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Modeling Microwave Emissions of Erg Surfaces in the Sahara Desert

Haroon Stephen, Student Member, IEEE, and David G. Long, Senior Member, IEEE

Abstract—Sand seas (ergs) of the Sahara are the most dynamic parts of the desert. Aeolian erosion, transportation, and deposition continue to reshape the surface of the ergs. The large-scale features (dunes) of these bedforms reflect the characteristics of the sand and the long-term wind. Radiometric emissions from the ergs have strong dependence on the surface geometry. We model the erg surface as composed of tilted rough facets. Each facet is characterized by a tilt distribution dependent upon the surface roughness of the facet. The radiometric temperature ($T_s$) of ergs is then the weighted sum of the $T_s$ from all the facets. We use dual-polarization $T_s$ measurements at 19 and 37 GHz from the Special Sensor Microwave Imager aboard the Defense Meteorological Satellite Program and the Tropical Rainfall Measuring Mission Microwave Imager to analyze the radiometric response of erg surfaces and compare them to the model results. The azimuth angle ($\phi$) modulation of $T_s$ is caused by the surface geometrical characteristics. It is found that longitudinal and transverse dune fields are differentiable based on their polarization difference ($\Delta T_s$) $\phi$-modulation, which reflects type and orientation of dune facets. $\Delta T_s$ measurements at 19 and 37 GHz provide consistent results. The magnitude of $\Delta T_s$ at 37 GHz is lower than at 19 GHz due to higher attenuation. The analysis of $\Delta T_s$ over dry sand provides a unique insight into radiometric emission over ergs.

Index Terms—Azimuth angle modulation, ergs, microwave emission, Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), polarization difference, radiometric temperature, sand dunes, Special Sensor Microwave Imager (SSMI/I).

I. INTRODUCTION

THE SAHARA desert is one of the most diverse terrains on Earth and consists of rocky mountains (hamadas), boulder and gravel zones (regs), and large sand seas (ergs) [1]. Erg bedforms are the most dynamic parts of the desert and undergo continuous transformation induced by the variations in the near-surface prevailing winds. In general, ergs have two scales of geometrical roughness, i.e., large-scale dunes and small-scale surface ripples that are spatially periodic [2]–[5]. Previous studies show that the microwave scattering from sand is dominated by surface scattering and is modulated by the sand bedform characteristics [6]–[8].

Microwave emission is a function of surface thermal and geometrical characteristics, and spaceborne radiometric temperature measurements have been used to classify different land surface types [9]–[13]. Azimuthal anisotropy of radiometric temperature has also been investigated. Yu [14] reported directional radiometric temperature variations caused by canopy geometry and row structure in cultivated maize fields. Prigent et al. [15] reported insignificant azimuth angle dependence over dry sand surface whereas Macelloni et al. [16] combined spaceborne radiometric temperature and backscatter measurements to study soil and vegetation. Some investigators have shown that there is strong azimuth angle modulation of microwave emission over the Antarctic surface caused by surface geometry [17]. This research shows that there is significant azimuth angle modulation over sand surfaces caused by sand bedform features.

Ergs have very low moisture content and have a homogeneous, temporally stable distribution of dielectric constant. Thus, temporal variabilities of scattering and emission from sand are mainly a function of geometrical characteristics. Emission also has an additional dependence upon the thermal characteristics of sand. Passive microwave sensors (radiometers) observe the radiometric temperature ($T_r$) of a target as a measure of its radiometric emission. The $T_r$ value observed is a function of the surface physical temperature and surface emissivity. Over a rough surface, $T_r$ measurements are modulated by the look direction and also depend upon the frequency and polarization of the instrument.

We use dual-polarization $T_r$ measurements at 19 and 37 GHz from the Special Sensor Microwave Imager (SSMI/I) aboard the Defense Meteorological Satellite Program (DMSP) [18], [19] and the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) [20] and simple electromagnetic models to study the radiometric response of erg surfaces. We introduce an observational empirical model that combines SSM/I and TMI data to estimate the $T_r$ azimuthal anisotropy over sand surfaces. It is shown that the observed $T_r$ is modulated by the look direction and that the modulation is a function of the surface profile. The modulation indicates the surface characteristics, i.e., dune types and their orientation. Shadowing and Sun illumination effects are ignored in explaining the radiometric behavior of sand.

