Guidelines for Assessing HF Radar Capabilities and Performance

Technical Report

CPSD #11-01

Submitted to the Standards Committee of the IEEE Ocean Engineering Society following the IEEE CWTM 2011 Conference

George Voulgaris

Coastal Processes Sediment Dynamics Laboratory
Department of Earth and Ocean Sciences
University of South Carolina
Columbia, SC

October 2011

List of Contents

Guidelines for Assessing HF Radar Capabilities and Performance

Prof. George Voulgaris
Dept. of Earth and Ocean Sciences
University of South Carolina,
Columbia, SC, 29208, USA

Preface

This document has been produced following the discussions on a special session on standards in Current, Waves, and Turbulence Measurements that was held on Tuesday March 22 from 1:00 to 3:00 pm as part of the IEEE CWTM 2011 Conference. This session was an open discussion moderated by Sandy Williams (chair of OES Standards Committee), Don Barrick (President and CEO of CODAR SeaSonde) and Steve Hold (member of OES Standards Committee). As part of the discussions the author of this document was assigned to prepare a report on the following items:

1. Spatial sampling (with Don Barrick)
    a. Volume resolution
    b. Profiling cell size, spatial spread, range
    c. Acoustic profiler qualifiers (signal strength, correlation, etc.)
    d. Acoustic Doppler sensitivity to particle properties and concentration
2. Remote sensing (with Don Barrick)
    a. HF radar range
    b. HF radar velocity resolution
    c. HF radar cell resolution, angular resolution, and accuracy.
3. Wave sensing (with Marinna Martini and Lucy Wyatt)
    a. Spectral resolution as a function of depth
    b. Sensitivity and range
    c. Directional resolution
    d. Sensitivity to interference

Although there is some overlap in the above listed subjects, this report focusses mainly on remote sensing in general and HF radar applications in particular. Although in some aspects the principles used are applicable to all items listed above. This report expresses the views of the author who has no financial interest with any instrumentation manufacturer and he disclosures that he is an owner and user of WERA phased array systems as well as acoustic instrumentation manufactured by Nortek, YSI/Sontek and Teledyne RDI.

1. Introduction

HF radar technology is a complicated technology that has developed over the years by experienced radar technology scientist and engineers. As the technology and its capabilities have advanced, HF radars have become widely available to user scientists and managers interested in oceanographic and environmental processes who are not necessarily familiar with the technology and the signal processing methods employed in radar technology.

The purpose of this document is to identify the important issues that control the quality and accuracy of HF radar derived measurements. These issues are presented mainly from the experienced user rather than from the radar technologist point of view. The document presents the important issues that control flow measurements and are required for their correct interpretation and calls upon the radar technologist community and manufacturers to provide the correct answers. Furthermore, this document aims at identifying the most important issues that users of such systems should be aware and hopefully help them ask the right questions when selecting a system for their particular application. Some of the issues described are set primarily by the principles of EM wave propagation, hardware, antenna layout and digital signal processing methods used. It is the objective of the author that this document is used as a guideline for defining the important parameters that need to be disclosed by system manufacturers, but also a guideline for scientists and engineers engaged in validation of HF radar system capabilities through intercomparison with other measuring devices (e.g., acoustic instruments, drifters, surface buoys etc.).

Also it should be noted that this document is a brief report and it does not aim to provide a comprehensive review of all aspects of HF radar development, signal processing and operational procedures. The reader is referred to consult the plethora of literature available in the subject and in particular the peer reviewed one.

2. Principle of operation & HF Radar sample volume

The HF radars emit EM waves at a particular frequency (f_r). These waves are coupled with the conductive sea surface and Bragg waves with a wavelength half of that emitted EM wave are propagating toward and away from the radar station. The backscattered signal is modulated by the sea surface waves during and received by the receiver antennas; then it is internally analyzed by the radar system to produce a Doppler spectrum ($\sigma(\omega)$, where ω is the radial frequency) of the return signal. This spectrum contains information on surface currents (first order cross-section), surface ocean waves (second order waves), targets on the sea surface (i.e., ships) as well as environmental and/or unwanted radio frequency interference (RFI) noise. Radar signal processing aims at initially reducing RFI from the Doppler spectrum and subsequently, depending of the application, remove targets for clear identification of the hydrodynamic signal (surface currents and/or waves) or eliminate the hydrodynamic signal (clutter) in order to clearly identify signal from targets such as ships.

