RADAR CALIBRATION WITH INDEPENDENT REFERENCE DATA

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ABSTRACT

In the past decades *FGAN*'s *Tracking and Imaging Radar* (*TIRA*) has been the most accuracy requirements demand for better calibration work. So far efforts suffer from absence of reference data to find out absolute offsets. *DORIS* system aboard French satellites *SPOT-2* and *SPOT-4* provides precise position data by DOPPLER frequency measurements with the help of a worldwide ground-station-network. In cooperation with *DGA*, France, several representative satellite passages were tracked by *TIRA* in January 2001. *DORIS* data of the same timeframe were used as position reference data to determine absolute bias in azimuth, elevation and range. Furthermore the statistical spread of *TIRA* data was analyzed for S/N-dependency to allow fast quality control. So far the calculated absolute biases were examined partly in dependence on their origin and their influence on quality of TLE-sets generated in-house.

Key words: Radar, *TIRA*, calibration, satellite, TLE, systematic errors, absolute bias

1. INTRODUCTION

Measurements of space objects using an unique experimental device (like the ground based *TIRA*) should provide capable data which are based on reliable calibration and good error treatment.

1.1 Increasing accuracy requirements

demand on consequently better calibration efforts. They were forced not only by smaller objects (like space debris particles and mini-satellites, e.g.) but also by request for more detailed radar images and for support of space robotics. Besides that, increasing TLE ('Two Line Elements') quality is desirable (e.g. to check the risk of capable experimental radar facility in Western Europe for observation of non-cooperative space objects. Increasing satellite collision).

1.2 Tracking and Imaging Radar *'TIRA'* :

Because *TIRA*'s size, weight, structure, function and peculiarities are potential sources for some of the errors to be discussed later, some features of the facility itself with regard to calibration need will be highlighted [1][2]:

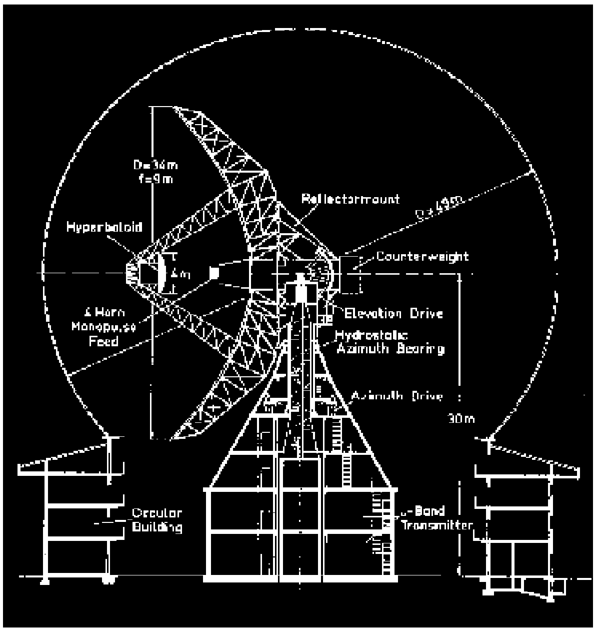

Fig. 1: Cross-sectional picture of TIR

Fig. 2: 'Outside-/inside-view' of TIRA's RADOM

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

TIRA is a fully computer controlled and highly engineered, pedestal mounted elevation-over-azimuth ‘*CASSEGRAIN*’ radar system. Angular resolution is better than 0.0003° in both axes. The movable part inclusive the 34-meter diameter parabolic aluminium reflector (dish panels adjusted with 0.5 mm rms-accuracy) can be accelerated with more than 6°/s^2 in azimuth. Four thyristor controlled DC-engines in each axis are electronically braced to prevent hysteresis effects in view of 240 t inert mass of total pedestal weight.

