LRNS

Executive Summary Report

(D-12)

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CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
1.0	22/06/2023	First version	LRNS Project Team

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1. INTRODUCTION

1.1. SCOPE AND PURPOSE

1.2. APPLICABLE DOCUMENTS

Internal code / DRL	Reference	Issue	Title	Location of record
AD-01	Appendix 1 to ESA AO/1-10712/21/NL/CRS (ESA-TDE-TEC-SOW-021363)	1.0	Statement of Work Fundamental techniques, models and algorithms for a Lunar Radio Navigation system	
AD-02	https://pdsgeosciences.wustl.edu/dataserv/gravity_models.htmhttps://pdsgeosciences.wustl.edu/grail/grail-l-lgrs-5-rdrv1/grail_1001/shadr/		Moon gravity field	
AD-03	https://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn36.html		Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2015	
AD-04	https://www.iers.org/IERS/EN/Publications/TechnicalNotes/tn36.html		IERS Conventions (2010). Gérard Petit and Brian Luzum (eds.).(IERS Technical Note; 36)Frankfurt am Main: Verlag desBundesamts für Kartographie und Geodäsie, 2010. 179 pp., ISBN 3-89888-989-6	
AD-05	REC SFCG 32-2R2, July 2019		Communication Frequency allocations and sharing in the lunar region	
AD-06	SFCG RES 23-5		Protection of Future Radio Astronomy Observatories in the Shielded Zone of the Moon	
AD-07	ITU RA 479-5		Protection of frequencies for Radioastronomical measurements in the shielded zone of the Moon	
AD-08	ITU SA 609		Protection criteria for radio communication links for manned and unmanned near-Earth	
AD-09	ITU Art. 22.22 to 22.25		ITU Radio Regulations, Space Services	

Table 1-1: List of Applicable documents

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1.3. Reference Documents

Internal code / DRL	Reference	Title	Location of record
RD.01	TNO-STDTLR-0214-TASI-LRNS	LRNS Concept Document (D1)	
RD.02	TNO-STDTLR-0215-TASI-LRNS	LRNS Trade-Off Analysis (D2)	
RD.03		LRNS Concept Requirement Document (D3)	
RD.04	RPT-STDTLR-0118-TASI-LRNS 03/03/2023	LRNS Technology Report (D4)	
RD.05	RPT-STDTLR-0162-TASI-LRNS	LRNS Service Definition Document (D6)	

Table 1-2: List of Reference documents

1.4. Definitions and Acronyms

ADC	Analog to Digital Converter
APSK	Amplitude Phase Shift Keying
AOCS	Attitude Orbit Control System
AoD	Age of Data
ATM	Asynchronous Transfer Module
BBR	Bid Baseline Review
BEIDOU	Běidǒu Wèixīng Dǎoháng Xìtǒng
BOC	Binary Offset Carrier
BPSK	Binary Phase Shift Keying
CCR	Concept Consolidation Review
CCSDS	Consultative Committee for Space Data Systems
CD	Concept Document
CDMA	Code Division Multi Access
CPF	Central Processing facility
DAC	Digital to Analog Converter
DOP	Dilution of Precision
DOWR	Dual One Way Ranging
DSN	Deep Space Network
DSSS	Direct Sequence Spread Spectrum
DVB-S2	Digital Video Broadcasting Satellite Second Generation
E2E	End to End
ECSS	European Cooperation for Space Standardization
EDRS	European Data Relay Satellite (system)
EGNOS	European Geostationary Navigation Overlay Service
ESOC	European Space Operations Centre
FR	Final Review
G1G	Galileo First Generation
G2G	Galileo Second Generation
GDOP	Geometric Dilution of Precision
GEO	Geostationary Earth Orbit
GLONASS	Globalnaya Navigazionnaya Sputnikovaya Sistema
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GPS	Global Positioning System

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GRACE	Gravity Recovery and Climate Experiment
GRAIL	Gravity Recovery and Interior Laboratory
GST	Galileo System Time
GUI	Graphical User Interface
HAS	High Accuracy Service
HSF	Human Space Flight
IAU	International Astronomical Union
ICD	Interface Control Document
ICRF	International Celestial Reference Frame
IMU	Inertial measurement unit
IGS	International GNSS Service
IGST	International Galileo System Time
ILRS	International Laser Ranging Service
IMU	Inertial Measurement Unit
ISL	Inter-Satellites Links
ISS	International Space Station
i-SRR	Intermediate System Requirement Review
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
KBRR	Ka-Band Range Rate
KPI	Key Performance Indicator
LCNS	Lunar Communication and Navigation Services
LNSP	LunaNet Service Provider
LEE	LRNS Ephemeris Error
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LLR	Lunar Laser Ranging
LO	Lunar Orbit
LRNS	Lunar Radio Navigation Service
LRO	Laser Ranging Observatory
LS	Lunar Surface
MA	Multiple Access
MAI	Multiple Access Interference
ME	Mean Earth/polar axis
MEO	Medium Earth Orbit
MOC	Mission Operation Center
MORE	Mercury Orbiter Radio-Science Experiment
NASA	National Aeronautics and Space Administration
NSN	Near Space Network
OCXO	Oven Compensated Crystal Oscillator
OD	Orbit Determination
ODTS	Orbit Determination and Time Synchronization
OS	Open Service
PAPR	Peak to Average Power Ratio
PCR	Preliminary Concept Review
PDOP	Position Dilution of Precision
PDT	Payload Data Transmission
PN	Pseudo Noise
PNT	Position, Navigation and Time
PPS	Pulses per Second
PRN	Pseudo Random Noise
PRR	Preliminary Requirement review
PRS	Public Regulated Service
PSD	Power Spectral Density
PVT	Position, Velocity and Time
QPN	Quadrature Pseudo Noise (modulation)
QPSK	Quadrature Phase Shift Keying

