IMPROVEMENT OF OPERATIONAL ORBIT DETERMINATION BY INCLUDING OPTICAL MEASUREMENTS FROM A 1M TELESCOPE

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ABSTRACT

For the last decades the operational orbit determination done at ESOC has been based mainly on active range and Doppler measurements provided by various ESA ground stations. Also antenna angles have been used sometimes, in particular during Launch and Early Orbit Phases (LEOPs) or when active ranging was not possible. For ESA's 15m ground stations the precision of those antenna angles is limited to about 0.01 degrees. This paper describes the approach of including highly accurate pointing data, which are called high precision tracking CCD measurements (HPTCCD), in the operational orbit determination. In order to obtain the data images of the spacecraft are taken by a telescope, equipped with a CCD camera, with the stars in the background of the image. The accuracy for this is in an order of 0.5 arcsec.

1. STATION DETAILS

The telescope to be used to gather the measurements described in this paper is installed in ESA's Optical Ground Station (OGS). This station and some ten other telescopes are part of the Teide Observatory on Tenerife, Canary Islands, which is situated about 15 km east to the Teide. The OGS was built for the in-orbit checkout of the Artemis spacecraft, which finally has been launched in 2001. After that the telescope was upgraded and has been used since then for space-debris observation and orbit determination by the ESOC Mission Analysis Section (MAS). How this station is used in the particular context of this purpose is described in [1], from where some information also went in this paper. However, since the OGS telescope was defective during the implementation of the new measurement type HPTCCD at ESOC Flight Dynamics all test were performed by means of similar data from the Zimmerwald Observatory (s. Fig 4) near Bern, Switzerland.

Inside the Optical Ground Station's 12.5 m dome (Fig. 1), which has been designed to cope with the high wind velocities there, the used 1m Zeiss telescope is located, supported by an English mount (Fig. 2).

Fig. 1 The ESA OGS ground station

Fig. 2 The OGS 1m-RCC-Zeiss-Teleskop

For taking the HPTCCD measurements a modified Ritchey-Chrétien configuration is used with a focal length of 4.47m. A CCD camera (Fig. 3) equipped with four CCD arrays is attached to the telescope such that in total a field of view of 0.7 deg x 0.7 deg is covered by 4096 pixels x 4096 pixels. This results in a resolution of about 0.62 arcsec.

Fig. 3. The OGS 4k x 4k Pixel CCD-Camera

The necessary precise time information is provided by a GPS receiver. With that both steering of the telescope and the time tagging of the measurements can be done with an accuracy of better than 1ms.

Fig. 4 The Zimmerwald ground station

The data retrieval process is done in an almost automatic way involving different processing and steering units as well as several models. In detail information on that can be found in [1]. In the sequel only a short extract is given:

Each observation is steered and controlled by a Sun workstation. In order to follow a spacecraft preliminary orbit information must be entered before. The workstation determines the position of the spacecraft every 0.1s and calculates pointing information from that. These information are passed to the telescope control computer, which actually initiates the pointing after having applied some corrections for atmospheric refraction and modelled deficiencies of the instrument and the steering system.

As it concerns the orbit information provided to the Sun workstation it turned out, that for the kind of orbits considered here, namely highly eccentric orbits of more than one day of revolution period, the standard two-line elements provided by US Space Command/NORAD were much to inaccurate. Instead of that special TLEs are provided by ESOC Flight Dynamics. These first take into account also small manoeuvres, e.g. to offload reaction-wheels, and second are in fact a serious of TLEs, where each individual one covers a few hours only.

The exposure time of a single CCD image is in an order of two seconds. The shortest readout time is about 19 seconds. This means that 2-3 images can be taken in a minute. The usual approach for the purpose described here is to take some images in a row and to do that again and again with an interval of about an hour in between.

Fig. 5 A typical CCD image

After having taken an image it automatically is processed in a way that the right ascension and declination values of the spacecraft are derived and some corrections are applied. Here it can be configured which corrections to apply. Alternatively the data can be corrected during the orbit determination done by ESOC Flight Dynamics. This part is discussed in chapter 3.

