Máni an exploration mission for the Moon

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A depiction of Máni and Sól (1895) Lorenz Frølich

Mission overview:

First mission with:

- targeted multi-angular photoclinometric
- topographic and surface properties mapping at <20 cm resolution.

Aim:

1) Support exploration: assist planning, de-risking landing (South Pole, Artemis, Argonaut, others…)
2) Determine the topography, photometry and micro-texture (μm) of the Lunar surface for exploration and science

ESO

First targeted multi-angular photoclinometric observation strategy

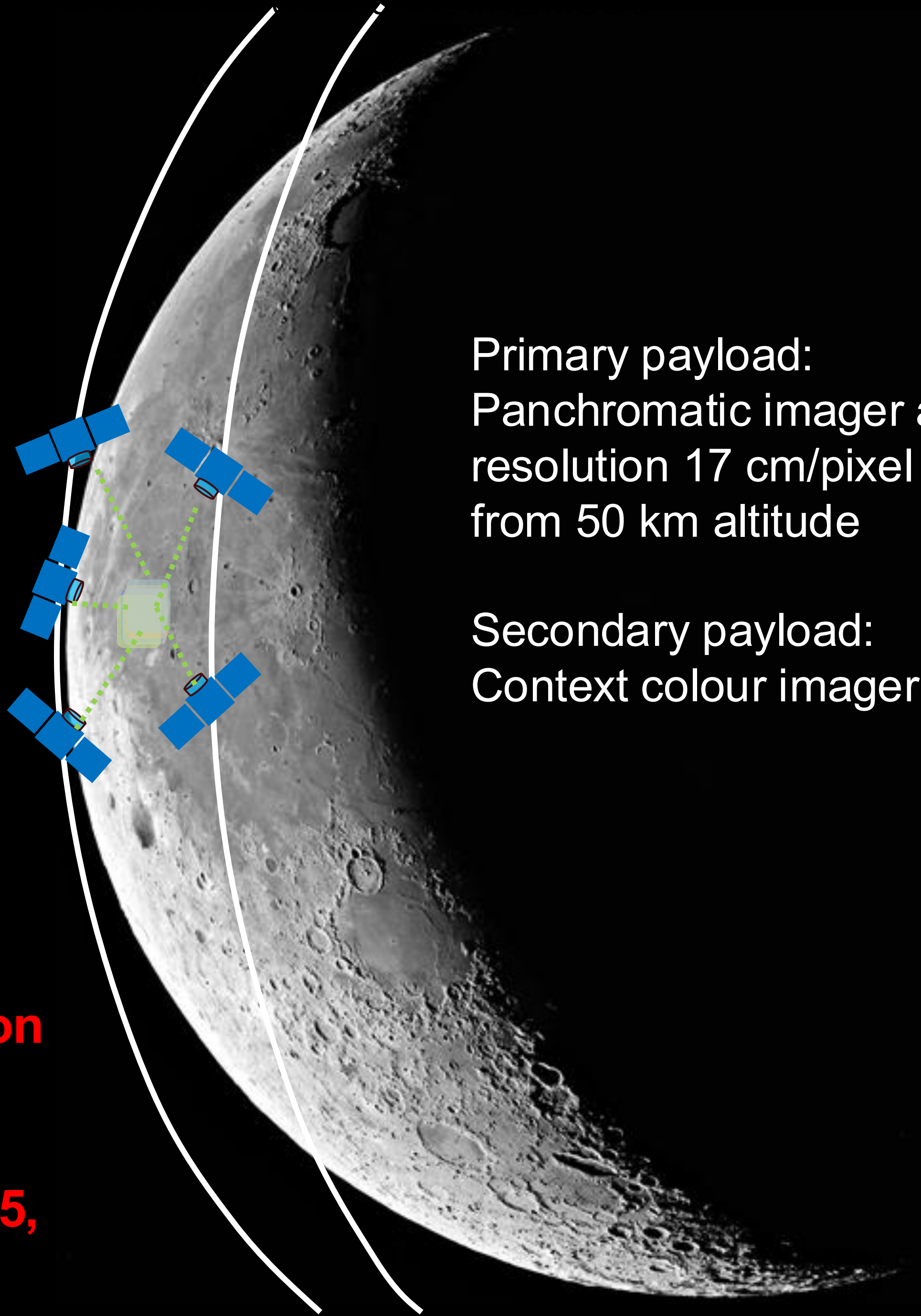
- 10 overlapping images of regions of interest

- Range of viewing angles exceeding 100°, and solar incidence angles differing by at least 20°

- 5 images x 2 overflights

Optimal Photometric geometries for a space mission by Hugo Lancery et al. , EPSC-DPS2025-267