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RAFS	Rubidium Atomic Frequency Standard
RF	Radio Frequency
RFI	Radio Frequency Interference
RINEX	Receiver Independent Exchange format
RMS	Root Mean Square
SA	Single Access
SAR	Search And Rescue (1)
SAR	State of the Art Consolidation Review (2)
S/C	Spacecraft
SDD	Service Definition Document
SDR	Software Defined Radio
SFCG	Space Frequency Coordination Group
SINEX	Solution (Software/technique) Independent Exchange
SISE	Signal in Space Error
SLR	Satellite Laser Ranging
SoW	Statement of Work
SNIR	Signal to Noise plus Interference Ratio
SNIP	Space Network Interoperability Panel
SQPN	Staggered Quadrature Pseudo Noise (modulation)
SRR	System Requirement Review
SS	System Simulator
SSC	Spectral Separation Coefficient
S/W	Software
SwaP	Size, Weight and Power Consumption
TAI	Temps Atomique International
TDRSS	Tracking and Data Relay Satellite System
TO	Trade Off
ToA	Time of Arrival
TR	Technology Roadmap
TRL	Technology Readiness Level
TT&C	Telemetry Tracking and Command
TTFF	Time To First Fix
TWSTFT	Two-Way Satellite Time and Frequency Transfer
UERE	User Equivalent Range Error
UM	User Manual
UQPKS	Unequal (power) Quadrature Phase Shift Keying
USNO	United States Naval Observatory
USCCS	User Spacecraft Clock Calibration System
UTC	Universal Time Coordinated
VLBI	Very Long Baseline Interferometry
WRC	Worldwide Radiocommunication Conference
WUL	Worst User Location

Table 1-3: List of Acronyms and Abbreviations

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1.5. DOCUMENT OUTLINE

The document is organized as follows

- Section 2 introduces the industrial consortium
- Section 3 provides an overview of the project and of driving requirements
- Section 4 presents the developed concept for Orbit Determination, Timing Synchronization, Reference Frames and Signals
- Section 5 focuses on peculiar aspects that are driving concept selection
- Section 6 provides the main conclusions

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2. INDUSTRIAL ORGANIZATION

Due to the grown interests on Lunar exploration and exploitation, several missions to the Moon has been planned for the coming years and a lot of initiatives (ARTEMIS, Cislunar, Lunanet, Moonlinght,….) are emerging in the world related to the Lunar navigation
In view of future Lunar Exploration Mission, ESA is supporting some initiatives aiming at defining reliable communication and navigation services.
In Q2 2021 ESA has selected a project called “Lunar Radio Navigation System (LRNS) with the main scope to define ODTS concepts, lunar reference frames and signal modulation techniques applicable to moon navigation services. The selected concepts will be assessed and validated through an ODTS simulator that will be developed as part of the project activities.

The consortium is led by Thales Alenia Space in Italy and composed by Telespazio Germany, Thales Alenia Space in France (supported by CNES), Telespazio Italy and Politecnico di Torino.

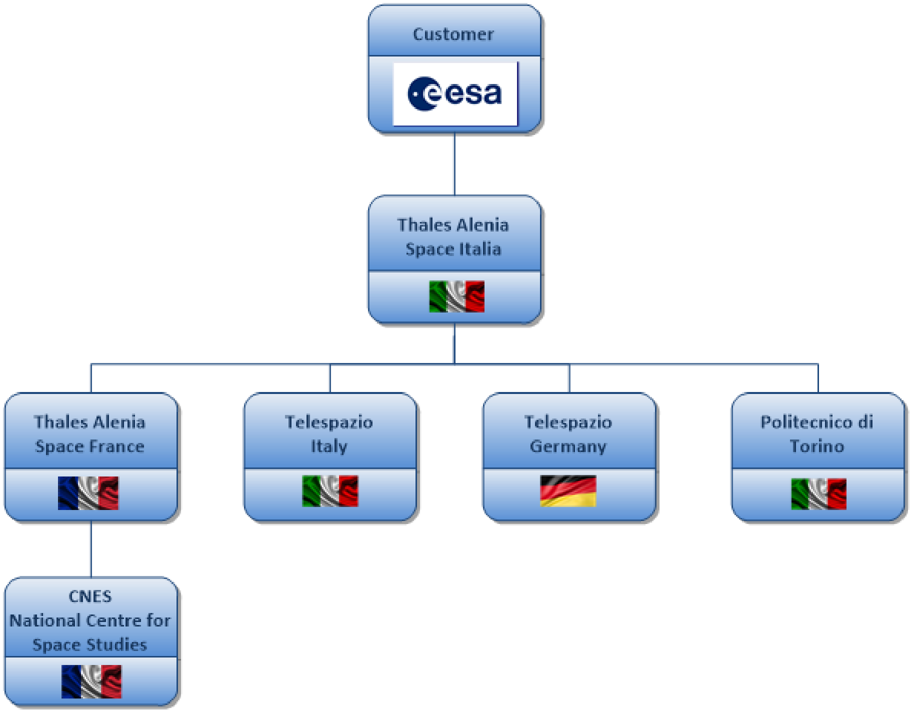

Figure 2-1 – Industrial Organization

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Roles and responsibilities of the industrial team are detailed here-below:

Thales Alenia Space	Thales Alenia Space Italia is the prime contractor of the study and is responsible for: • Timing Synchronization algorithms design; • Radio Frequency Signal modulation design; • E2E System Concept Validation.
Thales Alenia Space cnes CENTRE NATIONAL D'ETUDES SPATIALES	Thales Alenia Space France contributes to: ODTS Concepts Trade-off, Reference Frames Coordination and ODTS Concepts validation. National Centre for Space Studies (CNES) is responsible for Reference Frames algorithms design
TELESPAZIO a LEONARDO and THALES company	Telespazio Germany is Responsible for: • ODTS Concept Trade-off; • Orbit Determination Algorithm Design; • ODTS Simulator Design, Development and Integration.
	Telespazio Italy is Responsible for Radio Frequency Regulation and Standardization, Development Plan and Technology Roadmap
POLITECNICO DI TORINO	Politecnico di Torino contributes to Radio Frequency Signal Modulation and interference assessment.

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3. PROJECT OVERVIEW AND DRIVING REQUIREMENTS

Considering the growing number of missions that will reach the Moon in the coming years, the ESA Moonlight program has the main objective to design and develop a system/ infrastructure that can provide robust communication, navigation and time distribution services to different elements (orbiters, landing/ascending vehicles, rovers, etc.).