2. ORBIT DETERMINATION

As soon as the HPTCCD data and all measurements of the other types are retrieved ESOC Flight Dynamics can do an orbit determination. For this generally different orbit determination packages are in use depending on the kind of orbit to support. The package, to which the new measurement type has been added, is being used for all kind of orbits which are neither near-Earth spacecraft nor interplanetary. It is part of the Multi-Satellite-Support System (MSSS). The orbit determination program searches for a set of optimal elements (and parameters to be estimated) $p^{*} \in IR^{n}$

which fit optimally to a vector of measurements $M \in IR^m$

$$p^* = \frac{1}{2} \arg\min_{p} \left\| F(p) \right\|^2 \ , F(p) = W\{f(p) - M\} \qquad (1)$$

where $f(p) \in IR^m$ is the response of the measurement model of the orbit determination system. The orbit determination problem is solved iteratively by a modified Gauss-Newton method as described in detail for example in [5]. Also [2] is helpful as it concerns the numerical aspects. The Gauss-Newton method makes use of the following approximation of Eqn. 1

$$p_{i+1} = p_i + \Delta p$$

$$\Delta p_i = \frac{1}{2} \arg\min_{\Delta p_i} \left\| F(p_i) + \nabla F(p_i)^T \Delta p_i \right\|^2 \qquad (2)$$

which is iterated till the residuals $\left\| f(p_i) - M \right\|$ are small enough. To handle Eqn. 2 the Jacobian $\nabla F(p)^T$ needs to be determined for a set of elements p and the related model measurements $f(p)$. For this partial derivatives of the measurements are necessary which are derived in the sequel for the HPTCCD data in right ascension a and declination d .

$x(t)$	inertial spacecraft position at time t
$r(t)$	inertial direction station - spacecraft at time t
$R = R(t)$	topocentric station postition
$T = T(t)$	transformation matrix from inertial to topocentric co-ordinate system at time t
a, d	Right Ascension and Declination at the station

With that the inertial (J2000) station position can be expressed as

$$r(t) = x(t) - T^{-1}(t) R = \left| r(t) \right| \begin{pmatrix} \cos a \cos e \\ \sin a \cos e \\ \sin e \end{pmatrix} \qquad (3)$$

From this the partial derivatives for right ascension and declination w.r.t. $r(t)$ are determined as

$$\nabla_{r(t)} a = \frac{1}{r_1^2 + r_2^2} \begin{pmatrix} -r_2 \\ r_1 \\ 0 \end{pmatrix} \qquad (4)$$

and

$$\nabla_{r(t)} d = \frac{1}{|r|^2 \sqrt{r_1^2 + r_2^2}} \begin{pmatrix} -r_1 r_3 \\ -r_2 r_3 \\ r_1^2 + r_2^2 \end{pmatrix} \qquad (5)$$

Hence the partial derivatives w.r.t spacecraft position and velocity are

$$\nabla_{x(t)} a = \left[\nabla_{x(t)} r(t) \right]^T \nabla_{r(t)} a = \nabla_{r(t)} a \qquad (6)$$

$$\nabla_{x(t)} d = \left[\nabla_{x(t)} r(t) \right]^T \nabla_{r(t)} d = \nabla_{r(t)} d \qquad (7)$$

$$\nabla_{\dot{x}(t)} a = 0 \qquad (8)$$

$$\nabla_{\dot{x}(t)} d = 0 \qquad (9)$$

In order to estimate biases for station position one can conclude

$$\nabla_R r(t) = -T^{-T} = -T \qquad (10)$$

and thus

$$\nabla_R a = \left[\nabla_R r(t) \right]^T \nabla_{r(t)} a = -T \nabla_{r(t)} a \qquad (11)$$

$$\nabla_R d = \left[\nabla_R r(t) \right]^T \nabla_{r(t)} d = -T \nabla_{r(t)} d \qquad (12)$$

whilst for all kind of time biases the following partial derivatives w.r.t. time are necessary

$$\begin{aligned} \frac{d}{dt} a(t) &= \left[\nabla_{r(t)} a \right]^T \frac{d}{dt} r(t) = \\ &= \left[\nabla_{r(t)} a \right]^T \left\{ \dot{x}(t) - \left[\frac{d}{dt} T(t) \right]^T R \right\} \end{aligned} \qquad (13)$$

$$\begin{aligned} \frac{d}{dt} d(t) &= \left[\nabla_{r(t)} d \right]^T \frac{d}{dt} r(t) = \\ &= \left[\nabla_{r(t)} d \right]^T \left\{ \dot{x}(t) - \left[\frac{d}{dt} T(t) \right]^T R \right\} \end{aligned} \qquad (14)$$

3. CORRECTIONS TO BE CONSIDERED

The corrections to the range, Doppler and angular data measurements considered by the MSSS orbit determination program are mainly tropospheric and ionospheric corrections as well as a correction for the difference of UTC and UT1 in order to use the proper station position. For the new data type of course a UTC-

UT1 correction is necessary, too. Also a correction for the contribution of troposphere and ionosphere refraction is required (s. [3] for example). However, it needs to implemented in a slightly different way since both spacecraft and the stars in the background are a affected by those. Also there are additional effects, which need to be considered, too.

