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FSS and the challenges of operating a seismometer on the far side of the Moon

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Abstract

After four years on Mars onboard the InSight mission, the seismometers built for the SEIS instrument are set to fly to the Moon in 2025 onboard the Farside Seismic Suite (FSS) mission, as part of the NASA CLPS program. SEIS is a seismometer comprised of three very broadband seismometers (VBBs) and three short period seismometers (SPs). The Moon environment allows FSS to limit the instrument to only one VBB and three SPs. However, FSS will be landing on the far side of the Moon, in Schrödinger Crater, making it challenging to operate without the capability to perform real time commanding. The Moon day duration (28 Earth days) and the absence of atmosphere on the Moon surface lead to a very specific operational concept and mission scenario for FSS with respect to InSight. FSS is a low-cost mission that shall reuse as many components and features from InSight as possible to limit cost and mission complexity. This paper will present the FSS operations concept and how lessons learned from InSight Mars operations can be applied to FSS Moon operations. The first seven days on the lunar surface will be critical to the mission success and the commissioning activities will be introduced here. A focus will also be provided on the operational products, ground segment and mission center that will be reused for FSS.

Keywords: FSS, seismometer, InSight, operational concept, Moon, operations

Acronyms/Abbreviations

BEE	Back-End Electronics
C&DH	Command & Data-Handling System
CLPS	Commercial Lunar Payload Services
DTE	Direct-To-Earth
EDL	Entry, Descent and Landing
EPS	Electrical Power Subsystem
ESP	Europa Seismic Package
FBB	Feedback Board
FSS	Farside Seismic Suite
GDS	Ground Data System
IE	Instrument Electronics
InSight	Interior Exploration using Seismic Investigations, Geodesy and Heat Transport
IPGP	Institut de Physique du Globe de Paris
IRIS	Incorporated Research Institutions for Seismology
ISAE	Institut Supérieur de l'Aéronautique et de l'Espace
L0	Level-0 Scientific Product
L1	Level-1 Scientific Product
LITMS	Lunar Interior Temperature and Materials Suite

MarCO	Mars Cube One
MLI	Multi-Layer Insulation
MOS	Mission Operations System
MRO	Mars Reconnaissance Orbiter
MSFC	NASA Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PDS	Planetary Data Service
PE	Proximity Electronics
PI	Project Investigator
PRISM	Payload and Research Investigations on the Surface of the Moon
SDS	Science Data System
SEIS	Seismic Experiment for Internal Structure
SISMOC	SEIS Mars Operations Center
SP	Short-Period
sps	samples per second
TC	Telecommand
TGO	Trace Gas Orbiter
TM	Telemetry
VBB	Very Broad Band

1. Introduction

Following the highly successful InSight mission which just ended its operational phase at the end of 2022, this article provides the concepts and ideas for operating the VBB and SP sensors onboard the FSS (Farside Seismic Suite) Mission during all operational phases of the mission. After a brief description of the FSS mission and its heritage from the InSight Mission, along with the actors involved, this paper will provide information about the different phases of the mission and the associated mission operations concepts. A highlight will be provided on the challenges of operating a seismometer continuously on the surface of the Moon.

2. FSS Mission Description

2.1 Mission Overview

As part of NASA's Payload and Research Investigations on the Surface of the Moon (PRISM) program, the Farside Seismic Suite (FSS) mission will deliver a scientific investigation package to the Schrödinger Crater region on the far side of the Moon, in 2025. Its instrument suite is comprised of two seismometers highly inherited from the SEIS instrument onboard the InSight mission on Mars (operational from 2018 to 2022). On one hand, the vertical Very Broad-Band seismometer (VBBZ) is the most sensitive flight-ready seismometer ever built. On the other hand, the Short Period sensor (SP) is the most sensitive and mature compact triaxial sensor available for space applications. Along with the Lunar Interior Temperature and Materials Suite (LITMS) and LuSEE-Lite payloads, FSS' seismometers will be delivered to Schrödinger Basin onboard Draper's SERIES-2 lander, selected through the Commercial Lunar Payload Services (CLPS) program, NASA's recent intent to facilitate access to the lunar surface by deploying science packages using commercially developed spacecrafts.

