BAMS
Meeting Summary

Reference-Quality Emission and Backscatter Modeling for the Ocean

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ISSI Science Team Meeting Report on Development of a Reference-Quality Model For Ocean Surface Emissivity and Backscatter from the Microwave to the Infrared

What: Sixteen members of an International Space Science Institute team—from America, Asia, and Europe and with backgrounds in radiative transfer modeling, data assimilation, field campaigns, space agencies, and instrumentation—met to provide a reference-quality model for ocean surface emission and backscatter.
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In November 2019 an international science team of the International Space Science Institute (ISSI) met to discuss the challenge of developing a community reference-quality ocean emission and reflection model for use across a broad spectral range [microwave (MW) and infrared (IR), and possibly also visible] as well as supporting passive and active remote sensing. The need for this has been identified in various reports and international workshops. Notably, the European Commission Horizon2020 project, GAIA-CLIM[1] (see appendix for acronyms), identified that the lack of a reference-quality ocean emission and backscatter model was a major gap in our ability to provide absolute calibration of the satellite based observing system. The gap was also identified by the ECMWF–JCSDA–NWP SAF all-sky assimilation workshop in December 2015 and again in February 2020 and the twenty-first meeting of the International TOVS Working Group in December 2017.

An international science team was proposed to ISSI, and accepted, to develop a new model capability with these goals and characteristics:

- it is to be maintained and supported,
- there has to be traceable uncertainty estimation at each step,
- documented code needs to be freely available to the research community,
- it needs to incorporate new science for IR to MW with bidirectional reflectance distribution function (BRDF) capability, and
- it should provide support for passive and active applications.

The first meeting reviewed the science, what already exists, where there are gaps, and began to develop the plan of how to create this new community software. The reports and findings of the ISSI team are available online (at www.issibern.ch/teams/oceansurfemiss/; where presentations are also available). This is a short meeting report to bring the team's activities to the attention of a wider audience.

The first team meeting was split into three parts. First, the theoretical basis for such models was reviewed. This was followed by an examination of the current models available for practical applications and their evaluation. And finally, the work needed to bridge the gap between what exists and what is needed was considered.

Theoretical basis of models

As a first-order approximation (geometric optics models), the ocean surface can be described as a collection of flat surfaces with a bidirectional slope distribution. These models can be applied multispectrally and in both passive and active modes. The sea surface response is mainly a function of wind speed and direction and surface temperature (and salinity at the

[1] www.gaia-clim.eu/

low end of the frequency range). It requires statistics about the surface slope distribution, the dielectric properties of the seawater, the foam characteristics (both coverage and emissivity), and information about the downwelling radiation. In passive microwave models, the geometric optics models have a long history, starting in the 1960s with theoretical developments by Stogryn (1967), evaluated with measurements by Nordberg et al. (1969) and Hollinger (1971), in the 1–19 GHz range. Although this approach is not sufficiently accurate at low frequencies, it can be readily extended to higher microwave frequencies and to submillimeter wavelengths (Prigent et al. 2017), but do not meet current requirements at very low frequencies. Initially the Cox and Munk (1954) slope variance model, derived from visible observations of the Sun glint over the ocean, was widely adopted. For the simulations of active microwave observations, the geometric optics models have shown serious limitations for observing incidence angles above 15°, where the Bragg scattering dominates the signal (e.g., Mouche et al. 2005; Nunziata et al. 2009). As a consequence, these models are not suitable for the analysis of scatterometer or synthetic aperture radar (SAR) data. In the infrared, geometric optics methods also have been adopted with success (e.g., Masuda 2006).

The addition of the effect of small-scale roughness superimposed on the large-scale slopes was suggested by Wentz (1975) to improve the model at low frequencies. More recently, the slope variance model of Durden and Vesecky (1985), derived from a sea spectrum model, and using a cutoff wavenumber dependent on the sensors frequency, has also become popular. Two scale models have achieved considerable success, but there remain areas of uncertainty, including cases where the wind and waves are aligned differently (the so-called horseshoe pattern), cases where there is high wind speed with low wave height, breaking waves and allowing for ocean currents.

