ENHANCING THE KNOWLEDGE ON SPACE DEBRIS ATTITUDE AND POSITION COMBINING RADAR AND OPTICAL OBSERVATIONS

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ABSTRACT

The number of catalogued space objects has been steadily increasing since the 1960s. Satellite launches, rocket bodies associated with those space launches, and fragments caused by the breaking of objects in space have contributed to this growth. The University of Rome "La Sapienza" together with the Politecnico of Milano and National Institute for Astrophysics (INAF) study the behaviour of these orbiting objects to improve the knowledge of their state in terms of position and attitude. A possible way to improve the accuracy of objects position is to combine the information obtained through optical sensors merged with data from radar sensors. This paper will introduce the observation methodology and will show the results and possibilities obtained from the fusion of optical and radar data.

1 INTRODUCTION

The increase of artifacts placed in orbit every year exponentially affects the amount of space debris surrounding the Earth. The European Space Agency (ESA) has estimated that currently, there are about 750,000 orbiting debris larger than 1 cm [1], this situation worries both the space agencies of any country and the private industry operating in the aerospace sectors because possible collisions in flight between their systems and a debris swarm [2, 3]. Without the effect of orbital decay caused by atmospheric drag, the increase in the population of space objects would have been very large (Fig. 1). This involves an increasing international interest in Space Surveillance and Tracking (SST) and in the future studies on Space Traffic Management (STM). The Two-Line Elements (TLE) released by the North American Aerospace Defense Command (NORAD), are often characterized by low accuracy and short-term reliability. Frequent updates of the dynamic state estimate are necessary for Space Situational Awareness (SSA) analyses and reliable orbit propagation.

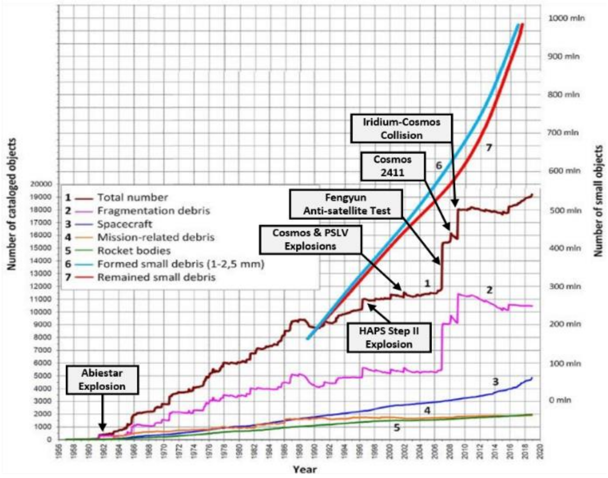

Figure 1. Space debris population over time [4]

Today the research is oriented towards continuous and frequent direct measurements of space debris which allow both to know the position of the object with very low margins of error and to contribute to the development of innovative techniques aimed at improving existing mathematical models. The knowledge of the state of the object is fundamental to understand the behaviour of the object itself, therefore it must be observed. Many observation systems are used for the observation of debris and their direct measurement: laser, radar and optical systems. Nowadays, the most advanced technique used for tracking space debris is their simultaneous observation through optical and radar sensors. In this context, the Italian Space Agency (ASI), acting as National Entity and operating its optical and laser sensors, the National Institute for Astrophysics (INAF) in collaboration with the Politecnico of Milano, operating its optical and radar sensors, and the Space Systems and Space Surveillance Laboratory of the University of Rome

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"La Sapienza" have been involved in enhancing the knowledge on space debris attitude and position combining radar and optical observations. In this paper is described the simultaneous observation of the same object using a radar and a telescope in order to obtain additional information on the attitude dynamics thanks to the valuable insights offered by the light curve obtained with the optical sensor and the signal-to-noise ratio curve produced by radar.

2 GROUND SENSOR DESCRIPTION

For the optical and radar simultaneous observation of the uncontrolled space object used for this paper, two systems are employed: Fast Imaging and Tracking System (FITS) and Bistatic Radar for Leo Survey (BIRALES).

