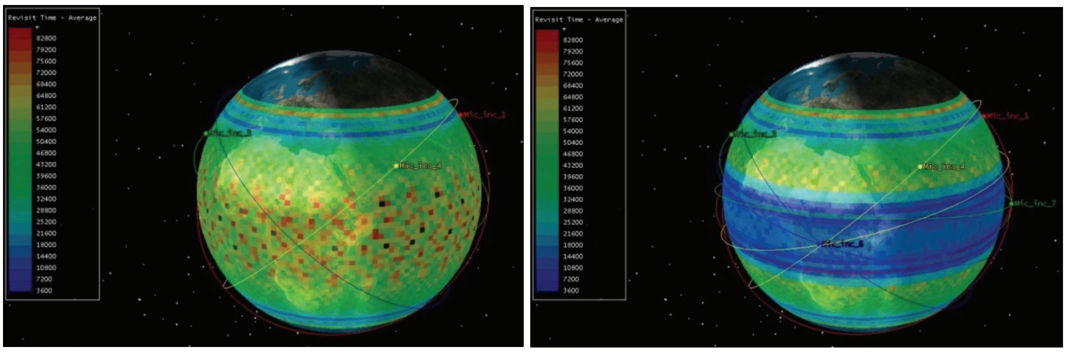


**Figure 14:** Revisit time analysis for a monostatic mission at 300km. Four satellites on the left and eight on the right.

A bi/multistatic passive mission cooperating with existing SAR satellites can be in following configurations:

- Slave Micro-Satellite located near the master
- Slave Micro-Satellite located on lower orbit
- Slave Micro-Satellite located on a rotated orbit to maximize the signal reflection

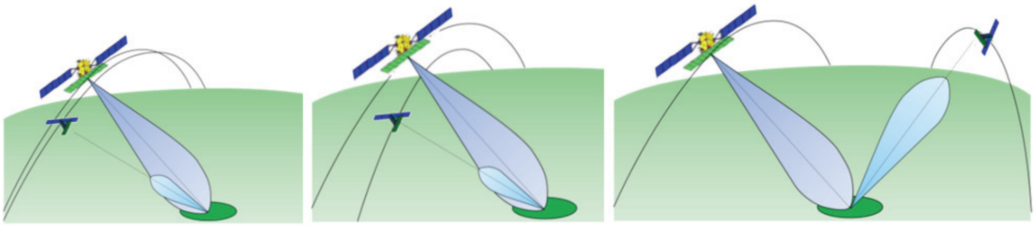


**Figure 15:** Bi-static passive configuration with Micro-Satellite close to the master (left), at a lower altitude (center) and on a rotated orbit (right)

The first passive configuration, with the slave satellite close to the master, can be used for interferometric applications, even if characterized by low power images due to smaller receiving antenna. Another acquisition mode for this configuration is the Displaced Phase Center technique, in which one or more slave satellites are located on the same master orbit but with a small delay. This permits to use the signal received by the different satellites to process a unique image. Stereogrammetry applications performed with a slave Micro-Satellite located on a lower altitude orbit will benefit of the smaller return path, obtaining good performances in terms of NESZ (as reported in the next paragraph). Even with a better performance in terms of power, the configuration is sensitive to the different motion of the satellites, in fact the slave satellite, located on the lower orbit, will have a smaller orbit period. As an example of cooperative mission with COSMO-SkyMed master satellite and a slave SSO orbit at around 300 km, visibility events would occur every 5.6 hours. Visibility events are defined with a maximum squint angle of 1.25° and would last for 10 minutes. Considering a 16 days scenario, which is the repetitive cycle of COSMO-SkyMed, the acquirable areas are reported in Figure 16 on the left, where the whole 4 satellites constellation is considered together with the left acquisitions capability. For a quasi-global coverage, 5 slave Micro-Satellites should be located on the lower orbit.