Among the initiatives related to the Lunar Navigation, the LRNS (Lunar Radio Navigation System) study, led by Thales Alenia Space Italy, has aimed at defining the main concepts for a dedicated Lunar Radio Navigation System:

- Orbit Determination and Timing Synchronisation algorithms (analyzing different approaches based on VLBI, ISL, GNSS Spaceborne Receiver, Satellite Laser Ranging, LRNS reference time definition and time transfer techniques
- Lunar reference frames (selenodetic and timing) and their translation to Earth Reference Frames;
- Signal modulation techniques for one-way and two-way services for precise LRNS.

The selected concepts have been assessed and validated through an ODTS simulator that has been developed as part of the project activities.

3.1. OBJECTIVES OF THE ACTIVITY

The objectives of this activity are:

- define orbit determination and time synchronisation (ODTS) algorithms for lunar radio navigation satellites;
- assess if the currently available lunar reference frames are suitable for precise radio frequency services and if not identify what is missing and propose a roadmap to cover the gap;
- assess applicable radio frequency regulations and assess if the currently in use GNSS signal modulations are suitable for lunar radio navigation, propose one or more modulation options compliant with applicable regulations and suitable to meet lunar radio navigation requirements, support ESA regarding aspects related with radio frequency spectrum regulations (e.g.: SFCG).
- Define a complete concept(s) covering ODTS, reference frame, time system, signal characteristics to be used in any potential lunar radio navigation system and concretely as input to a Phase B2 system study.
- Demonstrate the correctness of the proposed complete concept(s) (ODTS, reference frame, signal characteristics) making use of a ODTS simulator, to be developed as part of this activity.
- Define the development plan to reach high TRL for the defined concepts.

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3.2. Driving Requirements

The main requirements that have driven the project concern the definition of a threshold for the LRNS Ephemeris Error (LEE), defined as the instantaneous difference between the position and time of a LCNS satellite as broadcast by the LCNS navigation message and the true satellite position and time, expressed in a defined reference frame, and the age of data of the ODTS products. The requirements are briefly resumed in Table 3-1.

Requirement ID	Description
[REQ-1]	The LEE shall consider at least the following contributions: - LCNS satellites orbit error - LCNS satellite clock synchronisation error - LCNS selenodetic and timing reference frame induced errors - Relativistic effets
[REQ-2]	At least the following aspects shall be considered for the LRNS satellite segment: - Type of instruments required; - TRL level of the proposed instruments and applicability to lunar missions; - SWaP of each instrument; - - Instrument constrains such as pointing, peak power, etc.;
[REQ-3]	At least the following aspects shall be considered for the LRNS Earth ground segment: - Currently available ground infrastructure, realistic availability, operational constrains and operational cost; - New concepts shall be based on consolidated techniques/technologies in order to reach TRL8 by 2024-2025. (e.g.: a future missions is requiring this technology/technique and funding for the development has been identified)
[REQ-4]	At least the following orbit determination and time synchronisation techniques shall be considered: - GNSS spaceborne receiver for lunar applications - Ground based ranging - VLBI - Laser Ranging - Intersatellite link (ISL) among LCNS satellites and - potentially lunar surface assets - Precise RF time transfer - Precise optical time transfer
[REQ-5]	The RF modulation for the one-way service shall be derived from Earth GNSS modulations and the RF modulation for two-way service shall be derived from ground to space CCSDS modulations for two way ranging.
[REQ-6]	The ODTS simulator shall allow to configure the LRNS system characteristics such as: - LRNS satellite orbit. The ODTS simulator shall accept both Keplerian elements and time series of states (e.g.: CCSDS ephemeris file) - Location/capabilities of any lunar surface asset (if proposed)
[REQ-7]	The ODTS simulator shall implement reference frames and the transformations between them.
[REQ-8]	The ODTS simulator shall be used (potentially among other means) to demonstrate the concepts in section 4, implement models of the Earth, Satellite, Moon segments defined as part of the concepts.

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[REQ-9]	The ODTS simulator shall allow to perform parametric analysis in order to assess the impact of major contributors to the LEE.
[REQ-10]	The ODTS simulator shall provide in output the necessary data related with ODTS to allow a service volume simulator to compute the user position, velocity and time accuracy.
[REQ-11]	The square root of the sum of the square of the 4 components (3 orbit components and time, $SISE_{pos} = \sqrt{(x-\tilde{x})^2 + (y-\tilde{y})^2 + (z-\tilde{z})^2 + (ct-c\tilde{t})^2}$ of the LRNS Ephemeris Error (LEE) at maximum age of data (AOD) shall be less than 25 meters 95 percentile (TBC).

Table 3-1: Driving requirements.

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4. DEVELOPED CONCEPTS FOR ORBIT DETERMINATION, TIMING SYNCHRONIZATION, REFERENCE FRAMES AND SIGNALS

4.1.1. Orbit Determination

The OD state of art has been studied in areas of:

- Orbit modelling for lunar spacecraft
  - Lunar gravity field and required degree of expansion
  - Gravitational perturbations by Sun, Earth and other planets
  - Solar radiation pressure
  - Lunar albedo and infra-red radiation pressure
  - Relativistic effects
- Potential tracking techniques for lunar spacecraft
  - Radio range and Doppler on TT&C frequency
  - Use of Earth GNSS signals
  - Satellite laser ranging
  - Differencing techniques such as VLBI and SBI
  - Inter-satellite ranging
  - Tracking from within the lunar environment using LRNS signals
- Modelling of the broadcast navigation ephemeris information
  - Reuse of existing message formats from GPS / Galileo
  - Alternatives based on orthogonal polynomials
- Aspects of operational OD analysis
  - Location of tracking data sources
  - Location of OD analysis
  - Data volumes
  - Bandwidth for data download from LRNS spacecraft
  - Bandwidth for data upload to LRNS spacecraft
  - Ground segment data streams

Based on these findings, and considering the key requirements of the LRNS program regarding cost, performance and technology readiness, a trade-off analysis was made to define the most suitable OD concept. The trade-off, supported by simulation results, resulted in the definition of

