

# Quantifying Uncertainties in Land Surface Microwave Emissivity Retrievals

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**Abstract**— Uncertainties in the retrievals of microwave land surface emissivities were quantified over two types of land surfaces: desert and tropical rainforest. Retrievals from satellite-based microwave imagers, including SSM/I, TMI and AMSR-E, were studied. Our results show that there are considerable differences between the retrievals from different sensors and from different groups over these two land surface types. In addition, the mean emissivity values show different spectral behavior across the frequencies. With the true emissivity assumed largely constant over both of the two sites throughout the study period, the differences are largely attributed to the systematic and random errors in the retrievals. Generally these retrievals tend to agree better at lower frequencies than at higher ones, with systematic differences ranging 1~4% (3~12 K) over desert and 1~7% (3~20 K) over rainforest. The random errors within each retrieval dataset are in the range of 0.5~2% (2~6 K). In particular, at 85.0/89.0 GHz, there are very large differences between the different retrieval datasets, and within each retrieval dataset itself. Further investigation reveals that these differences are mostly likely caused by rain/cloud contamination, which can lead to random errors up to 10~17 K under the most severe conditions.

**Index Terms**—microwave radiometry, remote sensing, land surface emissivity, measurement uncertainty, systematic errors, random errors, brightness temperature.

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## I. INTRODUCTION

LAND surface emissivity at microwave frequencies contains a wealth of information on the physical, biological and hydrological states and processes of the Earth's surface. This forms the basis for remote sensing of a wide range of land surface states and processes such as soil moisture, vegetation characteristics and land cover dynamics [1]. In addition, land surface emissivity acts as the background signal for the retrieval of atmospheric variables, such as water vapor, rainfall and snowfall, and therefore greatly affects the accuracy and uncertainty in such measurements [2], [3].

Currently, global-scale land surface emissivities are mostly derived from satellite-based observations through radiative transfer calculations. Microwave radiometers onboard polar-orbiting satellites produce brightness temperature (Tb) measurements at the top of the atmosphere (TOA). With atmospheric temperature and moisture profile data, one can remove the portion of Tb originated from the atmosphere, to obtain the microwave emission from the land surface. Subsequently the land surface emissivity can be computed if the surface temperature effective for the emission is known [4]. Retrieval of emissivity can also be implemented in a variational [5] and/or iterative [6] framework in which many variables affecting the radiative transfer processes, including emissivity, can be estimated simultaneously.

Usually emissivity retrievals are only performed for clear days, due to the difficulty in estimating the atmospheric contribution from a cloudy or rainy atmosphere, and to the strong atmospheric scattering and absorption of land surface signals under such conditions, especially at higher frequencies. However, even for a cloud-free atmosphere, there are many error sources that lead to uncertainties in emissivity retrievals, including instrumental errors, inaccuracies in the atmospheric profile data, imperfect cloud screening, and misrepresentation of the land surface temperature [7]-[9]. In addition, the heterogeneity of the land surface radiometric properties and the shifts in instrument footprint locations introduce sampling errors that enhance the uncertainties.

Despite its importance, the uncertainty in emissivity retrievals has not been well quantified. The leading difficulty is the lack of "ground truth" data, especially on the global scale. Most of the field campaigns for land emissivity studies are short-lived and small-scale, and generally they are not carried out in coordination with any specific satellite-based instruments or overpasses. Without reliable reference data, the immediate impediment to uncertainty quantification is the inability to apportion the variability to measurement error or to natural variability of land surface emissivity.

In this work, we circumvent this difficulty by strategically selecting two types of land surfaces whose emissivities are largely constant: the Sahara Desert and the Amazon Rainforest. Then all the variation within a set of retrievals is caused by the uncertainties, defined as the spread among independent measurements.

Although this study is limited to these two types of land surfaces, it represents a practical effort to make progress in solving an otherwise intractable problem. Thus this study not only provides the first quantitative results, but also facilitates more educated inference on the magnitude of uncertainty over other surfaces.

The emissivity datasets and methodology we employed are described in the following Section. In Section III, we provide observational evidence to substantiate our assumption of the constant emissivity over the desert and rainforest areas. Based on such an assumption, we present results in Section IV to quantify the uncertainties. The results are then summarized and discussed in Section V.

## II. DATA AND METHODOLOGY

To support the upcoming Global Precipitation Measurement (GPM) mission, NASA's Precipitation Measurement Missions (PMM) Science Team formed the Land Surface Working Group (LSWG) to improve land surface characterization at microwave frequencies. LSWG has assembled a collection of clear-sky land surface emissivity retrievals from many contemporary space-borne passive microwave sensors, over selected, representative land surface types such as desert, rainforest, mid-latitude agricultural land, wet land and high-latitude cold regions [10]. The collection of sensors includes the Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), WindSat aboard the Coriolis satellite, the Advanced Microwave Sounding Unit (AMSU), and the Advanced Microwave Scanning Radiometer for EOS (AMSR-E). This data collection greatly facilitates inter-comparison and evaluation of land surface microwave retrievals, and enables us to assess the current skills and uncertainties.

In this study, we focus our evaluation on the three conical-scan microwave imagers: SSM/I, TMI and AMSR-E (Table I), because they have a similarly wide frequency range, and most of their channels have both vertical and horizontal linear polarizations. Instantaneous retrievals, including both ascending and descending passes, are used whenever available. Retrievals from different data providers for the same imager are all included as independent estimates, as they are mostly derived from different algorithms and/or with different ancillary data. A common one-year period, July 1, 2006 – June 30, 2007, is used for our study.

For SSM/I, retrievals from three Defense Meteorological Satellite Program (DMSP) platforms (F13, F14 and F15) are included. The data are provided by the Centre National de la Recherche Scientifique (CNRS), France, and the retrieval procedure is described in [4], [11]. TMI retrievals are produced by Nagoya University, Japan, with a similar method. For AMSR-E, two independent retrieval datasets are used. One is produced by NOAA's Microwave Integrated Retrieval System (MIRS) using a one-dimensional variational algorithm [5], and is denoted as AMSR-E (MIRS). The other is produced by NOAA's Cooperative Remote Sensing Science and Technology Center (CREST), and the retrieval procedure is documented in [12], [13].

This dataset is denoted as AMSR-E (CREST).

Uncertainty essentially is the quantification of the spread or disagreement among independent measurements of the same physical quantity. If each of the measurements has no systematic biases, then such spread arises solely from the random errors. However, most often each measurement has distinct systematic biases that contribute to the total uncertainty. Difficulty arises when there are no “ground-truth” data available: one is not able to separate systematic errors from random ones, and either type of error from the natural variability of the measured quantity. Under these conditions, uncertainty quantification is impossible.

A practical starting point to elude this difficulty is to quantify the uncertainty over areas where the physical variable, here microwave emissivity, is constant. This is the one case in which “ground-truth” data are not needed, as all the variations in the data are from the measurement errors. One may still not be able to identify the absolute amplitude of systematic errors, but their differences among independent measurements can be obtained, and these differences provide substantial insight into their reliability as an ensemble. Moreover, the random errors can be easily quantified, which more often are the dominant part of the total uncertainty.

