



Exploring the Moon using the Moonlight navigation service

Brijuni Conference, August 30th, 2022

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Quality

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We are going back to the Moon.....



Credits: BBC Science Focus Magazine

... and stay there

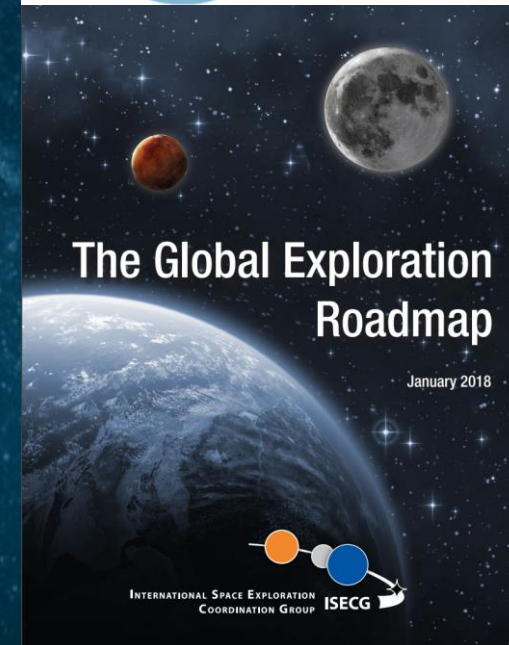
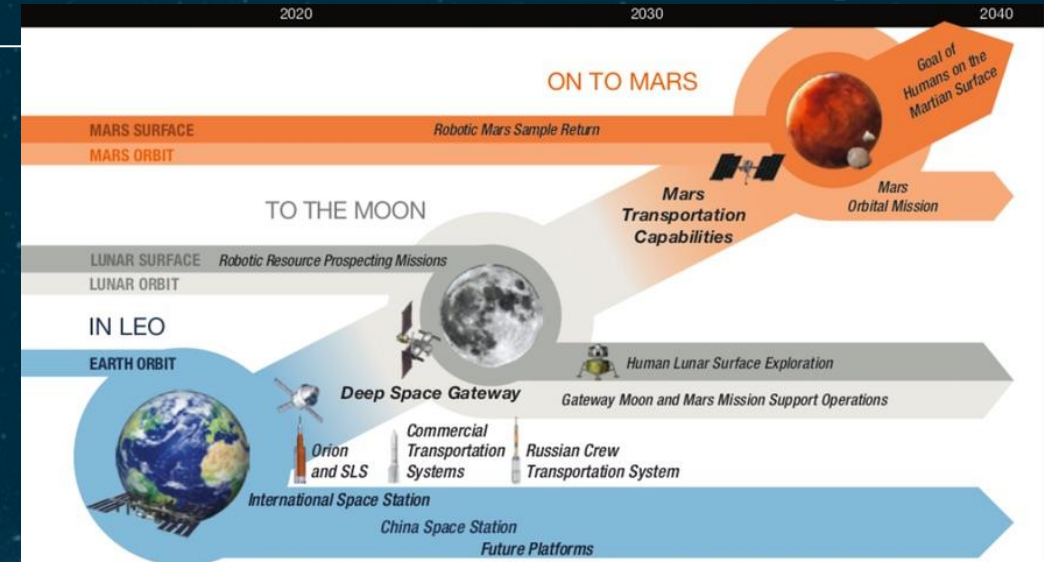
Why the Moon? Institutional plans

Institutional plans

International roadmap for exploration consider the Moon as the gateway for future human explorations

NASA and other space agencies has long standing plans for a Moon stable human base together with orbiting Lunar Gateway

ESA participation planned on Orion, Lunar Gateway (e.g. iHAB) and is planning his own missions: European Large Logistic Lander (EL3) and Cis-lunar transfer vehicle (CLTV)



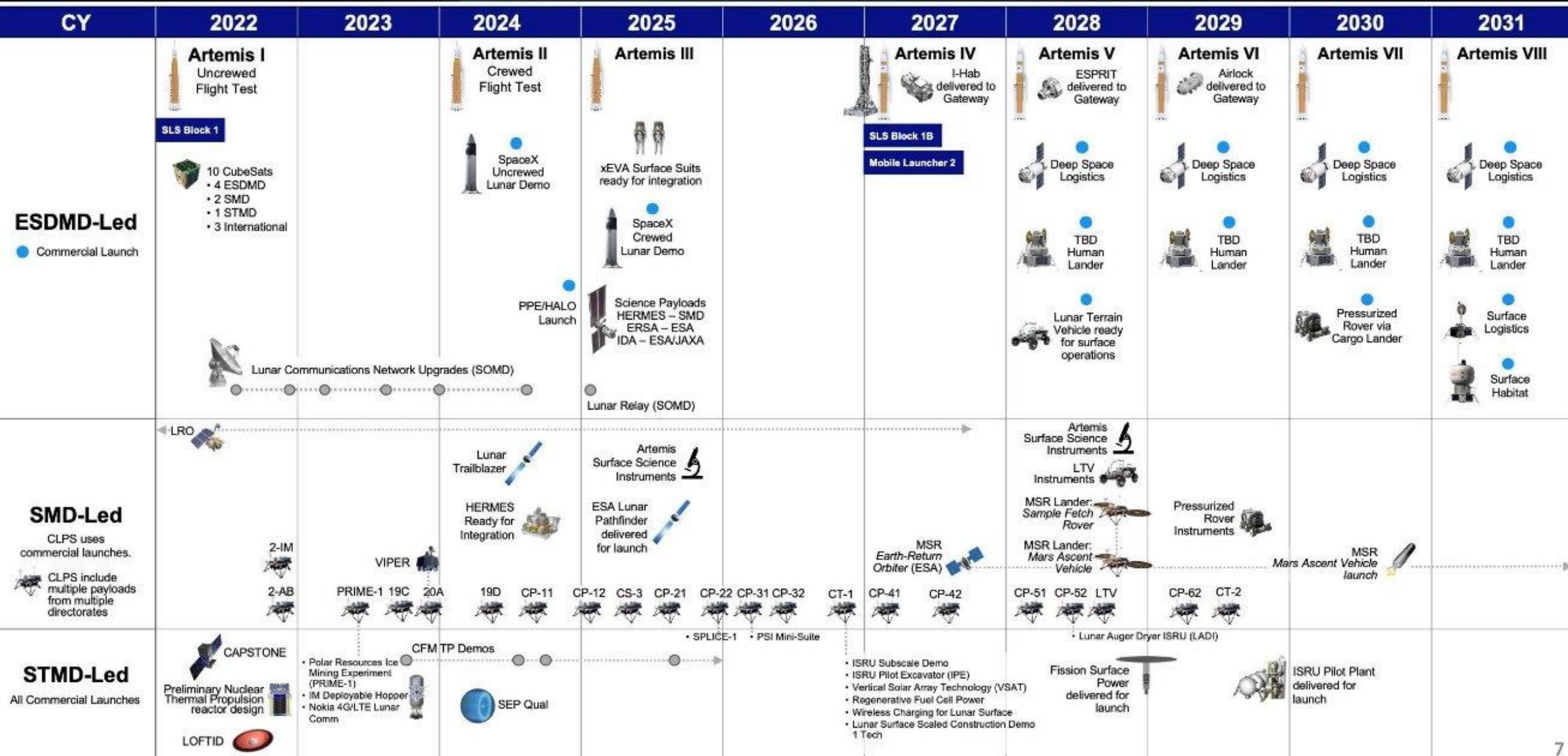
GLOBAL EXPLORATION ROADMAP CRITICAL TECHNOLOGY NEEDS

2019 International Space Exploration Coordination Group Technology Working Group

GER-018 – PRECISION LANDING WITH HAZARD AVOIDANCE

- Need 90m accuracy at 3-sigma uncertainty relative to pre-mission identified landing location. Need 0.3m (rock diameter) hazard recognition and avoidance as horizontal ground resolution.

Moon to Mars Planning Manifest



Imagery is meant to represent the calendar year in which the launch occurs. Does not include impact from FY22 appropriations.

Why the Moon? Commercial plans

Commercial plans

Moon resources might be very valuable

Multiple commercial companies planning to offer periodic flights to the moon

OUTDATED?



Billionaire closer to mining the trillions of dollars in riches

PUBLISHED TUE, JAN 31 2017 • 8:13 AM EST | UPDATE



Is Moon mining...



Op-ed | What is the best way to mine the moon?

NOKIA



MARKET LAB

AIRBUS

ASTROBOTIC



OHB

SURREY

"For us at Airbus Defence and Space, the moon is a very important topic," said Bart Reijnen, senior vice president of on-orbit services and exploration at Airbus Defence and Space. "Astrobotic is what we see as being the frontrunner in the world of commercial lunar transportation."

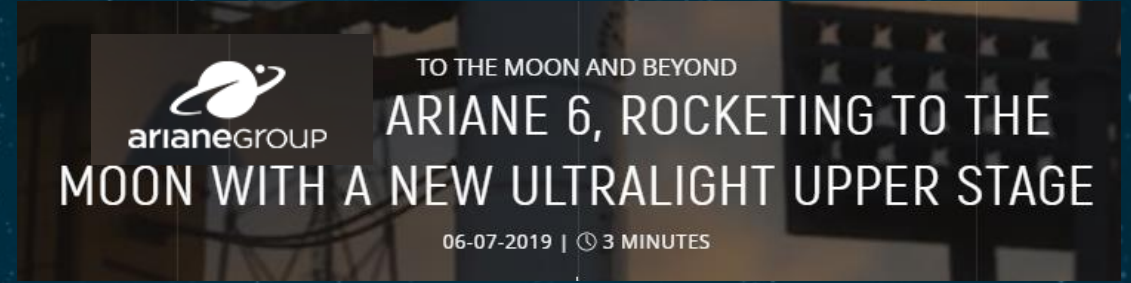
BLUE ORIGIN

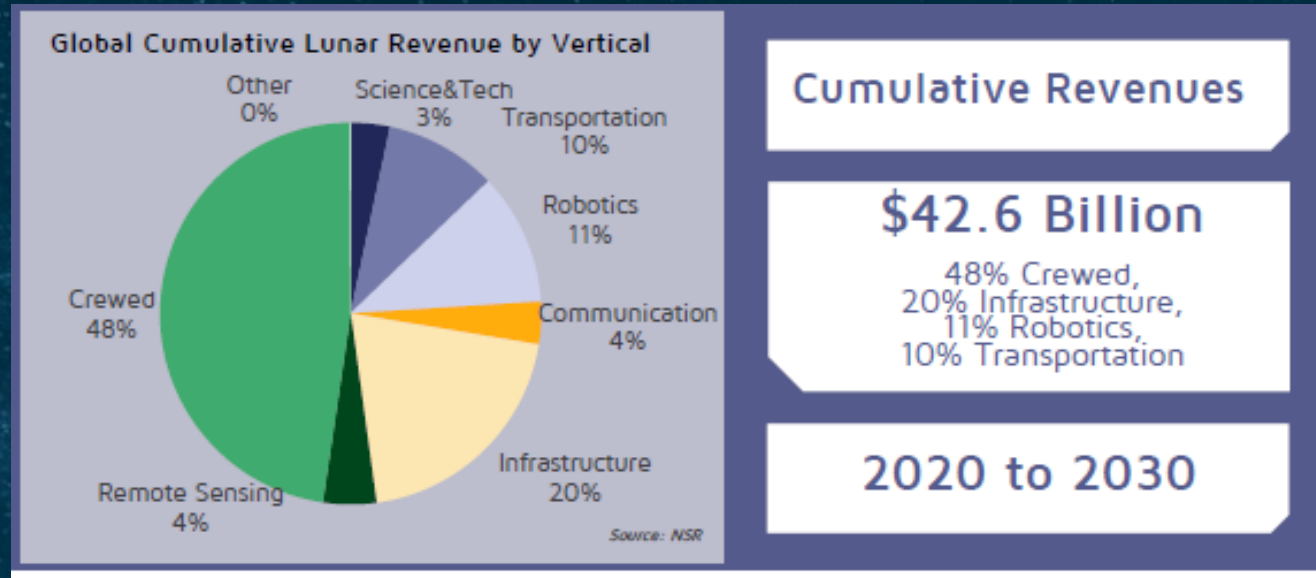
Why the Moon? Commercial plans

Nokia selected by NASA to build first ever cellular network on the Moon



Nokia selected by NASA to build first ever cellular network on the Moon





- The Moon market is strongly driven by North America programs and activities and by crewed missions.
- The East vs. West race is likely to be a driver for lunar market and growth of opportunities .

