MUSE4PNT

EXECUTIVE SUMMARY

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CHANGE RECORDS

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1. INTRODUCTION

1.1. SCOPE AND PURPOSE

This document provides a very brief overview of the work completed and the results obtained during the MUSE4PNT (NAVISP25) project.

1.2. REFERENCE DOCUMENTS

Internal code / DRL	Reference	Issue	Title

1.3. APPLICABLE DOCUMENTS

Internal code / DRL	Reference	Issue	Title

1.4. LIST OF FIGURES

1.5. LIST OF TABLES

1.6. DEFINITIONS AND ACRONYMS

Some acronyms might be missing.

ABS	Absolute
AOCS	Attitude and Orbit Control Systems
AOD	Autonomous Orbit Determination
ARTEMIS	Acceleration, Reconnection, Turbulence and Electrodynamics of the Moon's Interaction with the Sun
ATV	Automated Transfer Vehicles
BDS	Beidou Navigation Satellite System
CAPSTONE	Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment
CMOS	Complementary metal oxide semi-conductor
CNES	Centre National d'Etudes Spatiales
COLA	Collision Avoidance
CONFERS	Consortium for Execution of Rendezvous and Servicing Operations
CP	Chemical Propulsion
CPU	Central Processing Unit
CRL	Cutting Radial Line
DARPA	Defence Advanced Research Projects Agency
DLL	Delay-locked loop
DORIS	Doppler Orbitography by Radiopositioning Integrated on Satellite
DRO	Distant Retrograde Orbit
DSAC	Deep Space Atomic Clock
DSG	Deep Space Gateway
DSN	Deep Space Network
EGNOS	European Geostationary Navigation Overlay Service
ELO	Elliptical Lunar Orbit
EKF	Extended Kalman Filter
EOL	End of Life
EP	Electric Propulsion
EROSS	European Robotic Orbital Support Services
ESA	European Space Agency
ESPRIT	European System Providing Refuelling Infrastructure and Telecommunications
ESTRACK	European Space Tracking
FDMA	Frequency Division Multiple Access
FEEP	Field-Emission Electric Propulsion
FLO	Frozen Lunar Orbit
FSL	Free Space Losses
GAL	Galileo
GDOP	Geometric dilution of precision
GEO	Geostationary Earth Orbit
GIE	Gridded Ion Engine
GLONASS	Globalnaïa Navigatsionnaïa Spoutnikovaïa Sistéma

GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
GOES-R	Geostationary Operational Environmental Satellite R
GPS	Global Positioning System
GTDS	Goddard Trajectory Determination System
GTO	Geostationary Transfer Orbit
HEO	High Earth Orbit
HET	Hall Effect Thruster
HPCA	Hot Plasma Composition Analysers
HPF	High-Precision Filter
HPM	Hybrid Propellant Module
HTV	H-II Transfer Vehicle
HW	Hardware
I3DS	Integrated 3D Sensors
ILRS	International Laser Ranging Service
IMU	Inertial Measurement Unit
INS	Inertial Navigation Unit
IPS	Image Processing Software
ISR	Intelligence Surveillance and Reconnaissance
ISL	Inter-Satellite Link
ISS	International Space Station
JWST	James Webb Space Telescope
LCT	Laser Control Terminals
LEO	Low Earth Orbit
LiAISON	Linked, Autonomous, Interplanetary Satellite Orbit Navigation
LIDAR	Light Detection and Ranging
LL	Lunar Lissajous/Lagrange
LLO	Low Lunar Orbit
LNA	*Low Noise Amplifier*
LOD	Laser Obstacle Detector
LOI	Lunar Orbit Insertion
LOP-G	Lunar Orbital Platform-Gateway
LRO	Lunar Reconnaissance Orbiter
LTI	Lunar Transfer Injection
MEO	Medium Earth Orbit
MM	Macro Measurement
MMS	Magnetospheric Multiscale
MPD	Magneto Plasma Dynamic
MS2	Multi-Sensors Multi-Systems
MUSE4PNT	Multi-Sensors, Multi-System for space PNT applications
NASA	National Aeronautics and Space Administration
NAVISP	Navigation Innovation and Support Programme
NGBS	Next Generation Broadcast Service
NGRM	Next Generation Radiation Monitor
NRHO	Near Rectilinear Halo Orbit
NRO	Near Rectilinear Orbit

