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A LABORATORY INVESTIGATION ON ELECTROMAGNETIC BIAS IN SEA LEVEL MEASUREMENTS BY MICROWAVE ALTIMETERS

H. BRANGER *, L. BLIVEN ** and A. RAMAMONJIARISOA *

* I.M.S.T., 12 av. Général Leclerc, 13003 Marseille France

** NASA Goddard Space Flight Center / Wallops Island, Virginia 23337 USA

ABSTRACT

To contribute to a better understanding of the Electromagnetic Bias in radar altimetry, a serie of experiments was conducted in the I.M.S.T. large wind-wave facility using a focused beam radar set at 13.5 GHz frequency. For pure wind wave fields we found the bias to be a quadratic function of each of the commonly used parameters, namely the significant wave height, the wind speed, the water elevation skewness and significant slope. The bias divided by the significant waveheight is a linear function of these parameters. The coefficients in bias representation as a function of either the significant waveheight or the wind speed are significantly different from values obtained in field experiments. This led us to conclude that none of the latter parameters can be taken solely to account for all observed bias variations. Instead, dimensionless parameters such as the wave skewness or a dimensionless waveheight are shown to be more appropriate. They include more or less explicetely the state of development of the wind wave field of interest.

Keywords: Altimetry, Electromagnetic Bias.

1. INTRODUCTION

A radar altimeter determines its range by measuring the round-trip time of a pulse of electromagnetic waves to the sea-surface. The mean reflecting surface differs in elevation from the the mean sea level. The difference, called the Electromagnetic (E.M.) Bias, is probably the largest remaining source of error for which no fully satisfactory algorithm is yet established for corrections. E.M. Bias, which obviously depends on the hydrodynamic-electromagnetic properties of the sea surface, is commonly considered as a fixed percentage of the significant wave height (SWH). Such an approximation is not precise enough to achieve the range accuracy of a few centimeters required for the next spaceborne altimeter TOPEX-POSEIDON mission. Modulations of the ocean wave field by non linear wave-wave interactions, currents or residual swell would probably lead to E.M. Bias modulations that should be considered to improve the accuracy of the prediction.

Wind-wave research tank laboratory experiments enable systematic exploration of the influence of geophysical parameters on physical processes under accurately controlled and repetable conditions. Our purpose was to make simultaneous and colocated high spatial resolution measurements of both sea surface elevation and nadir backscattered power in the large I.M.S.T. wind-wave research tank (40mx3mx1m - figure 1-a) under numerous

well controlled environmental conditions. A focused beam radar set at 13.5 GHz frequency was mounted above the tank. The 3 cm spot size allowed us to visualize the sea wave trough/crest asymetry of the backscattered response and moreover to compute the "radar seen" sea surface wave height distribution.

Our main objectives were:

a) to compare the radar seen wave height distribution with the actual wave height distribution, the E.M. Bias beeing the difference between the means of the two distributions.

b) to relate the computed E.M. Bias values with standard geophysical parameters characterizing the wave field, such as the significant wave height, the wind speed, the wave height skewness and the significant slope.

