

Lunar Reference Time: ESA's Views

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Through various initiatives and studies (Moonlight, NovaMoon, LightShip/Marconi, SSI,...), ESA is preparing for the future provision of **Communication and Navigation Services** to the Moon, Mars and beyond.

To guarantee compatibility and inter-operability with other similar initiatives in the context of Lunar PNT, activities are coordinated with NASA and JAXA through LunaNet framework.

To reach inter-operability and initial multi-constellation PVT performance requirements, agreements on a 4D reference system and associated navigation/time transfer models and products are required.

Goal of this short presentation:

- Summarise navigation/timing needs and current Moonlight timing system architecture
- Provide our views on the definition of lunar reference time

Navigation/Timing Services Needs

Functional:

- address a wide range of users and requirements: cruise, orbiter, lander/ascender, rover, habitats, ...
- focus on relevant coverage (i.e moon's south pole, SV1- surface, SV2 - surface up to 200 km altitude)

Performance:

- Position/Velocity w.r.t. agreed reference frame: 1 ~ 100m / 0.1 ~ 10m/s
- Time w.r.t. reference timescale / UTC: 10 ns / 100 ns

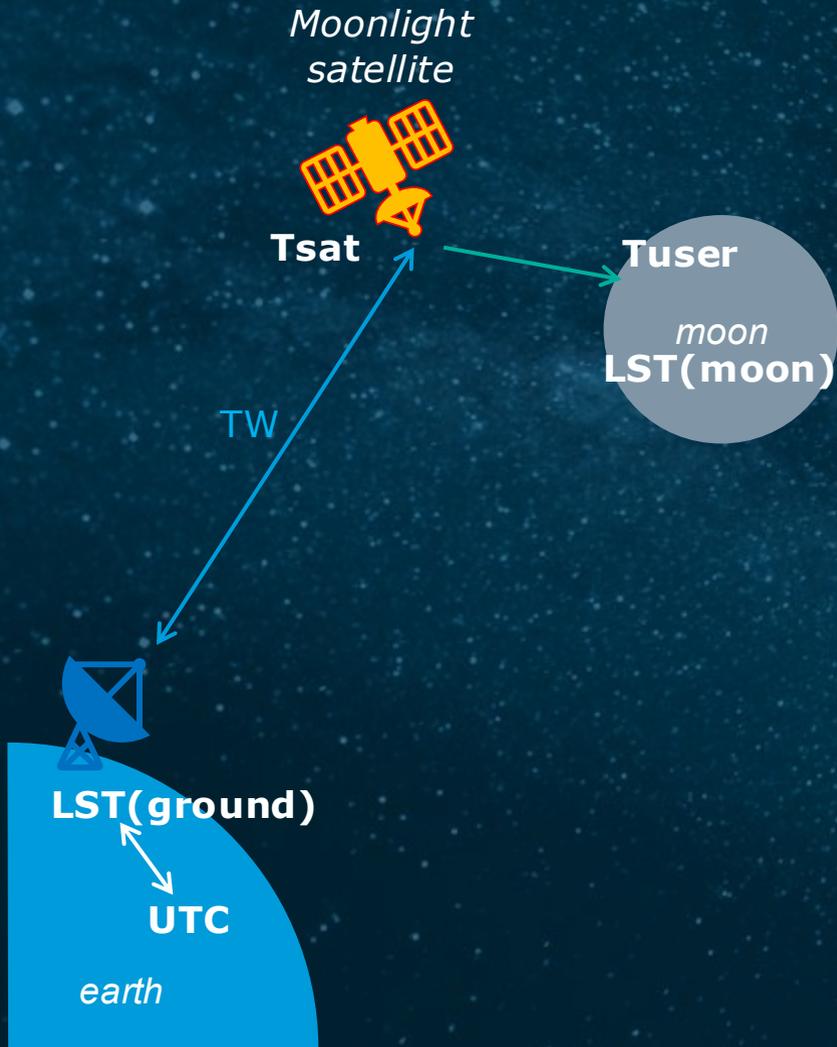
Operation:

- real-time, high availability
- compatible and inter-operable with other service providers (NASA, JAXA...)