FSS is one of the three customer missions embarked onboard the Mission 3 by Draper. Their landers will deploy swarms of rovers to the lunar surface to pioneer the discovery and development of lunar resources, enabling the steady development of lunar industry and human presence on the Moon (source *https://ispace-inc.com/missions*).

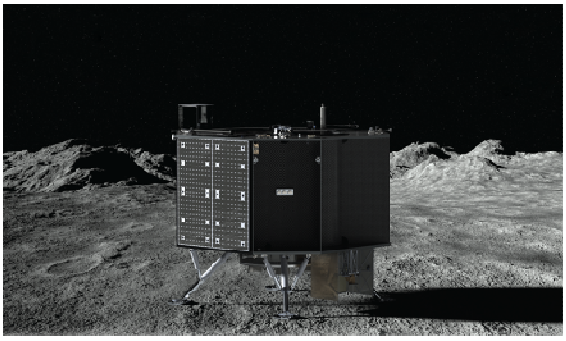

Figure 1: Draper's SERIES-2 Lander (Credits: Draper)

After landing on the lunar surface, the SERIES-2 lander will be operational during a Lunar day, ie. 14 Earth days, to allow instrument commissioning after what it will be permanently shut down during the Lunar night. The lander is not designed to survive the long and cold lunar nights, 14 consecutive days below -200°C. However, unlike InSight which needed the lander to be awake to allow instrument commanding, FSS is packaged as a self-sufficient payload, with independent power, communications and thermal control, allowing it to outlive its commercial delivery lander. Indeed 14 days is not enough time to properly investigate the lunar interior with seismometers, to that the FSS sensor suite has been designed to autonomously operate 4.5 months on the lunar surface.

It is with a constrained budget as a PRISM-class mission that FSS will address the following NASA Decadal Survey-level science goals:

Investigate deep lunar structure and the differences between near and farside activity: Understanding the absence of farside seismicity recorded on Apollo seismometers is fundamental to our understanding of the lunar deep interior. Does it reflect a nearside-farside difference in activity rate, or does seismic attenuation from partial melting in the mantle prevent observation of distant seismic events ?

Understand how the lunar crust is affected by the development of an impact melt basin: Dynamic models of impact processes predict deep structure beneath a well-preserved peak ring impact basin like Schrödinger Crater that can only be revealed through geophysical techniques.

Evaluate the current micrometeorite impact rate and local tectonic activity: Directly constraining micrometeorite impact rates has important implications for future lunar occupation. FSS will record 4 months of lunar background data created by micrometeorite impacts.

2.1 Instruments Overview

FSS is a cube that measures 40x40x40 cm and weighs around 50 kg. It is powered by solar panels with sufficient batteries to operate through the Lunar night.

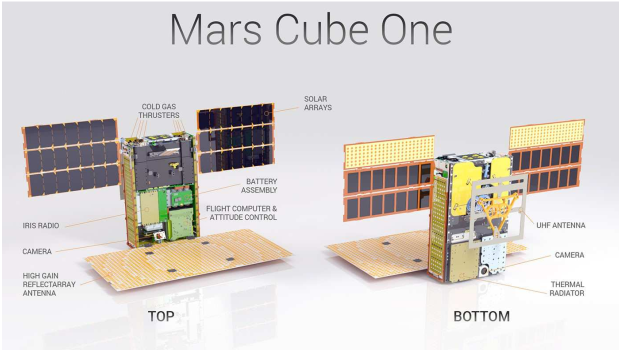

Figure 2: "Mars Cube One" (MarCO) CubeSat Overview (Source: NASA)

In search of cost reduction, FSS will reuse the flight spare avionics of the Mars Cube One (MarCO) cubesats, already flight-proven as they accompanied InSight on its cruise to Mars, allowing to relay its Entry, Descent and Landing (EDL) Phase almost real-time. The MarCO Command & Data Handling subsystem (C&DH) and Electrical Power Subsystem (EPS) provide ample resources at very low power, allowing the seismometer suite to keep performing science during the Lunar night, ie. 14 Earth days, with no communication to Earth.