- Baseline OD analysis approach: batch least squares analysis
- Baseline ground station network for tracking: three TT&C stations
- Baseline space segment elements needed in support of OD: default TT&C transponder, and SLR retroreflector
- A vision on possible future expansion by inclusion of e.g. LRNS receivers in the lunar environment
- Required tracking data availability
- Default OD solution parameters such as arc length, solution frequency, noise tolerance

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- Broadcast message contents
- Broadcast message validity periods
- Expected broadcast message accuracy
- Broadcast message binary representation and required bandwidth
- Quantification of OD contribution to SISE as function of age-of-data
- Initial results for UERE of lunar user

4.1.2. Time Synchronization

The TS state of art has been studied in areas of:

- Time Synchronization architecture:
    - Space Atomic Frequency Standards (SAFS) technologies;
    - Clock evolution control approach (steering process vs clock corrections);
    - Ground Atomic Frequency Standards (AFS) technologies;
    - Master Clock Station architecture and generation of LCNS Reference Time (LRT);
    - Ground-to-ground time synchronization techniques;
    - Time Transfer Methods: Earth to Moon Two-Way Time Transfer and One-Way Time Transfer based on autonomous on-board GNSS receiver;
    - Two-Way Time Transfer sessions;
    - Two-Way and/or One-Way observables processing;
    - Two-Way Time Transfer Error Budget;
    - Two-Way Time Transfer processing of measurements;
    - Two-Way Time Transfer Deep Space Transponder technology;
    - LRNS satellite time synchronization architecture;
    - Modelling of the broadcast navigation clock parameters information
- Time Synchronization process modelling:
    - Clock behaviour modelling: deterministic, stochastic and thermal error modelling;
    - Time Transfer noises modelling;
    - Time Transfer observables pre-processing algorithm;
    - Best estimation algorithm for the clock corrections computation;
- Time Synchronization accuracy computation:
    - SISE Clock Error computation methods;
    - Monte-Carlo analysis.

Based on these findings, and considering the key requirements and drivers of the LRNS program regarding cost, performance and technology readiness, a trade-off analysis has been made to define the most suitable TS concept. The trade-off, supported by simulation output, resulted in the definition of:

- Ground clock technology
- LCNS Reference Time Generation process
- On-board clock technology
- On-board Time Reference Generation process

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- Time Transfer approach
- Time Synchronization baseline concept
- Clock behaviour models of deterministic, stochastic and thermal errors;
- Time Transfer noises model;
- Time Transfer observables pre-processing algorithm selection;
- Estimation algorithm selection for the clock corrections computation;
- Time Synchronization accuracy contribution to SISE.

4.1.3. Reference Frames

The reference frames state of the art has been studied in terms of:

- Definition of existing Lunar Systems and their definitions, together with their practical applications and accuracies.
- Estimation of the external accuracies (relative accuracy between different realizations) of the most used Lunar Frames.
- Simulation to assess the impact of such Lunar Frames errors onto the LRNS (Lunar Orbits) and onto the positioning of Lunar users.

Due to the nature of these rotations errors, the impact is observed mainly along directions that do not degrade the Lunar user positioning performance. These analysis helped us conclude on the applicability of the existing Lunar Frames to LRNS.

Finally, different actions that should be taken in the years to come have been identified, along the gradual deployment of LRNS and other infrastructure on the Lunar surface, in order to increase even more the external accuracies of all Lunar Frames realizations.

4.1.4. Signals

In the frame of the LRNS Program, both one-way and two-way ranging signal solutions have been analyzed. A state of the art analysis has been performed concerning the following topics:

- GNSS signals
- PNT multiple access schemes
- PNT signal quality
- PNT signal modulations
- PNT multiplexing schemes
- Lunar multipath
- Lunar frequency regulations
- WiFi interference

Subsequently, a detailed tradeoff has been performed in order to define the best candidate LRNS signal concept. In particular, the tradeoff involved the definition of:

- Carrier frequency
- Multiple access scheme
- Multiplexing scheme
- Signal polarization

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- Number of signal components
- Definition of waveforms modulation
- Initial phases
- Power Sharing
- Chip-rates
- Sub-carrier rates
- Code length
- Code replica duration

The LRNS signal is composed by two components to exploit the Data and Pilot paradigm. While Data is the component responsible for the data transmission, the Pilot is the component responsible for the ranging performance. The Pilot design has been obtained analyzing the following Figure of Merits (FoM):

- Code Tracking Error
- Multipath Error Envelope
- Spectral Separation Coefficients
- Out of Band Unwanted Emissions (OBUE)
- Cross Correlation Function

Finally, the Pilot waveform have been selected assigning weight to the FoM scores, depending by the desired characteristics of the LRNS signal:

- Ranging Accuracy
- Acquisition and Tracking Robustness
- Multipath Robustness
- OBUE

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5. PECULIAR ASPECTS THAT ARE DRIVING CONCEPT SELECTION

5.1. PROPOSED BASELINE ODTS CONCEPT

5.1.1. Summary of OD baseline concept

1) The following OD baseline has been identified:

Space segment:

- OD based on terrestrial TT&C range data
- On-board TT&C transponder able to work in CDMA and in asynchronous mode (TC+TM+RNG or TC+TM+TS) (equipped with dedicated antennas: 1 MGA for normal mode (30 cm of diameter) and 2 LGAs (10 cm of diameter) for contingency operations)
- High accuracy SV internal delay calibration
- SLR retroreflector on each LCNS spacecraft for OD validation purposes (see also note at end of this section).

Note that, only as BACK-UP solution: On-board highly-sensitive GNSS receiver with antenna of 14 dBi (TBC) at boresight (TBC).

