Surface Statistics of the Saharan Ergs observed in the σ^o Azimuth Modulation

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***Abstract*— Saharo-Arabian deserts includes large expanses of sand dunes called ergs. These dunes are formed and constantly reshaped by prevailing winds. Previous study shows that Saharan ergs exhibit significant backscatter (σ^o) azimuth angle (ϕ) modulation. The phases of the modeled σ^o versus ϕ harmonics over the ergs are correlated to the orientation of the dune fields. Most of the vertical variation in ergs has low frequencies due to dunes (>100m) while high frequency variation is due to centimeter scale surface ripples. Although large scale features may be aperiodic, the small scale features are periodic and rapidly respond to changes in the prevailing wind which change their orientation and wavelength.**

In this paper, we use σ^o measurements from ERS scatterometer (ESCAT) and NASA scatterometer (NSCAT) to determine the surface profile statistics of the sand dunes. The total backscattering coefficient σ^o_T from the sand as a function of incidence angle (θ) and ϕ is modeled as a sum is the contributions from surface scattering, subsurface volume scattering and subsurface bedrock scattering. The σ^o variations with the θ for different ϕ directions are observed.

I. Introduction

The Saharo-Arabian deserts present one of the largest arid regions of Earth and constitute the most inhomogeneous land surface. It includes the Sahara desert in the North Africa and Arabian desert in the Arabian peninsula, each consisting of diverse terrains such as rocky mountains, small- and large-scale-gravel zones and vast sand-seas. The sand-seas (*Ergs*) exhibit very dynamic behavior attributed to the aeolian processes. The prevailing winds continue to reshape the deserts by eroding and transporting the sand particles. This results in a terrain with a variety of sand features including many types of dunes and small scale ripples.

Spaceborne microwave remote sensors have proven to be very useful tools for observing land surfaces. Scatterometer backscatter (σ^o) measurements are sensitive to both geometrical and dielectric properties of the surface, which, due to negligible moisture over the *ergs*, primarily depend upon the geometrical features.

ERS scatterometer (ESCAT) and NASA scatterometer (NSCAT) provide *C*-band and *Ku*-band σ^o measurements of the Earth's surface. These σ^o measurements have been used operationally to measure near surface wind fields over the ocean. The ESCAT provides vertical polarization whereas NSCAT provides both horizontal and vertical polarization σ^o data at multiple surface incidence and azimuth angles.

In this paper, σ^o measurements from ESCAT and NSCAT are observed for their incidence and azimuth angle dependence over the *ergs* of Sahara desert.

A. Winds and Dunes

The shape, size and orientation of the dunes and ripples are a function of both the wind characteristics and sand grain distribution. The speed of the wind is directly proportional to the drift potential, or the ability of wind to transport sand particles. The annual distribution of the wind direction may be characterized as narrow or wide unimodal, acute or obtuse bimodal, or complex (multimodal) based on its directional variability over time [1]. The narrow unimodal, wide unimodal and acute bimodal wind direction distribution result in transverse dunes i.e., the dune axis is perpendicular to the average wind direction. The dune shape also depends upon the available sand mass. In case of limited sand supply, crescent shaped dunes (Barchans) are formed. Relatively larger sand masses result in Barchnoid ridges and Transverse dunes.

The obtuse bimodal wind direction distributions form linear dunes where the axis of the dune is almost parallel to the average wind direction. Such dunes are characterized by a double slip side, one on each side of the ridge. Both the transverse dunes and linear dunes can extend to a few hundreds of kilometers.

Complex wind direction distributions result in complex dune formations. The most common formation is called a Star or Pyramidal dune having several limbs extending outward from a summit. Complex forms consisting of mixtures of the simple dune forms can also form.

Small scale ripples are superimposed on the dune surfaces. In comparison with the ocean wave spectrum the sand surface spectrum consists of fewer frequency components.

B. Study Area

In this study, we observe the *Ergs Occidental* and *Oriental* in Algeria and *Rub-al-Khali* (Empty Quarters) in Arabian peninsula as shown in Figure 1.

Erg Occidental surface composes mainly of star dunes, barchanoid ridges and liner dunes. *Erg Oriental* is dominated by star and complex dunes indicating high variability of wind direction. The *Rub-al-Khali* sand-sea has mainly barchanoid ridges and linear dunes with a few star dune fields on its eastern sides.

