Deliverable No.	4.2		
Deliverable Title	Work package 4.2: HF radars performance methodology - Common settings for HF Radar and new method for wave data		
Grant agreement number	MYCOAST EAPA_285/2016		
Status	Final		
Dissemination level	PU-Public		
Due date deliverable		**Submission date**	

INDEX

INDEX OF FIGURES

INDEX OF TABLES

1. EXECUTIVE SUMMARY

In work package (WP) 4.2 QUALITAS studied latest scientific publications around HFR capability to measure waves, different parameters that can affect performance (e.g. interference, calmed seas, offshore and inshore winds, bimodal seas, etc.) and different current methodologies that are being applied to assess the quality of the resulting wave data. QUALITAS will as well, as a technologic readiness level indicator, analyse to which extent HFR wave outputs are already being used for scientific and/or operational purposes among the involved HFR systems inside MyCoast.

QUALITAS reprocessed spectral data from selected HFR stations using different releases and options of the radar proprietary software. These data will be the input of the later described analysis.

In this WP, QUALITAS worked with the support of other project partners (PPs) with data from Sagres and Alfanzina HFR sites and also from Silleiro and Matxitxako sites. After several analysis from these sites we have stated that Sagres and Alfanzina would be the ones to invest in, since the environmental conditions were the most complex, and therefore the results to obtain would allow us to improve the wave data methodology. The reasons why QUALITAS wanted to focus its efforts on these stations were:

- All these systems have a clear stakeholder behind and they have had and presently have maintenance and operation contracts in place that guarantee high system uptimes and that its performance is under control.

- These areas have buoy and met-stations measurements close to the HF radars coverage area, which are needed in order to carry out the propose analysis

Although HF radar data was available from all stations mentioned, since Sagres station was the most complex one in terms of oceanographic conditions, efforts were made for analysing this station. It was understood, once this station had all the complexities solved, these procedures could be applied to any other station.

2. INTRODUCTION

QUALITAS led an action under WP4 to analyse and improve High Frequency Radar (HFR) wave outputs. This action establishes new methods for analysis of wave measurement capability, quality control and performance metrics for any HFR site. These new methods are intended to be tested in different HFR stations inside the programme's region. Main target of this activity is to access environmental and technology variables that influence the quality of different HFR sites for wave measurement, detect possible radar interferences due to human activities or others, and eventually conclude on the readiness of each site for acquisition of wave measurements. To this aim, we have analysed the performance of the HFR stations for wave measurement in different situations by modifying configuration parameters available on the radar proprietary software, testing different Software releases and comparing results with other available and overlapping measurements from other in-situ instruments. Also, we have been in close contact with the manufacturer in order to improve the way stations are acquiring (namely settings and improvement on different releases based on this work). This relationship with the manufacturer has been of great value in the way that it led us to critical information in order to improve the wave analysis methodology. In February 2020, we had a meeting in California with the manufacturer

where several issues were discussed, namely the improvements of the software related to the several topics discussed ahead in this report, that are now in the hands of the manufacturer to be developed in order to have the better high-value wave data.

3. HF RADAR PERFORMANCE ANALYSIS

The use of HF radar for collecting ocean waves information in near-real time is being more demanded as one could expect. As the HF radar network grows and matures, there will be a need for defining a set of best practices for the best possible data acquisition. Anticipating this need, this report intends to define the performance of HF radar systems and the improved methodology for improving the system settings and enhancing the wave data from HF Radar observations. This report defines a set of best practices developed from the extensive study of several HF radar stations, several oceanographic conditions and also extensive comparisons between in-situ and remote equipments operated by the different partners involved in this project. The best practices discussed in this document focus on the steps to follow in order to evaluate if wave data obtained from a certain HF radar station is either valid or not under a different set of conditions. Further revisions of this document are expected to expand to include other manufacturers of HF radar equipment. As with all best practice documents, there is an expectation that this will be a living document that will expand to encompass community feedback and suggestions; corrections, modifications, comments, and additions are welcome from the entire HFR community.

3.1 ENVIROMENTAL ANALYSIS

Initially, SeaSonde HF radars were designed to measure ocean currents, but gradually the interest in wave data results has increased and the development of this capability has been a huge challenge.
To get the best results from wave data, there are also some factors to take in consideration in what software settings concerns.

3.1.1 MORPHOLOGY OF THE AREA

In order to set the best settings for data acquisition it is needed a good evaluation of the morphology of the area surrounding the HF radar station, either the geographic morphology (the distance in height and length to the water level) and also the underwater morphology (bathymetry). This two parameters might highly influence acquisition of good data.
If the station is located far from the water you might expect higher attenuation of echoes, thus a reduced maximum range and lower signal-to-noise ratio. For instance, if you have a bathymetry that is quite complex (not parallel to the shoreline) reflexions in the wave propagation are induced and for that wave data should be analysed carefully. Below are some figures illustrating the ideal HF radar station installation (advised from CODAR) and also the complexity of the bathymetry in two different places (Sagres and Alfanzina).

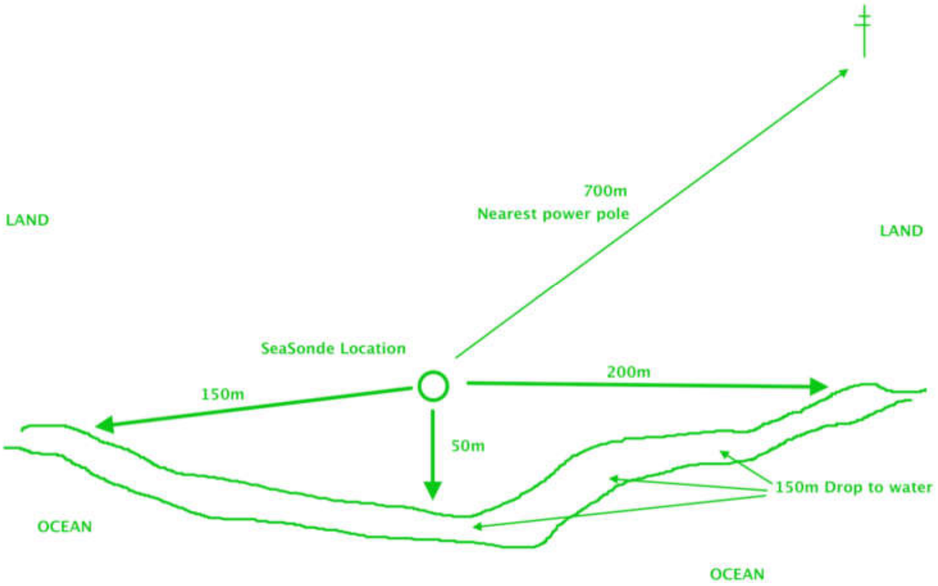


Figure 1. Ideal HF radar station installation (info from CODAR).

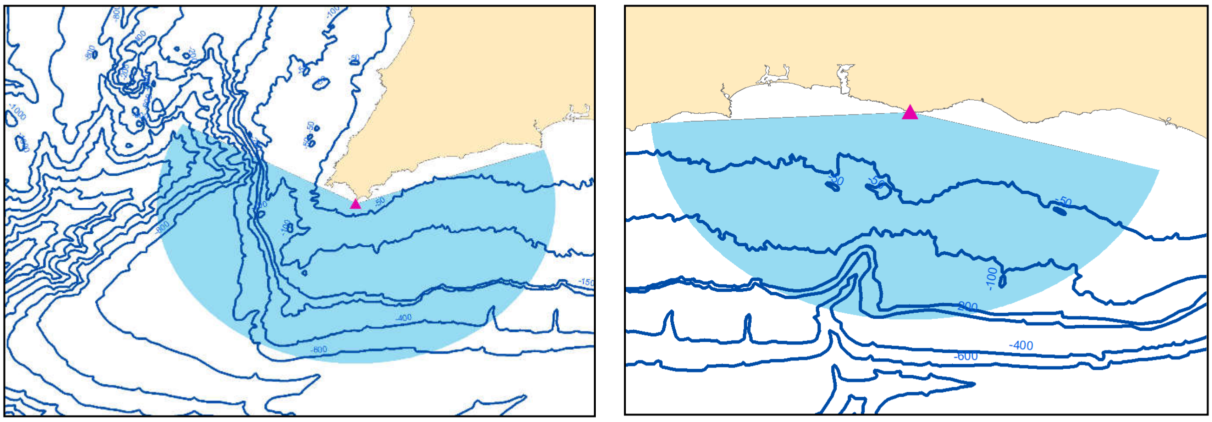


Figure 2. On the left figure wave data might be compromised; on the right figure wave data might give better results.

3.1.2 METOCEAN CONDITIONS

To make a good evaluation of wave data given by HF radar station, one need to have a good knowledge of the local oceanographic conditions and be aware of the most frequent wind and wave regimes existent in the studied area. For that is advised to have at least 6 months of meteo-oceanographic data of the area in order to cover seasonal variations, if for instances, one can have access to more than 1 year, even better.

If there are in-situ buoys in the study area, the parameters needed should be, Hs (significant wave height), Tp (period), dir (wave direction) and if available (wind direction). If no in-situ equipment is available, one can only rely on wave model information. Despite of the data source, wave buoy or wave model, be aware of the method that was used to obtain the wave height, direct or spectral.

3.2 SOFTWARE SETTINGS

Each station is chosen regarding the objectives, and that leads to different specifications, which affects both Currents and Waves. Example: a 13 MHz system will have lower maximum range than 5 MHz, but the spacial resolution will be better. Wave parameters will also change according with the selection of the system. The wave detection limits are dependent of the specific system, but that also occurs with currents.

For example, one need to choose between one of the four frequencies used (5 MHz, 13.5 MHz, 25 MHz and 42 MHz) depending on the objective since all have their own limitations (Figure 3).

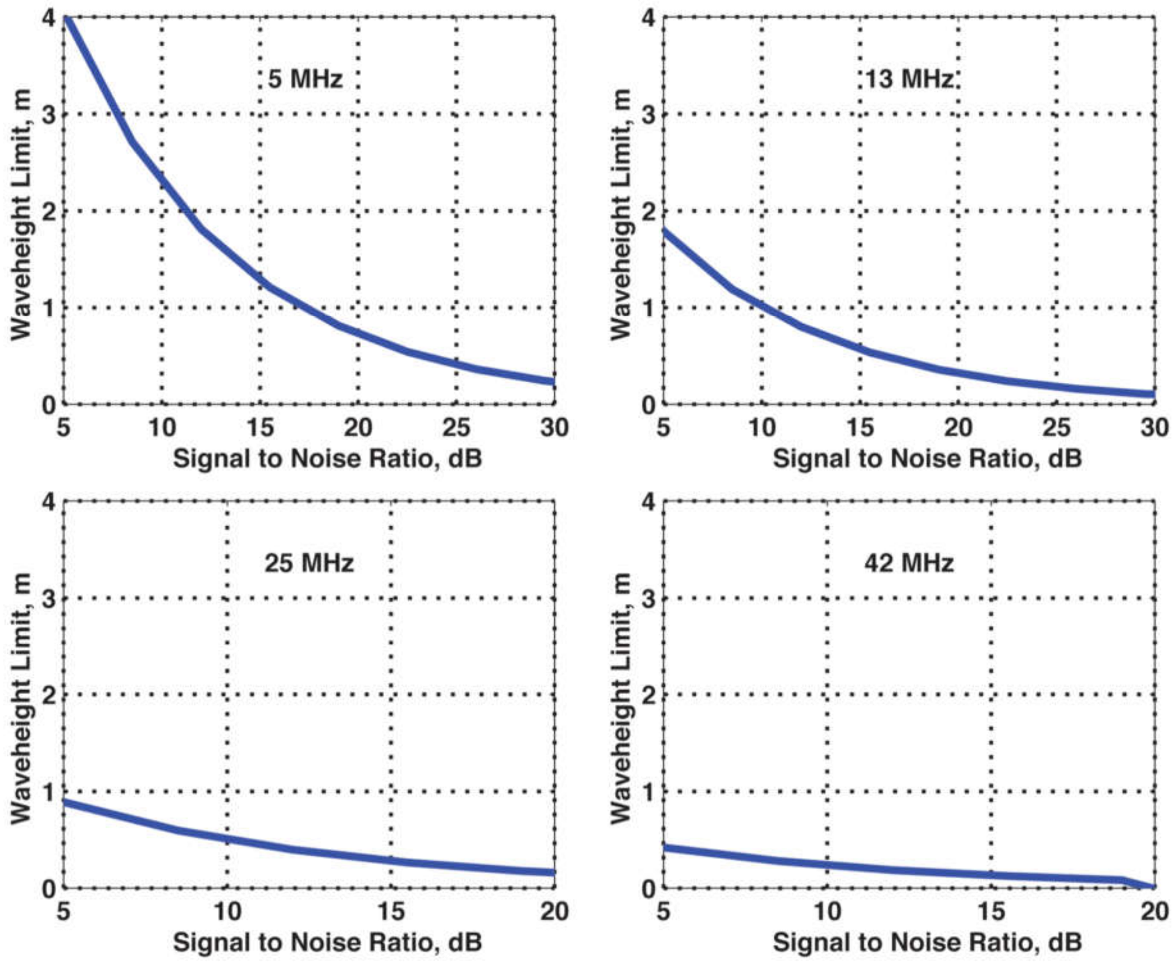


Figure 3. Limitations regarding SeaSonde for the 4 frequencies.

Example: For 5 MHz with a 30 dB SNR, the wave height must be well above 0.2 m. For SNR = 20 dB, wave heights below 0.8 m cannot be seen. On the other hand, at 25 MHz, for SNR = 10 dB, one can observe wave heights of 0.5 m. Therefore, much larger SNR is required for lower frequencies; these graphs are approximate, but tell you roughly what to expect. Typically, seeing SNR of 30 dB for any radar (Bragg peak above the noise) is considered very good. Or said another way, 2nd order must be visible at least 30 dB down from the Bragg peak; this is possible only under the best of conditions and for in close range cells.

To get the best wave data, there is also some factors to take in consideration in what concerns to software settings. For a preliminary analysis, in order to be able to obtain good quality wave data, several steps are needed to be taken:

a) First order settings (FOS)

First order settings will depend on which frequency you are working on. When establishing first order settings there are important features to take into account. In the example below, the Range Slice graphic from RC9 of Sagres station where you can visualize the radar echo spectra from circular range cells over the coverage area consist of dominant peaks produced by first-order Bragg scatter from waves with one-half the radar wavelength, from which current velocities are derived. In Figure 4 the radar spectrum was obtained from a SeaSonde system, measured at Sagres, Portugal, 11 September, 2017, 06.10 a.m., range 17 km. The Radar-echo spectral power (dB) from the three SeaSonde antennas is plotted vs. Doppler frequency for the Loop 1 antenna (A1, red), the Loop 2 antenna (A2, green) and the monopole (A3, blue). The curves are offset by 20 dB for better visibility. The first-order Bragg peaks at Doppler ± 0.38 Hz are surrounded by second-order echo, with the second-order peak visible at both sides of the negative and positive Bragg peak. In the first slice the pink lines are related to the radial settings while the second range slice are related to the wave settings. The light blue line is an indicator of spectral quality.

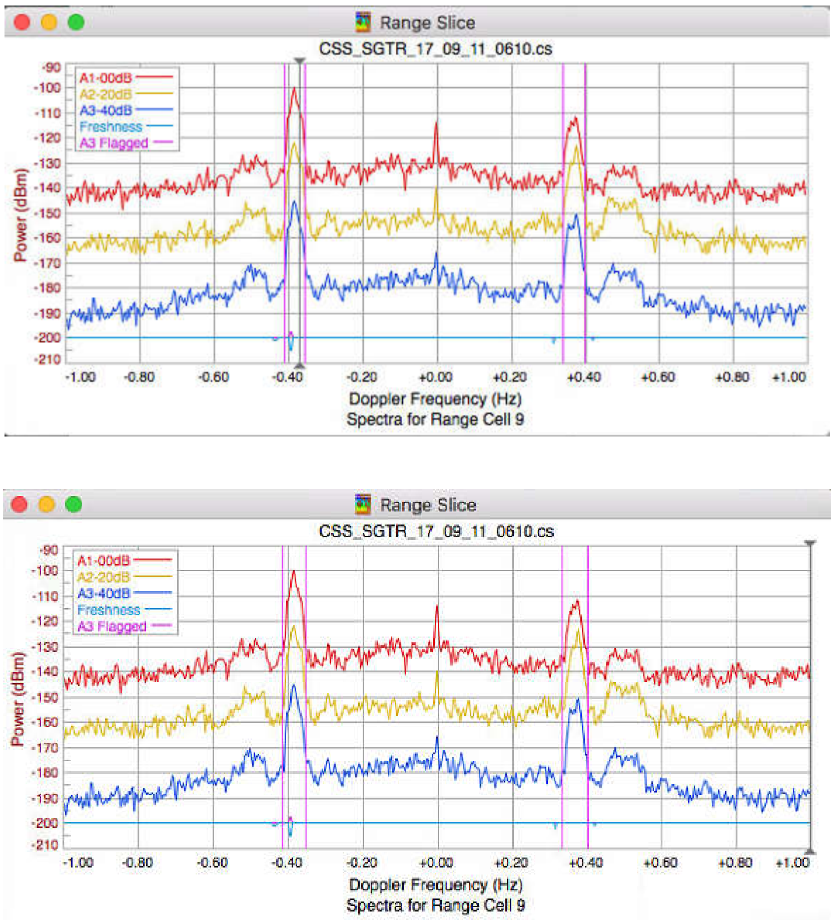


Figure 4. An example of an uncontaminated radar spectrum obtained from a SeaSonde system, measured at Sagres, Portugal, 11 September, 2017.

First-order peaks at positive Doppler frequencies are produced by echo from advancing Bragg waves; those at negative Doppler frequencies come from receding Bragg waves. The main issue to consider when setting the first order is to make sure that the first order peak defined in the radial settings menu is limited correctly as seen by the pink vertical lines visible in the first plot of Figure 4. The pink vertical lines show that the first order peak is limited correctly (Figure 4), also visible in Figure 6 on the plot on the left by the pink line limiting the first order peak in range. When defining wave settings, in the first order settings menu (Figure 5), one has to make sure also that the pink line is correctly excluding all the information regarding the currents information as seen in the right plot of Figure 6.

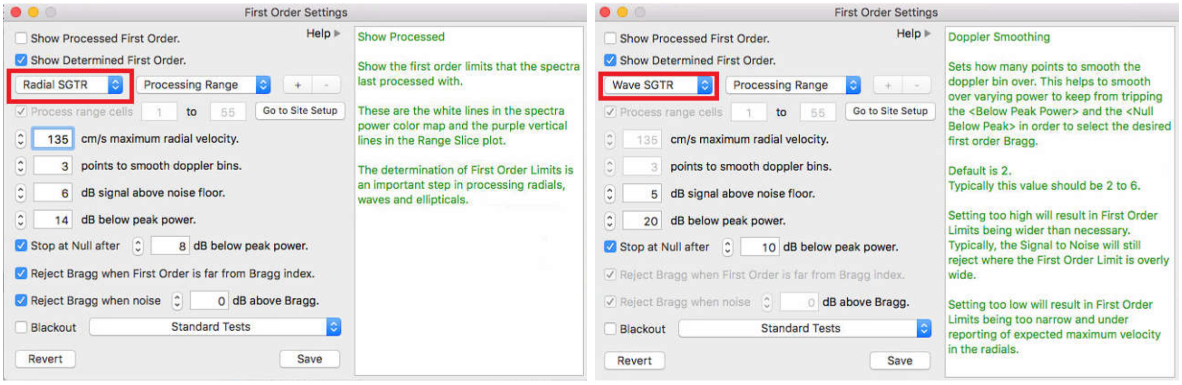


Figure 5. First Order settings menu where one can define de first order settings regarding the radial and wave settings (red square).

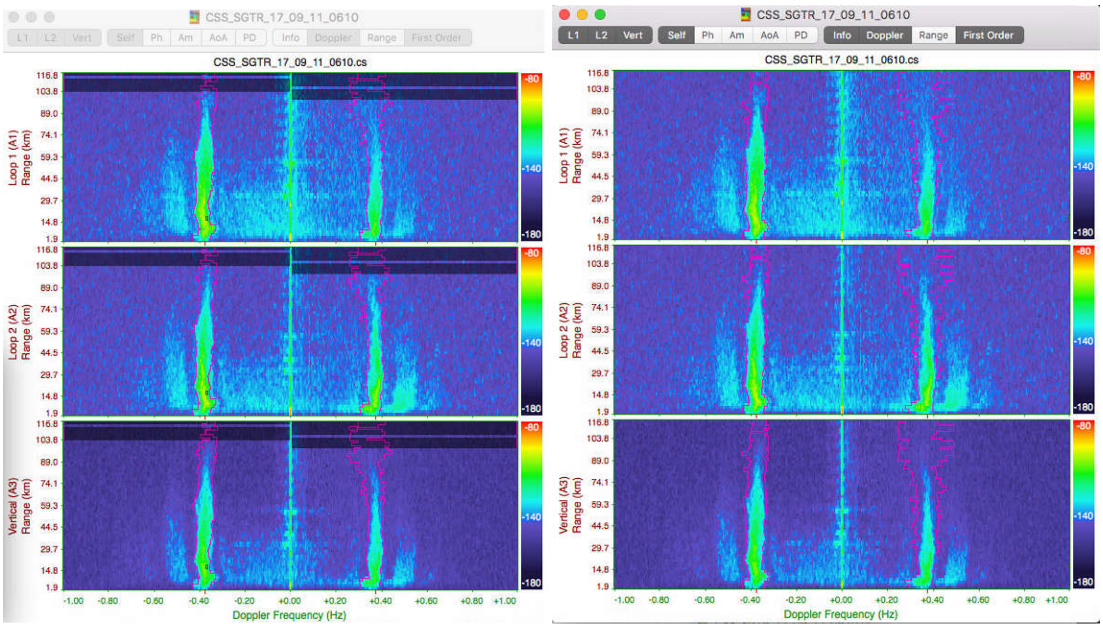


Figure 6. Color spectral plotter map shows significant vertical interference stripes over range, with radial velocity from the Doppler spectral shift as the horizontal axis, for the three antennas (loop1, loop2 and monopole) of the 13 MHz SeaSonde at Sagres, Portugal.

