VALIDATION OF REVISED MULTIBEAM ESTIMATION ALGORITHMS WITH DATA FROM TIRA/EFFELSBERG BISTATIC BEAMPARK EXPERIMENTS

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ABSTRACT

Since 2006 bistatic beampark experiments are conducted with FHR's TIRA L-band radar and MPIfR's Effelsberg radio telescope as a secondary highly-sensitive receiver. Due to its 100 m antenna and a cooled receiver objects down to one cm size should be detectable with the radio telescope, which was partly verified with data from the first bistatic campaign in 2006. But the subsequent campaigns 2007 - 2009 indicated an unexpectedly low detection performance which requires a comprehensive investigation of all relevant components of the processing chain, especially the newly developed estimation algorithms. Hence, the focus of this paper will be the revision and validation of the multi-beam estimation and calibration procedures. The results are demonstrated by comparisons based on data of the bistatic beampark campaigns of 2008 and 2009.

Key words: Space Debris; Beampark Experiment; TIRA; Effelsberg; Bistatic.

1. INTRODUCTION

The intense utilisation of space leads to a steadily growing space debris population especially in the LEO region and requires statistical debris models such as ESA's MASTER model to describe the current distribution and future evolution of the population. As the actual debris population is highly dynamic, the models have to be validated and updated frequently and regularly via measurements. For the cm-size object class in a LEO range window of 200-2000 km monostatic debris measurement campaigns, called Beampark experiments (BPE), are conducted by FHR (Fraunhofer Institute for High Frequency Physics and Radar Techniques) with its TIRA (Tracking and Imaging Radar) L-band radar since 1993.
Since 2006 BPE's are also realised in a bistatic configuration together with the Effelsberg radio telescope (EFFE) as a secondary receiver (see Figure 1). The radio telescope itself is equipped with a highly-sensitive, fully-

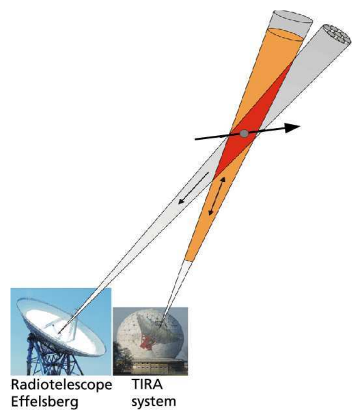

Figure 1. Configuration of a bistatic Multi-beampark experiment with TIRA and the Effelsberg radio telescope

polarimetric 7-beam L-band receiver [1] which principally enables the detection of objects down to 1 cm size at 1000 km range due to the radio telescope's 100 m aperture in combination with cryogenic cooling of the receiver frontend.
An overview of the complete processing chain from the receiver to the final detection list for a Multi-Beampark experiment (MBPE) is shown in figure 2: The incoming RF signals from the 14 receiver channels are sampled and stored within the data acquisition unit [1] which is externally triggered by the transmit pulse directly received from TIRA station. The raw data processing comprises matched filtering, detection and a grouping/linking step to assign single detections from the different channels to an object track. The corresponding processing routines were originally developed for monostatic beampark data from TIRA [2] and adapted for multi-beam raw data [3]. After a manual screening step the final estimation of the parameters characterizing an object's trajectory and RCS (Radar cross section) represents the most complex part of the data analysis. The presently implemented estimation algorithm is based on multi-dimensional maximum likelihood estimation and was tested with simulated data and partly verified with real data acquired in 2006 [4]. But

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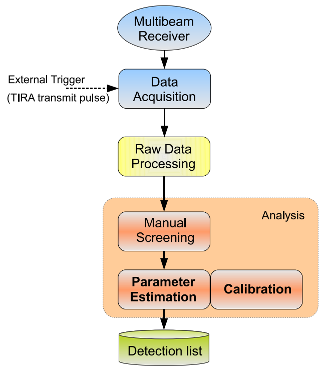

Figure 2. MBPE processing chain

the results from the measurement campaigns 2007 - 2009 indicate a degraded detection performance [5] which is presumably not caused by the receiver itself because this hardware part of the system was already successfully deployed within astronomical measurements at MPIfR.
Hence, a thorough investigation of the remaining components of the MBPE process chain is required. Due to the still experimental status of the estimation algorithm this paper focusses on revising the implemented estimation and calibration procedures.