- Business cases for commercial players are still in development as majority of opportunities are government-driven and funded.

Source: NSR “Moon Market Analysis” 2021

Moon exploration is the next global strategic priority in space exploration

A large number of missions planned already for this decade, requiring all their own Com & Nav provision means

The current model is not cost effective

Opportunity to ignite new services and contribute to sustainable Moon economy by providing a dedicated Lunar COMM and NAV infrastructure

Commercial Lunar Payload Services

- CLPS-delivered science and technology payloads

Large-Scale Cargo Lander

- Increased capabilities for science and technology payloads

Early South Pole Mission(s)

ESA UNCLASSIFIED - For Official Use

- First robotic landing on eventual human lunar return and In-Situ Resource Utilization (ISRU) site
- First ground truth of polar crater volatiles

Humans on the Moon - 21st Century

First crew leverages infrastructure left behind by previous missions



ESA Roadmap vision for Lunar Navigation Services

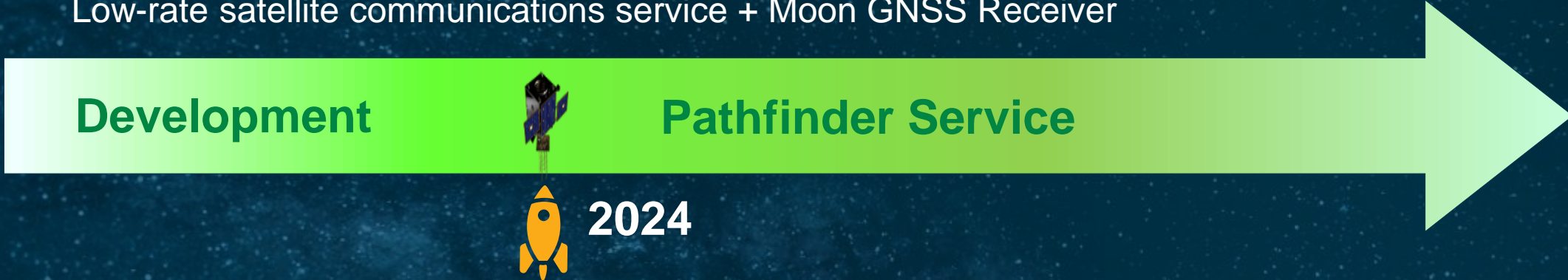


Phase 1: Use of Existing Earth-based GNSS Systems (2023 – 2027)	Phase 2: Moonlight NAV Initial Services (GNSS from Moon orbit) (2027 – 2035)	Phase 3: Moonlight NAV enhanced services (full Moon coverage) (2035 – onwards)
<p>Preliminary Lunar PNT services</p> <p>Supporting Earth-to-Moon transfer and Lunar orbit</p>	<p>Initial Moonlight Lunar PNT services</p> <p>Supporting low lunar orbit, Lunar landing and lunar surface navigation (South Pole coverage)</p>	<p>Enhanced Moonlight Lunar PNT services</p> <p>Full lunar surface coverage</p> <p>Improved PNT accuracy and availability services</p> <p>Integrity for PNT safety related applications</p>
<p>Earth-based GNSS (Galileo and GPS)</p> <p>Use of high-sensitivity GNSS space receivers with high-gain antennas</p> <p>Lunar Pathfinder GNSS Payload IoD</p>	<p>Earth-based GNSS (Galileo and GPS)</p> <p>Initial Lunar Navigation Satellites constellation GNSS-like services</p> <p>MOONLIGHT / LCNS: Initial Services</p>	<p>Enhanced Lunar Communication and Navigation Satellites constellation GNSS-like services</p> <p>Moon surface PNT Beacons / Local PNT Moon differential augmentations</p> <p>MOONLIGHT / LCNS: Enhanced Services</p>



STEP 1: LUNAR PATHFINDER

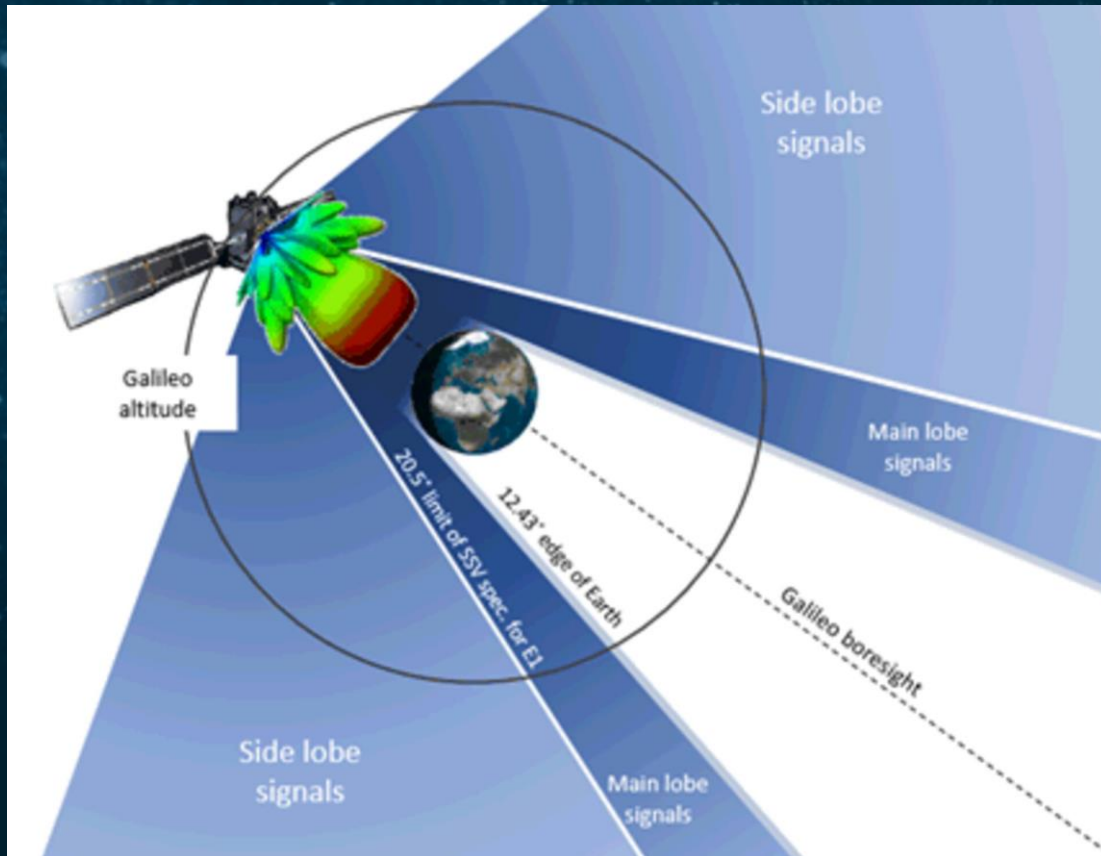
Low-rate satellite communications service + Moon GNSS Receiver



STEP 2: MOONLIGHT CONSTELLATION

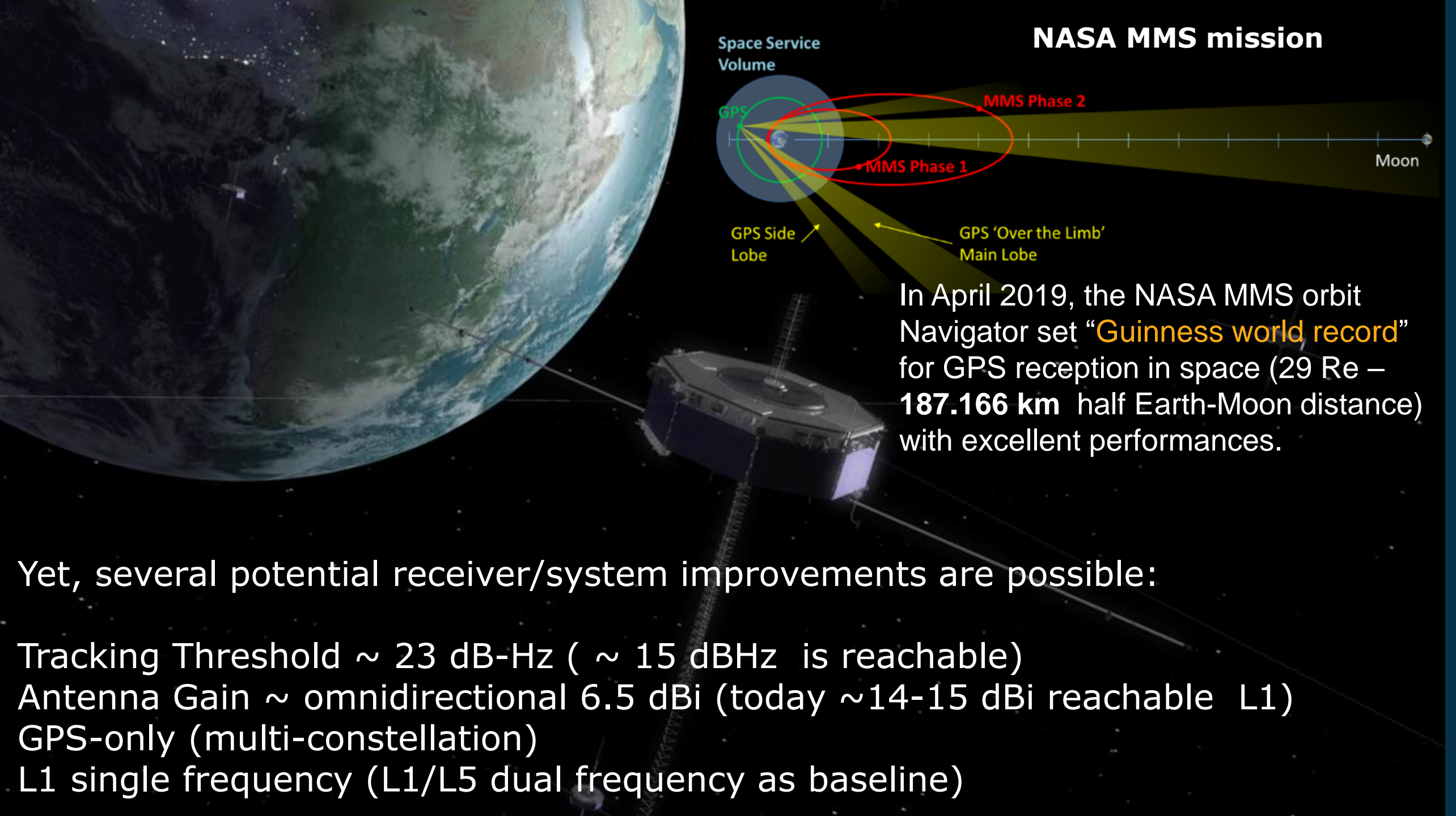
High-data rate satellite communications and navigation service





Some key challenges

- very low signal levels of GNSS signals (large distances and mostly coming from antenna sidelobes);
- Very poor geometry – high DOP
- limited access to navigation data;



NASA MMS mission

Space Service Volume

GPS

MMS Phase 2

MMS Phase 1

Moon

GPS Side Lobe

GPS 'Over the Limb' Main Lobe

In April 2019, the NASA MMS orbit Navigator set “**Guinness world record**” for GPS reception in space (29 Re – **187.166 km** half Earth-Moon distance) with excellent performances.

