SPECTRAL DEPENDENCE OF THE RESPONSE TIME OF SEA STATE TO LOCAL WIND FORCING

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ABSTRACT

Bistatic remote sensing using L-band GPS signals has been proposed as an alternative to using microwave radiometers and monostatic radar scatterometers for spaceborne ocean surface windspeed measurements. L-band scattered signals are sensitive to waves with longer wavelengths than are the signals sensed by conventional radiometers and scatterometers, which typically operate at higher frequencies. It is known that longer surface waves take more time to respond to surface winds, propagate further before decaying, and are generally less directly coupled to the local wind field. These factors could affect the ability of scattered GPS L-band signals to retrieve local wind fields. In this work, we attempt to quantify the relationship between the longwave spectrum and local winds by examining windspeed and surface slope measurements by buoys. Specifically, by applying a lag-correlator, it is observed that the average lag time decreases monotonically as the ocean surface wavelength decreases. It is found that 1 hour serves as a conservative bound on the average response time of L-band waves to local wind forcing.

Index Terms— Windspeed, Mean Squared Slope, GNSS, GPS, L-band

1. BACKGROUND AND MOTIVATION

Measurements of wind near the surface of the ocean are essential to the determination of momentum and energy fluxes at the air/sea interface and to the forecasting of weather phenomena such as hurricanes. The most widely used spaceborne approaches use passive microwave radiometers [1] and monostatic radar scatterometers [2]. The radiometer approach makes use of the dependence of emissivity on windspeed. Specifically, wind roughens the ocean surface and, if the wind is strong enough, the surface is partially covered with foam, which increases the emissivity [3]. Both the surface roughening and foaming respond nearly instantaneously to changes in local wind conditions. The radar approach makes use of Bragg resonant backscatter from the ocean, which is related to the wind-generated capillary waves. At the centimeters-scale wavelengths typical of scatterometers (QuikSCAT, for instance, operates in the Ku-band at 13.402 GHz), these capillary waves respond almost instantaneously to the local winds and they attenuate rapidly as they propagate away from the wind source [4]. Thus, radars are also sensitive to the local wind conditions.

There has been growing interest in using L-band systems to remotely sense the ocean surface winds, as L-band waves can easily “see through” precipitation. For example, bistatic quasi-specular scattering of GPS satellite signals operating at lower L-band frequencies have been proposed and demonstrated as an alternative way to remotely sense the ocean surface wind field [5]. This technique makes use of the fact that surface wind causes the ocean surface to roughen and the mean squared slope to increase. This, in turn, causes the power distribution of the cross-correlation between the reflected signal and the reference pseudo-random noise signal to widen [6]. In addition to the penetration ability of L-band waves, another major advantage of GPS over conventional radiometers and radars is that the cost and accommodation requirements of GPS receivers are significantly lower. However, the use of L-band signals results in an interaction with much longer ocean surface waves, which can take a longer time to respond to changes in wind.

The relationship between the local ocean surface wave spectrum and the local wind field is examined here. Of particular interest is the responsiveness of the portion of the wave spectrum with which L-band scattered signals will most strongly interact.

2. APPROACH

Mean squared slope (MSS) is the variance of the ocean surface slope process and is a measure of the roughness of the surface. In the following sections, we describe the computation of the MSS over different wavelength ranges of the wave spectrum. We also consider the lag time in response of each range of the wave spectrum to changes in the local windspeed. We are interested in the temporal responsiveness of the shorter portion of the wave spectrum, with which radiometers and radars interact, relative to the responsiveness of the longer portion of the spectrum, with which GPS signals interact.

3. DESCRIPTION OF DATA SOURCE

The NOAA National Buoy Data Center (NBDC) operates and maintains buoys in oceanic and coastal areas which collect various environmental data, including windspeed. Some buoys are also capable of providing omnidirectional spectrum data as a function of frequency (see Section 4). However, these buoys are not able to measure wavelengths as short as those that influence L-band bistatic scattering cross-sections; the shortest wavelength measured by the buoy under study is about 6.6m. Since shorter waves respond quicker to wind than longer waves, the average response time of ocean waves at the longer wavelengths measured by the buoys gives us an upper bound on the average response time of the shorter waves to which L-band remote sensing is sensitive.