Since the earliest studies, it has been clear that foam has a significant role (Nordberg et al. 1969; Webster et al. 1976). Both bubble rafts floating on the surface (whitecaps) and bubble plumes below the surface constitute sea foam. While bubble plumes are important for gas exchange and turbulent mixing, the whitecaps on the surface are of more interest for remote sensing (Anguelova and Gaiser 2011). The key parameters characterizing the sea foam are the void fraction (the amount of air contained in air–seawater mixture) and the foam layer thickness (Anguelova and Gaiser 2013). Close correspondence to observations at 1.4, 10.8, and 35 GHz is found when the upper limit of the void fraction varies with frequency. At higher, millimeter-wave frequencies, the role of scattering in the attenuation of foam needs to be accounted for with suitable scattering model, e.g., generalized multiparticle Mie (GMM; Xu and Gustafson 2001), which is an extension of Mie theory—an analytical solution of Maxwell's equations in terms of infinite series—to model light scattered by multiple spheres more accurately. Scattering losses monotonically increase for frequencies above 40 GHz contributing more than 25% to the total attenuation (extinction) in foam.

Practical models

Operational weather prediction systems need to assimilate millions of observations in just a few minutes, making many models too slow to be practical. Therefore, a range of simplified or parametric models have been developed. The team reviewed the capabilities, strengths, and weaknesses of three widely used models for simulating passive measurements: LOCEAN, RSS, and FASTEM. Developments in the context of the Community Radiative Transfer Model (CRTM) and for use with active sensors were also considered.

The LOCEAN model, developed specifically for L-band, uses a two-scale model for describing the sea surface roughness impact on brightness temperatures and foam emissivity and coverage models for describing foam impact on brightness temperatures. The LOCEAN model is based on Yueh (1997) for surface roughness and Anguelova and Gaiser (2013) for foam, though parameters of the wave spectrum and foam models have been adjusted using

Soil Moisture Ocean Salinity (SMOS) measurements. These adjustments, described in Yin et al. (2016), concern an empirical adjustment of a multiplicative factor in the wave spectrum (1.25 instead of 2 in the original model), of the void fraction at the air–foam interface (0.97), and of an effective foam thickness of 1.8 cm. In addition to these wind model adjustments, the LOCEAN team is working on better characterizing the uncertainties related to sea surface temperature (SST), in particular, the ones related to dielectric constant model issues and to conditional sampling effects.

The RSS ocean emissivity model uses a double Debye dielectric constant of seawater from Meissner and Wentz (2004, 2012) and is valid for a sea surface salinity (SSS) range between 0 and 40 psu and SST range between –2° and 32°C. The wind induced component covers the frequency range of 6–90 GHz (Meissner and Wentz 2012) with a special version for L-band (Meissner et al. 2014, 2018). The RSS wind emissivity model contains an anisotropic (wind direction independent) component and a wind-direction signal for all four Stokes parameters. In addition, it includes a term (omega term) that accounts for the atmospheric pathlength correction of the reflected downwelling radiation.

The FASTEM model, which is used by radiative transfer models such as RTTOV and CRTM, was developed specifically for fast calculations in the framework of data assimilation of raw radiances in a numerical weather prediction (NWP) system. The requirements were therefore speed of computation, availability of gradient code (K, tangent-linear and adjoint), and ability to reproduce as accurately as possible the outputs of a slower offline model. The original version (English and Hewison 1998) was written with the AMSU-A instrument in mind, optimized for accurate computations for a cross-track sounder with frequencies between 20 and 90 GHz, with best accuracy around 50 GHz. Since then, five new versions of FASTEM have been released (Liu et al. 2011; Kazumori and English 2015).

In CRTM version 2.3, the treatment of the ocean surface is divided into three categories: solar-impacted radiances, thermal infrared radiances, and microwave radiances. For solar radiance impacted channels, a "rough seas" BRDF is used, which provides the specular and Fresnel reflection angles based on the Cox and Munk slope approximation. For thermal infrared, the IRSSE model is used, as described initially in Nalli et al. (2008a,b). In the IRSSE, the wave-slope model is based on Ebuchi and Kizu (2002) and refractive indices from Wieliczka et al. (1989). As noted above, CRTM uses FASTEM for microwave wavelengths. CRTM 3.0 will support polarized atmospheric scattering, and surface reflection/emission through modified BRDFs. This will provide support for active sensor observations of the ocean surface, such as the normalized radar cross section (NRCS), and polarization induced by off-nadir radar beam reflections. A new generation of Advanced Radiative Transfer Modeling System (ARMS) is being developed in China at the China Meteorological Administration (Weng et al. 2020). Currently, ARMS, CRTM, and RTTOV all use FASTEM-6 for simulations of microwave radiance over oceans.

