AUTOMATED OPERATIONAL MULTI-TRACKING HIGH PRECISION ORBIT DETERMINATION FOR LEO MISSIONS

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Abstract: *The concept of Precise Orbit Determination (POD) appears more and more frequently in the operation of Earth observation and navigation missions. In the last few years GMV has developed, under contract with ESA, an evolution of the software package NAPEOS (Navigation Package for Earth Orbiting Satellites) to service navigation precise solutions (GPS, GLONASS, GALILEO constellations) but also to allow generation of POD solutions for any LEO mission flying a GNSS (Global Navigation Satellite Systems), SLR (Satellite Laser Ranging) or DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite) receiver, or any combination of them.*
Based on NAPEOS, GMV is developing a framework to ease the integration of POD systems in data processing chains.
This paper describes the architectures understood most suitable to accomplish this task together with the expected and encountered critical points and some of the results obtained executing a prototype of the target final solution.

Keywords: *POD, NAPEOS, LEO, GNSS, GPS, GLONASS, SLR, DORIS*

1. Overview of POD

Orbit determination is used for the operations of every orbiting spacecraft. Occasionally a mission calls for tighter requirements on the knowledge of the orbit than what is usually applied. When this is the case, methods of precise orbit determination (POD) are used. In general, missions that perform satellite geodesy are the most common ones needing POD. Such science goals as measuring the variations of Earth's gravity field, surface deformations, or the sea surface height requires that the accuracy of the orbit determination be better than the measured variations themselves which can be quite small. To improve the accuracy of the orbit over standard orbit determination methods, POD methods include higher order perturbations to the spacecraft's equations of motion due to the Earth's solid tides, ocean tides, the interaction with the Moon and Sun, and higher order gravity fields among other influences, which may not normally be considered. In addition to these perturbations, empirical accelerations to account for any unmodelled or mismodelled dynamics are usually estimated to further improve the accuracy.

2. Overall Architecture Description

The high flexibility of NAPEOS allows building a customized framework for an operational LEO POD with the following functionality:

- **Standardised interfaces**: data ingestion into the system is implemented through widely acknowledged data formats. Typically RINEX for GPS tracking data, CSTG for SLR data, SP3 for satellite ephemeris, CCSDS standard formats, etc.
- **Adequate pre-processing**: one of the key issues in the hands-off operations of a POD system is the ability to react to badly conditioned data and remove it from the POD processing chain. The earlier in the process that this happens the more reliable the overall process is. In the particular case of GPS based POD, the consolidation of GPS ephemeris and clocks is essential to allow the

processing of the LEO tracking. Even scenarios based on IGS[1] solutions can lead to operationally unstable situations that must be adequately managed.

- **Plug-in for mission dependent data ingestion**: typically the tracking data from the LEO satellite coming in the telemetry. Most missions have specific data formats and contents that require pre-processing and reformatting before entering the POD process.
- **Simulation capabilities**: the components used for POD can also be reused to simulate the POD scenario where the LEO satellite flies. NAPEOS provides a tracking simulation component that can reproduce with minimum adaptation the tracking macroscopic scenario seen by the POD system. Once the tracking data is simulated, it is possible to add the small mission specific effects (receiver characteristics, local clock effects, etc.) and then use the simulated data to analyse the POD performance.
- **Handle ancillary data**: not just the tracking data needs to be ingested for POD. To actually obtain the final level of accuracy attitude data, environmental data, constellation and ground station information need to be ingested properly to provide the POD with adequate tracking scenario.

The steps needed to get the above functionality begin (see Fig.1) with the checking and formatting of all the inputs: a-priori LEO orbit and external GNSS orbits and clocks, LEO observations that can be DORIS, SLR or GNSS, attitude quaternion's, manoeuvres and satellite configuration information like mass, dimensions, GNSS antenna offsets (ANTEX) ...
Then there is a pre-processing step in charge of cleaning the measurements, eliminating bad data that could corrupt the process, and computing a-priory clocks for the LEO satellite that either are usually unavailable or are typically impossible to propagate from previous clocks (see Fig. 2 for typical clock behaviour). The pre-processing step is paramount to be able to construct a robust infrastructure that allows a continuous processing with minimum supervision.
The final step is the POD process itself where the final orbits and clocks of the LEO satellite are computed. This last step uses the latest IERS standards to account for the modelling of all the forces acting on the satellite. Beside this, the modelling of the measurements has to take into account all kind of perturbations, for example the above mentioned antenna offsets.

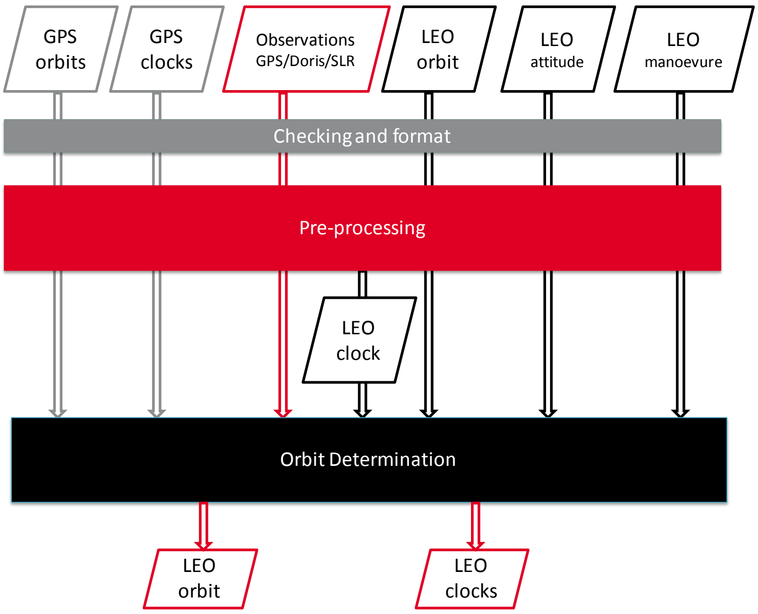


Figure 1: Workflow of POD

[1] IGS: International GNSS Service (http://igscb.jpl.nasa.gov/)

3. Test Scenarios

In order to test the above mentioned framework, several test cases have been prepared and carried out with NAPEOS. Four different satellites were used, CHAMP, Jason 1 and 2 and MetOp-A. All of them are Earth observation satellites with altitude between 450 and 1350 Km.
The goal of these scenarios is to check a potential operational scheme where the LEO satellite orbit and clocks are computed with centimetre accuracy taking into account ancillary data like attitude or manoeuvre information, in order to see that the capabilities of the system are able to handle with a continuous operation with minimum supervision.

