Italian Air Force Radar and Optical Sensor Experiments for the Detection of Space Objects in LEO Orbit

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ABSTRACT

Italian Air Force (ITAF) recognizes the relevance of a sensor architecture for a Space Surveillance & Tracking (SST) capability to protect its own space and satellite assets and infrastructure against the damage or destruction from collision with other space debris in orbit. In 2011, the Italian Government has delegated the ITAF, with collaboration of Italian Space Agency (ASI) and National Institute for Astrophysics (INAF), to study the feasibility of a national architecture using already existent assets and processing capabilities for SST. It was started a survey at national level and an experimentation using radar sensors, property of ITAF and INAF, both in monostatic and bistatic configuration. In 2014, the European Commission, with the Decision 541/2014/EU of 16th April, established an European SST framework, to promote the use of national assets and processing capabilities of Members State. Those national capabilities have to guarantee an initial European Architecture to provide an SST Services with the huge challenge of gradually becoming self-sufficient and independent in producing an integrated European space surveillance network.

The national contribution to European architecture will be composed of both radars and optical sensors since they have different capability and provide complementary type of information regarding targeted object. Collected data from networked sensors will be sent to a national integration centre in order to analyze it and make the orbit determination of the detected space debris using specific software tools.

In this paper we briefly describe the potential capabilities of these sensors and the results of preliminary tests carried out separately with a monostatic long range radar and an optical telescope managed by Italian Air Force (ITAF) for the detection of a subset of space objects in LEO orbit with the perspective to perform a sensor data fusion experiment in the near future. In particular, the optical sensor is a telescope properly designed for SST and is able to observe the portion of space above it with a coverage of 360°x90° in azimuth and elevation. The telescope is equipped with two CCD sensors: one with a wide field of view used for surveillance tasks and the second with a narrow field dedicated for tracking specific objects. The sensor is managed by an operating software system that allows user to remotely plan and schedule its daily activity and to make orbit determination and collision risk assessment in a completely automated way.

1. INTRODUCTION

Italian Air Force (ITAF) recognizes the relevance of a sensor architecture for a Space Surveillance & Tracking (SST) capability to protect its own space and satellite assets and infrastructure against the damage or destruction from collision with other space debris in orbit. In 2011, the Italian Government has delegated the ITAF, with collaboration of Italian Space Agency (ASI) and National Institute for Astrophysics (INAF), to study the feasibility of a national architecture using already existent assets and processing capabilities for SST. It was started a survey at national level and an experimentation using radar sensors, property of ITAF and INAF, both in monostatic and bistatic configuration. In 2014, the European Commission, with the Decision 541/2014/EU of 16th April, established an European SST framework, to promote the use of national assets and processing capabilities of Members State. Those national capabilities have to guarantee an initial European Architecture to provide an SST Services with the huge challenge of gradually becoming self-sufficient and independent in producing an integrated European space surveillance network.

The national contribution to European architecture will be composed of both radars and optical sensors since they have different capability and provide complementary type of information regarding targeted object. Collected data from networked sensors will be sent to a national integration centre in order to analyze it and make the orbit determination of the detected space debris using specific software tools.

Space is the Ultimate High Ground and the capabilities provided by space assets are considered enabler and multiplier for military operations. The relevance of protection of space has been globally recognized and SST capabilities ensure this protection. SST can be considered as the natural extension of the Control of the Airspace and, in this perspective, ITAF started an experimentation programme to upgrade and use existent Air Defence assets to provide, in collaboration with ASI and INAF, an initial National SST architecture.

The general architecture of a space surveillance system in terms of building blocks incorporates typical sensors and data processing centres that, once federated, could allow to set up a fully operative service, pointing out that the challenges raised up by the SST requirements could never be addressed by one space or ground based sensor, that alone would never be able to survey or track the whole space environment. This approach implies the availability of several sensors, both radar and optical, with performances good enough to ensure an improvement in the object observations and the availability of tools able to reliably plan and schedule dedicated measurement tasks and to compute the orbit determination in order to offer the service required by space operators such as deciding whether a collision avoidance manoeuvres is needed or not.

Space debris can be observed by means of radars and optical telescopes. The choice of the specific sensor strongly depends on the target objects (i.e. type, size, distance) and the observation mode.

Typically, radar measurements have been used for space debris in Low Earth orbit (LEO), because the radar power budget and operating wavelength are limiting factors for detection and accuracy of small objects at long ranges. On the other hand, optical telescope have been used for High Earth orbit (HEO), with the requirements to have clear and dark skies and the object illuminated by the sun during measurements. Ground-based radars are well suited to observe space objects because of their all-weather and day-and-night performance; furthermore, radars can control the transmitted signal that illuminates the target using coherent signal of well-known characteristics [1].

In addition, observation modes should be taken into account: survey, when the object position is not known and tracking when the object position is given or predicted with certain accuracy and the object is tracked to increase the accuracy of its trajectory data (position, velocity). Accordingly sensors used for SST can be generally divided into two groups: surveillance or tracking.

