Indian J.Sci.Res. 08 (2): 145-153, 2018
ISSN: 0976-2876 (Print)
ISSN: 2250-0138 (Online)

MICROWAVE ALTIMETER: AN IMPORTANT SENSOR IN ACTIVE REMOTE SENSING

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ABSTRACT

Remote Sensing has emerged as an important tool in the study of the ocean with the Microwave Altimeter emerging as one of the important sensors providing data for various prediction models. The knowledge of the working principle and the functional difficulties help in understanding the sensor in a better manner and make a pathway for development of new technologies in improving the capturing of data through remote sensing.

KEYWORDS: Remote Sensing, Sensor, Altimeter

REMOTE SENSING

According to National Institute of Oceanography (NIO), ocean covers 71% area of the earth (NIO, 2006) and so is expected to play a major role in determination of the weather and climate of the earth especially in light that the ocean is considered as the storehouse of energy for driving the earth-atmosphere climate/weather engine because of the very high specific heat of water (about 1000 times) in comparison to air and its several kilometer of water column. The ocean observations are very important for understanding the dynamics of the ocean in turn monitoring the weather and climate. Satellite technology with its remote sensing capabilities and information gathering systems tries to fulfill these requirements to a large extent, though not fully. The ocean in itself, apart from influencing the environment, has a large impact on human activities by virtue of its immense natural resources in terms of geological, chemical and biological productivity making the study of ocean an important area.

According to the United Nations General Assembly resolutions (General Assembly, United Nations, 1986) the remote sensing, is defined as, 'Remote sensing means sensing of the earth's surface from space by making use of the properties of electromagnetic wave emitted, reflected or diffracted by the sensed objects, for the purpose of improving natural resource management, land use and the protection of the environment.'

Satellite remote sensing is recognized as a powerful and essential means for monitoring global change of earth environment. There are two types of remote sensing viz., passive remote sensing (observation is made based on the self-emitted radiance or the electromagnetic radiation from sun) and active remote sensing (electromagnetic radiation of a band of wavelengths or specific wavelength is produced to illuminate the object and the interaction of this radiation is then studied by sensing the scattered radiance from the target). Based on the wavelength regions the remote sensing is classified into three types namely (1) Visible and Reflective Infrared Remote Sensing, (2) Thermal Infrared Remote Sensing and (3) Microwave Remote Sensing.

The ozone layer strongly absorbs the ultraviolet region and hence is avoided in the satellite remote sensing. The major limitations on the use of visible, infrared, and thermal infrared spectrum for operational estimation of parameters is their inability to observe through cloud cover. The microwave region of the electromagnetic spectrum is transparent to presence of clouds (Ulaby, Moore and Fung, 1981). However, there are preferred windows for observation in the microwave region, though less affected by atmosphere, especially for passive sensing. Figure 1 reflects the transparency of atmosphere for microwaves. Within 1-40 GHz band, the atmosphere is fairly transparent under clear sky conditions and frequency greater than 10 GHz are significantly influenced by the atmospheric attenuation indicating that the intensity of attenuation depends on the specific frequency (absorption spectrum) of the corresponding molecule. The variations in water vapour content can be detected due to the attenuation of water vapor (H_2O) being very strong in the specific frequencies (~ 22 GHz) and the most remarkable scattering in the atmosphere is due to raindrops. If the intensity of rainfall increases the attenuation increases and the frequency increases until about 40 GHz. The surface sensing frequencies are generally chosen below 40 GHz, as over 40 GHz the attenuation does not depend on the frequency. Theother possible windows are around 90 GHz and 135 GHz. Even the measurements at window frequencies are affected to some extent by water vapour, clouds etc. especially at higher frequencies.