Sand radiometric emission is described in Section II along with a simple facet model to explain the dual-polarization emission over sand dunes. Section II also includes the model simulation of $T_r$ azimuth angle ($\phi$) modulation over simple dunes. The $\phi$-modulation and time-of-day ($t_d$) modulation of the observed $T_r$ data and a comparison to model simulation results are given in Section III. This section also compares the $T_r$ observations at 19- and 37-GHz frequencies. A summary and conclusion follows in Section IV.

Three erg sites that have flat sand sheets, transverse dunes, and longitudinal dunes located at 31.7°N, 0.5°E (location 1), 17.5°N, 9.3°W (location 2), and 17.5°N, 15.3°W (location 3), respectively, are selected to study the $T_r$ response. The description of these dune types is given in [6]. The site information is extracted from [21].

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II. RADIOMETRIC EMISSION FROM SAND

In this section, a theoretical background of radiometric emission over sand is described. An emission model from layered media is applied to sand in Section II-A, followed by a description of a simple rough facet model of radiometric temperature in Section II-B. Section II-C presents the simulation of the model over simple dune shapes.

A. Background

Sand emission depends upon the desert surface geometry and volumetric dielectric and thermal characteristics. Mathematically, \( T_b \) is given by

\[
T_b(\theta, \phi, f, p) = \epsilon(\theta, \phi, f, p) T, \quad p = v, h
\]

(1)

where \( \theta \) and \( \phi \) are the incidence and azimuth angles of observation, respectively, while \( f, p, T, \) and \( \epsilon \) denote the frequency, polarization, physical temperature, and emissivity, respectively. \( v \) and \( h \) denote vertical (V-pol) and horizontal (H-pol) polarizations, respectively. For very dry soil, the electromagnetic wave penetration depth \( (\delta_p) \) is approximately equal to its free-space wavelength \([15],[22]\). The depth of sand that contributes to the measured \( T_b \) is called sampling depth \( (\tau) \) and is related to the penetration depth by \( \tau \approx 3\delta_p \cos \theta \).

For soils in the deserts, microwave radiation is estimated to come from soil layers down to depths of five wavelengths and at frequencies greater than 15 GHz, emission is proportional to surface skin temperature \([15]\).

The total emission is the sum of volume and surface emissions. Volumetric emission is nearly isotropic and unpolarized. The air–sand boundary transmission coefficient for V-pol and H-pol polarizations depends on \( \theta \), resulting in the \( \theta \)-dependence of \( T_b \). Furthermore, local incidence angle \( (\theta_f) \) of tilted facets changes with azimuth angle, resulting in \( \phi \)-dependence of \( T_b \). \( T_b \) observed by the radiometer is a result of volumetric emission of the sand, modulated by the look direction due to the local surface slope variations.

We use the radiometric emission model for a layered dielectric material given in \([23]\), eqs. 5.2.36a and 5.2.36b. This model is based on the fluctuating electromagnetic field theory of dissipative materials. The electromagnetic field is produced by the spontaneous local electric and magnetic moments arising from the thermally induced random motion of its charges. This model is derived for a stratified material with a temperature profile. The medium has \( n + 1 \) layers where the \( (n + 1) \)th layer extends infinitely below the \( n \)th layer. \( T_I \) and \( \epsilon_I \) denote the physical temperature and electrical permittivity of the \( l \)th layer, respectively, and \( d_{l-1} \) and \( d_l \) denote the distance of the layer’s upper and lower boundaries, respectively, from the air–sand boundary. In the model, the sampling depth is divided into \( n \) layers with the \( (n + 1) \)th layer being the remaining half space of sand below sampling depth. Thus, the distance of the lower boundary of the \( n \)th layer is equal to the sampling depth, i.e., \( d_n = \tau \).

