Joint European Research Infrastructure network for Coastal Observatory – Novel European eXpertise for coastal observaTories - **JERICO-NEXT**

Deliverable title	Report on first methodological improvements on retrieval algorithms and HF radar network design.
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Description	Report on first methodological improvements on retrieval algorithms and HF radar network design. Results obtained to date in Subtasks 3.2.1-3.2.2 will provide first recommendations on the implementation of improved techniques for HF radar systems (M24)
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1. Executive Summary

Deliverable 3.3 is based on the results of Subtasks 3.2.1 and 3.2.2, i.e. on research improvements on retrieval algorithms and data quality and network design, leading to the first recommendations on the implementation of improved techniques for the JERICO-NEXT HF radar network. The work builds on previous results of WP2 (D2.1) and WP5 (D5.13), and is synergic with developments within the Copernicus Marine Environment Monitoring Service (CMEMS) project INCREASE (Service Evolution 2016).

The results focus on the following three main aspects.

The basic set of QC tests defined in D5.13 and in the INCREASE deliverable D3.1 (http://www.cmems-increase.eu/static/INCREASE_Report_D3.1.pdf) has been further analysed and improved. Work has been performed within an extended group including scientists from the HF radar European community as well as from the US IOOS and the Australian ACORN networks. Additional QC tests with respect to the basic set identified in D5.13 have been considered and recommendations on how to include them are provided. An in-depth discussion regarding implementation methods for the tests and threshold setting is included.

A detailed study has been performed on the quality of velocity retrievals, their errors and mitigation in case of high environmental variability partially resolved by radar measurement. The specific case of highly variable shallow water depth and its effects on a phased array system (WERA) are considered, but the method is general and can be applied to other cases. Methods to quantify retrieval errors are recommended and the use of innovative QC tests and multi-parametric thresholds are investigated.

Methodological guidelines for the design of HF radar networks are provided. The first step consists in mapping societal needs and relevant observed variables, in order to identify areas of major interest. The choice of site locations should then minimize errors such as GDOP (Geometric Dilution Of Precision) and maximize coverage. A collaboration with Task 3.7 on the use of Data Assimilation technologies as a basis for observing system experiments is presently carried out.

2. Introduction

The JERICO-NEXT project includes new and promising instrumentations that are expected to improve the core observing system of Europe's coastal seas and oceans. Such instrumentations include HF radar systems, that are able to provide surface current and sea state information over extended regions (up to 100 km from the coast) with high temporal frequency (sampling intervals of the order of up to 20 minutes), with relative ease in terms of technical effort, manpower and costs.

Remote sensing of near-surface currents by HF-radar (Stewart and Joy, 1974; Paduan and Rosenfeld, 1996; Gurgel et al, 1999 and Rubio et al, 2017) is based on first order on the fact that electromagnetic radiation in the high-frequency range (8 to 37 MHz) is scattered resonantly by ocean surface gravity waves (Bragg scattering). The resonant interaction occurs with those surface gravity waves that have half of the electromagnetic radar wavelength (18.5 to 4 m) and a direction radially towards or away of the antenna array. The surface current along the radar look direction results from the speed difference between the theoretical phase speed of the Bragg waves and their actual speed measured by the radar. Subtracting the phase velocity of the Bragg waves gives the radial component of the near-surface current. The orbital paths of the resonant Bragg ocean surface wave with the wavenumber $\mathrm{k_{Br}}$ penetrate below the surface in a layer with a depth of $2\mathrm{k_{Br}}$, which is approximately 8 % of the Bragg wavelength.

In Europe, a unified HF coastal radar network is in the process of been implemented, and the work performed in JERICO-NEXT plays a crucial role in this direction. To be effective in the implementation of a coordinated development of coastal HF radar technology and its products, the work in JERICO-NEXT has been performed in strict contact and synergy with several other European initiatives. They include:

- the HF radar Ocean Observing Task Team, launched by EuroGOOS in 2015 to foster cooperation to meet the needs of the European Ocean Observing System (EOOS);
- the EMODnet Physics activities toward assembling HF radar metadata and data products within Europe in a uniform way;
- and the Copernicus Marine Environment Monitoring Service (CMEMS) project INCREASE (Service Evolution 2016), intended to set the necessary developments towards the integration of existing European HF radar operational systems into CMEMS.

Within JERICO-NEXT, HF radar activities are included in several Work Packages

(WPs). In WP2, Subtask 2.3.1 aims at reviewing state-of-the-art HF radar systems, harmonizing methodologies and promoting best practices for system planning, installation, data processing and analysis. In WP3, Task3.2 fosters research activities to improve the quality of surface current estimates from HF radars, their integration with other water column data and the design of radar networks. In WP5, Task 5.6 deals with common formats and Quality Control (QC) procedures for HF radar data.

WP2 Task 2.3.1 has already generated a first deliverable (D2.1), in month 12, and its content put the basis for the research work in WP3 Task 3.2. The first research results of Task 3.2 are summarized in the present deliverable, D3.3, produced in month 24. The topics of the D3.3 deliverables have been discussed during previous JERICO-NEXT meetings, in particular during the General Assembly in Helsinki (March 2017) and during the HF radar expert INCREASE workshop (September 2016).

The focus of D3.3 is on the results of Subtasks 3.2.1 and 3.2.2, i.e. on research improvements on retrieval algorithms and data quality and network design, leading to the first recommendations on the implementation of improved techniques for the JERICO-NEXT HF radar network. D3.3 is then expected to feed back to the WP2 deliverable D2.4 in month 40, either directly or through the WP5 D5.14 in month 36.

The results of the deliverable are presented in Section 3 and are organized in three main sub-sections. Section 3.1 summarizes research investigations toward improved retrieval algorithms and QC as carried out within a wide forum that includes the bodies mentioned above (EuroGOOS Task Team, EMODnet and INCREASE) as well as non-European contributors. Section 3.2 specifically focuses on one of the main sources of errors in HF radar data retrieval, presenting a specific research investigation on the effects of highly inhomogeneous environments. Finally, in Section 3.3, the different methodologies that have been defined for designing an integrated HF Radar network at regional scale are described.

3. Main report

3.1 Progress on common protocols and QC for HF radar data (Leader CNR-ISMAR, Subtask 3.2.1)

Work on HF radar common protocols and QC in JERICO-NEXT has been previously summarized in the deliverable D5.13, which defines the European Common data and metadata model, details data format and mandatory QC tests. Also, in the framework of the INCREASE project, deliverable D3.1 reports a sensitivity study on the impact of threshold values for the mandatory QC tests defined within JERICO-NEXT, with the aim of setting a methodology for the correct application of the tests in different regions.

These important achievements can be regarded as a first step along the complex way of the definition and implementation of operational standards for the forthcoming European HF radar network. The HF radar community has kept alive the discussions about these topics in the framework of Task 3.2, in order to further refine and improve the standard schemes taking into account new specific issues and the precious experience of the HF radar operators. All the discussions and activities have been carried on in strict collaboration with the support of the US colleagues managing the US Integrated Ocean Observing System (IOOS) through the Radiowave Operators Working Group (US ROWG). Also, other important external contributions have been given by other networks, such as the Australian ACORN network. The deliverables D5.13 and INCREASE D3.1 have been shared with this wide international community and a fruitful review about the comparison and analysis of HF radar data and metadata schemes has taken place. Based on the results of this discussion, a set of modifications and improvements are proposed, which will be potentially applied to the mandatory QC tests. Regarding the data format and data and metadata schemes for HFR data, they turned out to be robust and consistent with the requirements of interoperable data distribution, thus not requiring, at least for this stage, structural modifications.

Results on the proposed improvements on QC tests are presented in the following, as shared within the European HF radar community and including a point-by-point comparison with the US scheme. The results provide additional requirements with respect to the basic QC tests identified in D5.13 and discussed in the INCREASE deliverable D3.1. As a term of reference, the list of mandatory QC tests for radial and total data as defined inD5.13 (tables 3 and 4 for radial and total, respectively), are provided in the following:

- **Radial Velocity**

- Syntax
- Over-water
- Velocity Threshold
- Variance Threshold
- Median Filter
- Average Radial Bearing

- **Total Velocity**
  - Data Density Threshold
  - Balance of Contributing Radials
  - Velocity Threshold
  - Variance Threshold
  - GDOP Threshold

Definitions of each test, (as presented in the INCREASE deliverable D3.1), are included for completeness at the beginning of each following subsection.

3.1.1 Velocity Threshold QC tests for radial and total data

This test labels radial (total) velocity vectors whose module is bigger than a maximum velocity threshold with a “bad data” flag and radial (total) vectors whose module is smaller than the threshold with a “good data” flag. The output is a gridded QC variable with the same dimensions of the radial (total) velocity data variable, containing, for each cell, the flag related to the vector lying in that cell.

