NOVAMOON – Lunar local Differential PNT and Selenodetic Reference Station

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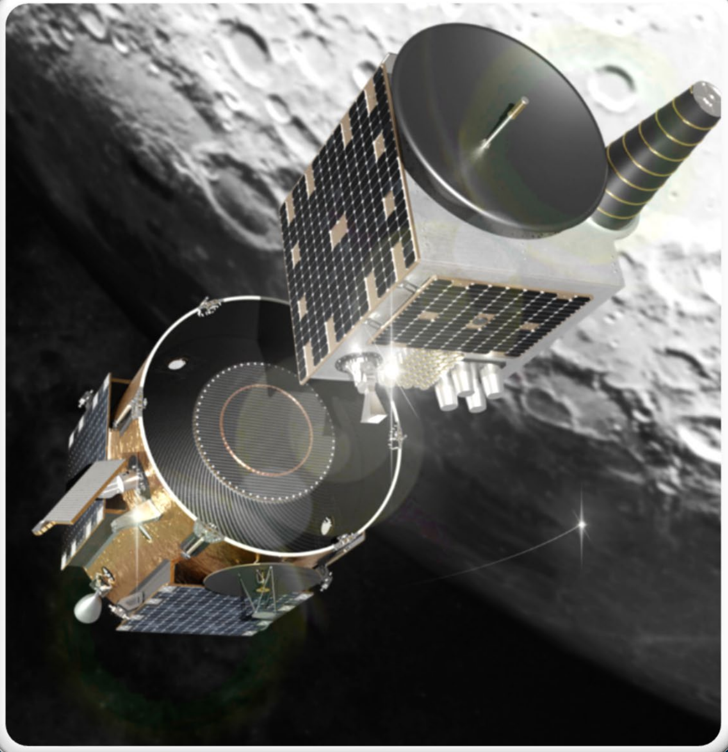
Dr Dimitrios Psychas

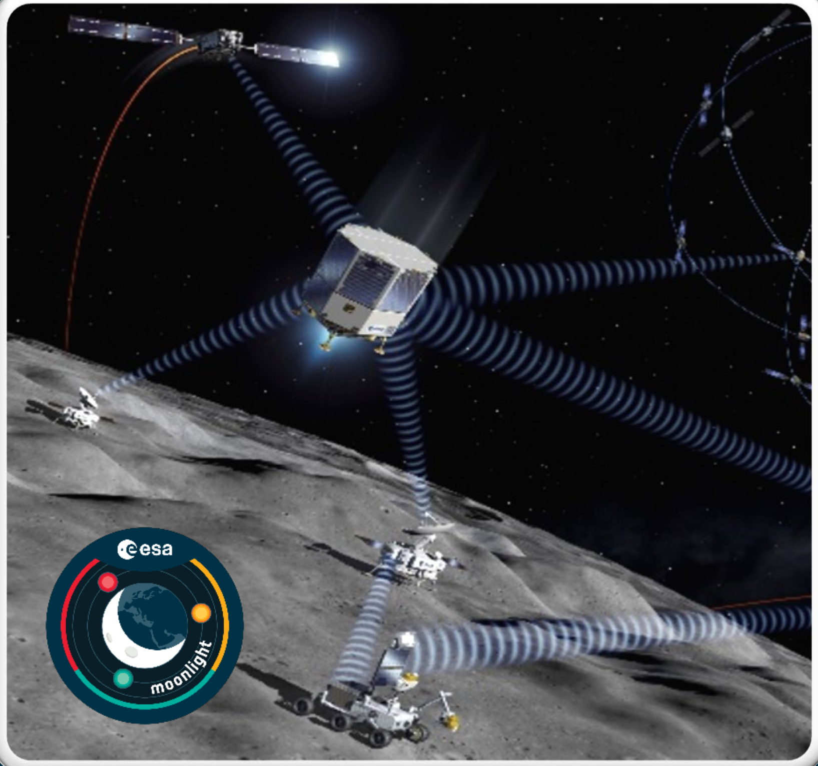
European Space Agency

ESA Roadmap For Lunar COMM and PNT Services



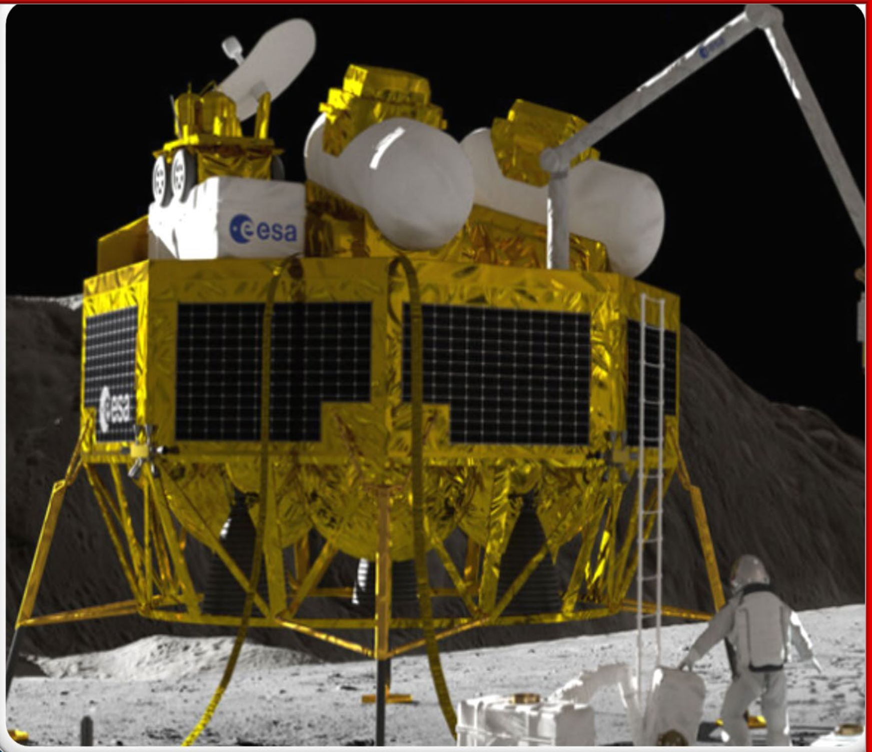
STEP 1:
LUNAR PATHFINDER

(LAUNCH in 2025 !)



STEP 2:
MOONLIGHT System

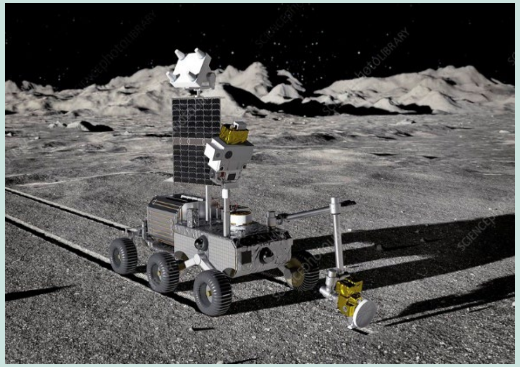
(Initial: 2028; Final: 2030)



STEP 3:
NOVAMOON: Local PNT Differential Station
(Launch: 2031)

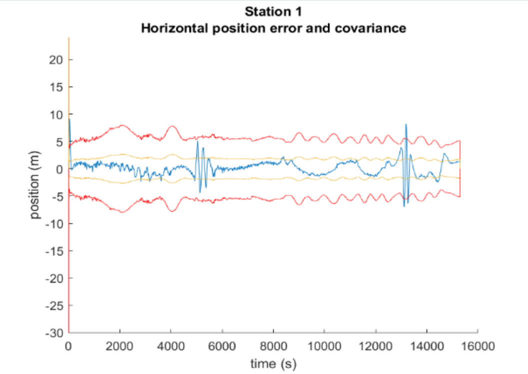
Moonlight FOC PNT Performances (from 2030)

Surface Rover



Real time
< 10 m
(95%)

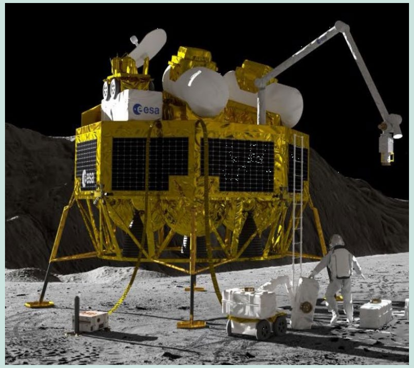
Post-processing
< 3 m (95%



3-5 meters

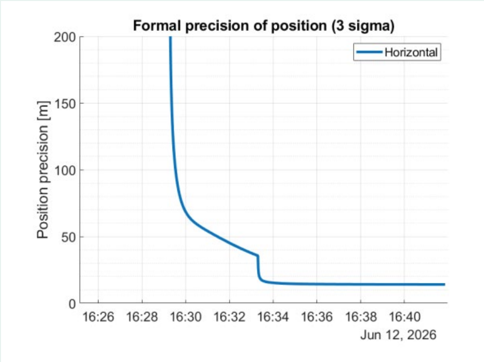
Ref: Navigation Performance of a Lunar Surface Rover Using LCNS Positioning Assuming Realistic ODTS Performances, EUROPEAN NAVIGATION CONFERENCE 2023

Lunar Lander



< 50 m (95%)

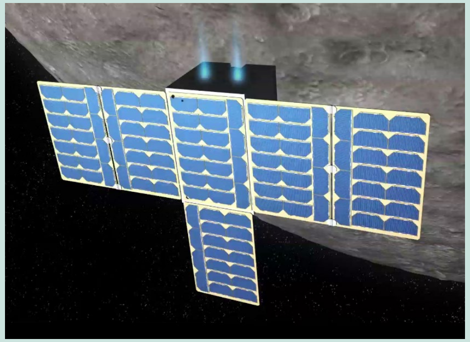
Landing accuracy



~20 meters

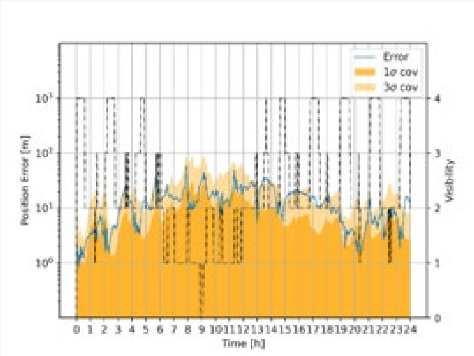
Ref: Positioning and Velocity Performance Levels for a Lunar Lander using a Dedicated Lunar Communication and Navigation System, Navigation Journal 2022

Lunar Orbiter



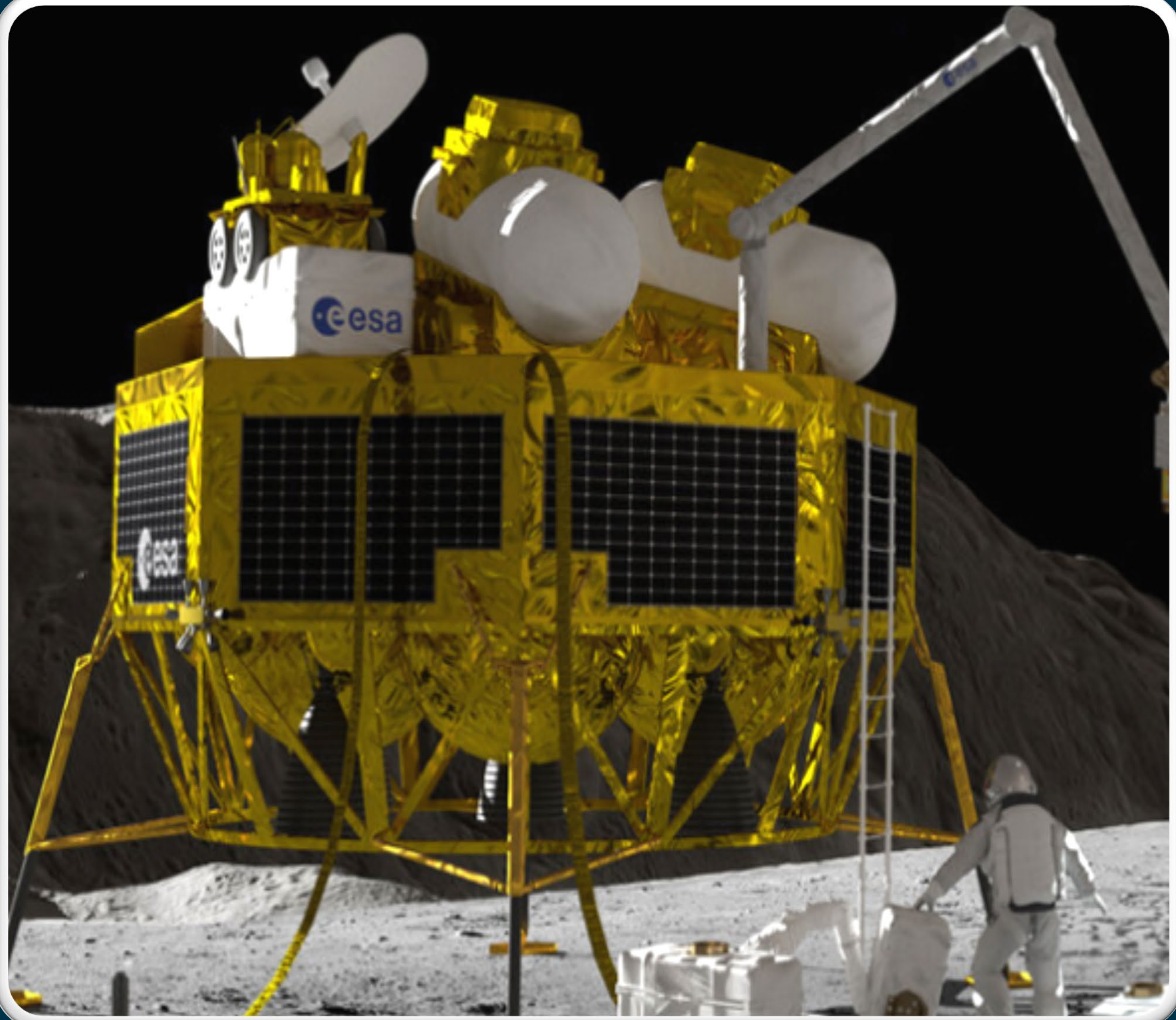
Real time
< 100 m
(95%)

