# Adjustments of Insight SEIS and APSS operations in an energy-limited context

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## Abstract

This paper presents the methods developed by Insight teams to overcome the energy issues due to the accumulation of dust on the solar panels, which strongly constrained surface operations. Thanks to a fine management of ops products and bold decisions when needed, we updated the concept of operations to succeed payloads operations despite a degraded power profile. SEIS was able to monitor Martian seismic activity despite available energy was less than a tenth of its initial capacity. In addition, the collaborations and joint work from all teams developed unique strategies to remove dust from the solar arrays.

**Keywords:** Mars, operations, lander, wakeup, payloads, energy, power, constraints, dust, ops products, power cycle, sequence

## Acronyms

AFT - Allowed Flight Temperatures.
C&DH - Command and Data Handling.
CNES – Centre National d'etudes spatiales.
DSN – Deep Space Network.
EBOX – Electronic BOX.
EOM - End Of Mission.
EPS - Electrical Power System.
ICC - Instrument Context Camera.
IDA - Instrument Deployment Arm.
IDC - Instrument Deployable Camera.
IDS - Instrument Deployment System.
IFG - InSight Flux Gate.
IOT - Instruments Operations Teams.
JPL - Jet Propulsion Laboratory.
LGO – Load and GO.
NASA - National Aeronautics and Space Administration.
PAE – Payloads Auxiliary Electronics.
PS - Pressure sensor.
SEIS - Seismic Experience for Interior Structure.
SISMOC - SeIS on Mars Operation Center.
SP - Short Period.
SWOG - Science WOrking Group.
TWINS - Temperature and WINds Sensors.
UHF - Ultra high frequency.
VBB - Very Broad Band.
$\tau$ - Optical depth.

# 1. Introduction

Insight's end of mission was declared in December 2022, more than four years after landing. The lander was no longer able to collect enough energy to maintain SEIS powered on, even for short periods. Six months before, the seismometer recorded its biggest Marsquake. A few days later, the spacecraft and payloads entered safe mode due to energy imbalance. The accumulation of dust on the surface of the solar panels, combined to a weak solar radiation at Insight landing site, dropped available energy to less than 10% of its initial capacity. Thanks to strong commitment and hard work, operational and scientific teams updated the way to conduct operations according to the available resources. While the SEIS and APSS instruments were designed to be permanently on, they have been regularly switched off to accommodate lack of power and avoid instruments safing due to overconsumption. We updated the concept of operations, transitioning from a continuous steady state to periodic power cycle (OFF / ON). Besides, jointly agreed by SEIS experts and manufacturers, a risky approach decreasing SEIS maintenance, allowed to reduce its power loads. Finally, unique experiments were established to try to remove dust from the surface of the solar arrays.
The purpose of this article is to show how energy drops affected Insight surface operation. First, we will introduce Insight mission and how dust constrained surface routine operations. Then, we will describe the work made by all teams to operate the instruments according to the available resources.

# 2. InSight mission overview

Insight landed on November 2018, in Elysium Planitia. It aims to record Martian seismic activity to determine the internal structure of the planet. SEIS, composed of VBB and SP sensors, was deployed on ground using the IDS, composed of the IDA (called the robotic arm) and the IDC camera. A scoop and a grapple are attached at the end of the robotic arm. A second camera ICC is located under the lander's deck. In addition, the APSS instrument measures atmospheric data with the PS (Pressure Sensor), the IFG (InSight Flux Gate) for the magnetic field and with the TWINS (*Temperature and WINds Sensors)* for the air temperature, wind speed and direction.

The Electrical Power System (EPS) collects and distributes energy to the payloads using two deployable solar panels. Two communication devices allows data exchange. UHF antenna to transmit and receive commands from the orbiters and X-band antenna for direct communication with Earth, mainly used for contingency purposes. Whereas the lander primarily sleeps to preserve energy, instruments are always powered on for continuous data acquisition. Activity plan defines the spacecraft start-up / stop time. During a wake, instruments receive sequences (set of commands) from the lander and transfer the collected data. Wakeups are planned according to the orbiter overflight passes, the lander and payloads activities.