Yet, several potential receiver/system improvements are possible:

Tracking Threshold ~ 23 dB-Hz (~ 15 dBHz is reachable)

Antenna Gain \sim omnidirectional 6.5 dBi (today $\sim 14-15$ dBi reachable L1)

GPS-only (multi-constellation)

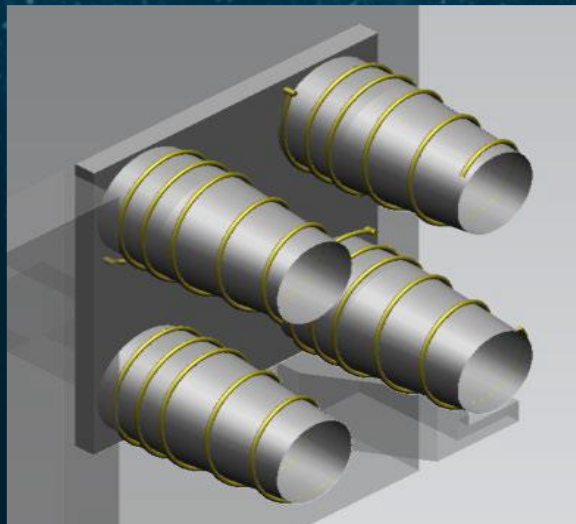
L1 single frequency (L1/L5 dual frequency as baseline)

Lunar Pathfinder experiment – GNSS receiver



Parameter	Value
Acquisition sensitivity	15dBHz
Tracking sensitivity	15dBHz
3D Position accuracy	< 100m RMS
3D Velocity accuracy	< 0.1 m/s RMS
Mass	1.3 Kg
Size	24x12x7cm
Power	< 12W
Constellations	GPS / Galileo L1/E1/L5/E5

SpacePNT NaviMoon Receiver Specifications



Parameter	Value
L1 boresight gain	15 dBi
L5 boresight gain	12 dBi
Polarization	RHCP
Mass	~2Kg
Size	26x26x28cm

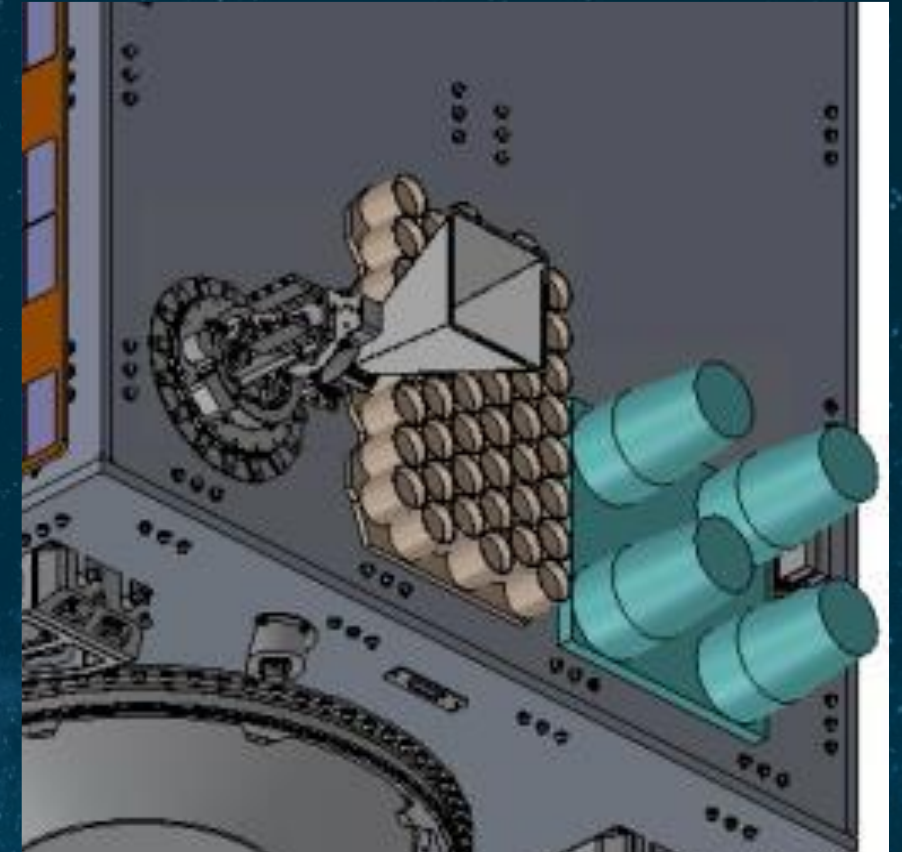
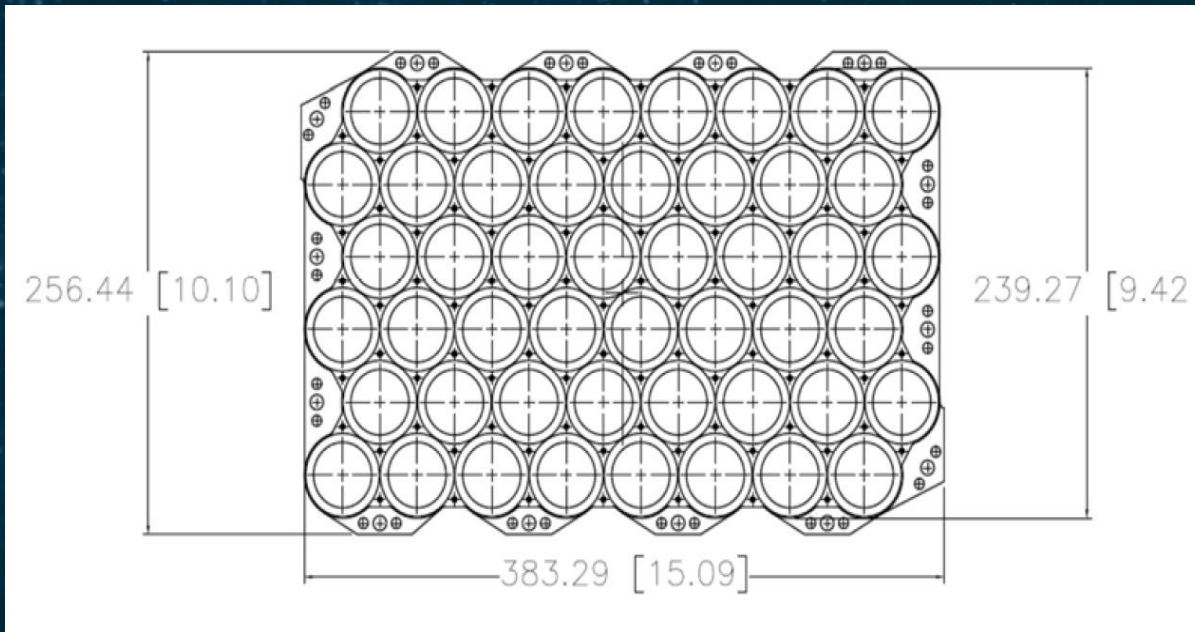
MDA Antenna Specifications

First ever demonstration of GNSS reception on Lunar orbit.



**NaviMoon Receiver and Low Noise Amplifier
Engineering Models delivered**

LRR Under Development by NASA



Technical Description:

- LRR is composed of 48 reflector cubes (1.6" diameter), based on the technology developed and flown by NASA on the Lunar Reconnaissance Orbiter (LRO) - Mass < 4 kg (TBC)

