Soil Moisture and Ocean Salinity (SMOS)

Systems Engineering Case Study

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Abstract

ESA's SMOS mission is the first to collect L-band data for soil moisture and ocean salinity, two fundamental measurements to Earth's water cycle. This case study highlights how the team leveraged systems engineering to produce an efficient yet effective satellite system to achieve mission objectives. This paper examines the mission's history, development, performance, requirements, risks, and lessons learned; and how the system continues to exceed its mission objectives, over 10 years later.

Background

Soil Moisture and Ocean Salinity (SMOS) is a satellite which forms part of ESA's Living Planet Program. The SMOS satellite is used to provide information on soil moisture and ocean salinity – two key variables in Earth's water cycle and climate. The payload on-board the SMOS is called MIRAS, Microwave Imaging Radiometer with Aperture Synthesis, which acts as a radio-telescope with many small antennas. MIRAs consists of a central structure with three arms, each of which has three segments. The L-band radiometer has 69 receivers mounted on the star-shaped three-arm antenna. Unlike other traditional satellites, this one looks down on Earth, rather than up into outer space. The SMOS payload is launched via a small spacecraft bus, called Proteus, which just about one cubic meter. After launch, it separates from the launcher and flies at an altitude of 763km. The first images from SMOS were gathered just a week after launch and has been producing images for over 10 years.

SMOS Satellite's Radiometer with Aperture Synthesis (MIRAS) creates images of emitted radiation. This L –band novel microwave imaging radiometer has the ability to penetrate through thick clouds, and can provide reliable estimates of surface and wind speeds during storms. Strong winds over the ocean create many whitecaps which in turn impact the amount of microwave radiation on the surface. Changes in these winds on the surface can be linked directly to changes in this radiation. SMOS also uses this sensor to capture images of brightness temperature. These images are then used to measure changes in ground moisture and seawater salinity by observing variations in microwave emission.

SMOS is also highly useful in determining ocean salinity, which helps us understand the role of the ocean through the global water cycle. Ocean salinity in combination with temperature can help us determine density and thus determine thermohaline circulation (THC). Ocean Salinity also plays a part in the regulation of CO2 uptake and thus can tell us a lot about the oceanic carbon cycle. These are all important points to make because unusual changes in salinity levels may indicate the onset of extreme climate events, such as El Nino.

The SMOS has a number of very practical applications, and is currently used by scientists all around the world. A high priority for scientists is the impact of environmental policy on the environment. SMOS helps us understand how water is cycled throughout the atmosphere and is crucial for understanding climate change. SMOS data can also be combine with data from other satellites to monitor the thickness of both thick and thin ice and can also help monitor the freezing and thawing of soil, also key factors in monitoring climate change. SMOS is also used for weather prediction, and it takes into account many environment variables like these.

Soil moisture is an important variable in the hydrologic cycle. Water and energy fluxes on the surface strongly depend on soil moisture. SMOS collects soil moisture data by measuring microwaves reflected by Earth's surface. Sensitivity to soil moisture is very high at the L-band in particular, compared to atmospheric disturbances. Measuring the soil moisture helps us understand climate and helps us improve both short-term and medium-terms weather forecasting. This is important to measure because it can help predict hazardous events like floods, droughts, and heatwaves. SMOS can also help monitor the conditions that can contribute to swarming locusts by monitoring soil moisture and the amount of green vegetation. And in general, SMOS can aid farmers and the United States Department of Agriculture to understand crop yields.

