Geochemistry on the Moon, from Earth:
Developing the Science Operations Center for DIMPLE

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DIMPLE (Dating an Irregular Mare Patch with a Lunar Explorer, Anderson et al., 2024) was selected in 2023 as part of the PRISM (Payloads and Research Investigations on the Surface of the Moon) program. DIMPLE will travel to and operate on the moon via a NASA CLPS (Commercial Lunar Payload Services) lander. The experiment will land on an Irregular Mare Patch called Ina and will utilize both the lander and a mobility asset (referred to here as a rover). The instruments on board the lander will be the Chemistry and Dating Experiment (CODEX, Anderson et al., 2003), a lander camera, and a Sample Handling Subsystem (SHS; which will include an arm, gripper, and rock saw). The rover will include a camera for observation and navigation and will collect rocks for analysis.

The overarching goal of DIMPLE is to determine the age and composition of the volcanic terrain at Ina. The age of this unique location has been estimated by crater counting to be ~33 Myr old (Braden et al., 2014), which would be evidence of very recent lunar volcanism. The baseline scientific goal is to collect and analyze four rock samples from the lunar surface at Ina over one lunar day. Each sample will be imaged and retrieved by the rover, then delivered to the lander where the sample handling system will then grip, image, and cut a fresh rock face for CODEX analysis. From these activities, we have identified 5 decision-making points that are essential for operations. Each decision-making point requires real-time assessment or confirmation from the DIMPLE team Science Operations Center (SOC) hosted at Southwest Research Institute in Boulder, Colorado.

To achieve this goal, we are carefully designing an operational setup that leverages near-real-time telemetry, data, and imaging. All spacecraft commanding (such as the operation of lander instruments, arm, gripper, saw, and rover) are expected to be sent from the SOC to the lander via the operations center of the CLPS lander provider. All data will stream from the lander to the SOC via a ground station and CLPS lander provider operations center. The SOC and CLPS lander provider operations center will be on 24/7 voice-loops. Working in close communication with CLPS, the SOC will be responsible for all scientific decision-making—informed by real-time data processing and analysis of rover and lander activities. Staff in the SOC will be cross trained to interpret geologic images, geochemical and isochron data, assess and diagnose lander- and rover-hosted payload system health, CODEX operations, as well as in operations and troubleshooting anomalies.

Over the next several sections, we describe in detail the plan for operations and data products that are planned for this state-of-the-art lunar experiment.

1. Concept of operations – from rover traverse to spots on rocks

The operational design has been workshopped by the science team to accomplish the baseline scientific goal of analyzing the age and composition of four lunar rocks from the Ina region. The SOC is then responsible for constructing an operational set-up to support this concept of operations. Here, we briefly describe the planned flow.

Prior to landing, the science team will communicate to the CLPS lander provider the target destinations for the rover (keeping in mind that these may change with additional imaging from the ground). Upon landing and following commissioning, the first sample will be collected from the lander site. The science team member on duty in the SOC will confirm which rock in the area will be the sample for analysis. Following this initial sample, the operational process will flow as follows.

Rover destination is specified by SOC, and the rover traverse is then conducted by the CLPS MOC. Imaging is done at various points along the traverse: en route geologic context, geologic context at sample site, rock collection at sample site, geologic context on return trip. When the rock sample is delivered to the lander within reach of the SHS, the SHS arm will retrieve the rock sample, image it, and then position the sample for cutting (the SOC scientist will utilize lander imaging to command an orientation of the sample). Upon confirmation from the SOC, the SHS will cut a fresh face and image it. The SOC scientist will then create a semi-automated data mask defining laser spot positions for CODEX analysis which is uploaded to the lander. CODEX analysis kicks off (nominal duration is approximately 20 hours); meanwhile, the next rover destination is specified and the loop repeats for each rock sample.

2. 24/7 operations over one lunar day – personnel, latency

Given that the operational lifetime of the instruments is expected to only last one lunar day (~14 Earth days), constant 24/7 operations are planned to achieve the baseline (and ideally additional) scientific goals. The SOC will be staffed with 7 personnel at all times, consisting of the following roles: shift scientist (1), image and rover analyst (1), CODEX operations engineer (1), SHS operations engineer (1), CLPS communication controller (2), and a shift strategist (1). Shifts are expected to be nominally 8 hours, with 30 minutes additional for shift-change communications. Personnel will be cross-trained where possible. We also plan to have a science back room, where science team members will be able to see and interpret data while not on shift. Personnel in the science backroom can communicate findings or concerns to the shift strategist. The CLPS communication controllers will be on voice-loops with the operations team of the CLPS lander provider and will be responsible for the delivery of command sequences.

