
# Smart Lander for Investigating Moon (SLIM)

## Results from the Moon Landing

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## Today’s report

Today, we are pleased to report on the results from the Smart Lander for Investigating Moon (SLIM) moon landing descent operation, that was conducted on 01/19 ~ 01/20, 2024.

1. Introduction on SLIM project
2. Actual landing descent progress (to an altitude of about 50m)
3. Results from image matching and evaluation of the pinpoint landing accuracy
4. Situation arising at an altitude of approximately 50m
5. Estimation of spacecraft behaviour after an abnormal occurrence
6. Post-landing spacecraft operations, and images obtained with the multi-band spectroscopic camera
7. Summary

# Mission Objectives of SLIM

SLIM (Smart Lander for Investigating Moon) is a JAXA project aiming to contribute to future lunar and planetary exploration by achieving the following two objectives.

## Objective A <u>Demonstration of high-precision landing technology on the moon</u>

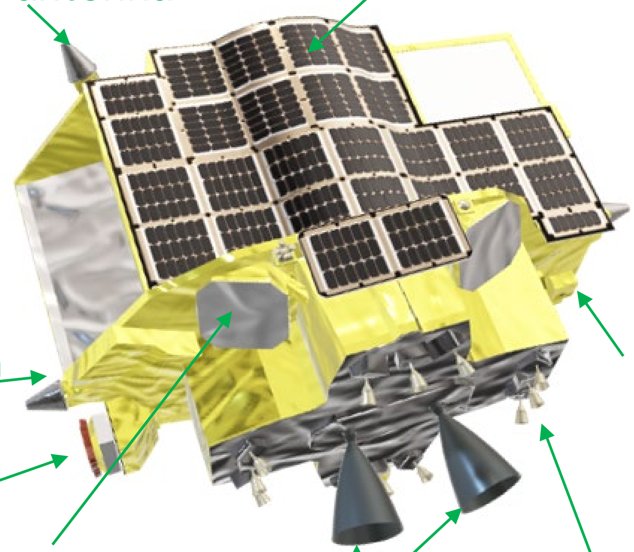
- Aimed landing accuracy of 100m compared to several kilometers to tens of kilometers of conventional lunar landers.
- Key technology includes "Vision-based navigation" and "Navigation, guidance and control"

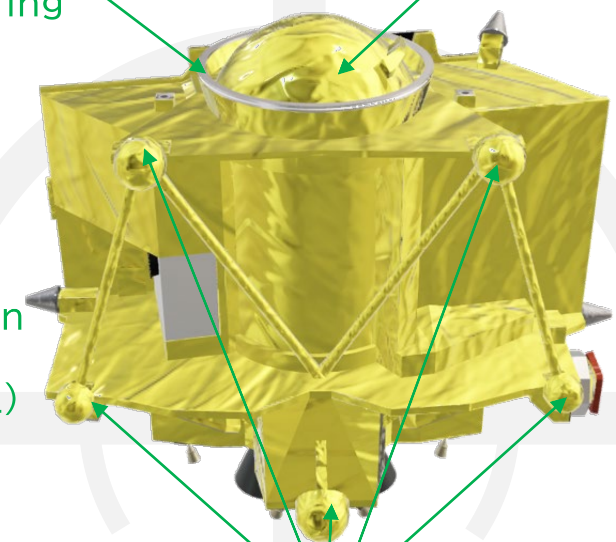
## Objective B <u>Realization of a lightweight lunar and planetary probe system to allow more frequent lunar and planetary exploration missions</u>

- Small, lightweight, and high-performance chemical propulsion system
- Weight reduction of core elements in most spacecrafts such as computers and power supply systems

# SLIM Configuration

- Mass: 200kg(Dry) / 700-730kg(Wet)
- Size: 2.4m x 1.7m x 2.7m



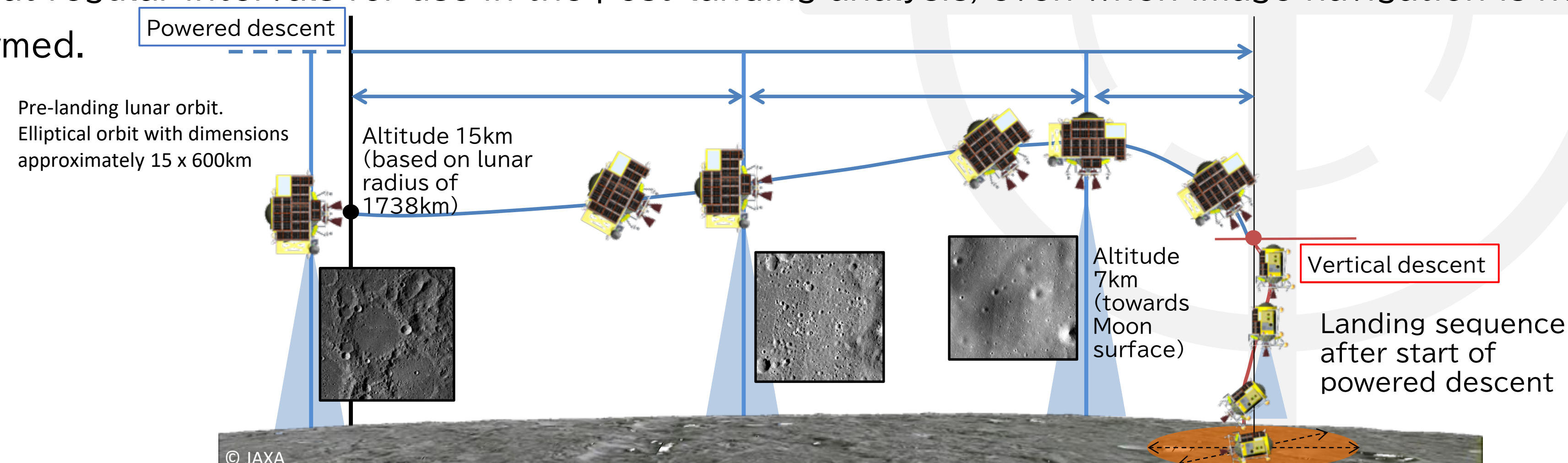




SLIM has adopted a fuel and oxidizer integrated tank to reduce weight. This cylindrical tank is also used as the structure base.

# Outline of landing sequence

1. Initiate the landing descent from lunar orbit and approach the target site on the lunar surface through **autonomous navigation and guidance control**, while precisely estimating the current position using **image-based navigation with the navigation cameras.**
2. From above the target site, precise measurement of altitude and terrain-relative velocity conducted using the landing radar that is integrated into the navigation guidance system.
3. Image-based obstacle detection is performed at approximately 50m above the landing site and landing is performed autonomously, avoiding hazardous boulders and other obstacles. That is, pinpoint landing is prioritised up to 50m above the surface, after which obstacle avoidance is prioritised for landing safety.

[Note] Spacecraft position and velocity are propagated by the onboard accelerometers and corrected to higher accuracy by image-based navigation. Additionally, the navigation camera images are also taken at regular intervals for use in the post-landing analysis, even when image navigation is not being performed.



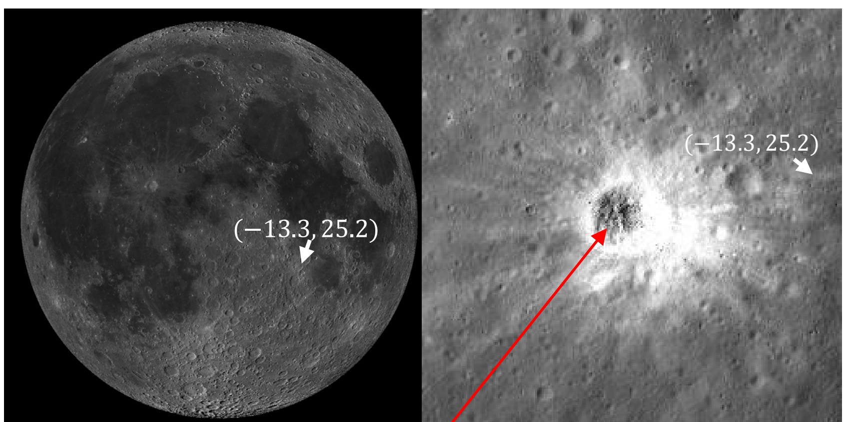
# Precise location information of the target landing site

Target landing site for SLIM*1 (Mean Earth/Polar Axis System (ME))

Longitude : 25.24889 [deg] / Latitude : -13.31549 [deg]

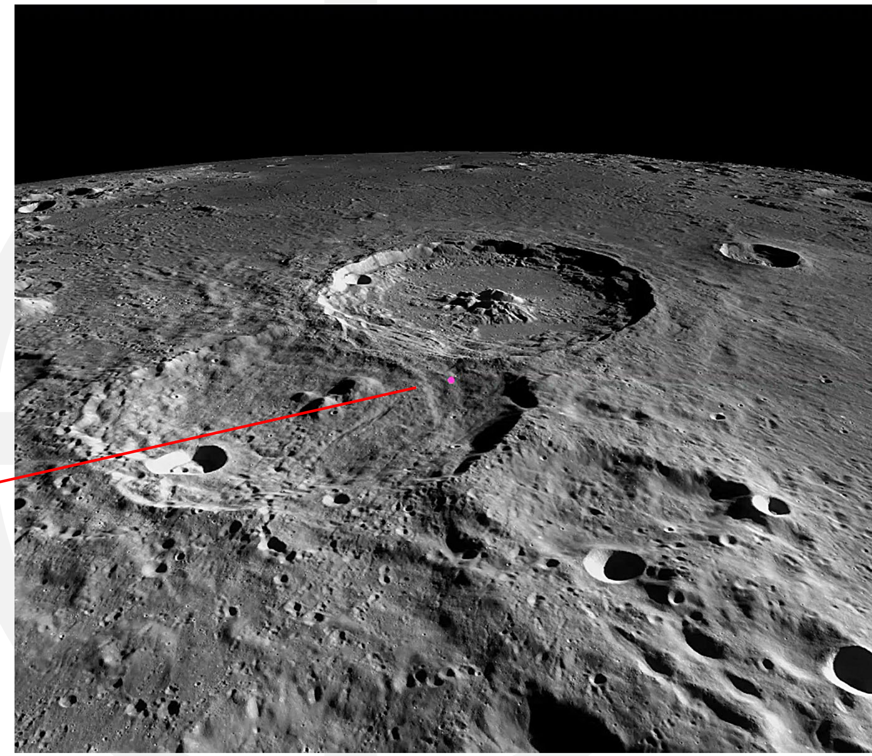
- The latitude and longitude of the target landing site was previously announced to the first decimal place (except to collaborative partners such as NASA and ISRO).
- However, the precise landing site is very important, and selected after lengthy discussions for both scientific significance and landing safety. This was the exact site chosen.