Sand is a spatially homogeneous medium. We model it as an infinite half space with isothermal horizontal strata and a smooth vertical temperature profile. Since sand in the Sahara desert has a low moisture content that does not change over time, we assume the sand to have a temporally stable dielectric constant. Moreover, we assume the sand dielectric constant to be spatially homogeneous within the footprint of observation. The vertical temperature profile of sand depends on time-of-day and season (time-of-year). During the day time, the sand surface temperature is higher than the subsurface temperature, and lower at night. We apply a mean diurnal temperature profile to the model and assume it falls off exponentially from a surface temperature \( (T_0) \) to a nominal subsurface temperature \( (T_{\tau}) \) over the sampling depth \( \tau \). After applying these considerations, the radiometric temperature for H-pol \( (T_{Ih}) \) and V-pol \( (T_{Iv}) \) given in \([23]\) becomes

\[
T_{Ih}(\theta) = \frac{k_0}{\cos \theta} \frac{\epsilon_f}{\epsilon_0} \frac{\epsilon_f'}{\epsilon_0'} \left[ \left| T_{TM} \right|^2 \right]
\]

\[\times \left[ T_I e^{-2k_{l-1}d_n} - \sum_{l=1}^{n} \left( T_I e^{-2k_{l-1}d_l} - e^{-2k_{l-1}d_{l-1}} \right) \right] \]

(2)

where \( k_0, \theta, \) and \( \epsilon_0 \) are the wavenumber, incidence angle, and electrical permittivity in the air, respectively. \( k_2 \) and \( k_{2\perp} \) are the wavenumbers and \( z \) component in the sand, respectively, \( \epsilon_f' \) and \( k_{2\perp}' \) denote the imaginary parts of complex electrical permittivity and \( k_{2\perp} \) in sand, respectively. \( k_z = k_0 \sin \theta \) is the surface component of incident wavenumber. \( T_{TM} \) denote the transmission coefficients between air and sand for H- and V-pol, respectively. \( T_I \) and \( T_{TM} \) are the physical temperatures of \( l \)th and \( (n + 1) \)th layer, respectively. In the derivation of (2), Tsang \([23]\) has taken into account the effect of reflections between layers.

Dry sand has a low relative electrical permittivity \( (\epsilon_f) \) and we use a nominal value of 2 + 10^{-4} in the simulation of (2) \([24]\). The corresponding Brewster angle is approximately 55°. The diurnal mean surface and subsurface temperatures are assumed to be 330 and 310 K with a sampling depth of 6 cm (about four wavelengths at 19 GHz) and \( n = 100 \) (101 layers). Fig. 1(a) shows \( \theta \)-response of both \( T_{Ih} \) and \( T_{Iv} \) computed from (2). At nadir, V-pol and H-pol \( T_b \) have the same value and \( T_{Ih} \) decreases as \( \theta \) is increased. On the other hand, \( T_{Iv} \) increases initially and reaches its maximum at the Brewster angle beyond which it rapidly rolls-off. \( T_{Iv} \) is higher than \( T_{Ih} \) for off-nadir incident directions and the difference between two radiometric temperatures is also a function of \( \theta \). We define the polarization difference \( (\Delta T_I) \) as

\[
\Delta T_I(\theta, \phi) = T_{Iv}(\theta, \phi) - T_{Ih}(\theta, \phi).
\]

(3)

The local incidence angle \( \theta \) is a function of look direction \( (\theta, \phi) \) and surface tilt \((\theta_s, \phi_s)\) where \( \theta_s \) and \( \phi_s \) are the spherical angles of the facet’s unit normal. Since SSM/I and TMI observations are made at fixed \( \theta = \pi / 2 \) for a fixed azimuth direction \( \phi \) the local incidence angle \( \theta \) depends only on \( (\theta_s, \phi_s) \). Thus, \( \Delta T_I \) is a function of tilt of the surface. This also makes the polarization of the emitted wave a function of the surface tilt, i.e., a wave from a tilted surface has a different polarization than from a flat surface. Fig. 1(a) also shows the incidence angle dependence of \( \Delta T_I \), which gradually increases with \( \theta \) \((\Delta T_I \) is zero at nadir), and decreases rapidly back to zero at grazing incidence angles. Plots 1(b)-(f) illustrate the sensitivity of \( T_I \) and \( \Delta T_I \) to other model parameters. The responses have insignificant dependence on surface temperature \(\text{[Fig. 1(b)]}\) and sampling depth.
and, and, and, and.

response over the sand model simulations for and radiometer. The tilt angle. The and, for practical is from a tilted facet (denoted by ) is the fraction of footprint area covered by the is the surface area illuminated at an incidence angle ; thus, any by -polarization to be and polarization is independent of these .