Command sequences will be generated by the SOC and then uploaded to the lander via the CLPS operation center in the form of relative time sequences (RTS). Given the highly interpretive and interactive nature of the rock analysis, command sequences will be uploaded in batches based on ‘science decision points’ (SDP) in our concept of operations flow. We have identified 5 SDP which will generate a batch of RTS commands: 1) decide on which rock to sample; 2) verify rock is gripped correctly; 3) verify positioned correctly for cut; 4) verify success of cut rock face; 5) verify precision of isochron analysis.

The image and rover analyst along with the shift strategist will identify a rock of interest. The command sequence as a result of SDP-1 will include a collection request consisting of the coordinates of the desired rock, a series of geologic context images before and after collection, and a command for the rover to return to the lander. Following SDP-2 and -3, the SHS engineer, and shift strategist will verify rock grip and positioning for the cut. Once the rock is cut, if the shift scientist approves the cut face at SDP-4, a grid of spot locations on the rock will be uploaded to CODEX to begin analysis. Finally, for SDP-5, the shift scientist and CODEX engineer will monitor the first series of spots and determine if the precision and behavior is nominal. If so, the instrument will be commanded to continue for the maximum number of points in the uploaded grid. The CODEX engineer will continuously monitor the downlinked data and use software to update an isochron. Once an isochron age with acceptable precision has been created and verified (fulfilling the science objectives), the science team can choose to end CODEX analysis before the maximum number of spots is reached.

To accomplish the tasks as described, we are requiring 18 hours of communication for every 24 hours with data acquisition at a rate of 225 kbps and data latency not to exceed 30 mins for science data and 1 minute for telemetry. In addition, SOC is requiring rover and lander images (of geologic context, calibration, and rock samples) be delivered to the SOC within 10 minutes of acquisition.

3. Real-time data analysis and data products

Data will be delivered to the SOC in the form of CCSDS RAW binary files containing CODEX data, telemetry and housekeeping data (Level 0 data). Images will be delivered as JPEG files. These data will be uncompressed and processed through our pipeline (**Figure 2**), resulting in three data product types over four levels of maturity. Following uncompression, the ephemeris, timestamps, and telemetry data will be appended to the CODEX and/or image file headers, resulting in the Level 1 data files.