3.1. Tracking System

The tests were carried out using different kinds of tracking. NAPEOS is able to process not only GPS data, but also SLR and DORIS, among other tracking systems. NAPEOS is able to use all kinds of tracking simultaneously, improving the final accuracy. Different tests have been done combining GPS, SLR and DORIS. Not all kinds of tracking are available in each satellite, so Tab. 1 shows the different combinations of tracking used for each satellite.

Table 1: Tracking used depending of the satellite

Satellite	GPS	GPS + SLR	GPS + SLR + DORIS
CHAMP	X	X	
Jason-1	X	X	X
Jason-2	X	X	X
MetOp-A	X		

CHAMP does not have DORIS while METOP-A does not have either SLR or DORIS.

3.2. GPS Orbits and Clocks used (IGS products)

When using GPS tracking data, it is necessary to fix the GPS satellite orbits and clocks to estimate the orbit and clocks of the LEO satellite from the tracking data.
There are different ways to obtain GPS orbits and clocks, although the best reliable source is IGS (Internationally GNSS Service). IGS provides different orbits and clocks solutions with different accuracies that range from 100 cm / 5 ns for the broadcast ephemeris to 2.5 cm / 75 ps. for the final solution. Table 2 shows the accuracies of the different solutions.

Table 2: Accuracies of IGS products

Solution	Accuracy	Latency
Broadcast (**BRDC**)	~100 cm (orbits) ~5 ns RMS (clocks) ~2.5 ns. SDev (clocks)	Real time
Ultra rapid – predicted half (**IGUP**)	~5 cm (orbits) ~3 ns. RMS (clocks) ~1.5 ns. SDev (clocks)	Every 6 hours
Ultra rapid – estimated half (**IGUE**)	~3 cm (orbits) ~150 ps. RMS (clocks) ~50 ps. SDev (clocks)	Every 6 hours
Rapid (**IGR**)	~2.5 cm (orbits) ~75 ps. RMS (clocks) ~25 ps. SDev (clocks)	Daily

Solution	Accuracy	Latency
Final (**IGS**)	~2.5 cm (orbits) ~75 ps. RMS (clocks) ~20 ps. SDev (clocks)	Weekly

Broadcast solution is the navigation message sent by the satellite directly. It is available in Real Time, but the accuracy is quite limited. Ultra rapid solutions are produced four times per day (i.e. every 6 hours there is a new solution) and includes an estimated part (1 day) and a predicted part (another day). It is useful for near real time solutions thanks to the availability of the predicted part, although the accuracy of the predicted part is not as good as the estimated arc. Then, every day there is a “rapid” solution that improves the accuracy but it does not contain a predicted arc. Lastly, the “final” solution achieves the best possible accuracy, but it is only available once every week and, like the “rapid” solution, it contains only the estimated arc.
Depending on the characteristics of the POD process, it is possible to use different IGS products. For example, CHAMP is a satellite that orbits at low altitude, so the estimated arcs used in our processing is just 1 day and 8 hours (1 day plus four hours in each extreme of the arc). It is possible to think in near real time solutions due to the relatively short estimated arc, so in principle it is possible to use all kind of IGS solutions. For other satellites like Jason-1/2 or MetOp-A, whose orbits are higher, the optimum estimated arc is longer (3 days), so it makes no sense to use neither the broadcast solution nor the ultra rapid solution. Table 3 shows the different IGS products used for each satellite in our tests.

Table 3: IGS products used with each satellite

Satellite	BRDC	IGU	IGR	IGS
CHAMP	X	X	X	X
Jason-1			X	X
Jason-2			X	X
MetOp-A			X	X

It is always possible to prepare cases where the estimated arc is shorter and then to use BRDC or IGU solutions, or to prepare mixed solutions where IGR and IGU solutions are mixed to obtain a 3-days arc. Multiple solutions are available and NAPEOS can handle this variability easily.
The IGS orbits are sampled at 15 minutes, while clocks are produced at both every 300 seconds and 30 seconds for the IGR and IGS solutions.
In our process IGS orbits and clocks are fixed, while LEO orbits and clocks are estimated. Different solutions have been computed depending on the clock data rate.

3.3. GPS Observables

When using GPS data, there can be different observables depending on whether the receiver is dual frequency or mono-frequency. Also, the availability of phase, together with the pseudo-range broadens the range of possibilities. Table 4 shows a summary of the observables used.

Table 4: GPS Observables

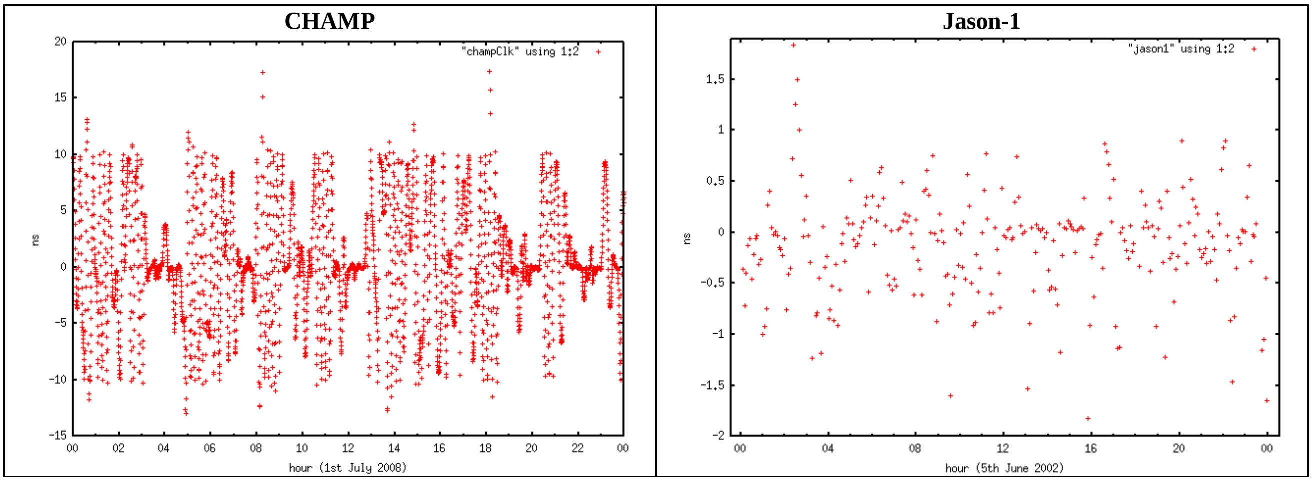
Name	P1	L1	P2	L2	Characteristics
P3, L3	X	X	X	X	Ionofree; code and phase; two frequencies
LP	X	X			graphical combination; code and phase; one frequency
P3	X		X		Ionofree; code only; two frequencies