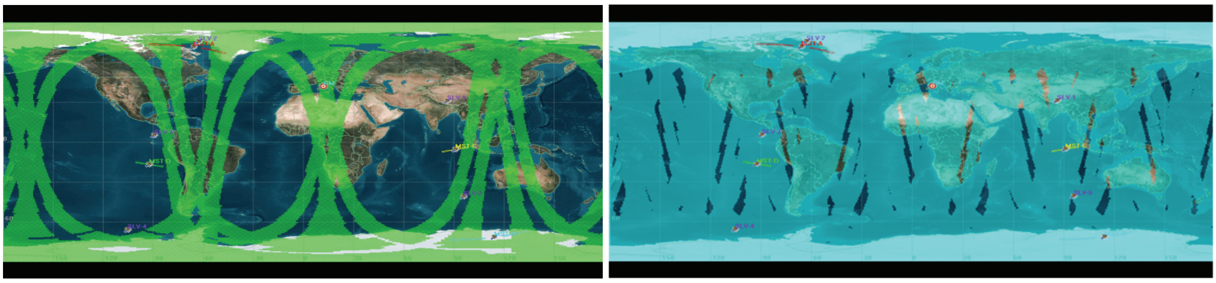


**Figure 16:** Acquirable areas on a 16 days scenario with 4 CSK master satellites and different slaves number: 1 slave satellite on the left; 5 slave satellites on the right

The third passive bistatic configuration consists in placing the slave satellite on a rotated orbit with respect to the master one. This configuration has the advantage of exploiting the signal reflection to increase the received power, while maintaining the acquisition opportunity during the whole orbit. A possible application of this configuration is imaging and stereogrammetry.

*SAR Instrument configurations*

For the Micro-Satellite applications, two instrument configurations are studied : monostatic and passive SAR.

A ***monostatic SAR*** configuration architecture is sketched in Figure 17, together with the acquisition geometry. The system parameters are summarized in Table 3. The antenna dimensions are related by the following expression:

$$A = L \cdot H = \frac{4 v_S \lambda R_S \tan\theta}{c_0} \qquad (1)$$

Where $v_s$ is the satellite speed, $\lambda$ is the wavelength, $R_s$ is the slant range, $\theta$ is the incidence angle and $c_0$ is the speed of light. The length of the antenna drives the minimum usable PRF in order to reduce the azimuthal ambiguity effect on the image. On the other hand, the height of the antenna, as well as the pulse length, will determine the swath size. The achieved performance are summarized in Table 3 in terms of main image parameters. The design specification take into account of the antenna length-height trade-off with respect to performance parameter and platform dimensions. The duty cycle of 10% ensures a power during acquisition below 850 Watt. The access region spanning from 20 to 50° of incidence angle is covered.

TWT devices in X-Band with peak power in the range 2-4 kW and duty cycle of 10% or more are widely available for avionic applications, WITH operative life of several thousand hours allowing expected mission and operational duty cycles (5 years, 5-10 min/orbit). Current performance budget is conservatively based on GaAs LNA performance, with input limiter for protection. The GaN LNA technology, currently under development, will reduce the number of limiter stages with a further improvement of the NF and, consequently, on NESZ.