MITM8, room Mars on Thursday, 11 September 2025, 17:00

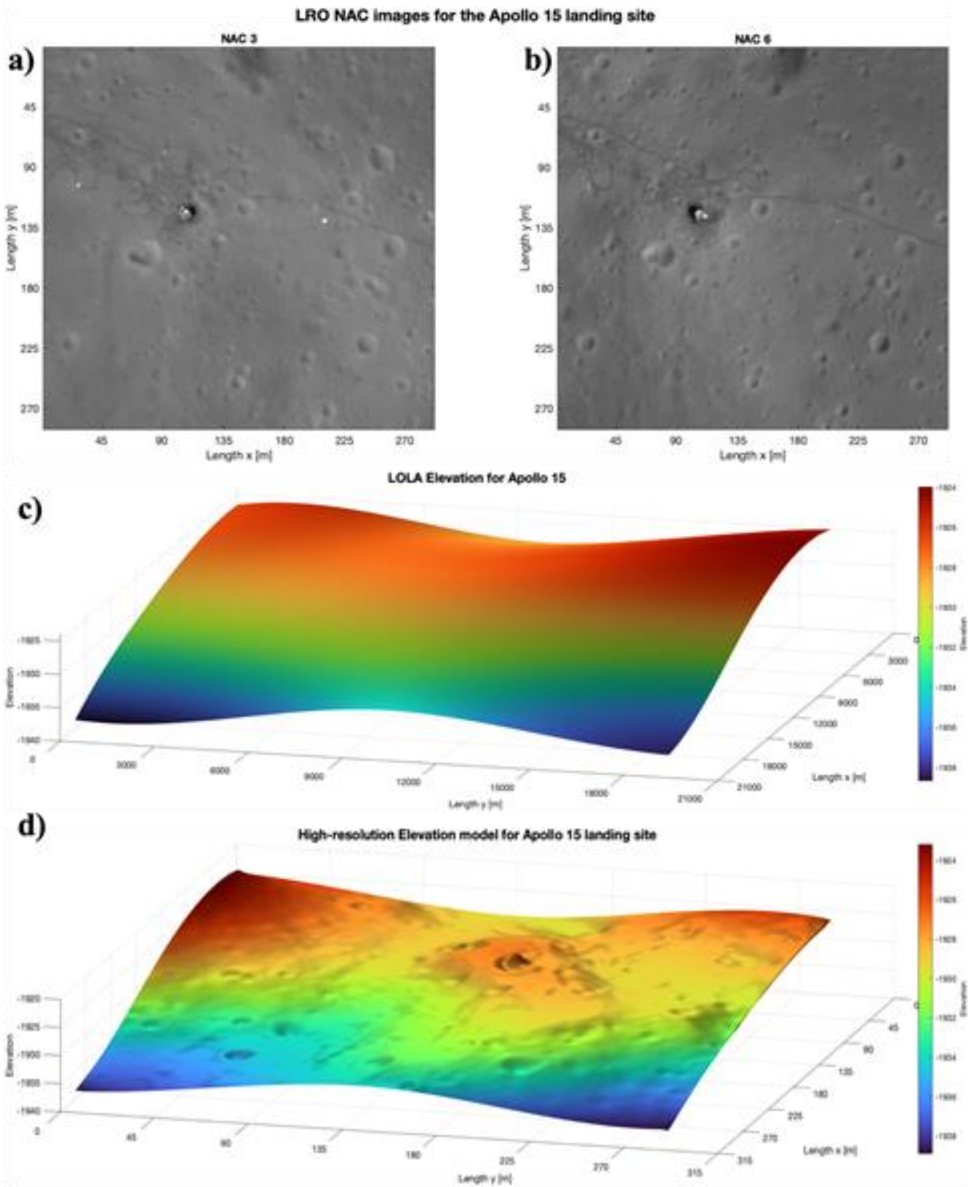


Primary payload:
Panchromatic imager at resolution 17 cm/pixel from 50 km altitude

Secondary payload:
Context colour imager

ES

Primary payload: Image and Topography



Multiple mapping data products:

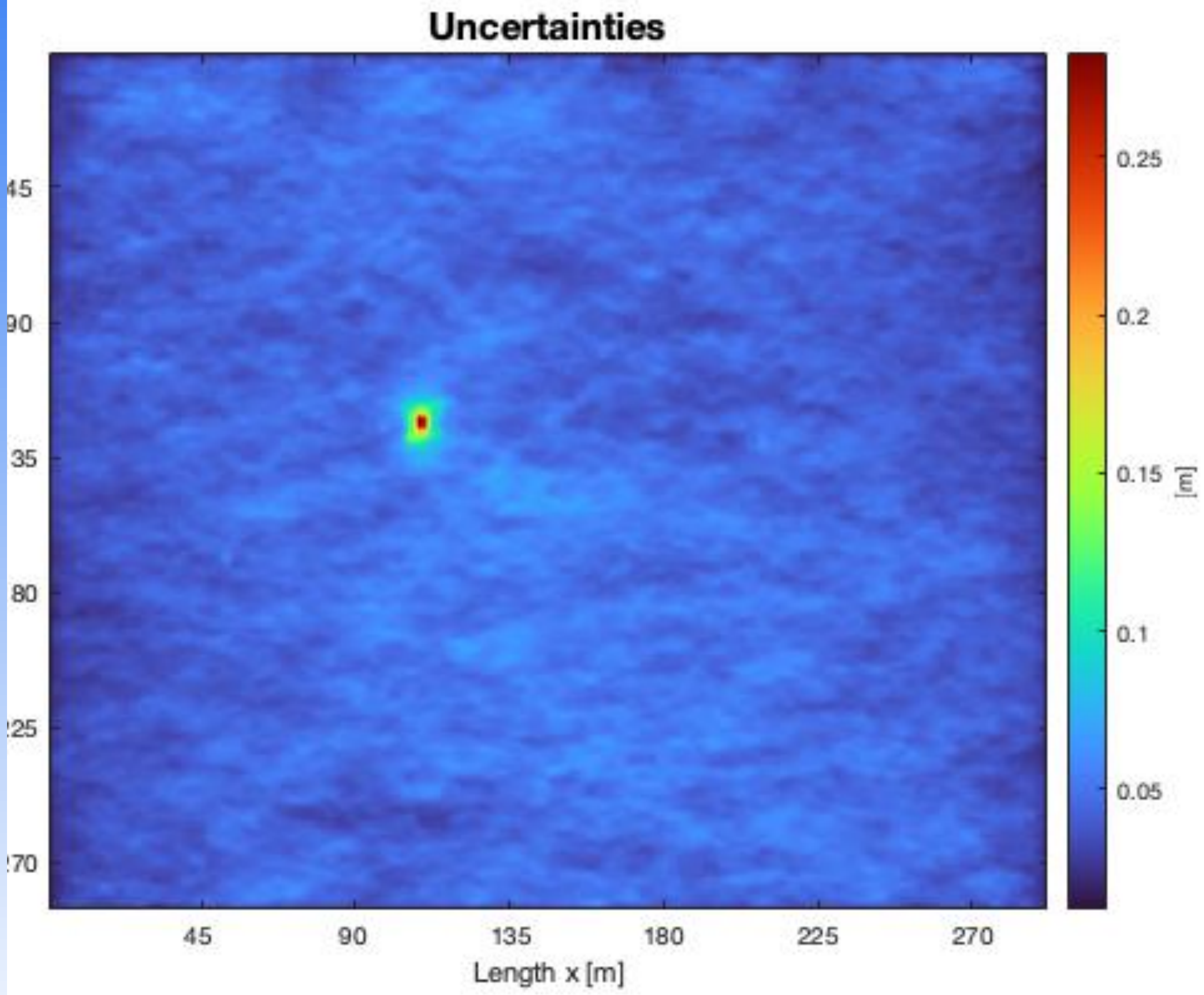
- **Image**
- **Topography**
- Reflectance properties
- Surface microtexture
- Uncertainties

Proof of concept using LROC NAC (~50 cm) on Apollo 15 landing site

Photoclinometry pipeline: Fernandez et al., 2022, PSS

1) 6 NAC images
2) LOLA prior information
3) Topographic maps at NAC resolution

Primary payload: Image and Topography



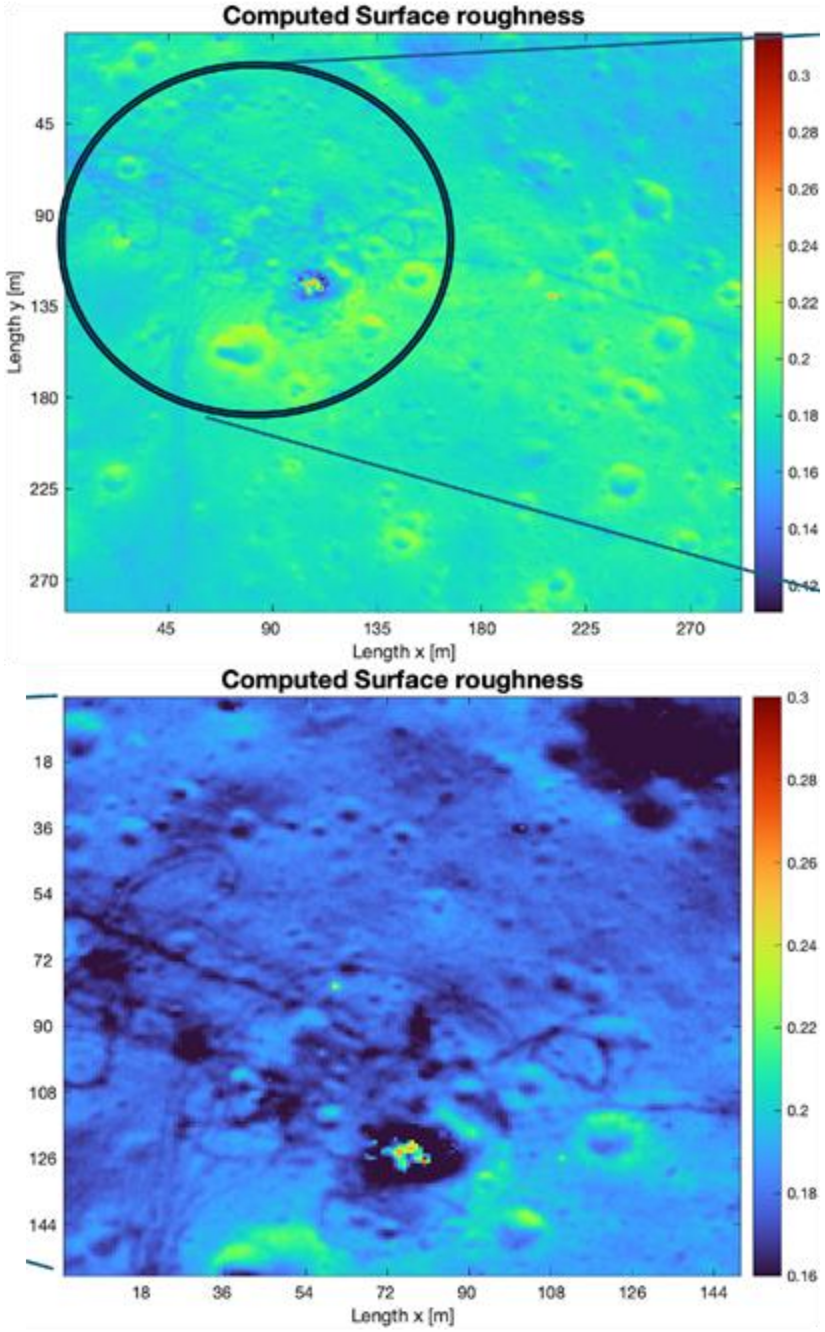
Multiple mapping data products:
- **Image**
- **Topography**
- Reflectance properties
- Surface microtexture
- **Uncertainties**

