# Moon Sensor Station to support lunar PNT and science as part of Moonlight

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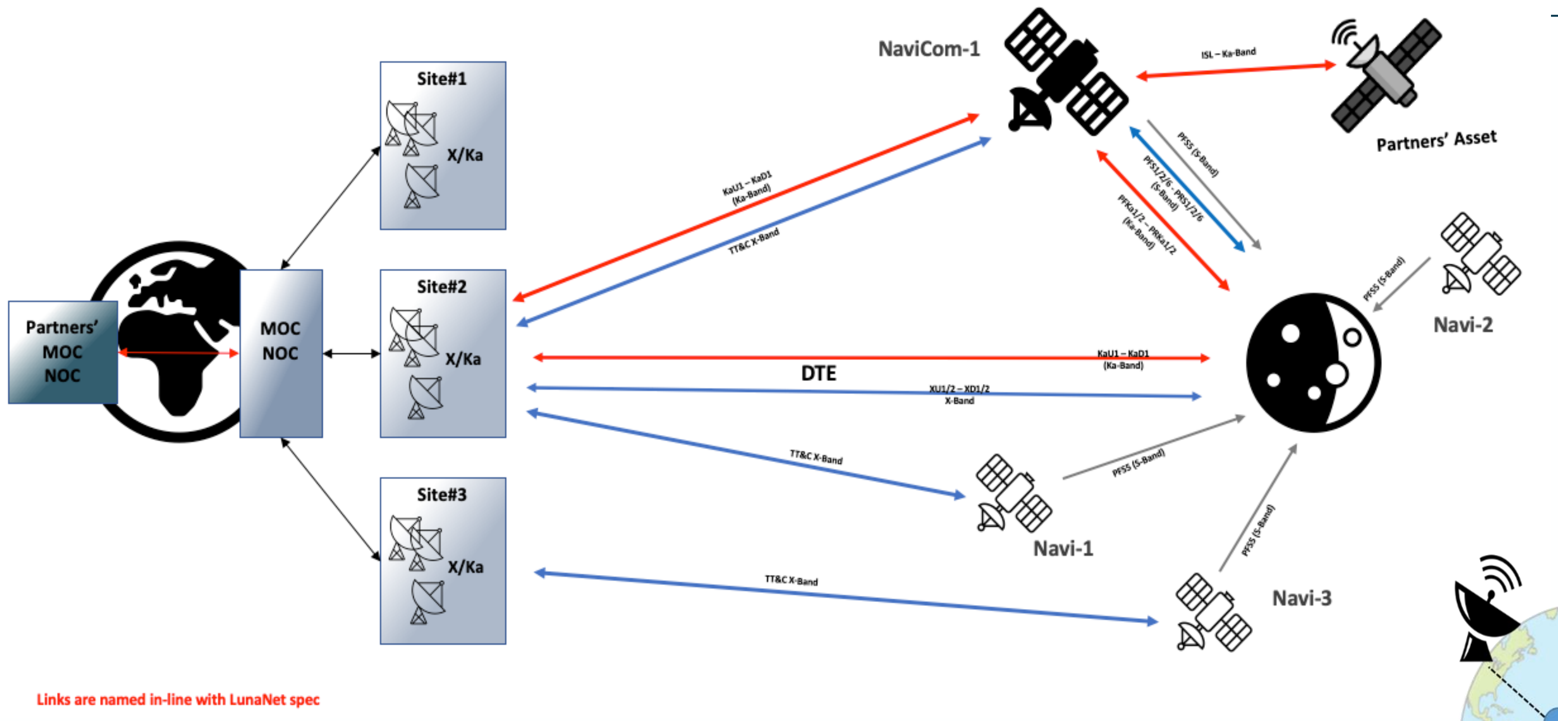
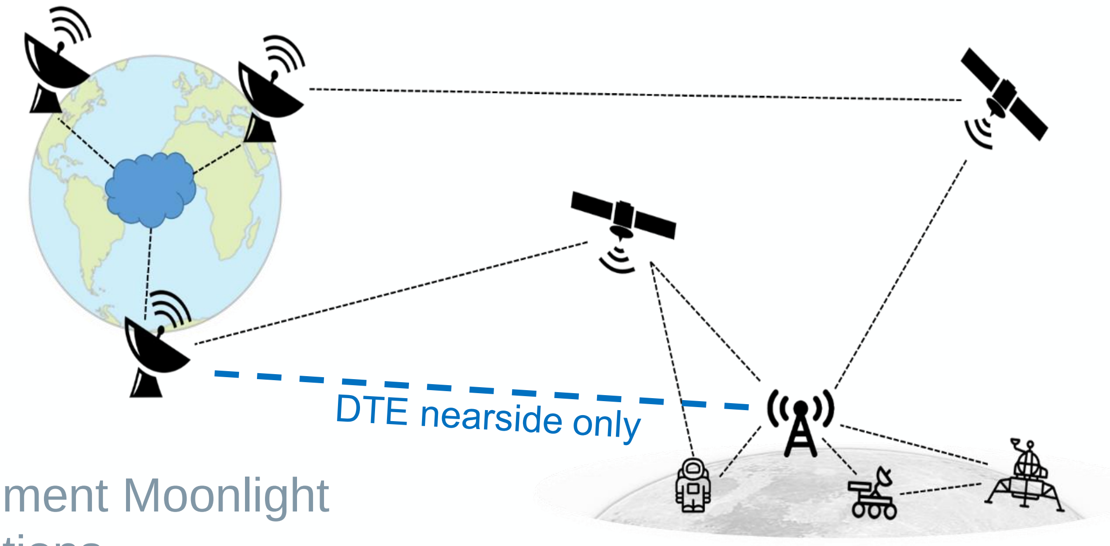
# MOONLIGHT CONTEXT




