EXECUTIVE SUMMARY

NEW CONCEPTS FOR ON-BOARD PRECISE ORBIT DETERMINATION (OBPOD)

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1. INTRODUCTION

1.1. PURPOSE

This document is the executive report of the project "New concepts for on-board Precise Orbit Determination".

1.2. SCOPE

This document is a deliverable by GMV in the frame of the project "New concepts for on-board Precise Orbit Determination".

1.3. ACRONYMS

The following table defines the acronyms used throughout the document.

Table 1-1: Acronyms

Acronym	Definition	Acronym	Definition
AD	Applicable Document	HEO	High Eccentricity Orbit
AGGA	Advanced GPS/GLONASS ASIC	IAR	Integer Ambiguity Resolution
BRDC	Broadcast ephemeris file	ISL	Inter Satellite Link
CAI	Cold Atom Interferometry	LEO	Low Earth Orbit
CPU	Central Processing Unit	MEO	Medium Earth Orbit
DIL	Document Item List	POD	Precise Orbit Determination
DORIS	Doppler Orbytography and Radiopositioning Integrated by Satellite	RD	Reference Document
ESA	European Space Agency	RF	Radio Frequency
GEO	Geostationary Orbit	RMS	Root Mean Square
GNSS	Global Navigation Satellite System	SAR	Synthetic Aperture Radar
GPS	Global Positioning System	SLR	Satellite Laser Ranging
GRACE	Gravity Recovery And Climate Experiment	TBC	To Be Completed
HAS	High Accuracy Service		

1.4. APPLICABLE AND REFERENCE DOCUMENTS

1.4.1. APPLICABLE DOCUMENTS

The following documents, of the exact issue shown, form part of this document to the extent specified herein. Applicable documents are those referenced in the Contract or approved by the Approval Authority. They are referenced in this document in the form [AD.X]:

Table 1-2: Applicable Documents

Ref.	Title	Code	Version	Date
[AD.1]	On-Board Precise Orbit Determination - New POD Concepts – SoW	DOPS-MGT-SOW-0026-OPS-GN	1.0	15/03/2016
[AD.2]	New Concepts for On-Board Precise Orbit Determination – GMV´s proposal	GMV 11000/16 V1/16	1.0	06/05/2016

Ref.	Title	Code	Version	Date
[AD.3]	AO/1-8495/16/D/CS "On-Board Precise Orbit Determination - New POD Concepts" – Minutes of Negotiation Meeting	ESA-OBPOD-MIN-0001	1.0	24/11/2016
[AD.4]	New Concepts for On-Board Precise Orbit Determination – Minutes of Kick-off Meeting	GMV-OBPOD-MOM-0001	1.0	24/01/2017
[AD.5]	Review of POD systems and mission needs	GMV-OBPOD-TN-0001	2.0	13/08/2020
[AD.6]	Identification of design drivers for potential new on-board POD concepts	GMV-OBPOD-TN-0002	2.0	13/08/2020
[AD.7]	Requirements identification for potential new on-board POD concepts	GMV-OBPOD-TN-0003	1.0	11/09/2020
[AD.8]	Identification and development of integral on-board POD concepts	GMV-OBPOD-TN-0004	1.1	04/11/2021
[AD.9]	Detailed analysis of the two selected on-board POD concepts	GMV-OBPOD-TN-0005	1.1	04/11/2021
[AD.10]	Final Report	GMV-OBPOD-FR	1.0	04/11/2021

1.4.2. REFERENCE DOCUMENTS

The following documents, although not part of this document, extend or clarify its contents. Reference documents are those not applicable and referenced within this document. They are referenced in this document in the form [RD.X]:

Table 1-3: Reference Documents

Ref.	Title
[RD.1]	G. Giorgi, et al. (2019), Advanced technologies for satellite navigation and geodesy, in *Advances in Space Research* 64
[RD.2]	Haagmans, Roger, et al. "ESA's next-generation gravity mission concepts." *Rendiconti Lincei. Scienze Fisiche e Naturali* (2020): 1-11.
[RD.3]	Carraz, Olivier, et al. "A spaceborne gravity gradiometer concept based on cold atom interferometers for measuring Earth's gravity field." *Microgravity Science and Technology* 26.3 (2014): 139-145.

