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Progress in the Measurement Techniques of Oceanic Surface Wind

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Abstract: *The Ocean covers 70.8% of the earth's surface and the Ocean Winds being the largest source of momentum for the upper ocean, affects the full range of ocean movement. Hence, the knowledge of the global wind field is desirable and it becomes imperative looking into the fluctuating nature of the ocean, to keep constant observation and collect the data. The measurement of winds is undertaken with the help of anemometers on ships and calibrated anemometers on weather buoys. The use of microwave sensors on the satellite has been helpful in overcoming the poor in-situ coverage by buoys and ships alike.*

Keywords: *Ocean Winds, Remote Sensing, Microwave Sensors*

1. Introduction

The ocean covers 70.8% of the earth's surface, which amounts to 361,254,000 km^2. There is only one ocean which is divided into three named parts by the international agreement: the Atlantic, the Pacific and the Indian Ocean (International Hydrographic Bureau, 1953). Seas, which are part of the ocean, are defined in several ways [1, 2]. A comprehensive framework containing provisions regulating, interalia, the limits of national jurisdiction, access to the seas, navigation, protection and preservation of the marine environment, scientific research etc. has been established in the UN Convention on the Law of the Sea, 1982, which was adopted in April 30, 1982 and came into force from November 16, 1994. India acceded to the Convention on June 29, 1995 [3, 4].

The local and remote atmospheric forcing due to wind stress, annual rainfall, annual average precipitation, rate of evaporation, heat and fresh water fluxes associated with the monsoon and meteorological disturbances, and receipt of solar radiation at the top of the troposphere plays an important role on the fluctuations observed in the oceanic parameters [5, 6]. The momentum flux (or wind stress) is a key parameter in many air-sea interaction studies. One major difference between airflow over the sea as contrasted with over land is that the sea surface is mobile which leads to a limitation in the use of classical theory to describe the marine surface layer, as the surface waves modulate velocity and pressure perturbations emanating upward from the surface. Therefore, the structure of the stress and velocity profiles over sea waves may deviate from similar overland situations. Wei *et. al.* [7] and Clayson and Chen [8] indicated that the diurnal Sea Surface Temperature (SST) variation can have an impact on the atmosphere over the western Pacific warm pool. The air-sea interaction on the daily scale may play an important role in the Madden-Julian Oscillation (MJO), and in turn the El-Niño and Southern Oscillation (ENSO) and climate [9, 10].

Ocean Winds are the largest source of momentum for the upper ocean, affecting the full range of ocean movement, from individual surface gravity waves to complete current systems. Ocean winds modulate air-sea exchanges of heat, moisture, gases and particulates. This modulation regulates the interaction between the atmosphere and the ocean, which establishes and maintains both regional and global climates. Observations of vector winds near the surface are used in models of the atmosphere and ocean surface waves, and they are required to force ocean circulation models. There is currently a high demand for ocean wind observations, particularly in view of the recent emphasis on storm and hurricane forecasting. The required wind observations must be timely, accurate and at high horizontal resolution as occasional, low resolution observations are of limited use in these models. Wind observations are particularly important for coastal regions where they are quite variable (in space and time) and where high wind speeds can cause large waves and flooding. In addition, sea surface wind vectors are required for operational activities at sea such as marine transport, offshore wind parks and other operations, pollution control and for wave and surf models. Accordingly, the knowledge of the global wind field is desirable and it becomes imperative looking into the fluctuating nature of the ocean, to keep constant observation and collect the data.