3.1 Atmospheric Corrections

The orbit determination program internally works with a model where no atmosphere is present. Because of this for every step a correction can be done which models the influence of both troposphere and ionosphere and corrects for that taking into account the spacecraft's position and elevation.

Now, naturally the HPTCCD data are corrected already according to position and elevation of the stars in the background. This of course needs to be taken into account in the correction steps of the orbit determination. It can be done for instance by de-correcting for the influence of the star's position and elevation and then applying the usual correction according to position and elevation of the spacecraft.

3.2 Stellar Aberration

Since the speed of light is not infinite the apparent direction d to a star is influenced by the observer's velocity v, namely by the orthogonal projection v_C of v on the two-dimensional subspace of d. This phenomenon is called stellar aberration. The apparent position is simply moved by an angle of Δa = $\arctan(v_C / c)$ in the direction of v_C.

The main contribution is caused by the movement of the Earth around the Sun (annual aberration). Here the maximum effect is about $0.0057 \text{ deg} \approx 20.5 arc\sec$. A less significant influence comes from the daily rotation of the Earth (diurnal aberration), which depends also on the observer's latitude and which is less than $0.3 arc\sec$.

3.3 Annual Parallax

The apparent direction to a star and with it also the HPTCCD measurements are also affected by the position of the Earth relative to the sun. The possible angular difference caused by that is maximal for the nearest star alpha centauri and two measurements which are separated by half a year. That means the contribution of this effect is certainly less than

$$\pm a\tan(1AU / 4.3ly) \approx 0.75 arc\sec$$

but normally less by orders of magnitude. The influence of the annual parallax thus is not taken into account since the expected accuracy is in an order of 0.5 arcsec only anyway.

4. EXAMPLES

4.1 Integral - Highly Eccentric Orbit

ESA's Gamma Ray satellite Integral was launched in 2002 on board of a Russian Proton launcher. Its orbit is highly eccentric with a revolution period of three days. The inclination amounts about 67 deg with the perigee in the southern hemisphere ($w \approx 300$ deg). Further details on the orbit can be found in [4]. Redu, Belgium, is the only ground station which provides tracking data, namely active range and Doppler measurements. The orbit determination is done every revolution using an orbit determination arc of two revolutions. The achieved orbit determination accuracy expressed by the RMS values of the residuals normally seen in MSSS is in an order of 3-5 metres (two-way range) and 0.5 mm/s (Doppler).

The example chosen consist of data from 2004/05/21 to 2004/05/27. These two revolutions are illustrated in Figs. 6 and 7. The dots show the spacecraft position when measurements have been recorded at Redu, whilst small circles show where images were taken from Zimmerwald, Switzerland. In total there were 664 range, 884 Doppler and only 24 HPTCCD measurements. Nevertheless, the achieved accuracy in terms of RMS values of the residuals were 4.8 metres (two-way range), 0.6 mm/s (Doppler) and 0.4 arcsec for the HPTCCD data.

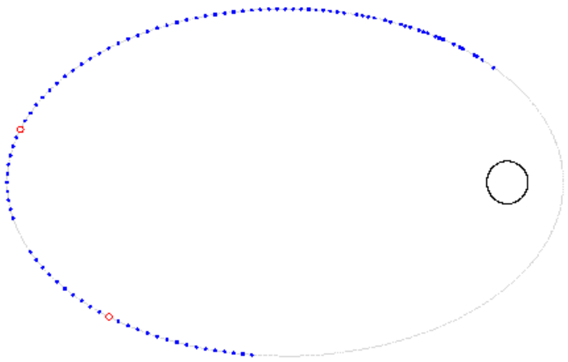

Fig. 6 Integral Orbit Determination – Rev. 1

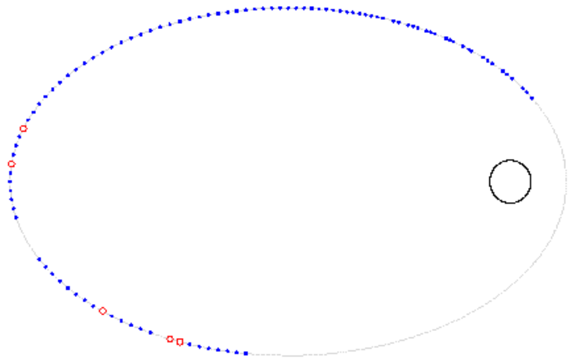

Fig. 7 Integral Orbit Determination – Rev. 2

4.2 SloshSat -GTO

SloshSat is a small satellite (about 1x1x 0.8 m^3), which will investigate the behaviour of fluids in micro gravity. It is planned to be injected by an Ariane 5 ECA into a geostationary transfer orbit with an perigee height of 250km in end of 2004. Since this spacecraft was designed to be flown by the Space Shuttle there are some limitations on the possible orbit determination accuracy. This is mainly for three reasons. First, there is no transponder onboard, which implies that only passive measurements can be used for orbit determinations. The available method for that are the station pointing information, when the station is in auto track mode, i.e. when the station follows the spacecraft's signal. Second it can be supported only from one station – which Kourou, French Guiana, has been selected for – because special equipment is necessary to communicate with the spacecraft. Third, measurements will be available only for relatively small arcs, since the transmitter will be witched on only outside the radiation belts and the signal might be too weak to allow the station to be in auto track mode.