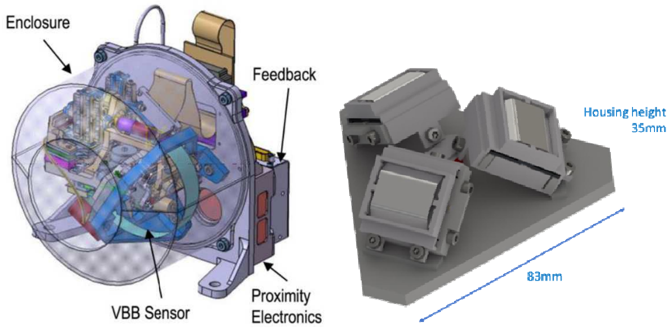

Figure 3: SeismoBox and VBB sensor (left) and triaxial SPs (right)

FSS is comprised of two seismometers: a vertical flight spare VBB, and a triaxial SP. The VBB is contained within the SeismoBox (Figure 3), which is an enclosure that allows venting to reach vacuum on the Moon, where ther is no atmosphere. Along with the SeismoBox is the VBB's Feedback Board (FBB) and Proximity Electronics (PE), which control the sensor and optimize its performances on the Moon. Unlike InSight, the lack of atmosphere on the Moon makes the environmental constraints less demanding with no surrounding wind that would cause noise. Therefore, there is no need to deploy the seismometers on the surface of the Moon, as it was the case for SEIS on Mars. FSS will accomplish its science goals from the lander deck.

Positioned next to the SeismoBox, the triaxial SP (cf. Fig. 4) will allow for measurements of seismic waves with shorter periods that the VBB cannot detect; they are not redundant, but complementary. The seismometers are connected to the Instrument Electronics (IE), which is a combination of space and commercial parts applicable to the lunar environment. Interfaces defined on the Europa Seismic Package (ESP) are used for the SP, and heritage InSight interfaces are used for the VBB. The IE is connected to the C&DH via a board that will act as an interface between the MarCO heritage, and the Instrument Electronics.

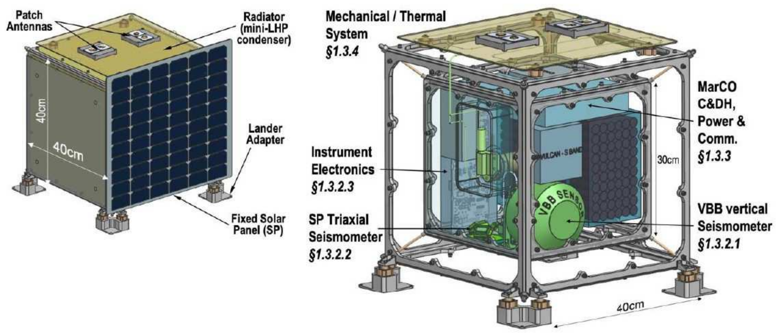

Figure 4: FSS Exterior and Interior Views (Source: NASA/JPL)

FSS is also equipped with four distinct basic thermal management elements:

- conductive isolation,
- radiative isolation,
- a low sink temperature radiator,
- and a passive variable conductance thermal link to the radiator.

The internal housing of the instrument, that contains all the sensors and electronics, is supported with Kevlar tension cables by the external housing, and insulated by ultra-low conductance thermal separators, and spacerless multi-layer insulation (MLI). Thermal model and baseline results indicate that FSS components within its Internal Housing will remain between 300 K and 318 K during Surface Operations, with 280 K daytime and 50 K nighttime lunar surface sink temperatures.

2.1 Actors

The Farside Seismic Suite Mission is an international collaboration between actors from the United States and Europe. Most of these actors were already involved on InSight or the MarCO cubesats launched along InSight.