Subsurface nominal temperature [Fig. 1(c)] and the imaginary part of complex electrical permittivity [Fig. 1(f)] alter the response but do not have significant effect on . The real part of complex electrical permittivity has the most significant effect on [Fig. 1(e)]. This analysis demonstrates that mainly depends on the real part of and, for practical purposes, is insensitive to other model parameters. This makes very suitable for modeling the response over the sand dune bedforms.

B. Facet Model

An erg is composed of large-scale dunes that are modeled as rough facets with a tilt distribution [6], [22]. Each rough facet is characterized by a tilt distribution , which is the probability of occurrence of a local unit normal in the direction. We model from a tilted facet (denoted by ) is the weighted average of from all parts of the facet where the probability distribution of tilt is used as the weighting function. as a function of look direction and polarization is given by

\[ T_{\text{id}}(\theta, \phi; p) = \int T_{\text{b}}(\theta'; p; T_{\text{r}}, T_{\tau}) P(\theta_s, \phi_s) d\theta' \]  

(4)

where is the local incidence angle, which is a function of the surface tilt ( and radiometer’s look direction ( and ). is the radiometric response of a flat facet (with zero tilt) as given in Fig. 1(a). A zero-tilt facet is azimuthally isotropic, i.e., then any azimuthal anisotropy results from the nonzero tilt of the facet surface. of a facet is given by

\[ \Delta T_{\text{id}}(\theta, \phi) = \int \Delta T_{\text{b}}(\theta') P(\theta_s, \phi_s) d\theta'. \]  

(5)

Note that dependence on polarization and thermal characteristics is dropped since is independent of these characteristics.

The response of the dunes is the linear combination of the responses from the individual dominant facets weighted by their projected area. Thus, we model the total radiometric response from dunes (denoted ) at -polarization to be

\[ T_{\text{kdl}}(\theta, \phi; p) = \frac{1}{A'} \sum_{n} A'_n \int T_{\text{b}}(\theta'; p; T_{\text{r}}, T_{\tau}) P_n(\theta_s, \phi_s) d\theta' \]  

(6)

where and are the projected areas of the antenna footprint and -th rough facet, respectively (Fig. 2). The summation is over all the dominant rough facets in the footprint of the sensor. If is the surface area illuminated at an incidence angle , and is the actual surface area of the facet with a local incidence angle , then . The tilt angle of the facet is related to its horizontal projection ( ) by . Using these relationships in (6) we obtain

\[ T_{\text{kdl}}(\theta, \phi; p) = \frac{1}{A'} \sum_{n} F_n^{\text{cos} \theta'_n} A'_n P_n(\theta_s, \phi_s) \int T_{\text{b}}(\theta'; p; T_{\text{r}}, T_{\tau}) d\theta' \]  

(7)

where is the fraction of footprint area covered by the -th facet that has a mean tilt angle and a mean local incidence.
angle $\theta'_n$, $F_n$ is related to the dune shape and is easily estimated for simple dunes. The net $\Delta T_{1b}$ over the dune field is given by

$$\Delta T_{1bl}(\theta, \phi) = \sum_{n} F_n \cos \theta_n \cos \theta \int \Delta T_{1b}(\theta') P_n(\theta, \phi) d\theta'. \tag{8}$$

\section*{C. $\Delta T_{1b}$ Response Over Model Dunes}

In this section we use the rough facet model [(7), (8)] to determine the simulated $T_{1b}$ and $\Delta T_{1b}$ response over simple dune surfaces. First, the simulation results over single tilted facets are presented. The facet radiometric response model [(4), (5)] is applied separately to two different facets tilted at 15° and 30° that correspond to the wind- and slip-side slopes of a transverse dune. The azimuth orientation $\phi_n$ of the facets is 60°. The $\alpha$-angle is defined as the sensor azimuth angle relative to the facet azimuth orientation given by $\alpha = \phi - \phi_n$. Fig. 3 shows the $\phi$-response of simulation results at a sensor incidence angle of 53° (corresponding to the incidence angle of SSM/I and TMI). The magnitude of $H$- and $V$-pol $T_{1b}$ $\phi$-modulation increases with the slope of the facet and minimum $T_{1b}$ occurs when $\alpha = 180^\circ$. $T_{1 lv}$ is higher than $T_{1 b h}$, and the difference $\Delta T_{1 b}$ is minimum at $\alpha = 0^\circ$ [Fig. 3(b)] since $\theta'$ is minimum at this $\alpha$-angle [Fig. 3(c)]. The maximum of $\Delta T_{1 b}$ and $\theta'$ occur at $\alpha = 180^\circ$. For steeper facets, $\theta'$ approaches grazing angles at $\alpha = 180^\circ$, resulting in a drop of $\Delta T_{1 b}$ at the facet grazing angle [Fig. 1(a)].

