Notes on Sea Spikes presentation at AP•S/URSI conference 7/11/01

Slide 1: Title slide

Slide 2: Talk outline

Slide 3: Data Sources:

The data used in this talk are taken from three experiments and two different radars. The 1990 SAXON FPN experiment had beam-limited scatterometers at L, S, X, Ku, and Ka bands mounted on the platform. A dual-polarization, X-band, pulsed radar, built at APL, was deployed for the first time during the 1995 COPE experiment (visible as a ball on the bow of FLIP). This same radar (rebuilt for higher power and to correct problems with squint angles and the failure of the power monitor that were discovered during COPE) was used in the 1996 MISE experiment.

Most of the data used in the spike analysis are from the COPE experiment. For comparison, one file from the MISE experiment was run, but more work needs to be done with this important data set. One day’s worth of files from the FPN data are included in the talk, the Ku-band data from 11/21/90. It was on this day that David Arnold of MIT used Andy Jessup’s dual-polarization Doppler scatterometer and stepped it through incidence angles from 20 degrees to 80 degrees in ten-degree increments.

I should note that the images and plots in this talk are all separate files, and can be expanded to whatever size the reader desires to examine details of interest. This would be especially helpful in finding the APL radar on FLIP in this figure, or viewing the particulars of the wave field in slide Nine.

Slide 4: Previous work at moderate incidence angles:

Much has been published regarding sea spikes at grazing incidence by L. Wetzel, D. Trizna, and others. But, for spikes at moderate incidences, Andy Jessup’s MS and PhD thesis work provides the standard by which other studies must be measured. He used a dual polarization Ku-band Doppler scatterometer from the FPN tower (for his Master’s thesis) and participated in the SAXON CLT experiment in 1988 with the same instrument for his PhD work. He acquired the data as digital quarter-second averages in power and Doppler parameters, from which he was able to retrieve Doppler bandwidth and center frequency, and wrote the raw (unaveraged) data to analog tapes. From his detailed analysis of the NRCS and the Doppler characteristics of his signals combined with coincident video, he concluded that for 70%-75% of the spikes encountered, if (at 45 degrees) the backscatter peaked above ~7.5 dB (at HH or VV polarizations) and the bandwidth peaked above 50 Hz, there was a wave breaking (i.e. generating visible white-capping) either in the radar beam-spot or within five meters down-wave of the beam-spot. He noted that there were many cases of otherwise significant (as defined above) spikes where no breaking crests were observed, and cases where waves were clearly breaking in the radar’s field of view, but no spikes occurred.

Given Jessup’s definition of sea spikes, I had assumed the analysis of sea spikes in the COPE data would be straightforward: average the data over a quarter of a second as he did, then just find the coincident (or, near co-incident, Jessup had noted that the bandwidth peak tended to occur after the power peak and just behind the crest of the breaking wave) power and bandwidth peaks and those would be the breaking-wave-generated spikes. However, 2D plots of center frequency versus bandwidth, where power levels are indicated by false-coloring (blue as low power through red as high power) revealed that for these relatively deep-ocean COPE data, the high power, high bandwidth population was missing, at all incidence angles and polarizations. There were high power signals that were narrow bandwidth, and high bandwidth signals that were low power, but rarely were both elevated in the same quarter-second sample window. After verifying that the COPE data were uncontaminated by unexpected signals, I checked to see if the strong, wide population could be retrieved by time-shifting the power 0.25 seconds relative to the bandwidth, since Jessup had said the bandwidth peak came later in time than the power peak. I could not. Jessup had sent APL his raw analog tapes to be digitized for archiving with a DAQ here (in fact, the same DAQ used to record the SAXON-FPN data). So, we digitized tape 65, which contains the data Jessup referred to as Run 12 in his dissertation and publications (two minutes of which are shown above left). The first hour (which
includes the data above) digitized without error; however, due to problems with the age of the analog tapes and the Instrumentation Recorders we were using to play them back, that hour was all we successfully acquired. But those data were sufficient for me to be able to verify Jessup’s conclusions about the timing and characteristics of his spikes, and show that his strong, wide population was indeed present, without undue analysis.