II. Surface Model

The *ergs* exhibit significant incidence angle response and azimuth angle modulation indicating a complex mixture of

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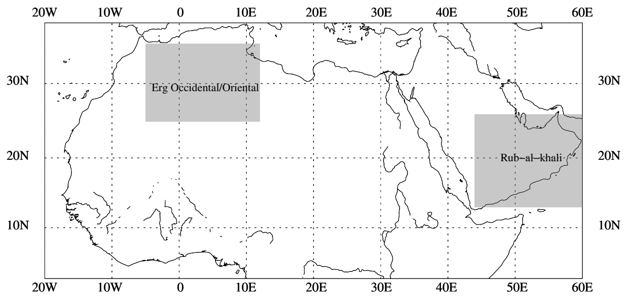

Fig. 1. Map locating study area in the Saharo-Arabian deserts.

both surface and volume scattering [2]. The backscatter from the *ergs* can be modeled as an ensemble of three contributions (Figure 2), i.e., a) surface scattering, b) subsurface volume scattering and c) subsurface bedrock scattering.

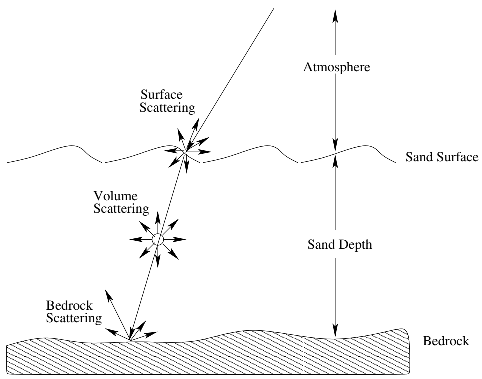

Fig. 2. Surface model of sand seas.

The total backscattering coefficient σ_T^o from the sand as a function of azimuth angle (ϕ) is modeled as

$$\sigma_T^o(\phi) = \sigma_s^o(\theta,\phi) + \sigma_v^o(\theta) + \sigma_b^o(\theta) \quad (1)$$

where $\sigma_s(\theta,\phi)$ = surface scattering σ^o at θ and ϕ
$\sigma_v(\theta)$ = volume scattering σ^o at θ
$\sigma_b(\theta)$ = bedrock scattering σ^o at θ.

The surface scattering coefficient can be modeled as

$$\sigma_s^o(\theta,\phi) = \sigma_m(\theta) + \sigma_{dunes}^o(\theta,\phi) + \sigma_{ripples}^o(\theta,\phi) \quad (2)$$

where σ_m^o = mean response
$\sigma_{dunes}(\theta,\phi)$ = surface scattering from large dunes
$\sigma_{ripples}(\theta,\phi)$ = surface scattering from small ripples.

σ_m^o does not vary with ϕ while $\sigma_{dunes}^o(\theta,\phi)$ and $\sigma_{ripples}^o(\theta,\phi)$ are the the contributions from low and high frequency vertical variations of the surface, respectively. Surface scattering is a function of the look angle and the surface roughness characteristics. The incidence angles at which Bragg scattering occurs are dependent on the spectrum of the surface profile.

The volume scattering component results from incident electromagnetic waves that have penetrated into the subsurface. The sand material generally has a very low dielectric constant and this allows the electromagnetic wave to penetrate to depths as deep as the parent bedrock. The scattering from the subsurface is primarily caused by the sand particles which can be assumed to be homogeneous and thus result in isotropic backscattering. Thus the volume scattering is assumed to be an additive term that varies spatially with sand depth.

Bedrock scattering is the contribution from the parent rock on which the sand mass rests. The scattering from bedrock is a function of the look angle, bedrock surface roughness, as well as the depth of the sand mass on it which attenuates the signal.

Previously σ^o has been modeled as a linear function of θ. Over the erg surface the response is found to be better modeled as a quadratic equation

$$\sigma_s^o(\theta) = A + B(\theta - \theta_{ref}) + C(\theta - \theta_{ref})^2 \quad (3)$$

where θ_{ref} is the reference angle (40°), A is σ^o (dB) at θ_{ref}, B is the slope (dB/°) and C is the curvature (dB/°/°).

Sand dunes exhibit an azimuthal dependence in σ^o. The σ^o involves both surface and volume scattering; however, its variability with ϕ depends primarily upon the geometric properties of the surface, the local slope, and small scale features such as surface waves, pebbles and rocks.