The IOOS network requires the Velocity Threshold QC Test as mandatory both for radials and totals data. The thresholding strategy is conservative as the single operators are in charge of setting the thresholds based on their experience within the monitored area and utilized HF radar technology (i.e. HF radar device). The ACORN Australian network implementation of the velocity threshold for both radials and vectors is based on a similar conservative approach, in which thresholds are dynamically set based on offline, delayed-mode tests and comparisons with independent measurements (drifters, when available; moored current meter data) performed on a regular basis (Cosoli and Middleditch, 2016).

The strategy proposed by the European HF radar community is also similarly conservative, i.e. it is suggested not to use restrictive limit values for the velocities (both radial and total) in order to avoid discarding large numbers of seemingly valid measurements (e.g. extreme events might be considered as bad data).

As a rule of thumb, it is suggested to start the process of definition of the threshold value based on the range definition of Oceans Network Canada (ONC) https://www.oceannetworks.ca/data-tools/data-quality. Range (minimum/maximum values) originates in the statistics of the previous year of data. The limits are set as +/- 3 standard deviations around the mean (99.7% of the data are within 3 standard deviations of the mean) without considering seasonal effects.

The methodology described in INCREASE D3.1 can then be used to refine the choice of the threshold values, which are specific for each site.

3.1.2 Variance Threshold QC tests for radial and total data

This test labels radial (total) vectors whose temporal variance is bigger than a maximum threshold with a “bad data” flag and radial (total) vectors whose temporal variance is smaller than the threshold with a “good data” flag. The output is a gridded QC variable with the same dimensions of the radial (total) velocity data variable, containing, for each cell, the flag related to the vector lying in that cell.

The IOOS network does not apply the Variance Threshold QC Test neither for radial nor for total data. This strategy comes from the fact that the IOOS network is mainly composed by Codar SeaSonde systems, and the Codar manufacturer suggests not to use variance data for real-time QC, as documented in the fall 2013 CODAR Currents Newsletter http://www.codar.com/newsletter_09_2013.shtml. The indication is due to the fact that the CODAR parameter defining the variance is computed at each time step, and therefore considered not statistically solid.

The European HF radar community is favourable to keep the Variance Threshold QC test in the mandatory QC test list for HF radar real-time data because variance tests give valuable information about the performance of the radar systems, but results should be interpreted properly. High spatial variance may suggest:

1) significant spatial current variability over the radar cross section associated with true geophysical signals;
2) increased numbers of anomalous Doppler velocities due to sub-optimal Signal to Noise Ratio (SNR) values (having Doppler velocities with negative SNR values at one of the two loops or at both of them is much more frequent than one may expect);
3) a combination of the two.

As for point 1, Codar SeaSonde systems provide an intermediate radial velocity at 1˚ resolution, which is then reduced through averaging to a 5˚ bearing resolution. This is accompanied by a spatial variance. This is then compared to the radial velocity, which is not necessarily a true average, since in most cases it is the median values of all the radial currents collected within the integration time over each bearing and range.

Most of the anomalous velocities arise from poorly constrained first order settings and incorrect merging schemes. More attention should be given on these points. The ACORN network experts have spent a significant amount of time over the past months to fine tune these parameters across Australia and results are showing a major benefit in terms of accuracy, number of spikes, and resolved geophysical structures. For instance, default values for the 1st order settings for the Codar SeaSonde systems in Western Australia were significantly biasing currents by up to a factor of two when compared to currents from moorings, drifters, or surface current data from the WERA systems in the region of overlap. This was particularly clear in the region of strong shear associated with the offshore jet-type Leeuwin current system, responsible for a spread of the Doppler lines over a very narrow interval of range cells. This phenomenon is difficult to track properly as the jets and the associated meanders vary in range offshore and as such require a constant monitoring and a proper interpretation of the sampled ocean Doppler spectra. Refinements show a very good agreement between WERA and SeaSonde systems in their regions of overlap, as illustrated below “before” and “after” the adjustment of the processing parameters.

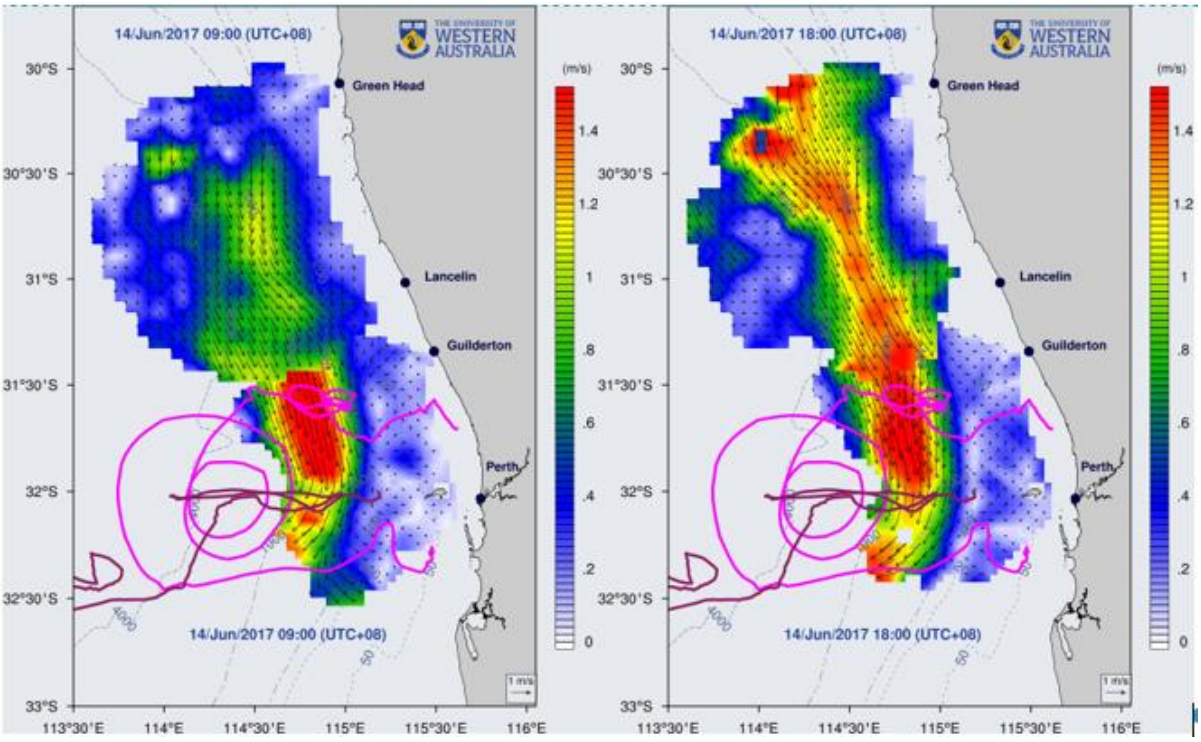

Figure 1 - The jet stream associated with the surface Leeuwin current stream “before” and “after” the fine tuning of the 1st order settings and the merging method for the SeaSonde radials. The left panel shows the originally processed current map, where the lower half is derived from WERA data (9.335 MHz operating frequency, 33 kHz bandwidth, 4 W peak power) and the upper half from SeaSonde data (4.463 MHz operating frequency, 25 kHz bandwidth, 8 W peak power) derived from the default processing settings for SeaSonde radials. The discontinuity in current speed in the left picture denotes the separation zone between the SeaSonde radar (Lancelin and Green Head stations), and the WERA radar (Guilderton and Perth stations). After fine tuning on the first order settings and the radial merging method a better agreement between the measurements was found (right panel).

3.1.3 Temporal Gradient QC tests for radial and total data

This test is not presently included in the European test recommendations as defined in the D5.13 and INCREASE D3.1 deliverables. The IOOS network, on the other hand, in order to take into account the uncertainties related to velocity variability, includes this test for radial data on each cell of the radial and total velocity fields. The Temporal Gradient QC test consists of the comparison, per each radial bin or grid cell, of the current hour velocity vector with the previous and next ones. If the differences are bigger than a threshold (specific for each radial bin or grid cell and evaluated on the basis of the analysis of one-year-long time series), the present vector is flagged as bad data. Of course this method implies a one-hour delay in the data provision (the next hour file has to be waited for).

An initial approach adopted by the Mid-Atlantic Regional Association Ocean

Observing System (MARACOOS) to determine reasonable temporal gradient thresholds specific for each monitored region, is to set the threshold at the value of $\mathrm{mean} + 2\,std$, where mean is the spatial average (on the entire velocity radial or total field) of the temporal average of the gradient at each radial bin or grid cell, and *std* is the spatial average (on the entire velocity radial or total field) of the standard deviation of the gradient at each radial bin or grid cell. However, temporal gradient statistics can be quite different for different sections of the radial coverage (i.e. near the coast and bay mouths, in the area of Gulf Stream influence, etc.). The next round of QC flag testing will apply different thresholds for different bins instead of employing a single threshold for each station based on a spatial average.