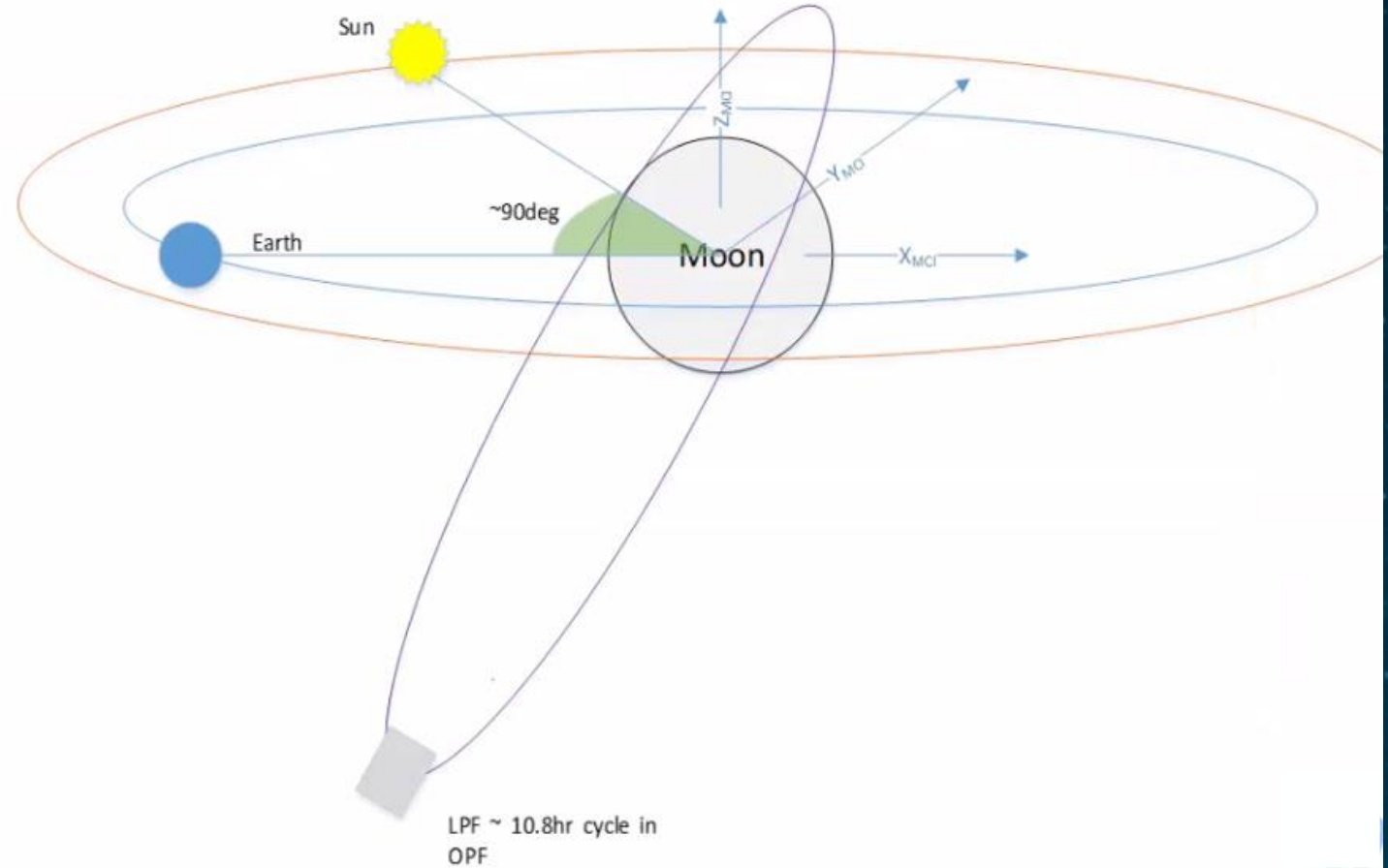
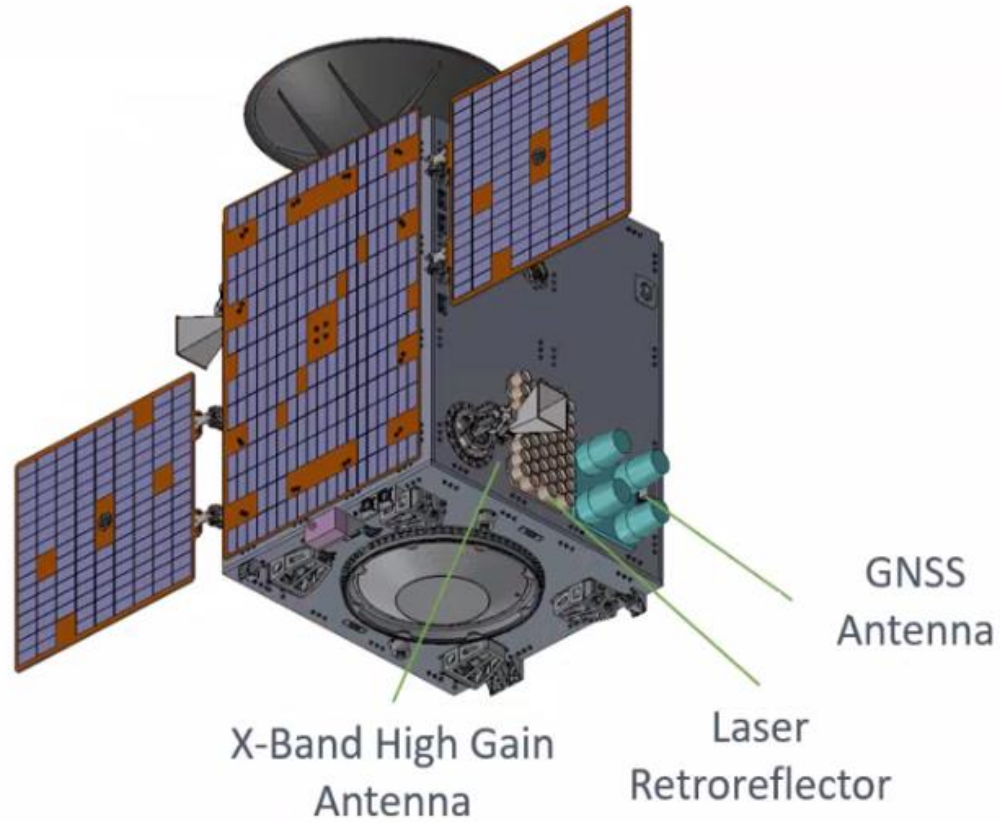
First time ever three ranging techniques (GNSS, Laser and X-band ranging) are used simultaneously on lunar orbit

Lunar-Capable Laser Ranging Stations



- Only four stations within the International Laser Ranging Service (ILRS) currently perform Lunar Laser Ranging: Apache Point, Grasse, Matera, and Wettzell. To this we will add ESA planned enhanced Tenerife-based Laser Ranging station

Lunar Pathfinder Satellite – Launch Q1 2025



001 6871

Lunar Pathfinder experiment performances

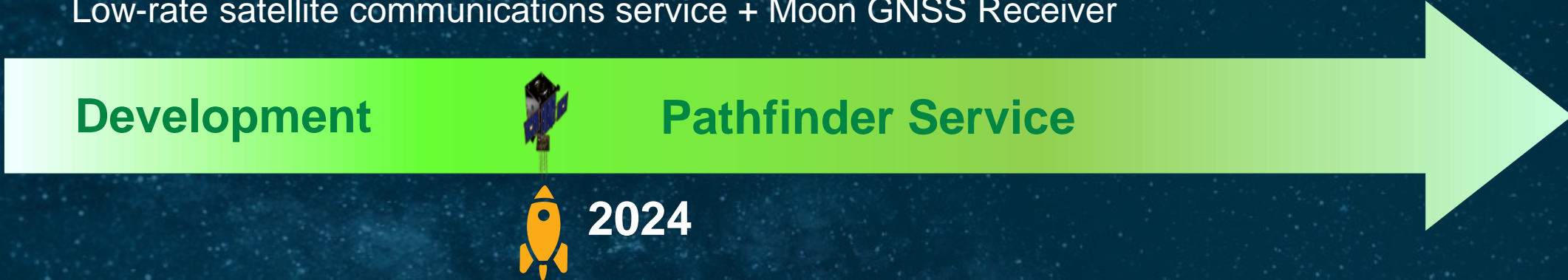
Orbit can be determined **in real-time on-board with accuracy down to 59m 3D RMS** when the receiver is fully **autonomous**, meaning it demodulates the GNSS navigation message from the broadcasted signals

In case the GNSS navigation message is available all the time, **the accuracy is improved down to 41m 3D RMS**



STEP 1: LUNAR PATHFINDER

Low-rate satellite communications service + Moon GNSS Receiver



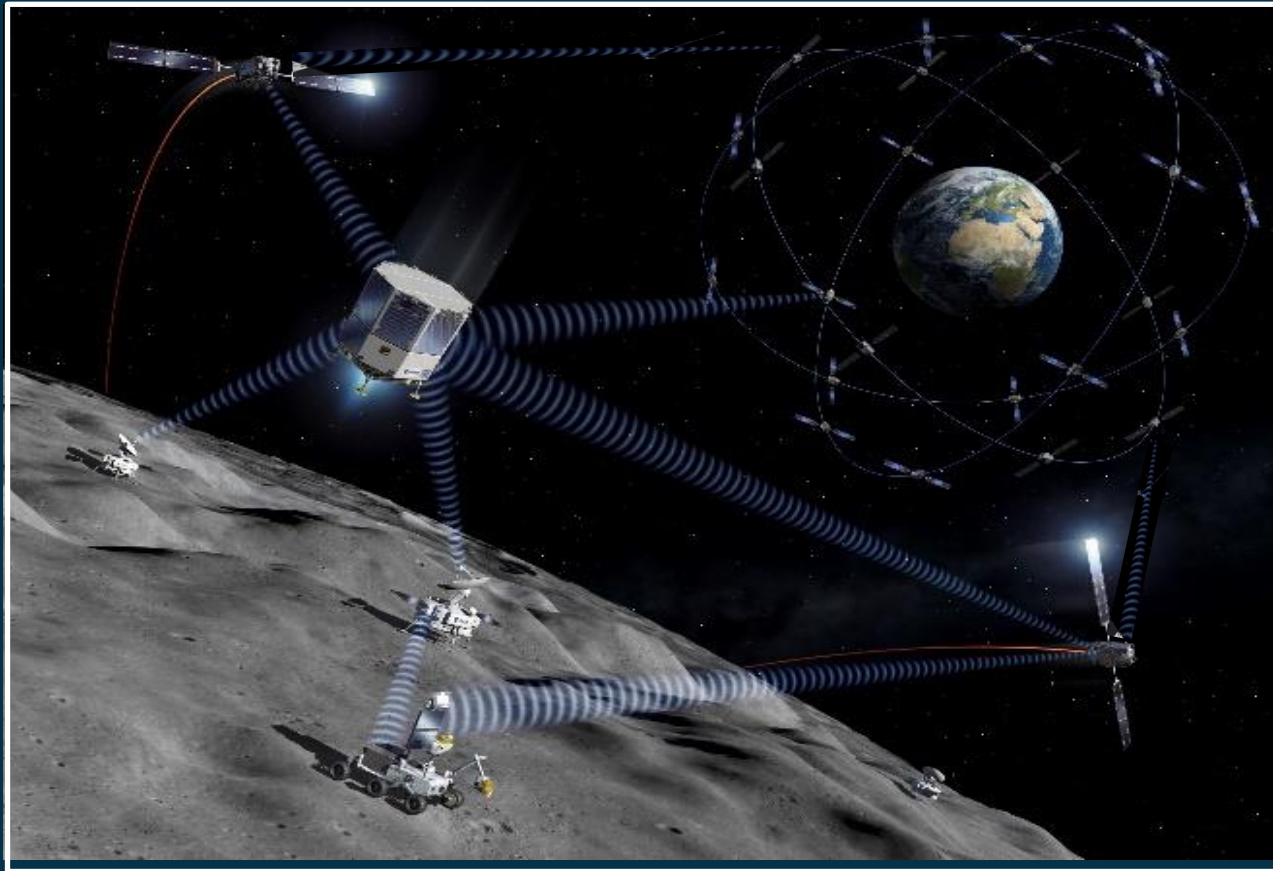
STEP 2: MOONLIGHT CONSTELLATION

High-data rate satellite communications and navigation service



Step 2: Moonlight

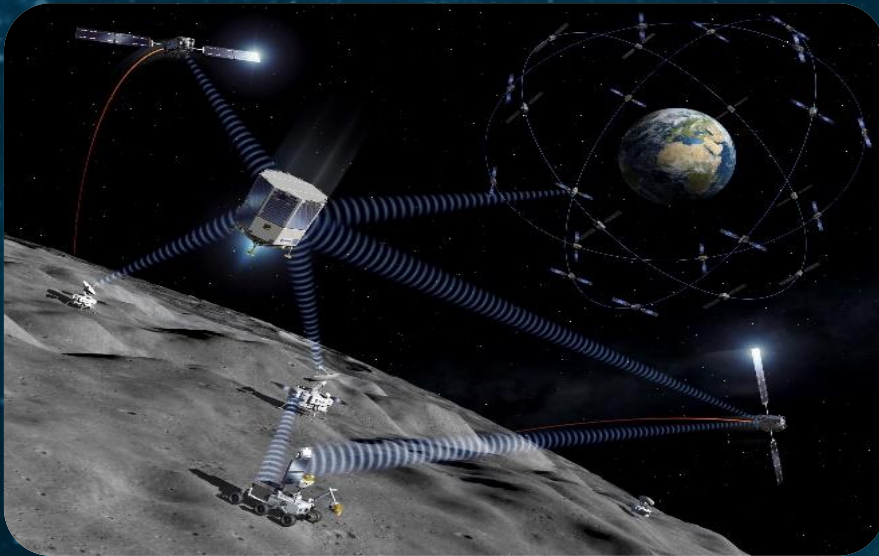
Dedicated Lunar Communication and Navigation System



- Based on the use of GNSS technologies this system will provide real-time position, velocity and time to lunar surface and Cislunar users from 2027
- Moonlight will create a complete new paradigm on lunar exploration and a major boost to future lunar economy:
A great opportunity for Europe !