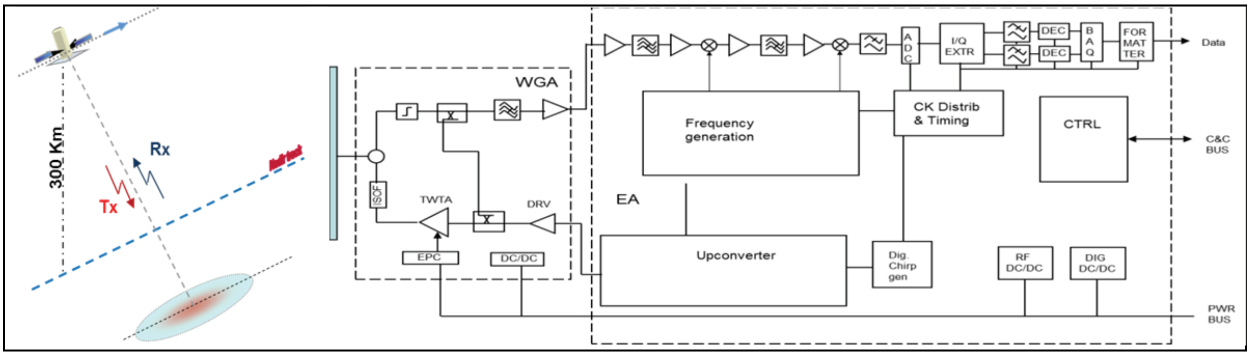



**Figure 17 :** Micro-Satellite SAR geometry (left) and SAR Monostatic Architecture (right)

| | | |
|---|---|---|
| **Carrier Frequency** | 9.6 | [GHz] |
| **Signal Bandwidth** | 300 | [MHz] |
| **Orbit height** | 300 | [Km] |
| **Access region** (incidence angle) | 20-50 | [°] |
| **Swath** | 5 | [Km] |
| **Range Resolution** @34° incid. angle | 1 | [m] |
| **RAR** | -30 | [dB] |
| **NESZ** over incidence angle range | -17- 12 | [dBm2/m2] |

| | | |
|---|---|---|
| **Peak RF power** | 2.5 | [KW] |
| **Duty Cycle** | 10 | [%] |
| **Nominal PRF** | 10 | [KHz] |
| **Nominal Pulse length** | 10 | [µs] |
| **Mass** | 24 | [Kg] |
| **Antenna length** | 2.0 | [m] |
| **Antenna height** | 0.4 | [m] |
| **Noise Figure** | 4.5 | [dB] |

**Table 3:** System and performance parameters (left) and radar design specifications (right)

A ***Bi-static SAR*** configuration can be considered in tandem with monostatic active SAR satellite; as seen in the previous section, this configuration may be very effective for cooperative missions with active SAR satellite already operating in orbit. As example, assuming COSMO Second Generation SAR Satellite as master, a microsatellite passive SAR satellite may be used at a lower or similar orbit to implement a bi-static solution. The acquisition geometry is shown in Figure 20, together with a monostatic architecture of the instrument which is supposed to be receiving only. In this case the mass of the electronics is extremely reduced with respect the monostatic case, for a total of about 15 Kg with a power consumption around 55 Watt. The achievable performances are in Table 4.

A further configuration with two or more micro-satellite may enable interferometric and polarimetric capabilities with a further wide range application scenario, as described in previous section.

| | | |
|---|---|---|
| **Carrier Frequency** | 9.6 | [GHz] |
| **Signal Bandwidth** | 300 | [MHz] |
| **Orbit height** | 300 | [Km] |
| **Access region** (incidence angle) | 15-45 | [°] |
| **Swath** | 15 | [Km] |
| **Range Resolution** (*) driven by TX BW | 1(*) | [m] |
| **NESZ** @45deg incidence angle | -18 | [dBm2/m2] |

| | | |
|---|---|---|
| **Mass** | 15 | [Kg] |
| **Antenna length** | 3.36 | [m] |
| **Antenna height** | 0.67 | [m] |
| **Noise Figure** | 4.5 | [dB] |