For this study, we selected two land surface types, the Sahara Desert and the Amazon Rainforest. In these regions, the desert roughness and the vegetation properties of tropical forest are not expected to change significantly with time. Since roughness and vegetation are two key controlling factors for microwave emissivity at these frequencies, they can be used as a constant-reference surface. This property has been exploited for validation and calibration of other land surface parameter retrievals (e.g., [14], [15]). In the following section, we will substantiate this assumption with long-term AMSR-E observations. Though the true value of the assumed constant emissivity is unknown, we can compare the independent retrieval datasets and their disagreements to infer the magnitude of the uncertainties, including both systematic and random errors. The two sites we used in this study are designated by LSWG as “Desert” and “Amazon2,” located at (22°N, 29°E) and (2°N, 55°W), respectively.

### III. CONSTANT EMISSIVITY OVER STUDY SITES

To prove that the land surface emissivities are approximately constant over the Desert and Amazon2 sites, we examined the microwave polarization difference index (MPDI) over these two locations. MPDI is essentially a normalized measure of the polarization. The MPDI is computed from the daily AMSR-E Tb data over the three-year period of July 2004 through June 2007, for all weather conditions. Tb-based MPDI is defined as [16]:

$$MPDI_T = \frac{Tb_v - Tb_h}{Tb_v + Tb_h}$$

where  $Tb_v$  and  $Tb_h$  are the TOA Tb of vertical and horizontal polarization, respectively, for a specific frequency and scan angle. Similarly, emissivity-based MPDI is defined as:

$$MPDI_\varepsilon = \frac{\varepsilon_v - \varepsilon_h}{\varepsilon_v + \varepsilon_h}$$

where  $\varepsilon_v$  and  $\varepsilon_h$  are the land surface emissivity of vertical and horizontal polarizations, respectively, for a specific frequency and scan angle.

MPDI is closely related to the land surface states. This is because with a clear-sky atmosphere, the polarization difference originates exclusively from the land surface; the atmosphere's attenuation and emission generate no additional polarization, serving only to suppress the polarized signals down below. Thus Tb-based MPDI, which contains both signals from the land surface and (un-polarized) signals from the atmosphere, can be shown to be a lower-bound estimate of the emissivity-based MPDI.

For a non-scattering, plane-parallel atmosphere and for a given scan angle and frequency, the TOA brightness temperatures for vertical and horizontal polarizations can be computed by the following integrated radiative transfer equations (e.g., [4]):

$$\begin{aligned} Tb_v &= T_a^\uparrow + T_a^\downarrow (1 - \varepsilon_v) e^{-\tau} + T_s \varepsilon_v e^{-\tau} \\ &= T_a^\uparrow + T_a^\downarrow e^{-\tau} + (T_s - T_a^\downarrow) \varepsilon_v e^{-\tau} \end{aligned} \quad (1)$$

$$\begin{aligned} Tb_h &= T_a^\uparrow + T_a^\downarrow (1 - \varepsilon_h) e^{-\tau} + T_s \varepsilon_h e^{-\tau} \\ &= T_a^\uparrow + T_a^\downarrow e^{-\tau} + (T_s - T_a^\downarrow) \varepsilon_h e^{-\tau} \end{aligned} \quad (2)$$

where  $T_a^\uparrow$  and  $T_a^\downarrow$  are the upward and downward (including cosmic background) radiation through the atmosphere,  $T_s$  the land surface temperature, and  $\tau$  the atmospheric optical depth along the view path, respectively. Then from (1) and (2) one can derive

$$\begin{aligned}
MPDI_T &= \frac{Tb_v - Tb_h}{Tb_v + Tb_h} \\
&= \frac{(T_s - T_a^\downarrow)e^{-\tau}(\varepsilon_v - \varepsilon_h)}{2(T_a^\uparrow + T_a^\downarrow)e^{-\tau} + (T_s - T_a^\downarrow)e^{-\tau}(\varepsilon_v + \varepsilon_h)} \\
&= \frac{MPDI_\varepsilon}{1 + \frac{2(T_a^\uparrow + T_a^\downarrow)e^{-\tau}}{(T_s - T_a^\downarrow)e^{-\tau}(\varepsilon_v + \varepsilon_h)}}
\end{aligned} \tag{3}$$

and since  $\varepsilon_v + \varepsilon_h \approx 2$  for most land surfaces, the above equation can be approximately rewritten as

$$MPDI_T \approx \frac{MPDI_\varepsilon}{1 + \frac{T_a^\uparrow e^\tau + T_a^\downarrow}{T_s - T_a^\downarrow}}. \tag{4}$$

As  $T_s > T_a^\downarrow$  for the Earth's clear atmosphere in the frequency range under study, we have

$MPDI_T \leq MPDI_\varepsilon$ . In other words, the Tb-based MPDI is a lower-bound estimate of the emissivity-based MPDI. The more transparent the atmosphere is (the smaller the values of  $T_a^\uparrow$ ,  $T_a^\downarrow$  and  $\tau$  are), the closer the two MPDI will become.

Fig. 1 shows the Tb-based MPDI for all the six AMSR-E channels, over the Desert (Fig. 1a), Amazon2 (Fig. 1b) and a third LSWG site, the Southern Great Plains (SGP; Fig. 1c). Over the three-year period, the MPDI for both Desert and Amazon2 remains fairly constant. In contrast, SGP MPDI values exhibit strong seasonal variations across all the channels that are related to the seasonal variations in vegetation and soil moisture. Though the data contain both clear and cloudy days, the latter only serve to further reduce MPDI values and do not obscure variations during clear days. Comparing Figs. 1a and 1b with 1c, we can verify that our assumption of constant emissivity over Desert and Amazon2 is valid.

Over Desert, the MPDI values are large, and so are the differences among the channels. This is consistent with the well-known strong polarization signature over desert areas [17]. Nevertheless, over the three-year period, the values are remarkably constant, especially for lower frequencies, which are not sensitive to the atmosphere. Slight seasonal variations are present in the water vapor channel (23.8 GHz), which suggests they are mostly atmosphere-induced. The synchronized, less pronounced fluctuations in the 89.0 GHz channel indicate their atmospheric origin as well.

Over Amazon2 (Fig. 1b), the MPDI values are much lower, and close to zero for all the frequencies. This is consistent with the fact that over dense forest the microwave signals are not strongly polarized. Despite the

dense canopy, the lower frequencies exhibit slightly higher MPDI values, indicating some of the emission from the soil surface transmits through the canopy. Overall one can see MPDI remains fairly constant and very small across all the channels. Thus it is reasonable to assume the emissivity values over Amazon2 are approximately constant too.

We also examined another arbitrarily selected, distant desert site (22°N, 5°W) and Amazon site (7°S, 70°W). The temporal variation in their respective MPDI time series is similarly small (not shown), indicating the stationarity of MPDI over these two types of surfaces is robust feature.