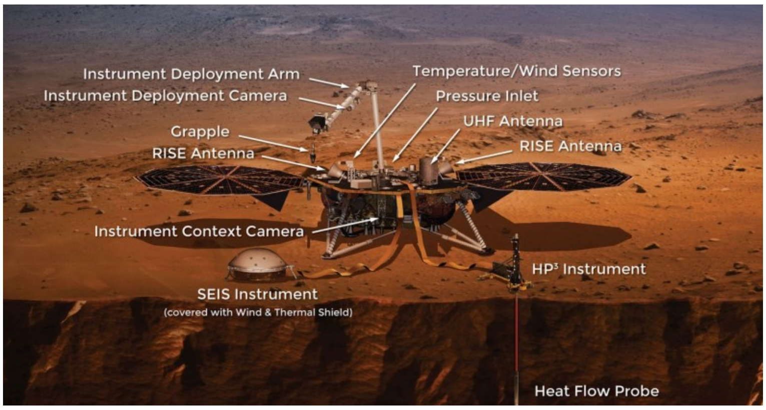


*Figure 1 – Insight lander and payloads*
*Image Credit: NASA/JPL-Caltech*

At CNES Toulouse, the SISMOC is responsible of SEIS and APSS commanding and data processing. Instruments data are received on ground several times. Payloads commanding occurs every two weeks. In collaboration with the Science WOrking Group (SWOG), the Instrument Operations Teams (IOT) establish the payloads activities. For science activities, SWOG defines the expected configuration for all sensors and an associated timeframe. Periodically, IOTs request maintenance activities to ensure data quality. Then, IOTs provide to JPL a scheduled list of the operational products to perform it. JPL planners gather inputs from all teams to build the activity plan. The plan is transmitted to the orbiters using the NASA DSN network and forwarded to the lander during overflight pass.

Beneficing experiences from previous solar powered missions, the EPS provides a comfortable margin to use all payloads. Four power profiles define the use of payloads according to the available energy. Depending on the power restrictions, payloads are switched off to fit the available resources.

- **Full monitoring**: Used during nominal surface operation phase. All payloads can be powered on.
- **Restricted**: Depending on science interest (varying according to the local season), some sensors are turned off to reduce energy consumption, ranging from *full monitoring* down to *minimal* profile.
- **Minimal**: Only SEIS payload is on, in particular VBBs sensors.
- **Survival**: All instruments are off. Only spacecraft systems (C&DH, electrical power system and telecom) are on.

## 3. Insight power collection trends

Solar radiation at ground level drives the performance of the solar arrays. Depending on the quantity of dust particles in the sky and clouds, the atmosphere gets opaque and reduces the power collected by the lander. The optical depth ($\tau$) measures the opacity of the atmosphere. Computed using sky images, acquired by the cameras, $\tau$ helps to predict the available energy for the incoming sols and consequently to plan the activities of the spacecraft and the instruments.

During dust storm season, persistent strong wind lift a lot of dust in the atmosphere. Occasionally, local dust storm can turn into a global one and engulf the entire planet, completely obstructing solar radiation at ground level. Such events strongly affected Insight operations. Their consequences ranged from activities removal to instruments safing.

Besides, the accumulation of dust on the surface of the solar arrays restricted the power collection. Following dust storm events, all the suspended particles raised by wind, fall back at ground level and cover the lander creating a layer of dust. The dust factor is the estimation of the quantity of dust on the surface of the solar arrays. At landing, with clean solar panels, the dust factor is equal to one. The figure 2 shows the accumulated dust on the spacecraft (dust factor value close to ~0.15). The picture is made of several images acquired by the IDC camera in April 2022, 8 months before End Of Mission (EOM).

In early phase, we expected dust devils (convective vortices loaded with dust) to clean the lander, as the Opportunity and Spirit rovers experienced. However, no natural cleaning happened despite dust devils tracks found near Insight landing site identified thanks to orbiters images.

