Compatibility of FMCW Modulated HF Surface Wave Radars with Radio Services

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***Abstract*—High-Frequency (HF) radars are operated in the 3-30 MHz frequency range and have been used for several decades now. Sky-wave systems are able to keep large areas under surveillance, e.g. the whole northern coast of Australia. Some of these systems have caused severe interference to other radio services like the Russian "Woodpecker". Currently, a network of ground-wave HF radars is beeing installed along the US coast. Due to the large number of systems, they can no longer be operated on an experimental license and care must be taken to avoid radio frequency interference with other radio services and radars. This paper discusses different modulation techniques for HF radar range resolution and their compatibility with other users of the HF spectrum.**

I. Introduction

Due to their over-the-horizon detection capabilities, High-Frequency (HF) radars regain attention now. In contrast to sky-wave HR radar systems, which make use of the ionosphere as a mirror to achieve long ranges up to some thousands of kilometres, HF Surface Wave Radars (HFSWR) depend on ground-wave propagation along a conducting layer, which e.g. can be constituted by salty ocean water. The working range of these shore-based HFSWRs depends on the frequency and transmit power used and is up to 350 km at 3 MHz. Besides echoes from targets, e.g. ships or airplanes, there is a strong signal scattered back to the radar due to the roughness of the ocean surface (Crombie 1955 [2]). This signal can be exploited to measure maps of ocean currents (Barrick 1977 [1]), sea state, and wind.

HFSWR are operated in the 3-30 MHz frequency range and need to share the radio spectrum with other radio services. Care must be taken to avoid Radio Frequency Interference (RFI) and to optimize the compatibility of the different uses of the spectrum. Due to the daily cycle of the ionospheric conditions, communication paths from the radar to different areas around the world may be open or closed. Besides the frequency allocation to different radio services governed by the International Telecommunication Union (ITU), some flexibility in the selection of the HFSWR's operating frequency is required.

Several modulation techniques for range resolution are available, which have a different influence on the interference caused to other radio services. An early paper on this topic has been published by Shearman [10] in 1980. Also, the transmit power used and the directivity of the antennas affect the severity of the interference. This paper discusses the different modulation techniques and their potential impact on radio services as well as the disruption by external signals caused to the radar echoes.

II. HF Radar Modulation Techniques

The initial modulation technique to achieve range resolution in radar systems is to transmit short HF pulses and listen for the echoes. The time delay between the transmitted pulse and the received echo is measured and gives the range of the reflecting object or patch of the sea. More recent developements make use of a coded pulse to increase range resolution and suppress unwanted echoes from the ionosphere (Ponsfort *et al.* 2003 [9]). Another technique makes use of a linear frequency chirp. This is called Frequency Modulated Continuous Wave (FMCW) and provides range resolution in frequency domain. The advantages and disadvantages as well as their potential impact on other radio services are discussed in the following paragraphs.

A. Range Resolution by Pulses

The range between the radar and a target can be determined by measuring the time delay between a transmitted electromagnetic (EM) wave pulse and it's echo. The length of the pulse refers to the radar's range resolution, e.g. a 16 μs pulse length corresponds to 2.4 km range cell depth. In a Doppler radar, these pulses must be part of a contiuous EM wave train to keep the coherence. The delay between two consecutive pulses gives the maximum range echoes can be received. Pulse width and delay govern the transmit-to-receive (TR) ratio, which in case of 256 range cells is 1:256. If an average transmit power of 50 W is required, this gives a peak power of 12.8 kW. This high power value is difficult to generate and dangerous to handle. Coded pulses help to reduce the TR ratio; however, the waveform generation and the receiver become more complex.

The radio spectrum of a pulsed radar (16 μs pulse width) is shown in Fig. 1. The 3 dB bandwith is 1/16 μs = 62.5 kHz. The tails of the envelope reach -30 dB at 1 MHz offset. At a pulse repetition frequency of 2 kHz, a spectral line can be found every 2 kHz. A shortwave sigle-sideband (SSB) receiver detects all these lines and can be tuned anywhere within the $\geq \pm 1$ MHz frequency range to detect the radar signal as a continuous and constant tone. If the radar signal is stronger than a radio service at the same frequency, the information transmitted by the radio service is corrupted constantly.

If on the other hand a radio service appears anywhere within the radar's receiver bandwidth of 62.5 kHz, all echoes with a power below the radio service will be masked and the radar's working range will be reduced accordingly. The only solution is to either increase the radar's transmit power, which increases the interference to other radio services even outside the radar's receiver bandwidth, or to move to a clear radar operating frequency.