<u>JPL (Jet Propulsion Laboratory, Pasadena, CA, USA)</u>

JPL is in charge of managing all technical and implementation aspects of the project. It is also in charge of the instrument suite and instrument electronics (IE). Finally, it is responsible for providing flight spares and software, archiving the data at both IRIS and the PDS, providing the FSS Back-End Electronics (BEE), as well as the C&DH and EPS inherited from MarCO. JPL is leading the science investigations with the mission PI. He is coordinating and leading the FSS science team.

<u>University of Michigan (Ann Arbor, MI, USA)</u>

University of Michigan is in charge of designing, manufacturing, testing and providing the flight computer C&DH (Command and Data Handling) and the board that interfaces between the IE to the existing MarCO flight spare C&DH, and supporting software upgrades

<u>CNES (Centre National d'Etudes Spatiales, Toulouse, France)</u>

CNES is in charge of developing the VBB seismometer, as well as defining and operating the FSS Operations Center (FOCSE) that will be located in CNES facilities in Toulouse, France. It is also in charge of VBB and SP seismometers downlink operations, such monitoring health and safety for the instrument suite, producing Level-0 Scientific Products (L0) from telemetry packets. However JPL will handle instrument commanding duties and the preparation of flight products to be uplinked to FSS.

IPGP (Institut de Physique du Globe de Paris, Paris, France)

IPGP is the home laboratory of the VBB PI. The role of IPGP is to lead the FSS Instrument Data Service. It is also in charge of performing data processing and management via software already developed for InSight, and preparing the station metadata as well as verifying the instrument response.

Imperial College London (UK), University of Oxford (UK) and Kinemetrics Inc. (Pasadena, CA, USA)

Imperial College London, University of Oxford and Pasadena-based Kinemetrics Inc. are in charge of developing the three SP seismometers, with the latter being in charge of their manufacturing, testing and delivery.

ISAE (Institut Supérieur de l'Aéronautique et de l'Espace, Toulouse, France) and NASA Marshall Space Flight Center (Huntsville, AL, USA)

ISAE and NASA's MSFC are in charge of performing lunar science during the Surface Operations phase.

3. FSS Operations Concept

The Apollo missions brought, along with other payloads, several seismometers to the surface of the Moon. Due to operational constraints and the need to have a constant visibility with the landing site in the event of an anomaly, all Apollo missions landed on the nearside of the Moon.

To get to know the lunar interior better, FSS will, as its name indicates, land on the farside of the Moon, which is never visible from Earth. All communications will have to be relayed through a satellite in Lunar orbit; as it was the case for the Martian orbiters ESA's Trace Gas Orbiter (TGO), and NASA's Mars Reconnaissance Orbiter (MRO), Odyssey and MAVEN orbiters which relayed telemetry (TM) and telecommands (TC) between InSight and Earth.

On some rare occasions, such as EDL, InSight performed Direct-To-Earth (DTE) X-band communication passes. It will not be the case for FSS, and two orbiters will relay all telemetry and telecommands. The entire M3 mission, for which FSS is one of the customers, is actually led and managed by the Draper company. The lander itself is built and operated by Draper, which also conceives, develops, and operate the M3 operations center. Draper is also in charge of delivering and operating the two relay orbiters required to communicate with the far side of Moon. During the first lunar day after landing (14 Earth days); the orbiters will relay both lander and FSS communications. After the second lunar day, when the lander is expected to have become inactive following the first lunar night, the orbiters will relay FSS communications back to Earth and forth. FSS has its own radio transmitter and communication system to be able to communicate with the Draper operations center autonomously during its 4 months mission. The Draper operations center is refered to as "Vendor Relay Ground Station" on Figure 6 in §3.3.

3.1 Launch, Cruise, Moon Landing and Commissioning Phase

FSS will not be mostly inactive during its 1-month cruise phase to the Moon. Therefore, power will solely be used for thermal control if required. Attitude control accommodation will be assured by the commercial lander to keep FSS within its thermal limits. One or several in-flight checkouts will be executed during the cruise phase, likely only one for the VBB and the SP sensors. These checkouts include cycling parts of the instrument suite, such as discharging the batteries, powering the survival heaters, turning the VBB and SP seismometers on and off, and testing the C&DH.