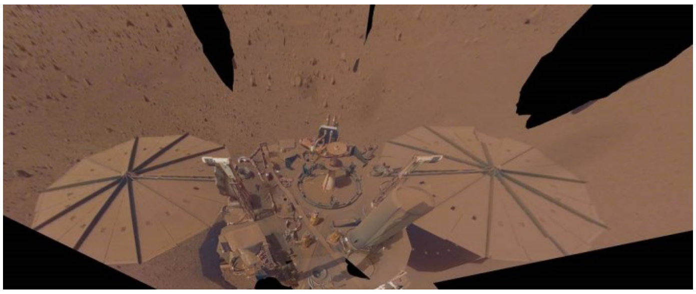

*Figure 2-InSight's final selfie*
*Image Credit: NASA/JPL-Caltech*

The figure 3 displays the daily available energy, τ and dust factor since landing. Both τ (red curve) and the dust factor (black curve) share the main Y-axis. τ values depend on the atmospheric conditions, the dust factor decreases proportionally to the mission duration and is worsened by dust storm events. The secondary Y-axis displays for each sol the remaining energy (in %) compared to landing. Colored dashed lines show the dust removal experiments. Solar array shakes are shown in yellow, solar array cleanings in green. The black dashed line marks the end of payloads commissioning, near Sol 100.

