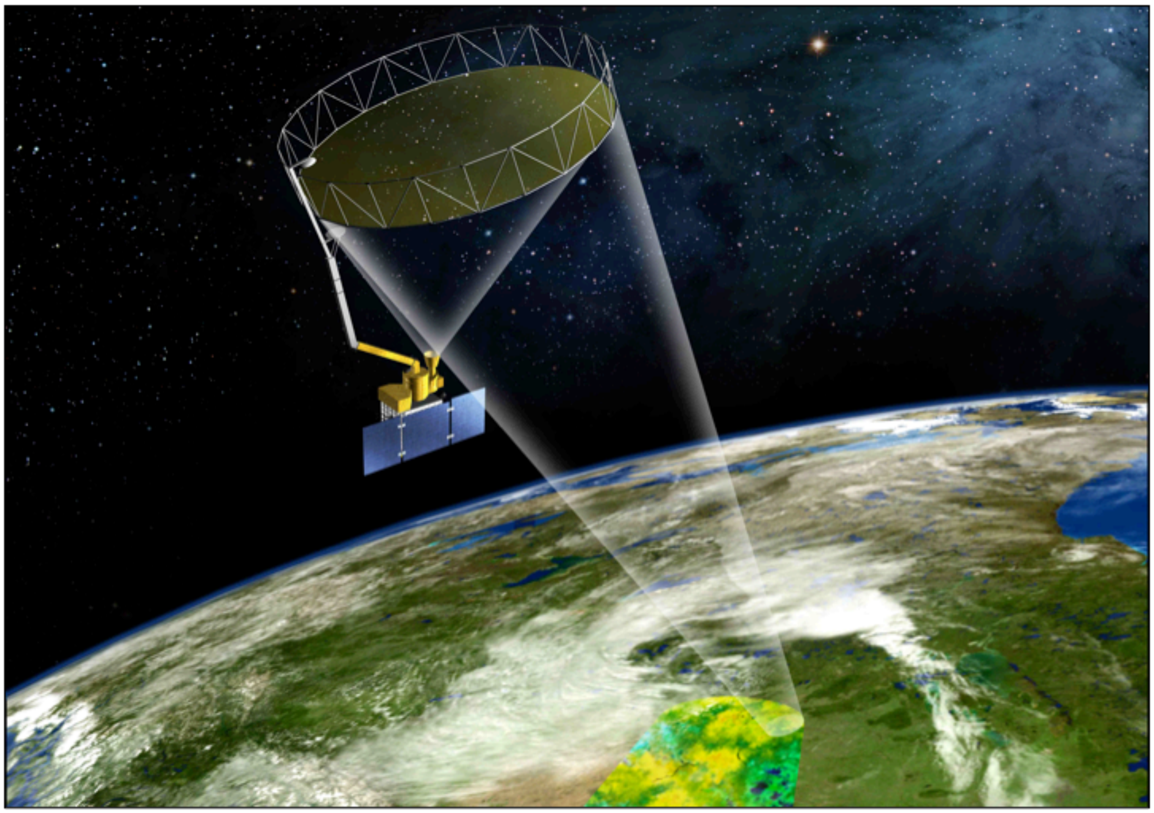
2011 SMAP Applications Workshop Report

USDA South Building, Washington DC
October 12-13, 2011



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Executive Summary

The NASA Soil Moisture Active Passive (SMAP) mission is one of four first-tier missions recommended by the National Research Council's Committee on Earth Science and Applications from Space (Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond, Space Studies Board, National Academies Press, 2007). The SMAP mission will be launched in 2014 and will provide global measurements of soil moisture and freeze/thaw state. These measurements will be used to enhance understanding of processes that link the water, energy and carbon cycles, and to extend the capabilities of weather and climate prediction models. SMAP science measurements will enable applications including drought and flood guidance, agricultural productivity estimation, weather forecasting, climate predictions, disease risk assessment and national security.

The primary goal of SMAP's mission applications activity is to engage the community of practice to build strong support for SMAP applications through a broad program of meetings, publications and scientific research. Through its open-community SMAP Applications Working Group (AppWG), SMAP held its second Applications Workshop on October 12-13, 2011. This document provides a summary of the discussions and context in which the second applications workshop was held. Seven Early Adopters selected in March 2011 made presentations, and descriptions of their research are provided in this report. The discussions held in breakout groups regarding potential applications and challenges to these applications are also provided.

Some of the challenges discussed during the meeting include improving access to SMAP data products through the use of graphical data formats and databases, making SMAP products available with the shortest possible latencies (within budgetary constraints), conducting research on long term soil moisture data records and anomalies, working with NASA Applied Sciences Program (ASP) principal investigators, engaging end users in pre- and post-launch calibration and validation activities, and making value-added products (generated during pre-launch observing system experiments) available for application development.

At the workshop, the AppWG emphasized the benefits of coordinating the applications plans of all NASA Decadal Survey missions, in particular the Global Precipitation Mission (GPM) and ICESat2. Additional workshops in 2012 and 2013 will be conducted in smaller, thematic-based formats. Five workshops are planned as an outcome of this year's workshop to include a SMAP-ICESat2 freeze/thaw joint mission workshop, a GRACE-GPM-SMAP multi-sensor water cycle workshop, and three thematic workshops in the forestry, computer modeling and simulations, and disasters and hazards domains.

During its existence, the SMAP mission has been committed to the dual role of providing useful data products for both science and applications, as described in the 2007 NRC Decadal Survey report. Through successive applications workshops, the SMAP mission has and will continue to involve users of satellite data products in its mission activities. As NASA increases its focus on engaging with missions, SMAP applications will continue to be pathfinders for the broader community.

1. Introduction

The NASA Earth Science Division made a commitment to "discover and demonstrate applications that inform resource management, policy development and decision making" (NASA Earth Science Division Applied Sciences Program, Program Strategy, 2010–2015). The NASA mission teams are taking a lead role in meeting this challenge by identifying applications early in mission life cycles. A primary goal of the SMAP mission is to engage SMAP end users and build broad support for the use of SMAP data through a transparent and inclusive process. The SMAP AppWG has grown from 200 members in 2009 to over 300 members (http://smap.jpl.nasa.gov/science/applicWG), and is committed to improving upon how SMAP mission data will be used in the future. The SMAP AppWG communicates with its membership through emails, through the website, and with workshops.

The SMAP AppWG held its second Applications Workshop on October 12-13, 2011, at the U.S. Department of Agriculture (USDA) South Building in Washington, DC. Attendees included representatives from state and federal agencies, operational centers focused on natural hazards and disasters, international organizations, and academia. The workshop aimed to engage SMAP thematic users with applications in water resource management, agriculture, disasters, climate, weather, ecosystems forecasting, and public health to improve interactions with the SMAP mission.

The meeting included a welcome from Ann Mills, the USDA Deputy Under Secretary for USDA Natural Resources and Environment. She described her enthusiasm for the work of the SMAP Early Adopters and emphasized the need for continued interdisciplinary research related to USDA applications. Drs. Brad Doorn and Jared Entin, representing NASA Headquarters and the SMAP mission, introduced the planned SMAP data products and highlighted potential SMAP applications. Dr. Susan Moran (SMAP Applications Working Group Chair), Dr. Molly Brown (SMAP Applications Coordinator), and Ms. Vanessa Escobar (SMAP Applications Deputy Coordinator) coordinated and facilitated SMAP application activities.