*1… More precisely, the target landing site was defined via the lunar image, and the latitude and longitude were at these values.




credit:NASA/LRO

SHIOLI Crater



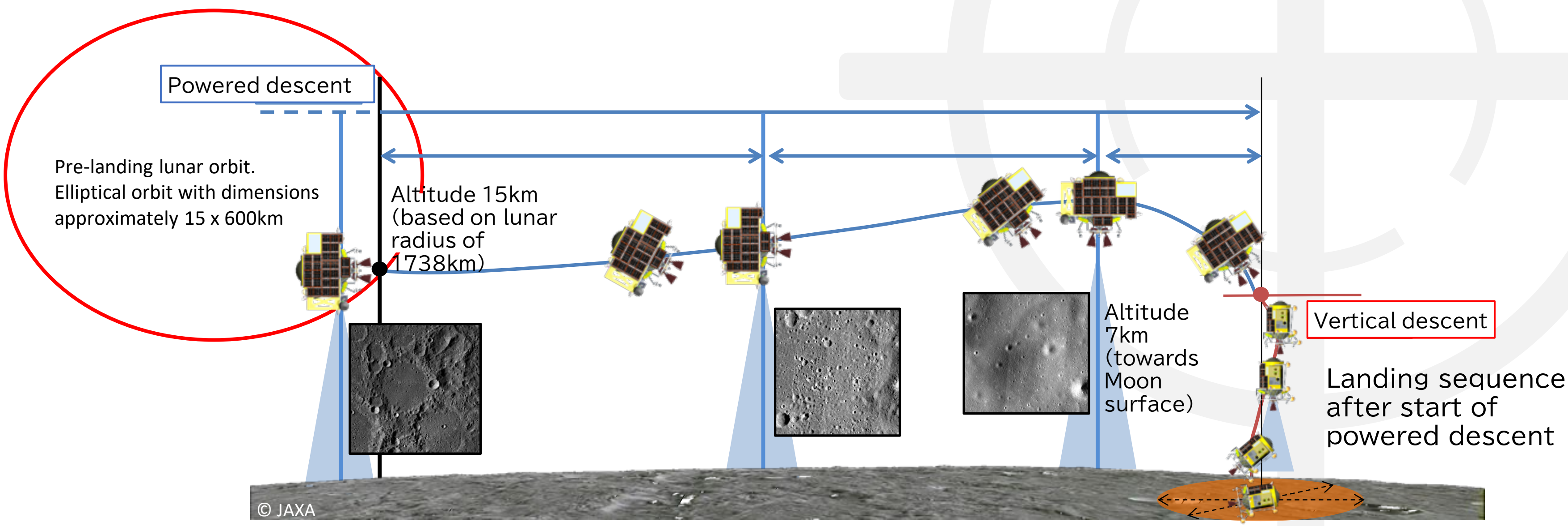
©Daichi Fujii, LRO

Credit :X @dfuji1
https://x.com/i/status/1748103951336227113

# ▶ Actual descent & landing

[Before the start of the landing descent]

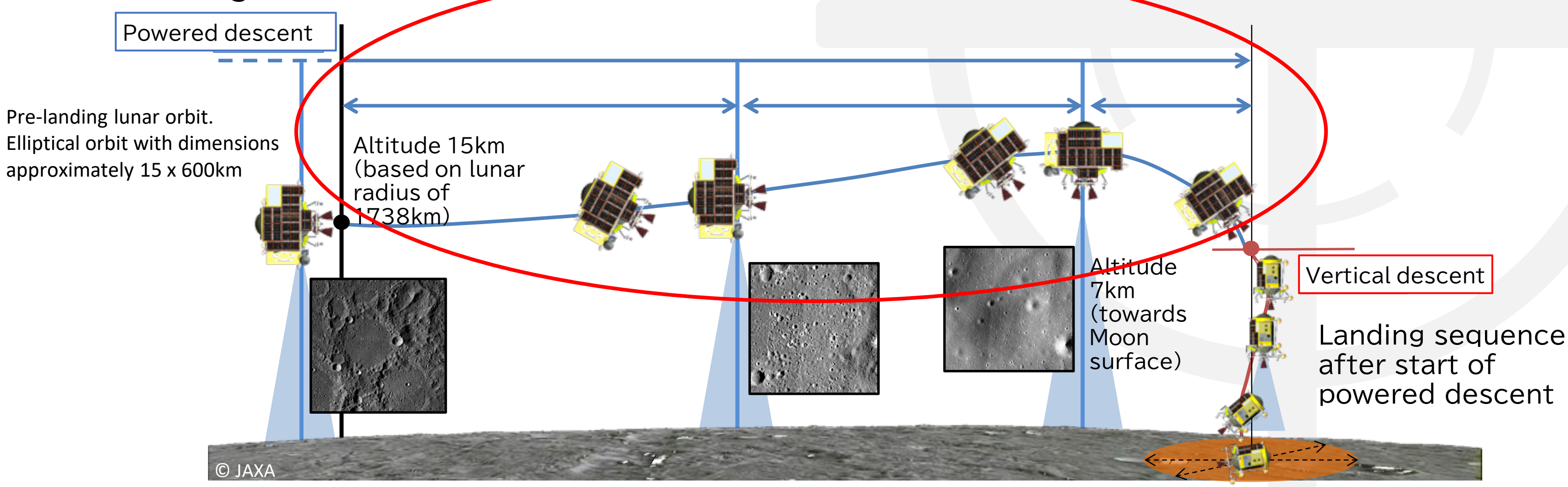
- Prior to the start of the powered descent, image matching navigation was performed in three areas(1/19 23:52:43, 23:54:43, 23:56:45 JST)
- All image matching was successfully completed twice in each area, and orbit correction (guidance calculation) on the spacecraft from the results was successful. The final decision to begin landing descent was therefore made (at around 23:59 JST).
- The main engines began to fire as planned, and the powered descent phase, the first half of the landing descent sequence, began (23:59:58 JST)



# Actual descent & landing

[During the powered descent phase]

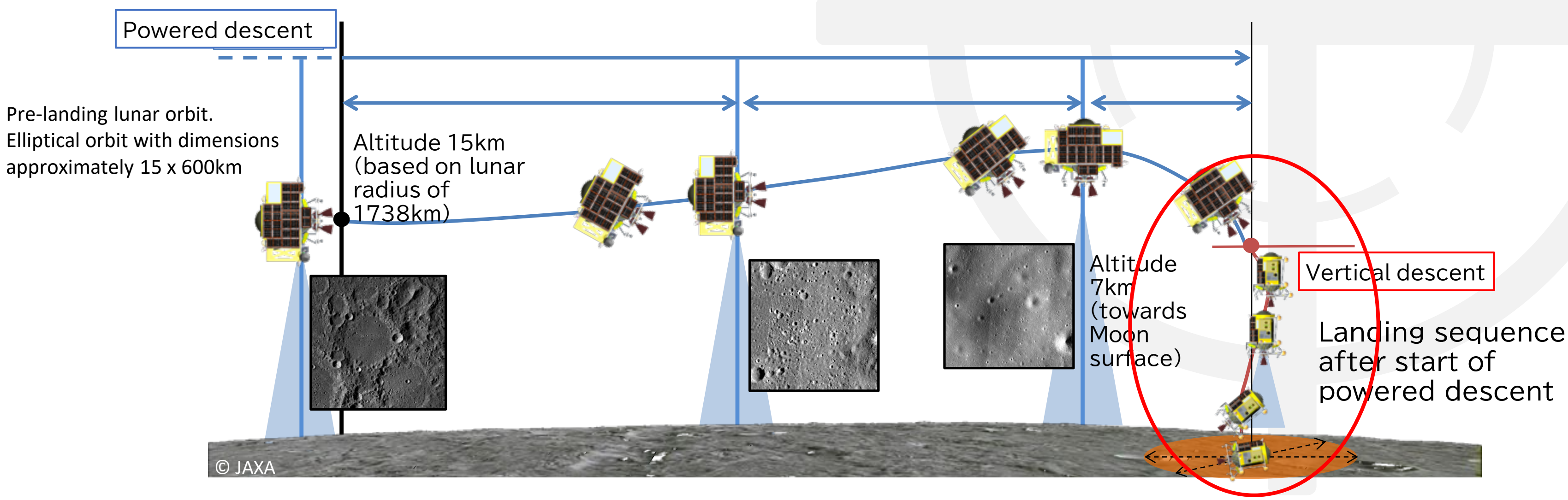
- After the start of the powered descent, the spacecraft descended almost in line with the planned trajectory.
- During the powered descent phase, image matching were performed twice in each of two areas, both completed successfully. In the first area, a position correction of approximately 200m altitude / 100m horizontal position was applied, and in the second area, a position correction of about 1km altitude / 200m horizontal position was applied. This was immediately reflected in the planned trajectory from the guidance recalculation.
- At the end of the powered descent phase, the spacecraft was at an altitude of approximately 6.2km as planned, with a good horizontal position error of less than about 100m. The vertical descent phase then began.