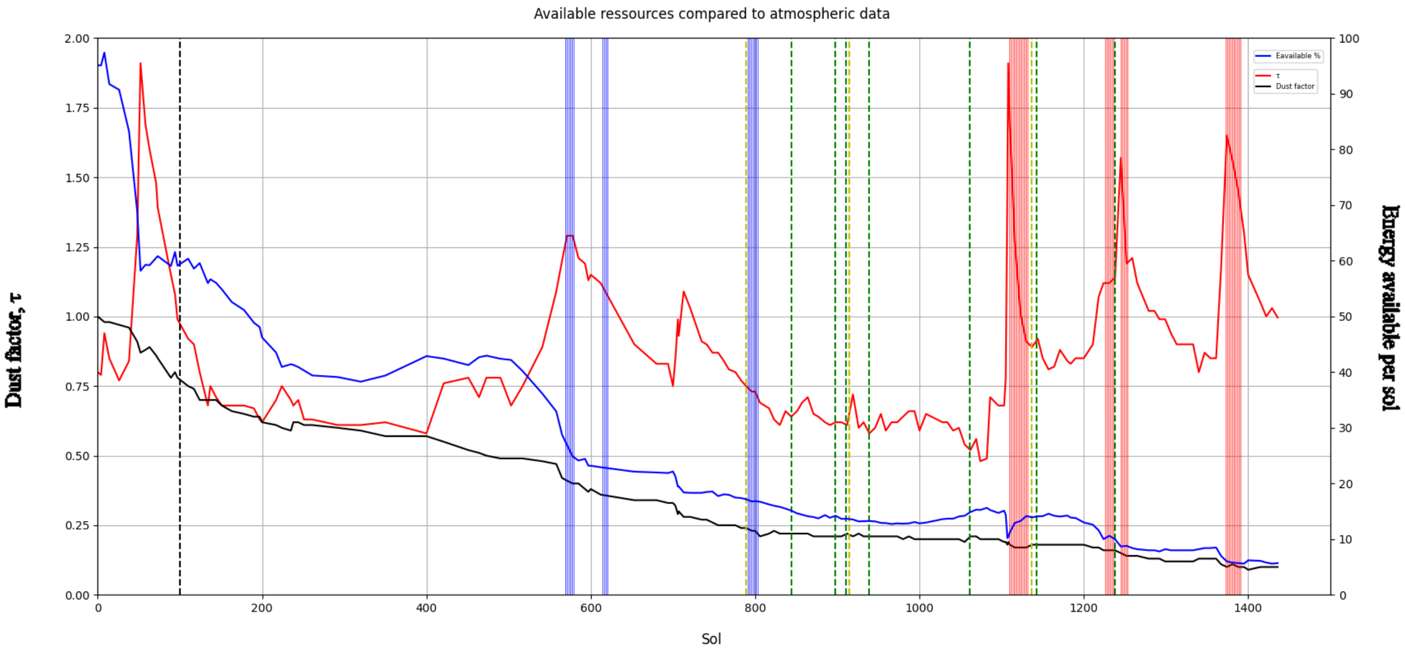


*Figure 3 - Insight atmospheric and EPS measurements*

The plot reflects the effects of atmospheric events on the EPS efficiency. Each significant τ increase (τ >=1) reduced the available energy. One of the biggest occurred shortly after landing because of a dust storm. While the available energy sharply dropped, Insight measurement showed τ reached 1.9. At the end of payloads commissioning, the remaining energy had dropped to ~70%. In parallel, the accumulated dust on the spacecraft increased (decreasing the dust factor). As a result, less than 50% of initial resources were available on Sol 200.

Although the first dust storm experienced by Insight had no impacts on daily operations, every other events constrained routine surface operations and forced us to adapt the way to conduct them. For SEIS, the first consequence occurred near Sol 580 (July 2020), following a moderate dust storm (τ ~1.25). We stopped SEIS heater to save power, as remaining energy dropped to a quarter of its initial capacity. The additional power was helpful to maintain APSS sensors on. However, few weeks later, we had to turn off some of the APSS sensors to match the available power.

During summer 2022, EPS reached 10% of its initial capacity. Several APSS sensors and spacecraft sub-systems were turned off with no expectations to use them in near future. Although SEIS VBB sensors were prioritized to maximize data acquisition until EOM (declared in the last days of 2022), daily power cycle were performed in this timeframe.

In total, Insight experienced six dust storms. Four big events (τ >=1.5) and two moderate (τ >=1.0). In 2022, SEIS entered safe mode four times (shown in light red areas), either due to power imbalance (automatically triggering spacecraft and payloads safing) or ground-commanded to quickly reduce the power loads and avoid power imbalance. In light blue, we display APSS safings. The first one was also ground commanded to meet energy requirements. The other ones, we triggered by the spacecraft and safed APSS only.

We observe an increase of energy from Sol 250 until Sol 400 and from Sol 950 to Sol 1100. In this timeframe, the power situation slightly improved, benefiting from a less opaque atmosphere (τ close to ~ 0.7) and no degradation of the dust factor. Besides, Mars aphelion occurred near Sol ~270 and Sol ~ 950. Thereafter, the solar radiation increased, as Mars was getting closer to the sun.

Solar array cleaning experiments were mainly performed in 2021 (from Sol 840 to Sol 1060). They were successful and provided small gains in power. The last tentative was performed on Sol 1238. No further tries were possible, as the robotic arm required too much power. It retired in final position, with IDC pointed to the sky for imaging.

# 4. Payloads operations in an energy-limited context

As soon as project determined power constraints were higher than expected, all teams jointly worked to find methods to save power and fit in the available resources. All the work aimed to reduce the power loads of the payloads and the spacecraft. At CNES, we optimized SEIS and APSS activities in order to shorten wakeups duration. We enhanced existing operational products; we created new ones for precise purposes.
In collaboration with SEIS experts, we significantly save power through a risky-approach. All the work allowed conducting payloads operations despite a strongly restricted power profile.

## *4.1. Optimizing operational products*

SEIS commanding relies on blocks and sequences. Blocks execute a set of commands in a row. Sequences group several blocks to perform any activity (Configuration change, motor displacement, sensors switch on / off, etc.). After validation and testing, blocks and sequences are transferred to JPL. Ops teams select the appropriate sequences to model any activity of the instrument. On-shelf operational products ease daily operations as we can use them for each uplink cycle without additional testing. The characteristics of blocks and sequences (duration, power loads, flight rules, etc.) are determined and ensures nominal execution on-board.