The $T_{1 b}$ $\phi$-response of a tilted facet depends upon the slope and azimuth orientation of the facet: $T_{1 b}$ is inversely proportional to the local incidence angle. $T_{1 lv}$ and $T_{1 b h}$ have distinct $\phi$-responses, and $T_{1 lv}$ is higher in magnitude than $T_{1 b h}$. $\Delta T_{1 b}$ is directly proportional to $\theta'$. The minima and maxima of $\Delta T_{1 b}$ $\phi$-modulation over tilted facets correspond to $\alpha$-angles of 0° and 180°, respectively. In the next two subsections, the results of the simulation over model longitudinal and transverse dunes are presented.

1) Longitudinal Dunes: A longitudinal dune is characterized by two slip sides and a flat interdune area as shown in Fig. 4 [6]. The slope of both slip-sides is 30° to 35° (the angle of repose of sand) and their azimuth orientations differ by 180°. The long axis of the dune is 90° relative to the azimuth directions of the slip-sides and is along the mean wind direction that formed the dune. We model the longitudinal dune as a composite of three rough facets that correspond to two slip-sides and an interdune flat surface. The cross section of a longitudinal dune shown in Fig. 4(c) indicates the minimum and maximum local incidence angles resulting from the slopes of the facets as viewed by a sensor at an incidence angle of 53°. As $\phi$ changes, $\theta'$ of the facet changes between the minimum and maximum values. In the model simulation, the two slip-sides have a Gaussian tilt distribution for $(\theta_n, \phi_n)$ with means (30°, 170°) and (30°, 350°) and standard deviations of 5° each. The covariance between $\theta_n$ and $\phi_n$ is assumed to be zero in this research. The flat interdune facet has a mean tilt of (0°, 0°) with a standard deviation of (5°, 10°) and zero covariance. Fig. 5 shows the model $T_{1b}$ and $\Delta T_{1b}$ results. The two slip-sides of the longitudinal dune result in two maxima in $T_{1 h s}$, and two minima in $T_{1 l v}$, $\phi$-responses. The $\phi$ angle at which these maxima or minima occur correspond to the azimuth directions of the facets. This opposite behavior of $T_{1 lv}$ and $T_{1 h s}$ results in minimum $\Delta T_{1 b}$ when $\phi$ is along the azimuth directions of the slip-sides. $\Delta T_{1 b}$ is minimum when a slip-side has a near nadir view and increases when $\phi$ is changed from this direction. Simultaneously, the contribution from the other slip-side starts increasing and this results in an azimuth modulation signal in $\Delta T_{1 b}$ with peaks occurring when $\phi$ is along the axis of the dune. $\Delta T_{1 b}$ is maximum at $\phi$ directions along the axis of the dune.

2) Transverse Dunes: A transverse dune has a wind-side slope of 10° to 15° and a slip-side slope similar to a longitudinal dune. The azimuth directions of these two sides differ by 180°. The axis of the dune is defined similar to a longitudinal dune, but the wind direction that produces this dune corresponds to the azimuth direction of the slip-side, i.e., perpendicular to the long axis of the dune. We model the transverse dune as a composite of three rough facets that correspond to a slip-side, a wind-side, and an interdune flat surface [6]. Fig. 6(b) illustrates the three-facet model for a transverse dune. Fig. 6(c) shows the cross section of a transverse dune where the shaded portion represents the range of possible local incidence angles for each facet viewed at $\theta = 53°$.