The European HF radar community is favourable to the inclusion of this test in the mandatory QC test list for HF radar real-time data and it is in the process of defining the implementation methodology to be proposed for the operational QC of HF radar data. This however limits the application to near-real time observations and prevents the use of the latest observations.

The implementation option that is under discussion is to follow the RTQC9 (“Rate of Change in time”) for time series as defined by EuroGOOS based on SeaDataNet 2007. According to this strategy, the central value (i.e. the current hour velocity value in each radial bin or grid cell) is compared to the surrounding values and limited by a threshold equal to $2 \cdot (2\sigma_{\mathrm{v}})$, where σv is the standard deviation of the current velocity in each radial bin or grid cell. This is proposed as a starting point for refining the operational threshold value, which should assure that changes between successive radial (total) velocity measurements at each bin (grid point) are within an acceptable range for the monitored area.

It has to be noticed that some caution has to be taken in defining the threshold choice strategy. In fact, the implementation of the Temporal Gradient QC test at the Australian ACORN network has proven that, by using the statistics of the first order derivatives and their distributions to define realistic threshold values (99% CL- 95% CL) works very well in detecting anomalous values in both vector components and radial velocities, but this requires relatively long data sets (in a statistical sense). This could be conflicting with new installations. Some further discussion is therefore needed, in order to assess if, at least for the new radar sites, analysing a one-month time series for determining the thresholds could work properly.

In general, radar systems using Direction Finding (DF), like the Codar SeaSonde systems, require a long integration time (10-15 minutes) to provide accurate measurements and can produce data output on different temporal rates (30 to 180 minutes). However, these parameters depend on the operating frequency, the desired resolution of ocean current variability, and the noise levels. Long integration times are also recommended for the WERA systems when run in a Direction-Finding mode.

Beam Forming (BF) systems, like the WERA systems, can provide accurate current data with integration times of just a few minutes (5 to 10 minutes).

Based on these facts, the European HFR community is discussing the proposal of keeping the Variance Threshold QC test in the list of mandatory QC tests for HF radar real-time data as is and explain in the “comment" subfield of the QC variable devoted to the Variance Threshold QC test that DF systems apply the Temporal Gradient QC test and not the Variance Threshold one.

3.1.4 Balance of Contributing Radials QC test for total data

This test checks if the number of radials coming from the different contributing sites are balanced for the combination into the total velocity vectors. Each data cell is labelled with a “bad data” flag if the requested balance ratio is not achieved and with a “good data” flag if the balance ratio is achieved. The output is a gridded QC variable with the same dimensions of the total velocity component data variables, containing, for each cell, the flag related to the vector lying in that cell.

The IOOS network does not apply the Balance of Contributing Radials QC Test for total data.

As detailed in the document INCREASE D3.1, the WERA software always combines radials into totals with a 1:1 ratio of the radials coming from the contributing sites, if the radial velocity currents are mapped onto a Cartesian grid. Although not common, examples exist in which WERA radial currents are mapped onto a standard polar- or even elliptical-type grid as for SeaSonde radar systems.

In SeaSonde Codar data, the information about the number of contributing radial vectors per site to each total vector is contained in the variables S1CN, S2CN, SnCN, where n is the total number of contributing sites. These variables are contained in the LLUV format of the proprietary .tuv total files generated by the Codar Combine Suite software. This means that radar operators not using the Codar proprietary software, but for instance the Matlab library HF radar_Progs, for the radial combination and data processing have no access to this information.

Since the policy of the European HF radar community is to define a battery of QC tests that could be the most general possible (i.e. not dependent on proprietary software), a solution to this issue is under discussion. In particular, the community is exploring a way for modifying the original HF radar Progs package scripts (released under Gnu General Public License) in order to provide information about the number of radials coming from each contributing site as standard output to be used for the QC test. This task will be accomplished in order to keep the Balance of Contributing Radials QC test in the list of mandatory QC tests for total data, since it has proven to be a very powerful QC test in real-time mode especially if the distribution is strongly unbalanced and the unweighted least-squares fit with constant search radius is used (Cosoli and Bolzon, 2015) (this is the standard approach for most of the Codar SeaSonde systems).

3.1.5 Radial Count QC test for radial data

This test is not presently included in the European recommendations in D5.13 and INCREASE D3.1, while the IOOS network requires the Radial Count QC Test as mandatory for radial data. This test labels radial data having a number of velocity vectors bigger than the threshold with a “good data” flag and radial data having a number of velocity vectors smaller than the threshold with a “bad data” flag. The output is a scalar QC variable assuming “good data” value if the number of velocity vectors present in the radial file is above the threshold and the “bad data” value if not.

The IOOS Radial Count QC Test threshold is set to 300 over-water velocity vectors per radial file. The choice of the threshold value comes from the long-time experience of the network managers and it is evaluated from lumping all the network radars together and looking at the cumulative density function and selecting the value around 10%.

The European HF radar community is favourable to the inclusion of this test in the mandatory QC test list for HF radar real-time data and it is in the process of defining the implementation methodology to be proposed for the operational QC of HF radar data.

The implementation option which is under discussion is to set the radial count threshold as the minimum value of the averages (evaluated on a long-time series, likely one year in order to take into account seasonal variability) of the number of over-water velocity vectors contained in the radial files from all the network (or subnetwork) sites.

3.1.6 Signal to Noise Ratio QC test for radial data

This test is not presently included in the European and IOOS networks. The European HF radar community is considering the inclusion of a test on the signal to noise ratio (SNR) of the Doppler lines of the measured signal in the mandatory QC test list for HF radar real-time radial data, since it is a powerful QC metric, as it gives an indication of the signal strength from which the radials are computed. This test aims at ensuring that the measured signal is sufficiently above a noise level, since if it is too low, radial quality is not reliable. It labels radial data having a SNR of the Doppler lines that exceeds the minimum value on both monopole and loop antennas with a “good data” flag and radial data having a SNR value lower than the threshold either on the monopole or on both loop antennas with a “bad data” flag. The output is supposed to be a scalar QC variable assuming “good data” value if the SNR exceeds threshold values on both monopole and either of the loop antennas and the “bad data” value if not.

The inclusion of the test in the mandatory QC test battery, as well as the implementation strategy, are now under discussion. Examples of the actual implementation of this test for RT operations (specifically for SeaSonde systems) are described for instance in Cosoli and Bolzon (2012). This method is currently under implementation in the ACORN network; preliminary tests have already provided satisfactory results both in RT and DM modes.

Another example of implementation approach for SeaSonde systems, as it is currently running in SOCIB, described in Lana et al. (2015), consists in computing the average of the minimum of the SNR from the 3 channels for each network radial site (e.g. SNR-SITE=ave(min(SNR1,SNR2, SNR3))) and then, the minimum from all existing sites is obtained (e.g. SNR=min(SNR-SITE1, SNR-SITE2)) as the value to be compared against the threshold (set to 20 dB in the SOCIB case).

For WERA systems, this test is of straightforward implementation, since information on the spectral peak amplitude is immediately available in the standard WERA radial data output.

All the other tests included in the mandatory QC test list for HF radar real-time radial and total data, and that are not mentioned in this document, have been considered reasonable by the IOOS experts.

3.1.7 Summary of proposed improvements on QC tests with respect to D5.13

As a summary of the discussions reported above, we provide two tables that summarize the proposed improvements on QC tests for radial and total velocities with respect to the basic tests recommended in Table 3 and 4 of D5.13

QC test	Proposed improvement
Syntax	Confirmed as consistent QC test (Table 3 D5.13)
Over-water	Confirmed as consistent QC test (Table 3 D5.13)
Velocity Threshold	A conservative strategy for the threshold definition is proposed, based on a statistical rule of thumb for the first setup and on a dynamic threshold setting built on offline, delayed-mode tests and comparisons with independent measurements.
Variance Threshold	Improvements in the threshold definition have been proposed, in order to take into account the processing differences between different HFR manufacturers. In particular, a refinement strategy for the threshold tuning is proposed, based on the comparison of Codar derived data with current measurements from moorings, drifters, or surface current data from the WERA systems.
Median Filter	Confirmed as consistent QC test (Table 3 D5.13)
Average Radial Bearing	Confirmed as consistent QC test (Table 3 D5.13)
Temporal Gradient	To be included in the mandatory QC test list for HF radar real-time data. Implementation options are under discussion.
Radial Count	To be included in the mandatory QC test list for HF radar real-time data. Implementation options are under discussion.
Signal-to-Noise Ratio	To be included in the mandatory QC test list for HF radar real-time data. Implementation options are under discussion.