2. BACKGROUND OF THE ACTIVITY

Carrying out precise orbit determination on-board in comparison to traditional ground based processing can be an advantage either to satisfy an on-board immediate need, to communicate quickly the information to a user, or to achieve an increased autonomy from the ground infrastructure. Examples of **applications** that benefit or would benefit of on-board POD are radio occultation, LEO formations, new generation of GNSS systems, autonomous station keeping for LEO, MEO and GEO satellites, new generation gravitational missions or very high performance optical and RF instrument, with different requirements in terms of accuracy, latency and complexity.

Current on-board orbit determination concepts are in most cases an integral part of the satellite avionics. However, it is believed that the full capability of on-board precise orbit determination requires new concepts. For this reason, this study shall investigate the conceptual approach for an on-board precise orbit determination system, which is not based on the current use of state of the art on-board avionics alone. Furthermore, it should be investigated in which way the avionics and a future on-board POD system could be **enhanced** and **interfaced** with other elements of the system in an optimal way. In this context, the overall integration and associated interfaces to instrumentation, on-board systems and also space to ground, inter-satellite and ground to space interfaces should be investigated.

The concept should consider **technologies** like multiple GNSS constellations, for which new devices like AGGA-4 support up to 36 GNSS channels, DORIS, Satellite Laser Ranging (SLR) and how to operate inter-satellite and ground to space links, as potential data sources for the on-board precise orbit determination system. Nonetheless, the analysis is not limited to these existing technologies; indeed, it aims to anticipate the upcoming techniques that shall shape the future of on-board POD applications (including potential breakthroughs in computing, clock performances, etc.).

It is important to remark that the on-board POD concepts identified in this document, are described and analysed from a preliminary **conceptual approach** point of view, considering that their applicability may start from several decades (at least 20 years) from now. For this reason, the level of maturity of certain technologies is taken for granted. Again, the aim is to identify promising fields for future on-board POD applications rather than short-term evolutions.

This study will allow, for several scenarios of real time, near real time and non-real time (minutes, hours, days) and several satellite orbits (LEO, MEO, GEO, HEO), to **determine expected performance indicators** of the new on-board POD system concepts in terms of the autonomy of the system, robustness, highest achievable accuracy, performance, complexity and availability to name a few.

The objectives of the activity are:

1. **Development** of new concepts for on-board precise orbit determination (POD) for satellites in LEO, MEO, GEO and HEO orbits, including information on the concept itself and on system aspects. The scope of the activity is to identify potential new concepts for future applications, in a time frame from several decades onwards.
2. **Identification** and development of key drivers and requirements for these new on-board POD concepts.
3. **Detailed analysis** of selected new on-board POD concepts.

3. SUMMARY OF ACTIVITIES

Applications and current concepts

Precise orbit determination refers to the computation of satellite´s orbits with accuracies below 10 cm in LEO, compared with standard orbit determination that obtain accuracies of few meters. The key to achieve high accuracies are the quality of observations and the quality of the navigation/positioning data. GNSS, DORIS, SLR and ISL provides high accurate measurements. However, its use on-board requires accurate navigation/positioning data. See [AD.5] for more information.

With DORIS, the on-board navigation system knows the precise location of ground-based beacons, allowing an accurate and precise reconstruction of the measurements to obtain accuracies around 10-20 cm 3D RMS in real-time, and between 5 and 10 in the radial direction.

With GNSS, the limiting factor is the accuracy of the GNSS navigation data. Currently, this navigation data has accuracies between 0.3 to 1 metre for the GNSS orbits, and between 0.2 to 0.5 ns for the GNSS clocks (numbers are based on GPS and Galileo systems). These accuracies allow obtaining accuracies on-board in the range of decimetres to metres.

Currently it is not possible to use SLR on-board, as this technology relies on the accurate measure of the travel time of a laser pulse, from a ground telescope, so the information it is not available for its immediate use on-board.

ISL are starting to be used on some missions for communications and ranging, and it has a huge potential thanks to its high accuracy and precision, but currently it is not used for on-board POD.

Summarizing, only with DORIS it is possible to perform on-board POD currently. This study has identified the needs, requirements and technologies to develop new on-board POD making use of GNSS in all cases.