Interdune flat facet, wind-side, and slip-side are assumed to have Gaussian tilt distributions for $(\theta_n, \phi_n)$ with means (0°, 0°),...
and standard deviations (30°, 10°), respectively. The covari-
cation caused by the tilted rough surfaces. Since 
modulation occurs 
observed by TMI

modulation with a lower mean value due 

Sand in the tropics undergoes a diurnal cycle of tempera-
ture variation. The solar incident radiation intensity is a func-
te of time-of-day and season (time-of-year). Illuminated by 
the Sun during the day, sand absorbs the Sun’s radiation, which 
increases its internal and surface temperature. Sand cools down 
during the night by dissipating thermal radiation. Fig. 7 shows 
the resulting diurnal variation of $T_{1h}$ and $T_{1h}$ observed by TMI 
and SSM/I sensors. The data is acquired during Julian day (JD) 
185-2002 and JD 238-2002 and is shown for three erg targets: 
flat sand sheet, transverse dunes, and longitudinal dunes. The 
two sensors show good cross-calibration and similar diurnal 
modulation. $\Delta T_{1h}$ is also plotted and reveals higher noise over 
the dunes (compared to sand sheet) due to the higher $\phi$-modula-
tion caused by dune surface geometry. The small variation of 
$T_{1h}$ over the sand sheet indicates insignificant $\phi$-modulation.

As previously noted, $\Delta T_{1h}$ is dependent on the surface profile 
characteristics and dielectric constant. The local incidence angle 
over a flat sand sheet [Fig. 7(d)] is almost equal to the incidence 
angle of observation ($\theta = 53°$) and does not change with the

III. SPACEBORNE $T_{1h}$ OBSERVATIONS

In this section, dual-polarization 19- and 37-GHz $T_{1h}$ mea-
urements from TMI and SSM/I over Saharan ergs are used to 
analyze the radiometric emission behavior of dunes in compari-
son with model prediction. TMI and SSM/I make $T_{1h}$ mea-
urements at an incidence angle of 52.75° and 53.4°, respectively. The scan pattern of TMI and SSM/I sensors, in combination 
with the orbit geometry of the ascending and descending passes, 
provides $T_{1h}$ measurements sampled at many azimuth angles.

The orbit of the TRMM satellite is inclined at approximately 
30°. The orbit longitude of the ascending node shifts every re-
ppeat cycle. This helps TMI acquire $T_{1h}$ measurements of the 
target sampled at various times-of-day. SSM/I acquisition of the 
target is made in a sun-synchronous orbit at two times-of-day. 
We combine SSM/I data from three DMSP satellites (F13, F14, 
and F15) to obtain six times-of-day measurements (30°, 50°, and 70°), respectively, and standard deviations (3°, 5°), (3°, 10°), and (3°, 10°), respectively. The covari-
cation between $\theta_d$ and $\phi$ is zero. Fig. 5 shows the model results 
for a transverse dune. The $T_{1h}$ $\phi$-response is similar to longitudi-
dinal dunes, but has a higher magnitude of modulation. In the 
$\Delta T_{1h}$ response, the global minimum in the $\phi$ modulation occurs 
in the azimuth direction of the slip-side of the dune whereas a second minimum occurs at the wind-side azimuth direction. Fig. 5(d) and (e) summarizes the $\phi$-modulation of the observed data described in Section III.

The analysis of model simulations over individual facets and 
composite facet surfaces suggests that $T_{1h}$ and $T_{1h}$ have signif-
icant $\phi$-modulation caused by the tilted rough surfaces. Since 
$\Delta T_{1h}$ is independent of the thermal characteristics of the surface, its $\phi$-modulation is only dependent upon the dielectric constant 
and surface geometrical characteristics. Model simulations at 
37 GHz give similar $\phi$-modulation with a lower mean value due 
to higher attenuation. The $\Delta T_{1h}$ $\phi$-modulation of model dune 
surfaces reflects the presence of tilted facets and helps identify 
the underlying dune types.
azimuth angle resulting in a $\Delta T_{b}$ of about 30 K (Fig. 1). Over transverse dunes [Fig. 7(e)] the tilt of wind- and slip-sides results in more contribution at relatively smaller local incidence angles, thus reducing $\Delta T_{b}$. Over the slip-side, the minimum $\theta$ is 18° (Fig. 4). This is also evident from the longitudinal dunes [Fig. 7(f)] where $\Delta T_{b}$ is further reduced due to the presence of two slip-sides. It should also be noticed that $\Delta T_{b}$ also has a minor diurnal variation. The azimuth angle sampling of the data contributes to $\Delta T_{b}$ diurnal variation. The diurnal variation of the surface emissivity and surface small-scale features (ripples) and Sun inclination also contribute to $\Delta T_{b}$ diurnal variation. This $t_{d}$-response is well modeled by a second-order harmonic equation shown with dashed lines.