The azimuth angle modulation is modeled as a simple second-order harmonic equation given by

$$\sigma^o(\phi) = A + M_1 cos(\phi - \phi_1) + M_2 cos(2\phi - \phi_2) \quad (4)$$

where A is the mean σ^o (dB), M_i is the magnitudes of i^{th} order harmonic and ϕ_i is the phase angle of i^{th} order harmonic.

As previously noted, the erg surface profile has two main spatial frequency components, corresponding to the two predominant features. The low spatial frequency (wave number) component corresponds to the large scale dunes whereas the high wave number component corresponds to small ripples on the surface of the dunes. The first order harmonic is thought to be related to the lower wave number features (dunes) which mainly contribute to the general surface slope variability over the foot print; whereas the second and high order harmonic result from the higher wave number features i.e., the small scale surface ripples. Both the harmonics are generally stable over considerable durations of time, though the second order parameters exhibit small seasonal variations. The surface ripples alter considerably in shape and orientation due to the changes in the prevailing wind patterns. Since the overall configuration of large dunes is usually stable, the small surface ripples must be the cause of second order seasonal variations.

III. Incidence Angle Response

Figure 3 shows the σ^o versus θ-response over barchanoid ridges and linear dunes for both ESCAT and NSCAT data. In the plots, raw σ^o measurements for common azimuth angles of ESCAT and NSCAT during the mission overlapping time period in early 1997 are used. Almost in every plot abrupt fluctuations in the σ^o values can be observed at certain θ values. These may be caused by the Bragg scattering at these