# ▶ Actual descent & landing

[During the vertical descent phase]

- After entering the vertical descent phase, altitude measurements by the landing radar were successfully initiated.
- Image matching was performed twice each at an altitude of approximately 4000m and 500m, and this was successful. The amount of horizontal position correction was about 100m and 50m, respectively, and the resulting position correction control was also successfully implemented.
- At an altitude of 50m, image-based obstacle detection was also successfully performed, and the spacecraft autonomously identified the safest location in the image, which was then used at the final landing target.
- Based on this information, we believe that <u>the landing descent to an altitude to 50m was very good</u>.

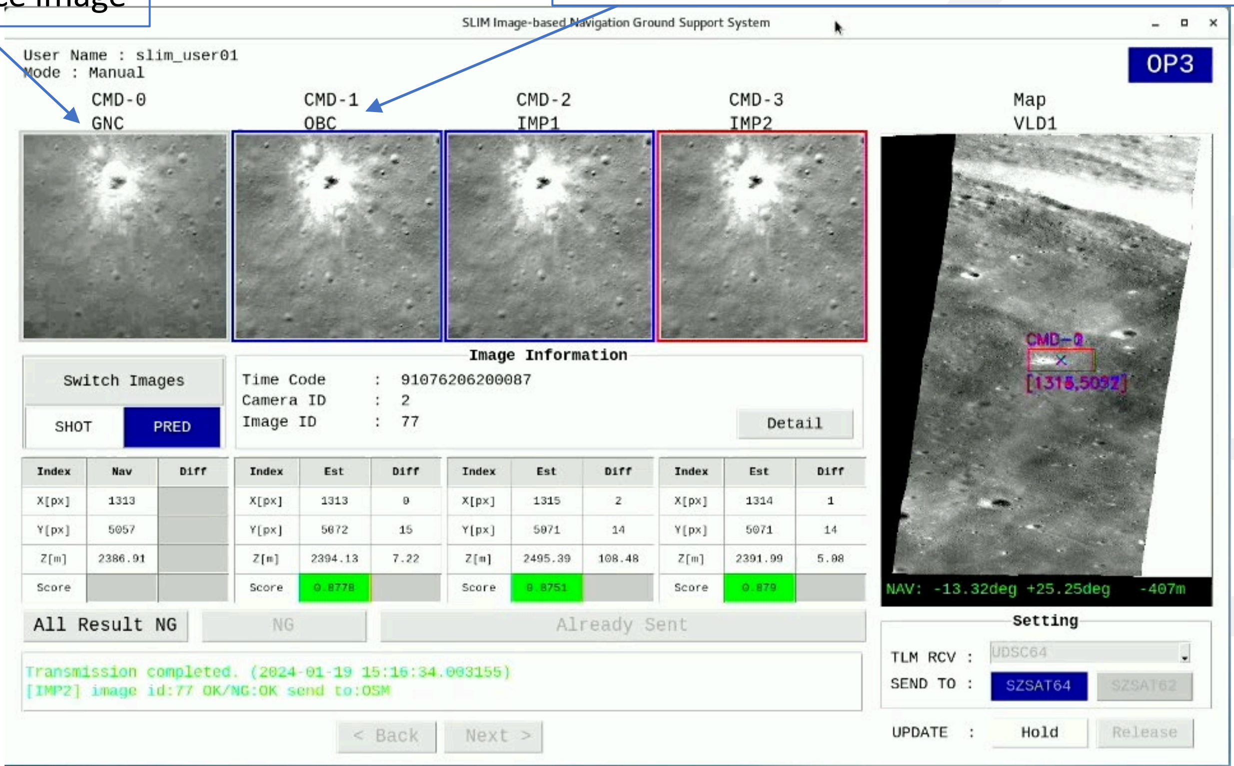


# Evaluation to ~50m altitude / image matching

- Image matching navigation was conducted twice on the spacecraft for all seven areas, and all completed successfully.
- For the purpose of ground support in the event of an anomaly, image matching using a more computationally intensive algorithm was also performed on the ground based on the images transmitted from the spacecraft.
- All the results were consistent, and all 14 image matching navigation resulted were determined to be accurate.

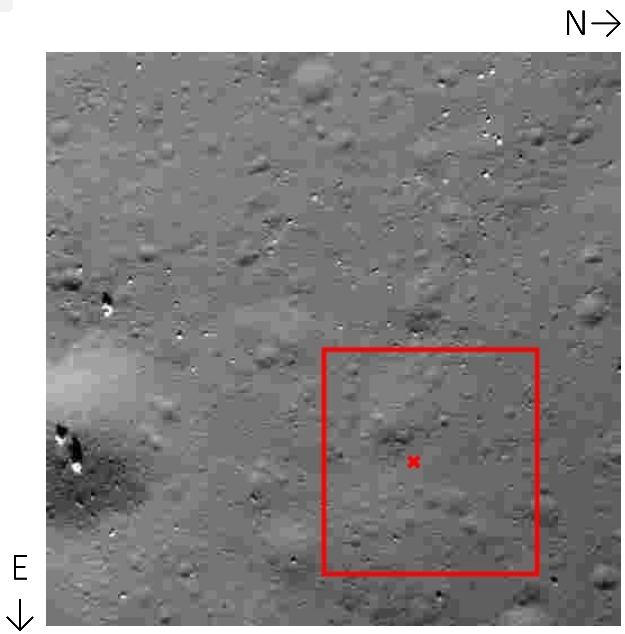
Lunar surface image

Lunar surface topographic map near the location estimated by the onboard image navigation (CG)

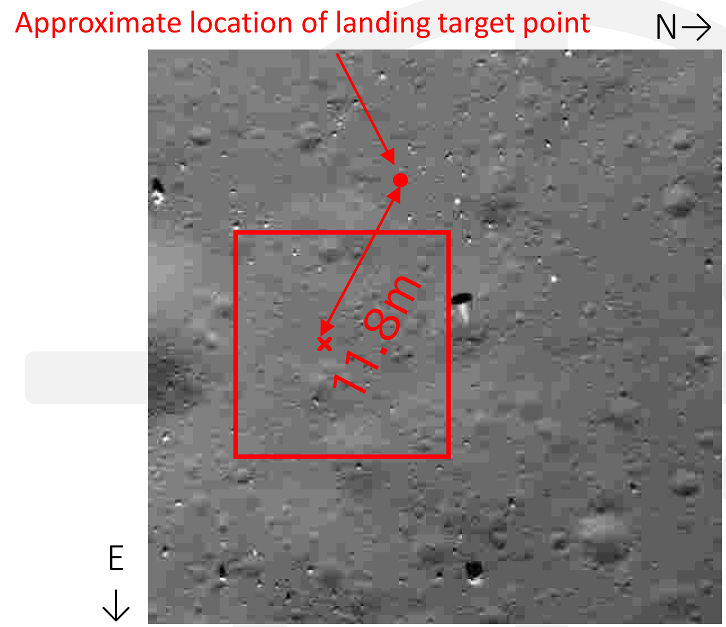


# ▶ Evaluation to ~50m altitude / obstacle detection

- Obstacle detection was performed twice, both times completed successfully.
- The images used for detection were later evaluated and all the sites chosen are believed to have been relatively safe.
- The result from the second detection was adopted for the final landing target (about 12m east-southeast from the previously set landing target)




Obstacle detection #1 results
(Red dots. Red box is the spacecraft footprint including guidance errors)