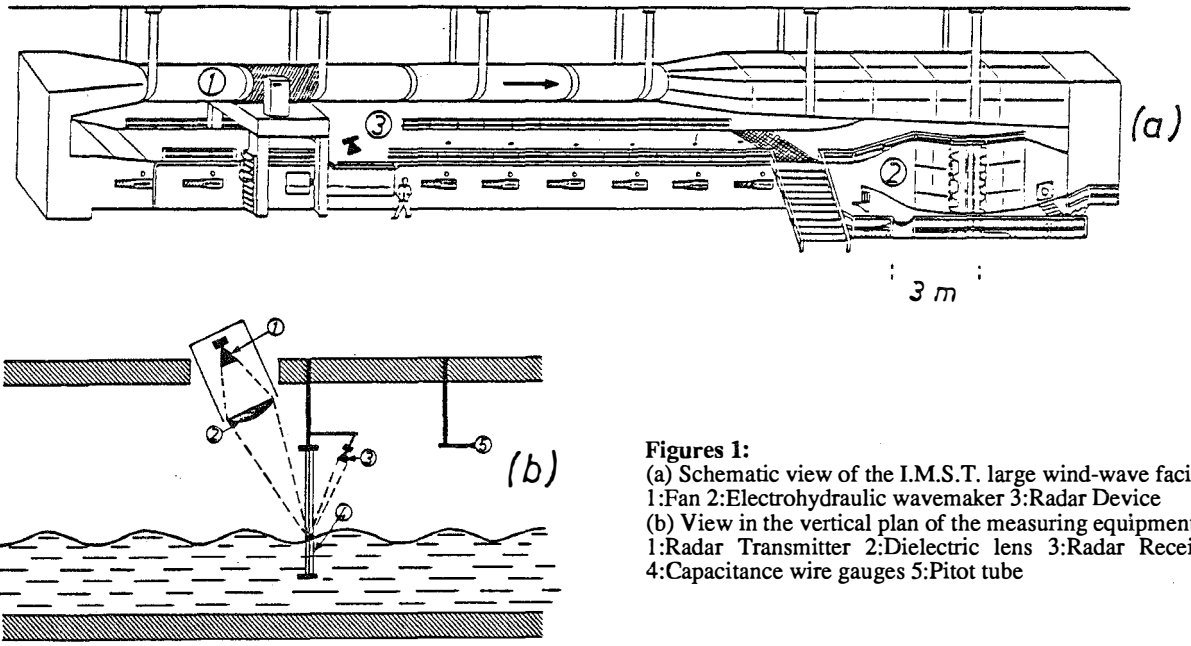
c) to compare the wind-wave tank E.M. Bias values with open field measurements in order to give some clues for the prediction of all the observed Bias variations.

The experimental arrangement is described in section 2. Data processing procedures are detailed in section 3. Main results are shown in section 4 and discussed in section 5.

2. EXPERIMENTAL ARRANGEMENT

The operating frequency was 13.5GHz, one of the future TOPEX mission operating frequency. We used a focused beam radar set in a bistatic configuration (figure 1-b). The transmit and receive horns were located at the same but opposite 10° off nadir angle. The bistatic configuration is equivalent to a nadir monostatic configuration because, in both cases the scattering facets are the zero slope facets of the sea waves. Before hitting the sea surface, the microwaves were focused by a 30" diameter dielectric lens. The spot size was found to be 3 cm at the one meter focal lenght. The dielectric lens which had been first designed by Parsons and Miller [1] for the NASA/GSFC Wallops Flight Facility, was kindly lent to I.M.S.T. The radar system we used was derived from the scatterometer designed by Bliven et al [2]. Absorbing material at appropriate locations reduced multipath reflection. The signal to noise ratio was found to be excellent, namely 60dB.

The mean reflected power from water surface at rest at a level h , namely $P_{cal}(h)$, was determined as follows: starting with the tank full of water, we drained it slowly while acquiring on a computer the water level h delivered by a capacitance probe, and the radar backscattered power



Figures 1:

- (a) Schematic view of the I.M.S.T. large wind-wave facility
 1: Fan 2: Electrohydraulic wavemaker 3: Radar Device
 (b) View in the vertical plan of the measuring equipment
 1: Radar Transmitter 2: Dielectric lens 3: Radar Receiver
 4: Capacitance wire gauges 5: Pitot tube

$P_{cal}(h)$. In order to prevent the tank water height level dependence on the backscattered power, we defined a Reflectivity coefficient $r(t)$ as :

$$r(t) = P(t) / P_{cal}(h(t))$$

$P(t)$ and $h(t)$ being respectively the backscattered power and the water elevation at instant t . $r(t)$ ranged from 0 to 1, the maximum value corresponding to a flat horizontal sea surface all over the illuminated spot.

The water surface elevation and slopes were measured using 3 capacitance probes with 5mm separation in an L. configuration located within the radar spot. The probes delivered a range measurement with a ± 0.2 mm precision. Test runs made with and without the wave gauges, showed that the reflectivity coefficients were decreased by less than 1% when the probes were present within the radar spot. The mean wind speed was measured with a Pitot tube with a precision of a few cm/s. Measurements, made at 28m, were free from reflection from the wave absorber.