Surveillance sensors continuously scan large areas of the space with the aim to observe all the items in transit, to find out new objects and to determine their orbital data. The intention is to populate and update a catalogue that will guarantee knowledge of the current and expected space situation. This type of activity includes, preferably, the use of sensors with a large field of view.

Tracking sensors are used when a very high-accurate data are needed about a specific object, when for example it has been predicted it could collide with an operational satellite. So the highest quality of data is necessary to improve these predictions and assist the satellite operators to plan in case any necessary avoidance manoeuvres. In this case, it is preferable to use radar/optical sensors characterized by reduced field of view with a consequent gain in terms of pointing accuracy.

Some sensors can perform just one of these tasks, while others are able to have dual roles within the full system.

The objective of the present document is to give an overview of the ITAF contribution, and in particular of the Aero-Space System Engineering Group of Flight Test Wing, to the implementation of a national capability in the field of SST of space debris based on already existing assets and also to give a perspective of what the future evolution of the system could be.

The paper is structured as follows: Section 2 describes the radar sensors used in recent experiments performed by ItAF in coordination and collaboration with other organizations, including some of the results achieved in those tests. Section 3 presents the new optical sensor acquired by ITAF and its technical features; in addition, the results of preliminary experiment executed with the telescope are shown in this part. Section 4 briefly discusses on the sensor integration activity and data fusion study/test that ITAF is planning to do in the next months.

2. RADAR SENSORS

In the SST architecture radars have been used in both a monostatic (a single antenna for both transmitter and receiver) and bistatic (transmitting from one antenna and receiving from another antenna) configuration. In the bistatic mode, an additional receiver antenna, separate from the emitting antenna, is used. This allows a greater sensitivity, which enables the detection of smaller objects, and flexibility for networking different kinds of antennas.

In the last year ITAF conducted two separate experiments on space debris detection in LEO employing two main radar assets in different configurations:

- RAT 31DL radar - Fixed/Deployable Air Defence System (FADR/DADR) as monostatic radar;
- Northern Cross antenna array in bistatic configuration.

Monostatic Radar

Radar Description

The RAT 31DL is a solid state D-band long range radar with transmitter modules distributed along the antenna array (fig. 1). It provides flexible surveillance and tracking capabilities adaptable to various kinds of threats, in particular Air Breathing Target (i.e. aircraft, missile) and Tactical Ballistic Missile (TBM). This is achieved through multiple, simultaneous, independently phase controlled pencil beams, which provide, in conjunction with advanced signal processing techniques, a great flexibility in scanning and very high data rate. It has been developed by Selex ES and ITAF currently employs fourteen items as Air and Missile Defence radar in the national territory.

RAT 31DL system was selected for the SST experiment because of its capabilities to direct high elevation beam pointing (when in TBM tracking mode) and to be externally cued against an existing track.

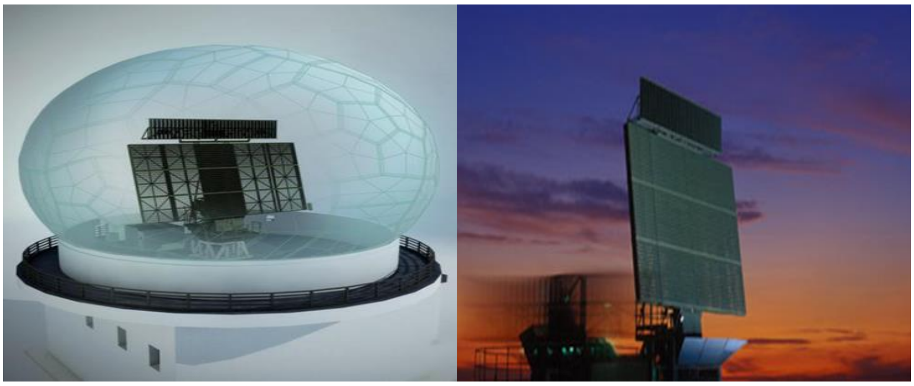

Fig. 1: RAT 31DL fixed configuration (respectively with and without radome)

Experiment

The main objective of the test was to demonstrate some initial space sensing capability exploiting existing national radar performances. The test has been prepared and carried out together with Selex ES, that was responsible for the software modification and the management of the radar installed in the Borgo Sabotino Air Force Base. In fact, as described in detail in [2], the RAT 31DL involved in the test has been optimized for space objects detections in the timing, waveform and processing features via minimal software adjustments, since it was not originally designed and developed for SST purposes. For the test a subset of candidate space objects has been selected from the NORAD catalogue using up-to-date TLE for position reference in order to satisfy the key requirements of being visible from the radar site.