LLO accuracies

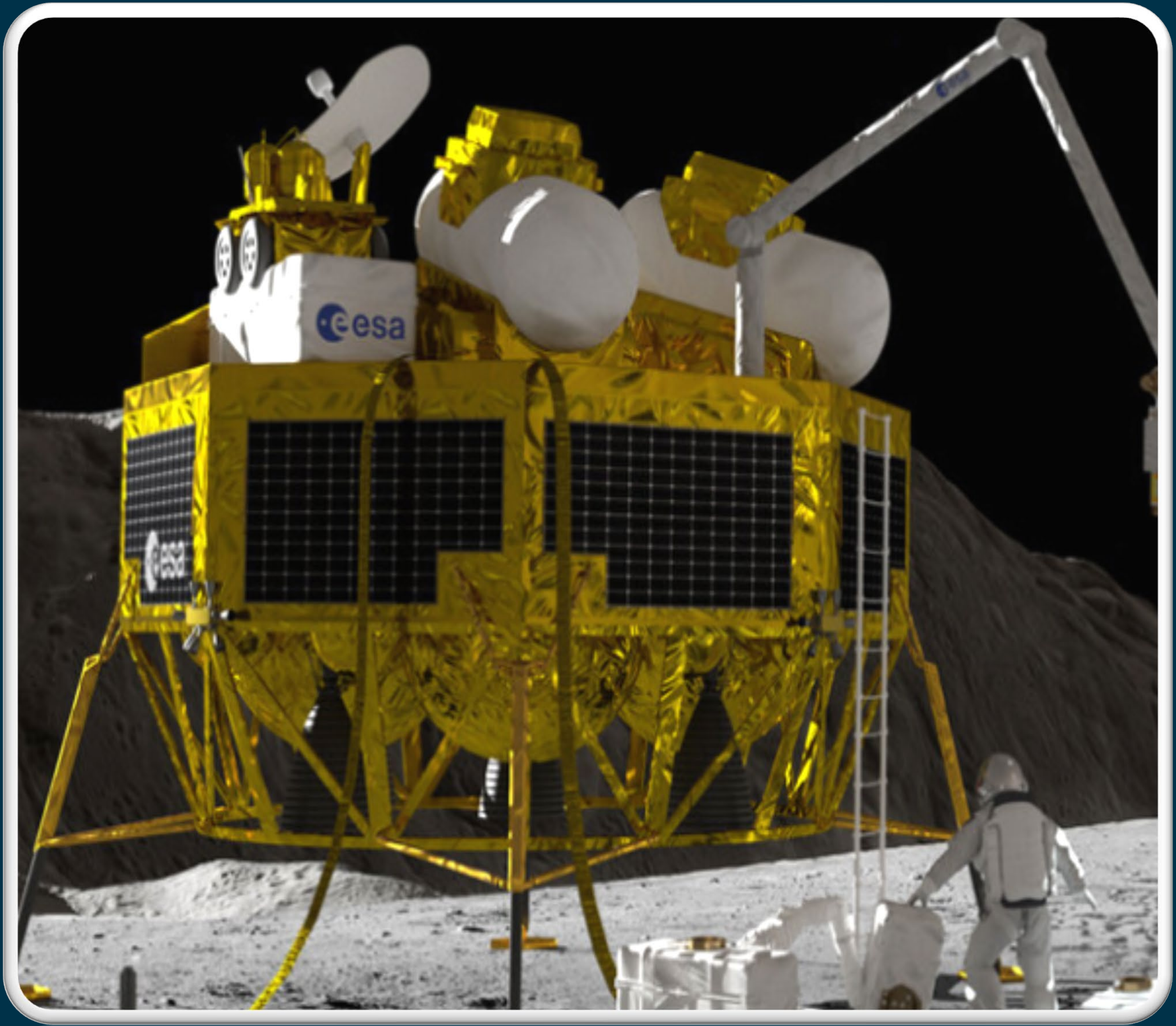


30-60 meters

Ref: Navigation performance of Low Lunar Orbit satellites using a Lunar Radio Navigation Satellite System, ION-GNSS 2023



HOW MAY WE DO BETTER (e.g. reaching ~1m range lunar surface accuracies) ON A SHORT TERM after MOONLIGHT FOC is deployed?

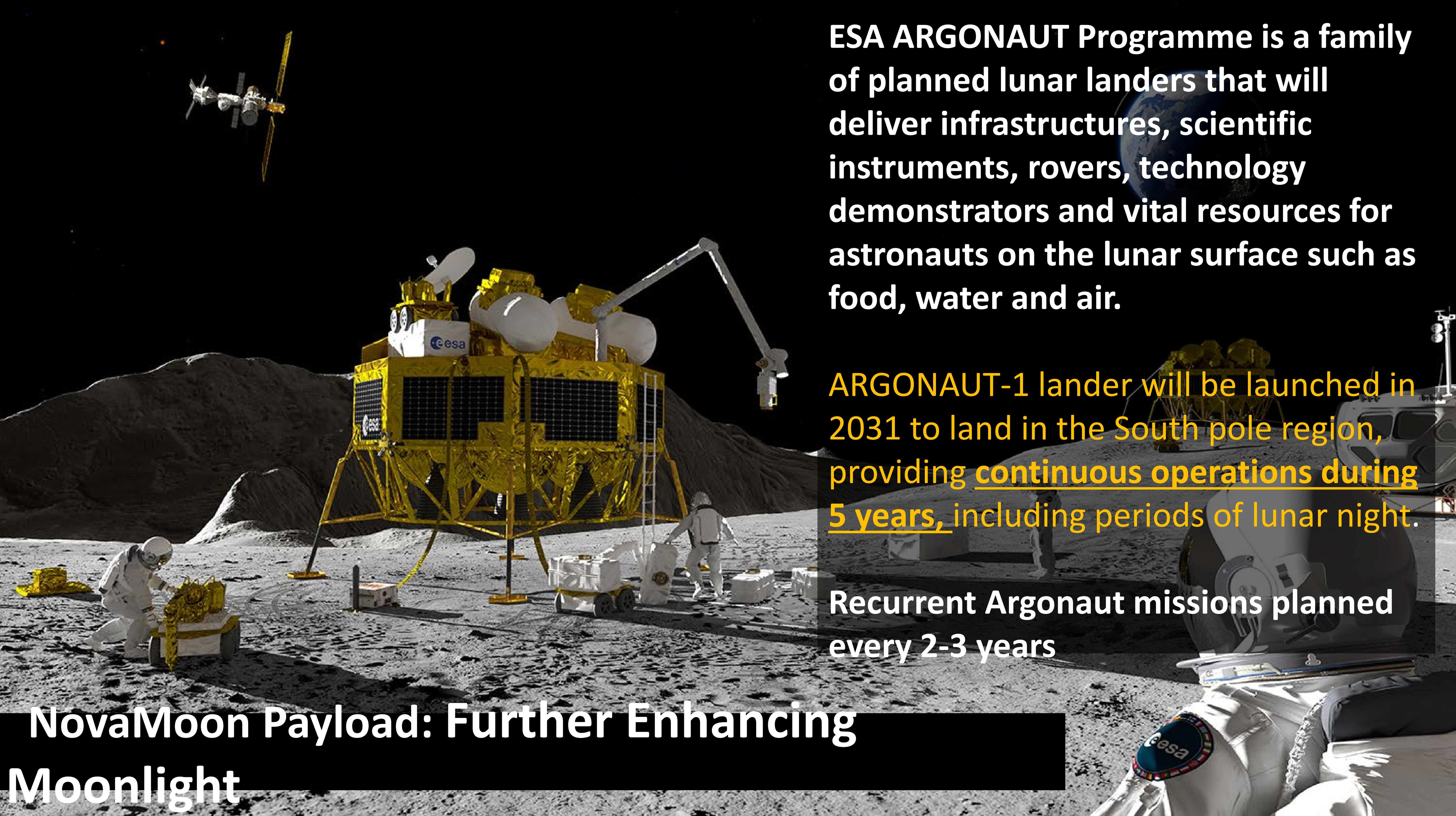


HOW MAY WE DO BETTER (e.g. reaching ~1m range lunar surface accuracies) ON A SHORT TERM after MOONLIGHT FOC?

NOVAMOON Local PNT Differential Selenodetic and time-reference Station

Integrated on ESA's Argonaut-1 lander

(Launch: 2031)



ESA ARGONAUT Programme is a family of planned lunar landers that will deliver infrastructures, scientific instruments, rovers, technology demonstrators and vital resources for astronauts on the lunar surface such as food, water and air.

ARGONAUT-1 lander will be launched in 2031 to land in the South pole region, providing continuous operations during 5 years, including periods of lunar night.

Recurrent Argonaut missions planned every 2-3 years

NovaMoon Payload: Further Enhancing Moonlight

NovaMoon Mission

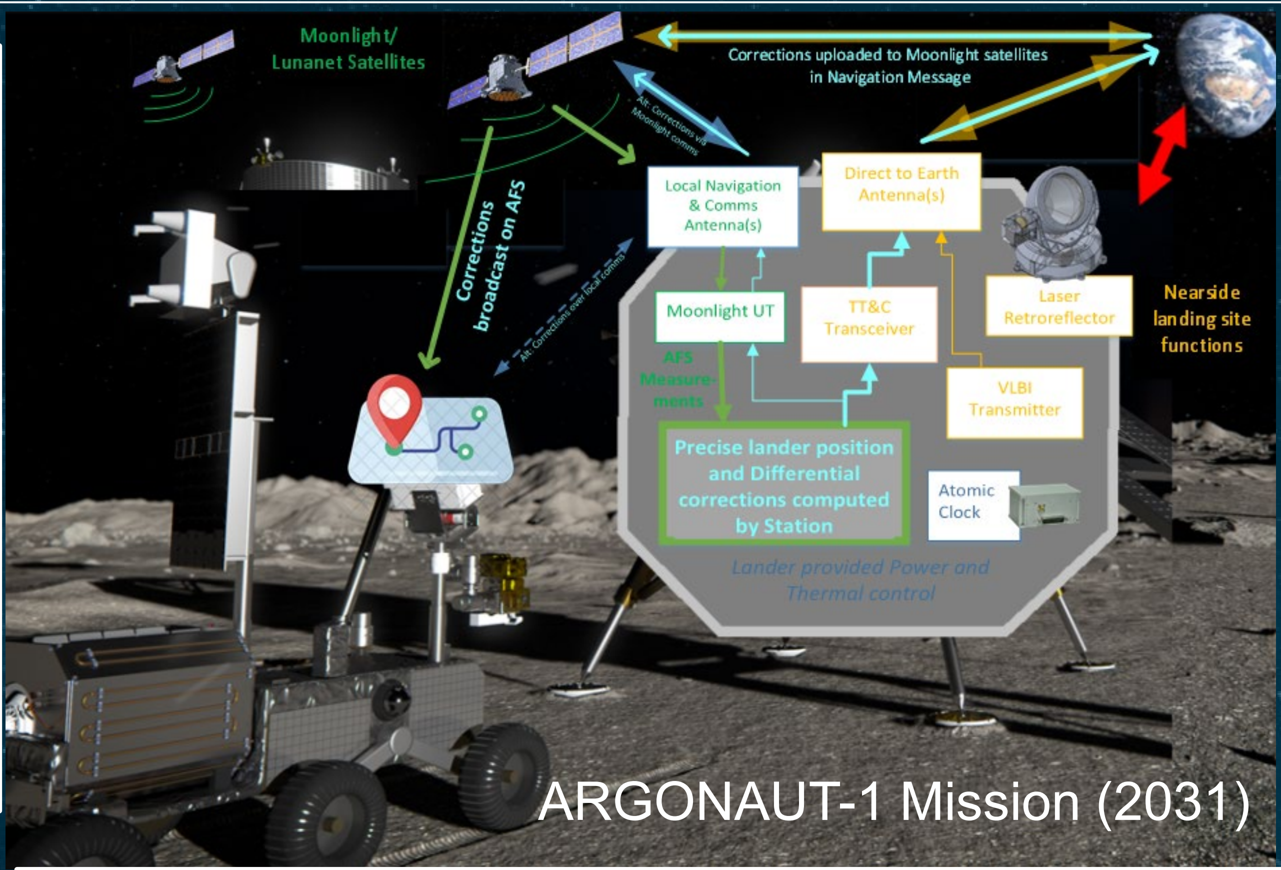
To Provide a lunar-based local differential, selenodetic and timing station to enhance Moonligh services and support scientific experimentation internationally.