When the first order settings are defined, the system is working for most common daily sea conditions. When the atmospheric pressure gradient, at the air-sea interaction layer, is strong enough, it can cause several different events like storms, meteotsunamis, cyclones, etc…, depending on its intensity, moist and potencial heat.

Not always the settings defined during the system installation are tuned for this kind of events and therefore there is a need to keep in mind that data resulting from these events might be over or under estimated due to high levels of energy that are processed with the default settings. As seen in Figure 7 and Figure 8 that represent a storm that occurred in December 2017 and March 2018 (Ana and Emma Storms), waves coming to the radar have such a strong signal that it is difficult for the system to separate currents from wave information, so the system might be including and merging waves information signal with currents signal.

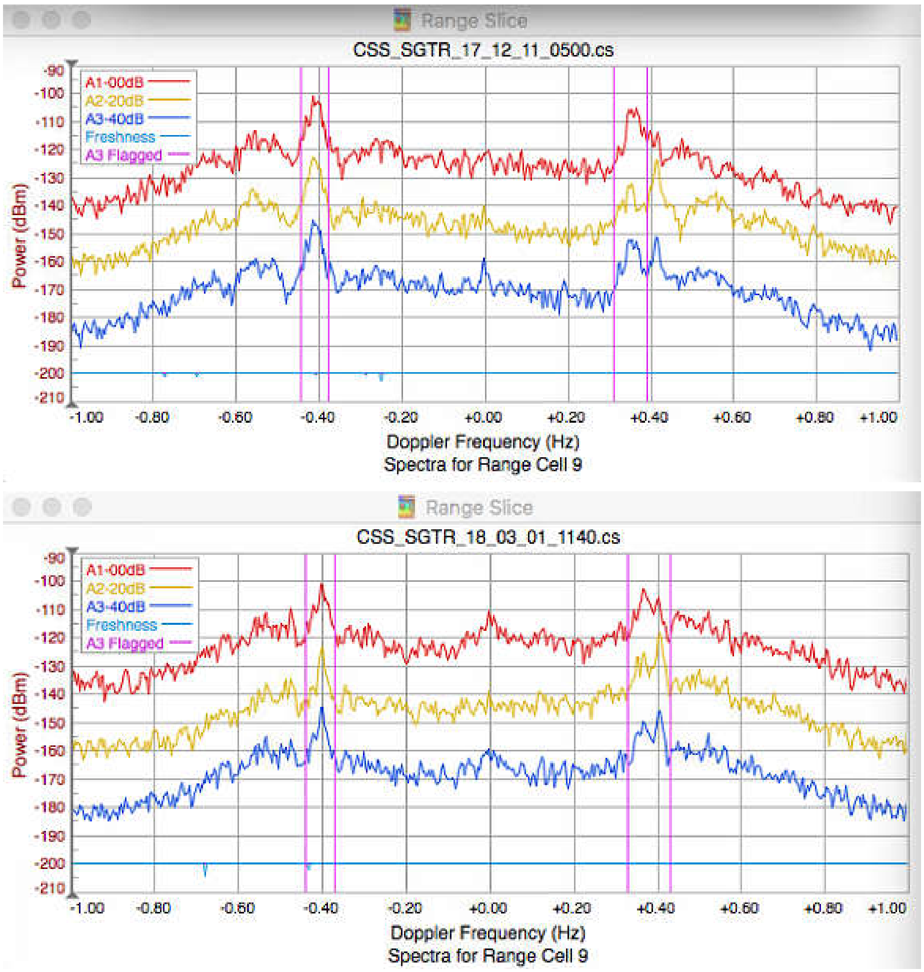


Figure 7. An example of an uncontaminated radar spectrum obtained from a SeaSonde system, measured at Sagres, Portugal, December and March, 2017.

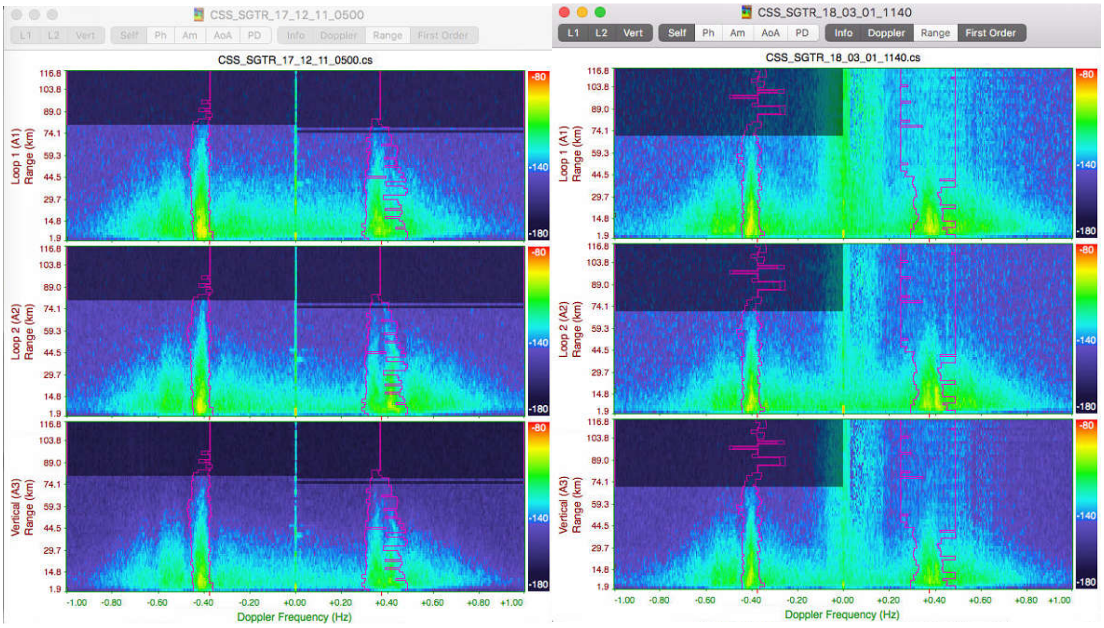


Figure 8. Color spectral plotter map shows significant vertical interference stripes over range, with radial velocity from the Doppler spectral shift as the horizontal axis, for the three antennas (loop1, loop2 and vertical) of the 13 MHz SeaSonde at Sagres, Portugal.

b) Coastline settings

The coastal settings are quite important in order to get more accurate data sets. When talking about coastline settings, which comprehends:

- **coastline cuttoff settings** where one can set the best coastline bearings from the site that covers the ocean;
- **wave bearing limits settings** where one can set the limits where dominant waves are expected to come from;
- **coverage time settings** which sets the final wave coverage time of merged short-time wave from CSS in minutes;
- **output interval settings** that sets the final wave output in minutes.

If for instances you set a coverage time of 240 min instead of 120 min, you will have a total of 7 CSS files instead of 3 CSS files and this will slow up the system response to the existing variability of the ocean conditions. Also the choice of the range cells (RC) in which you want to make the processing of the data is important. This will depend on the frequency one is using. For the case of Sagres, the coastline settings established are presented in Table 1**Error! Reference source not found.**. The coverage area to be processed is established from RC2 to RC16, as shown in Figure 9 on the area marked in blue.

Table 1 Example of coastline settings for Sagres station.

Coastline Settings	Value
Coastline Cuttoff	70º - 290º
Wave bearing limits	100º - 314 º
Coverage time	95 min
Output interval	10 min
Range cells	2 – 16

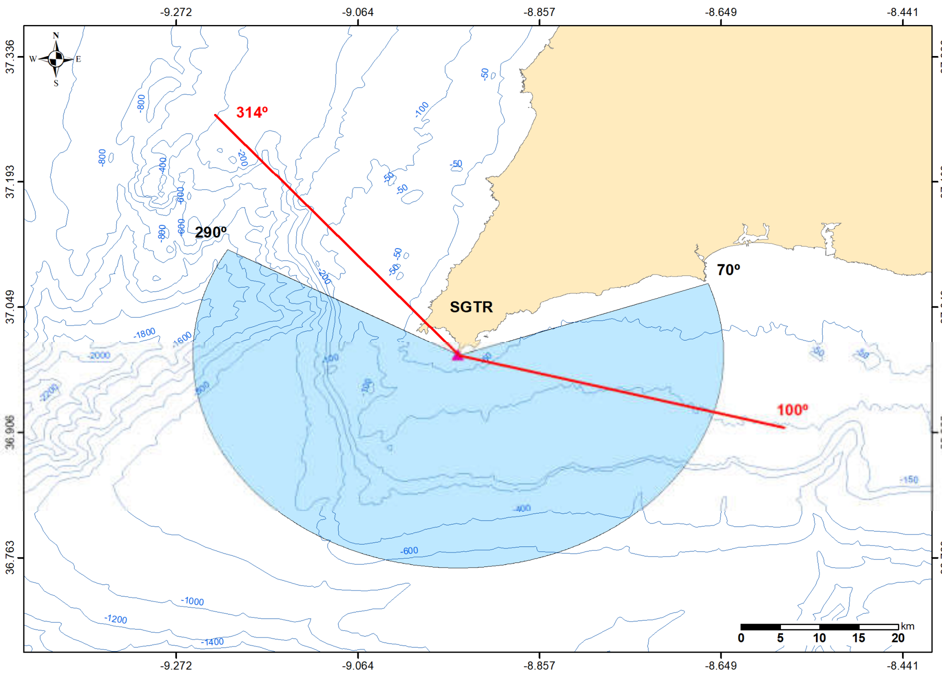


Figure 9. Establishment of coastline settings: coastline cutoff angles (black) and wave bearing angles (red).

c) Software version

Which version are you working with? Versions older than R8U3 don't allow the use of the measured pattern obtained by the Antenna Pattern Measurement (APM) (Figure 10). An ideal standard pattern is used by default. According to Figure 11, in the rectangle marked in red there is the option to modify the use of APM pattern (only for R8U3 or higher). R8U3 also has new wave outlier filtering and averaging across range cells, meaning that the primary form of wave output is range-less; wave data from all ranges have been processed to reduce the noise inherent in HF Radar wave measurements (Figure 11, Figure 12 and Figure 13). A new processing tool can be used offline to quickly reprocess the un-averaged wave output to optimize outlier filter settings. In addition, filtered, ranged wave output files are available in a sub-folder so that range-specific output can be still examined.

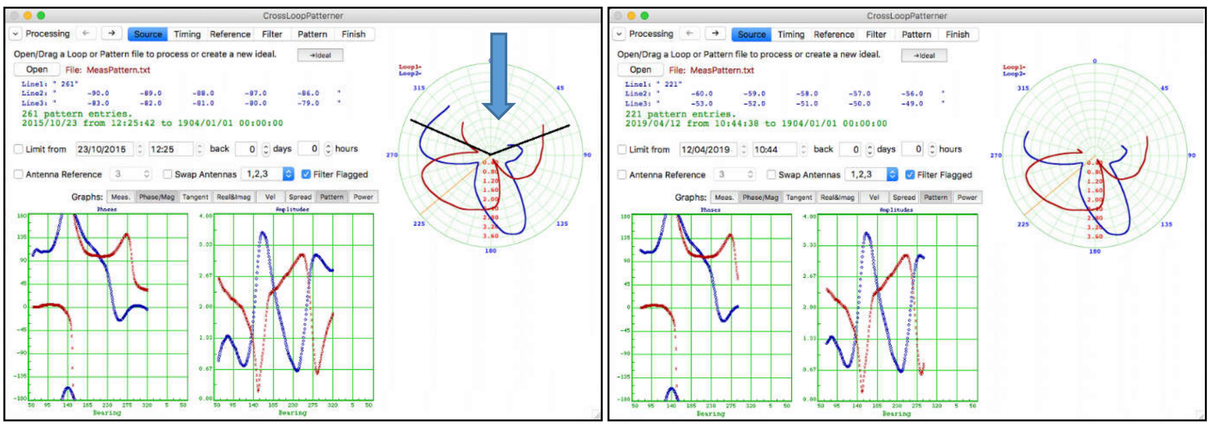
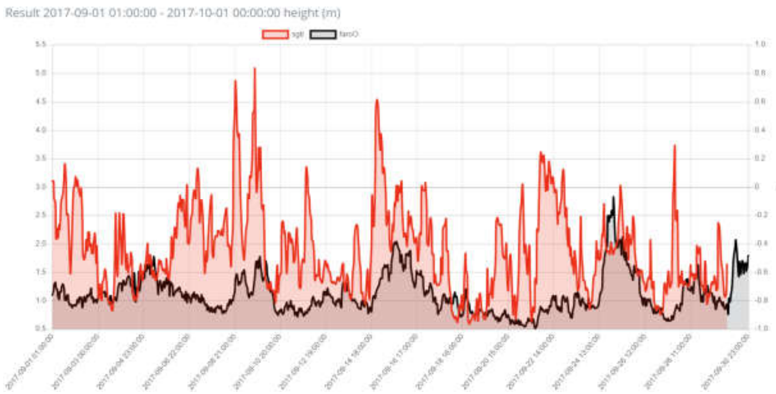


Figure 10. Difference in the MeasPattern after limiting the angles.

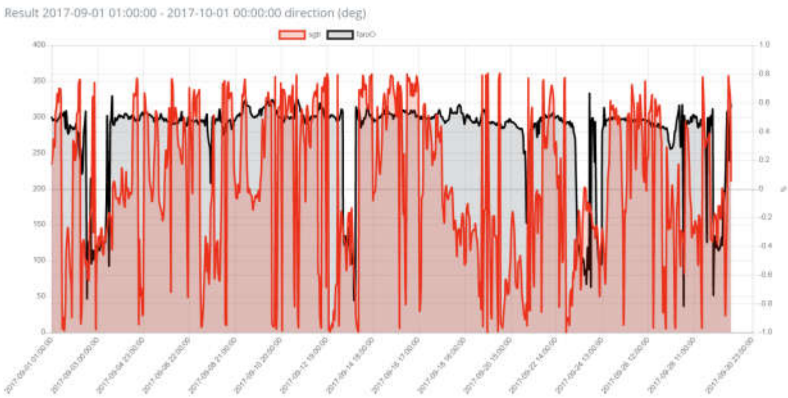
```
AnalysisOptions.txt
1 2 0          ! 1 Radial Processing: 0(Off),1(On); RadPtFilter: 0(Off),>=1(min pts); RadSmooth: OBSOLETE
1              ! 2 Wave Processing:  0(Off),1(Model),2(Spectral),3(Both)
0              ! 3 OBSOLETE File Archiving
2 0            ! 4 Antenna Pattern: 0(Ideal),1(Measured),2(Both); ForceAmplitudes: 0(Off),1(Header Ampl Adj),2(SeaEcho)
0              ! 5 Spectra Header Override: 0(Use CS Info),1(Use Header Info)
1              ! 6 CSA Processing: 0(CSA->'Rad '),1(CSS only)
0 0 1          ! 7 Wave Processing: Offshore Waves: 0(Off),1(On); Bragg Symetry 0(Off),1(On); InnerWaves 0(Off),1(On)
0              ! 8 Elliptical Processing: 0(Off),1(On)
1              ! 9 Ionosphere Noise: 0(Ignore), 1(Reject Offending Bragg/RangeCells)
0              !10 ShortTime Rad/Ellipticals: 0(Off), 1(Output)
0              !11 Special FirstOrder: 0(Off), 1(Enable)
0              !12 Average CS FirstOrder: 0(On), 1(Disable)
0              !13 Merging Method: 0(Default:Median), 1(Median), 2(Averaged)
0              !14 Pattern Method: 0(Default:Pattern), 1(Pattern), 2(Water Only), 3(Anywhere)
0              !15 Waves Follow Wind Direction: 0(Don't), 1(Do)
0              !16 FirstOrder Method: 0(standard), 1(notNearBragg), 2(innerBragg),3(innerBragg+notNearBragg)
1              !17 WaveModelSlider Method: 0(Average), 1(Median)
0              !18 PatternEndPoints: 0(Remove), 1(Keep for 360deg coverage)
1              !19 DopplerInterpolation: 0(Off), 2(Double), 3(Triple), 4(Quadruple)
0              !20 Use Bragg: 0(Both), 1(Pos/Left), 2(Neg/Right), 3(Both)
0              !21 Enable Radial Metric Output: 0(Off), 1(Enable), 2(Enable MaxVel.)
0              !22 Enable Radial Filler Output: 0(Off), 1(Area Filter+Interp), 2(Area Filter Only)
0              !23 Override WaveModel Period limits: 0(default), 1(Use Header limits L32)
1              !24 WaveModel Pattern: -1(Default Follow Radial), 0(Ideal), 1(Measured)
```

Figure 11. Parameters to modify if using reprocessing Innerwaves or Offshore waves (rectangular in green) and using the Meas Pattern from APM (rectangular in red).

These changes are made on the MeasPattern settings. It will restrict the wave direction interval.

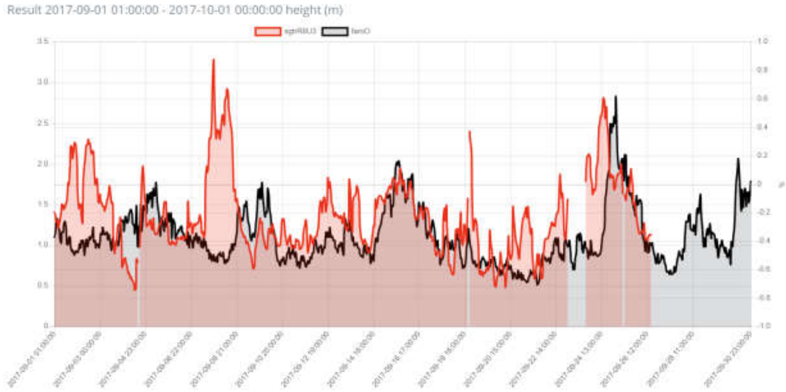


Variables	Value
RMS	1.12 m
CI	0.231
Availability SGTR	96.80%
Availability buoy	100.00%
Number of data	720
Average difference	0.82



Variables	Value
RMS	1.20 deg
CI	0.218
Availability SGTR	96.80%
Availability buoy	100.00%
Number of data	720
Average difference	71.79

Figure 12. Metrics results regarding the Hs (Significant wave height) and wave direction using R7U4 when no measure pattern is used for reprocessing.



Variables	Value
RMS	0.595
CI	0.206
Availability SGTR	82.78%
Availability buoy	100.00%
Number of data	720
Average difference	0.34

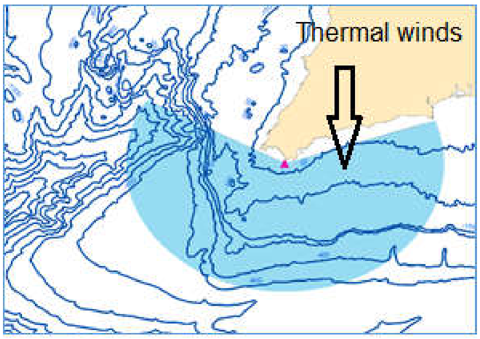
Variables	Value
RMS	10.90 deg
CI	0.085
Availability SGTR	82.78%
Availability buoy	100.00%
Number of data	720
Average difference	38.59

Figure 13. Metrics results regarding the Hs (Significant wave height) and wave direction using R8U3 when no measure pattern is used for reprocessing.

d) Sidebands

Are the sidebands configured correctly? Depending on the main regime of the local wave field, one can have mainly onshore waves (towards the station), offshore waves (away from the station) or both. In our case, after a lot of study we figured it would be better to reprocess data including inner Waves (Figure 11, line 7), since the thermal wind, changing direction twice along the day, in southern Portugal is quite intense as seen by the wind direction variation (Figure 14).

So, there is a set of software settings that need to be fine-tuned and this will depend on each station, since they are all exposed to different conditions.



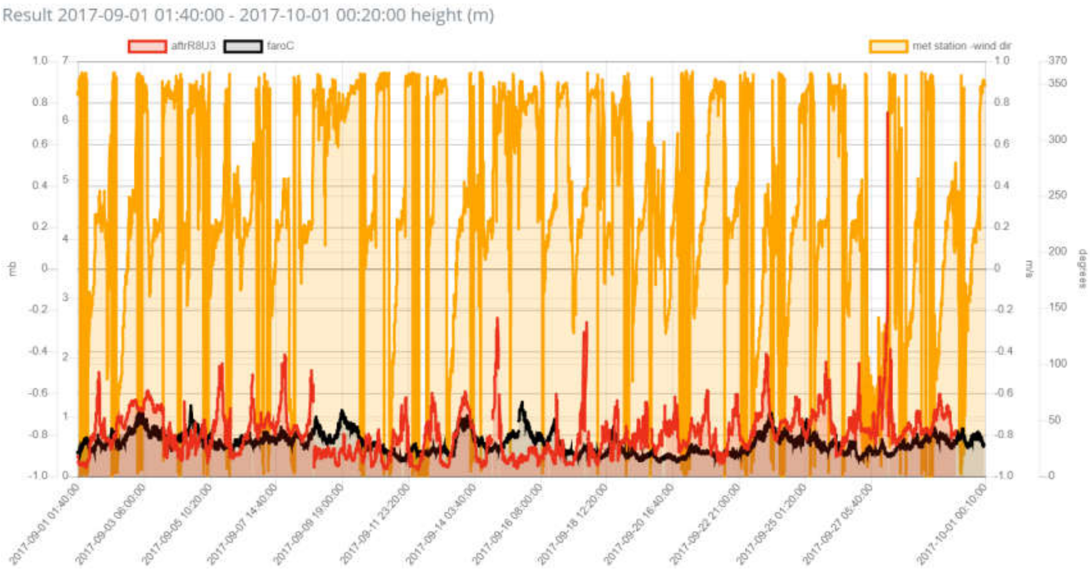


Figure 14. Presence of thermal winds during September 2017 in the southern Portugal marked in orange provided by a met station.