This left me in a quandry. Where had the strong, wide points gone? On searching the literature (Trizna, Reno, Smith and Poulter, Frasier et al.), I noted that each of these authors defined their sea spikes as exceeding the mean cross-section for one second or longer. Bill Plant reported that in wavetank measurements conducted in the Marseilles tank, the cross section remained elevated after the passage of the crest of a paddle-generated breaking wave. Andy Jessup, in a long phone conversation with me, had emphasized the importance of the concurrent bandwidth peak in linking sea spikes with breaking waves. Using this apparently counterintuitive (the name ‘sea spike’ implies high power, not long time-width or wide bandwidth) information, I developed the definition of sea spike as outlined in the next viewgraph.

Slide 5: Generalized Spike Definition:

There has been some corroborating evidence presented that bandwidth is very important in correlating cross section and wave breaking. This waterfall plot of short time-averaged Doppler spectra from Keller, Plant, and Valenzuela shows the excess bandwidth associated with a breaking wave (see the high frequency excursion between the ‘0’ and the ‘s’).

When I searched the COPE data for spikes meeting this generalized definition, I was able to retrieve the strong, wide population of spikes, so I was ready to proceed with characterization.

Slide 6: Sea Spike Time Duration HH-pol:

A sampling of the time and bandwidth characteristics of the spikes in the COPE data yielded interesting conclusions. At 64 degrees incidence for HH polarization, the 2D false color distribution at the upper right (where the color bar at the lower left indicates the number of occurrences in any one bin) shows that the largest majority of spikes are still less than one second in length, but that these have narrower bandwidths (peaking at 40 Hz, according to the distribution at the upper left) associated with them than do the longer time-duration spikes. Also, there is a tendency for the peak bandwidth to increase monotonically with increasing time duration. From the 1D distribution in the lower right, there are twice as many spikes where the power exceeds the mean for only a half a second, or two samples, as there are for spikes where the power is elevated for one second.

It should be noted that Jessup, who used only PEAK power and PEAK bandwidth in his final spike determinations, found his spike distributions changed when he dropped his averaging window from 0.25 seconds to 0.125 seconds. I tested to see if that was true with this definition by re-averaging this high wind, upwind run for 0.1 seconds and 0.05 seconds. I did not find an appreciable difference in either the spike distribution or population densities as the averaging times changed. This is not surprising, since the time window of significance for the spike definition was the one-second threshold.

Slide 7: Sea Spike Time Duration VV-pol:

The VV-pol spike characteristics were similar to the HH-pol spike characteristics as delineated in the notes on the previous slide, with the exception that there was not the same tendency for the spike bandwidth to increase with increasing time duration.

Slide 8: Ground Truth with Video Data:

A video camera with a wide-angle lens was mounted adjacent to the fan-beam radar antennas to keep track of the FOV. On September 18th, the winds dropped to less than 1 m/sec, so Rick Chapman, who conducted the COPE field campaign, took advantage of the break to measure the antenna pattern of the radar, both in azimuth and elevation. The LADAS, a laser slope spectrum imaging system mounted on a 3.5 m wide
catamaran, was moored 36 m away from FLIP, with a 1 m in diameter mooring buoy 48 m further out from the LADAS. Rick stepped across the LADAS in two-degree intervals, providing a check on the ranging calculations (the right-hand plot). The separate HH and VV antennas were squinted about one degree or so in opposite directions off the center, so calculating HH/VV polarization ratios would prove nonsensical. The angle at the center of the video image is given by the pitch-and-roll-corrected depression angle for the video/radar mount, and the rest of the angles were determined using angular spreading coefficients calculated from images of measured targets at known distances back in the lab. The radar DAQ gave the user the option of setting the timing delay to the first range bin, and the width of each of the range bins in time, then recorded these values in the header of each data file. Thus, processing in the lab allowed the conversion of the data from range bin to center incidence angle. Further, since the radar antennas and video camera were mounted at 19.5 m above the sea surface and the angles were known, distances to the LADAS and buoy were calculated from the data. The range bins were about 3 m in length, so the mooring buoy fell in a single range bin of the radar returns. The LADAS, with its multiple reflecting mounting structures, was wider in radar range bins than in reality by about a factor of three, but, the distances known from the field and calculated from the video images and radar data (using the center of the LADAS signature for the radar) agreed to within 3 m and/or a half a degree of each other.