2. REVISION OF THE IMPLEMENTED ALGORITHMS FOR PARAMETER ESTIMATION

2.1. Estimation Procedures

The estimation of trajectory parameters and RCS for a debris object flying through the bistatic observation volume (see figure 1) is based on the assumption of straight line passages with constant RCS and was realised as a three-step estimation involving genetic algorithms and the Nelder-Mead simplex method [4].
The object trajectory is uniquely defined by a six-parameter vector ω in the EFFE antenna coordinate system whose x_a, y_a-plane is perpendicular to the Effelsberg antenna axis. $\omega = (\Theta, \Phi, \alpha, t_{\text{CPA}}, v, R_{\text{CPA}})$ comprises the passage offset angle Θ to the line of sight, the passage direction Φ ($\Phi = 0°$ means direction of y_a-axis), the tilt angle α w.r.t. the x_a, y_a-plane, the time of closest approach (CPA) to the line of sight t_{CPA}, the object velocity v and the range R_{CPA} at CPA [5].
The Signal-to-Noise ratio SNR_r^i at the output a single receiver channel i is then obtained by applying the bistatic radar equation [6]:

$$\text{SNR}_r^i = \frac{P_r^i}{N_i} = \frac{a\ G^i(\omega)}{N_i}\ ,\ i = 0..6 \tag{1}$$

with the received power P_r^i and the noise level N_i.

The parameter a only depends on the RCS while $G^i(\omega)$ contains the trajectory-dependent antenna gains of both sensors, the bistatic ranges and the transmit power:

$$G^i(\omega) = \frac{P_t \cdot G_{TIRA}(\omega) \cdot G^i_{\text{EFFE}}(\omega)}{R^2_{\text{TIRA}} \cdot R^2_{\text{EFFE}}} \tag{2}$$

From equation (2) it becomes obvious that an accurate estimation of ω is essential for determining the actual antenna gains and, as a consequence, obtaining a good RCS estimation.
An analysis of the implemented routines revealed a mistake in the conversion of the offset distance from LOS w.r.t. the EFFE antenna coordinate system to the offset angle Θ described in topocentric (SEZ, South-East-Zenith) coordinates.
In addition, the representation of an object trajectory in antenna coordinates required some minor modifications and is now described as follows:

$$\vec{r}_a(t,\omega) = \vec{r}_{a,\text{CPA}} + \begin{pmatrix} v\cos\alpha\sin\Phi \\ v\cos\alpha\cos\Phi \\ v\sin\alpha \end{pmatrix} (t - t_{\text{CPA}}) \tag{3}$$

with the object position at CPA

$$\vec{r}_{a,\text{CPA}} = R_{\text{CPA}} \sin|\Theta|\ \vec{u}_{a,\text{CPA}} \tag{4}$$

The unit vector $\vec{u}_{a,\text{CPA}}$ lies within the x_a, y_a-plane ($z_{a,\text{CPA}} = 0$) and is obtained by a rotation of the unit vector $\vec{u}_{a,x}$ w.r.t. the z_a-axis:

$$\vec{u}_{a,\text{CPA}} = \text{rot}_{z_a}\left(\frac{\pi}{2}(1 + \text{sgn}\Theta) - \Phi\right)\ \vec{u}_{a,x} \tag{5}$$

The sign of Θ in equation 5 takes into account the two possibilities of an object flying through the antenna pattern (LOS on left/right side) for a given magnitude of Θ.

Besides the estimation routines, two additional corrections regarding equation (1) and (2) were implemented:
The external noise received by the EFFE antenna results in a noise temperature of 16 K, assuming an elevation of 75 deg [2] and has to be added to the noise temperatures of the single horns.
Secondly, a range offset of 20.16 km was added to the bistatic range due to the delayed arrival of the TIRA transmit pulse trigger at Effelsberg.

2.2. Multi-Beam Calibration

Calibration measurements before and after a beampark campaign usually are performed to obtain a calibration factor for the subsequent calculation of an debris object's absolute RCS [2]. In the case of multi-beampark campaigns they also are a useful means to verify the principal function of the multi-beam estimation algorithms and the receiver frontend's orientation w.r.t. the antenna coordinate system.
To enable comparisons with estimated trajectories of calibration objects which are determined by the multi-beam

estimation procedures, a reference trajectory of the calibration measurement is required. The generation of such a trajectory is based on the tracking data acquired by the TIRA system during a bistatic calibration measurement and requires the following steps (see figure 3):
For a proper time window around $t_{\text{CPA,EFFE}}$ the corresponding azimuth, elevation and range measurements are cut out from the TIRA tracking data of and smoothed by applying a polynomial fit. The position vectors are then transformed from TIRA topocentric to EFFE topocentric coordinate system. After the transformation into the EFFE antenna coordinate system using the antenna pointing of the real measurement setup the six parameters of the reference trajectory can be determined via equations (3) - (5). The calibration results for MBPE-1/08 and