NICER	Neutron-star Interior Composition Explorer
NKF	Navigation Kalman Filter
OD	Orbit Determination
OOP	On-board Orbital Propagator
OOS	On-Orbit Servicing
OR	Orbit Raising
PCO	Prograde Circular Orbit
PDOP	Position Dilution of Precision
PLL	Phase Locked Loops
POD	Precise Orbit Determination
PPU	Power Processing Unit
PPT	Pulse Plasma Thrusters
QZSS	Quasi Zenith Satellite System
RAAN	Right Ascension of the Ascending Node
REL	Relative
RF	Radiofrequency
RPO	Rendezvous and Proximity Operations
RSGS	Robotic Servicing of Geosynchronous Satellites
RT	Real Time
SAR	Synthetic Aperture Radar
SC	Spacecraft
SEP	Solar Electric Propulsion
SEXTANT	Station Explorer for X-ray Timing and Navigation Technology
SK	Station Keeping
SLR	Satellite Laser Ranging
SOI	Sphere of Influence
SSV	Space Service Volume
SV	Space Vehicle
SWS	Solar Wind Sensor
TAS	Thales Alenia Space
TDOA	Time Difference of Arrival
TDOP	Time Dilution of Precision
TDRSS	Tracking and Data Relay Satellite System
TERPROM	Terrain Profile Matching
THEMIS	Time History of Events and Macroscale Interactions during Substorms
TM/TC	Telemetries and Telecommands
TOF	Time-Of-Flight
TRAN	Terrain-Relative Absolute Navigation
TRN	Terrain Reference Navigation
TRRN	Terrain-Relative Relative Navigation
TSV	Terrestrial Service Volume
TTC	Telemetry Tracking and Command
TTFF	Time To First Fix

2. BACKGROUND AND OBJECTIVES

The main objective of the Multi-sensor, Multi-system for Space Position, Navigation and Timing (MUSE4PNT) was to develop a multi-sensor, multi-system, PNT system to increase the on-board level of autonomy of spacecraft. In particular to increase the autonomy during orbit raising and docking of space vehicles employing electric or chemical propulsion systems.

In order to achieve this main objective a number of scenarios have been developed targeting a range of orbits and rendezvous locations. These are as follows:

- Geostationary Earth Orbit absolute positioning
- Rendezvous with a geostationary orbiting spacecraft
- Absolute positioning during two lunar transfer orbits (direct lunar injection and low energy transfer)
- Rendezvous in a Near-rectilinear halo orbit.

The considered scenarios provided sufficient range of environments and conditions to allow the results and conclusions to be extrapolated and applied to a greater range of orbits.
The activity helps significantly in the area of “Space Servicing” where close proximity approaches are required allowing inspection. In particular, visual inspections of a failed or failing satellite (to assess the tumbling) or docking to a failed satellite in order to service the subject or to push it to a graveyard orbit.
Position uncertainty during autonomous manoeuvres e.g. orbit raising/de-orbiting requires that the local knowledge during low thrust (i.e. with electric propulsion) is accurately determined.
Current orbit raising assumes semi-autonomous control assisted by GNSS, with long time integral to measure increasing altitude and trajectory of the satellite, by integrating other sensors it may be possible to improve positioning performance while lowering the time integral.
For autonomous control, and/or close manoeuvre of two spacecraft in relation to each other (i.e. rendezvous & docking), the relative positive and movement needs to be understood and controlled in a more timely fashion with tightly closed loop between measurements and estimates of thruster actuation. As such the current approaches require significant ground monitoring and control.
The use of hybrid GNSS unit that incorporates a low power Inertial Navigation System and potentially other sensor capabilities (e.g. millimetre wave RADAR/LIDAR, Stereo cameras, ..etc), provides a mechanism through which control can be fully or highly autonomous for close manoeuvre in combination with methodologies for modulating electric thrusters.
The understanding of the spacecraft epoch, position, orientation and velocity gradient with a capable hybrid GNSS Unit may provide further mission management opportunities to maximise propellant utilisation.

3. WORK PERFORMED & KEY RESULTS

This section outlines the key tasks performed in order to reach the stated objectives above.

3.1. TASK 1: REVIEW OF CURRENT STATE OF THE ART

The core purpose of this phase was to review and understand to the maximum extent the existing data pertinent to the project. This included a review of:

- The current navigation landscape highlighting the main requirements and how they are evolving with or impacted by the GNSS Space Service Volume extension.
- All the relevant orbits to be considered during the study, presenting them mainly in terms of volume and distance from Earth.
- The different transfers relevant to a spacecraft orbiting in the Earth-Moon system.
- The existing propulsion technologies and highlighting the state of the art in terms of electric propulsion.
- Existing sensors first as individual subsystem and then as navigation suites with existing MS2 concepts.
- Existing concepts for close-proximity flying and docking

3.2. TASK 2: DEVELOPMENT OF USE CASES AND SCENARIOS

Once the current state of the art was understood this phase of the project introduced and developed in detail key scenarios and use cases for single spacecraft or constellations missions where an MS2 system could result in improved performance. This selection was based on multiple factors: performance enhancement, cost reduction, key enablers, etc. In order to focus the activity the project considered the following specific missions:

- Orbit raising and station keeping of an electric geostationary satellite
- Hybrid constellation management
- Navigation to and around the Moon

In addition to the absolute positioning uses a similar activity was performed but considering use of MS2 for rendezvous missions. In particular:

- LEO and GEO in-orbit servicing
- Lunar rendezvous

Based on this research and considering scope of the current project the following missions were considered for architecture and EKF design:

- Autonomous navigation of an electric platform for geostationary in-orbit servicing – Figure 3-1.
- Autonomous navigation for Rendezvous with the Lunar Gateway (with two trajectories considered – Direct transfer and low-energy transfer) - Figure 3-2.

