# EXECUTIVE SUMMARY REPORT

## POSITRINO

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# 1. EXECUTIVE SUMMARY

## 1.1. INTRODUCTION

POSITRINO is an ESA NAVISP-I project kicked-off in 1Q 2019 devoted to study the possibility of using neutrinos for Position, Navigation and Time applications. The consortium is led by GMV-UK with University of Liverpool as subcontractor. Given the innovation required to deliver the project, an external advisory board formed by European and non-European delegates with expertise in the relevant fields is being set up.

Neutrinos are among the most abundant particles in the universe, nearly massless, travel at speeds near the speed of light and are electrically neutral. Neutrinos can be generated through man-made sources like nuclear reactors and particle accelerators or by natural sources like the sun and other celestial bodies.

Neutrinos only interact via the weak force and gravity. Since gravitational interaction is extremely weak and the weak force has a very short range, neutrinos can travel long distances unimpeded through matter, reaching places inaccessible to GNSS signals.

Different activities have been undertaken in the past by different research organizations, including NASA and Universities, with the goal of using neutrinos for communication or PNT applications.

The **main objective of this project is to provide an early design of a Neutrino PNT system and analyse its feasibility for certain applications** for which there are no other PNT technologies available, or if there are, they are too costly or provide poor performances.

In the project a state-of-the-art review on neutrino physics and previous work on the potential use of neutrinos for communication and positioning has been performed. In addition, the potential applications for a Neutrino PNT system and their associated requirements has been performed.

A preliminary list with potential applications investigated in the project covers **submarine navigation** and subsurface positioning.

## 1.2. POSITRINO ARCHITECURE

Different options for the design of a Neutrino PNT system have been investigated in POSITRINO. In particular, different neutrino sources, detectors or PNT algorithms have been trade-off in order to select the most suitable baseline design.

The **Baseline design** for the Neutrino PNT system and **operational concept** is based on:

- **Neutrino sources**: accelerators based on **Pion decay at rest process** producing an **isotropic flux** of high energy neutrinos.
- **User equipment** including:
    - **Neutrino detector miniaturized** based on **coherent neutrino nucleus scattering process** with an **enhanced interaction cross-section** while allowing the **portability** of the user equipment.
    - HW and SW for neutrino detection and PNT computation.
    - Additional sensors such as Inertial Measurement Unit (IMU).
- **Neutrino PNT Control Center** with different functions: service provision, maintenance, databases management, etc.
    - Position of the neutrino sources in database available to the user before operations.
    - Database with several design parameters of the Neutrino PNT system related with the Ranging Windows and relevant for the PNT Algorithm will also be available.

- Synchronization of the system and user equipment before operations based on **atomic clocks at User Equipment Level**. The system (Neutrino Generators) would be synchronized using GNSS.

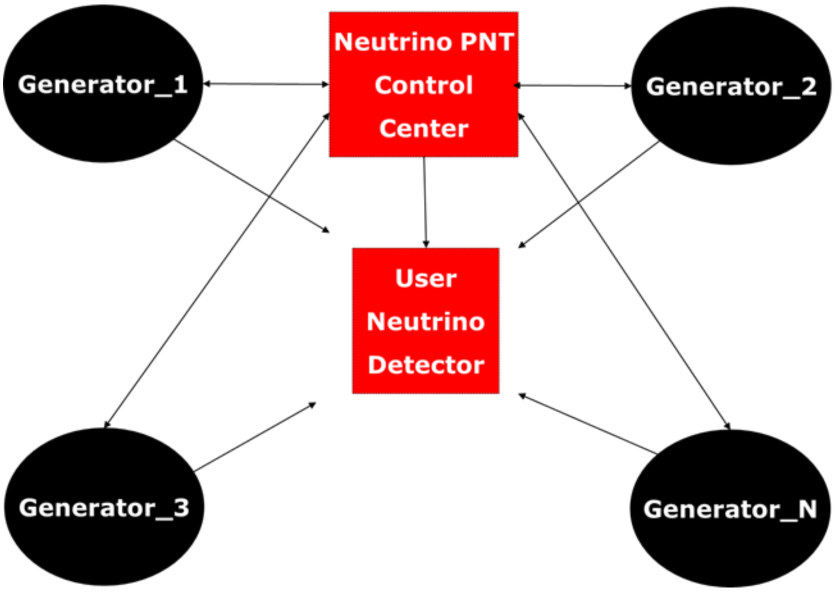


**Figure 1-1: Neutrino PBT High-Level Physical Architecture**

We **do not consider codification of information in the neutrino beam** since basically, the **transmission data rate is extremely low** even if the source emits the neutrinos in collimated beams, which has a severe impact in the potential service area of the Neutrino PNT system. Then, **no information on the time of emission is encoded in the neutrino beam**.