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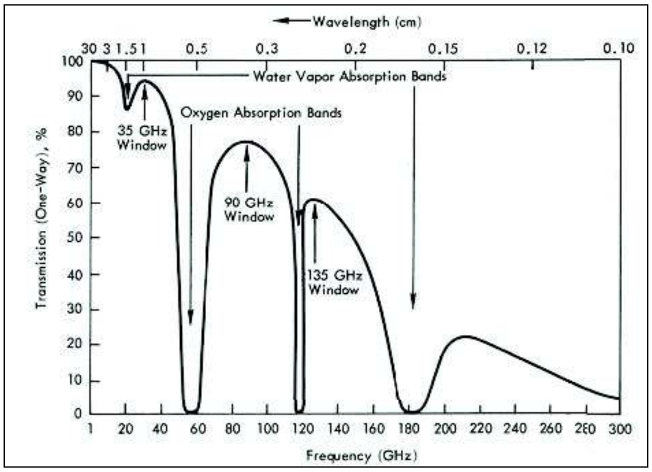

Figure 1: Percentage transmission of microwave through the earth's atmosphere, along the vertical direction, under clear sky conditions

The sensors i.e. the device to detect the electromagnetic radiation emitted or reflected from an object, used for passive remote sensing are microwave radiometer and microwave polarimetric radiometer whereas for active remote sensing the sensors used are scatterometer, altimeter and Synthetic Aperture Radar (SAR).This paper focuses on the microwave remote sensing through the Microwave Altimeter along with the hindrances being faced in the functioning of the sensor and the way the product from this sensor contributes in predictions.

MICROWAVE ALTIMETER

A satellite microwave altimeter transmits a short pulse of microwave radiation of known power toward the sea surface at satellite nadir (point directly beneath the satellite). The pulse interacts with the sea surface and part of the incident radiation reflects back to the satellite giving the information on range from the two-way travel time of the pulse (Brown, 1977 and Alpers, 1978). The power and shape of the returned signal can be used in determining the near-surface wind speed and significant wave height.

A microwave altimeter is a radar precisely measuring the range from the radar antenna to the ocean surface (Fu, Chelton and Zlotnicki, 1988)and this measurement of altitude is called altimetry.The use of spaceborne radar altimeters have been increasedin oceanographic studies and applications (Willis, Fu, Lindstrom and Srinivasan, 2010),especially at the front of gathering quantitative information on wind speed, significant wave height (SWH), and sea surface height (SSH) on a global scale since almost two decades (Gommenginger,Srokosz, Challenor and Cotton, 2002). The information can be gathered about the sea surface topography by accurately knowing the geoid (the gravitational equipotential closest to the time averaged sea-surface height), which is related to surface geostrophic current.The significant wave height and surface wind speed can be obtained by analyzing the shape of returned pulse and the backscattering cross-section, which if made globally, facilitate creation of much needed wind-wave climatology of the oceans, otherwise considered a 'data-sparse' region.

Empirical models with the help of many differing numerical approaches and datasets, have been devised to improve satellite altimeter ocean wind speed retrieval (Brown, Stanley and Roy, 1981; Chelton and McCabe, 1985; Dobson, Monaldo, Goldhirsh and Wilkerson, 1987; Witter and Chelton, 1991; Glazman and Greysukh, 1993; Young, 1993; Freilich and Challenor, 1994; Lefevre, Barckicke and Ménard, 1994). The global altimeteric ocean wind product is mostly limited to climatological use and validation in view that it precludes wind direction detection and the altimeter's nadir-pointing geometry only permits estimates of surface wind speed along a narrow (~ 2 km) swath (Young, 1999).

PRINCIPLE OF ALTIMETRY

A microwave radiation of short pulse with known power is transmitted at satellite nadir by the altimeter toward the sea surface which interacts with the sea surface, and part of the incident radiation reflects back to the satellite, giving the range from the two-way travel time of the pulse. The range R,in terms of altimeter-observed time delay (t),from the satellite to the mean sea level is given by:

$$R = \hat{R} - \sum_{j} \Delta R_j \quad \ldots \quad (1)$$

where $\hat{R} = ct/2$ = Range computed neglecting refraction based on the free-space speed of light c.

ΔR_j (j = 1, 2, ….) = Corrections for the various components of atmospheric refraction and for biases between the mean electromagnetic scattering surface and mean sea level at the air-sea interface.

The range estimate must be transformed to a fixed coordinate system, to be useful for oceanography, for which the range measurement is then converted to the height h of the sea surface relative to the reference ellipsoid by,

$$h = H - R = H - \hat{R} + \sum_j \Delta R_j \quad \ldots \quad (2)$$

The progressive technological developments have improved the point-to-point measurement precision as evident from various reviews of satellite altimetry (Cheney; Douglas, Sandwell, Marsh and Martin, 1984; Douglas, McAdoo and Cheney, 1987; Tournadre, 1999; Tournadre, Lambin - Artru and Steunou, 2009).