The basic GPS observables are pseudo-range or code (P) and phase (L), each of them in two frequencies, so in total there are 4 observables: P1 and P2 for the pseudo-range and L1 and L2 for the phase.
POD process relay on removing efficiently the ionosphere delays in the signal; that can be done using different combinations of these basic observables:

- The basic Ionofree combination (P3 for the pseudo-range and L3 for the phase) is constructed as:
$$P_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 P_1 - f_2^2 P_2\right) \tag{1}$$
$$L_3 = \frac{1}{f_1^2 - f_2^2}\left(f_1^2 L_1 - f_2^2 L_2\right) \tag{2}$$
- In case of having just one frequency, it is possible to build the so-called graphical combination to remove the ionosphere delay:
$$LP = \frac{P_1 + L_1}{2} \tag{3}$$
This observable is also free of ionosphere like the combinations P3 and L3 above but retains the integer ambiguity from L1
- In case only the pseudo-range is available, the process uses only P3 and not L3.
- The case when just one frequency and just pseudo-range is available is not considered since this represents a too degraded scenario.

3.4. Orbit and Clock Initialization

The a-priori LEO orbit used for initializing the POD process are either obtained from other centre (CNES, GFZ, GODDARD) or it can be initialized using other methods like the predicted orbit from the previous run or a TLE, for example.
The a-priori LEO clocks are initialized in the pre-processing step, because it is not possible to obtain this information from a propagation of a previous clock in an operational environment. See Figure 2 for different behaviour of satellite clocks (those used in this paper).



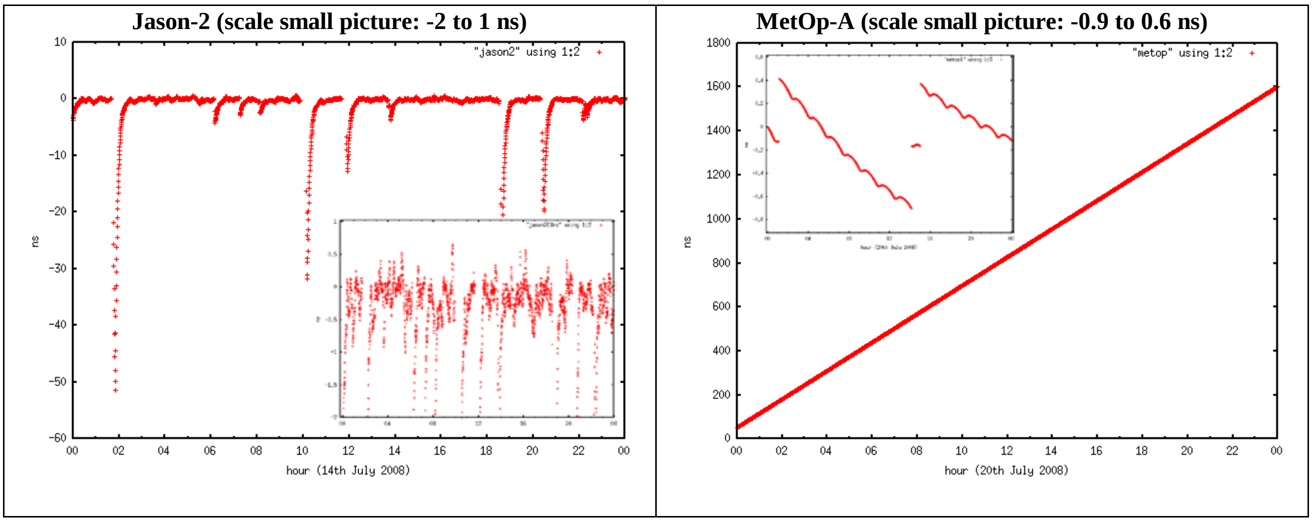


Figure 2: LEO´s clock biases

Satellites like CHAMP have a very noisy clock that jump between ±10 ns in less than 30 minutes, while MetOp-A has a very stable clock that although it has a steep drift, once removed the clock jump less than 1 ns in several hours.
These examples show that unless the clock is very good, it is not possible to predict it behaviour.

3.5. Ancillary Data

In an operational environment, the precise attitude of the satellite is usually available and it is important to obtain the best results in the POD. NAPEOS is able to apply the attitude´s quaternion in the POD process, but in case it is not available, there are several attitude modes built in, like the GPS attitude mode, or the Yaw Steering mode. New modes can be included easily in case it is necessary.
Satellite´s manoeuvres information is important from the operational point of view. In order to have a robust system that does not need manual intervention, manoeuvre information has to be taken into account in the POD. NAPEOS is able to handle manoeuvres if they are supplied; it calibrates them and outputs the final orbit taking into account each manoeuvre.
In the examples provided, Jason-2 suffered one small manoeuvre in the middle of the processing period without suffering any operational problem or any accuracy degradation.
Table 5 shows the characteristics of the manoeuvre. The first column shows the initial value used (approximated values representing an along-track manoeuvre) while the second column shows the calibration estimated by NAPEOS (percentage of error)

Table 5: Manoeuvre characteristics (Jason-2 – August 27th 2008)

Component	Value (acceleration in mm/s)	Calibration error (%)
Radial	0.0015	-1.24 %
Along-track	3.5571	-0.008 %
Cross-track	0.0061	-0.15 %

Figure 3 shows the minor impact that the manoeuvre has in the orbital estimation of the satellite. It represents the comparison against CNES solution. This estimation was obtained using GPS data but similar results are obtained adding SLR or DORIS. It can be seen that the accuracy of the POD solution is below 6 cm all the time.