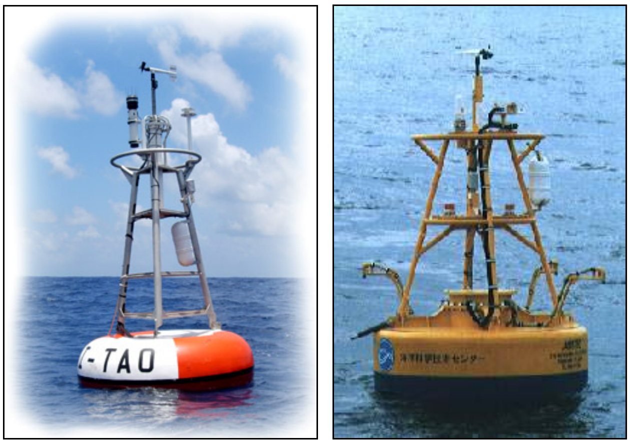
2. Measurement of Wind

2.1. Anemometers on Ships

The observers reading anemometers on ships four times a day at the standard Greenwich times report the data via radio to the meteorological agencies. The biggest error is the sampling error as very few ships carry calibrated anemometers and those that do, tend to be commercial ships participating in the Volunteer Observing Ship program. These ships are then met in port by scientists who check the instruments and replace them if necessary, and who collect the data measured at sea are not experts in this field. The accuracy of wind measurements from these ships is about ± 2 m/s [2].

2.2. Calibrated Anemometers on Weather Buoys

The most accurate measurements of winds at sea are made by calibrated anemometers on moored weather buoys. There are a few such buoys, scattered around the world, which provides data from remote areas rarely visited by ships like Tropical Atmosphere Ocean, TAO [figure 1(a)] array in the tropical Pacific. But most tend to be located just offshore of coastal areas. National Oceanic and Atmospheric Administration (NOAA) operates buoys offshore of the United States and the TAO array in the Pacific. The best accuracy of anemometers on buoys operated by the US National Data Buoy Center (NDBC) is the greater of ± 1 m/s or 10% for wind speed and $\pm 10^{o}$ for wind direction [11]. Other buoys operating are Triangle Trans-Ocean Buoy Network, TRITON [figure 1(b)] buoys in the western Pacific by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC); Pilot Research Moored Array in the Tropical Atlantic (PIRATA) developed by Brazil, France, and the United States; National Data Buoy Programme (NDBP) by National Institute of Ocean Technology (NIOT) Chennai, India and Woods Hole Oceanographic Institution (WHOI). The Global Tropical Moored Buoy Array is a multi-national effort to provide data in real-time for climate research and forecasting. It is a contribution to the Global Ocean Observing System (GOOS), Global Climate Observing System (GCOS), and the Global Earth Observing System of Systems (GEOSS). Major components include the TAO/TRITON array in the Pacific, PIRATA in the Atlantic, and RAMA in the Indian Ocean.



(a) **(b)**

Fig1. *(a) Image of TAO Buoy [Courtesy: NOAA] and (b) of TRITON Buoy [Courtesy: JAMSTEC]*

2.3. Remote Sensing

Remote sensing, as part of the general assembly resolutions of the 95th plenary meeting of the United Nations, December, 1986, is defined as [12],

'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 improv-

ing natural resource management, land use and the protection of the environment.'

The designation of various regions of the electromagnetic spectrum of relevance to remote sensing and their wavelengths are given in table 1. The spectral range of near IR and short wave infrared, being more influenced by solar reflection rather than the emission from the ground surface, is sometimes called the reflective infrared (0.7-3 µm). Thermal infrared is primarily used for temperature measurement, while microwave is utilized for radar and microwave radiometry [13].

Table1. *Designation of various regions of the electromagnetic spectrum of relevance to remote sensing and their wavelengths*

Optical Infrared (OIR) Region	
Visible	0.4 – 0.7 µm
Near infrared (nIR)	0.7 – 1.5 µm
Shortwave infrared (SWIR)	1.5 – 3 µm
Mid – wave infrared (MWIR)	3 – 8 µm
Long wave infrared (LWIR)/ Thermal infrared (TIR)	8 – 15 µm
Far infrared (FIR)	Beyond 15 µm
Microwaves	
P band	0.3 – 1 GHz (30 – 100 cm)
L band	1 – 2 GHz (15 – 30 cm)
S band	2 – 4 GHz (7.5 – 15 cm)
C band	4 – 8 GHz (3.8 – 7.5 cm)
X band	8 – 12.5 GHz (2.4 – 3.8 cm)
Ku band	12.5 – 18 GHz (1.7 – 2.4 cm)
K band	18 – 26.5 GHz (1.1 – 1.7 cm)
Ka band	26.5 – 40 GHz (0.75 – 1.1 cm)