**Table 4:** Bi-static SAR (receiver), System and performance parameters (left), radar design specifications (right)

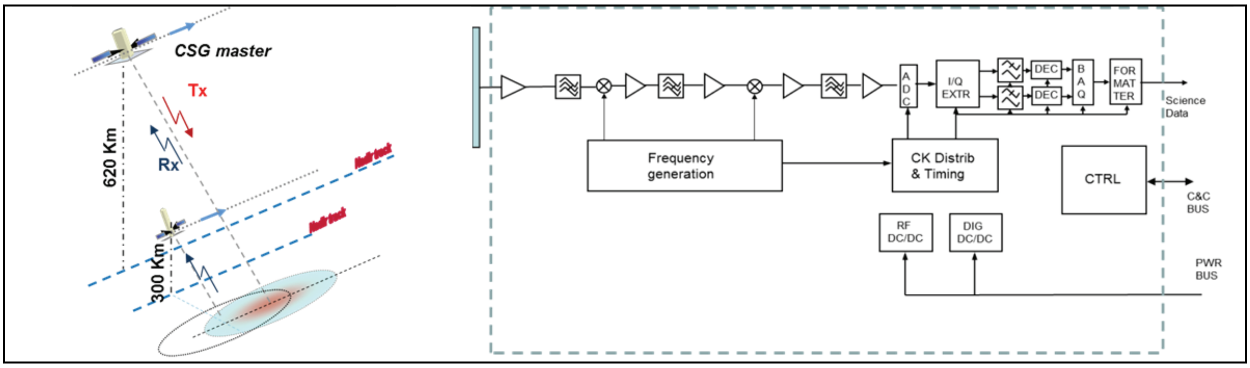



**Figure 20 :** Bi-static geometry (left) and receiving only SAR Architecture (right)

***Debris detection and Monitoring***

Space debris now represents a major and growing threat to space activities as their number increases with in-orbit collisions. Several Nations are willing to establish Space Surveillance and Tracking (SST) support services to assess the risks of in orbit collisions, detect and characterize in-orbit fragmentations, break-ups or collisions, and assess the risks of the uncontrolled re-entry of space objects and space debris into the Earth's atmosphere.

SST activities for space debris observation and tracking are today mostly based on ground-based sensors such as telescopes and military radars coupled with processing facilities. Space based optical measurements are relatively new (developed in last decade), while at the moment radar sensors are not used in orbit for these purposes.

It is worth noting that large part of Space Debris are still not detected as explained in the following graph [5].

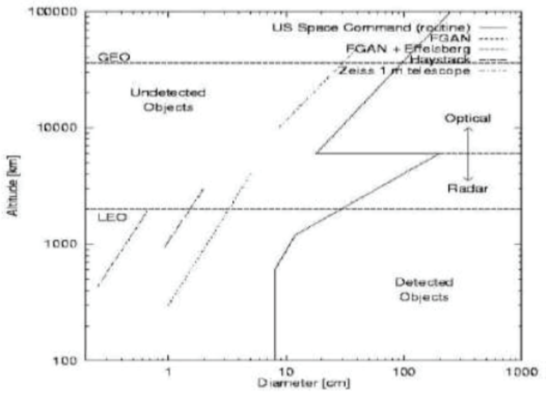



**Figure 22:** Space Debris distribution. R. Jehn. Debris Detection and Observation Systems, International Interdisciplinary Congress on Space Debris, McGill University, Montreal, 7-9 May 2009

Ground based space debris detection suffers from limits related to temporal and spatial observation constraints, atmospheric hindrances, and detection performance especially w.r.t. debris with size smaller than 10 cm. Accordingly Space based detection of a debris may complement ground based surveillance assets for SSA in terms of an easier Small Debris Conjunction Prediction e.g. one or two orbits in advance.

In parallel to large scale international initiatives for SSA, specific systems could be deployed whit the intent to:

- serve as proprietary continuous reliable source of debris information in a specific context (e.g. LEO) in support to operational satellite systems (e.g. Earth Observation satellites, telecommunication, etc.)
- possibly actively contribute to the international initiatives as a “node” of a much larger information network forming the basis of the current and future operational SSA/SST systems.

The detection of debris can be performed by optical and radar instruments embarked on small satellites in LEO, and selecting proper sensor characteristics micro-satellites can be conceived. In this respect, Micro-Satellites are very attractive as they would allow an easier implementation of constellations allowing an increased coverage of the space environment surrounding LEO and a higher frequency of measurements for characterization of debris orbital parameters and attitude. Mission analysis is performed to define suitable orbits of constellation, adopting statistical approach to detection with validated tools like Meteoroid and Space Debris Terrestrial Environment Reference (MASTER 2009, ESA), and Program for Radar-Optical Observation Forecasting (PROOF 2009, ESA).