Identification of needs

POD is used primarily by several scientific mission, including geodesy and geodynamic, in charge of studying the Earth´s rotation and movements, altimetry, in charge of studying the changes in water masses on Earth, particularly over oceans and to study the sea level rising. Then, SAR/InSAR, in charge of obtaining images with radar, and to study the deformation of the terrain due to Earth quakes, for example. Radio-occultation, in charge of observing how the GNSS signals are bended on the atmosphere to derive profiles of pressure, temperature and humidity, which are used on the weather prediction models. Finally, interferometry, to combine the RF signals coming from galactic sources, and received on two or more telescopes. POD is also needed for absolute and relative navigation. Finally, POD is also key for the GNSS systems, to compute the navigation message. See [AD.5] for more information.

In terms of future mission needs, this project has assumed that the accuracies obtained currently on-ground, with short latencies (e.g. few tens of minutes since the availability of the data), will be the goal for future on-board POD systems. Overall speaking this means less than 5 cm 3D RMS for LEO missions. This level of accuracy is currently possible with on-ground processing with short latencies, thanks to the availability of real-time accurate GNSS navigation, and the use of complex POD algorithms. See [AD.7] for more information.

New technologies

To achieve better accuracies, several new technologies and services are investigated. Firstly, it is necessary to improve the GNSS navigation data. This can be done transmitting real-time GNSS corrections to the navigation message. This is already available through private services designed for users on-ground, but that can also be used on-board in LEO. The upcoming Galileo High Accuracy Service (GAL HAS) will also provide, free of charge, GNSS corrections to at least GPS and Galileo navigation messages. These corrections will make a significant improvement over current on-board GNSS orbit determination systems. Firstly, it will allow using the carrier-phases in addition to the code. This will allow using accurate observables, but will require modifications on the algorithms used, in particular the measurement reconstruction (to handle the phase ambiguity), the orbit modelling (to increase its fidelity or to use kinematic approaches), and the parameter estimation methods used (to increase the number of parameters being estimated in some cases). Additionally, it will allow resolving the integer ambiguity, a technology that in post-processing increases the accuracy of the solution, and that in real-time processing reduces the convergence time. See [AD.8] for more information.

Besides the GNSS corrections, three technologies have been investigated. The first one are the optical Inter-Satellite Links for ranging, but also for communications and time-transfer. [RD.1] describes its use for these three purposes. ISL for ranging is being used in GRACE/GRACE-FO, achieving nanometre precisions, and micrometre accuracies. This technology has a huge potential for future space missions thanks to the huge bandwidth that can be used for communications. Optical links can also be stablished between ground stations and satellites, or between GEO and LEO satellites, as it is the case with Sentinel-1 and -2.

The second technology are the optical clocks, as proposed in [RD.1]. Here, the clock is a composite of an optical cavity and a Doppler free spectrometer. Each of these devices has remarkable stability performances in different time regimes (short term for the optical cavity and medium term for the Doppler-free spectroscopy). On-ground test has proven Allan deviations in the order of 10^{-15}.

Clocks are key elements on all technologies used for precise positioning, including GNSS, DORIS, but also SLR and ISL. In particular, using GNSS requires to estimate the clock bias of the receiver´s clock in addition to the orbit. This is currently done using the so-called snapshot approach, on which an independent clock bias is computed for each epoch. This is needed as the stability of the clock is not good enough to use a clock model. The problem with this approach is that the radial component of the orbit is correlated with the clock estimation, so it is possible that orbit mis-modelling on the radial component are absorbed by the estimated receiver clock. The use of future optical clocks allow estimating clock models that help to separate the clock estimation from the radial component. Additionally, on HEO orbit, high performance clocks will enhance the navigation performance, in addition to support better tracking of weak GNSS signals improving longer integration times.

The third technology is the use of advance accelerometers, like the Cold Atom Interferometry (CAI) (see [RD.2], [RD.3]), which are being developed to support future geodesy and geodynamic missions. An accelerometer measure the non-conservative accelerations caused by the drag, the solar radiation and the Earth radiation (albedo, infra-red). These perturbations are difficult to model because they can change over time (e.g. drag), and require a careful modelling of the satellite geometry and properties when illuminated. Accelerometers can be used in two fundamental different ways. The first one uses the measured accelerations in substitution of the non-conservative forces, when propagating the orbit. This is the approach proposed, for instance, for LEO satellites. The second approach, which has been proposed for modelling the solar radiation on GNSS satellites, is to use the accelerations to better estimate non-conservative forces.

New on-board POD concepts

Several new on-board POD concepts are proposed (see [AD.8] for an extensive description), making use of the technologies described above. All of them relies on using GNSS, so all of them make use of GAL HAS to improve the navigation data. It has been proposed using GAL HAS, but it is also possible to use other GNSS correction provider that could arise in the future, or any of the commercial services that are working already. This technology is necessary to allow using the carrier-phases together with a better orbit modelling.