Models for active microwave responses off the ocean surface at incidence angles above 20° were then reviewed. The detailed spectrum in phase and amplitude of the small ocean scales needs to be modeled in order to estimate the interference of microwaves with the ocean topography in different azimuth directions. The uncertainty of physically based models, which are informed by satellite microwave measurements, remains relatively high at about 1 dB (20%) (e.g., Fois et al. 2015); this is much higher than the instrument stability of 0.1 dB. Nevertheless, these models are very useful for designing instruments at different wavelengths and predicting their sensitivity and performance.

Validation and evaluation

The team reviewed a number of recent studies. LOCEAN, RSS, and FASTEM simulations from 1.4 to 89 GHz using satellite observations from SMAP and AMSR-2 are documented by Kilic et al.

(2020). In addition the team noted the importance of reducing uncertainties in permittivity modeling and SST for improving accuracy of satellite salinity retrieved in the Arctic Ocean, and considering vertical stratification effects when validating satellite salinities (at ~1 cm depth) using in situ measurements classically taken at a few meters depth, especially in freshwater plumes. An empirical formulation for the azimuthal variation of emissivity, based on AMSR and SSMIS data, is documented by Kazumori and English (2015). Comparisons of the RSS model with a model developed at the Naval Research Laboratory are described in Bettenhausen et al. (2006) and Bettenhausen and Anguelova (2017). The team also reviewed new results validating a semitheoretical two-scale radiative transfer model for ocean emissivity/reflectivity for frequencies between 1.4 and 36 GHz (Dinnat et al. 2018). This included a comparison of dielectric models (Ellison et al. 1998, 2003; Klein and Swift 1977; Meissner and Wentz 2012; Stogryn 1997; Stogryn et al. 1995; Zhou et al. 2017). All these comparisons show some consistent themes: the RSS dielectric constant model fits observations well; a two-scale model coupled with the spectrum model by Yin et al. (2016) fits data at multiple frequencies once the foam model is adjusted to account for the larger penetration at low frequencies; there are issues at low SST and high wind speed. In general, it was concluded that uncertainty is not well characterized, as noted by Dinnat et al. (2003, 2019).

These models need to be able to support new generation satellite observations. The EUMETSAT Polar System Second Generation (EPS-SG) will continue and enhance the capabilities already available from the EPS First Generation satellites. For EPS-SG, a number of missions have been identified, which include the Microwave Sounding (MWS) mission, the Microwave Imaging mission (MWI), the Ice Cloud Imaging (ICI) mission, and the Scatterometry mission (SCA). More details on these missions can be found in the respective science plans.[2] MWI measurements can be collocated with SCA measurements in order to characterize sea surface roughness and even beam filling conditions. The Copernicus Imaging Microwave Radiometer (CIMR) mission, currently in development at phase B2, was also presented. CIMR has been identified by the European Space Agency (ESA) as one of the high-priority expansion missions in support of the Arctic Policy of the European Commission. CIMR will be implemented as a high-spatial-resolution polarimetric conical imager providing information on the full Stokes vector with channels from 1.4 to 36.5 GHz.

[2] www.eumetsat.int/website/home/Data/ScienceActivities/ScienceStudies/SciencePlansforfuturemissions/index.html

Next steps

Based on the presentations and other information, the meeting then assessed what constitutes state of the art, what could be used in a reference model, and where there are gaps.

Several seawater permittivity (dielectric constant) models are currently being used in microwave RTM calculations and for retrieving environmental parameters:

1) Klein–Swift model (Klein and Swift 1977): The Klein–Swift model was one of the first seawater permittivity models for microwave frequencies and it is still widely used. It is a single Debye relaxation model. The Debye parameters were fitted based on laboratory measurements at low frequencies. It can be used for frequencies below Ku-band, but the single Debye fit becomes increasingly inaccurate at higher frequencies. As no cold SSTs (below 5°C) were used in the parameter fit, the Klein–Swift model accuracy is questionable at very low SST. At higher SST, Aquarius and SMOS salinities retrieved with this model are in relatively good agreement with in situ salinity (Dinnat et al. 2019).
2) Meissner–Wentz model (Meissner and Wentz 2004, 2012): The Meissner–Wentz dielectric model for pure water and seawater is a double Debye relaxation model. The Debye parameters were fitted based on laboratory measurements at L-band and W-band. The fit

was carefully edited to account for observations from passive microwave satellites (SSM/I and WindSat). More recently the model has also been tested and used for retrievals with AMSR-2, GMI, and the Aquarius and SMAP salinity missions.