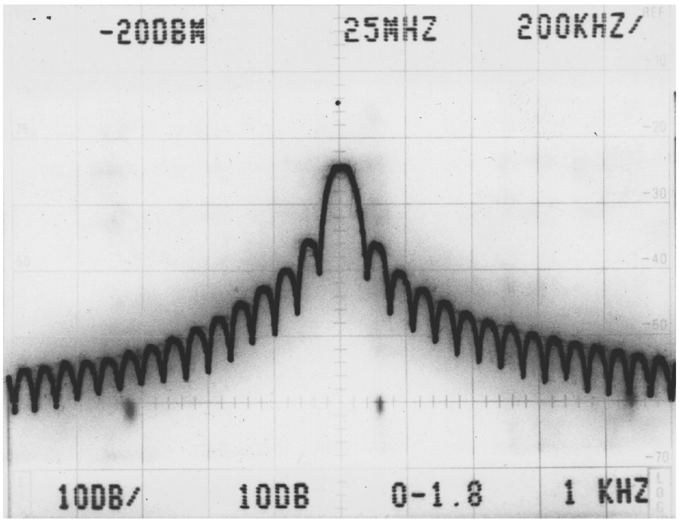

Fig. 1. The radio spectrum of a pulsed coherent radar system at 16 μs pulse length and 2 kHz pulse repetition frequency. The spectrum analyser's settings are 200 kHz per div. horizontally and 10 dB per div. vertically. The center frequency is about 25 MHz, the IF filter bandwidth is 1 kHz. The spectrum covers a wide frequency frequency range and reaches -30 dB at ± 1 MHz.

B. Range Resolution by FMCW

Within an FMCW radar, range resolution is achieved in frequency domain by making use of a linear frequency chirp. Linear frequency chirps are easy to generate with Direct Digital Synthesizers (DDS), which are available since some 10-15 years. In former times, only Voltage Contolled Oscillators (VCO) were available and the linearity of the chirp was difficult to achieve. Deviations from the linear frequency ramp lead to smearing between range cells.

Fig. 2 shows the principle of FMCW modulation as it has been implemented with the WERA HF radar (Gurgel *et al.* 1998 [5]): A linear frequency chirp with the bandwidth B covering the range f_0 to $f_0 + B$ and the chirp's period T is transmitted. The backscattered received signal from all ranges r is then "deramped" by mixing it with the transmitted chirp. This way, a time delay Δt is transformed to a frequency offset Δf:

$$\Delta t = \frac{2r}{c} = \Delta f \frac{T}{B} \tag{1}$$

By reordering Equ. (1), the echo's range can be described by:

$$r = \Delta f \frac{T}{B} \frac{c}{2} \tag{2}$$

The EM wave's phase speed c is the speed of light.

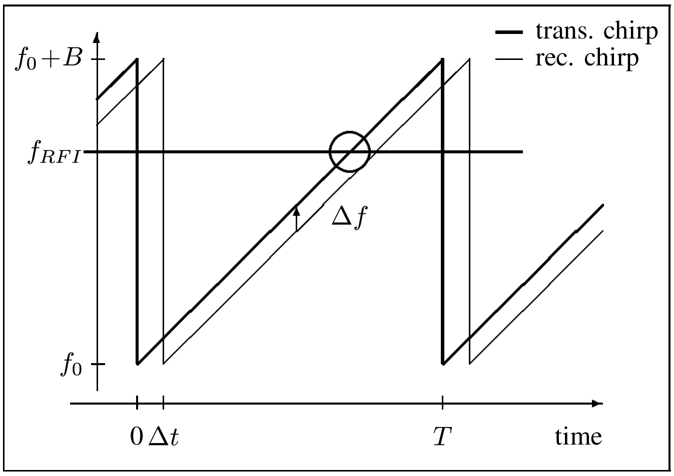

Fig. 2. Description of the FMCW radar signal: A frequency chirp starts at f_0 and linearily increases the frequency with time to $f_0 + B$ during the chirp period T. The chirp passes the operating frequency of a radio service at f_{RFI}. See text for details.

A FFT with a spectral resolution of Δf_{quant} over a single deramped chirp resolves ranges r_{quant}, quantized to:

$$\frac{1}{T} = \Delta f_{quant} = \frac{B}{T} \frac{2r_{quant}}{c} \quad \rightarrow \quad r_{quant} = \frac{c}{2B} \tag{3}$$

After the FFT, each spectral line represents the backscattered signal from within a range cell. Before applying the FFT, a windowing function has to be applied to reduce range smearing introduced by the phase incontinuity between chirps (Gurgel and Antonischki [4]). Range resolving FFTs for consecutive chirps track the phase variation within the range cells and form a time series, which contains the Dopper information within this range cell.

The radio spectrum of a FMCW radar is shown in Fig. 3. In this example, the bandwith B is 500 kHz and the chirp periode T is 0.26 s. The signal drops down very quickly and reaches -60 dB at 300 kHz off the chirp bandwith.

