Waves Tiger Team Report

February 2012; Revised June 2012 & July 2012

Executive Summary and Recommendations:

- Wave height is by far the highest priority parameter in public demand. HF radar (HFR) has demonstrated that this can be robustly measured in real time, with no hardware in the water, as a dual-use output from many US IOOS HFRs. Other lower-priority parameters are listed in the body of the report below.
- QA/QC of wave-parameter outputs is needed for operational use (i.e., remove outliers). This effort is underway at the R&D level among IOOS academic partners but will require funding to be completed for operational level QC.
- Not all of the approximately 130 HFR systems in the national network are capable of robust wave outputs. Utility depends on the radar frequency and on conditions at the site: maximum currents; bathymetry; max/min expected wave-height range.
- An assessment of which US IOOS HFRs are capable and recommended for wave parameter outputs should be undertaken by IOOS partners and the IOOS Program Office, with inputs from algorithm developers/testers.
- Real-time HFR wave outputs into NDBC from selected sites should occur. Wave output data formats that are acceptable to NDBC should be identified.
- A design for the ingest, storage, and dissemination of the HFR wave outputs is needed.
- There should be a few HFR sites designated for wave inputs to WFOs (Weather Forecast Offices), for evaluation and feedback.
- At some point, an amendment should be made to the NOAA IOOS "A National Operational Wave Observation Plan" (2009) to reflect HFR wave parameter utility and readiness.

Initial Purpose of Tiger Team: The team's purpose was to examine wave parameters as they are being produced by HF radars of all brands, and ultimately decide which might be ready for ingestion into public web servers as robust, accurate, meaningful, and reliable. An amendment might be made to the NOAA IOOS "A National Operational Wave Observation Plan" (2009) to reflect this readiness.

Wave Parameters and Priority Level of Utility/Importance:

Parameters listed below should be understood to fall into three potential spatial categories that might be observable by HF radar: (i) Spatial average over a broad area around a single HF radar; (ii) A small-cell (nearly a point) measurement at given location; (iii) A spatial map of the listed wave parameters (either from a single radar or overlapping pair coverage). High priority is to provide these wave parameters over the full range of expected wave energy -- lowest to highest.

1. Significant Wave Height

2. Wave Period (centroid, mean, peak)
3. Wave Direction (centroid, mean, peak)
4. Bimodality (waves of two periods from different directions)
5. Wave Scalar Energy Spectrum
6. Wave Direction vs. Frequency
7. Wave Energy Spectral Spread
8. Full Wave Height Directional Spectrum ("first five", comparable to wave buoy)

Decision Criteria for Operational Readiness:

The criteria listed below should constitute a basis of an "operational readiness" decision. The temporal and spatial sampling readiness should be spelled out (e.g., broad area average vs. detailed spatial map).

1. Demonstration of Real Time Operability: This requires that the radar's field processor runs all required wave algorithms, with any necessary QA/QC tools, such that it displays and stores the final data products that are candidates for operational consideration. It does not mean that a radar collects and archives raw or intermediate data products in real time, for later off-line processing.

2. Real-Time Availability of Wave Data on Several Public Websites: Wave capability can be deemed credible and ready if it is demonstrated to run on several radar systems and their processors, and is presented in real time on public websites for others to use and compare, at least qualitatively if not quantitatively. This shows that it is operational but caveats should be listed spelled out, e.g., where wave data may be less trustworthy. Should also link to nearby buoy data, where available, for comparison.

3. Who Does the Comparisons (not exclusively a developer): To strengthen credibility, data on a public website should be able to be observed by anyone and compared: with buoy data in the vicinity; with news reports; with hindcasts, nowcasts, or forecasts. Wave experts besides the developer and from other organizations are necessary in such comparisons to establish accuracy, robustness, and confidence by repeated observations over an extended period of time.

4. Continuous Records over Years, Multiple Radars, Multiple Seasons: Operational integrity must be established by collecting and comparing data from multiple radars running the same software, over all seasons and several years. Sensor data used for comparisons should also span these durations. Comparison differences should be explained and have a physical basis. Claims of successful comparisons and validations done only over days, weeks or a month are not adequate to establish operational readiness.