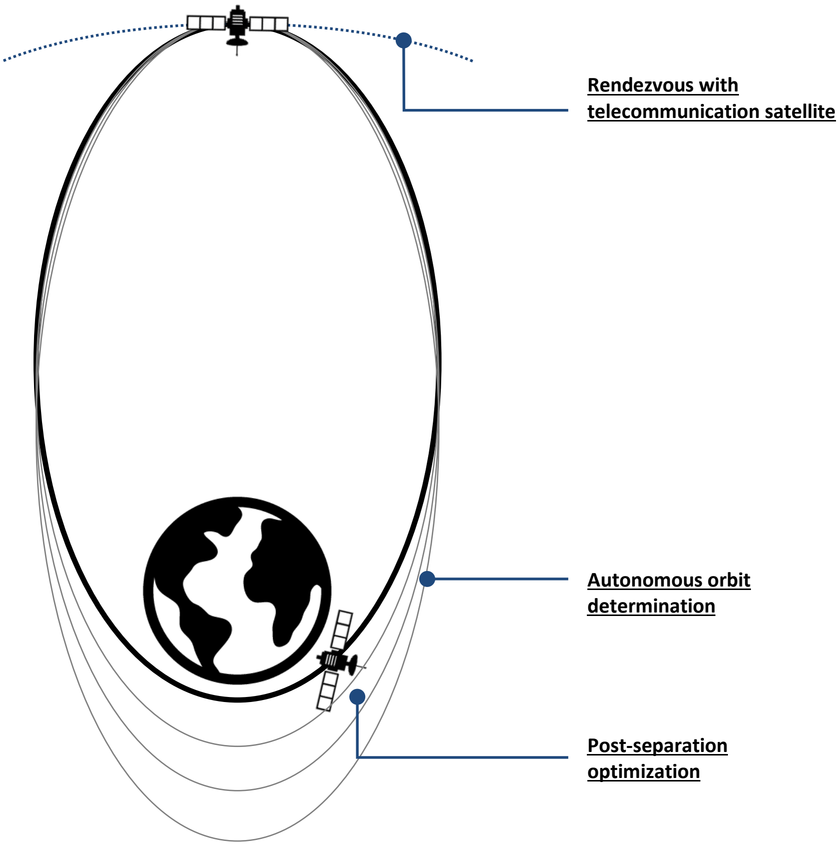

Figure 3-1: Electric platform for geostationary in-orbit servicing.

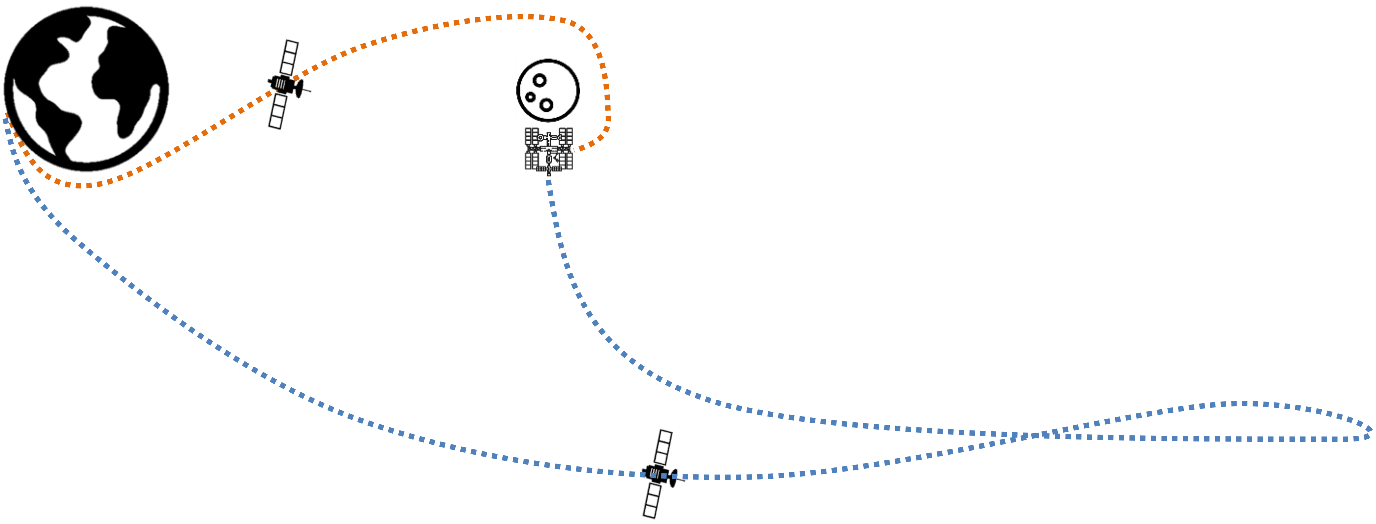

Figure 3-2: Autonomous navigation and rendezvous in cislunar orbit. In red, direct transfer. In blue, low-energy transfer.