Initial Moonlight concept with 4 lunar orbiters and DTE links for ODTS




Potential to augment Moonlight with surface stations

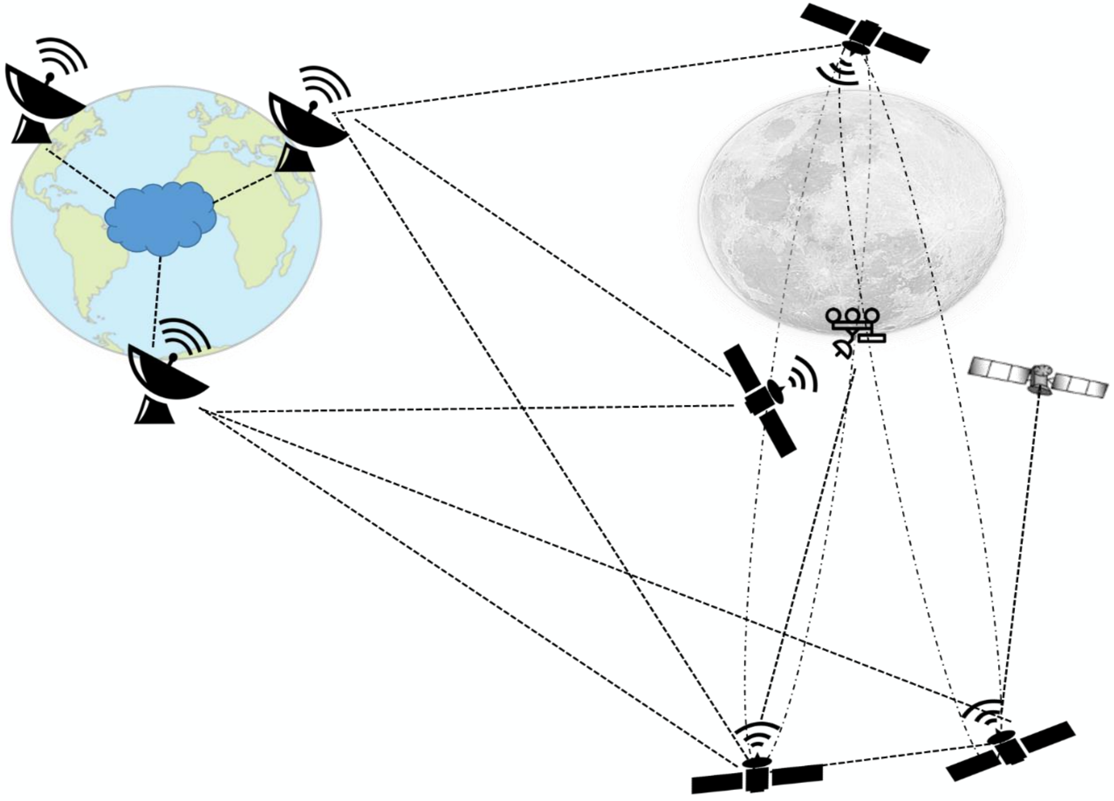
# MOON STATION POTENTIAL BENEFITS - LCNS

1) **Improved Orbit Determination & Time Synchronisation** of LCNS satellites:

- Much improved geometry for ranging observations with LCNS satellites compared to the-Earth based observations, which all observe the orbits from approx. the same direction.

    Better geometry => faster convergence

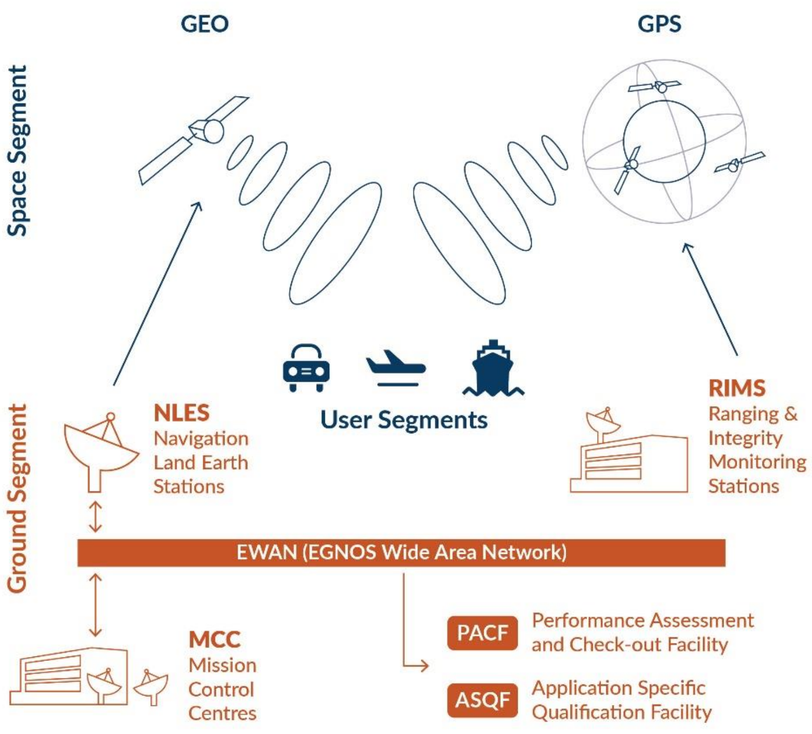
    and better accuracies for orbit predictions



# MOON STATION POTENTIAL BENEFITS - LCNS

2) **Monitoring of Signal in Space**, similar to EGNOS RIMS or Galileo Sensor Stations on Earth:

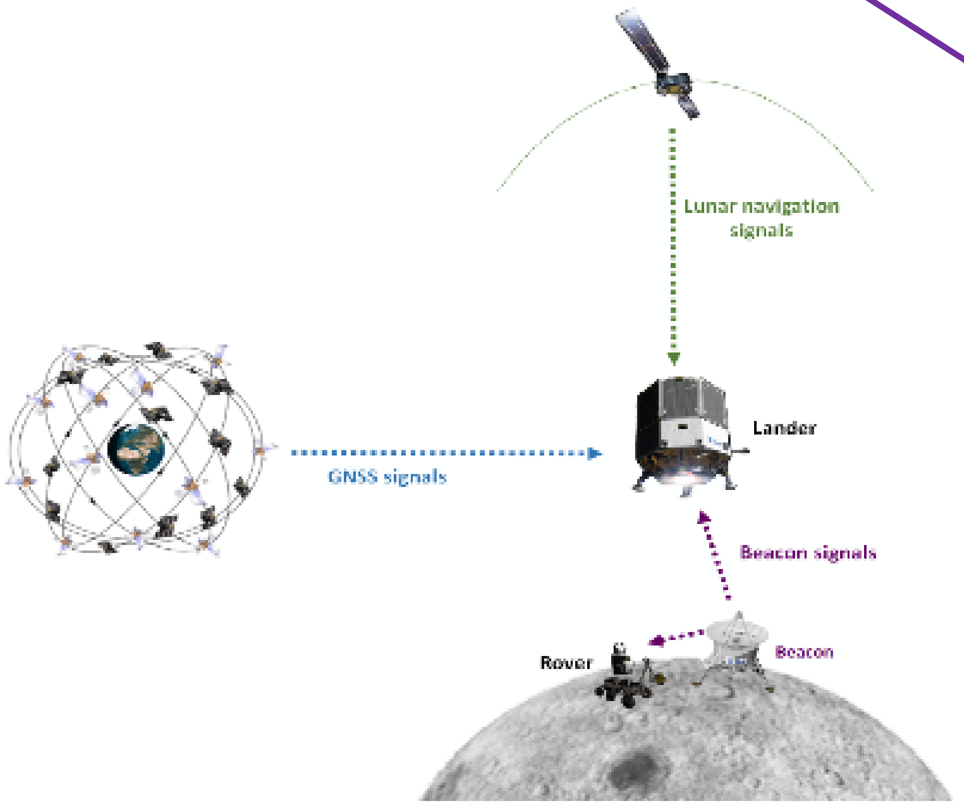
- Generate differential corrections:
    - Moon Station at fixed known position allows for differential corrections to broadcast LCNS navigation message (predicted satellite orbit position and clock offset) can reduce Signal in Space Error (SISE) and thus improve the positioning performance.
    - Lack of atmosphere allows Moon Station corrections to be effective over long baselines
- Generate alerts to support critical operations such as Entry, Descent and Landing (EDL) phase
- Evidence for SLAs with LCNS customers
- LCNS system validation and verification – including multi-technique ranging for cross-validation

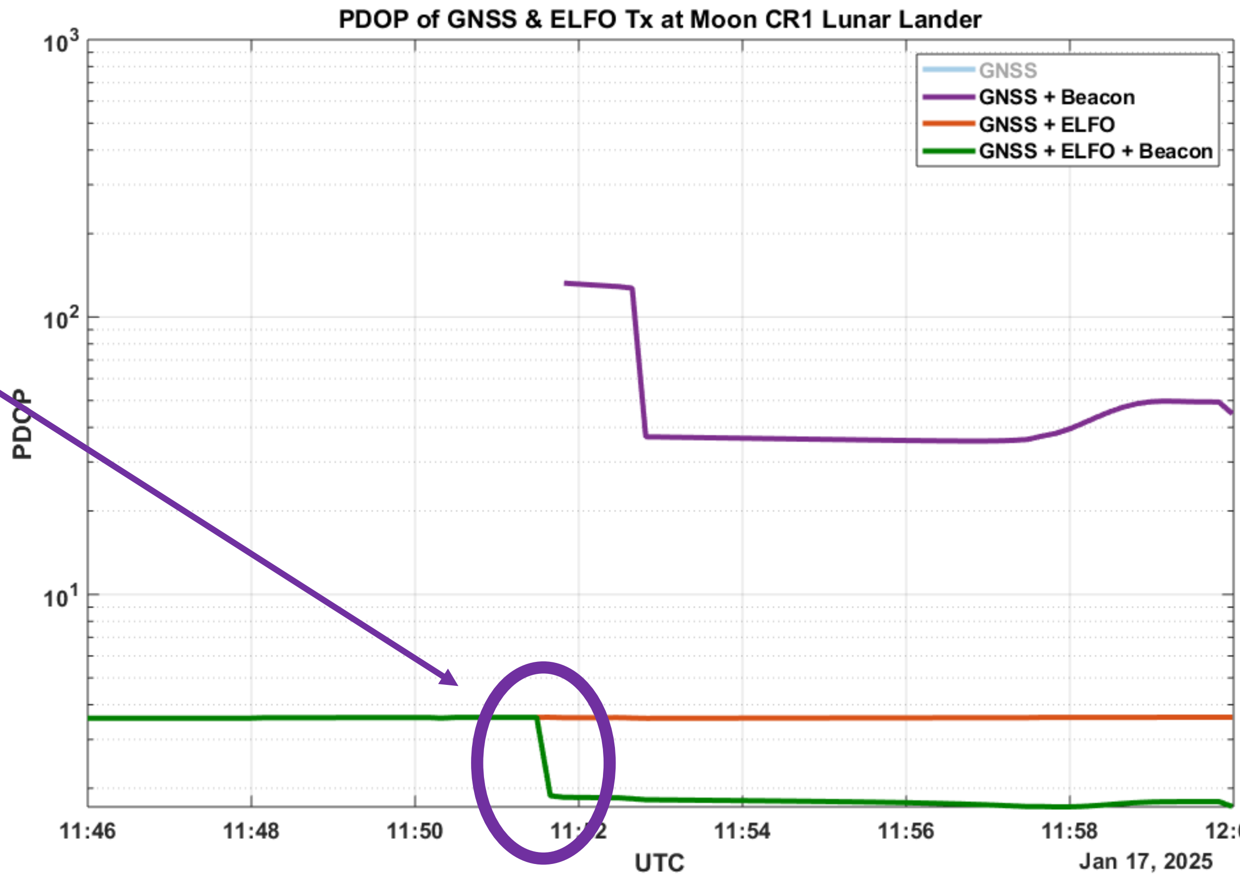


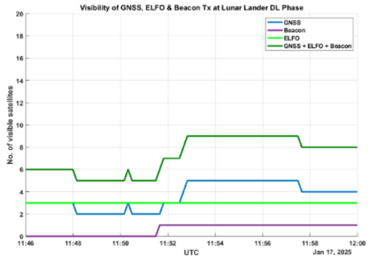

Equivalent on Earth with EGNOS
https://egnos-user-support.essp-sas.eu/new_egnos_ops/egnos-system/about-egnos