As one can see from Figure 14 the presence of the thermal wind is quite strong in southern Portugal. This also can be seen in the spectra files (Figure 16). The second order peak higher at the left of the spectra indicates the presence of offshore winds and also, this effect is only noticeable at range cell (RC) 6 and higher (Figure 16). In Figure 16 there are two examples of Range Slices, one ate RC6, where second order is not yet quite significant and another at RC12 where second order presents a high power signal, also seen in the Spectra file by the red lines representing each RC. Being this a system of 13.5 MHz, each RC has a width of 1.8547 km, means that the system is only getting signal at ~14 km from coast. As Sagres is installed on a cliff of ~50 m high (Figure 15) the wind-blown from land is only "seen" by the HF radar far offshore (Figure 16).

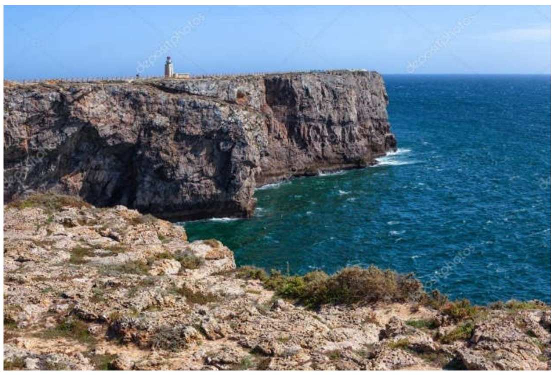


Figure 15. Sagres cliff.

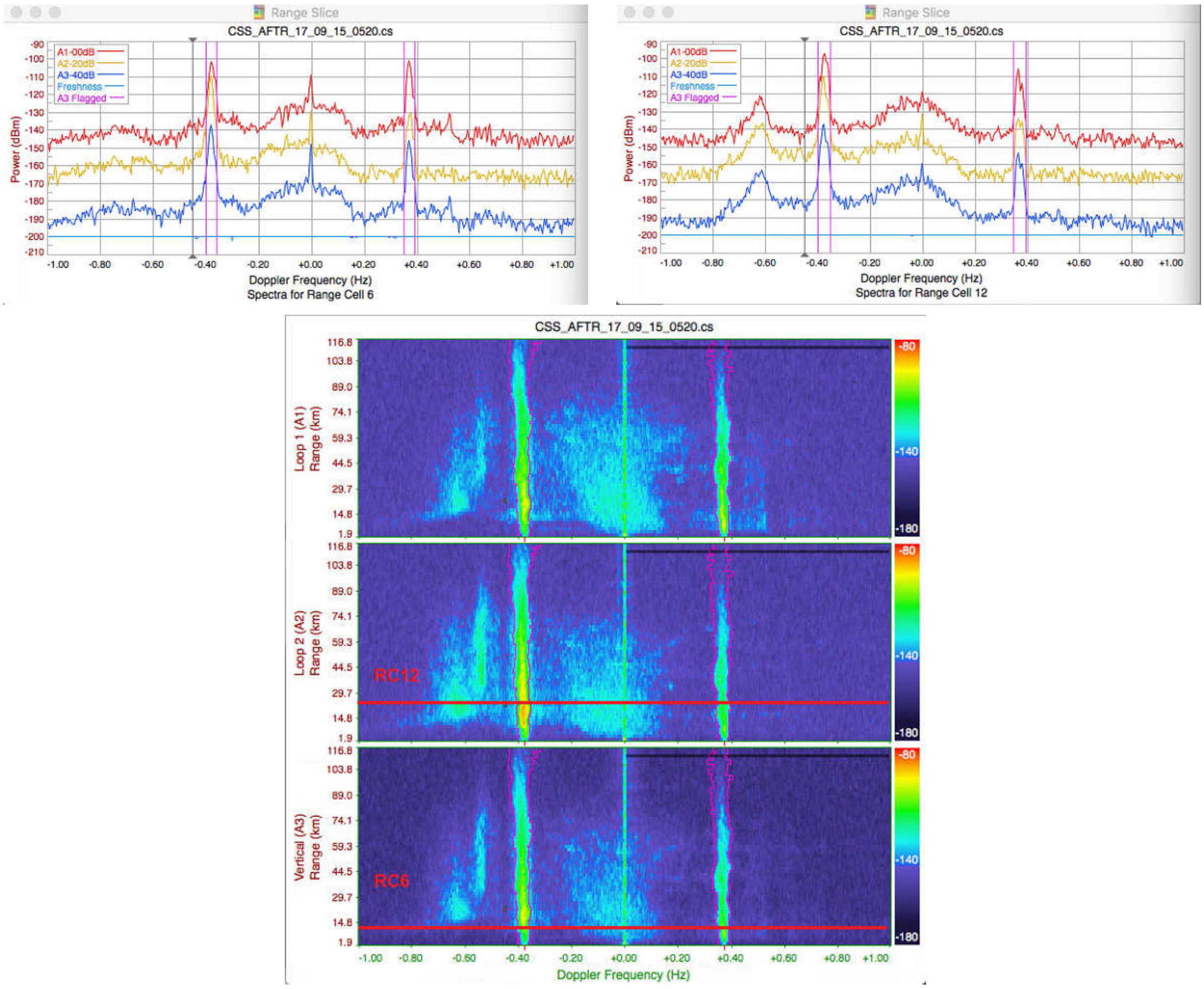


Figure 16. Range slice and spectra file from an example of thermal winds with an example with RC6 and RC12.

3.3 RADIALSITE RELEASE 8 VERSUS RELEASE 7

Preliminary conclusions about performance of Release 7 vs. Release 8 wave software:

- It seems that R8 can improve wave data by removing spurious outliers in the wave measurements and also shows improvements on wave direction data, but it does not seem to improve systematic measurement errors that could be caused by specific environmental conditions. In Figure 17, Figure 18, Table 2 and Table 3 are shown two examples of two months (November and December) and respective statistics of each one proving the improvement of significant height data and wave direction data.
- There seems to be no difference in the calculation wave period between the two versions.

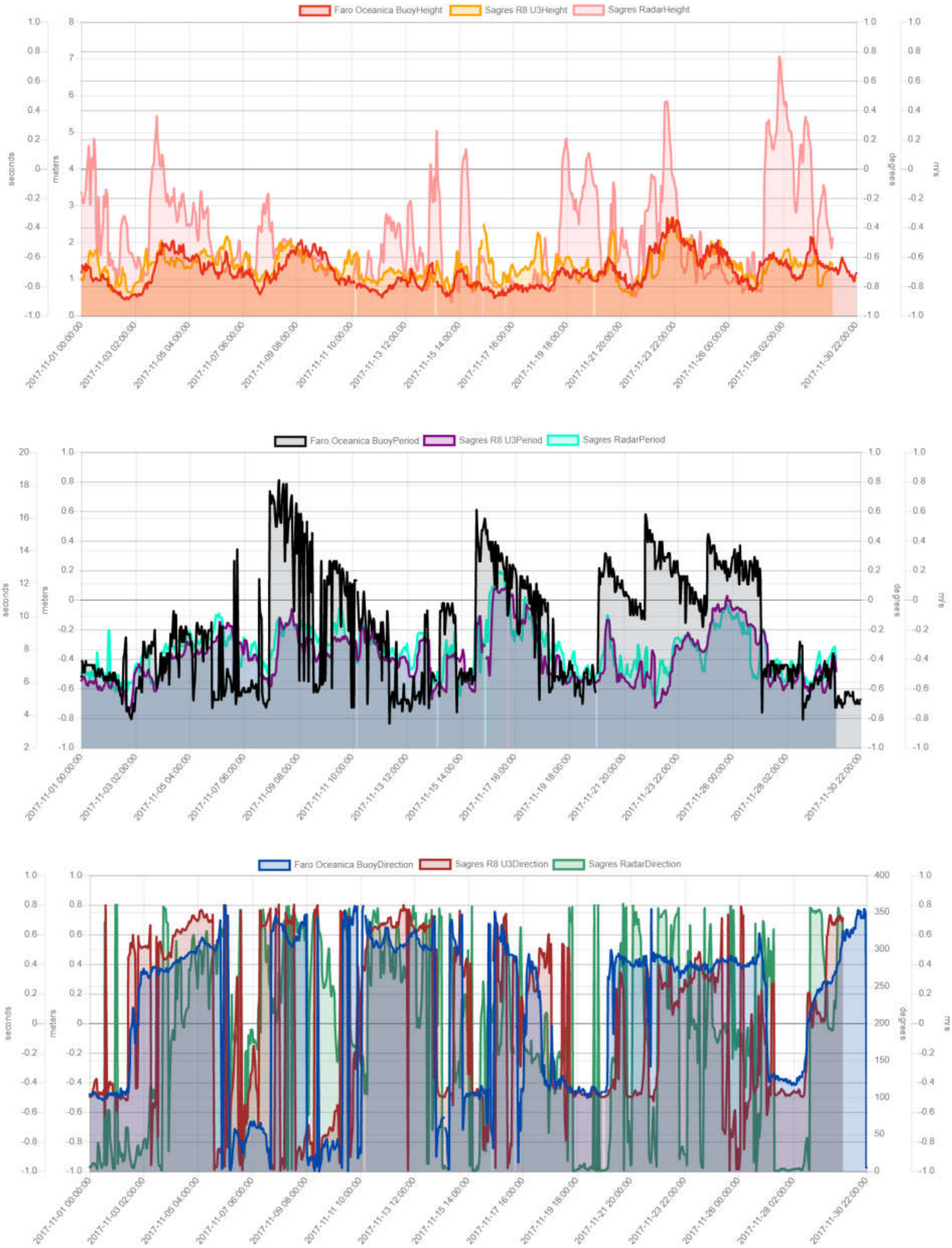


Figure 17. Comparisons between HF radar with R8 and R7 with the oceanic buoy of month of November, regarding the main parameters (Hs, Tp, Dir).

Table 2. Statistics of the parameters plotted above, comparing R8 with R7.

Variables	Value Hs (m)
RMS	0.398
CI	0.617
Availability SGTR R8	96.66%
Availability buoy	99.58%
Number of data	696
Average difference	0.302

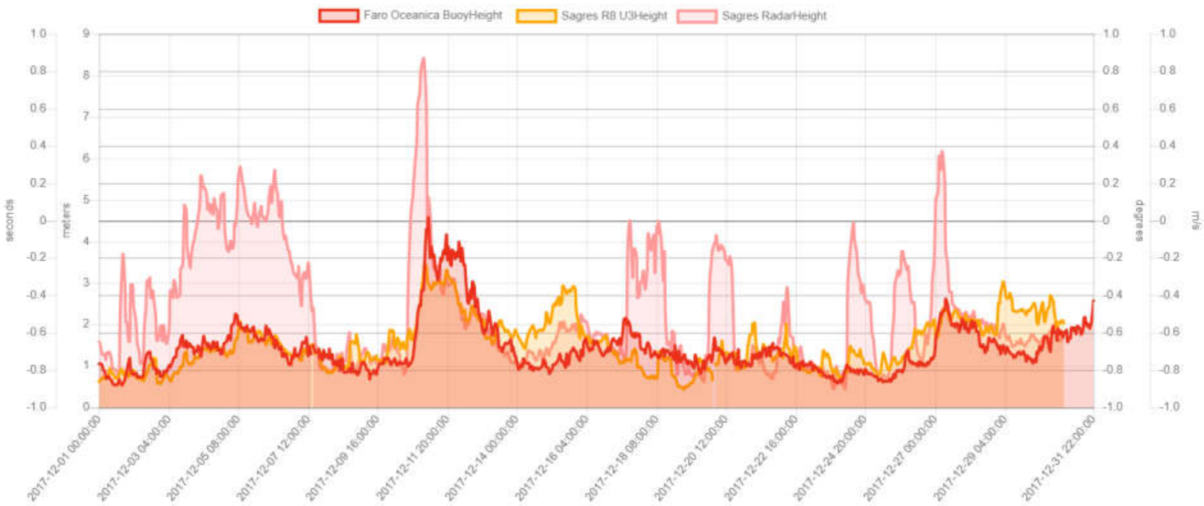
Variables	Value Hs (m)
RMS	1.548
CI	0.373
Availability SGTR R7	96.59%
Availability buoy	99.58%
Number of data	717
Average difference	1.053

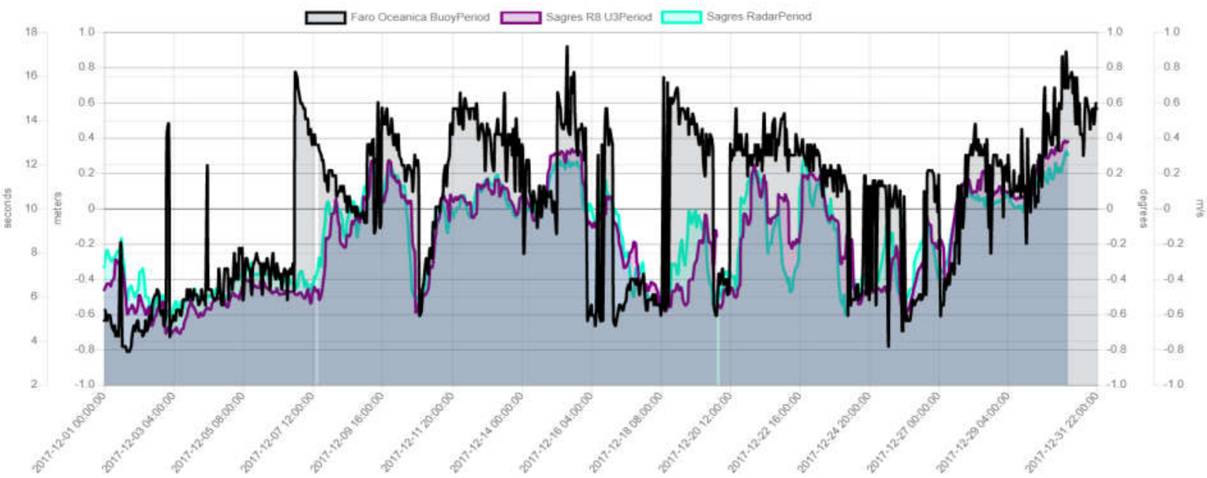
Variables	Value Tp (s)
RMS	3.497
CI	0.468
Availability SGTR R8	96.66%
Availability buoy	99.58%
Number of data	696
Average difference	2.546

Variables	Value Tp (s)
RMS	3.391
CI	0.448
Availability SGTR R7	96.59%
Availability buoy	99.58%
Number of data	717
Average difference	2.516

Variables	Value Dir (deg)
RMS	0.056
CI	0.364
Availability SGTR R8	96.66%
Availability buoy	99.58%
Number of data	696
Average difference	42.7

Variables	Value Dir (deg)
RMS	2.898
CI	0.309
Availability SGTR R7	96.59%
Availability buoy	99.58%
Number of data	717
Average difference	83.852





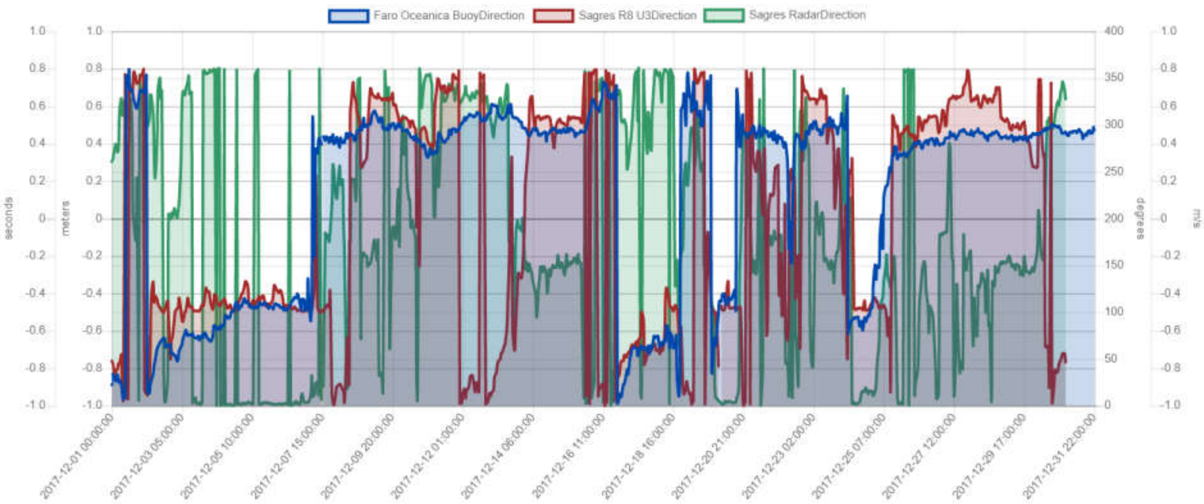


Figure 18. Comparisons between HF radar with R8 and R7 with the oceanic buoy of month of December, regarding the main parameters (Hs, Tp, Dir).

Table 3. Statistics of the parameters plotted above, comparing R8 with R7.

Variables	Value Hs (m)
RMS	0.554
CI	0.633
Availability SGTR R8	96.77%
Availability buoy	99.86%
Number of data	720
Average difference	0.397

Variables	Value Hs (m)
RMS	1.587
CI	0.423
Availability SGTR R7	96.79%
Availability buoy	99.86%
Number of data	743
Average difference	1.037

Variables	Value Tp (s)
RMS	3.101
CI	0.612
Availability SGTR R8	96.77%
Availability buoy	99.86%
Number of data	720
Average difference	2.201

Variables	Value Tp (s)
RMS	3.056
CI	0.6
Availability SGTR R7	96.77%
Availability buoy	99.86%
Number of data	743
Average difference	2.207

Variables	Value Dir (deg)
RMS	7.79
CI	0.496
Availability SGTR R8	96.77%
Availability buoy	99.86%
Number of data	720
Average difference	36.807

Variables	Value Dir (deg)
RMS	7.38 deg
CI	0.126
Availability SGTR R7	96.77%
Availability buoy	99.86%
Number of data	743
Average difference	98.05

In the future we will need to better understand how the APM is being used by the wave calculation software and how this can improve wave measurements, not only for the purpose of the calculation of the wave height but also for the direction and the period of the waves.

3.4 IMPORTANCE OF WIND MEASUREMENT

According to Almeida et al., 2011 "The south of Portugal is a region sheltered from the most dominant and important swell source, the North Atlantic. Besides the long travel distance involved, storms generated in the North Atlantic have to circumvent the southern Portuguese continental shelf to reach the coast. These factors contribute to an important dissipation of storm energy and wave height, which

can consequently introduce different patterns into storm variability. The local storm wave climate is also influenced from the southeast by stormy waves originating in the Gibraltar Strait region (Levante storms).” From Figure 19 one can see how sheltered the southern Portugal is related to the North Atlantic storms and how Sagres (most southwestern point of Portugal) is subjected to the oceanographic variability that comprises this area.

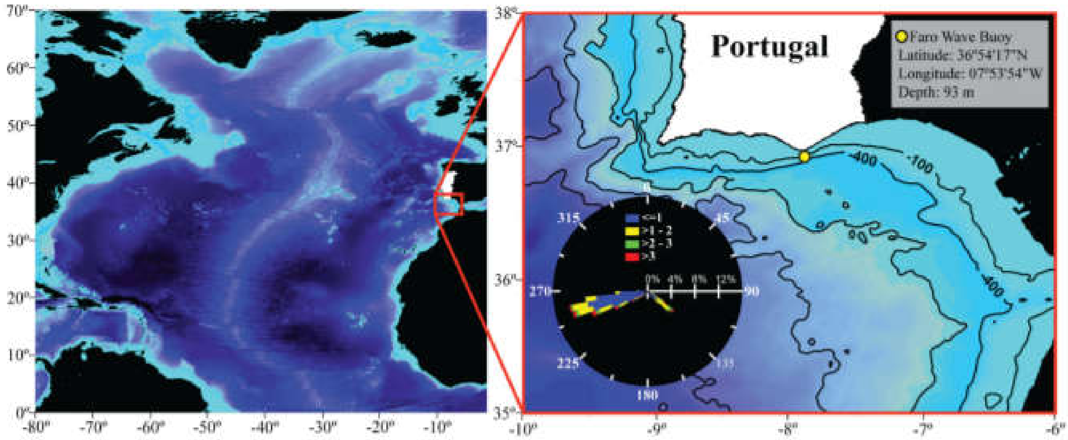


Figure 19. Location of the Faro buoy (the same as the simulated wave model point) and the wave rose distribution for the measured data (Almeida et al., 2011).