The considered rendezvous trajectory is shown in Figure 3-3 and Table 3-1 for GEO and Figure 3-4 and Table 3-2 for the Lunar case.

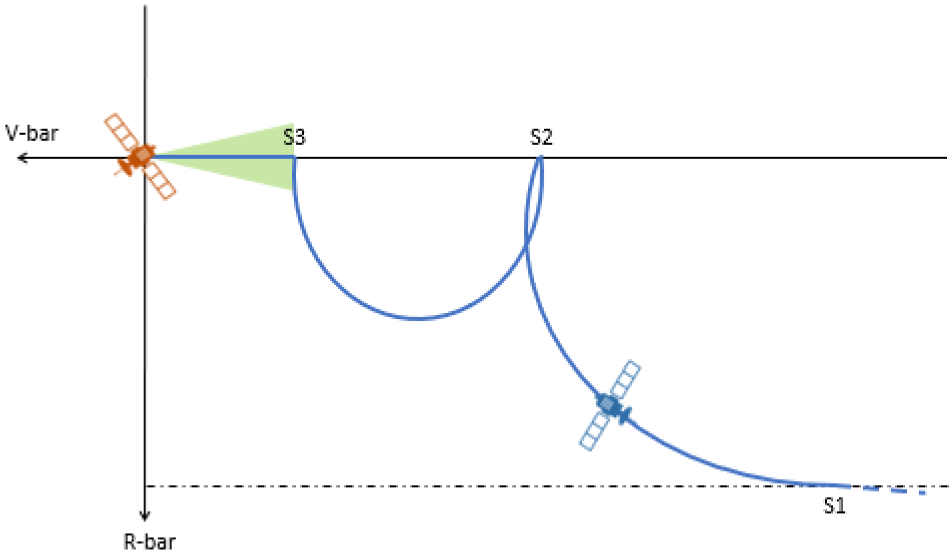

Figure 3-3: Rendezvous phases – GEO scenario.

Table 3-1 : Intermediate points for the reference RDV scenario in GEO (LOF reference frame).

Point	Distances [m] in LOF		
	X	Y	Z
S1	-50000	0	5000
S2	-2000	0	0
S3	-100	0	0

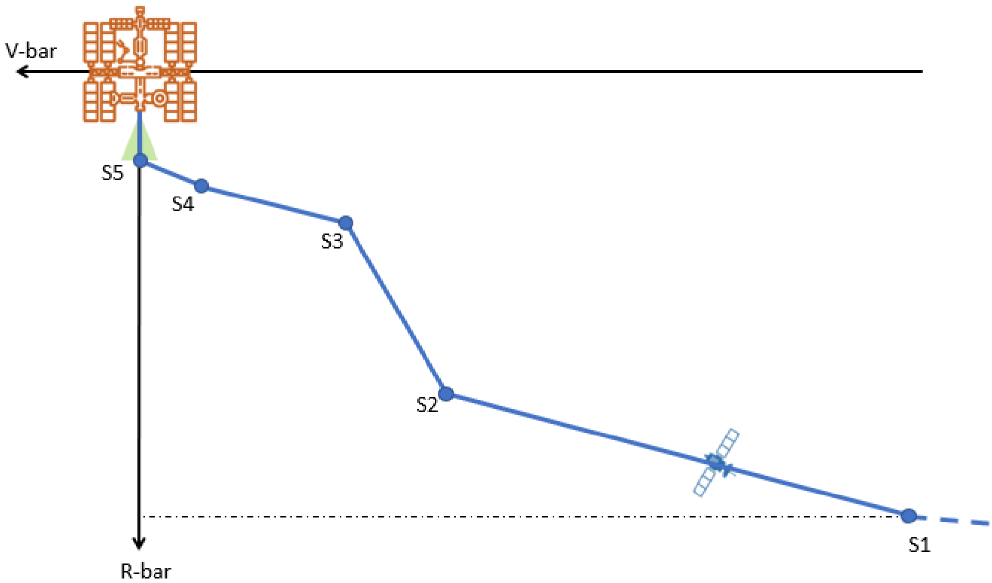

Figure 3-4 : Rendezvous phases – lunar scenario.

Table 3-2 : Intermediate points for the reference RDV scenario in Lunar orbit (Moon LVLH reference frame).