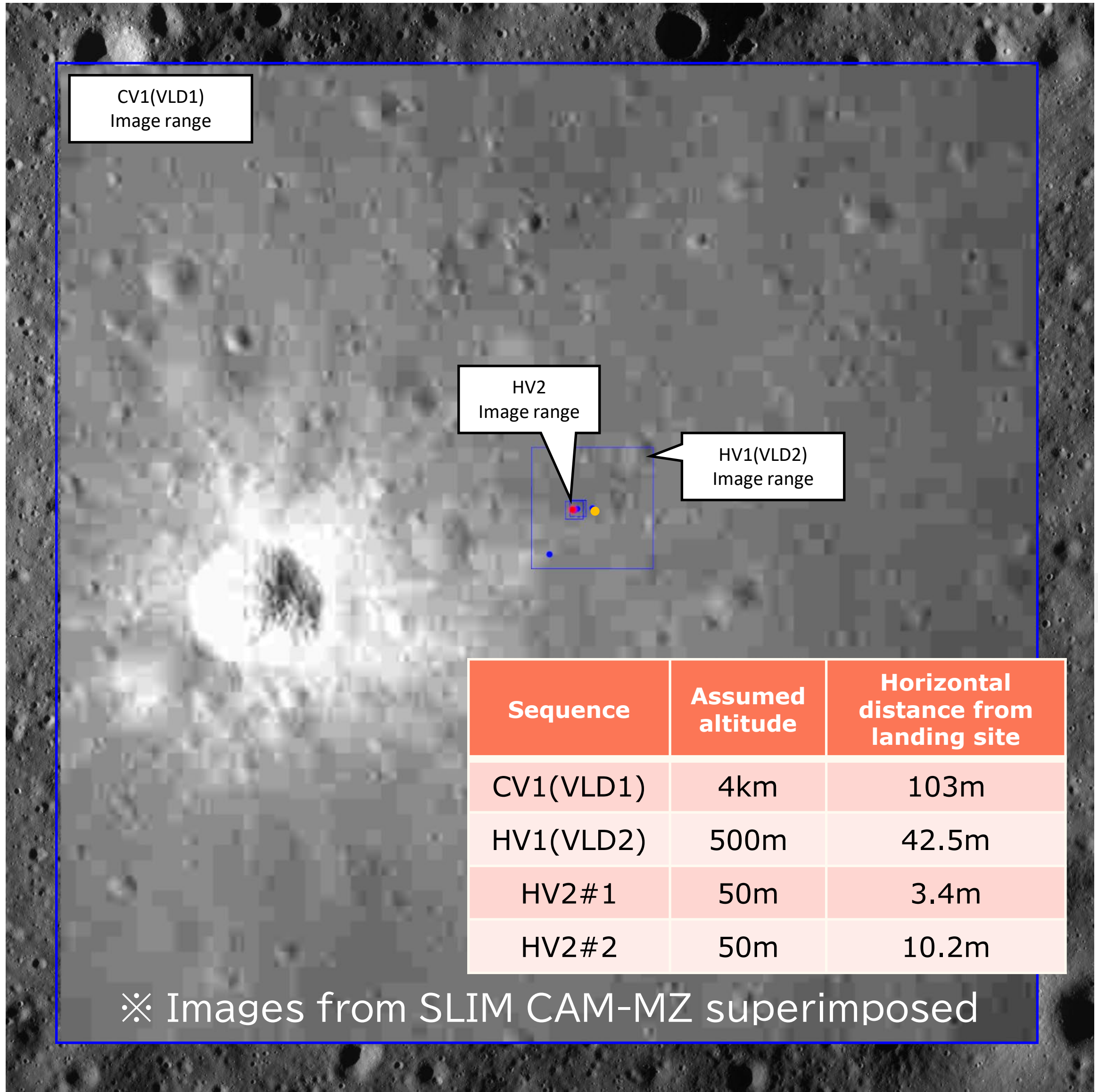

Obstacle detection #2 results
(Red dots. Red box is the spacecraft footprint including guidance errors)

※ images squired from the SLIM navigation camera (CAM-MZ)

# Evaluation to ~50m altitude / toward the target site

- The evaluation was conducted using images from Chandrayaan-2, which has relatively high resolution and was also used in the selection of the landing target site.
- Specifically, the task was to find features in the Chandrayaan-2 image in common with the navigation camera image and identify the area where the two images overlapped.
- The right figure shows the situation at two altitudes (CV1, HV1) and during obstacle avoidance (HV2). The central blue dot and the red dot is the target landing site selected prior to launch.
- As the altitude drops and the spacecraft approaches the lunar surface, the centre of the field of view of the navigation camera gradually approaches the target landing site, as a result of the navigation guidance control.

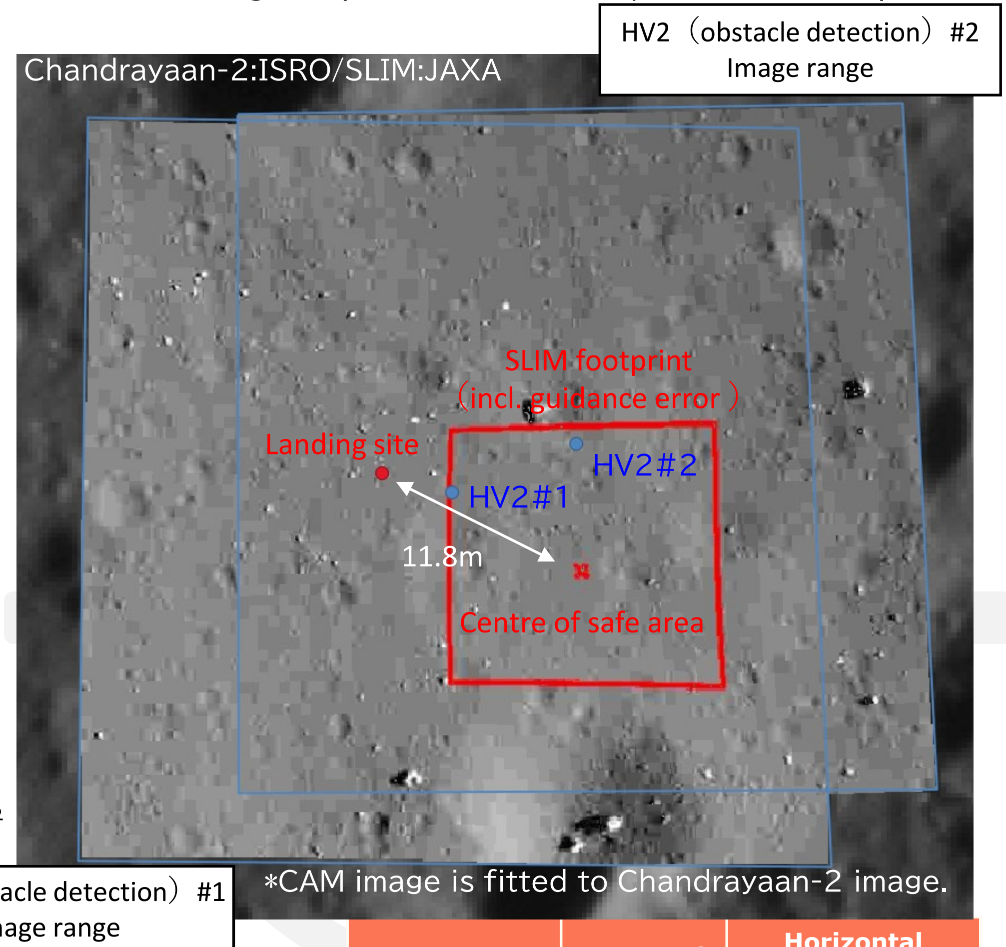
Chandrayaan-2:ISRO/SLIM:JAXA




| Sequence | Assumed altitude | Horizontal distance from landing site |
|---|---|---|
| CV1(VLD1) | 4km | 103m |
| HV1(VLD2) | 500m | 42.5m |
| HV2#1 | 50m | 3.4m |
| HV2#2 | 50m | 10.2m |

# Evaluation to ˜50m altitude / pinpoint landing accuracy

- Lower right figure shows an enlarged view of the vicinity of the image for obstacle avoidance. Blue dots indicate the centre position of the first (#1) and second (#2) image capture (blue box), which corresponds to the horizontal position of SLIM, and its distance from the target landing site is shown in the lower right table.
- From the figure, it was estimated that the positional accuracy during the obstacle detection is estimated as about 3 ˜ 4m for #1 and 10m for #2.
- As mentioned above, after this altitude, the landing target position was reset with priority given to landing safely (obstacle avoidance). Therefore the <u>pinpoint accuracy is estimated to be approximately 10m or less</u>.
- Furthermore, #2 is highly likely to have already drifted eastwards due to the abnormal event described below, and the <u>actual pinpoint accuracy is likely to have been about 3 ˜ 4 m.</u>




*CAM image is fitted to Chandrayaan-2 image.

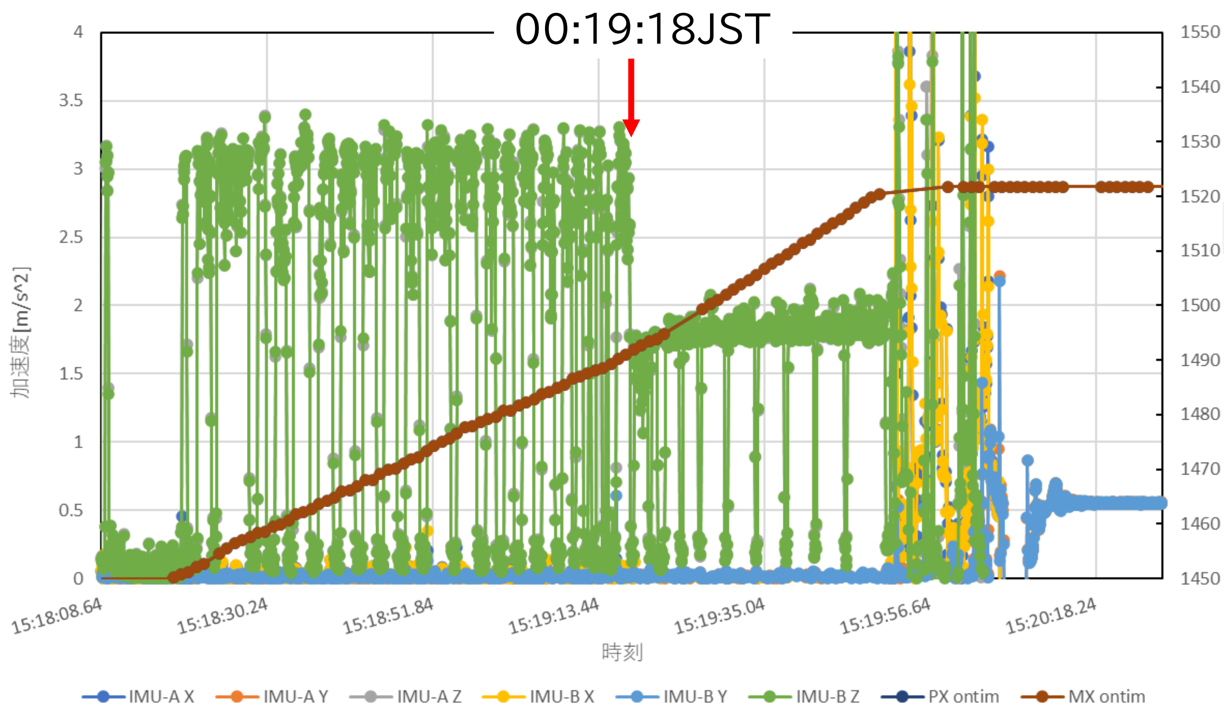
After obstacle avoidance, landing is aimed at the centre of the safe area in the diagram. Safety is now prioritised by selecting to avoid obstacles ahead of accurately landing at the target site (the spacecraft therefore aimed at a site 11.8m away from the target site). Pinpoint landing accuracy is therefore evaluated before the obstacle avoidance.

| Sequence | Assumed altitude | Horizontal distance from landing site |
|---|---|---|
| HV2#1 | 50m | 3.4m |
| HV2#2 | 50m | 10.2m |

# Event occurrence at an altitude of approx. 50m

- The spacecraft descended smoothly to an altitude of approximately 50m, but close to this point, an abnormality occurred in the propulsion system.
- Specifically, at around 00:19:18, the total thrust generated by the two main engines suddenly decreased to about 55%.
- Examination of the temperature behaviour after landing revealed that the −X side of the two main engines was not exhibiting the expected temperature increase (propellent value temperature rises due to heat soak-back).
- It is therefore likely that an abnormality occurred in the −X side main engine at this altitude.