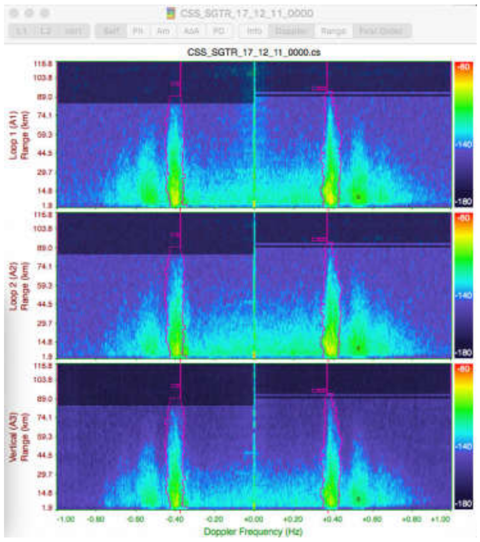
With Sagres station being situated in such a peculiar place where oceanographic conditions can have such a high variability, the combination of the different oceanographic conditions can originate results that can difficult the wave data analyses when there is no wind information. Wind information has such a huge importance that can “simplify” the analyses and help you understand why sometimes data is not what you are expecting to be.

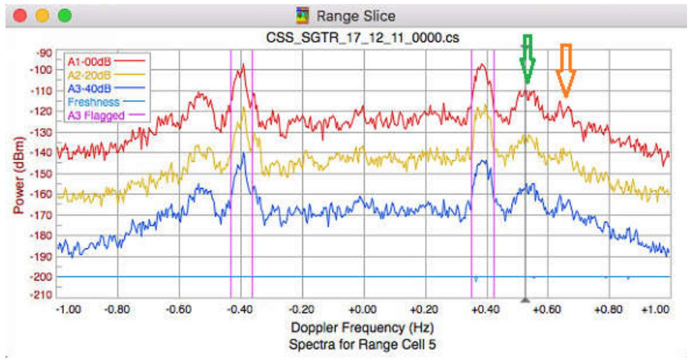
Since Sagres is often exposed to several oceanographic regimes, either generated by storms forming in the Atlantic, either by storms generated in Gibraltar, or even by local strong winds, if you do not have wind information is often difficult to understand the wave data given by the radar. In this cases particularly and many others like thermal winds, quick direction shifts of wind direction, quick increase or decrease in wind velocity, wind info can help systematize in what conditions your system can perform better.

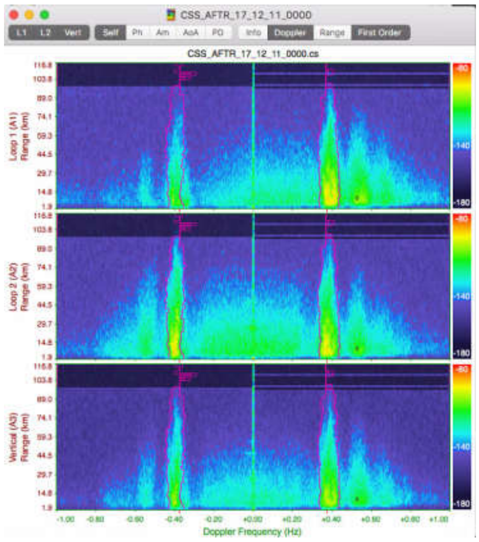
Sagres presents quite often bimodal seas, meaning that the radar is measuring at the same time swell, different sets of swell or even wind waves, both of them are characterize by having different periods and directions. When you are looking at significant wave height from a time step, where you have bimodal seas, you need to be sure what you are looking at. Is the wave data related to swell, to different sets of swell, to wind waves or both? If you do not have wind information, this not clear.

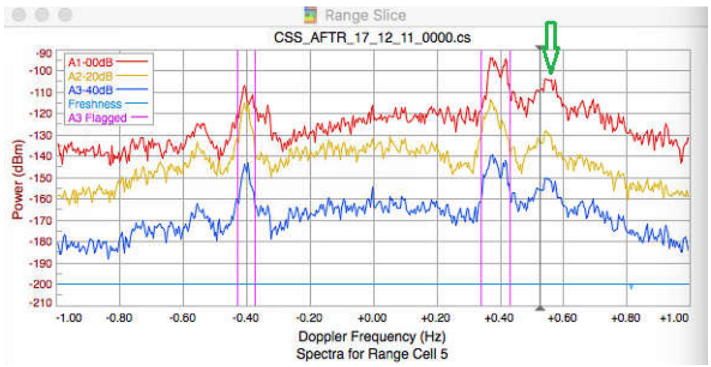
Once you have wind data (direction and velocity) you can correlate it to Range Slice information. From Range Slice you can interpolate the Tp value for each peak you identify, and compare to wind data and conclude if the peak is being generated by swell or wind waves.

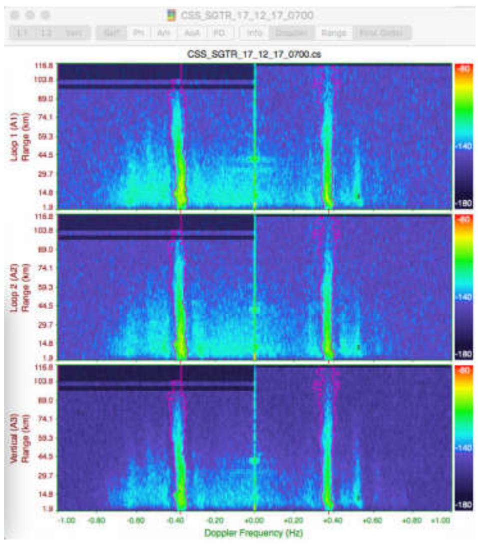
Below in Figure 20 there are two examples from Sagres and Alfanzina stations for the same time step, where one can see that Sagres presents bimodal seas while Alfanzina does not.

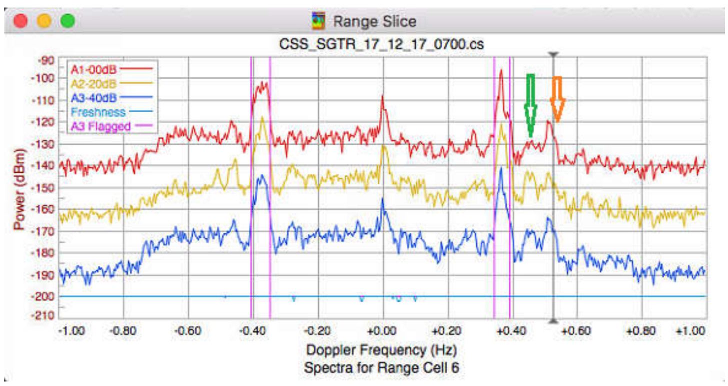

CSS_SGTR_17_12_11_0000.cs
Loop 1 (A1) Range (km)
Loop 2 (A2) Range (km)
Vertical (A3) Range (km)
Doppler Frequency (Hz)


Range Slice
CSS_SGTR_17_12_11_0000.cs
A1-00dB
A2-20dB
A3-40dB
Freshness
A3 Flagged
Power (dBm)
Doppler Frequency (Hz)
Spectra for Range Cell 5


CSS_AFTR_17_12_11_0000
CSS_AFTR_17_12_11_0000.cs
Loop 1 (A1) Range (km)
Loop 2 (A2) Range (km)
Vertical (A3) Range (km)
Doppler Frequency (Hz)


Range Slice
CSS_AFTR_17_12_11_0000.cs
A1-00dB
A2-20dB
A3-40dB
Freshness
A3 Flagged
Power (dBm)
Doppler Frequency (Hz)
Spectra for Range Cell 5


CSS_SGTR_17_12_17_0700.cs
Loop 1 (A1) Range (km)
Loop 2 (A2) Range (km)
Vertical (A3) Range (km)
Doppler Frequency (Hz)


Range Slice
CSS_SGTR_17_12_17_0700.cs
A1-00dB
A2-20dB
A3-40dB
Freshness
A3 Flagged
Power (dBm)
Doppler Frequency (Hz)
Spectra for Range Cell 6

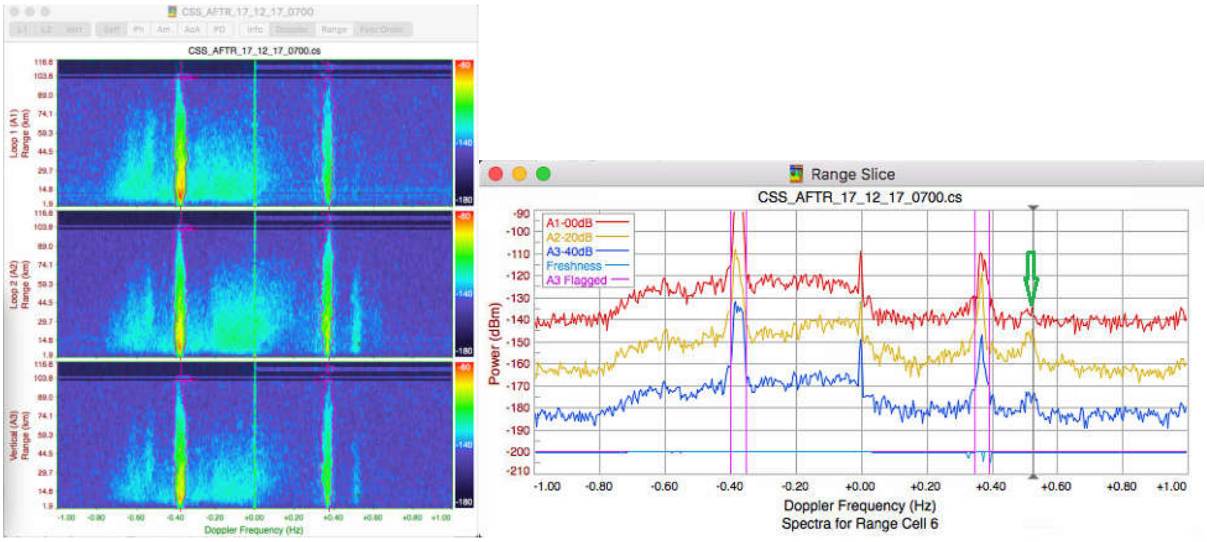


Figure 20. Examples demonstrating evidences of bimodal seas in Sagres station when compared to Alfanzina station for the same time steps.

Unless you have an *in-situ* equipment able to measure wind information in the range of the HF radar station we feel that the installation of an anemometer near the station is imperative. Sagres station has one anemometer installed since September 2019, because the *in-situ* equipment (offshore buoy) able to provide wind data was ~80 km distance and this distance is quite big in order to make good validations (Figure 21).

Figure 21. Anemometer installed in Sagres HF radar station.

4. COMPILE NECESSARY MODELLED AND OBSERVED DATA

The quality of HFR wave measurements is greatly dependant on the existing met-ocean (wind, wave, currents) and environmental (e.g. radio interference, ionospheric noise, interference, calmed seas, offshore and inshore winds, bimodal seas, etc.) conditions at each time in the radar coverage area. As part of this task we want to classify HFR wave data according to different met-ocean and environmental conditions. We used data provided by other in-situ instruments (buoys, met-stations), models (CMEMS, ECMWF, IH) and own HFR QC flags to establish these conditions and classify HFR wave data accordingly.

We propose to select a 6 month data and analyse 1 month at a time or less. This analyses will depend also on the equipment frequency, since the ones with higher frequency have lower resolutions regarding small phenomena while lower frequency equipments will reveal regional and small frequency phenomena like thermal winds, quick wind and wave direction inversions.
For each HFR site entering the analysis, the following data sets for that period in different points inside the radar coverage area need to be obtained and archived for later analysis:

- HF radars
    - Position, frequency, water depth, coastline shape and direction, antenna pattern, waves software version and configuration of the site
    - Real-time measurement data: wave height + period + direction, wind direction
- Buoys and met stations close to the HFR coverage area
    - Position, bathymetry, coastline shape and direction
    - Real-time wave height + period + direction, wind direction + intensity
- Models
    - COPERNICUS wave and wind data

Variables that should be taken into account to classify HFR wave data accordingly:

- Distance from the radar (km)
- Bathymetry
- Wave data provided by models and buoys (Hs, wave dir, Tp)
- Wind velocity and direction provided models and buoys in the coverage area of the radar. In case there is no wind data we recommend the installation of an anemometer near the HF radar station, although we recommend that a wind sensor should be installed in the station for more accurate data.
- QC information provided by the HFR software (SNR, valid Doppler cells…)

After gathering all the data necessary to make the comparisons needed there are statistical parameters that we feel should be taken into account:

- Bias
- CI
- Data availability %
- RMS
- Slope
- Average difference
- RMSn
- Intercept
- Maximum difference

Two examples of the approach of this methodology are the papers already published regarding the HF radars, one off SW of Portugal in Annex 1 (*Fernandes M, Fernandes C, Barroqueiro T, Agostinho P, Martins N, Alonso-Martirena A. 2018. Extreme wave height events in Algarve (Portugal): comparison between HF radar systems and wave buoys, 5as Jornadas de Engenharia Hidrográfica, Lisboa, 19-21 de Junho, p. 222-225*) and the other in the NW of Spain that can be visualized in Annex 2 (*Basañez, A.; Lorente, P.; Montero, P.; Álvarez-Fanjul, E.; Pérez-Muñuzuri, V. Quality Assessment and Practical Interpretation of the Wave Parameters Estimated by HF Radars in NW Spain. Remote Sens. 2020, 12, 598.*).

5. VARIABLES AND CONDITIONS THAT AFFECT DATA QUALITY

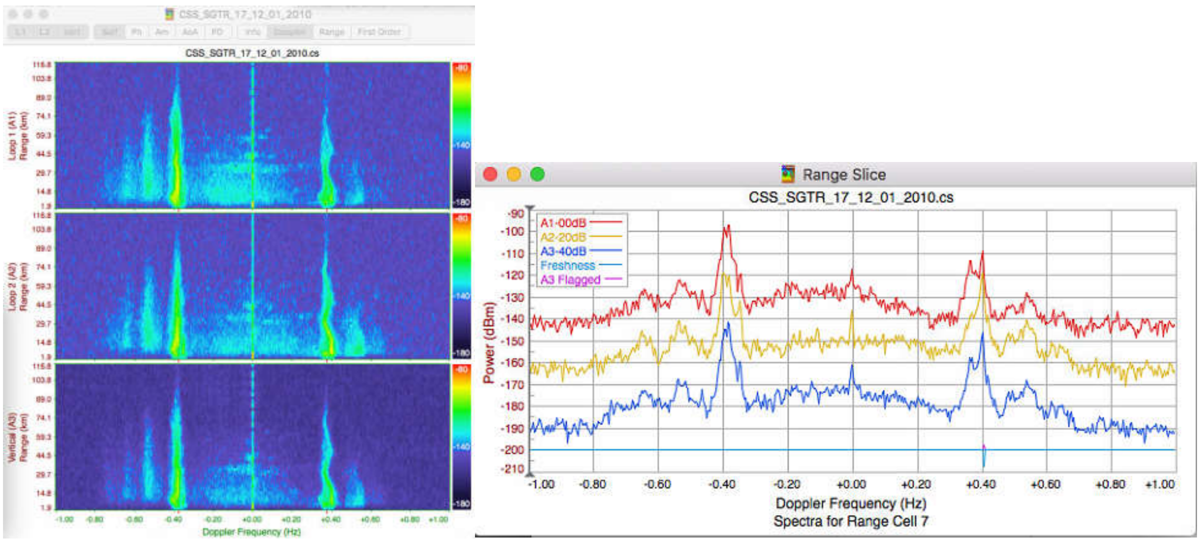
In very dynamic environments HF radar wave measurements can play an essential role to considerably increase the knowledge of these complex physical processes and their interactions.

Several analysis were made in Sagres and Alfanzina station, considering different scenarios with different oceanographic conditions and the results showed that the following met-ocean conditions could impact quality of HF radar wave measurements.

- Presence of **bi-modal seas** (which can be checked in CMEMS data and HFR spectra)

  Bi-modal seas present bi-modal characteristics, meaning that we can have swell mixed with wind waves, both with different directions inducing 2 or more different oceanographic conditions. The HF radar will not measure both directions, it will indicate, if one can say, the direction of the averaged energy comes from (centroid of the spectral energy) or, in the best scenario, the direction of the most energetic one. If for the radar, the most energetic one is the local wind, it will probably give low periods and low significant wave heights. If you are comparing HF radar data with a buoy that can be several km offshore and does not feel the effect of local wind than the buoy will measure only the swell (high periods and high waves). This can result high overestimation values.

  In Figure 22 there are some examples of bimodal seas during December 2017 and in Figure 23 the plot of wave parameters from HF radar and offshore buoy. In the first spectra file example (01/12/2017 20:10) the bimodal sea is located at the negative side of the spectra (meaning waves moving away from the radar). When looking at Figure 23 there is almost no overestimation since wave and wind are going in the same direction (green box in Figure 23). Once you look at the other two examples from the spectra files (14/12/2017 18:20 and 15/12/2017 18:10) there is also the presence of bimodals seas but this time at the positive side of the spectra (waves moving to the radar). When looking again at grey box in Figure 23 the overestimation is this time quite high since the wind direction is shifting too much and is not coherent with wave direction.



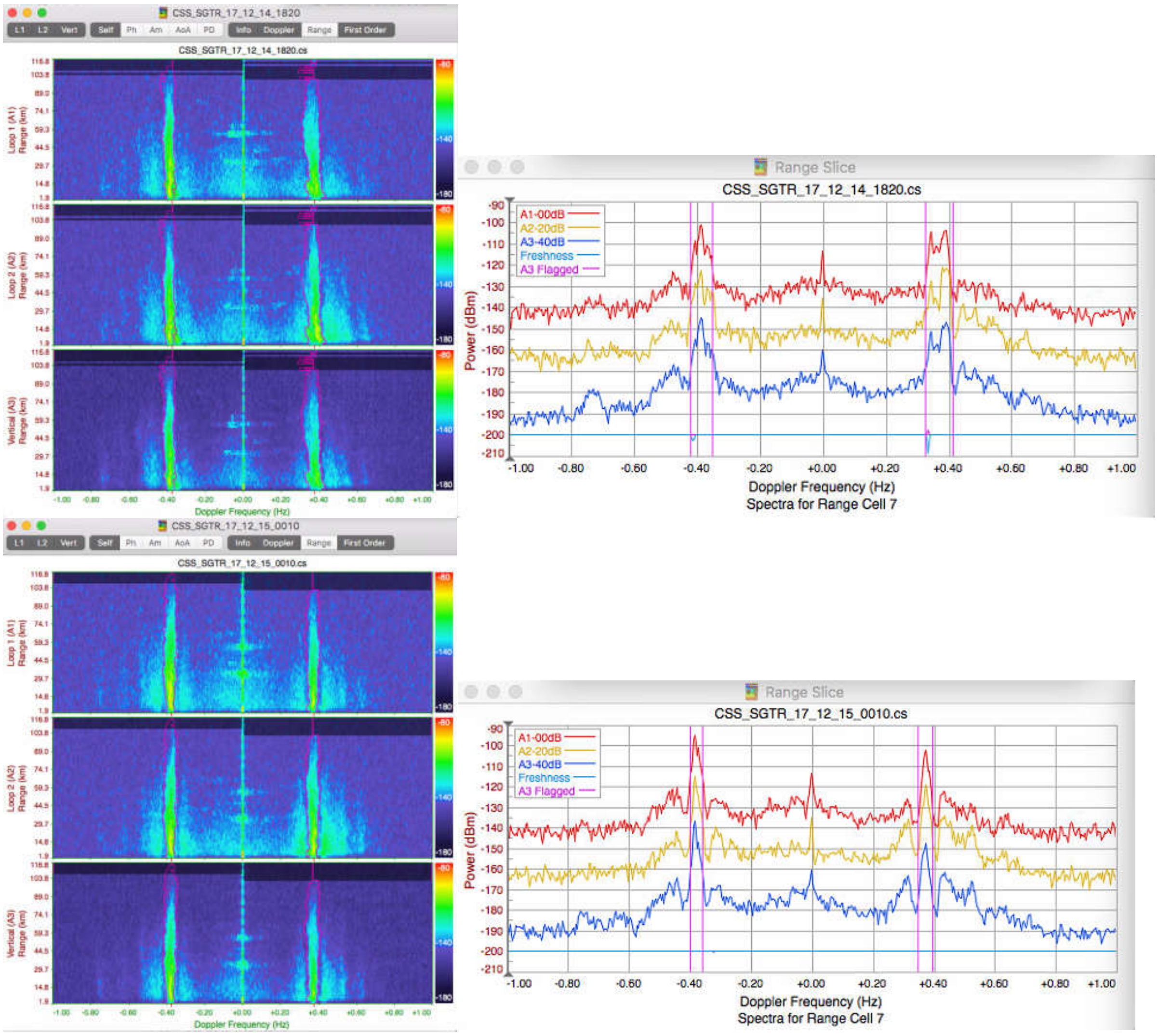


Figure 22. Examples demonstrating evidences of bimodal seas in Sagres station.

