Soil Moisture Ocean Salinity (SMOS) salinity data validation over Malaysia coastal water

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Abstract. The study of sea surface salinity (SSS) plays an important role in the marine ecosystem, estimation of global ocean circulation and observation of fisheries, aquaculture, coral reef and sea grass habitats. The new challenge of SSS estimation is to exploit the ocean surface brightness temperature (Tb) observed by the Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) onboard the Soil Moisture Ocean Salinity (SMOS) satellite that is specifically designed to provide the best retrieval of ocean salinity and soil moisture using the L band of 1.4 GHz radiometer. Tb observed by radiometer is basically a function of the dielectric constant, sea surface temperature (SST), wind speed (U), incidence angle, polarization and SSS. Though, the SSS estimation is an ill-posed inversion problem as the relationship between the Tb and SSS is non-linear function. Objective of this study is to validate the SMOS SSS estimates with the ground-truth over the Malaysia coastal water. The LM iteratively determines the SSS of SMOS by the reduction of the sum of squared errors between Tb SMOS and Tb simulation (using in-situ) based on the updated geophysical triplet in the direction of the minimum of the cost function. The minimum cost function is compared to the desired threshold at each iteration and this recursive least square process updates the SST, U and SSS until the cost function converged. The designed LM’s non-linear inversion algorithm simultaneously estimates SST, U and SSS and thus, map of SSS over Malaysia coastal water is produced from the regression model and accuracy assessment between the SMOS and in-situ retrieved SSS. This study found a good agreement in the validation with R square of 0.9 and the RMSE of 0.4. It is concluded that the non-linear inversion method is effective and practical to extract SMOS SSS, U and SST simultaneously.

1. Introduction
The study of sea surface salinity (SSS) plays an important role in the marine ecosystem, estimation of global ocean circulation and observation of fisheries, aquaculture, coral reef and sea grass habitats. Salinity has direct relation to the earth’s water cycle and indirectly affects the weather and climate. In ocean study, SSS is a counterpart of sea surface temperature (SST) and it determines the water density which drives ocean currents. Changes in SSS level are caused by addition or removal of freshwater and this is considerably evident along the coastal water. Conventional methods to observe SSS (i.e., by means of hydrolab taken in the excursion by vessel) are very time consuming, expensive and limited to small area. On the other hand, remote sensing technique has proved as an efficient technique in mapping the SSS at regional or global scale. Several algorithms have been introduced to measure the SSS by...
space-borne data. There are limited studies on salinity conducted particularly for coastal waters of Malaysia [1] and in fact, most of them applied more on the sea-truthing than the satellite-based measurements. Most of the satellite derived SSS was obtained by optical remote sensing data though this approach has disadvantages of interferences produced by atmospheric condition, weather and cloud covers.

Therefore, it was a major challenge to globally study the SSS in Malaysia in the past years until the Soil Moisture and Ocean Salinity (SMOS) satellite was launched in 2009 to provide high degree of accuracy of SSS using microwave sensor. The SMOS satellite offers best retrieval of soil moisture and ocean salinity thanks to the Microwave Imaging Radiometer Using Aperture Synthesis (MIRAS) that measures microwave radiation emitted from the earth surface at 1.4GHz L-band. As a result, the study of salinity with the SMOS satellite renders advantage in tropical condition and thus it becomes important for better understanding and monitoring of SSS in Malaysia. The SSS estimation using SMOS data is basically as a function of ocean surface brightness temperature (Tb) which is associated to dielectric constant, SST, wind speed (U), incidence angle, and polarization. Though, the SSS estimation is an ill-posed inversion problem as the relationship between the Tb and the SSS is non-linear function so that the estimation is not straightforward.