Ground segment:

- Three dedicated TT&C stations ((X band: 90 cm diameter dish for normal mode, and 11 m diameter dish for contingency mode per site (assuming onboard SSPA Tx Power of 10W for both normal mode and contingency modes) or K band: 25 cm diameter dish for normal mode, and 13 m diameter dish for contingency mode per site (assuming onboard SSPA Tx Power of 10W for both normal mode and contingency modes). However, it is recommended to have for redundancy scopes two parabolic diameter antennas in each site)) at longitudinal separation of around 120 degrees to obtain global coverage and possibly at low latitude avoid short tracking passes and poor visibility (low elevations) of LRNS SVS.
- Six Master Clock atomic frequency standard: two per each ground station considering the operative and the redundant one. It shall be an Active Hydron Maser or equivalent technology.
- High accuracy Station internal delay calibration (to derive the actual range measurements, the excess delay due to the ground station ranging measurements equipment must be suitably calibrated. The station must be endowed with an internal delay calibration system in X band (K band))).
- SLR tracking provided by the International Laser Ranging Service (calibration with SLR shall be performed every 6 months (TBC))
- GMS/GCS dedicated functions.

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- GNSS reference/weather station located close to identified TT&C stations (for weather, tropospheric and ionosphere data calibration).

2) Future evolutions of the operational system concept impacting on performance of the OD solution might be:

Space segment:
Two main options have been identified:

- Use of one or more (future) LCNS receivers in Low Lunar Orbit either as an integral element of the LCNS system (e.g. CubeSat launched as piggy-bag payload on some future lunar lander), or an LCNS receiver of opportunity, on an already planned lunar orbiter such as Lunar Pathfinder;
- To use a dedicated ISL for ranging on future LCNS spacecraft.

Ground segment (Moon):

- Installation of LCNS reference receivers on future lunar landing sites. This is likely to happen in any case, and the observation data from such receivers can be integrated in the OD processing without any changes of the LCNS space segment itself

3) If dedicated LCNS TT&C stations are not feasible

Ground segment:

- Collect S-band tracking from multiple existing stations (ESTRACK, DESCANSO, …) to the extent that adequate temporal coverage is reached.

Note: Regarding the possible use of SLR retroreflectors on at least one spacecraft: this could have the operational advantage of focusing all available SLR tracking windows on a single spacecraft, as opposed to further reducing the already sparse SLR dataset by splitting it over multiple satellites. However, in terms of spacecraft production and testing, having different designs for LCNS spacecraft is probably a burden rather than a cost-saving. The baseline will therefore be to have retroreflectors on all spacecrafts.

5.1.2. Summary of TS baseline concept

1) The following baseline concept is proposed:

On-board Local Time:

- Use three mini-RAFs in free-running mode with a combination unit for the realization of on-board time

Lunar Reference Time:

- Use a Master Clock Approach (preferably Hydrogen maser) with a GNSS Timing Receiver on Earth
- Use asynchronous 2-way time transfer on the same TT&C link that is used for OD

As back-up solution:

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2) If the GNSS on-board receiver can be demonstrated to be sufficiently accurate:

On-board Local Time:

- Use the mini-RAF combo not only for the payload OLT but also as GNSS receiver clock
- Estimate linear or quadratic clock corrections from the GNSS data, relative to GNSS reference time

Lunar Reference Time:

- No explicit master clock is required, the GNSS reference time becomes LRT.

5.1.3. ODTS baseline - Summary and conclusions

The key advantage of the presented ODTS concept is that both OD and TS make use of the same tracking signals, namely, standard TT&C ranging (on X-band (the possibility to also use together X/Ka bands can be considered)).
A highly-sensitive GNSS receiver on board to support both OD and one-way TS is **only** a back-up solution.
This approach is relatively low on SWaP, adding only the DST and its dedicated antennas (both for normal mode and contingency operations) and HPA chains and SLR retroreflector to the LCNS spacecraft, and adding at most the master clock and GNSS timing receiver to the ground segment.
In addition, both the OD and TS concepts consist of a relatively simple baseline option, with optional extensions that can even be added at a later stage of the mission. For OD, this extension consists of the LCNS tracking options described above.
For TS, the baseline consists of the use of a terrestrial master clock with 2-way time transfer.

The Two-Way Time Transfer concept in LRNS is proposed to be implemented via the use of Deep Space Transponder technology based on the evolution of the TASI prototype developed as part of the HERO (High pErformance time & fRequency link – microwave) project.
The Two-Way Deep Space Transreceiver foreseen on-board all LRNS satellites is provided with a way of operations of ranging and time synchronization alternating to each-other. Two-way time transfer measurements needed for Time Synchronization are shared in time with ranging observables needed for Orbit Determination, for this reason a sharing approach has been established setting the subdivision of the overall locking window in a time window dedicated to ranging activities (OD window) and one another dedicated to the time transfer (TT window).
Two-way time transfer measurements needed for Time synchronization are shared in time with ranging observables needed for Orbit Determination according to an asynchronous approach (asynchronous TT). 5 minutes dedicated to TT each 45 minutes. Each single measurement is integrated over a time interval of 1second. 1 sample per second is collected on-board of the LRNS satellite and provided to the ground for pre-processing.
Since the synchronous approach (synchronous TT) cannot be taken into consideration due to the available mode of operations of the Deep Space Transponder (DST) selected as baseline (HERO-like), the TS concept that seems to be the most performing is the option of a locking

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window of 45 minutes and time transfer window of 5 minutes. The increasing of the sample collection rate results being more fruitful than a wider time interval of averaging of the data.
Similar performances in terms of SISE Clock Error at 95% can be reached with a synchronous or asynchronous TT approach. In this project the asynchronous TT approach has been proposed since it is the only approach supported by the DST selected as baseline.
In next phases of the project it is recommended to also consider the possibility to implement a synchronous TT approach in order to guarantee an increased observability of the on-board clocks in terms of clock monitoring, anomaly detection, faults identification and feared events reactions through telecommands.
On the side of Two-Way versus One-Way TT technique, considering TS component, it should be noted that the terrestrial master clock option is in principle the baseline, and the use of the GNSS solution is optional. This is because at this stage it is still unclear whether the performance of the on-board GNSS option is sufficient to reach the 25 m at 95% SISE requirement and also it is able to decode GNSS navigation message onboard.
In the case of GNSS receiver may be installed on board, It will for instance be possible to start the LCNS mission with TT&C ranging only, using the GNSS just for the TS task to prove if it is capable to perform it.
Alternatively it would be possible to use the GNSS just for tracking, and the terrestrial master clock with a 2-way TTC link for time synchronization.
Regarding the ground station network, it would be feasible to initially use existing stations for as far as available (for instance because a dedicated ground station network has not yet been completed), and bridge any substantial gap in temporal coverage with GNSS data. At a later stage, the LCNS system could then switch to a dedicated GS network that offers better coverage, and improved performance.
The same on-board hardware can therefore be used in various configurations, and the two required systems (TT&C and GNSS) not only complement each other but also act as each other's redundant back-up.
We believe that the above logic offers a powerful and flexible ODTS concept, at minimum impact on SWaP and potentially reusing existing ground segment components, depending mainly on station availability.