Proof of concept using LROC NAC (~50 cm) on Apollo 15 landing site

Photoclinometry pipeline: Fernandez et al., 2025, in prep.
1) 6 NAC images
2) LOLA prior information
3) Topographic maps at NAC resolution with uncertainties on height and slope

De-risking / landing site selections

Primary payload: Photometry



Multiple mapping data products:

- Image
- Topography
- **Reflectance properties**
- Surface microtexture
- **Uncertainties**

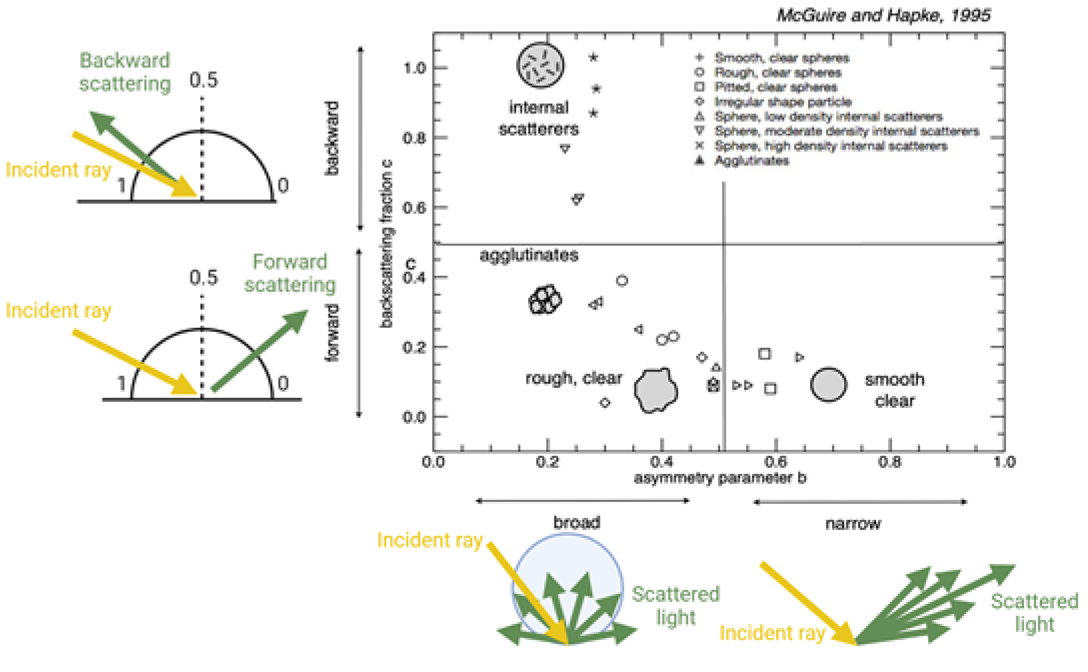
Proof of concept using LROC NAC (~50 cm) on Apollo 15 landing site

Photoclinometry pipeline: Fernandez et al., 2025, in prep.

1) 6 NAC images
2) LOLA prior information
3) Topographic maps at NAC resolution
4) Photometric behaviour with uncertainties

Non Lambertian behaviour depends on surface micro-texture/composition

Primary payload: Microtexture



Derived micro-texture properties at µm scale (roughness, grain size, grain shape…)

Multiple mapping data products:

- Image
- Topography
- Reflectance properties
- **Surface microtexture**
- **Uncertainties**

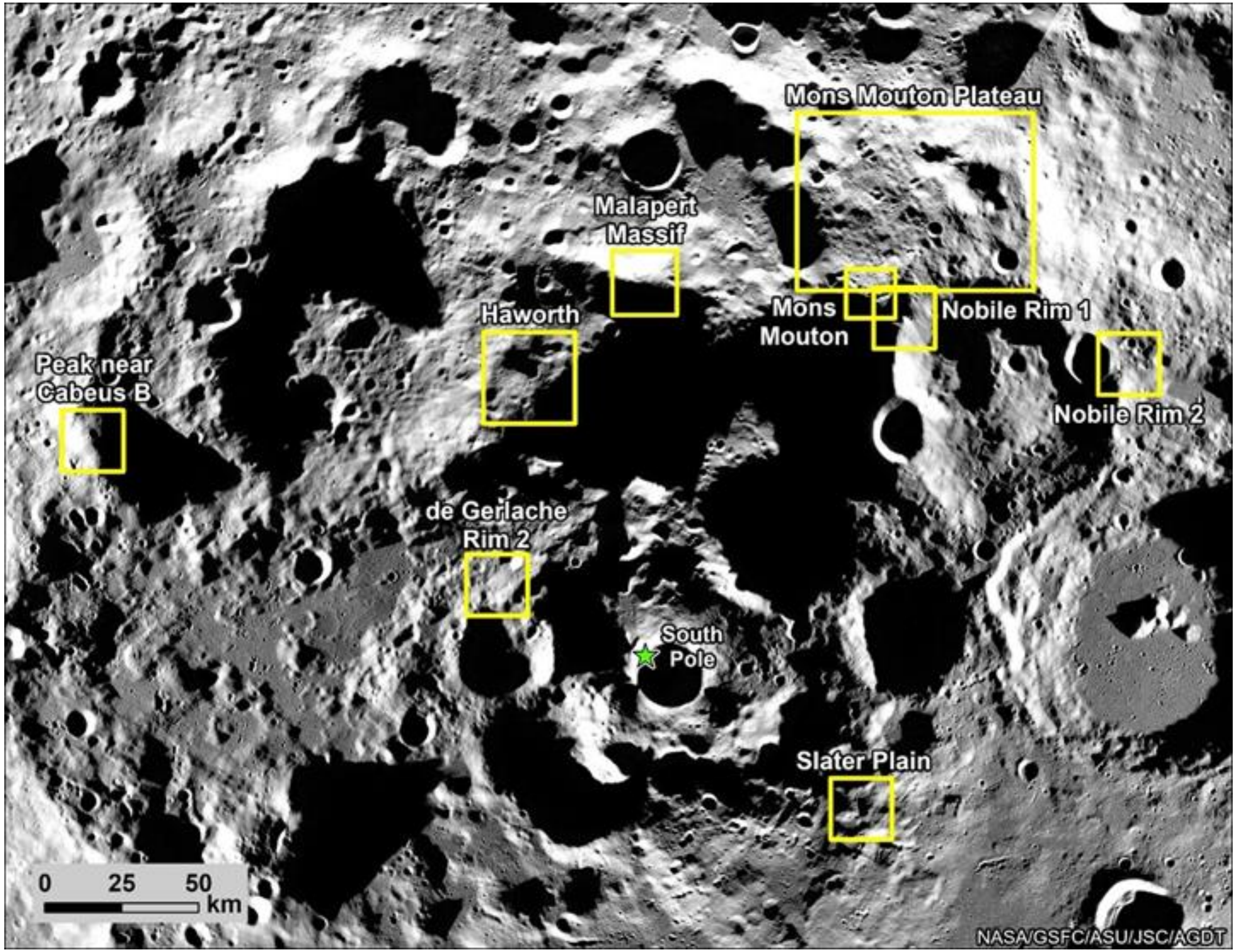
Proof of concept using LROC NAC (~50 cm) on Apollo 15 landing site