3) The Ellison model (Ellison et al. 1998): The Ellison model is also a double Debye relaxation model and is based on laboratory measurements over a wide frequency range. No satellite measurements were used in its derivation. An edited version of this model is currently used in the FASTEM (Liu et al. 2011).

The team concluded that it is necessary to assess the uncertainty of the permittivity models in order to be able to decide how useful the models are for radiative transfer application. Several error sources enter the derivation of the various permittivity models:

1) Random noise in the laboratory measurement.
2) Absolute biases: They are difficult to distinguish from satellite calibration offsets and are basically taken out when calibrating the satellite to the RTM.
3) Most important are errors in the permittivity model that depend on SST and SSS. Those errors will result in cross-talk biases in environmental retrievals of SST, SSS, wind speed, and water vapor.

SST and SSS dependent uncertainties in the Meissner–Wentz dielectric model will be assessed by the team. This will be based on comparing the real and imaginary parts of the permittivity model as well as the flat surface emission with the results of the laboratory measurement at W-band (Guillou et al. 1998), which are regarded as very reliable, as well as with the recent L-band laboratory measurements by Lang et al. (2016).

Regarding the roughness model, the two-scale approach is considered the most appropriate, but quantifying uncertainty is difficult. Roughness and foam are separated in some models but are sometimes treated together. The best choice of wave spectrum is not clear, nor is the extent to which wave spectra from an NWP wave model can give instantaneous estimates rather than a wave spectra for a given wind speed. This will be further investigated. There is also an important question of physical consistency across different observations (passive, active; microwave, infrared). Therefore, it is necessary to provide backscattering and emission in a consistent way from the same model. It was noted that the group needs to engage more with the active community, and this will be followed up.

The team was clear that the model needs a state of the art foam model. The major topics related to the foam emissivity that emerged from the presentations for further discussion were 1) choice and further improvement of an RTM for foam emissivity e_f, 2) choice and further improvement of a parameterization of foam fraction (whitecap coverage) W, and 3) assessing the uncertainties of e_f and W. The foam fraction is usually assumed to follow a power law in the form $W = aU^b$ (Monahan and O'Muircheartaigh 1986), where U is 10-m-altitude neutral equivalent wind speed and a and b are empirical coefficients. The consensus in the group was to investigate alternatives to the $W(U)$ parameterization used in FASTEM (with $b = 2.55$; Monahan and O'Muircheartaigh 1986) with expressions based on satellite retrievals of W. The group also discussed the need to use W parameterizations that include more variables in addition to wind, e.g., atmospheric stability, SST, and wave field characteristics. Group discussion led to suggestions for future developments (in the time leading up to the second science team meeting, which will happen toward the end of the 2-yr duration of the team), and finally the agreed upon responsibilities for specific contributions by the team members. The group noted that significant effort is needed to characterize uncertainties in the foam component of the model.

Planning for community model development

The group agreed on some specific actions to take the activity forward. These are recorded in the full meeting report on the ISSI web page, along with the presentations given. The team is open to engage with other interested scientists, though space at the ISSI facilities is limited, but if appropriate a larger workshop could be held, if a suitable venue can be found. The next physical team meeting will most likely be held early in 2021.

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Appendix: Terms and Acronyms

AMSU-A	Advanced Microwave Sounding Unit A
AMSR-2	Advanced Microwave Scanning Radiometer 2
Aquarius	Microwave L-band radiometer and scatterometer
ECMWF	European Centre for Medium-Range Weather Forecasts
EPS	European Polar System
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FASTEM	Fast Emissivity Model
GAIA-CLIM	Gap Analysis for Integrated Atmospheric Essential Climate Variable (ECV) Climate Monitoring
GMI	Global Precipitation Measurement Microwave Imager
ICI	Ice Cloud Imaging mission
IRSSE	Infrared Sea Surface Emissivity
ISSI	International Space Science Institute
JCSDA	Joint Center for Satellite Data Assimilation
LOCEAN	Laboratoire d'Océanographie et du Climat: Expérimentations et Approches Numériques
MWI	Microwave Imaging mission
MWS	Microwave Sounding mission
NWP SAF	Satellite Application Facility for Numerical Weather Prediction
RSS	Remote Sensing Systems
RTM	Radiative Transfer Model
RTTOV	Radiative Transfer for TOVS
SAR	Synthetic aperture radar
SCA	Scatterometry mission
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity

SSM/I	Special Sensor Microwave Imager
SSMIS	Special Sensor Microwave Imager/Sounder
TOVS TIROS	Operational Vertical Sounder
TIROS	Television Infrared Observation
WindSat	Microwave polarimetric imager

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