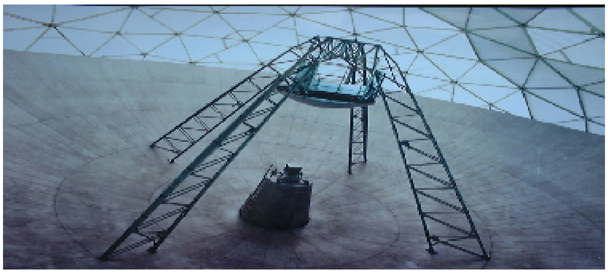

Fig. 3: Photo of the subreflector and the support system

Fig. 1, Fig. 2, and Fig. 3 give an idea of size, stability, and precision problems. The monopulse tracking radar (L-Band) has an 3-dB beamwidth of 0.5°, the built-in imaging radar (K_u-Band) of 0.035°.

Atmospheric refraction affecting parameters of troposphere are measured nearby *TIRA*.

1.3 Up to now calibration (without absolute reference)

Referring to target positions and S/N-ratio, different methods have been used in the past to improve calibration status. But they are provided with disadvantages and/or they are time consuming. All of them are lacking the possibility to permit information on <u>absolute</u> offset correction to meet true position values.

The **ground based** methods (in far-field distance second emitter on top of a hill) are negatively affected by multipathing and non-symmetry in the far-field antenna pattern (mainly in elevation).

Calibration satellites (spheres, cylinder, e.g.) were used for amplitude and phase alignment. While tracking the spacecraft along a calculated section of orbit even the relationship between the electrical axes of the L- and Ku-Band system can be found by a net-structured ‘miniscan’ in AZ/EL azimuth/elevation plane). However, the precise orbit of calibration satellites which would be used as reference for position calibration is not known.

Statistical methods, e.g. phase/amplitude corrections by smoothing method at pieces of constant amplitude allow remarkable (but only relative) off-line corrections unless processing electronics does not change its characteristics. Orbital methods solving the motion equations by numerical integration need three or more consecutive passages.

‘**Conventional**’ methods by which systematic errors were assessed, based on the knowledge of the antenna constructions and electronic design.

Astronomical methods provide precise angular reference data. However, strong radio-stars like *CYGNUS-A* and *CASSIOPAIA* are rather extended sources than point-radiators [3]. They are not available at all azimuth and elevation angles.

With the opportunity to use the precise position data of the French system *DORIS* aboard *SPOT-2/-4* satellites as independent reference data for *TIRA* radar system the chance is given to determine <u>absolute</u> bias errors in angular and range measurements.

2. THE MEASUREMENTS

A first tracking of the satellites *SPOT-2* and *SPOT-4* was carried out in March 2000. According to common intentions under leadership of *ESOC* planned observations were made in January this year.

The task was to achieve at least 6 passages (simultaneously with 10 m radar *ARMOR* on board of French research vessel *MONGE* mostly at *BREST* harbor). In order to find possible addictions to azimuth (AZ) or

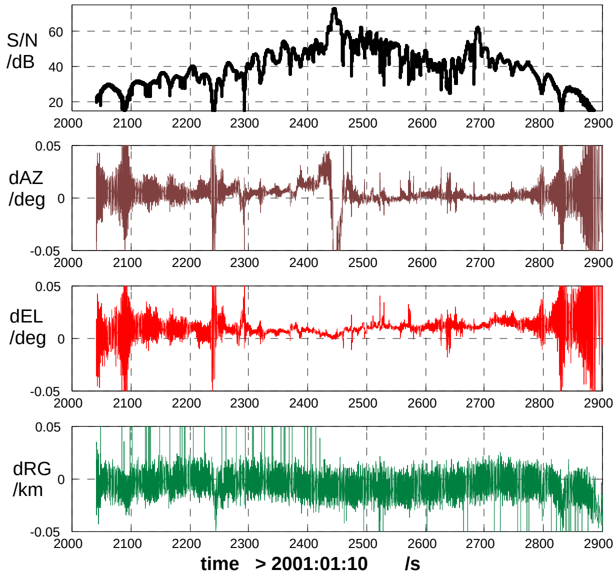

Fig. 4: TIRA’s amplitude data and spread of angle and range data of a whole visibile passage

Elevation (EL) in the topocentric radar scenario right-/left-hand flight passing as well as low/medium/high (max. EL at closest point of approach ‘CPA’: 0°-30°, 30°-60°, 60°-90°) passages should be covered.