The SMAP applications user community is made up of a broad, diverse community of researchers, decision-makers and others, including the SMAP Applications Working Group (AppWG), the SMAP Applications Team, and the SMAP Early Adopters (EAs) (description of the Early Adopters is found in Section 2.2). The SMAP AppWG is an open community of practice that accepts members through registration on the SMAP website. A community of practice is a group of people who share a concern or a passion for something they do and learn how to do it better as they interact regularly. Two key roles for members of the SMAP AppWG are: (1) SMAP application development, and (2) feedback to the SMAP mission. Both roles are facilitated by partnering with SMAP Science Definition Team members (http://smap.jpl.nasa.gov/science/team) and by communicating with the SMAP Applications Team as defined in the SMAP Applications Plan. The SMAP AppWG also plays a role in the design of SMAP calibration and validation (Cal/Val) activities. Tasks include providing applications-related input to the design of field campaigns and the selection of field sites.

The AppWG contains subgroups of thematic researchers who volunteered to participate in SMAP activities and provide feedback to the SMAP mission. Feedback and communication from the AppWG maximizes the relevance of activities for particular thematic applications. The SMAP Applications Team is focused on reaching out to these communities and engaging them in SMAP activities though the working group.

The 2011 Applications workshop showcased pre-launch research efforts from the Early Adopters (EAs). The Early Adopter program promotes applications research to provide a fundamental understanding of how SMAP data products can be scaled and integrated into organizations' policy, business and management activities to improve decision-making efforts. SMAP Early Adopters are defined as those groups and individuals, from within the Community of Practice, who have a direct or clearly defined need for SMAP-like soil moisture or freeze/thaw data, and who are planning to apply their own resources (funding, personnel, facilities, etc) to demonstrate the utility of SMAP data for their particular system or model. The goal of this designation is to accelerate the use of SMAP products after launch of the satellite by providing specific support to Early Adopters who commit to engage in pre-launch research that would enable integration of SMAP data in their applications. The 2011 SMAP Early Adopters include efforts from Environment Canada, European Center for Medium Range Weather Forecasts (ECMWF), NOAA, Masdar Institute (UAE), USDA National Agriculture Statistics Services (NASS), the International Research Institute for Climate and Society (IRI), and Agriculture and Agri-Food Canada (AAFC).

The overall strategy for the SMAP Applications Program is designed to develop a community of end users and decision makers who understand SMAP capabilities and are interested in using SMAP products in their applications. The SMAP Applications Plan (http://smap.jpl.nasa.gov/science/wgroups/applicWG/) is a living document that will be updated regularly in the context of SMAP science requirements and input from the

SMAP Applications Community of Practice. The Applications Team will update the plan in late 2011 as a result of the findings of the workshop, and will then post the revised plan to the SMAP website for distribution.

This report is organized as follows. The background for defining NASA architecture related to SMAP is presented in Section 2. Information on the context in which SMAP is conducting applications research and outreach is provided in Section 3. Section 4 provides a summary of the workshop discussions, including the seven Early Adopter presentations and the breakout sessions. The report concludes with short-term actions needed to expand and accelerate SMAP applications and long-term ideas for coordination of such efforts across all Decadal Survey missions (Section 5).

2. Background

2.1. NASA Context and Architecture

The report of the National Research Council's (NRC) Decadal Survey, "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond," was released in 2007 after a two-year study commissioned by NASA, NOAA, and USGS to provide consensus recommendations to guide the agencies' space-based earth observation programs in the coming decade. SMAP was in the top tier of high priority mission concepts and was selected by NASA for development in 2008, with launch currently targeted for October 2014.

The Decadal Survey report underscores a desire for a stronger connection between earth science missions and applications user communities. Specifically, it states that "...addressing the environmental challenges will not be possible without increased collaboration between Earth scientists and researchers in other disciplines including the social, behavioral, and economic sciences, and policy experts. It is necessary now to build on the paradigm of earth system science and strengthen its dual role—science and applications. This duality has always been an element of earth science, but it must be leveraged more effectively than in the past...." (NRC 2007).

The more recently published NASA Climate Architecture document (NASA 2010) summarizes the role that SMAP will play in the broader set of measurements made by NASA. The data sets and models that NASA produces contribute to improved products and services by NASA's domestic and international partners. In particular, NASA's new global observations improve the quality, coverage, timeliness, and scope of environmentally focused information products. Such use requires full engagement between NASA and its partners (NASA 2010). The SMAP applications activities and the applications workshop focused on bringing these partners together with SMAP mission scientists. The objective was to maximize the impact that the SMAP mission will have on the products and services of a broad range of earth system analyses.

2.2. Early Adopters

The 2011 SMAP Applications Workshop had two areas of focus. The first was to have the opportunity to present reports of Early Adopter research to the SMAP AppWG. The second focus was an opportunity for attendees at the meeting to interact with SMAP mission representatives and communicate applications of SMAP data that they know about in their domain and to discuss challenges. The SMAP Early Adopters who presented at the workshop, along with their project titles, are listed in Table 1.

2.3 SMAP Data

Table 2 shows the baseline SMAP products that are planned to be provided routinely after launch. Detailed descriptions of these products are provided in Appendix V. However, potential data users need data now that will enable them to plan on flags, data structure and format while they are amending current algorithms so that they are ready for SMAP data after launch. They also need soil moisture proxy data for developing new algorithms as well as developing new relationships. Below are the data that will be available during the pre- and post-launch period that were discussed during the workshop.

2011 SMAP Early Adopters	
Stephane Blaire	
Meteorological Research Division, Environment Canada (EC)	Assimilation of SMAP active and passive data in the Canadian Land Data Assimilation System (CaLDAS)
Lars Isaksen and Patricia de Rosnay	
European Centre for Medium-Range Weather Forecasts (ECMWF)	Implementation of monitoring of SMAP soil moisture and brightness temperature at ECMWF
Xiwu Zhan	
NOAA National Environment Satellite, Data and Information Service, Center for Satellite Applications and Research (NOAA-NESDIS-STAR)	Transition of NASA SMAP research products to NOAA operational numerical weather and seasonal climate predictions and research hydrological forecasts
Hosni Ghedira	
Masdar Institute, United Arab Emirates	Estimating and mapping the extent of Saharan dust emissions using SMAP-derived soil moisture data
Zhengwei Yang and Rick Mueller	
National Agriculture Statistics Service (NASS)	US national cropland soil moisture monitoring using SMAP
Amor Ines and Stephen Zebiak	
International Research Institute for Climate and Society (IRI), The Earth Institute at Columbia University	SMAP for crop forecasting and food security early warning applications
Catherine Champagne	
Agriculture and Agri-Food Canada (AAFC)	Soil moisture monitoring in Canada

Table 1. SMAP Early Adopter Projects

2.3.1 SMAP Pre-Launch Data

SMAP Early Adopters were chosen through a selective process from within the SMAP Working Group Community of Practice and will have access to pre-launch simulated SMAP data products. These pre-launch simulated SMAP data are managed and operated by JPL and are provided to a limited set of users so that they will have information on format, data range and metadata.