The sea-surface height given by equation 2, h is affected by undulations of the geoid h_g about the ellipsoidal approximation, tidal height variations h_T, and the ocean surface response h_a to atmospheric pressure loading, accordingly the dynamic sea-surface height is thus estimated as (figure 2)

$$h_d = h - h_g - h_T - h_a$$

Thus, $$h_d = H - R + \sum_j \Delta R_j - h_g - h_T - h_a \quad (3)$$

The reflected pulse shall be from a small area for better resolution and the same can be achieved through two techniques viz., beam limited (in this larger antenna directs narrow beam towards the surface) and pulse limited (in this a relatively wide beam and short pulses are used). For the beam limited type, the size of the required antenna becomes quite large and hence is not the type of sensor that can be used if precision is required in wave height measurements. For the pulse limited type, even 1 m size of antenna is good enough for a wave height of 20 m. A pulse striking a smooth surface first illuminates a point which becomes larger until the leading edge of the pulse reaches the surface, up to which the scattered power increases linearly with time. Then the illuminated area becomes an annulus of constant area and the scattered power remains more or less constant until it encounters with edge of antenna beam.

The radius of the footprint on the surface (r) is given by

$$r = \sqrt{2hc\tau} \quad \ldots \quad (4)$$

where, h - height of the satellite, c - speed of light and τ - pulse width. For rough sea, the scattered pulse spreads with time and the radius increases to

$$r = \sqrt{2hc\tau'} \quad \ldots \quad (5)$$

where, $\tau'^2 = \tau^2 + 16H_{1/3}^2 \ln\left(2/c^2\right)$; $H_{1/3}$ - significant wave height.

It takes longer duration for the pulse to grow to full strength in rough sea provided the pulse width is quite small compared to the wave height, in contrast to the smooth surface where the reflected pulse grows to its full strength within the pulse length. The more the roughness, larger the time for return signal to grow. Hence the slope of the leading edge of the reflected pulse is inversely proportional to the wave height. The significant wave height is obtained by sampling the pulse shape of the leading edge in a series of electronic gates. Higher the number of gates, higher will be the precision of pulse shape i.e. wave height. As wind speed is obtained by backscattered power, increase in number of gates affects wind speed accuracy. Therefore a balance has to be made between the accuracies of SWH and wind speed.