Five of the six measurements planned were indeed carried out with *TIRA* and *ARMOR* in so-called ‘co-visibility’. Supplementary *TIRA* tracked eight passages until the end of January in 2001.

Measurements were immediately processed, corrected from so far known systematic errors (without application of one of the possible refraction correction models) and transmitted to *DGA*, France. In countermove *DORIS* data from *CNES* were received via *DGA*.

3. DATA QUALITY: STATISTICAL SPREAD

Beside the very critical refraction and propagation errors and the already mentioned (absolute) offsets accuracy can be quantified as random measurement error in range (and angles AZ/EL, respectively). It is well-known that it is depending on measured amplitudes and inversely proportional to square root of double S/N-ratio. The necessary assumptions are: S/N large enough and no beamshape loss in range (by oblique in angle e.g.). For AZ and EL linearity in monopulse-discrimination-function should be provided.

Before investigation of bias errors the usually dominating S/***N***- dependent data spread was estimated. The intention was to establish a method for quick control of future *TIRA* satellite tracking data and to compare *TIRA* with *DORIS* data in standard deviation. Thus *DORIS* data could prove to be suitable as reference.

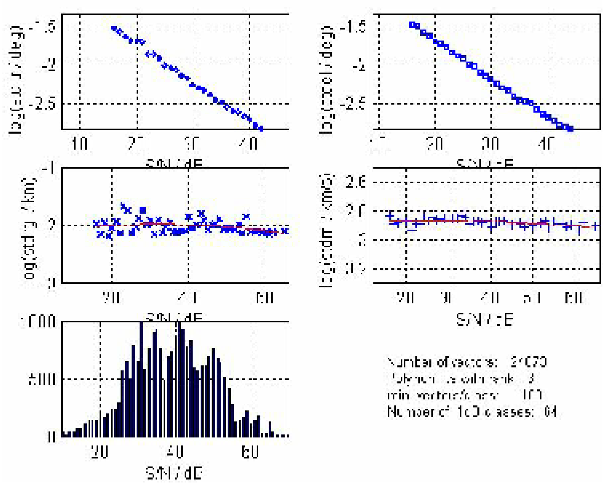

Fig. 5: Quality control by S/N-dependency of spread

Each passage of satellite tracking was divided into hundreds of segments. Within these pieces of a few seconds the data were polynom-fitted by a suitable rank. The smoothed result was used as a 'backbone' to calculate the rms measurement errors along time axis in traverse TR =AZ*cos(EL), in elevation EL, and in range RG (in range rate RR for *TIRA*, too). The whole available passage was treated the same way, so far not yet distinguishing between low elevation regions and area around CPA.

Standard deviations of TR and EL are smaller than 13 milli degrees and of RG smaller than 10 m. In the case of *DORIS* the corresponding value in RG is about 0.3 m. Consequently *DORIS* data are almost two magnitudes more precise and therefore proved to be really good qualified as reference data.

After sorting spread data in classes divided by amplitude sections and then produce logarithmic plot in ordinate, the expected linearity in slope was found indeed. The analysis of variance from straight line could be interpreted as warning signal for data quality loss in future measurements of *TIRA* (see Fig. 5).

However, above 45 dB the expected linear behavior is interrupted. In our case by hardware caused switching between circuit stages (including hysteresis errors).

As already mentioned, the investigated statistical spread in measurement data gives information about quality, but provides no help for finding (absolute) bias.

For that two different approaches were developed:

One can be done by calculating TLE-values of *TIRA* as usual and of *DORIS* data as comparative reference base; a second way was used through directly determined statistical deviations based on (constructed) equally spaced samplepoints in time axis.

