OCEAN SALINITY RETRIEVAL APPROACHES FOR THE SMOS SATELLITE

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ABSTRACT

Retrieval of sea surface salinity from SMOS radiometer measurements is a challenging task performed by using forward model algorithms in an iterative convergence scheme. The commission phase for the SMOS Level 2 ocean salinity processor has been successfully completed, and the algorithms have been partially verified. Salinity has been retrieved, and priorities determined for future improvements in the retrieval algorithms.

We describe how the SMOS Level 2 Ocean Salinity processor can be used, and characteristics of the output products, together with advice on product use. Some preliminary results confirming the existence of mid-latitude shallow fresh layers are also presented.

1. INTRODUCTION

The Soil Moisture and Ocean Salinity (SMOS) mission is one of the European Space Agency (ESA) Earth Explorer Missions, successfully launched on 2 November 2009. The 6 month commissioning phase ended in May 2010; this paper reviews the Level 2 Ocean Salinity (L2OS) processor developed by the L2OS team of ESL and ARGANS (the industrial contractor) used to retrieve Sea Surface Salinity (SSS) from SMOS data.

The SMOS instrument is a Microwave Imaging Radiometer using Aperture Synthesis (MIRAS), measuring L band (1400-1427 MHz) signals. Over the ocean these Stokes vector brightness temperature signals (TB) are a function of the sea surface dielectric constant, which in turn has a (low) sensitivity to salinity and water temperature. The MIRAS instrument generates overlapping large area snapshots once every 1.2 seconds, so brightness temperatures for each surface grid point on an Icosahedron Snyder Equal Area (ISEA) [1] 4H-9 grid are available from a large number (typically 100-200) of different incidence angles (typically 60 degrees to nadir and beyond). Level 1c (L1c) products are generated by the Data Processing Ground Station (DPGS) for each half-orbit, mapping MIRAS measurements onto ocean ISEA grid points. Each L1c product contains TB measurements for all snapshots; together with additional snapshot data including instrument position, incidence and azimuth angles, and total electron count (TEC). L band surface emission forward models developed by ESL are used in the L2OS processor to predict TB measurements at each incidence angle: components include contributions from flat sea emissivity, roughness, foam, external reflections from atmosphere, sun, moon and galactic sources. An iterative convergence scheme [2] is used by the processor to refine predictions by comparing predicted and measured TBs until an optimum fit is achieved [3].

Processor details are available in the SMOS L2 OS Algorithm Theoretical Baseline Document (ATBD) and the SMOS L2 OS Detailed Processing Model (DPM). Latest versions of all the SMOS L2 OS documents can be found on the SMOS L2 OS web site:

http://www.argans.co.uk/smos/pages/deliverables.php

Each forward model requires additional geophysical values for each grid point, such as water temperature, wind, sea surface roughness, wave age. The L2OS processor ingests an L1c product together with a matching European Centre for Medium-Range Weather Forecasts (ECMWF) data set of geophysical parameter values, and outputs a user data product (UDP) and data analysis product (DAP). The UDP and DAP contain retrieved salinity and other geophysical parameters for each half-orbit grid point. Details of all L2OS input and output products including the UDP and DAP can be found in the SMOS L2 OS Input-Output Data Definition (IODD) and SMOS L2 and Auxiliary Product Data Products Specifications (L2 Product Spec.) [4].

Success in retrieving accurate salinity values depend on SMOS instrument limitations (noise, stability, image reconstruction); accurate knowledge of sea surface conditions (temperature, roughness, etc.); and good forward models.

Instrument limitations are well-characterised and progress continues to be made in improving Level 1 algorithms and techniques. The issue of radiometric contamination caused by proximity to land is of special significance for ocean salinity, since many sites of interest to oceanographers are at the land/sea interface. Noise, RFI and instrument stability also need monitoring in the L2 processor, and can cause erroneous retrievals.