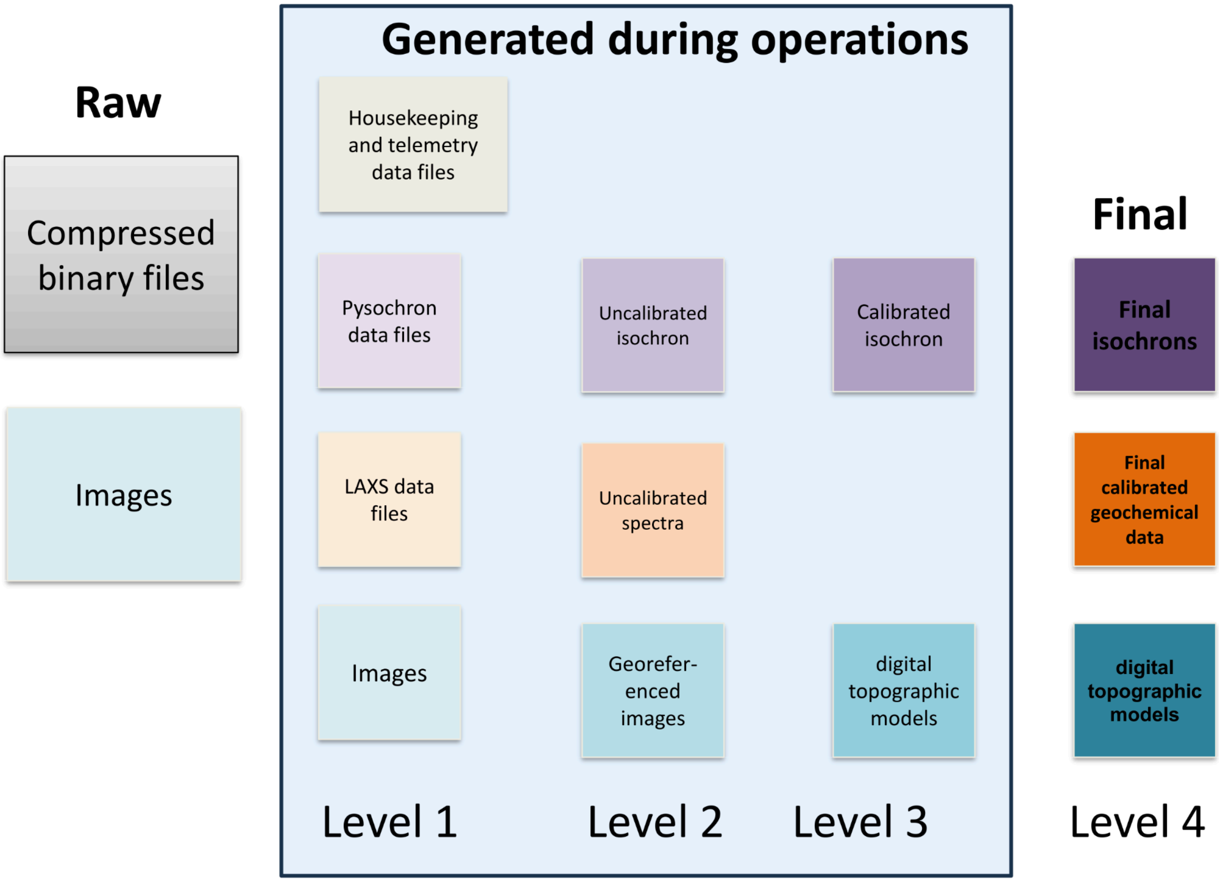

Figure 2. *Data processing pipeline for the three data products.*

3.1 Level 1 to Level 2 data

Images from the rover will be plotted geospatially along the traverse path and displayed on the image and rover operations console. Stereo images from the lander will be processed through our topographic processing data tool (based on the NASA Ames Stereo Pipeline). Images of rocks will be processed with a machine-learning assisted tool to generate a spot-analysis mask that generates laser shot locations on a grid which are uplinked to the lander, informing CODEX where to perform analysis for each spot on the sample. The rock image with CODEX analysis mask will be archived in the sample analysis database (described further in Section 3.4).

The CODEX data will be run through our isochron software (called Pysochron, example output in **Figure 3**), producing diagnostic plots for each laser spot. This Level 2 product will be used by the shift scientist and CODEX engineer to determine behavior and precision. In addition, the Level 1 CODEX data will be processed through the geochemical software, called LAXS, generating uncalibrated spectra and associated diagnostic plots. Again, the shift scientist will use these data to verify precision and behavior.