Manoeuvre		Point	Relative distances [m] In the Moon LVLH frame		
			V-bar	H-bar	R-bar
#1	Start	S_1	-145155.622	-15401.421	35122.367
	Stop	S_2	-8665.710	-1112.706	17439.251
#2	Start	S_2	-7624.678	-1045.924	17293.265
	Stop	S_3	-4285.115	-512.763	1458.462
#3	Start	S_3	-4267.268	-508.479	1373.040
	Stop	S_4	-436.323	-51.701	450.665
#4	Start	S_4	-346.572	-41.215	428.922
	Stop	S_5	0.643	0.071	199.568

3.3. TASK 3: ARCHITECTURE DESIGN AND SIMULATION

3.3.1. Architecture Trade-off

Based on the chosen scenarios, and positioning requirements derived for those scenarios, system and satellite architectures were elaborated together with an associated concept design. For each of the missions identified above a number of navigation architectures have been identified for the absolute and relative navigation portion of the mission. Technical trade-offs have been performed of the developed navigation architectures in order to identify the risks and benefits of each approach.

For absolute positioning the following key metrics were used to perform the trade-offs: accuracy (position and velocity); acceleration estimation accuracy; time to first fix; time estimate accuracy; coverage; accommodation (SWAP); complexity; cost; reliability and risk; on-ground operational complexity/management; infrastructure (ground and space); customer benefit; customer acceptability (system reliability and TRL). As certain parameters have a greater effect on the mission architecture than others a weighting is applied.

3.3.1.1. Autonomous navigation of an electric platform for geostationary in-orbit servicing

3.3.1.1.1. Absolute positioning

Five possible architectures were defined which would meet the previously defined requirements. A qualitative and quantitative trade-off was then conducted to select the optimum architecture for this study.

Based on the trade-off conducted, the optimum navigation architecture for the study was selected as an architecture which uses a GNSS, STR and INS (formed of accelerometer and gyroscope). This architecture allows the system a greater autonomy than traditional systems while also achieving high accuracies for position, velocity and acceleration and also the attitude of the SC. This architecture scored significantly better overall than the other architectures considered for both the in-orbit servicing mission and for absolute navigation in a Galileo orbit.

3.3.1.1.2. Relative Positioning

For relative positioning the navigation architecture is instead conditional to the ability of the target spacecraft to co-operate. In this study the following architectures and test cases were considered:

1. **Non-cooperative and prepared target** (a prepared target refers to a target which has been prepared, before launch, for rendezvous through the inclusion of concentric contrasting circles and/or a docking target that consists of a black and white patterned target background and a square stand-off alignment cross – these systems both improve the relative position error of visual camera navigation algorithms): the relative navigation system for this architecture will be only composed of VISCAM (NAC and WAC). This represents the most promising, autonomous and low cost architecture with which a rendezvous with a prepared target can be performed.

2. **Co-operative and prepared target** (the target provides its absolute positioning and attitude information directly to the chaser satellite and is prepared in the same way as above): the relative navigation system for this architecture will contain several VISCAM (NAC and WAC) and Inter Satellite Link (ISL) providing target GNSS data and rotation state.

3.3.2. Autonomous Navigation for Rendezvous with the Lunar Gateway

3.3.2.1. Absolute Positioning

For a mission towards the Moon, the architecture selected for missions in GEO (GNSS, INS, and STR) is taken as a baseline. This architecture is capable of achieving high performance navigation for a reasonable cost. Nevertheless one of the biggest challenges for missions to cis-lunar space is to be able to keep these levels of performance on the way.

Previous studies have demonstrated that GNSS navigation can be carried out to cis-lunar space. However, these studies showed some non-compliances to the defined requirements and the need to use four GNSS antennas demonstrated that additional sensors to complement the architecture should be considered in order to have a robust autonomous navigation system.

Before starting a detailed trade-off of navigation sensors the range of action of each sensor was considered. Based on this analysis RF and SLR ground stations are discounted for lunar navigation as they do not fit with the main objectives of the study to increase on-board autonomy. In addition SBAS receivers are discounted as it is unlikely that they are able to achieve accurate positioning above LEO or MEO altitudes. Following this first analysis a subsequent trade-off was performed aimed at high-lighting the complementary sensor most relevant for addition to the architecture defined for navigation inside the GEO volume. The conclusion from this trade-off is that the best three sensors are:

- Cameras to track celestial bodies
- Cameras to track lunar features
- Radio-frequency lunar beacons

Given the low-cost of camera technology and the ranges of action the use of the three technologies together is recommended. Later results from EKF simulations have also shown this to be the case.

As a radio-frequency lunar beacon network has not been studied in great detail to date a first iteration design based on using a terrestrial DORIS network on the moon has been proposed.

The navigation architectures taken forward for further study are shown in Table 3-3 and Table 3-4.

Table 3-3: Consolidated navigation architecture for GEO.