The electromagnetic radiation in the visible, near infrared, thermal infrared, and microwave regions are used by the sensors on-board space platforms to measure diverse physical, biological, and geological parameters of the ocean. The ultraviolet region is avoided in satellite remote sensing because of its strong absorption by the ozone layer. In visible and near-infrared region, optical sensors operating over narrow spectral channels are used to measure color of the ocean which contains useful information regarding water constituents, near shore bathymetry and turbidity. Measurements taken over multiple windows in the thermal infrared region are used to derive SST corrected for atmospheric effect. One of the major limitations on the use of visible, infrared, and thermal infrared spectrum for operational estimation of oceanographic parameters is their inability to observe the sea surface through cloud cover. The microwave region of the electromagnetic spectrum is transparent to presence of clouds. Synergistic use of optical and microwave remote sensing data has provided unique opportunity in addressing several outstanding oceanographic applications, particularly in tropics. Sensors operating in microwave frequency bands are capable of providing ocean surface winds in different resolutions and swaths over global oceans.

Microwave remote sensing enables the observation of atmosphere, land, oceanic and cryospheric parameters, including precipitation, sea surface temperature, ice concentration, snow depth, water content, surface wetness, wind speed, atmospheric cloud water and water vapour in all weather conditions without any restriction by cloud or rain (except under heavy rain effect) through preferred windows [14], which is an advantage over the visible and/or infrared remote sensing. Moreover, unique information is provided by microwave remote sensing on for example, sea surface wind vectors and surface wave parameters, which are derived from frequency characteristics, Doppler effect, polarization, backscattering etc., which cannot be observed by visible and infrared sensors.

3. MICROWAVE SENSORS

The instruments onboard the satellites that use the principle of remote sensing to provide the required data are known as sensors and the sensors which operate in the microwave region are of the electromagnetic spectrum are known as microwave sensors.

3.1. Microwave Altimeter

A satellite microwave altimeter is a radar that precisely measures the range from the radar antenna to the ocean surface [15], and the measurement of altitude is called altimetry. The altimeter transmits a short pulse of microwave radiation with known power toward the sea surface at satellite nadir (the point directly beneath the satellite). This pulse 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 [16-19]. Near-surface wind speed and significant wave height can be determined from the power and shape of the returned signal.

3.2. Microwave Scatter Meter

The radars by which the measurements of the normalized radar cross section (NRCS), at microwave frequencies and incidence angles between 20^{o} and 70^{o} have been used to infer ocean surface winds from satellites are called Scatter meters [20-22]. The space-borne scatter meter instrument transmits microwave pulses and receives backscattered power from the ocean surface. Changes in wind velocity cause changes in ocean surface roughness, modifying the radar cross-section of the ocean and the magnitude of the backscattered power. At the present time, the microwave scatter meter is the only satellite sensor that is capable of providing information of both wind speed and wind direction.

3.3. Synthetic Aperture Radar

The radar is made to illuminate to one side of the nadir off the platform to overcome the 'right-left' ambiguity hence the name Side Looking Radar. For remote sensing, side-looking imaging radars are broadly classified into two categories: (a) Real Aperture Radar – usually referred to as SLAR (Side-Looking Airborne Radar) or SLR (Side-Looking Radar) and (b) Synthetic Aperture Radar (SAR) [13, 23].

