BI-STATIC RADAR MEASUREMENTS USING ESA'S 15 METER GROUND STATIONS

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ABSTRACT

A recent upgrade in two of ESA's 15 meter ground stations, lead to the possibility to perform bi-static radar measurements to track un-cooperative targets. This paper presents the results of such a measurement campaign, in which range-rate data was recorded using ERS-2 / Envisat satellites as radar targets. By post-processing this range-rate data an orbit can be determined. The accuracy of this orbit can be evaluated by comparing it to the operational orbit. As a reference also TLE (two-line elements) data are processed and compared to the operational orbit. This shows that the orbit based on our measurement gives an improvement to the TLE based orbit in along-track and radial accuracy, yet suffering from an out-of-plane degradation.

1. BACKGROUND

The European Space Agency (ESA) is developing a ground based radar system for low earth orbits (LEO) space surveillance. The radar system will be able to systematically survey and track all objects above a certain size. Based on these data, the system will maintain a catalogue with physical and orbital information. Space surveillance, among others, is important for the re-entry assessment of objects and for the safety of operational spacecraft (collision avoidance).

Currently, European assets capable of detecting LEO objects are limited and ESA relies largely on a catalogue provided by the US and on information provided by other nations. Europe plans to build up its own space surveillance capabilities [1], making it more independent from other nations and also improving the quality of the available space surveillance data. The ground based radar system for LEO space surveillance [2] forms a part of an entire surveillance strategy including also detection of objects in other orbits (MEO and GEO).

In preparation of these activities, it was found that the ESA tracking (ESTRACK) network could be used to perform basic bi-static radar measurements. This measurement campaign and its results are described in the paper.

2. INTRODUCTION

Thanks to a recent upgrade in two of ESA's 15 meter ground stations, namely Villafranca (near Madrid) and Maspalomas (Canary Islands, Spain), ESA now has the capability of performing bi-static radar measurements.

This technique was applied to track un-cooperative targets and to improve the orbital information. The upgrade was performed as part of the ISS Proximity Communication Equipment activity [3] and led to an S-band receive capability of Villafranca and Maspalomas in the uplink-band. This receive capability can be directly used for bi-static radar measurements, as is described in Section 3. The section also explains the detailed measurement setup, lists the measurement campaigns performed and visualizes some of the raw data measured. The orbit determination that can be derived from this data is presented in Section 4 together with an analysis on the achieved orbit determination accuracy. Finally, Section 5 summarizes the main results of the ESTRACK bi-static radar measurement campaign.

3. BI-STATIC RADAR MEASUREMENTS

3.1. Measurement set-up

The bi-static radar measurements were performed using the following set-up: uplink from the Kiruna (Sweden) ground station, reflection from the desired target and reception at Villafranca ground station (other ground station combinations are also possible). Figure 1 depicts this set-up. Due to the extensive load of the Kiruna ground station, the measurements were performed during routine uplink operations to the ERS-2 or Envisat satellite. Thus ERS-2 and Envisat were the target from which the uplink signal was passively reflected and then received at the Villafranca ground station.

ERS-2 and Envisat have an altitude over ground of approx. 785km and the operational uplink frequency is 2048.854 MHz. Using the standard bi-static radar equation [4] and assuming an average radar-cross-section (RCS) of around 17.4m^2 for ERS-2 and 26.8m^2

Proc. '5th European Conference on Space Debris', Darmstadt, Germany
30 March – 2 April 2009, (ESA SP-672, July 2009)

for Envisat, we should obtain a carrier-to-noise-power density (C/N_0) of more than 25 dBHz (depending on the time of the pass). It is emphasized that these RCS values are just averaged values - the observed RCS is expected to vary by one or more orders of magnitude around these values.

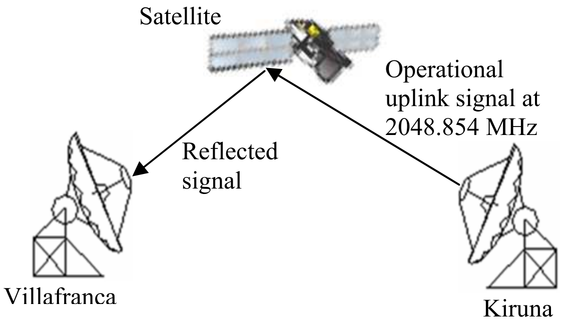

Figure 1 Bi-static radar measurement set-up. Transmission from Kiruna (Sweden) and reception at Villafranca (Spain)

In Villafranca the receiver phased-locked-loop (PLL) bandwidth has to be able to track the frequency change caused by the Doppler rate (approx. 50 to 200 Hz/s). For the loop filter in the receiver ("IFMS") this leads to a suggested minimum bandwidth of around 30 to 50 Hz. Since each IFMS can internally use two independent receivers and the fact that each ESTRACK station has the capability of using two redundant receive chains, a total of 4 independent receivers are available for each measurement. This flexibility is used, to configure each receiver with a different loop filter bandwidth, namely: 30 Hz, 50 Hz, 100 Hz and 200 Hz are used as PLL loop bandwidth.