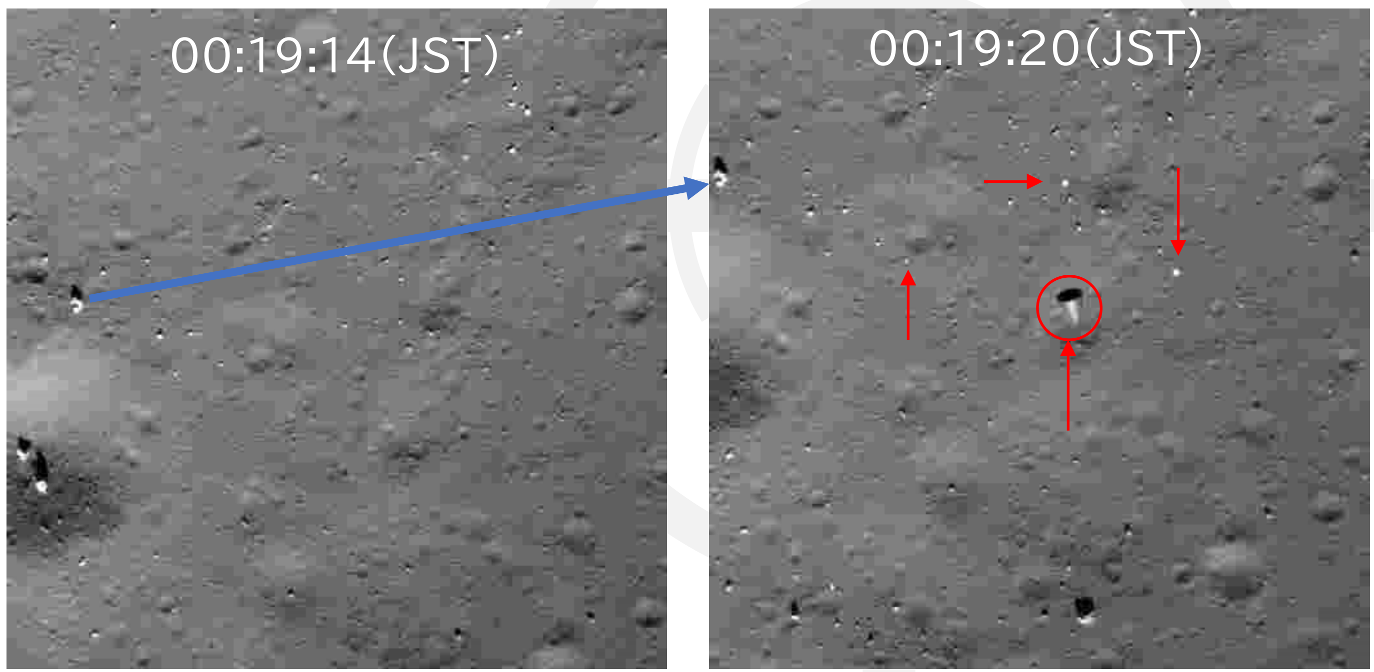
- The brown line is the accumulated injection time of the main engine, and the green line is the acceleration measured by the accelerometer, which detects the acceleration generated by the injection of the two main engines.
- Although the injection instruction to the main engines remained almost constant, the total thrust generated as measured by the accelerometer suddenly dropped to about 55% after 00:19:18.



# Event occurrence at an altitude of approx. 50m

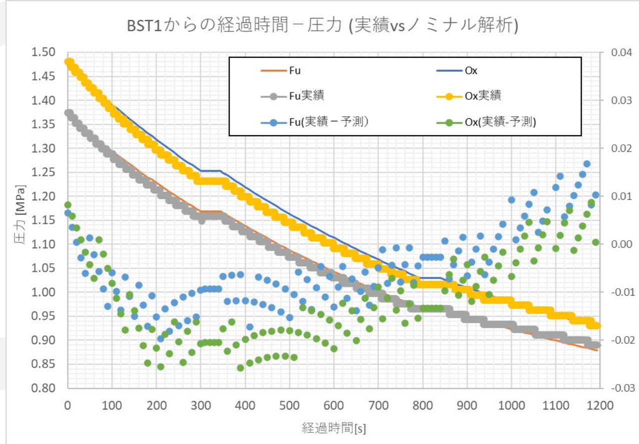
- Two navigation camera images taken near the time of the abnormality are shown below
- Immediately after the abnormality in the main engine thrust, the navigation camera images show spots of light and objects that had not been seen in the previous image
- Since one of these has a nozzle-like shape, it is assumed that some kind of abnormality occurred near the main engine on the −X side at around 00:19:18, causing the nozzle to break and fall, resulting in the loss of most of the thrust generated by the main engine on the −X side

- The blue arrow indicates the corresponding feature in both images
- The red arrows show spots of light or objects not seen in the left image

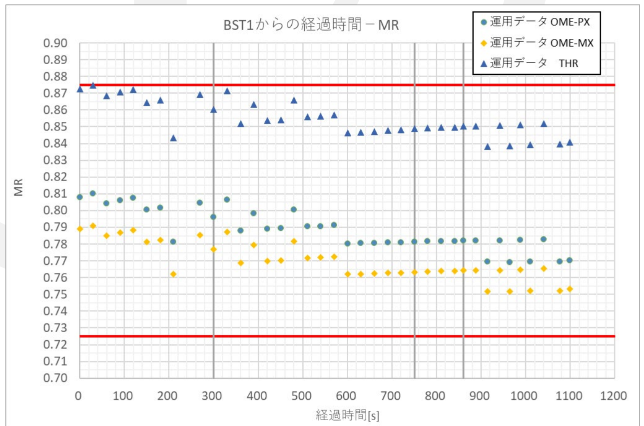


# Event occurrence at an altitude of approx. 50m

- A total of eight post-launch trajectory changes and the power descent phase have used the main engine under higher supply pressure and higher engine load conditions, but the main engine has not shown any signs of abnormality until just prior to this event.
- Moreover, comparison of the two main engines at the time of the incident suggests that the –X side engine has mild combustion conditions compared to the +X side engine.
- The Project therefore believes that it is highly likely that <u>an external factor and not the main engine itself affected the –X side main engine</u>.
- The cause is still being investigated and there will be further reports when more details are available.




- Example of main engine related data. SLIM uses a blowdown propulsion system, designed to gradually reduce the propellant supply pressure. After launch, the supply pressure of both fuel and oxidizer gradually decrease as propellant is consumed, and the load on the engine also decreases (see top diagram).
- The mixing ratio (MR) of oxidizer and fuel is another important factor that determines the load on the engine, but the MR of the –X size engine is believed to be always lower than that of the +X side engine and therefore, the load on the –X side engine was relatively smaller than that on the +X side engine.



# Estimation of behaviour after the abnormality occurred

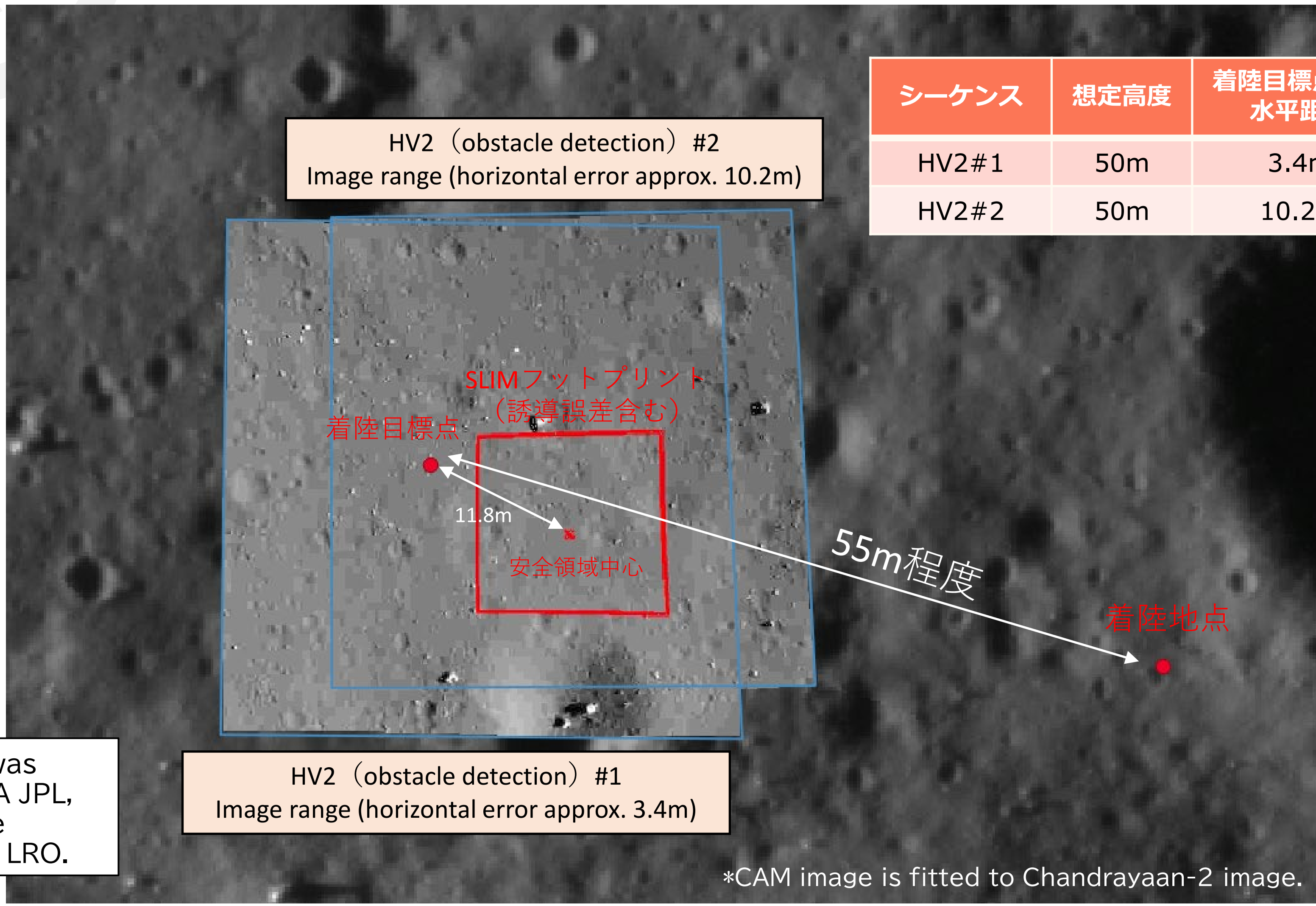
Current estimate of the spacecraft behavior after the abnormality occurred at around 00:19:18.