For the example given here a situation during the routine phase of the mission has been chosen. An orbit determination is planned to be done over two revolutions. The expected angular measurements from Kourou as it can be seen in Figs. 8 and 9 are represented by dots. These data are taken when the spacecraft is above 19000 km altitude but closer to the ground station than 22000 km Additionally Tenerife HPTCCD data were assumed to be available at the positions highlighted by small circles.

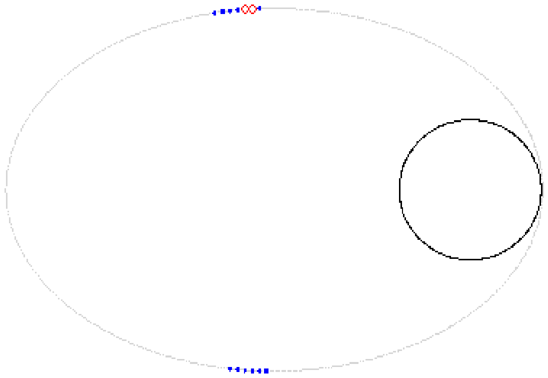

Fig. 8 SloshSat Orbit Determination – Rev. 1

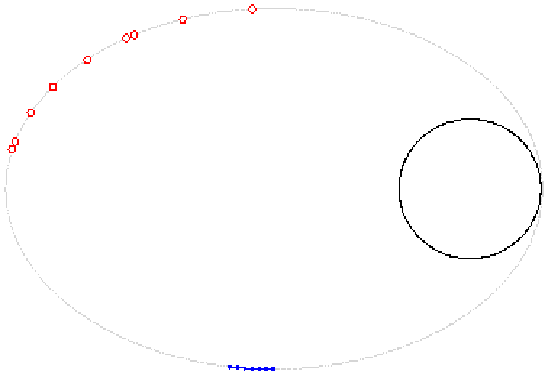

Fig. 9 SloshSat Orbit Determination – Rev. 2

The difficult situation here is not to achieve small residuals. This in fact is no problem with the limited number of measurements. More problematic is, that the resulting accuracy of the determined elements might be low, which could result in poor orbit predictions. In order to assess this the following approach has been taken:

A serious of some thousands of orbit determinations were done. For this the nominal orbit information provided by Arianespace were used and different sets of angular measurements were generated (normally distributed, zero mean and the expected noise of 0.01 deg for the auto track angles and 0.5 arcsec for the HPTCCD data). For each orbit determination initial guesses were used which were disturbed according to the variance/covariance information also given by Arianespace. After having done all of these orbit determinations the resulting variance/covariance information have been propagated and the (mis-) pointing information derived such that about 98% of all cases were covered. The results as given in Table 1 are divided in two parts. On the left hand side the used tracking data passes are mentioned. On the right hand side the resulting pointing accuracy (in deg) is printed. The pointing accuracy has been assessed at the beginning of the possible tracking interval, i.e. at a height of 19000km

Table 1. SloshSat Orbit Prediction Accuracy

Station / Measurement Type	Mispointing (deg)
Kourou Angles	0.174
Tenerife HPTCCD	0.0026
Kourou Angles and Tenerife HPTCCD	0.0024

The big improvement coming with the HPTCCD is obvious.

5. PROS AND CONTRAS

Obviously there are both advantages and disadvantages of the new measurement type compared to the ones used traditionally. For sure on the negative side is that data of this type are available only when

- it is night at the observatory but the spacecraft is illuminated by the sun, which excludes the usage of these data for low-Earth spacecraft
- the sky is clear
- the spacecraft is bright enough
- a priori orbit information is precise enough

Another disadvantage might be that only 2-3 measurements per minute can be provided. On the other hand this doesn't play a role normally since the measurement weight can be chosen very high because of the high accuracy the data comes with. Also there can be circumstances where HPTCCD measurements are available but not other data. For example active range and Doppler measurements can be taken only, when an uplink is done and if a transponder is available. Even ordinary station pointing measurements still require the spacecraft transmitting a radio signal, whilst HPTCCD are completely passive. The last but actually overwhelming advantage is certainly the high accuracy, which make that with a few angular data of this type only already a good orbit determination is possible.

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