Due to the large distance (around 3300 km) between the two ground stations used, the joint visibility of the satellite from both stations is limited to a few minutes in time. Measurements showed that during this short time it is possible to phase lock the receiver at the Villafranca ground station to the reflected carrier signal. Once the receiver is locked, Doppler measurements are recorded. From this Doppler recording bi-static range-rate data are computed and used in the orbit determination process. Using a-priori information (as from two-line elements (TLE) data from the US Space Surveillance Network) it is possible to reconstruct a satellite orbit (cf. Section 4).

With the given hardware constraints (transmit power: <380 Watt) the measurement setup is restricted to observing large objects. Furthermore in the frequency band used, no auto-tracking capabilities are available at the two receive ground stations and thus, program-track had to be applied.

3.2. Measurement campaigns

In the following, the results of three measurement campaigns with Envisat and ERS-2 are presented. Table 1 gives an overview of these measurement campaigns.

Measurement campaign	Date	Envisat observations	ERS-2 observations
I DOY[1]196-200	14-18 July 2008	5 day passes	5 day passes
II DOY[1]211-214	29 July – 1 Aug. 2008	3 day passes	4 day passes
III DOY[1]61-64	2-5 March 2009	3 day and 3 night passes	4 day and 2 night passes

Table 1 Overview of measurement campaigns

During the first two measurement campaigns (I+II) only day passes of ERS-2 and Envisat were observed. It should be noted that ERS-2 follows the same orbit trajectory as Envisat just with a delay of around 30 minutes. From the several day passes available, the one with the longest joint visibility from the transmitter (Kiruna) and receiver (Villafranca) ground station was chosen. An example of such an orbit is depicted in Figure 2. In all these day passes, the Kiruna ground station first has visibility and then Villafranca station follows (North to South ERS-2/Envisat orbit trajectory).

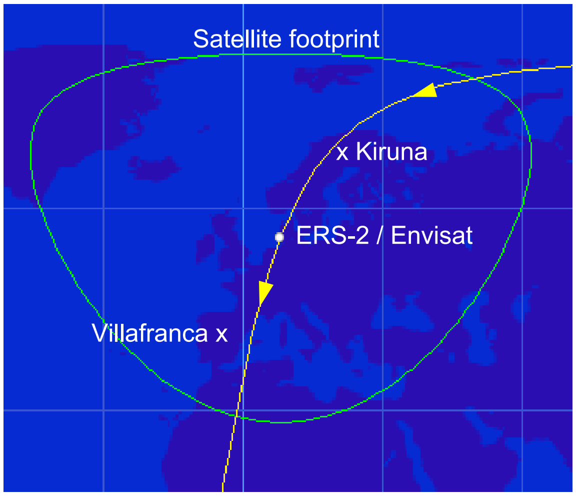

Figure 2 Typical ERS-2 / Envisat satellite orbit for a day pass (taken from Orbitron prediction software)

During the third measurement campaign (III), also the night passes were recorded. For night passes, the sequence of visibility is switched, i.e. during these passes Villafranca ground station first has visibility followed by the Kiruna station, as is shown in Figure 3.

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[1] DOY: day of year

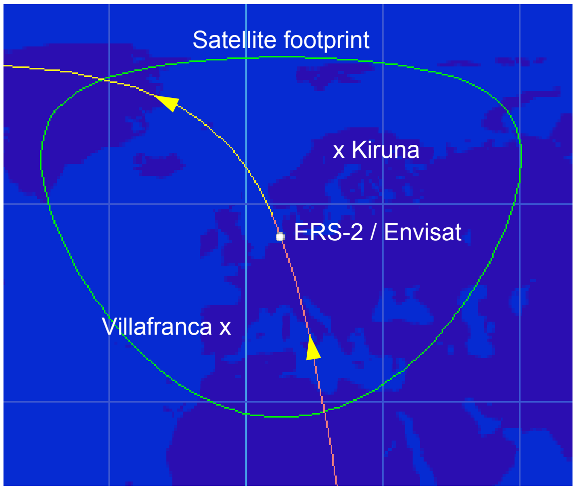

Figure 3 Typical ERS-2 / Envisat satellite orbit for a night pass (taken from Orbitron prediction software)