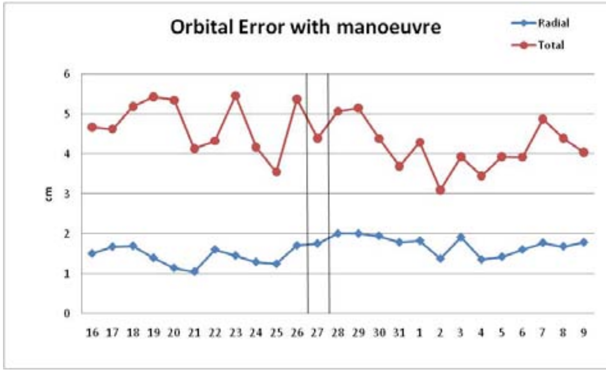


Figure 3: Jason-2 accuracy with manoeuvre on Aug 27th

4. Description of the Satellites

Four different Earth observation satellites have been used in this study: CHAMP, Jason-1, Jason-2 and MetOp-1. Table 6 shows the main characteristics of the satellites.

Table 6: LEO satellites used

	CHAMP	JASON-1	JASON-2	MetOp-A
Launch Date	July 15th, 2000	December 7th, 2001	June 20th, 2008	October 19th, 2006
Instruments	GPS, SLR	GPS, DORIS, SLR	GPS, DORIS, SLR	GPS
Altitude	454 km (initial)	1336 km	1336 km	817
Inclination	87º	66º	66º	98.7º
Mass	522 kg	490 kg	525 kg	4100 kg
Dimensions	750 x 8333 x 1621 mm	954 x 954 x 1218 mm	1000 x 1000 x 3700 mm	1760 x 6600 x 5200 mm
Figure	 **Courtesy of GFZ**	 **Courtesy NASA/JPL-Caltech**	 **Courtesy CNES / D. Ducros**	 **Courtesy ESA**

5. Accuracy Results

This section explains the Orbit Determination results obtained with each satellite. In principle each satellite has to be configured independently taking into account their characteristics. For example CHAMP is orbiting at just 453 km above the Earth, so the drag is much more intense than in the others satellites analysed here. Thus the arc length used in the orbit estimation cannot be very long because the mismodelling of the atmosphere would degrade the solution; meanwhile MetOp-A and Jason 1-2, since they are orbiting much higher than CHAMP, the arc length can be longer; in principle, the longer the arc is, the better the accuracy is, with an optimum value between 3 and 4 days. The solution chosen here was to use an arc length of one day plus 4 hours in each extreme for CHAMP and three days for the other satellites.
For each satellite different solutions have been done depending on:

- The type of tracking used: GNSS (G), SLR (S), DORIS (D)
- The type of IGS solution used for the GPS orbits and clocks: IGS, IGR, IGUE, IGUP, BRDC
- The type of GPS combination: Iono-free, code only (P) and graphical combination (LP)
- The type of GPS clock data rate: 30s or 300s

There will be a short description of each case before showing the results.
Finally, just to mention that data used in the following tests were obtained from public services except for MetOp-A that was provided directly by EUMETSAT.

5.1. CHAMP

For CHAMP the POD is based on estimating an arc of 1 day plus four additional hours in each extreme. Different solutions have been computed using a combination of GPS and SLR. Table 7 shows the different test cases used with CHAMP.

Table 7: POD solution for CHAMP

POD solution name	Tracking (see 3.3 for details)	IGS solution	IGS clock rate
GS_30s	GPS (P3, L3) + SLR	IGS	30 s
GS_300s			300 s
IGS_30s	GPS (P3, L3)		30 s
IGS_300s			300 s
IGSP_30s	GPS (P3)		30 s
IGSP_300s			300 s
IGSLP_30s	GPS (LP)		30 s
IGSLP_300s			300 s
IGR_300s	GPS (P3, L3)	IGR	
IGUE_300s		IGUe	
IGUP_300s		IGUp	
BRDC_300s		BRDC	

The period used for the POD with CHAMP was between July and October 2008.
In order to assess the accuracy obtained with the different solutions, the orbits have been compared against different references (see Tab. 8 for a description of the comparisons). Each comparison covered one whole day, excluding the additional four hours.
Firstly an external reference was used (GFZ) to compare the best solutions, those that use multiple tracking (GPS and SLR) and IGS final orbits for GPS. Figure 4 shows the average, over the whole set of days used, of RMS of the three main directions and the total one. It can be seen that NAPEOS matches with GFZ on less than 10 cm. The main degradation here is the reduction of clock rate from 30 to 300 seconds.
The second group of comparisons (see Tab. 8 in the middle) uses our own IGS_30s solution as reference. It tries to evaluate the accuracy´s degradation with respect to IGS_30s when using only GPS tracking and using the best IGS orbits and clocks. Figure 5 shows the results where it is clear that reducing the clock rate to 300 seconds degrades the solution in about 5 cm, but changing the observable to code only (P3) or the graphical combination (LP) produce a degradation of up to 20 cm even using the high clock rate.

Table 8: Comparison strategy for CHAMP

Reference	Comp w.
GFZ	GS_30s GS_300s IGS_30s

Reference	Comp w.
IGS_30s	IGS_300s IGSP_30s IGSLP_30s

Reference	Comp w.
IGS_300s	IGSP_300s IGSLP_300s IGR_300s IGUE_300s IGUP_300s BRDC_300s

The final set of comparisons (see Tab. 8 in the right hand side) compare those solutions with the less accurate inputs against our internal IGS_300s. All solutions here use a clock data rate of 300

seconds and different kind of IGS orbits & clocks and different kind of observables. Figure 6 shows the results. Here it can be seen the minimum impact of using the IGS rapid solution instead of the final one. In the worst scenario where the broadcast solution was used, the accuracy degraded up to 70 cm with respect to the solution IGS_300s.
Finally Fig. 7 shows the overlap comparisons using 4 hours in the middle of two consecutive arcs. Most of them agree in less than 5 cm. It is remarkable that the IGUP solution only agrees up to 35 cm. The reason is because of using different predictions in each run.