Photometry pipeline:

Schmidt et al., 2015, 2019, Icarus

1) 6 NAC images
2) LOLA prior information
3) Topographic maps at NAC resolution
4) Photometric behaviour with uncertainties
5) Surface microtexture

Key exploration goals



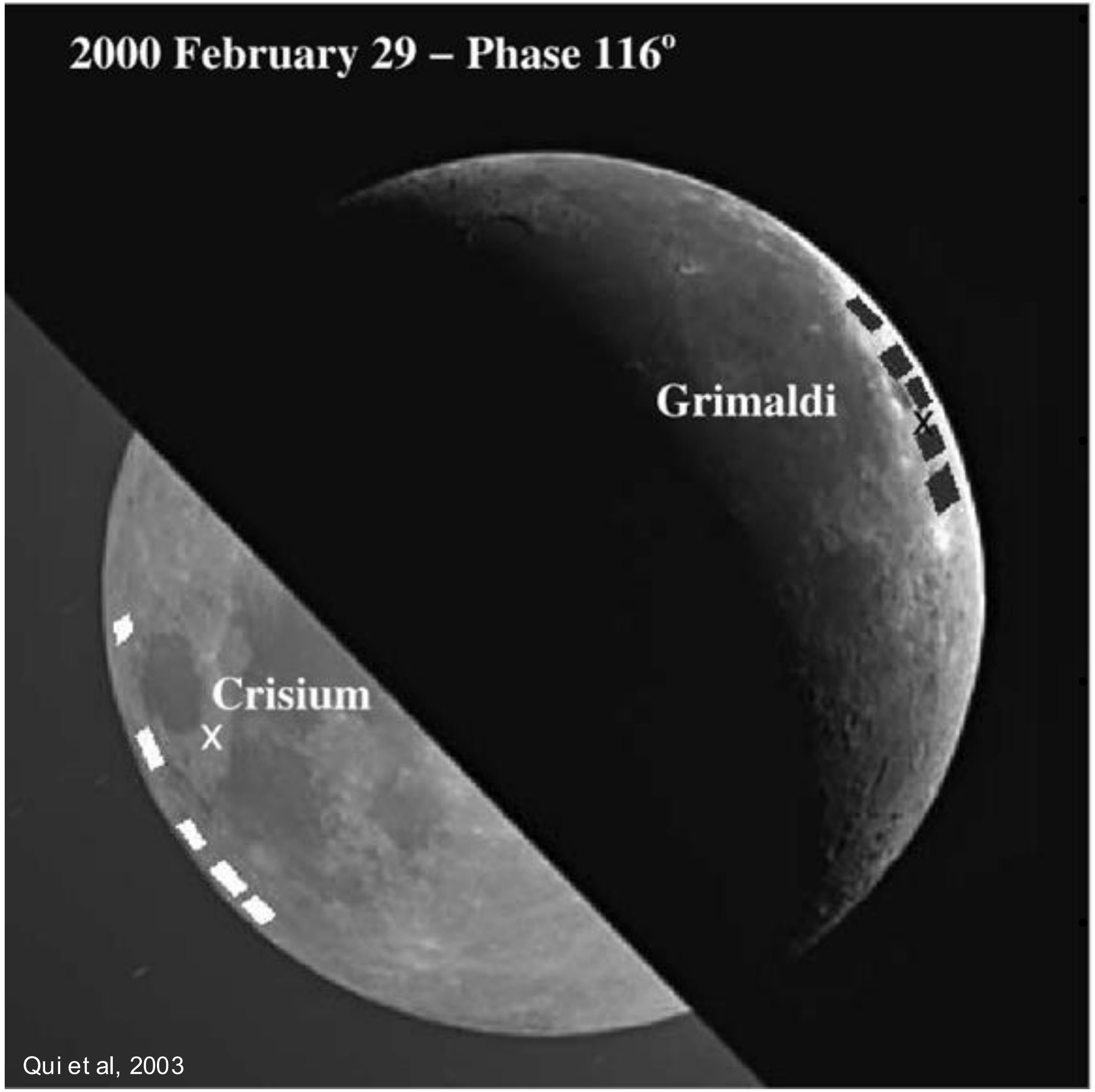
Artemis III landing site candidates near the Lunar South Pole

Map sites of importance to future human and robotic exploration:

- ROI across the Lunar surface
- Lunar South Pole

=> low circular polar orbit with inclination >89°

Examples of key science goals



Lunar Flashes: current Lunar impact rate?
The high-resolution Máni images and topography

Age and composition of Irregular Mare Patches?
Máni map => age and nature of these enigmatic landforms

Effects of space weathering on Lunar regolith
Decipher the processes creating the regolith and estimate the evolution timescale.

Volcanic cave conduits – formation and evolution?
Mapping of the Lunar pits' interiors.