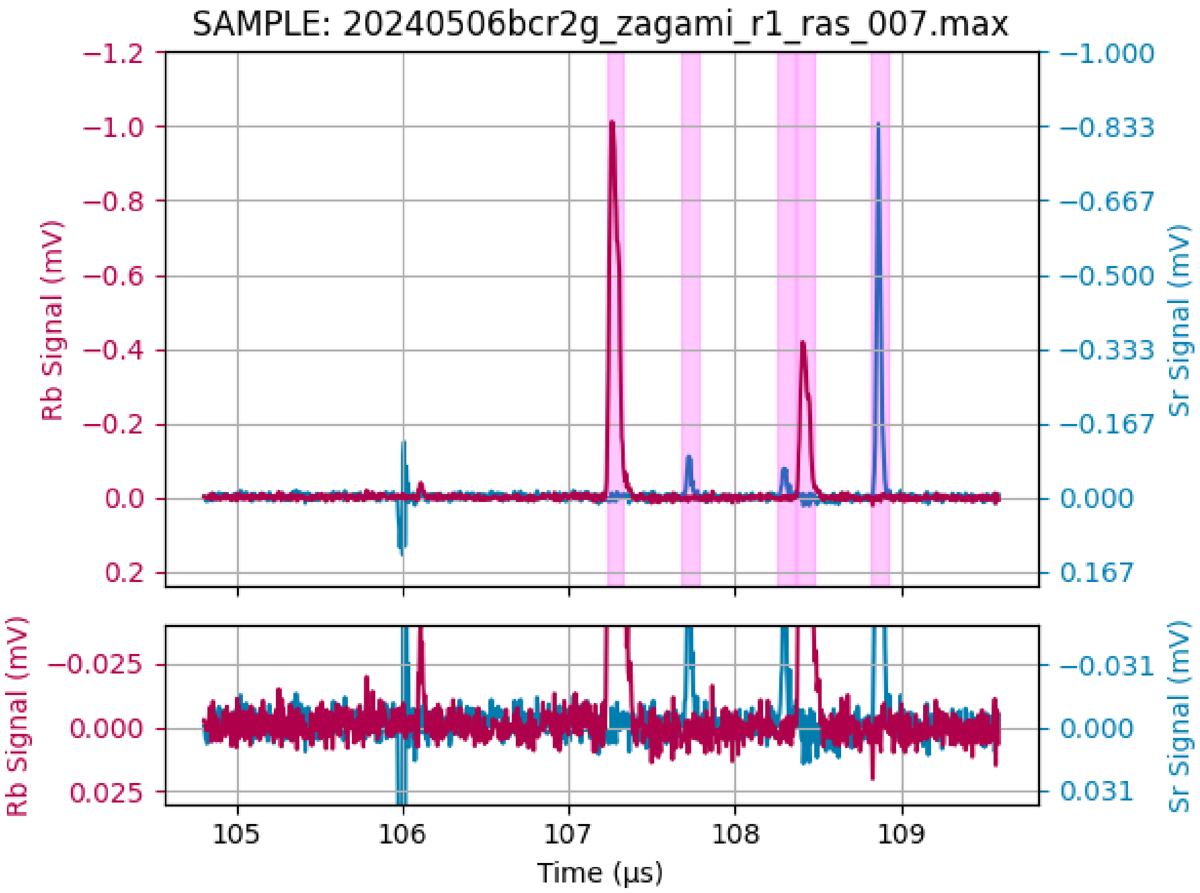

***Figure 3**: Example plot automatically generated by the Pysochron software package. This particular type of plot shows the signals of Rb and Sr (Rb is maroon; Sr blue) for a particular .max file (.max files are the file format generated by CODEX). Pink shading on the top plot highlights the peaks of interest. Lower plot has a different y-axis scale to visually show the noise relative to signals.*

3.2 Level 2 to Level 3 data

Stereo images will be calibrated to flat and dark field filters. The images are then geometrically calibrated with SPICE kernels. 3D visualization using the calibrated images will be used for rock identification, characterization, and geological context.

Simultaneously, Rb and Sr spectra are calibrated within the Pysochron pipeline by 1) determining the ratios of ^{87}Sr/^{86}Sr and ^{87}Rb/^{86}Sr; 2) selecting integration period of spectral peaks, calculating the mean, desaturating and normalizing; 3) Correcting using reference material data. Geochemical data is then calibrated in a similar manner, by 1) determining the integration period of the spectral peaks and 2) correcting using reference material data. The corrected and calibrated isochrons and spectra will be plotted, displayed, and archived.

3.3 Level 3 to Level 4 data

Digital topographic models are generated from the stereo images. Isochron and geochemical data are further corrected in bulk, rather than spot-by-spot correction as in the Level 3 data. Level 4 data is expected to be generated following lunar operations and will be posted to the PDS within 6 months.

3.4 Maintaining a sample analysis database

Each rock sample will result in 400-2000 individual spots of analysis. To allow for immediate and long-term continuity of retrieving data associated with specific rocks and spots, we are developing a sample analysis database. Similar to a Wiki, the database will have all relevant information for each sample and spot (i.e., collection time and collection settings, rock and spot ID, rock and spot images, and point to the path in the science archive where all data products are hosted for each level of data).

4. Conclusions

The DIMPLE lander and rover instrument suite will be the first example of *in situ* radioisotope dating on the moon. The execution and success of this project relies on a near-real-time operations scheme to collect, prepare, and analyze at least 4 lunar rock samples over a single lunar day. We have outlined the operational design for a Science Operations Center that hosts instrument and scientific experts, working in tandem with the lander provider's Mission Operations Center. Working in shifts, the DIMPLE engineering and science team will define rover traverse destinations, identify samples (lunar basalts) for analysis, and monitor instrument health and data precision. At each scientific decision point (SDP), commands will be generated and delivered to the MOC for uplink to the lander. As the lunar rocks are analyzed, data will stream to the SOC via the MOC and be processed through an automated pipeline resulting in three main data products: geochemical spectra, isochrons, and stereo images. The outcome of this novel experiment will help to constrain the age and formation mechanism for the Irregular Mare Patch, Ina.

5. References

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