NOVAMOON – First ever Lunar differential, Selenodetic and time station

1. **Reference local differential station on the lunar surface**

(augmenting and monitoring Moonlight and potentially other LCNS systems)

Sub-meter **level** accuracies over the whole Lunar South Pole !



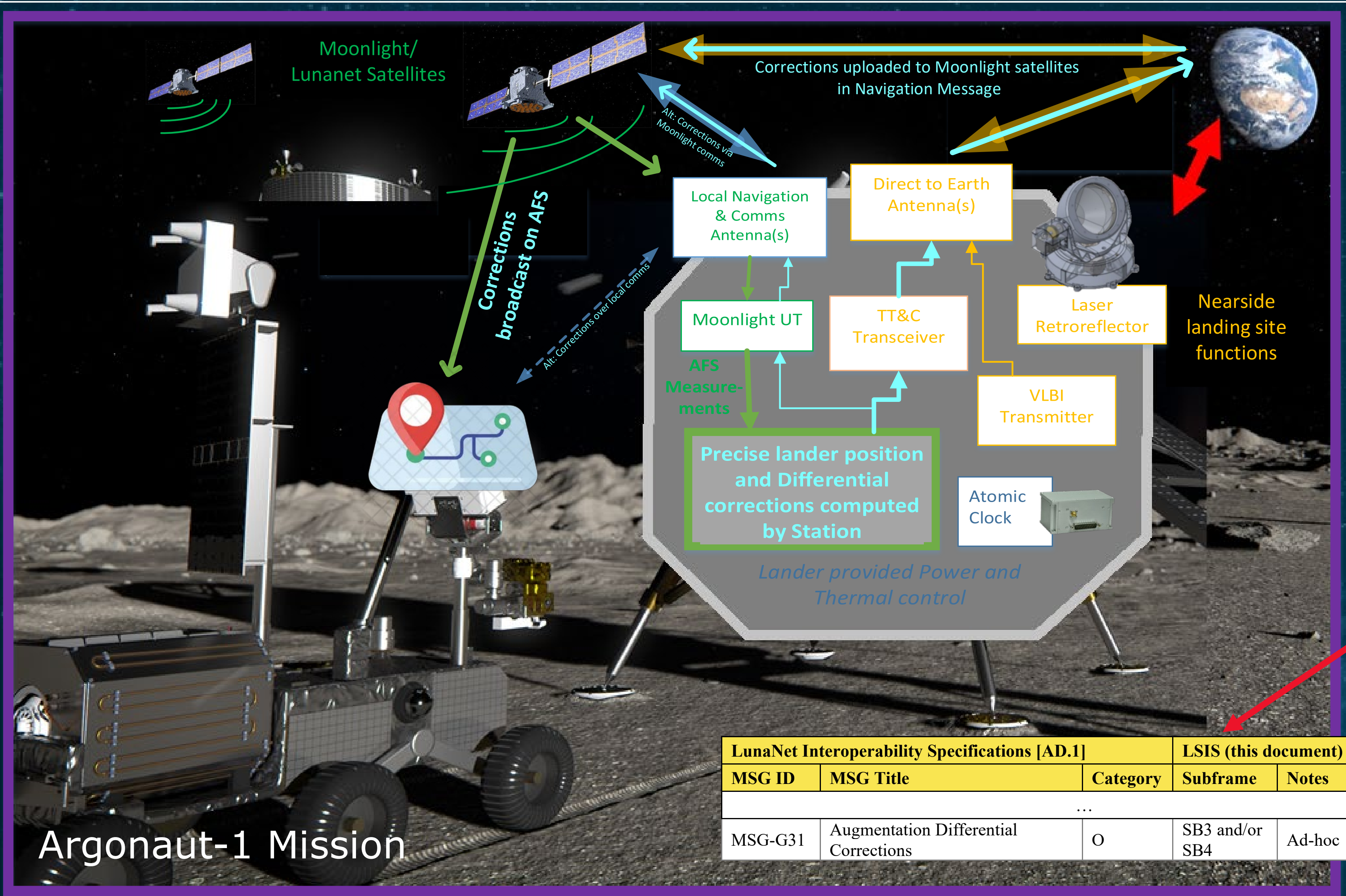
2. **International "geodetic" Reference station on the lunar surface (4 collocated ranging techniques)**

Towards an accurate Lunar Refence Frame realisation

3. **International "Lunar Time-reference" Laboratory**

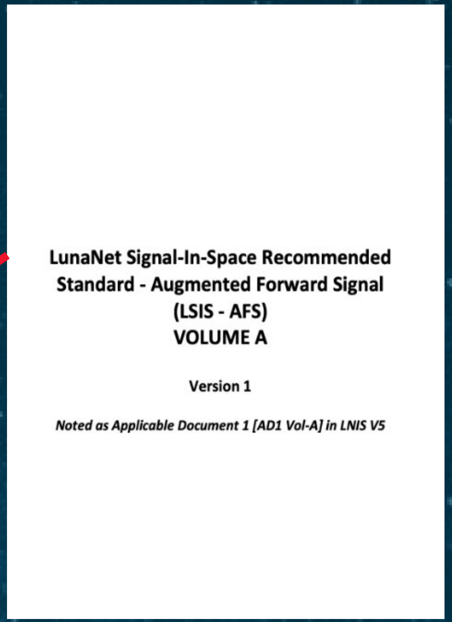
Supporting experimentation and setting the basis for future lunar-base time realisations

NOVAMOON Differential Station: Concept of Operations



LunaNet Interoperability Specifications [AD.1]			LSIS (this document)		
MSG ID	MSG Title	Category	Subframe	Notes	LNIS 1.0
…					
MSG-G31	Augmentation Differential Corrections	O	SB3 and/or SB4	Ad-hoc	yes

Moonlight fully compatible


LunaNet Signal-In-Space Recommended Standard - Augmented Forward Signal
(LSIS - AFS)
VOLUME A

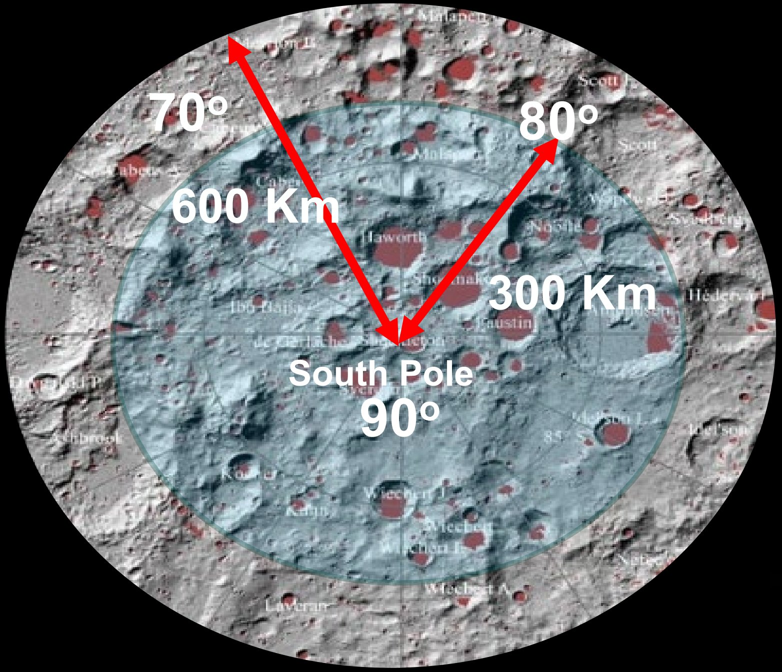
Version 1

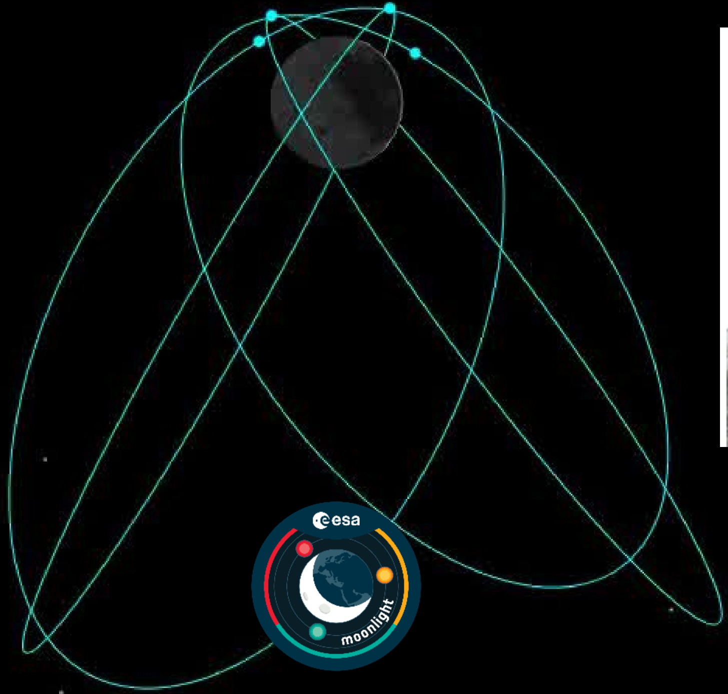
Noted as Applicable Document 1 [AD1 Vol-A] in LNIS V5

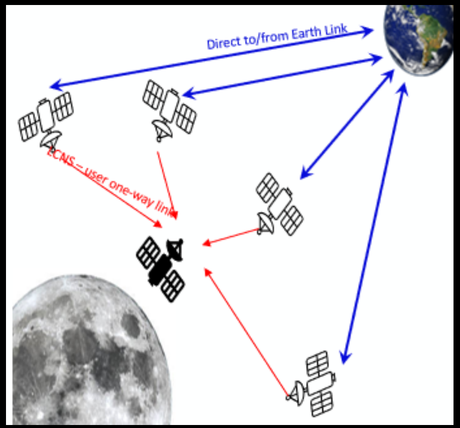
LunaNet standards compatible

Single NOVAMOON station may provide Sub-meter accuracies over the whole South pole (Artemis Lunar exploration area)

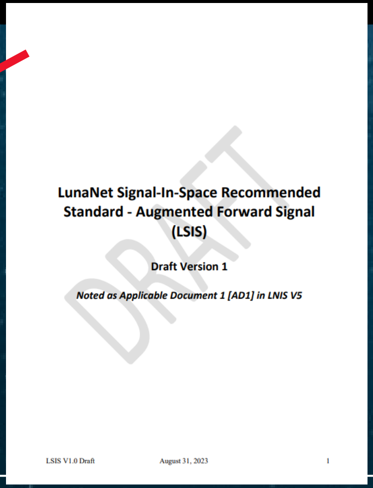
ARTEMIS SERVICE AREA







ODTS estimation



LunaNet Signal-In-Space Recommended Standard - Augmented Forward Signal (LSIS)

