EXECUTIVE SUMMARY REPORT

GNSS SPACE SERVICE VOLUME EXTENSION (GN4SVEXT)

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1. INTRODUCTION

1.1. PURPOSE

This document identifies and assesses the design drivers for potential changes of the Ground segment operations derived primarily from the GNSS Space Service Volume Extension.

1.2. SCOPE

This document is a deliverable by GMV in the frame of the GNSS Space Service Volume Extension.

1.3. ACRONYMS

The following table defines the acronyms used throughout the document.

Table 1-1: Acronyms

Acronym	Definition	Acronym	Definition
AOCS	Attitude and Orbit Control System	ISL	Inter Satellite Link
BOC	Binary Offset Carrier	IT	Information Technology
CBA	Cost Benefit Analysis	LEO	Low Earth Orbit
CSAC	Chip Scale Atomic Clock	MEO	Medium Earth Orbit
DIL	Document Item List	MOM	Minutes of Meeting
DORIS	Doppler Orbytography and Radiopositioning Integrated by Satellite	NAPEOS	NAvigation Package for Earth Orbiting Satellites
ESA	European Space Agency	PCO	Phase Centre Offset
ESR	Executive Summary Report	PCV	Phase Centre Variations
GEO	Geostationary Orbit	POD	Precise Orbit Determination
GLONASS	GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (GLObal NAvigation SAtellite System)	QZSS	Quasi-Zenith Satellite System
GNSS	Global Navigation Satellite System	RD	Reference Document
GPS	Global Positioning System	SAR	Synthetic Aperture Radar
GPU	Graphics Processing Unit	SOW	Statement of Work
GTO	Geostationary Transfer Orbit	SSV	Space Service Volume
HAS	High Accuracy Service	SW	Software
HEO	High Eccentricity Orbit	TASS	TDRSS Augmentation Service for Satellites
ICG	International Committee on GNSS	TDRS	Tracking and Data Relay Satellite
IRNSS	Indian Regional Navigation Satellite System	TN	Technical Note

1.4. 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]	GNSS Space Service Volume Extension – SoW	DOPS-MGT-SOW-0025-OPS-GN	1.0	23/05/2016
[AD.2]	GNSS Space Service Volume Extension – GMV´s proposal	GMV 11650/16 V1/16	1.0	12/07/2016
[AD.3]	GNSS Space Service Volume Extension – MoM Negotiation	GMV-GNS4VEXT-MIN-0001	1.0	17/10/2016
[AD.4]	GNSS Space Service Volume Extension – MoM KoM	GMV-GN4SVEXT-MOM-0001	1.0	24/11/2016
[AD.5]	Review of existing GNSS POD concepts	GMV-GN4SVEXT-TN-0001	1.6	17/12/2018
[AD.6]	Impact analysis of GNSS SSV Extension on existing GNSS POD concepts	GMV-GN4SVEXT-TN-0002	1.2	17/12/2018
[AD.7]	Impact analysis of GNSS SSV Extension on existing GNSS POD system software design	GMV-GN4SVEXT-TN-0003	1.1	17/01/2019
[AD.8]	Impact analysis of GNSS SSV extension on existing operational concepts	GMV-GN4SVEXT-TN-0004	1.1	01/02/2019
[AD.9]	Identification of drivers for potential on-board technology changes	GMV-GN4SVEXT-TN-0005	1.2	18/06/2020
[AD.10]	Identification of drivers for potential new POD concepts	GMV-GN4SVEXT-TN-0006	1.2	26/06/2020
[AD.11]	Identification of design drivers for potential new operational concepts	GMV-GN4SVEXT-TN-0007	1.2	26/06/2020
[AD.12]	Identification of design drivers for the communication between the Ground and the Space segment	GMV-GN4SVEXT-TN-0008	1.2	26/06/2020
[AD.13]	Identification of design drivers for potential changes of the Ground segment operations	GMV-GN4SVEXT-TN-0009	1.2	26/06/2020

2. BACKGROUND OF THE ACTIVITY

A few years ago, there were only two Global Navigation Satellite Systems (**GNSS**) fully operational, the US GPS and the Russian GLONASS. Currently, in the year 2020, there are two additional global operational systems, the European GALILEO and the Chinese BEIDOU, and two regional GNSS systems, the Japanese QZSS and the Indian IRNSS. This means that there are over 120 GNSS satellites for potential users.

Each GNSS have at least three civil frequencies and more than two types of new GNSS signals, e.g. Binary Offset Carrier (BOC), Alternative BOC modulation (AltBOC). The complexity for the processing of the GNSS signals has increased substantially and the aspect of interoperability has gained importance for all GNSS users.