Result

Known limitations (i.e. targets further than the RAT 31DL instrumental range and faster with respect to conventional air and missile radar target) cause relevant degradation and processing loss with respect to the nominal radar performances. To overcome some of them, targets beyond the instrumental range (so called ambiguous zone) were also processed generating a special waveform with pulses transmitted at a constant Pulse Repetition Time (PRT) corresponding to about 500 Km (in such a way the first echo of objects ranging between 800 and 1000 Km is received between 300 and 500 Km at the second time frame).

The result of the demo was that the radar detects some satellites and space debris having RCS greater than 15 m^2 and located at a distance of up to 1000 Km with a probability of 70% and a radial accuracy of 50 m and an angular accuracy of 0.25°.

As reported in [2], the results demonstrate a good matching between TLE trajectory and raw measurements, especially for object with high RCS, while slight bias errors were observed in the measurements of smaller targets. At the end, the test was considered successful because the radar has demonstrated good SST performances consistent with its power-aperture limitations.

Bistatic Radar

Radar description

This bistatic radar, known as BIRALES and used for survey, is composed by two assets (as shown in fig. 2):

- the transmitter is the Flight Termination System (FTS), owned by ITAF and located at Salto di Quirra Joint Test Range in Sardinia;
- the receiver is the antenna array named Northern Cross (NC), located at Medicina (Bo) and operated by INAF.

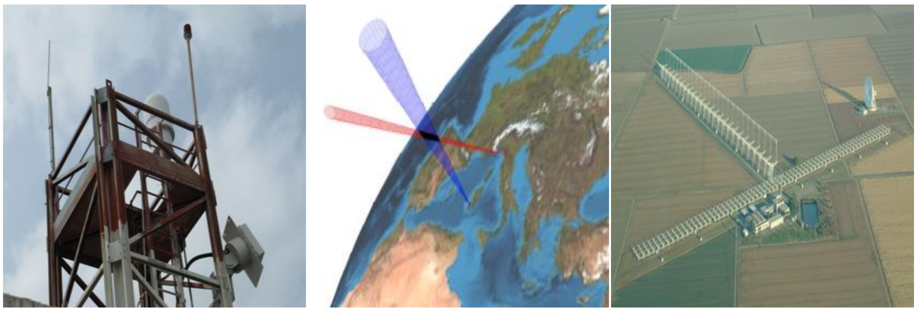

Fig. 2: BIRALES bistatic radar (FTS on left and NC on right hand side)

FTS is a powerful transmitter currently used by ITAF for safety purposes during the system trials in the range. It consists in a power amplifier able to supply an average and levelled power of 4 kW in the bandwidth 400-455 MHz coupled with an omnidirectional antenna and wide beam directional antenna. The transmitter is usually used in CW mode; anyway the equipment is able to receive in input a modulation signal.
Northern Cross antenna is a transit instrument, steerable in declination only and therefore able to point at objects that transit over the local celestial meridian. The radio telescope operates at UHF band and it is composed of two perpendicular arms that cover a surface of approximately 27000 m^2: East/West (E-W) and North/South (N-S) direction. The E-W arm is a unique antenna with a 564 m long and 35 m wide cylindrical-parabolic reflector surface, whilst the N-S arm is composed of 64 parallel cylindrical-parabolic shaped antennas. Two important capabilities of the receiver are the multi-beaming, that enables the characterization of the transit direction of the scattering object inside its field of view (in terms of right ascension and declination or alternatively in azimuth and elevation), and the ranging enabled only when coupled with a transmitter that uses a dedicated, synchronized waveform and modulated signal.
The architecture is very flexible and modular and is suitable to realize an effective sensor dedicated to detect orbiting objects of very small RCS and to measure the range and angular information necessary to calculate and/or update space objects trajectories.

Experiments

Two observation campaigns have been performed in 2013 and end of 2014 with different objectives:

- test the sensitivity of the system and the minimum RCS detectable using only one receiving antenna (a section of the E-W arm of the NC);
- test the multi-beam approach using a receiving antenna array (BEST-2 composed of 32 Rx).

Those tests were planned and executed by a joint team composed of personnel from ITAF and INAF, with the collaboration of ASI in the planning phase for the selection of a subset of targets from NORAD database. Regarding the receiver part, in the first campaign a sector of the E-W arm of the NC radio telescope was used, for a total collective area of about 2800 m^2. In the second observation test the BEST-2 array part of N-S arm (composed of 8 cylindrical parabolic antennas with 32 Rx) was used for a total collective area of about 1400 m^2.