After landing, all operations are mostly independent of the lander. Initial FSS deployment operations will be commanded by Mission Operations System (MOS) at JPL, and will begin once the commercial lander commissioning has ended, ie. a day after landing. Various FSS components will be switched on and checked out, such as the C&DH and the radio communications system.

The IE will then be switched on, and the seismometers will begin data acquisition. Should there be any software update, they will be uplinked and checked at this point. The SP will be calibrated, followed by VBB initial recentering and calibration. Telemetry data will be analyzed by the Operations Teams for verification.

Hence a key decision point in the mission scenario is when FSS will disconnect itself from the lander to become autonomous from a power and communications point of view, even though it will remain on the lander deck. Once FSS' health and safety is checked, as well as satisfactory results from VBB and SP science checkout, it will be commanded to permanently disconnect from the lander.

3.2 Lunar Surface Operations

Once FSS commissioning phase is completed, the instrument suite is able to perform high-quality seismic science on the far side of the Moon continuously.

To do so, FSS will operate in three different modes, mostly defined by power requirements, as pictured in Figure 5 below: the Lunar Day Science mode, the Lunar Day Science + Telecom mode, and the Lunar Night Science mode.

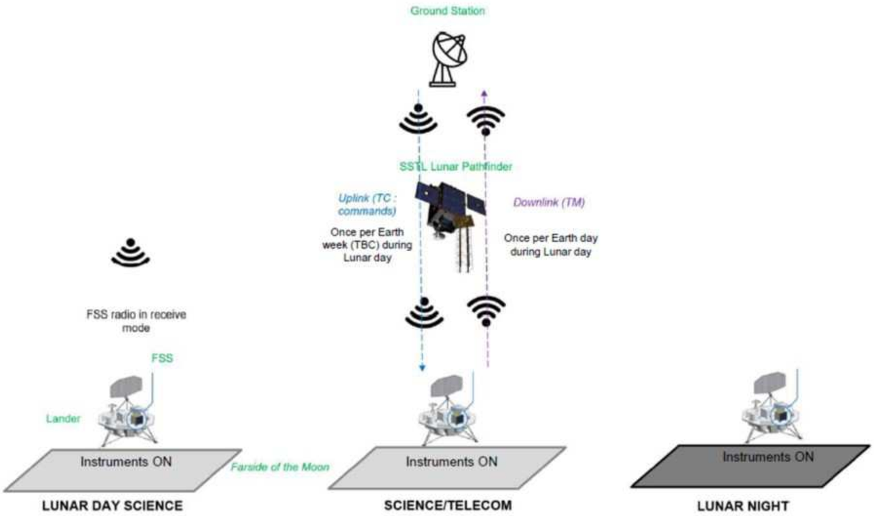

Figure 5: FSS Surface Operations Modes

<u>Lunar Day Science Operations</u>

When FSS is switched to Lunar Day Science-only mode, all of its units are powered, the EPS is charging the batteries with power from the solar panels, and the thermal system is shunting heat energy through radiators as required.

The IE is writing heartbeat, and as well as high-frequency (100 samples-per-second, sps) data from the seismometers, and low-frequency (4 sps) housekeeping data to its NAND flash memory. The instrument data is transferred to the C&DH regularly.

The Flight Computer switches the modem to Receive-only mode, ie. FSS will not emit telemetry to the orbiter, and no communication passes are planned. However, FSS will execute commands it receives, such as VBB recentering or transition to Lunar night.

<u>Lunar Day Science and Telecom Operations</u>

The Lunar Day Science + Telecom mode includes all of the activities from the Lunar Day Science mode, with the downlink of science data and housekeeping telemetry to Earth through planned communication passes during orbiter overflights.

On one hand, one TC uplink is planned per Earth week during Lunar day, ie. twice a month as a Lunar day lasts 14 Earth-days. On the other hand, TM downlink is planned to occur every Earth day during Lunar day.