In SLAR, the antenna beam produces a narrow beam width in the along-track (azimuth) direction, while the beam width in the cross-track (range) direction is broad and defines the swath. A short pulse is transmitted by the radar and on striking the ground, a part of it is backscattered to the antenna. The time delay associated with the received signal gives the distance of the target from the antenna and hence the location. The backscattered intensity which depends on the sensor and terrain characteristics is also measured by the radar. SLAR has the limitation that it cannot produce fine resolution radar imagery at long range. In 1951, it was first realized that the Doppler spread of echo signal could be used to synthesize a much longer aperture (and hence the name Synthetic Aperture Radar, SAR) to greatly improve the resolutions of a side-looking radar. In SAR, a side looking antenna mounted on a moving platform emits a series of coherent pulses. Subsequently they are coherently integrated and the return so generated appears as if they have been produced by an array of elements which simultaneously transmitted a pulse.

3.4. Microwave Radiometer

Radiometers are passive microwave radar systems [14], which measure microwave emissions from objects, generated due to collisions of molecules inside the object, at various frequencies and polarizations. Space borne microwave radiometers on polar satellites are being used for sensing the earth's surface and the atmosphere globally and with a fairly high repetitive frequency. Radiometry is the measurement of incoherent radiant electromagnetic energy. Passive microwave radiometry measures naturally emitted microwave energy, expressed in terms of brightness temperature, which is based on a surface's physical, electrical and thermodynamic variables. The ocean surface's properties affect the physical-electrical interactions, which then determine the surface's microwave emission [24]. Microwave radiometry is mainly used because it is independent of the sun and can penetrate clouds, rain and other objects to an extent.

4. New Generation of Microwave Sensors

4.1. GPS for Oceanography

The reflection of electromagnetic radiation from the ocean surface contains information about the statistical properties of the sea surface, which is indirectly related to the near-surface meteorological conditions, have long been recognized. This relationship forms the basis of most of the oceanographic radar remote sensing systems, which are monostatic radar and measure the power of the backscattered radiation. The possibility of using the radio navigation signals from the Global Positioning System (GPS) as a source of illumination in a forward-scattered radar remote sensing instrument for sea surface roughness is one of the upcoming advance technique for ocean remote sensing [25].

This measurement technique is unique, not only in the use of a biostatic geometry with existing sources of radio frequency illumination, but also in the use of the correlation properties of the pseudo-random noise (PRN) signal transmitted by GPS as opposed to requiring a direct measurement of received power. The theoretical reflected signal is then derived by extension of the cross-correlation process used for direct GPS signals and the characteristics of the leading edge are emphasized, to identify analogies and differences with the traditional altimetry waveform. In particular, the behavior of the derivative of the leading edge suggests a useful algorithm for extracting the mean sea height, wind speed and significant wave height. An overall range accuracy rms value is predicted for several antenna gains, pointing directions and different geometric scenarios. When averaging many measurements, the range error is progressively reduced yielding predicted accuracies in sea height with associated spatial and temporal resolutions. The advantage of the dense and rapid surface coverage afforded by the existing GPS constellation would enable new oceanographic applications such as eddy monitoring and the tracking of fast barotropic waves, which play important role in the transport of momentum, heat, salt, nutrients, and other chemical properties of the ocean.

4.2. Interferometer Radiometry

Interferometric radiometers produce brightness temperature images out of the measured cross-correlations between pairs of output signals measured by a large number of receivers [26, 27]. This technique is the core of MIRAS (Microwave Imaging Radiometer by Aperture Synthesis), the main payload of the ESA Earth Explorer Opportunity Mission, Soil Moisture and Ocean Salinity (SMOS), launched in 2006.