Simulated SMAP data products are currently available at the National Snow and Ice Data Center (NSIDC), and are based on a first version of SMAP global simulation software (*GloSim1*) that produces simulated (SMAP-like) radar and radiometer Level 1 data products. These simulated Level 1 data products are then used to generate Level 2 and Level 3 simulated retrieved geophysical data products. The land surface parameters used for this global data simulation come from two sources, a 0.01-deg North American dataset and a 0.25-deg Global Land Data Assimilation System (GLDAS) dataset (Rodell et al. 2004). The North American dataset is used whenever the instrument points inside the North American domain, while the GLDAS dataset is used whenever the instrument points elsewhere. The GLDAS dataset covers latitudes from 60S to 90N.

The simulated data products currently available for early adopters are intended for use in model implementation and for better understanding of flags and data formats that will be present in actual SMAP data. It is important to note that these simulated data sets *are not proxies of SMAP data and are not of sufficiently high quality to be used as valid input for scientific research.*

Product	Description	Gridding (Resolution)	Latency*	
L1A_TB	Radiometer Data in Time-Order	-	12 hrs	Instrument Data
L1A_S0	Radar Data in Time-Order	-	12 hrs	
L1B_TB	Radiometer T_B in Time-Order	(36x47 km)	12 hrs	
L1B_S0_LoRes	Low Resolution Radar σ_o in Time-Order	(5x30 km)	12 hrs	
L1C_S0_HiRes	High Resolution Radar σ_o in Half-Orbits	1 km (1-3 km)***	12 hrs	
L1C_TB	Radiometer T_B in Half-Orbits	36 km	12 hrs	
L2_SM_A**	Soil Moisture (Radar)	3 km	24 hrs	Science Data (Half-Orbit)
L2_SM_P	Soil Moisture (Radiometer)	36 km	24 hrs	
L2_SM_AP	Soil Moisture (Radar + Radiometer)	9 km	24 hrs	
L3_FT_A	Freeze/Thaw State (Radar)	3 km	50 hrs	Science Data (Daily Composite)
L3_SM_A**	Soil Moisture (Radar)	3 km	50 hrs	
L3_SM_P	Soil Moisture (Radiometer)	36 km	50 hrs	
L3_SM_AP	Soil Moisture (Radar + Radiometer)	9 km	50 hrs	
L4_SM	Soil Moisture (Surface and Root Zone)	9 km	7 days	Science Value-Added
L4_C	Carbon Net Ecosystem Exchange (NEE)	9 km	14 days	

* The SMAP Project will make a best effort to reduce the data latencies beyond those shown in this table
** Research product with possible reduced accuracy
*** Over Outer 70% of Swath

Table 2. SMAP Data Products and Average Data Latencies

2.3.2. SMAP Post-Launch Data

After launch of the SMAP observatory, there will be a three-month checkout (commissioning) phase, followed by a three-year routine science data acquisition phase. The initial post-launch Level 1 data products will be delivered to the public three months after commissioning. Post-launch Level 2, 3, and 4 data will be made available for public access six months after commissioning. These data will be beta version products that will not have been fully validated. The initial validated Level 1 products will appear six months after commissioning, or about nine months after launch. Initial validated Level 2, Level 3, and Level 4 products will appear twelve months after commissioning, or about fifteen months after launch.

The SMAP project has committed to deliver data products to the DAAC with average latencies shown in Table 2 during nominal mission operations. However, the project expects that data products will nominally be available with shorter latencies than the aforementioned commitments. Data flows will be interrupted in the event of an on-orbit or ground-system anomaly.

3. NASA Applied Sciences Program and SMAP

SMAP application activities fall into a broader context of NASA's Mission Applications Program, which is part of the Earth Science Division's Applied Sciences program. This framework seeks to engage the science data user communities early in the mission design process and engage with the community of practice for each NASA mission. It also focuses on ensuring that mission scientists have sufficient information about the needs of the different user communities so that the products developed are broadly relevant. The mission applications program is helping to improve the effectiveness of efforts to integrate NASA products into multidisciplinary decision-making activities and services. The communities that will be engaged include agriculture and water management activities, insurance company risk assessments and corporations seeking to understand weather risks in their supply chain risk, and emergency response from military and civilian agencies.

In late September 2011, NASA Headquarters held a “Missions Applications” workshop in Arlington, VA that focused on providing a broad program of interaction with NASA missions. The workshop attendees concluded that communities who may use new NASA data should be identified during the inception of the mission concept and should work closely with mission science and development teams to target specific mission data needs and requirements during all phases of development. Significant and sustained interaction and feedback between the NASA teams, the scientists and communities of data users from a diversity of arenas is necessary during the development of the products to ensure their ultimate usability. The SMAP mission applications experience formed the basis of this effort and continues to be an important pathfinder for the effort.

The objective of the missions applications effort is to ensure that users of NASA data are involved with the mission team, contribute to accomplishing mission goals, and become powerful advocates for NASA and the Earth science missions. Strategic engagement with key individuals and organizations will create strong partnerships in science, business, and emergency response that will inform mission development from inception through launch and sustain it during periods of budgetary stress.

The Mission Applications Program focuses on:

- Identifying the community of practice and ensuring that each mission is invested to produce products of maximum value for the community;
- Implementing the NRC Decadal Survey and NASA Climate Architecture goals;
- Involving the community of practice in the mission development life cycle in the early stages of decision-making;
- Compiling user requirements from the community for the mission; and
- Ensuring a sustained interaction with the community of practice to maximize impact of NASA Earth science investments, including funded projects and programs through research calls.

Communities who may use new NASA mission data such as SMAP should be identified as early as possible in mission planning so that user needs are weighed with the needs of science. The applications program plans to work with the mission leadership to ensure that applications needs are incorporated into the calibration/validation activities as well as science studies. Documents such as an ‘Applications Traceability Matrix’ can provide an overview of what a mission will accomplish relative to high-level objectives and needs of the applied science community.

Figure 1 below summarizes the SMAP activities from 2009 through launch. The figure displays how the overall activities during Phase B, C and D provide continuity and continuous investments during the last phases before launch. The figure summarizes many of the activities planned by the applications program and that are described in the SMAP Applications plan. In particular, notice that the next SMAP applications workshop will be held during the year that SMAP will be launched, in 2014. In the meantime, SMAP plans on having smaller, thematic workshops and tutorials held at the site of organizations and institutions interested in SMAP observations and science. If you are interested in hosting such a workshop, please contact the applications coordinator Molly Brown.