A shortwave SSB receiver tuned to a fixed frequency, e.g. f_{RFI}, detects a short pulse (transient) every T seconds, when the radar's chirp passes by (marked by the circle in Fig. 2). Most of the time, the communication channel at f_{RFI} remains unaffected by the swept carrier transmitted by the radar. Modern digital communication techniques make use of foreward correction, i.e. redundant information is added for error recovery, and normally can cope with this kind of interference.

If the radar itself receives a transient signal within the received chirp, this will be seen as spurious spectral lines within the Doppler spectrum. Radar control and signal processing steps to reduce the influence of these RFI signals are shortly described in the following paragraphs and can be

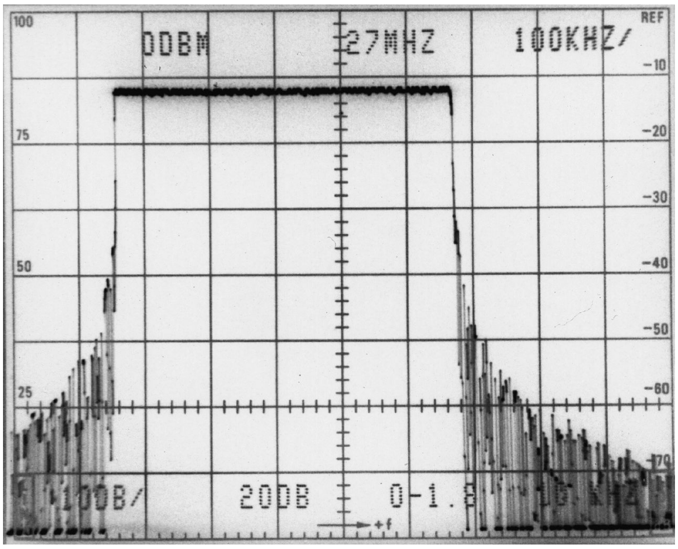

Fig. 3. The radio spectrum of a FMCW radar system at 500 kHz chirp width B and 0.26 s chirp period. The spectrum analyser's settings are 100 kHz per div. horizontally and 10 dB per div. vertically. The center frequency is about 27 MHz, the IF filter bandwidth is 10 kHz. The spectrum rapidly drops to -60 dB at 300 kHz off the radar operating frequency.

found in more detail at Gurgel *et al.* 2007 [7]. In contrast to a pulsed radar, the deramped signal of a FMCW system does not contain high frequency components and a receiver bandwidth of about 1 kHz is sufficient to cover the Doppler spectra at $\pm 1/(2T)$ Hz of up to 256 range cells.

To overcome the requirement of a high dynamic range in a FMCW radar due to simultaneous transmission and reception causing a strong received signal from the direct path, an interrupted FMCW waveform (FMICW) can be used to alternate transmit and receive time slots. This approach has been implemented with the CODAR SeaSonde HF radar system (Paduan and Rosenfeld 1996 [8]). Because of switching times, these systems get a blind range in front of the radar and care must be taken not to aliase signals from far ranges to narrow ones. Due to a swept spectrum instead of a swept carrier, a shortwave SSB receiver will detect a short tone every T seconds.

III. FMCW RADAR CONTROL AND SIGNAL PROCESSING

To reduce the impact of RFI on the radar measurements, several steps in radar control and signal processing are required. In a first step, the radio spectrum should be monitored to locate frequency bands with low usage to define the possible range of radar operating frequencies. The next step implements dynamic adaption of the radar operating frequency to the actual radio spectrum usage prior to 10-15 minute radar runs. Finally, RFI appearing during radar operation is reduced by a special algorithm based on the structure of the RFI. The steps 2 and 3 mentioned above have been implemented with the WERA HF radar and are described in more detail in the following paragraphs.

A. Statistics of radio spectrum usage

Depending on the range resolution required for the application of the HF radar, a specific bandwidth is required (cf. Table I). In addition, the working range of the HF radar depends on the operating frequency band. Low frequencies result in high ranges, e.g. 8 Mhz gives 200-300 km range, while high frequencies result in lower ranges, e.g. 30 Mhz gives 30-50 km. Before installing an HF radar, the frequency band should be scanned with a spectrum analyser at the planned site, as there may be local radio services and other signals from world-wide radio transmitters, which pop up due to ionospheric reflections. The day to night cycle should be monitored during several days.

Resolution	Bandwidth
400 m	375 kHz
480 m	313 kHz
600 m	250 kHz
800 m	188 kHz
1000 m	150 kHz
1200 m	125 kHz
1500 m	100 kHz
2400 m	62.5 kHz
3000 m	50.0 kHz

TABLE I
RANGE RESOLUTION STEPS IMPLEMENTED WITH WERA AND THE REQUIRED BANDWIDTH.