History

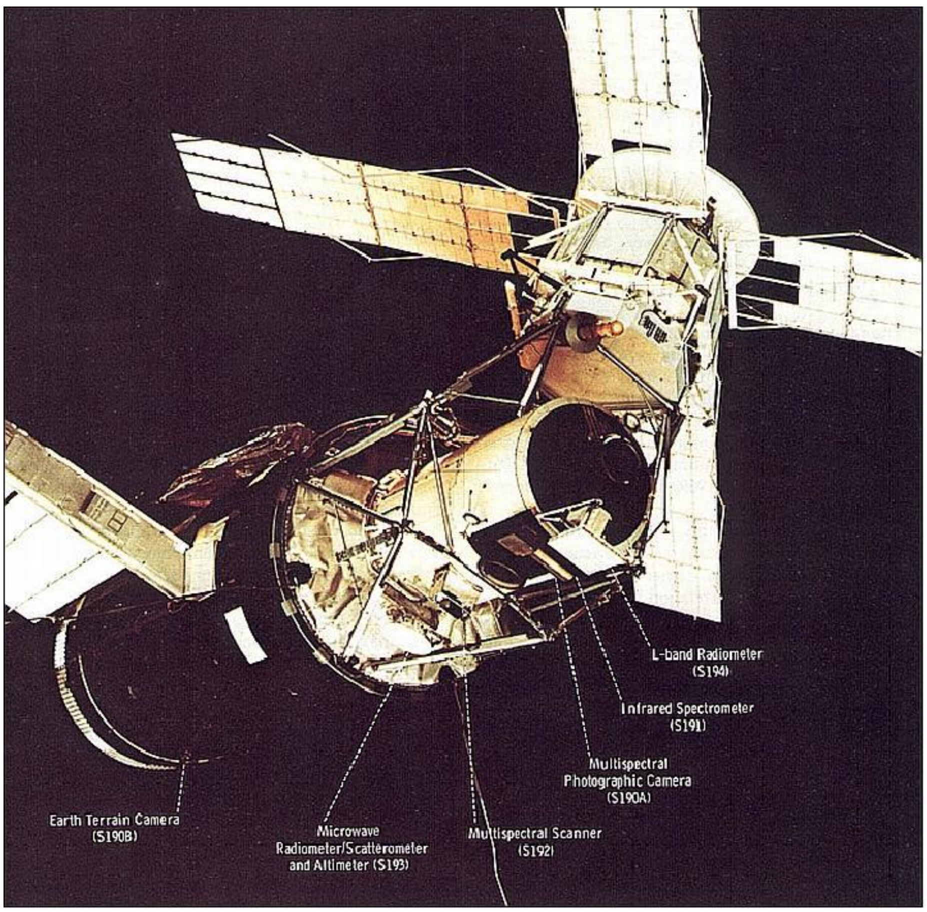


Figure III-1 Skylab Space Station *(image credit: NASA)*

In 1973, 26 years prior to the approval of the SMOS explorer mission, the first L-band radiometer experiment of its kind, called S-194, onboard the Skylab Space Station, made an attempt to collect soil moisture. ESA's Program board for Earth Observation selected SMOS

Earth Explorer Mission for implementation after several years of technological advancements. From 2000-2002, a number of feasibility studies were made to narrow in on scope and definition of the project.

The SMOS mission went through several phases leading up to and including its implementation: analysis and identification of needs, feasibility study, preliminary definition, detailed definition, ground implementation, qualification and production testing, utilization and data exploitation, and disposal—which has yet to happen.

The SMOS science objectives were to globally monitor both soil moisture and ocean salinity, and to improve understanding on ice- and snow-covered surfaces. The main driving force behind SMOS objectives were to help advance climatological, oceanographic, meteorological, hydrological, agronomical, and glaciological science. Progress for weather forecasting, climate monitoring, and extreme events depended on the success of the SMOS mission and the observations of soil moisture and ocean salinity.

During the preparation phases, a number of specific measurement goals laid out for both soil moisture and ocean salinity, and how accurate and often measurements needed to be taken. The system design needed to provide accuracy of 4% volumetric soil moisture, about the same as being able to detect about a teaspoon of water mixed into a handful of soil. The design also needed to be able to observe down to 0.1 psu, which is about the same as detecting 0.1 gram of salt in 1 liter of water. Following the preparation phases, the team worked on the development and testing, and Flight Acceptance Review, and upon meeting its requirements, was shipped out to the launch site.