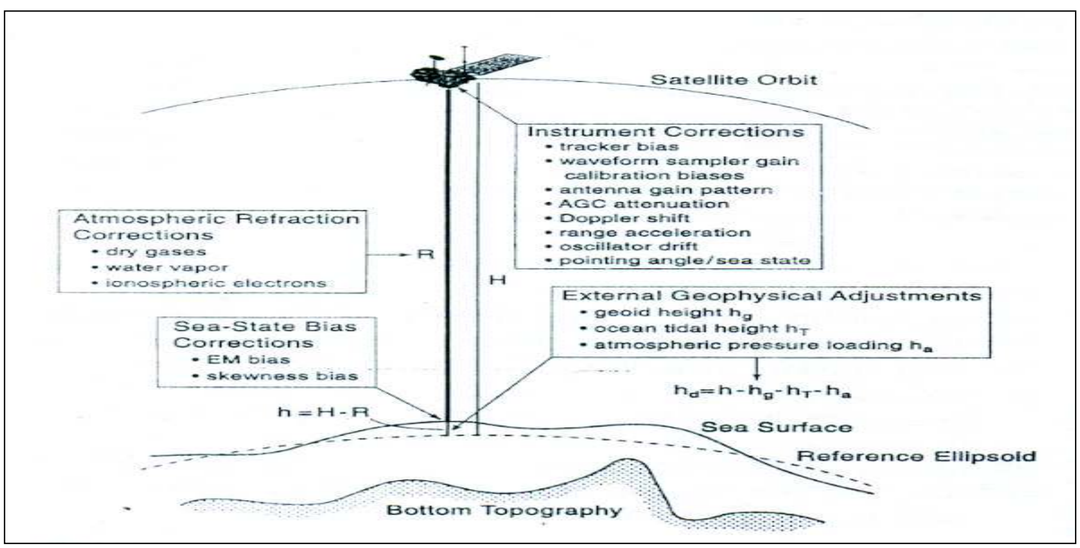

Figure 2: Schematic diagram of the range measurement by an altimeter

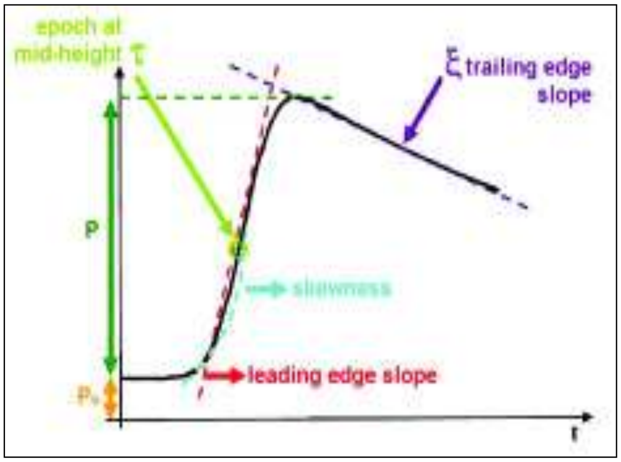

Figure 3: Basic schematic outlines of a return echo over the ocean

Three distinct properties of the reflected radar pulse viz, travel time, pulse shape and pulse amplitude provide information about sea surface topography, sea surface waves and sea surface roughness, respectively. However, the Brown model can be used to describe analytically the characteristic shape of the echo waveform (figure 3) over an ocean surface and six parameters can be deduced, by comparing the real (averaged) waveform with the theoretical curve:

- *epoch at mid-height*: Gives time delay of the expected return of the radar pulse (estimated by the tracker algorithm) and thus the time the radar pulse took to travel the satellite-surface distance (or 'range') and back again.
- *P*: Amplitude of the useful signal. In turn thebackscatter coefficient (σ^o) which is amplitude with respect to the emission amplitude.
- P_o: Thermal noise
- *leading edge slope*: Can be related to the significant wave height (SWH)
- *skewness*: Leading edge curvature
- *trailing edge slope*: Linked to any deviation from nadir of the radar pointing.

SUITABLE FREQUENCY CHANNELS FOR ALTIMETRY

The frequencies most well suited to satellite altimetry fall within the microwave frequency range of 2-18 GHz in turn according to the frequency band allocations, this encompasses S-band (1.55-4.20 GHz), C-band (4.20-5.75 GHz), X-band (5.75-10.9 GHz), and Ku-band (10.9-22.0 GHz) radar frequencies. However, a Ka-band altimeter, AltiKa operating at 35.75 GHz, in contrast to the general range,has been launched jointly by India and France in the year 2013.

Graybody emission of electromagnetic radiation from the sea surface is very weak and the reflectivity of water is high in this frequency band, thus allowing easy distinction between radar return and natural emission. At frequencies higher than 18 GHz, atmospheric attenuation rapidly increases, thus decreasing the power of the transmitted signal that reaches the sea surface and the reflected signal that is received by the altimeter. At lower frequencies, Faraday rotation and refraction of electromagnetic radiation by the ionosphere increase and interference increases from ground-based civilian and military sources of electromagnetic radiation related to communications, navigation, and radar. In addition, practical design constraints on the size of spaceborne antennas set a lower limit on the frequencies useful for satellite altimetry. The antenna footprint size on the sea surface is proportional to the wavelength of the electromagnetic radiation and inversely proportional to the antenna size. Spatial resolution of altimetric measurements from smaller antennas is enhanced by a technique known as pulse compression.

ATTENUATION AND CORRECTIONS IN ALTIMETRY

Most of the altimeteric measurement errors occur over length scales of greater than a few hundred kilometers which are important for precise studies where the geoid height is needed or oceanographic studies. The short-wavelength altimeter noise dominates the error budget while focusing on the gradient of the sea surface. There are at least two factors that impose limits on the resolution and accuracy of gravity field recovery from satellite altimetry viz., the ocean depth (~ 4 km) that attenuates the short-wavelength gravity signals and the short-wavelength noise from ocean surface waves (typically > 1 m). The radar pulse reflects from an area of ocean surface (footprint) that grows with increasing sea state. The superposition of the reflections from this area stabilizes the shape of the echo, however it also smooths the echo so that the timing of its leading edge is more uncertain. The combination of these two limitations makes it difficult to improve the resolution (Fu and Cazenave, 2001).