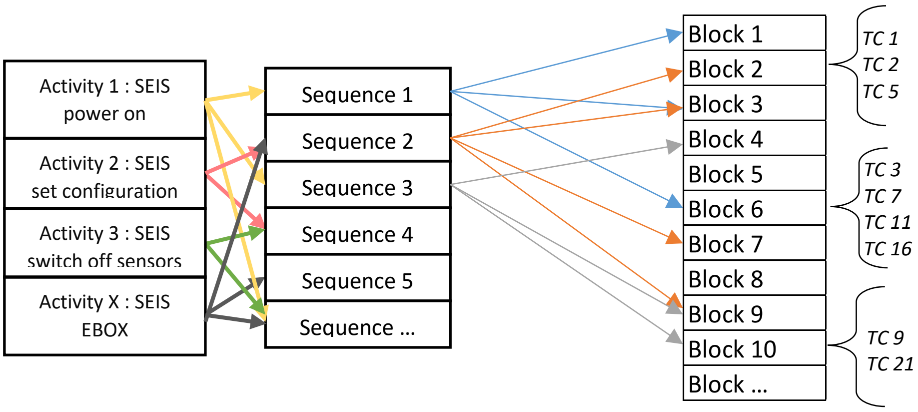


*Figure 4 - SEIS blocks and sequences concept*

Prior to landing and during commissioning, we developed a whole set of blocks and sequences without energy constraints expectations. They provided margin to ensure nominal execution and contextual steps for on-ground analysis. When energy issues appeared, we reviewed all of them. We removed all unnecessary steps and adjusted their duration based on on-board execution. In addition, we regularly updated instruments data processing models to fit the allocated time.

Along with the increase of the power constraints, we developed new sequences. Regular activities (configuration, maintenance, etc.) often performed in a row but commanded through several sequences were aggregated into one bigger sequence. It allows a faster execution of the overall activity thanks to removal of all the sequences margins and the unused time between the executions of each sequence. In this context, we created switch on / off sequence for every sensors, as none of our existing products aimed to do so. By mission design, all sensors were commanded together. Later, we developed power cycle sequences, enabling the

instrument electronics (SEIS EBOX & APSS PAE) prior to sensors switch on. All over the mission, we enhanced their content with possible configuration and / or maintenance activities.
The new sequences allowed SEIS to be set in science mode as quickly as possible and avoid having lander wakeup time unused.

Besides, to provide reactivity, we developed a set of LGO products. These sequences requires additional testing and validation as they are sent directly to the lander from earth (using X-band) and executed as soon as reception. They can be used outside of nominal communication windows, to quickly decrease power loads and consequently avoid power imbalance, in case of unexpected changes of the atmospheric conditions.

Following SEIS safing in 2022, we grouped all the sequences used to recover and resume science data acquisition into recovery sequences. Following each occurrence, we updated their content to minimize sensors unavailability. As a result, the time required to unsafe and resume SEIS in nominal mode following the last safing occurrence was executed five time faster than for the first one.

The figure below shows all SEIS and APSS sequences executed per sol since landing. The top plot shows all power cycling sequences. The second plot shows configuration, maintenance, LGO and untagged (not on-shelf product, sequence used only once) sequences. We also display SEIS / APSS safings using red / bleu areas.
The figure highlights the diminution of activities during the extended phase. The optimized power cycling sequences were mostly used, as power was too tight to perform any other activities.