# MOON STATION POTENTIAL BENEFITS - LCNS

3) **Additional ranging source** to improve geometry for user and reduce Dilution of Precision:

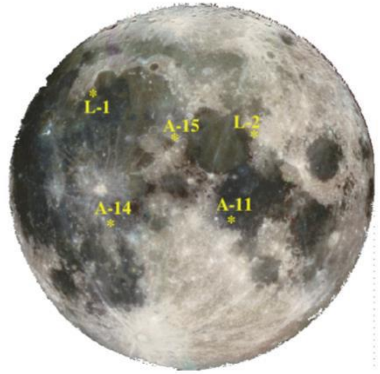


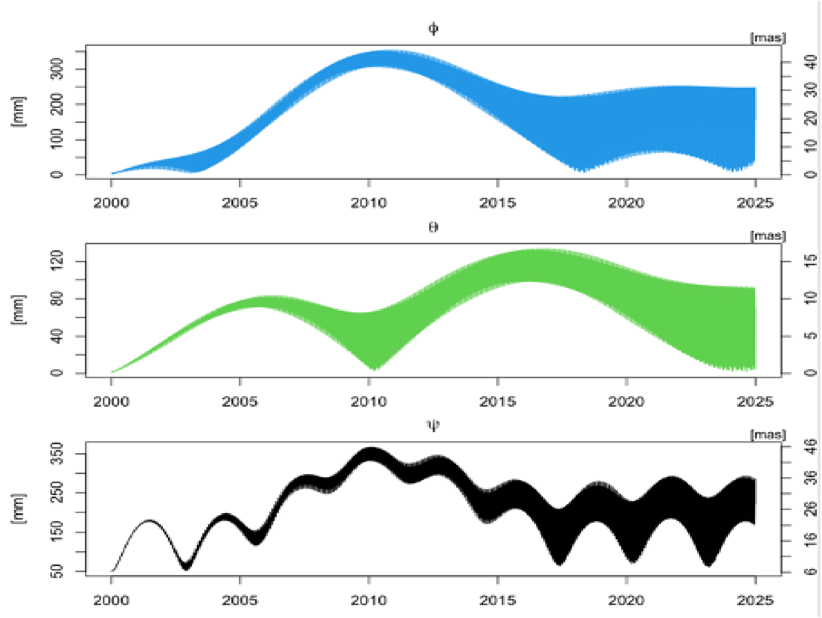




- Near-far effect for users close to beacon need to be mitigated
- Large curvature of moon limits the coverage of beacon signal for surface users

# MOON STATION POTENTIAL BENEFITS – Science (and Moonlight!): Selenodesy




*Location of the existing Lunar Laser Retro Reflectors (note the gap at the South Pole)*




*Propagation covariance INPOP21a (1-sigma)*

- At present, the precision and accuracy of Lunar reference frames are limited by data accumulation, physical modelling and numerical fit
- With the most up-to-date modeling, the precision of the libration angles is estimated between 30 to 50 cm over 5 years
- An additional station on the Moon surface would:
  - Improve the geometric coverage of the Moon surface
    - Disentangle the different contributions of the libration mis-modeling
    - Characterize and improve frame accuracy (especially from a multi-technique station)
    - Support the study of physical unknowns (e.g., solid core displacement, visco-elastic contribution to deformation)
  - Increase the amount of collected data

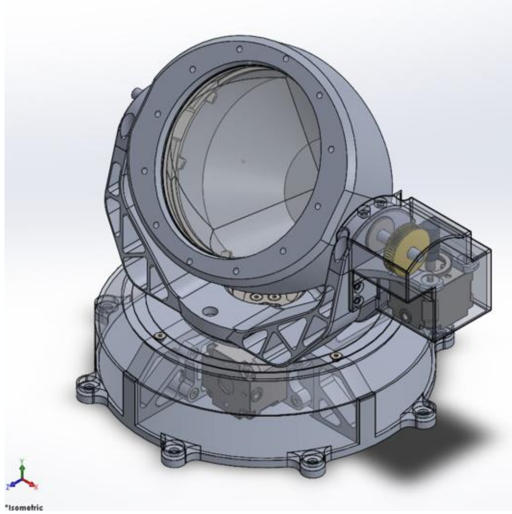
# MOON STATION POTENTIAL BENEFITS – Science: Fundamental Physics

Laser ranging experiment to the Moon are routinely used to test Einstein's Equivalence Principle.

The MoonLIGHT Pointing Actuator (MPAc) experiment is placing a 100 mm corner cube reflector on the Moon (@Rainer Gamma). The hardware will allow reaching mm-level accuracy in LLR measurements and improving General Relativity tests:

| Science measurement / Precision test of violation of General Relativity | Apollo/Lunokhod * few cm accuracy | MoonLIGHTs ** mm |
|---|---|---|
| Parameterized Post-Newtonian (PPN) β | $\|\beta-1\| < 1.1\times10^{-4}$ | $10^{-5}$ |
| Weak Equivalence Principle (WEP) | $\|\Delta a/a\| < 1.4\times10^{-13}$ | $10^{-14}$ |
| Strong Equivalence Principle (SEP) | $\|\eta\| < 4.4\times10^{-4}$ | $3\times10^{-5}$ |
| Time Variation of Gravitational Constant | $\|\dot{G}/G\| < 9\times10^{-13}yr^{-1}$ | $5\times10^{-14}$ |
| Inverse Square Law (ISL) - Yukawa | $\|\alpha\| < 3\times10^{-11}$ | $10^{-12}$ |
| Geodetic Precession | $\|K_{gp}\| < 6.4\times10^{-3}$ | $6.4\times10^{-4}$ |

* Williams et al., PRL 93, 261101 (2004).
** Martini et al., Plan. & Space Sci. 74 (2012), 276-282.
** Ciocci et al., Adv. Space Res. 60 (2017), 1300-1306.
** Dell'Agnello et al., in Frascati Physics Series Vol. 66 (2018).



Rubino et al, Jul 2021

Additional CCRs deployed at dedicated sensor stations will help to further improve those limits.