#### IV. RESULTS

In this section, we first present the basic characteristics of both the systematic and random errors, including their statistical distributions shown as histograms. To gain additional insight, we then examine the errors in MPDI space, with comparisons with AMSR-E Tb data. Finally, we provide diagnostic analysis on the sources of some of the error features identified in the study.

##### A. Systematic and Random Errors

Land surface emissivity retrievals over the two evaluation sites show considerable systematic and random errors. Figure 2 shows box-and-whisker plots for the six datasets and for both polarizations. Over the Desert site (Figs. 2a and 2b), the ensemble as a whole showed the expected behavior – vertically polarized emissivity decreases with frequency (Fig. 2a) while horizontally polarized emissivity increases (Fig. 2b) [17]. However, there are considerable systematic differences between the mean values from each retrieval dataset, indicating most of them, if not all, have systematic errors, regardless of the unknown “ground truth.” The systematic differences are the smallest at lower frequencies (6.9 and 10.65 GHz), reflecting partly their insensitivity to atmospheric effects. The random errors also show a strong dependency on frequency. The higher frequencies (85.5/89.0 GHz) tend to have the highest spread from their mean values, suggesting again atmospheric effects are the source. The vertically polarized channel of SSM/I F15 at 22.2 GHz shows extremely high values (Figs. 2a and 2c). This is caused by an instrument problem documented in [18].

Over Amazon2 (Figs. 2c and 2d), the magnitude of the systematic differences among the retrievals is similar to that of the Desert site, except that the differences at the higher frequencies (85.5/89.0 GHz) are much larger. Similarly, the random errors are also much higher at these frequencies. This also suggests that the atmospheric effects are playing an even larger role here, considering Amazon2 has a much moister atmosphere and many more cloudy/rainy days, than the Desert site.

There is a lack of smoothness in the mean emissivity spectra at either site. For example, CREST's AMSR-E retrievals fashioned a bump at 23.8 GHz in its horizontal polarization at the Desert site, but it has a dip at 36.5 GHz in both polarizations at Amazon2. Other retrievals show such bumpiness in varying degrees. We believe the emissivity spectra should be smooth and monotonic, because over the frequency range under study the land surface does not have any physical known mechanism that responds differently to a particular frequency. Thus the roughness in the shapes of the emissivity spectra is another manifestation of systematic errors.

### *B. Histograms of Emissivity Retrievals*

Further insight into the uncertainties can be obtained from histograms of the retrievals. Figure 3 shows the histograms of horizontally polarized emissivities for both sites. Overall the Desert site exhibits a gradual increase in H-pol emissivity with frequency (left) from all the retrievals, while over Amazon2 the emissivities are largely confined in the range of 0.9 to 1.0 for all the frequencies. Consistent with Fig. 2, there are considerable differences among the mean value of each of the retrievals over either site, a strong indicator of the existence of systematic errors. In addition, for each retrieval dataset, there is a range in spread around its mean emissivity value, with the shape of the histogram indicating the distribution of the random errors.

Over Amazon2, all the emissivity histograms are single mode, while over Desert, some of the retrievals, such as TMI and AMSR-E (MIRS), exhibit dual modality at some of the frequencies. We speculate this might be related to the strong diurnal cycle in the variation of the surface temperature and the microwave penetration depth, which makes it tricky to represent the effective emission characteristics in the retrieval process [13], [17], [19], [20].

### *C. Uncertainties in MPDI*

Because MPDI can largely cancel the effect of errors in atmospheric contribution and surface temperature, we also examined the uncertainties in MPDI computed from the emissivity retrievals. This will reveal how much of the error is common in both V- and H-pol channels, and how much is not. If a significant portion of the error in an emissivity retrieval is common to both channels, MPDI will show much lower systematic and random error amplitudes than the emissivity values alone. Indeed, as shown in Fig. 4a, MPDI values over Desert show much better agreement among the retrievals, except AMSR-E (MIRS). This suggests most of the systematic errors in the emissivity retrievals are common to both channels. In addition, the variance becomes much smaller, indicating both channels have the same random error as well most of the times. Similar conclusions can be drawn for Amazon2 (Fig. 4c) for most of the frequencies, except for 85.5/89.0 GHz which shows fairly large systematic and random errors. Obviously the errors at the highest frequencies are larger and

less co-varying between the vertical and horizontal polarizations.

For comparison, we also studied the MPDI computed from AMSR-E TOA  $T_b$  values over these two sites (Figs. 4b and 4d). Interestingly, the spectral shapes between emissivity-based (Fig. 4, left) and  $T_b$ -based MPDI (Fig. 4, right) are strikingly similar. Since  $T_b$ -based MPDI is the lower bound of emissivity-based MPDI, any values in the former (Fig. 4, right) higher than those in the latter indicate systematic errors in the emissivity retrievals, such as the F15 retrievals at higher frequencies over Amazon2 (Fig. 4c). In addition, there is an elbow in  $T_b$ -based MPDI at 23.8 GHz over either site, due to the strong water vapor attenuation in the atmosphere. But such a depression should not be present in emissivity-based MPDI, had the atmospheric effect been completely removed in the retrieval process. But its very existence (Figs. 4a and 4c) suggests otherwise. This is understandable because there is no way to recover the polarization difference from the TOA  $T_b$  if such a signal is strongly dissipated through the atmosphere. Therefore satellite-based direct retrieval of land surface emissivity in this frequency range (21-24 GHz) will remain a challenge, and a feasible solution is interpolation from its more transparent neighboring frequencies, as done by the Tool to Estimate Land-Surface Emissivities at Microwave frequencies (TELSEM) [21].

#### *D. Error Diagnosis*

To further understand the causes of the errors, we inspected the daily emissivity spectra and their variations over our 1-year study period, for the various sensors for both sites. As an illustrative example, Fig. 5 shows a collage of daily emissivity retrievals from SSM/I on DMSP F13 over the Amazon2 site, for both polarizations and both morning (AM; descending) and afternoon (PM; ascending) passes. The emissivities for both polarizations are of similar values, as expected over such a site. Most of the emissivity spectra are confined within the range of 0.9-1.0, but there is considerable variation, driven largely by the seasonality. This variation is more likely introduced by the errors in both land surface temperatures and atmospheric profiles used in the retrievals. The impact of water vapor attenuation at 22.2 GHz for the vertical polarization, in the shape of an elbow, from either AM or PM passes, is obvious (Figs. 5a and 5c). Such an elbow does not manifest itself in the horizontal polarization due to the lack of the 22.2 GHz (Figs. 5b and 5d).

Figure 5 also reveals that the dominant source of random errors at the highest frequency (85.5 GHz) is likely the contamination from cloudy or rainy skies. As one can observe, during the morning passes, there were very few outliers at 85.5 GHz. But the afternoon passes saw a significant number of outliers with drastically reduced emissivity values in both polarizations at this frequency (Figs. 5c and 5d). This coincides with the rainy time of the Amazon precipitation diurnal cycle [22], and the outliers indicate strong scattering from ice particles aloft. This suggests that the cloud screen step in the retrieval processes missed a number of

cloudy and rainy conditions, resulting in enhanced random errors.