Development

The SMOS system was led by a team comprised of members from the European Space Agency (ESA) and the National Centre for Space Studies (CNES). Funding responsibilities were divided between ESA and CNES during development and operation phases. The ESA SMOS Mission Manager oversaw the overall mission, and the CNES Mission Project Manager oversaw the satellite performance and operation. For important high-level decisions, ESA's Earth and Science Advisory Committee was involved and worked to oversee the teams.

The motivation around the project was simple and well-defined from the very beginning—To provide L-band measurements of soil moisture and sea surface salinity, and to contributed to cryospheric research. The design was fairly complex, with both flight and ground components to be considered, but the technology used in SMOS is not new. The complexity of the mission required components to be broken up into many different smaller tasks and then divided between the ESA and CNES teams.

The development model used for the SMOS system was the Vee. The mission followed a series of lifecycle phases, from 0 to A-F, and ending with ESA Long Term Data Preservation and valorization (LTDP+). As with any systems engineering focuses project, the requirements were well defined in the beginning of the lifecycle and the process took place in Phase 0. Each phase of the development was directly linked to the testing and worked in parallel, with multiple components of land and flight requiring testing. Successful Flight Acceptance Review (FAR) occurred at the end of the Development and Testing (DT) which allowed the system to be ready for launch.

Performance

The SMOS System underwent a series of calibration activities to assess the functionality of the mission instruments both before and after deployment into the atmosphere. Level 1 data processing is responsible for the measurements and calibration of the MIRAS instrument. All of the algorithms used in the data processing fall under the level 1 data processing components. The level 2 products include the data designed for consumption by the scientific users. These products contain all of the soil moisture, vegetation, brightness temperature, and sea surface salinity.

The SMOS system has fulfilled its mission objectives of providing L-band measurements of soil moisture and ocean salinity, but the system has provided much more than expected. The original duration of the mission was planned to be 3 years, but the SMOS satellite has been in full operation for over 10 years and 4 months and continues to provide useful data for a number of other scientific explorations on the Earth’s surface.

Requirements

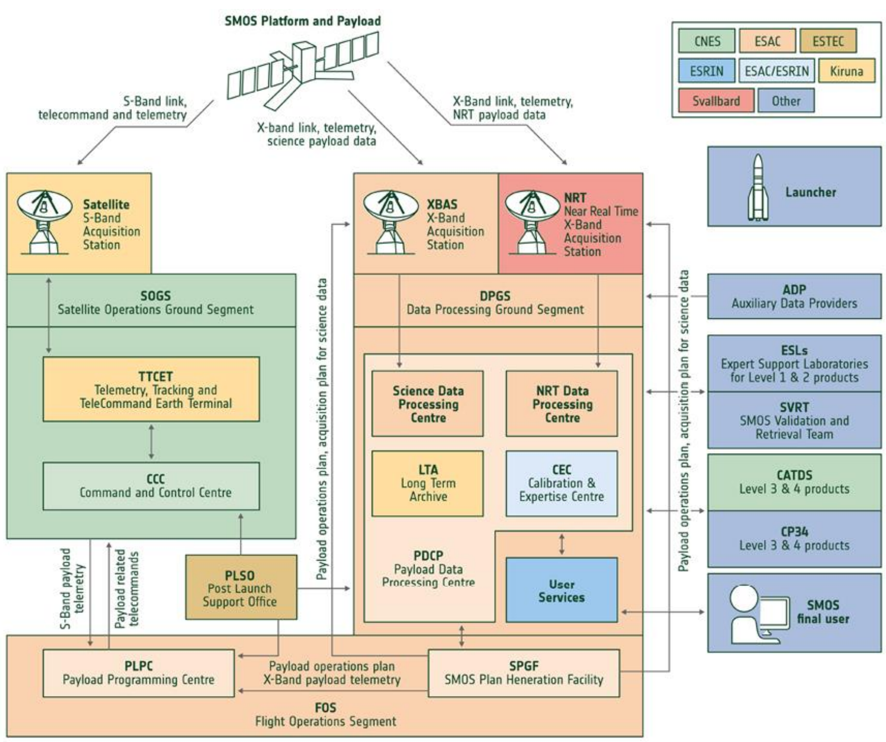


Figure V.5-1 - SMOS System Architecture (ESA)