3. DATA PROCESSING

Before being digitized at 300 Hz on the I.M.S.T. HP-1000 computer, the two analog 10dB and 20dB Gain Radar output and the three wave gauges analog signals were low-pass filtered with a cutoff frequency of 100 Hz to avoid aliasing effects. For each experiment run, 300000 samples per line were recorded, representing a time span per test of 16 min 40 s.

The elevation $h(t)$ was determined from a single probe. The sea wave along-wind and cross-wind slopes were obtained by differentiating the elevation readings from two adjacent probes and dividing by the 5 mm spatial separation.

We combined the 10dB Gain radar signal and the 20dB Gain one to perform a double decade high precision backscattered signal $P(t)$. The reflectivity coefficient $r(t)$ was computed, as previously defined, using $P(t)$, $h(t)$, and the calibrated Look-up table $P_{cal}(h)$.

In order to compute the E. M. Bias, we performed a "radar seen sea surface distribution" ([1]) : the elevation measurements were sorted into a fixed number of elevation bins. If "i" is the index of the elevation bin, N_i the number of observations sorted in that bin, r_{ij} the reflexion coefficient of sample i sorted in bin j , then :

- the "actual elevation pdf value" of bin number "i" is equal to the ratio of the number of samples that belong to this bin to the total number of data samples:

$$pdf_{Height}(i) = N_i / \sum_k N_k \quad (1)$$

- the "radar seen elevation pdf value" of bin number "i" is set by normalizing the sum of the reflected power of all the samples that belong to this bin by the total amount of reflected power:

$$pdf_{Radar}(i) = \sum_j r_{ij} / \sum_k \sum_n r_{kn} \quad (2)$$

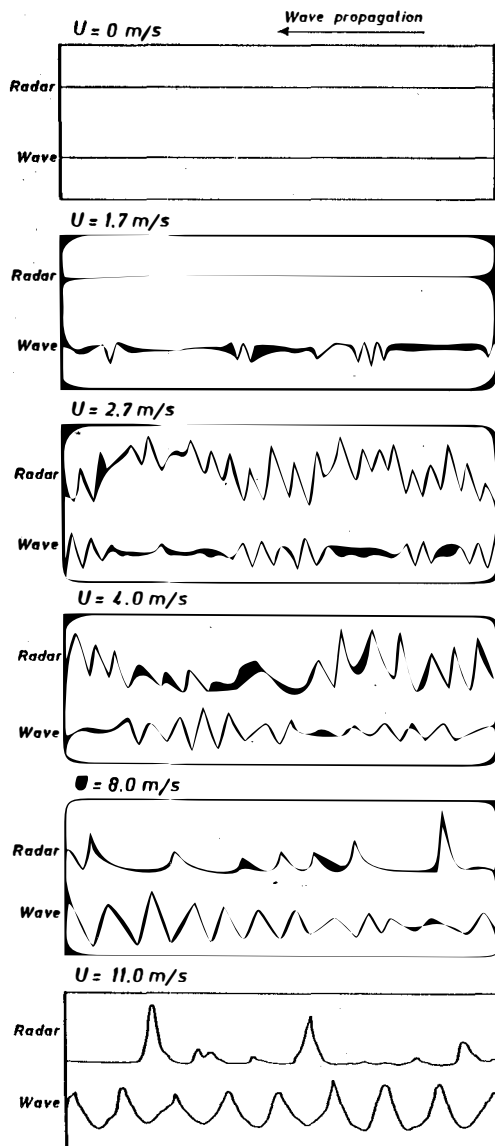
The E. M. Bias, was directly derived from expressions (1) and (2) by differentiating the mean values of the two distributions:

$$E.M. Bias = \sum_i h_i * (pdf_{Radar}(i) - pdf_{Height}(i)) \quad (3)$$

The standard deviation: σ , the skewness : λ_3 and the kurtosis : K_4 , of the surface elevation distribution and of the radar distribution were also estimated. Moreover, we computed for each experiment the significant wave height ($SWH = 4 * \sigma$), the dominant frequency n_0 of the energy containing the waves (from FFT analysis), the dominant wavelength l_0 of the energy containing the waves (from the linear dispersion relationship for deep water gravity waves), and the significant slope ($S = SWH / 4 * l_0$).