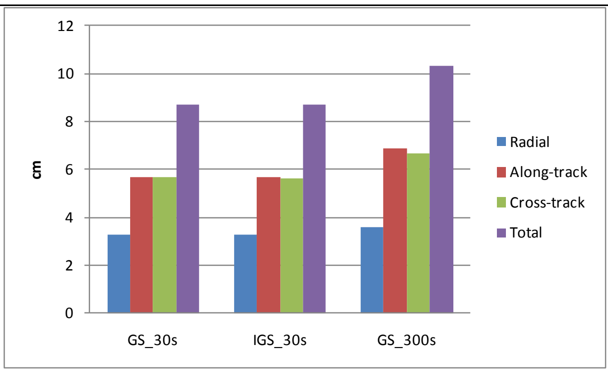


Figure 4: CHAMP comparisons against GFZ

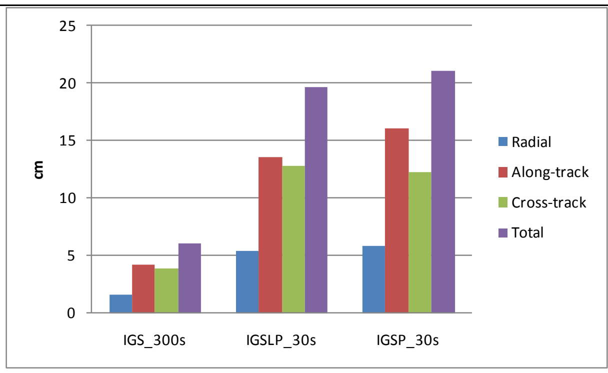


Figure 5: CHAMP comparisons against IGS_30s

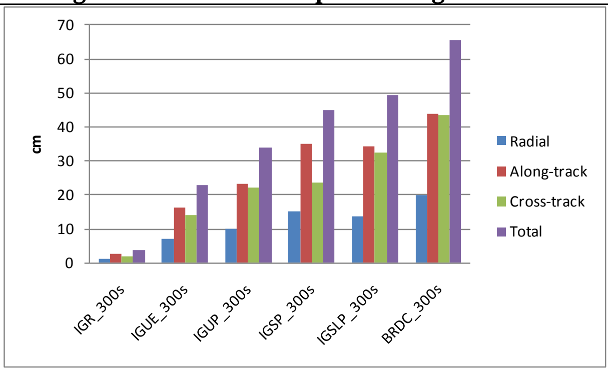


Figure 6: CHAMP comparisons against IGS_300s

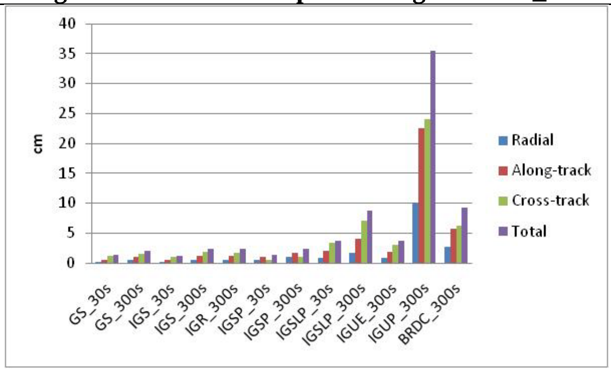


Figure 7: CHAMP overlap comparisons

5.2. JASON-1

For Jason-1 the POD is based on the use of a 3 days estimation arc to improve as much as possible the accuracy of the orbit. Different solutions have been computed using a combination of GPS, DORIS and SLR. Table 9 shows the different test cases used with Jason-1.

Table 9: POD solution for Jason-1

POD solution name	Tracking (see 0 for details)	IGS solution	IGS clock rate
GSD_300s	GPS (P3, L3) + DORIS + SLR	IGS	300 s
GS_300s	GPS (P3, L3) + SLR		
IGS_300s	GPS (P3, L3)		
IGSP_300s	GPS (P3)		
IGSLP_300s	GPS (LP)		
IGR_300s	GPS (P3, L3)	IGR	

In this case the period used for the Orbit Determination is June 2002, where there were no IGS clock solution at 30s date rate, so only solutions with 300s data rate are available.
The accuracy of the orbits has been analyzed comparing against Goddard (GSFC) solution and against internal solutions. The comparisons use only the intermediate day, so the tails of the estimation are not included. Table 10 shows the comparison strategy for Jason-1.

Table 10: Comparison strategy for Jason-1

Reference	Comp w.	Reference	Comp w.
GSFC	GSD_300s GS_300s IGS_300s	IGS_300s	IGSP_300s IGSLP_300s IGR_300s

The best solutions (those that use multiple tracking and IGS final orbits and clocks) have been compared against GSFC solutions; the results can be seen in Figure 8. The three solutions analyzed shows similar results, with errors below 5 cm, half of what was obtained with CHAMP. This is because the effect of the atmospheric drag is much lower at Jason-1's altitude so the modelling is more accurate.
A second group of solutions have been compared against our internal IGS_300s solution (it can be seen on Tab. 10 in the right hand side). Solutions here are those that use only GPS tracking and degraded inputs. Figure 9 shows the results of these comparisons. It can be seen that using IGS rapid solution produce almost the same result as using the IGS final one. Then using different observables degrades the solution around 20-25 cm that again is around half of what was obtained with CHAMP.
Finally Fig. 10 shows overlap comparisons using 12 hours in the middle of two consecutive arcs. The best solutions agree below 2 cm while the worst solutions agree below 6 cm.