Table 1 – Improvement on QC tests for radial velocity data. Tests found to be consistent and confirmed with respect to Table 3 D5.13 are shown in green, tests for which improvement are proposed, are shown in red.

QC test	Proposed improvement
Data Density Threshold	Confirmed as consistent QC test (Table 3 D5.13)
Balance of contributing radials	A strategy for modifying the original HF radar Progs package scripts (released under Gnu General Public License) has been proposed, in order to provide information about the number of radials coming from each contributing site in

	Codar derived data.
Velocity Threshold	A conservative strategy for the threshold definition is proposed, based on a statistical rule of thumb for the first setup and on a dynamic threshold setting built on offline, delayed-mode tests and comparisons with independent measurements.
Variance Threshold	Improvements in the threshold definition have been proposed, in order to take into account the processing differences between different HFR manufacturers. In particular, a refinement strategy for the threshold tuning is proposed, based on the comparison of Codar derived data with current measurements from moorings, drifters, or surface current data from the WERA systems.
GDOP Threshold	Confirmed as consistent QC test (Table 3 D5.13)
Temporal Gradient	To be included in the mandatory QC test list for HF radar real-time data. Implementation options are under discussion.

Table 2 – Improvement on QC tests for total velocity data. Tests found to be consistent and confirmed with respect to Table 3 D5.13 are shown in green, tests for which improvement proposed, are shown in red.

3.1.8 Processing Levels

As a minor output of the ongoing discussion within the European HF radar community about the improvement of the European common model for real-time HF radar data, it has been decided to remove the “C” sublevels from the Processing Levels scheme proposed in the document Jerico-Next D2.1. The actual Processing Levels scheme is reported in Table 3.

Processing Level	Definition	Products
LEVEL 0	Reconstructed, unprocessed instrument/payload data at full resolution; any and all communications artifacts, e.g. synchronization frames,	Signal received by the antenna before the processing stage.

	communications headers, duplicate data removed.	(No access to these data in Codar systems)
LEVEL 1A	Reconstructed, unprocessed instrument data at full resolution, time-referenced and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing.	Spectra by antenna channel
LEVEL 1B	Level 1A data that have been processed to sensor units for next processing steps. Not all instruments will have data equivalent to Level 1B.	Spectra by beam direction
LEVEL 2A	Derived geophysical variables at the same resolution and locations as the Level 1 source data.	Radial velocity data
LEVEL 2B	Level 2A data that have been processed with a minimum set of QC.	Radial velocity data
LEVEL 3A	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency	HFR total velocity data
LEVEL 3B	Level 3A data that have been processed with a minimum set of QC.	HFR total velocity data
LEVEL 4	Model output or results from analyses of lower level data, e.g. variables derived from multiple measurements	Energy density maps, residence times, etc.

Table 3: Processing Levels for HFR data.

3.2 Improvements of algorithms for HF radar data in presence of complex bathymetry and current variability, and associated Quality Control (Leader HZG, Subtask 3.2.1)

Within Section 3.2 an in-depth study of the impact of environmental variability on HF radar current retrievals is presented. This issue is related to the general QC test discussion in Section 3.1, and it is expected to contribute to the setting of new and advanced diagnostic methods and threshold definitions. The problem of environment variability is indeed quite general and the present research provides methodologies for testing as well as improvements that can be applied in several cases.

The specific focus is on current retrieval difficulties in the presence of strong current and/or bathymetry changes within the spatial as well as temporal resolution of the HF radar. Results summarized in the following show and quantify the presence of the resulting errors by comparison of HF radar retrieved surface currents to measurements of a shipborne acoustic Doppler current profiler (ADCP). Furthermore, different methods are presented on how to tackle these issues resulting in an additional quality control parameter, which helps to better understand HF radar retrieved surface current fields. In addition, a method is described to reduce the impact of radio-frequency interferences on the measured ocean current maps, which often lead to large errors in HF radar retrieved surface currents.

3.2.1 The German HF radar network

For this study (Section 3.2) the HF radar data of the German network were utilized which covers the German Bight of the North Sea. The German Bight is a shallow water environment with water depth of approximately 30 m. The surface currents are mainly driven by the tides with strong temporal and spatial changes in speed and direction. The HF radar network in the German Bight (Figure 2) consist of three phased array Wellen Radar (WERA) Systems, which are located on Sylt, Büsum and Wangerooge.

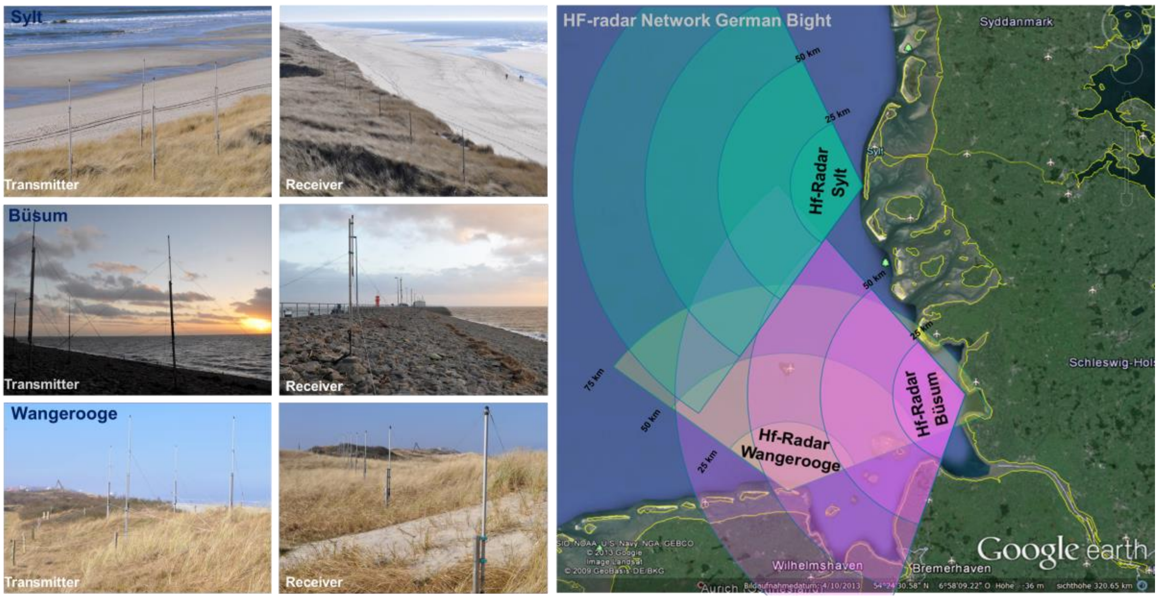

Figure 2: The photographs show the setups of the German HF-radar network consisting of the transmit and receive antenna arrays on Sylt, Büsum and Wangerooge. The map depicts the coverage and overlap of the radar sites.

All Systems transmit via a rectangular array of four antennas with an average power of 32 W. The Systems on Sylt and Büsum operate at 10.8 MHz with a linear receive array consisting of 12 antennae, while the Wangerooge radar operates at 12.1 MHz with a 16 antennae array. Each radar covers a 120° field of view with a 3° azimuth and 1.5 km range resolution. All systems are operated continuously with an hourly program, where 58 minutes are for measurements and the remaining 2 minutes are utilized to find the best-suited frequency around the selected frequency band. The three radars are operated simultaneously with frequency modulated continuous wave modulation (FMCW). Decoupling was obtained by chirping up one system and chirping down the other two. The acquired data are preprocessed at each radar site and then forwarded to the main server at the Helmholtz-Zentrum Geesthacht (HZG), Germany, were the final products are generated and uploaded to the data base of the Coastal Observing System for Northern and Arctic Seas (COSYNA) (Bascheck et al., 2017).

The radial component of the ocean surface current with respect to the radar look direction is retrieved at each radar site utilizing only 20 minutes of data. These components typically cover a range distance of 100 km within an azimuth of 120° covered by the radar (Figure 3: left hand side). The surface current components are forwarded to the main server at HZG were the data are subject to quality control and fused to a surface current vector field (Figure 3: right hand side). The radar network resolves surface currents every 20 minutes, which are made available on the COSYNA web portal within 30 minutes of acquisition (http://codm.hzg.de/codm/).