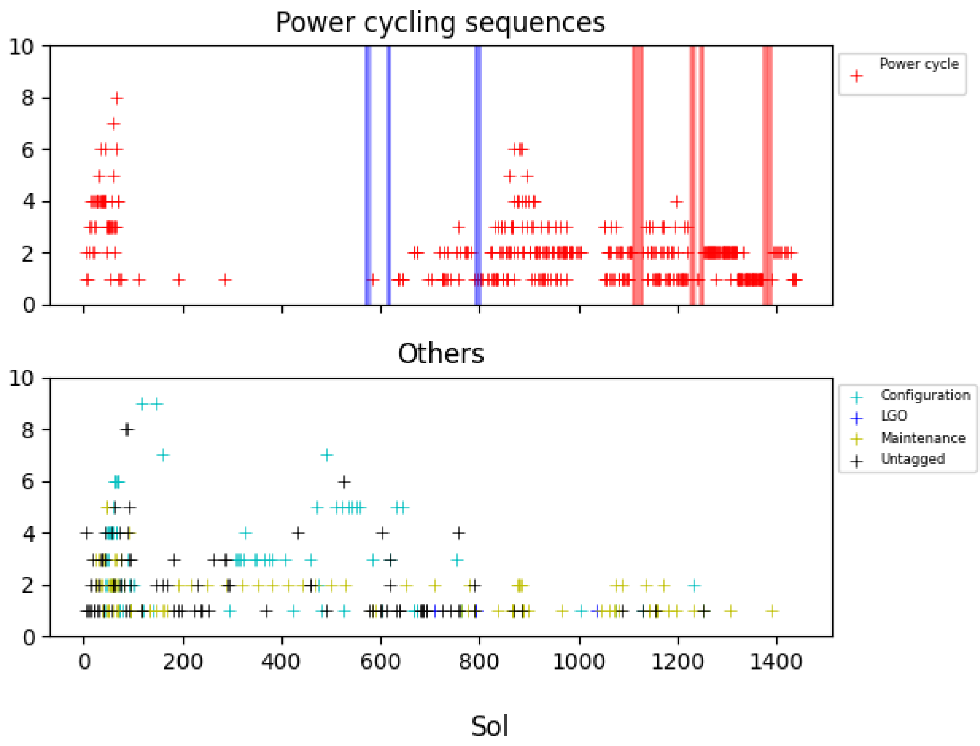


*Figure 5 - SEIS and APSS sequences per sol since landing*

During payloads commissioning, many activities were executed as part of instrument testing. Then, until the first APSS safing (Sol ~590), while rare power cycle sequences were performed (one on Sol ~190 and on Sol ~280), many sequences (configuration changes and untagged) were executed as part of science activities. In parallel, maintenance sequences were executed periodically to ensure data quality.
Then, along with power restrictions, less and less sequences were performed. Aggregated power cycle sequences utilization increased and were the only sequences used. Instrument maintenance were performed sporadically, when energy allowed.

### *4.2. Decrease of instrument's maintenance and protection*

A major power gain for SEIS was to disable its heater. We agreed with partners to stop it, knowing the requirements to do it were not reached. Although it significantly saved power, it added complexity to schedule SEIS activities. A more careful monitoring had to be taken to ensure EBOX and sensors temperature remained in AFTs (*Allowed Flight Temperatures*).
Later, when facing cold periods, we agreed to lower SEIS AFTs expanding its operating timetable. Then, due to the implementation of all power saving methods (less wakeups per sol, shorter wakeup duration, etc.) the temperature near SEIS decreased as less heat was dissipated by the hardware. Moreover, with the removal of the lander heaters, the updated SEIS AFTs did not allow SEIS activities. As a result, a waiver was defined to remove all SEIS AFTs. In this context, the seismometers could be powered cycle at any time of the sol. Associated sequences were modified to accommodate the update of the AFTs.

Additionally, we changed the frequency of non-essential activities. We stopped periodic SEIS tilt measurement, despite low recurrence and low power load. We decreased the periodicity of the SEIS flash maintenance activity from every 30 to 60 sols. Finally, when wakeups duration had to be the shortest as possible, we agreed to execute SEIS & spacecraft activities in parallel, accepting the potential of risk of communication errors.