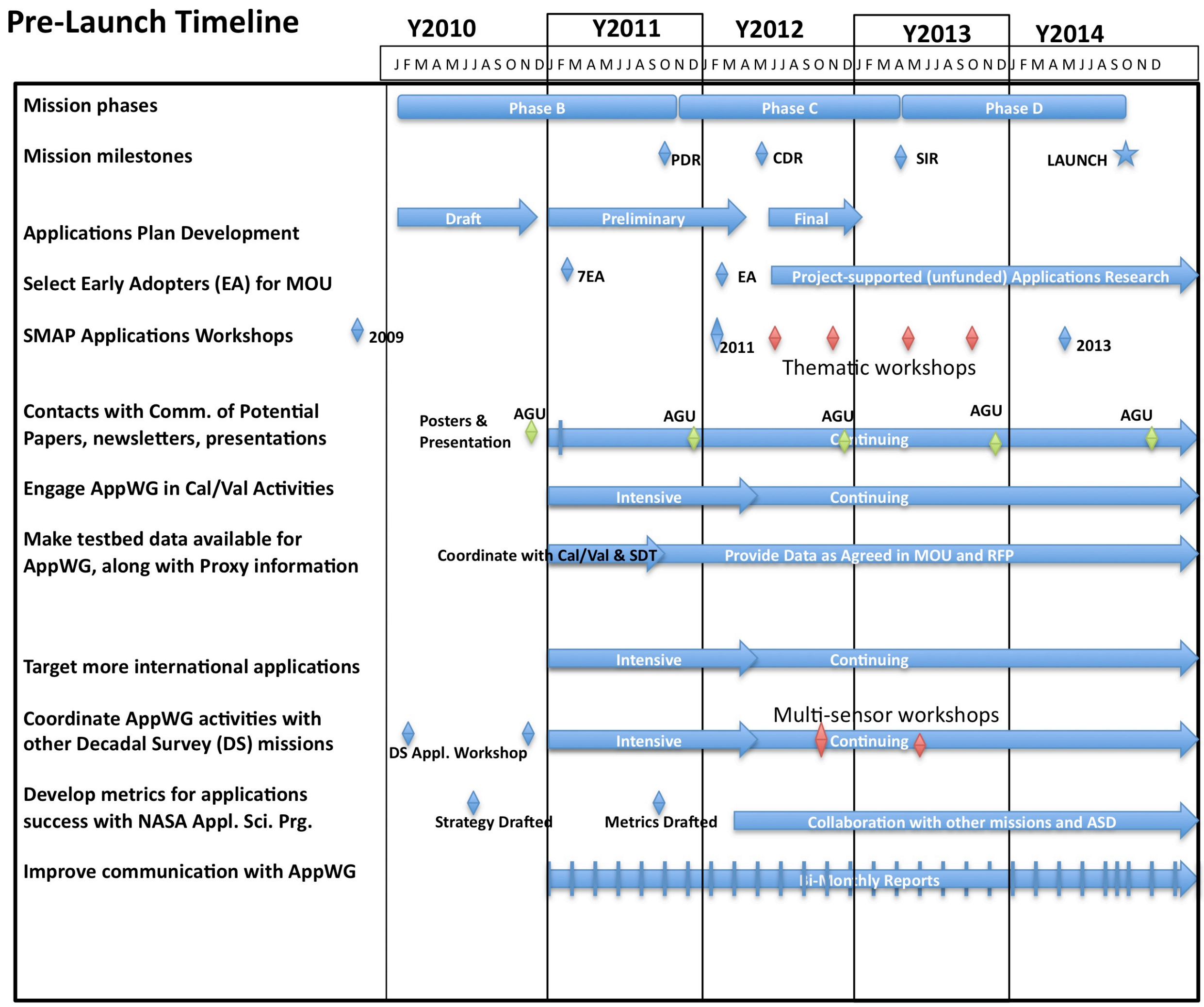

Figure 1. Timeline for SMAP Applications activities from 2009 through launch.

4. Workshop Results

The SMAP Applications workshop began with a series of presentations by the SMAP mission leadership, describing SMAP instruments and the data they will produce. These presentations were followed by seven Early Adopter research demonstrations, ranging from weather modeling, agriculture, flood monitoring, and food security monitoring. These presentations gave an overview of the applied research that is ongoing and the approaches that are being taken in incorporating the data into current systems and processes.

After the Early Adopter presentations, four thematic breakout groups were organized to answer the following questions:

- What are the known and potential SMAP applications?
- What are the technical challenges for integrating SMAP data into models and processes?

Summaries of the main recommendations from these breakout groups are presented in section 4.2.

4.1. Early Adopter Presentations

Early Adopter presentations were the highlight for Day one of the workshop, with seven researchers describing their applied research. The first three presentations were focused on assimilating soil moisture observations into weather models. Marco Carrera presented for Stephane Belair and Environment Canada. The focus of the presentation was to explain how SMAP data will be used in a data assimilation in the Canadian Land Data Assimilation System (CaLDAS). Three approaches are being contemplated by Environment Canada for assimilating SMAP data into their system beyond the currently operational assimilation of screen-level data to analyze surface temperatures and soil moisture:

- joint assimilation of screen-level, brightness temperature data, and backscatter data for surface temperatures and soil moisture
- sequential assimilation that includes screen-level data of surface temperatures and SMAP data for soil moisture
- a hybrid approach that uses screen-level data used as forcing (stronger constraint on first guesses) and SMAP data assimilated for soil moisture

Patricia de Rosnay from the European Centre for Medium-Range Weather Forecasts gave the next talk. She presented the work ECMWF is doing to prepare to ingest SMAP data. The observations will be used to correct errors in the short forecast from the previous analysis time. The ECMWF assimilates 7 – 9,000,000 observations every 12 hours to correct the 80,000,000 variables that define the model's virtual atmosphere. This is done by a careful 4-dimensional interpolation in space and time of the available observations; this operation takes as much computer power as the 10-day forecast. Using proxy datasets from the European Soil Moisture Ocean Salinity (SMOS) and the Advanced Scatterometer (ASCAT), the researchers have shown an improvement in estimating soil moisture in the model. Pre-launch preparation for SMAP L1C_TB and L2_SM_A monitoring will include using the SMAP Testbed product when available, in particular the flags and data formats. Further plans include:

- SMAP L1C_TB monitoring will use the Community Microwave Emission Model (CMEM) and seasonal brightness temperature bias correction
- SMAP L2_SM_A monitoring based on ASCAT type bias correction to rescale L2_SM_A
- Post launch: investigate the impact of SMAP data assimilation on NWP

Following the ECMWF contribution was Xiwu Zhan from NOAA, who covered the data assimilation approach of NOAA's weather/aeasonal climate forecasting models of GFS/NAM models and the CFS/Drought monitoring tool. NOAA plans to use the ensemble Kalman filter data assimilation approach to integrate SMAP data into the Global Forecasting System (GFS) and the National Centers for Environmental Prediction (NCEP). Dr. Zhan also reported on research focused on including SMAP data in flash flood models and other hydrological models.

The fourth Early Adopter presentation focused on smaller-scale research and integration of SMAP into models. Hosni Ghedira presented research on integrating SMAP data into desert dust modeling. Based on models using MODIS brightness temperature data, Dr. Ghedira showed research about how SMAP data can be used in the identification and tracking of dust clouds. The use of the new high spatial resolution of SMAP-derived soil moisture is expected to improve the accuracy of estimating dust emissions maps, due to the underlying processes that are moisture dependent.

Zhengwei Yang, in collaboration with Rick Mueller from the US Department of Agriculture National Agricultural Statistic Service (NASS), presented research on incorporating SMAP data into national cropland soil moisture models. The objective of NASS's early adopter study is (1) to determine the feasibility of using SMAP mission results to support US national crop condition monitoring and other NASS operational data needs for crop yield monitoring, (2) to improve NASS cropland soil moisture monitoring results in consistency, reliability, objectivity and efficiency, and (3) to reduce survey cost and burden. Although NASS has not yet incorporated a soil moisture proxy dataset to tune its yield model, that is the next step.