Based on these statistics, gaps in the usage of the radio spectrum should be identified, which are wide enough to fit the required radar bandwidth. The location of the gaps within the spectrum may vary with time and a special scan algorithm described below will dynamically relocate the radar operating frequency. The complete frequency range including daily variations should be requested from ITU through the national agencies.

B. Adaptive frequency management

The licensed frequency band is scanned prior to each 10-15 minute radar run by switching the radar's transmitter off and starting linear frequency chirps covering the entire frequency range. The chirp duration is set to about 1.8 seconds and 32 scans are recorded. In this mode, the radar acts like a spectrum analyser. Fig. 4 shows an example of these scans. It can be seen, that some radio sources transmit at a constant frequency and others are switched on and off. For finding the best "gap" in the radio spectrum, the average receiver power of the 32 scans is used.

The algorithm locates the cleanest radar operating frequency by summing the power within a selected bandwidth for all possible center frequencies within the scan. The windowing function required to avoid range smearing has to be taken into account, as this is the power the radar is actually using for the range resolving FFT. If the sum of the power within the selected bandwidth is too high, a narrower bandwidth from Table I is used. In this case, the range resolution of the WERA is coarser and the measurements have to be interpolated. However, in situations with strong RFI it is better to reduce

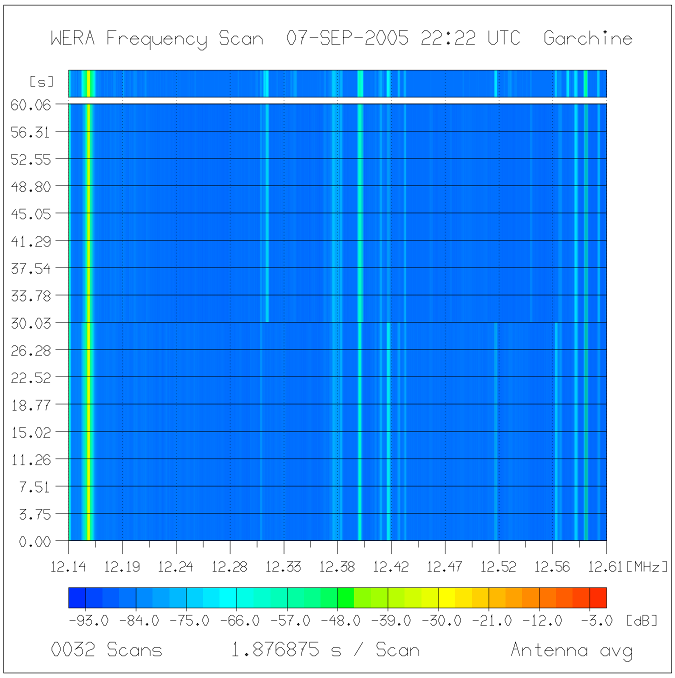

Fig. 4. A frequency scan showing the radio spectrum utilisation in the range 12.14–12.61 MHz. 32 single chirps covering the temporal variation during one minute as well as the average at the top of the figure can be seen. The colour scale represents the receiver power in dB.

the range resolution instead of getting no measurement at all. This adaptive frequency management implements some kind of "listen-before-talk" functionality.

C. RFI reduction

Of course the adaptive frequency management does not help, if new radio signals appear during the measurement cycle, but a frequency re-adjustment every 10-15 minutes helps to avoid most of the RFI. To remove the remaining RFI, a special algorithm has been developed to recover radar signals which contain RFI only, i.e. without radar echoes scattered back by ships or the ocean surface. The algorithm acts like the transmitter beeing switched off during the data run, while actually transmitting the frequency chirps.

This signal is used to identify and cancel the RFI fraction of the radar signal. In some rare situations, the filter algorithm is not able to remove all interference, especially when the external signal contains strong modulation. In this case, the contaminated fractions of the timeseries are skipped during processing.

IV. Data quality after RFI removal

The processing steps lined up above have been implemented with the WERA HF radar. Experiments in France near Brest, in Portugal at Figueira and in Germany at the North Sea have shown a significant increase in data quality, compared to former experiments at fixed radar frequencies and without the RFI reduction algorithm. Sea echoes and ship targets can be seen more clearly and the times with measurements of low quality or reduced range are significantly marked down. If an HF radar is used for ship tracking or tsunami detection, a high data quality is required and observation time gaps must be avoided. Ship tracking experiments have been done with WERA and the algorithms and results have been published by Dzvonkovskaya and Rohling (2006) [3] and Gurgel and Schlick (2005) [6].

V. Conclusion

The compatibility of pulsed and FMCW HF radars with other radio services has been discussed. The FMCW technique shows several advantages, both in the impact on radio services and on radio services interfering the radar. A method to select an optimum operating frequency and to reduce RFI from the radar echoes has been shown. Together, these methods help to increase the amount of clean and undistorted data, which is a strong requirement especially for applications like ship tracking and tsunami detection.

Acknowledgment

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