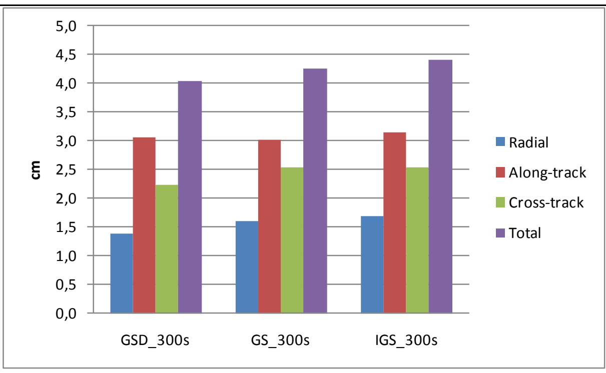


Figure 8: Jason-1 comparisons against GSFC

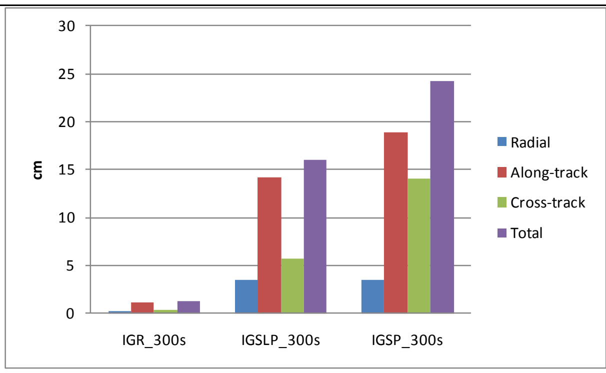


Figure 9: Jason-1 comparisons against IGS_300s

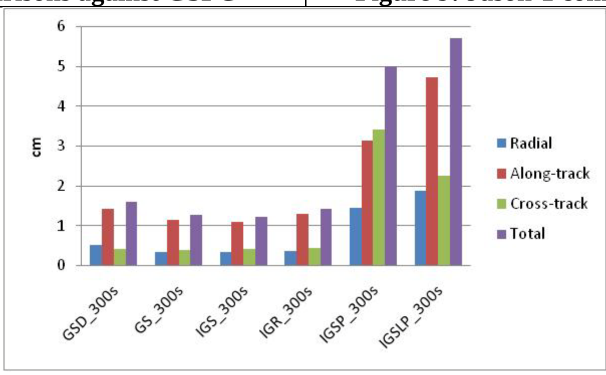


Figure 10: Jason-1 overlap comparisons

5.3. JASON-2

Jason-2 case is pretty similar to Jason-1; the POD is based also on estimating an arc of 3 day to improve as much as possible the accuracy of the orbit. Different solutions have been computed using a combination of GPS, DORIS and SLR. Table 11 shows the different test cases used with Jason-2.

Table 11: POD solution for Jason-2

POD solution name	Tracking (see 3.3 for details)	IGS solution	IGS clock rate
GSD_30s	GPS (P3, L3) + DORIS + SLR	IGS	30 s
GSD_300s			300 s
GS_30s	GPS (P3, L3) + SLR		30 s
IGS_30s	GPS (P3, L3)		
IGS_300s			300 s
IGSP_30s	GPS (P3)		30 s
IGSP_300s			300 s
IGSLP_30s	GPS (LP)		30 s
IGSLP_300s			300 s
IGR_300s	GPS (P3, L3)	IGR	

The period used for the POD with Jason-2 was between July and October 2008. In this time interval there were IGS clock solutions with data rate of 30s, contrary to Jason-1 case, so solutions with this data rate are available here.

The accuracy of the orbits has been analyzed comparing against CNES solutions and against internal solutions. The comparisons use only the intermediate day, so the tails of the estimation are not included. Table 12 shows the comparison strategy for Jason-2; it uses three different references. The CNES external reference is used with the best solutions, those that uses the three tracking system and the best IGS solutions. The results can be seen on Fig. 11 and matches below 5 cm like with Jason-1.

Table 12: Comparison strategy for Jason-2

Reference	Comp w.	Reference	Comp w.	Reference	Comp w.
CNES	GSD_30s GSD_300s GS_30s IGS_30s	IGS_30s	IGS_300s IGSP_30s IGSLP_30s	IGS_300s	IGSP_300s IGSLP_300s IGR_300s

The second set of solutions (in the middle in Tab. 12) uses our internal IGS_30s solution to evaluate the degradation obtained when using lightly worst input and only GPS tracking data. The results can be seen on Fig. 12.

Finally our internal IGS_300s solution is used as reference to compare the rest of the solutions (seen in the right hand side in Tab. 12). Figure 13 shows the results.