<u>Lunar Night Science Operations</u>

During the 14-Earth-days-long Lunar night, FSS is switched to Lunar Night Science-only mode. In this configuration, only the instrument suite is powered: EPS is powering the Instrument Electronics, and the thermal system is turned off. During this period, FSS will not receive commands as its modem is turned off as well.

The IE is writing heartbeat, 100-sps science data and 1-sps housekeeping data to its NAND flash. The instrument data is transferred to the C&DH once per Earth day. Appropriate electronics to transition to Lunar Day operations is active.

During all those phases, data volumes are constrained by the orbiters on the surface of the Moon. However unlike on Mars for InSight, the data volume restrictions will be limited on the Moon thanks to the two relay orbiters and the link budgets capacity between the Moon and Earth. On FSS, the data volumes allowed by the orbiters are hence much more favorable and will exceed the data produced by the instruments on average: 2.8Gbits/day. Furthermore, FSS only has one VBB when SEIS had three, generating a more limited amount of data: only 450Mbits/day. The long nights (14 Earth days) however add the constraint to have a significant amount of data to transmit when transmissions can resume, and the mission has been sized to accommodate that constraint.

3.3 Ground Operations

As for many aspects of the project, FSS' Mission Operations System (MOS), Ground Data System (GDS) and Science Data System (SDS) benefit from a strong heritage from the InSight mission. Most of the FSS MOS and GDS operations will take place at JPL, while most of the SDS operations will take place at the SEIS Mars Operations Center (FOCSE-SISMOC, the CNES operations center for SEIS), that will also support FSS operations. IPGP will provide support for the science operations through the development of the FSS Data Portal (data distribution to the FSS science community) and the Lunar Quake Service (moonquakes classification and characterization).

First, JPL is responsible for designing and managing the operations process and interfaces throughout the mission, translate activity requests from science team and operators into FSS uplink formats, downlink FSS instrument telemetry and ancillary data through relay service (the Draper Control Center), and forwarding FSS telemetry with status reports to SISMOC. Jointly with SISMOC, JPL will provide high-level health and safety monitoring of the instruments and anomaly analyses of the instruments.

Then, CNES is in charge of providing detailed monitoring of the seismometers and potential anomaly analyses, as well as generating and forwarding L0 Products to IPGP, and generating science activity sequences with the science team.

Finally, IPGP is responsible for defining science requirements of the VBB seismometer, generating the Level-1 Scientific Products (L1) and scientific results of the mission, handling science data distribution policy, developing data calibration parameters and waveforms, and seismic event detection. As part of the science team, IPGP will provide inputs to JPL and CNES for weekly activity plans of the seismometers.

Weekly meetings will be conducted between JPL, FOCSE and IPGP to assess the quality of the seismic data downlinked. Even though not required for nominal routine operations, the Project Investigator (PI) may convene meetings to plan and review commanding needs for upcoming telecom overflights.

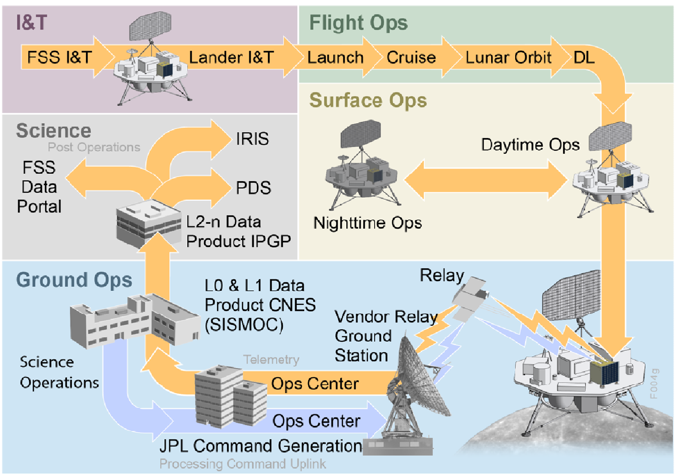

Figure 6: FSS Operational Workflow (Source: NASA/JPL)

Upon activity requests from IPGP and CNES, JPL's engineering and instrument teams will generate sequences to perform maintenance, calibration and configuration of the instruments. The variety of activities performed with the VBB and SP sensors will be limited, and mostly consists of maintenance recentering for the VBB and calibrations. JPL's Mission Operations System generates the sequences for the instruments, handles the conversion to binary files bundle files, and uplinks to the Moon through the relay service provider. The overall communication plan and relay passes planning will be managed by Draper for the entire M3 mission, including the lander and the other commercial missions during the first lunar day, i.e. the first 14 days of the mission.