 Flexible landing site	 Higher Service Availability	 Higher Autonomy of Operations	 Faster Orbit Determination (75%)
 Higher Nav Accuracy	 Higher landing accuracy	 Navigation over night & shadow	 Simpler on-board Nav sensors

Service development Approach: ESA supporting infrastructure development and acting as Anchor customer



Data transport

Tele-operations

Audio/Video streaming

Third-party payloads

Over-the-top Services

Absolute Position

Absolute Velocity

Universal time

Alert & Information

Search and Rescue

- Public-Private Partnership: Private sector as service provider
- A dedicated constellation of satellites around the Moon

Conceptual Moonlight/LCNS System

3. LUNAR SPACE SEGMENT (LSS)

- LCNS satellites will include a Precise orbit determination and time synchronisation (dedicated close-loop from Earth G/S)
- Each satellite will include dedicated NAV Payload transmitting GNSS-like signals (1 way ranging) and, potentially, an enhanced 2-ways lunar NAV service

4. MOON SURFACE SEGMENT (MSS)

- Lunar PNT ranging beacons might be deployed in specific areas (e.g. South pole, permanent sites) to improve ranging geometry, ODTS or provide local area services

5. LUNAR USER SEGMENT(LUS):

- combined COM/NAV users
- NAV only user terminals may also be conceived

1. EARTH GROUND SEGMENT (EGS)

- Dedicated NAV Ground segment providing precise Orbit, time Synchronisation and NAV augmentation messages to Lunar orbiting satellites and Lunar ranging beacons

2. MOONLIGHT CONSTELLATION (LSS)

- An initial constellation of 3 to 5 dedicated Lunar orbiting satellites could be initially envisaged
- System should be upgradable to improve lunar coverage and services and internationally interoperable

Capitalising on ESA's unique GALILEO Expertise

Moonlight – Initial Mission Assumptions



Commercial & Institutional Missions



Open Interface



Interoperability



Beyond 2026



Scalability



Standardisation



Support all Mission Phases



1000Km Service Volume [to 70,000 km]

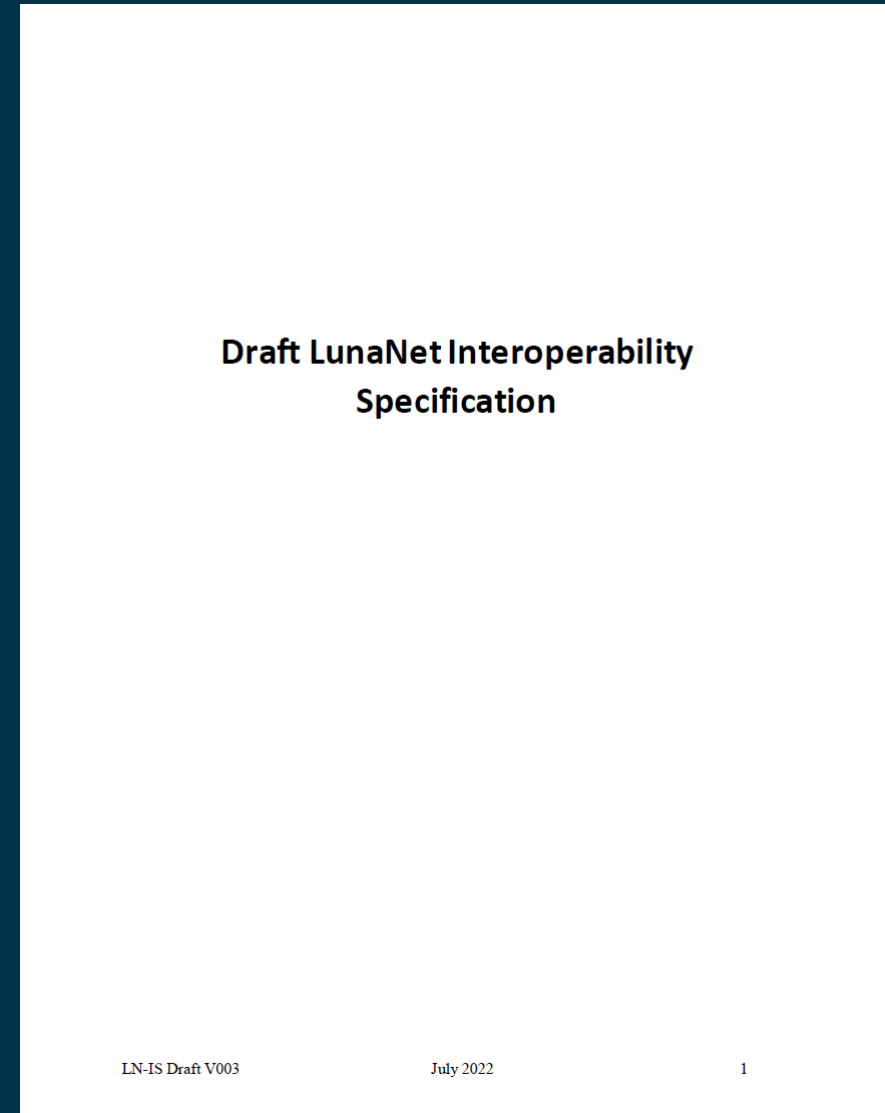


South Pole Coverage [to Far side & Global]

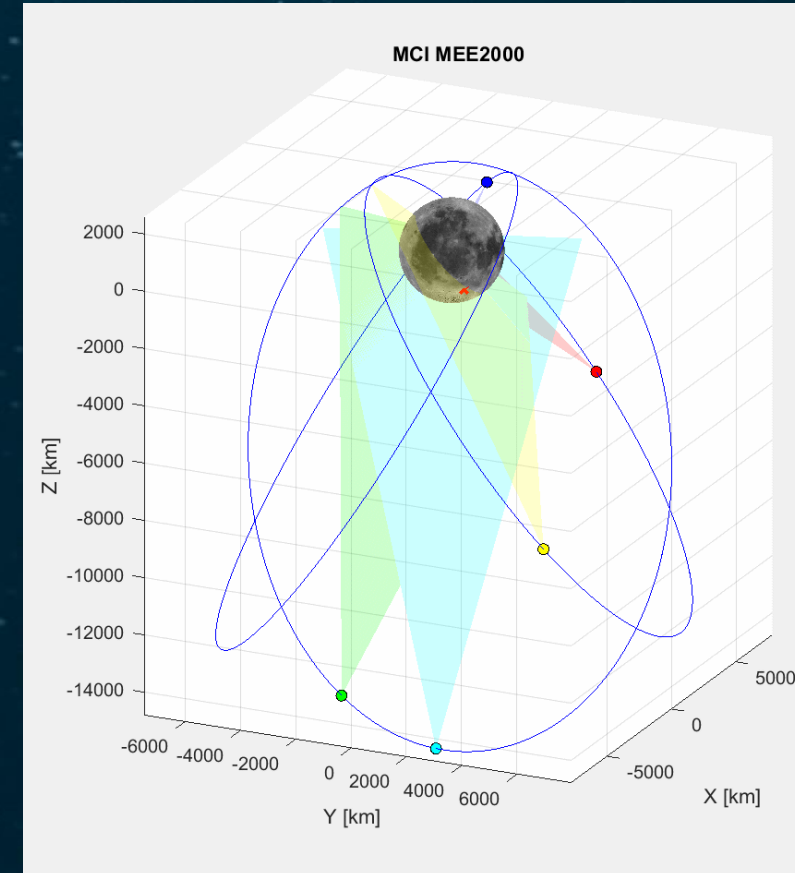
Moonlight is intended to be built against approved international standards and to ensure its interoperability with other potential similar services.

Interoperability Discussions

- Issue 3 of Draft LUNANET interoperability framework published
- High-level of convergence ESA/NASA and well established joint working groups
- Interaction with IOAG under establishment



- An initial constellation with 3 to 4 satellites in Eccentric Lunar Frozen orbits (ELFO) may be sufficient to cover initial Lunar PNT services (South Pole coverage and low lunar orbit).
- Reuse of GNSS-like technologies is proposed (signal generation, ODTS process, user receiver). High-TRL and excellent industrial/institutional experience in Europe



User signal definition and User terminal

- The user terminal can be a state of the art, TRL9, spaceborne GNSS receiver with minor modifications (e.g. change of RFFE carrier frequency and filters)
 - Faster development
 - Consolidated user CONOPS
 - Easier integration in lunar user missions



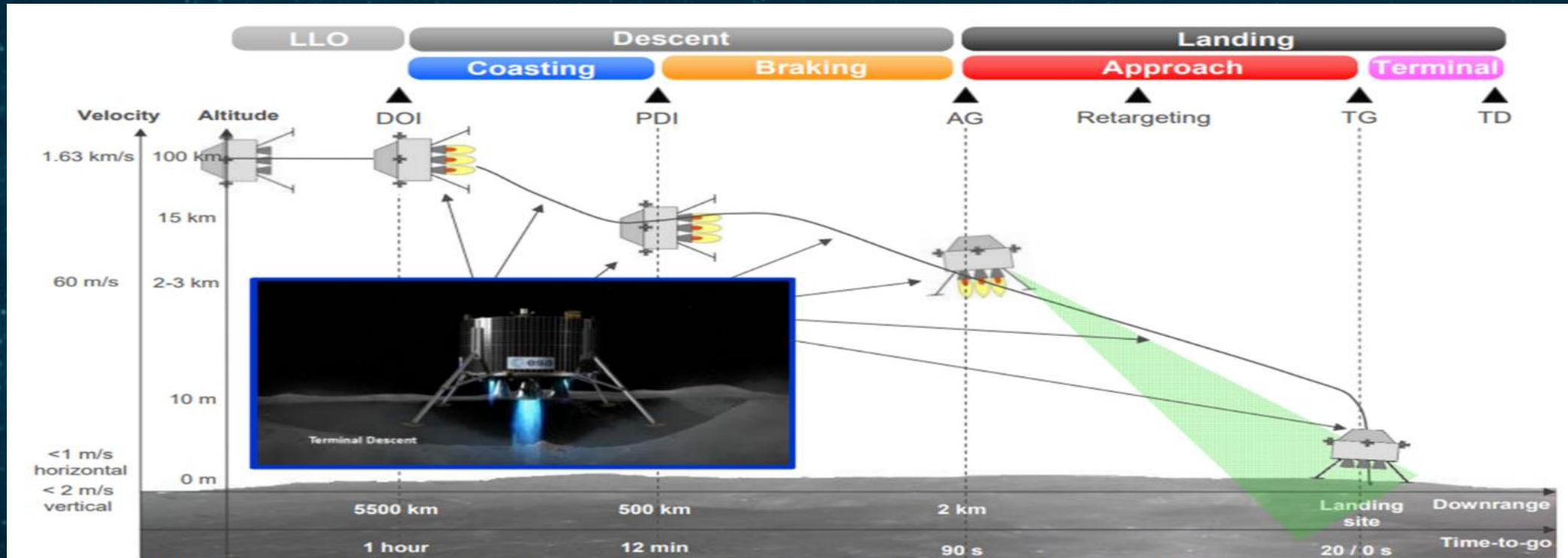
State of the art Lunar landing

- Lunar landing has been performed since the 60s/70s, with both human and robotic missions
- Global Exploration Roadmap Critical Technology Needs identifies the need to land within **90m 3-sigma** from the targeted landing location
- Current technology could achieve to meet these targets, however it requires complex on-board equipment, with very large Size, Weight and Power (SWaP) and it does not work in all conditions