Sensors	ABS-N	REL-N (Non-Coop)	REL-N (Co-op)
GNSS receiver	X		
Accelerometer	X		
Star tracker	X		
Gyroscope	X		
Visible light cameras		X	X
Relative GNSS			X

Table 3-4: Navigation Architecture in Lunar space.

Sensors	ABS-N	REL-N (Non-Coop)	REL-N (Co-op)
GNSS receiver	X		
Accelerometer	X		
Star tracker	X		
Gyroscope	X		
Visible light cameras	X	X	X
Lunar Beacons	X		

Relative GNSS	X
ISL	X

For each of the architectures and missions identified above an extended kalman filter and associated simulator has been developed which has allowed the performance of each to be assessed. In both cases increasing the number of sensor inputs to the EKF has resulted in a significant improvement in the position knowledge error of the associated filters resulting in position estimations which meet the requirements.

For the absolute navigation filters, errors are driven by the double integration of accelerations in the INS and the distance from the GNSS constellation or moon. This results in a decrease in absolute estimator performance during the WSB trajectory when the spacecraft is a great distance from the Earth and Moon. This is largely driven by difficulties in estimating the GNSS clock error due to the small number of GNSS satellites visible at these ranges. While the addition of camera-based lunar ranging is able to improve this slightly, the high error in the camera position estimates at this time (again due to the large distance to the moon) is not sufficient to improve the position error enough to allow the EKF to more accurately approximate the GNSS clock error.

The first iteration of the lunar beacons has demonstrated the ability to design a system capable of providing accurate range-rate information to spacecraft in lunar orbit. Unfortunately, integrating this new sensor requires a multi-modal filter, able to only consider certain sensors at certain points in the trajectory. However, considering the accuracy in range-rate information provided by the beacon network it is likely that including these sensors in a sensor fusion system will greatly increase the accuracy of the solution in the portion of the transfer trajectory (or in lunar orbit) where the other sensors considered operate with reduced accuracy. Based on this initial design iteration, lunar beacons deserve further work in the future.

For relative navigation, as expected, co-operative rendezvous systems show higher performance than autonomous systems. For autonomous systems both in GEO and Lunar orbit the filters are not able to converge on an accurate solution at the S1 point. However, as the chaser spacecraft approaches the target the measurement accuracy improves. This implies that for future rendezvous missions the chaser spacecraft will need further sensor data (either from ground in the case of a target which is not able to be co-operative or from a co-operative target) in order to make the initial approach. This may be a key mission design driver in future missions targeting the removal of previously launched satellites, with impacts on operations costs. Past the S1 point the non-cooperative filters are able to converge to a sufficient accuracy measurement which may allow systems to operate autonomously beyond this initial point.

Both systems have demonstrated that the use of cameras has an impact on the accuracy of the position estimation. For a full system design it will be important to consider the requirements for the camera in each of the mission phases, both transit phases where the absolute position is important and rendezvous phases where the relative position is important. It would be most efficient from a system design perspective to minimise the number of cameras required. As the relative navigation case already requires both a wide angle camera and a narrow angle camera, the requirements for each should be studied to determine if one (or both) can also be used as the sensor input for the lunar range and bearing algorithm.

3.4. Task 4: Key-Tools Identification and Pre-developments

This task investigated the technological maturation needed to implement the MUSE4PNT architecture, both for absolute and relative navigation. Emphasis has been put on the key enabling technologies for the mission:

- Camera and sensor technology.
- IMU technologies.
- GNSS receiver and lunar beacons.
- Image processing and EKF algorithms.
- High-performance processing platforms for space.

The findings are positive for the implementation of the architecture. For imaging sensors and camera systems, there are ongoing projects that match the requirements for MUSE4PNT such as APELLA – CIS120 from Teledyne e2v. Also, the Mars rover *Perseverance* that landed in 2021 uses numerous CMOS sensors including several instances of the AMS CMV-20000 detector and two On Semi KAI-2020CM CCD sensors. These also match the requirements and show that high-performance sensors are available for space at TRL9.

High-performance IMU technologies are mature at TRL9, but it was investigated if the TAS-UK MEMS IMU could be used as a cost-efficient alternative. The specs of the IMU are positive, and shortcomings compared to non-MEMS IMU's could be mitigated by the multi-sensor approach of the navigation filter. Further simulations are needed to verify this qualitative assessment.

The lunar beacons are at the lowest TRL and will need a major research and engineering effort to be implemented. Given their potential to significantly support PNT solutions in the cislunar environment, a development plan to increase the TRL from TRL 2 to TRL 9 could be implemented in time for sustainable operations around the moon. Prior to this, a number of key fundamental decisions must be made on the ranging solution, receiver design, and inter-beacon synchronisation that will determine the critical functionalities of the system.