4. WIND AND WAVES SPECTRAL RELATIONSHIP

It has been shown that MSS can be obtained from the wave number omnidirectional surface elevation spectrum $S(k)$, which has units of m^3: [7] [8]

$$MSS \triangleq \int_0^\infty k^2 S(k) dk \tag{1}$$

Where k is the wavenumber. MSS is a unitless quantity. The term $k^2S(k)$ in (1) is referred to as the wave number omnidirectional slope spectrum. NBDC provides the omnidirectional spectrum as a function of frequency, $S(f)$, with units of m^2/Hz or m^2s, and refers to this quantity as the spectral wave density. Typically for buoys $S(f)$ is only available from 0.03 Hz to 0.40 Hz. Since MSS is defined in terms of $S(k)$, we need to convert $S(f)$ to $S(k)$. In performing this conversion, we make use of a dispersion relation that assumes the waves are over large water depths [7]:

$$w^2 = gk \tag{2}$$

$$4\pi^2 f^2 = gk \tag{3}$$

where w is the angular frequency and $g \doteq 9.80\ m/s^2$. It can then be shown that

$$S(k) = \frac{g}{8\pi^2 f} S(f) \tag{4}$$

For these relationships to hold, we choose a buoy far away from coastal zones to provide the omnidirectional spectrum data. NBDC Station 42058 is selected; it is located in the middle of the Caribbean Sea with a nominal position of 14°55'23" N, 74°55'4" W. Available data from this buoy for years 2008 and 2009 are analyzed.

In summary, $S(f)$ measured by the buoys can be converted to $S(k)$ using (4). k can be obtained from f using (3). Finally (1) is invoked to compute the MSS. Since the buoys measure the omnidirectional spectrum as a function of a discrete number of frequencies, the integration is approximated in calculating the MSS.

In order to assess the time responsiveness of the ocean surface to external wind forcing as a function of the surface wave spectrum, the integral over the slope spectrum given by (1) is sub-divided into n segments and integration is carried out over each segment individually in order to estimate the portion of the variance in the surface explained by each segment of the surface slope spectrum, or:

$$MSS1 \triangleq \int_{kstart}^{k1} k^2 S(k) dk \tag{5}$$

$$MSS2 \triangleq \int_{k1}^{k2} k^2 S(k) dk \tag{6}$$

$$\ldots$$

$$MSSn \triangleq \int_{kn-1}^{kend} k^2 S(k) dk \tag{7}$$

Where $MSSi$ is the MSS of the ith segment, $kstart$ corresponds to the longest available wavelength and $kend$ to the shortest available wavelength.

The number of segments chosen is 5. The available wavenumber range is divided into the 5 segments so that the MSS for each segment is approximately the same. In other words, the magnitudes of $MSS1$ through $MSS5$ are roughly the same. Note that this is not the same as putting an equal number of wavelengths in each bin. The longer wavelengths contribute significantly less to MSS than the shorter wavelengths because of the k^2 term in the definition of MSS. Thus, in practice, $MSS1$ results from integrating over a slightly wider interval than $MSS2$, which integrates over slightly more than $MSS3$, and so on. For each segment, we define the center frequency of the segment to be the arithmetic mean of the two frequency limits (corresponding to the two wavenumber limits) in the integration, and the wavelength corresponding to the center frequency is defined as the center wavelength.

