EXECUTIVE SUMMARY

LIFELINE

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1.0	29/11/2021	9	Initial version of the Document delivered for FR milestone.

1. EXECUTIVE SUMMARY

1.1. INTRODUCTION

LIFELINE is an ESA project kicked-off in 4Q 2020 devoted to perform a feasibility study of a Relativistic Positioning System. The consortium is led by GMV with Aalta Lab as subcontractor.

All GNSS in operation at present are based on Newtonian physics and rely on global reference frames fixed to Earth. Relativistic effects are treated as deviations that need to be corrected. A practical RPS would consist, for example, in a constellation of satellites, each one broadcasting not only its General Relativity coordinates (proper times or other observables) at emission but also the coordinates that it receives from the other satellites. RPS establishes inherently a local reference frame based only on the dynamics of the satellites and, as a consequence, it is completely independent of a terrestrial frame.

Several theoretical concepts have been proposed in previous activities for the use of Relativistic PNT System (RPS) and the required relativistic reference frames.

The objective of LIFELINE is to identify the benefits of (RPS) and study the feasibility of exploiting those concepts into a practical implementation of a PNT system. In particular, such feasibility should bring RPS theoretical concepts, into a practical high-level system architecture together with the identification of required supporting critical technologies for its implementation (e.g. on-board atomic clocks, inter-satellite links).

In the project:

- A state-of-the-art review on previous activities on Relativistic PNT systems has been conducted, the Mission Requirements for the LIFELINE RPS have been proposed, theoretical concepts and their practical exploitation have been explored and potential Use Cases have been identified,
- Trade-offs between different System Concepts and Theoretical ideas have been performed in order to propose an Architecture for LIFELINE RPS, the supporting technologies have been assessed and a methodology for the assessment of the proposed architecture based on simulations has been proposed.
- Simulations conducted and associated analyses have allowed to fine-tune the architecture and identify the benefits of RPS and expected performances. Differences and complementarities with classical GNSS have been identified, a Proof-Of-Concept has been proposed and the suitability of the RPS concept for the identified Use Cases has been assessed.

1.2. STATE-OF-THE-ART, MISSION REQUIREMENTS, THEORETICAL CONCEPTS AND PRACTICA EXPLOITATION

In LIFELINE DL1, a state-of-the-art review on RPS is provided, Mission Requirements for RPS are defined, theoretical concepts are explored and the practical exploitation of theoretical ideas is discussed.

The classical concept of positioning system for GNSS would work ideally if all satellites and the receiver were at rest in an inertial reference frame. But at the level of precision needed by a GNSS, one has to consider curvature and relativistic inertial effects of space-time. There are two very different ways of including relativity in a positioning system:

- Keep the Newtonian conception of absolute time and space, and add a number of post-Newtonian corrections depending on the desired accuracy. The two main corrections come from gravitational frequency shift between the clocks - due to the local position invariance principle - and from the Doppler shift of the second order - due to relative motion of satellites and users.
- Use a relativistic positioning system. This is a complete change of paradigm, as the constellation of satellites is described in a general relativistic framework. This new scheme for positioning potentially allows the definition of a very stable and accurate primary reference system.

Bartolomé Coll proposed in 2003 the project "Système de Positionnement Relativiste" (SYPOR), i.e. Relativistic Positioning System, an alternative to the scheme of usual positioning systems. The idea is to give to the constellation of satellites the possibility to constitute by itself a primary and autonomous positioning system, without any a priori realization of a terrestrial reference frame. This new positioning system leads to numerous advantages, among which we can cite:

- a better understanding of the principles of positioning systems;
- the new coordinates defined are measurable directly (they are user independent). They constitute a physical coordinate system, which is not the case of the other coordinate system. These open new possibilities in experimental physics and astronomy;
- it can be used for extra-terrestrial navigation with the use of pulsars as clocks;
- it is a primary reference frame which is not tied to the Earth: it is independent of the Earth dynamics and continental drifts;
- the relativistic effects are already included in the definition of the positioning system, so there is no need to synchronize the clocks a priori.

The relativistic positioning system is defined with the introduction of emission coordinates. They have been reintroduced recently by several articles. They have different names in the literature: "null coordinates", "emission coordinates".

The main characteristics about the design of RPS are:

- immediate: a user knows its proper coordinates without delay;
- gravity-free: they exist in any generic spacetime ;
- generic: they do not necessitate the prior knowledge of the gravitational field ;
- auto-locating: the user knows its emission coordinates as well as the coordinates of every satellites in the emission coordinate system;
- autonomous: additional set of information which allows any user to determine its position in any reference frame of interest.

In LIFELINE we have focused the RPS design on Autonomous RPS since they are the best RPS subclass.