FITS is part of the Sapienza Scientific Optical Network (SSON) [1]. The system is composed by the Remote Space Debris Observation System (RESDOS), located in Rome (RM), and the Sapienza Coupled University Debris Observatory (SCUDO) located in Collepardo (FR). The observatories (Fig. 2) have a mutual distance (baseline) of about 80 km, and both are equipped with a scientific CMOS, which allows a high framerate and therefore an acquisition of several measurements. The system has the same optical tube and camera and also are equipped with a GPS sensor in order to ensure the simultaneous observation of the same target at the same time.

Figure 2. Fast Imaging and Tracking System (FITS): are shown respectively on the left SCUDO observatory, located in Collepardo (FR), and on the right RESDOS observatory, located on Rome (RM).

Moreover, the mount used to move the telescope are able to track every satellite in every orbital regime (LEO, MEO, GEO). A summary of the main characteristics of the system are reported in Tab. 1.

Table 1. Main characteristics of FITS observatory system

FITS main characteristics		
Sensor	Type	sCMOS
	Resolution	5.5 Mpx
	Sensor diagonal	22 mm
	Max fps	100
Telescope	Focal length	750 mm
	Diameter	150 mm
	Mount type	Equatorial

BIRALES operating at 410-415 MHz, is composed of a transmitting antenna named TRF (Radio Frequency Transmitter) located in Sardinia (7-meter dish with 10 kW of maximum power), instead the receiving antenna is a portion of the Northern Cross Radio Telescope, located at Medicina (Bologna). This system in shown in Fig. 3 and have a baseline of about 580 km.

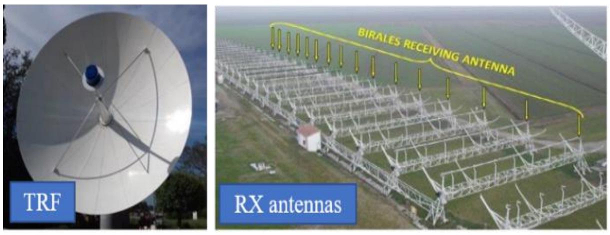

Figure 3. Bistatic Radar for Leo Survey (BIRALES): on the left the transmitter located in Sardinia while on the right the receiving antennas located at Bologna.

Considering the variation in time of the Signal to Noise Ratio (SNR) after a radio reflection from an orbiting object, we can generate a sort of "light curve" to determine the periodic rotation or the attitude of the object.

3 OPTICAL LIGHT-CURVE

The light-curve of an object is the variation over time of its apparent magnitude. To calculate the apparent magnitude of the object it is necessary to determine which stars are present in the field of view in each frame and therefore it is necessary to solve the stellar field of the images. The resolution of the stellar field is carried out thanks to the use of the Astrometry.net software [6] which outputs the resolved image, or the image in which are present the celestial coordinates for each pixel coordinate, and a text file. The text file contains information on the stars used to resolve the star field. More specifically, for each star, the file includes: celestial coordinates, pixel coordinates and bolometric (B) and visual (V) catalogue magnitudes. The star catalogue used to solve the star field by Astrometry.net is the Tycho-2 [7]. The Tycho-2 Catalogue contains positions, proper motions and two-colour photometric data for the 2.5 million brightest stars in the sky. The magnitude error is lower than 0.1 for stars with magnitude 10 and then gradually rises to at most 0.4 at magnitude 12 and fainter. The position and magnitude measurements of Tycho-2 stars are based on observations made by the astronomical satellite Hipparcos, built by the European Space Agency in order to map the entire sky. The United States Naval Observatory (USNO) used Hipparcos data for the compilation of the Astrographic Catalog / Tycho Reference Catalog, including about one million stars, therefore the use of Tycho-2 was preferred both for the high number of stars and to be precise in terms of magnitude.