The next talk, entitled "Soil Moisture Monitoring at Agriculture and Agri-Food Canada" was given by Catherine Champagne of the EarthEarth Observation Service, Agri-Environment Services Branch, Environment Canada. The talk focused on the EA project led by Dr. Champagne, which focused on providing information for "place-based" policies that need site specific geospatial information. The project seeks to provide information for performance evaluation of programs. Environment Canada has a need for reliable, regular information for science-based decision making and SMAP data will meet this need by enabling accurate assessments of drought and flood conditions in agricultural areas. It will also help the Canadian Government to better prepare and respond to disasters through the National Drought Model/Canadian Drought Monitor, regional yield modeling, live stock tax deferral program, climate production risk committee, and input to disaster relief (Agri-Recovery Programs). Although the program is just getting started, the EA research will be critical for future improvements of Environment Canada's agricultural program.

The final EA talk was by Amor Ines and Steve Zebiak entitled "SMAP for crop forecasting and food security early warning applications". The work focuses on implementing an ensemble-Kalman Filter (EnKF) that was used to assimilate SSM/I soil moisture into the Decision Support System for Agrotechnology Transfer (DSSAT) and the Cropping System Model (CSM). These models are used for the simulation of crop growth and yield, and soil and plant water impacts on food production. The EnKF-DSSAT-CSM approach presented by Dr. Ines showed a very impressive improvement in the correlation between estimated and actual crop yields from R=0.52 to 0.83. Dr. Ines presented significant reductions in yield errors for agricultural landscapes in Iowa dominated by corn. When the same assimilation was used in Georgia, with a much more complex landscape, however, only an improvement in the yield estimate error was demonstrated (from 2045 to 1108 kg/ha), but no improvement in correlation was found. These results bode well for reduced errors in seasonal yield estimates in developing countries once the SMAP data are available.

After the EA talks were complete, Fiona Shaw and Nigel Davis, representatives from Willis Financial, presented an overview of their activities on risk management and information products, highlighting how they will use SMAP data once available. Willis represents a classic end user for SMAP data, with the broad immediate applicability of the data to a wide range of insurance companies, and challenges of being outside of the traditional remote sensing community. Fiona Shaw described the 'Willis Research Network', which supports open academic research and the development of new risk models and applications. Their ethos is to provide an open forum for the advancement of the science of extreme events through close collaboration between universities, insurers, reinsurers, catastrophe modeling companies, government research institutions and non-governmental organizations. Through collaboration with NASA, the SMAP mission and the University of Reading, Willis hopes to conduct research needed to incorporate SMAP data into its products to improve risk estimates in the future.

4.2. Outcomes

The recommendations from the four breakout groups are the main outcomes of the workshop and are summarized below by breakout group.

Agriculture and Forest Resources:

The challenges that the forest resources and agriculture sectors face include how to fund and motivate the research before the launch of SMAP. In addition, many of the operational agencies have difficulty convincing their management to invest in using data that has no long-term strategy for continuous measurements. Since SMAP is an experimental mission , it is not clear whether measurements obtained during the life of the mission will be continued afterwards. The group urged a larger emphasis on multiple-sensor proxy datasets that bring together all available satellite radar and radiometer datasets that can observe soil moisture to enable a historical dataset that can support both applied research before launch as well as continuity after launch.

Climate and weather:

Climate and weather groups focused on large-scale modeling approaches that will likely experience problems ingesting HDF5 file format datasets and will need as much advance notice as possible as to the flags, range and other data parameters that will be included in these files. Early documentation is important for those working with large models such as weather and climate forecasters. These groups are also very concerned about having the lowest possible latency – perhaps by decoupling the latency of the radiometer data from the radar data would ensure lower latency SMAP products that are usable by the modeling community. By decoupling the products, the lowest possible delay before product delivery can be obtained. They would also like to see the distribution of latencies instead of just one number (the maximum allowed) for each product. This will allow them to focus on where to put their energies.

This group also had the following recommendations for overcoming challenges for the community in integrating SMAP data:

- Place SMAP within a broader integrated observing system, by emphasizing the synergies that SMAP has with other sensors and observational data
- Outreach (to scientific leadership community) needs to quantify societal and economic impact.
- How do Early Adopters interact with the SMAP Project (reports, meetings)? How do the SMAP Project and other Early Adopters benefit from the findings of each Early Adopter? The SMAP applications team needs to integrate the early adopters into its activities in a specific and meaningful way throughout the pre-launch period.
- We need to seek ways to include applications such as empirical algorithms and expert analysis that are not using physically based numerical models.

Water Resources:
The water resources breakout group thought that the most important value of soil moisture data is the ability to constrain the soil moisture parameter in land surface models. Soil moisture is a critical factor when used in concert with other inputs in models, and thus SMAP is an extremely important mission. Existing modeling such as the Land Information System and the Terrestrial Observation and Prediction System (TOPS), as well as agency programs such as those in NOAA and USDA, should be set up for automatic ingest of SMAP data prior to SMAP launch.

For many communities, baseline soil moisture climatology is needed. Research is needed to investigate complementary SMAP products such as the relative soil moisture change and qualitative soil moisture products that will allow for interpretation of soil moisture estimates. These will enable the observations to be most useful, as they will be comparable to current estimates and modeled parameters currently in use. An integrated program that includes information from a wide range of sensors that provide information on water resources is a critical backdrop to the observations that will come from SMAP.

Disasters and Public Health:
The hazards group discussed challenges of making the SMAP data usable and accessible by the hazard community. The group pointed out a need for a long-term record to identify anomalies (differences between the current and the average situation) for improved decision making. Disasters and Public Health have two primary data user types in the represented community: the expert data user/researcher, who will be able to work with NASA HDF5, download the data via ftp and work with other sources of data; and the long-term decision-support user, who will need operational access to the data through html access (like geotiff and standard graphical data formats other than hdf5). Disasters and public health users operate on short response times, so the use of SMAP and other NASA data products must be easily integrated, with timeliness, accuracy and data volume taken into consideration. These groups recommended NASA consider enhancing their end user services to accommodate some long-term needs that will further compliment the needs of expert/research users.

5. Conclusions

The SMAP applications team and the representatives from the AppWG identified near-term actions required by user communities to help expand and accelerate SMAP applications and discussed long-term ideas for the coordination of such efforts across all Decadal Survey missions. Some of the challenges presented by the AppWG during the workshop include implementing open access to SMAP data products, making SMAP products available with the shortest possible latencies (within budgetary constraints), establishing a group of applied researchers that are early adopters of SMAP data, working with NASA Applied Sciences Program (ASP) principal investigators in integrating SMAP data into their projects, engaging end users in pre- and post-launch calibration and validation activities, and making value-added products generated during pre-launch observing system experiments available for application development.

Several of the breakout group discussions focused on data accessibility and data format. As a result of the workshop, the SMAP applications team will form a subcommittee with membership drawn from the AppWG that will suggest ways to broaden data accessibility within the framework of the National Snow and Ice Data Center that will host the data after launch, including new file formats and html-accessible data pages where data can be easily accessed by a broad community.