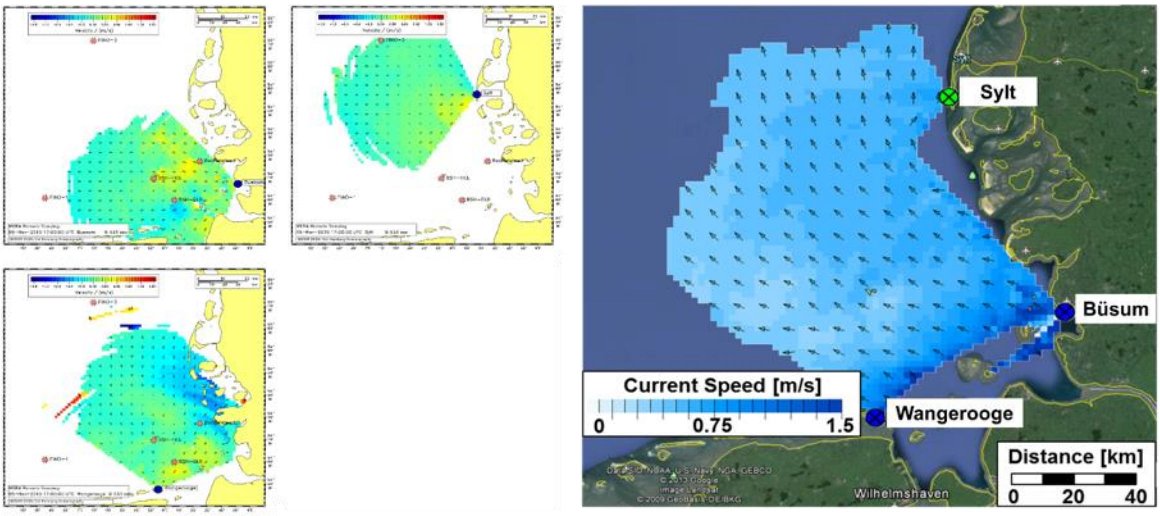

Figure 3: On the left-hand side a typical example of the radial surface current components of the individual radars Sylt, Büsum and Wangerooge are depicted. The right-hand side shows an example of a 20 min mean current field resulting from all three radar sites.

3.2.2 Removal of radar frequency interferences and ship echoes

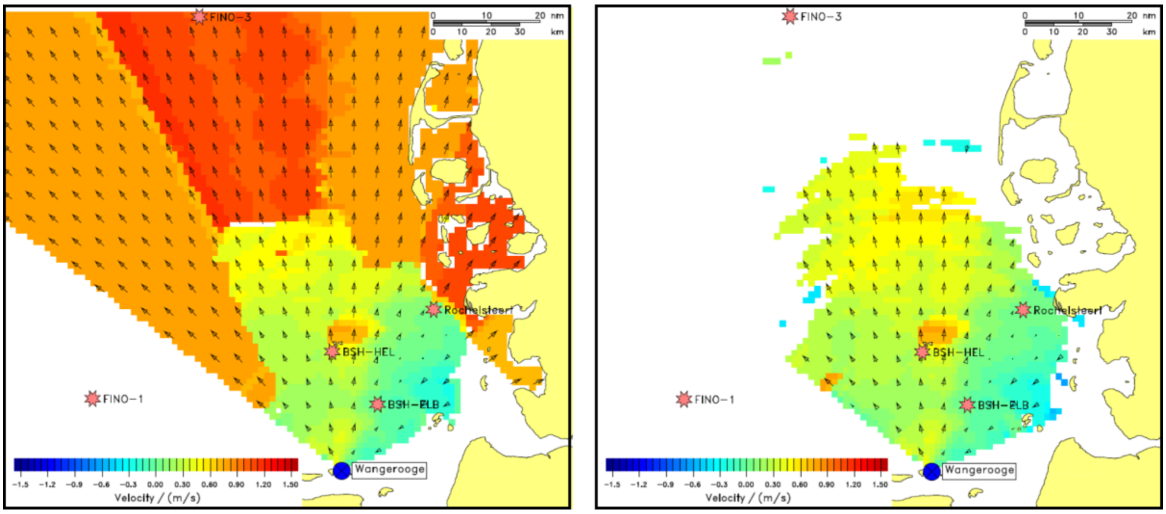

Figure 4: Radial surface currents retrieved from the WERA System at the island Wangerooge. The left-hand side was processed without applying any corrections for radar frequency interference (RFI). The right-hand side shows the radial currents after applying the RFI correction.

HF radar current measurements are often effected by radar frequency interference (RFI), which contaminate the backscatter Doppler spectrum and make it difficult to identify the first and second-order echoes. If the RFI signal is not removed from the data this leads to constant current speed estimates in particular in the far ranges outside of the nominal coverage, but also within realistic current retrieval ranges (Figure 4 left hand side). RFI is in particular a problem for systems operating at low frequencies (8 to 20 MHz). The WERA systems operated in the German Bight have a technique implemented that simultaneously acquires data sets containing the sea return signals including the RFI signal and solely the RFI signal. This allows to remove the RFI contribution from the total sea return signal. A detailed description of the separation of the sea signal from the RFI signal is given by Gurgel et al, (2007).

In an additional step the Doppler spectra are analyzed for ship induced signals, which are then removed from the Doppler spectra. These signals can also affect the current and wave retrieval results, if they are located close to the Bragg peaks. This algorithm is based on the ship-detection and tracking algorithm developed by Dzvonkovskaya et al, (2008), which is reduced to the range Doppler dimension and excludes the entire ship tracking part. The ship signals detected in the range Doppler spectra are removed by replacing them by the local background noise. A similar approach was proposed by Heron et al (2011), who applied quality control measures, such as the identification of ship signatures and spurious spikes in the Doppler spectra before calculating the radial velocity from the Doppler frequency.

These resulting “cleaned” range-Doppler spectra are used to extract the location of the first-order Bragg peaks, which are utilized to retrieve the radial surface current speeds. Figure 4 (right hand side) shows the resulting radial current speed map after all these corrections. It can be seen that after applying these corrections the constant currents in the far ranges have been removed. In addition, the range extension of reasonable currents (non-constant) has been significantly increased by 10 to 15 km. Nevertheless, there are still some artefacts left which lead to errors in the retrieved radial current fields.

3.2.3 HF radar current errors due to changing currents or bathymetry

HF radars have a limited resolution in space and time and therefore any changes of surface current directions and/or speeds will lead to different measured Bragg wave velocities within the radar resolution cell as well as over the integration time of the radar system. It is very unlikely that the resulting radar retrieved Bragg wave velocity estimates will be equivalent to the mean current velocity in radar look direction, in particular as the measured Bragg speed changes are caused by temporal directional as well as speed changes. Therefore, it is very important to find a way for checking the radar-retrieved currents for the possibility of having been influenced by significant current changes in sub resolutions or within the integration time. A further question is what changes in the currents magnitude and/or direction are significant with respect to the resolution and integration time.

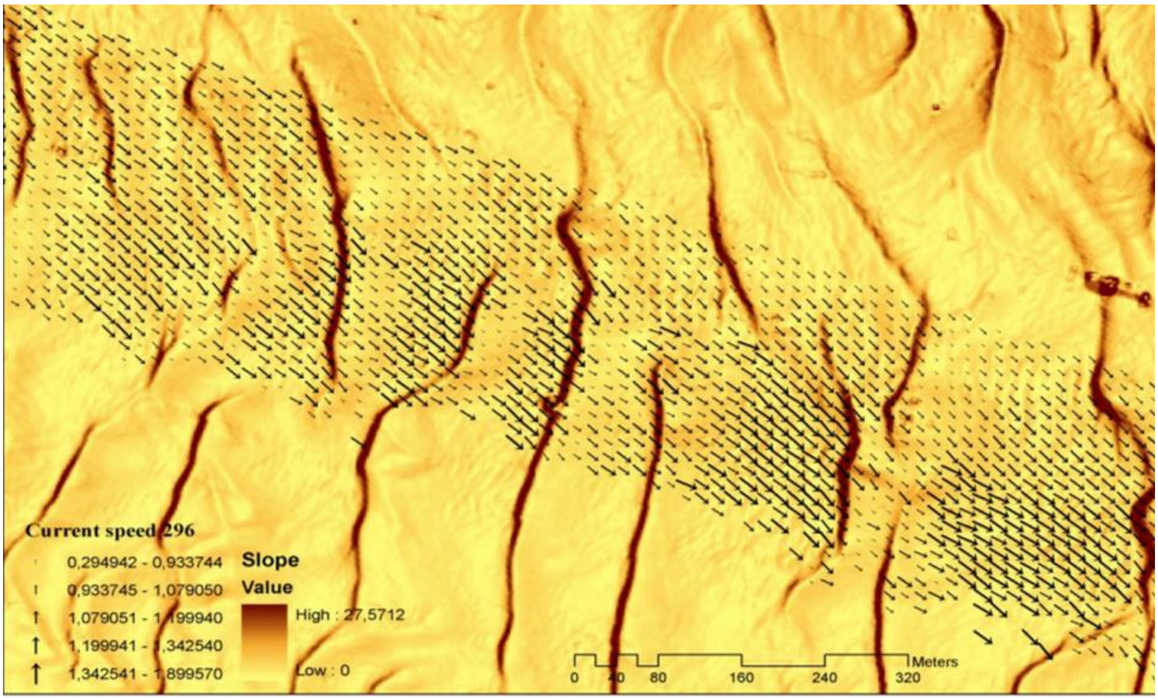

Figure 5: Underwater sand dunes of the coast of the island Sylt at a mean water depth of approximately 20 m. The color-coding represents the slopes of the bathymetry as measured by a multibeam echo sounder. The vectors represent the surface currents measured with two coherent on receive marine radars at a 30 m resolution.