4. ILLUSTRATIVE RESULTS

A set of 93 experiments under well controlled conditions have been conducted (wind speed from 0 to 15m/s, paddle wave generator from 1.1Hz to 2.1Hz, and combinations of both wind waves and paddle waves). The

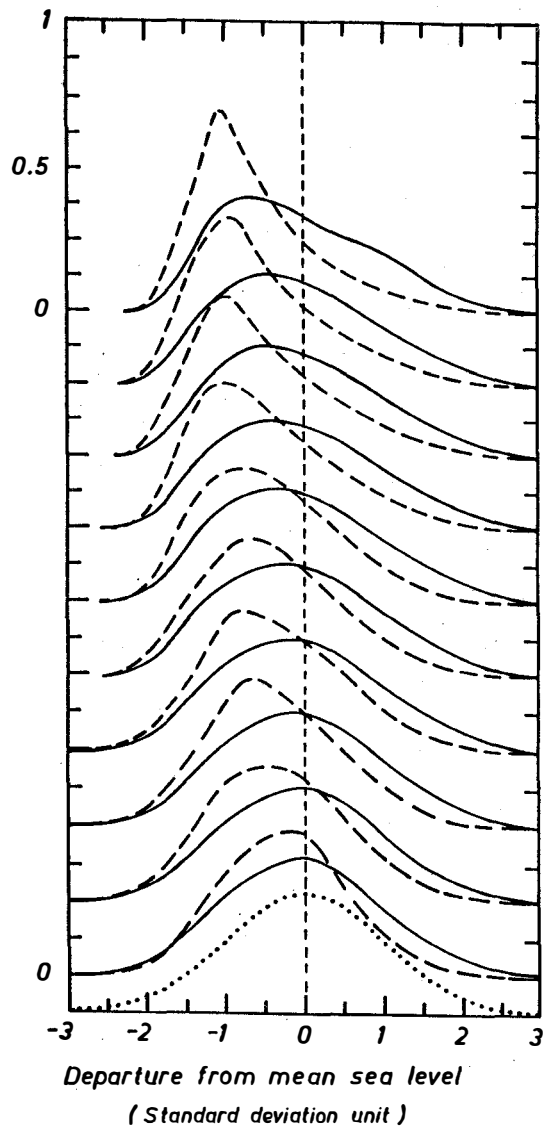


Figures 2:

(a) samples of time variations of the water deflection surface level and the reflected radar signal at various wind speed.

short presentation which follows will concern only the cases of pure wind waves. A subsequent article [3] will report on more detailed results from the complete set of experiments.

Figure 2(a) displays typical samples of the time variations of the water deflection level and the corresponding radar reflected signal. With the water surface at rest ($U=0\text{m/s}$) no parasitical reflection is observed. At $U=1.7\text{m/s}$, the radar appears to be sensitive to small water surface oscillations of few centimeters wavelengths. The fact of interest with regard to the electromagnetic bias is seen at $U=2.7\text{m/s}$ and $U=4\text{m/s}$, namely, the reflection is much larger over the wave trough than over the wave crest. Then, the radar signal oscillates at the frequency of the dominant wave. For wind speed higher than about 8m/s , a large enhancement of the reflected signal is observed in front of breaking crests. These results confirm previous observations by Lifermann [4] under similar environmental conditions which related the signal



(b) probability density functions of waveheight (—) and "radar seen waveheight" (---). Wind speed respectively: 1.7; 3.1; 4.1; 5.5; 6.6; 7.7; 8.9; 10.2; 11.6; 14.1 m/s, from the bottom to the top of the figure. ((.....)Gaussian distribution).

enhancement above the particular geometry of the breaking crests as identified by Bonmarin [5].