## V. SUMMARY AND DISCUSSION

Due to the lack of ground truth data, quantifying the uncertainties in satellite-based land surface emissivity retrievals has been a challenge. We initiated an effort to evaluate such retrievals from microwave imagers over two types of land surfaces, the Sahara Desert and the Amazon Rainforest. The true emissivity over either type of land surface can be treated as virtually constant, as supported by a three-year AMSR-E Tb polarization difference record (Fig. 1). This enables us to identify both the random errors and many aspects of the systematic errors. Among the several retrieval datasets based on SSM/I, TMI and AMSR-E that we examined, there are substantial systematic differences, especially at higher frequencies (Fig. 2). The range of the systematic differences is approximately 1~4% of the mean values (equivalent of 3 to 12 K Tb) over the desert site and 1~7% (3 to 20 K) over Amazon, generally increasing with frequency (Table II). Within each particular dataset, the random errors are in the range of 0.5~2% (2~6 K) over both sites, except for SSM/I aboard F13 and F14, which had much larger random errors (10~17 K) over Amazon at 85.5/89.0 GHz, due to the atmospheric contamination as shown in Fig. 5.

These error components arose from various sources. Based on our analysis, we can summarize the error sources as the following:

1. For systematic errors, inaccuracies in the atmospheric profile data and in the surface temperature data are the primary sources. Over Desert, the impact of the former seems insignificant, probably due to the low water vapor content in the atmosphere. Similar MPDIs (except MIRS) (Fig. 4a) but differing emissivities (Figs. 2a and 2b) suggest that the surface temperature differences and errors are primarily responsible for the systematic differences. To compound the problem, the strong diurnal variation of the surface temperature and penetration depth over desert makes it difficult to represent the effective values. On the other hand, over Amazon<sup>2</sup>, the fact that the emissivities (Figs. 2c and 2d) are notably different between the datasets, and the random errors in the emissivity-based MPDI (Fig. 4c) are much higher than those of the Tb-based MPDI (Fig. 4d), indicates both factors are responsible.
2. Retrievals within the water vapor attenuation band (21-24 GHz) are systematic outliers and are less reliable (e.g., Figs. 4a and 4c). This is understandable because the signals from the land surface are strongly dissipated by the atmosphere, and TOA Tb measurements contain little information content originated from the land surface. Thus direct satellite-based retrievals in this frequency range will remain a challenge. Interpolation between more transparent neighboring frequencies has been shown to be a feasible solution [21].
3. Random errors with each retrieval dataset are both frequency- and location-dependent: higher

frequencies saw much more deviation from the mean values than lower frequencies (Fig. 2), and Amazon2 had more dispersion than Desert (Fig. 2 and Fig. 4). Further investigation revealed strong evidence that scattering by atmospheric hydrometeors is the dominant cause (Fig. 5), indicating rain/cloud contamination in the presumed clear-sky retrievals. Additionally, since it consistently decreases the emissivity, the scattering process also causes a systematic drop in the mean emissivity values (e.g., Figs. 2c and 2d).

Apparently the retrieval of land surface emissivity, especially the instantaneous values, is a challenging task. In addition to factors highlighted in this study, many other ones, such as instrument errors (e.g., [18]), calibration errors, differences in locations and resolutions of the satellite footprints, spatial and temporal sampling errors, and representativeness of surface properties over highly heterogeneous and dynamic surfaces (e.g., desert) [13], [19], [20], all contribute to the complexity of the retrieval process and the associated errors. It is therefore necessary to recognize the limitations in these instantaneous retrievals, and to develop strategies to alleviate their impact while exacting as much useful information as possible. For example, the monthly emissivity atlas produced by Prigent et al. [11] and the climatology dataset used by TELSEM [21] employ extensive quality control and long-term averaging over multiple measurements from multiple sensors. We believe these measures can dramatically reduce both the systematic and random errors.

Our study is confined to only two sites, and the results are certainly not representative of the other types of lands surfaces, or even the rainforest and desert themselves. Over highly variable surfaces, such as desert, the interplay of the error sources can differ dramatically from one site to the next. Nevertheless, we believe the two sites over these extreme types of land surfaces give one an educated estimate on the range of errors over the land surface as a whole. This supplements another study by Ferraro et al. [10] which compared the systematic differences over a few LSWG sites in the continental United States. Together both studies yield considerable insights into the factors and processes affecting the uncertainties in these retrievals. Such insights will be helpful in future studies of a broader scope.

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He conducted research in climate dynamics and geophysical fluid dynamics at UCLA. He was also one of the developers at UCLA for the popular Advanced Spectral Analysis SSA-MTM Toolkit. Between 2000 and 2002 he had been working in the Internet industry, holding such positions as systems manager and chief technology officer. He started to work for NASA Goddard Space Flight Center in 2002, first on the development of the Land Information System (LIS), which won NASA's Software of the Year Award in 2005. More recently he has been evaluating and validating satellite-based precipitation measurements, and also working on land surface emissivity modeling to support NASA's Global Precipitation Measurement (GPM) mission.

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He conducted research in environmental and water resources systems analysis. His primary research area is decision-making under uncertainty. Of secondary interest is the accounting of uncertainty in modeling via Bayesian methods, the development of computationally-based decision support tools, and the optimization of large-scale systems. Applications extend from the adaptive management of water quality, water distribution systems modeling, water quantity management, assessment of the external damages of power generation, integrated solid waste management, and energy modeling. Most recently he helped to develop extensions in the NASA Land Information System (LIS) to carry out uncertainty estimation via Markov chain Monte Carlo methods for Bayesian analysis for application to land surface and land surface-coupled models including microwave emissivity models.

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He currently holds an assistant professor position at New York City College of Technology, CUNY. His research focus is land remote sensing using microwave measurements with focus on soil moisture and land surface emissivity.

He has been able to retrieve land surface emissivity for more than 6 years from AMSR-E observations on board Aqua satellite. His research interest includes using satellite information in vegetation structure profile, soil moisture estimation, snow cover prediction, precipitation, and estimation of soil freeze / thaw state. He is a registered Professional Engineer (PE).

**Filipe Aires** the Ph.D. degree in statistics from the University Paris–Dauphine, Paris, France, in 1999.

He was with the NASA Goddard Institute for Space Studies, New York, for five years as a post-doc and research scientist. He then obtained a CNRS (Centre National de la Recherche Scientifique ) research scientist position at the Laboratoire de Météorologie Dynamique, Paris, France.

