ANALYSIS OF ON-BOARD ORBIT EPHEMERIS IMPACT ON CBERS-2 IMAGE PROCESSING

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ABSTRACT

The second China-Brazil Earth Resources Satellite CBERS-2 was launched in October 2003, by the chinese Long March 4b rocket. CBERS-2 carries three main payload sensors: WFI (Wide Field Imager), CCD high resolution camera, and IRMSS (Infra-Red Multi-Spectral Scanner) to meet the image user requirements. The orbit is sun-synchronous with frozen eccentricity and perigee. It was realized that the ephemeris data of the image were nearly useless for ground processing of the images. With this motivation it was carried out an analysis of the on-board computation and the main sources of errors which impacts in the accuracy of the ephemeris handed to the image users. The paper shows the results of the analyses and the final error budget, as well as proposes means to deal with the present system. Finally, suggestions are also made to enhance the overall system of on-board ephemeris generation envisaging the CBERS-3 and 4 satellites.

1. INTRODUCTION

The second China-Brazil Earth Resources Satellite CBERS-2 was launched successfully in October 21st 2003, from the Taiyuan Chinese launch base by the Long March 4b rocket. It is ensuing the CBERS-1 satellite, for a typical remote sensing mission with applications to deforestation and fire control mainly in Amazon region, hydrology, agriculture, urban growth, ground occupation, soil geology, Amazon surveillance from defense ministry, and environmental projects in general. CBERS-2 carries three main payload sensors: WFI (Wide Field Imager), CCD high resolution camera, and IRMSS (Infra-Red Multi-Spectral Scanner) to meet the multiple application requirements. The nominal sun-synchronous orbit is 98.50435 degrees inclined at 778km altitude with frozen eccentricity and perigee requirements. An indigenous computer dedicated to AOCS (Attitude and Orbit Control System) executes the on-board control algorithms. Such a computer forwards also the flow of ephemeris to be tagged to the images recorded by the cameras. Ground orbit determination is performed three times a week by the control centers and then a set of corresponding orbit parameters is computed and uploaded to feed the on-board orbit prediction algorithm. The on-board orbit model accounts for the geopotential (J_2, J_3, J_4) and drag perturbation (semimajor axis decay rate $\dot{a}$ and eccentricity rate $\dot{e}$) in non-singular elements, in a very simple scheme. Limitations of computer core also restricts the floating point word to 3 bytes length for computations, which translates roughly to mantissas of 6 significant figures (where the 6-th one is doubtful). It has been complained by the image users that the ephemeris tagged on the image was nearly useless for ground processing of the images and they were even appealing to 2-lines ephemeris available through Internet, but still with no satisfactory results. With this motivation it was carried out a complete analysis of the on-board ephemeris generator and the main sources of errors which impacts in the accuracy to the ephemeris delivered to the end user. The work is focused in the following analysis: influence of geopotential model truncation, orbit parameters fitting error, and effect of 3-byte floating point operations. The paper shows the results of the analyses for each individual source of error. The final error budget shows the best accuracy which can be achieved by the system currently implemented, as well as proposes to the user means to overcome the shortcomings arising from the system. Finally suggestions are also made to enhance the overall system of on-board ephemeris generation regarding the new series of upcoming CBERS-3 and 4 satellites.

2. ORBIT PERTURBATIONS

In general terms an artificial satellite motion is represented by a set of ordinary differential equations in the form:

$$\boldsymbol{a} = \boldsymbol{a}_{Kepler} + \boldsymbol{a}_{Geop} + \boldsymbol{a}_{Drag} + \boldsymbol{a}_{RP} + \boldsymbol{a}_{Sun} + \boldsymbol{a}_{Moon} + \dots$$

where $\boldsymbol{a}$ is the acceleration and the subscripts Kepler, Geop, Drag, RP, Sun, Moon represent the Keplerian, geopotential, atmospheric drag, radiation pressure, Sun gravitation, Moon gravitation accelerations respectively. The Keplerian motion ($\boldsymbol{a}_{Kepler}$) plays the main role and the other terms are considered perturbations, being summed up to compose the dynamic model of the orbital motion. Furthermore many other simplifications can be made to make the problem treatable. For the geopotential perturbation we can write:

$$
\begin{aligned}
\boldsymbol{a}_{Geop} &= \textit{funtion of}\left(\sum J_n + \sum \sum (C,S)_{n,m}\right) \\
&\overset{f}{=} \quad J_2 + J_3 + J_4 + \cdots \\
&\quad (C,S)_{1,1} + (C,S)_{2,1} + (C,S)_{3,1} + (C,S)_{4,1} + \cdots \\
&\quad (C,S)_{2,2} + (C,S)_{3,2} + (C,S)_{4,2} + \cdots \\
&\quad (C,S)_{3,3} + (C,S)_{4,3} + \cdots \\
&\quad (C,S)_{4,4} + \cdots
\end{aligned}
$$

where $\overset{f}{=}$ is intended to represent *function of* ( ), the J_i dependent terms are called zonal terms, and $(C,S)_{n,m}$ dependent terms are called tesseral and sectoral terms. A common practice in many analytical theories is to account for the J_i terms truncated up to a certain degree while neglecting the others. Table 1 yields an idea of the relative magnitudes of the perturbations acting on LEO (Low Earth Orbit) and GEO (Geostationary Earth Orbit) satellites.