Quantifying Earths albedo – a key parameter in climate models
The Moon used by Earth satellite as a calibration target (Grimaldi and Crisium)

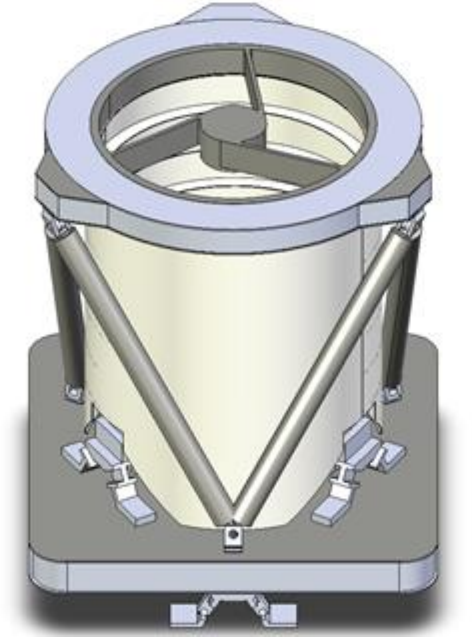
Optical payload

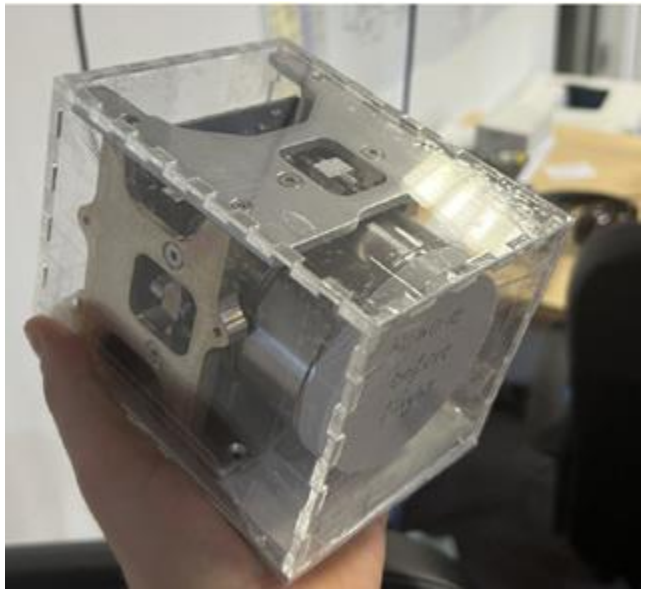
Developed by Scanway

Based on existing bigger Earth Observation systems (InCubed project - SEMOVIS)

Pre-phase-A study:
1) Primary: 300 mm aperture Ritchey-Chrétien-type telescope and 2D panchromatic camera with heritage

2) Secondary based on 1U telescope (SOP1U/65)





Left: Technical drawing of the primary payload – SOP300. Right: Secondary payload SOP1U/65 – flight model for a different project imaged within a protector.

Parameter	Unit	Value
Primary payload: SOP300		
GSD @ 50 km	m	0,17
Mass	kg	~25
Aperture	mm	300
Pixel pitch	um	3,45
MTF @ Nyquist	-	Very close to diffraction limit (on design level)
Secondary payload: SOP 1U/65		
GSD @ 50 km	m	~1,5
Mass	kg	1
Aperture	mm	65
Pixel pitch	um	3,45

Máni high-speed communication payload

Provided by Paradigma Technologies

High-throughput Ka-band transmission subsystem: 2 transmitter modules and a fixed 50 cm antenna at 25.5–27.0 GHz

Link budget simulations: 70 Mbps with ESA ground stations (Cebreros, Malargue) + compatible with commercial ground stations

520mm reflector (left) and Paradigma Technologies transmitter module (right)

Máni spacecraft

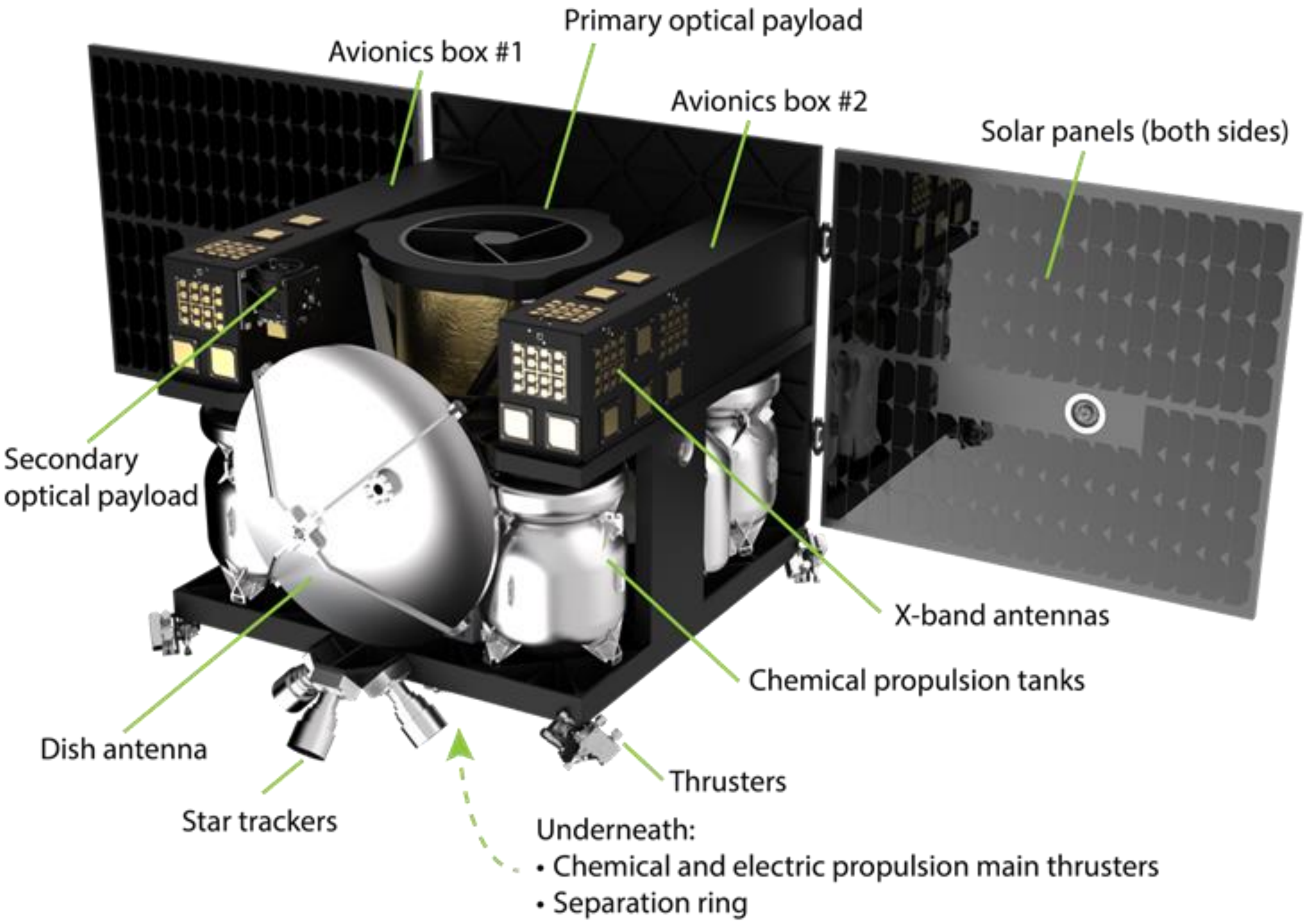
Built by Space Inventor

Microsatellite: total mass of ~210 kg

- Designed around the large primary payload
- As compact as possible to minimise moment of inertia
- Agile for acquiring numerous observation angles

Dimensions are 0.85 x 0.85 x 0.75 m (solar panels closed)