5.1.4. Signal-In-Space Error results

A detailed set of Monte-Carlo style simulations was performed to assess the actual Signal-In-Space-Error over a broad variety of data simulation options on both OD and TS software. The OD SISE results do not depend on the TS SISE values, but the clock estimation depends to some extent on the orbit accuracy. Nonetheless, the results for OD and TS have been combined by means of a root-sum-square approach because combination of the simulation results in some more direct way was not practical. The velocity SISE and clock drift error are also shown in Table 5-1. The results are summarized in Figure 5-1 and Figure 5-2. From the pictures it is possible to see that [REQ-11] is verified up to an Age of Data of nearly 6 hours for position and clock.

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Errore. Non si possono creare oggetti dalla modifica di codici di campo.

Table 5-1 OD MonteCarlo settings.

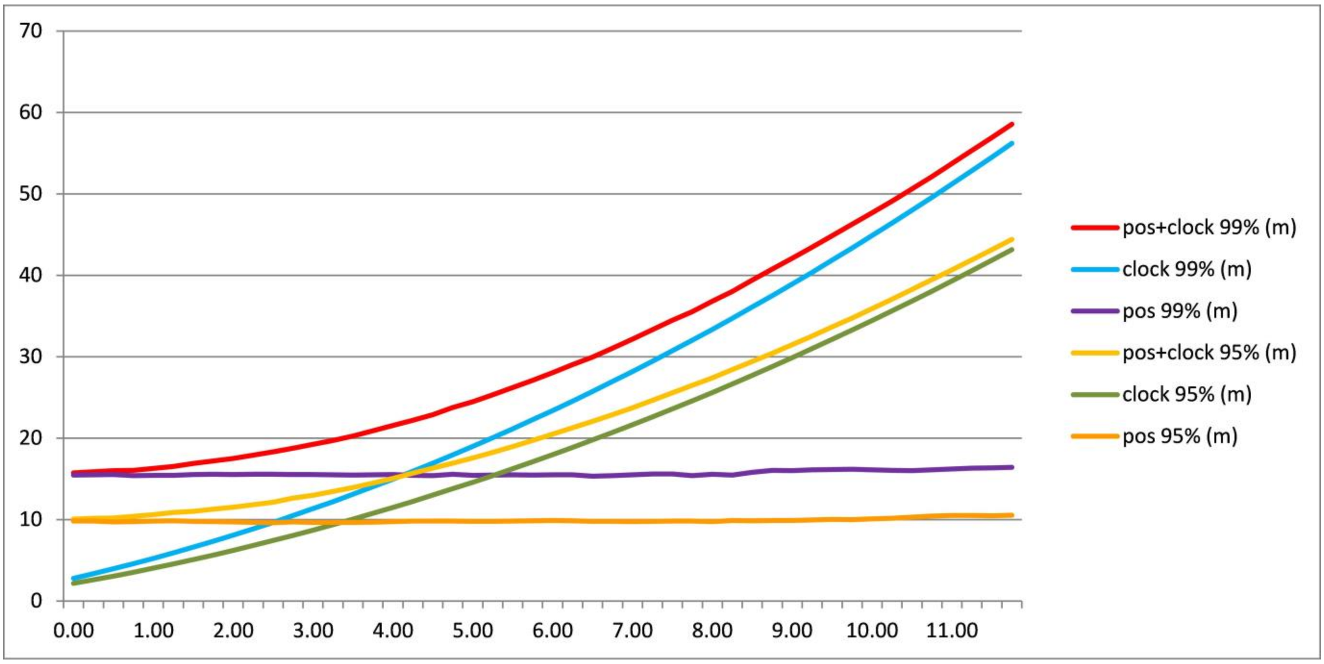

Figure 5-1 SISE results (position and clock) as function of the AoD (hours).