Figure 2(b) shows the probability density functions (p.d.f) of the actual waveheight and the radar seen waveheight as defined in section 3 with increasing wind speed. Two facts are obviously of main interest :

- both distributions exhibit larger and larger asymmetry
- the distributions depart more and more each other, the radar p.d.f being more asymmetrical than the waveheight p.d.f. Detailed investigation on the p.d.f will be found in [3].

Figure 3 shows the absolute bias as defined by expression (3) as a function of U, SWH, λ_3 and β . They are commonly used parameters in analysing the electromagnetic bias. The correlation of the E.M. Bias with each of these parameters yields :

$$\text{EM.B. (cm)} = .027 - .015*U - .007*U^2 \quad (r^2=0.99) \quad (4)$$

$$\text{EM.B. (cm)} = .03 - .09*SWH - .007*(SWH)^2 \quad (r^2=0.99) \quad (5)$$

$$\text{EM.B. (cm)} = -.027 - 2.26*\lambda_3 - 9.24*\lambda_3^2 \quad (r^2=0.98) \quad (6)$$

$$\text{EM.B. (cm)} = -.083 - 42.5*\xi - 2455.*\xi^2 \quad (r^2=0.95) \quad (7)$$

r^2 being the square of the correlation coefficient between the regression curve and the measured values. U is in m/s and SWH is in cm.

The variations of the E.M. Bias as a percentage of SWH are shown on figure 4. Ignoring the smallest values which correspond to a very small wind velocity ($U=1.7\text{m/s}$), the correlations with each of the previous parameters seem more to be linear than quadratic. They yield:

$$\text{EM.B. (\%SWH)} = -4.85 - .78*U \quad (r^2=0.98) \quad (8)$$

$$\text{EM.B. (\%SWH)} = -6.38 - .96*SWH \quad (r^2=0.96) \quad (9)$$

$$\text{EM.B. (\%SWH)} = +.92 - 30.*\lambda_3 \quad (r^2=0.96) \quad (10)$$

$$\text{EM.B. (\%SWH)} = +.45 - 466.*\xi \quad (r^2=0.97) \quad (11)$$

U is in m/s and SWH is in cm. Note that JACKSON's theoretical law predicts: $\text{EM.B. (\%SWH)} = -25.*\lambda_3$ ([6]) and HUANG's first order theoretical law predicts: $\text{EM.B. (\%SWH)} = -100*\pi*\xi$ ([7])

The variations above will be discussed in detail in [3]. The discussions will take benefit of theoretical or semi-empirical relationships established within the field of wind waves development ([8], [9], [10]).

5. PRELIMINARY DISCUSSIONS

While the bias from fields observations remains generally smaller than about 5% of SWH , laboratory measurements yield significantly larger values. In addition, these values evolve rapidly with respect to U , SWH , etc... If we want to predict the E.M. Bias with the algorithm: " $\text{EM.B. (\%SWH)} = -a - b*U$ ", b should be of order 0.8 in the tank and of order 0.2 in open field [11]. Clearly neither U nor SWH can be taken as a single parameter to account for all observed bias variations. A dimensionless variable characterizing the state of development of the wind wave fields need clearly to be introduced. At least the influence of the fetch have to be considered explicitly or implicitly. The respective bias from laboratory and fields observations would correspond to different ranges of appropriate parameters. This is preliminarily illustrated by figures 5 and 6 which report on our laboratory results together with some values from fields observations ([11], [12], [13]). The parameters are respectively the wave height skewness λ_3 and the adimensionless significant height, $g*SWH/U^2$, introduced by Rodriguez [14], related with the dimensionless fetch, $g*X/U^2$.

Within extended ranges of parameters values, the continuous variations of the bias is quite striking. This would be of crucial interest to determine the bias evolutions with much higher accuracy. Detailed investigation in that matter is under way.