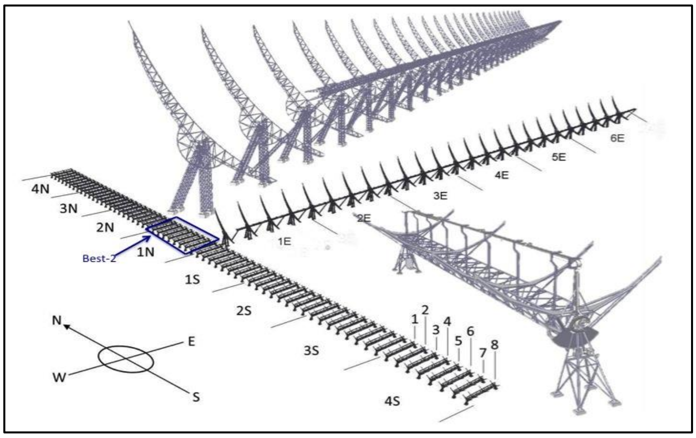

Fig. 3: Northern Cross and BEST-2 antenna array

Result

The first phase of the testing has confirmed the capability of the asset to detect objects with RCS very small, in particular:

- sub-meter objects into a distance from Earth to an altitude between 300 km and 1000 km;
- objects greater than 1 m^2 from 1000 km to 1700 km of altitude.

The results obtained were very promising and led to consider this first phase of testing as a proof of good sensitivity and sufficient accuracy. In fact, the data obtained from these campaigns showed a sensitivity of the system that exceeded expectations. During the test it was able to get time/frequency graphics with an echo detection of a very small space debris (RCS = 0.54 m^2, altitude = 796 km, bistatic slant range = 1782 km).

In the second experiment described in detail in [3], an initial multi-beam capability was tested. It was possible to recover a pattern from the multi-beam picture and to reconstruct the trajectory with a further post-processing algorithm. With further developments, the algorithm will be able to retrieve orbital information of the space objects from such patterns.

The performances of the orbital data processing unit have been assessed through dedicated numerical tests. An example is reported hereafter in the frame of a simulation involving the proposed bistatic sensor for the observation of an object with a RCS of 6.5 m^2. The tracklet, i.e. the trajectory covered by the satellite or debris inside the FoV of the antenna, has been plotted from post processing analysis.

The resulting maximum error on the estimation of the values of right ascension and declination was 0.02 deg and 0.06 deg, respectively. The error on the position components is equal to a few tens of meters, whereas the error on velocity components is less than 10 m/s. The uncertainty on position is on the order of a few tens of meters and the ones on velocity are again around 1 m/s [3].

3. OPTICAL SENSOR

ITAF has recently installed an optical sensor for SST in Pratica di Mare AFB that is operated by personnel of Aero-Space System Engineering Group of Flight Test Wing.

PdM-MITE Telescope

Sensor description

PdM-MITE is a telescope properly designed for SST by GMSpazio and Officina Stellare and is able to observe the portion of space above it with coverage of 360°x90° in azimuth and elevation (fig. 4).

Fig. 4: PdM-MITE Telescope (left) and its FoV (right)

It is built with an exclusive Riccardi-Honders flat field optical design, with a diameter of 350 mm and a Focal ratio F/2.8. It is also equipped with two CCD sensors: one with a wide field of view used for surveillance tasks and the second with a narrow FoV dedicated for tracking specific objects. It is mounted on a platform in equatorial layout designed for high speed tracking and pointing purposes. It is furthermore equipped with a remotely controlled filter wheel able to manage five standard filters that gives the possibility to investigate the spectrum of the light reflected by the target. The system architecture and data flow is reported in figure 5.

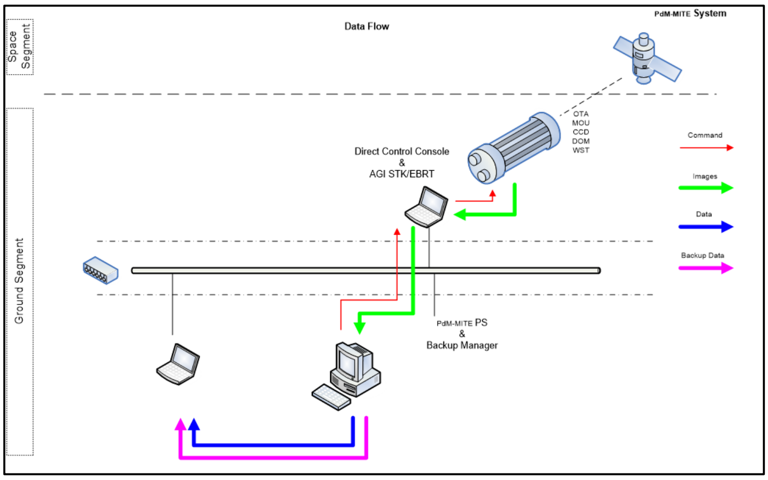

Fig. 5: PdM-MITE Architecture and data flow

Operating modes

The sensor has been designed for the following operating modes:

- Survey: the sensor can scan a portion of the sky selected by the user in order to detect any objects in that area; as default it can scan the area following spiral or linear movements, otherwise the operator can set some waypoints for a specific search path;
- Tracking: cued by an ephemeris file (.tle or .e), the sensor can track an object passing in the sensor's field of view.