IRIG time codes, generated by a single card in the radar DAQ, were inserted into both the microwave and video data, so true time and space coincidence could be determined. For wave analysis, the IRIG times were converted to SMPTE and projected onto the video data stream, as can be seen in the video image on the left. The time is displayed as hh:mm:ss:ff, where ff is frame number (30 frames per second on the Video 8 tapes), on the portion of the image where the rain-shield for the radar is visible (smooth area with black circles).

To cut down the time involved in visually examining the ocean surface where spikes were measured, three incidence angles were chosen for video verification. I used 53.8 degrees, 64.3 degrees, and 74.9 degrees. On the video image above, I have over-plotted rectangles corresponding to the radar beam-spot for each of those range bins (the 64 degree rectangle is on top of the LADAS).

Slide 9: Ground Truthing with Video: Waves:

The coincident videotapes were digitized using the Matrox Millennium frame-grabber card and the fgrab utility under RedHat Linux 6.2. To track the evolution of the sea surface before and after the spikes, I had sought to digitize the video at the rate of acquisition, i.e. 30 frames a second. However, the fgrab software had an internal glitch that prevented it from running any faster than about 12 frames per second. Fortunately, this worked out to be sufficient for our purposes. It was also at the limit of accuracy for the IRIG to SMPTE conversion hardware.

To get the most out of this slide, I suggest the reader expand each of these annotated video frames to full-size to examine the details I’ll be referring to here.

As with the video ground-truth frame shown in the previous slide, the SMPTE time code was projected onto the image, and the lab calibrations were used to convert lines and scans to azimuth and elevation angles. To examine the development of the sea surface in detail, I selected a minute of imagery on either side of the spike beginning and end for annotation and animation. I drew squares representing the surface projection of the range bin of interest on each digitized frame so I could focus on the radar beam-spot as the waves moved through it. To provide a visual indication of how the power and bandwidth were changing, I plotted both these quantities as a pair of slider bars to the left of the beam spot for HH-pol or to the right for VV-pol. If the viewer expands the upper left video image he or she will see that there are two vertical thresholds drawn on the log Power (this showed more detail in the dynamic range of the returned power), one dotted and and solid. The dotted line is the mean power, and the solid line is one third of the maximum power. On examining Jessup’s data, I deduced that the one-third max power threshold corresponded roughly to his −7.5 dB breaking wave threshold. The solid line on the bandwidth slider bar is the average bandwidth minus the wave-following bandwidth. Again, from Jessup’s data, this corresponded roughly to his 50 Hz threshold. The vertical line in the image is a mooring line for FLIP, and does not interfere with either the main beams or the side-lobes of the radar. Once these two-plus minutes of imagery were
annotated, they were converted to Gifs and animated using the software package Image Magick. I could run the animations forward and in reverse, and at any speed I so chose, until I was comfortable I understood what the radar was seeing. I also built in the option of printing out the frame closest to the time of the peak of the returned power (which I have printed as a part of the image header), so I had a permanent record of particularly informative sequences.

I examined video imagery for spikes at both polarizations and the three incidence angles I referred to in the notes for the previous slide under the following conditions: high winds (~10 m/s) at upwind (with the swell waves aligned with the wind waves) and at 135 degrees to upwind (FLIP acted as its own wind-shadow, so I couldn’t use the full downwind cases), mid-winds (5-7 m/s) at upwind, 135 degrees to the wind, and crosswind. The swell waves were, for nearly all cases, from the Pacific toward the radar. This gave them the maximum fetch possible, and, for the mid-wind crosswind case the swells were generally more responsible for spikes in the data than were the wind-generated waves. There was no time-coincident video for the high-winds crosswind case, and, in the interests of time and my own sanity, I chose not to visually verify the high wind and mid-wind cases where the winds were at 45 degrees to the radar look direction. I reached several conclusions while completing the video verification of the spike determinations. First, for these data, there was no easy way to discriminate between breaking waves (using Jessup’s definition of generating visible whitecapping) and non-breaking steep waves. He had also sent APL the video he had used to verify his spikes, and a quick examination of the waves imaged revealed why breaking was easy for him to see, while it was difficult for determine in the COPE data. The Chesapeake Light Tower (CLT) is in 13 meters of water, and, for the cases Jessup examined in detail, the winds were from the northwest, the waves had a fetch of only 32 Km, or, the distance from the mouth of the Chesapeake Bay to the tower. The waves were steep and triangular in shape, with only short linear wave fronts. Once these waves steepened, they generally broke with visible whitecapping and their wave energy dispersed. Pacific swells have gentle slopes and long, linear wave fronts (as can be seen in the image at the upper left) that sometimes ran across the entire video FOV. A portion of the wave front would whitecap, but the whole wave generally remained intact, so, outside of some spilling, the swell waves would move through the beam without dispersing, unlike the CLT waves.