Fig. 8 depicts the azimuth angle variation of observed $T_{b}$. The magnitude of the azimuth angle modulation is lower than the diurnal modulation but reveals useful information about the surface bedform characteristics. Combining the data from two sensors results in a denser azimuth angle sampling. The high variance in the data is due to sampling of data at different times-of-day. The analysis of the $T_{b}$ azimuth angle variation at a narrow range of $t_{d}$ reveals that $T_{b}$ $\phi$-modulation also follows a second-order harmonic relationship shown with dashed lines.

The $T_{b}$ observations have coupled dependence on the $t_{d}$ and $\phi$. The magnitude of azimuth modulation is very low compared to the magnitude of the diurnal variation. Based on the observed $\phi$- and $t_{d}$-modulation of both $T_{b}$ and $\Delta T_{b}$, a descriptive empirical observation model is used to remove the $t_{d}$ dependence of the data. We use a simple additive model given by

$$\Delta T_{b}(t_{d}, \phi) = T_{sat} + T_{d}(t_{d}) + T_{\phi}(\phi)$$  \hspace{1cm} (9)
Using both TMI and SSM/I data improves the radiometric temperature of the sand surface. Although the mean values of the radiometric temperature of the sand surface are shown in Fig. 5(d) for 37 GHz. The plots from the model and observations are consistent with the theoretical model used in Section II. The solid lines correspond to the 19-GHz observed data and slices at particular $\phi$ and $t_d$. The solid lines correspond to the data and perform a surface fit to the data using a least squares solution. The accuracy of the fit to this model depends upon the $\phi - t_d$ sampling of the data. $\phi$-modulation after removal of $t_d$ dependence from observations is consistent with the theoretical model used in Section II. Fig. 9 shows the $\phi - t_d$ sampling of the combined TMI and SSM/I data over two target areas. Although the sampling is irregular, sparse, and contains large gaps, the least squares fit provides a reasonable estimate of the model parameters. Using both TMI and SSM/I data improves the $\phi$-sampling of observations. $T_{1w}$ and $T_{1h}$ dependence on $t_d$ and $\phi$ is also modeled by a sum of two second-order harmonics.

$$T_{1w}(t_d) = N_1 \cos \left( \frac{\pi}{12} (t_d - t_{d1}) \right) + N_2 \cos \left( \frac{\pi}{12} (2t_d - t_{d2}) \right)$$

$$T_{1h}(\phi) = M_1 \cos(\phi - \phi_1) + M_2 \cos(2\phi - \phi_2)$$

Fig. 10 illustrates the surface fit to the 19-GHz observed data and slices at particular $\phi$ and $t_d$. The solid lines correspond to the model parameters to remove the $t_d$ dependence of $T_{1w}$ and $\Delta T_{1w}$ to retrieve the $\phi$-modulation of the data shown in Fig. 5(d)–(f). The plots from the model and observations show similar results for both types of dunes. The comparison confirms that the presence of tilted facets modulates the radiometric temperature of the sand surface. Although the mean values of $T_{1w}$ and $T_{1h}$ for the model simulation are slightly
different from the observations, the modulation characteristics are similar. In the case of $\Delta T_{\text{hy}}$, both the mean and the magnitude of the $\phi$-modulation are consistent between the model and the observations. Fig. 11 shows similar $\phi$-modulation from observations at 37 GHz. The mean $T_{\text{hy}}$ and $\Delta T_{\text{hy}}$ are lower than 19 GHz due to higher attenuation. Table II lists the root mean square (rms) errors of different model fits used. RMS error is the square root of the mean of the squared differences between the model and the observations. The additive ($t_{\text{hy}}, \phi$) second-order harmonic model reduces the rms error of fit compared to the individual second-order harmonic fits for $t_{\text{hy}}$ and $\phi$. The facet model of layered sand has higher rms error than the observation model; however, all the models fit better to the $\Delta T_{\text{hy}}$. Given the uncertainties in the assumptions used in the facet model, it is remarkably accurate. The fits have higher error over transverse dune area due to higher surface profile variations than the longitudinal dune area. Moreover, the rms error increases with frequency. The correlation coefficients between facet model and empirical observation model fit for $T_{\text{hy}}, T_{\text{hx}}$, and $\Delta T_{\text{hy}}$ of longitudinal dunes are 0.22, 0.79, and 0.95, respectively, and 0.60, 0.91, and 0.95, for transverse dunes.