# MOON STATION POTENTIAL BENEFITS – Science: Fundamental Physics

Observation of quantum correlation strength in photonic states over:

- Long distances
- Large variations of the gravitational potential

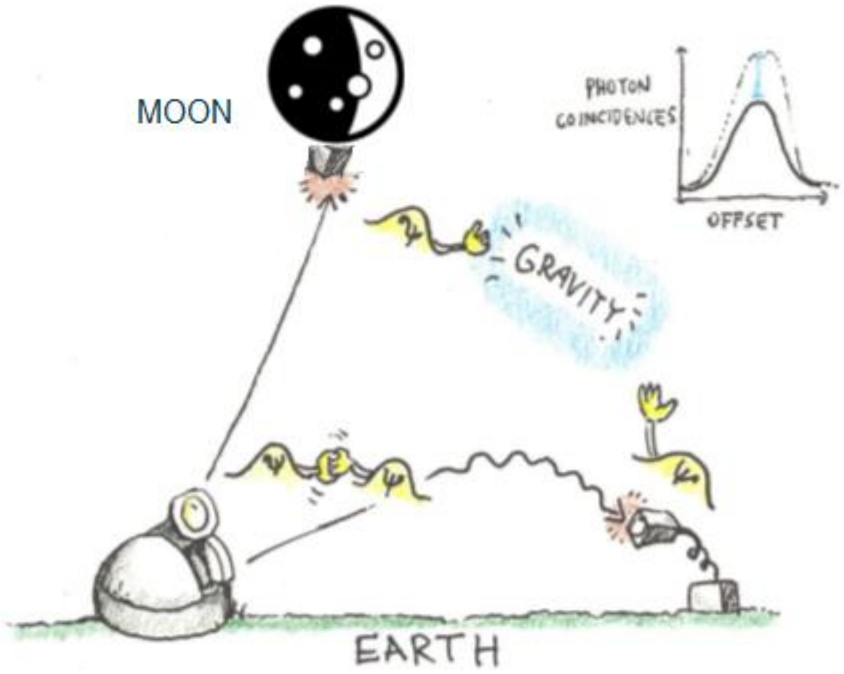
A number of theoretical models attempt to predict how quantum correlations evolve in a curved space–time with contradicting results.

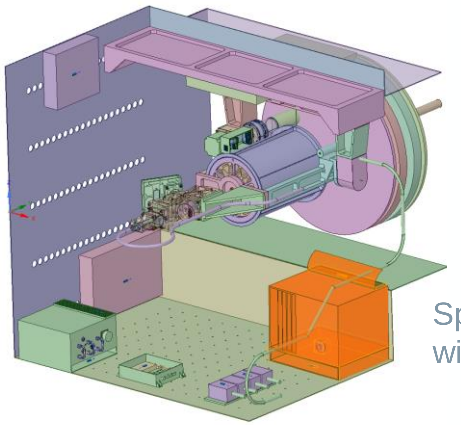
In the experiment, a pair of entangled photons is generated on the Earth. While one photon is detected locally, the other is sent towards the Moon sensor station and detected there.

A sensor station equipped with a polarization-sensitive single-photon detection system can be used to test the boundaries between quantum mechanics and general relativity.

The experiment can additionally be used to:

- Synchronize clocks at the sensor station to ground clocks
- Test quantum cryptography and quantum key distribution schemes
- Develop space-grade technology



SpaceQuest mission with ISS

# MOON STATION POTENTIAL BENEFITS – Science: Ionosphere

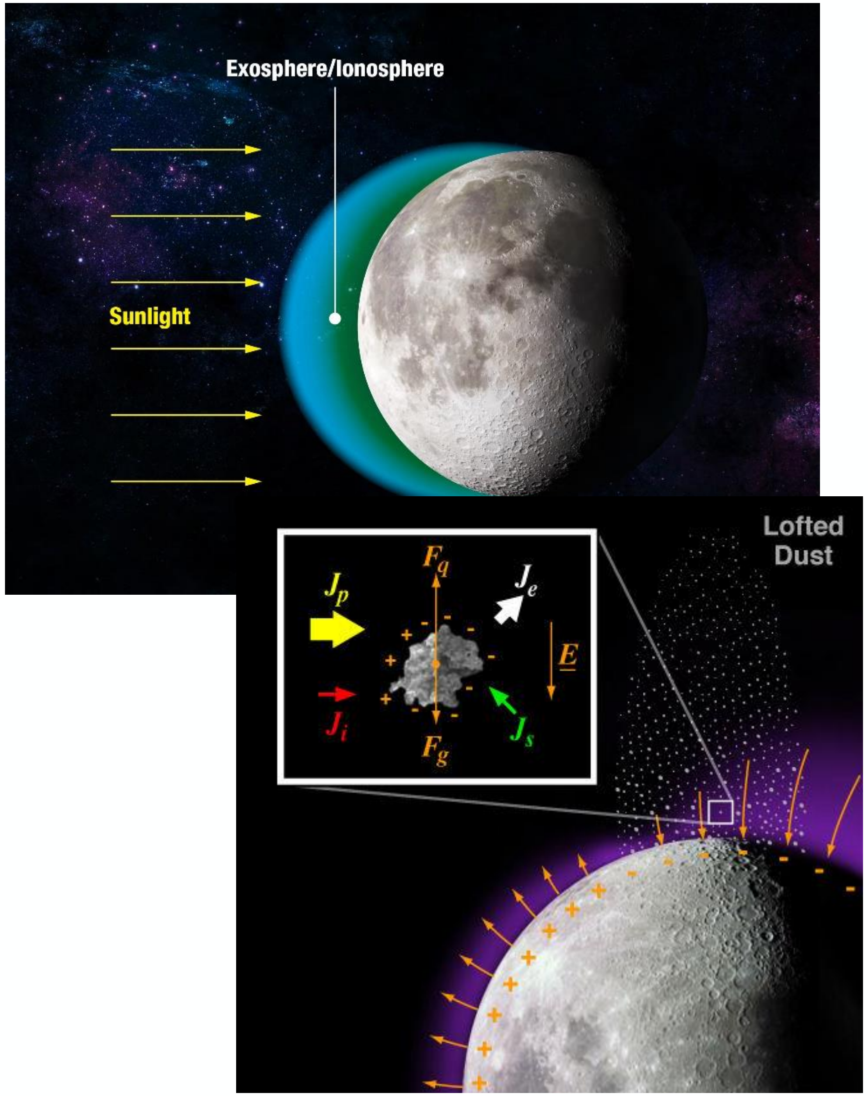
Thin lunar exosphere in combination with dust clouds supports a low density lunar ionosphere that is not well understood.