Draft Version 1

Noted as Applicable Document 1 [AD1] in LNIS V5

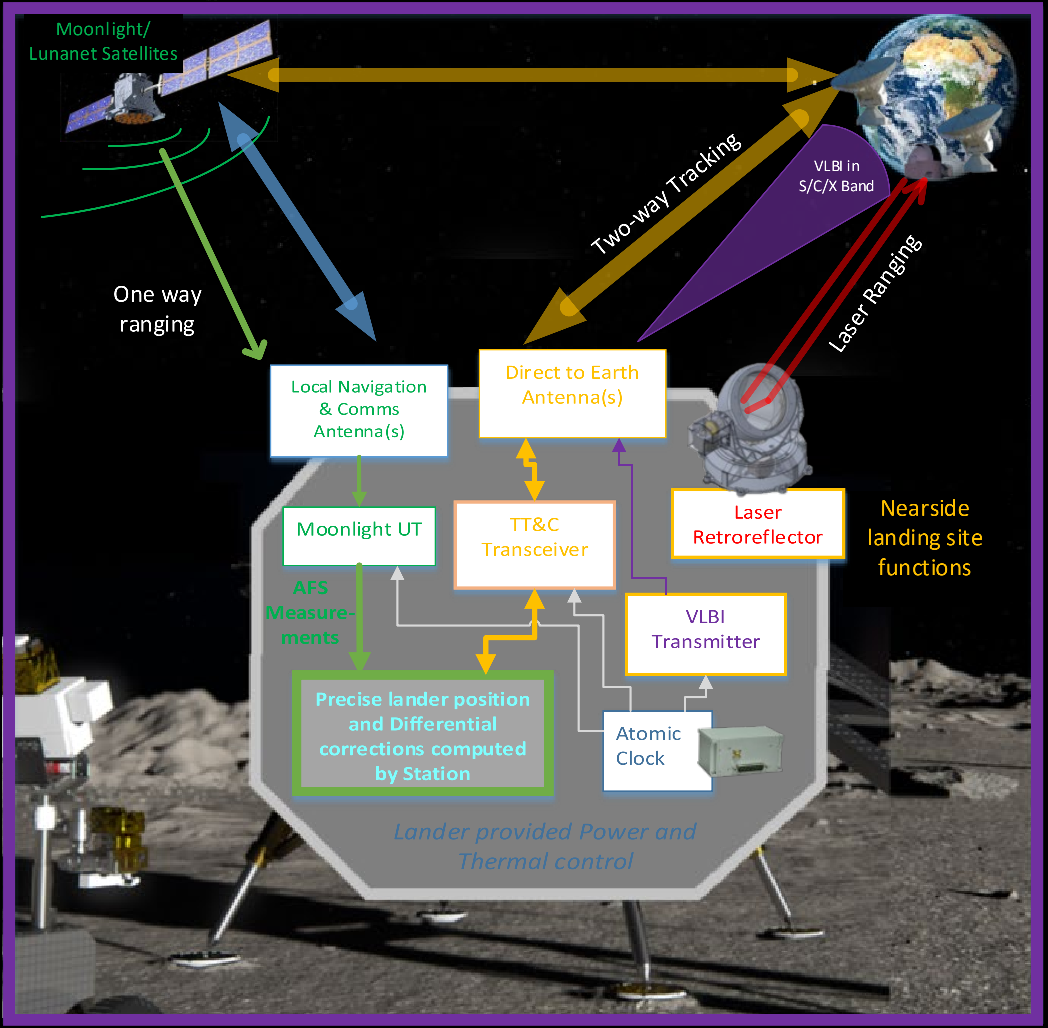
LSIS V1.0 Draft August 31, 2023 1

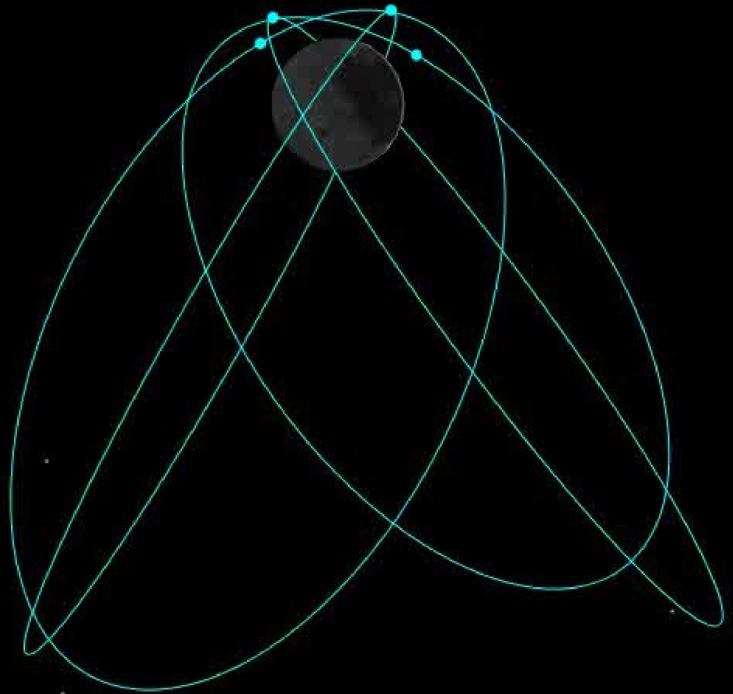
LunaNet Interoperability Specifications [AD.1]			LSIS (this document)		
MSG ID	MSG Title	Category	Subframe	Notes	LNIS 1.0
…					
MSG-G31	Augmentation Differential Corrections	O	SB3 and/or SB4	Ad-hoc	yes

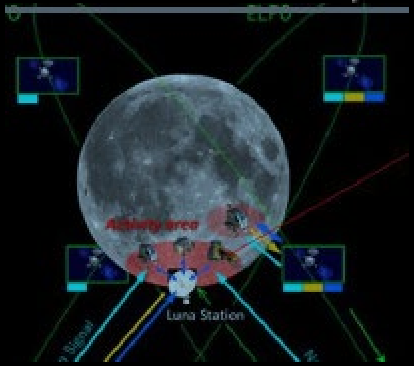
Our analysis demonstrate that a Single station will serve the whole South Pole

- NO ionosphere
- NO troposphere
- Minimum Orbital projection error
- Lunar South pole message reception

NOVAMOON as a LunaNET Monitoring Station: May monitor MOONLIGHT SiS status and performances and (if desired) Partner Agencies Systems







A first reference station on the Moon surface

Provision of precise orbits and clocks

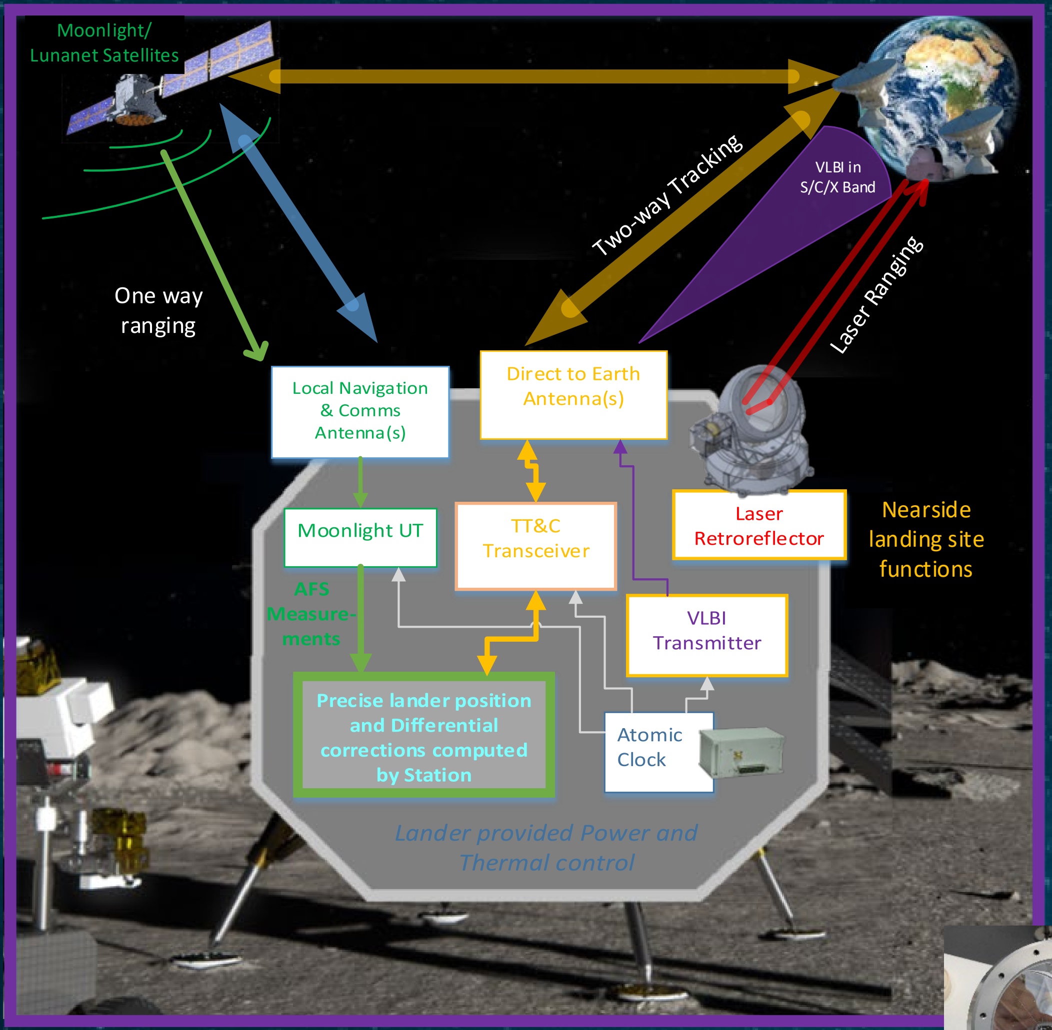
Lunar Base Station Localisation

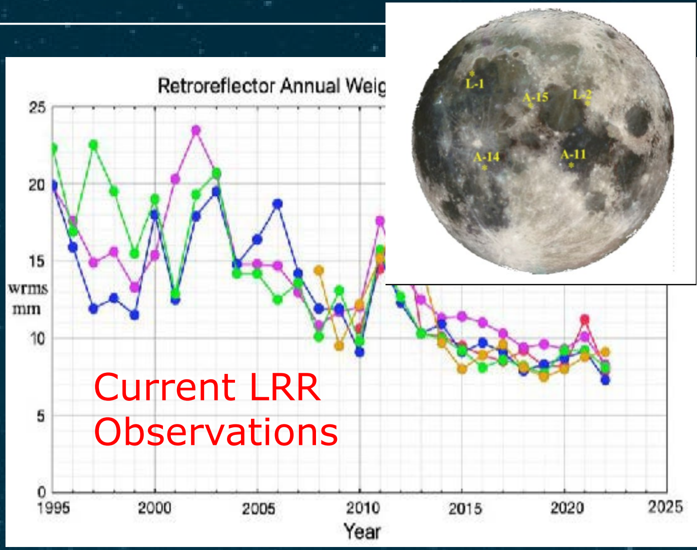
cm-level position determination for the first time ever on the Moon !

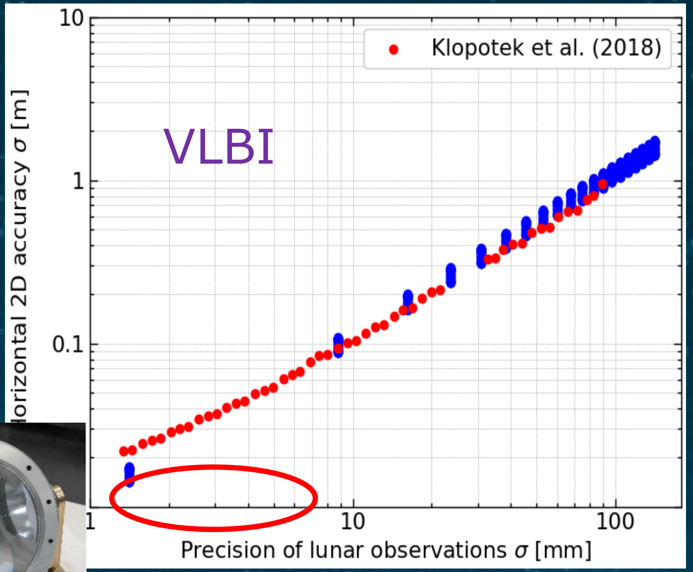
Four co-located geodetic techniques on-board:

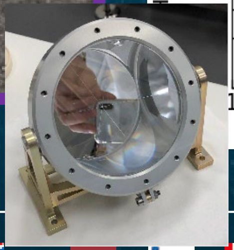
- GNSS PNT (Moonlight)
- VLBI transmission
- Advanced Laser Ranging Retrofelector
- Two-way Direct To Earth

3D localisation accuracies down to <u>cm-level</u> for the first time ever !