The results reveal the dominant effect of surface geometry and are similar to those found from model simulations. The simulated and observed $\Delta T_{\text{hy}}$ reveal significant similarity in magnitudes and phases. The difference in $T_{\text{hx}}$ and $T_{\text{hy}}$ between the model simulation and the observed data may be due to ignoring the Sun inclination and because the subsurface temperature profile used does not represent the actual sand thermal conditions.

### IV. SUMMARY AND CONCLUSION

Radiometric emissions from erg surfaces are analyzed using SSM/I and TMI dual-polarization $T_{\text{bx}}$ observations. Combining the data from the two sensors improves the azimuth angle sampling of the data. The observed $T_{\text{bx}}$ versus $\phi$ is modulated by the surface geometrical characteristics and reflects the presence of dominant dune facets. $\Delta T_{\text{hy}}$ has negligible dependence on the thermal characteristics of the surface and its $\phi$-modulation varies with changes in the surface geometrical characteristics.

A simple rough facet model is used to model the $T_{\text{bx}}$ response from the erg surface. Large-scale dunes are treated as composed of dominant facets. An emission model based on fluctuating electromagnetic field theory for dissipative materials is used to estimate the $T_{\text{bx}}$ and $\Delta T_{\text{bx}}$ incidence angle response for a flat sand surface. The total $T_{\text{bx}}$ from dunes is the weighted sum of $T_{\text{bx}}$ response from its dominant facets. When modeled as surfaces composed of multiple rough facets, longitudinal and transverse dunes exhibit significant differences in their $T_{\text{bx}}$ and $\Delta T_{\text{bx}}$. $\phi$-modulation: $\Delta T_{\text{bx}}$ decreases whereas $T_{\text{bx}}$ increases due to a decrease in $\theta$. Thus, a tilted facet reveals its presence as a minimum in $\Delta T_{\text{bx}}$, $\phi$-response, where the magnitude of the $\Delta T_{\text{bx}}$ reflects the tilt of the facet. The model simulation results are consistent with the satellite observations over areas of known dune types. Model simulation and satellite observations at 19 and 37 GHz provide similar information about the dune shape and type.

TMI-acquired $T_{\text{bx}}$ observations at many times-of-day reveal the diurnal temperature cycle of the sand surface. The time-of-day dependence is removed by using a descriptive empirical observation model with two additive second-order

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### TABLE I

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<th>Facet model</th>
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### TABLE II

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Fig. 11. (a)–(c) simulated $T_{\text{bx}}$ and $\Delta T_{\text{bx}}$ response over triple-facet transverse and longitudinal dune models. (d)–(f) $T_{\text{bx}}$ and $\Delta T_{\text{bx}}$ response derived from SSM/I and TMI observed data at 37 GHz.
harmonics. Although there is significant $T_{10}$ diurnal dependence, it is shown that $T_{10}$ $\phi$-modulation of 2–5 K is observed as a result of surface geometrical characteristics. The $\phi$-modulation of $\Delta T_{10}$ depends upon the tilt and orientation of the facets in the footprint of the sensor and can be used to distinguish between longitudinal and transverse dune surfaces. A logical extension of this result is to invert the proposed model to extract surface geometry from the $T_{10}$ observations. The $\phi$-modulation caused by surface geometry is quite significant and needs to be taken into consideration while studying such surfaces or calibrating radiometers over such terrains. The complementarity of passive and active remote sensing can be explored by combining microwave emission and scattering observations over sand surfaces. The analysis can be extended to other surfaces with periodic geometries such as snow for a better understanding of their radiometric emissions. The understanding of radiometric emissions over such surfaces can help in the design of future precision radimeters. We note that this research ignores the shadowing and Sun illumination effects in explaining the radiometric behavior of sand.

REFERENCES