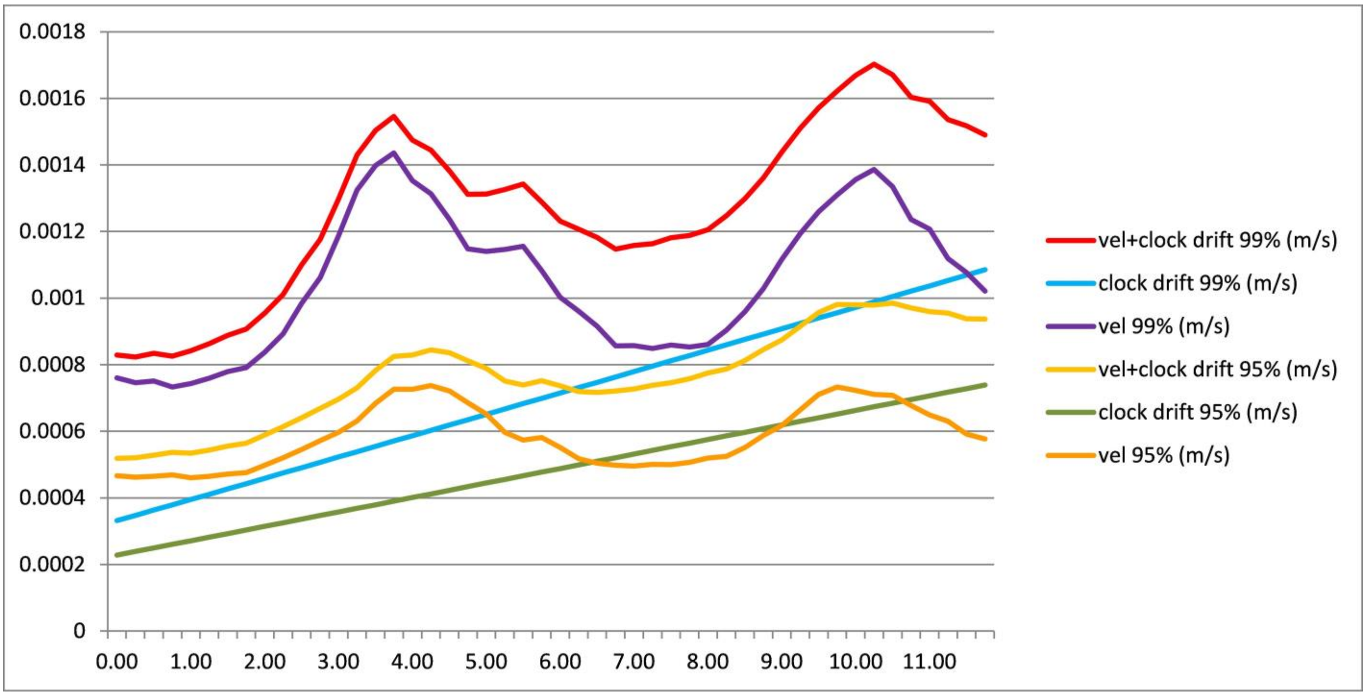

Figure 5-2 SISE results (velocity and drift) as function of the AoD (hours).

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5.1.5. Future improvements of Lunar Ephemeris and Libration Angles

As of today, the main limitations to the achievable accuracy of the Lunar ephemeris and Euler angles are the following:

1. Earth-Moon physical modelling
2. Laser ranging being the only available technique
3. Poor geometry of the LLR-ILRS system
4. Limited Lunar Control Network and LLR performances

Currently, only three ILRS ground stations are used for laser ranging. Other observations are outdated, and the Moon's LLR cluster is suboptimal. The majority of observations rely on Apollo 15 LLR, reducing geometrical strength. Laser facility properties affect observation frequency and quality, and some ILRS stations have limited ranging capabilities due to solar noise.

In a first phase, expanding the ILRS infrastructure and upgrading Lunar laser ranging capabilities would enhance LLR observations. Improvements in Earth-Moon dynamics modelling are also suggested: the additional station and data would aid in observing Lunar centre of mass and physical librations.

In a second phase, exploring other Earth-based techniques alongside LLR will be crucial. VLBI shows to be promising, offering high observability of Lunar librations and tides, with potential for centimeter-level accuracy in determining Lunar surface position. Additional LLR placements in sensitive regions would increase sensitivity to Lunar motion.

Finally, once the fully operational LRNS constellation will be established, it will provide additional observations to enhance selenodetic reference systems. LRNS receivers on the Moon's surface will collect range and range-rate data, improving geometry and serving as control points. Post-processed LRNS ODTS and co-localization with LLR or VLBI transmitters will contribute to accuracy assessment and cross-comparison. This approach, dependent on LRNS maturity, will aid in assessing realizations and identifying biases in the LLR technique.

5.1.6. Selected concept for LRNS Signal

This paragraph summarizes the selected LRNS signal concept. Table 5-2 and Table 5-3 show the frequency plan of the one-way signal and its main features, respectively. Note that f0 is the fundamental frequency 1.023 MHz widely used in Earth GNSS.

Signal Frequencies	
Frequency Range [MHz]	2483.5 - 2500
Center Band Frequency [MHz]	2491.75
Actual Carrier Frequency [MHz]	2492.028

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Actual Carrier Frequency [f0]	2436
Actual Frequency Range [MHz]	2484.056 – 2500
Actual Transmitting Bandwidth [MHz]	15.944

Table 5-2 Frequency Plan.

Signal Parameters					
Multiple Access Scheme	**Reference Frequency Range**	**Multiplexing Scheme**	**Number of Components**	**Signal Waveforms**	**Polarization**
CDMA	2483.5 - 2500 MHz	Linear Multiplexing	2 (Pilot + Data)	BPSK/BOC	RHCP

Table 5-3 Signal parameters.

The Data + Pilot paradigm allows to combine a narrowband and a wideband components. The Pilot channel is a wideband signal, indeed high frequency components are more robust to multipath and improve the ranging performance. However, the ranging performance of a signal and the performance of transmitting data are often in conflict. For the data transmission, the frequency components of a good signal shall be concentrated near the carrier frequency.
The BPSK(1) is the most promising solutions for Data channel since it is a robust component in terms of acquisition and tracking reliability, while for the Pilot channel it has been selected the BPSK(5) as a performing component in terms of ranging accuracy, multipath robustness and acquisition/tracking performance.

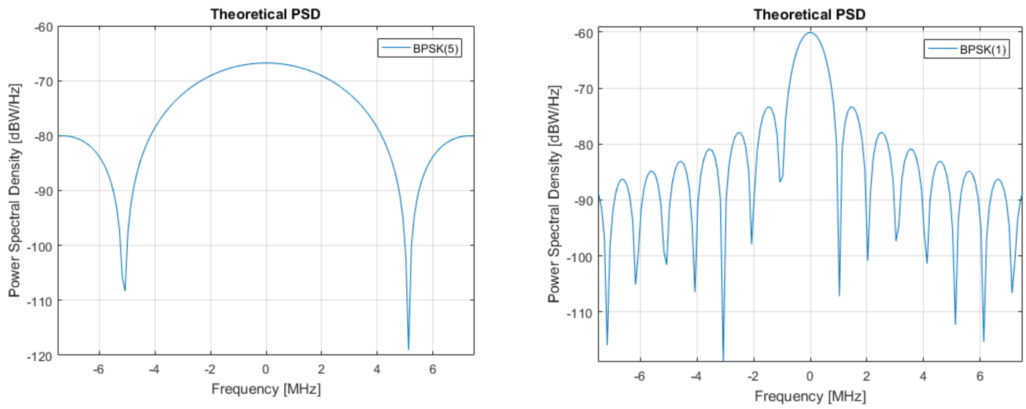

Figure 5-3 Pilot (left) and Data (right) component PSD.