Ionosphere made of ionised dust instead of gas is new to planetary science.  Unknown variation with time, moon phases and solar cycles.

Moon Station LCNS receivers could support this analysis observing the navigation signal delay similar to Ionospheric monitoring on earth with GNSS Sensor Stations

Some adaption needed due to single frequency navigation signal but aided by lack of tropospheric effects around the moon.

**OTHER IDEAS FOR SCIENTIFIC BENEFITS?????**

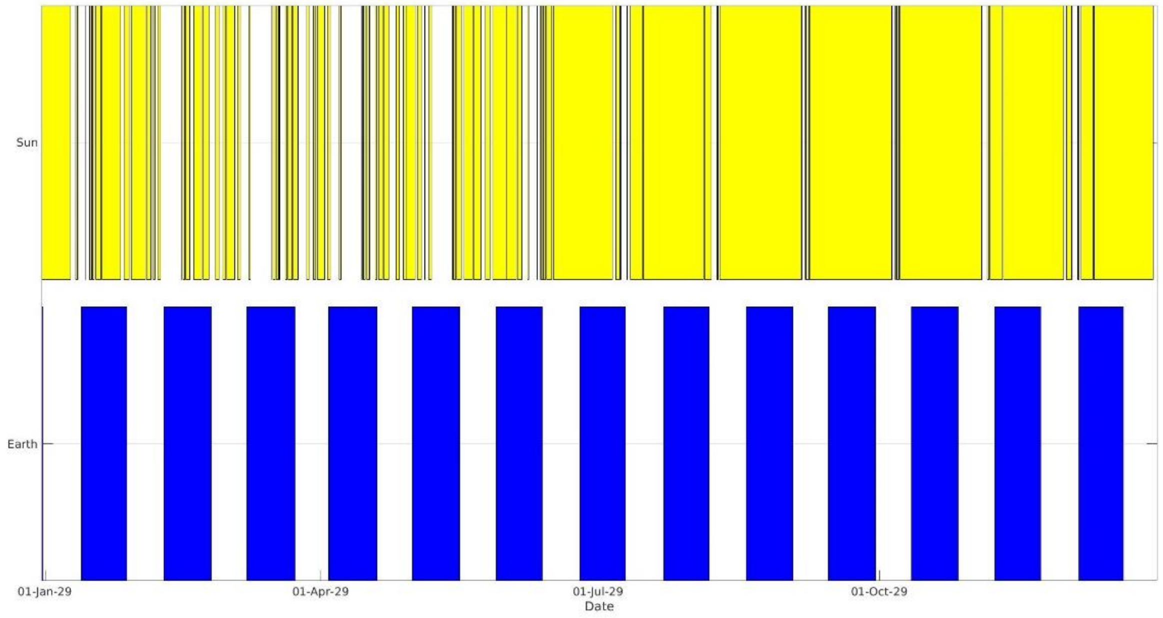



Credit: NASA

# LUNAR ENVIRONMENT & CONSTRAINTS: SOLAR POWER & EARTH VISIBILITY

Lunar equatorial region has an approx. 14 earth day/night cycle but South Pole has areas of very high sun illumination

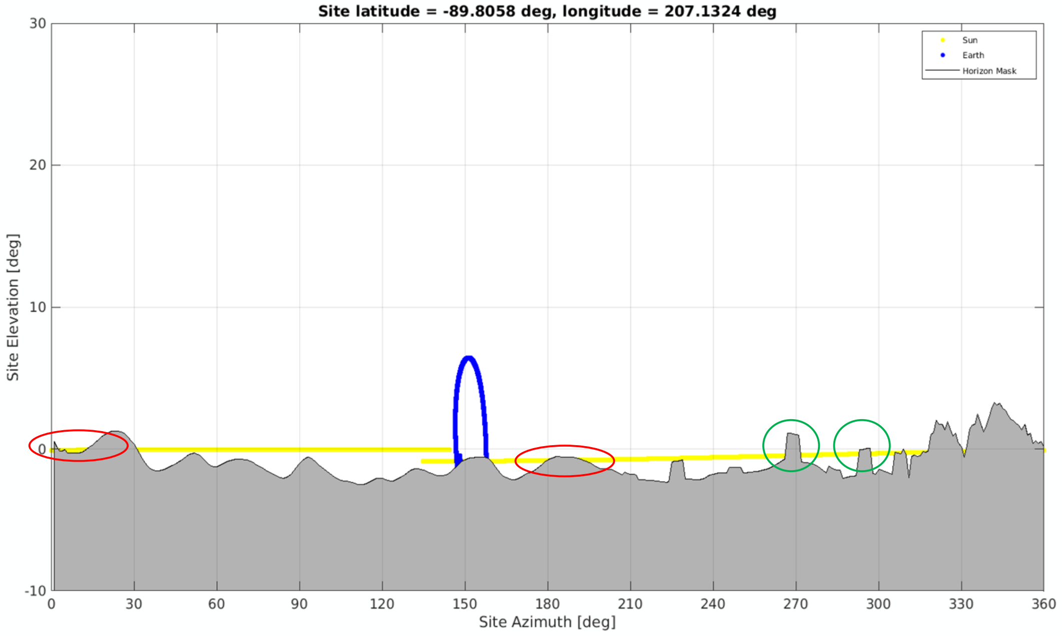
However, large variation in sun illumination (and earth visibility) depending on selected landing site, height above the surface and the mission timeframe (seasonal variations):




Shackleton crater rim, Sun and Earth visibility for 2029

Impacted by the local terrain mask:

- Examples of unpredictable transients with Sun at edge of horizon marked in Red
- Example full illumination blockages marked in Green