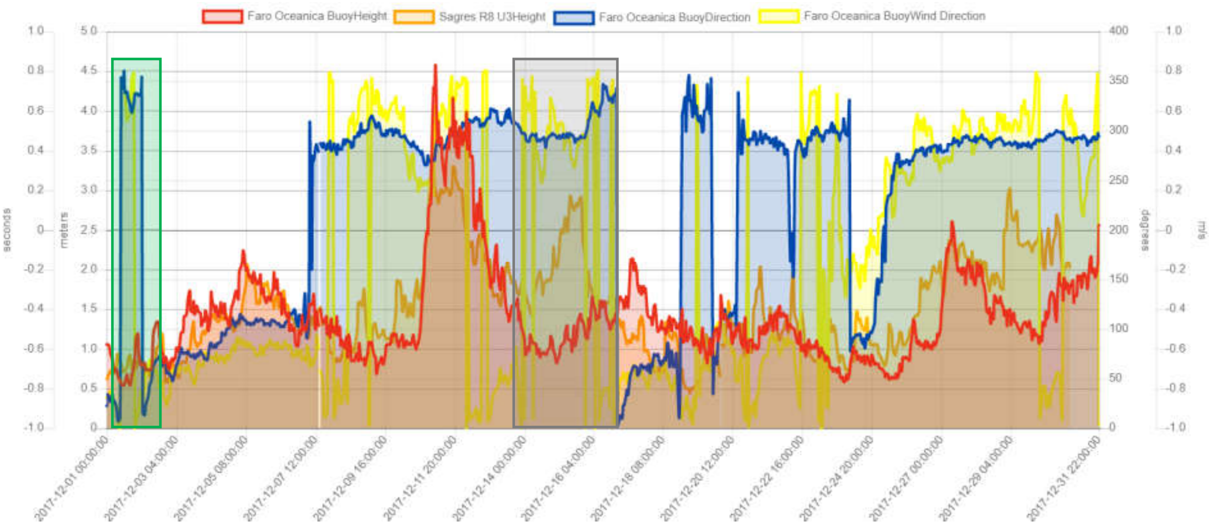
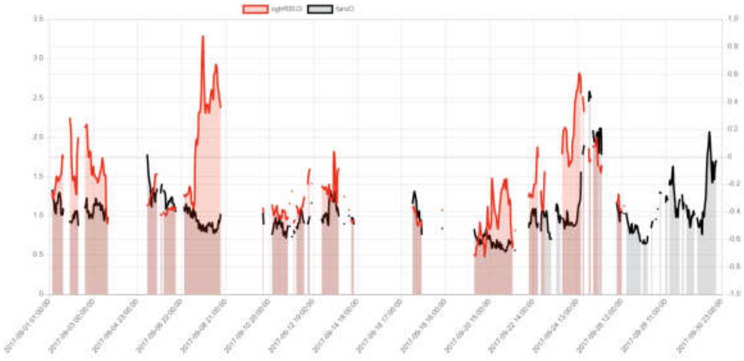


Figure 23. Plot of Hs from buoy (red) and radar (orange), wave dir (blue) and wind dir (yellow) from buoy. Green box – wave and wind in the same direction; grey box – wave and wind in opposite directions.

- **Wind and wave direction**.
  It seems HFR wave data is better when wind speeds are higher (> 5m/s) either if wave and wind are in opposite or have the same directions and seen in Figure 24, Figure 25, Figure 26, Figure 27, Figure 28 and Figure 29 from months of September, November and December 2017.



	Wind < 5m/s
Variables	**Value Hs (m)**
RMS	0.72
CI	0.164
Availability SGTR R8	40.28%
Availability buoy	53.06%
Number of data	290
Average difference	0.203

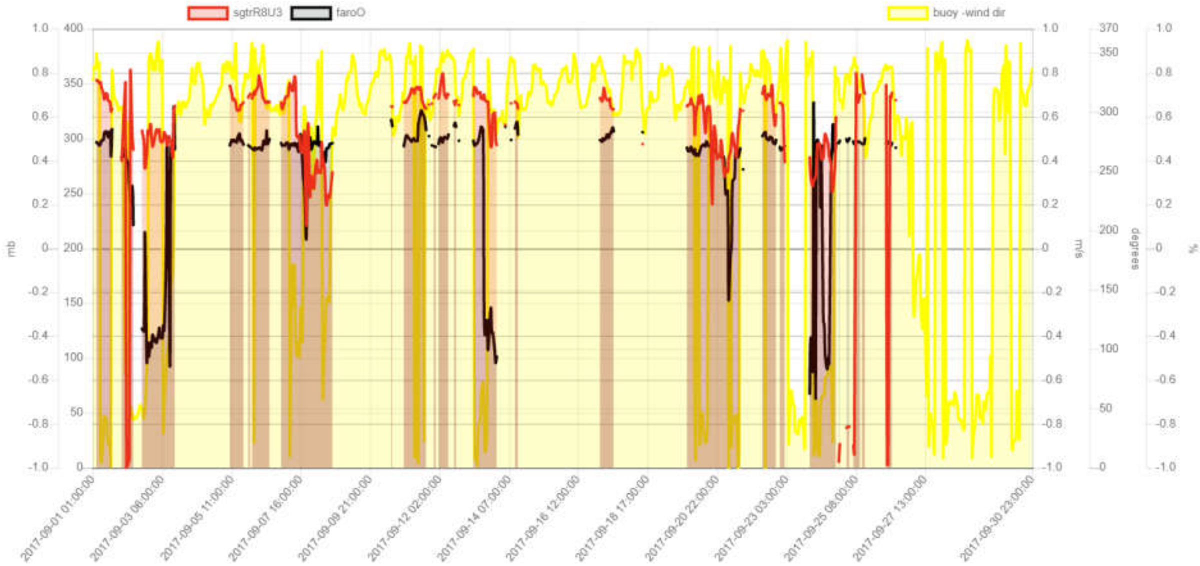
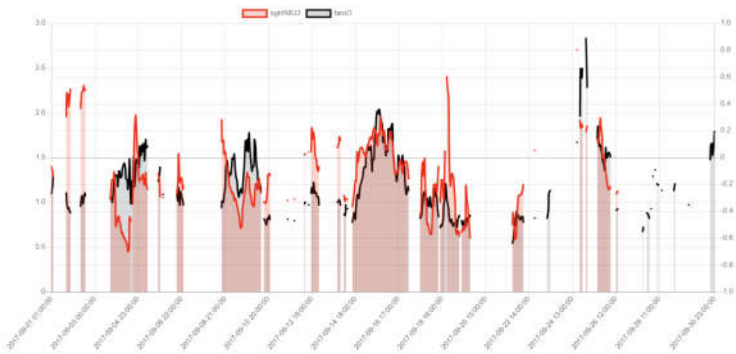


Figure 24. Plot of wave direction from HFR (red) and buoy (black) for September 2017 and wind direction (yellow) from buoy < 5m/s for Sagres station.



	Wind > 5m/s
Variables	**Value Hs (m)**
RMS	0.448
CI	0.364
Availability SGTR R8	40.83%
Availability buoy	44.58%
Number of data	294
Average difference	0.138

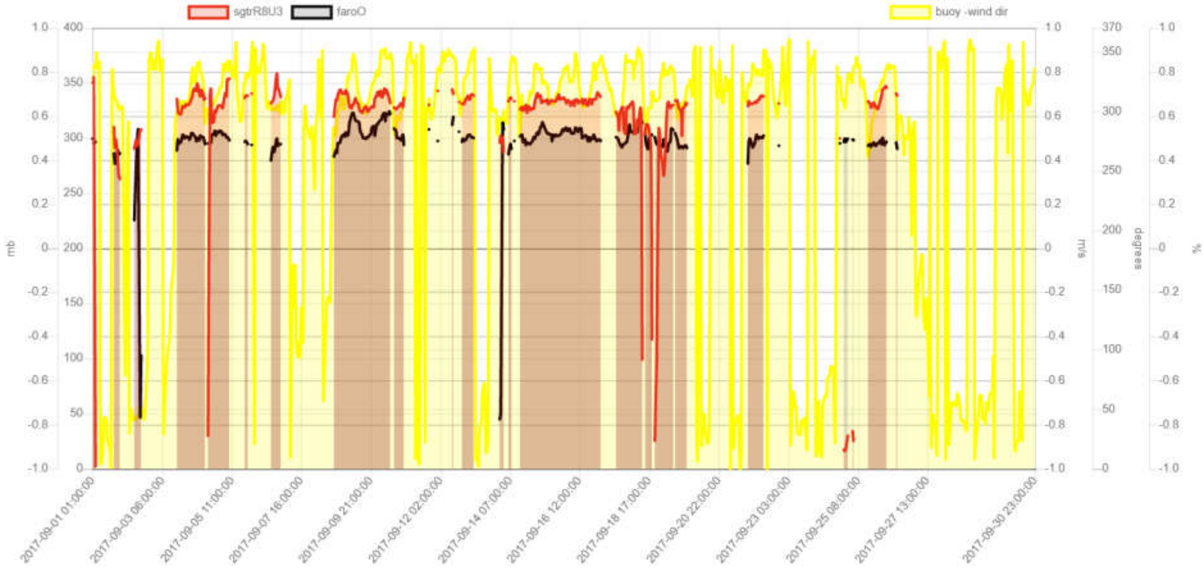
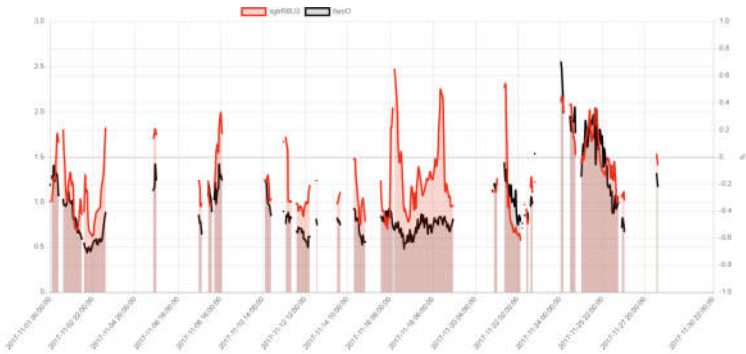


Figure 25. Plot of wave direction from HFR (red) and buoy (black) for September 2017 and wind direction (yellow) from buoy > 5m/s for Sagres station.



	Wind < 5m/s
Variables	**Value Hs (m)**
RMS	0.465
CI	0.581
Availability SGTR R8	40.69%
Availability buoy	40.83%
Number of data	293
Average difference	0.146

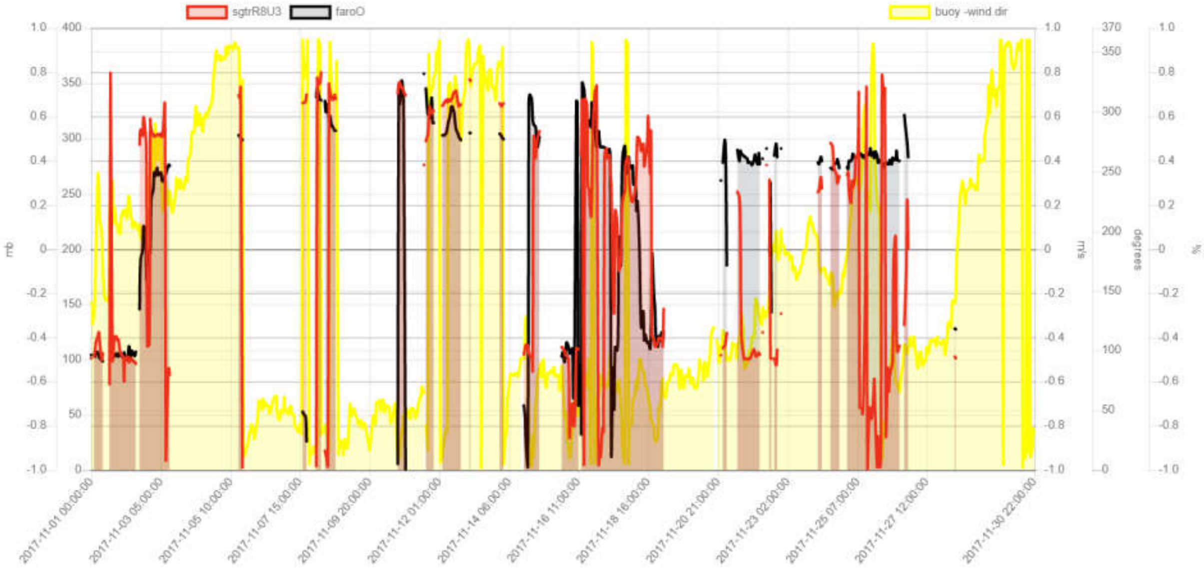
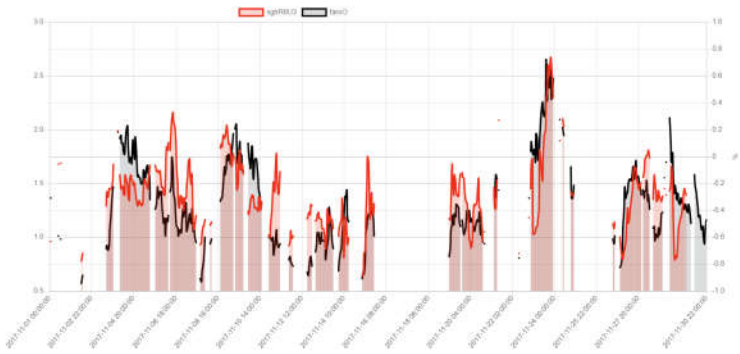


Figure 26. Plot of wave direction from HFR (red) and buoy (black) for November 2017 and wind direction (yellow) from buoy < 5m/s for Sagres station.



	Wind > 5m/s
Variables	**Value Hs (m)**
RMS	0.337
CI	0.61
Availability SGTR R8	49.58%
Availability buoy	52.36%
Number of data	357
Average difference	0.139

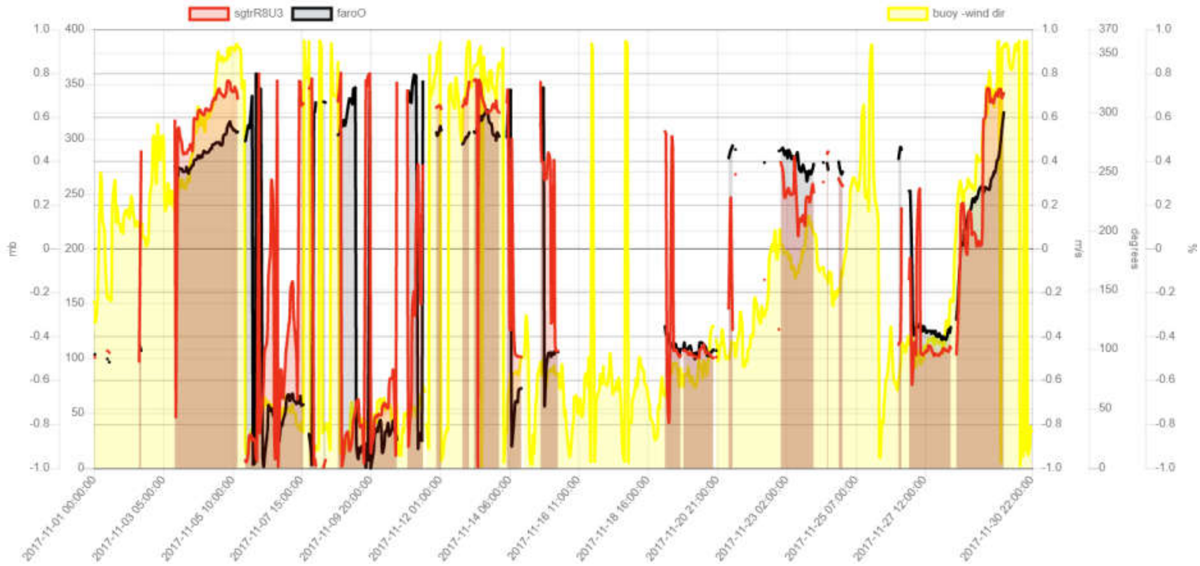
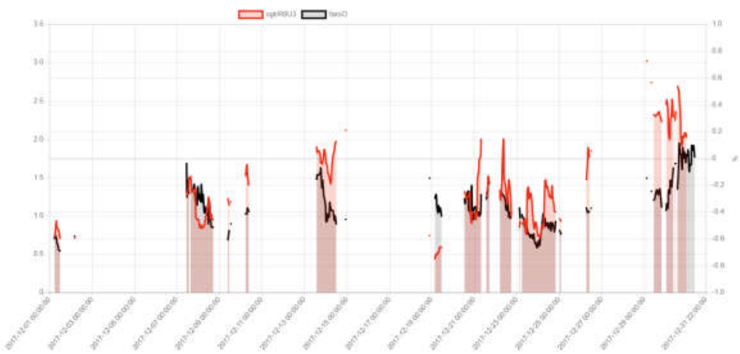


Figure 27. Plot of wave direction from HFR (red) and buoy (black) for November 2017 and wind direction (yellow) from buoy > 5m/s for Sagres station.



	Wind < 5m/s
Variables	**Value Hs (m)**
RMS	0.534
CI	0.564
Availability SGTR R8	26.61%
Availability buoy	27.82%
Number of data	198
Average difference	0.109

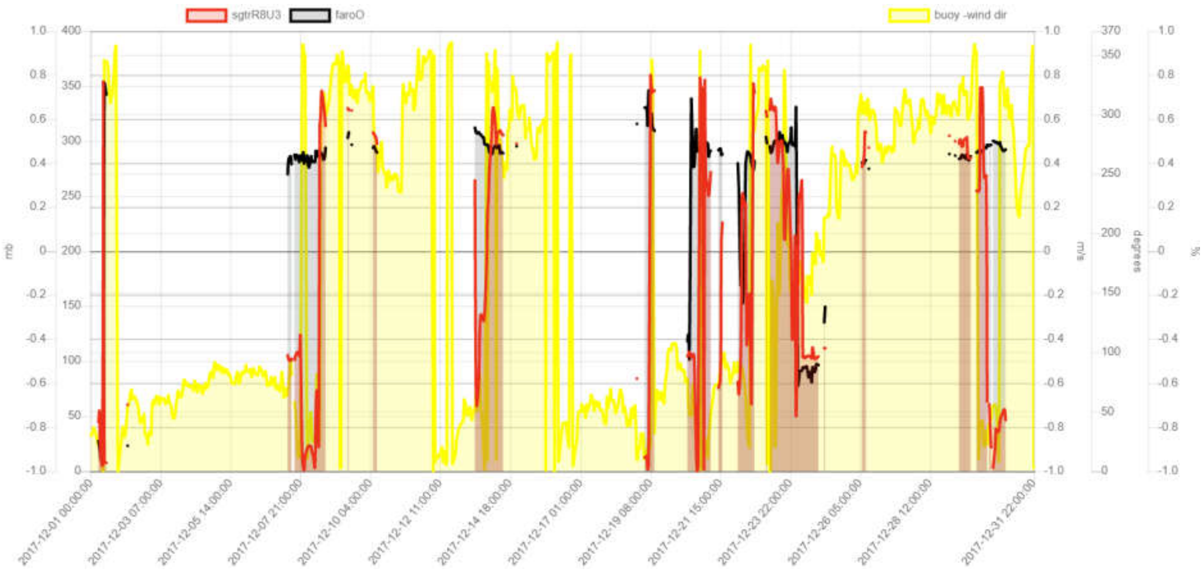


Figure 28. Plot of wave direction from HFR (red) and buoy (black) for December 2017 and wind direction (yellow) from buoy < 5m/s for Sagres station.

	Wind > 5m/s
Variables	**Value Hs (m)**
RMS	0.549
CI	0.675
Availability SGTR R8	68.01%
Availability buoy	69.89%
Number of data	506
Average difference	0.273

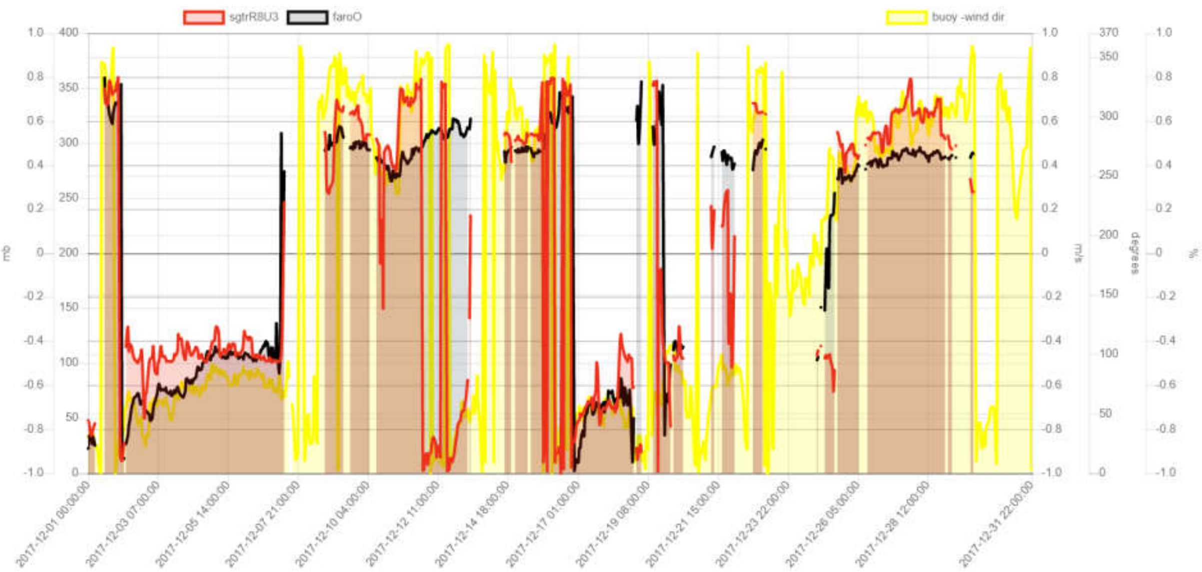


Figure 29. Plot of wave direction from HFR (red) and buoy (black) for December 2017 and wind direction (yellow) from buoy > 5m/s for Sagres station.