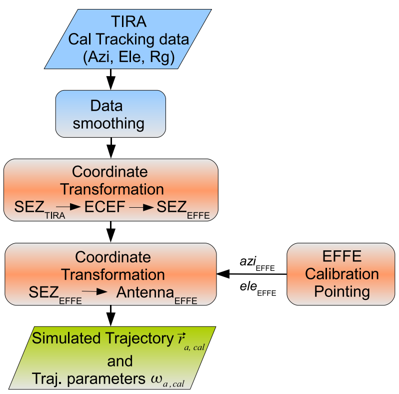

Figure 3. Generation of a reference trajectory for MBPE calibration measurement

MBPE-1/09 are listed in table 1 (mean values and standard deviations of the right column are calculated from 50 runs of the estimation procedure). The estimated trajectory from MBPE-1/08 shows a good accordance with its reference except for the range at CPA. This may be caused by the limited range measurement accuray of the TIRA tracking data as only unmodulated pulses are permitted for multi-beam calibration. Considering a pulse length of 1 ms corresponding to a range resolution of 150 km, a Cramér-Rao lower bound [6] resp. maximum achievable accuracy of ca. 10 km is obtained for a SNR $>$ 30 dB .
In contrast to MBPE-1/08 there are significant differences between estimated and reference trajectory of the MBPE-1/09 calibration, especially for the mean estimated values of range $R_{\text{CPA,EFFE}}$ and velocity v and the standard deviation of the direction angle Φ.
This is probably caused by degraded data from raw data processing and requires further investigation which is beyond the scope of this paper.

Finally, the verification of the receiver frontend orientation is done by overlaying the 7-beam antenna pattern with the estimated calibration trajectory and checking the

Table 1. Comparison of reference and estimated trajectory parameters (Calsphere-4) from the MBPE campaigns 2008 and 2009

Parameter	Reference	Estimation (MBPE-1/08)
t_{CPA} [s]	43203.1	43204.6 ± 0.01
R_{CPA} [km]	1262.8	1274.3 ± 1.4
v [km/s]	7.29	7.69 ± 0.16
Θ [deg]	0.04	0.03 ± 0.001
Φ [deg]	179.4	182.8 ± 0.4
α [deg]	-0.24	0.014 ± 0.24
Parameter	Reference	Estimation (MBPE-1/09)
t_{CPA} [s]	35801.6	35800.9 ± 0.02
R_{CPA} [km]	1335.7	1381.3 ± 1.8
v [km/s]	7.27	6.87 ± 0.28
Θ [deg]	0.03	-0.01 ± 0.047
Φ [deg]	359.2	26.8 ± 27
α [deg]	0.26	0.046 ± 0.282

plausibility of direction angle Φ and offset angle Θ regarding the order of detections in the single beams.

3. VALIDATION RESULTS

The modifications and corrections described in the previous section are validated by comparing the changes of the statistical results (i.e. the detection lists) for MBPE-1/08 and MBPE-1/09 after repeating the last step of the MBPE processing chain (see figure 2).
The subsequent figures 4 - 7 illustrate the changes of RCS detection rates and the altitude-dependent object size distribution before (black colour) and after the applying the modified estimation procedures (red colour). For the MBPE-1/08 data set a marginal shift of the detected RCS towards lower values is visible, with an increased detection rate between -20 dBsm and -48 dBsm, for MBPE-1/09 more distinctive between -20 dBsm and -52 dBsm. These RCS values still are about 9 dB above the expected NERCS (Noise Equivalent RCS) of the 7-beam receiver derived from calibration data in 2006 [4].
Looking at the corresponding object size distributions, for MBPE-1/08 no real improvement of for the minimum object size at 1000 km range w.r.t. the detection threshold (dotted line) is visible (figure 6) whereas the results for MBPE-1/09 indicate a moderate reduction down ca. 1.8 cm object size (figure 7).

Hence, it becomes obvious that the predicted minimum object size of 1.1 cm at 1000 km range is definitely not reached, yet and an extended investigation and testing of further parts of the MBPE processing chain, namely data processing and raw data acquisition, is necessary.