Table 1. Orbit perturbations relative magnitude

Perturbation	LEO secular	LEO short period	GEO secular	GEO short period
J_2	1	10^{-3}	10^{-3}	10^{-5}
C_{nm}	10^{-3}	10^{-6}	10^{-4}	10^{-8}
Lunisolar	10^{-4}	10^{-7}	10^{-3}	10^{-5}
Drag	10^{-1}	10^{-7}	0	0
Radiation pressure	10^{-5}	10^{-8}	10^{-4}	10^{-6}

3. IMAGE EPHEMERIS TRUNCATION

INPE's image processing staff has been complaining for a long time about the CBERS-1 and 2 ephemeris which comes together with the images. Table 2 shows the corresponding ASC values after translation of the telemetry stream of binary data coming to the image reception station. It is clear that the data has been truncated to six significant figures, where in the case of position components, right leading zeroes are placed in the 7-th digit, or in other words, the meter level information is lost. For the velocity components, the mm/s digit is many times lost. It is clear that the 6-th digit is doubtful.

Table 2. Sample of orbit data contained in the image

x (m)	5385500
y (m)	-4606750
z (m)	387047
$\dot{x}$ (m/s)	-752.319
$\dot{y}$ (m/s)	-1501.59
$\dot{z}$ (m/s)	-7401.37

A deeper investigation into the on-board computer of CBERS-1 and 2 showed that all the floating point data flow and computations were carried out by 3 bytes. This word length reserved 1 byte for exponent and 2 bytes for the mantissa. The exponent byte has 1 bit for signal. The mantissa bytes reserve 1 bit for signal so that 15 bits are available for the number representation. This means that the last significant figure is roughly $1/2^{15}$ or that the 6-th digit is doubtful. This was quite a surprising aspect as the flight dynamic people normally do not care for such aspects when making their orbit determinations or uploading ephemeris to the satellites. It means that when dealing with floating point operations of CBERS onboard computer, we could have three sources of error:

- Upload of orbit ephemeris,
- On-board orbit computation,
- Telemetering of image orbit ephemeris.

In short, even if all the ground orbit determination is performed with full accuracy, the 3-byte floating point word truncation is not able to forward the full accuracy. We found cases in which the ground computed semimajor axis had a difference of hundreds of meters compared to that in the on-board computer memory. To our dismay it meant also that no matter how good were the on-board orbit model the limited word length would prevent a better accuracy. Finally, the telemetry download of image ephemeris being also in 3-byte word meant that something more would be lost in this process. It was therefore concluded that in fact the ephemeris generated by the on-board computer was poorly accurate giving plain reason for the image users. Table 3 shows some of the typical ground computed ephemeris and the corresponding 3-byte truncation on the on-board memory.

Table 3. Some typical orbit ephemeris

Orbit element	Ground computation	On-board memory
h (m)	770896.629732933	770880
$-e\sin\omega$	-1.11127641016856E-3	-1.11126E-3
$e\cos\omega$	-3.63378013050231E-5	-3.63383E-5
i (rad)	1.71977489576618	1.71972
Ω (rad)	0.541415014143613	0.541412
$\omega + M$ (rad)	-2.70492091080009	-2.70495

In principle the on-board orbit predictor was required to allow an error of up to 4km in three days, which is the maximum interval without ephemeris upload. This requirement seems to be accomplished, however certainly it does not fit the needs of the image users.

Discussions with the on-board computer designers of CBERS-2 led us to the conclusion that the present hardware can not afford a better floating point implementation, mainly due to limited ROM, RAM, and the CPU speed. As such other means had to be searched to circumvent the problem.

4. USING TWO-LINES NORAD MODEL

One of most popular analytical models for orbit computations is the NORAD (North American Defense) model known as SGP4 model [1]. Besides the model, the exchange of orbit ephemeris is greatly facilitated by the so-known two-lines elements data (2 lines of 80 ASC characters each). Such data is regularly generated by NORAD and most of ephemeris of the known orbiting objects are available through Internet (e.g. www.celestrak.com). CBERS-2 satellite has its two-lines available in Internet. INPE's control center also generates them in a regular basis every 2 to 3 days, that is, three times a week.