For optimum results, Soil Moisture and Ocean Salinity (SMOS) mission uses microwave radiation emitted from the Earth’s surface at L-band (1.4 GHz) using an interferometric radiometer [28]. Moisture and salinity decrease the emissivity of soil and seawater respectively, and thereby affect the microwave radiation emitted from the surface of the Earth. Interferometry measures the phase difference between electromagnetic waves at two or more receivers, which are a known distance apart-the baseline. The SMOS radiometer by way of 69 small receivers, exploiting the interferometry principle, measures the phase difference of incident radiation. The technique is based on cross-correlation of observations from all possible combinations of receiver pairs. A two-dimensional ‘measurement image’ is taken every 1.2 seconds. As the satellite moves along its orbital path, each observed area is seen under various viewing angles. From an altitude of 763 km, the antenna will view an area of almost 3000 km in diameter. However, due to the interferometry principle and the Y-shaped antenna, the field of view is limited to a hexagon-like shape about 1000 km across called the ‘alias-free zone’. This area corresponds to observations where there is no ambiguity in the phase-difference.

4.3. Polarimetric Radiometry

WindSat is the first polarimetric radiometer in space, developed by the Naval Research Laboratory for the U.S. Navy, and by the National Polar orbiting Operational Environmental Satellite System. The principle objective of WindSat is to obtain global wind vector maps by validating the feasibility of measuring wind direction over the ocean surface using microwave radiometry. Accurate retrieval of ocean wind speed and direction from space-borne microwave radiometers requires knowledge of effect of changes in surface properties, on the brightness temperature measured by passive remote sensing instruments. Wind roughening of the ocean in the form of small scale (capillary) waves, large scale (gravity) waves, and whitecaps (with resulting foam) allow such instruments to remotely sense the wind vector. However, near-surface radiometric observations are still very much needed to improve the quantitative knowledge of the effects of changing surface conditions, including foam and roughness, on microwave emissivity [29]. The polarimetric microwave emission from the sea surface depends on the local wind direction and speed. A polarimetric radiometer measures a complete signature of the emitted energy, including all information about its directional nature, or polarization.

Radiation fields are fully characterized using Stokes parameters. The first (T_v) and second (T_h) parameter describes the vertically and horizontally polarized brightness temperatures respectively, whereas the third (T_3) and fourth (T_4) parameter describe the linearly and circularly polarized components respectively. The measurement of the first three Stokes parameters enables the determination of surface wind speed and direction in sea areas [30-33] which is valuable for many meteorological and oceanographic applications. Space borne polarimetric measurements have an additional benefit of being unaffected by Faraday rotation.

4.4. Polarimetric Scatterometry

Space borne wind scatter meters provide useful measurements of ocean surface winds and are important to climatological studies and operational weather forecasting. The scatter meters use measurements of the co-polarized backscatter cross-section at different azimuth angles to infer ocean surface wind speed and direction. The current scatter meter designs, although successful, have limitations like degraded wind performance in the near-nadir and outer regions of the measurement swath, and a reliance on external wind information for vector ambiguity removal [34].

A polarimetric scatter meter simultaneously measures co-polarized backscatter and the polarimetric correlation of the co- and cross-polarized radar returns from the ocean surface. Based on general symmetry properties of the polarization components of the backscattered electromagnetic field from the wind-induced sea surface, it has been shown that the normalized co-polarization and cross-polarization backscattering cross sections $(\sigma_{HH}, \sigma_{VV} \text{ and } \sigma_{HV})$ are symmetric with respect to the wind direction [35-38], while the correlation between co-polarized and cross-polarized backscattering $(\sigma_{hvvv} \text{ and } \sigma_{vhhh})$ are odd functions with respect to the wind direction [36, 37]. The different symmetry properties between the co-polarization and polarimetric correlation signatures can, in principle, be used to improve the ability to resolve wind direction ambiguities as well as generally enhance the overall wind retrieval performance across the measurement swath.

5. CALCULATIONS OF WIND

Satellites, ships, and buoys measure winds at various locations and times of the day. To calculate the monthly averaged winds over the sea, the observations to be used are averaged and gridded. The surface analysis calculated by numerical weather models is one source of gridded winds over the ocean. The strategy used to produce the six-hourly gridded winds is called sequential estimation techniques or data assimilation. Measurements are used to prepare initial conditions for the model, which is then integrated forward in time until further measurements are available. The model is there upon re-initialized. The initial condition is called the analysis. All available measurements including observations from weather stations on land, pressure and temperature reported by ships and buoys, winds from scatterometers in space, and data from meteorological satellites are used in the analysis. The model interpolates the measurements to produce an analysis consistent with previous and present observations [2].