Concerning the Mission Requirements proposed for LIFELINE RPS, it is to be highlighted the following. The RPS PNT system shall provide a Global Positioning, Navigation and Timing service to ground and space users, with no regression with respect to current GNSS, providing additional benefits for specific Use Cases, improved performances and considering users requiring PNT users in terrestrial reference frames.

For the practical exploitation it has been identified the need of Inter-Satellite Links in order satellites could exchange their proper times, improved on-board clocks, the possibility to perform on-board computations for orbit and clock determination and technologies for processing additional information.

The following specific Use Cases and a-priori benefits of RPS have been identified:

- Scientific applications: As RPS concepts basically rely on Relativity, the development of RPS will be an ideal test of the Theory of Relativity. The development of RPS would allow to perform accurate measurements of the space-time curvature around the Earth and could be an interesting test of Fundamental Physics theories.
- Geophysics: Different Geophysics applications requiring a high degree of accuracy in the positioning currently make use of GNSS-based techniques such as improved Earthquake modelling or Ocean Dynamics. Taking into account the specific high accuracy needs of Geophysics applications, the potential improvement of satellite positions which could provide RPS concept makes Geophysics Sector as one of the more promising Use Cases for RPS concept.
- Metrology: By connecting space and ground clocks in a worldwide network RPS could allow to distribute universal time scales with improved long term stability and accuracy.
- PNT Space Service: RPS could be suitable for Navigation in Space. In the previous years, particular interest has been put in Space Navigation based in pulsars. Different potential Use Cases have been identified such as landing of spacecraft, space mining, rover guidance or navigation in deep space. The autonomy, universality and independence properties of RPS are the features which could make RPS concept suitable for Space Navigation.

1.3. TRADE-OFFS, ARCHITECTURE, SUPPORTING TECHNOLOGIES AND SIMULATIONS PLAN

In LIFELINE DL2 an Architecture for the Relativistic Positioning System is proposed together with a description of the needed supporting technologies. A two-layers constellation is proposed, the Chief layer implementing the RPS concepts and a Deputy layer similar to current Galileo constellation.

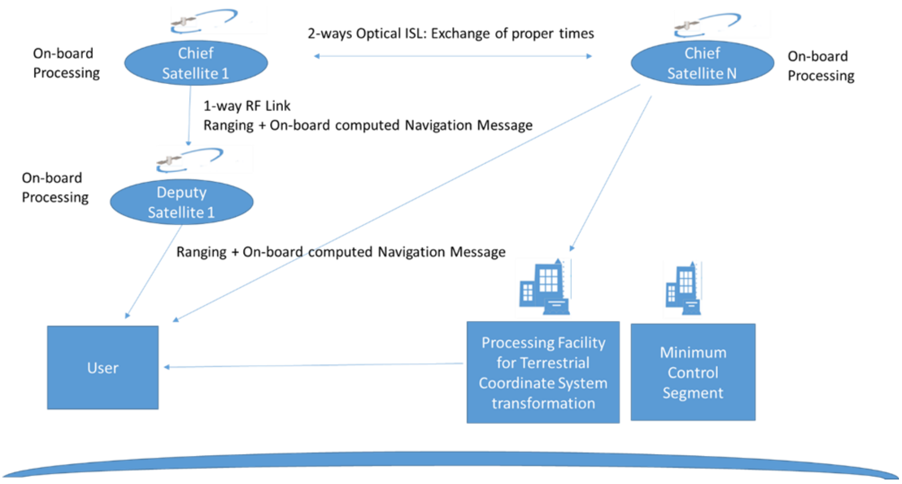
Discussions and trade-offs between different theoretical concepts, design options (such as on-board vs on-ground processing) and Inter-Satellite Links were conducted. In LIFELINE we focus on Autonomous and Standard RPS. This is, LIFELINE RPS is an auto-locating system that process additional information (dynamical and observational data) and then, it is usable in the terrestrial frame. In DL2 the Autonomous RPS, Emission Coordinates and quasi-minkowskian coordinates concepts are described, as well as how to relate QMC with usual reference frames and introduces the asynchronous auto-location concept and Relative Orbit Determination.

Optical ISL is a key fundamental ingredient of LIFELINE RPS Architecture for the exchange of proper times between satellites of the Chief constellation allowing **time transfer** at the **picosecond** level. Assuming technological feasibility in the future, we also propose **on-board processing** for the Chief Constellation satellites for reducing the ground segment and increasing the autonomy of the system.

An assessment of the supporting technologies needed for the LIFELINE RPS design, including on-board clocks and technologies for processing additional information has been also performed. In particular, for the Chief constellation it is proposed to use the best clocks available in order to provide the best accuracy possible: cold atomic clocks and H-maser for short term stability. In addition, other on-board technologies proposed are:

- Star Trackers to determine the orientation of the Chief satellites orbital plane with respect to distant stars in order chief satellites can give the link to the ICRF.
- Laser Retro Reflector to improve the model of the satellite orbits, in particular for non-gravitational effects.
- VLBI beacons to allow to determine the absolute orientation of the satellite constellation in a non-rotating inertial frame.

LIFELINE RPS Architecture is depicted in the next figure.



The Space Segment is composed of:

- First Layer, also called **<u>Chief Constellation</u>**, composed of satellites in **IGSO orbits**:
  - Which exchanges proper times by means of **two-way Optical Inter Satellite Links**,
  - The visibility conditions for the RPS concept to work is that **each chief satellite shall have the visibility of at least <u>one</u> another chief satellite at any time**, with the asynchronous auto-location concept.
- Second Layer, also called **Deputy Constellation**, composed of satellites in **MEO orbits**:

   - It is proposed that the MEO constellation will be as similar as possible to **current Galileo constellation** to maximize **backward compatibility with current GNSS** systems.
   - The links between Chief constellation and Deputy constellations will be the usual **1-way RF links**.

Simulations to test LIFELINE RPS Architecture are proposed with the main goal to:

- estimate the accuracy of the coordinates of the chief constellation satellites determined by the exchange of the emission coordinates, and
- estimate the accuracy of the positioning solution of a ground user.

PECS SW is used as a starting point for the simulations with some modifications identified.

1.4. SIMULATION RESULTS, BENEFITS, SUITABILITY FOR USE CASES AND PROOF-OF-CONCEPT

Simulations have been conducted to assess the Architecture of RPS. In particular, the goal is to assess the potential accuracy improvement provided by RPS. To assess the system architecture and potential benefits, the accuracy of the Quasi-Minkowskian Coordinates (QMC), calculated by the system, was determined and used as a measure of its feasibility/quality.

For the tests, we used existing RPS software, which can:

- simulate the satellite orbits in a perturbed space-time,
- calculate the Emission Coordinates (EC) of the satellites and of the ground user,
- and based on the satellite ECs, retrieve the satellite relative orbits.

The proposed RPS system consists of 3 segments: a chief constellation, a deputy constellation and a ground user. The main conclusions from the simulations are provided hereafter:

- **Chief constellation**: the main goal is to determine whether it is possible to retrieve the relative orbits between two chief satellites to a high accuracy merely by exchanging their proper times. The final outcome of the minimization depends on the mutual orientations of the satellites' orbits: the more different the orbits, the more likely it is that we can determine their relative orientations. Additionally, satellites, which are on the same orbits, should not be paired in the orbit determination process. For satellites belonging to different orbital planes the differences between the simulated and the retrieved QMCs are below 1m.
- **Deputy constellation**: the goal is to test whether it is possible to retrieve the orbits of the deputy satellites. There are two approaches to determination of the deputy orbits:
   - Use the same method as for the chief satellites: choose one chief satellite, "pair" it with a deputy satellite and use the minimization to retrieve the relative orbit of the deputy with respect to the chief. The results show that it is always possible to determine the orbit of the deputy satellite. A very good accuracy in the orbit determination is obtained, the differences between the simulated and the retrieved QMCs are around **1.5 cm.** Regardless of the choice of the chief satellite, the final accuracy of the retrieved orbit of a deputy satellite remains the same. Note, however, that in order to use this approach for the deputy constellation, also the deputy satellites need to have as accurate clocks as the chief satellites.
   - Use a positioning algorithm: choose 4 chief satellites with known orbits and use quadrilateration to determine the QMCs of the deputy. The accuracy of the retrieved QMCs is between 1 m and 100 m, but most often around 10 m, which is a consequence of the selected quadrilateration algorithm. With a different algorithm, the accuracy of the retrieved QMCs could be much better.
- **Ground user**: the accuracy achievable is around **1m**.

The simulations conducted for assessing the proposed Architecture haven't point to significant modifications of the proposed RPS Architecture but some indications for the detailed design of RPS

Architecture have been derived. Our analysis has pointed out that the **paired Chief satellites must have orbits sensibly different**, for instance must sit in **two different orbital planes**.

In addition, the actual **configuration depends** also on the **way in which the orbit of the deputy constellation is determined**:

- If the orbit is determined through **quadrilateration** each deputy constellation must see 4 chief satellite at all time,
- while using the "**minimization approach**", only needs to see one chief satellite. The price to pay is having **precise cold/optical atomic clocks also in the deputy constellation**.