Given this different wave behavior, I stopped attempting to discriminate breaking and non-breaking waves, even though I had numerous cases of spikes peaking above the thresholds equivalent to Jessup’s breaking wave cases.

What I found, however, was equally as interesting, at least for the generation of sea spikes. Over the entire data set, 80%-85% of the time, spikes (as defined in slide 5) occurred in the radar data when a wave-generated water surface of steep slope and high curvature filled the beam-spot. The high curvature surface took several general forms: straight-on swell waves (the two images in the left-hand column), a rough dihedral where two waves crossed at an angle in the beam (the two images in the center column), and a high-curvature surface to the left or right of the crossover region of two swell waves at angles to each other (the two images in the right-hand column). At times the spike would occur when the crossing region of two waves would develop a concave dish, but no cases illustrating that are presented here. In this slide, the top row of images represents the surface at the frame closest to the time of peak power, and the bottom row the images of the surface closest to the time of peak bandwidth. The straight-on swell wave spikes show much the same behavior as Jessup found: the power peaks just ahead of the crest of the wave, and the bandwidth just behind it. For the crossing wave spikes, the power would elevate above the mean, would stay high, and the bandwidth stay wide for the duration of passage of the crossing wave pattern through the beam.

So far as I know, the correlation between spikes and crossing wave patterns is new in the discussion of sea spike behavior.

Given the high degree of correlation between spikes and water surfaces of high curvature, I proceeded to compile statistics on sea spike densities as a function of radar parameters and wind and wave conditions, as shown in the next two slides.

**Slide 10: Wind Dependence of Spike Density:**
This slide illustrates the sea spike density (number of spikes per unit time, where for these plots, the unit of time is a twenty minute data file) as a function of wind speed and azimuth for the three incidence angles verified. As with the previous slide, I suggest the viewer expand each graph to examine the details contained within.

At high winds, the spike densities were found to be highly directional relative to the mid-wind cases. At high winds, there were generally four times as many spikes occurring when the radar was looking upwind as when it was looking almost downwind. At mid-winds, while the largest spike density was at upwind, there were half as many spikes off upwind as at upwind. As was mentioned earlier, this may be due to the spikes resulting from the swells, which were nearly always propagating into the radar look direction from the Pacific. Also, it became increasingly clear from the video verification that at 53.4 degrees and mid-winds the swells and dominant wind-waves reflected off the body of FLIP, generating spikes when these reflected waves met the on-coming waves for the cross and near-downwind cases. This was not true for the higher incidence angles, so the spike densities (certainly at 75 degrees) represent spike properties from the wind-generated and swell waves only, not from FLIP perturbing the wave field.

**Slide 11: Polarization Dependence of Spike Density:**

This slide shows the most surprising result to arise from this study. As with the previous slide, the spike densities are plotted as a solid line for the HH spike density, and the VV spike densities are plotted with a dashed line. Only here the spikes are plotted as a function of incidence, not azimuth, angle. The plot on the left is from the SAXON-FPN data set, specifically the Ku-band data collected on 11/21/90, when two-minute data files were collected over an entire day and a range of incidence angles of 20 degrees to 80 degrees. Since this is a beam-limited system, the area of the beam spot on the water surface increases with incidence from a few square meters to a few tens of square meters. The center and right-hand plots are from COPE and MISE, where the APL fan-beam X-band system was used to collect data from incidence angles near-simultaneously, and because the system is range-gated, the area of the beam-spot remains nearly fixed across all incidences. (It does widen and lengthen slightly at high incidences, but remains less than three meters by four meters even at 75 degrees incidence in COPE and 80 degrees incidence in MISE.)