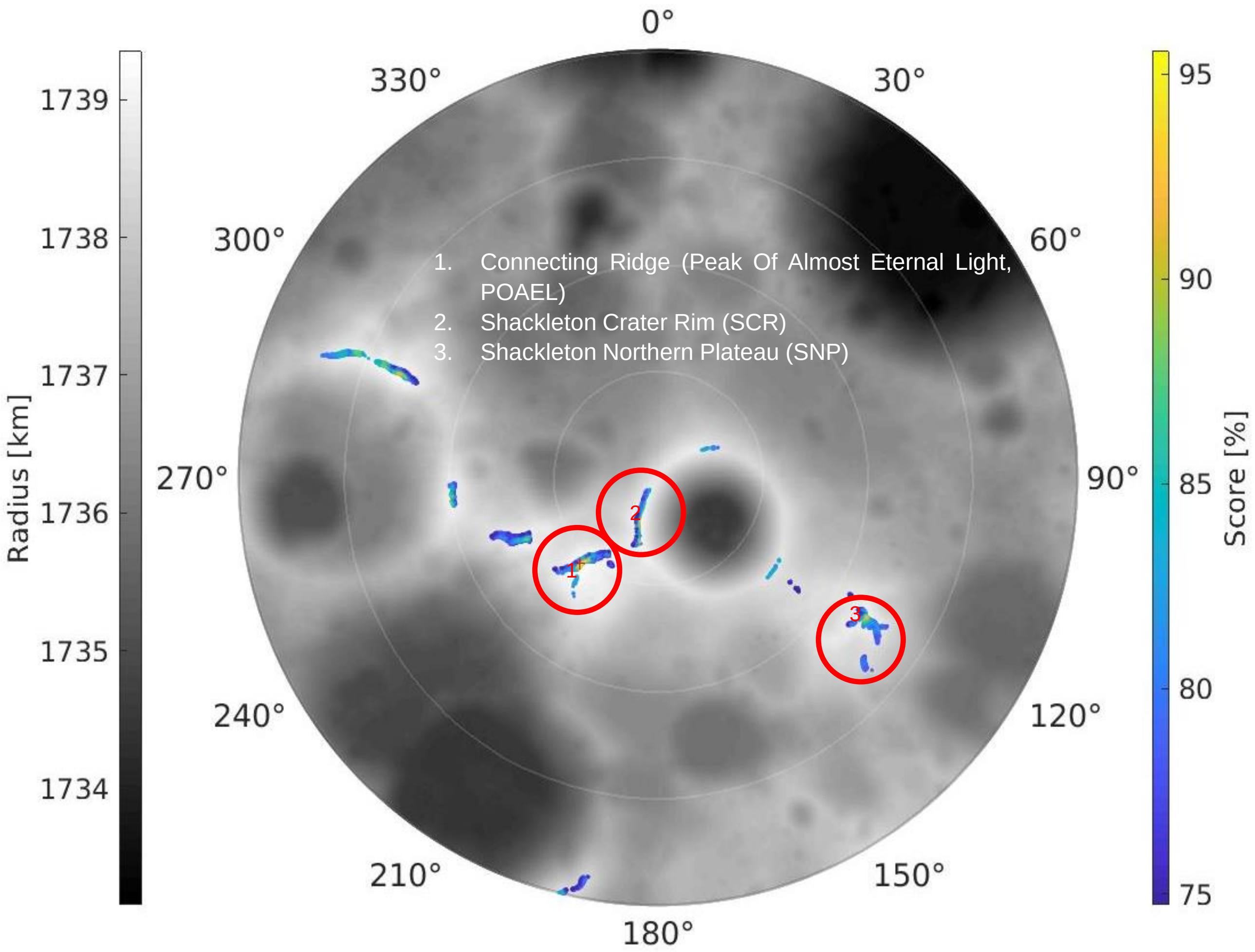

Shackleton crater rim, solar transient analysis

Analysis from ESA POLESTAR CDF

# LUNAR ENVIRONMENT & CONSTRAINTS: LANDING SITES

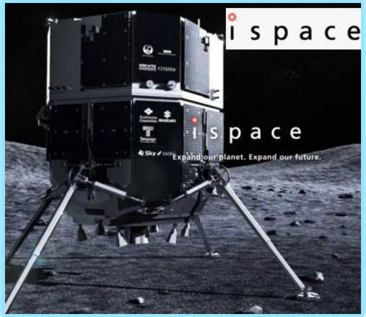
Potential South Pole landing areas can be defined according to the current lander capabilities and a sun illumination sizing case:

- >200m landing ellipse (Moonlight can help here!)
- AND average illumination is equal to or above 50 % over the simulated timeframe
- AND the longest continuous shadow period does not exceed 14 consecutive Earth days
- AND the slope does not exceed 15 degrees




Analysis from ESA POLESTAR CDF

# LUNAR ENVIRONMENT & CONSTRAINTS: LANDER CAPABILITIES





Many different lander options in development (CLPS, LSAS, EL3) all with their own characteristics and capabilities.

Limited resources for payload in terms of:

- Mass (16-1700kg @ ~1M$/kg)
- Volume
- Power/energy provision especially during lunar night
- Data link to Earth
- Dust/radiation protection
- Landing accuracy in terms of location and orientation (azimuth and elevation)

Additional constraints in terms:

1. mass distribution and payload units placement
2. heat exchanged with lander => units that need tight temperature control such as atomic clocks means large radiators and powerful heaters to manage extreme hot and cold cases.
3. distance from surface

# MOON STATION FUNCTIONAL ANALYSIS

In order to realise the potential benefits:

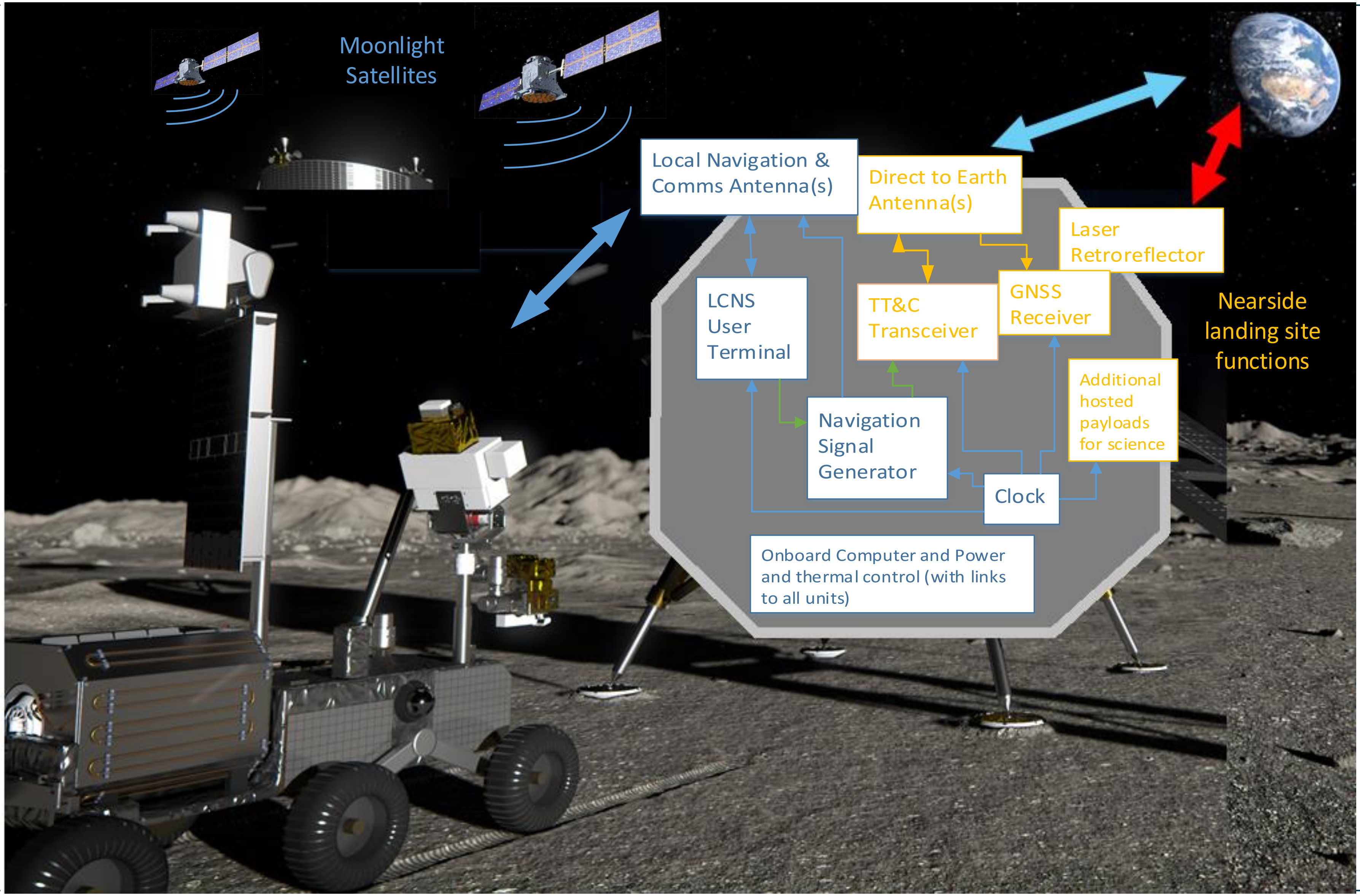
Core Functions:

- Perform ranging/doppler/time synchronisation with LCNS system
- Generate a navigation signal that augments or complements the LCNS satellite one-way signals (additional source and/or corrections to satellites signals)
- Receive and monitor the LCNS satellite navigation signals
- Exchange data with Earth (via TT&C DTE link or LCNS comms User Terminal)

Additionally for near-side stations:

- Perform ranging/doppler with Earth using multiple techniques: PN ranging, LRR, VLBI, SBI, GNSS
- Host additional units such as single photon detector for quantum experiments

# MOON STATION HIGH-LEVEL ARCHITECTURE




Initial budget estimations:
Mass: 30-65kg
Power: 100-180W

Inc. all margins

Exact payload budgets dependent on potential reuse of lander capabilities for payload functions (TT&C, OBC, PSU etc)

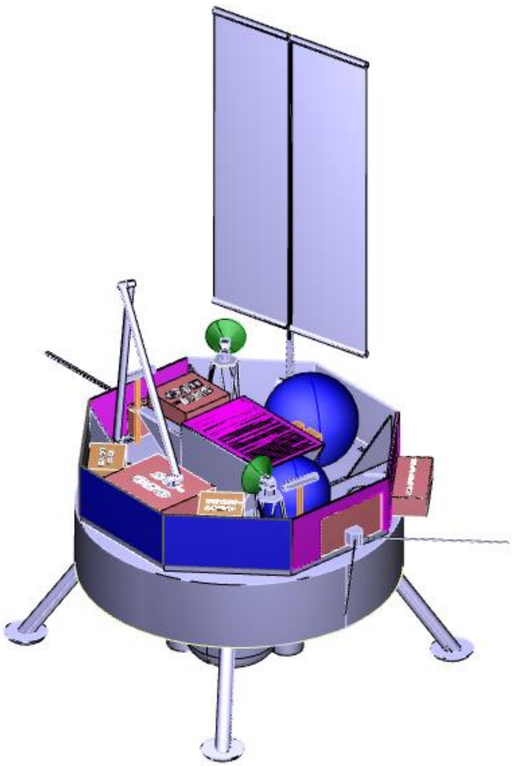
# CONCLUSIONS & ROADMAP

Stations located on the lunar surface have the potential to greatly improve the Moonlight system performance as well as provide significant benefits to science

However, the lunar environment is harsh and the journey from earth to the landing site is arduous, which puts significant constraints on the station design and implementation especially for any long term operation on the surface.

An activity to study the potential and constraints in more detail and breadboard the needed critical functionalities is due to start shortly as part of the ESA NAVISP programme: **NAVISP ELEMENT 1-62:** PNT MOON SURFACE BEACON DEMONSTRATOR

The next step after this could be an in-space technology demonstrator or initial deployment with the Moon Station being a hosted payload aboard one of the lunar landers such as ESA's European Large Logistics Lander (EL3)



# QUESTIONS?

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