Thales Alenia Space Italy is studying the fusion of Optical and Radar on a same Micro-Satellite :

- **OPTICAL instrument**: high sensitivity due to absence of atmosphere, optimized telescope aperture, *optimum illumination condition.*
- **RADAR instrument:** proximity to the object (increasing S/N), measurements in any light condition, observables as Doppler, distance and radar cross section. *Complementary with respect to optical.*
- **High operational flexibility**: quick access to specific objects, data fusion for reliability and accuracy.

Concerning the ***Optical instrument design***, the key parameters considered for the study are a PSF = 0.5 pix as it maximizes the accuracy in the centroid determination, FOV = 5 to maximize the SNR and the number of objects detectable while reducing the revisit time, and F# > 1.2 as enforced construction limits (the theoretical limit is F# > 0.5). Furthermore the capability to detect Debris 10 cm sized was considered, with an instrument Aperture of 20 cm to allows a better sensitivity within a still reasonably small size, and an Exposure time of 0.2 second. The preliminary results achieved were:

- 10 cm sized debris : up to 1000/700/100 km if the angular velocity is 3/6/30 °/min;
- 50 cm sized debris up to 4000/1000 km if the angular velocity is 5/30 °/min;
- 100 cm sized debris up to 10000/6000/4000/1000 km if the angular velocity is 3/10/25/30 °/min.

Image simulation were performed with images containing 10 cm sized debris at 1000 km range, with exposure time of 0.2 seconds. The results were very positive when looking at Galactic latitude of 90° (best case, smallest star density), while the worst case was around 0° (due to highest star density). These limitations of optical instrument, where higher star density may make the detection more difficult in particular sun illumination or celestial background cases, suggest that radar measurements may be useful to improve debris detection probability. Furthermore in principle a Radar detection capability may also Early Warning data for collision avoidance.

The ***Radar instrument design*** should be aimed at detecting different classes of debris targets, with a significant dynamic range in terms of mean Radar Cross-Section (RCS) within a specific Cell Under Test (CUT) defined by the Radar Field of View, and real time radar signal processing capabilities at a given reference distance. The aim is to cover the gap in detection of objects between 1mm/1cm up to 10cm, that cannot be easily detected by ground-based radars or optical telescopes.

Although millimetre waves at 95 GHz (or eventually at 77 GHz) may allow fitting expected debris RCS into the optical region as demonstrated by feasibility studies made in past decade (WARDEN study [6]), a specific focus has to be addressed to Ka-Band Radar solution (as reference 35.76 GHz), both in terms of technological capability and signal processing techniques. Indeed Ka-Band may offer improved performance for detection of smallest debris, since the corresponding RCS would increase: as example a 3mm diameter debris, RCS is around-30dB in X-Band, and -10dB in Ka-Band. Ka-Band also offers higher antenna directivity, and in the LEO operational scenario dynamic range will not be affected by propagation losses typical of Earth atmosphere.

On the other end technologies for Ka-Band radar in space were consolidated in last decade, leading to the development of performing solutions offering a significant reduction in mass, physical dimensions and power that allow implementation fully compatible with Micro-Satellites (e.g. the Thales Alenia Space recently developed Ka-Band Radar Doppler Altimeter for EXOMARS mission, a Low Power Radar in Ka-Band for real time velocity and altitude measurement during descent to Mars, with an overall Mass Budget < 15Kg including 4 antennas).

The instrument architecture considered (see figure below) is based on Monostatic FMCW radar concept, embarking a digital-core and outlined as a system of subsystems in terms of hardware, software, and firmware implementation perspectives as well as in terms of operative mode functionalities. Debris target echoes may appear at the receiver as a delayed and Doppler shifted replica of the transmit signal, and converted via coherent de-ramping (e.g. using homodyne mixing). The receiver linearity allows coping with multiple target echoes due to the superposition principle whereas spectral analysis on the IF bandwidth allows focusing on selected target ranges. FMCW concept is considered because of its inherent power efficiency; specific techniques have been considered for adaptive leakage cancellation among TX/RX, which are typical of this configuration.