The imaging processing algorithms (used for the visual camera range and bearing information based on lunar images) such as RANSACK are well-established and have been shown to run with reasonable performance on both FPGA's and space-grade processors. The MEKF algorithm has been used in space since the 60's and is mature at TRL9. The main challenges are modelling, tuning and the numerical stability of the filter. The UDU factorization helps on the numerical stability and should be investigated further. This method is also well-established at TRL9 having been used in many space missions.

Analysis of the used algorithms shows that their processing requirements are modest and could be achieved with existing space-grade processing platforms such as the LEON4 / GR740 and RTG4 FPGA for accelerated image processing. However, there is a drive to develop a European space processing platform to reduce dependence on US technology that is subjected to export restrictions. The DAHLIA platform based on the NanoXplore NG-Ultra and ARM Cortex R52 is the most mature of these efforts, undergoing qualification for TRL7, but the De-RISC platform based on the open-source RISC V architecture is an interesting alternative.

3.5. TASK 5: MS2 REQUIREMENTS & ROADMAP

This phase developed a Preliminary High Level System Requirements. Based on the scenario and architectural design concept, a preliminary set of system high level requirements shall elaborated which could satisfy the target objective.

These requirements also identify the dependencies on other associated/supporting systems which may be relied upon in order to achieve the objective.

A development Roadmap for a future missions showing the major milestones and steps necessary in order to fully develop MS2 has also been developed (shown in Figure 3-5 and Figure 3-6).

This roadmap has also identified potential follow on activities towards NAVISP Element 2 and other ESA R&D funded studies.

An abstract has also been submitted to the Royal Institute of Navigation for presentation at Navigation 2021. (Title: Multi-Sensor Fusion for Space PNT).