Requirements Overview

The SMOS requirements are broken up into 4 segments: Satellite Operations and Ground Segment (SOGS), Data Processing Ground Segment (DPGS), Flight Operations Segment (FOS), and "other". Since SMOS is a satellite, there a number of requirements focus on its position and orbit, and around considerations of space debris and deorbiting. From a data perspective, there are requirements around mission performance, what type of data the satellite will collect, and specific requirements around both soil moisture and ocean salinity performance.

Satellite Operations and Ground Segment Requirements

The Satellite Operations and Ground Segment consists of the Command and Control Center and the Telemetry Tracking and Telecommand Earth Terminal which is required to handle the tracking of the payload and the housekeeping of the instruments.

Data Processing Ground Segment Requirements

The Data Processing Ground Segment handles all components related to the data processing and data archiving. There are requirements around satellite data processing, interfaces, and implementation. The Operational requirements include Operational Scenarios, Communication Scenarios, Launch and Early Orbit Phase (LEOP), Commissioning and Nominal Phase, Monitoring Command and Control, Satellite Operational Modes, and Autonomy and Fault Detection. The Product Assurance and RAMS includes requirements also fall under the DPGS and have requirements around Reliability, Availability, Maintainability, Safety, and Parts Materials and Processes. A number of requirements around were defined for Assembly, Verification, Satellite Models, Ground Support Equipment, and Facilities.

Flight Operations Segment Requirements

The Flight Operations Segment handles all requirements around Environment, this includes Ground, Launch, In-Orbit, Thermal, Gravitational Field, Geomagnetic Field, Solar and Earth Electromagnetic Radiation, Earth Atmosphere, Plasma, Electromagnetic Compatibility, Radiation Environment, and Contamination. The design and performance requirements around Microwave Imaging Radiometer Aperture Synthesis (MIRAS) fall under the FOS. Under each of these high-level requirements are functional, performance, and design requirements.

Other Requirements

The last group covers all external interface requirements, including auxiliary data, level 3 and level 4 data products and processing, and associated laboratories.