The radar will provide for Multi-pulse integration; since the background will be characterized by extremely low (or no) clutter, lower detection thresholds are allowed in the signal processing chain to increased detection probability of small debris at medium range.

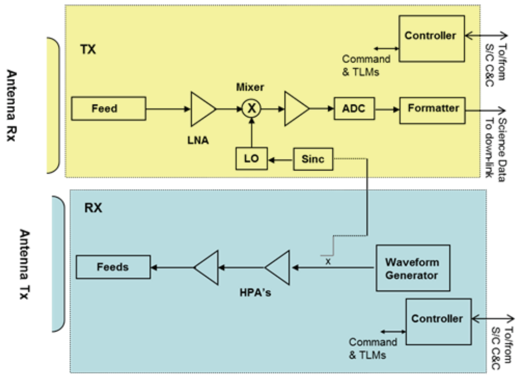
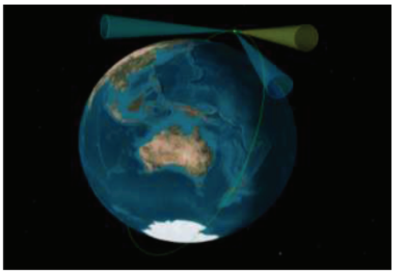



**Figure 23**: Ka-Band Radar FMCW architecture for Micro-Satellite

As summary the debris detection mission can be developed around a Micro-Satellite concept with an optical and a radar instruments, injected into a Sun-Synchronous dawn-dusk Orbit at ~1000 km altitude. The key features of such system would be :

- High revisit rate over the selected orbits,
- Front-down looking configuration would be selected for optical instrument;
- Side looking configuration is preferred for radar instrument;
- In these conditions the Optical instrument will have the optimal phase angle w.r.t. the Sun;
- The Radar would operate at close distance from the debris to be observed.



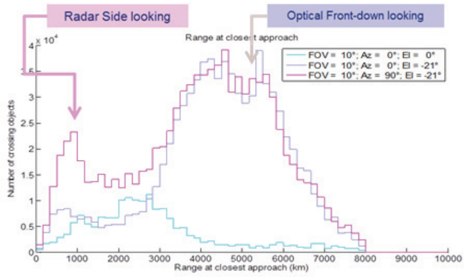



**Figure 24**: Micro-Satellite mission concept with optical and radar instruments in LEO (left) and number of crossing objects vs. range at closest approach (right)

*Coverage and revisit in LEO can be further and progressively improved by a Constellation approach*, that can be very effective also in costs thanks to the small spacecraft sizes: increasing the number of Microsatellites on the same orbital plane, or additional Microsatellites on different orbital planes. This may allow to pursue two simultaneous missions objectives/concepts :

- ***Global LEO Surveillance*** as part of and SST system in SSA frame, aiming to integrate its data with the existing one coming from other sensors of the network and observing the LEO;
- ***Protection of specific space assets*** in specific orbits/sectors (e.g. National systems), providing early warning data to support possible collision avoidance manoeuvres, focusing the observation to smaller areas and hence reducing the number of needed Microsatellites.

***Atmosphere sensing and Meteorology, Microwave Radiometers***

Microwave Radiometry include a wide number of different instruments and payloads. Suitability of these instruments for Microsatellites is due to both the simplicity of the instruments (like in the case of altimetry) or to the great advantage offered by constellations of payloads (like in the cases of altimetry, push-broom multi-frequency instruments, and interferometric payloads). The possible applications span from the oceanic topography at support of the Sea state and oceanic currents monitoring, to the climatology applications like the study of the water cycle by analysis of the Sea, Land and Atmospheric physical parameters.