This is the first study of SMOS that was carried out in the coastal water of Malaysia and therefore, its objective is to validate the SMOS SSS estimates with the ground-truth measurements. This study applies the Levenberg Marquardt inversion model to inversely estimate the SSS from the Tb measures by incorporating the SST and the U data. In this case, iterative non-linear least square fitting was used and later the accuracy of SMOS SSS retrieval was computed. This paper involves 4 sections; Section 2 discusses on the technical aspect of SMOS data and associated in-situ measurement taken for validation and emphasizes on the iterative non-linear SMOS SSS retrieval using Levenberg Marquardt. Section 3 presents the result of validation between the SMOS and in-situ retrieved SSS and later, discuss on the challenges in executing the methodology. Finally, Section 4 provides conclusion on the SMOS validation and remark on related future research.

2. Data and methods

2.1. Soil Moisture and Ocean Salinity (SMOS) data
The Soil Moisture and Ocean Salinity (SMOS) satellite developed by European Space Agency (ESA) was launched on 2 November 2009. The SMOS mission is to provide the high accuracy retrieval of soil moisture and ocean salinity [2]. The SMOS platform equipped with the radiometer so-called Microwave Imaging Radiometer Using Aperture Synthesis (MIRAS) with ability to measure microwave radiation emitted from the earth surface based on the concept of interferometry (Pinori et al., 2008). Onboard MIRAS gives accurate observation of soil moisture and ocean salinity within a hexagon-like shape of field of view with spatial resolution of 35 km and 3 days revisiting time. This study uses the SMOS L-band microwave level 1C data (hereafter referred as SMOS L1C) provided by the European Space Agency (ESA) and was acquired through the EOLISA tool [3]. The SMOS L1C data contains the snapshot of Tb pixels which have been geometrically sorted and geolocated in an equal area grid system. Data attributes and geolocation of SMOS L1C are extracted and viewed through the BEAM platform. The BEAM platform also allows user to handle the SMOS L1C with the features for analysis and data exportation as shown in Figure 1.
2.2. In-situ data measurement
The sea-truth data records the information of sea surface salinity, sea surface temperature and wind speed which have been carried out in August 2009 along the coastal water of Malaysia as shown in Figure 2. The study area is in the Exclusive Economic Zone (EZZ) that is rich with marine resources and habitat. The in-situ data was provided by Universiti Malaysia Terengganu (UMT) and Southeast Asian Fisheries Development Center (SEAFDEC).

2.3. Iterative non-linear inversion algorithm
The emissivity model defines the SSS from the non-linear function of dielectric constant, $\varepsilon$ and brightness temperature which are digitally measured at different incidence angles, $\theta$ and polarization, $\rho$ in the SMOS pixels. In this study the semi-empirical emissivity model for rough surface devised by Camps et al, 2004 is applied in which the dielectric constant as a
function of the in-situ geophysical triplet (e.g., $SS_{in}$, $SST_{in}$, and $U_{in}$), the incidence angle
and the polarisation was converted to $Tb$ simulated (hereafter referred to as $Tb_{sim}$). To estimate
the $Tb$ from the SMOS pixel (hereafter denoted as $Tb_{meas}$) the non-linear and parametric
inversion algorithm must be considered and in this case, this study applies the Levenberg-
Marquardt (LM) method. This method uses the least square objective function called cost
function as follows.

$$
\chi^2(\text{SSS}_{SMOS}, \text{SST}_{SMOS}, \text{U}_{SMOS}, \theta, \rho) = \sum_{i=0}^{N-1} \left( \frac{Tb_{i}^{\text{meas}} (\theta_i, \rho_i) - Tb_{i}^{\text{sim}} (\text{SSS}_{in}, \text{SST}_{in}, \text{U}_{in})}{\sigma_{Tb_{in}}^{2}} \right)^2
$$

(1)

where $N$ is number of observations which has collocated SMOS pixel close to in-situ point
and $\sigma_{Tb_{in}}^{2}$ is the variance of $Tb_{sim}$. The LM iteratively determines the SSS of SMOS by the
reduction of the sum of squared errors based on the updated geophysical triplet in the direction
of the minimum of the cost function. The minimum cost function is compared to the desired
threshold in each iteration and this recursive least square process updates the geophysical
triplet until the cost function converged [4]. Figure 3 summarises the SMOS data inversion by
LM method of which the outputs of SMOS derived SSS, SST and U are simultaneously
determined.