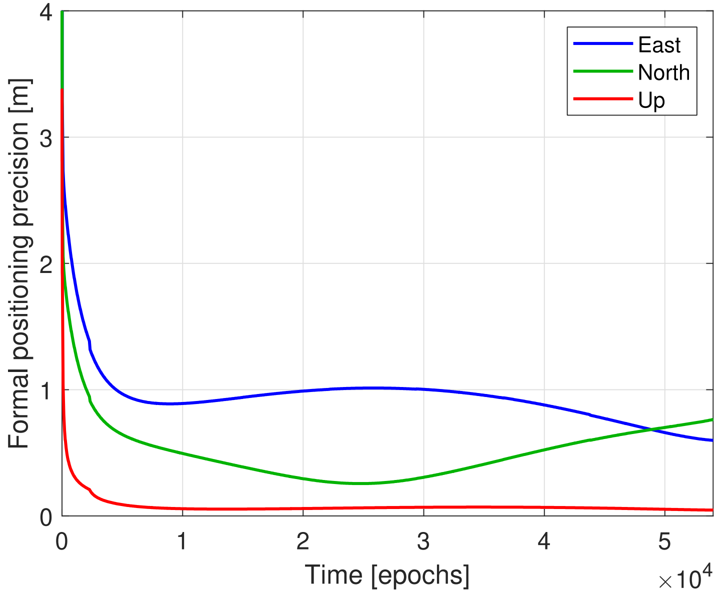




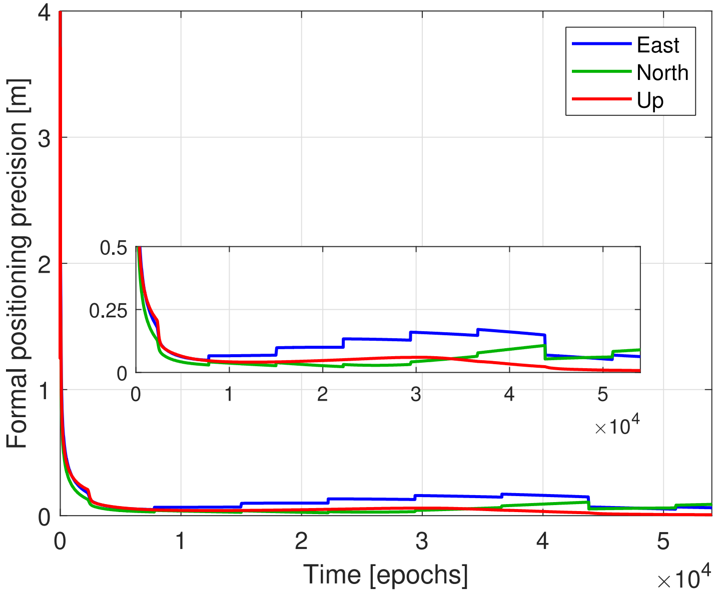
Accuracy of Lunar surface rover in dynamic mode
(using Moonlight augmented by NovaMoon)

Expected performance Moonlight + NovaMoon at Lunar South Pole (covariance analysis)

Code-only corrections



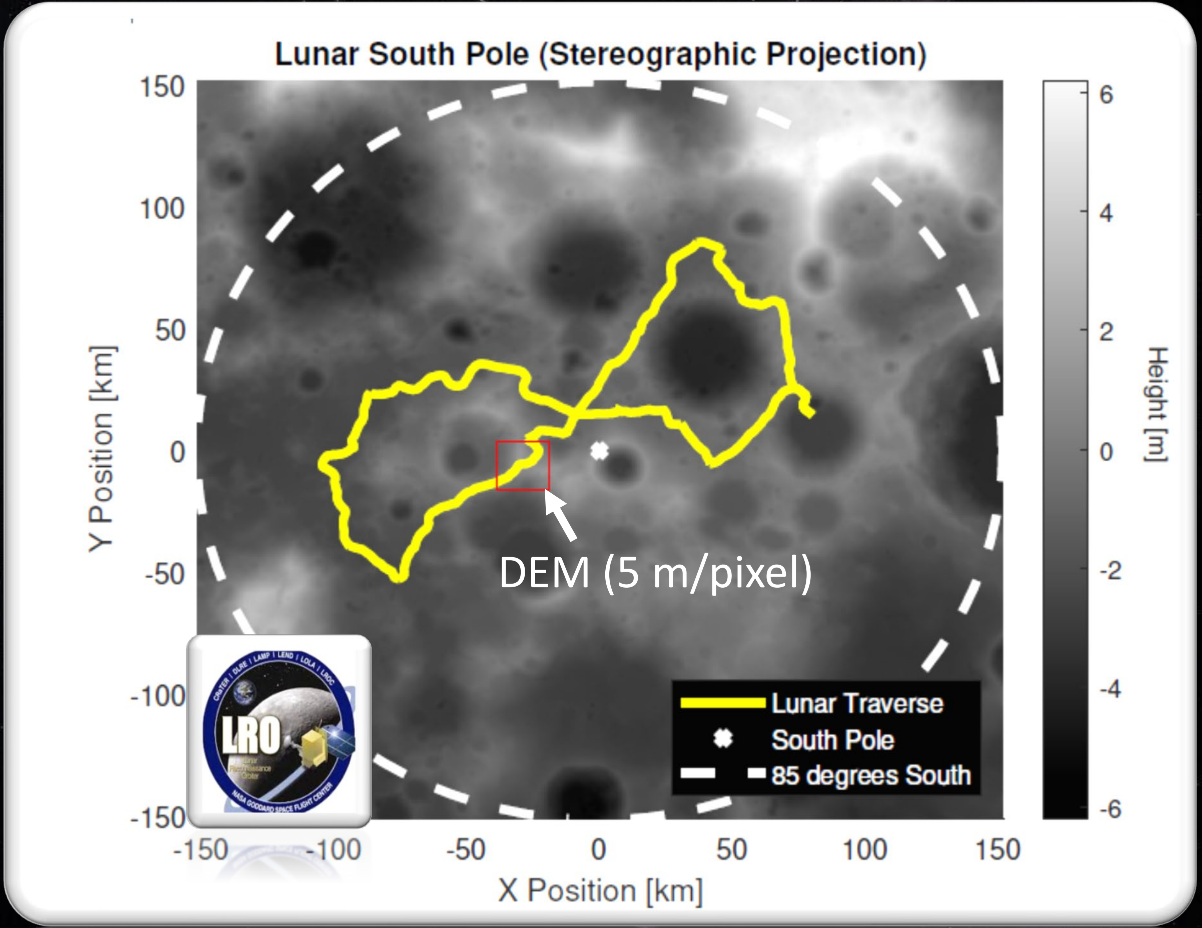
Code and phase corrections



Precision at: sub-meter level | few-dm level

Dynamic Lunar Rover- Performance using Moonlight + NovaMoon + DEM (Detailed Simulation)

- Availability of **1 Hz code and phase measurements** collected by a single baseline in South Pole:
    - Rover receiver in dynamic mode
    - Base receiver at a **known location in South Pole**
- Simulated **15-hour time** interval **with at least 3 satellites in common view**
- Baselines considered: **10, 100, 500 km**
- Use of LRO **DEM information** with an uncertainty of 5 m
- Moonlight NAV Constellation of 4 satellites (SISE ~ 10m 95%)
- Quality of measurements is assumed to be identical at both receivers. Code: **30 cm (high quality) or 1 m (low quality)** at zenith

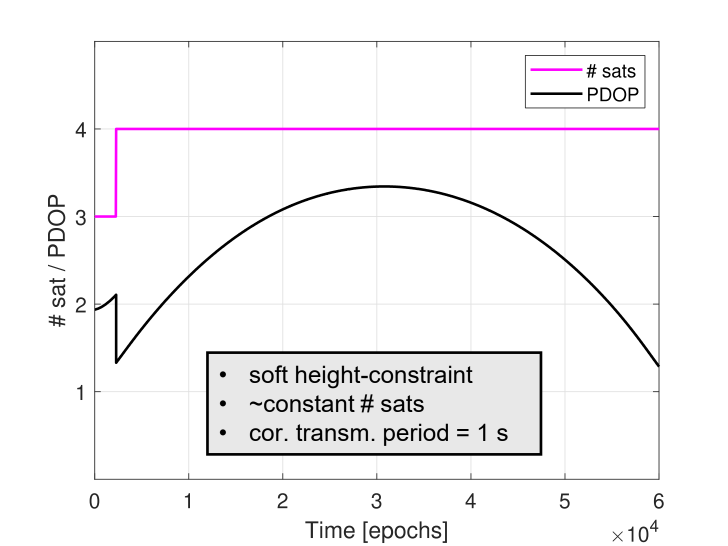


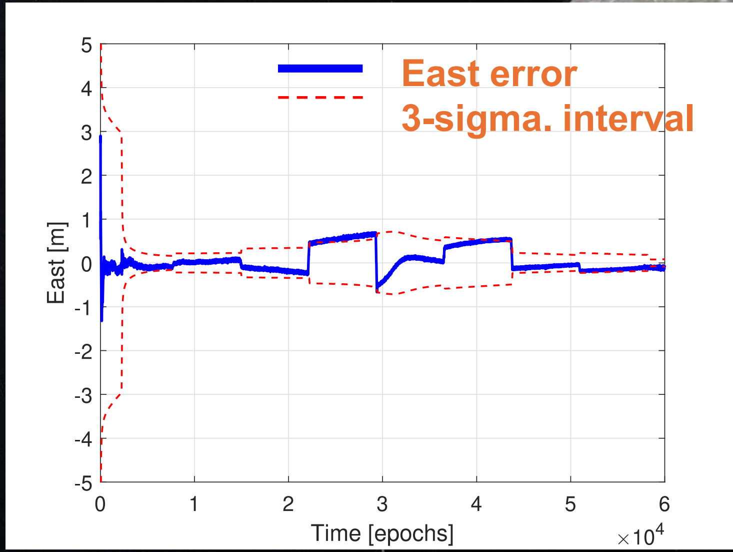
Lunar surface rover in dynamic mode
(15 hours simulation)

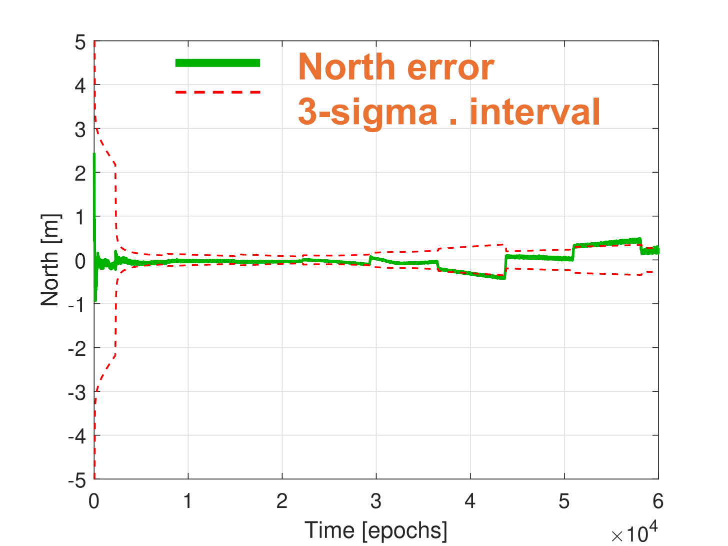
Aitken

Coordinate System: Planetographic, +East, -180 - 180

Simulation Analysis assuming 1s update rate



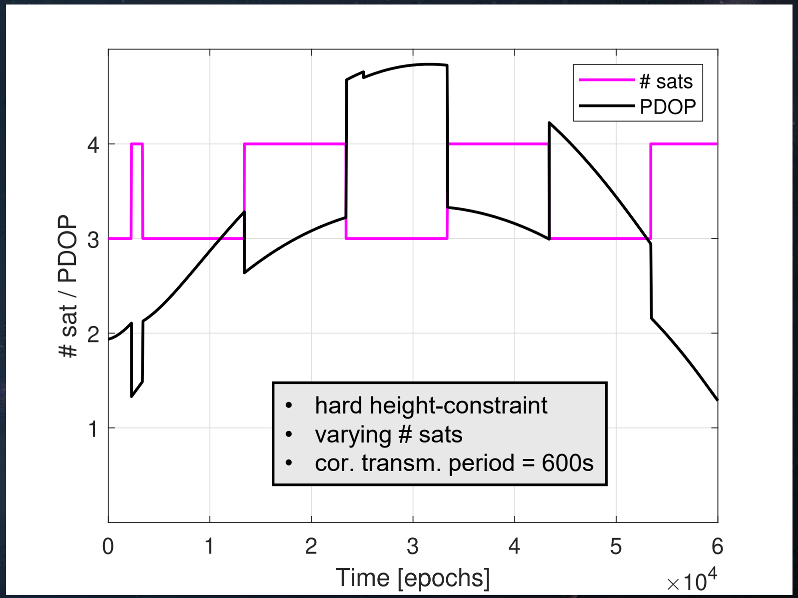


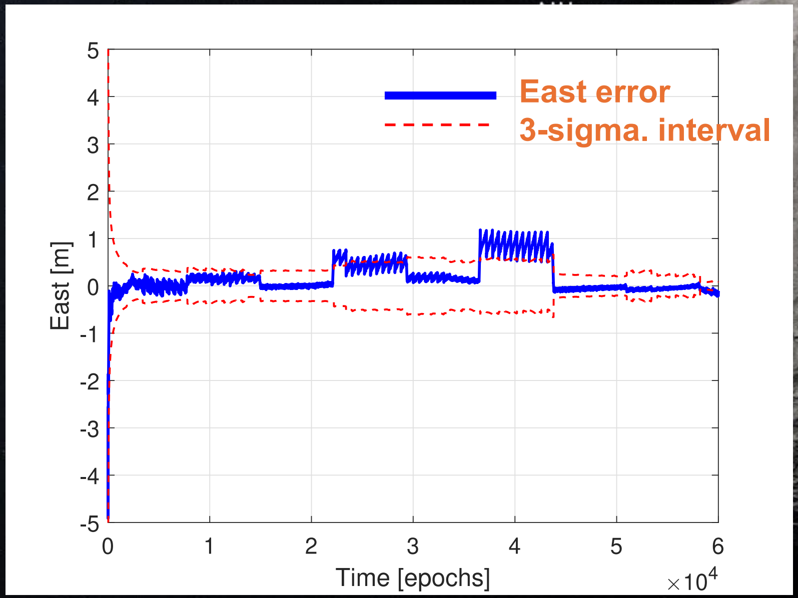


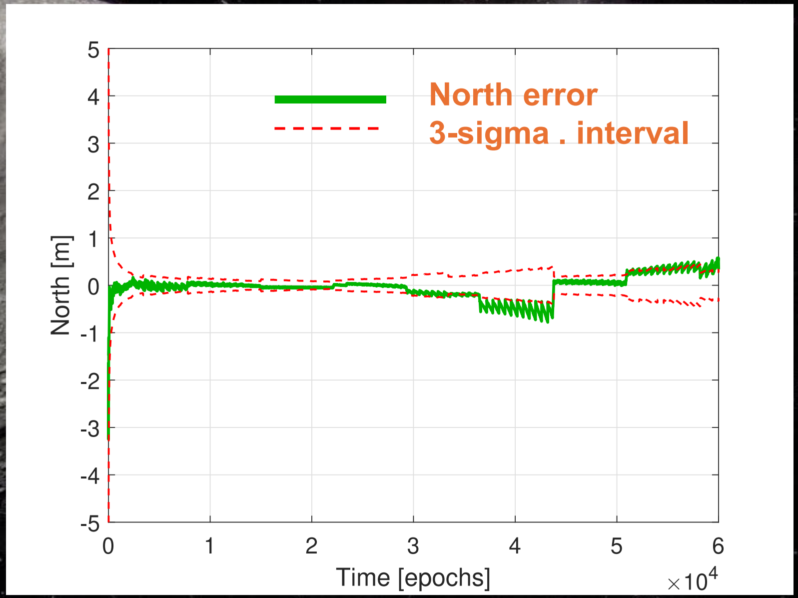
Sub-meter performance can be consistently achieved