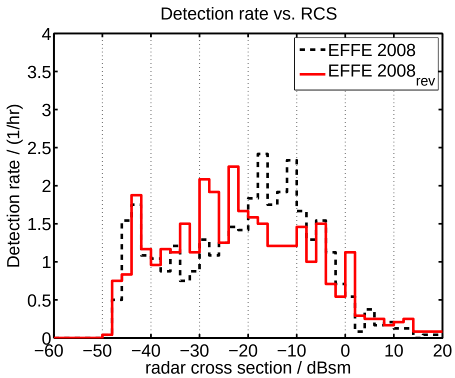

Figure 4. RCS detection rates for MBPE-1/08

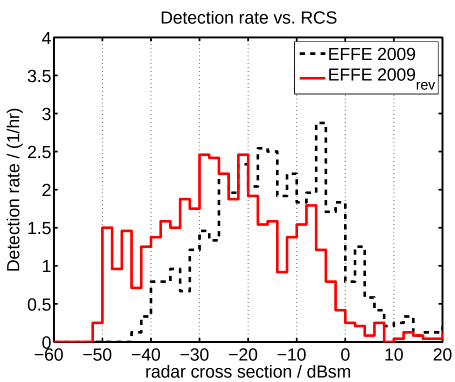

Figure 5. RCS detection rates for MBPE-1/09

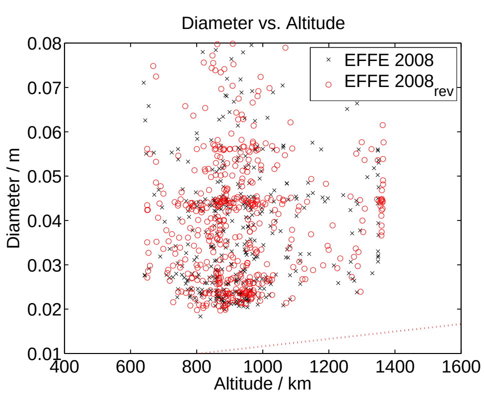

Figure 6. Altitude-size distribution for MBPE-1/08

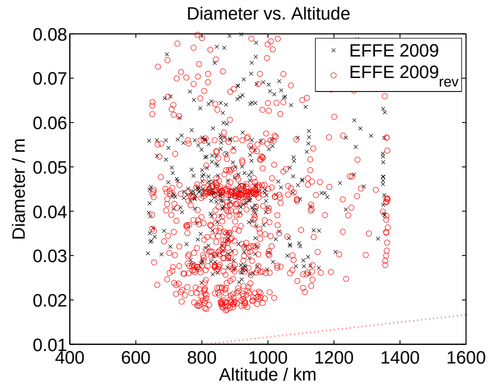

Figure 7. Altitude-size distribution for MBPE-1/09

4. CONCLUSIONS AND FURTHER WORK

The presented results showed a moderate improvement of detection sensitivity involving the modified multi-beam estimation procedures. But, due to the different results for MBPE-1/08 and MBPE-1/09, this improvement also depends on the pre-processed raw data. Hence, as a next step, the MBPE processing stages before the analysis section, i.e. raw data processing and data acquisition have to be subject to further investigations.
After finishing this work, the complete processing of the data from the last Multi-beampark campaign in 2010 can be performed.

REFERENCES

1. R. Keller, M. Naalbach, et al.. Multi-Beam Receiver for Beam-Park Experiments and Data Collection Unit for Beam Park Experiments with Multi-Beam Receivers, *ESA/ESOC Final Reports of Study Contract No. 16173/02/D/HK and 17823/03/D/HK*, Darmstadt, dec 2006
2. L. Leushacke, D. Mehrholz, et al.. Radar Detection of Mid-Size Space Debris, *ESA/ESOC Final Report of Study Contract No. 10182/92/D/IM*, Wachtberg, nov 1994
3. L. Leushacke, K. Letsch, et al.. Bi-Static Radar Measurements and Data Analysis, *ESA/ESOC Final Report of Study Contract No. 17820/03/D/HK(SC)*, Wachtberg, dec 2009
4. G. Ruiz and L. Leushacke and R. Jehn and R. Keller. Improved FGAN/MPIfR Bi-static Debris Observation Campaign: Experiment Outline, Analysis Algorithms and First Results, *Proc. International Astronautical Congress*, Valencia, Spain, 2006
5. K. Letsch and L. Leushacke and others. First Results from the Multibeam Bistatic Beampark Experiments at FGAN, *Proceedings 5th Europ. Conf. on Space Debris*, Darmstadt, Germany, mar 2009
6. M. I. Skolnik, (1990), *Radar Handbook*, McGraw-Hill, New York