Clear-Sky Attenuation

The transmittance t_λ for cloud-free tropical, midlatitude and subpolar atmospheres is a function of frequency ranging between 1 and 300 GHz, at normal incidence (incidence angle θ = 0^o). The one-way attenuation is defined as (1 - t_λ). A moderately strong water vapour absorption is seen at 22.235 GHz and 183.31 GHz apart from a strong oxygen absorption at 50-70 GHz and 118.75 GHz due to the confinement of the water vapor and oxygen molecules almost entirely in the troposphere that extends to altitudes of less than 18 km in the tropics and about 10 km at midlatitudes.The differences between the curves in figure 4 reflects that atmospheric transmittance generally decreases with increasing frequency mainly due to the presence of water vapor, for a dry subpolarand a moist tropical atmosphere. Although clear-sky attenuation of σ_o is relatively small, a significantly large effect of oxygen and water vapor is there on the two-way propagation speed of the radar signal. Therefore, for accurate altimetric estimation of the range from the satellite to the sea surface by satellite altimetry, corrections for the oxygen and water vapor two-way path delays are critical.

Cloud Attenuation

Microwave remote sensing is not restricted to cloud-free conditions as clouds are relatively transparent to microwave radiation unlike them being completely opaque to infrared and visible radiation. This a major advantage as at any given time about 60% of the tropical ocean and more than 75% of the mid-latitude ocean are typically cloud covered. The attenuation of altimeter radar signals by cloud liquid water droplets, like the attenuation by oxygen and water vapor molecules, is governed by Rayleigh scattering since the droplets are much smaller than the Ku- and C-band radar wavelengths of ~2 and ~6 cm, respectively. At any point along the path of propagation, cloud attenuation is therefore proportional to the cloud liquid water droplet density at that location. Attenuation by clouds also depends on the temperature of the droplets.Cloud attenuation of the radar signals depends on the vertical profile of the cloud droplets as attenuation increases with increasing frequency of the radar signal and with decreasing temperature (i.e., increasing altitude). At the Ku-band frequency of 13.6 GHz, cloud attenuation is generally less than a few tenths of a dB per km of cloud thickness. Cloud attenuation is a factor of 2-3 smaller at the secondary C-band altimetric frequency of 5.3 GHz.A Ka-band (35 GHz) altimeter would be much less affected by the ionosphere than one operating at Ku-band, and would have enhanced performance in terms of vertical resolution, time decorrelation of echoes, spatial resolution and range noise. However, attenuation due to liquid water (clouds and rain) in the atmosphere is high for Ka-band. Preliminary studies of Ka band altimeter have shown that light rain can strongly attenuate the radar signal and distort the altimeter echo waveform. Clouds droplets with lower absorption coefficient than the rain drops, can have a significant impact on Ka-band radar signal and cannot be neglected as done for Ku-band altimeters.