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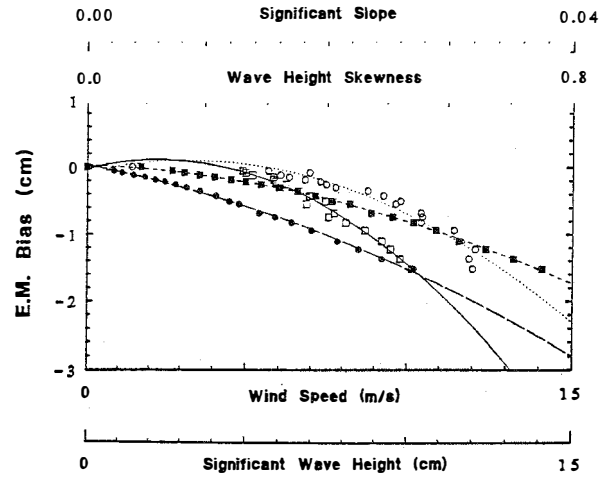


Figure 3: The absolute E.M. Bias (cm) as a function of wind speed (■), significant wave height (●), waveheight skewness (□) and significant slope (○).

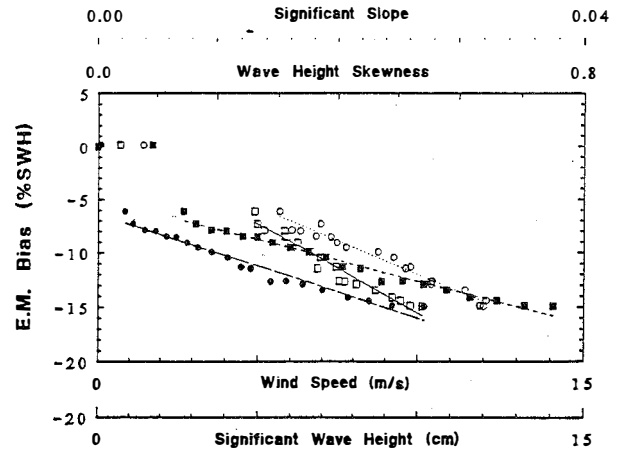


Figure 4: as in figure 3 except E.M. Bias(%SWH) replaces E.M. Bias(cm).

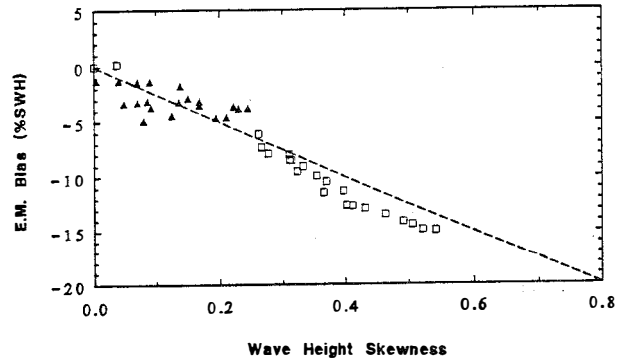


Figure 5: The relative E.M. Bias(%SWH) as a function of waveheight skewness: □ Laboratory; ▲ field (Choy et al [12]); --- JACKSON's theoretical law ([6])

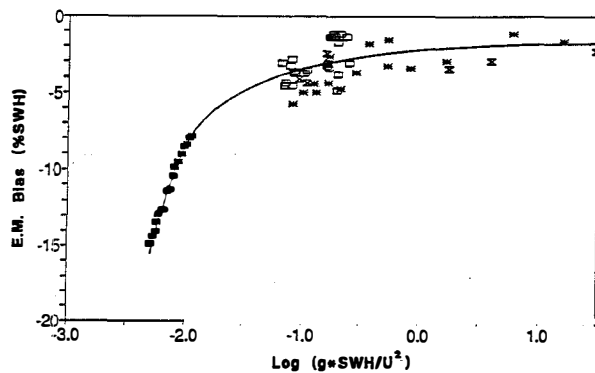


Figure 6: The relative E.M. Bias(%SWH) as a function of the dimensionless significant waveheight $g*SWH/U^2$:
 ■ Laboratory; * Melville et al [11]; × Melville et al [13]; □ Choy et al [12]; — average curve estimated from these data

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