One of the advantages of HF radar technology is that the systems are able to generate this Doppler spectrum (and the information contained within) at various locations of the radar coverage area, providing a spatial coverage achievable only by the deployment of a large number of in situ sensors or by numerical modeling. Reliability of the radar derived information as well as their accuracy requires knowledge of the exact location on the sea surface the signal is coming from, as well as its lateral and vertical extend, quantities that define the location and sample volume of the radar system. Accurate definition of the latter defines the spatial scales that can be resolved by a HF radar and allows placing comparisons of radar derived quantities with those from in-situ instrumentation, with different sample volume(s), within an appropriate context.

The location of the area of the ocean the backscattered signal comes from is defined in radial coordinates by the range (r) and the azimuth (θ_r) from the radar location and a reference orientation (usually defined by the radar Rx antenna and orientation). Thus accurate definition of the location of the sample volume requires knowledge of the ability (i.e., accuracy and resolution) of the radar in defining range and azimuth.

3. Range Estimation

The radar frequency (f_r) and the bandwidth (B) are usually set during installation and conform to the transmitting license issued by the authorities responsible for issuing such permits (FCC in the US). Most commonly radars transmit a Frequency Modulated Continuous Waves (FMCW) signal that continuously spans the predefined bandwidth (B) around the central radar frequency (f_r). The time it takes for spanning this bandwidth B depends by the scan rate and is called the transmit chirp duration (T).

Radar theory defines that the distance along a radar radial is a multiple of the range cell depth (dR) which is defined as dR=c/2/B, where c is the speed of light. During data processing a convolution of the Tx chirp signal with the Rx signal is carried out and following an FFT the range cell depth (dR) is related to spectral resolution (dF). Application of different filters during the FFT process can change the resolution (dF, or spectral bandwidth) of the spectral analysis which is always the reciprocal of the record length transformed or given by the ratio of sampling frequency over number of points being FFTed. The effect of filtering is that the bandwidth of the spectral analysis is always larger than that of the spectral resolution by a factor (n_f) defined by the time window used prior to FFT.

Window Type	**Spectral resolution increase factor (n_f)**
Rectangular	1.00
Hanning	1.50
Hamming	1.36
Kaiser-Bessel	1.80
Truncated Gaussian	1.90

Table 1. Deterioration of spectral resolution by the application of different types of filters (from Randal, 1987).

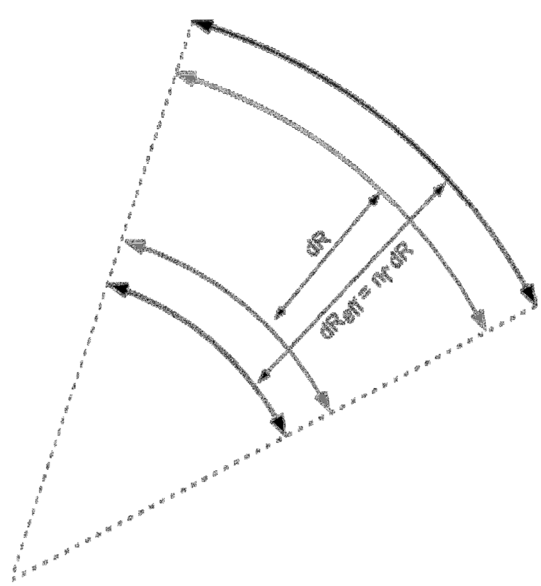

Figure 1. Schematic diagram showing the difference between nominal range (dR) defined by the bandwidth (B) used during transmission and the effective range cell depth(dR_{eff}) that accounts for the effective decrease in spectral bandwidth during the conversion of the range cell definition from time lags to frequency increments. The value of nf depends on the filters used (see Table 1).

Thus due to the application of filters prior to FFT, the nominal range cell depth dR can be increased by an amount similar to that of the spectral resolution (see Figure 1)**. For clarity purposes, it is suggested that the term "effective" range cell depth is defined that takes into consideration the application of filters in defining the range cell depth.**

4. Azimuth estimation

The estimation of the azimuth (angle) that source of the received signal is located for phased array systems depends on the ability of the system to steer the beam of the Rx array. This process is called beam forming and it is used to define a directional signal reception. The maximum angle of steering that can be achieved by beam forming depends predominantly on the number of antennas that constitute the array (usually 8, 12 or 16 for commercially available phased array systems), its configuration (i.e., linear or curved), the electronics, environmental noise, as well as the particular beam forming method and weights (constant *vs.* adaptive) used. The conventional method to define the steering ability of a beam forming method is through the use of beam pattern diagrams that graphically describe the sensitivity of a beam to signals from different directions. This sensitivity is described for each main direction by the main lobe which is aligned with the direction the beam is steered to. The width of the mean beam indicates how focused the system is. In addition to main lobes there are commonly side lobes the amplitude of which indicates the sensitivity of the system to signal originating from directions other than that of the main lobe. In general, the width of the main lobe as well as the amplitude of the side lobes increase with increased angle from the array normal. Currently it does not seem to be a common way to describe the directional resolution of a system**. It is recommended that the width of the main lobe at -3db is used to define the angular resolution of the radar (see Figure 2). This width should be expressed as an angle and it should be reported for different steering angles. A minimum number of three angles is recommended that correspond to Rx array normal (0 degs), ±45 degs and ±60 degs (the maximum recommended for phased array systems). In addition, although the amplitude of the side lobes is normally kept constant when the beam is steered, in quality assessment the side lobe suppression (i.e., ratio main lobe to side lobe, e.g. 30 db) should be reported..**

Although beam width as defined above is useful in determining the lateral extend of the sample volume (see Figure 1) which naturally will increase with range from the radar, it does not relate to the resolution and accuracy of beam steering. Since beam forming and steering is based on the application of phase differences in the signals received by each antenna, the accuracy of steering depends on a number of parameters that amongst other include accurate knowledge of cable lengths (static phase differences) distance between array elements.

Differences in cable lengths can be accommodated through an accurate calibration procedure which for the purposes of setting standards it is assumed that they are always carried out. In a simplified manner the equation shown below describes the relationship between direction a signal comes from (θ), phase difference applied to the signal of two adjacent array elements (Δϕ), the wavelength (λ) and the distance (d) between the antennas:

$$\theta = sin^{-1}(\frac{\Delta\phi \cdot \lambda}{2\pi d})$$

any error in defining the phase difference or distance between antennas will be propagating in the estimation of the angle of the signal, or beam steering angle. Thus the resolution in beam steering angle and accuracy depends on the resolution in estimating and applying phase differences and accurate knowledge of the distance.

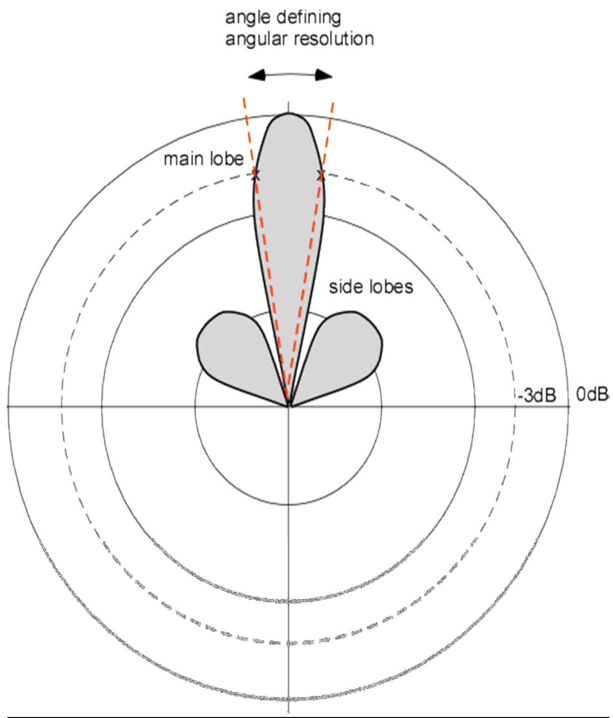

Figure 2. Schematic diagram showing a hypothetical beam pattern for a specific direction and the methodology suggested for defining angular resolution as a beam width (in degrees) that corresponds to a -3dB gain. Note that beam pattern can change with direction. As a consequence different angular resolutions might apply for different

The independent nature of beam width resolution that defines the lateral extent of the sample area and the beam steering angle resolution and accuracy is schematically shown in Figure 3. In there, it is easily shown that independent sample areas are achieved only when the beam steering angle is greater than the beam width angle. The beam can be steered at angles smaller than that of the beam width, if resolution allows, but in this case any physical properties derived (e.g., radial currents) are not to be considered independent, as part of the backscattered signal is common to the adjacent cells. Use of a steering angle increment less than that of beam width angle is equivalent of applying a moving filter on high resolution data. Although smoothed data might contain information from adjacent cells, the weighing is different and this might be allowable or even recommended for certain applications such as target detection, as the target will appear stronger at the steering angle coinciding with the target azimuth from the radar site.

At this point it should be mentioned that the above remarks are more applicable to beam forrming (phased array) systems that have an aperture defined by the number of antennas used in the array. When a very small number of antennas is used (<4) the aperture (i.e., angular resolution) becomes very small (i.e., wide angle) and phase shifting cannot be applied. Under these conditions, the steering is achieved by analyzing the signal in the frequency domain using appropriate algorithms; this method is called Direction Finding and the angular resolution is based on the algorithm used. The angular resolution for direction finding systems depends on the algorithm used and the length of the signal (temporal averaging) used**. It is recommended that the manufacturers of such systems report the angular resolution as function of time-averaging or for a specific averaging period**.

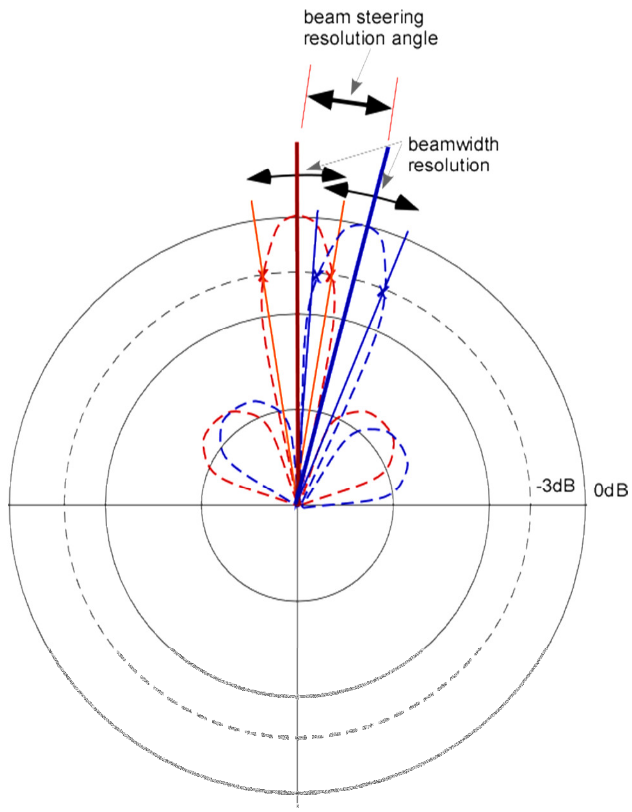

Figure 3. Schematic diagram showing hypothetical beam patterns for two different beam steering angles. It is clearly shown that the beam width resolution that defines the width of the radar sample volume can be different from that of the steering angle increment. When the steering angle increment is smaller than the beam width angle, there is an overlap of sample areas.

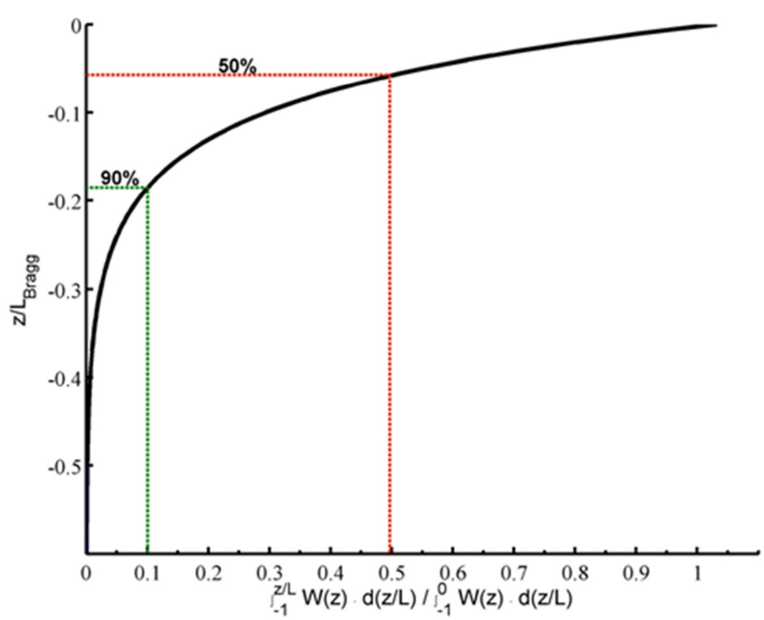

Figure 4. Cumulative weight function representing the penetration of the radar signal below the sea surface. W(z) denotes the vertical distribution function of the Stokes velocity.