Instead, we propose a PNT Algorithm based on the concept of Ranging Windows, this is:

- Each Neutrino source would fire only during a certain time interval while the others are shut down in order to allow **source discrimination**.
- During the fire interval of each source, the source would fire in **pulses**, with the **length of each pulse linked to the target accuracy**.
- The time between pulses is defined in order to be able to determine from which pulse a detected neutrino come.

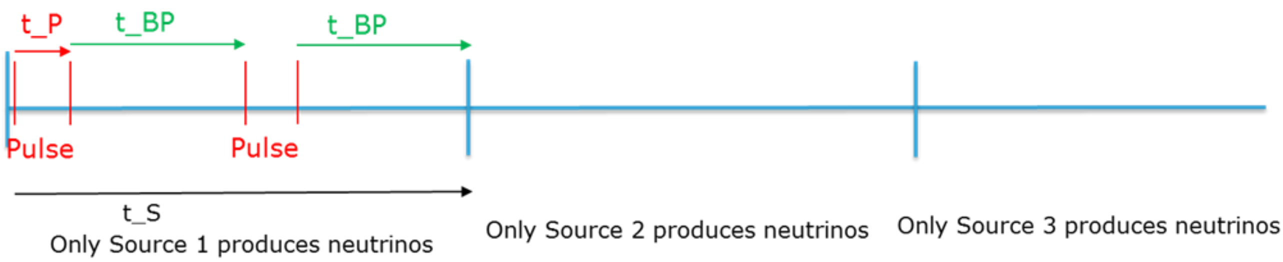


**Figure 1-2: Neutrino emission pulses for Ranging Window concept**

It is assumed that the Neutrino PNT User Equipment will be coupled with additional sensors depending on the specific application such as IMU. The Sequential Equivalent Trilateration algorithm for the hybridization has been defined in order to take into account the large time between neutrino measurements.

It is also relevant to mention that, concerning the **COHERENT Detectors**:

- We have provided an educated guess on the **Geometry** of the complete detector to be put in a submarine. We consider that it could be constituted by highly segmented crystals, each read out individually and packed closely together since this design might be beneficial for background mitigation and characterization. The weight of each individual crystal could be in the range 10-100kg, the same order of magnitude as for the COHERENT experiments. Nevertheless, any argument on the Neutrino PNT detector optimized geometry can't be well informed without detailed simulations and an analysis for the optimization of the signal/background ratio taking also into account the operational constraints of a submarine.
- We have also provided an educated guess on the **Power Consumption** of the Neutrino detector. The main power requirements for the COHERENT experiment are for the high voltage (800-1000V) in the PMT, power consumption ~ 50W and the detection of the light in the muon veto panels along with the associated electronics to read out the signal. These functions are typically powered by high voltage supplies that can be connected to a 240V single phase supply that doesn't exceed 10A, ~2.4kW maximum. The power consumption for 10000 crystals with MPPCs/SiPM technology would be of the order 5kW.

Concerning the **generated Neutrino flux**, a detailed survey of other neutrino generators with emphasis on the maximum fluxes available has been performed. The consortium has found examples of neutrino experiments which produce a higher neutrino flux than the reference values considered in POSITRINO experimentation. In particular, the European Spallation Source neutrino Super Beam ESSnuSB aims to use the linac at the European Spallation Source with upgrades to operate at a power of 5 MW and at an energy of 4 GeV producing 5.08× 〖10〗^23 ν/year, **one order of magnitude larger than DAEδDALUS in the same energy range.**

Concerning the competing **background** with the Neutrino PNT signal:

- The **background from the electron anti neutrinos that originate from the reactor are below the threshold of sensitivity of the detector, which allows for the detector to measure this process**.
- The **neutron background from the reactor is well controlled by the shielding** that was simulated in this document **and the CEvNS signal is above the background**.
- The neutron background induced by cosmic rays has a tail which populates the region of the CEvNs signal, some of this background can be reduced by muon tagging which would require further study.