Implementation:

- reuse as much as possible Earth-GNSS concepts, models and techniques, when justified
- models shall be in line with agreed standards and scientific resolutions
- models shall be scalable to cover other bodies (Mars, ...), as far as possible
- reduced complexity on the user side

Current Moonlight Timing System Architecture



- 1) The TW observable will provide: $T_{sat} - LST(\text{moon}) + \Delta t_{rel} + c \Delta x$
 - $LST(\text{moon})$ is aligned with a given lunar reference time (e.g. LRT - LunaNet Reference Time)
 - Δt_{rel} is the relativistic correction that depends on the Station-Satellite position and relative velocity, **in the selected reference frame/timescale!**
- 2) Knowing the Station-Satellite relative position and velocity, the Moonlight Ground Segment will compute, estimate and model the quantity $T_{sat} - LST(\text{moon})$ (for a (mini) RAFS-like clock, a second order polynomial model is deemed OK)
- 3) Simultaneously, in the same way as for Galileo, the Moonlight Ground Segment will estimate and model the quantity $LST(\text{ground}) - UTC$, ($LST(\text{ground})$ is steered to UTC)
- 4) The Moonlight Ground Segment, via the Moonlight satellite, will broadcast the clock model parameters to the moon user
- 5) The moon user will estimate its PVT solution, from which it will extract the quantities $T_{user} - T_{sat}$, $T_{user} - LST(\text{moon})$, and $T_{user} - UTC$ (position-dependant accuracy currently under investigation)

NovaMoon: Lunar Differential, Selenodetic and Timing station

1. Install **the first-ever reference local differential station on the lunar surface**

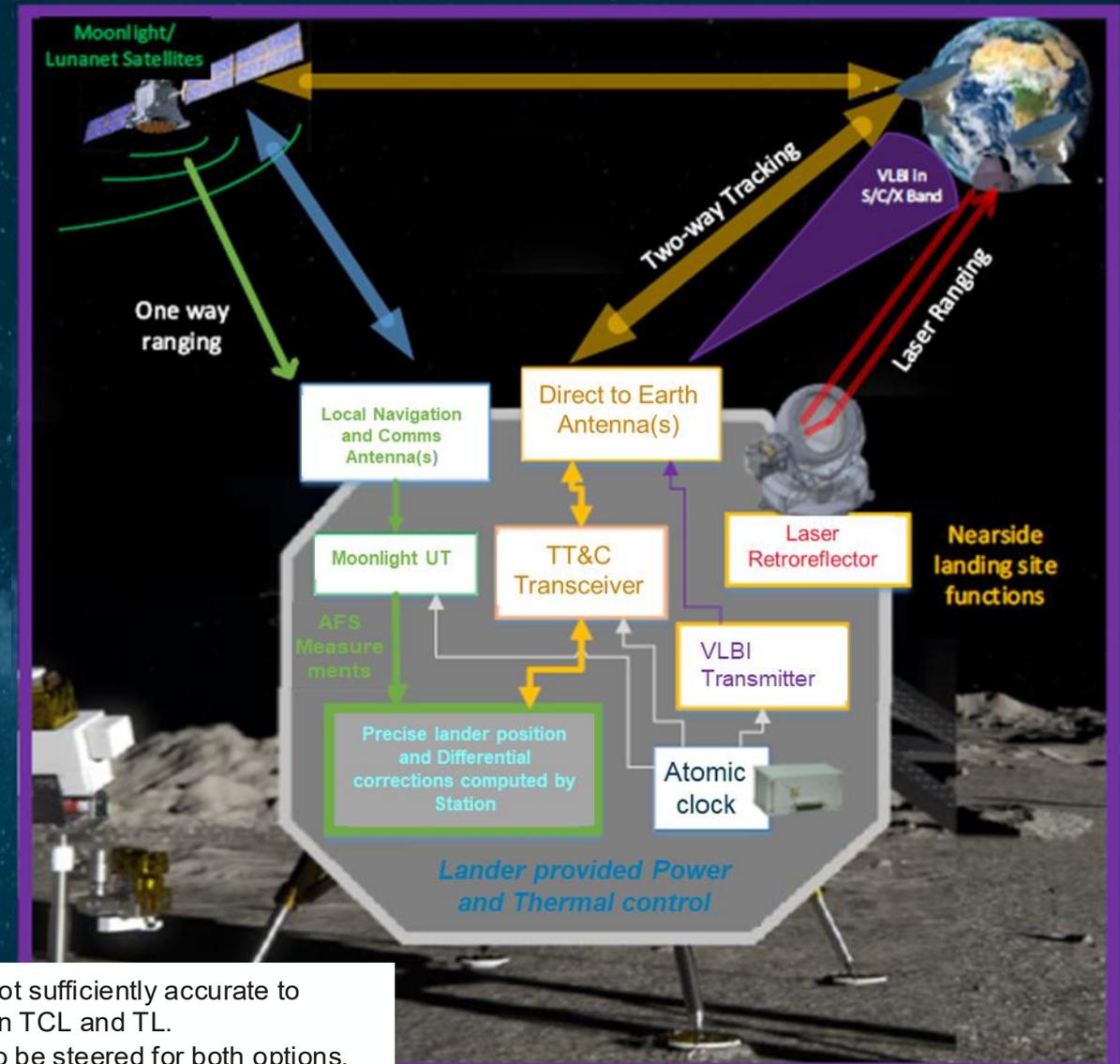
Compute and broadcast Moonlight NAV satellite pseudo-range corrections → **decimeter level** navigation accuracies over the Lunar South Pole to standard LunaNet users.