Large space institutions can land on the Moon, but the current approach is not suitable for a sustained human and robotic presence on the Moon

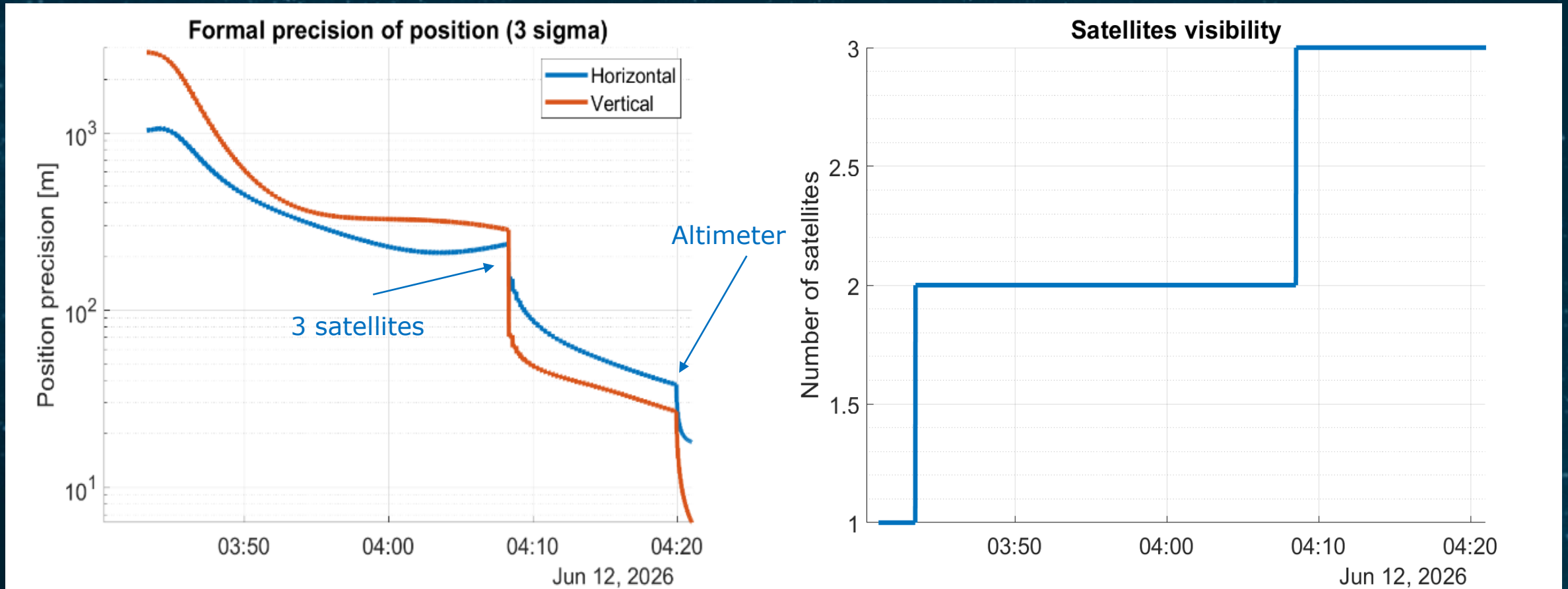
Current visual based landing technology works well, but not in all conditions and it is expensive

Moonlight User Navigation Algorithm



Note: the velocity, altitude, downrange, delta-V and time values are provided to give an order of magnitude

Landing performances (25m 3-sigma SISE)

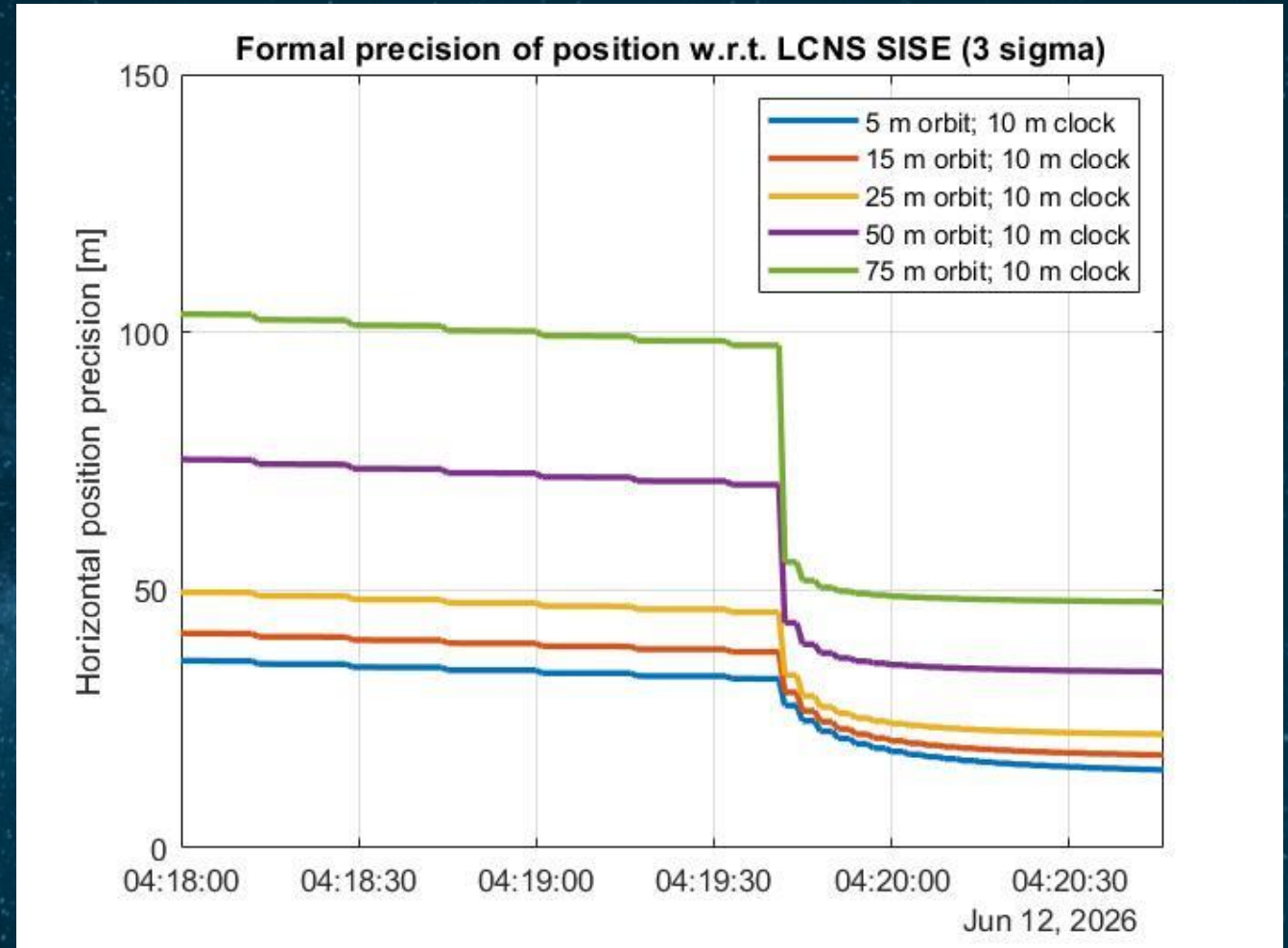


The achieved final landing horizontal precision is below 20 m 3-sigma !!

Landing performances – SISE analysis

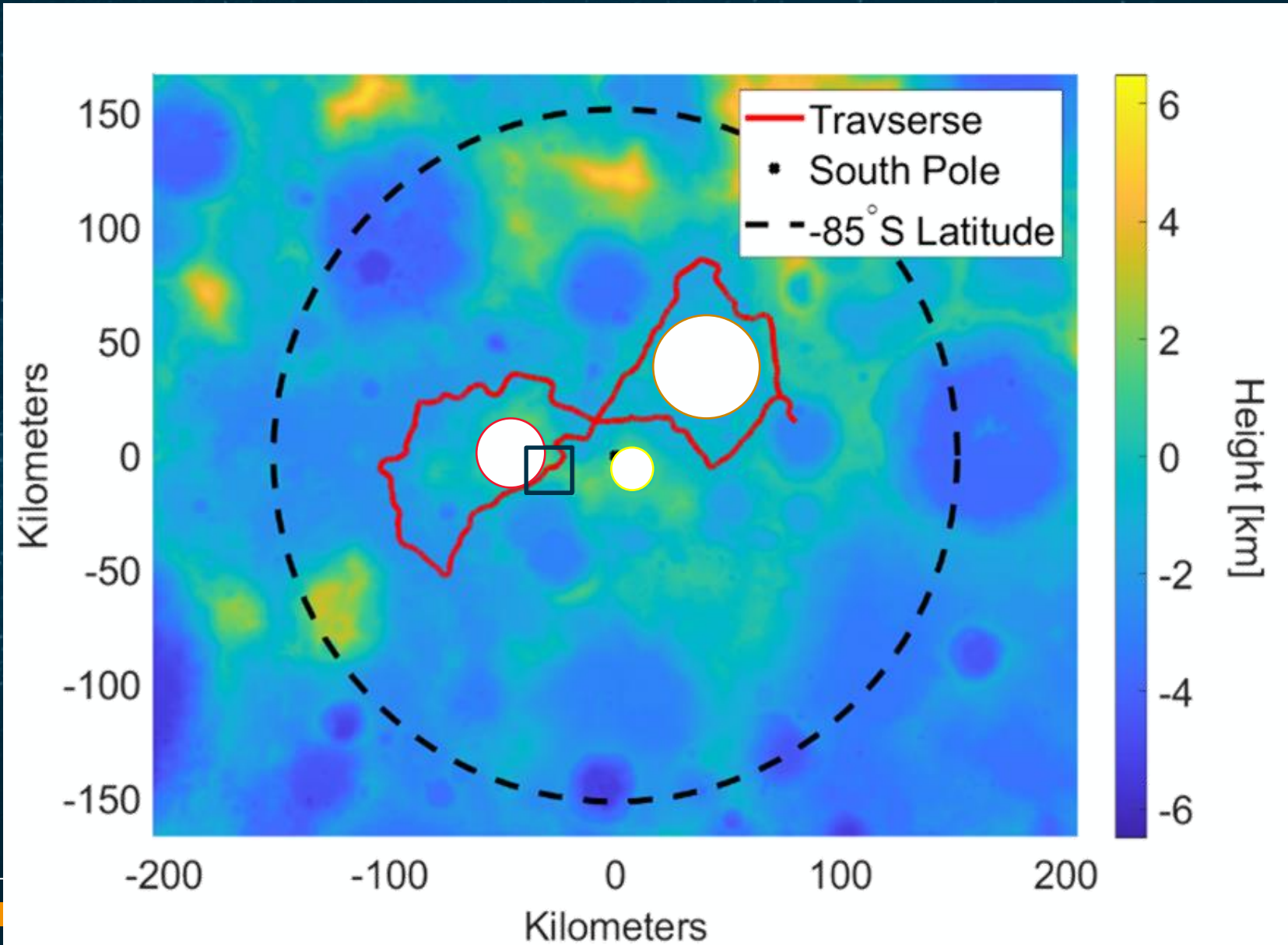
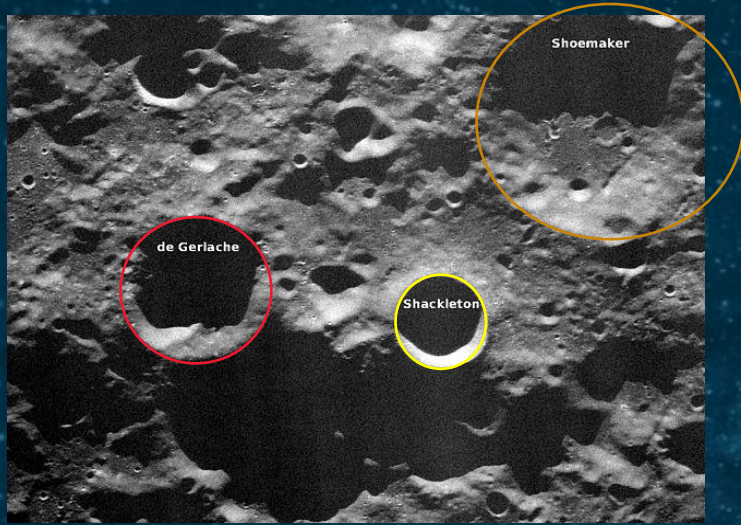
The performances of a GNSS like system are mainly driven by the Signal In Space Error that includes the error in the determination of the satellite orbit and the synchronisation of the on-board clock to a reference time