The higher the difference in angles between wind and wave direction the less accurate data will be. In Figure 30 is the scheme, where direction of wind is fixed at 0-90º while wave direction is rotating through all four quadrants.

For example for SGTR during December 2017, when comparing data from wind and wave that come both from the same direction (0-90º) one can see from Table 4, Table 5 and Figure 31 and Figure 32 that those data are the ones with better correlation regarding wave direction and significant wave height.

As one starts to increase the difference in angle between the two (wind and wave) the results start to degrade as seen in table Table 4 and Table 5 with the values marked in yellow and red, also visible on the respective graphics from Figure 34, Figure 35, Figure 36, Figure 37.

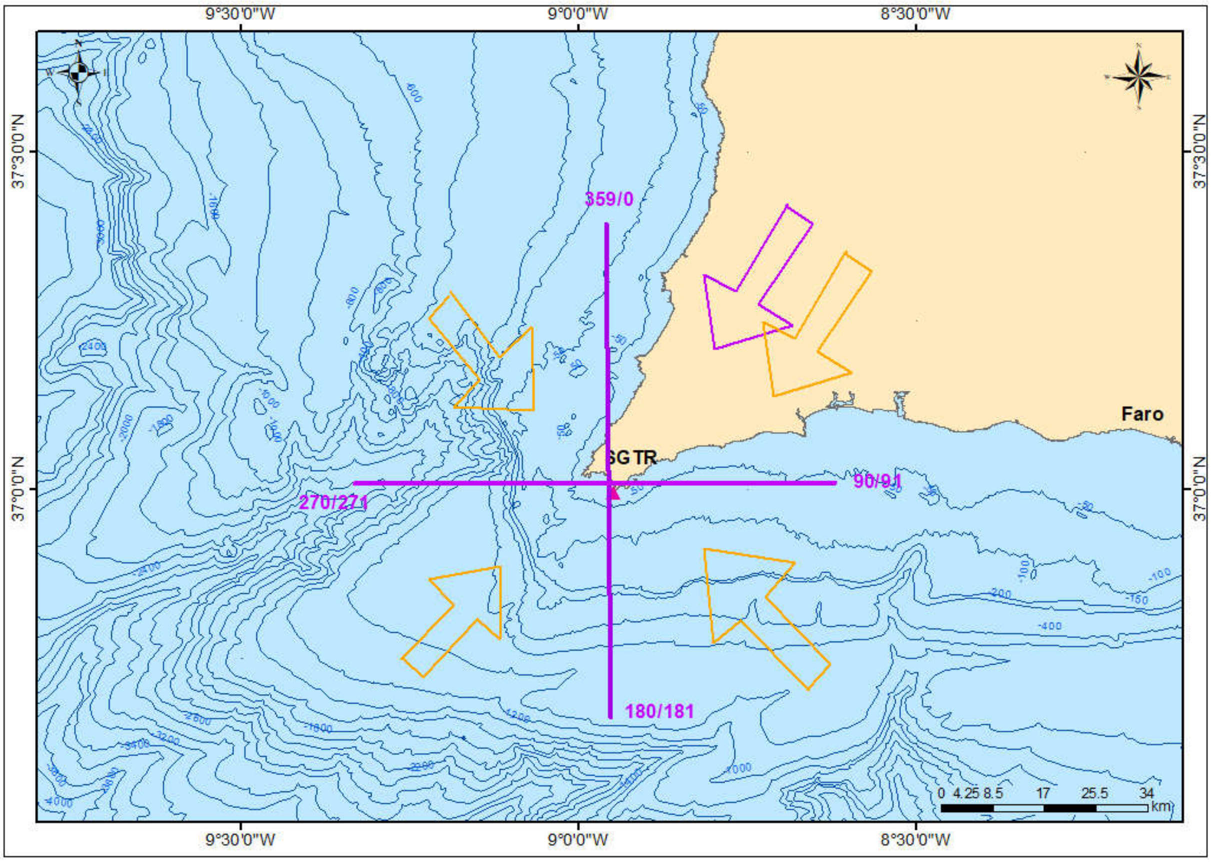


Figure 30. Map with wind direction fixed at 0-90º (pink) and wave direction rotation through the four quadrants (0-90º, 91- 180º, 181-270º and 271-359º).

Variables	Wind 0-90 Wave 0-90	Wind 0-90 Wave 91-180	Wind 0-90 Wave 181-270	Wind 0-90 Wave 271-359
RMS	3.938º	11.154º	54.336º	7.727º
CI	0.674	0.388	-0.934	-0.13
Availability SGTR R8	15.86%	10.22%	0.54%	20.97%
Availability buoy	15.86%	10.22%	0.54%	21.24%
Number of data	118	76	4	156
Average difference	27.9º	10.825º	104.54º	76.208º

Table 4. Statistics for wave direction between HF radar and buoy, varying wave and wind direction from buoy.

Variables	Wind 0-90 Wave 0-90	Wind 0-90 Wave 91-180	Wind 0-90 Wave 181-270	Wind 0-90 Wave 271-359
RMS	0.412 m	0.252 m	0.314 m	0.486 m
CI	0.63	0.585	-0.422	0.593
Availability SGTR R8	15.86%	10.22%	0.54%	20.97%
Availability buoy	15.86%	10.22%	0.54%	21.24%
Number of data	118	76	4	156
Average difference	0.053 m	0.019 m	0.002 m	0.076 m

Table 5. Statistics for significant wave height (Hs), varying wave and wind direction from buoy.

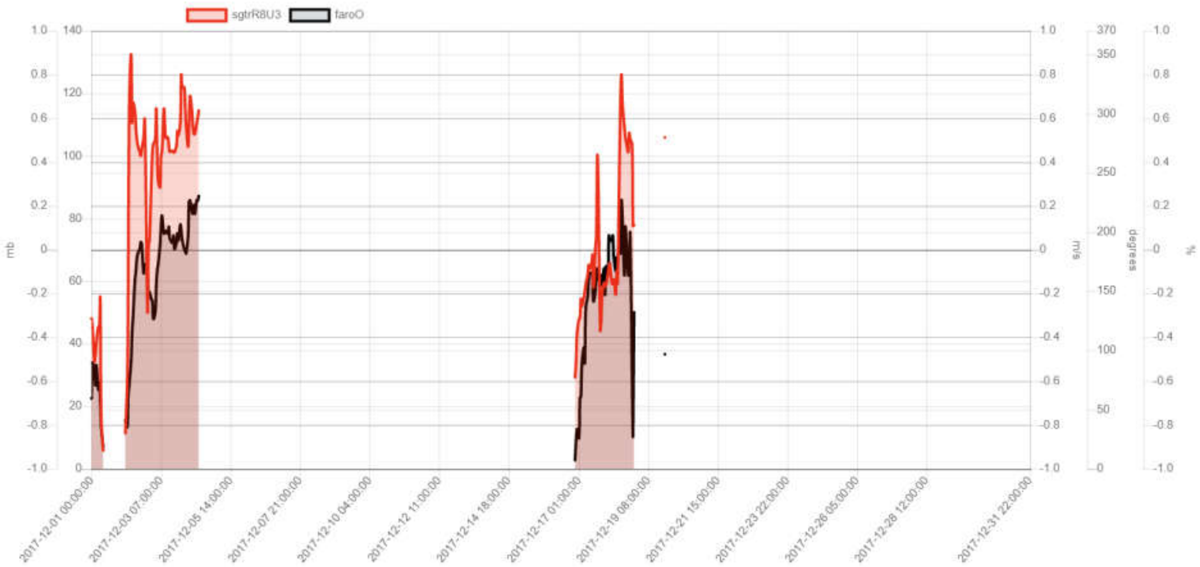


Figure 31. Plot of wave direction from buoy (black) and radar (red), when wind direction from buoy (0 – 90º) and wave direction from buoy (0º - 90º).

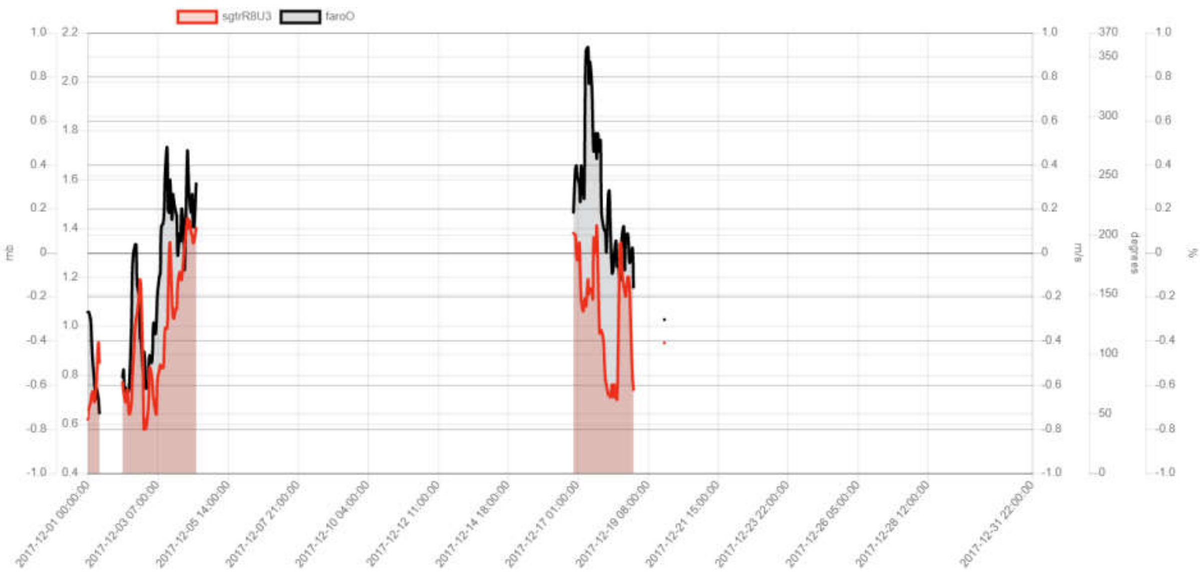


Figure 32. Plot of Hs from buoy (black) and radar (red when wind direction from buoy (0 – 90º) and wave direction from buoy (0º - 90º).

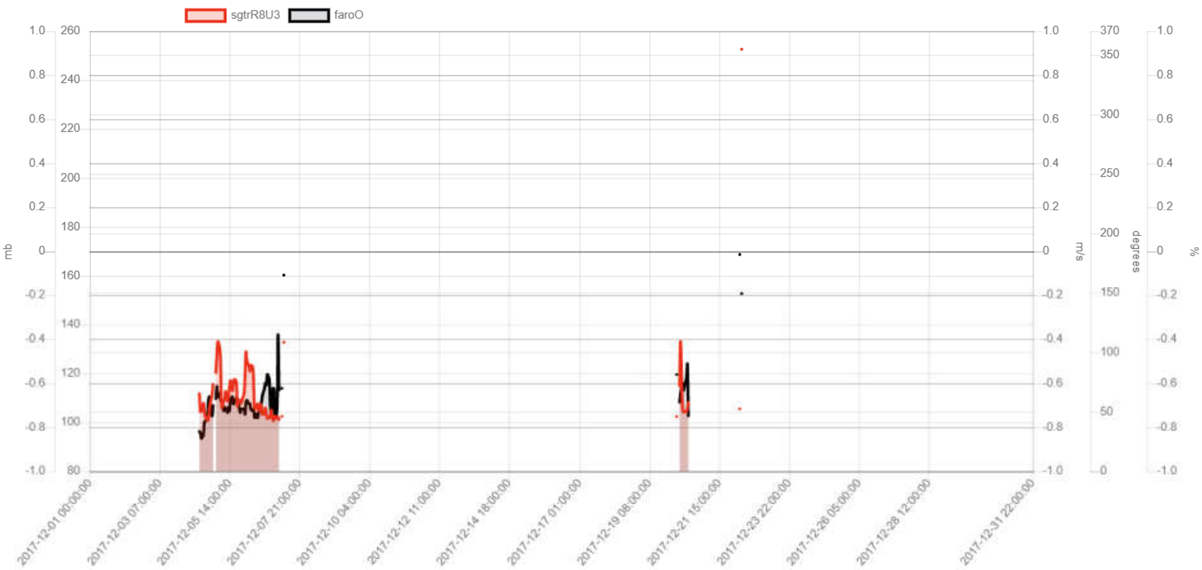


Figure 33. Plot of wave direction from buoy (black) and radar (red), when wind direction from buoy (0 – 90º) and wave direction from buoy (91º - 180º).

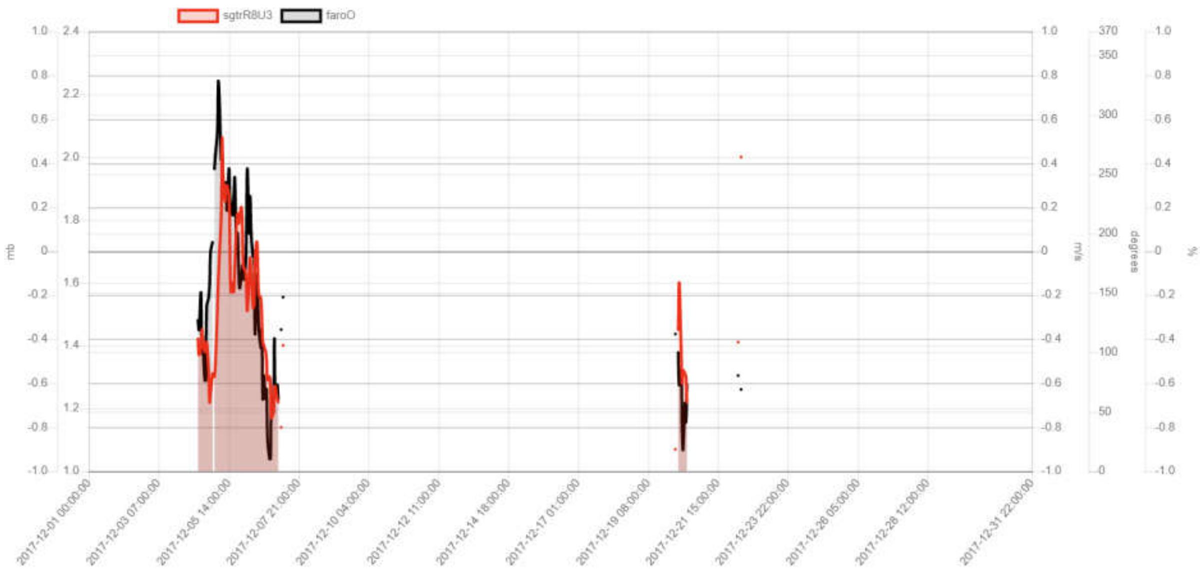


Figure 34. Plot of Hs from buoy (black) and radar (red when wind direction from buoy (0 – 90º) and wave direction from buoy (91º - 180º).

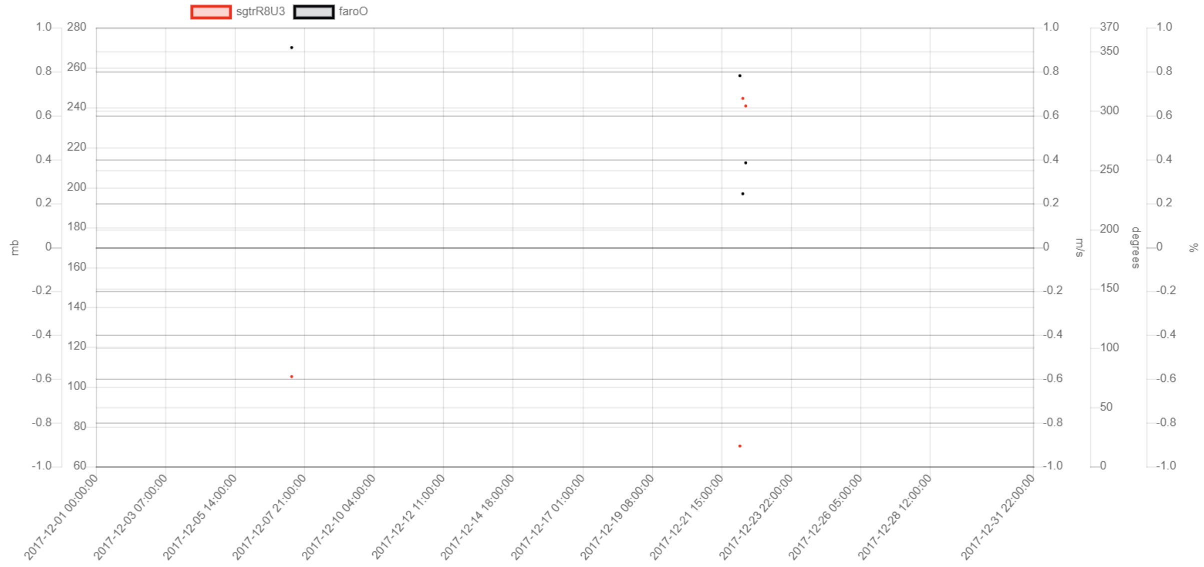


Figure 35. Plot of wave direction from buoy (black) and radar (red), when wind direction from buoy (0 – 90º) and wave direction from buoy (181º - 270º).

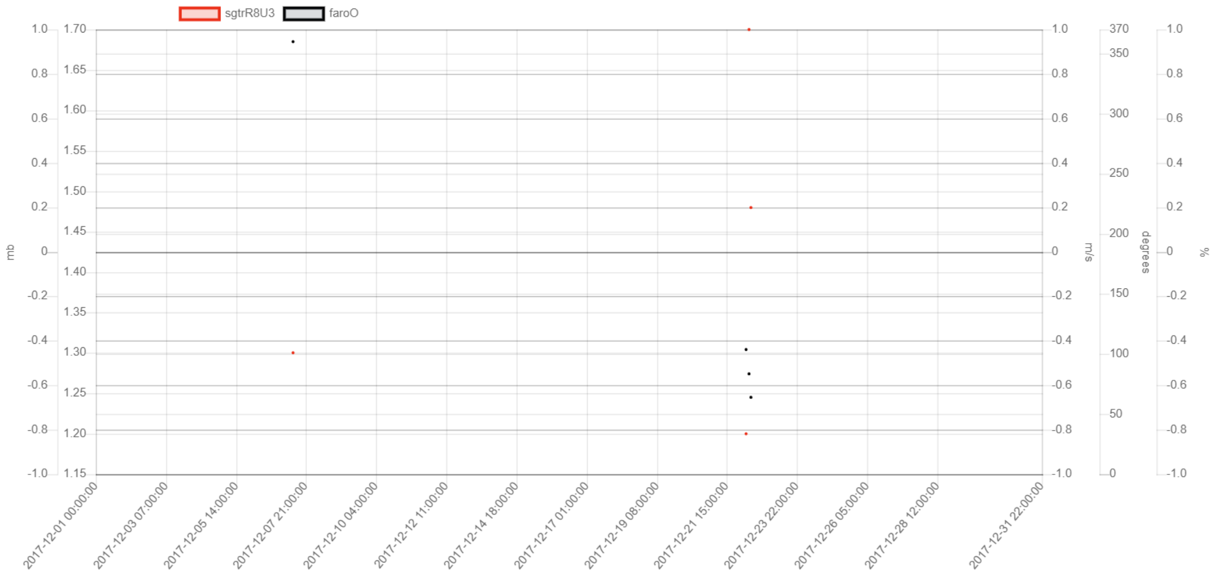


Figure 36. Plot of Hs from buoy (black) and radar (red when wind direction from buoy (0 – 90º) and wave direction from buoy (181º - 270º).

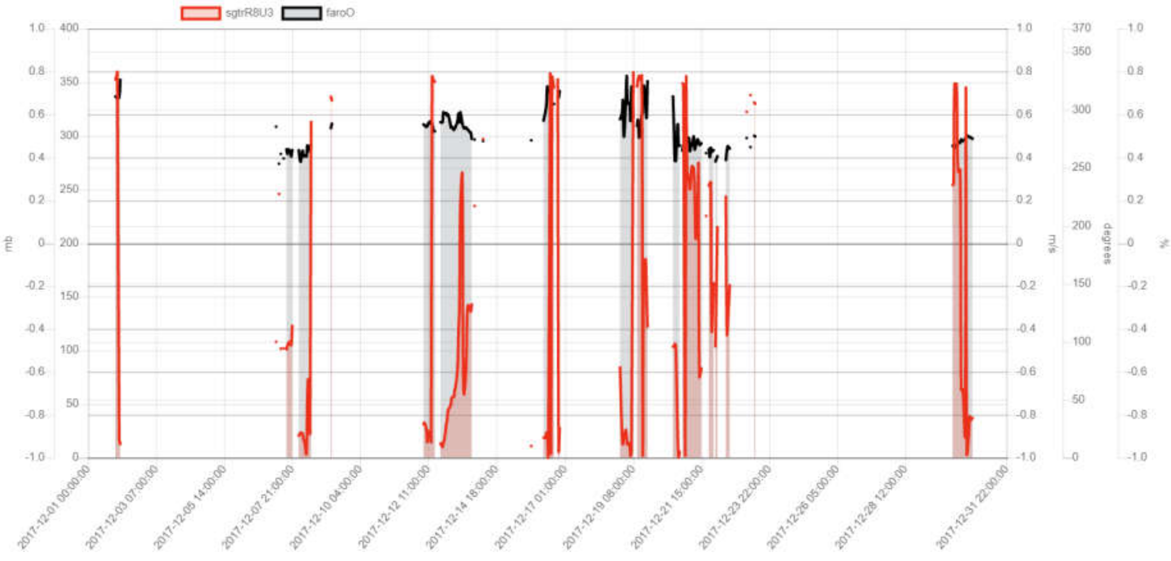


Figure 37. Plot of wave direction from buoy (black) and radar (red), when wind direction from buoy (0 – 90º) and wave direction from buoy (271º - 359º).