### *4.3. Dust removal strategies*

Insight is a unique mission, both from science perspective as it provides huge amount of seismic data and from an operational point of view thanks to the establishment of unique strategies to try to overcome energy issues. The first method attempted to remove dust from the solar panels using the lander solar array deployment motors. The process consists of repeatedly powering on the solar arrays deployment motors to "shake" the solar arrays and try to dislodge dust. Despite few tries (sols 788, 915 and 1137), there was no visible difference in dust coverage nor noticeable increase in the energy collection.
Later, we tried the solar panels cleaning method. The process required two parts. First collect regolith with the scoop then drop it nearby the solar array (generally on the lander's deck). To optimize the cleaning, the drop of regolith had to be executed in a windy environment. The blown dust particles would carry out dust particles thanks to the saltation effect. In total, seven attempts were performed on sols 884, 897, 911, 939, 1061, 1143 and 1238. Except the last one, they were all performed on the western solar array. APSS monitored the drops to help the analysis. SEIS was off for the first campaign (from 884 to 939) to spare power as this activity requires a lot of power to warm then move the robotic arm. The first attempt provided a direct power increase of four percent (providing enough power to turn on one TWINS sensor during one Sol). The other cleaning attempts were less efficient; possible explanations include a less windy environment or because the scoop collected less regolith than on the first try.

## 5. Transition from a continuously powered on state to periodic power cycle

All this work was done in order to purse science despite lack of power. It hit us when we had to prioritized activities, as the remaining energy was too low to conduct all of them. Every two weeks, JPL, SWOG and IOTs gathered to describe their request. Based on the criticality, the science interest and the available power, requests were either accepted for the upcoming uplink cycle or delayed to the next one. While instruments maintenance activities were not part of the ranking system at the beginning of the mission, they were added to it at some point.

Figure 6 shows APSS sensors availability from Sols 660 to 1020. Early phase of the mission is not shown as the sensors were permanently on. We do not show sensors uptime from Sols 1020 to EOM, as available energy allowed sporadic data acquisition, following the same pattern as described with figure 7.