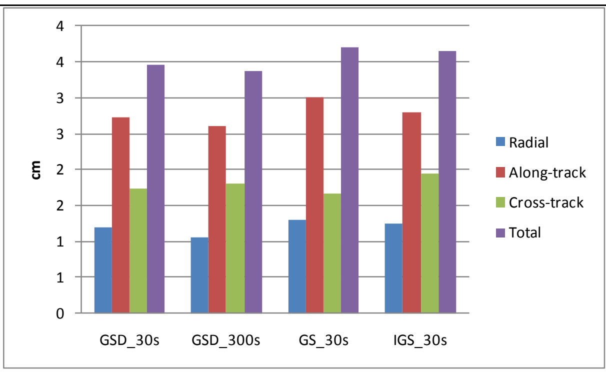


Figure 11: Jason-2 comparisons against CNES

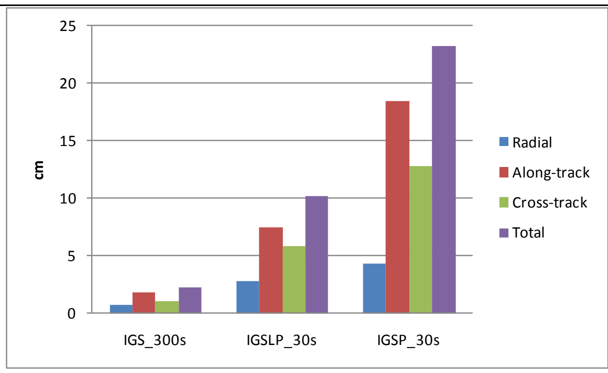


Figure 12: Jason-2 comparisons against IGS_30s

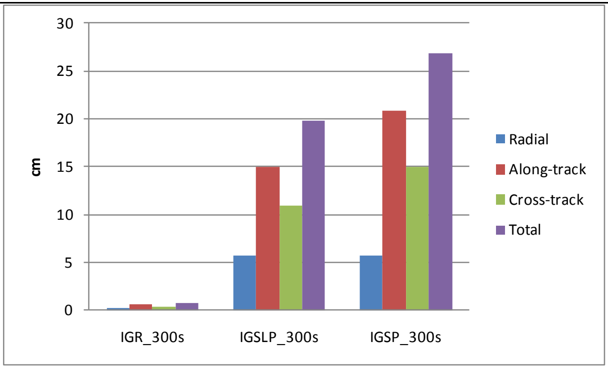


Figure 13: Jason-2 comparisons against IGS_300s

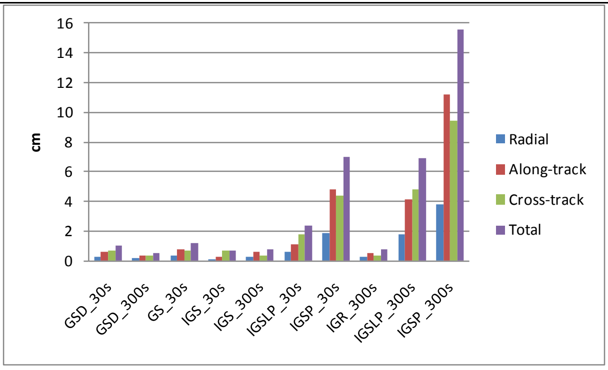


Figure 14: Jason-2 overlap comparisons

In general the results are similar to those obtained with Jason-1. Reducing the clock rate of IGS or using the rapid instead of final IGS solutions has a minor impact. The use of the graphical combination or the code only degrades the accuracy around 20-30 cm.
Finally Fig. 14 shows the overlap comparisons using 12 hours in the middle of two consecutive arcs. The best solutions agree on less than 1 cm while the rest shows that it agrees most with high clock rate and then the graphical combination more than the code only solution.
In this scenario the Antenna Phase Centre correction was also estimated as part of the normal orbit estimation process. These estimations can be used to calibrate these values after the launch of the satellite. Figure 15 shows these estimations and Tab. 13 contains the average of each APC axis and the standard deviation, where it is clear that the variation is in the order of millimetre.

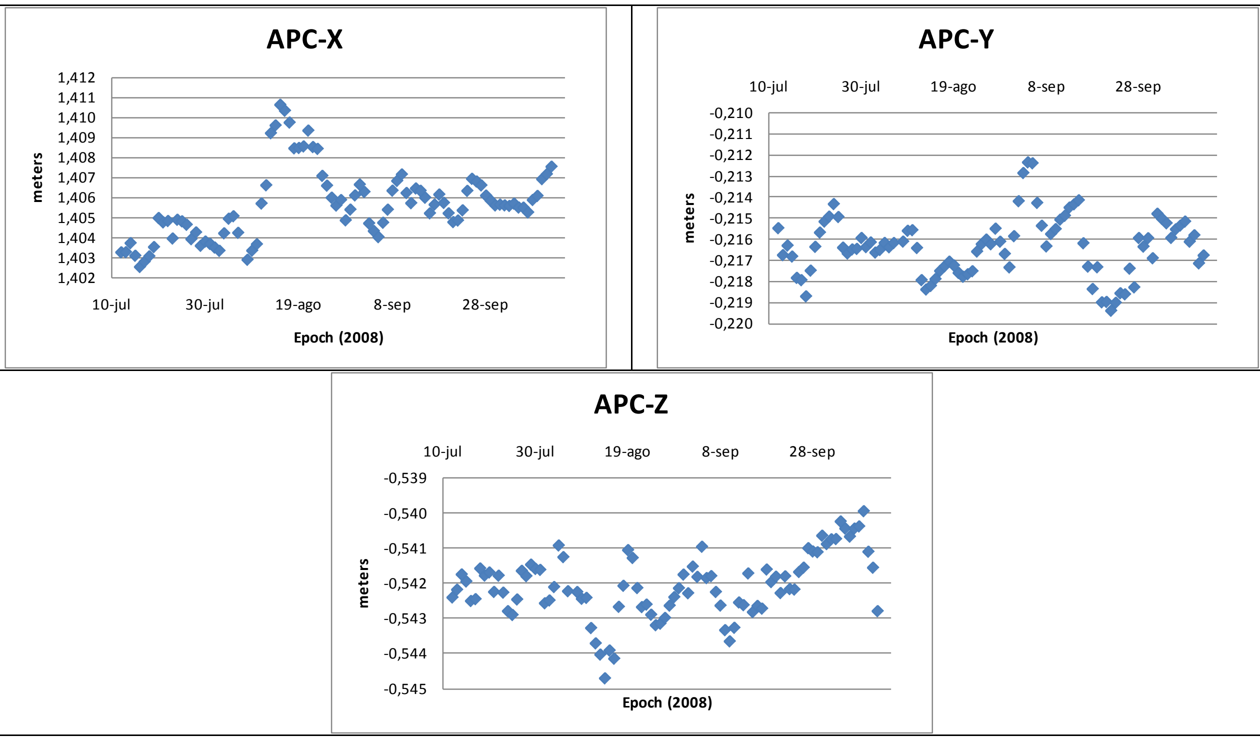


Figure 15: Antenna Phase Centre estimation (using GPS and SLR tracking)

Table 13: POD solution for MetOp-A

APC	X	Y	Z
Average (m)	1.4056	-0.2164	-0.5421
Standard deviation (mm)	1.767	1.415	0.918

5.4. METOP-A

Finally MetOp-A case is similar to Jason-1/2; the POD is based also on estimating an arc of 3 day to improve as much as possible the accuracy of the orbit. Different solutions have been computed using only GPS, because this satellite does not have either DORIS or SLR. Table 14 shows the different test cases used with MetOp-A.