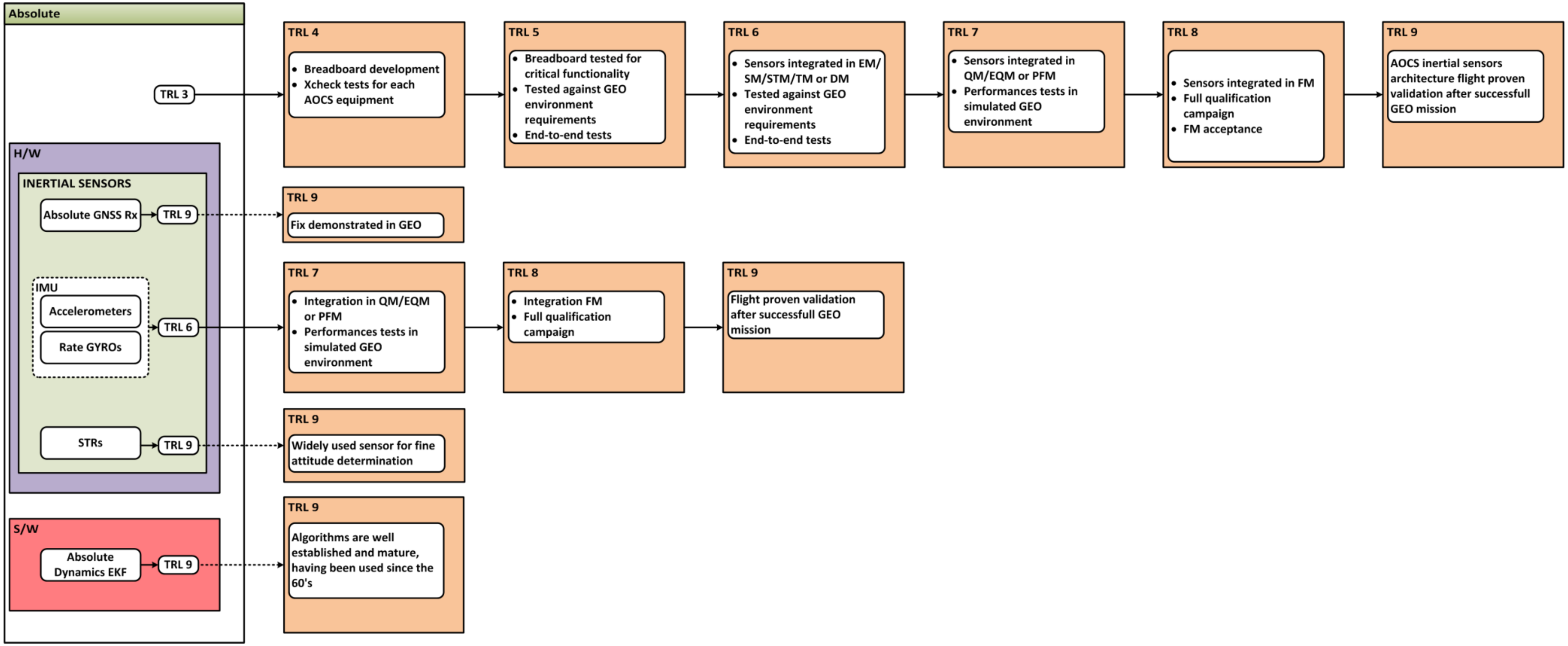

Figure 3-5: GEO mission absolute navigation architecture TRL roadmap

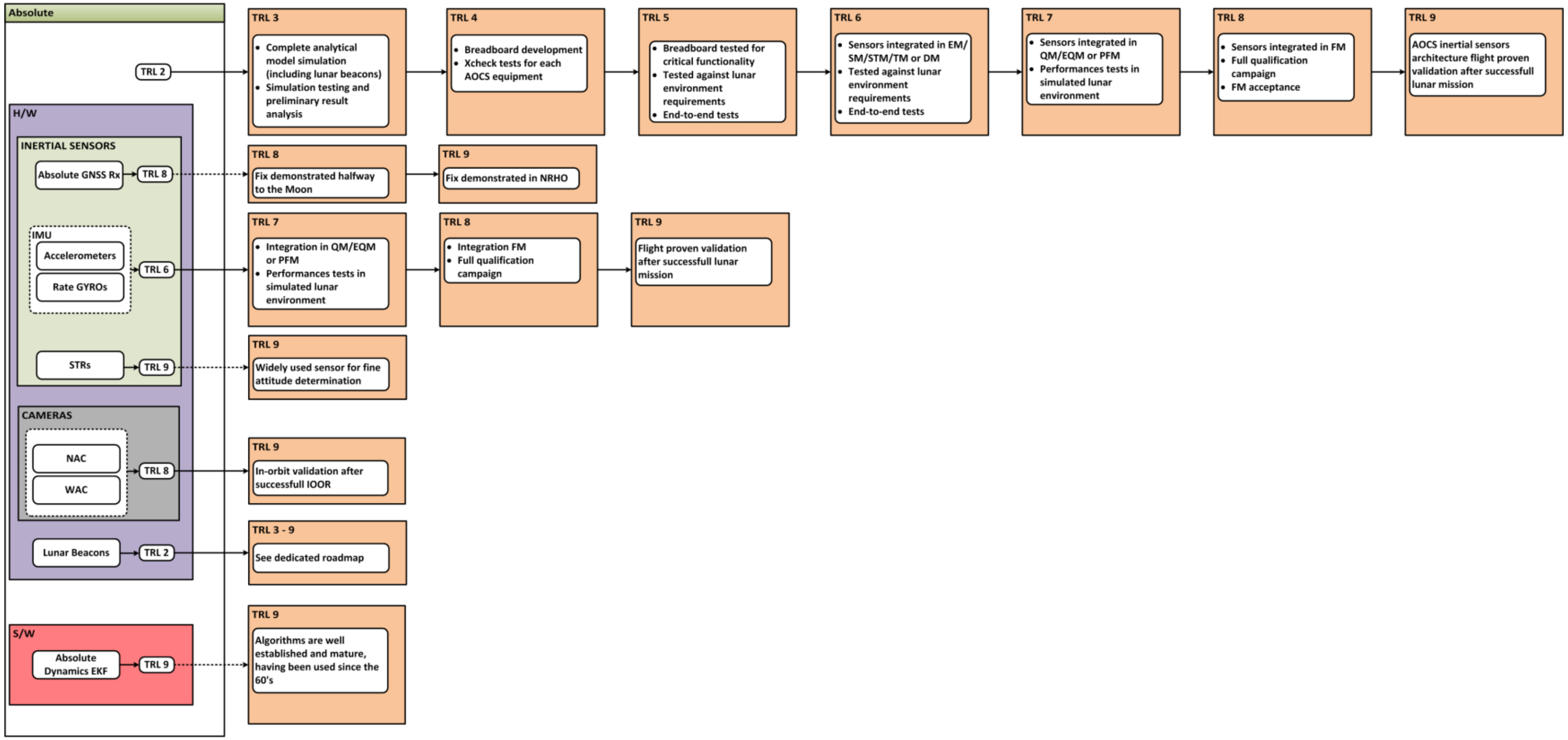

Figure 3-6: Lunar orbit mission absolute navigation architecture TRL roadmap

4. CONCLUSIONS

MUSE4PNT has demonstrated the increased performance achievable both for absolute and relative positioning through the use of sensor fusion. Based on the preliminary high level system requirements and a technology readiness roadmap for an hypothetical future GEO or Lunar mission, it would be a great opportunity to pursue the study and the development of multi-sensor fusion for space PNT through further ESA funded R&D activities (NAVISP or others): this will help to bring the navigation suite architecture selected during NAVISP25 to a higher TRL, and will also help to design and develop the breadboards required to validate the system design. The aim of the project would be to develop a sensor fusion suite targeted at a specific orbit (likely Earth orbit first) for (as a minimum) absolute navigation positioning (but also considering adding a relative navigation sensor fusion suite later) into a marketable product. The specific design of the final product will first need to be assessed in order to target the correct market. For example developing an all in one package for the growing in orbit servicing market may be of interest.

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