## 1.3. EXPERIMENTATION RESULTS

An experimentation has been performed in POSITRINO for assessing the feasibility of the Neutrino PNT design, in particular.

- Simulations using GENIE SW in order to estimate the probability of detecting a signal neutrino arriving to the detector. These simulations have taken into account the Neutrino sources physics based on the process Pion decay at rest and the COHERENT detectors processes.
- Simulations using a PNT tool in order to estimate the PNT performances.

Different scenarios have tested with different configurations representative of different key design parameters of the Neutrino PNT System, namely:

- The neutrino flux generated in each neutrino source in terms of number of neutrinos generated per flavor and per unit time.
- The number of neutrino sources considered for the Neutrino PNT system.
- The distance between the sources and the detector, including simulation of the propagation of the flux which decreases as $1/r^2$ being r the distance source-detector.
- The neutrino detector material such as Xenon, Iodum, etc which is related with the interaction cross-section.
- Detector weight (and size), which on the one hand should be minimized due to operational constraints of the Neutrino PNT applications but on the other hand, the number of neutrinos detected increases with the detector weight.

- It is also possible to configure characteristics of the neutrino signal generated, this is, the neutrino peak length and the spacing between peaks, the fire windows for the different sources emission, according to the Neutrino PNT concept.
- IMU performances.

In the following figure as an example it is shown that the IMU-standalone solution (red line) is degraded until the accuracy requirement is not met while the hybrid IMU + Neutrinos PNT solution (blue lines) achieve a stationary state.

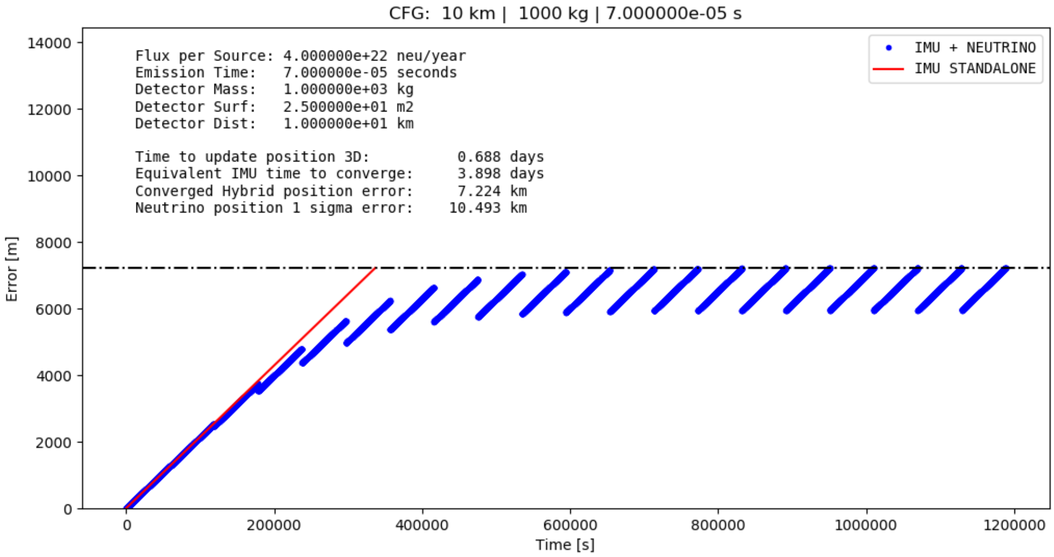


**Figure 1-3 Hybrid and IMU standalone solution for an accuracy requirement of 10 km and 1000 kg of detector mass**

The following conclusions can be extracted from the simulations conducted.

Focusing on Submarine application, the results of the PNT experimentation show that **the feasibility of the Neutrino PNT concept is in the limit with current technology**. In particular, for submarine applications, a Neutrino PNT system could provide an added value if a neutrino flux of 2-3 orders of magnitude larger than the one considered in the DAEDALUS design is achieved.