Ten years ago, any GNSS constellations were designed to provide adequate support to space users on or below Low Earth Orbits (LEO). However, in 2012 the US decided to extend the GPS support for space users from LEO only to space missions into Geostationary Transfer Orbit (GTO), Medium Earth Orbits (MEO), Geostationary Orbit (GEO) and High Eccentricity Orbits (HEOs). For this reason, the US introduced in their GPS III next-generation satellites, a set of requirements to support the so-called GNSS Space Service Volume (**SSV**) extension. The GNSS SSV refers to the volume of space, from low MEO to GEO, on which GNSS could provide service to future space users. It is specified requiring a minimum signal power and availability on high-altitude (specified at GEO). Since such a GNSS SSV extension is quite difficult to achieve for only one system standalone, the US started to lob within the activities of the International Committee on GNSS (ICG) all other GNSS service providers to take up also requirements to support the GNSS SSV extension in their next generation of satellites. In 2014 all GNSS service providers confirmed their commitment to support this initiative in general. This allows exploiting the interoperability among the different GNSS to maximize the satellites in view.

The GNSS SSV extension will change the entire approach for Precise Orbit Determination (**POD**) concepts related to LEO, MEO, GTO, GEO and HEO satellite missions. The number of GNSS observations that can be used for POD will increase significantly due to the increased number of satellites and signals. The GNSS SSV extension will also impact the evolution of the on-board GNSS receiver technology, ground segment designs, space operations or communications.

Summary of objectives

This project has two main objectives. The first objective was to **analyse the impact of the GNSS SSV** extension on the following aspects for space users in LEO, MEO, GEO, GTO and HEO:
- GNSS POD concepts
- GNSS POD SW designs
- Operational concepts
- On-board technology
- Ground operations

The second objective was to **identify and analyse key drivers** (understood as key technologies) that will have a significant impact on one of the following areas:
- On-board technology
- POD concepts
- Operational concepts
- Communication demands
- Ground segment operations

3. SUMMARY OF ACTIVITIES

The **first task** (reported in TN#1 [AD.5]) made a thorough review of all aspects related to the use of GNSS for space applications, including:

- A review of the GNSS systems (GNSS constellations, signals and frequencies).
- A description of the GNSS SSV extension in terms of requirements to the GNSS signals to provide support in high orbital regimes.
- A description of GNSS interoperability, which is key for multi-GNSS processing.
- A review of the main aspects of the POD concepts. The POD concepts are subdivided into:
  - Observation types: e.g. raw, linear combinations and differences.
  - Navigation types: absolute and relative.
  - Modelling types: dynamic, kinematic and reduce dynamic
  - Parameter estimation methods: batch vs. sequential
  - Processing types: real-time vs. post-processing
  - POD approach: network vs. standalone
  - Location: on-board vs. on-ground
- A review of POD algorithms, e.g. clock modelling, integer ambiguity resolution, dynamical models, etc.
- A review of SSV implementation aspects
- A review of current POD SW packages, e.g. NAPEOS and BERNESE.
- A review of the POD applications, which includes navigation (absolute and relative), geodesy, altimetry, SAR/InSAR, and radio-occultation.

The first task provides the necessary background for the **second task**, which was to analyse the impact of GNSS SSV. Considering the different aspects of the GNSS SSV (e.g. constellations, signals, reference systems, etc.), a matrix approach was used on which in one side are the impactors and in the other the impacted elements. The impactors considered are the followings:

- GNSS constellations: understood as the increased amount of GNSS satellites in view.
- GNSS signals and modulations: all GNSS constellations transmit several signals.
- GNSS frequencies: most GNSS constellations transmit in up to three different frequencies.
- GNSS clocks and HW biases: to address the relationship between HW biases and the realization of GNSS system clocks, and how the user synchronize to it. In this case, interoperability is very important to clarify how a common GNSS clock can be realized.
- Emitter antenna: to address the properties of the antennas in terms of gain, power and biases.
- Time and reference systems: to address the different systems used by each GNSS constellations, and the alternatives for accurate users.
- GNSS receiver and receiver antenna: to address the characteristics of each receiver (e.g. channels, biases) and the characterization of the antenna (PCO/PCV)
- Orbital regime: to consider that there will be users in all orbital regimes from LEO up to HEO.
- GNSS user clock: to consider the impact of the properties of the user clock, in particular on clock modelling.
- Information technology: to consider the impact of the advances on IT, including artificial intelligence, machine learning, big data, GPU, etc.
- Interfaces: to have a global overview of GNSS interfaces, including space to space, and space to ground.
- Security: to consider aspects as spoofing, jamming, and cybersecurity.

The impacted elements are subdivided into three areas, which map to the three technical notes that are prepared in the frame of the second task. They are:

- TN#2 [AD.6] analyses the impact on GNSS POD concepts, which are decomposed as described above (observations, navigation, etc.). The analysis is focussed on the theory, rather than on the implementation aspects.

- TN#3 [AD.7] analyses the impact on GNSS POD SW design, which are decomposed into:
  - SW modules
  - Interfaces

  - Dynamic behaviour

  The analysis identifies the areas that need to be adapted to consider the GNSS SSV, and users in all orbital regimes.