When operating 2.5 x 0.85 x 0.75 m



Launch opportunities, trajectory, and orbit

Chemical and electric propulsion

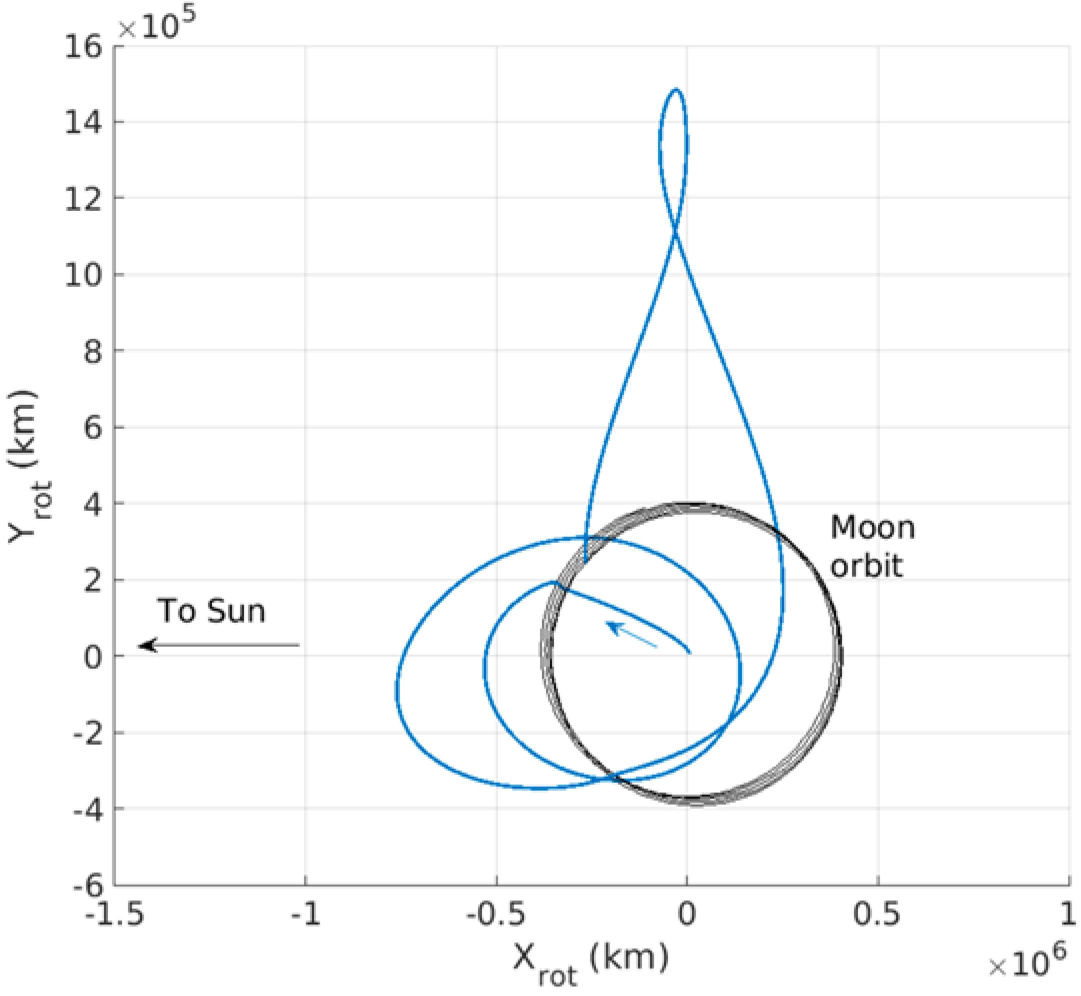
Minimal constraints on the launcher except lunar transfer orbit (LTO) of ~210 kg

Launch: RFA One, Ariane 62/64 and Falcon 9

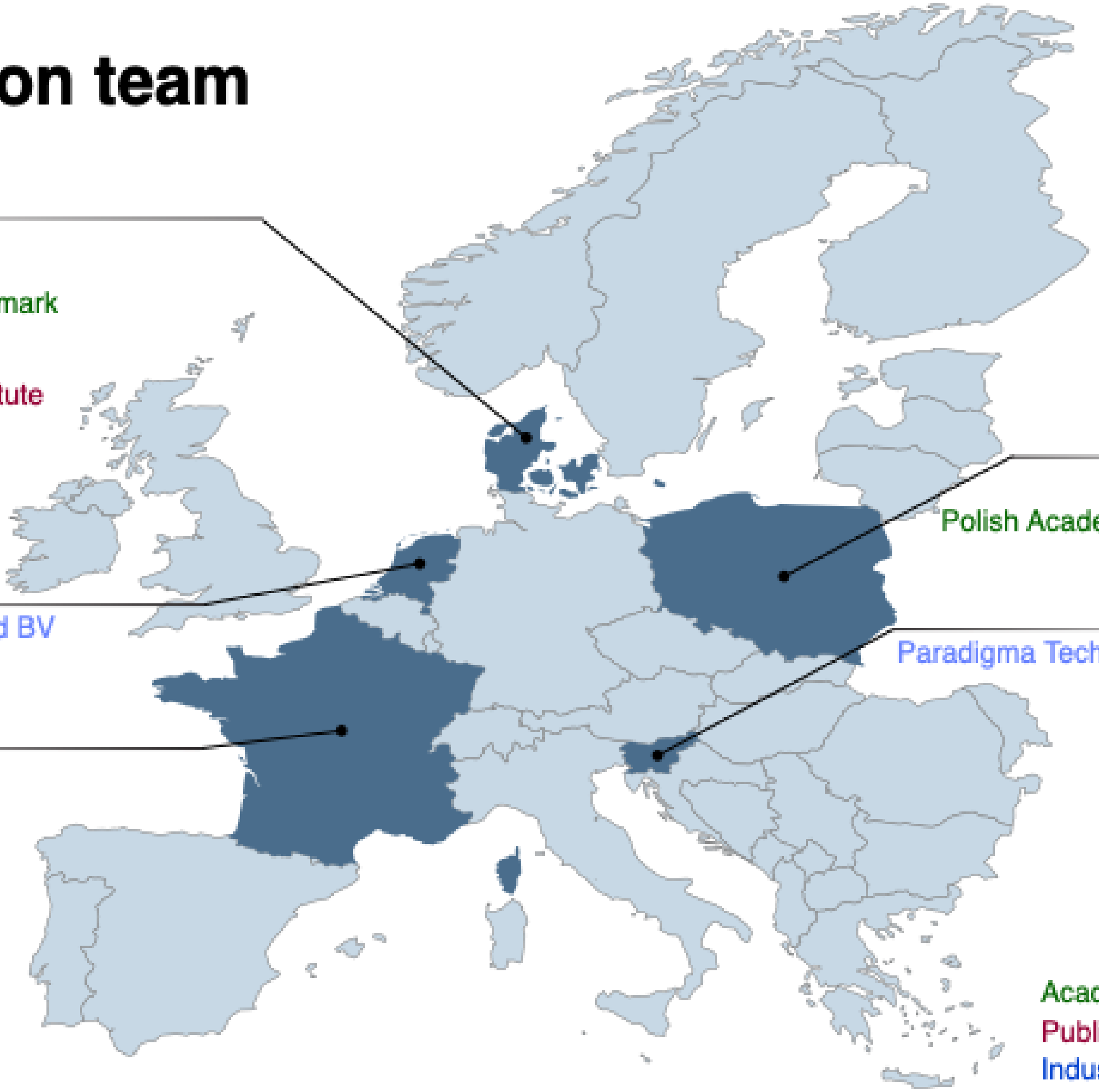
50 km polar orbit with inclination >89° require a lot of orbit maintenance manoeuvres.