His research interests focus on satellite remote sensing of the Earth and statistical analysis of the climate. In earlier works, he analyzed climatic signals such as El Nino, using statistical techniques such as independent component analysis. He has also defined new tools for the characterization of climate feedback. He has developed multi-instrument and multi-parameter remote sensing algorithms to retrieve atmospheric variables such as temperature, ozone, or water vapor profiles, and surface variables such as surface skin temperature, vegetation indices, or infrared or microwave emissivities. He specialized in the exploitation of the multi-wavelength synergy. Instruments involved in his work include for example IASI, AMSR-E, AMSU, HSB, MHS, SSM/I, ERS, TOVS, GOME II. He has recently developed for CNES, the French spatial agency, the SAPHIR/MADRAS water vapour algorithms for the French–Indian mission Megha-Tropiques launched in 2011. He is presently involved in various studies linked to the retrieval of IR and MW surface emissivities and atmospheric retrievals over land such as Global Precipitation Mission. He is developing a long-term global soil moisture dataset based on multi-wavelength satellite observations. He is the co-founder and CEO of Estellus, a startup in the domain of remote sensing and climate impacts.



**Sid-Ahmed Boukabara** received his Engineer and Master of Science degrees in signal processing from the *National School of Civil Aviation (ENAC)*, Toulouse, France and from the *Institut National Polytechnique de Toulouse*, France, respectively, both in 1994. He obtained his Ph.D. in remote sensing from the *Denis Diderot University* in Paris, France in 1997. He was then involved in the calibration/validation of the European Space Agency (ESA)'s ERS-2 microwave radiometer and has worked on the synergistic use of active and passive microwave measurements. He then joined AER Inc. in Cambridge, Massachusetts, as a staff scientist and worked on the design, implementation and validation of the NPOESS/CMIS physical retrieval algorithm, on the NASA SeaWinds/QuikSCAT wind vector rain flag and on the development of the atmospheric absorption model MonoRTM, dedicated to the microwave and laser applications. In 2005, he joined NOAA/NESDIS in Camp Springs, Maryland and is leading an effort to develop the capability of assimilating passive microwave measurements in all-weather conditions using a combination of variational technique algorithm and the Community Radiative Transfer Model (CRTM). Since 2009 he also serves as the deputy director of the U.S. Joint Center for Satellite Data Assimilation (JCSDA). His principal areas of interest include radiative transfer modeling, spectroscopy, algorithm development and satellite data assimilation.

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She has been studying land rainfall observed with Tropical Rainfall Measuring Mission (TRMM) at Hydrospheric Atmospheric Research Center (HyARC) of the Nagoya University since 2002. She is currently working on the development of a land surface microwave emissivity algorithm with satellite measurements in order to improve rain retrieval for the development of DPR/GMI combined algorithm as part of Japan Aerospace Exploration Agency (JAXA) Global Precipitation Measurement (GPM) mission projects.

**Hirohiko Masunaga** earned his Ph.D. in astrophysics from University of Tokyo in 1999.

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TABLE I  
FREQUENCIES OF THE MICROWAVE IMAGERS

Frequencies of Microwave Imagers (GHz)						
SSM/I			19.35	22.2 (V)	37.0	85.5
TMI		10.65	19.35	21.3 (V)	37.0	85.5
AMSR-E	6.9	10.65	18.7	23.8	36.5	89.0

TABLE II  
MEAN AND STANDARD DEVIATION OF EMISSIVITY RETRIEVALS

Frequency (GHz)	6.9	10.65	18.7/19.35	21.3/22.2/23.8	36.5/37.0	85.5/89.0
Desert, V-pol						
SSM/I F13			0.976 (3.1)	0.965 (3.4)	0.948 (2.9)	0.901 (3.9)
SSM/I F14			0.975 (4.0)	0.964 (4.4)	0.948 (3.3)	0.901 (4.3)
SSM/I F15			0.980 (3.5)	<del>1.014</del> (8.0)	0.952 (3.3)	0.907 (3.4)
TMI		0.989 (5.5)	0.992 (4.4)	0.982 (4.5)	0.967 (3.4)	0.935 (3.8)
AMSR-E (MIRS)	0.983 (1.9)	0.980 (2.2)	0.986 (2.7)	0.987 (2.8)	0.966 (4.0)	0.934 (6.5)
AMSR-E (CREST)	0.959 (3.7)	0.958 (3.4)	0.954 (3.0)	0.943 (3.0)	0.926 (2.6)	0.910 (2.6)
<b>Max - Min</b>	<b>0.024 (7.2)</b>	<b>0.031 (9.3)</b>	<b>0.038 (11.4)</b>	<b>0.044 (13.2)</b>	<b>0.041 (12.3)</b>	<b>0.034 (10.2)</b>
Desert, H-pol						
SSM/I F13			0.831 (2.8)		0.839 (2.7)	0.834 (4.3)
SSM/I F14			0.831 (3.6)		0.841 (3.1)	0.832 (4.6)
SSM/I F15			0.836 (3.1)		0.848 (2.9)	0.841 (4.0)
TMI		0.812 (4.7)	0.843 (4.1)		0.861 (3.5)	0.867 (4.0)
AMSR-E (MIRS)	0.786 (1.8)	0.793 (2.0)	0.819 (2.9)	0.833 (3.5)	0.827 (4.0)	0.829 (6.7)
AMSR-E (CREST)	0.767 (3.1)	0.779 (2.8)	0.805 (2.8)	0.827 (3.6)	0.820 (2.8)	0.856 (3.2)
<b>Max - Min</b>	<b>0.019 (5.7)</b>	<b>0.033 (9.9)</b>	<b>0.038 (11.4)</b>	<b>0.006 (1.8)</b>	<b>0.041 (12.3)</b>	<b>0.038 (11.4)</b>
Amazon2, V-pol						
SSM/I F13			0.953 (3.1)	0.939 (4.5)	0.930 (4.2)	0.896 (15.7)
SSM/I F14			0.951 (3.2)	0.937 (4.6)	0.928 (3.2)	0.902 (10.8)
SSM/I F15			0.958 (2.7)	<del>1.030</del> (12.0)	0.933 (2.7)	0.912 (6.3)
TMI		0.949 (2.7)	0.955 (3.2)	0.945 (3.6)	0.936 (3.2)	0.931 (5.3)
AMSR-E (MIRS)	0.960 (1.5)	0.954 (1.7)	0.961 (1.9)	0.955 (1.9)	0.943 (1.8)	0.934 (4.0)
AMSR-E (CREST)	0.948 (2.3)	0.939 (2.4)	0.940 (2.6)	0.938 (2.5)	0.916 (2.9)	0.968 (1.9)
<b>Max - Min</b>	<b>0.012 (3.6)</b>	<b>0.015 (4.5)</b>	<b>0.021 (6.3)</b>	<b>0.018 (5.4)</b>	<b>0.027 (8.1)</b>	<b>0.072 (21.6)</b>
Amazon2, H-pol						
SSM/I F13			0.951 (3.0)		0.926 (3.2)	0.899 (16.8)
SSM/I F14			0.952 (3.1)		0.930 (3.2)	0.902 (11.5)
SSM/I F15			0.957 (2.8)		0.937 (2.8)	0.919 (6.9)
TMI		0.945 (2.7)	0.952 (3.2)		0.936 (3.2)	0.922 (5.3)
AMSR-E (MIRS)	0.947 (1.5)	0.948 (1.8)	0.959 (2.0)	0.954 (2.1)	0.943 (1.9)	0.935 (4.2)
AMSR-E (CREST)	0.939 (2.2)	0.933 (2.4)	0.938 (2.5)	0.935 (2.4)	0.914 (2.8)	0.966 (1.9)
<b>Max - Min</b>	<b>0.008 (2.4)</b>	<b>0.015 (4.5)</b>	<b>0.021 (6.3)</b>	<b>0.019 (5.7)</b>	<b>0.029 (8.7)</b>	<b>0.067 (20.1)</b>