Table 5-4 summarizes the characteristics of the lunar one-way ranging signal modulations:

One-way Ranging Signal

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Parameter	Data	Pilot
Initial Phase	I component	Q component
Power Sharing	50%	50%
Waveform	BPSK(1)	BPSK(5)
Chip-rate	1.023 Mchip/s	5.115 Mchip/s
Code-length	1023	5115
Code replica duration	1 ms	1 ms

Table 5-4 LRNS Signal modulation.

5.1.7. Technology Roadmap of baseline elements

In the frame of the LRNS project, the technology readiness of the systems that are part of the current baseline has been analyzed in order to provide a schedule for their future development that will lead to a proposed flight model aligned to the needs of the project. The development steps of the technologies that are not ready to fly are resumed in the following

1. **MSPA antenna with APE and APM mechanisms:**
   - The TT&C on-ground processor including modulator CDM-M has TRL of 3-4 and is the unit that seems to need the highest improvement up today.
   - The On board deep space transponder is not a ready solution, but needs to be adapted from a device that already exists that could be HERO (detailed in Section **Errore. L'origine riferimento non è stata trovata.**) or the classical solution adopted for BepiColombo mission (this solution is currently the candidate under analysis). For these reasons, the current TRL is to be assumed 4.
   - The on board tracking system is currently addressed with TRL 5.
   - The on board MGA antennas (that could be in-house developments at TAS based on previous heritage – however products from other antenna manufacturers could be evaluated), that will be part of the whole TT&C onboard system including also:
     - SSPA 10-15 W RF output
     - RF filters
     - Circulators
     - Switches
     - Antenna Pointing Mechanism (APM)
     - Antenna Pointing Electronics (APE)
     - Hemispherical LGAs

   For what concerns current availability on the market of MGA antenna plus APM and APE, Kongsberg antenna and the Galileo 2nd generation antenna for ISL have been taken into account but their development needed to suit LRNS needs lead to schedule the FM readiness in 2030.

2. **Integrated Deep Space Transponder:**

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The current version of the IDST already implements the CDMA approach. However, it does not include TS functionalities that are being validated in LRNS study. All other functionalities can be considered at high TRL due to flight heritage and will not be tested in the breadboard. The TS will be included in the IDST design after the BB activities. For what concerns the development that will lead this technology to flight model for LRNS purposes, it is possible to foresee the following schedule for two units:

- EM needed to reach TRL 6 with functional and performance validation completed in t0+12 months.
- 1 PFM in order to perform test EM of S/S and RF suitcase. The delivery should be completed in t0+2.5 years.

3. Earth based TT&C tracking stations:

Currently, it is possible to assess with a high TRL, corresponding to a flight proven solution, the stations' subsystems already used in the previous missions that these stations have supported, such as the antenna, the RF subsystem and the computer control hardware.

For what concerns the subsystems in charge of analyzing the satellites' data in the TM, TC and RNG functions, compute the orbit analysis and monitor the payload, the current TRL is assessed to 4. In order to implement LRNS baseline, the main development of the ground segment will be performed on the ground CDM-M modulator and the transponder that implements ranging and two way time transfer functions. The reason behind this assessment is that these subsystems need to be tailored with respect to the current mission. These subsystems will be subject to development in the framework of Moonlight project in order to ensure their proper development up to TRL 9 prior to the Initial Operational Capability of the constellation.

The schedule that will lead to this development will be defined in the framework of the project, going through intermediate milestones and reviews such as:

- EM (TRL 6 – model demonstrating the critical functions of the element in a relevant environment) to be delivered in T0 + 1 year.
- PFM EQM (TRL 7 – model demonstrating the element performance for the operational environment) to perform test. Expected Delivery date: T0 + 2.5 years.

4. Mini Rubidium Atomic Frequency Standard Clocks:

The current TRL of mini-RAFS with respect to LRNS needs is assessed to be 4-5. The technological assessment provided by Orolia consists in two main points:

- Excellent short- and long-term frequency stability;
- Improvement of thermal sensitivity with thermal compensation.

The next steps that the company will go through to improve the technology are: the reduction of the temperature sensitivity and the increase of the temperature range with improvement of temperature controller and thermal design. Currently, the development of this technology has not seen further evolutions since two years, given the ESA's lack of interest. However, considered that there is the need of a first lunch of a LRNS satellite by 2027, it is envisaged the need to support the roadmap of the clock.

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The main goal should be to encourage the clock product evolution in order to get a higher TRL within 2025 even if re-design and re-qualification will be needed, mainly concerning the temperature sensitivity improvement and the interface optimization to obtain an output frequency compatible with LRNS needs.
According to Orolia, they should be able to achieve qualification of the Mini-RAFS with 2 or 3 models targeting TRL 7-8 in a realistic time frame of 3 years. The costs will depend on the number of developed models and the number of requirements to be satisfied, but it will be around 3-6 M€.

5. Signal Generation Unit:
A schedule similar to the one of the IDST is proposed:

- EM needed to reach TRL 6 with functional and performance validation completed in t0+12 months.
- 1 PFM in order to perform test EM of S/S and RF suitcase. The delivery should be completed in t0+2.5 years.

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CONCLUSIONS

At the end of the Project, the consortium led by Thales Alenia Space has presented a candidate baseline which shows the selected concepts for Orbit Determination, Timing Synchronization, Reference Frames and Signals.

The main outcomes of the work performed in the Lunar Radio Navigation System project are the following:

- Define the main concepts for a dedicated Lunar Radio Navigation System in terms of:
  - Orbit Determination and Timing Synchronisation algorithms (analyzing different approaches based on VLBI, ISL, GNSS Spaceborne Receiver, Satellite Laser Ranging, LRNS reference time definition and time transfer techniques;
  - Lunar reference frames (selenodetic and timing) and their translation to Earth Reference Frames;
  - Signal modulation techniques for one-way and two-way services for precise LRNS
- Assessment and Validation of the selected concepts through development of a dedicated ODTS software.
- Definition of a baseline to be followed for the system development.

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