The Draper control center transmits the command sequences to the lunar relay satellite, which then forwards them to FSS on the Lunar surface. Then, the relay receives downlinked instrument telemetry data from FSS and forwards them to its receiving station on Earth. The provider then receives telemetry downlinks from the relay, and forwards them to JPL's Ground Data System.

GDS receives telemetry packets from the relay provider and, after performing minor packet quality analyses, generates a report and forwards them to CNES' FOCSE for processing into higher-level products. The products are delivered to IPGP for distribution through the FSS Data Portal, and finally archived to the Incorporated Research Institute for Seismology (IRIS) and the Planetary Data System (PDS) Geoscience node through JPL's Science Data System. JPL SDS reformats into the PDS-4 format before archiving to the PDS GS at Washington University.

The reuse of InSight ground segment

Since the SEIS and FSS instruments are very similar, the data they generate are also very similar. It has been decided to reuse the same ground segment and to instantiate a new version of the SISMOC ground segment at CNES for FSS. Not all SISMOC features are required for FSS, but the ground segment architecture and interfaces remain the same. Insight has ended its operational phase in December 2022, but SISMOC will remain active for post-treatments and data availability purposes until the end of 2025.

If data format should remain similar, it won't be the case for the commands (or 'TCs' for Telecommands) sent from the ground to FSS. The flight software will be different between both missions and FSS inherits the C&DH and flight software from the MarCO cubesats. They are less complex but also less capable than the InSight payload system developed by Lockheed Martin. InSight flight software and commanding relied heavily on command blocks offered by the VML (*Virtual Machine Language*) language used by InSight. The command dictionary has to be redeveloped for FSS to fit the FSS C&DH and flight software. The plan is the reuse the same activity dictionary, minus the SEIS activities that will not exist on FSS (no leveling system or tiltmeters for instance, and no need to perform event request for high-resolution data). The challenge, in addition of course to develop the new flight software and telecommand dictionary (which is handled by JPL), is hence to adapt the intermediate layer between the activity dictionary and the actual TCs in order to keep it as close as possible to SEIS operations for the ground segment and the FSS and SEIS operational teams.

Perpetuation of the teams

CNES has made sure the operational and some of the development team members remain involved in FSS development phase and future operations. One of the key aspects of the success of SEIS operations is to ingest, process and distribute successfully the data to the science community. A lot of processing is needed to transform raw data into useful seismic data, especially time correlation aspects. The SISMOC is a complex set of tools and processing chains, and a certain level of expertise has been acquired by the SEIS exploitation team through the years. Those team members will be involved in FSS operations as well, and have already started transitioning part-time to FSS activities in parallel with InSight duties. The hardware itself consists in the delivery of a new VBB sensor to JPL, after a retrofit from the martian to the lunar gravity, and an integration into the SeismoBox provided by JPL. The project manager at CNES and the instrument manager at IPGP are both SEIS alumni with a strong expertise in the development, testing and qualification of the VBB.

4. Conclusion

Throughout the successful four years spent on the Martian surface listening to Marsquakes and impacts, SEIS' seismometers unveiled the interior of Mars like never before. As early as 2025, it is on the Moon that the VBB and

SP will be delivered and record seismic waves, to obtain key information about the deep lunar interior, and our natural satellite's farside seismicity. As a very ambitious mission, FSS will try to bring answers to questions asked in NASA's Decadal Survey with a challenging budget. Once again, seismology is bringing Earth's nations together in collaboration towards a better comprehension of our planetary neighborhood.

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