In case of the German HF-radar network, changes of currents are expected on small spatial and under certain situations also temporal scales. In particular in coastal shallow water regions (< 20 m) with strongly changing bathymetry we expect strong variations in current speeds as well as directions. Figure 5 shows the modulation of a surface current field due to underwater sand dunes within the German Bight. The data were acquired just off the coast of the island Sylt, Germany at a water depth of approximately 20 m with currents speeds varying between 0.5 and 1.5 m/s. The color-coding represents the slopes of the sand dunes showing the strong bathymetry fluctuations in space, which lead to the strong speed changes of the current field at the surface (Kakoulaki, 2009). The surface currents were measured by two of HZGs coherent on receive marine radar systems, which were operated at X-band at a resolution of approximately 30 m (Cysewski et al., 2010). These surface current modulations are often observed in the coastal regions of the German Bight were bathymetry changes on small scales are frequent and water depths are often below 20 m.

3.2.3.1 Investigation of HF radar current errors due to bathymetry changes

To investigate the error of surface currents due to an inhomogeneous bathymetry we have compared the HF radar retrieved surface current to those measured by a acoustic Doppler current profiler (ADCP). Therefore, ADCP measurements were acquired on a track between Büsum and the island of Heligoland, which is located approximately 60 km westward and between Büsum and the island of Sylt approximately 80 km up the German coast.

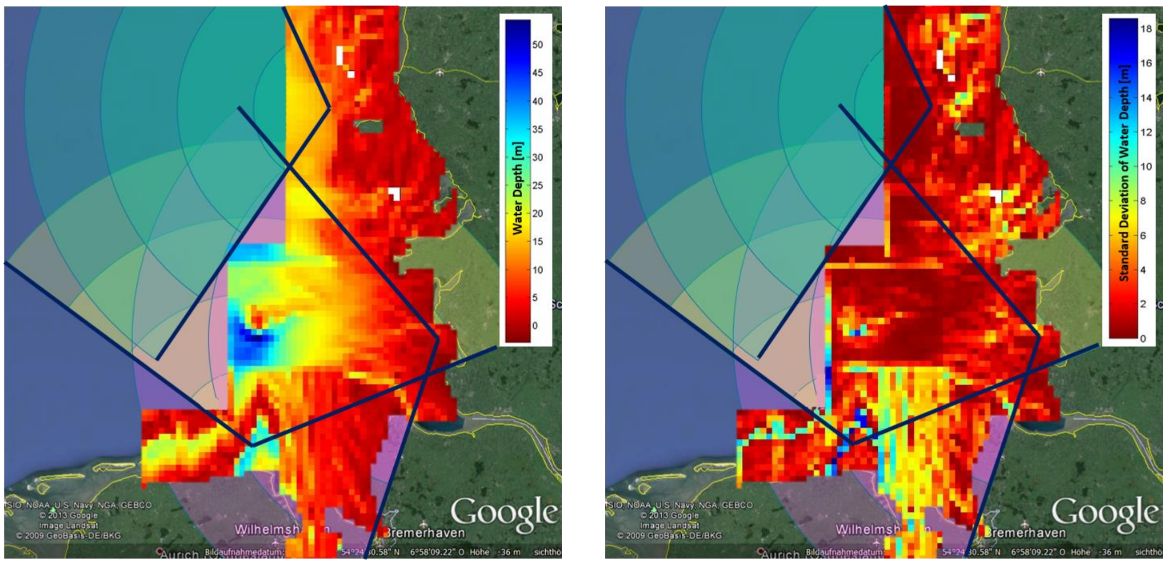

Figure 6: Bathymetry map on a 2 x 2 km grid (left hand side) and the standard deviation of the water depth retrieved on a 2 x 2 km grid resulting from high resolution bathymetry maps (right hand side).

The ADCP measurements were integrated between 2.22 and 2.72 m, which was the closest layer to the surface that could be measured by the setup on the RV Ludwig Prandtl. Note, that this is approximately 1 m below the water depth, which is associated to the HF-radar retrieved surface currents. In addition the data were collocated in time and space to the Wangerooge HF radar and projected in the radial direction to Wangerooge. The overall comparison between Büsum and Heligoland showed a bias of 0.035 m/s and a standard deviation of 0.13 m/s. However, the measurements acquired in the coastal waters between Büsum and Sylt showed significant differences, which we associate to strong bathymetry changes within the resolution cells of the HF radar. To investigate this more closely we retrieved the standard deviation of the water depth on a 2 x 2 km grid from high resolution bathymetry maps. The resulting maps for bathymetry and standard deviation on a 2 x 2 km grid are shown in Figure 6. The results of the comparisons of HF-radar currents and ADCP currents for the ship tracks between Büsum and Sylt are shown in Figure 7. Here we plotted the standard deviation of bathymetry versus the differences in current speed and the colour coding refers to the water depths. The differences increase significantly with standard deviation and decrease with water depth. For a standard deviation below 3 m or a water depth above 12 m the radial velocity difference between the HF-radar and the ADCP are below 0.4 m/s and mostly below 0.2 m/s. For low water depths and high standard deviations of water depth, the radial velocity differences are as big as 1.2 m/s. This behaviour confirms what we have stated in section 3.2.3.

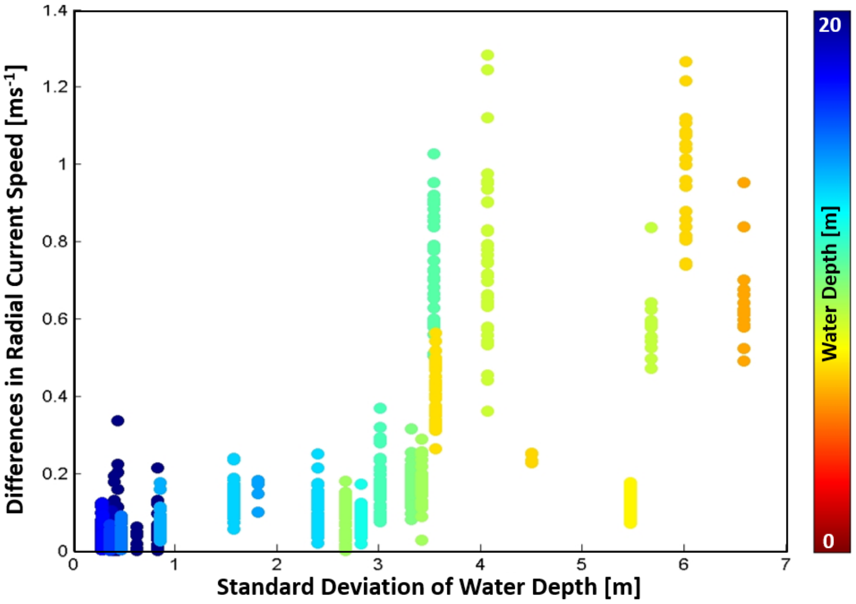

Figure 7. Standard deviation of water depth resulting from Figure 6 versus differences in radial current speeds of HF radar and ADCP. The color coding represents the water depth.

3.2.3.2 Reduction of surface current errors by back tracking

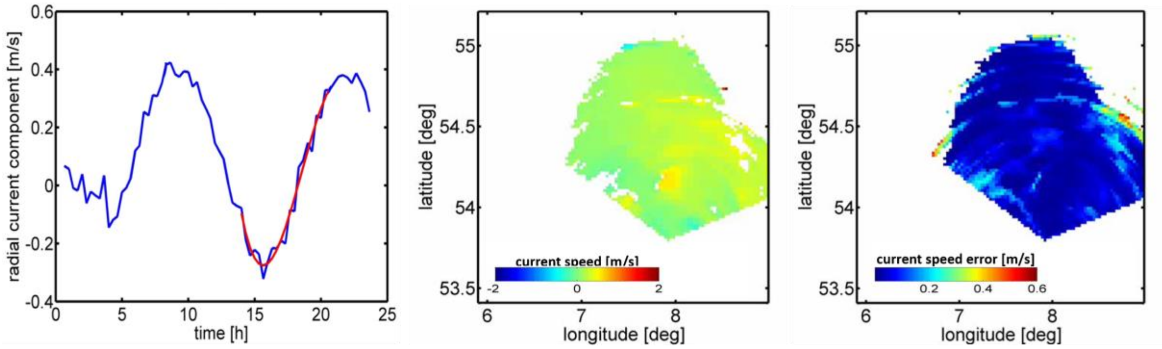

Figure 8: Time versus HF-radar retrieved radial current speeds at a single grid cell is plotted on the left-hand side. The red line represents a fitted third order polynomial. The central panel shows the HF-radar retrieved radial current speeds. The right-hand side gives the root mean square error between the HF-radar measurements and the polynomial fit of the last 7 h at every individual grid cell.