A specific example is a Precipitation Mission based on an active Rain Doppler Radar (RDR), operating in Ka-Band for accurate precipitation rate measurement. The radar can operate at 35.7 GHz, providing vertical profiles of the precipitation along three narrow beams, one at Nadir and two closely spaced from Nadir in the fore and aft directions . Passive radiometer channels can be implemented (Nadir or co-located beams 18/24/37 GHz) to have reference passive sensing of atmosphere in the same frequency bands.

Studies and development for an highly integrated radar/radiometer payload for altimetry was already performed by Thales Alenia Space (Alti-Ka project). Furthermore the adoption of new technologies like System On Chip switch/receiver will further improve the miniaturization of this instrument thus improving the advantage for a microsatellite constellations due to very low mass, power, envelope and data rate budgets required.

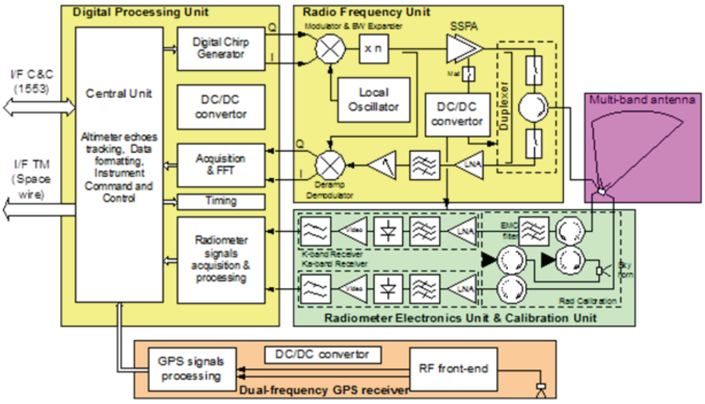



**Figure 25:** Functional scheme of integrated Ka-Band Radar/Radiometer instrument for altimetry

Other possible implementations of a MW radiometer for microsatellite constellations are:

- Push-broom Radiometer;
- Interferometric (Synthetic-Aperture) Radiometer.

The first one would cover applications that require large swath with low resolution while the second one would cover applications requiring smaller swath with higher resolution. However the variable constituted by the number of satellites provides an additional degree of freedom in the assessment of architecture definition against mission objectives.

These implementations find their justification on the basis of the assumption that technology for high precision formation flying would be available. On that basis one can imagine to design a “distributed payload/instrument” with very low cost, lightweight and low power elements.

## REFERENCES

[1] J. Richard et al. : “An innovative spaceborne radar concept for global maritime surveillance”, *IGARSS July 2010*

[2] A.Torre, C.Germani, et al. “Compact SAR: an innovative high resolution instrument for small satellite”, ARSI & KEO Conference, November 2014 ESA-ESTEC

[3] A. Meschini , L. Di Cicco, G. Galluccio: “The development of a large unfurlable reflector assembly”, Workshop on Large Deployable Antennas ESA/ESTEC, October 2012

[4] P.Capece , L.Borgarelli, M. DiLazzaro, U.Dimarcantonio, A.Torre.: “Cosmo Skymed Active Phased Array SAR Instrument”, RADAR Conference Rome 2008.

[5] R. Jehn. Debris Detection and Observation Systems, International Interdisciplinary Congress on Space Debris, McGill University, Montreal, 7-9 May 2009.

[6] R.Battaglia, M.Ferri, V.Dainelli, F.Sarullo. “WARDEN: W-Band advanced radar for debris early notification from ISS”, Aerospace Conference 2003, Proceedings 2003 IEEE (Volume 1)

[7] Recommendations From The Gamble Project For Future Missions And Research Programmes

[8] R. K.Raney and D. L. Porter, WITTEX: An Innovative Multi-Satellite Radar Altimeter Constellation.

[9] P. D. Cotton, Y. Menard, Future Requirements For Satellite Altimetry