The second concept proposes to use accelerometers to improve the orbit modelling. Two approaches are proposed: i) to use the accelerations directly on the propagation model, and ii) to use the accelerations indirectly to improve the modelling of non-conservative forces. The selection of one or the other depends on the final use. For instance, its direct use could enhance the real-time orbit determination, while the indirect use could improve the predictions computed on-board for mission purposes like generating navigation data, or predicting events.

The third concept proposes to use advance clocks, as described in [RD.1], to allow estimating clock models, instead of using the typical snapshot approach. Clock modelling allow separating better the errors in the radial direction from the errors in the clock bias. Additionally, clock modelling is useful for navigation if there are data gaps that prevent updating the state-vector with measurements. This could be the case on HEO, or other high-altitude mission. Finally, for sequential algorithms (e.g. Kalman filter), the use of a high-stable clock is useful to constrain to clock model estimation, which should improve the orbit determination. These advance clocks are still under development, and have to be tested on-board. Additionally, this concept makes use of optical cavities which are used to generate optical links, so this technology is a good option for future missions carrying optical links as well.

The fourth and last concept proposes to use optical links for ranging and time-transfer. Optical links can be used between satellites, but also between a ground station and a satellite. In both cases, it is proposed to use a modulated optical link that allows the receiver to measure a distance. The link also include data that contains the positions and time of the emitter. This allows using them for orbit determination, but also to improve clock synchronization. The use of optical link imposes constraints on the design of the satellite, to locate the laser free of obstacles, to guarantee a good platform´s stability, and also platform´s pointing. The use of optical links from ground stations will be limited by the weather constraints.

Two concepts

From the concepts proposed above, ESA decided to explore in detail two concepts + scenarios: the first one is the use of optical inter-satellite links on a LEO constellation, for relative navigation. The second is the use of advance clocks on a HEO mission, for absolute navigation. This is described in detail in [AD.9].

For the first concept, two scenarios are explored: the first one is the use of Sentinel-3A & B satellites during its tandem phase, where both satellites are flying in the same orbit, separated by ~230 km. The second scenario is the use of satellites in the orbit used by Starlink, where satellites in the same plane are separated by more than 4000 km.

The performance analysis is done using simulated data. GNSS data is simulated using the characteristics of the Sentinel-3 and -6 real GNSS data to configure the simulation, in terms of noises (correlated and uncorrelated). The ISL are simulated including a Gaussian noise of 10 micrometres. A simplified prototype of a Kalman filter is used to assess the accuracy. This prototype includes a simplified propagation model that includes the most important perturbations (geopotential, third body, relativity, drag and solar radiation), but with limited accuracy. The filter uses the GNSS observables of two connected satellites, and the ISL. The filter estimates the absolute position/velocity and time of each satellite, but by using the ISL, the solution is constrained in terms of relative navigation.

Considering that the GAL HAS is not available yet, it is assumed that the navigation data has different noise levels (in terms of orbital error, they are 5, 10, 20 and 100 cm). The results show that while the absolute error mimic the accuracy of the GNSS navigation data, the relative error is significantly lower. The use of the ISL has a remarkable impact on the baseline direction (millimetres errors), but has none, or even could degrade the perpendicular directions. The accuracy in the other directions should be improved by establishing ISL with satellites in other orbital planes within the same constellation; this will increase the complexity in terms of connectivity plan and processing scheme (considering different satellites on the processing, at different times).

In terms of computational power, it has been found that the use of data at 1Hz, plus the processing the data of two or three satellite on each satellite, will be a hard constraint for current CPUs. This could be compensated by reducing the number of parameters estimated (e.g. not considering empirical accelerations), and by reducing the data rate (e.g. from 1 sec to 30 seconds), but these trade-offs require additional analysis.

For the second concept, it is explored the use of advance clocks on a mission in HEO. The reference orbit of Proba-3 has been used. In this case, a Kalman filter is used for navigation, including all the representative forces (geopotential, third body, relativity, drag and solar radiation). The orbit modelling of a HEO is a challenge compared with other orbital regimes because of the significant changes in the size of the perturbations along the orbit (e.g. drag is only important during perigee). The performance assessment showed that the time step used by the Kalman needs to be adapted along the orbit; while during the apogee, 60 seconds is enough, during the perigee, this has to be reduced to 1 second. Then, the sensitivity of the GNSS receiver is of paramount importance; in the analysis two threshold are used, 20 and 35 dB-Hz, showing that with 20 dB-Hz, the GPS+GAL tracking is good all over the orbit, while with 35 dB-Hz, it is impossible to obtain the necessary tracking except during the perigee.