Standard deviations are shown in brackets in numbers equivalent to brightness temperatures (degrees Kelvin – K), assuming a physical temperature of 300K. The range (Max-Min) of mean emissivities for each frequency also has an equivalent Tb shown in

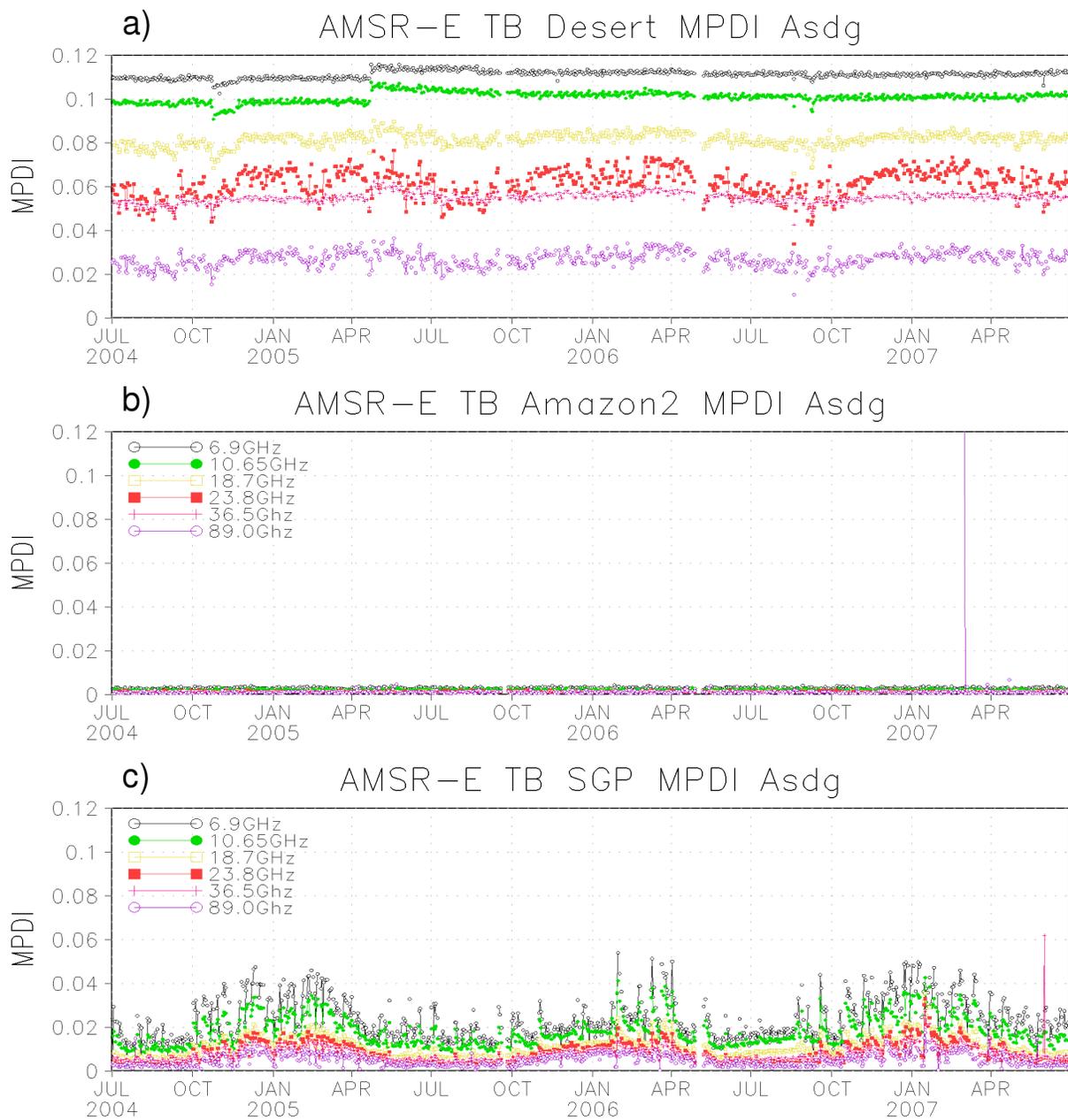


Fig. 1. MPDI calculated from AMSR-E brightness temperatures (Tb) for ascending passes of a three-year period (July 2004 through June 2007), over the three LSWG sites: a) Desert, b) Amazon2 and c) SGP.