The need for integrated, multi-sensor soil moisture products was also very clear from the discussion at the workshop. The need to conduct research on long-term soil moisture data records and anomalies through fusion of multiple L-band sensors was mentioned by all four breakout groups. Although SMAP simulated data are available, these datasets are only useful for understanding data format and flags, but are not useful for developing new models, or changing existing or developing new relationships. Soil moisture proxies will also permit investigation of the relative soil moisture change and historical soil moisture products that will allow for interpretation of soil moisture estimates. This kind of qualitative understanding will be critical for the broad adoption of satellite-derived soil moisture estimates across multiple communities.

The AppWG emphasized how coordinating the applications plans of all NASA Decadal Survey missions would be a scientific and operational benefit to society. Additional workshops for 2012 and 2013 will be conducted in smaller settings and based on thematic interest, to include joint workshops with other NASA missions. These smaller settings will permit a more intense and focused discussion of the uses of SMAP data as well as regional settings to engage individuals and organizations who are unable to travel to the Washington, DC area.

The following five workshops are tentatively planned as an outcome of the 2nd Applications Workshop:

- Modeling community workshop identifying uncertainties for future resources, coordinated with Arizona universities in February 17, 2012
- A forest workshop with the United States Forest Service planned in Raleigh, North Carolina for April 2012
- Water Resources and Disasters Workshop planned with JPL in June 2012
- GRACE-GPM-SMAP multi-sensor water cycle workshop planned to be held at Goddard in July 2012
- SMAP Freeze/Thaw-ICESat2 joint mission workshop planned for September 2012 at the Alaskan Satellite Facility in Fairbanks, Alaska

The workshop outcomes also highlighted SMAP applications that needed additional support. SMAP freeze/thaw data are currently viewed as “underrepresented products” within the user community. The program will also focus in the coming year on increasing the representation of Level 4 carbon product users to better understand how SMAP data products can be used to answer critical carbon cycle questions. The AppWG is eager to engage in early adopter research and help demonstrate how SMAP will be used. A need to bridge ice and snow detection capabilities between multiple missions was highly supported by the attendees.

Mission applications is a new strategy redefining an era where duality will be addressed more effectively than in the past. The traditional process of how mission products are conceived needs to be more balanced by recognizing and integrating user communities who will be strong advocates of the science products. The NASA Mission Applications effort extends beyond that of posters and websites. It is based on user relationships and effective communication. Focused two-way conversations engaging end users and promoting innovative ways of using NASA products in science, business and decision making environments are what will make future missions and this effort successful. SMAP applications efforts will continue to be pathfinders for how to work with the community of practice for all missions. The goal of the SMAP Applications Program is to engage user communities and prepare them to take advantage of products from Day 1 after launch.

6. Acknowledgements

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Appendix I. Applications identified in Breakouts

Theme	Application	Details
Water Resources	Land Surface Models are a critical way water resources are monitored and soil moisture is an important input	Existing NASA models (Land information system (LIS), Terrestrial Observation and Prediction System (TOPS)
	Drought models	SMAP and precipitation information are critical for drought models
	Modeling Northern Latitude Land, Lakes, Permafrost identification	SMAP and MODIS inputs
Agriculture and forestry	Crop insurance models	Identifying risk and likelihood of crop insurance payout due to excessively wet or dry conditions. USDA currently uses a synthetic sensor-net with MODIS, TM, NEXRAD, AWIPs Flood models can be improved using the freeze/thaw information in northern fields
	Crop yield forecasting	Forecasting of yield and Integration with NDVI phenology models NASS weekly crop condition, qualitative to quantitative assessment
	Forest monitoring – post-fire assessment	Post-fire characterization modeling for the Burned Area Emergency Rehabilitation (BAER) plans that focus on reducing erosion and other post-fire threats.
	Forest monitoring – drought	Drought conditions leading to pest or fire susceptibility
	Sea ice characterization from L1C products	Collaboration with ICESat2, estimate sea ice thickness
Weather/Climate	Weather models such as the Weather Research and Forecasting model (WRF)	Soil moisture is boundary condition and/or initial condition for atmospheric and hydrologic modeling
	Ecosystem Modeling	Applications in ecological forecasting are really important
	Fire forecasts	Weather implications on fire conditions – interact with the US Forest Service
	Weather forecasts of extreme weather	US Weather Service models – estimates of strong winds/hurricanes
	Public health models and early warning of poor air quality	Dust forecasting due to improved humidity information.
	EPA Water quality models (BASINS, others)	Soil moisture is a critical input and can greatly improve runoff estimates
Disasters/Hazards	Pre-event Forecast flooding conditions	Models that provide the type of flooding (flash flood vs inundation), Mitigating (from a risk management point of view)

	Post-event flood maps	Flood outline - verify claims and loss accumulation (reinsurance) Mitigate loss by allowing faster economic recovery
	Daily inundation maps, flood insurance	Forecast flooding conditions - type of flooding (flash flood vs inundation),
Hazards/Disasters	Flood mitigation	Mitigating (from a risk management point of view), Post-event, Flood outline - verify claims and loss accumulation (reinsurance), Mitigate loss by allowing faster economic recovery
	Operational drought monitor (US and international).	Stages of drought severity (Integrating products for better expert review during drought monitor production (One tool in the "toolkit". Soil moisture can be used as a precursor to vegetation stress)
	Wildfire monitoring	Soil moisture linked to vegetation stress - Annual adjustments to insurance premiums. Wildfire prevention and mitigation.
	Public health models	Finding triggers of diseases like cholera. Boundaries between wet and dry conditions, complement early warning systems. Outbreak prevention and mitigation.
	Seasonal snow accumulation	Snow - using soil moisture as a baseline at the beginning of a season to calculate snow accumulation
	Landslides	Landslide risk monitoring maps in conjunction with precipitation models

Appendix II. Registrations for Workshop

2011 Soil Moisture Active Passive Workshop

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Appendix III. SMAP Applications Workshop Agenda

2nd Soil Moisture Active Passive (SMAP) Applications Workshop
Location: Jefferson Auditorium, USDA South Building,
Independence SW, Washington, DC 20250
October 12-13 2011

The NASA Soil Moisture Active Passive (SMAP) mission has a targeted launch date of 2014. It will provide global measurements of soil moisture and freeze/thaw state (http://smap.jpl.nasa.gov/). SMAP applications include improving drought and flood guidance, agricultural productivity estimation, weather forecasting, climate predictions, disease risk assessment, and national defense.
This workshop is focused on sharing information about SMAP applications and informing the SMAP Mission about the challenges facing users of SMAP data.
The SMAP Workshop objectives *are to articulate specific uses of SMAP data within the user community and to improve communication between the user community and the science development of the SMAP Mission.*
Expected Workshop Outcomes*: further maturation of the SMAP Applications Plan and improved awareness of SMAP data*