- The abnormality occurred while the spacecraft was hovering. One of the two main engines was lost due to an abnormality, but the dual main engine design allowed a certain level of redundancy to avoid a situation where a moon landing would have been impossible.
- However, a single main engine could only generate a thrust equivalent to the lunar gravity, making it difficult to fully control the descent speed. The spacecraft continued to descent at a rate of 2 ~ 3m/s from around 50m.
- The two main engines were also designed to cancel each other's lateral thrust, so the loss of one engine on the −X side produced a horizontal velocity toward the −X side.
- At the end of hovering, the onboard navigation guidance control system detected an abnormality and executed a mode transition. <u>The spacecraft continued to fire the main engine while changing the attitude to reduce lateral movement, and autonomously proceeded with the sequence towards the landing mode sequence</u>. During this process, LEV-1 and LEV-2 (SORA-Q) were separate at an altitude of about 5m.
- With a lateral velocity, the spacecraft landed in an almost upright standing position (at about 00:19:52). <u>The rate of descent upon landing was about 1.4 m/s, which is slower than the specified range (1.8 ~ 2.8 m/s)</u>. However, landing conditions such as the lateral velocity and attitude exceeded the specified range and produced a large attitude fluctuation after landing that resulted in a settled attitude different to expected.

# ▶ Estimated landing site

➢ Relationship between the spacecraft position at the time of obstacle detection and the estimated landing point. The spacecraft moved east from its position during its nominal descent (about 55m to the east)

Chandrayaan-2:ISRO/SLIM:JAXA




| シーケンス | 想定高度 | 着陸目標点との水平距離 |
|---|---|---|
| HV2#1 | 50m | 3.4m |
| HV2#2 | 50m | 10.2m |

Landing position was estimated by NASA JPL, based on an image captured by NASA LRO.

# Estimated landing site

- After landing, the final attitude of the spacecraft is believed to be an almost vertical position with the main engine facing upwards and the solar panels facing west, as shown in the figure, based on data from the spacecraft.


CG image created from the estimated landing position and attitude

Credit:JAXA / CG Production:Mitsubishi Electric Engineering Corporation

# Operation immediately after landing

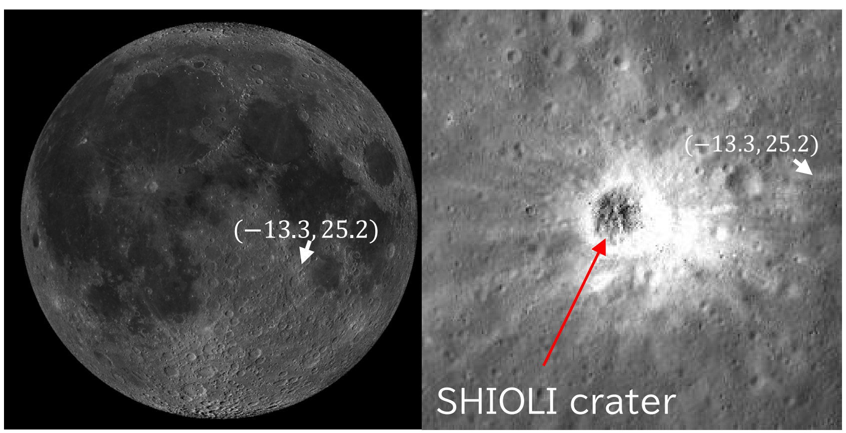
- Immediately after it was determined that the spacecraft had landed, it was confirmed that power was not being generated from the solar cells.
- Since communication with the spacecraft had been established, the pre-arranged abnormality response procedures were implemented in sequence.
- Operation summary (dated 01/20)
  - 0:20 ~ around 1:30 Data download from spacecraft, unnecessary equipment turned off, turn off heaters etc.
  - 1:30 ~ around 1:50 Transition to NASA Deep Space Network (DSN) station operation due to to end of domestic ground station visibility hours.
    Trials to reduce power consumption by changing communication settings.
  - 1:50 ~ around 2:35 Taking into account remaining battery level, we decided to start observation using the multi-band spectroscopic camera.
  - 2:57 Battery disconnected from power system by command, and spacecraft power was turned off.
- The above operation allowed <u>retrieval of all the technical data and image data recorded on the spacecraft during the landing descent</u>.
- Battery disconnection was a measure to avoid the permanent loss of the spacecraft due to over-discharge. Since SLIM can operate once power generated from the solar cells exceeds the required level, it is expected to operations will resume once the generated power is restored in the future. The remaining battery charge (SOC) when the battery relay is off was about 12%.

# Observation with the multi-band spectroscopic camera (on the day of landing)

- Observations with the multi-band spectroscopic camera (MBC) were conducted for approximately 45 minutes after landing. Implementation details:
  - Single-band imaging with launch lock (exposure time determined by the auto-exposure)
  - Launch lock release
  - Scan imaging
    - To prevent the temperature of the spacecraft transmitter from exceeding the guaranteed operating temperature, instead of capturing 333 image in 35 minutes, the scan was terminated after 15 minutes. 257 of the 333 images were therefore taken and downloaded.
- In the above operation, the launch lock for the movable mirror was successfully released and the movable mirror operated normally. The auto-exposure function and single band imaging also worked as expected.
- In addition, from the images obtained by the image scan, observation candidate targets were identified that are expected to yield scientific results in more detailed observations.

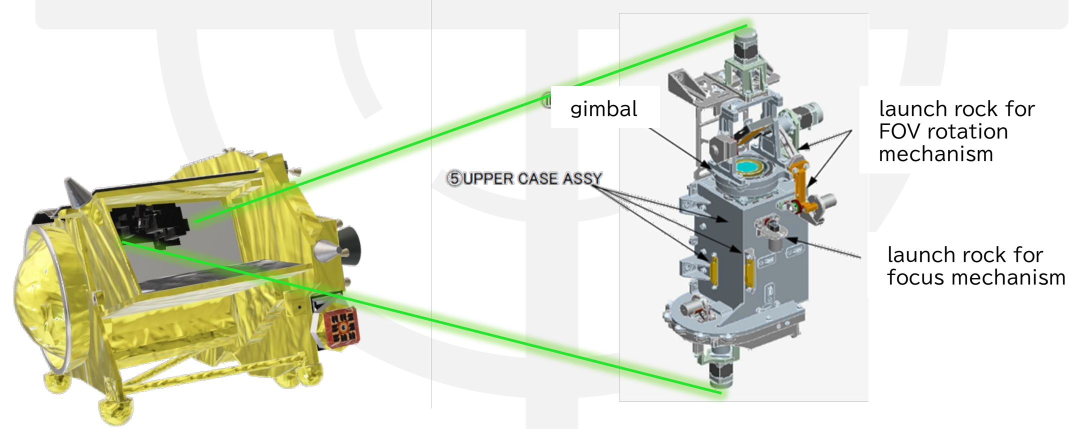
# ▶【Note】multi-band spectroscopic camera (MBC)

- SLIM's target landing site, located near SHIOLI crater, was selected from the places where rocks ejected from luna mantle is thought to exist.
- After successful landing, MBC onboard SLIM carries out 10-band spectroscopy observation.
- **Rocks estimated to be derived from luna mantle will give us important hint to unravel the origins of the Moon.**
  - **A prevailing theory on the Moon's origin is "giant-impact hypothesis", however, the details of the impact is under discussion. Especially, it is still unrevealed which one mainly form the moon, ejecta from the Earth or the impactor.**
  - Key information to answer this question is the lunar mantle's composition, mineral composition ratio or the ratio between iron and magnesium.
  - MBC has capability to analyze the composition of the target rock with 10-band spectroscopic observation. After successful landing, MBC observes rocks or regolith around the landing point, and try to estimate the lunar mantle's composition.
  - **Note that this observation becomes possible only when the lander can land at specific target precisely.**




NASA/LRO

SLIM target landing site
(left:location on the Moon、right:closed-up view around SHIOLI crater)