3.1 Automatic video analysis for light-curve acquisition

The FITS system allows to obtain two simultaneous videos of the same object from two different sites. The problem is therefore that of finding an automatic procedure that processes the thousands of frames that compose the video and extract the variation of the luminous intensity of the object, with an associated error for each measurement.

To perform the described operations automatically, a code has been written, equipped with a graphic interface, whose high-level flowchart is shown in Fig. 4. The code receives the video as input and for each frame performs photometric calculations in order to derive the stars to be used as a reference for the calculation of the light curve of the object. This light curve is then normalized and filtered and output from the code.

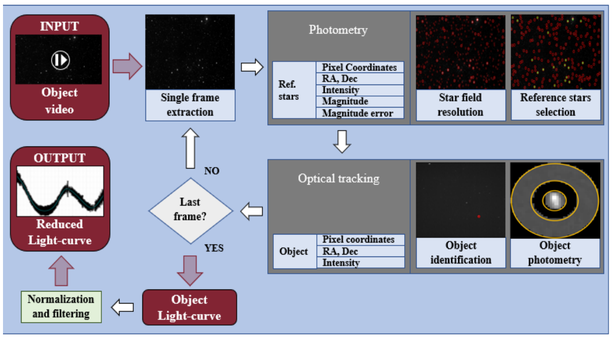

Figure 4. High-level flow-chart of the software for video analysis

For calculation of the star intensity a software aperture of star dependent radius is centred on the pixel coordinate of the object and then the pixels in this area (A) are summed; this is the total integrated photometric source signal (S). In order to remove the background (B), the Eq. 1 is applied:

$$I = S - n_{pix} \cdot B \qquad (1)$$

Where n_{pix} is the total number of pixels contained within the area A and B is the background. It can be seen in Fig. 5 that the intensity value of the object depends on the radius of the circle that is used to outline it.

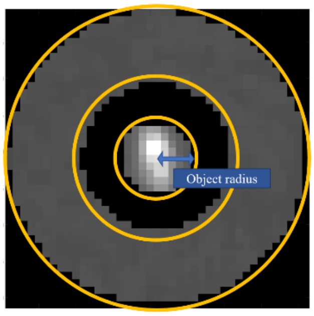

Figure 5. Aperture photometry routine. The inner circle is used for the total integrated source signal (S) calculation, while the external annulus is used for the background calculation

The apparent magnitude of the object in the frame is calculated using the catalogue magnitude of one star in the Field of View (FoV), known thanks to the field resolution, and the calculated intensities, of the object and of the star, as shown in Eq. 2.

$$mag_{obj} = mag_{star_{j,cat}} - 2.5log\left(\frac{I_{obj}}{I_{star_j}}\right) \qquad (2)$$

The magnitude is then calculated respect to all the others in the field, so it is possible to associate to the object an apparent magnitude equal to mean of the calculated magnitudes plus or minus the standard deviation of the measurements. Is possible also to select only one sub-group of stars present in the FoV, in order to minimize the standard deviation of the magnitude error.

3.2 Space debris and operative satellite light-curve

Many tests were needed to calibrate the software parameters to get a correct calculation of the magnitude of the stars and the object and also to follow correctly the objects in the video frames. Once the analysis of the video is completed, it is possible to retrieve the light-curve of the object. Fig. 6 shows the variation of the magnitude over time and also the relative error for each point of the curve. The considered passage over Italy is that on 18/01/2021 at 18:21:23 of the space debris COSMOS 1875 (SSN 18340). In particular, the blue curve represents the calculated magnitude, while the black lines show the error associated to each point, and thus an error plot.