- TN#4 [AD.8] analyses the impact on three domains:
  - Operational concepts for space missions
  - On-board technology, in particular the GNSS receiver, oscillator and AOCS
  - Ground segment operations

The **last task** was to identify and assess key drivers, understood as key technologies, which will have a significant impact on space users using GNSS. GNSS SSV extension will allow implementing significant changes in the way future space missions are constructed and operated. This will enable the development of new technologies, and simultaneously, new technologies can improve the capabilities of GNSS.

The first step was to perform a high-level Cost-Benefit Analysis (CBA), on a list of potential drivers, which initially consisted of more than 20 elements. The CBA was done on each POD layer, which are:
- On-board technology, in particular the GNSS receiver, oscillator and AOCS.
- POD concepts, as described above.
- Operational concepts.
- Communications between the ground and space segment and between space satellites.
- Ground segment operations.

The CBA scores each potential driver, on each of these POD layers. The impacts consider the following criteria:
- <u>Capabilities</u>: It provides new capabilities not available currently, or whether it limits existing capabilities.
- <u>Performance</u>: in terms of accuracy, availability and reliability.
- <u>Operations</u>: It allows new operational concepts to carry-out functions not previously feasible. It reduces the overall cost of operations or reduces the complexity of operations. Alternatively, whether it requires costly or complex operations.
- <u>Robustness</u>: It allows to overcome one or more perturbations affecting the nominal operations. Alternatively, whether the driver has low robustness or it impacts negatively the robustness of the mission.
- <u>Development</u>: in terms of design, implementation and validation of HW and SW elements. This is linked to transition cost.

Each of these criteria has a different weight in the final score; capabilities and performance are considered the most important criteria followed by operations and robustness, and finally development.

A final score is derived per potential driver, taking into account the average over the POD layers. The list of drivers with a higher score is the following:

- The development of artificial intelligence algorithms for GNSS
- The availability of public services providing GNSS corrections for space users
  - Galileo high accuracy service (HAS)
  - TDRS augmentation service for satellites (TASS)
- The exploitation of interoperability on GNSS
- The development of autonomous navigation subsystems based on GNSS
- The popularization of chip-scale atomic clock (CSAC) in future on-board receivers
- The requirement to achieve cm level accuracy on-board in LEO or equivalent accuracies in higher orbital regimes
- The development of moon/mars relays satellites or beacons to extend the GNSS coverage
- The development of technology based on quantum effects (interferometers for ranging, inertial sensors, security and computing)
- The development of optical ISL and optical clocks
  - Optical ISL for ranging, time-transfer and communications
  - Optical clocks for space use (time-transfer)
- The development of high-sensitivity tracking systems

The second step was to analyse the impact of each of these key drivers on the five POD layers:

- On-board technology, reported in TN#5 [AD.9]. These key drivers will require changes on the on-board technology, and simultaneously, they will allow new capabilities on-board.

- New GNSS POD concepts, reported in TN#6 [AD.10]. These key drivers will impact the GNSS POD concepts and how it is implemented on SW.

- New operational concepts, reported in TN#7 [AD.11]. These key drivers will enable new operational concepts not available currently.

- Communications needs between the ground and space segment reported in TN#8 [AD.12]. These key drivers will impact communications, either reducing or increasing them.

- Ground segment operations reported in TN#9 [AD.13]. These key drivers, through the new operational concepts, will impact the assets and operations done on the ground segment.

It is interesting to note the wide range of technologies that have been considered in this project. The level of maturity of them is very different, having some ready in the following years (e.g. Galileo HA Service), while other will require significant developments to show its full potential (e.g. artificial intelligence or quantum computing).
In any case, this project has made the first evaluation of all of them, identifying how they could impact on the satellite design, POD and space operations, paving the way to future studies on those technologies that have more potential.

4. RECOMMENDATIONS

The study analysed a large number of technologies related to GNSS, POD and navigation. Among others, the main recommendation for further developments are:

- To develop multi-GNSS receivers for space, increasing significantly the number of channels and tracking all civil signals. This is a necessary step to fully exploit all the benefits on science and operations of multi-GNSS.
- To develop a common GNSS system time, that can be realized in real-time and in post-processing, to allow consistent use of interoperable multi-GNSS, for coarse and high-accurate users.
- To develop high-sensitivity GNSS tracking receivers to allow extending its use to high orbital regimes. This should be coupled with the previous point (multi-GNSS) to increase significantly its capabilities.
- To develop new mechanisms to disseminate high-accuracy multi-GNSS corrections using MEO or GEO relays. This is a necessary step to allow new on-board POD concepts and to improve the reliability of navigation systems.
- To develop new POD concepts fusing GNSS with other observables, in particular, optical inter-satellite links and accelerometers, or DORIS for altimetry missions.
- To develop advance clock systems allowing clock modelling. This has benefits on science, but also in operations.
- To develop robust autonomous navigation systems based on GNSS. Multi-GNSS and autonomous integrity mechanisms should enhance robustness.
- To investigate potential uses of artificial intelligence on GNSS and navigation.

END OF DOCUMENT