All measurements were performed using the operational Kiruna uplink signal, with increased uplink power. The measurements were performed using a transmit power range of approximately 50 to 380 Watt (depending on the pass). Yet, when ranging (RG) and/or telecommand (TC) signals were on the signal power was split among the carrier signal and TC and/or RG. RG and TC were turned on, depending on mission requirements.

3.3. Measured data

The elevation angle of Kiruna and Villafranca are shown for the two types of recorded passes: day pass (Figure 4) and night pass (Figure 5). This is important to remember since the RCS of the spacecraft is largely depending on the angle at which the spacecraft is illuminated and the angle in which the receiver ground station is looking towards the spacecraft.

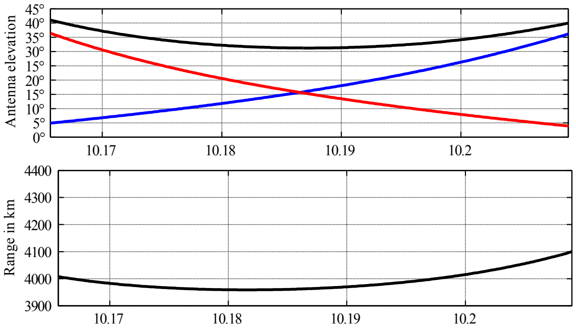

Figure 4 Envisat day pass (DOY 62 in 2009). Top figure: Elevation angle of Kiruna antenna (red), Villafranca antenna (blue) and combined (Kiruna+Villafranca antenna, black) versus time of day. Bottom figure: Signal path range (Kiruna – satellite – Villafranca)

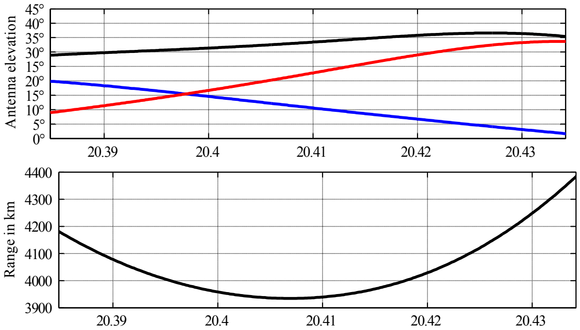

Figure 5 Envisat night pass (DOY 64 in 2009). Top figure Elevation angle of Kiruna antenna (red), Villafranca antenna (blue) and combined (Kiruna+Villafranca antenna, black) versus time of day. Bottom figure: Signal path range (Kiruna – satellite – Villafranca)

At the Villafranca ground station a spectrum analyzer records the received spectrum at the intermediate frequency of 70.1 MHz. Two examples, one for a day and one for a night pass are given in Figure 6 and Figure 7, respectively.

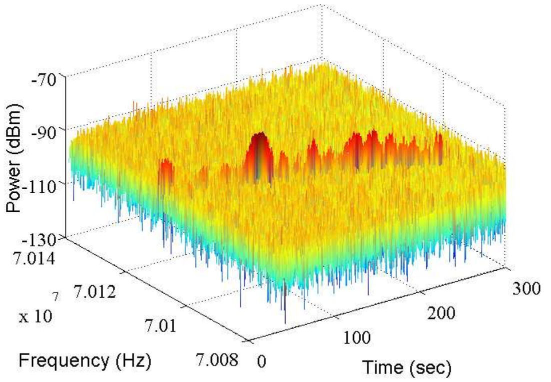

Figure 6 Envisat day pass (DOY 62 in 2009): In the spectrum analyzer recording the time dependant Doppler shift and signal level can be observed

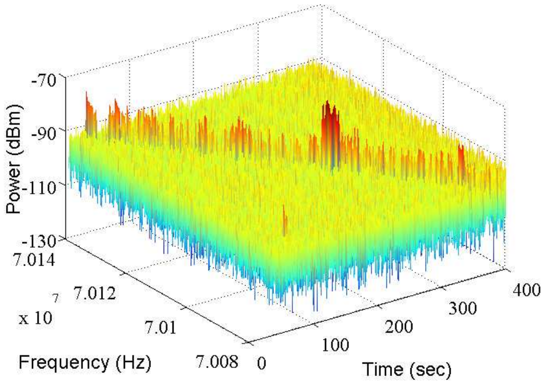

Figure 7 Envisat night pass (DOY 64 in 2009): In the spectrum analyzer recording the time dependant Doppler shift and signal level can be observed

From these figures it can be seen that the Doppler shift for the night pass changes much more than for the day pass. Thus the observed night passes experience a higher *Doppler rate* than the day passes.