To remove errors remaining in the HF radar currents due to RFI, ship signals and other sources we can look into the time history of our HF radar retrieved measurements. Therefore, it is not sufficient to just look into the last few measurements. In case of the German Bight we have decided to consider the last 7 h, which represent about half a tidal cycle. To this measured time series, we perform a least square polynomial fit Seemann et al., 2011. We obtained best results by fitting a third order polynomial and by having at least 50 % of data points during the 7 h time period. The results of HF radar range velocities at a single grid cell are shown in Figure 8 (left hand side), where the blue line connects the individual HF radar retrieved data points (clearly reproducing the tidal signal) and the red line represents the fitted third degree polynomial. This procedure is repeated at every single grid cell of the radial velocity field presented in Figure 8 (centre panel). The resulting root mean square errors at every single grid cell are plotted in Figure 8 (right hand side). Most of the HF radar retrieved currents seem to have a low root mean square error when compared to the polynomial fit. However, there are a few locations were the root mean square error is particular large (>0.3 m/s). In these regions, the RFI removal seems to have not removed all interferences.

In case of a small root mean square error the areas with a large difference to the polynomial fit could be interpolated and flagged accordingly. Those grid cells that show up with a large root mean square error should be flagged as bad as the grid cells seem to be effected by significant errors over the last couple of hours (7 h). The selection of the best suited threshold for the root mean square error is a compromise between true measurement errors and false alarms. By analyzing HF radar data acquired under various hydrodynamic conditions (e.g. tides, winds and waves) a fixed value of 0.15 m/s was selected. Inclusion of this process in the operational processing of the German Bight HF radar network is ongoing.

3.2.3.3 Masking of areas with high likelihood of large current errors due to bathymetry

As a first step, we use the bathymetry and inhomogeneity maps shown in Figure 6 as a quality indicator for radar retrieved current. Therefore, we can mark all the HF radar currents that have been acquired at a location with a water depth below 10 m or an inhomogeneity above 3.5 m. However, in addition to the water depth and inhomogeneity, the current speed at these locations is of major importance, as the modulation of the surface currents due to the bathymetry is strongly dependent on the current speed. As part of on going activities, we are focusing on the derivation of a single proper threshold for these three parameters to allow proper flagging of HF radar currents retrieved in presence of complex bathymetry and current variability.

3.2.3.4 Attempts for identification of HF radar current errors due to changing currents or bathymetry

The variation of surface currents within a resolution cell as well as during the integration time of a HF radar measurement leads to a broadening of the first-order Bragg lines in the Doppler spectra. Within the WERA software running at the HZG the estimation of accuracy of the radial currents is based on estimating the bandwidth of these first order Bragg lines. However, during our investigations within the coastal regions of the German Bight we have observed that this magnitude, as implemented in our operational WERA software, is not performing well to identify the areas of inhomogeneity’s. Due to the high importance of the inhomogeneity’s in the coastal waters of the German Bight we are currently investigating the behavior and shape of the first order Doppler peaks in time and space under inhomogeneous and homogenous situations as well as under different tidal phases to hopefully optimize the accuracy estimations under these complex situations.

3.3 Integrated HF radar network design at regional scale. (leader AZTI, Subtask 3.2.2)

Up to now, the development of the HF radar networks in Europe has been based on national and local initiatives. The main drivers have been Maritime safety, Metocean monitoring and forecast, and Research (Mader et al., 2016). In addition, other applications for Marine resources and Coastal and marine environment managements are emerging. Even though most of the systems have been implemented from national initiatives, the coordination at European level is playing an increasing role in the different fields of applications. To achieve joint efficient capabilities and a core-knowledge approach for the common challenges along the European coasts is the leitmotiv basement for structures like the European Maritime Safety Agency, the Copernicus Marine Environment Monitoring Service, the European Marine Observation and Data Network (EMODnet), the Horizon 2020 program (including European Research Infrastructures) or the OSPAR commission.

In the coming years, an increase in the current growth rate of HF radar systems is expected (around 7 new radial stations per year between 2009 and today). The deployment of new HF radars has been recommended for most ROOSs (NOOS, IBI-ROOS, MONGOOS, Black Sea GOOS) in the strategy for the future of the coastal observing network (Deliverable 1.11 JERICO 2015, The joint European Research Infrastructure Network for Coastal Observatories: Achievements and Strategy for the Future).

Structuring initiatives, first at regional level like TOSCA (Bellomo et al. 2015) or IBERORED (www.iberoredhf.es), and now at European level with the EuroGOOS HF Radar Task Team and the JERICO-Next Research Infrastructure Project, have put in place the room for discussing as a community a roadmap to increase the use of HF radar data, as a part of the coastal observing system. A fundamental axis of this roadmap is to discuss the possibility to share a joint strategy for developing the network with priorities to fill the existing gaps. This strategy will be based on common drivers, targeted stakeholders and structures at European level, and regional considerations (more than national or local).

The JERICO-Next subtask 3.2.2 aims to improve the locally-driven development of existing HF radar network by providing a methodological guideline to design an integrated radar network at regional scale. In this deliverable, a progress report of the recently started tasks will introduce the different methodologies that have been chosen for designing an optimized observing network. Later on, different scenarios of expansion for the HF radar network will be obtained and presented in D3.4 (M46).

To build the regional scenario for HF radar expansion three different approaches will be used. One approach is based on the needs for observations and monitoring in the different coastal areas (see subsection 3.3.1). A second approach is based on the technical aspects of HF radars which drive their possible locations and coverage (see subsection 3.3.2). And finally, an approach based on technologies for data assimilation in line with developments in Task 3.7 and JRAP6 (subsection 3.3.3).

3.3.1 From the societal needs

Following the "Framework for Ocean Observing" (FOO; UNESCO 2012), the AtlantOS project recently performed an analysis of the capacities and gaps of the present Atlantic Ocean Observing System (AtlantOS Deliverable D1.3). The first step is to define observing objectives related to one or more societal relevant needs. Considering the regional context of the study area, these objectives will be associated to a set of relevant phenomena and essential ocean variables (EOV).

The involved phenomena will point out the appropriate time and space scales of the observations and the EOVs. This will give a set of suitable observing platforms and sensors, obviously considering the technological limitations of the state of the art.

Many societal benefit areas and societal drivers along the European coasts lead to the first level of link between physical phenomena and the EOV Surface currents. HF radar systems provide high frequency (<hourly) near real time synoptic observations of surface currents in wide coastal areas (10-200km) (Rubio et al 2017). This technology represents a unique opportunity for significantly contributing in the monitoring of numerous physical phenomena like: circulation, fronts and eddies, tides, coastal processes, air-sea fluxes, surface waves, mixed layer, or extreme events (following AtlantOS Deliverable D1.3 list).

A second level of analysis lies in the opportunity to monitor the transport of a passive particle, organism or substance. This gives a key role to HF radar data for the correct understanding of biogeochemical, biological or pollutants distribution monitored in general in a limited number of fixed stations or lines (ferrybox, gliders).

Of course, current research for integrating HF radar data with wider horizontal coverage from satellite and vertical coverage obtained from profilers (ADCPs in fixed stations or gliders) should be considered.

Consequently, a lot of operational services based on HF radar data can be provided for applications in maritime safety, met-ocean monitoring and forecast, and coastal and marine environment managements. Previous works (JERICO-NEXT Deliverable D1.1, EEA 1995, EEA, 2008a, b and the EU-DEVOTES project) emphasized the need for improved monitoring of environmental threats in European coastal environment.

The capacity of sustained HF radar systems contributes to serve the mentioned observing objectives.

The combination of land-based HF radars allows to plan a quasi-total coverage of the coastal area (for example in most of the US coasts). Some technical restrictions, that will be described in the next section could appear. But, mainly, economic reasons lead to a need of prioritization for the development of the network. For that, first criteria will be obtained by mapping geographical distributions of the needs and/or observing objectives at regional level. This will be done in the next phase of the Task, using different indexes like maritime traffic intensity, other human activities information (e.g. through dedicated EMODnet portal), or environmental sensitivity.