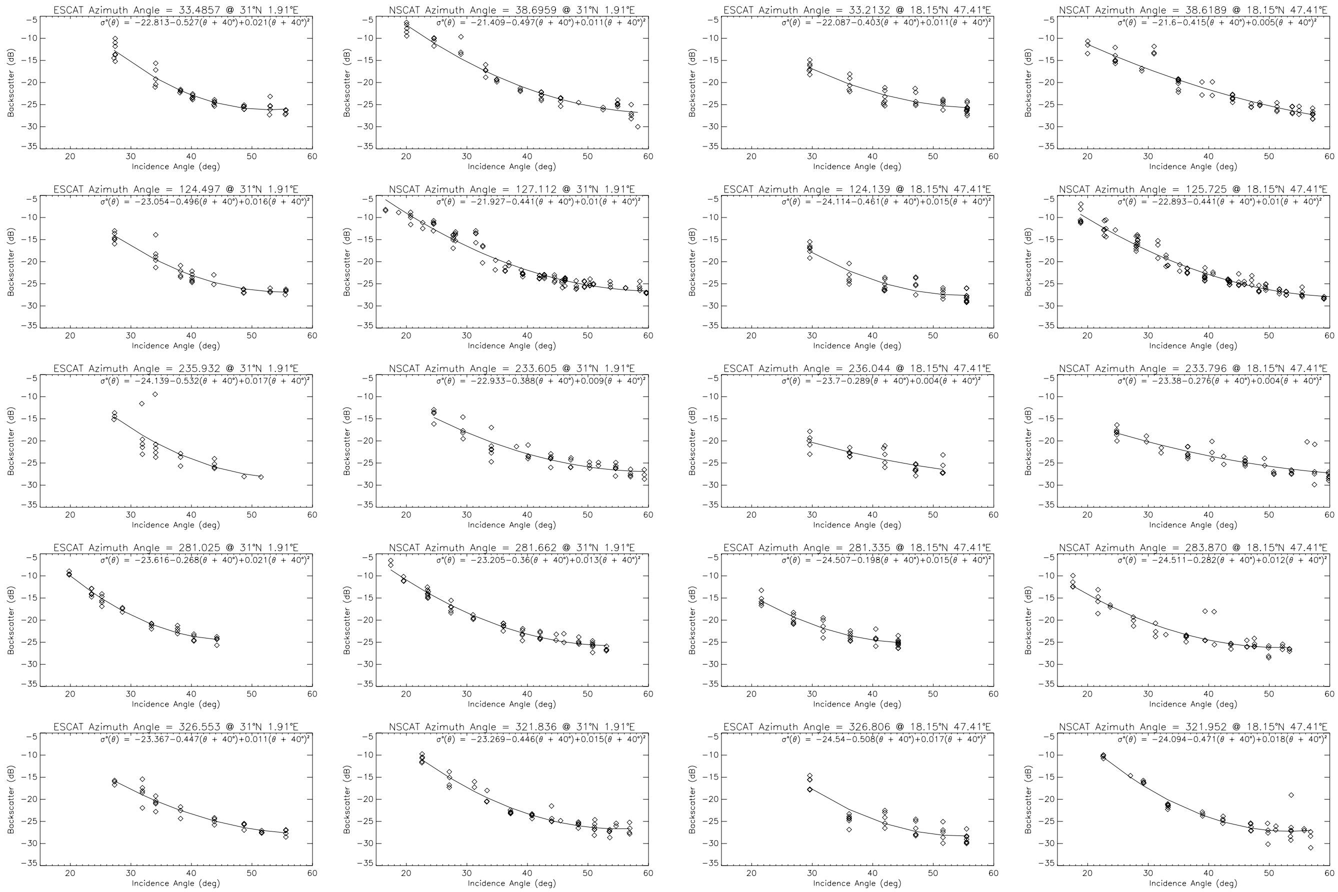

Fig. 3. σ^o versus θ and ϕ in ESCAT and NSCAT over barchanoids (31°N 1.91°E) and linear dunes (18.51°N 47.41°E).

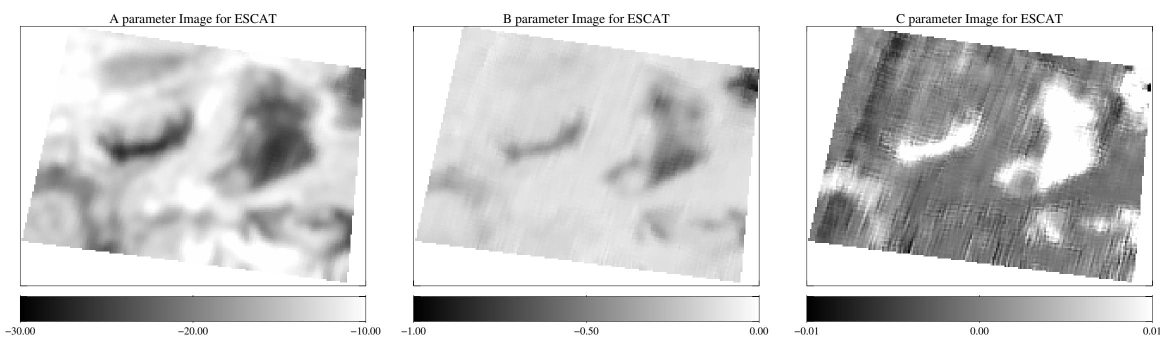

Fig. 4. Parameters of the quadratic incidence angle model fit to the ERS data over the *Erg* Occidental/Oriental.

incidence angles. The Bragg scattering from a surface spatial frequency of 5cm would result a spike at 33° in ESCAT data and two spikes at 25° and 39° in the NSCAT data.

The plots are made for five different ϕ directions. Clearly, the quadratic incidence angle dependence model fits the data more accurately. Both *Ku*-band and *C*-band data reveals consistent response, confirming that the azimuth modulation must be caused by the geophysical factors and not the instrument noise.

Figure 4 shows the spatial distribution of the parameters of the quadratic fit to the ESCAT σ^o versus θ response over the *Erg* Occidental/Oriental. The curvature (C) reveals high spatial coherence to the sand-sea boundary.

IV. Conclusion

A σ^o over the sand surface is modeled as composed of surface scattering, subsurface volume scattering and subsurface bedrock scattering. *C*-band and *Ku*-band σ^o variations with θ and ϕ are observed over the *Ergs* Occidental/Oriental and Rub-al-Khali. Both NSCAT and ESCAT show consistent results and a quadratic model is found to give a better fit to the σ^o vs θ data.

References

[1] E. D. Mckee, *A Study of Global Sand Seas*, Washington, USA: United States Government Printing Office, 1979.

[2] H. Stephen and D. G. Long, *Azimuth Modulation of Backscatter from SeaWinds and ERS Scatterometer over the Saharo-Arabian Deserts*, Proceedings of Intl. Geosc. and Rem. Sens. Symp., Toronto, Canada, pp. 1780–1782, 24-28 July 2002.