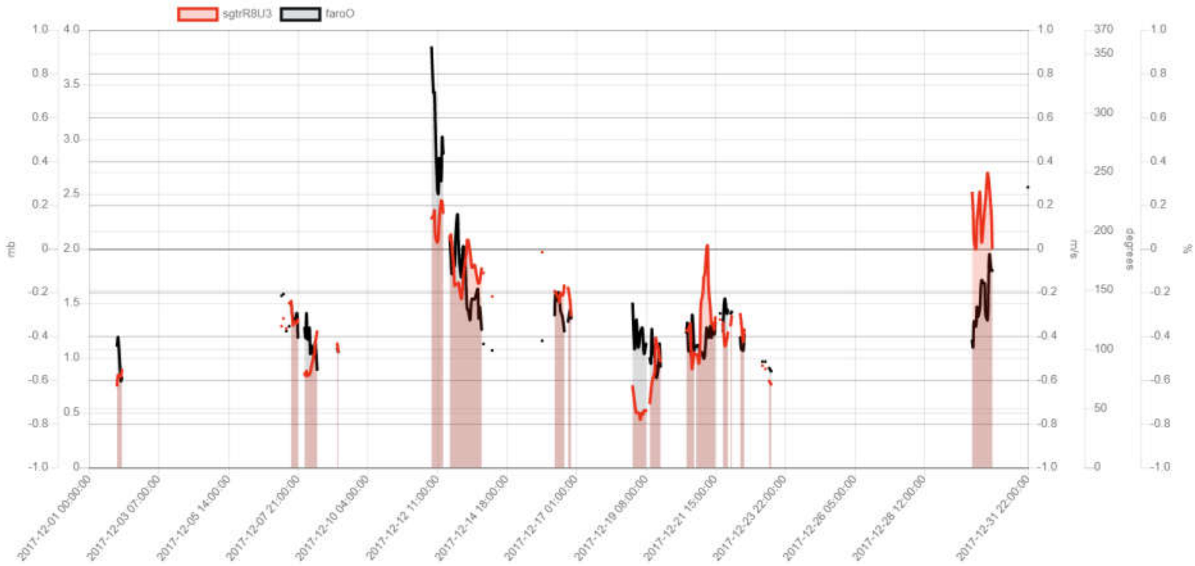


Figure 38. Plot of Hs from buoy (black) and radar (red), when wind direction from buoy (0 – 90º) and wave direction from buoy (271º - 359º).

But one can also have examples when you have wind and wave on the same direction and the wind speed is low or high, you are expecting good data and still that might not occur and the difference can present itself quite high (Figure 39). As demonstrated in Figure 40 the reason of very high overestimation is not that the permissions made are not correct but simply because the spectra is full of interference which will induce the overestimation seen in Figure 39 (black arrow).

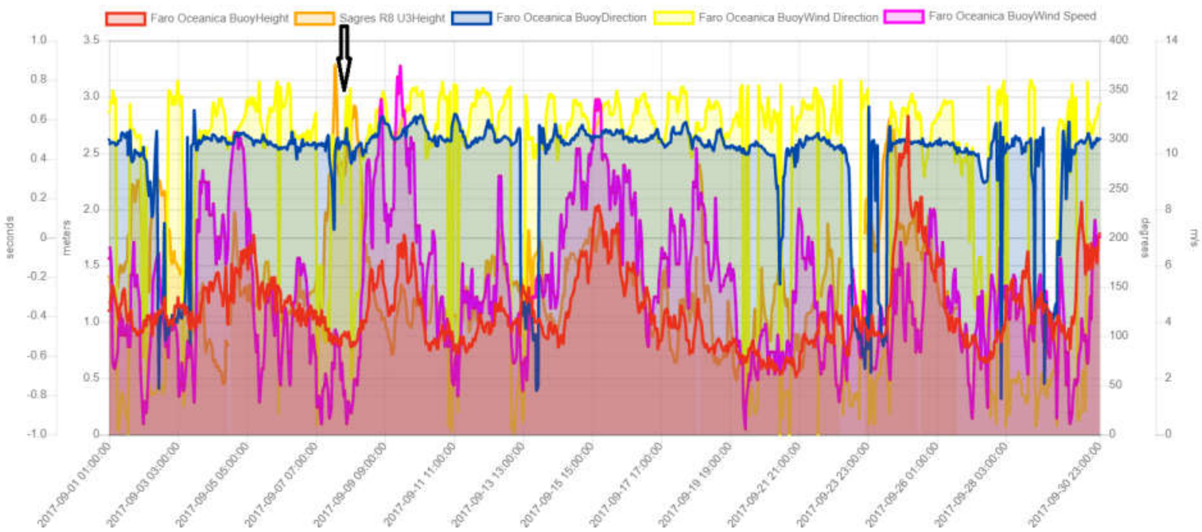


Figure 39. Plot of Hs from buoy (red) and radar (orange), wave dir (blue) and wind dir (yellow) from buoy, wind speed (pink). Indication of overestimation with black arrow.

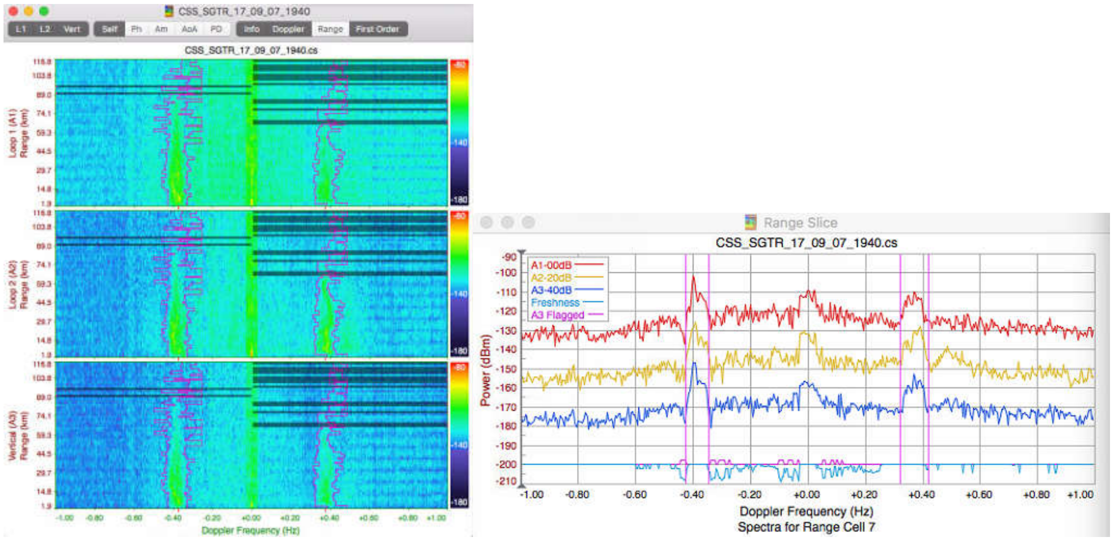


Figure 40. Example demonstrating evidences of interference in Sagres station.

- **Wave period**.

  For example in Sagres, it seems that waves above 10s combined with wind can serve as a confirmation of the presence of bimodal seas generating an overestimate in Hs whenever there is enough difference in the direction of the long swell waves and the wind direction.

  In Figure 41 is plotted the month of November 2017 with period data from HFR and buoy and wind speed from buoy. The blue horizontal line marks the 10s period. In Figure 42 it is plotted the significant wave height from HFR and buoy for the same month and the green circle marks the area where period is above 10s. From Figure 43 and Figure 44 one can see that the wind is low (meaning local wind) and has a different direction from wave in that time step enough to induce bimodal seas.

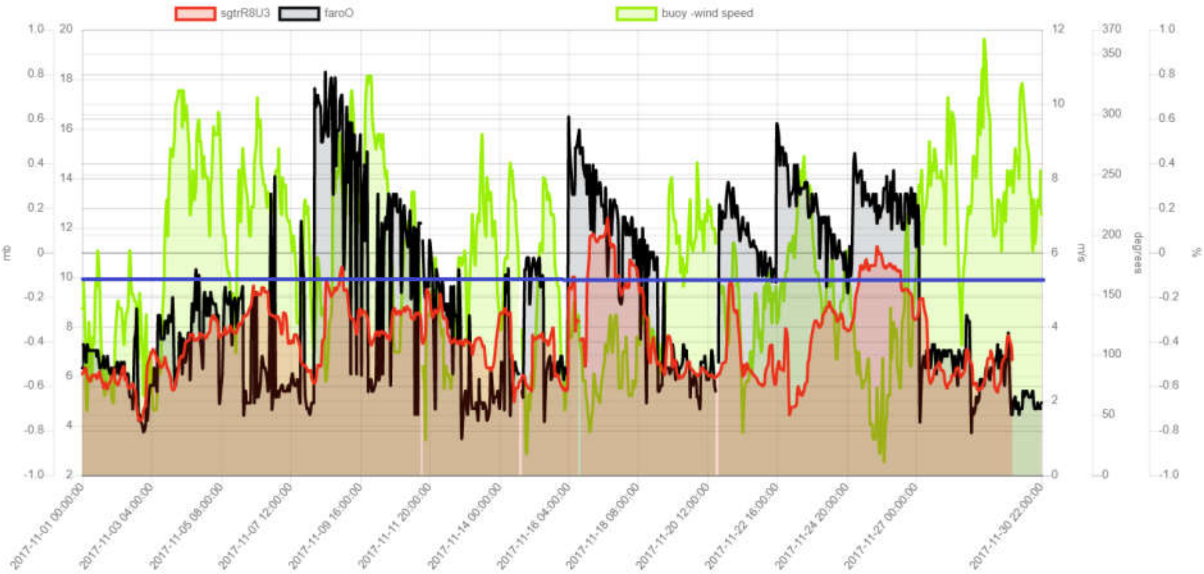


Figure 41. Plot of HFR and buoy period (Tp) and wind speed from buoy for November 2017 in SGTR.

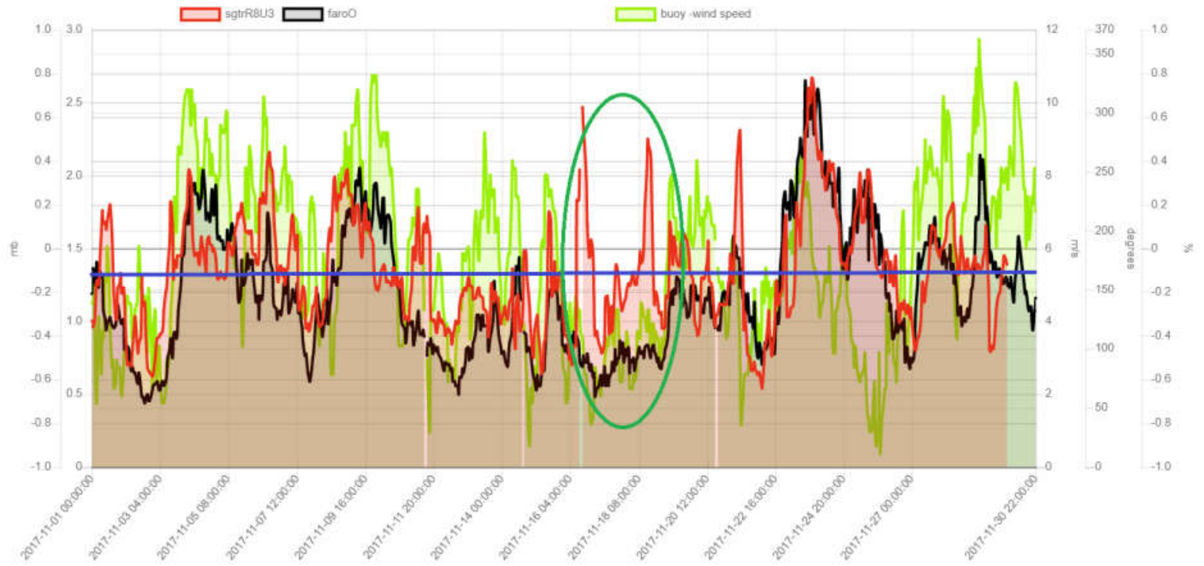


Figure 42. Plot of HFR and buoy significant height (Hs) and wind speed from buoy for November 2017 in SGTR.

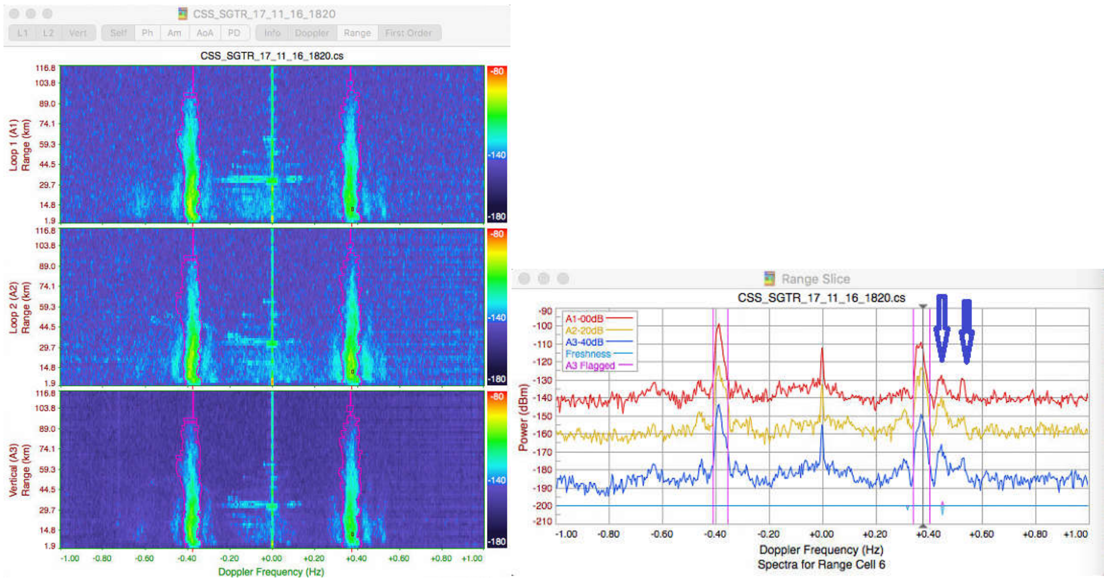


Figure 43. Spectra color map and Range slice from the area delimited in the green circle above exemplifying the presence of bimodal seas of 16/11/2017 at 18:20.

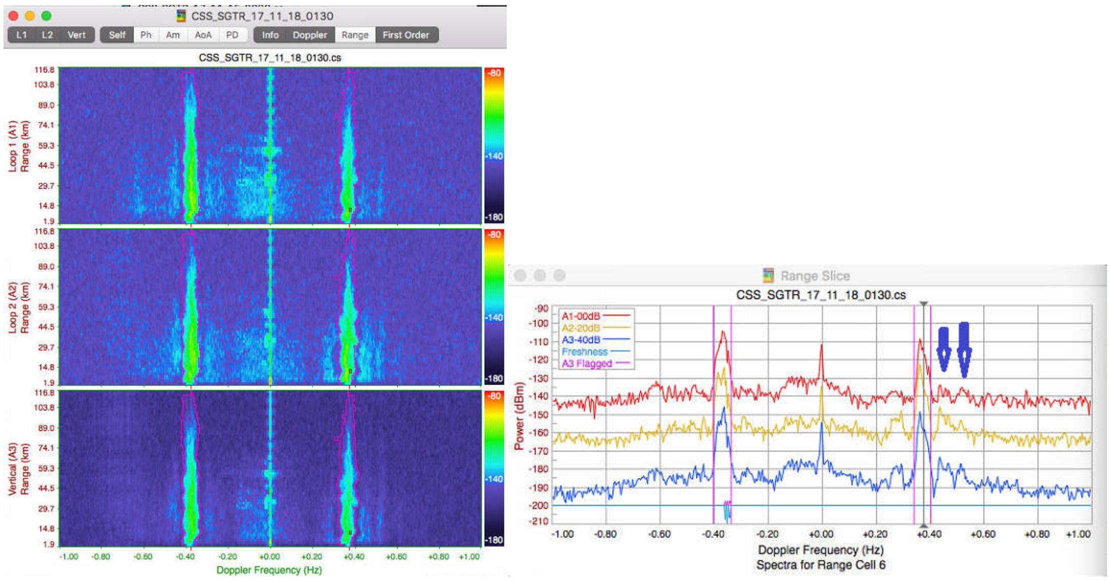


Figure 44. Spectra color map and Range slice from the area delimited in the green circle above exemplifying the presence of bimodal seas of 18/11/2017 at 01:30.

- **SNR and noise floor**

  HF radar performance in places with low SNR or high noise floor is harmed, very specially for the waves measuring purpose.

  In the case of AFTR and VATR stations in Portugal (Figure 45), there are some evidences regarding to SNR and noise floor stated below:

  - In places where the noise floor is steadily high or the SNR is low, one should expect very low quality/availability of waves data (Figure 46 and Figure 48);
  - In places where the SNR is low (dependent on station frequency, see Figure 3) there can be problems, this might be the case in stations that are at long distance from the sea which might be not ideal for waves measurement (Figure 45 with the location of VATR station, Figure 46 and Figure 48). The signal can be highly attenuated and the

range is significantly lower. In the case of AFTR the range can go till ~120 km (Figure 47 or Figure 49) while VATR the range decreases to ~70 km (Figure 48).

- In places where the noise floor is regularly low and the SNR is above 30 db, there is a good potential to produce good waves data from HF radar (Figure 47 and Figure 49).

A noisy environment may make impossible to calculate waves or may produce unwanted wrongful spikes at times. High noise floor and low SNR is something which can nowhere be fully discarded.

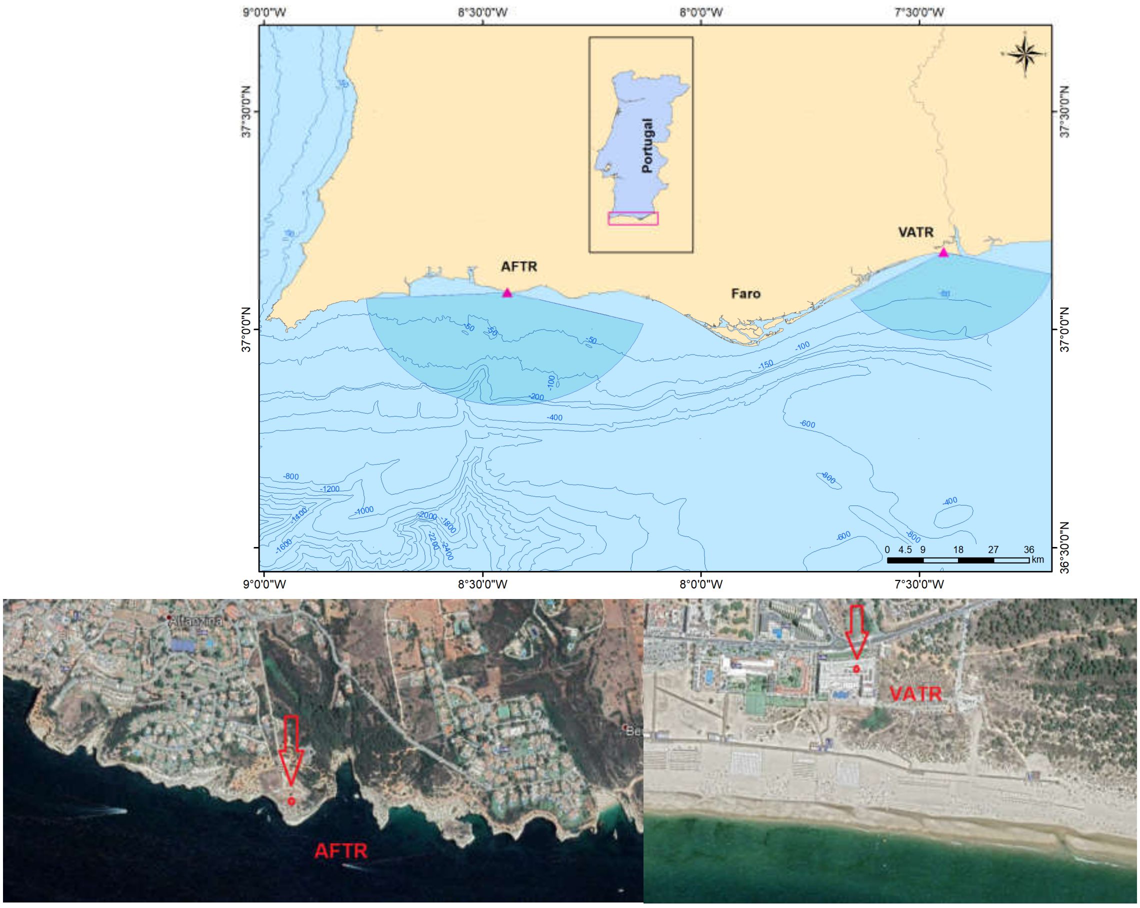


Figure 45. Location of two stations VATR and AFTR.