Even with large orbit and clock error the final performances are well within the 90m 3-sigma requirement. Staying below 50m 3-sigma will allow to safely land on peaks of eternal light

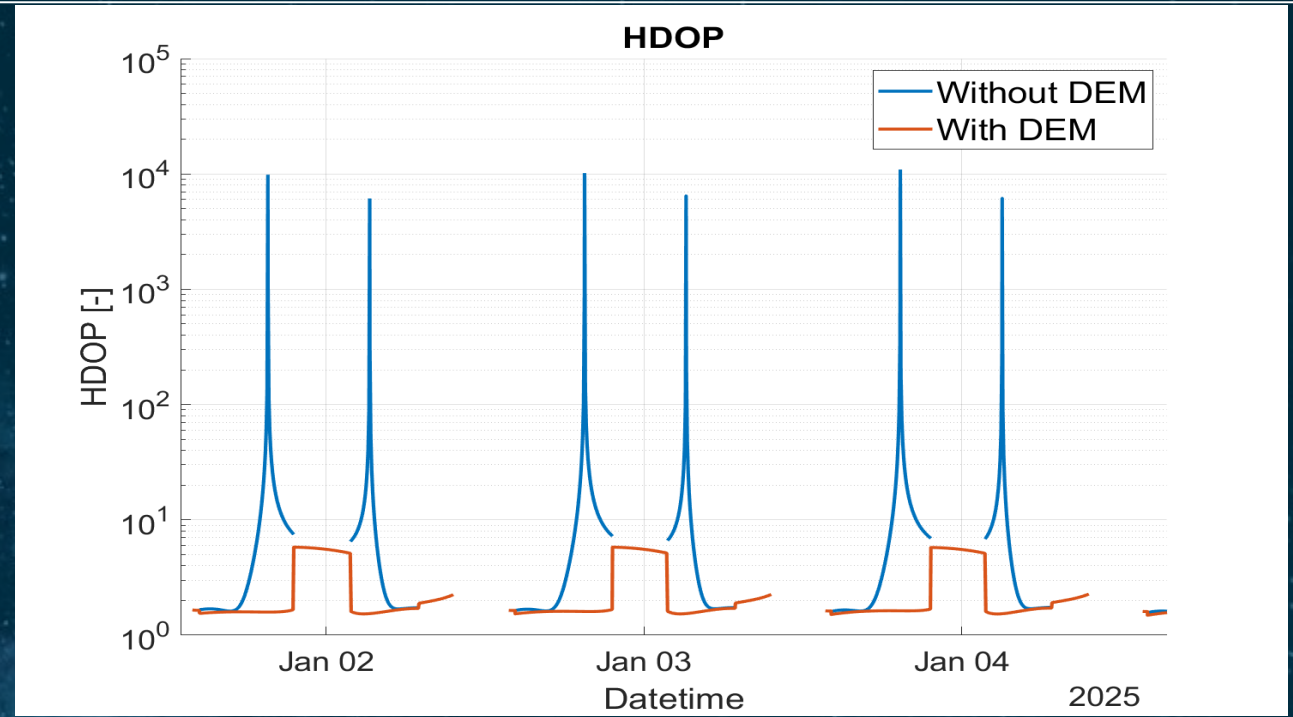
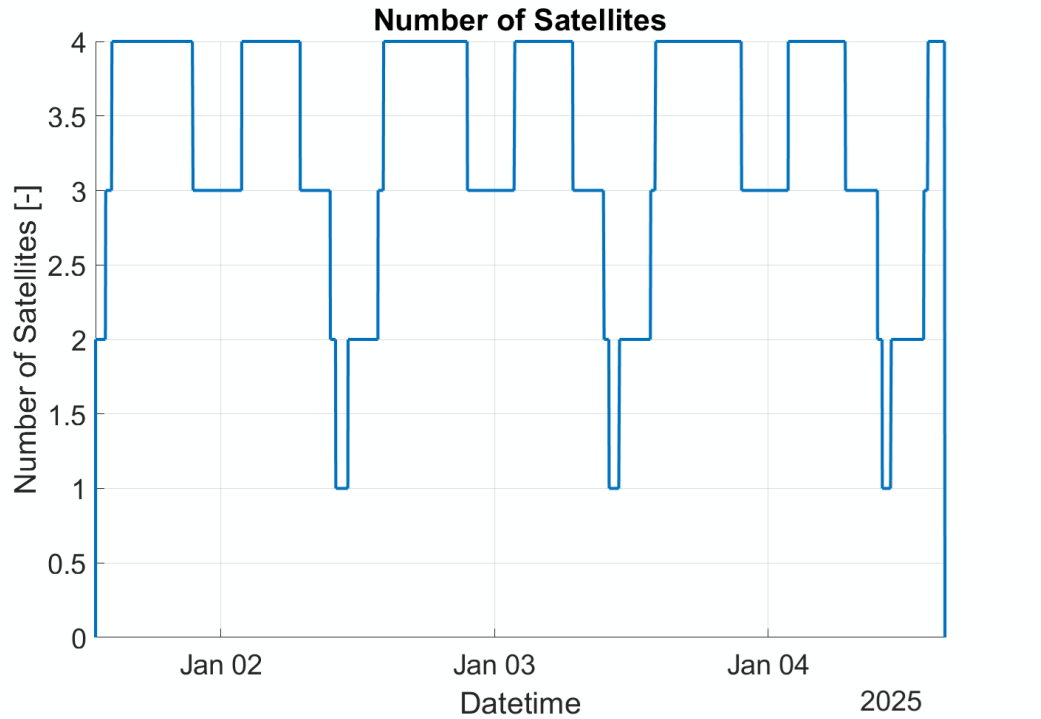


P. Giordano et als., “Moonlight navigation service - how to land on peaks of eternal light”, International Astronomical Congress 2021, Dubai

Lunar Surface – LCNS performances with DEM

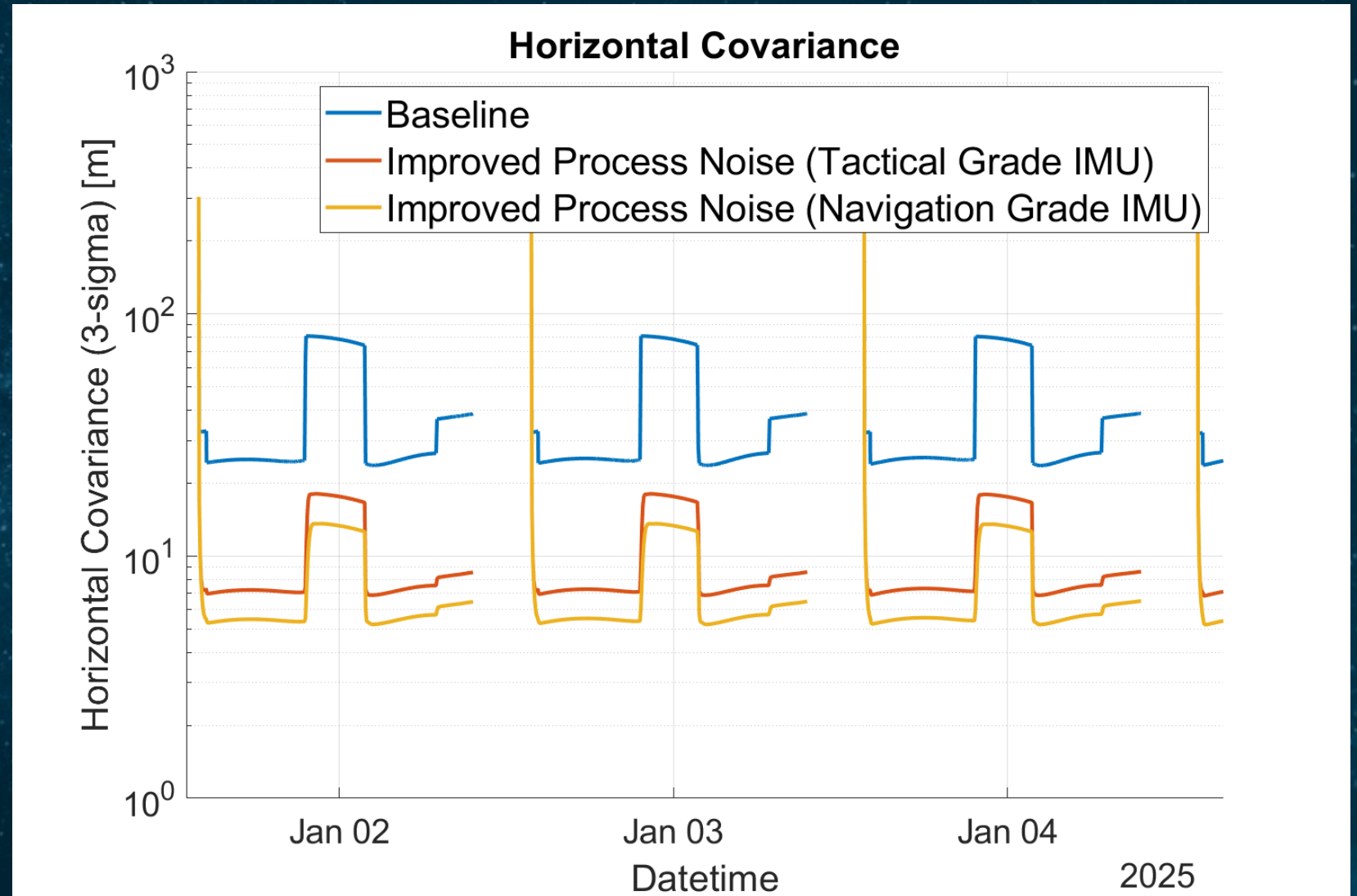


Surface performances with and without DEM



Scenario	Availability [%]	Longest Continuous Availability [hr]	68 th Percentile [m]	95 th Percentile [m]	99.7 th Percentile [m]
Without DEM	52.0	5.2	80.3	242.8	810.2
With DEM	82.2 (+ 60%)	19.9 (+ 282%)	3.9 (- 95%)	8.4 (- 96%)	8.6 (- 99%)