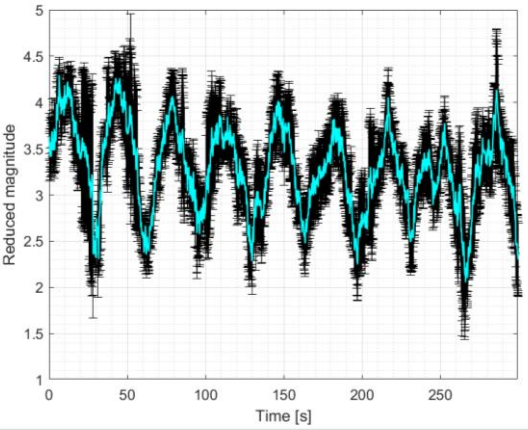

Figure 6. The light-curve obtained with RESDOS observatory. The space debris in consideration is COSMOS 1875 (SSN 18340) and the passage is that over Rome of the 18/01/2021 from the 18:21:23 to 18:26:23 UTC

With FITS system it is also possible to obtain the light-curve of the same object at the same time. Fig. 7 shows an example of light-curves obtained during a bi-static observation taken from RESDOS and SCUDO observatories. In particular, this is the observation of the operative Earth observation satellite SMAP during its passage of 2020/12/14 from 16:49:30 to 16:53:27 UTC. In these plots the error is not represented for visualization purposes. The red curve is the light-curve obtained from RESDOS observatory, while the blue one from SCUDO observatories.

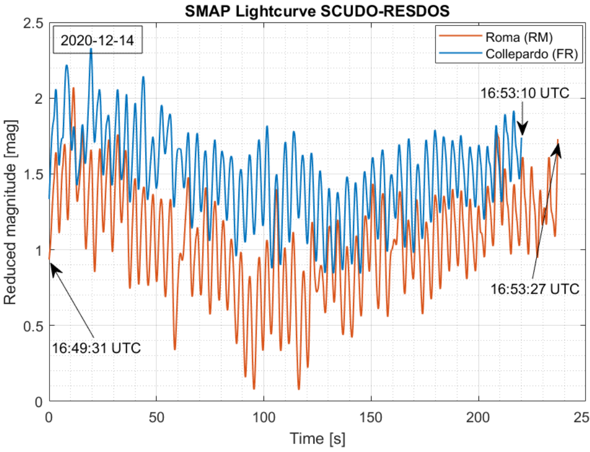

Figure 7. SMAP bi-static light-curve obtained with FITS system during the passage of 2020/12/14 from 16:49:30 to 16:53:27 UTC

4 SIMULTANEOUS RADAR AND OPTICAL OBSERVATION

The NOAA-17 satellite (NORAD ID #27453, Int. designator 2002-032A) was launched in 2002 and was deactivated in 2013 after its instruments began to fail. According to the Space Force's 18th Space Control Squadron (18SPCS), NOAA-17 exploded on 2021/03/10 at 07:11 UTC. Sixteen fragments have been associated to the event. Coincidentally, the 18SPCS spotted another weather satellite's breakup few days later, this time of China's Yunhai 1-02, which launched in September 2019. The squadron is tracking 21 pieces of debris from the incident. The opportunity to observe the NOAA-17 object using FITS and BIRALES simultaneously occurred on 2021/03/31. The optical and radar light curves obtained are shown below.

4.1 NOAA-17 RADAR AND OPTICAL LIGHT-CURVE

Similarly to the approach adopted for optical light-curves, the variation of the power of the signal received by a radar sensor (either in monostatic or bistatic configuration) during the observation of a pass of a space object can be linked to its possible tumbling motion. Considering the variation in time of the Signal to Noise Ratio (SNR) after a radio reflection from the orbiting object, we can generate a radar light-curve to study the periodic rotation or the attitude of the object.

Based on its configuration, BIRALES can be used to this purpose by recording the SNR during the pass of the object inside the sensor FoV. An example of the measurements obtained is reported in Fig. 8 and Fig. 9. The measurements refer to pass of the satellite NOAA-17 over BIRALES on March 31, 2021 (from 01:46:10 UTC to 01:46:20 UTC) after its break-up event occurred on March 10, 2021. More specifically, the radar image reported in Fig. 8 illustrates the power of the signal received plotted against time and frequency. Figure 9 integrates instead over the channels to report the SNR time profile measured during the passage.