	Lunar transfer scenario: WSB from LTO launch	
Mission phases	Chemical propulsion only	Hybrid propulsion system
WSB manoeuvres	CP delta-v: 100 m/s	CP delta-v: 100 m/s
Lunar orbit capture	CP delta-v: 120 m/s	CP delta-v: 120 m/s
Orbit lowering	CP delta-v: 675 m/s	CP delta-v: 250 m/s EP delta-v: 900 m/s
Orbit maintenance	CP delta-v: 150 m/s	CP delta-v: 150 m/s
Decommissioning	CP delta-v: 10 m/s	CP delta-v: 10 m/s
Total delta-v	**CP: delta-v: 1055 m/s**	**CP delta-v: 630 m/s EP delta-v: 900 m/s**

Example of most likely class of mission trajectories: WSB transfer from an Lunar Transfer Orbit launch



Máni mission team



Denmark
Space Inventor A/S
University of Copenhagen
University of Southern Denmark
Aalborg University
AarhusUniversity
Danish Meteorological Institute

The Netherlands
Dawn Aerospace Nederland BV

France
Université Paris-Saclay

Poland
Scanway S.A.
Polish Academy of Science

Slovenia
Paradigma Technologies d.o.o.

Academic partner
Public entity partner
Industrial partner

Conclusion and perspectives

Máni pre-phase-A study at ESA shows photoclinometry and photometry can be implemented

Mature technology and hardware within 50 M€ cost

Ready for launch ultimo 2028 after approval by the Ministerial ESA in November 2025

Highest spatial resolution images and topographic maps of the Moon available (17 cm)

Surface microtexture down to μm scales through photometry

Facilitate and de-risk future exploration missions (Artemis, Argonaut, etc…) and enable new scientific investigations

Máni spacecraft

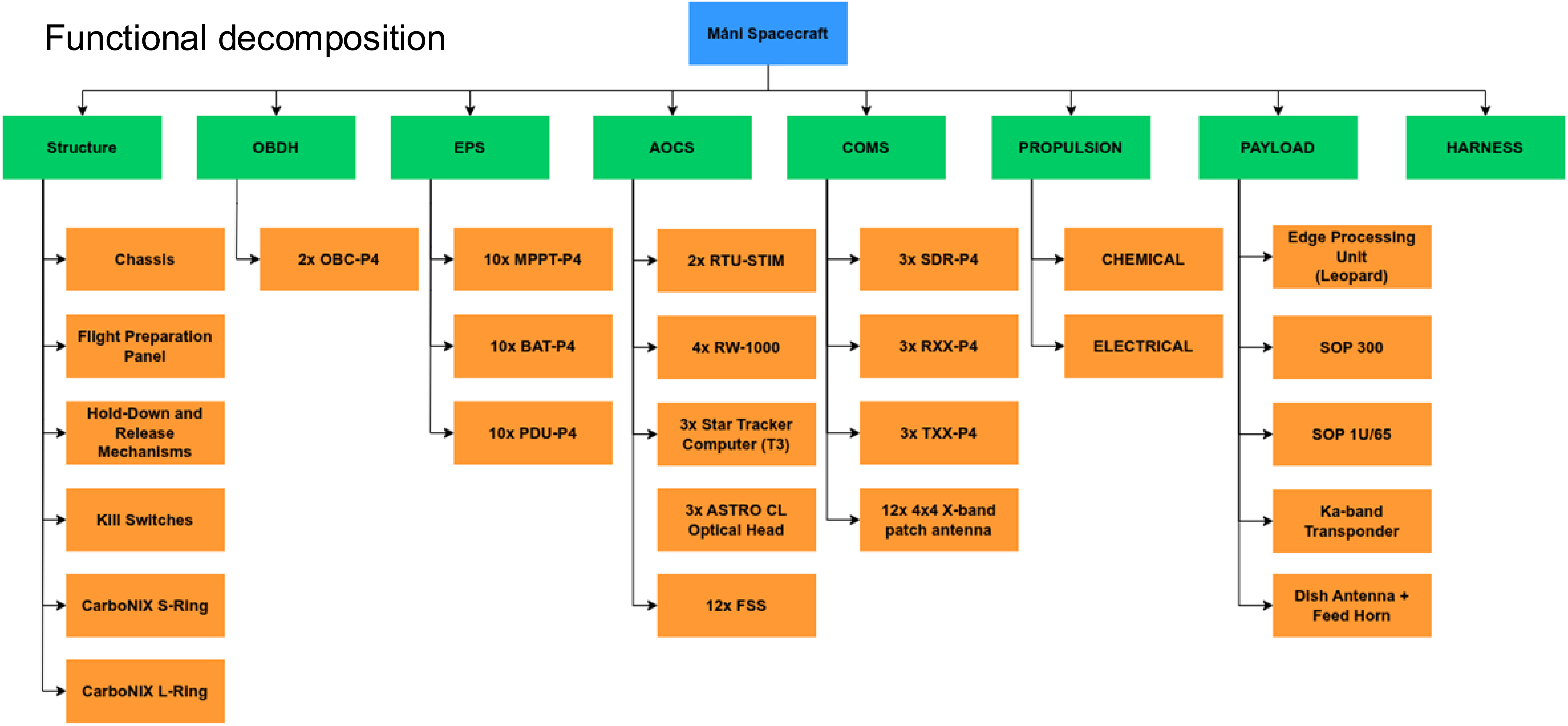
Mass budget

Element	Mass [kg]	Percentage of Total Mass [%]
Optical Payloads	28.00	13.1
Payload Ka-band Transmitter	5.5	2.6
Platform Mechanical Structure	43.9	20.5
Solar Panels	11.3	5.3
EPS	9.8	4.6
OBDH	0.3	0.2
TMTC	2.0	1.4
AOCS	7.6	3.5
Chemical Propulsion	64.0	29.9
Electric Propulsion	36.0	16.8
Associated Harness	4.8	2.2
TOTAL (Launch Mass)	214.0	
TOTAL (Separated Mass)	210.4	

Launch Mass and Separated Mass refer, respectively, to the total launch mass including the two elements of the separation ring between the spacecraft and the launch vehicle, and to the mass that is separated from the launch vehicle

Máni spacecraft

Functional decomposition



Máni spacecraft

Subsystem overview

Subsystem	Module	Functionality	Quantity	Manufacturer
Optical Payload	SOP 3000	Main Payload	1	Scanway
	SOP 1U/65	Secondary Payload	1	Scanway
	ATCS	Payload Thermal Control	1	Scanway
	Leopard PDU	Power Distribution	1	KP Labs
Payload Data Download	Ka-band Transmitter	Radio for Payload data download	1	Paradigma Technologies
	Dish Antenna	Antenna for Payload data download	1	Anteral
Propulsion	Electrical	Propulsion for Orbit Transfer and Station Keeping	1	Dawn + Partner
	Chemical	Propulsion for Orbit Transfer and Station Keeping	1	Dawn
Platform EPS	3G30A	Solar Cell	715	AzurSpace
	MPPT-P4	Maximum Power Point Tracker	10	Space Inventor
	BAT-P4	Battery Package	10	Space Inventor
	PDU-P4	Power Distribution Unit	10	Space Inventor
Platform OBDH	OBC-P4	On-Board Computer	2	Space Inventor
Platform AOCS	RTU-STIM	Inertial Measurement Unit	2	Space Inventor
	WHL-1000	Reaction Wheel	4	Space Inventor
	T3 ST Computer	Star Tracker computer	3	Space Inventor
	ASTRO CL Optical Head	Star Tracker Optical Head	3	Jena Optronik
	FSS	Sun Sensor	12	Space Inventor
TMTC	SDR-P4	Software-Defined Radio	3	Space Inventor
	TXX-P4	Transmitter	3	Space Inventor
	RXX-P4	Receiver	3	Space Inventor
	X-band 4x4 patch antenna	Antenna for X-band communication	12	Space Inventor

Mission phases

LEOP and Commissioning: The spacecraft will autonomously detect separation from the launcher and enter a power-positive safe mode that enable establishment of communication with the mission operations center. As part of the commissioning phase, check-out of the spacecraft and payload health will be performed and the solar panels will be deployed

Transfer phase: In the baseline scenario of an Lunar Transfer LTO launch to WSB transfer, the spacecraft will perform one or more Lunar fly-bys to meet the required arrival geometry. Following Lunar orbit insertion, the transfer phase concludes with orbit lowering to the intended operational orbit.