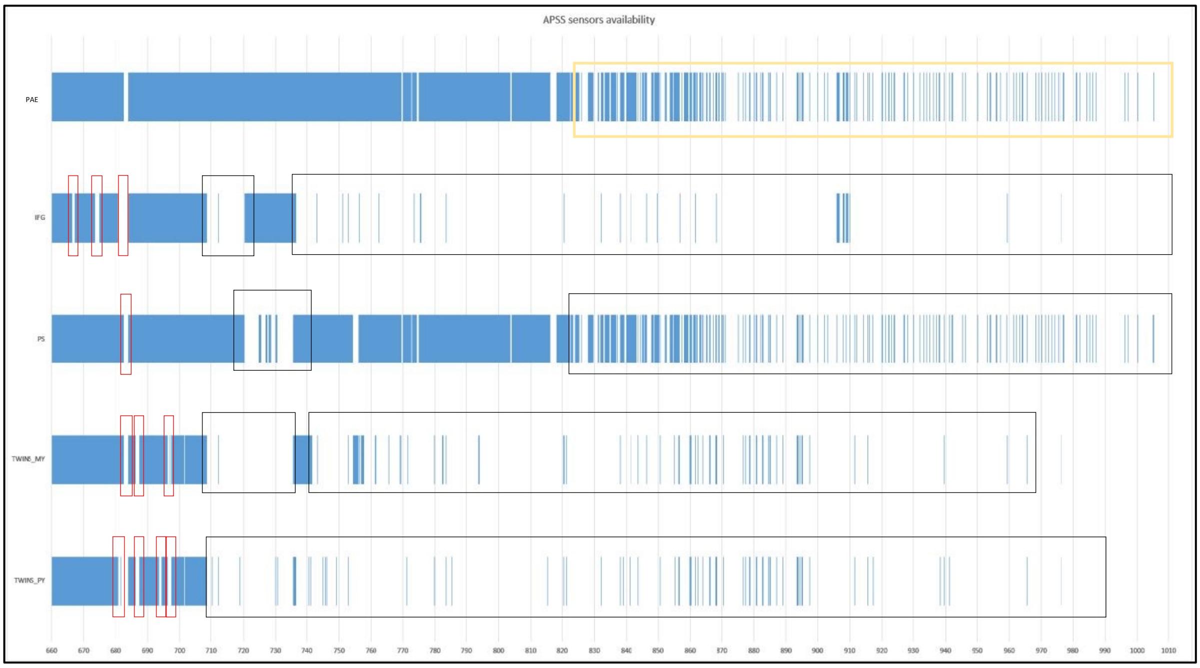


*Figure 6 - APSS uptime from Sols 660 to 1020*

From Sol 650 to Sol 800, lack of power forced us to switch off some sensors during short periods (1 or 2 sols) (shown in red box). Depending on the restrictions, one or several sensors were turned off, providing additional power to conduct the activities selected during bi-monthly meetings.
Then, sensors unavailability increased (black boxes) proportionally to power restrictions. APSS periodic power cycle started from Sol 800 until EOM (shown in yellow box) as energy constraints were too high. In this timeframe, few APSS activities were performed, lasting several hours as explained below (with figure 7).

Figure 7 illustrates an APSS activity plan. It shows sensors uptime from sols 1074 to 1087. Over the plan, the PAE and sensors are occasionally turned on, as part of three different activities (displayed with colored boxes). Each activity is scheduled according to SWOG request.

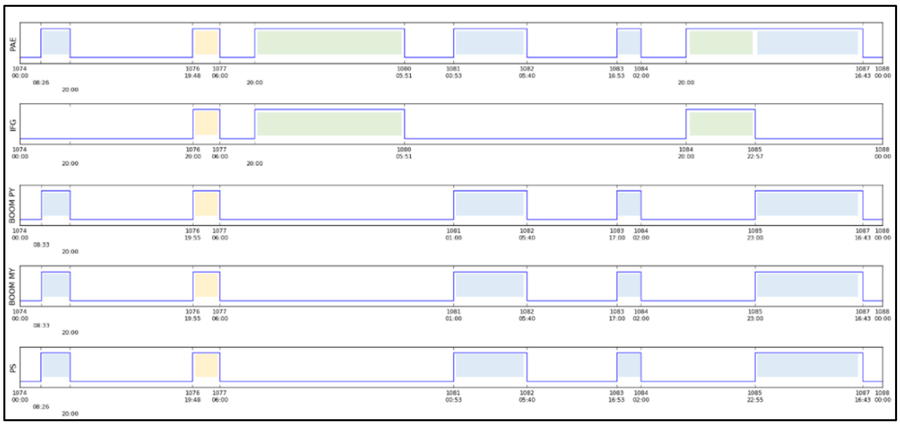


*Figure 7 - APSS sensors power changes from Sols 1074 to 1084*

APSS operations stopped on Sol 1250 – beginning of 2022, as project decided to prioritized SEIS VBBs.

Figure 8 shows SEIS availability since landing. SPs power cycles were mainly performed from Sols 860 to 890 (highlighted with the black square) - June 2021, when facing cold period on Mars. It provided additional power for SEIS VBBs. Later, starting at the end of 2021 until February 2022, discontinuous SPs acquisitions were possible due to slight energy improvement (see section 3). However, due to the lack of energy, science team decided to not power the SPs anymore and prioritize VBBs.


*Figure 8 - SEIS sensors availability since landing*

SEIS VBBs power cycle began during the first quarter of 2022 (red square). Ops teams ensured they were off during noisy period of the sol and enabled during the smoother time of the sol to improve Marsquake detection and analysis. Over the last months of the mission, the uptime decreased, reaching extremely low values few weeks before EOM. SEIS activity plan included only power cycle sequences. VBBs acquisition time lasted less than two sols, spread over five blocks of eight hours.

## 6. Conclusion

Insight's mission fulfilled all science objectives despite a harsh environment and consequent power restrictions. Some of the main seismic events, namely the largest Marsquake and the biggest meteorite impact ever recorded were acquired while SEIS and APSS sensors performed daily power cycle. It was possible thanks to the commitment and collaboration of all involved teams. Through flexible payloads management and innovative solutions to save power, instruments successfully recorded data for more than a year despite highly degraded power profile. The Insight teams were able to adjust Insight concept of operations to face lack of power and established unique methods.