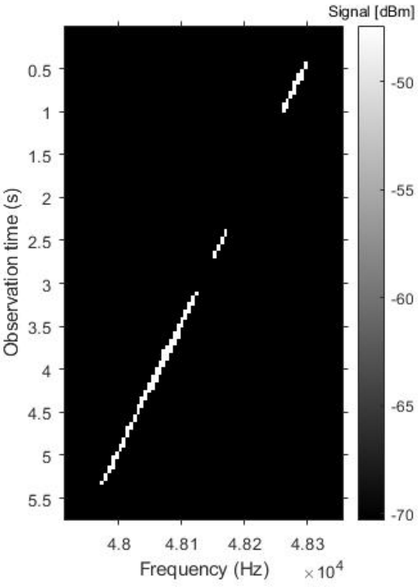

Figure 8 – Signal received by BIRALES during the pass

of NOAA-17 on 31 March 2021 plotted against time and frequency (real doppler is obtained by subtracting 35kHz in the frequency axis).

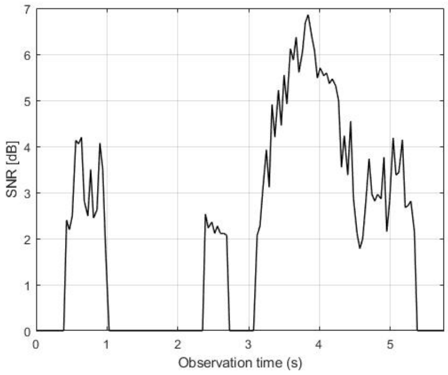

Figure 9 – SNR time profile received by BIRALES during the pass of NOAA-17 on 31 March 2021.

The SCUDO observatory was used for the optical observation of NOAA-17. The recorded passage taken over the observatory lasted about two minutes and presented a maximum elevation of about 35 degrees. In particular, the video start at 01:42:52 UTC and ends at 01:45:12 UTC, so with a frame rate of ten, 1400 frames were recorded. The NOAA-17 light-curve regarding this particular passage is shown in Fig.10.

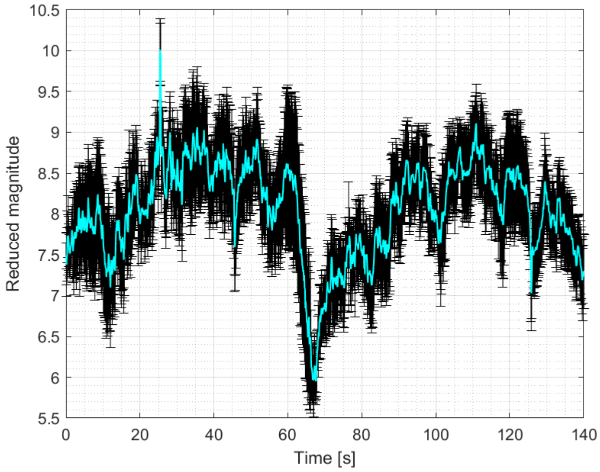

Figure 10. NOAA-17 optical light-curve recorded from SCUDO observatory of the 2021/03/31 from 01:42:52 UTC to 01:45:12 UTC

5 CONCLUSION

In this article it has been shown how it is possible to obtain light curves using both optical and radar instruments. In particular, FITS system managed by S5Lab and BIRALES administered by Politecnico of Milano and INAF were used. The two systems are employed in the observation of the object NOAA-17, ten days after its explosion occurred on 2021/03/10. The optical and radar light curves obtained respectively from the analysis of the video of the object, and from its radar image, show an evident variability probably related to the uncontrolled motion of the object. This observational technique appears to hold great promise for improving the attitude and position estimate of uncontrolled objects in low Earth orbit [8]. This type of mixed systems plays a fundamental role for objects in the re-entry phase, which are subject to numerous and difficult to model perturbations of the trajectory.

6 ACKNOWLEDGMENT

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