Because the ephemeris coming with the image of CBERS-2 was of poor accuracy, image processing users were using the two-lines generated either by INPE or Internet. Indeed they were not fully aware of the limited accuracy of this model. Figure 1 shows the osculating (instantaneous) semimajor axis and eccentricity along two CBERS orbits, generated by numerical integration of a full dynamic orbit model. Semimajor axis presents half orbit frequencies and eccentricity shows other frequencies with different amplitudes. It is not probable that an analytical theory can capture all the details of the orbit elements.

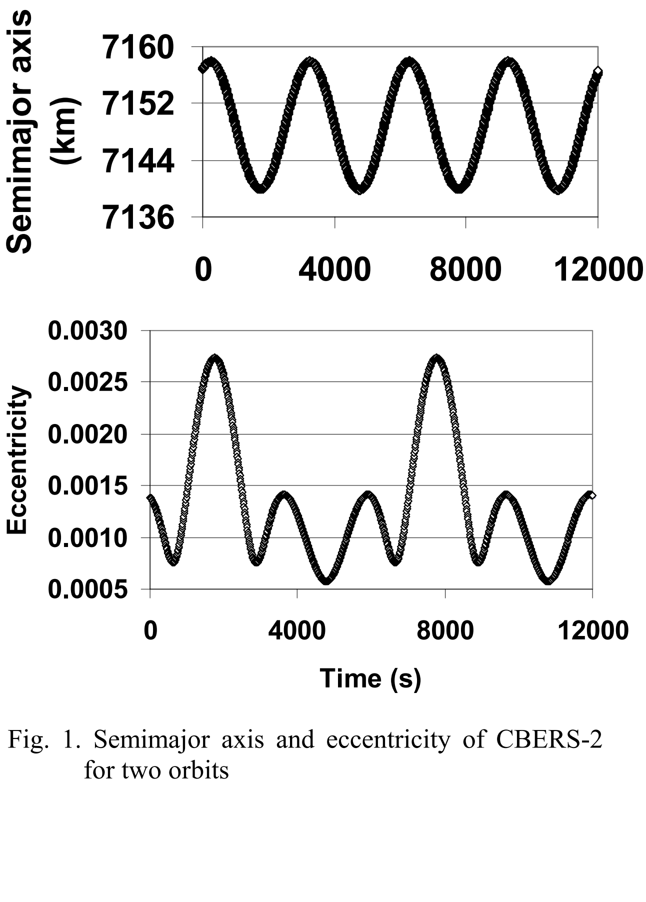

Fig. 1. Semimajor axis and eccentricity of CBERS-2 for two orbits

It is known that the NORAD model for LEO satellites accounts for the geopotential perturbation considering the zonal terms J_2, J_3, J_4 , and the drag effect is considered analytically by B^* (aerodynamic ballistic coefficient) and a simplified atmospheric model. As an example, if we consider a truncated J_2, J_3, J_4 model, what is the difference with a more complex model? Figure 2 shows the difference between using a 22x22 order and degree geopotential perturbation model and a model considering J_i, i=2,3,4. It is seen that the along track error can grow wildly up to 2km in 2 orbits. Radial and normal track errors are less pronounced. Table 4 extracted from [2] depicts the expected prediction error. Thus the errors of Fig. 2 are consistent with the ones described in [2].

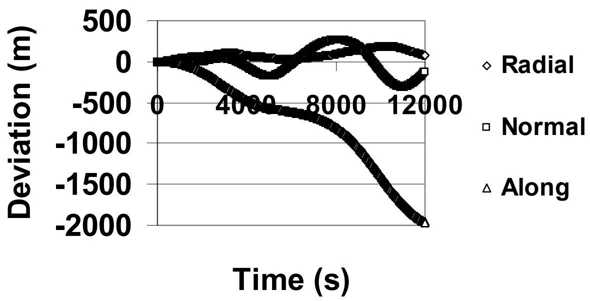

Fig. 2. Difference between 22x22 and J_2, J_3, J_4 geopotential model

Table 4. Fit/Prediction of NORAD SGP4 model [2]

Case	h_p (km)	h_a (km)	e	i (°)	SGP4 error (km)
1	235	243	0.0007	15	1.64/6.25
2	230	242	0.0009	45	0.88/3.80
3	218	237	0.0014	75	1.43/97.94
4	222	259	0.0028	15	0.75/5.16

In practice the flight dynamics people try a best fit of the orbit predictions to the NORAD model. It can be done twofold: either an orbit determination scheme to fit tracking data to NORAD model, or a fit of the very precise orbit predictions to the NORAD model. In both ways it is not guaranteed an accuracy level better than hundreds of meters. Figures 3-5 shows the error of the fitting between a 3-day numerical orbit integration (with geopotential perturbation (22x22), atmospheric drag (high solar flux), Sun-Moon gravitational effect, and solar radiation pressure) and the NORAD SGP4 coefficients model.