4. SYSTEMATIC BIAS ERRORS: TLE-METHOD

By means of in-house software programs (*BABST)* a set of TLE is calculated from *DORIS* reference data. Then a recursive optimization method tried to find best fit approach to time corresponding *TIRA* TLEs which are based on measured tracking results (Fig. 6). The differences between *TIRA* measurements and *DORIS*

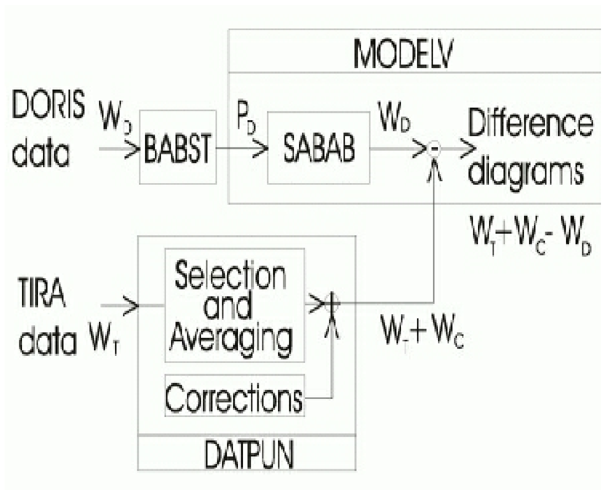

Fig. 6: Sketch of the 'TLE-method' in principle and some tools of it

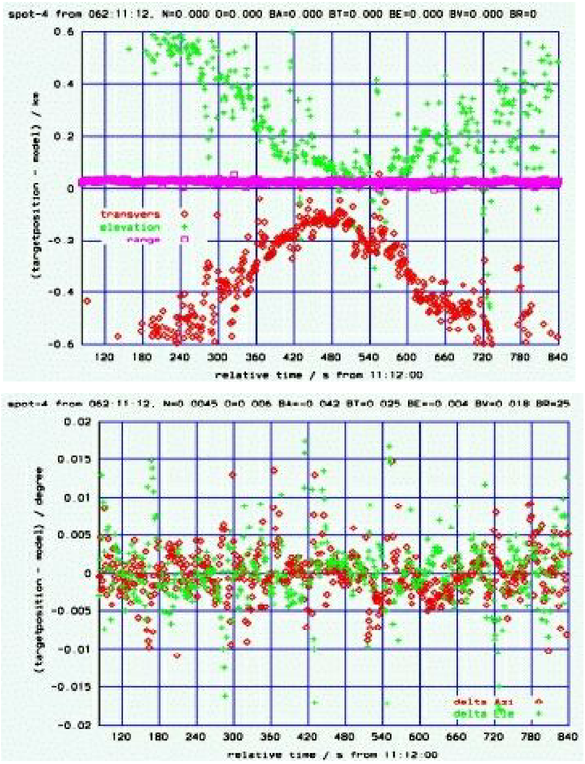

Fig. 7: Differences between TIRA measurements and *DORIS* reference data for a *SPOT-4* passage on 062:11:12, 2001.

Top: no corrections applied, bottom: all known systematic errors corrected.

reference data are shown in Fig.7. From this set observation vectors W_D (time, AZ, EL, RG) synchronized in time with *TIRA* measurements were gained (*SABAB*).

5. SYSTEMATIC BIAS: STATISTICAL METHOD

Because the time sampling of the two independently produced data was unequal, an interpolation of *DORIS* data is required. In view of the observed data rms-spread linearity looks to be good enough for the interpolation method. Other time errors (e.g. earth rotation during pulse travel time between emission and reception) are neglected.

The time-synchronized *D-ORIS* data were subtracted from the corresponding TIRA observation vectors before calculating statistics. Fig. 8 shows the differences (thus the reference biases) in azimuth AZ, elevation EL, and range RG between *TIRA* and *DORIS* data for one selected passage. Attention should be paid to the fact that CPA in this measurement involved very high elevation (> 85°). That is why azimuth suffers a short tracking recess. In future such passage parts should be treated in separated evaluation procedures.