System and Elements Hierarchy

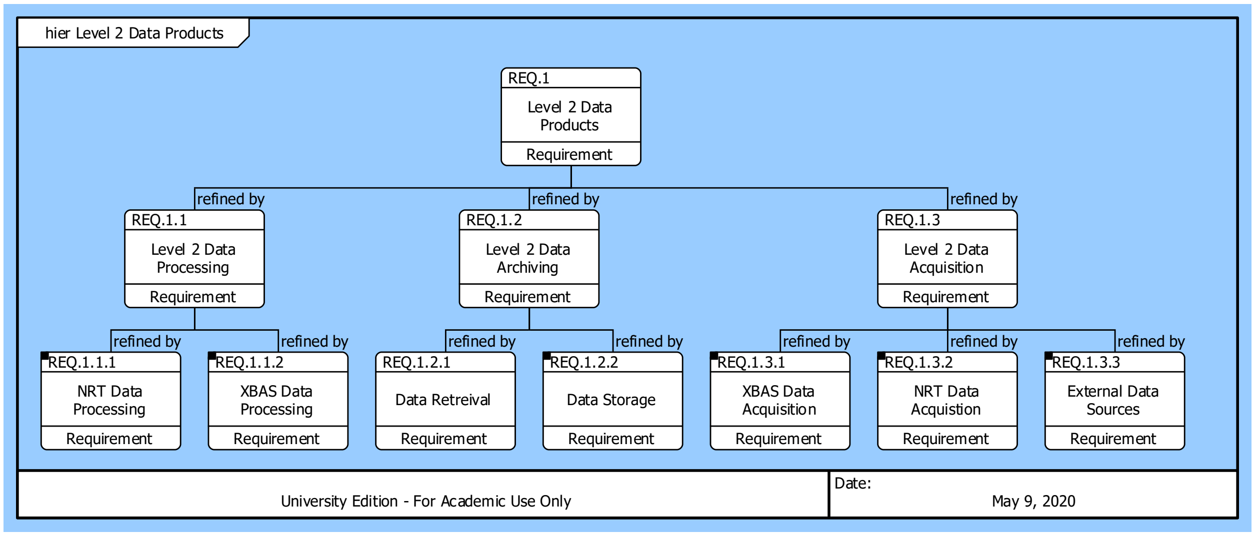


Figure VI-1 Level 2 Data Products System Hierarchy

Requirements Traceability Matrix

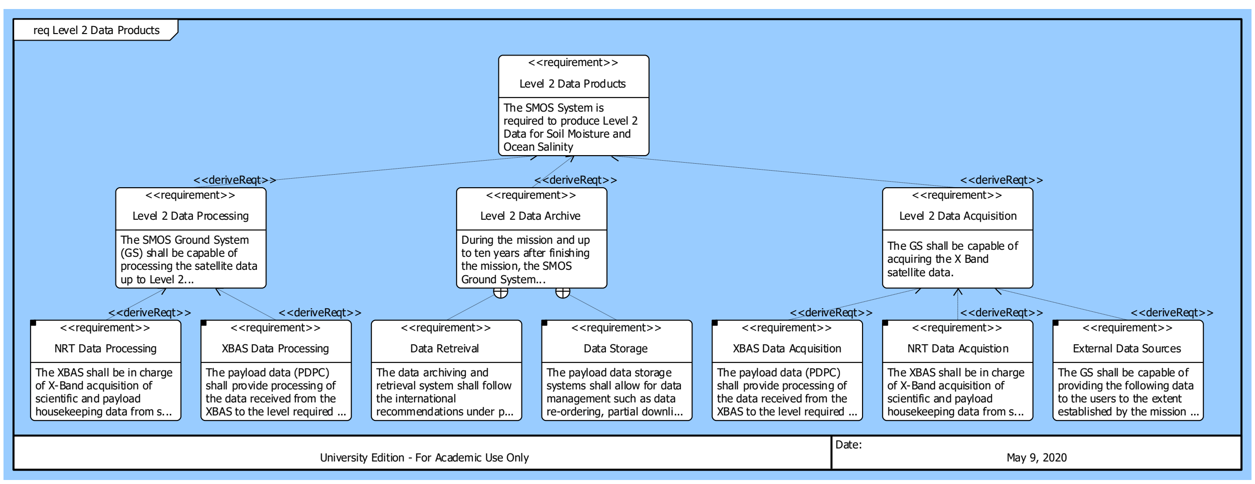


Figure VII-1 Level 2 Data Products System Hierarchy

Functional Decomposition

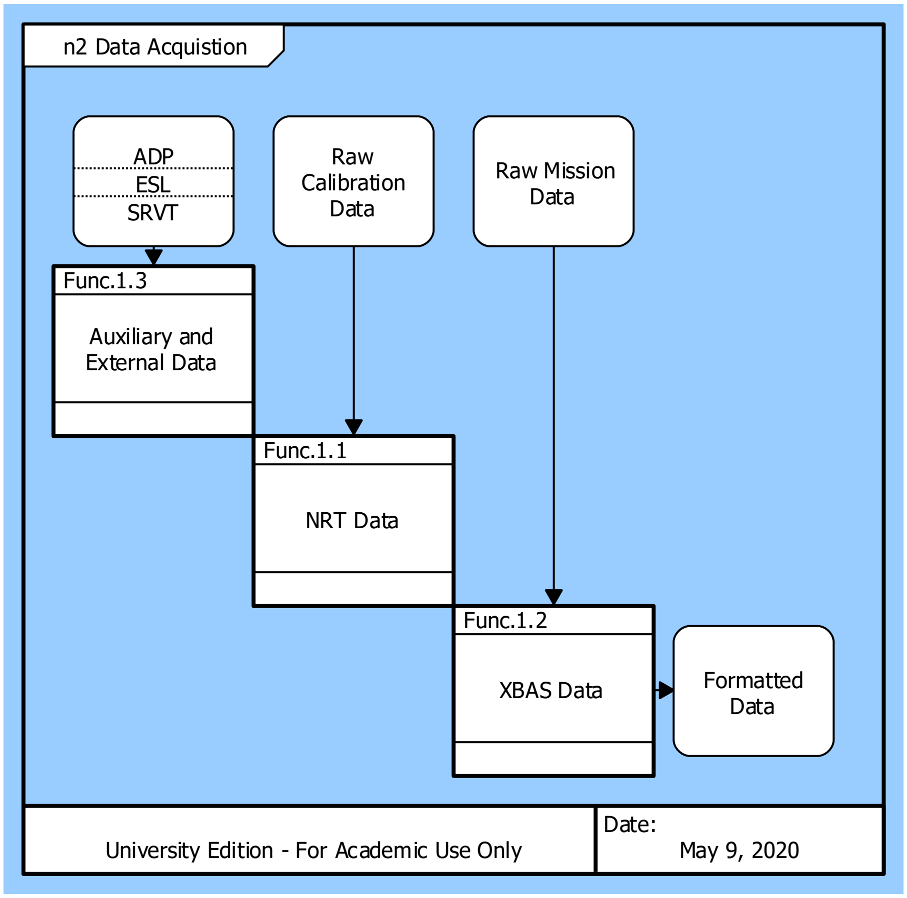
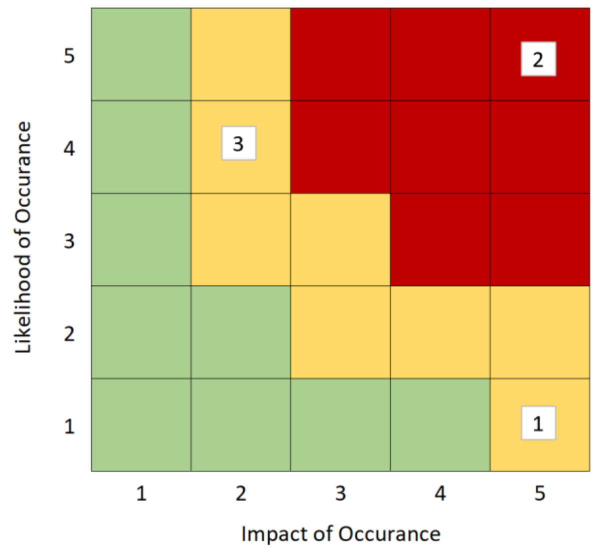


Figure VIII-1 Level 2 SMOS Data Acquisition N2 Diagram

The Soil Moisture and Ocean Salinity (SMOS) System Architecture is split up into the satellite, ground operations, payload, and data processing ground segment components. For this decomposition, the focus is on the data processing ground segment (DPGS) which is responsible for level 2 data products. The level 2 products include the data designed for consumption by the scientific users. These products contain all of the soil moisture, vegetation, brightness temperature, and sea surface salinity.

The functions of DPGS Data Acquisition are Auxiliary and External Data, NRT Data, and XBAS Data. There are inputs of data that come from external sources, namely Auxiliary Data Providers (ADP), Expert Support Laboratories, and SMOS Validation and Retrieval Systems. These sources flow into the Auxiliary and External Data Sources function. Raw Calibration data is an input to the NRT Data Function, and Raw Mission Data is an input to the XBAS Data Function. The sub-functions are low-level enough to be the performance requirements of the functional requirements.