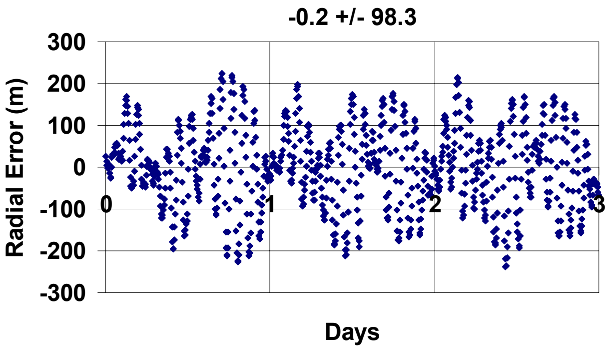

Fig. 3. Radial error of the fit

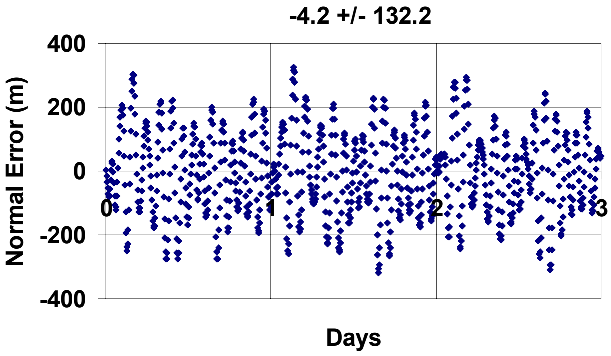

Fig. 4. Normal error of the fit

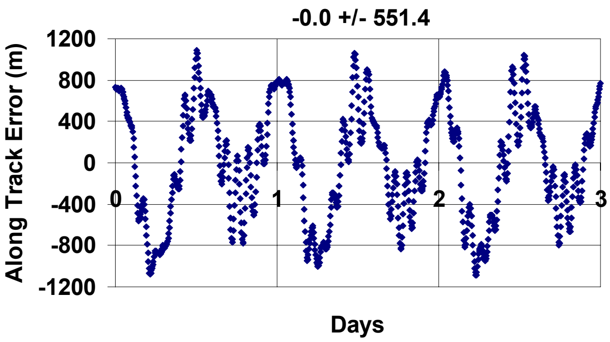

Fig. 5. Along track error of the fit

The radial and normal directions had a fit around 100m in the three days. However, the along track component had a fitting standard deviation of 550m. Looking the figures one notices that some frequencies of the orbital motion were not captured by the NORAD model, this being magnified in the along track motion direction.

It means that using the NORAD model for ephemeris matches on the image may sometimes present errors of 1000m although on the average the error is zero.

5. CURRENT AND FUTURE EPHEMERIS PROCESSING STRATEGY

Requeriments for the CBERS mission in terms of image processing products were somewhat loose or undefined. It was not expected that such level of errors were present in the ephemeris tagged in the image. Discussions with the on-board computer project staff made clear the unfavourable aspect of the on-board ephemeris computation (see section 3). Ephemeris computed on-board delivered nearly useless accuracy to image processing people.

The first attempt was to use two-lines elements obtained by Internet or computed by INPE's control center. However it was soon realized that it provided limited accuracy (see section 4). In any case it was the first step to make geo-referencing to the CBERS images.

There is one approach going on presently. It uses control points on ground (landmarks like rivers crossing, bifurcation paths, or some scene peculiarities) to match the image to the ephemeris, so that the ephemeris correction is valid to that particular scene. This solution turns out to be very troublesome due to a lot of hand work, which prevented automation to freed the image operators.

In phase of implementation is the use of precise orbit prediction of INPE's control center to the image processing people. It will deliver the orbit positions every minute to each single image taken by CBERS-2. Interpolation could be done through Chebyschev polynomials as a standard procedure. Because it was not a primordial and operational task of control center operators it is being decided who will be responsible by this activity. It releases a bit the operator's work but still is considered a provisional solution until CBERS-3.

For the future, the requirements for image products of the next CBERS satellites (CBERS-3 and 4) are being re-stated. At level 2 of the image processing procedure, the positioning accuracy should be better than 200m without any ground ephemeris processing [3]. This implies a GPS receiver on-board as well as an improved on-board computer.

References

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