It is important to remark that:

- We've being conservative in the weight considered for the detector weight: 1000 and 10000kg respectively. Typical submarine weight are of the order 10.000 tones and this could make room to detector weights of the order 100-1000 tones. As the number of neutrinos detected grows linearly with the neutrino detector weight, this could improve the results by one or two orders of magnitude respectively.
- We've also being conservative with respect to the generated Neutrino flux, which is the key parameter to improve the performances of the Neutrino PNT system. We've considered the number provided in the design of DAEDALUS experiment but this does not mean that this number corresponds to the current cutting-edge technology in particle accelerators. In addition the generated neutrino flux could be improved in the future with new particle accelerators design within certain physical and operational limits.

Due to this arguments, we think that the Neutrino PNT concept could be in the limit of being feasible as per the outcomes of this first study on a novel Neutrino PNT concept. The results of the experimentation show the difficulties to build a Neutrino PNT system but are not that far to become this novel idea feasible.

We think that in the **short-medium term the Neutrino PNT system may be feasible** if:

- **Neutrino detector technology** based on the Coherent elastic neutrino-nucleus scattering is **improved** for **enhancing the neutrino detector rate**.
- And **considering cutting edge technology** for the **Neutrino sources**, possibly with a need of evolution in the next years in order to enhance the generated Neutrino flux.

## 1.4. ROADMAP TOWARDS PROOF-OF-CONCEPT DEFINITION

A Roadmap for future Neutrino PNT activities has been defined with the objective of performing an end-to-end Proof-Of-Concept for the Neutrino PNT Design.

The following activities have been identified as potential continuation of POSITRINO activities to further consolidate and extensively test the Neutrino PNT concept:

- Act-1: Develop **enhanced tools** and conduct **additional simulations** on the competing background and PNT algorithms and performances,
- Act-2: **Small Detector Prototype** development and associated **trials** to test High Energy Physics processes at the detector level,
- Act-3: Develop a complete prototype for **User Equipment**, including the hibridization with other sensors and the PNT processing,
- Act-4: Conduct **experimentation** with **User Equipment** near a neutrino generator to test the particle physics aspects, including the detection rate, discrimination of the backgrounds, etc.
- Act-5: **Define end-to-end Proof-Of-Concept**,

  The main objective would be to put the User Equipment prototype in a submarine, and to test the number of neutrinos detected per unit time and even to assess the PNT performances, at least with one source firing Neutrino following the Ranging Windows pattern.
- Act-6: **Execute end-to-end Proof-Of-Concept**, in order to prove all the critical elements of the Neutrino PNT system design.

The Neutrino PNT future activities Roadmap is depicted in the following figure.