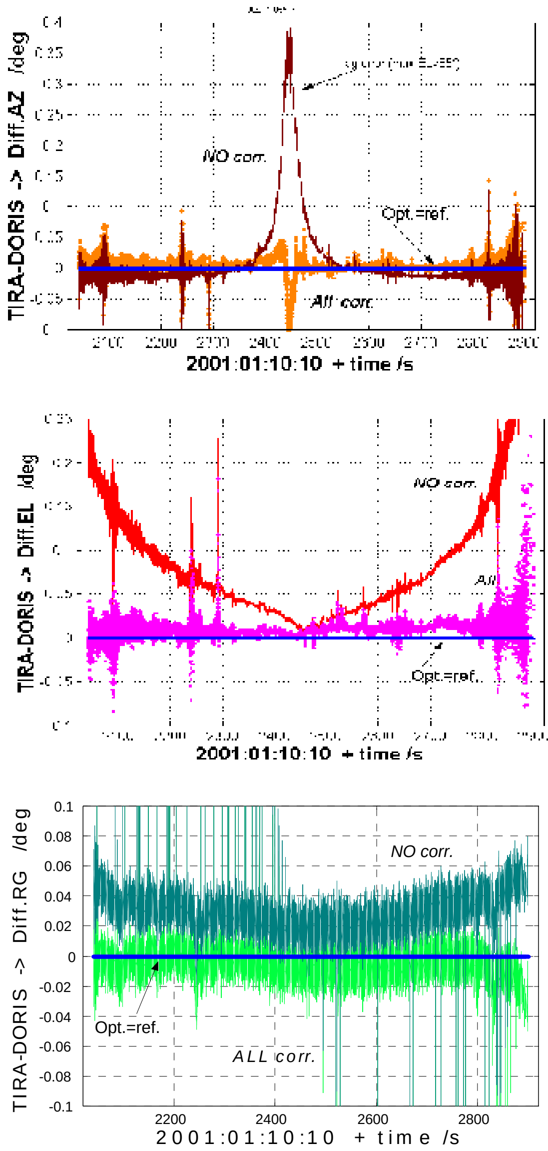

Fig. 8: Combined effect of all found bias corrections in AZ (top), EL (middle), and RG (bottom)

6. SIGHTED SINGLE SYSTEMATIC BIASES

In an heuristic manner with help of the 'TLE-method' definite errors corrections were tested and optimized. By producing data sets without a definite single error their effects were investigated and encircled in quantity.

The intention was to find the best combination. For a useful proceeding simple error models for the bias sources have to be set up. Obviously a range shift between 20 m and 25 m is given as systematic offset.

System inherent are also AZ-(<-0.047°) and EL-(< 0.003°) shifts.