Finally, the use of an advance clock has a remarkable improvement over the apogee, where errors are reduced by a factor of 4 using GAL HAS (assuming an error of 10 cm in the GNSS navigation data).

However, this analysis has made several assumptions which shall be confirmed in the future, in particular, whether it is possible to track good carrier-phases up to 20 dB-Hz.

In terms of computational power, the expected CPU consumption is below the limit of current technology.

4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be derived from this study:

1. This study has analysed the use of three new technologies: accelerometers, advance clocks and optical links, to enhance GNSS based on-board POD concepts.

2. The study has assumed that the baseline for any future on-board POD concept is the use of GNSS with corrections coming from Galileo/GNSS High Accuracy Services (GNSS HAS).

3. This study has assessed in detail two concepts proposed by ESA, being the first the use of GNSS and ISL for relative navigation in LEO, and being the second the use of GNSS and advance clocks for navigation in HEO.

4. On concept#1, the use of ISL improves the orbital accuracy significantly in the direction of the ISL, but no positive impact was found on the perpendicular directions to the ISL.

   The impact of establishing ISL contacts with satellites in other orbital planes within the same constellation, or even with external satellites (e.g. in GEO), should be investigated as a way to increase the accuracy in 3D through the use of ISL.

5. On concept#1, the strategy proposed distribute the resolution of the problem (relative navigation) across the whole constellation, due to the computational needs to solve the whole problem together.

   It is recommended to study how to solve the POD of the whole constellation globally, perhaps on ground, with a continuous downlink / uplink between the space and ground segment.

6. On both concepts, the accuracy of the navigation data used (i.e. the GNSS orbits and clocks) has a direct impact on the achievable orbital error, however, this could be related with a sub-optical fine-tuning, a limited orbit modelling accuracy, or that the final accuracy is mainly driven by the observation noise.

   It is recommended that future activities on this area enhance the orbit and measurement modelling and the fine-tuning of the filter, which has a significant impact on the final results..

7. On concepts#2, it has been showed that an optimal configuration for the apogee will not be optimal for the perigee. It has been assessed the impact of the data rate, with a significant improvement over the perigee with higher data rates, indicating that the dynamical model used over the perigee was sub-optimal and the filter requires higher data to overcome the discrepancies.

   It is recommended that future activities on this area develop dynamical models that depend on the argument of perigee to adapt it to the different perturbations along the orbit.

8. The use of Galileo High Accuracy Service (or any other GNSS HAS) has a significant impact compared to the use of the BRDC. However, it is still unclear the performance that these systems will have, in terms of orbit and clock accuracy, but also in term of availability.

   It is recommended to study in detail the impact of GAL/GNSS HAS as soon as a real stream of data is available.

9. It should be explored the benefits of Integer Ambiguity Resolution (IAR) with GAL/GNSS HAS. This topic has not been analysed in detail in the frame of this activity, beyond to describe the overall architecture. Additionally, it is unclear the benefits of this technology on high orbital regimes, on which the carrier phases could be too noisy to resolve the integer ambiguity, or even the float ambiguity.

10. It has been found that the computational resources needed for concept #1 is quite high, due to the high data rate used (1 Hz), and the high number of parameters to process on each. The requirements seems to be beyond what it is available currently.

    It is recommended to perform additional trade-off analysis to optimize the complexity of the concept vs. the computational needs with respect to the required accuracy.

11. For concept#2, it has been proved the benefits of using a service like GAL/GNSS HAS with respect to BRDC. However, a number of assumptions has been done due to the lack of reliable information on the characteristics of the GNSS signals on high altitudes. In particular, it is unclear the level of noise of the carrier phases tracked over the secondary lobes.

12. For concept #2, the performance of the clock has a direct impact on the performance over the apogee. The use of High Performance Clocks reduces the errors over the apogee by a factor of 4. Therefore, its usage on high-altitude missions is welcomed. However, it is also clear that optical clocks are still on the development phase, requiring yet to be tested on-board.

END OF DOCUMENT