Using LCNS, IMU and the DEM we achieve sub 10 m 3-sigma horizontal accuracy



Some LCNS User Benefits (1 of 2)



Smaller Terminal
>8x power reduction



> x8 more data
for same Terminal



Backup/
Redundancy



Risk Reduction



Higher Nav
Accuracy



Higher landing
accuracy



Navigation over
night & shadow



Simpler on-board
Nav sensors

Some LCNS User Benefits (2 of 2)

□ Based on Internal CDF Study comparing Lunar Sample Return Mission with/without LCNS



Flexible landing site



Higher Service Availability



Higher Autonomy of Operations



Faster Orbit Determination (4x)



Longer Surface Operations



Operational Cost Savings

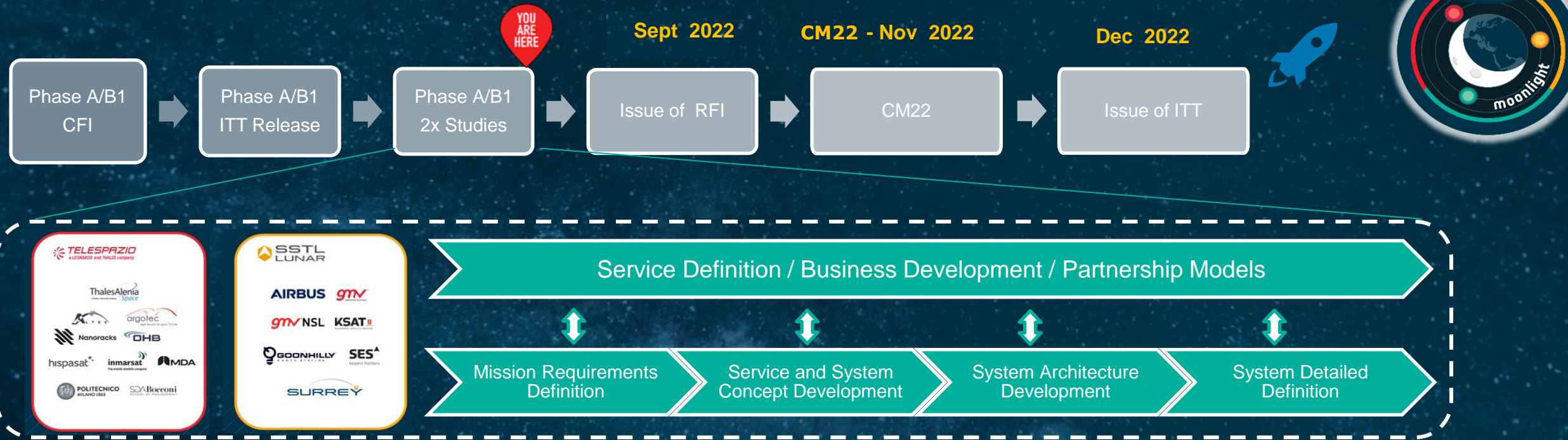


Higher Science Return (more payload/data)



New mission concepts

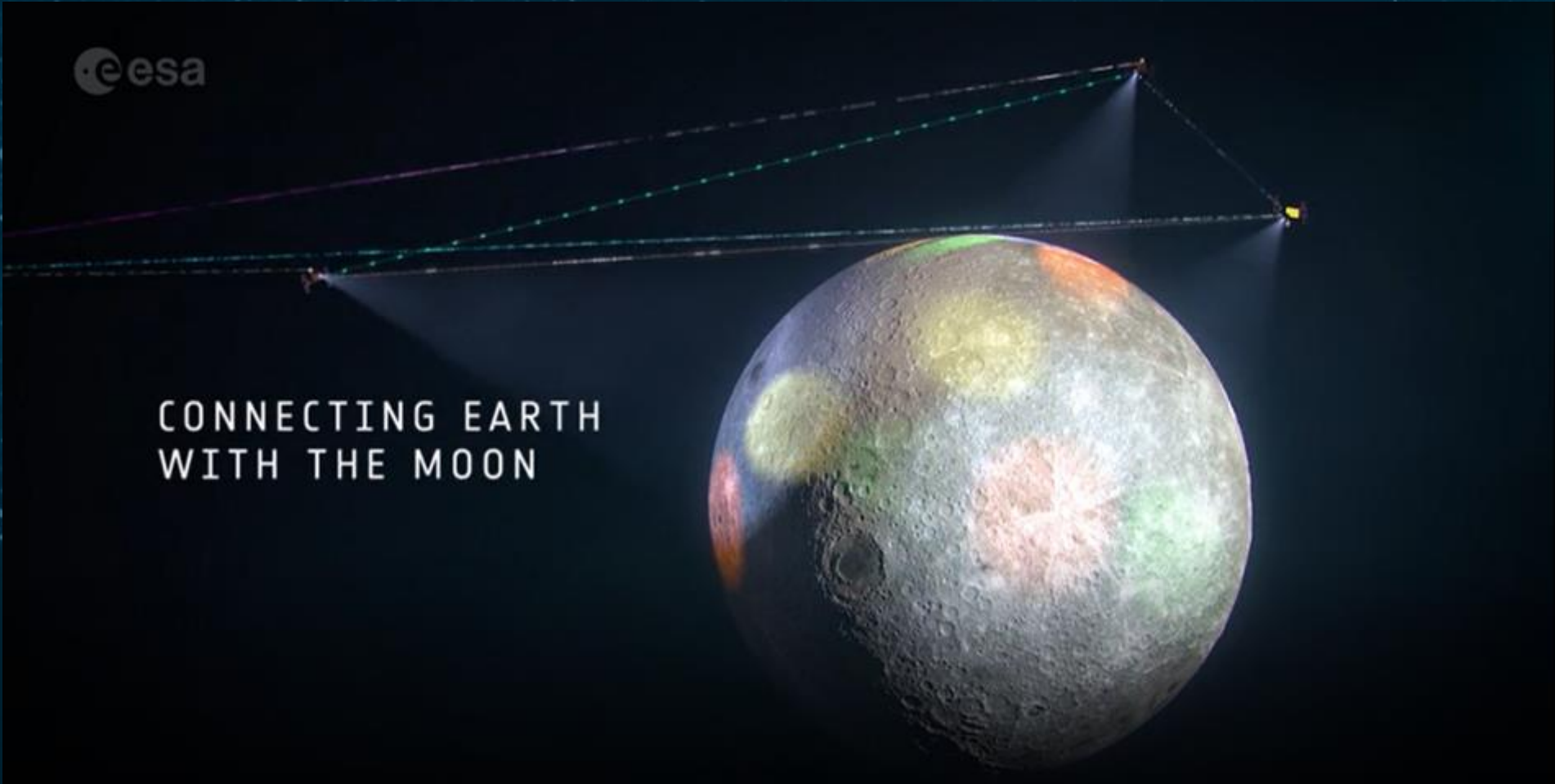
1. ESA Preparatory studies on-going 2021/2022 (two parallel contracts)



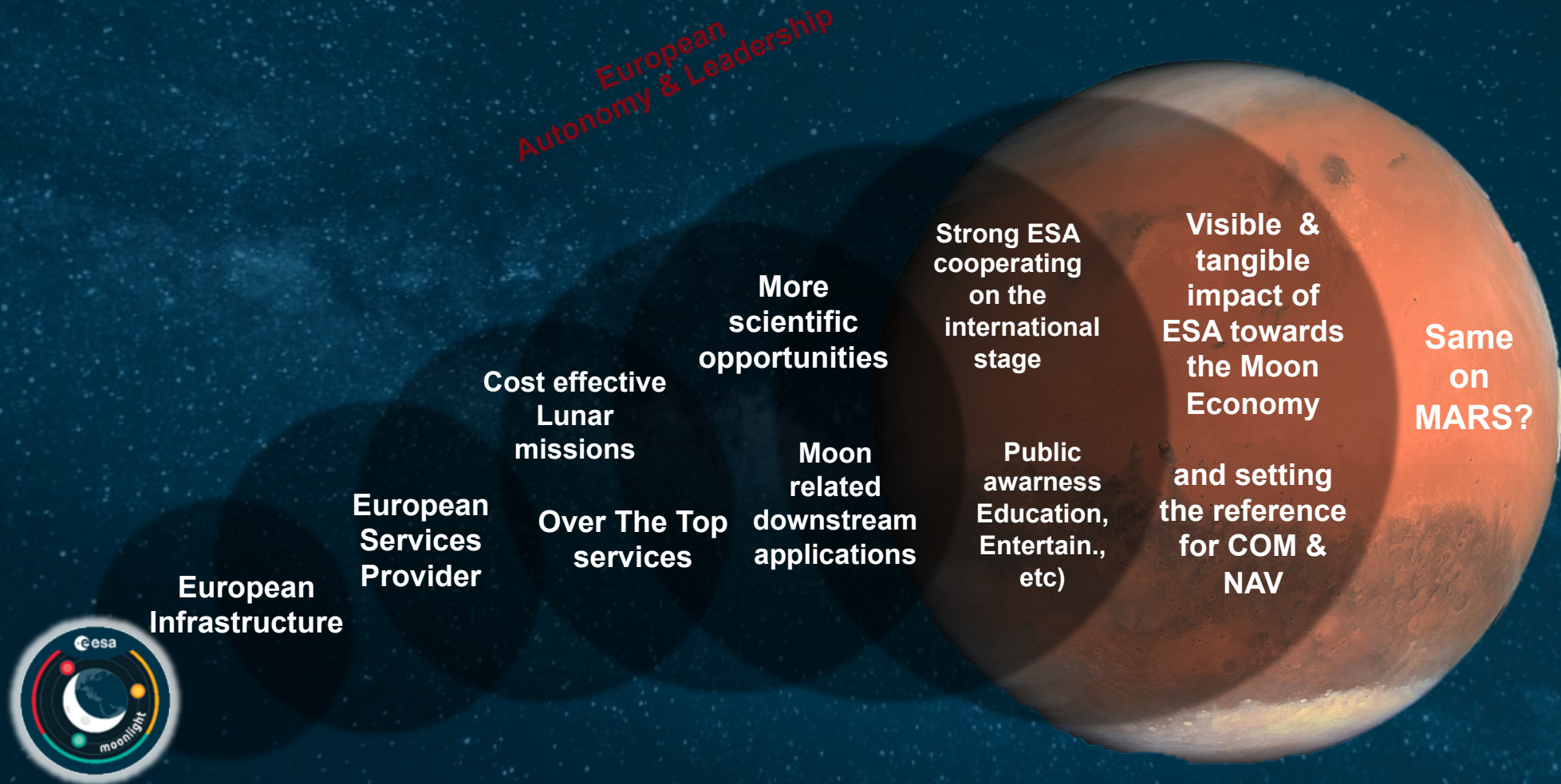
2. ESA intends to issue an RFI for full Moonlight implementation ~ Sept 2022

3. Complete ITT will follow ESA Ministerial endorsement expected in Nov 2022, allowing full implementation during 2023-2026 – Initial services planned for 2026/2027

Moonlight video



Moonlight – A Unique Opportunity for Europe





Thank you !!

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