The receiver will follow the changing Doppler on the carrier signal via its PLL. The Doppler rate thus only has an effect in determining a suitable PLL bandwidth (cf. Section 3.1)

The observed signal power and lock status at the receiver for different loop bandwidth are shown in Figure 8 (day pass) and Figure 9 (night pass).

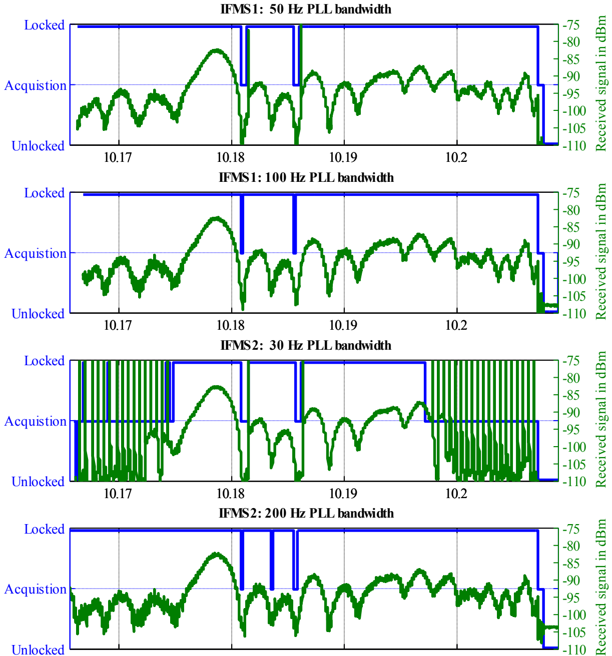

Figure 8 Envisat day pass (DOY 62 in 2009): Receiver lock status (blue line) and received signal power (green line) versus time of day for four different PLL loop bandwidths *Note: the spikes observed during acquistion are internal default values produced by the receiver and should be disregarded*

Each pass, with its slightly changed geometry lead also to a quite different signal power distribution over time. No clear prediction on when peaks and minima are to be observed could be made. For most passes the receiver stayed locked for a total of a few minutes. This is considered a good performance, given the fact that the joint visibility from both ground stations was normally just 5 to 6 minutes.

Taking the noise floor at the receiver of <-131 dBm/Hz and the high received signal powers of up to -75 dBm into account, we obtain a C/N of 39 dB (for a loop bandwidth of 50 Hz). This gives us a margin of up to 31 dB over the lock threshold (8dB) and means that even much smaller targets could be detected.

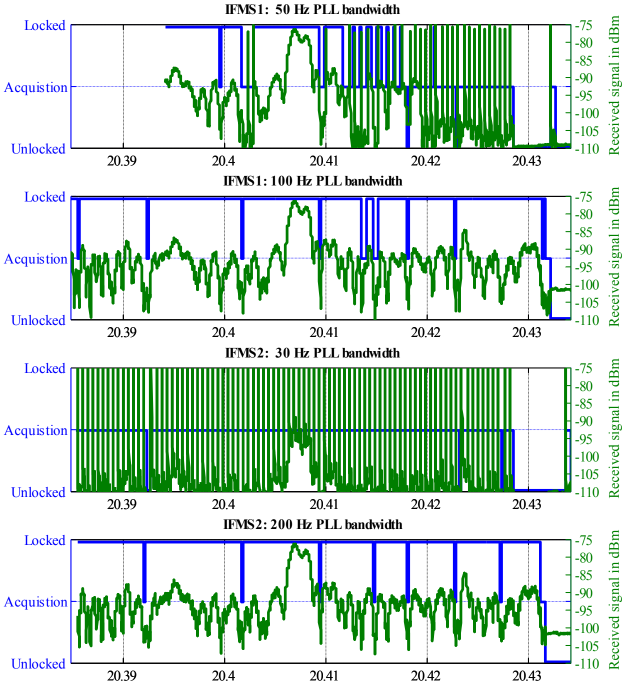

Figure 9 Envisat night pass (DOY 64 in 2009): Receiver lock status (blue line) and received signal power (green line) versus time of day for four different PLL loop bandwidths. *Note: the spikes observed during acquistion are internal default values produced by the receiver and should be disregarded*

4. ORBIT DETERMINATION

Orbit determination, using the acquired data, was carried out at the ESA/ESOC Space Debris Office using an adapted version of the routinely used tool ODIN (Orbit Determination with Improved Normal equations) [5,6].