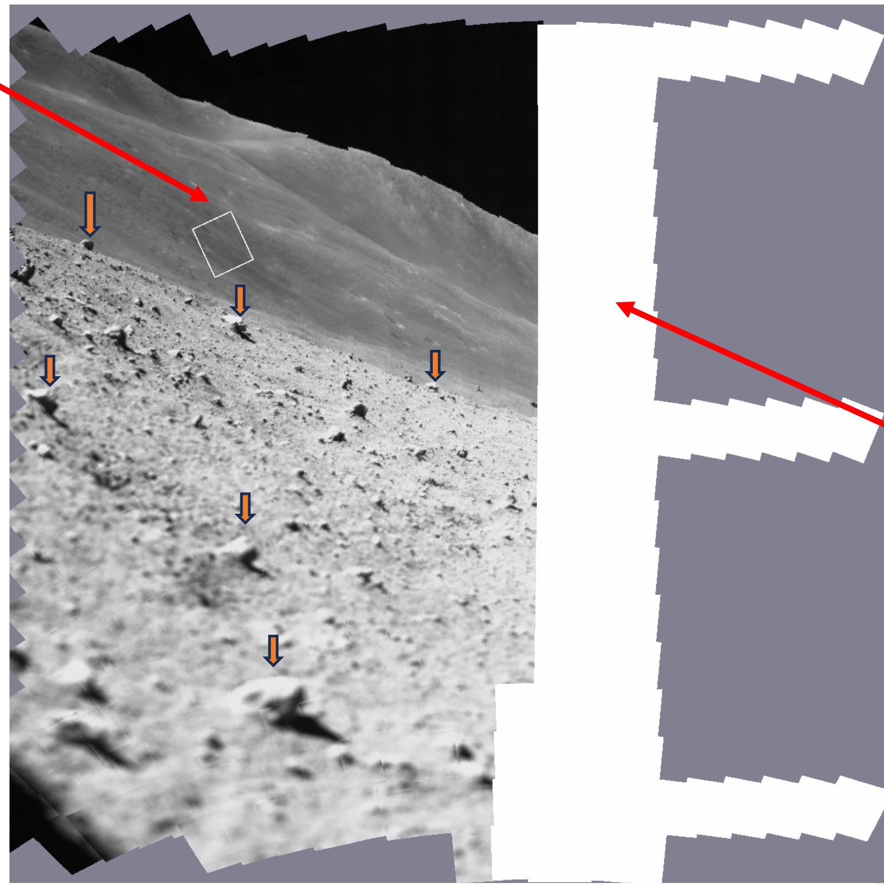



MBC and its mounting position on SLIM

# Observation with the multi-band spectroscopic camera (on the day of landing)

Image mosaic obtained by joining the 257 images from the scan imaging

Image capture range of one image shot



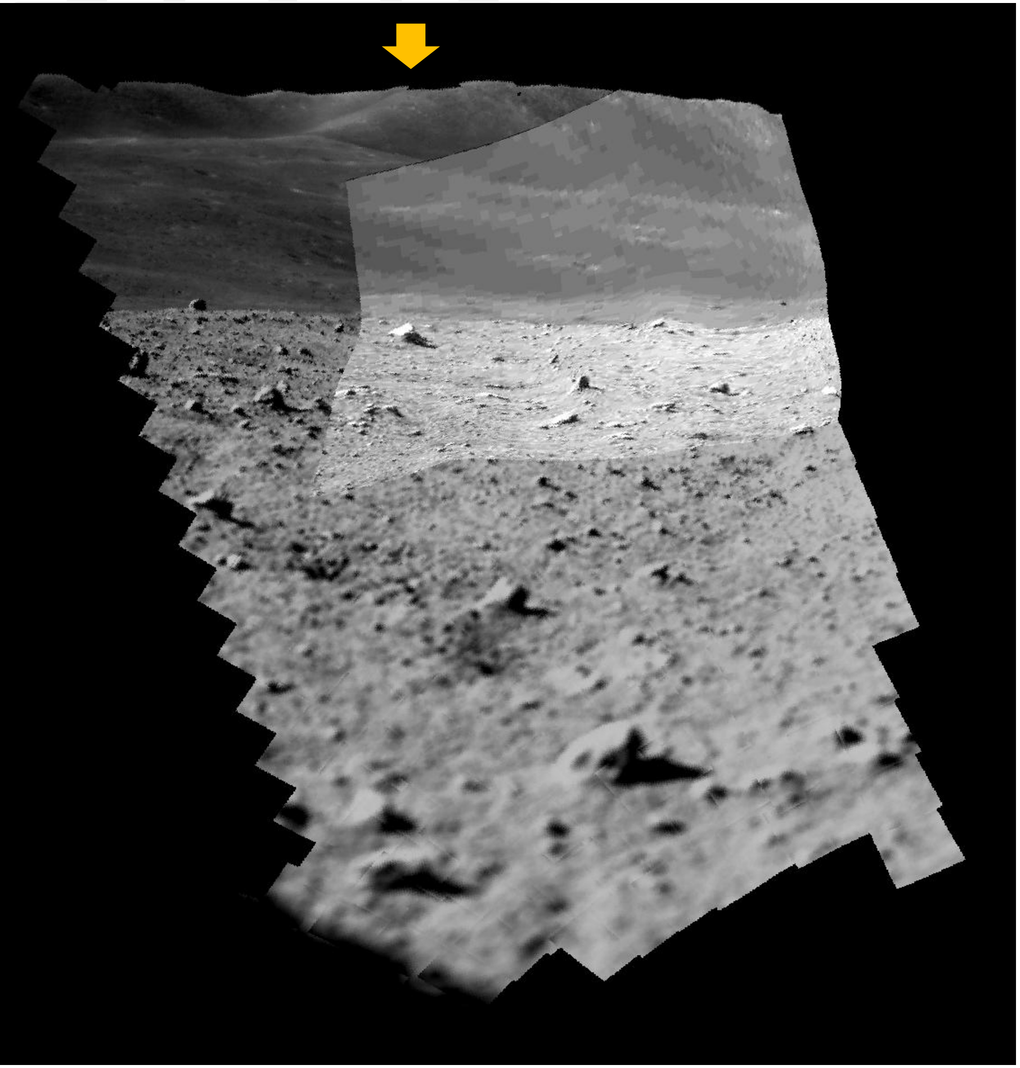
JAXA, RITSUMEIKAN UNIVERSITY, THE UNIVERSITY OF AIZU

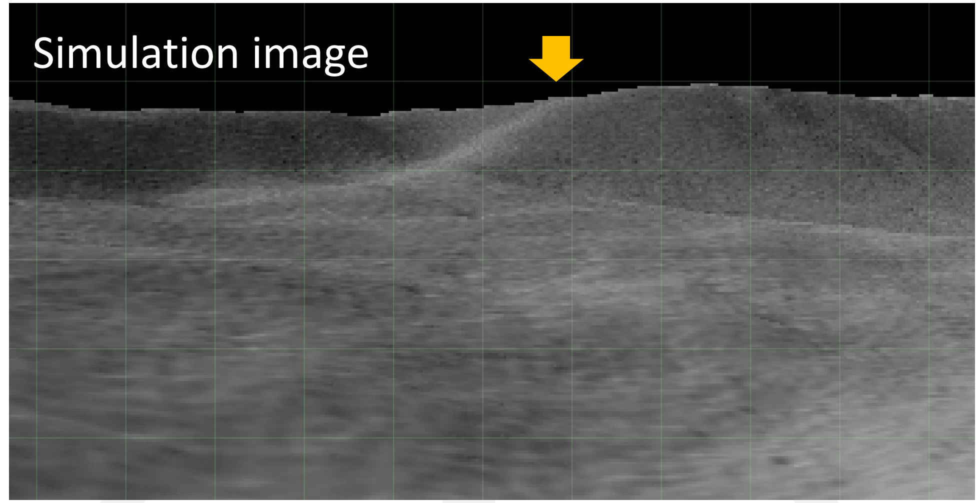
Originally, the right side of the image should have been in the upward direction.

White areas are without data because the scan was terminated at the half-way point.

⇩ Indicate candidate observation sites

# Observation with the multi-band spectroscopic camera (on the day of landing)






Landscape simulation based on DTM of KAGUYA TC

CAM-PX:JAXA
MBC:JAXA, RITSUMEIKAN UNIVERSITY, THE UNIVERSITY OF AIZU

Navigation camera (CAM-PX) matching with multi-band spectroscopic camera (MBC) scan images.
Slightly whitish are in the upper right is the CAM-PX image

# Results of ultra-small rovers, LEV-1 and LEV2 (SORA-Q)

Just before landing, SLIM deployed two ultra-small rovers, LEV-1 and LEV-2 at an altitude of about 5m.

- LEV-1 and LEV-2 worked on the Moon surface fully autonomously, and in a cooperative manner.
- LEV-1 carried out experiments of hopping locomotion.
- LEV-2, also known as "SORA-Q", succeeded to take a snapshot of SLIM. The image data was transmitted to LEV-1 via Bluetooth, and LEV-1 directly transmitted the data to the Earth (Fully autonomous and cooperated).
- Note that LEV-1 weighs approx. 2.1kg, and LEV-2 only weighs approx. 0.25kg.

  *1 … SORA-Q was developed by JAXA/TOMY Company/Sony/Doshisha Univ.


Artist image of the ultra-small rovers (LEV-1, LEV-2) on the moon

# Results of ultra-small rovers, LEV-1 and LEV2 (SORA-Q)

**Captured by LEV-2's front camera, then transmitted to the Earth by LEV-1.**

- LEV-2 selected "the best shot", which effectively captured SLIM and its vicinity, through several taken images.
- Then sent the image to LEV-1 via Bluetooth, and LEV-1 sent it to the Earth directly.
- NO ground support for these behavior. It was fully autonomous.

- Note that again, LEV-1 weighs approx. 2.1kg and achieved direct transmission to the Earth. LEV-2 provided us this impressive photo without any ground support, although only weighs approx. 0.25kg.