![Figure 3. Processing block diagram of SMOS sea surface salinity retrieval by LM method.](image)

3. Result and analysis

This study focuses on validating the result of SSS, SST and U from LM estimation and these
geophysical parameters are estimated in two polarimetric modes, vertical and horizontal.
Result of LM in both polarisations is presented to give insight on which polarisation impact
the most of the LM result.

3.1. Analysis of the cost function in different polarization mode

The LM proved that advantage to determine solution with the minimum cost function
converged at the fine selection of SSS, SST and U. Figure 4 depicts the bowl-shape nature of
the cost function for different polarimetric modes. Horizontal polarisation mode allows fast
convergence to find the minimum of cost function and thus, determine the solution for SSS,
SST and U with very steep decay. This is not the case in vertical mode as the convergence
speed is slowerto require more processing time. In fact, the minimum of cost function is
obviously lower in horizontal than that of the vertical (around 1.2) and as a result, the
accuracy of geophysical triplet for both polarisations is different.
Figure 4. The sum of the squared error ($\chi^2$) as function of SSS, SST and U for horizontal and vertical polarimetric SMOS pixel. (a) Horizontal – SSS vs. SST, (b) Vertical – SSS vs. SST, (c) Horizontal – SSS vs. U, and (d) Vertical – SSS vs. U.

Table 1. Correlation matrix of SSS, SST and U in horizontal and vertical polarizations.

| Vertical | SSS  | SST  | U    |
|----------|------|------|------|
| SSS      | 1.0000 | -0.5945 | 0.5948 |
| SST      | -0.5945 | 1.0000 | -1.0000 |
| U        | 0.5948 | -1.0000 | 1.0000 |

| Horizontal | SSS  | SST  | U    |
|------------|------|------|------|
| SSS        | 1.0000 | -0.3717 | 0.3723 |
| SST        | -0.3717 | 1.0000 | -1.0000 |
| U          | 0.3723 | -1.0000 | 1.0000 |

The LM produces correlation matrix that summarizes the degree of correlation between geophysical parameters and their attributes in different polarization. Table 1 summarizes the correlation matrix at vertical and horizontal polarization modes. SSS has inverse relation with SST in both modes and this also found by Bai Zhang (2004). SSS has direct correlation with U because the wind speed is one of the parameters that determined the sea roughness which has strong impact to salinity in the ocean. Yet, the impact of U in the SSS retrieval using LM is lower in horizontal mode. This study later considers the result obtained in horizontal polarisation to use in the validation of SMOS SSS.

3.2. Regression analysis between SMOS and in-situ derived SSS

Regression analysis is carried out to find the degree of correlation between the SMOS and in-situ derived SSS and thus validate the accuracy of SMOS data. The study used 26 out of 33 collocated samples after extracting sample with higher outlier. Figure 5 presents the regression plot of SSS by applying a linear fitting. The result shows remarkable R-square of 0.9 and R of 0.89 and this suggested that the LM method provides higher accuracy retrieval of SSS from the Tb observation. The RMSE of SSS estimate is ± 0.4390 psu. Finally, map of SSS is produced from validation model as in Figure 6.
Figure 5. Regression plot between the SMOS and in-situ derived SSS over the Malaysia coastal body.

Figure 6. Map of sea surface salinity over the study area.

4. Conclusions
This study suggests that the SMOS L1C data has advantage to provide high accuracy of salinity information for Malaysia coastal water. Despite of the fact that the retrieval of the SMOS L1C data requires ill-posed solution, the Levenberg-Marquardt iterative non-linear inversion method demonstrates its capability to estimate the geophysical parameters (SSS, SST and U) simultaneously by incorporating the in-situ data. The method also provides solution in both polarimetric modes and this study found that horizontal polarization conveys trustworthy solution. SMOS derived SSS has RMSE of 0.43 psu and this is sufficient to map salinity of the ocean at synoptic scale. This study anticipates long-term observation of SMOS to provide better and comprehensive validation exercise.

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