Rain Attenuation

Radar signals are attenuated by raindrops from both scattering and absorption, hence has a much greater effect on the radar signal than water vapour, clouds or dry gases. The rain cells that are smaller than the illuminated area of the antenna footprint, in addition to reducing the measured value of σ^o distort the shape of the radar signal that is returned from the sea surface. The effects of rain contamination are often apparent from erratic variation of σ^o, significant wave height and two-way travel time. It's important to identify altimeter observations for which rain contamination is highly probable as in some cases, the effects of rain contamination can lead to more subtle but significant errors in altimetric estimates of these three quantities. At frequencies below 10 GHz the rain attenuation is dominated by absorption. The scattering contribution becomes increasingly important with increasing rain rate and increasing frequency. The total attenuation of a radar signal increases with increasing rain rate, increasing frequency and increasing columnar thickness of the rain. Precise correction for two-way attenuation by raindrops thus requires knowledge of not just the rain rate but the vertical distribution of raindrops, information of which is difficult to obtain from satellite measurements. Goldhirshinvestigated three methods of estimating vertical profiles of rain-rate from radar measurements of backscatter at frequencies of 13.6 and 35 GHz from a hypothetical dual-frequency altimeter (Goldhirsh, 1988) and concluded that difficulties exist with each method due to the complexity of the combined effects of attenuation and backscatter on the signals received by the radar and that further research needs to be undertaken before the methods could be applied operationally to correct for rain effects on multi-frequency altimetric estimates of σ^o. The attempt is not made to correct radar measurements for rain attenuation of σ^o due to the difficulties in obtaining rain-rate profiles from satellite data rather rain-contaminated altimeter observations are flagged and excluded from further geophysical analysis. Ideally, the flagging would be based on a threshold rain rate of a few millimeters per hour as errors of this magnitude are comparable to the attenuation from dry air or water vapor or cloud liquid water droplets. The estimation of rain rate can be done from measurements of the microwave radiance emitted by the ocean and the intervening atmosphere at an appropriate combination of frequencies. All the algorithms developed till date requires measurements of brightness temperatures at both horizontal and vertical polarization at an oblique incidence angle. The ability to identify rain-contaminated altimeter data requires coincident measurements from a nadir-looking passive microwave radiometer onboard the altimeter satellite due to the highly transient nature of rainfall. The presently available rain-rate algorithms cannot be used with a nadir-looking radiometer as at normal incidence angle there is no distinction between horizontal and vertical polarization.

Instrument Corrections

In order to achieve the goal of an overall accuracy of the order 2 cm or better for range estimates, the onboard tracker estimates of two-way travel time must be carefully corrected for a number of instrumental errors. The requirements for altimeter estimates of σ^o and $H_{1/3}$ are not as stringent as for the range estimates but the corrections must be applied to these as well. Chelton*et. al.* describes most of the instrumental corrections at length (Chelton, Walsh and MacArthur, 1989) and only a brief summary is given in the below sections:

Doppler-Shift Error

The changes in the frequency of the returned signal appears as an error in the estimated two-way travel time and one source of frequency change is the Doppler shift from the relative velocity between the altimeter and the sea surface.

Oscillator Drift Error

Any error in knowledge of the oscillator frequency results in an error in the estimated two-way travel time that is proportional to the number of cycles counted, as the altimeter measures time by counting cycles of an oscillator. The frequency and stability of the oscillator are known prior to launch. The oscillator needs to be calibrated on frequent or a weekly basis due to the slow drifts of the oscillator from aging and the effects of radiation on the crystal that controls the oscillator frequency. This calibration is based on the timing of the reception of telemetry signals at the ground receiving stations.

Sea-State Corrections

The pulse reflected from the small wave facets within the antenna footprint that are oriented perpendicular to the incident radiation are the returned signal measured by an altimeter and the shape of the returned waveform is determined by the distribution of these specular scatterers rather than by the actual sea surface height distribution within the footprint. The biases in the estimate of mean sea level that arise because of differences between the distributions of the scatterers and the sea surface height must be corrected for the altimeter range measurements. The time interval between the time that the pulse is transmitted and the time that the midpoint of the leading edge of the returned waveform is received is used to estimate the range from the satellite to the sea surface. This half-power point corresponds to the return from the median height of the specular scatterers, referred to as the electromagnetic (EM) sea level. Two effects cause the EM sea level estimated by the onboard tracking algorithm from averaged returned waveforms differ from the true mean sea level viz., the height difference between mean sea level and the mean scattering surface (figure 5) and secondly the skewness bias arising due to the height difference between mean scattering surface and the median scattering surface that is actually measured by the onboard tracker as the two-way travel time corresponding to the halfpower point on the leading edge of the returned waveforms. The total of the EM and skewness biases is referred to as the total sea-state bias. The ground-based waveform retracking techniques can be used to estimate the skewness bias however, it does not provide insight into the EM bias.