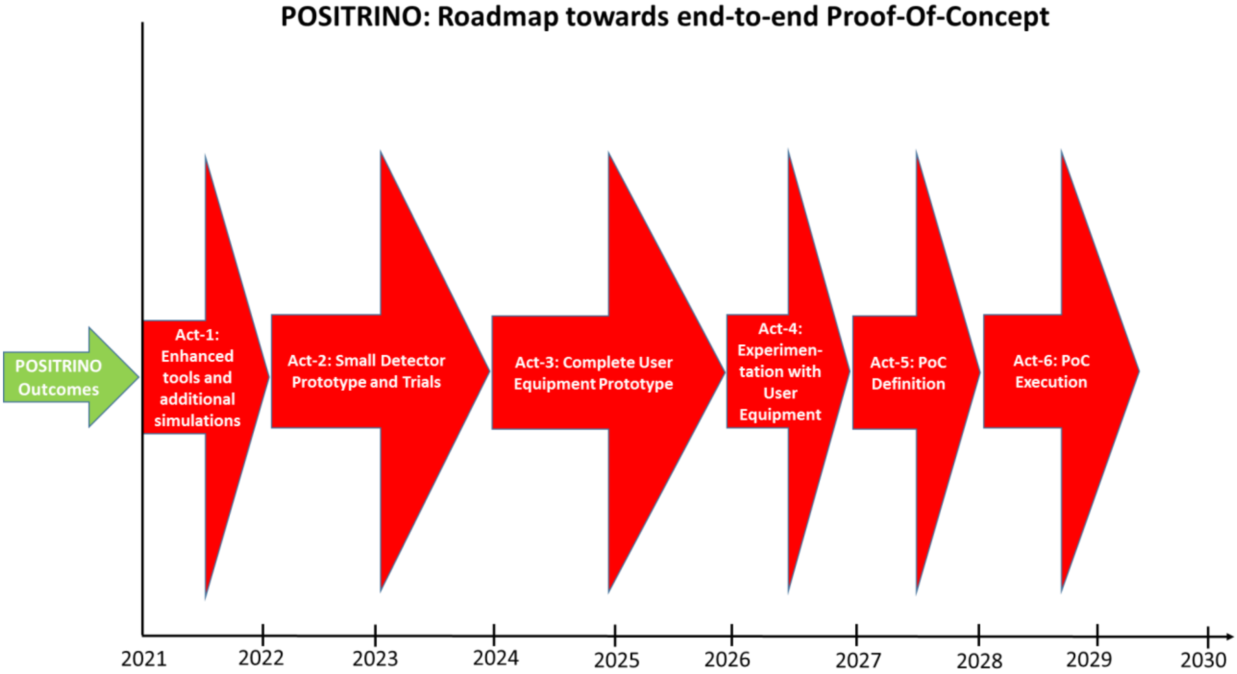


**Figure 1-4: Roadmap towards a Neutrino PNT PoC**

The different activities including the execution of the Proof-Of-Concept could take around **8-9 years**. It is important to remark that we've assumed sequential activities but some of them could take place in parallel or with overlaps so the total duration of the different activities could be shorter.

## 1.5. CONCLUSIONS

A design for a Neutrino PNT System has been defined in the project. Although a PNT system based on neutrino particles may be possible, important challenges like scale to operational size, neutrino detection and the discrimination of the signal vs background should not be ignored. Neutrinos are difficult to detect, and neutrino detectors are necessarily big and costly. Studying concepts for miniaturization of neutrino detectors which at the same time provide acceptable detection rates has been an important aspect in the project.

Simulations have been run to test the concepts proposed. The tests performed cover two user cases: submarine navigation and subsurface positioning. Although the none of the two application is feasible with current technology, our results show that although subsurface positioning is not a feasible option in the near future, submarine navigation could be realized with some important but reasonable progress in source and neutrino detector technology.

The execution of the future activities described in section 1.4, in particular, the end-to-end PoC would fully demonstrate the feasibility of the Neutrino PNT concept and would extensively test the performances and the benefits provided by such idea. At this stage, when the PoC executed, the **TRL** associated to the Neutrino PNT concept could be around **7**, this is, the demonstration of a prototype of the system in an operational environment.

Then, still a number of complex activities with a huge investment and effort associated would be needed for deploying a Neutrino PNT System ensuring a widely adoption at least for the identified Use Cases in POSITRINO project. Let us remark that the development of a Neutrino PNT System would imply a comparable effort and investment, in the same order of magnitude (or being optimistic, 1 order of magnitude below) as a system like Galileo.

From a very high-level point of view, the following activities would be needed for the deployment of an operational Neutrino PNT System after the concept of Neutrino PNT is demonstrated through the PoC:

- Detailed Market analysis to further identify and characterize Use Cases for the Neutrino PNT System, including a SWOT analysis and comparison with other PNT technology competitors,
- Detailed Cost Benefit Analysis (CBA) on the development of the Neutrino PNT System for go / no-go decision,
- System development activities for the development of the Neutrino PNT System, including Neutrino Sources, Neutrino PNT Control Center and User Segment:
    - System Specification,
    - System Design,
    - System Development,
    - System Validation and Verification,
    - Standardisation and certification of the Neutrino PNT User Equipment,
    - Qualification of the System,
    - Development of the Concept Of Operations (CONOPS),
    - Maintenance,
    - Promotion activities.

It is **recommended that ESA evaluates the possibility to launch the recommended first activity on Enhanced tools and Additional Simulations** to further progress on the maturation of the Neutrino PNT Concept.

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