2. Install **the first-ever International “geodetic” Reference station on the lunar surface**

Co-locating 4 geodetic techniques: Moonlight Rx, VLBI Tx, LLR and Two-way DWE ranging → locate the Argonaut lander station at **few cm-level** accuracy, setting the international standard for stations supporting the Lunar Reference Frame.

3. Install **the first-ever “Time Laboratory” station on the lunar surface**

Supporting the realisation of lunar reference times and the standardisation of lunar time transfer protocols.



The NovaMoon baseline clock is not sufficiently accurate to sense the frequency offset between TCL and TL. A possible optical clock will have to be steered for both options.

ESA System Analyses show that:

- In the initial phases, LCNS System Time will be realised on Earth, and transferred to the clocks in the moon vicinity, accounting for the relevant relativistic corrections.
- Early clocks on the moon deployed by ESA are expected to not be able to sense the frequency difference between TCL and TL.
- Users with strict accuracy requirements need to align their clock to the lunar time reference.
- Even in the future, Clocks on the moon will have to be traceable to UTC and will therefore have to be compared with a reference on the Earth.

Recap of the two options being considered:

Option 1: Lunar Coordinate Time (TCL) – coordinate time of the LCRS (Lunar Celestial Reference System)

- A perfect clock on the moon selenoid would drift about $\sim 3 \mu\text{s}/\text{day}$ w.r.t. the reference.

Option 2: Lunar Time (TL) – frequency-scaled version of TCL characterized by a rate that would match that of an ideal clock on the Moon selenoid.

Our views on Lunar Time Reference definition

- ESA confirms that Options 1 and 2 can be accommodated in the current Moonlight design

- ESA underlines that **Option 1 is preferred** on the grounds that:
 1. The analogy with Earth (TCG/TT) does not apply, as the practical realisation will originate on Earth and remain linked to it.
 2. Definition is independent of external inputs (e.g. selenoid)
 3. Introducing a new scaling of coordinate time would also require scaling spatial coordinates and the mass parameters of celestial bodies, adding unnecessary complexity and potential for errors.
 4. Same simple and straightforward approach can be applied to other bodies (e.g. Mars,...)
 5. No design nor operational drawbacks for Lunar Navigation/Timing have been identified
 - Measurement from Earth – no difference between approaches
 - Holdover in case of Earth connection loss – no difference between approaches (both depending on clock stability)
 - Need of interoperability – simpler implementation if ephemerides are in TCL
 - Traceability to UTC – simpler implementation

- ESA identifies implementation risks with TL
- ESA identifies no technical difficulties with implementing TCL
- ESA will work with NASA and JAXA under the LunaNet framework to support full interoperability.
- In parallel ESA will work in collaboration with the BIPM and National Metrology Institutes to guarantee the correct realization of lunar reference timescales and their measurement with respect to UTC, as recommended in the draft CGPM resolution.