5. <u>Meaningful Tests of Specific Claims</u>: Radars will not measure the same quantities as buoys. A claim that a measured quantity is meaningful and useful must be proven. We give two examples:

a. Measurement of wave parameters averaged over an area, e.g., 20 km about the radar. How does one know whether and how this compares with a buoy deployed within the area? Long-term measurements and comparisons along the lines of the previous criteria should be used to establish that the claimed area measurements of the radar are meaningful, accurate, and useful, and over what temporal scales. If the radar area measurement consistently agrees with a point/buoy measurement over these temporal scales, credibility and utility of the area average is established.

b. Mapping of wave parameters over an area, e.g., 40 km about the radar, on a 3-km grid scale. If this claim is made, validation must be done at several points within the mapped area at the same time, implying at least two spaced comparison sensors. A single sensor is inadequate. One must consistently establish that a mapped quantity at one point compares best to the other-sensor measurement at that point, and correlations with other locations are consistently poorer. The claim of mapping has no meaning if the observed spatial variability cannot be established quantitatively by independent means.

6. <u>Segregation and Assessment of Spatial/Temporal Statistical Variability</u>: Wave measurements are noisy, because the sea surface itself is a Gaussian random variable (to lowest order). Data products should have minimum variability over time and space that is not related to meaningful, changing wave conditions. A "scatter plot" that has a 45° regression line (no bias) but looks like a shotgun blast on the page is not useful or desirable. Do the wave parameters claimed ready for operational use have this random variability minimized, or at least clearly assessed and available to the user? Have the sensor tradeoffs been considered and presented among various types of averaging (temporal and spatial), vis-a-vis averaging over features that are meaningful? For example:

a. What is the RMS wave height variability of a radar output averaged over 20 km in space and one hour in time? How does this compare to the rms fluctuation of a buoy-measured waveheight over the same temporal scale?

b. What is the RMS wave height variability of radar outputs mapped every 3 km and outputted every ten minutes? How does this compare with the same quantity averaged over one hour? How do these two vary with mapped position in the radar coverage area? Existing wave hindcast model data could be used to do similar spatial averaging; this would be an informative evaluation for both hindcast and HFR data.

7. <u>Clear Revelation of Limitations</u>: Forty years experience with HF radar wave and current monitoring have made clear the physical limitations of these measurements. Although every HF radar can accurately measure currents, not all can produce meaningful wave measurements. The second-order echo on which it depends is much more susceptible to limiting degradations. These must be spelled out for existing and

new potential sites where radar wave measurements are proposed, so that they can be taken into account when considering for operational use. For example:

a. When waves are too high at a given radar frequency, the basis for everyone's extraction methodology breaks down. So the question: what are these limitations for a given radar and its frequency based on the local wave climatology?
b. When waves become too low at a given radar range and frequency, the weak second-order echo needed becomes buried in the noise/interference.
c. How do strong currents or horizontal current shears, combined with antenna pattern sidelobes and other distortions, impact wave outputs?

Many potential radar sites can be eliminated from wave considerations in light of the above limitations. Even those included must have flags in the output files that detect and remove data when these limitations are exceeded. Is this being done at radar sites being considered for operational use? Risk to human life can be involved if erroneous data are used for many operations. Nonetheless, there a significant number of existing sites that have no upper wave height limitations (mid and low frequency systems). Low wave height threshold limitations can often be overcome -- where it is important -- by waveform and antenna/power gain modifications. It should noted that utility of data from an HFR site for quantifying local wave climatology over extreme conditions may be compromised if limits exist.

Who Makes the Decisions for Operational Readiness? A separate committee from the operational/user community should examine the above readiness criteria for a candidate radar/location. This committee should not include any of the developers of the radar wave output software or methodology (e.g., Barrick, Lipa, Haus, Wyatt, Gurgel, etc.). The developer may present his/her candidate to the committee, advocate for their claims, but should have no vote on the outcome. The committee should evaluate any case presented and give feedback to the developer as to outcome, deficiencies, and how to improve the claimed outputs in order to gain acceptance.

The subject of file outputs, formats, metadata, for operational ingestion are all wide open, because it is assumed that any selected sensor/software developer will modify its data files to conform to desired preferences.