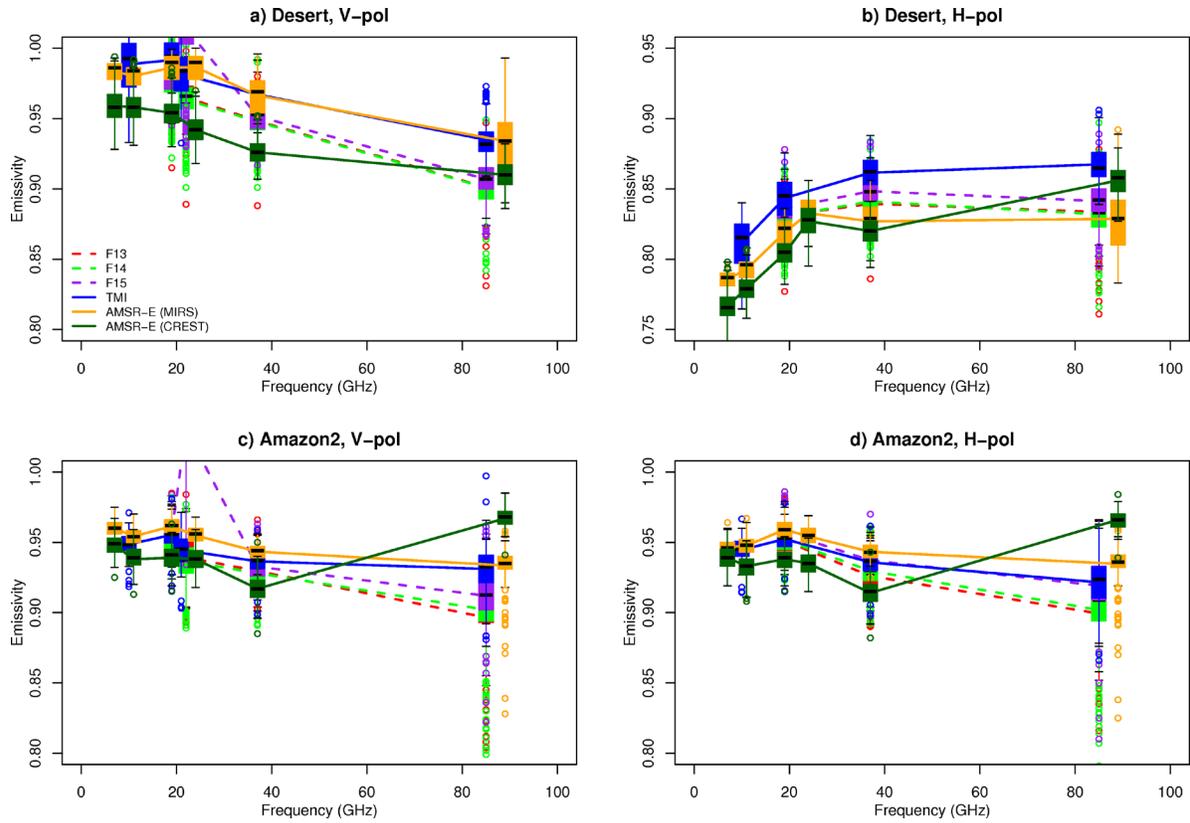


Fig. 2. Inter-comparison of microwave emissivity retrievals at two LSWG sites: Desert (top) and Amazon2 (bottom), over a one-year period from July 1, 2006 to June 30, 2007, for SSM/I (F13, F14 and F15), TMI and AMSR-E. Both vertical (left) and horizontal (right) polarizations are shown.

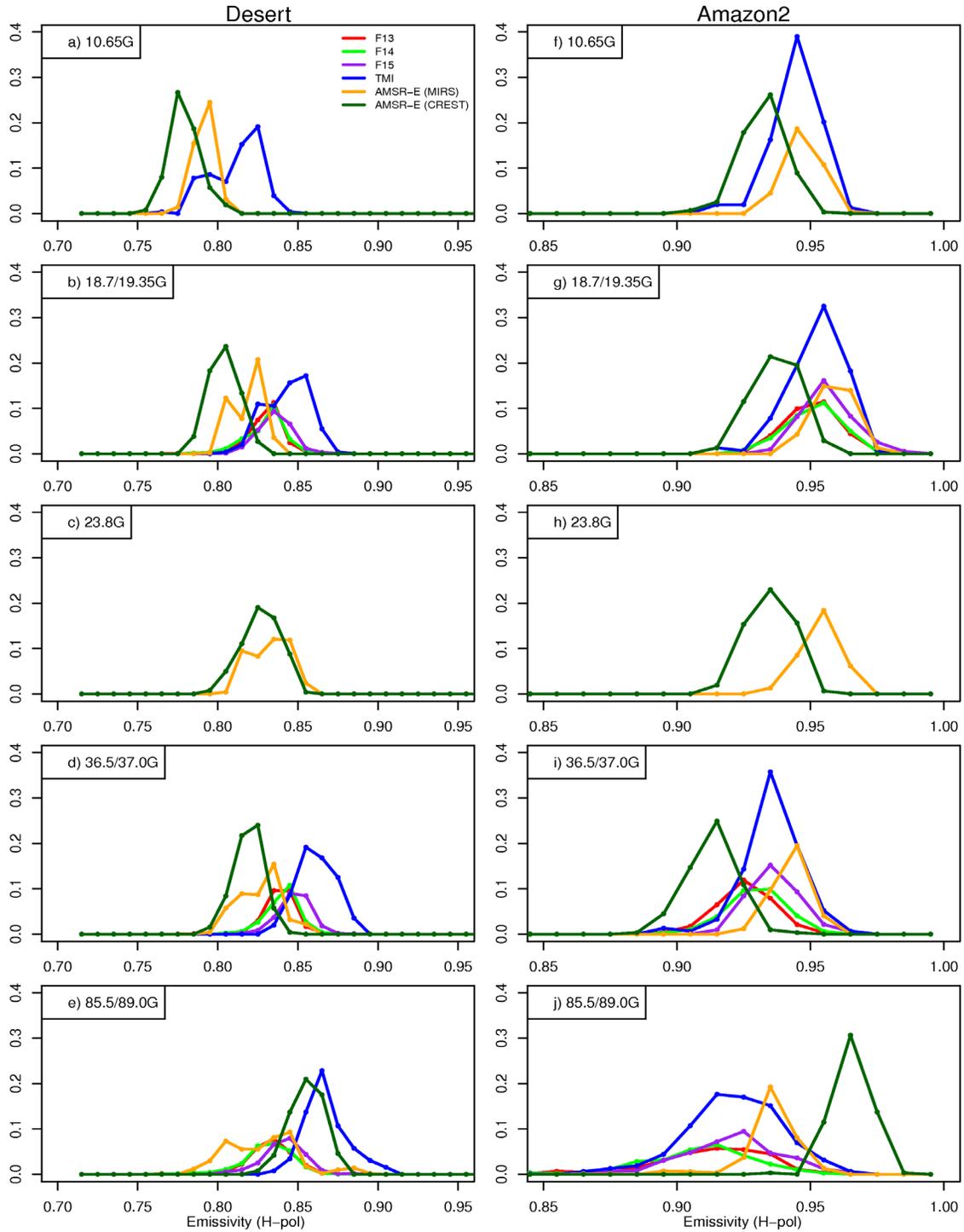


Fig. 3. Inter-comparison of the histograms of the H-pol microwave emissivity retrievals at two LSWG sites: Desert (left) and Amazon2 (bottom), over a one-year period from July 1, 2006 to June 30, 2007, for SSM/I (F13, F14 and F15), TMI and AMSR-E, for various frequencies.