Forward model TB emission calculated by the L2OS processor depends on a number of L band contributions including contributions from the Klein & Swift flat sea model, roughness models, foam, noise from external sources (reflection from sun, moon & galactic background radiation). In addition, the signal modelled at the surface is modified by atmospheric effects, including geomagnetic and Faraday rotation. The L2OS processor calculates the sum of all modelled contributions at the surface, and then applies a transformation of the Stokes vector (including atmospheric effects) to the satellite instrument so the TBs can be compared to actual measurements. Modelling contributions due to roughness is a major area of active research: the L2OS processor incorporates three forward models for roughness contributions: the Two-Scale model from LOCEAN (selected in configuration 1), the SSA model from IFremer (configuration 2), and the Empirical model from BEC (configuration 3).

In addition to these three models, a cardioid forward model [5] retrieves a parameter (A_card, selected in configuration 4) related to the dielectric value of the sea surface, which is expected to contribute to the detection of detect sea-ice.

For further details of each model, refer to the ATBD. We anticipate that some of these models will perform better than others under different geophysical conditions – once these have been identified it may be possible to improve the L2OS processor by selecting the appropriate model adaptively. Until then, L2OS products will contain three different salinity values (together with other retrieved values and flags), which may not always agree.

In use, the L2OS processor reads L1c and ECMWF input products (together with all other auxiliary data and configuration files) as specified by the job order, processes the data (which can take typically 4-6 hours), then writes UDP & DAP products together with associated reports. The nominal forward model (two-scale) generates modelled TBs which are transformed to SMOS antenna (instrument) level and compared with measured TBs: extreme out-of-range measurements are discarded by this discrimination step. Grid points too near to land, with too few measurements, missing ECMWF data, heavy rain, too much contamination from external noise sources (sun or moon glint, galactic noise) or sea ice, are not processed further. Flags are set in the UDP to indicate why grid points are ignored (see ATBD, IODD & L2 Product Spec [4]). For each valid grid point the processor runs the forward model 4 times: once with each of the configurations for the 3 forward models (two-scale, SSA & empirical); and lastly with the fourth configuration for the cardioid model. Each UDP & DAP therefore contains four sets of retrieved geophysical data (SSS1 from two-scale configuration 1, SSS2 from SSA configuration 2, SSS3 from empirical model configuration 3, and A_card from configuration 4), together with associated flags and other data.

End-users may wish to use the UDP (and maybe the DAP) without running the L2OS processor – DPGS processed products are available. Understanding the OS retrieval algorithms will give insight into data quality & constraints. Scientists wishing to experiment with the L2OS algorithms may wish to run the processor in different configurations or modify source code, & analyse results.

2. USING THE L2 OS PROCESSOR

The L2OS processor runs under Linux on 64 bit machines with at least 5G RAM (see OPCRR). Users can run the processor from the command line with a job order (a file defining all input and output files, including configuration, L1c and ECMWF) as a single parameter; or via a Java graphical user interface (GUI) which allows easier editing of configuration options, monitoring progress, and selection of breakpoints. Actually the GUI is just a shell launching the processor. There are two variants of the L2OS processor: the operational processor (OP) and the prototype processor (PP); both made using conditional compilation from the same C source code. Both can be used from the command line or via the GUI: conventionally the OP is used from the command line, and the PP via the GUI. The OP is used in the DPGS to automatically process SMOS L1c data (together with ECMWF) to make L2OS UDP & DAP, and will also be used for reprocessing as the algorithms evolve.

Installation and use of the OP & PP are described in the L2 OS Operational Processor Software Release Document (OPSRD), L2 OS Prototype Processor Software Release Document (PPSRD), L2 OS Operational Processor Software User Manual (OPSUM)

& L2 OS Prototype Processor Software User Manual (PPSUM). New users should follow carefully the OPSRD and ensure the installation test works before continuing. The L2OS delivery (downloadable from the L2OS web-site) includes data for two sample half-orbits, one dual and full polarisation. Each data set includes the L1c and ECMWF inputs required by the processor, and reference UDP and DAP outputs. Also included are job orders which can be used to verify installation, and as starting points for investigations.