The raw data is composed of time-tagged delta delay and time-tagged power information and needs to be translated to a single timing reference, interpolated and re-formatted to match the requirements of the orbit determination software ODIN. To achieve this, a relation between delta delay Δt and range-rate dR/dt is used:

$$\frac{dR}{dt} = \frac{(\Delta t_{i+1} - \Delta t_{i-1})c}{t_{i+1} - t_{i-1}}.$$

As ODIN does not support bi-static range-rate data, an intermediate implementation was introduced into the development version. The measurement reconstitution process requires the formulation of the frequency shift

$$\Delta f_d = \frac{1}{\lambda}\left(\frac{dR_1}{dt} + \frac{dR_2}{dt}\right),$$

which is based on the bi-static range rate given by

$$\frac{\partial R}{\partial t} = \frac{(\vec{v}_{sat} - \vec{v}_{stat,1})(\vec{x}_{sat} - \vec{x}_{stat,1})}{\left|\vec{x}_{sat} - \vec{x}_{stat,1}\right|} + \frac{(\vec{v}_{sat} - \vec{v}_{stat,2})(\vec{x}_{sat} - \vec{x}_{stat,2})}{\left|\vec{x}_{sat} - \vec{x}_{stat,2}\right|}$$

and the partial derivatives w. r. t. the satellite state:

$$\begin{aligned}\frac{\partial \frac{\partial R}{\partial t}}{\partial x_{sat}} &= \frac{1}{\frac{\partial R_1}{\partial t}}\left[(v_{x,sat} - v_{x,stat,1}) - \frac{\partial R_1}{\partial t}\frac{(x_{sat} - x_{stat,1})}{\left|\vec{x}_{sat} - \vec{x}_{stat,1}\right|}\right] \\ &+ \frac{1}{\frac{\partial R_2}{\partial t}}\left[(v_{x,sat} - v_{x,stat,2}) - \frac{\partial R_2}{\partial t}\frac{(x_{sat} - x_{stat,2})}{\left|\vec{x}_{sat} - \vec{x}_{stat,2}\right|}\right]\end{aligned}.$$

For the orbit determination we assumed that a-priori information on the orbital elements is available. We used a recent TLE of Envisat from ESA's DISCOS (Database and Information System Characterizing Objects in Space) database to simulate this a-priori information. As the orbit determination using only range-rate information might become unstable, which results in convergence to a sub-minima, we introduced 10 ranges with an RMS of 0.05 km at all pass boundaries into the orbit determination process. Those ranges are available from the steering profiles of the antenna. All bi-static range-rate measurements were screened after the first attempt to identify outliers.

The quality of the resulting orbit basically depends on the following aspects:

- The confidence interval for the orbital parameters after the orbit determination process
- the residuals of the observations after the least-square fit
- the standard deviation between the resulting orbit and an exact reference orbit (i.e. flight dynamics operational orbit)

At the orbit determination epoch 2009/03/04 02:00 we obtain the following results from the orbit determination:

- Semi-Major Axis 7151.903 +/- 0.0014 km
- Eccentricity 0.0025658 +/- 0.0000122
- Inclination 98.5928 +/- 0.0008 deg
- Right Ascension of the Ascending Node 131.8582 +/- 0.0016 deg
- Argument of Perigee 76.7841 +/- 0.4840 deg
- True Anomaly 177.2699 +/- 0.4793 deg

The size and quality of the residuals may be assessed with the help of Figure 10. The RMS of the accepted bi-static range-rate measurements is 0.000345 km/s, and for the introduced ranges 0.008 km.