3.3.2 Impact of the operating frequency and sites locations

The theoretical maximum range from the coast covered by radars depends on the operating frequency. Common maximum coverage values for various direction finding systems operating respectively at 5 MHz or 13MHz are 180 km x 180 km or 70 km x 70 km (Rubio et a. 2017). Upon deciding the use of specific frequencies, the wave climate must be considered. The Resonant Bragg Scattering, basic principle of the HF radars, depends on the wavelengths of the transmitted signal and surface waves. The needed ocean wavelengths for the two aforementioned frequencies are respectively around 30 m and 10 m. It represents a clear limitation for using long ranges (4-5 MHz) in closed basins like the Mediterranean or the Baltic seas.

Moreover, to obtain surface current vectors, an HF radar installation must include at least two radar sites, each one measuring the radial velocity in its look direction. Thus, once the radial components of the surface currents are calculated, they can be combined in the overlapping area, to provide a surface current vector map. As considering possible locations of the radar sites, the geometrical possibilities offered by the shape of the coastline will impact the expected Geometric Dilution Of Precision (GDOP, Chapman et al.,1997) of the data. It causes lower reliability of velocity vectors at the edge of the observed domain, as well as along the baseline connecting receiving antennas. GDOP mapping will be performed in the study areas in order to consider that geometrical factor in scenarios that look for the maximum coverage along the coast. In Figure 9, an example of GDOP distribution with 20 HF radar sites in the Gulf of Mexico shows the geometrical effect, mainly in the precision of the longshore component of the total current at the edge of the domain, and in the cross-shore component in some specific areas close to the coast due to baseline effect (Flores-Vidal et al 2015).

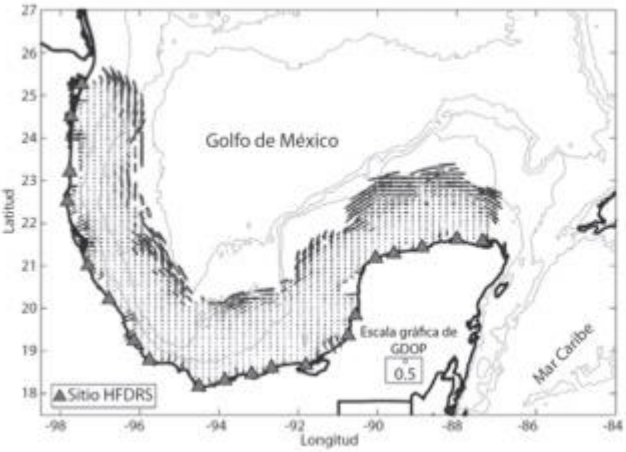

Figure 9. GDOP of the covered area with 20 HF radar sites (Flores-Vidal et al 2015)

3.3.3 Use of numerical tools for integrating the ocean phenomena distribution

Existing technologies for data assimilation (DA) are used for performing observing system experiments (OSEs) and observing system simulation experiments (OSSEs). In Task 3.7 of the WP3 (Milestone 41 report), based on OSE/OSSEs methods, a first analysis has been implemented in the Bay of Biscay for designing a new radar site that will complete two existing stations (G. Charria, P. De Mey, Milestone 41 report and D3.11 Optimal OSE/OSSE infrastructure). Array Modes (ArM, Le Hénaff et al., 2009; Charria et al., 2016; Lamouroux et al. 2016) method, based on ocean model ensembles, has been used (Figure 10).

Then, the authors developed recently a user-friendly open-source tool, called Stochastic ocean Observing Network Assessment Toolkit (SONAT), to extend the application of this methodology for designing multivariate, multiplatform ocean observation networks. The first version of SONAT was developed by Actimar for IFREMER thanks to a grant from the regional project ROEC (French region and ERDF funds). Through numerical models or observed variance fields for studied variables, this methodology provides an opportunity to integer a quantitative characterization of the distribution of ocean phenomena in the analysis. This approach also highlights the key role of observing network in monitoring ocean variability.

So, this specific tool will be used to add a level of information dealing with the distribution of ocean phenomena in the prioritization analysis of the future HF radar networks at regional level. This will be done in the IBI (Iberian-Biscay-Irish) region. That information will also allow to optimize the future impact of HF radar data in assimilation systems of the numerical models.

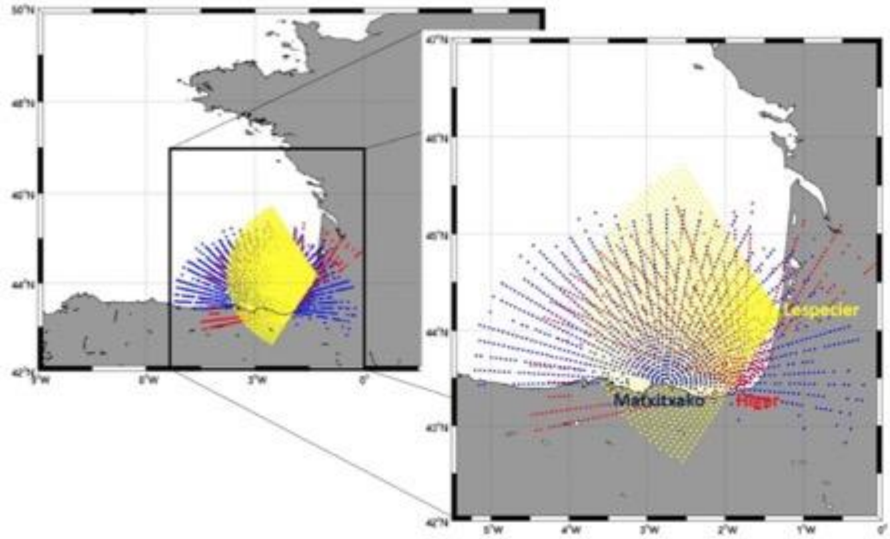

Figure 10: Illustration of three HF radar systems in the South-Eastern part of the Bay of Biscay including two existing systems (Matxitxako and Higer) and a future system deployed during JERICO-NEXT in 2017 (called "Lespecier").

3.3.4 Summary of the suggested methodological steps

In order to perform a gap analysis and to define future scenarios of development at regional level, the next steps in this work will be:

1. to update the inventory of the current systems (last version Mader et al. 2016)
2. to gather geographical distributions of the needs at regional level
3. to use a quantitative way (like GDOP estimations) to consider the impact of the shape of the coastline and the location of future radar sites on the data uncertainties
4. to map the main characteristics of the involved phenomena (intensity, space and time scales)
5. to test the use of a specific tool for integrating quantitative characterization of some ocean phenomena and for optimizing the future impact of HF radar data in assimilation systems.

4. Conclusions

In this deliverable, the first methodological improvements obtained within Task 3.2.1 and Task 3.2.2 are reported, providing improved technical recommendations for the JERICO_NEXT HF radar systems. The results focus on three main aspects summarized in the following.

1) The basic set of QC tests that has been defined in deliverable D5.13 and in the INCREASE deliverable D3.1 has been further analyzed and improved. Work has been performed within an extended group including scientists from the HF radar European community as well as from the US IOOS and the Australian ACORN networks. With respect to the basic set considered in D5.13, further tests and improved implementation methods are recommended. Results are summarized and compared with previous D5.13 recommendations in Table 1 and 2.
2) A detailed study has been performed on the quality of velocity retrievals, their errors and mitigation in case of high environmental variability partially resolved by radar measurement. The specific case of highly variable shallow water depth leading to high spatial variability in surface currents and its effects on a WERA system have been investigated. However, these errors will occur with any HF radar operated in environments with large spatial or temporal current variability on sub radar resolution e.g. river mouth, complex bathymetry or wind fields. Methods to identify multi-parametric thresholds are recommended, which are useful to mark current retrieval results in areas with complex bathymetric environments such as the coastal areas of the southern North Sea. These thresholds have a spatial and temporal variability. The development of further innovative QC tests is ongoing.
3) Methodological guidelines for the design of HF radar networks have been defined and they are recommended as a conceptual basis for the implementation of regional network development. A threefold methodology is presented. The first step consists in mapping societal needs and relevant observed variables, in order to identify areas of major interest. The choice of site locations should then minimize errors such as GDOP and maximize coverage. A collaboration with Task 3.7 on the use of Data Assimilation technologies as a basis for observing system experiments is presently carried out.

5. Annexes and references

Data citation: HF radar data and mooring data from Western Australia are sourced from the Integrated Marine Observing Systems (IMOS). IMOS is supported by the Australian government through the National Collaborative Research Infrastructure Strategy and the Super Science Initiative.

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