High-level **System Requirements** for the RPS concept proposed in LIFELINE are identified in LIFELINE DL3:

- Two Services are requested: a Relativistic Service and a Classical Service backward compatible with current GNSS,
- Chief constellation is defined based on satellites in IGSO/GEO orbits and MEO constellation is defined equivalent to current Galileo constellation with visibility constraints: each Chief satellite shall have at least one Chief satellite in view at any time, each MEO satellite shall have at least 4 Chief satellites in view at any time,
- Optical ISL communications is requested for Chief satellites with time transfer performances at the picosecond level,
- On-board processing is requested, which could allow to simplify the Ground Segment,
- Improved on-board clocks are requested for Chief satellites: PFS and H-maser in order they can realize Time Scale in space,
- Technologies for processing additional information are requested: Star Trackers, Laser Retroreflector and VLBI Beacons,

An analysis on the **differences and complementarities** of LIFELINE RPS with respect to current GNSS has been conducted. Taking into account that:

- the Deputy constellation proposed for LIFELINE RPS Architecture is equivalent to current Galileo constellation,
- A Legacy mode is defined for Legacy users,

This implies that the proposed LIFELINE RPS can be viewed as an extension of current GNSS, being backward compatible with current systems while providing a purely Relativistic mode for specific RPS users.

Future activities have been identified in LIFELINE DL3 in order to mature the RPS Concept, in particular:

- Consolidation of RPS Architecture and Low Level Design, including Chief Constellation optimization and RPS Algorithmics,
- Development of End-To-End Demonstrator,
- Execution of End-To-End Experimentation,
- Cost Benefit Analysis,
- Detailed Definition, Preparation and Execution of Proof-Of-Concept.

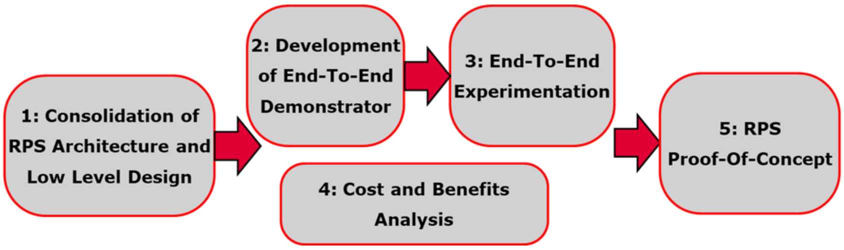
For the **Proof-Of-Concept** it is proposed to define a PoC Plan based on launching a subset of satellites of the Chief constellation equipped with supporting technologies to test and demonstrate relevant RPS Functions:

- Optical ISL to test exchange of proper times and relative orbit determination functions,
- On-board Processing SW and HW functions for testing orbit and clocks on-board determination,

- PFS and H-Maser clocks, to demonstrate the clock performance in space and the realization of Time Scale in space,
- Technologies for processing additional information to test the functions associated to Star Trackers, Laser Retroreflector and VLBI Beacons,
- User Equipment Prototype with Relativistic Algorithms implemented to test RPS function at User Level.

The investment on the PoC could be made profitable by using the IGSO satellites for a Regional European improvement of current Galileo constellation.

In order to further progress on the RPS Concept, it is recommended to launch the activities depicted in the following figure.



1.5. CONCLUSIONS

Current GNSS are based on classical physics treating relativistic effects as deviations. In this work we address a different approach for treating relativistic effects based on Relativistic Positioning Systems (RPS) which would naturally incorporate the Theory of Relativity. Theoretical ideas on RPS can be found in the literature, while in this work we mainly focus on practical implementation aspects.

Specific Use Cases for RPS concepts have been identified such as Geophysics, Metrology, Scientific Applications and Space Exploration. Mission Requirements target for the definition of the RPS concept have been identified and Theoretical Concepts have been explored.

An Architecture for the RPS has been proposed, composed of a two-layer constellation. The first layer with satellites in IGSO/GEO orbits equipped with Optical ISL, high performance clocks and other technologies for processing additional data, exchange their proper times and constitutes by itself a primary reference frame. The second layer would be equivalent to current Galileo constellation to maintain backward compatibility.

Simulations have been conducted to test the performances achievable and potential benefits for the RPS concept have been identified: improvement in the satellites orbits determination and the autonomy property are the most relevant general benefits, on top of specific added value for the Use Cases previously mentioned.

System Requirements, differences and complementarities with current GNSS and future activities towards an RPS Proof Of Concept have been identified.

Future work still remain before being able to assess the implementation of RPS concepts. A lower level architectural design, the optimization of the Chief constellation in terms of number of satellites and orbital parameters, additional simulations, the execution of a solid Proof-Of-Concept and Cost and Benefits Analyses are future activities that should be conducted to further explore the feasibility of Relativistic Positioning Systems.

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