Impact of delays in the corrections transmission

Simulation Analysis when corrections provided with a delay of 600 secs and limited satellite availability



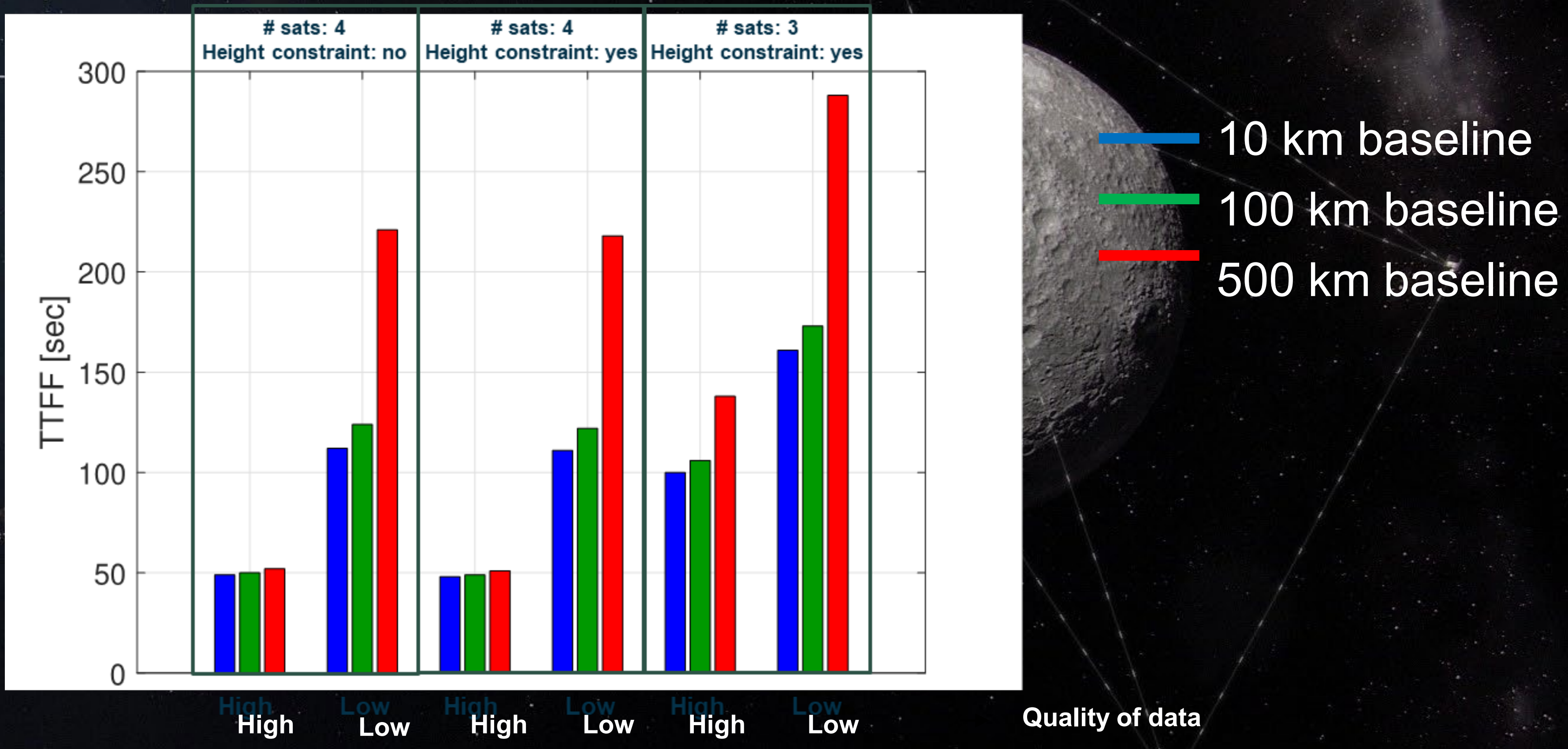




Sub-meter performances are maintained with corrections latency reaching 600s and with limited satellite availability

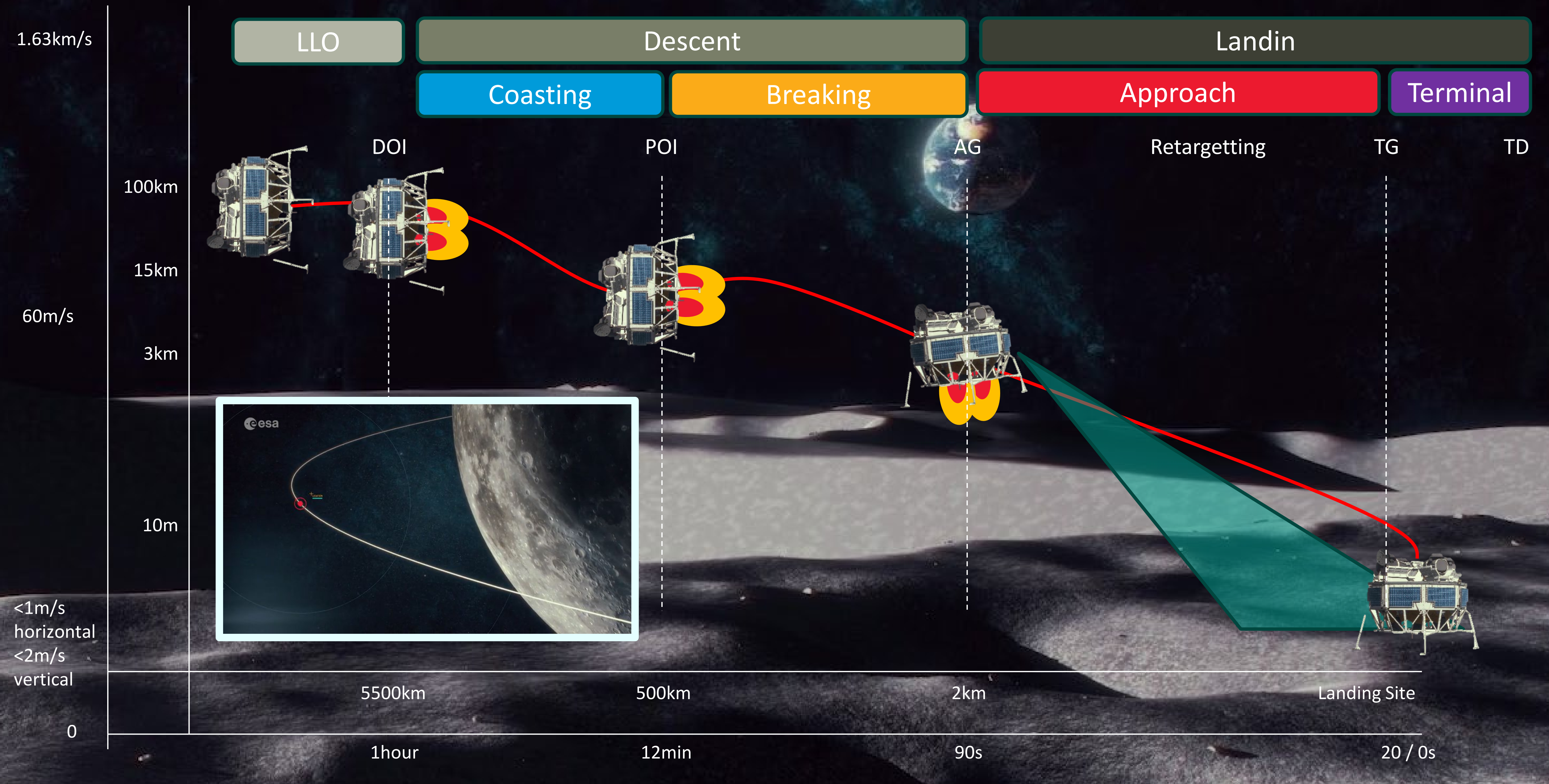
Impact of baseline length

Time-To-First-Fix (TTFF): timespan needed to reach HNSE of 1m

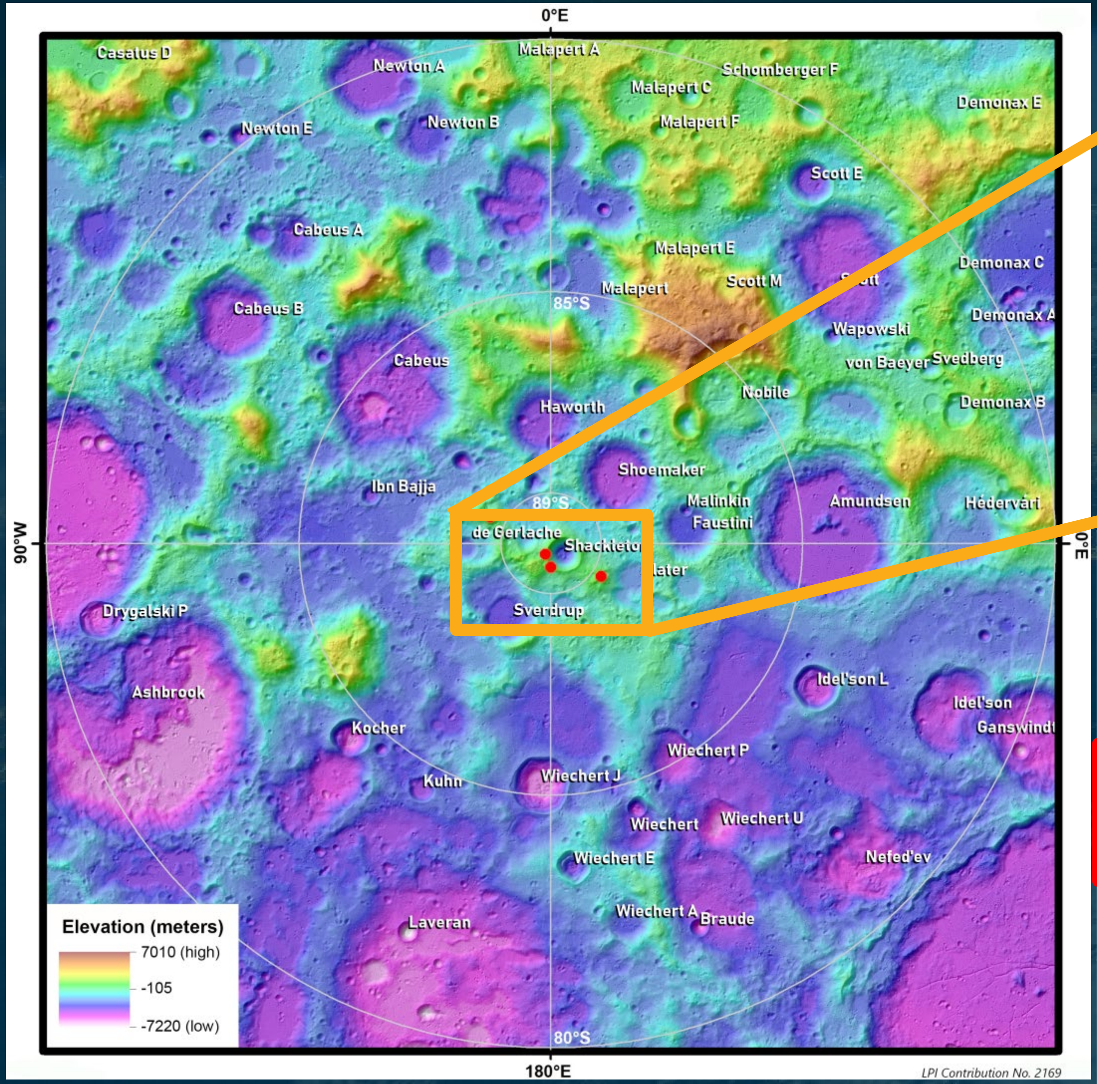


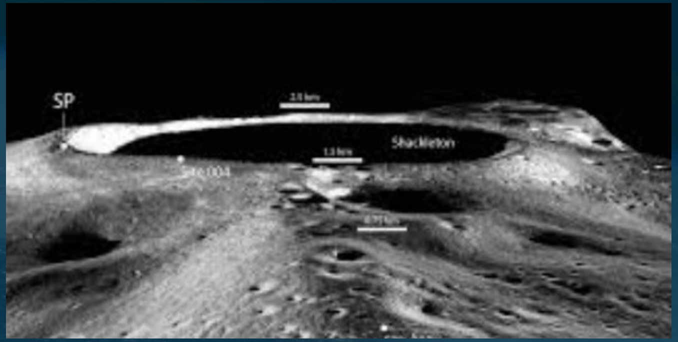
A longer the baseline affects the TTFF but maintains the same accuracy performances upon convergence