4.1. Manual Identification

The next step is to estimate the time lag between temporal variations in the MSS for *each wavenumber segment* and temporal variations in the local windspeed. It should be noted that the correlation coefficient between the wave spectrum and the local wind field is a random variable. It is affected by physical mechanisms such as the decay of surface waves, which governs the degree to which the local sea state will be affected by wind fields elsewhere. While the decay rate itself is deterministic, the effect of this decay on the correlation coefficient depends on how fast the wind field is changing as a function of position, which is a random process. This is especially true for longer portions of the wave spectrum. When there is sufficient correlation between the wave spectrum and the wind field, a lag time can be identified, which is a random variable because of the decorrelation effects. Here we limit the scope of the work to determination of the average lag time.

By manually selecting prominent features (such as a gust of wind) and observing the lag between windspeed and MSS, we can obtain an order-of-magnitude estimate that will serve to define the "window" for the more accurate and precise method introduced in the next subsection. This is demonstrated graphically in Figure 1.

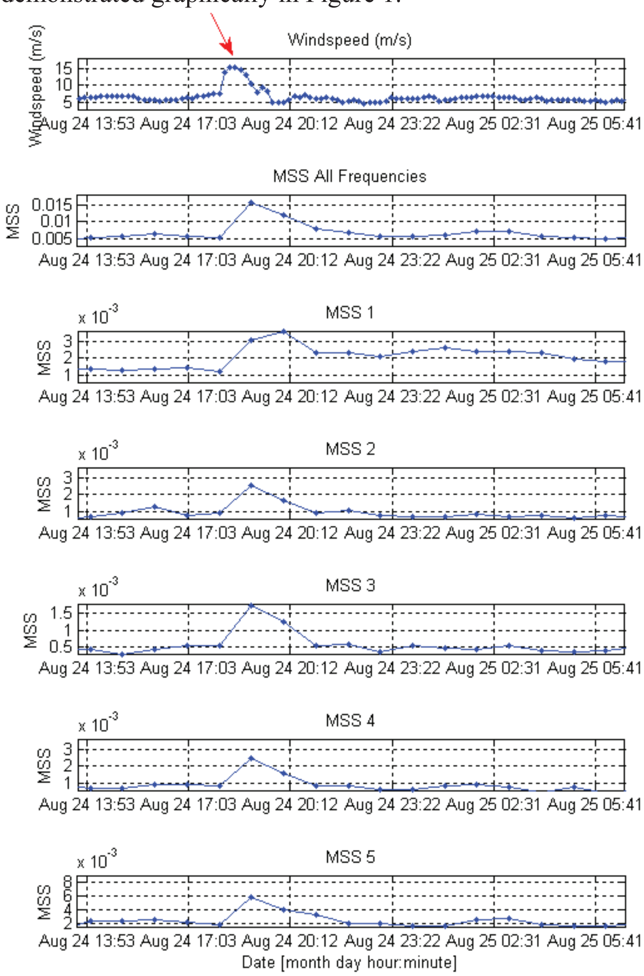

Figure 1: Top to Bottom: Windspeed, MSS integrated over all wavelengths, and MSS in wavelength segments 1 to 5. The feature of interest here is the prominent gust in windspeed (indicated by the red arrow). Corresponding peaks in all MSS plots are also evident, and the time lag between the gust in windspeed and the peaks in each MSS can be manually estimated.

Taking the difference between the time of the local maxima in the windspeed and MSS signals, the estimated lag times for all MSS signals in this case fall between 0.5 and 1.5 hours.

4.2. Lag-Correlator Estimator

To examine the aggregate response lag time, we make use of a lag-correlator. The lag-correlation between two continuous-time real-valued signals $r(\tau)$ and $s(\tau)$ can be defined as:

$$\psi_{rs}(t) \triangleq \lim_{T\to\infty} \int_{-T}^{T} r(\tau' + t)s(\tau')d\tau'. \tag{8}$$

Stated another way,

$$\psi_{rs}(t) = r(t) \star s(-t). \tag{9}$$

where $\star$ denotes linear convolution.