There are two configuration files: private (CNF_L2OS) and public (AUX_CNFOSD or AUX_CNFOSF). During commissioning SMOS operated alternate weeks in dual polarisation (DP) and full polarisation (FP) modes; the operational mode is now fixed as FP. In DP mode SMOS makes alternate snapshot measurements in horizontal and vertical polarisation; in FP mode the instrument performs cross-polarisation measurements as well as vertical & horizontal. The L2OS processor job order specifies a public configuration file matching the L1c polarisation. During commissioning the L2OS team determined that the TBs provided by L1c contained a systematic bias pattern at the antenna level. Ocean Target Transformation (OTT) tables matching the L1c polarisation mode are used to correct this bias – Fig. 1 shows an example. OTTs are generated once to match each new L1 release/configuration by running the forward models and averaging the difference between measured and predicted TBs using climatology.

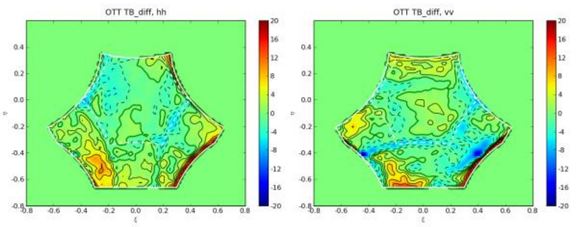

Figure 1. Sample OTTs for horizontal (left) & vertical (right) polarisations

The private configuration file provides a convenient method for quickly checking new job orders and configurations: instead of processing a complete half-orbit (taking several hours), users can specify either a few (one or more) grid points, or a region by latitude/longitude (the GUI has a nice interface for this – Fig. 2). The installation test processes a single grid point for speed.

Figure 2.Selecting a region via the GUI

Many options may be modified in the public configuration file (AUX_CNFOSD/F), which includes sections for each of the four retrieval configurations (sequentially at the start of the file, and some global settings (near the end). Options are available to select the retrieval mode, forward models (foam, galactic noise, roughness models), control the convergence algorithm (maximum number of iterations, Marquardt control values & cost function errors), specify & select source for first guesses & priors. Each configuration item is described in the PPSUM, ATBD, DPM, IODD, and also via the GUI (as the GUI versions of AUX_CNFOSD/F contain additional meta field descriptions). Thresholds (for all 4 configurations) set levels used by the processor for measurement discrimination, grid point selection (e.g. sun/moon glint), and classification of geophysical values.

Job orders select each of the products used by the processor; input product names are written in the UDP and DAP product headers and associated reports. Each time a new version of the L2OS is released, the configuration control documents SMOS L2 OS Auxiliary Data Files Configuration Control (ADFCC) and SMOS L2 OS Prototype Processor Auxiliary Data Files Configuration Control (PPADFCC) are also updated – users can cross-reference these with names and versions in product headers and reports.

3. L2OS PRODUCTS

The UDP (typically 25M) contains retrieved salinity on the ISEA grid for each half orbit, and is intended for oceanographers, input to L3/L4 processors, and for other end-users – refer to the IODD or L2 Product Spec [4] for a detailed description of all fields and flags. The DAP is much larger (typically 300M) and contains forward model prior and retrieved geophysical values for each grid point together with some data not available in the UDP (e.g. distance to centre of SMOS track), delta TBs for each configuration for all measurements, and flags used for lookup table (LUT) diagnostics. The DAP is intended for users interested in performing detailed scientific analysis of each forward model.

Fig. 3 shows an example of salinity retrieved by the L2OS processor from a dual polarisation ascending orbit product, with a zone of low salinity just above the equator probably due to rainfall from the inter-tropical convergence zone. An enlargement of this zone can be seen in Fig. 4, together with rainfall predictions from ECMWF. Surface fresh water layers are frequently seen near the equator where the ocean is stable, and cause shallower mixed layers.