Output Observation data

The images acquired are analyzed and processed for the extraction of the orbital parameters (figure 6), so for each image there is an automatic stars matching process (based on the known stars found in the star database). The time sync is performed by a GPS sensor, which allows knowing the exact time of shot.

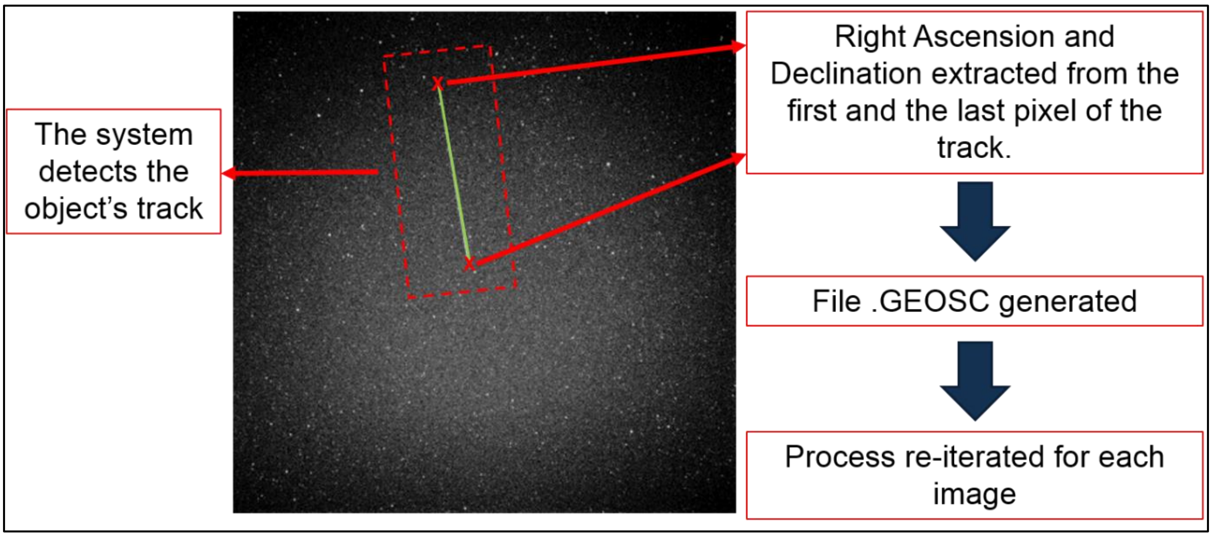

Fig. 6: Process for extraction of orbital parameters of a LEO satellite

Due to the star matching algorithm, the error on the position estimation is independent of the mechanical properties of the system and is only dependent on the astrometry algorithm. At this moment it is possible to obtain a position estimation of the tracklet within a RMS error, dependent on the stars matched, of approximately 0.8 arcsec in the LEO band.

The extraction of the coordinates for the first and the last pixel is a choice still under test that was made in order to increase the number of data available for orbit determination. Dealing mostly with LEO, MEO and GEO satellites, the numbers of data available for analysis are (assuming no weather issue and the full-time availability of the sensor):

- for a LEO satellite, typical in-sight times are within 5-8 minutes. So, assuming a shot every 30 seconds, up to 16 images can be obtained from a single transit. Considering that a LEO satellite is in-sight for up to three passes per night, usually two, the number of images can significantly increase (40-50);
- for a MEO satellite, typical in-sight times are up to 6 hours so the number of images acquired per night can be up to several hundreds;
- for a GEO satellite, in-sight times are all night long so the number of images acquired per night can be more than one thousand.

Once the tracks have been analyzed and the coordinates have been extracted, the program parser generates a ".geosc" file containing all the data to feed the orbit determination software with.

Orbit Determination process

Once the orbital parameters have been extracted from the images and the ".geosc" file has been created, the AGI software Orbit Determination Tool Kit (ODTK) is used to perform orbit determination. Data are processed by the program in order to obtain the ephemerides of the tracked object, with the objective of progressively refine the determination performing day-by-day observations. ODTK is a very complex tool whereby the user can modify and tailor the numeric model for obtaining accurate determination and prediction of the orbit of an observed object. The more is precisely tailored the numeric model, the best will be the orbit obtained.

Test

Tests for verifying sensor's performance are still in progress, focusing on LEO satellites for purposes of interest of the armed force whose aim is to obtain an Initial Operational Capability for SST.

Interesting results have been obtained observing a LEO satellite named ENVISAT, ESA non-operational satellite for Earth Observation. This specific satellite has been selected being characterized by: big dimensions (easy to see), stable orbit and no maneuver.

The satellite has been observed during the nights of 31st of August 2015 (two orbits), 1st of September (one orbit) and 2nd of September 2015 (one orbit).

Result

During the 1st night (31st of August), ENVISAT was in-sight for two consecutive transits:

- first image at 19:23:38, last image at 19:30:18, 21 shots, 9 detections of the satellite for the 1st orbit;
- first image at 21:03:51, last image at 21:09:11, 17 shots, 11 detections of the satellite for the 2nd orbit.