Example Moon Landing Profile Using Moonlight & NovaMoon



ESA Simulations analysis
(example of landing at Shackleton-Henson Ridge)



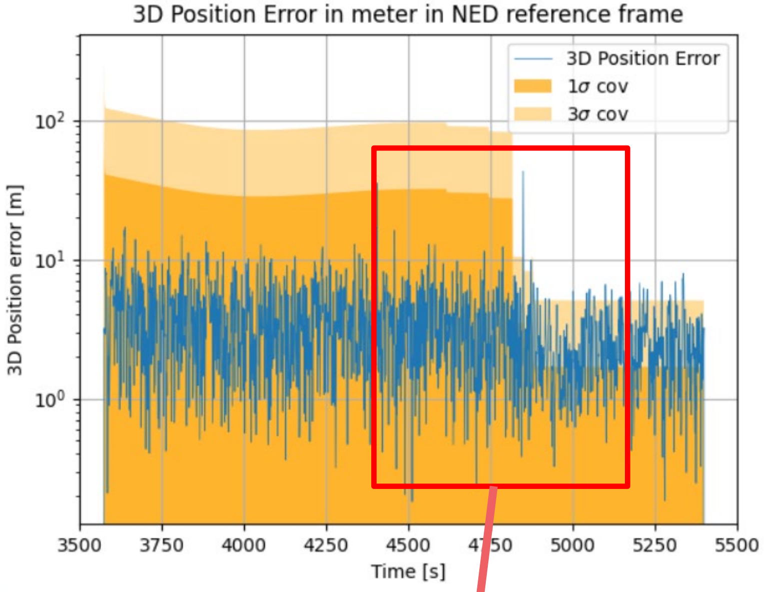


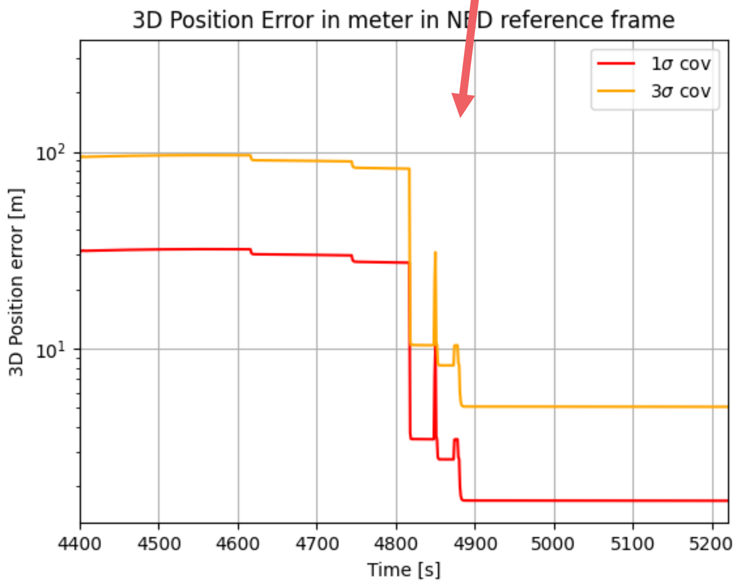
Selected example site for NovaMoon simulation analysis

id	name	lat	lon	minus y [m]	plus y [m]	minus x [m]	plus x [m]	length [m]	width [m]
1	Shackleton Crater Rim	-89.7552	-158.162	2346	2254	183	417	4600	600
2	Shackleton-Henson Ridge	-89.4765	-138.135	1078	722	1050	2950	1800	4000
6	Peak near Slater	-88.8107	123.624	125	175	75	125	300	200
7	Peak at De Gerlache Rim (DGR2)	-88.6406	-68.1379	805	995	1486	1814	1800	330

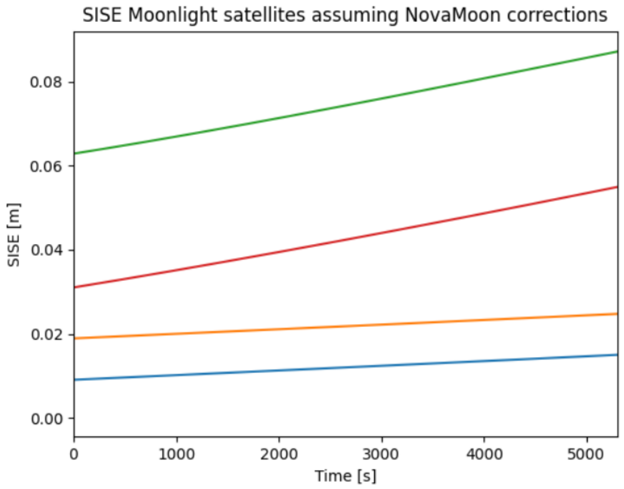
Initial lander results with NovaMoon and Moonlight (reduced SISE)

esa





- The Moonlight SISE requirement is 10m 95% (FOC) and NovaMoon estimated SISE improvements to 0.5m (TBC) 95%.



NovaMoon, by providing differential correction which would reduce the SISE of the satellites, will improve landing accuracy ~ 4 meters (rms)

	Min	Max	Mean	68th perc.	95th perc.	99th perc.
3D error	0.18179 m	42.911m	**3.5585m**	4.1379 m	8.3266 m	11.932 m

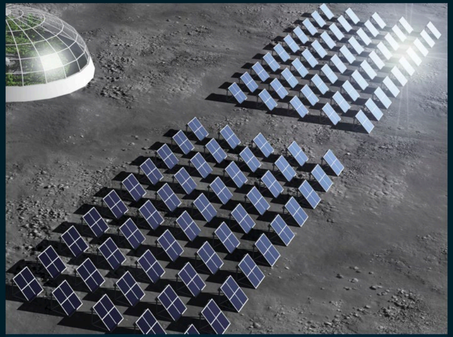
With the potential to provide an additional integrity & safety layer

Boosting lunar exploration and human sustainable presence

With NOVAMOON submetre/decimetre-level navigation accuracies will be available on real time on the Moon.

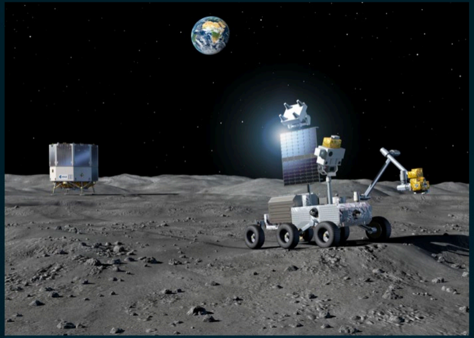
This will enable autonomous surface robotic and safe human transportation, highly accurate and safe lunar landing operations, conduct precise lunar mapping, support lunar operational logistics, develop smart infrastructures, engage in construction and manufacturing, efficient management of resources, push lunar mining industry, among others.

Electricity



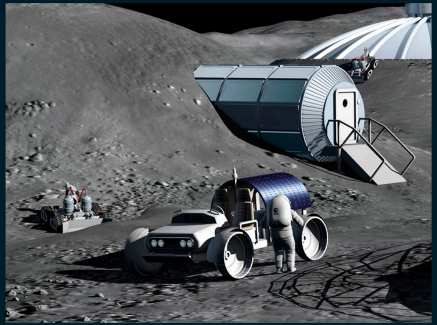
Solar panels: artist's impression of Moon base concept. © ESA–P. Carril

Water, Hydrogen, Oxygen



Prospecting: artist's impression of a Moon lander and rover. © ESA–P. Carril

Transport & Logistics



Transport vehicles: artist's impression of Moon base concept. © ESA–P. Carril

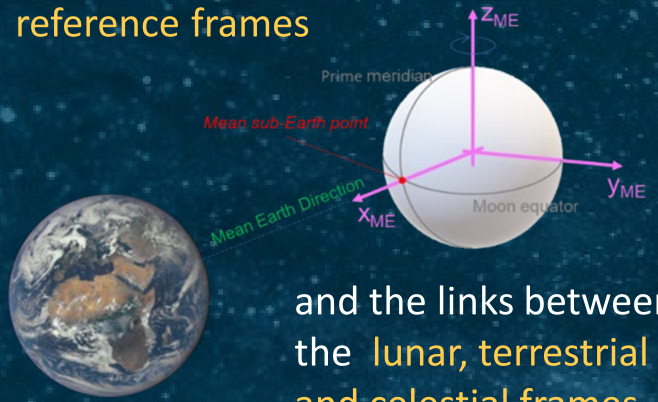
Safe & Accurate Landing

Construction & Manufacturing

Habitat construction: artist's impression of Moon base concept. © ESA–P. Carril

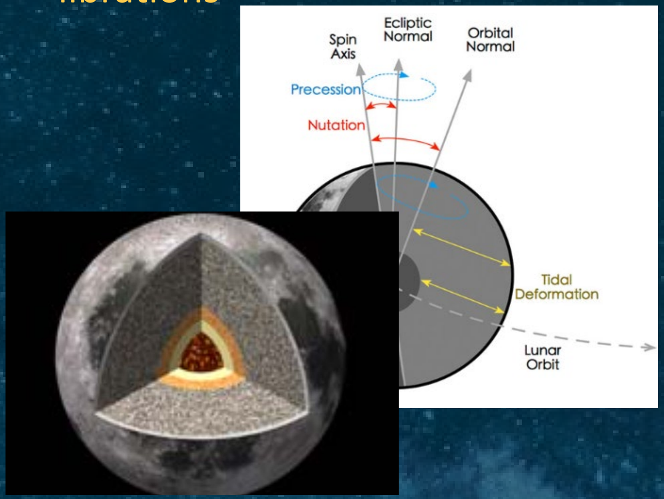
A wealth of potential scientific research

Enhancing the accuracy of Lunar reference frames



and the links between the lunar, terrestrial and celestial frames

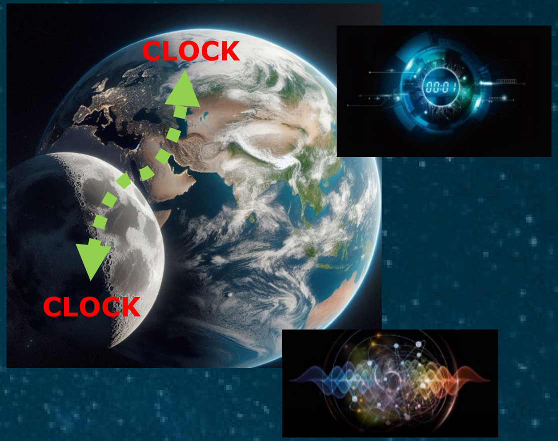
Allowing precise measurements of the Moon tidal deformations and Moon librations



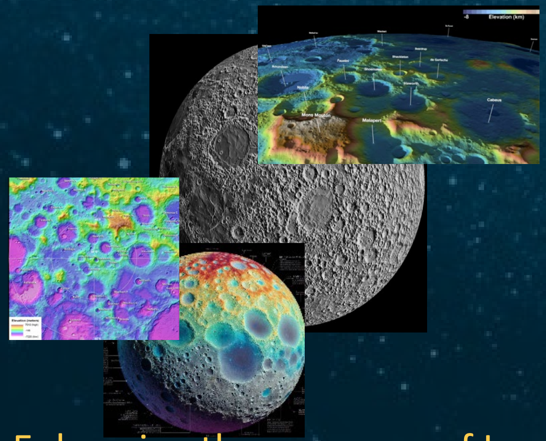
Improving the knowledge of the lunar gravity field, Moon rotation, solid core displacement, Moon interior, etc

A major step towards the on-site realisation and experimentation of the Lunar reference time and its link with UTC

Unique Fundamental Physics tests may be conceived thanks to the exceptional Earth-Moon relativistic long-baseline testbed.