Jessup had found that at 45 degrees incidence, the number of spikes per unit time (sea spike density) is about the same for HH and VV polarizations at upwind. This was true for all three experiments here. I should remind the viewer that Jessup’s CLT data were taken at high winds (friction velocities of 48 cm/sec) upwind in 13 meters of water and at 32 Km fetch. The FPN data were collected at ~6 m/sec at a little over 45 degrees azimuth, in water of 30 meters depth and several hundreds of Km of fetch. The COPE data were high winds and upwind, in 120 m water depth, at essentially infinite (Pacific-wide) fetches, and the MISE data were collected at 8 m/sec winds from 30 degrees azimuth, in water of 8 m depth, at Atlantic-wide fetches. Thus, Jessup’s conclusion about the equivalence of HH and VV polarization spike densities at upwind and 45 degrees incidence has been verified over about as wide a range of ocean conditions as may be obtained.

Now we come to the most potentially controversial result of this study. Over this same broad range of ocean conditions, as the incidence angle increases, for sea spikes defined as in slide five, VV-polarization spikes were found to be from 1.5 to two times as common as HH-polarization spikes. It is given in the scattering community that at extreme grazing (89 to 90 degrees incidence), the HH-pol backscatter is spikier than the VV-pol backscatter. Further, the HH-pol backscatter is ALL spikes at extreme grazing, while the VV-pol cross sections retain some mean scatter. It is with these facts that I postulate we can explain this unexpected polarization dependence with increasing incidence angle. Remember that I required not that the PEAK cross-section exceed a specific high threshold, but that the total cross-section only exceed the mean for a time width of one second. If the backscatter is either zero or a high value, as it is at grazing at HH polarization, then there will be relatively little time when the cross section values reside close to the mean. Thus, the returned power will have to be significantly elevated during a one second time window for a spike to be counted under this study’s definition. At VV-polarization with increasing incidence angle, there is still a vestigial mean cross-section that remains, even at high incidences. Thus, at VV-pol, it is possible through simple summation (of a mean level plus a low spike) for the cross sections to remain elevated above the mean level without having to spike (in the
classical sense of producing extremely high returned power signals) for a full one second and meet the spike selection criteria for power I have chosen here.

This hypothesis may be tested by removing the bandwidth criterion for the spike definition, then counting the number of spikes that are occur. If the presence or absence of a mean level were all that was necessary to declare a high signal a ‘spike,’ then the bandwidth criterion should have no effect on the relative spike densities for HH and VV polarizations. When I performed this test, the absolute number of spikes found jumped for both polarizations, all tested incidences and wind conditions by, on average, a factor of three, but the polarization dependencies did not reverse.

Slide 12: Conclusions:

I would like to emphasize this final conclusion again in these notes. There are many classes of spikes, not all of which could be examined in this study. Given that the transmitted power monitor channel failed early on and that the HH and VV polarization antennas were squinted just enough off each other that polarization ratios could not be calculated, it would not be possible, in the COPE data set, to search for either spikes defined by the polarization ratio going to one, or to seek out those super-events where the HH polarization cross section exceeded the VV-pol cross section. Given sufficient funding, I would like to fully examine the MISE data set, where neither of these problems occurred, and compare the unity polarization and super-event spike densities with the spike density of these Jessup-type spikes.

It would also have been helpful had there been other measurements of spike density at both polarizations published. Frasier et al. used their X-band FOPAIR system to image the ocean surface at mid-incidences in the Pacific in April and May of 1995. But in their publications, they only report HH-polarization spike properties, after stating that Bragg scattering is sufficient to explain the cross sections they measured at VV-polarization.

Slide 13: Future Work:

For a full list of publications used in this presentation, the reader should consult the following papers, between which the viewer may obtain most of the pertinent references for sea spiking studies in the open literature:

