Features and Limitations of Ocean Surface Dynamics Measurements by means of the Ocean-Radar “WERA”
presented at Workshop on Typhoon Wind and Wave Statistics, Taiwan 2009

Thomas Helzel, Matthias Kniephoff, Leif Petersen, Markus Valentin
Helzel Messtechnik GmbH, Carl-Benz-Str. 9, 24568 Kaltenkirchen, Germany

Day, Local Time, 11 am - 2:30 pm

Night, Local Time, 8 pm - 11:30 pm

© HELZEL Messtechnik GmbH

e-mail: helzel@helzel.com
Features and Limitations of the Modular Oceanography Radar System WERA

1. Introduction
   Principle of the Oceanography Radar

2. Features of this Radar Technology

3. Limitations due to Environmental and Physical Conditions

4. Boundary Conditions for WERA Installations

5. Conclusions
1.1 Introduction
Principle of the Oceanography Radar

WERA is a shore based remote sensing system using the over the horizon radar technology to monitor ocean surface currents, waves and wind direction. A vertical polarised electromagnetic wave is coupled to the conductive ocean surface and will follow the curvature of the earth.

The rough ocean surface interacts with the radio wave and due to the Bragg Effect back-scattered signals can be detected from ranges of more than 200 km.
1.2 Introduction
Principle of the Oceanography Radar

The back-scattered radar signal will be Doppler shifted with a specific frequency offset given by the velocity of the gravity wave that is responsible for the Bragg scattering.

These Doppler shifted signals will be symmetrical around the centre frequency as long as the ocean surface does not move. An ocean current will shift these Bragg lines up or down in frequency.
1.2 Introduction
Principle of the Oceanography Radar

The various data can be derived for these spectra, such as Ocean currents, Waves, Wind Directions and Targets. The radar ranges to provide these data are different, e.g. as listed below for a normal, medium and long range system:

- Ocean Currents: 50 km 100 km 200 km
- Wind Direction: 40 km 80 km 160 km
- Vessel Tracking: 35 km 70 km 140 km
- Wave Data: 23 km 45 km 90 km
2.1 Features of this Radar Technology

From standard range systems at the west coast of Florida. The WERA system is operating in FMcw mode with 28 W power, the settings are:
- 16 antennas @ fo = 16.04 MHz
- sweep time = 0.3 sec
- measurement time = 10 min (2048 samples)
- Range cell size = 1.5 km

WERA data are kindly provided by Prof. Lynn K. (Nick) Shay, RSMAS, for more information and results visit:
http://iwave.rsmas.miami.edu/wera
2.2 Features of this Radar Technology

Surface current map during the passage of Tropical Storm Henri on 2003/09/03

© HELZEL Messtechnik GmbH
2.3 Features of this Radar Technology

Time series comparison of surface currents derived from WERA and ADCP (about 3m below surface) during the experiment for u-component (top panel) & v-component (lower panel) in cm/s.

The grey hatched area depicts the time when Tropical Storm Henri passed north of the HF radar domain.

Data are kindly provided by Prof. Lynn K. Shay at RSMAS and Prof. Bob Weisberg at USF.
2.4 Features of this Radar Technology

Statistics from this comparison, on the right panel. The WERA returns are displayed on the map.

Data are kindly provided by Prof. Lynn K. Shay at RSMAS and Prof. Bob Weisberg at USF.
2.5 Features of this Radar Technology

From the same system as before but located at the east coast of Florida and operating with a temporal resolution of 5 min. (1024 samples) and the same spatial resolution of 1.5 km.

The WERA systems is continuously operational at this location since summer 2004. The data sets include the Hurricane seasons and impressive animations are available from the Hurricane Jeanne passing through the WERA domain east of Miami. Please contact Prof. Nick Shay to get more information:

nick@rsmas.miami.edu
These data set is kindly provided by Prof. Nick Shay, RSMAS Miami

It shows the passage of the hurricane Jeanne through the WERA domain east of Miami, Florida. The Hurricane made landfall north of the field of view. The strong along-shore current is the Gulf Stream. The wind speed and direction is displayed by means of an arrow on land. These data are unfiltered, non-averaged WERA data.

WERA system parameters:
16 channel, 16.3 Mhz
Temporal resolution 10 minutes
Spatial resolution 1.5 km
Range: typical 90 - 100 km
2.6 Accuracy of WERA

Results from the French coast, Brest, operational since Sep. 2005

Data are kindly provided by ACTIMAR

On this map the points for validation are marked.
2.6 Accuracy of WERA

Current map:
1 measurement all 12 min.
1 map all 30 min.
Spatial resolution: 1.5 km
fo = 12.4 MHz
16 antenna array
2.6 Accuracy of WERA

Validation with ADCP Pro4, located more than 30 km off-shore

RMS ADCP = 0.464 m/s, RMS difference = 0.155 m/s,
Correlation = 0.947
2.6 Accuracy of WERA

Significant wave height

1 map per hour

Directional Wave Spectra are available as well. For more information please visit:

www.seaviewsensing.com
2.6 Accuracy of WERA

Validation with a Wave Rider Buoy, located >30 km off-shore

RMS buoy = 3.15m, RMS difference = 0.60m, Correlation = 0.885
2.7 New Applications: Wind Measurements

Map of wind direction and wind speed
1 map per hour
2.7 New Applications: Ship Tracking

Since ships are moving targets, just one radar should be sufficient for this application. This was tested with the displayed experiment.

Trajectory of a ship measured using 1 radar (Pointe de Brézellec)

- 62Km far from the radar
- 300m precision on 2 validation points
- Automatic algorithms to be implemented
2.7 New Applications: S A R

During this experiment a drifting buoy was used to verify the accuracy of different trajectory methods. WERA based trajectories showed the best accuracy. To see a documentation of the complete please contact Dr. Vincent Mariette at Actimar: mariette@actimar.fr

Drift using WERA currents measurement around Ushant

© HELZEL Messtechnik GmbH
2.8 WERA for longest Ranges

WERA in Georgia & South Carolina (USA)
Mode: BF 12 antennas
Frequency: 8.35 MHz
Range Cell Size: 3 km
Integration Time: 9 Min
Range: 110 – 180 km

Data are kindly provided by Dana Savidge (SKIO) and George Voulgaris (USC)

This maps with up to 200 km range was generated during daytime.
2.9 Features of this Radar Technology

Maps of data coverage, averaged from Mai to August 2006
Showing significant variation between day and night cycles

Data are kindly provided by Dana Savidge (SKIO) and George Voulgaris
3.1 Limits due to Environmental Conditions

In most cases the radar range is the most important parameter.

The range depends on:

- Ground wave attenuation (Radar Frequency)
- Wave Conditions
- Conductivity of the Ocean surface (Salinity)
- Signal to Noise Conditions
3.2 Range Limits

- The operation **frequency** is the most important parameter to provide a defined **range**.
- The **lower** the operating **frequency** the **longer** the **range**.

The **variation** of the **range** during day and night cycle, caused by external **interference** increases with decreasing **frequency**.

![Graph showing Range of 1-st order beam versus Frequency](image)

The graph shows the relationship between **beamformed Range in km** and **Frequency in MHz**. The equation is given as:

\[ y = 1354.5x^{-0.9791} \]

with an **R^2 = 0.867**.
3.3 Range Limits, Frequency

Range of 1-st order beam versus Frequency

Tests with different WERA installations all with linear array (12 or 16 antennas) 08th of May 2006

\[ y = 1354.5x^{-0.9781} \]

\[ R^2 = 0.867 \]
3.3 Range Limits, Frequency

Maps of data coverage, of WERA system at 8.38 MHz.

Showing significant variation between day and night cycles.

6 weeks of WERA data are kindly provided by Dana Savidge (SKIO) and George Vougaris (USC)
3.4 Range Limits, Wave Height

The range is effected by the actual wave conditions as well. On the plot the range on the North Sea at a significant wave height of 0.6 and 4 m is displayed (full line and dashed line). The dotted line represents the system noise floor.

Data from: Gurgel et al, HF radars: Physical limitations and recent developments, 2000
3.5 Range Limits, Salinity

The salinity is the most important environmental parameter for the range. On this graph the attenuation of a 27 MHz radar on the North Sea (solid line), the Baltic (dashed line), on a lake and on ice is displayed.

Data from: Gurgel et al, HF radars: Physical limitations and recent developments 2000
3.6 Range Limits, Signal to Noise

The Signal/Noise ratio can be increased by increasing the **Signal Power** by increasing the transmitted RF power. The effect is minor.

**Range versus Transmitter Power**
tested at 8.35 and 10.85 MHz WERA 12 Channel Systems

\[
y = 18.634 \ln(x) + 7.9393
\]

\[R^2 = 0.9394\]
3.7 Range Limits, Signal to Noise

The Signal/Noise ratio can be increased by decreasing the Noise Power by using low noise techniques. WERA is the one and only Ocean Radar that uses the non-interrupted FM-cw technique. This lowest noise technique is not “invented” by the WERA team, it is indeed a very old technology used since the 1950’s, but it is optimised for the oceanographic applications.

The technical requirements for this kind of radar are much higher than for an interrupted or pulsed radar, - but there are a lot of advantages of this technique. For these reasons we decided that it is worth the effort to build such a radar.

On the next slides we explain why!
3.7 FM-cw Radar

A continuously swept rf-signal is transmitted. The reflected signal has a frequency offset compared to the actual transmitted signal, thus the distance is frequency encoded.
3.7 FM-cw Radar

For this reason all FM radar systems are using RF-signalsthat are slowly swept over the defined bandwidth.

![Graph showing Slow Sweep with time in ms on the x-axis and frequency in MHz on the y-axis. The graph shows a linear sweep from 9.98 MHz to 10.1 MHz over the time range of 0 to 100 ms, followed by a rapid change to 101 MHz at 100 ms, then a rapid change back to 10.1 MHz at 120 ms.]
3.7 FM-cw Radar

The reflected signal has a **small frequency offset** compared to the actual transmitted signal. That means the required receiver bandwidth is small.

**Sweep with Sea Echos**
3.7 FM-cw Radar

The **purple marked area** represents the **energy band** that carries the information.

The diagram shows a time in ms on the x-axis and frequency in MHz on the y-axis. The transmitted signal is represented by a solid line, and the echo signals are shown as a shaded area. It is noted that the echo signals are always lower in frequency than the transmitted signal.
3.7 FM-cw Radar

Signal Attenuation on the Ocean @ 16 MHz
3.7 FM-cw Radar

There are two methods to pick-up these signals.

The FM-i-cw method.

The transmitter is alternating between transmit and receive mode. The FM chirp is interrupted (-i-).

The FM-cw method.

Transmitter and receivers are active simultaneously.

Why WERA is using this method?
3.7 FM-cw Radar

The **purple marked area** represents the **energy band** that carries the information.

![Diagram](image-url)

- **Transmitted Signal**
- **Echos are always lower in frequency than the transmitted signal**
3.7.1 FM-i-cw Mode

The frequency chirp is interrupted to allow the receiver to collect the sea echo without getting in the strong transmitted signal. The gating “gap” for the receive mode must be long enough to pick up all signal energy from the long ranges.
3.7.1 FM-i-cw Mode

The frequency **chirp** is **chopped** to allow the receiver to collect the sea echo without getting in the strong transmitted signal. The gating “gap” for the receive mode must be long enough to pick up all signal energy from the long ranges.

The triangle represents the **energy** that carries the information.
3.7.1 FM-i-cw Mode

Signal Attenuation on the Ocean @ 16 MHz
3.7.1 FM-i-cw Mode

Atten versus Range

Range Filter caused by Gating*

*additional filters can be added for further reduction of the dynamic range

Gated systems signal amplitude

Signal Attenuation on the Ocean @ 16 MHz
3.7.1 FM-i-cw Mode

Atten versus Range

Signal Attenuation on the Ocean @ 16 MHz

Range Filter caused by Gating*

*additional filters can be added for further reduction of the dynamic range

Gated systems signal amplitude

-6 dB @ 50 % of the max. range
3.7.1 FM-i-cw Mode

Comparison of close-in noise generated by the modulation of a WERA and a “perfect” FM-i-cw system, simulated with the best state of the art signal generator. (Rhode&Schwarz)

“Perfect” FM-i-cw

WERA FM-cw

FM-cw is at least 6 dB better
3.7.1 FM-i-cw Mode

Advantages of the interrupted mode:
- Perfect decoupling between transmitter and receiver

Disadvantages of the interrupted mode:
- Losing signal energy, more than factor 4 (6 dB) (> 3 dB in receiving and >3 dB for transmitting)
- Fixed range filter implemented, cutting off 50 % of the signal energy already at 50 % of the maximum range (3 dB)
- Producing RF noise due to transmitter switching more than 4 time more noise (6 dB)
3.7.2 FM-cw Mode

WERA Sweep with Sea Echos

All signals from all ranges are received during the entire sweep period.

Transmitted Signal

Echos are always lower in frequency than the transmitted signal
3.7.2 FM-cw Mode

Signal Attenuation on the Ocean @ 16 MHz

Atten versus Range

Atten in dB

Range in km

© HELZEL Messtechnik GmbH
3.7.2 FM-cw Mode

Signal Attenuation on the Ocean @ 16 MHz

WERA signal amplitude

*Within the first range cell, the direct path signal will dominate at about -20 dB
Signal Attenuation on the Ocean @ 16 MHz

*Within the first range cell, the direct path signal will dominate at about -20 dB

No attenuation @ 50 % of the max. range
3.7.2 FM-cw Mode

+ No gating results in a clean radio spectrum
+ No self generated noise within the used band
+ Very low noise outside the used band
  almost no interference
  with other radio band users
+ Low power transmitted

  e.g. results in:
  range of >120 km
  @ 11 MHz
  @ 4 Watts-cw
3.7.2 FM-cw Mode

Advantages:
- **Long ranges** (> 200 km @ 8 MHz) with low transmitting power (< 30 W)
- **Best Signal/Noise**
  highest temporal resolution (e.g. 5 min for current maps)
- Almost no interference with other radio band users

Demands to use this mode:
- Requires **special site geometry** (spatial separation)
  (horizontal ~ 100 m or ~ 10 m vertical)
3.8 Limits due to Antenna Configurations

The Receive Antenna configuration of the radar is another important parameter. There are two different types of configurations to get the required azimuthal information.

With “Direction Finding” methods it is possible to use very compact antenna systems and to get a field of view with extreme wide azimuth. The resulting Doppler Spectra are good enough to derive ocean current velocity.

The combination of array type antenna configurations with “Beam Forming” methods provides a high resolution of the Doppler Spectra that allows to derive current and wave information within a limited azimuth of typically +/-60°.
3.8.1 Direction Finding

This technique allows to use a very compact antenna array, with 4 monopole antennas configured in a square with half a wavelength diagonal spacing.

The range, $r$, for the annulus is determined by frequency offset (time delay). This parameter is very accurate and stable over the entire range.

The received signals on individual antennas have the same amplitude but different phases.
3.8.1 Direction Finding

Doppler shift versus azimuth for a uniform alongshore ocean current.

The resulting spectra is broadened by Doppler shifts varying with azimuth.
3.8.1 Direction Finding

The **Direction Finding** technique allows to use a **compact antenna array**, 4 antennas configured as a square with a diagonal length of half a wave length of radar frequency.

**Advantages** of this configuration:
- **Compact** site geometry
- **Reduced costs** for hardware
- **Field of View** more than 180°

**Disadvantages**
- Very **sensitive** to external **interference**
- **Unsuitable** in high **dynamic** ocean areas
- **Unsuitable** for **disaster** warning systems
3.8.2 Beam Forming Antenna Configuration

The range, $r$, for the annulus is determined by frequency offset (time delay). This parameter is very accurate and stable over the entire range.

Each antenna receives individual amplitude and phase information.

The Beam Forming algorithm will steer a narrow beam over a defined angular range, typically +/- 60°.
3.8.2 Beam Forming Antenna

Along shore ocean current

The information of one range is angular encoded.

Doppler shift versus azimuth for a uniform alongshore ocean current, giving various Doppler shifted signals for different angles.
3.8.2 Beam Forming Antenna Configuration

Angle, $\theta$, is determined by relative phases at the antennas.

Each pixel is uniquely determined.

The azimuth accuracy is determined by the number of antennas and will slightly degrade with increasing angle, (limited at about +/- 60°).
3.8.2 Beam Forming Antenna Configuration

Spectrum of one 3 km range cell of long range, 16 channel WERA Pixel location: 90 km offshore
3.8.2 Beam Forming Antenna Configuration

Advantages of this configuration:
- A focus (beam) selects dedicated areas resulting in reliable information even in dynamic ocean areas.
- Very clear and sharp spectra for each pixel.
- Directional wave spectra available for up to 50% of the current mapping range.
- Lower sensitivity to external interference.
- High reliability, redundant channels.

To be taken into account:
- Limited Field of View (typical +/- 60°).
- Longer area at the shore line required.
- More expensive than the compact version.
3.9 Resolution of Current Velocity

The operating frequency has an important effect on the accuracy of ocean current measurement as well. To achieve a defined accuracy the required measurement time is determined by the operating frequency.

Lower frequency results in longer averaging time to get the required accuracy.
4.1 Conclusions

- The shore based radar system WERA is a powerful oceanographic instrument giving **reliable information** about large ocean areas.

- The **outstanding temporal resolution** makes WERA a perfect component for time critical applications like disaster warning systems.

- It is **easy to install** and **flexible** for various application making it attractive for scientific experiments as well as for permanent installations.
4.2 Conclusions

- It is possible to use shorter linear arrays, down to 8 antennas, if the correct window function is used and the limited angular field of view can be accepted.

- The new Beam Forming software has increased the flexibility of setting up a receive array for WERA in curved or random spaced orientation.

- The site geometry, Tx to Rx array orientation, is getting more flexible as well, by means of optimisation of the transmitting beam pattern.
4.3 Conclusions

- The WERA Site can be configured more compact and the radar can be operated below 10 Watts, resulting in a just slightly reduced range, 80% of standard range.

- With further reduction to a power below 1 W the overall length of the antenna arrays (Tx + Rx) can be strongly reduced, resulting in a range of about 50% of the standard range.

- Due to the low noise operation mode (FMcw) of WERA, even with an RF power of less than 10 Watt, the range of a WERA system is excellent.
4.4 Some Important Side Effects

- The transmitting rf power for the compact WERA is below any dangerous level and does not require special permits even if the antennas are in public reach.
- The expected interference to other radio band users or other radar sites is strongly reduced.
- The compact site is very easy and fast to install. A temporary site can be installed with 2 engineers in less than 3 hours.
5. Acknowledgement

We would like to thank:

Lynn K. Shay (RSMAS) and Bob Weisberg (USF), providing their WERA and ADCP data from the Florida coast,

Vincent Mariette providing data and results from SURLITOP project,

Dana Savidge (SKIO) and Rich Styles (USC) for providing the brand new data sets from their long range systems

and Klaus-Werner Gurgel (Uni Hamburg) for providing the new beam forming algorithms.
Thank you very much!