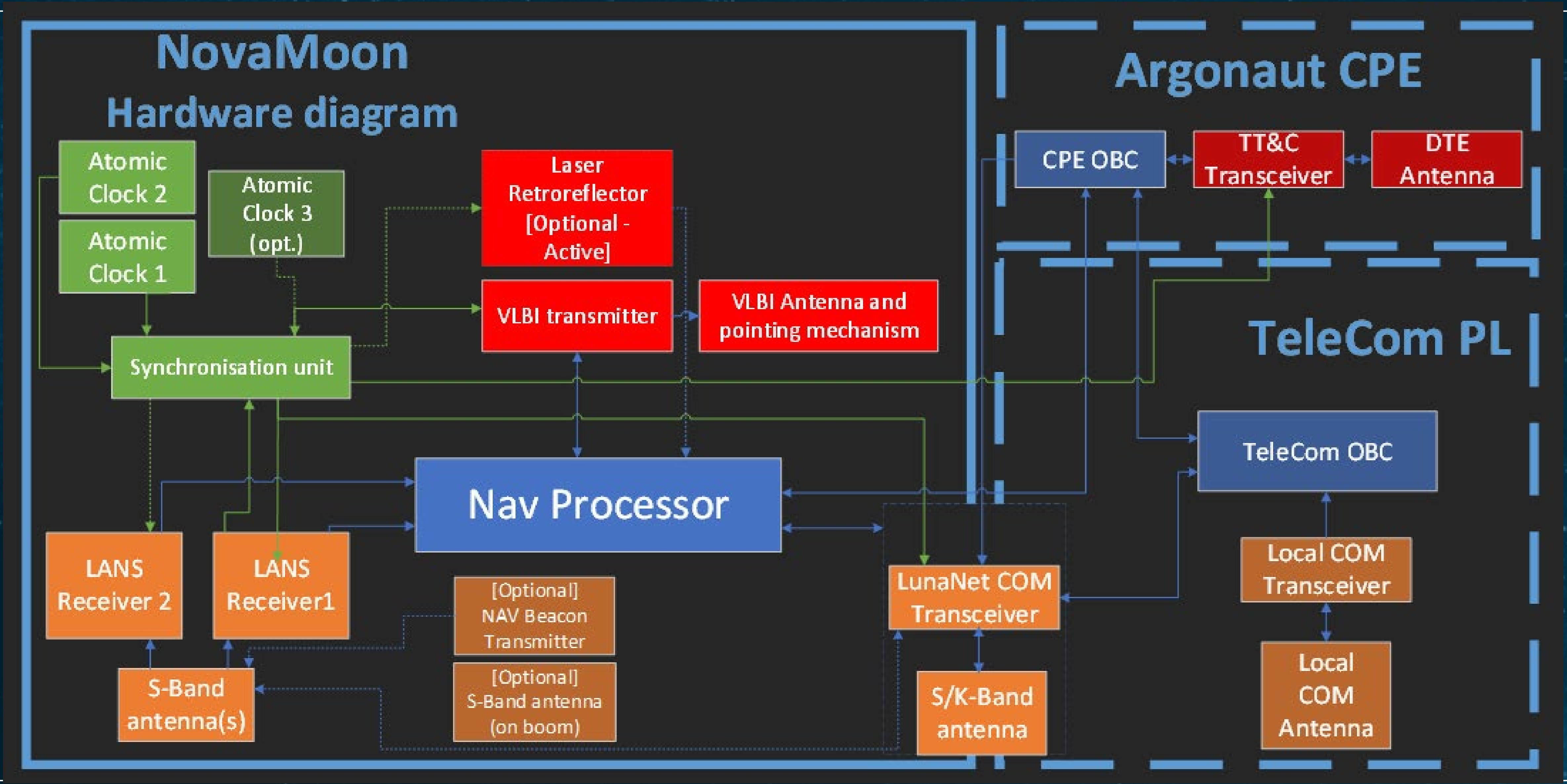
With an active laser ranging time-tagging photons in space could help to research in quantum communication



Enhancing the accuracy of Lunar DEM maps allowing new lunar missions to happen

NovaMoon will catalyse the establishment of leading scientific groups and drive cutting-edge research across multiple disciplines

NovaMoon Payload Architecture (incl. options)



Initial Budget Estimations

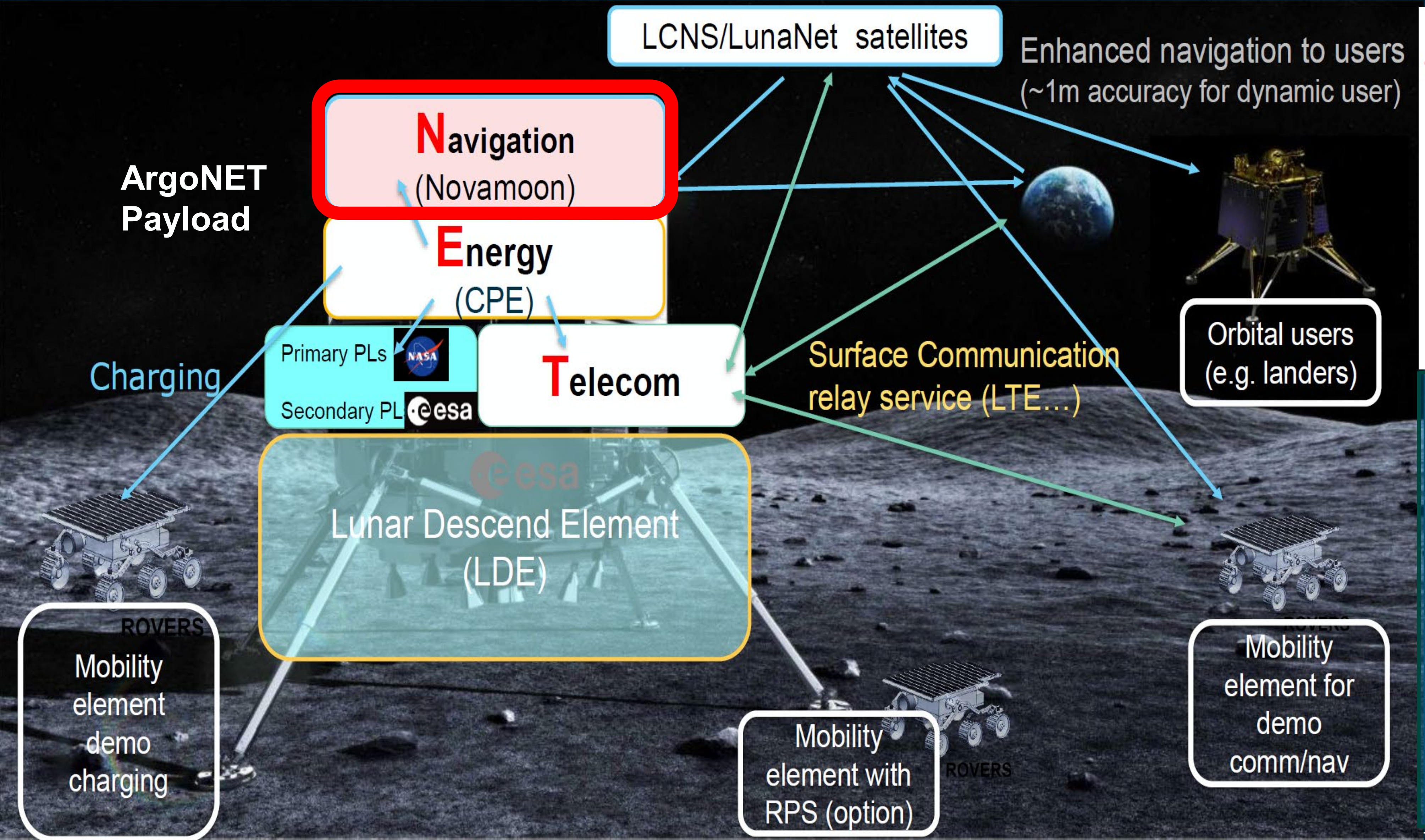
	Unit ID	Function Mapping	Element	Location	Baseline	Power Peak (W)	Power Nominal (W)	Mass (kg)	Notes
			NovaMoon						
TIMING-UNIT	**U1**	MF02/CF08	**Timing**						
TIMING-UNIT	U1.1		Atomic Clock 1	Internal	Y	10	10	*0.5*	
TIMING-UNIT	U1.2		Atomic Clock 2	Internal	Y	10	10	*0.5*	
TIMING-UNIT	U1.3	F26	Atomic Clock 3 (Option)	Internal	N	10	0	*0.5*	*Cold redundancy*
TIMING-UNIT	U1.4	F13	Synchronisation unit	Internal	Y	35	35	*8*	*Internally redundant*
COM-UNIT	**U2**	MF01/F23	**Communications**						
COM-UNIT	U2.1		Moonlight COM transceiver	Internal	Y	40	0	*2*	
COM-UNIT	U2.2		COM S-band Antenna	External	Y	0	0	*0.5*	
NAV-UNIT	**U3**	CF04/CF05/CF06 /CF07/F12/F13/ F14/F15/F16/ F17/F18/F19	**Navigation**						
NAV-UNIT	U3.1		LANS Receiver 1	internal	Y	18	18	*1*	
NAV-UNIT	U3.2		LANS Receiver 2	internal	Y	18	18	*1*	
NAV-UNIT	U3.3		NAV S-band Antenna(s)	External	Y	0	0	*1*	
NAV-UNIT	U3.4	CF03/F22	Navigation processor	internal	Y	10	10	*0.6*	
NAV-UNIT	U3.5	F20	LANS Transmitter (Option)	internal	N	30	30	*1*	
NAV-UNIT	U3.6	F27	Extendible Boom (Option)	External	N	TBD	TBD	*TBD*	
VLBI-UNIT	U4	CF03/CF09.	**VLBI**						
VLBI-UNIT	U4.1		VLBI Transmitter	internal	Y	20	0	*1.5*	
VLBI-UNIT	U4.2		VLBI Antenna	external	Y	0	0	*2*	
VLBI-UNIT	U4.3		APM	external	Y	12	0	*5*	
LASER-UNIT	U5		**Laser Ranging**						
LASER-UNIT	U5.1	CF03/CF10	Laser Retroreflector MPac	external	Y	12	0	*5*	
LASER-UNIT	U5.2	F25	Laser Retroreflector INRRI (Option)	external	N	0	0	*0.025*	
LASER-UNIT	U5.3	F24	Active Laser Retroreflector (Option)	external	N	35	0	*10*	

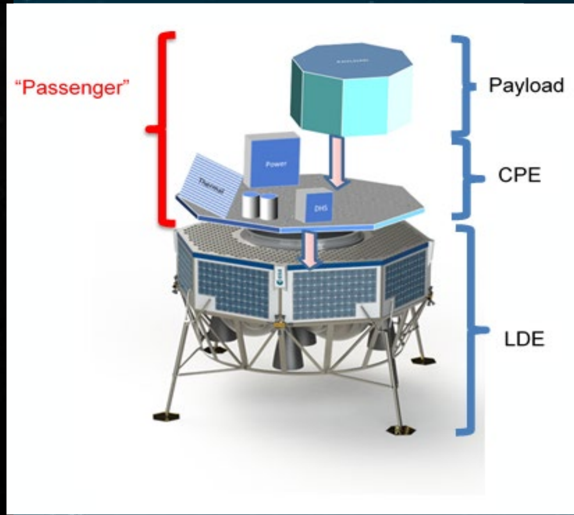
Based on existing technologies, a first assessment of the mass and power may be performed including redundancy

Peak Power if also VLBI and laser pointing mechanisms are activated – only needed initially/occasionally for detailed campaigns

	Power Peak (W)	Power Nominal (W)	Mass (kg)
Total Baseline	185	101	28.6
w/ Margin (20%)	222	121.2	34.32
Total Baseline w/ options	260	131	40.125
w/ Margin (20%)	31	157.2	48.15

NovaMoon Payload will be integrated in ESA's Argonaut- 1 Mission (launch in 2031)





Long –Term service

Argonaut-1 will operated for a 5 years, including Lunar nights.

Argonaut recurring missions every 2 years, which could include recurrent NovaMoon Payloads.

The NovaMoon payload will provide ....

esa

1. A first-ever PNT local differential station on the lunar surface providing sub-metre accuracies
2. The possibility of continuous monitoring of Moonlight and partner Agencies Lunar Navigation Systems
3. An International Selenodetic Reference station established on the Moon (supporting the Moon reference frame realisation and scientific research)
4. A lunar reference 3D position established at cm-level
5. A Lunar time reference station on the Moon surface with long-term operating atomic clocks on the lunar surface supporting lunar time physical realisation and detailed experimentation
6. The possibility of doing Moon rover Navigation on lunar night conditions
7. A unique opportunity for international scientific research in multiple fields