During the 2nd night (1st of September), ENVISAT was in-sight for one pass:

- first image at 20:26:54, last image at 20:32:34, 18 shots, 14 detections of the satellite.

During the 3rd night (2nd of September), ENVISAT was in-sight for one transit:

- First image at 19:46:56, last image at 19:53:56, 12 shots, 10 detections of the satellite (figure 7).

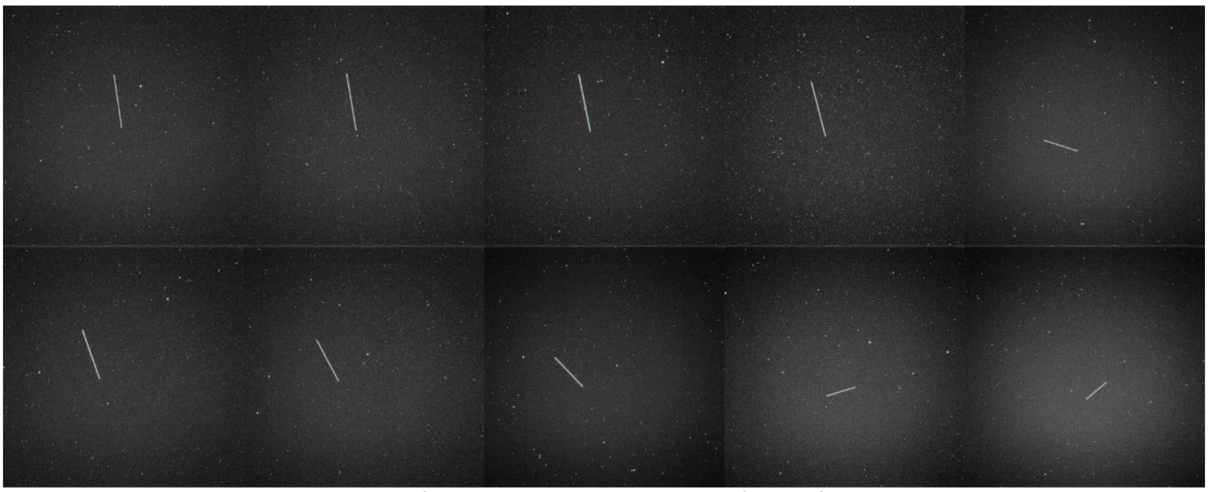

Fig. 7: Detections of ENVISAT during the night of 2nd of September 2015

Processing the data through the three nights, the position uncertainty (2-sigma) of ENVISAT has evolved as depicted in figure 8. In the graphs it is clearly identified an improvement of the uncertainty on the position due to the increment of the available data from different observations. The position uncertainty cross-track, where the optical sensor gives his best performance, evolves from a maximum of 42 m to a maximum of 37.22 m. The radial position uncertainty, due to the missing ranging measurements, evolves from a maximum of 150 m to a

maximum of 60 m. Finally, the position uncertainty in-track, caused by the missing information related to the tracked satellite’s speed, decreases from a maximum of 550 m to a maximum of 240 m.
Plots of Residual and Residual QQ distribution are also provided (figure 9).