With negligible flow deformation anchored buoys and meteorological towers offer near ideal measuring conditions but the measuring height is for practical and economical reasons very limited [39]. Observations from ships are economically feasible and practically attractive but suffer from ship motions and site dependent flow distortion effects. Research and oil platforms are near ideal from a practical point of view but the flow deformation can be immense. Another problem is to which degree the measurements represent undisturbed marine conditions. A large coastal gradient in wind speed and air temperature fields is resulted due to the thermal stratification changes in coastal regions [40]. However, the new space technologies has increased our capabilities to perform wind observations in the marine Atmospheric Boundary Layer.

5.1. Surface Analysis from Numerical Weather Models

Analysed (global or regional) winds are one of the essential forcing parameters for Ocean Circulation and Ocean Wave Models. Such winds are routinely generated by Weather Forecasting Centres by assimilating weather parameters (in-situ as well as satellite measured) in the forecasting models.

The winds are produced using weather model run by the European Centre for Medium range Weather Forecasts (ECMWF), 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 [41]. The National Centre for Medium Range Weather Forecast (NCMRWF) in India is also generating Analysed winds in global grids [42].

6. CONCLUSION

The knowledge of the global wind field is desirable in view of the fact that about seventy percent of the globe is covered by the oceans (which unlike the land surface is highly dynamic) and the role played by it in understanding important oceanic processes and having several critical societal applications. However, this has long been limited by poor in-situ coverage by buoys and ships alike. The distribution of such observations is highly variable in time and space and as such is not adequate to truly resolve global ocean winds. Development of recent remote sensing techniques (space-based observations of ocean and atmosphere) has boosted up such studies as it provides synoptic and repetitive coverage of the ocean in contrast to the sparse, isolated and inaccessible in-situ buoy or ship observations. Through high-resolution spatial and frequent temporal sampling by satellites, approximately 90% of the global ocean vector winds are now sampled daily at a 25 km resolution by a single satellite sensor. Application of microwave sensors under all weather conditions has considerably enhanced the database of this parameter. The combined data of the sensors, with differing features, capable of providing ocean surface winds in different resolutions and swaths over global oceans apart from other parameters after combinely being used can help study the oceanic winds in a better way in turn other oceanic processes.

REFERENCES

[1] National Institute of Oceanography (NIO); 2006: Sagar – A pocketbook on the ocean with special reference to the waters around India, Dona Paula, Goa.

[2] Stewart, R. H., 2008, Introduction To Physical Oceanography, Department of Oceanography, Texas A & M University.

[3] Brownlie, I., 2003, Basic Documents in International Law, Fifth Edition, Indian Edition, Oxford University Press, New Delhi, India.

[4] Sharma, O.P., 2009, The International Law of the Sea - India and the UN Convention of 1982, Oxford University Press, New Delhi, India.

[5] Shenoi, S. S. C., Shankar, D. and Shetye, S. R., 2002, Differences in heat budgets of the near – surface Arabian Sea and Bay of Bengal: Implications for the summer monsoon, J. Geophys. Res., 107 (C6), 3052.

[6] Shetye, S. R., 1993, The movement and implications of the Ganges – Brahmaputra runoff on entering the Bay of Bengal, Curr. Sci., 64 (1), 32 – 38.

[7] Wei, L., Rucong, Y., Hailong, L. and Yongqiang, Y., 2001, Impacts of Diurnal Cycle of SST on the Intraseasonal Variation of Surface Heat Flux over the Western Pacific Warm Pool, Adv. Atmos. Sci., 18 (5), 793 – 806.