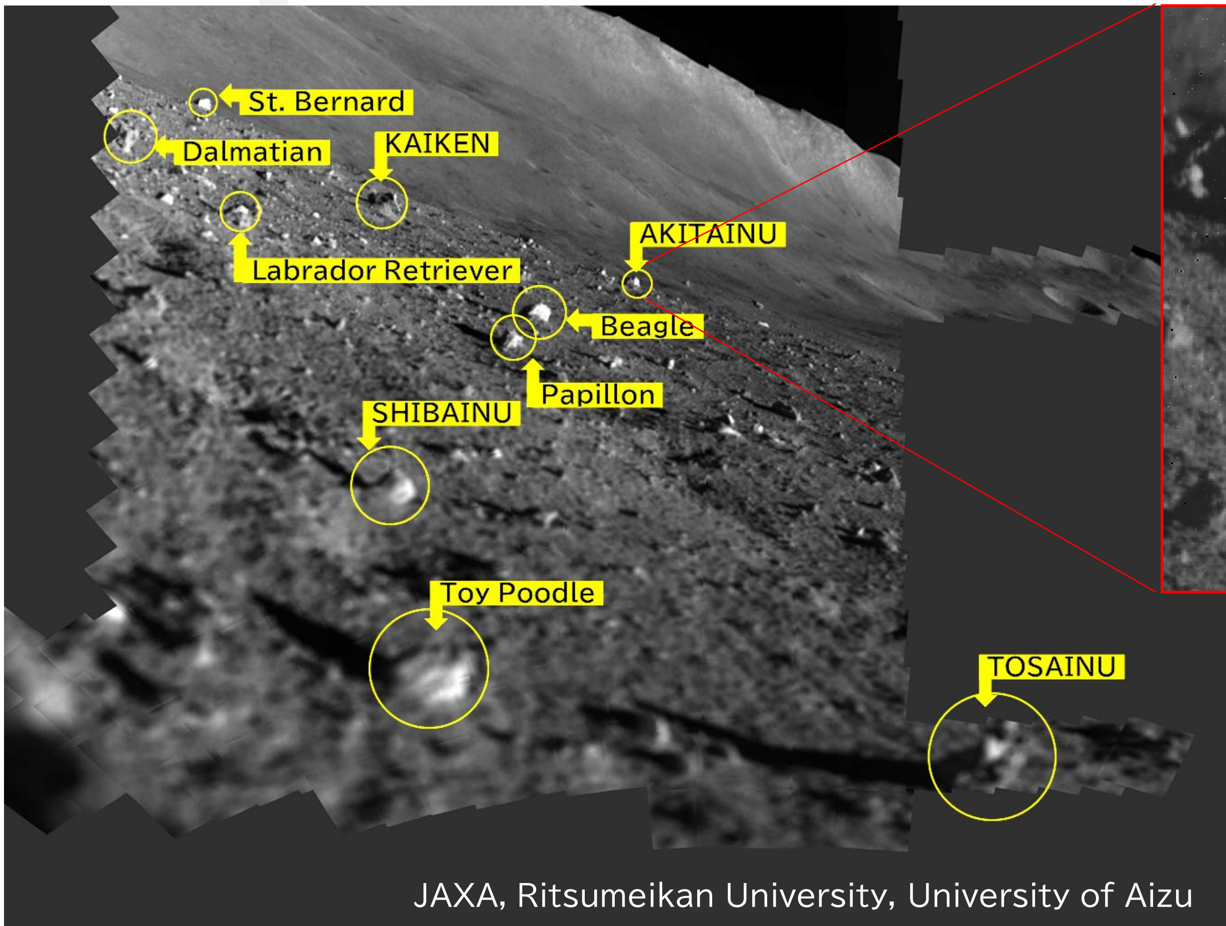
# Operation after power restoration

- According to the change of sun direction, the condition to generate electric power was gradually restored. Finally, the communication with SLIM lander was established again on the night of 28th, January.
- After the basic health check on the SLIM lander, soon the observation with multi-band spectroscopic camera was started.
- Scientific observation team succeeded 10-band spectroscopic observation on 10 target rocks. The number of observed rocks exceeds the expectations before landing.
- They started the analysis on the observed data, to identify the type of the rocks and estimate their mineral composition.

- After MBC observation, the location of landing became night on 31st, February. SLIM lander is now turned-off again.
- Although SLIM lander is not designed to survive the moon night condition, we will try to establish the communication and try several operations include MBC observation again in late February.

# Operation after power restoration

- Left phot is the 10 target rocks in the 10-band spectroscopic observation after the power restoration. Due to the change of solar illumination conditions, target rocks are selected again after the restoration.
- Right photo is the detailed image with 1-band(1.65$\mu$m) on “AKITAINU”.




JAXA,
Ritsumeikan University,
University of Aizu

Automatically focused with MBC, and as a result, the distance is estimated to be about 18m, and the size of AKITAINU is estimated to be about 63cm in width.

# Summary (results from moon landing descent 1/2)

- SLIM successfully conducted the landing descent operation until an altitude of about 50m, just prior to performing obstacle avoidance.
- In particular, all 14 image-matching navigation steps, including the navigation results, were conducted normally.
- The appropriate point to evaluating the pinpoint landing accuracy of SLIM is just before obstacle avoidance. The result of that evaluation indicate a pinpoint landing accuracy of less than 10m, and probably about 3~4m.
- At an altitude of approximately 50m, an abnormality occurred which resulted in the loss of one of the two main engines.
- Due to having a level of redundancy, SLIM did not suffer a catastrophic failure that would prevent landing, but continued a slow descent and moved gradually to the east. The ultra-small rovers (LEV-1 and LEV-2 (SORA-Q)) were successfully separated at an altitude of about 5m and delivered to the Moon's surface. The spacecraft landed at a descent rate lower than the specified range. However, as landing conditions aside from the descent rate were outside the specified range, the spacecraft settled at a different attitude than expected.
- The landing location is estimated to be about 55m east of the landing target. The attitude after stabilization is considered to have the solar panels facing west, and the Sun was positioned to the east at the time of landing, resulting in a loss of power generation by the solar cells.

# Summary (results from moon landing descent 2/2)

- After landing, communication with the spacecraft was established, but power generation from the solar cells could not be confirmed. Therefore, in accordance with the abnormality situation response procedure, data including images during the landing descent were acquired, scan imaging was initiated with the multi-band spectroscopic camera, and the battery disconnected from the power supply on command in order to maintain spacecraft functionality. This causes SLIM to power off.
- According to the change of sun direction, the condition to generate electric power was gradually restored. Finally, the communication with SLIM lander was established again on the night of 28th, January.
- Scientific observation team succeeded 10-band spectroscopic observation on 10 target rocks.
- The location of landing became night on 31st, February, and SLIM lander is now turned-off again.
- We will try to establish the communication and try several operations include MBC observation again in late February.

# Summary(results & issues)

- Although detailed data evaluation needs to be continued, it is believed that SLIM was able to demonstrate the landing technology for all the planned engineering test items, with the exception of the two-step landing dynamics.
- In particular, the demonstration of the image matching technology and pinpoint landing accuracy of less than 10m (perhaps 3~4m) has been achieved is a major accomplishment for future lunar and planetary exploration.
- Regarding the lunar activities after landing, the operation of LEV-1 and LEV-2 (SORA-Q) on the lunar surface, after successful separation from the SLIM lander and delivery to the surface, has been confirmed, and these were successfully delivered to the Moon's surface. Multi-band spectroscopic camera achieved 10-band spectroscopic observation on 10 target rocks, thus further scientific results can be expected.

- On the other hand, it is necessary to conduct a detailed study on the abnormal events that occurred before and after the obstacle detection to identify the causes and clarify issues and countermeasures for the future.
- The engineering technology developed for SLIM, including the two-step landing dynamics that could not be demonstrated this time, will be organised and prepared for transfer to future missions.
- The results of future operations and studies are intended to be announced in a timely manner.

# ▶ Summary(results & issues)

| | Engineering test target items | status | Evaluation etc. |
|---|---|---|---|
| Minimum success | Develop image-matching navigation, which is essential for high-precision landing, and combine this with other navigation systems to result in a navigation error of about 100m. | Achieved | All 14 image matching runs conducted on orbit were completed successfully. Based on the landing accuracy obtained, the navigation accuracy was evaluated to be less than 10m. |
| | Provide a simple shock-absorbing mechanism for soft-landings | Under investigatio n | |
| | Realise a compact, lightweight, high-performance chemical propulsion system. | Under investigatio n | |
| | Weight reduction of the core elements of the spacecraft, including the computer and power supply system. | Achieved | A compact and lightweight computer and power supply system were developed and installed. Both instrument functioned normally from launch to post-landing, contributing to the success of the pinpoint landing. |
| Full success | Realise autonomous landing guidance rules that can take into account navigation guidance errors while detecting obstacles. | Achieved | The landing guidance rules worked well before and after the obstacle detection, demonstrating the performance of the pinpoint landing. The obstacle detection results were also confirmed to be valid. |
| | A high-precision landing (accuracy of 100m) on the Moon's surface performed by a spacecraft equipped with these technologies, and results verified. | Achieved | Based on evaluations near obstacle detection, pinpoint landing accuracy was less than about 10m (perhaps 3~4m). Even after the subsequent events, the spacecraft is estimated to have landed about 55m from the target landing site. |
| | Spacecraft remained functional after landing. | Achieved | After landing, the spacecraft continued to operate, and data obtained during the landing descent was reproduced and received on the ground. |
| Extra success | After reaching the Moon's surface, the mission continued for a period until sunset. | Ongoing | Once power generation from the solar cells is resumed, observation operations are planned with the multi-band spectroscopic camera for a period of time. |

※ The overview of Project objectives were quoted in the press kit and other descriptive documents, but given in more detail in this report for the purpose of comparison.


From the era of “Landing where we can”
to “Landing where we want”
Thankyou for your support
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SLIM
LEV SORA-Q
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