Table 14: POD solution for MetOp-A

POD solution name	Tracking (see 3.3 for details)	IGS solution	IGS clock rate
IGS_30s	GPS (P3, L3)	IGS	30 s
IGS_300s			300 s
IGR_300s		IGR	
IGSP_30s	GPS (P3)	IGS	30 s
IGSP_300s			300 s
IGSLP_30s	GPS (LP)		30 s
IGSLP_300s			300 s

The period used for the POD with MetOp-A was between July and September 2008.
No external solutions are available currently, so only internal comparisons have been done. The comparisons use only the intermediate day, so the tails of the estimation are not included. Table 15 shows the comparison strategy for MetOp-A.

Table 15: Comparison strategy for MetOp-A

Reference	Comp w.	Reference	Comp w.
IGS_30s	IGS_300s IGSP_30s IGSLP_30s	IGS_300s	IGSP_300s IGSLP_300s IGR_300s

The best solutions are compared against IGS_30s that is considered the best possible solution in this scenario, while IGS_300s is used as reference with those solutions that uses IGS clock rate of 300 seconds. Figure 13 shows the results with the first reference while Fig. 14 shows those with the second reference. In both cases it can be seen that the main impact is on using different observables and not on using different IGS solutions.

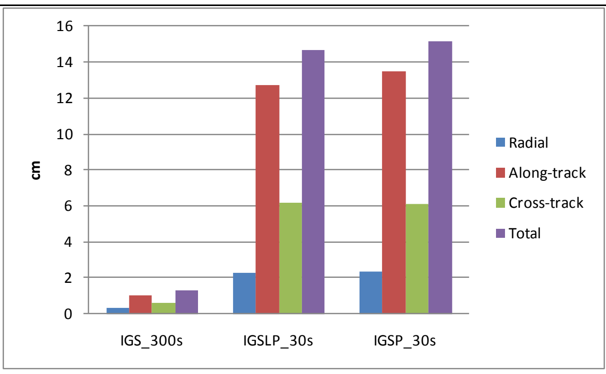


Figure 16: Jason-2 comparisons against IGS_30s

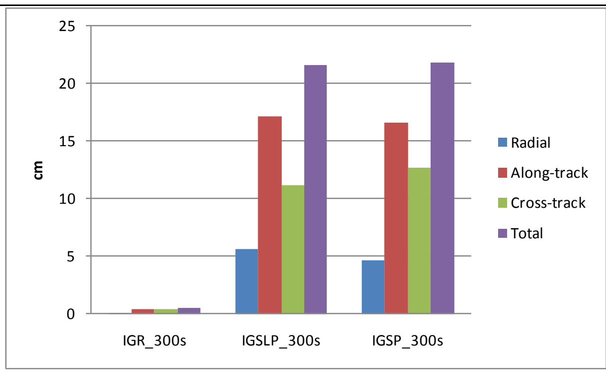


Figure 17: Jason-2 comparisons against IGS_300s

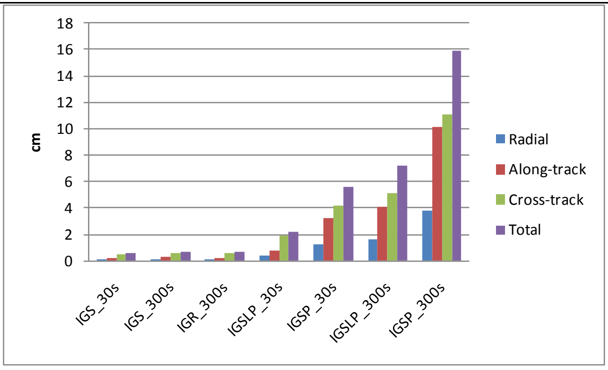


Figure 18: MetOp-A overlap comparisons

Finally Fig. 18 shows the overlap comparisons using 12 hours in the middle of two consecutive arcs. The best solutions agree on less than 1 cm, while the worse solutions´ agreement increases steadily while degrading the inputs (best high clock rate, best graphical combination than only code).

5.5. Summary of Results

Figure 19 shows the typical accuracy obtained with different methods and satellites using the operational procedure described above.

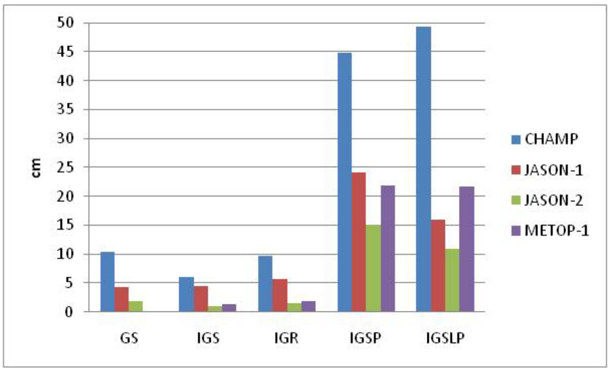


Figure 19: Expected accuracy

Solutions that use the best possible inputs (IGS final or rapid solutions, a GPS double frequency receiver) obtained solutions better than 5 cm for LEOs above 800 km, and less than 10 cm for lower LEOs.
In case the satellite does not include a double frequency GPS receiver but a mono-frequency one, the accuracy is degraded to less than 25 cm for LEOs above 800 km, and less than 50 cm for lower LEOs.
Accuracy is worse when using less accurate GNSS-navigation solutions or less accurate observables, but an accuracy of around half a meter is even possible under these circumstances.
This architecture has a high internal consistency as it can be observed comparing consecutive arcs (overlap comparisons)

6. Conclusions

We have described how an operational POD procedure can be prepared with NAPEOS to obtain centimetre level accuracy for LEO satellites.
The procedure needs minimal supervision and therefore can be included in any LEO POD automatic procedure. It can handle ancillary information like manoeuvres and attitude information.

NAPEOS allows to set-up different scenarios depending on the requirements of the mission, mainly accuracy and processing times. NAPEOS also allows using different kind of tracking simultaneously like GNSS observables, DORIS or SLR.

In the examples presented, several typical LEO missions have been processed using different tracking systems, different GPS observables and different IGS navigation solutions, so covering a wide range of scenarios.

The accuracy obtained range from less than 5 cm to 1 meter depending on the kind of orbit, tracking and GNSS-navigation inputs used.