[8] Clayson, C. A. and Chen, A., 2002, Sensitivity of a Coupled Single – Column Model in the Tropics to Treatment of the Interfacial Parameterizations, J. Climate, 15 (14), 1805 –1831.

[9] Slingo, J. M., Inness, P., Neale, R., Woolnough, S. and Yang, G., 2003, Scale interactions on diurnal to seasonal timescales and their relevance to model systematic errors, Annals of Geophysics, 46 (1), 139 – 155.

[10] Dai, A. and Trenberth, K. E., 2004, The Diurnal Cycle and Its Depiction in the Community Climate System Model, J. Climate, 17 (5), 930 – 951.

[11] Beardsley, R. C., Enriquez, A. G., Friehe, C. A. and Alessi, C. A., 1997, Intercomparison of Aircraft and Buoy Measurements of Wind and Wind Stress during SMILE, J. Atmos. Oceanic Technol., 14 (4), 969 – 977.

[12] General Assembly, United Nations, Principles relating to remote sensing of the Earth from space, A/RES/41/65, 95th plenary meeting, 3 December 1986. [Online] http://www.un.org/documents/ga/res/41/a41r065.htm.

[13] Joseph, G., 2003, Fundamentals of Remote Sensing, Universities Press, Hyderabad, India.

[14] Ulaby, F. T., Moore, R. K. and Fung, A. K., 1981, Microwave Remote Sensing: Active and Passive, Vol. I: Microwave Remote Sensing Fundamentals and Radiometry, Artech House, Inc., Norwood, MA, USA.

[15] Fu, L. – L., Chelton, D. B. and Zlotnicki, V., 1988, Satellite Altimetry: Observing Ocean Variability from Space, Oceanography, 1 (2), 4 – 11.