Risk



1	Potential damage due to space debris
2	Satellite component launch schedule slippage
3	SMOS data handling and archiving loss

Figure IX-1 SMOS Mission Risk Matrix

It is essential to identify risks early in the project lifecycle and continuously re-evaluate, identify, and treat risks in order to prevent negative cost and schedule implications. The SMOS (Soil Moisture and Ocean Salinity) system has a number of different risks due to the complexity of the system. The risks identified are satellite vulnerability, satellite component launch schedule, and SMOS data handling and archiving, to name a few.

The success of the SMOS project depends on the functionality of the satellite system. The satellite provides scientists with key data they need to perform the mission objectives. Satellites have a particular vulnerability due to potential damage due to space debris. This risk is identified as low likelihood and has high consequence; therefore, it is categorized as a medium risk. This risk has implications to operations and safety; if damage from debris is severe, the mission objectives are at risk. The safety risk is potential health impact of debris falling back to earth. There is not much that can be done to mitigate this risk, and therefore we must accept this risk.

The project timeline depends on the successful commissioning of the satellite via launch into low earth orbit. The success of the launch vehicle is essential, but it is also important that this activity occurs on schedule. Schedule slippage poses serious risk to project schedule and cost. Many factors can impact this risk like weather, timeline of building key components, and political/regulatory factors. This risk has high likelihood and high consequence; therefore, it is a high risk. To mitigate this risk, the team will expend additional budget and resource to prevent any impacts to the launch date.

The last risk is SMOS data handling and archiving. A key component to fulfilling the mission objectives is the availability and archiving of SMOS data collected by the SMOS satellite. This risk has a low likelihood and a medium consequence and therefore can be considered a low risk due to the due diligence of the design team early on in the project lifecycle. The initial design of the DPGS Data Processing Ground Segment has a number of features built in with this risk in mind. The risk will be mitigated by the management and maintenance of the data processes and archiving components and has built in redundancy.

Lessons Learned

Several countries were involved in the SMOS Mission, and it was managed by two separate organizations: The European Space Agency (ESA) and the National Centre for Space Studies (CNES). This introduced a layer of complexity, and it was crucial that the team remained organized and managed effectively. The management of the project was split, but to ensure that all areas of the project were monitored, a manager from each agency was assigned to a set of the mission operations. The success of this dynamic can be accredited to the fact that both teams held their own Operations Coordination Group and their own Anomy Review Boards (ARBs) to handle severe anomalies that could impact either the SMOS system or a subsystem of SMOS. And to unite the two teams from a higher level, the Inter-Agency/Establishment Technical Coordination Group (TCG) was implemented. The due diligence on behalf of both teams is a key takeaway that can be applied to other projects in the future.

The life cycle process that was followed was the Vee. There was a strong emphasis on testing, where development and verification & validation worked hand in hand. This allowed the team effective and thorough testing, and a successful launch—crucial to this type of system.

With SMOS lessons learned, the ESA has leveraged the MIRAS technology to research new and improved was to upgrade the instrument for better spatial resolution. CNES is also in the process of studying the merging of the temporal 2D interferometry concept with spatial to help with improved performance. With no end in sight, several foreign agencies are stepping up to work on follow-on missions for continued L-band observations from space.

Conclusion

Several technological advancements made the SMOS mission possible. Without a systems engineering approach, the SMOS mission would not have fulfilled all its goals. The SMOS system's success is due to the team's adoption of system science, system thinking, and system dynamics, and a methodologic approach to the requirements process, stakeholder engagement, acquisition and supply, integration and test, and deployment.

This case study highlighted SMOS' history, development, performance, requirements, risks, and lessons learned with a special focus on systems engineering approach. The main takeaways from this study is one of huge success behalf of the ESA and CNES teams. The approach is always easy to follow, and it requires a lot of dedicated engineers and the like to deliver a successful system.

The sheer number of scientific outcomes achieved by SMOS speaks volumes. The mission has delivered beyond its original goals, not only providing data on soil moisture and ocean salinity, but by continuing to provide new data products as they become available, which means more scientific findings for the whole world. The SMOS system delivered beyond its initial lifecycle of 3 years, and is still in use over 10 years later, and will continue to provide valuable data for the foreseeable future.

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