Lag-correlation is then applied to the MSS and windspeed signals, with $s(\tau)$ representing the windspeed and $r(\tau)$ representing MSS. The length of the MSS signal required to produce a stable lag time estimate is about 150 days; this was demonstrated by simple trial-and-error. The length of the windspeed signal is 10 hours shorter with a length of 150 days-10 hours, because from previous manual identification result we expect the lag time to be less than 10 hours. After synchronizing the sampling periods of windspeed and omnidirectional spectrum data, and carrying out the lag-correlation, the independent variable (time) corresponding to the maximum in the cross-correlation function gives an estimate of the time MSS lags the windspeed. This is done for all 150-day periods of time for which contiguous data is available for the two years.

5. RESULTS

A monotonic decrease in MSS lag time with spatial wavelength is consistently observed over each 150-day period in the two years examined; the results for year 2009 are shown in Figure 2.

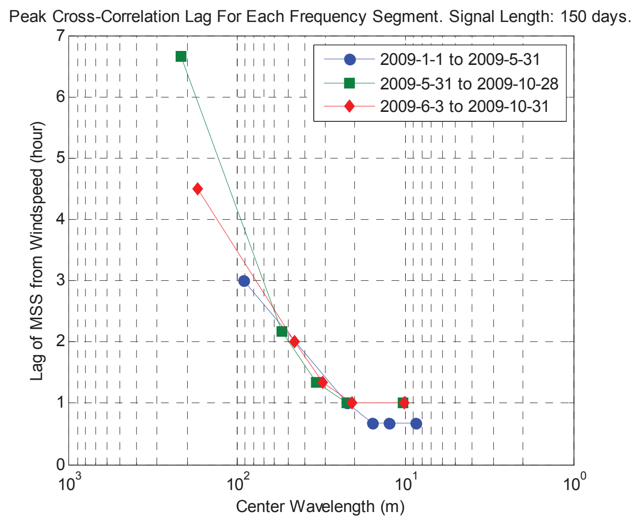

Figure 2: MSS lag time as a function of 5 wavenumber segments for year 2009. A monotonically decreasing relationship is observed. Note wavelength decreases from left to right.

It is observed that waves with wavelengths on the order of 10 meters have an average lag time of approximately 1 hour, which serves as an upper bound on the average lag time of shorter waves to which L-band signals are sensitive. It should be noted that this lag-time is of significance only when windspeed changes drastically. In calm wind conditions, the measurement errors of L-band systems due to the lag time are insignificant. If we define a drastic change (conservatively) as a change of more than 6 m/s in windspeed over an hour for the location under study in the Caribbean Sea, these drastic changes account for less than 0.2% of the cases in 2009 for which contiguous data is available.

6. CONCLUSION

The motivation for this investigation is to determine the response time of L-band waves to changes in local wind conditions. Mean Square Slope (MSS), the expected average power of the surface slope process, is used to characterize ocean waves, and it is clearly seen to follow changes in windspeed. MSS is calculated for different intervals of the surface wave spectrum provided by the NBDC buoys, and a lag-correlation analysis is used to systematically find the lag time between MSS and local wind variations as a function of ocean surface wavelength. When the time duration of signals being examined is sufficiently long, it is observed that lag time (MSS response time to wind changes) decreases monotonically as wavelength decreases. The lag time is at most 1 hour at a wavelength of about 10m; thus we have an upper bound on the average response of L-band waves to changes in wind.

One other aspect needing further study is the degree of decorrelation between the local sea state and local wind field. The effects of surface wave attenuation (or lack thereof) can be studied either analytically, by deriving a relationship between the e-folding distance as a function of wavelength, or empirically, by examining the magnitude of the correlation coefficient for smaller time segments, instead of the time of maximum correlation as has been done here.

It is desirable to make the upper bound on response time as restrictive as possible. To this end, one important addition to the current analysis would be gathering and analyzing omnidirectional spectrum at shorter wavelengths, so that a more accurate response of ocean waves as a function of wavelength can be derived.

7. REFERENCES

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