5. Doppler spectrum

The radar derived Doppler spectrum for a particular range cell and azimuth is the result of temporal averaging defined by the radar operator and by the specific characteristics of the system used (radar frequency, f_r, bandwidth B; transmit chirp duration T). The origin of the signal for phased array systems is confined to the spatial area defined by the sample area as characterized by the effective range depth cell and beam width angle, defined in the previous sections. For direction finding systems, the Doppler spectrum contains signals from a specific range cell and from all azimuthal directions superposed. In addition, the Doppler spectrum captures flow of the surface layer of the ocean that extend to a depth below the sea surface defined by the Bragg wavelength but weighted with a weighting function that decrease exponentially with distance below the sea surface (Figure 4). This weighting function is defined by the Stokes profile for the wave with a wavenumber corresponding to the Bragg wave that corresponds to the radar operating frequency. Calculations based on the Stokes velocity profile suggest that 50% of the vertically integrated signal is integrated over a depth approximate 5% the wavelength of the Bragg wavelength, while 90% of the averaging extends to depths 18% of the Bragg wave lengths. For a 24MHz system these depths correspond to 0.34 and 1.12 m below the sea surface.

The resolution of the radial velocity estimate depends on the resolution in detection of the spectral peak. This depends on the SNR but also of the spectral resolution which in turn depends on the number of points used for its creation and the filters (if any) that have been applied to the range and azimuth sorted data points prior to FFT. This resolution is given by:"

$$\Delta u = \frac{c \cdot f_s}{2 \cdot n \cdot f_r T}$$

Where n is the number of samples used in the spectrum estimation, fs is the sampling frequency c, the speed of light and fr is the radar operating frequency

At this juncture it should be noted that although radial resolution depends on Doppler spectral resolution, an accuracy better than the above mentioned resolution can be achieved through the utilization of specially defined peak detection algorithms. A commonly used algorithm defines the location of the Doppler peak taking a frequency-mean weighted by the power levels of each individual frequency. This is obtained by selecting a number of frequencies around an initially selected peak based on maximum energy. This approach is widely used in acoustics as well in radars and other applications that require accurate detection of peaks. It provides the position of the peak with much higher resolution than the spectral frequency bin.

It is recommended that the resolution and accuracy in peak detection in Doppler spectrum is defined by disclosing the method utilized for peak detection.

6. Comparison of HF Radar derived velocities with in-situ data

In the literature, a number of studies can be found that aimed at comparing the velocities derived by HF radars to those deducted from the deployment of in situ instrumentation. Correlation coefficients, RMS differences and bias between the two data sets are usually calculated and reported. **However, prior to deducting any conclusions from comparisons of any two flow measuring devices, a detailed analysis and comparison of the sample volume of the two instruments need to be performed.** In particular, any comparison should acknowledge:

a. *Differences in sample area*. HF radar sample volumes are usually much larger than those of in-situ sensors. An HF sample area is defined by the effective range cell depth and the beam width at a particular radial direction (see sections 3 and 4). For an upward looking acoustic instrumentation this is defined by the divergence of the acoustic beams which depends on acoustic beam angle from the vertical and water depth. Thus for an ADCP with a beam slanted 20 degs off the vertical, the extend of the sample area near the sea surface is $2 \cdot \sin(20^o) \cdot h$, where h is the water depth**. It is suggested that dimension of sample volumes for both radar and in situ instruments are always reported**

b. *Differences in vertical integration of measured flow.* The vertical integration of acoustic profilers is defined by the bin size. Since these sensors suffer from interference with the sea surface the closest to the sea surface they can measure depends on water depth (h) and it is usually given by $(1-\cos(20^o))*h$ (assuming a 20deg off the vertical beam orientation). Thus the center of the bin closest to the sea surface is always at $(1-\cos(20^o))*h + 0.5*binsize$. This geometric argument is valid for a mean sea level, but when waves are present this distance needs to be increased by at least a distance half the significant wave height (wave crest)**. It is recommended than when an in-situ station data is used, the location of the sample volume (center of bin) is reported in relation to the sea surface after accounting for signal contamination for wave conditions**.