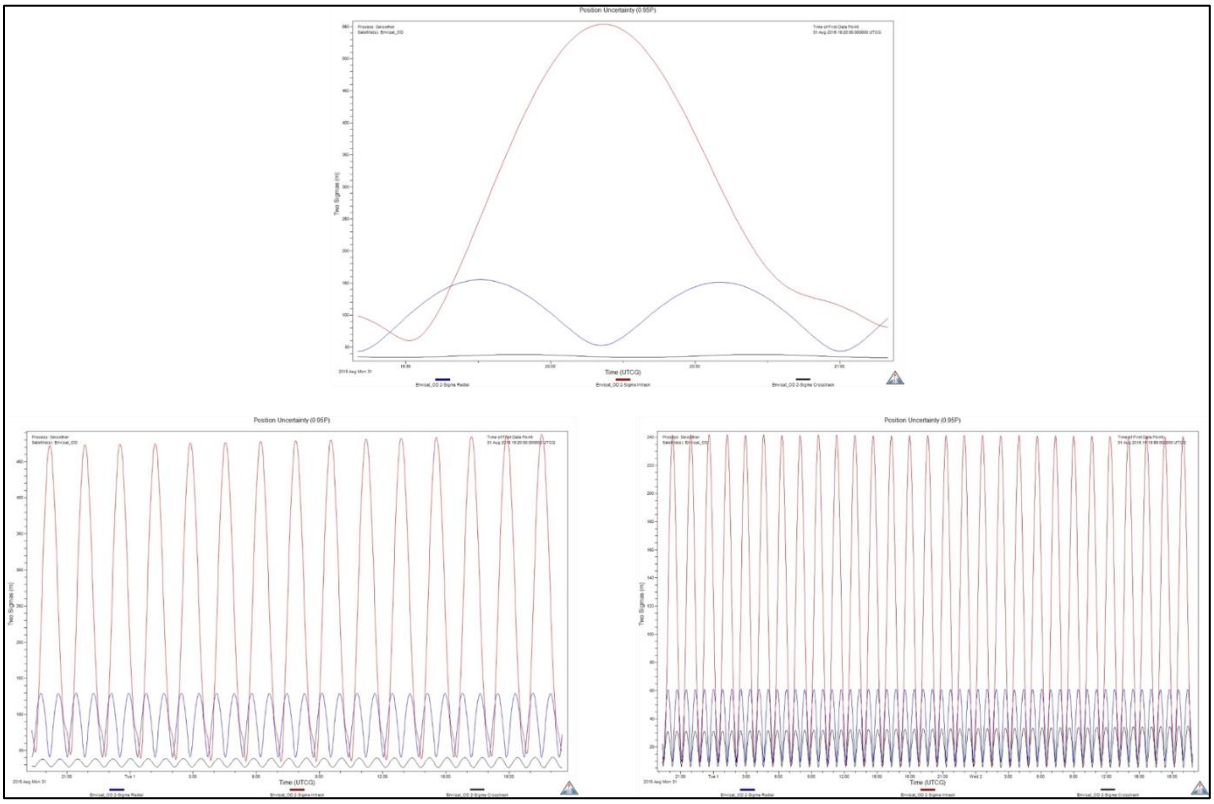

Fig. 8: Position Uncertainty (2-sigma)

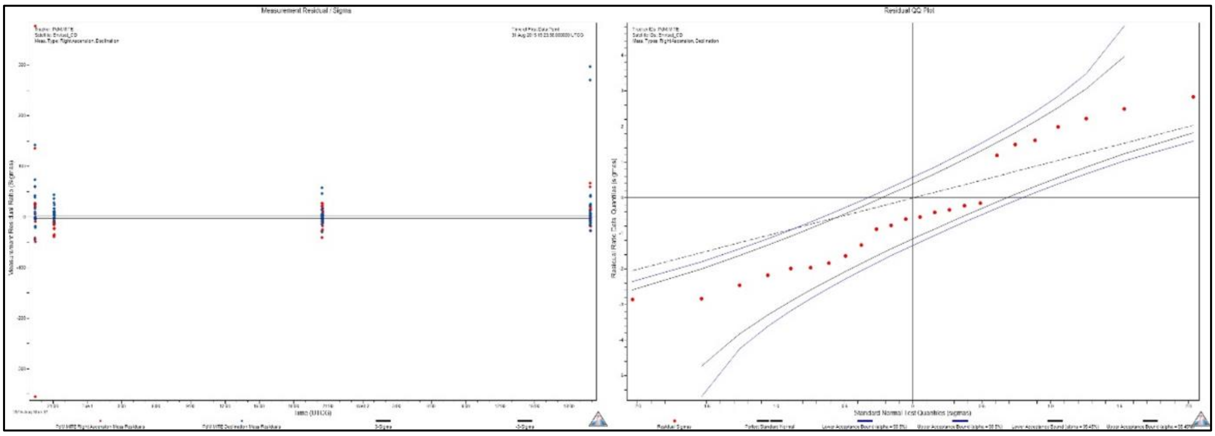

Fig. 9: Residual and Residual QQ

4. SENSOR INTEGRATION & DATA FUSION

The SST architecture that the nation is developing will consist of survey and tracking sensors, the data processing chain and the applications that will generate and disseminate the SST products. The sensor integration and control centre will be the core of the architecture and will be located in Pratica di Mare AFB in a restricted area in order to handle also classified information. Currently, this area is already used as a stand-alone control room for the PdM MITE telescope, but in the near future, it will be network linked with many of the national deployed sensors. In this manner it will be able to receive raw observations (that need to be further processed) and sensor measurements (in terms of right ascension and declination for optical sensors and range, Doppler, azimuth and elevation for radar sensors). Once received this data, using the software tool already installed in the control room it is possible to determine the orbits of the observed objects, correlate the

measurements with previous collected data of the same objects or identify new objects, update the space object catalogue and plan and schedule new observation requests (both routine survey or dedicated tracking). The applications will use the space object catalogue to generate SST data products, such as conjunction warning and re-entry warning messages. In this way in the sensor integration and control centre, a synthetic Recognised Space Picture can be produced, i.e. a consistent and coherent scenario representing the real time picture of space populated with existing moving objects, offering specialized features and analytic capabilities for measurements, reports and graphs, but also capable to simulate forthcoming events evaluating the effects of different decisions in order to assist satellite operators in their activities.
Before sensors have been integrated, it is of interest to determine the potential benefit in orbital estimation of using multiple, heterogeneous and geographically dispersed sensors. A sensor data fusion experiment is planned to be performed in the next month using the existing assets in order to verify if the measurements collected from different sensors and locations can improve the accuracy of the object orbit determination.
The following objectives could be fixed for this experiment:

- use together data from FADR radar and PdM MITE telescope, thus adding ranging data to angle measurements in order to improve position uncertainty in the orbit determination process;
- use PdM MITE telescope observations data to cue FADR radar;
- use PdM MITE telescope orbits to provide self-cue, using its own prior observations instead of TLE from NORAD;
- use BIRALES radar measurements to cue PdM MITE telescope and/or FADR radar;
- use PdM MITE telescope with other optical sensors in order to get ranging data from different angle measurements.

Before making a live test, simulation experiments are going to be executed. System Tool Kit (STK), Orbital Determination Tool Kit (ODTK) and Orbiter Space Flight Simulator are the tools employed for setting up a valid simulation environment. Orbiter was used as primary scenario generator to create the main target orbital object and the FADR radar (reporting range, azimuth and elevation) and PdM MITE telescope models (providing right ascension and declination). In addition, two pieces of software were developed: an interface to share the target orbital motion in Orbiter with STK and ODTK tools and a parser software to convert the format of the real radar output data into ".geosc" format mode, in order to use ODTK software for orbit determination.

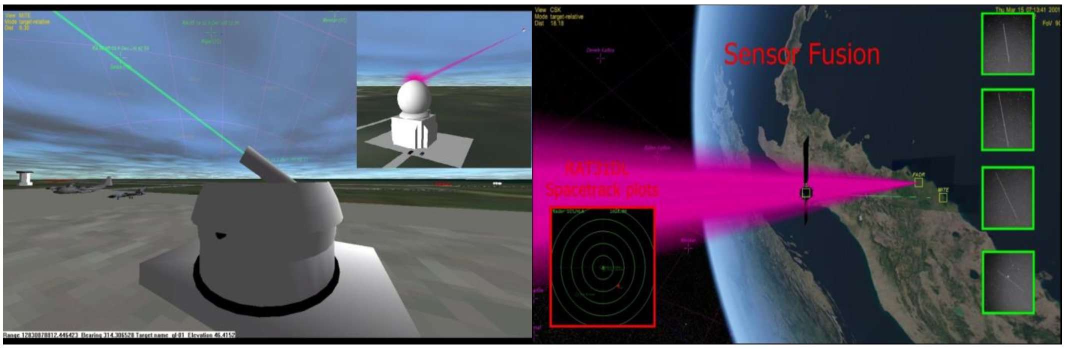

Fig. 10: PdM MITE telescope and radar FADR models (left) and concurrent observations from sensors (right)

In the figure 10 some snapshots of the simulation experiment are shown, whilst figure 11 reports a preliminary result that shows a reduction in the position uncertainty.

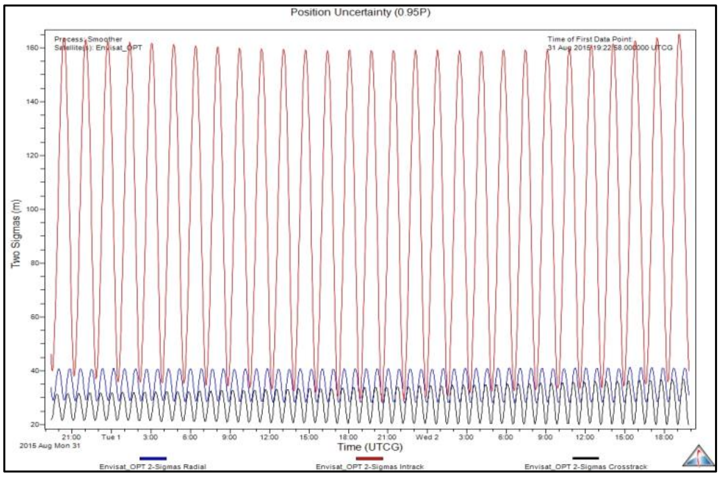

Fig. 11: Position Uncertainty (2-sigma) with optical/radar data fusion

5. CONCLUSION

In this paper some of the activities carried out by Italian Air Force with the support of other national organizations in the SST framework have been illustrated. Three different sensors included in the national SST architecture have been described with their performance and experiment results. These tests demonstrated that those sensors are compliant with the requirements defined by EU SST Consortium and led to consider that initial Italian SST capability can give an important contribution to the huge challenge of gradually becoming self-sufficient and independent in producing an integrated European space surveillance network. Challenges raised up by the SST requirements could never be addressed by one space or ground based sensor, that alone would never be able to survey or track the whole space environment. This approach implies the availability of several sensors, that provide complementary information. For this reason ITAF has focussed its effort on the sensors integration activity and has planned to perform a data fusion experiment between optical and radar measurements. Further studies, analysis, tests and architecture upgrades will be implemented in the near future in order to guarantee an end-to-end SST service.

6. REFERENCES

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