Nominal operations: Upon entering the operational orbit, we envision five separate phases for the mission:

- ***Data acquisition***: This phase represents the primary phase of the mission – the acquisition of images of mapping regions of interest – and it thus will be a priority to maximise the amount of time that be dedicated to this phase.
- ***Calibration***: We need to perform recurring calibration activities to ensure and verify the validity of the pre-launch calibration
- ***Communications***: We envision the use of the ESTRACK Ka-band antennas for science data downlink from the spacecraft, and lower data-rate downlink (X-band) for TMTC
- ***Orbit maintenance***: A low Lunar circular orbit at an inclination of 90° is highly unstable, and we will thus have to conduct orbit maintenance manoeuvres regularly
- ***Sun pointing safe-mode***: If an anomaly is encountered, the spacecraft will enter a power positive safe mode.

End of life strategy: Controlled crash on the Lunar surface

Data and link budget

Link Budgets were computed for both the Ka-band (science data downlink), and X-band (TMTC uplink/downlink). The calculations include LLO (Low Lunar Orbit), and WSB (Weak Stability Boundary), for different ground stations. Link budget is calculated for elevation (above the horizon for the ground station) in steps of 10°, implying that 10° reflect the worst-case scenario for each link investigated.

Overall, the Máni mission will be able to rely on several ground stations for both up- and downlink of TMTC and science data.

We estimate that a maximum data volume of ~5.4 GB can be acquired per Earth day. Assuming an average data downlink rate through the ESTRACK Ka-band ground stations of ~80 Mbits/s, 10 minutes of downlink time per day on average would be sufficient to downlink all data from the primary imager.

We estimate that TMTC for all subsystems of the spacecraft will comprise no more than 50 Mbyte/day. Assuming a 0.80 Mbit/s downlink rate, 9 minutes of daily X-band downlink would be sufficient to downlink all data.

Orbit	Ground Station	Case	Elevation [deg]	Symbol Rate [Mbaud]	Net margin [dB]
WSB	ESA Kourou-1	X-band Uplink	10	0.04	11.74
	CERBEROS-1	X-band Uplink	10	0.04	20.86
		X-band Downlink	10	0.04	9.79
	KSAT	X-band Downlink	20	3.20	3.16
LLO	ESA Kourou-1	X-band Uplink	10	0.80	10.47
	CERBEROS-1	X-band Uplink	10	0.80	19.59
		X-band Downlink	10	0.80	8.52
		Ka-band Downlink	20	80.00	4.10
	KSAT (50 MHz)	Ka-band Downlink	20	40.00	3.60
	KSAT (25 MHz)	Ka-band Downlink	20	20.00	6.61

Programmatic Approach

Due to the high TRL for nearly all mission hardware, we do not identify any need for major development of critical technologies to implement the mission. Hence, a core programmatic approach for the Máni development is that we, while considered a microsatellite, will adhere to the ESA ECSS standards defined for cubesats and deliverables and requirements associated with such missions.

On the system level a PFM approach will be implemented consisting of the following deliverables:

- Flatsat comprising a selection of EM units. This unit can later be used as simulator during phase E/F
- Structural and Thermal model (STM) of the satellite to be used for environmental qualification tests
- Satellite PFM
- Associated ground support equipment including fueling equipment required at launch site

The overall schedule and major milestones/reviews are outlined below assuming kick-off in September 2025.

- KO phase A/B1 (or A/B): Sep 2025
- SRR: KO + 4 month
- Kick-of phase B2/C/D: Primo 2026
- PDR: Q2 2026
- CDR: Q1 2027
- IRR: Q1 2028 (flight HW needs to be ready here)
- TRR: Q2 2028
- FAR: Q4 2028
- Launch: Ultimo Q4 2028
- LEOP: TBD days
- Commissioning and transfer into low Lunar polar orbit: End LEOP + TBD months
- Operational phase: 3 years from injection to operational orbit

Programmatic Approach

The necessary development work for all critical technologies is included in the mission timeline and mitigations and/or alternatives have been identified for the development of risk areas. Specifically, we identify three primary risk areas for the hardware development:

Spacecraft structure: This is a new design made specifically for the Máni mission, but it is based on heritage experience from prior platforms – including integration with propulsion systems provided by Dawn Aerospace. As part of the mission development, it will go through the necessary qualification to reach TRL 8 prior to launch.

Hybrid propulsion system: The chemical (CP) and electric propulsion (EP) separately have TRL 8/9, but Dawn Aerospace needs to integrate them to a hybrid propulsion system for the Máni spacecraft. Dawn develops CP in house, so the primary risk identified relates to who will supply the electric pro-pulsion system. Several alternative EP suppliers have been identified already at this stage that can provide an EP system with the required performance, so this is considered a minor risk.

Primary optical payload: A core part of delivering the mission data products, but while it is a delicate and complex instrument, the risk associated with its development is reduced drastically as it is a down-sizing of a telescope that is part of ongoing more mature ESA missions. Thus, we see little risk to the instrument development but rather note the synergistic benefit to ensure optimal performance from preceding and parallel LEO and Lunar mission development at Scanway.

For the overall mission implementation, primary risk identified is the availability and selection of launcher. Outside of establishing the launch window for the mission, the selection of launcher will enable finalization of transfer trajectories and transfer time, and enable final sizing and CP/EP trade-off analysis for the propulsion system.

CONOPS

The spacecraft will track a region of interest on the surface during the overflight of that region. This approach serves to reduce any motion blur of the acquired images and increases the chance that images acquired during that overflight fully overlap.

For a circular polar orbit at 50 km altitude, a point on the Lunar surface will be in view for approximately 8.5 minutes. During this timeframe we aim to acquire 5 overlapping primary images. We will return to the region of interest on a subsequent orbit at least one Lunar sidereal period later to acquire another 5 images under the different lighting conditions needed to complete the mapping of that region of interest.

~5 data-acquisition overflights of sunlit regions of interest can be performed per orbit – or ~60 overflights in an Earth day.

Under ideal circumstances, this enables the mission to map ~2730 km^2/year, or ~8200 km^2 mapped over a three-year mission lifetime.

We envision that the scientific and exploration regions of interest will typically be larger than what can be imaged with a single image and thus require multiple adjacent overflights to build the requested coverage mosaic to meet the science and/or exploration goals

CONOPS

For each candidate mapping region of interest, a detailed science rationale with associated hypotheses will be identified, and the ability of the Máni mission to test those hypotheses will be carefully assessed. As part of this work, the mission science team will engage with the broader scientific community to ensure that a compelling list mapping regions of interest are compiled prior to mission operations commences

For mission operations, it will be a point of emphasis for the mission partners to involve students in mission operations wherever possible, thus leveraging the large, combined student population found among the academic mission partners.

Máni