c. *Velocity components to be compared.* Velocity comparison between the two sensors and applicable statistics should be performed on the radial velocities only. This requires estimation of the radial velocity from the in situ station, along the direction of the radar beam. 2-D vectors derived from the combination of two or more radial velocities include errors coming from the geometric configuration; these are not necessarily errors associated with the accuracy of a radar system**. It is recommended that comparison of velocities is performed only on radial velocities.**

d. Differences in temporal integration times. All natural phenomena in the ocean they exhibit natural variabilities that operate at different temporal scales. Any flow measurement is a statistical description that assumes that this quantity has been sampled at appropriate sample rates that capture the phenomenon without aliasing but also for a period long enough so that includes a suitable number of full periodic cycles (for example, averaging over 5 sec in a wave dominated environment will result in inaccurate measurements of mean velocity; on the other hand averaging over 5 min or sampling every 5 min is not suitable for resolving wave properties). On the other hand, SNR or other instrumentation inherited conditions might require sampling over a period that is much larger than the period required to accurately describe a processes. **It is recommended that the manufacturers of HF radar systems clearly define the minimum periods of data collection required for accurate measurements, or accuracy as function of integration time,** In addition very long sampling periods might violate the stationarity of the measurement (e.g., long averaging in a tidal environment) as the statistical properties measured change with time. Thus the integration period of a measurement might affect the results**. It is recommended that HF radar signals are integrated over period sufficient to resolve the natural variability while ensuring stationarity of the signal. Furthermore when HF radar signals are compared to in-situ sensor results the integration period should be of similar magnitude and any differences should be clearly identified.**

e. *RMS differences as statistical description of comparisons.* Correlation coefficients are useful in expressing the correlation and linearity between two parameters but by themselves do not reveal any information about accuracy. On the other hand RMS differences are useful but need to be reported as a function of the range of velocities being encountered. For example a result indicating an RMS difference of 10cm/s in flows rarely exceeding 15cm/s is indicative of a large discrepancy. On the other hand if the flow ranges used in the calculation of the RMS differences where over values extending to 100 cm/s, then this same RMS difference might be indicative of good agreement**. It is suggested that any RMS differences reported are normalized by the range of values encountered. As range the value of twice the standard deviation is recommended, which assuming a normal distribution describes the range over which 95.6% of the data are found.**

f. *Comparing agreement between two sensors.* Despite the above recommendations, the statistical approaches described above assume that the in situ measurements represent true flow conditions, ignoring the fact that any measurement is an approximation and contains its own errors. Voulgaris et al (2011) argued that a better presentation of the agreement between two methods can be achieved by testing the two radial velocity estimates for equality of biases and variances utilizing the method introduced by Altman and Bland (1983) and Bland and Altman (1986; 1987). This method is based on the fact that the two variables (u_{radar} and $u_{in\ situ}$, in our case) represent measurements of real world conditions by different methods (radar and in situ sensors, respectively). The covariance of the difference ($\Delta u = u_{radar} - u_{in\ situ}$) and the sum ($Su = u_{radar} + u_{in\ situ}$), relates to the difference of the individual velocity estimate variances. Regression analysis between the mean velocities from the two sensors and their differences is carried out and the slope is an indication of differences in variances (i.e., zero slope indicates that the two measurements have the same variability) while the intercept is indicative of a bias by one of the sensors. **It is recommended that any quantities from two sensors are examined for bias and equivalence in variances as described in Voulgaris et al. (2011).**

7. Concluding Remarks

Some recommendations and definitions required for understanding data provided by HF radars have been presented along with guidelines for the comparison of HF radar data with in-situ data. HF radar manufacturers are encouraged to adhere in reporting the parameters described in this report and fully disclosing methods used in data processing. Utilization of open source code in processing is highly recommended as it provides transparency and confidence to the experienced user for the system used. By no means the recommendations provided here are exhaustive, but simply constitute the first step toward standardization.

References cited

Altman, D.G. and J.M. Bland, 1983. Measurement in Medicine: the Analysis of Method Comparison Studies. The Statistician, 32, 307–317.

Bland, J.M. and D.G. Altman, 1986. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet, i, 307-310.

Bland, J.M. and D.G. Altman, 1995. Comparing methods of measurement: why plotting difference against standard method is misleading. Lancet, 346, 1085-7.

Randall, R.B, 1987. Frequency analysis. Publisher Bruel & Kjaer, ISBN 87 87355 07 08, 3rd Edition

Voulgaris, G., N. Kumar, K.-W. Gurgel, J.C. Warner and J. H. List, 2011. 2-D Inner-Shelf Current Observations from a Single VHF WEllen RAdar (WERA). Current, Waves and Turbulence Measurements (CWTM), IEEE/OES 10th Working Conference on., 20-23 March, 2011, pp 57-65 ISBN: 978-1-4577-0022-4