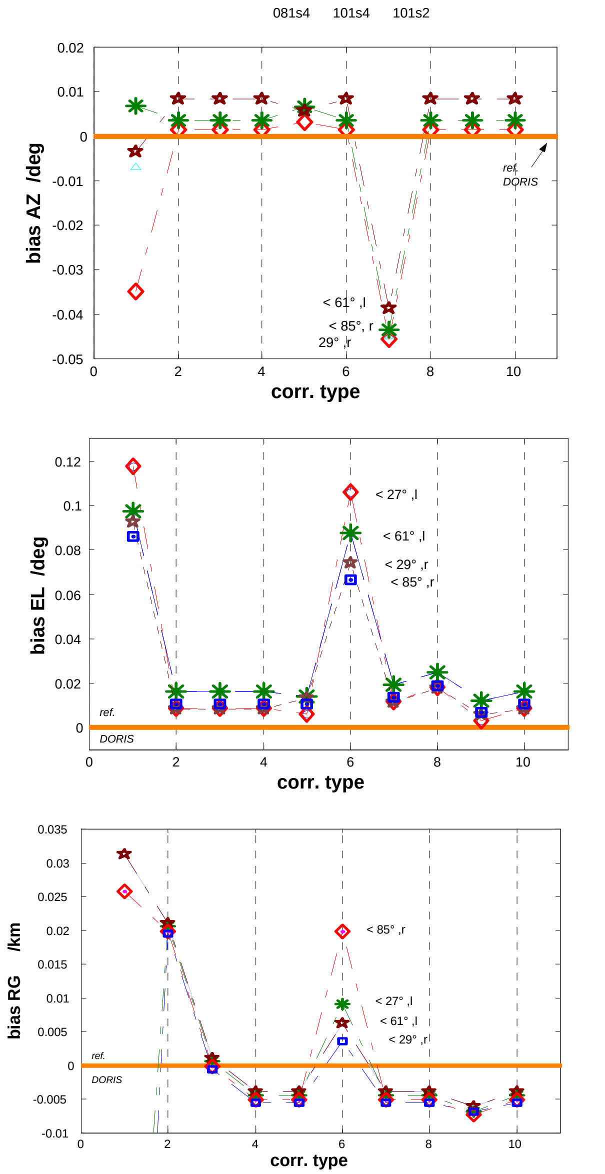

Fig. 9: Contributions of single systematic bias as function of different EL-Max. and for r,l-hand passages

LEGEND: *<u>CORRECTION 'TYPE'</u>*

1 = no correction made at all

All corrections, but

2 = no range shift (of 25m)

3 = range shift of 20m (-->RG)

4 = no correction in velocity

5 = no slant in vertical axis

6 = not any refraction

7 = no corr. in AZ+EL shift

8 = no correction in tetra pod

9 = other refraction corr. Model

10 = with all estimated correction

More complicated, but still to localize is the slightly tip of *TIRA's* mechanical vertical (AZ-) rotation axis. It is tilt to the North by < 0.006° and eastwards < 0.008°. The local plumb line deviation can be neglected because < 0.002°. All these values as well as the precise geographic position of axles intersection point are 1997 determined **[4].** Changing AZ gives EL-depending correction values following a sinusoid curve by the AZ axis-tip.

That functionality is taken into consideration for the raw data and need no further analysis.

Not yet terminated are investigations on the two following points:

The contribution of the 'tetra pod', the subreflector support system (see Fig. 3) is estimated to a 0.01° dependency multiplied with cos(EL). Dynamic effects during acceleration or deceleration are still uninspected.

For the atmospheric refraction correction different error models exist. In spite of them this part causes major problems in system error correction, especially at low elevation angles. In troposphere the model parameters are temperature, humidity and atmospheric pressure. But they were measured nearby radar station instead of differential along the whole propagation path. Always changing weather circumstances and parameter combinations make error determination in this topic very difficult.

Finally it can not be excluded that other (so far unconsidered) system bias errors make a contribution worth mentioning.

Some of these learned and/or measured system errors were tested so far referring to their effect on AZ-, EL-, RG- bias for at least four elevation levels and a pair of r,l-passages.

Careful examinations show the complicated relations between error sources and their different effects on passages divided in AZ-, EL-, RG-view.

7. CONCLUSION AND OUTLOOK

Fact is that accuracy demands are still increasing (e.g. by smaller space debris objects) and that leads to more precise calibration requirements.

Data of *DORIS* positioning system aboard of the satellites *SPOT-2/-4* are well suited as reference for *TIRA*, they are at least by a factor ~30 better in AZ-, EL-, RG-deviation spread.

At present time sufficient representative passages have been measured by ground based radar station *TIRA* for which also *DORIS* data were made available.

S/N - dependence of standard-deviations were estimated. This method allows data quality control.

Two approaches for bias determination using *DORIS* reference data were applied:
a) differences through TLE-calculations/-comparison and
b) directly achieved deviations by statistical means.
Rather good corrections for systematic error biases were found and are in use at *TIRA* system.

In future work more complete error models for the *TIRA* system will be developed. Evaluation of *DORIS* data and reference data gained from other satellites (*CHAMP* with GPS, *ERS-2* with LASER) are planned.
Improvement of error models by examination of bias-/spread-dependencies in greater detail have to be pushed ahead and possibly (so far disregarded) error sources have to be examined.

8. ACKNOWLEDGMENTS

The authors are thankful to the *TIRA* operation crew, also to *CNES* for exchanging *DORIS* data with *TIRA* data, to *ESA* for management support and especially to Dr. P. Ameline, DGA, France, with all involved colleagues.

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