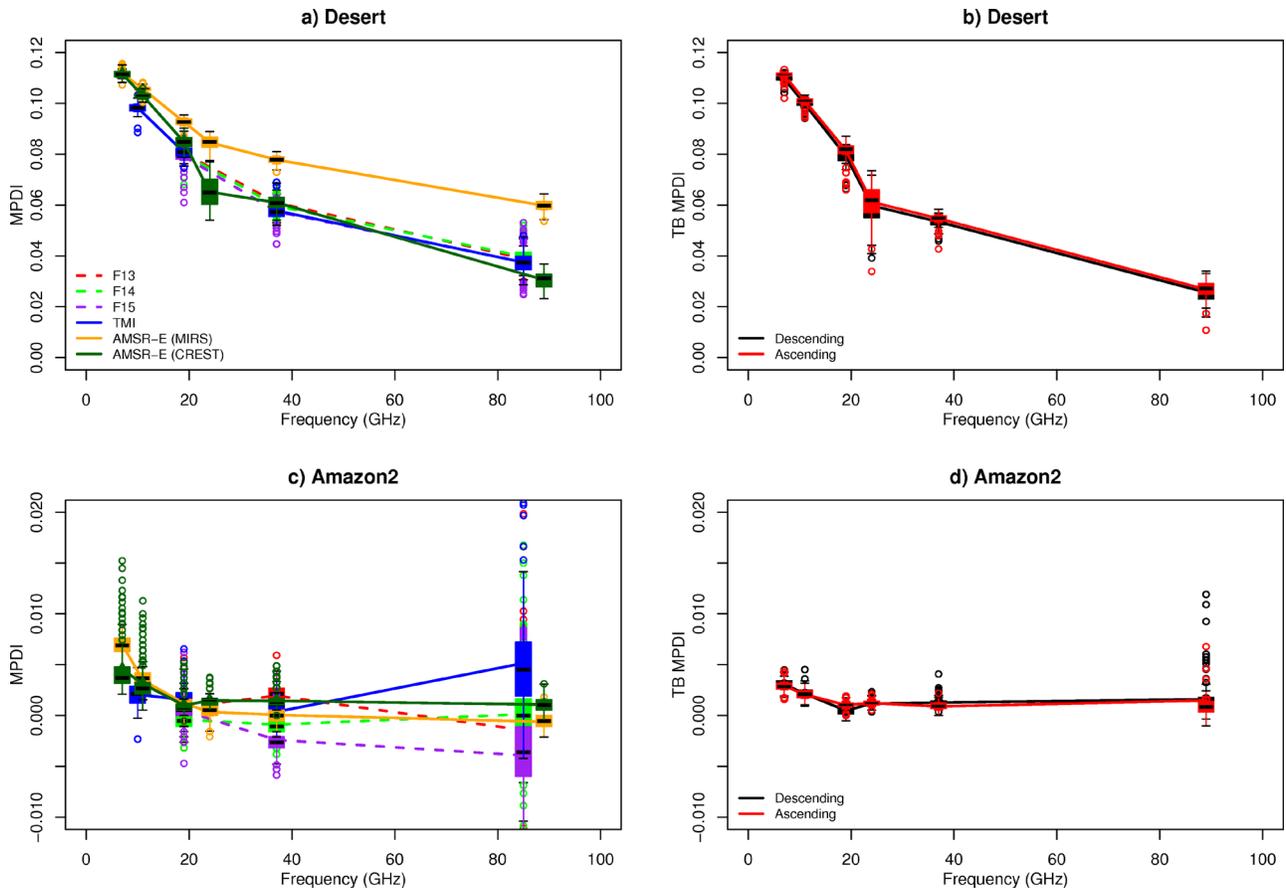


Fig. 4. Inter-comparison of emissivity-based MPDI values (left) at two LSWG sites: Desert (top) and Amazon2 (bottom), over a one-year period from July 1, 2006 to June 30, 2007, for SSM/I (F13, F14 and F15), TMI and AMSR-E. For comparison, AMSR-E Tb-based MPDI values over the same two sites are also shown (right).

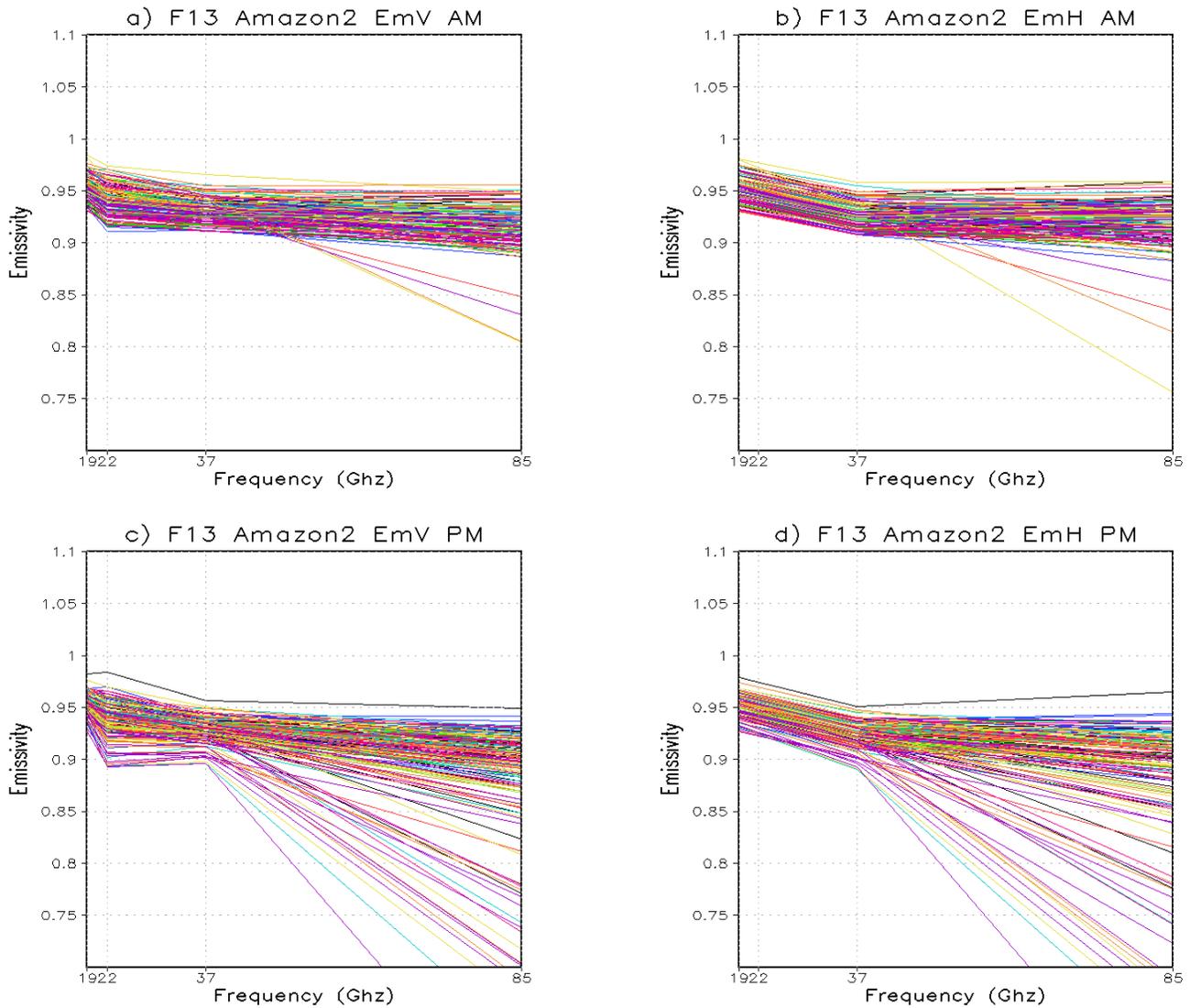


Fig. 5. Daily microwave emissivity retrievals over Amazon2 (bottom), over a one-year period from July 1, 2006 to June 30, 2007, for SSM/I F13. Both vertical (left) and horizontal (right) polarizations, as well as descending (AM, top) and ascending (PM, bottom) passes, are shown. Each daily retrieval is designated by a colored line.