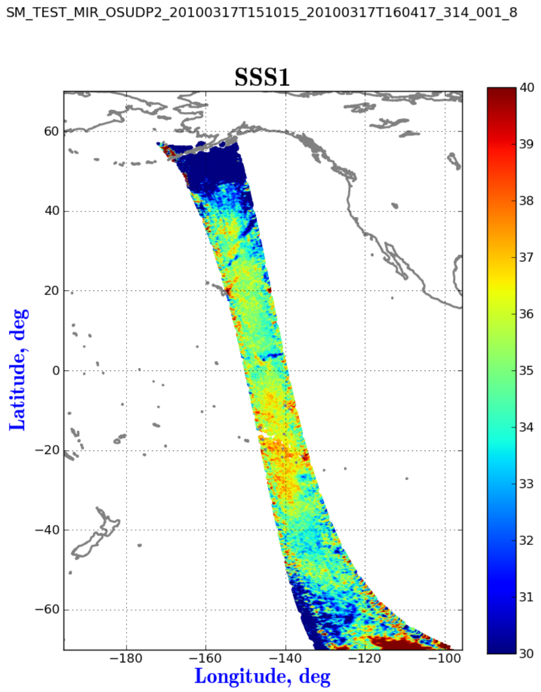

Figure 3. L2OS UDP product salinity (17 March 2010)

The occurrence of similar shallow fresh layers in mid-latitudes has been predicted by an ocean model [6] supported in one case by Argo float data. Also visible in Fig. 3 at 35 north is a low salinity zone associated with a depression. These new images from SMOS are a much better confirmation of the existence of mid-latitude shallow fresh layers since the spatial extent of the freshwater band can be seen. There are clearly opportunities for further analysis and comparison with rainfall data over time.

Also in Fig. 3 at 20 north radio frequency interference (RFI, radial lines at approx +/-45 degrees) emanating from Hawaii. The negative impact of proximity to land on salinity retrieval can be seen near Alaska.

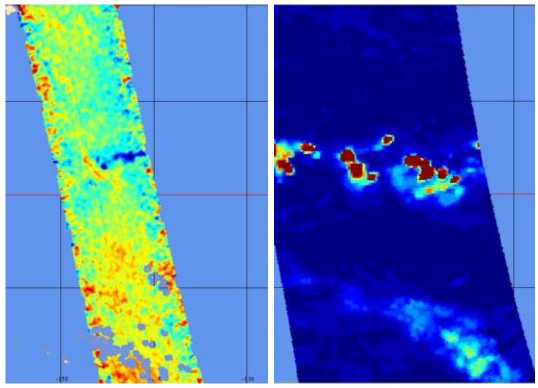

Figure 4. Low salinity surface water (left, SMOS L2OS UDP) associated with rainfall (right, ECMWF)

Both the UDP and the DAP are in an ESA specified format, and can be read using a number of tools. The products are in two parts: an XML format header, and a binary format part containing data values. The header includes a Specific Product Header (SPH) containing aggregated statistics describing retrieved data quality. The statistics are gathered by classifying the quality of measurement data at each grid point; the number of grid points rejected by the processor for various reasons; the number of successful retrievals for grid points far from the coast (i.e. in the ocean), near to the coast, in regions contaminated by sea-ice; and with high, normal or low values for salinity, temperature and wind speed. Example statistics in Fig. 5 extracted from an SPH show the proportion of good and poor quality grid points selected from L1c after measurement discrimination, and results (successful retrievals & associated average error) for those classified as sea (i.e. far from coast), and near to the coast.

	Good quality	Poor quality
Selected	83%	17%
Sea	95%	96%
Retrieved	66%	61%
Sigma	1.19	1.69
Near coast	5%	4%
Retrieved	29%	14%
Sigma	1.36	2.67

Figure 5. Sample quality information for retrieved salinity extracted from an L2OS SPH

Users may wish to examine the SPH to evaluate product quality before selecting products and reading binary geophysical data, which can otherwise be time consuming.

For visualisation, use either the SMOS Data Viewer (SDV) or the SMOS-Box add-on to BEAM/VISAT (SBOX). Neither can visualise the DAP. However, users can browse data values from both the UDP & DAP with SDV, and plot graphs/charts (but without data filtering – see below). SBOX can also make graphs/charts of the UDP.