12 October Wednesday		
7:30am	**Registration and Coffee**	
8:30-11:45am	Ann Mills, Deputy Under Secretary, USDA/NRE *(15 min)*	USDA Welcome
	Brad Doorn, NASA HQ *(15 min)*	SMAP Welcome, Charge to Workshop
	Jared Entin, NASA HQ *(25 min)*	SMAP Mission Overview
	Molly Brown, NASA *(15 min)*	SMAP Applications Plan
	9:40-10 am Break	
	Susan Moran, USDA	Early Adopters Presentation-Opening
	Early Adopter Presentations: Three of seven Early Adopters will present their research and how they expect SMAP data to be used in their application once it exists.	
	Dr. Stephane Belair and Dr. Marco Carrera (Environment Canada) *(30 min)*	*Assimilation and Impact Evaluation of Observations from SMAP Mission in Environment Canada's Predictive Systems (CaLDAS)*
	Dr. Lars Isaksen and Dr. Patricia de Rosnay (ECMWF) *(30 min)*	*Implementation of SMAP brightness temperature and soil moisture at ECMWF*
	Dr. Xiwu Zhan (NOAA): *(30 min)*	*Transition of NASA SMAP research to NOAA Operational Numerical Weather and Seasonal Climate Predictions and Research Hydrological Forecast*
11:45 - 1:00pm	**Lunch**	
1-3:00pm	Early Adopter Presentations Continued: Remaining four of seven Early Adopters will present.	
	Dr. Hosni Ghedira (Masdar Institute, UAE): *(30 min)*	*Estimating and Mapping the Extent of Saharan Dust Emissions Using SMAP –derived soil moisture data*

	Dr. Zhengwei Yang/Mr. Rick Mueller (USDA NASS) *(30 min)*	*U.S. National Cropland Soil Moisture Monitoring Using SMAP*
	Dr. Catherine Champagne (Agriculture and Agri-food Canada): *(30 min)*	*Soil Moisture Monitoring in Canada*
	Dr. Amor Ines and Dr. Stephen Zebiak (IRI): *(30 min)*	*SMAP for Crop Casting and Food security Early Warning Application*
3:00-3:15pm	Fiona Shaw and Nigel Davis, (Willis, UK)	*International Applications of SMAP for Engaging the Insurance and Financial Services Sector*
	3:15pm-3:30pm Break	
3:30-4:30pm	Barry Weiss, NASA	Data Set discussion, description and DAAC
The SMAP Early Adopters are a subset of the SMAP Community of practice. They have access to the SMAP pre-launch simulation data streams and conduct applications demonstrations in collaboration with the SMAP SDT. Early Adopters are users who submitted a proposal and demonstrated a direct or clearly defined need for SMAP-like soil moisture data, and who have sufficient interest and/or personnel to demonstrate the utility of SMAP data for their particular system or model. They share their experience with us to improve our understanding of the benefits and challenges of using SMAP data.		

The rest of the workshop will be characterized by small-group discussions (break-outs), organized by SMAP Thematic Groups to answer:

- *What are the known and potential SMAP applications?*
- *What are the technical challenges for integrating SMAP data into models and processes?*

13 October Thursday		
7:30am	**Registration and Coffee**	
8:30-8:45am	Susan Moran-USDA	Describe Charge to Break out Groups
8:45-11:30am	**Break out groups:** Organized by thematic group *Disasters* *Human Health* *Water Resources* *Ecosystem Forecasting* *Weather* *Agriculture and Forestry* *Climate*	
	10:00-10:15am Break	
11:30-1:00pm	**Lunch**	
1:00pm-4:30pm	**Reports from Breakout and Panel Discussion:** Each thematic breakout group will have an elect representative to present outcomes of the thematic break out session. The representatives will form a panel to encourage discussion.	
	3:00-3:30 pm Break	
	Molly Brown, NASA	Feedback and Group Discussions
4:30pm	**Workshop Adjourn**	

Appendix IV. SMAP Applications Workshop Charge

2011 SMAP Applications Workshop
Charge for SMAP Applications Break out Session
October 13, 2011

***Mission Objective:* SMAP will provide a capability for global mapping of soil moisture and freeze/thaw state with unprecedented accuracy, resolution, and coverage. SMAP science objectives are to acquire space-based hydrosphere state measurements over a three-year period to:**

- *Understand processes that link the terrestrial water, energy and carbon cycles*
- *Estimate global water and energy fluxes at the land surface*
- *Quantify net carbon flux in boreal landscapes*
- *Enhance weather and climate forecast skill*
- *Develop improved flood prediction and drought monitoring capabilities*

Thematic Discussions for

- *Disasters*
- *Human Health*
- *Water Resources*
- *Ecosystem Forecasting*
- *Weather*
- *Agriculture and Forestry*
- *Climate*

- Understand how each thematic group plans to use SMAP data.
    - What is the research SMAP will support (flood, modeling, weather) - This will allow us to understand how thematic group needs differ from each other
    - How does SMAP compliment/support other mission product (this may be a topic for a different audience but something that can be explored)
- What product attributes are most relevant to each group's focus
    - Discuss resolutions, access to data and the resources available through the DAAC
        - Identify what resolution serves what population
- How will the use of SMAP data influence science and models relevant to each area
    - What are the expected outcomes when using SMAP data
    - How will these outcomes be applied? What is (are) the societal benefit(s)?
- Incorporating SMAP data into thematic research should influence decisions: Provide examples from your research
    - Improved flood predictions
    - Inform weather alert centers

Appendix V. SMAP Data Product Descriptions

Level 1 Products

Level 1B Radar (L1B_S0_LoRes)

- Continuous over all surface types (global land and ocean).
- Each granule contains time ordered data that covers one spacecraft half orbit.
- Contains Earth-located, calibrated radar backscatter co-pol and cross-pol (HH, VV, HV) measurements in time-order.
- Provides calibrated backscatter measurements for approximately ten range-resolved "slices" of the full radar FOV footprint. Each slice has dimensions of ~30 km by 5 km.
- Forward looking and aft looking measurements are stored separately.
- Includes spacecraft orbit and attitude information and instrument pointing geometry.
- Provides reference to cylindrical and polar 36 km EASE grid coordinates for each footprint.

Level 1B Radiometer (L1B_TB)

- Coverage continuous over all surface types (global land and ocean).
- Each granule contains time ordered data that covers one spacecraft half orbit.
- Contains the following Earth-located, calibrated data for each EFOV, where an EFOV is a 39 km by 47 km ellipse:
    - Apparent aperture (antenna) temperatures
    - Top of ionosphere brightness temperatures
    - Surface referenced brightness temperatures
- Contains all four Stokes parameters (V, H, 3rd & 4th).
- 3^{rd} Stokes used for Faraday Rotation correction.
- Time, frequency and polarization diversity used for RFI detection and removal.
- Forward looking and aft looking measurements are stored separately.
- Includes spacecraft orbit and attitude information and instrument pointing geometry.
- Provides reference to cylindrical and polar 36 km EASE grid coordinates for each footprint.

Level 1C High Resolution Radar (L1C_S0_HiRes)

- Coverage is limited to land and coastal ocean regions (1000 km from coast).
- Each granule contains data from one spacecraft half orbit, geographically ordered in a 1-km along-track /cross-track swath grid.
- Contains Earth-located, calibrated radar backscatter co-pol and cross-pol (HH, VV, HV) measurements.
- Resolution varies from 1 km at the swath edge to 3 km at 150 km from the nadir sub-track.
- Forward looking and aft looking measurements are stored separately.
- Includes spacecraft orbit and attitude information and instrument pointing geometry.
- Provides reference to global and polar 1 and 3 km EASE grid coordinates.