[16] Brown, G., 1977, The average impulse response of a rough surface and its applications, IEEE Trans. Antennas Propag., 25 (1), 67 – 74.
[17] Alpers, W.R., 1978, Measurement of ocean wave heights using Geos 3 altimeter, J. Geophy. Res., 83 (C10), 5011 – 5018.
[18] Fu, L. – L. and Cazenave, A., 2001, Satellite Altimetry and Earth Sciences: A Handbook of Techniques and Applications, Academic Press, London (UK).
[19] Lee, H.K, Radar altimetry methods for solid earth geodynamics studies, Report No. 489, The Ohio State University, Columbus, September 2008.
[20] Moore, R. K. and Fung, A. K., 1979, Radar determination of winds at sea, Proc. IEEE, 67 (11), 1504 – 1521.
[21] Brown, R. A., 1983, On a Satellite Scatterometer as an Anemometer, J. Geophys. Res., 88 (C3), 1663 – 1673.
[22] Stoffelen, A., 1998, Scatterometry, Ph.D. Thesis, University of Utrecht, The Netherlands, ISBN 90-393-1708-9 [Online] http://www.library.uu.nl/digiarchief/dip/ diss/01840669/inhoud. htm.
[23] Ulaby, F. T., Moore, R. K. and Fung, A. K., 1982, Microwave Remote Sensing: Active and Passive, Vol. II: Radar Remote Sensing and Surface Scattering and Emission Theory, Addison Wesley Publishing Company, Massachusetts, USA.
[24] Robinson, I. S., 2004, Measuring the Oceans from Space: The principles and methods of satellite oceanography, Praxis Publishing Ltd., Chichester, UK.
[25] Garrison, J. L., Komjathy, A. Zavorotny, V. U. and Katzberg, S. J., 2002, Wind speed measurement using forward scattered GPS signals, IEEE Trans. Geosci. Remote Sens., 40 (1), 50 – 65.
[26] Corbella, I., Camps, A., Zapata, M., Marcos, F., Martínez, F., Torres, F., Vall – llossera, M., Duffo, N. and Bará, J., 2003, End – to – end simulator of two – dimensional interferometric radiometry, Radio Sci., 38 (3), 8058.
[27] Skou, N. and Le Vine, D., 2006, Microwave Radiometer Systems: Design and Analysis, Artech House, 2nd edition, Norwood, MA, 7 – 23.
[28] Philippe, W., Jacqueline, B. and Yann, K., 2003, Selecting an optimal configuration for the Soil Moisture and Ocean Salinity mission, Radio Sci., 38(3), 8051.
[29] Rose, L. A., Asher, W. E., Reising, S. C., Gaiser, P. W., St Germain, K. M., Dowgiallo, D. J., Horgan, K. A., Farquharson, G. and Knapp, E. J., 2002, Radiometric measurements of the microwave emissivity of foam, IEEE Trans. Geosci. Remote Sens., 40 (12), 2619 – 2625.
[30] Yueh, S. H., Wilson, W. J., Dinardo, S. J. and Li, F. K., 1999, Polarimetric microwave brightness signatures of ocean wind directions, IEEE Trans. Geosci. Remote Sens., 37 (2), 949 – 959.
[31] Laursen, B. and Skou, N., 2001, Wind direction over the ocean determined by an airborne, imaging, polarimetric radiometer system, IEEE Trans. Geosci. Remote Sens., 39 (7), 1547 – 1555.
[32] Piepmeier, J. R. and Gasiewski, A. J., 2001, High – resolution passive polarimetric microwave mapping of ocean surface wind vector fields, IEEE Trans. Geosci. Remote Sens., 39 (3), 606 – 622.
[33] Lahtinen, J., Pihlflyckt, J., Mononen, I., Tauriainen, S. J., Kemppinen, M. and Hallikainen, M. T., 2003, Fully Polarimetric Microwave Radiometer for Remote Sensing, IEEE Trans. Geosci. Remote Sens., 41 (8), 1869 – 1878.
[34] Tsai, W. – Y., Nghiem, S. V., Huddleston, J. N., Spencer, M. W., Stiles, B. W. and West, R. D., 2000, Polarimetric scatterometry: a promising technique for improving ocean surface wind measurements from space, IEEE Trans. Geosci. Remote Sens., 38 (4), 1903 – 1921.
[35] Wentz, F. J., Peteherych, S. and Thomas, L. A., 1984, A model function for ocean radar cross sections at 14.6 GHz, J. Geophys. Res., 89 (C3), 3689 – 3704.
[36] Nghiem, S. V., Yueh, S. H. Kwok, R. and Li, F. K., 1992, Symmetry properties in polarimetric remote sensing, Radio Sci., 27 (5), 693 – 711.
[37] Yueh, S. H., Kwok, R. and Nghiem, S. V., 1994, Polarimetric scattering and emission properties of targets with reflection symmetry, Radio Sci., 29 (6), 1409 – 1420.

[38] Wentz, F. J. and Smith, D. K., 1999, A model function for the ocean – normalized radar cross section at 14 GHz derived from NSCAT observations, J. Geophys. Res., 104 (C5), 11499 – 11514.

[39] Peña, A., Gryning, S. –E. and Hasager, C. B., 2008, Measurements and Modelling of the Wind Speed Profile in the Marine Atmospheric Boundary Layer, Boundary Layer Meteorol., 129 (3), 479 – 495.

[40] Niros, A., Vihma, T. and Launiainen, J., 2002, Marine Meteorological Conditions and Air – Sea Exchange Processes Over the Northern Baltic Sea in 1990s, Geophysica, 38 (1 – 2), 59 – 87.

[41] Goldenberg, S. B. and O'Brien, J. J., 1981, Time and Space Variability of Tropical Pacific Wind Stress, Mon. Weather Rev., 109 (6), 1190 – 1207.

[42] Kamineni, R., Rizvi, S. R. H., Kar, S. C., Mohanty, U. C. and Paliwal, R. K., 2002, Assimilation of IRS-P4 (MSMR) meteorological data in the NCMRWF global data assimilation system, Proc. Indian Acad. Sci. (Earth Planet. Sci.), 111 (3), 351 – 364.