SDV is available from:

ftp://193.146.123.166/smos/software/SMOSView

SBOX is available from:

http://www.brockmann-consult.de/beam-wiki/display/SBOX/SMOS+Toolbox+for+BEAM

For grid points and measurements rejected by measurement discrimination and configuration selection thresholds, the L2OS processor writes an invalid data value (-999) into each field. All other fields contain values generated by the retrieval algorithm, even if the convergence algorithm fails. Users must therefore view salinity and geophysical maps plotted by SDV and SBOX carefully, since neither automatically performs filtering. There are a number of quality indicators and flags that should be used to filter results: verification of these (including the quality index (Dg_quality_SSS_1/2/3/A_card) continues to be an active area of research: refer to the SMOS L2OS Product Verification Report (PVR). Users are advised to filter using a combination of quality flags derived from the Marquardt algorithm (Fg_ctrl_chi2, Fg_ctrl_chi2_P, Fg_ctrl_sigma, Fg_ctrl_reach_max_iter, Fg_ctrl_marq) and the error associated with the retrieved parameter (Sigma_SSS1/2/3/A_card) – see the ATBD & IODD for details. Fig. 6 shows an example plot of Sigma_SSS1 and the associated control flag Fg_ctrl_sigma_SSS1.

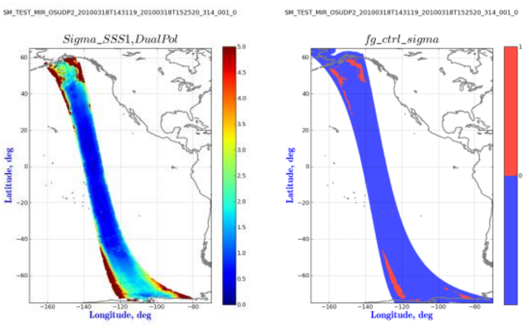

Figure 6. Sigma_SSS (left) & Fg_ctrl_sigma

Reading UDP/DAP using other tools is certainly possible: there is a MATLAB API capable of reading all SMOS data, and an XML R/W API for more advanced users wishing to program their own applications (this is the API used by DPGS processors, including L2OS).

Salinity values are available in the UDP together with an associated sigma (goodness of fit between forward model and actual measurements). Note that at present other retrieved geophysical parameters are not available in the UDP – wind speed (WS) and sea surface temperature (SST) are copied from ECMWF. All retrieved geophysical parameters are available (together with priors) in the DAP. UDP science flags indicate various geophysical conditions of interest, e.g. high/low SSS/SST/WS, ice, rain, distance to coast, and could be used as additional filters for analysis (e.g. to investigate the relationship between retrieval quality and WS).

4. FUTURE DIRECTIONS

Although the SMOS commissioning phase is complete we acknowledge that substantial work remains to be done before the L2 OS processor can be said to have achieved the design objectives. Some of these areas are inter-dependent on developments at L1, and we foresee close collaboration with the L1 team. Urgent issues include land contamination (Fig. 7), impact of RFI (Fig. 3 & Fig. 7), TEC accuracy & retrieval, and OTT stability/sensitivity.

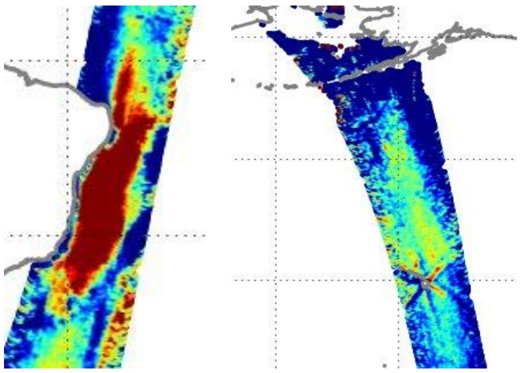

Figure 7.Land contamination (left) & RFI (right)

As the L1 & L2 processors evolve, reprocessing campaigns will be performed and improved products will become available. Long term goals for L2 OS include completing verification and performing in-situ calibration.

5. REFERENCES

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