Level 1C Radiometer (L1C_TB)

- Coverage continuous over all surface types (global land and ocean).
- Contains Level 1B radiometer data (L1B_TB) re-mapped onto a 36 km EASE grid.
- Each granule represents one spacecraft half orbit.
- Latitude and longitude listed for each EASE grid cell.
- Forward looking and aft looking observations stored separately.

Level 2 Products

Level 2 High Resolution Radar (3 km Soil Moisture) (L2_SM_A)

- Each granule contains one half orbit of data posted on 3 km cylindrical EASE grid cells.
- Product lists only those EASE grid cells that contain data.
- AM Product covers entire Earth land mass, PM product restricted to land north of 45 North Longitude
- PM data acquired specifically for freeze-thaw retrievals.
- Employs 1 km High Resolution radar L1C data averaged over 3 km cylindrical EASE grid cells to reduce Kp noise.
- Soil moisture retrievals employ snapshot and/or time-series algorithms.
- Provides freeze-thaw state and transient water body information that the other Level 2 soil moisture processes require.
- Includes quality masks for urban areas, mountainous terrain, dense vegetation, snow and ice.

Level 2 Radiometer (36 km Soil Moisture) (L2_SM_P)

- Each granule contains one half orbit of data posted on 36 km cylindrical EASE grid cells.
- Product lists only those EASE grid cells that contain data.
- Provides retrieved soil moisture over land with 0.04 cm^3/cm^3 accuracy for low-to-moderately vegetated areas.
    - Low to moderate vegetation definition is vegetation_water_content <= 5 kg/m2.
    - SMAP will provide soil moisture for areas with vegetation water content > 5 kg/m2, but retrievals in these areas are not counted in our 0.04 cm3/cm3 retrieval accuracy metrics
- Requires transient water body and freeze-thaw state retrievals generated with high resolution radar retrievals.
- Estimates soil moisture based on AM observations.
- Includes quality masks for urban areas, mountainous terrain, dense vegetation, precipitation, snow and ice.

Level 2 Active/Passive (9 km Soil Moisture) (L2_SM_AP)

- Each granule contains one half orbit of data posted on 9 km cylindrical EASE grid cells.
- Product lists only those EASE grid cells that contain data.
- Merges radar and radiometer channels using a time series algorithm and spatial heterogeneity of L1C radar product.
- Provides retrieved soil moisture over land with 0.04 cm^3/cm^3 accuracy for low-to-moderately vegetated areas.
    - Low to moderate vegetation definition is vegetation_water_content <= 5 kg/m2.
- Employs transient water body and freeze-thaw state generated with high-resolution radar retrievals.
- Includes quality masks for urban areas, mountainous terrain, dense vegetation, precipitation, snow and ice.

Level 3 Products

Level 3 High Resolution Radar (3 km Soil Moisture) (L3_SM_A)

- Composite of all Radar Level 2 half orbit products where local acquisition time is the same UTC day.
- Multiple measurements may overlap at high latitudes. Algorithm currently selects measurements acquired closest to 6 AM solar time (TBC).
- Posted on cylindrical 3 km EASE grid cells.
- Product lists all EASE grid cells, regardless of whether data are available.
- Soil moisture retrievals use snapshot and/or time-series algorithms.
- Based exclusively on AM data.

Level 3 Radiometer (36 km Soil Moisture) (L3_SM_P)

- Composite of all Radiometer Level 2 half orbit products where local acquisition time is the same UTC day.
- Multiple measurements may overlap at high latitudes. Algorithm currently selects measurements acquired closest to 6 AM solar time (TBC).
- Posted on 36 km cylindrical EASE grid cells.
- Product lists all EASE grid cells, regardless of whether data are available.
- Provides retrieved soil moisture over land with 0.04 cm^3/cm^3 accuracy for low-to-moderately vegetated areas.
    - Low to moderate vegetation definition is vegetation_water_content <= 5 kg/m2.
- Based exclusively on AM data.

Level 3 Active/Passive (9 km Soil Moisture) (L3_SM_AP)

- Composite of all Active/Passive Level 2 half orbit where local acquisition time is the same UTC day.
- Multiple measurements may overlap at high latitudes. Algorithm selects measurements acquired closest to 6 AM solar time.
- Posted on 9km cylindrical EASE grid cells.
- Product lists all EASE grid cells, regardless of whether data are available.
- Provides retrieved soil moisture over land with 0.04 cm^3/cm^3 accuracy for low-to-moderately vegetated areas.
    - Low to moderate vegetation definition is vegetation_water_content <= 5 kg/m2.
- Based exclusively on AM data.

Level 3 Freeze/Thaw (L3_FT_A)

- Each product represents a single calendar day UTC.
- Posted to a 3 km polar EASE grid with 1 to 3 km spatial resolution.
- Quantifies daily freeze/thaw state as a binary condition for land surface.
- Employs the 1 km Level 1C high resolution radar data and a time-series change detection algorithm to infer freeze/thaw state.
- Provides 80% freeze/thaw state classification accuracy.

Level 4 Products

Level 4 Surface and Root Zone Soil Moisture (L4_SM)

- Global output represents 3 hour intervals at 9 km resolution with 7-day latency.
- Product subdivides into instantaneous measures for specified time and averaged values over a three hour time span.
- Employs SMAP L1C Radiometer, Level 3 High Resolution Radar Soil Moisture, and Level 3 Freeze/Thaw products.

- Assimilates SMAP data into a state-of-the-art land surface model to derive global estimates of root-zone moisture.

Level 4 Carbon (L4_C)

- Daily global maps of net ecosystem CO_2 exchange (NEE) at 9 km resolution with 14-day latency.
- Quantifies the net carbon flux in boreal landscapes.
- Reduces uncertainty with regard to existing carbon sinks on land.
- Applies a soil decomposition algorithm driven by SMAP L4_SM and Gross Primary Production (GPP) inputs to compute net land-atmosphere CO_2 exchange (NEE).
  Accuracy commensurate with tower based CO_2 observations. (RMSE ≤ 30 g C m^{-2} yr^{-1} or 1.6 g C m^{-2} d^{-1}).

HDF 5 Data Product Format

- HDF5 combines a robust data model with a file format and a user library
  - Major object components:
    - Datasets – major product content
    - Dataspace – description of product content shapes
    - Datatypes – flexible means to type data
    - Groups – flexible means to group data
    - Attributes – descriptive elements
  - Supports a large variety of platforms and common software languages
    - IDL and Matlab both have well defined and easy to use HDF5 interfaces
  - Has considerable heritage – introduced in 1999-2000
  - Provides a highly flexible architecture to read, extract and write data
  - Operates efficiently with very large data sets
  - Large numbers of new technology data service providers function well with HDF5
- Support available through the HDF Group.
  - Website at http://www.hdfgroup.org/

Product Quality Information

- Product metadata – covers the content of the entire product
  - Overall quality information for entire product content
    - Completeness – fraction of expected data that appears in the product
    - Range Check – fraction of data pixels that fall within an acceptable range
    - Quality Check – fraction of data pixels that are deemed acceptable quality
    - May include more based on ISO 19157 standard
- Associated with each pixel – enables users to assess quality of each individual element
  - Quantitative error bar whenever possible
  - Bit flags for qualitative information
    - Individual bits flag individual conditions
    - In general, '0' indicates desirable conditions, '1' represents questionable or undesirable conditions
    - When the overall bit flag value is zero, the data are clean