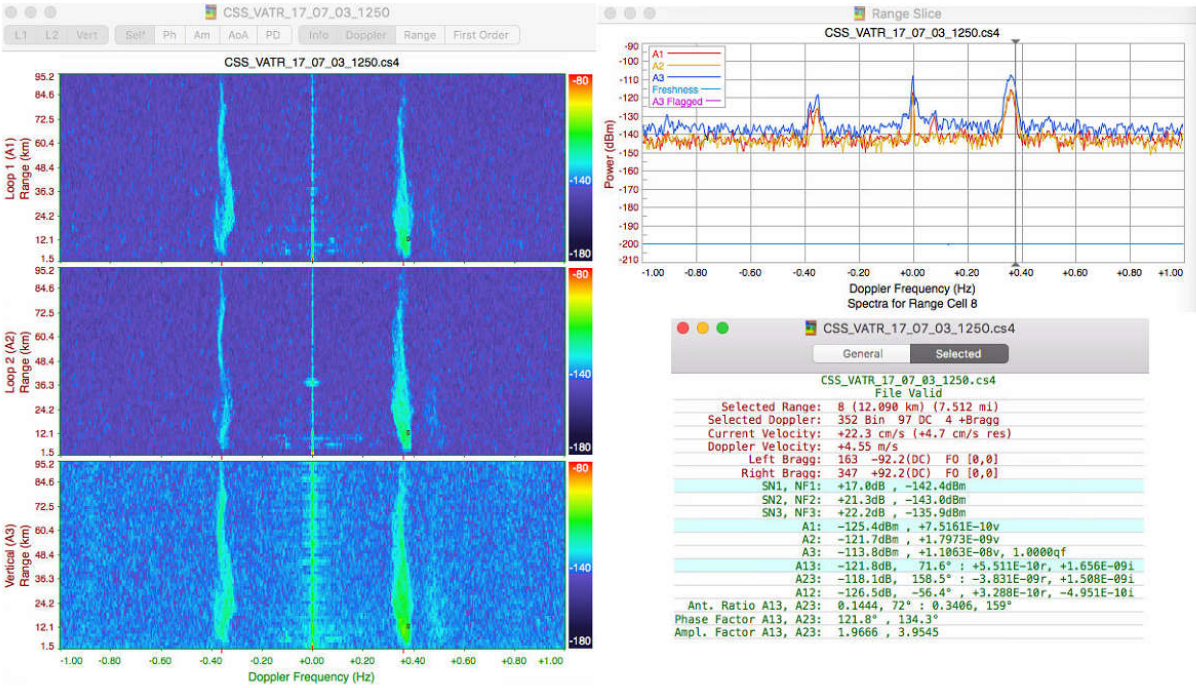


Figure 46. Spectra information, range slice and spectra color map from VATR from 03/07/2017, 12:50.

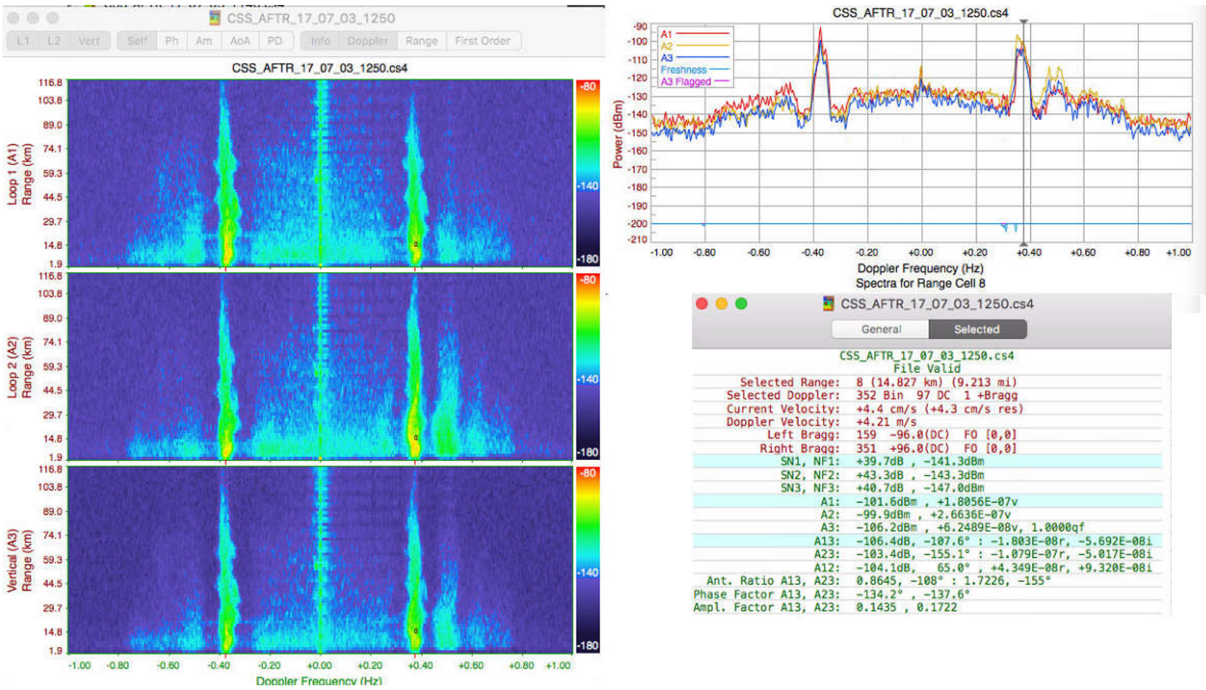


Figure 47. Spectra information, range slice and spectra color map from AFTR from 03/07/2017, 12:50.

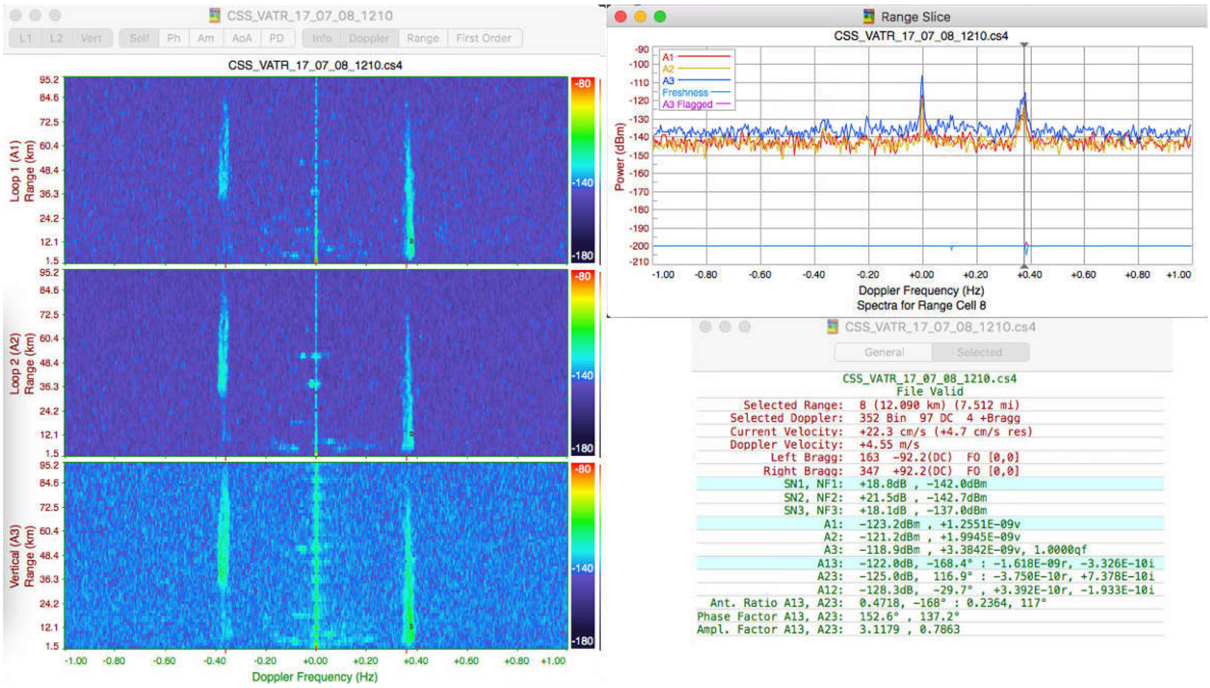


Figure 48. Spectra information, range slice and spectra color map from VATR from 08/07/2017, 12:10.

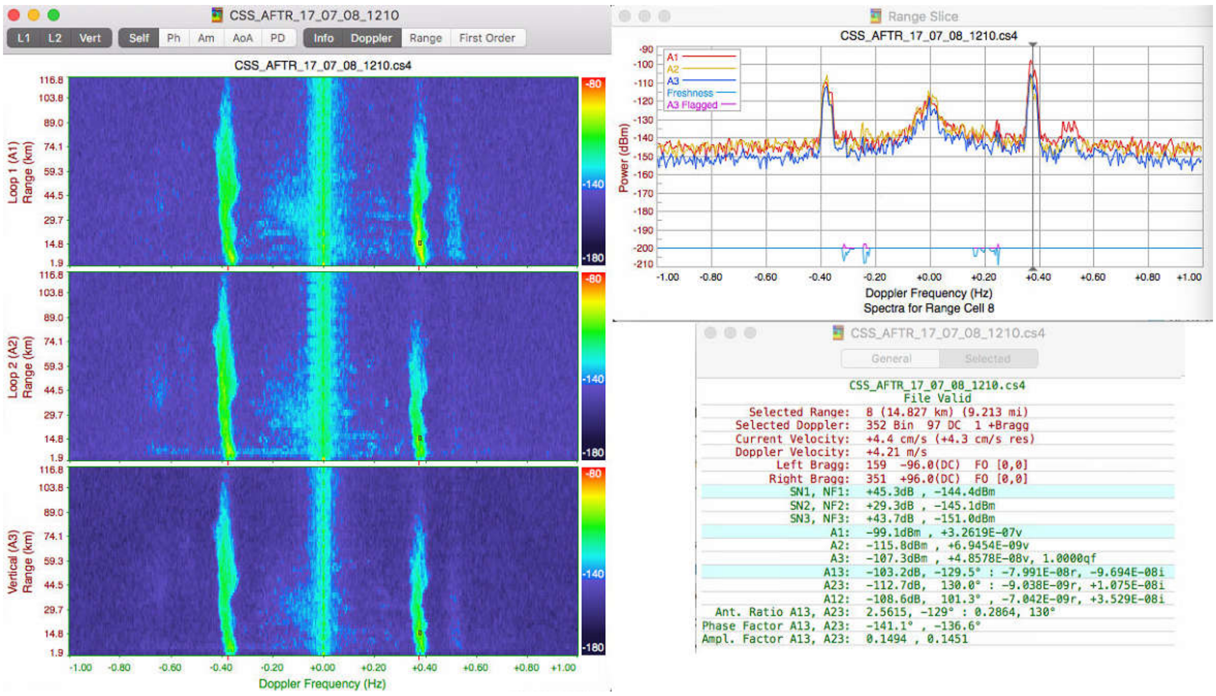


Figure 49. Spectra information, range slice and spectra color map from AFTR from 08/07/2017, 12:10.

In addition to this we know intense currents and high interference do impact the quality of the SeaSonde waves output. We are not focusing at this point in these two variables since the Sagres and Alfanzina radars and most of the sites along the Portuguese coast will not meet problems for those two conditions.

6. CONCLUSIONS

At the end of the statistical analysis we were able to correlate HF radar performance for wave measurement vs. existing met-ocean and environmental conditions for Sagres HFR site and for each HFR wave data set obtained during task 2.

The main target of this activity was to access environmental and technology variables that influence the quality of different HFR sites for wave measurement, detect possible radar interferences due to human activities or others, and eventually conclude on the readiness of each site for acquisition of wave measurements.

A set of best practices were developed from the extensive study of several HF radar stations. This includes several steps to follow: analysis of oceanographic conditions and also extensive comparisons between in-situ and remote equipments, environmental analysis (morphology of the area and met ocean conditions), software settings (first and second order settings, coastline settings, software versions and sidebands), importance of wind and all the variables and conditions that affect data quality (wind and wave direction, wave period, SNR and noise floor).

These results will help to assess the suitability and readiness of each HFR sites for wave measurement in order to get each station working at its best performance, which will vary from station to station conditioned by the settings already mentioned.

SEASONDE WAVE WVLM FILE FORMAT

Wave Model processing produces monthly WVLM files which are text based built upon the **Columnar Table Format (CTF)** which is covered in a separate document which you should be familiar with before reading this document.
With Radial Release 8, all the processed ranges have been filtered down leaving the result without a range; the files will still contain a distance column set with nan and range cell column set with 1.

Identification
The first keyword of the file will typically be **'%CTF: <version>**' describing the version of the CTF file. Before version 1.00, the file will be missing this key; however, it is still readable with this standard. If the CTF version is 2 or greater then the file will not likely be readable by current readers that expect 1.x
Within the first **ten** lines of the file will must be a keyword of:

%FileType: <type> <subtype> <name>
The <type> must be **WVMD** to identify it as wave model data.
The <subtype> identifies when significant changes have been made and latest is **WVM7**. Even if there are other values here, the file will still likely be readable.
File Naming
File name should be use for archiving the data, not as a software determination of whether the file is a valid **WVLM** file, date stamp or contents.
The filenames follow the time-stamped CTF naming convention WVLM_XXXX_YYYY_MM_DD_HHMM.wls.
'XXXX' is the four character site name.
'YYYY' is the year
'MM' is the two character month from 01 to 12 'DD' is the two character day from 01 to 31 'HH' is the two character 24 hour from 00 to 23 'MM' is the two character minute from 00 to 59
The wave files will typically have a filename extension of '.wls'
Wave files are typically stored on a monthly basis. This means that each wave file will contain up to a month of wave data.

Keywords
%CTF: 1.00
Identifies the file as a Columnar Table Format. The 1.00 version will change in the future if any major changes are needed in reading the format. If the CTF version is 2 or greater then the file will not be readable by current readers that expect 1.x
%FileType: WVMD <subtype> <name>
WVLM Identifies the file as a Wave file. The <subtype> identifies version of this format.
WVM1 is the first wave model single range version.
WVM2 is the second version of single range wave model data, in which the table data was expanded to show full date of each entry.

WVM3 is for first multiple ranges (one range per table) wave model data. Table data is expanded to show range distance and spectra range cells. These have a flaw where the range distance is off by one range cell spacing.
WVM4 is for multiple ranges where the range distances are not offset by one range cell. These have a flaw where the wave direction can be severely off if the coastline is not north/south; The only fix is to reprocess.
WVM5 is for multiple ranges where wave directions are correct.
WVM6 added columns of wave doppler points WDPT and wave method MTHD. These files were only produced by pre-release software.
WVM7 added columns of wave doppler points WDPT, wave method MTHD and vector flag FLAG and adds much more metadata.

%UUID: D1D12866-7794-403F-9481-0A840978F8A9

A universally unique identifier for each file. This key is created using Mac OS X call CFUUIDCreate. Each UUID key has a very, very high chance of being unique. This key will change if the file is reprocessed. Search the Internet for more information on UUIDs.

%Manufacturer: CODAR Ocean Sensors. SeaSonde.

Identifies that the file came from SeaSonde. If you create the Wave History file, put your Identity here.

%Site: XXXX ""

Contains the four-character site code followed by optional user friendly site name.

%TimeStamp: 2008 10 13 00 00 00

Identifies the start time in year, month, day, hour, minute, second of the data collected in the file. The time column in seconds is referenced from this time.

%TimeZone: "PDT" -7.000 1

Identifies the timezone used as label, hours from UTC, and non zero if daylight saving time was in effect.

%Origin: 38.3173167 -123.0724667

Is the <latitude> <longitude> of the SeaSonde Site.

%TimeCoverage: 0.250 hours

The time each vector covers is plus & minus half this value from the timestamp.

%RangeResolutionKMeters: 2.92572 km

Range resolution of each range cell from the processed cross spectra.

%AntennaBearing: 180.0

Antenna bearing CW from True North.

%RangeCells: 31

Number of range cells from the processed cross spectra.

%DopplerCells: 512

Number of doppler cells from the processed cross spectra.

%TransmitCenterFreqMHz: 13.475000

Transmitter center frequency from the processed cross spectra.

%TransmitBandwidthKHz: -51.269531

Transmitter bandwidth from the processed cross spectra. Negative value is a down sweep.

%TransmitSweepRateHz: 2.000000

Transmitter sweeprate from the processed cross spectra.

%CoastlineSector: 75.0 215.0 %% Start CW to Stop in Deg NCW

Defined coastline sector that wave processing used from start True clockwise to stop True.

%CurrentVelocityLimit: 150
Maximum allowed current velocity used to determine first order Bragg.
%BraggSmoothingPoints: 3
Doppler cell point smoothing used to determine first order Bragg.
%WaveBraggNoiseThreshold: 3.0
Noise factor threshold used to determine first order Bragg.
%WaveBraggPeakDropOff: 100.0
Peak dropoff factor used to determine first order Bragg.
%WaveBraggPeakNull: 50.0
Peak null factor used to determine first order Bragg.
%MaximumWavePeriod: 17.0
Maximum allowed wave period to calculate.
%WaveBearingLimits: 90.0 124.0 %% Start CW to Stop in Deg NCW
Sector to limit where waves are allowed to come from.
%WaveUseInnerBragg: 0 %% 0 No, 1 Yes
Was processing using the inner Bragg energy.
%WavesFollowTheWind: 0 %% 0 No, 1 Yes
Was processing told to have waves always follow the wind direction.

Columnar Table Data:
If the wave data is multi-range, there will be multiple tables for each range and preceding each table will be %Distance: and %RangeCell: keywords for that table. There is also a table column for distance and range cell, while redundant, this allows you to more easily read the all the tables into a large array and already have the distance in the array.
%Distance: 3.98070 km
Distance to range cell for following table wave results.
%RangeCell: 4
Range cell for following table wave results.
%TableType: WAVL WVM7
<type> must be **WAVL** which indicates table is Wave History
<subtype> is WVM7 to identify the version which contains period, energy, direction info.
%TableColumns: 17
This can be used with the table type and subtype to determine if all the expected columns are in the file,
Use this to parse the column data to ensure that you are always compatible with future column changes.

%TableColumnTypes: TIME MWHT MWPD WAVB WNDB ACNT DIST RCLL WDPT MTHD FLAG TYRS TMON TDAY THRS TMIN TSEC
This key describes the datum for each column in order. Using this key (extremely recommended) will provide compatibility with future unknown
%TableType <subtype>. The %TableColumnTypes: contains a list of four-char- codes describing each column of the table data in order.
The known column codes are:
TIME seconds of the wave info from the date stamp

MWHT wave model height in meters for every one of three waves. 999 if not calculable.
MWPD wave spectra period in seconds. 999 if not calculable.
WAVB wave from direction in degrees. 999 or 1080 if not calculable.
WNDB wind from direction in degrees.
ACNT number of CSS that went into averaging the result. (May be less than maximum possible CSS during coverage time due to non- calculable entries not included in average.)
DIST distance of result from origin in kilometers.
RCLL range cell of result from cross spectra.
WDPT number of doppler points used for wave calculation.
MTHD wave method used for result:

when doppler displacement is less than 30% of the bragg index.Wave period is 1 / doppler displacement and wave height & direction come from fitting the model to the CSS.

when doppler displacement is greater than 30% of the bragg index. Wave period, height & direction from fitting a wave model spectrum to the CSS.

same as method 2 except that wave direction follows wind direction due to short period waves.

FLAG vector flag. This is a composite value (think binary) 0 normal.
(+1) the merged vector result included wave directions at the bearing limits.
(+2) the merged vector sources were all at the wave directions at the bearing limits.
(+4) the merged vector sources contained different wave methods.
TYRS year of data point.
TDAY day of the month of the point **THRS** hour of the day of the point **TMIN** minute of hour of the point
TSEC seconds of the minute of the point

%TableRows: <count>

tells reader software how much data to expect.

%TableColumnTypes: TIME MWHT MWPD WAVB WNDB ACNT DIST RCLL TYRS TMON TDAY THRS TMIN TSEC

%TableStart: <tablenumber>

<tablenumber> will be missing for the first table.
Before the table data starts two comments are added to help visually identify the data columns.
Then a line for each table entry which start with a ' ' space.
Followed by a line for each Table Row of data. Each line is preceded by a space. Spaces (no tabs) are used between columns.

%TableEnd: <tablenumber>

Marks the end of the table. <tablenumber> will be missing for first table.
After the table(s) the file is followed by processing time and the tools that created the wave file.

%ProcessedTimeStamp: 2016 08 04 22 54 44

Time when the wave file was last updated.

%ProcessingTool: "WaveModelForFive" 11.5.0
%ProcessingTool: "WaveModelFilter" 2.0.0
%ProcessingTool: "SpectraToWavesModel" 11.5.0

%ProcessingTool: "WaveModelArchiver" 12.0.0
%ProcessingTool: "AnalyzeSpectra" 10.9.3
All the processing tools and their version number which worked on the data.
%End:
Marks the end of the file.

Example Table:

```
%Distance: 17.87350 km
%RangeCell: 12
%TableType: WAVL WVM7
%TableColumns: 17
%TableColumnTypes: TIME MWHT MWPD WAVB WNDB ACNT DIST RCLL WDPT MTHD FLAG TYRS TMON TDAY THRS
TMIN TSEC
%TableRows: 1
%TableStart:
%%  Time       --------Wave   Wind
%% FromStart   Height Period  Dir.    Dir. Spectra   Distance       Range Doppler  Wave    Vector
Time
%% (seconds)   (m)     (s)     (deg)   (deg)   Count   (km)    Cell    Points  Method  Flag
Year Mo Dy Hr Mn  S
799200  0.84   5.99   0.0     320.0   3       17.8735 12      16      2       4
2008 03 10
  %TableEnd;
```