Several studies have reflected the evidence of sea-state effect on altimeter-derived wind and the results range from substantial impacts to no impact (Wu, 1999). The wind speed and significant wave height currently form the basis for correcting the sea surface height measurements for sea state bias errors resulting from the presence of ocean waves on the surface via the electromagnetic bias algorithm and hence the accurate estimates of these parameters become essential (Gaspar and Florens, 1998). However, while it is generally accepted that altimeter significant wave height is now of comparable accuracy to that of moored buoys (Carter, Challenor and Srokosz, 1992 and Gower, 1996), the issue of altimeter wind speed retrieval has remained an active area of research.

Analysed winds, globally or regionally, are routinely generated by Weather Forecasting Centres by assimilating weather parameters (in-situ as well as satellite measured) in the forecasting models which act as one of the essential forcing parameters for Ocean Circulation and Ocean Wave Models. The weather model run by the European Centre for Medium range Weather Forecasts (ECMWF), calculates a surface analysis, including surface winds and heat fluxes every six hours on a $1^{o}\times1^{o}$ grid from an explicit boundary-layer model. Calculated values are then archived on a 2.5^{o} grid. Other surface analyses used in oceanography include: 1) analyses calculated by the numerical weather model run by the NOAA National Centers for Environmental Prediction, 2) the Planetary Boundary-Layer Data set produced by the U.S. Navy's Fleet Numerical Oceanography Center FNOC, and 3) surface wind maps for the tropics produced at Florida State University (Goldenberg and O'Brien, 1981).

In India, the National Centre for Medium Range Weather Forecast (NCMRWF) also generates the analysed winds in global grids. The operational analysis and the forecast suite at NCMRWF is based on a T80L18 global spectral model and Spectral Statistical Interpolation (SSI) scheme for data analysis. The data obtained from Altimeters play a crucial role.

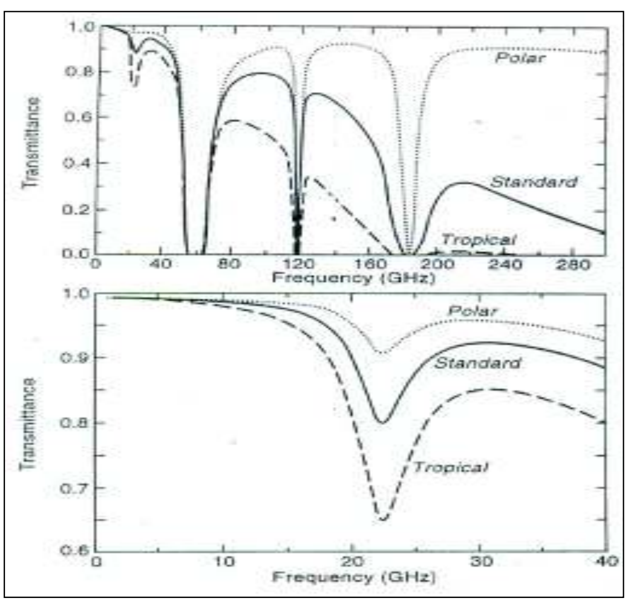

Figure 4: The transmittance at normal incidence angle for cloud-free subpolar (dotted line), midlatitude (solid line) and tropical (dashed line) atmospheres as a function of frequency. The frequency range 0 to 300 GHz is shown in the upper panel and an enlargement for the frequency range 0 to 40 GHz is shown in the lower panel

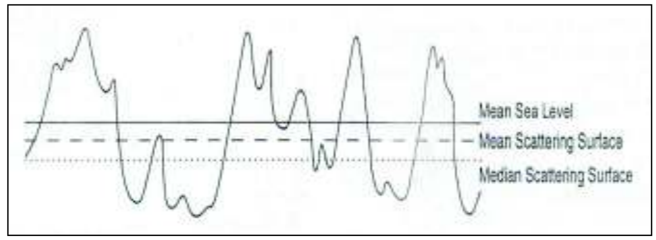

Figure 5: Schematic representation of the distinctions between mean sea level (thin horizontal line), the mean scattering surface (dashed line) and the median of the distribution of specular scatterers (dotted line) for a rough sea surface

CONCLUSION

The microwave altimeter though has certain limitations in the form of mentioned attenuations remains one of the useful microwave sensors being used in the remote sensing with the implementation of applicable instrument corrections. The data collected by the altimeters jointly being used with the data collected from other sensors can act as a boon in remote sensing applications.

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