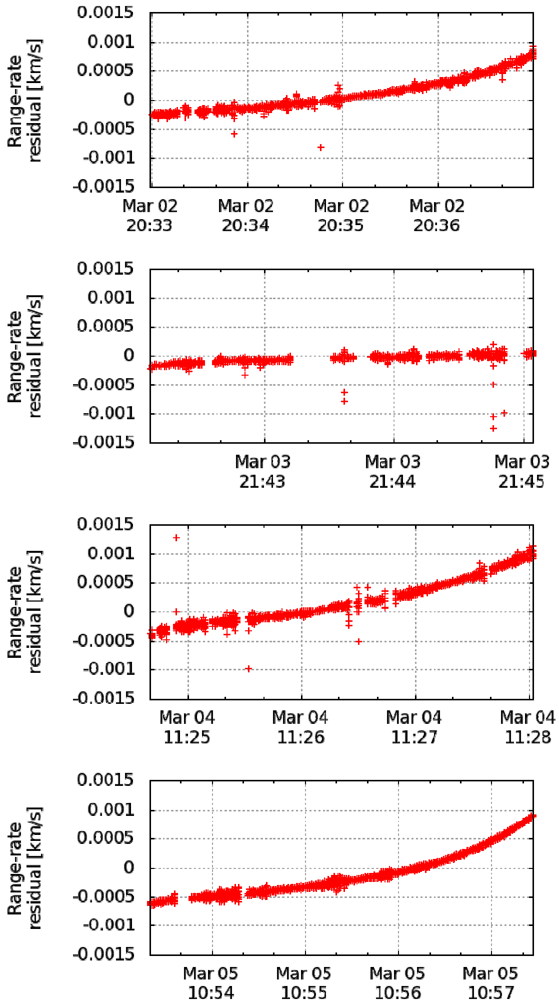

Figure 10 Residuals of bi-static range-rates after an orbit determination considering 4 observed passes of Envisat

As a general benchmark of the bi-static orbit determination results, it is desirable to have an improvement w. r. t. the TLE data. For ERS-2/ENV the TLE data typically show the following accuracy, as estimated from a comparison of a TLE (epoch 2008/01/13) to the operational orbit of Envisat (provided by ESOC's Flight Dynamics Division):

- Radial (*U*): 148m
- Along-track (*V*): 635m
- Out-of-plane (*W*): 180m

We may benchmark our results through a comparison to the operational orbit of Envisat. Figure 11 plots the residuals between a propagation of our orbit determination result and the operational orbit. The drift and systematic in the along-track component suggest that semi-major axis and eccentricity are the weakest determined elements. The analysis of this 4-day arc from 2009/03/02 00:00 to 2009/03/06 00:00 gives now the following accuracy:

- Radial (*U*): 34m
- Along-track (*V*): 107m (offset)
- Out-of-plane (*W*): 286m

We observe that our accuracy compared to the TLE, is worse in out-of-plane component, but better in along-track and radial components. The statistical basis has to be enlarged to verify if the high radial accuracy can be maintained for other observations. Furthermore the offset in the along-track component is still to be investigated. Eliminating the offset could lead to a better along track accuracy.

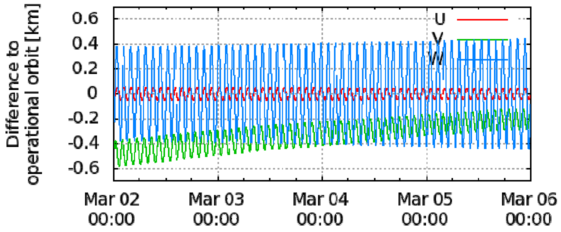

Figure 11 Residuals in radial (U), along-track (V) and out-of-plane (W) components between a propagation of our orbit determination result and the operational orbit of Envisat.

5. CONCLUSIONS AND OUTLOOK

In this paper it is demonstrated that ESA's tracking ground stations can be used to perform bi-static radar measurements on an un-cooperative target. From the recorded range-rate data and using an extension of the tool ODIN, an orbit determination can be achieved. The obtained orbit determination results are of comparable overall accuracy to TLEs, but with better along-track and radial information, however with degraded out-of-plane accuracy. The highest accuracy can be achieved by combining North-South with South-North tracks for the orbit determination.

The observed data suggests that even much smaller objects of down to 80cm diameter at a range of up to 2000km might be detectable. Problems may arise with the short lock times and the resulting orbit determination. Thus, the limits of this bi-static radar set-up will have to be further analysed and verified by measurements.

For future investigations also a fusion of bi-static range-rate data with radar/optical tracks in an orbit determination attempt is of interest.

6. ACKNOWLEDGMENTS

The authors would like to thank everybody involved in the recording and processing of the bi-static radar data. Special thanks go to Åge Riise, Lucy Santana, Dirk Kuijper, Duncan Warren, Peter Droll, Marco Lanucara, the Villafranca M&O team and the ERS-2/Envisat mission team.

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