Ultra-Wideband Forward Scattering Radar: Definition and Potential

M. Cherniakov[1], Cheng Hu[2], M. Gashinova[1], M. Antoniou[1], V. Sizov[3], L.Y. Daniel[1]

1. University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
2. Beijing Institute of Technology, 100081, China
3. Moscow Institute of Electronic Technology, 124498, Moscow, Russia

Abstract

This paper is dedicated to the newly introduced subclass of Bistatic Radar, namely: Ultra-Wideband Forward Scattering Radar. The system's concept and high potential for several applications is investigated and some preliminary results are demonstrated.

Keywords: Ultra-Wideband radar, forward scattering radar

Introduction

Forward scattering radar (FSR) is a special configuration of bistatic radar (BR), where the bistatic angle β_b is around 180^0. The fundamental difference between both monostatic and bistatic radars on one hand, and FSR on the other, is in the physical mechanism behind the scattered signal formation. In traditional (back-scattering) radars a target is illuminated by an electromagnetic (EM) field and part of the reflected energy is detected by the receiving antenna. If a target is constructed from an ideal absorbing material, no reflection occurs and this target should be invisible. In contrast, FSR is based on an effect of shadowing the illuminating EM waves; the received signal strength is not strongly related to the target material, except in the highly unlikely case that the material is transparent to EM fields. The target presence reduces the power of the transmitted signal, as an approximation we can consider this target as a secondary antenna which has the target's silhouette and a negative gain. A description of the basic FSR system along with an investigation of its advantages and limitations is readily available in the open literature [1-4]. FSR traditionally operates using continuous wave (CW) or narrowband modulated ranging signals. A typical FSR topology is shown in Fig.1.

The FSR system has some key advantages, such as: robustness to stealth targets; enhanced radar cross section (RCS) of conventional targets; very long target coherent integration time and so consequently, the effective applicability of inverse synthetic aperture signal processing for automatic targets recognition.

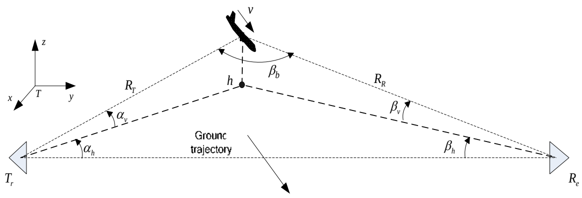


Figure 1 *FSR topology*

The limited operational area (a very narrow spatial angle estimated as $\pm 10 - 20°$ or so relative to the baseline) and the absence of range resolution are the major FSR drawbacks. The latter has a crucial effect on FSR applications due to the high clutter level collected from the overall area between the transmitter and the receiver. Nevertheless, FSR has been used for air targets detection [4-6], tracking [7], ground targets detection and classification [8] and it has also found a niche operating in microwave fences [9]. In all of these applications, narrowband FSR has been proposed. In this paper, we will demonstrate the concept of Ultra Wideband FSR (UWB FSR) and begin to explore its potential for some practical applications.

UWB FSR concept

UWB radar. An UWB signal is defined either as any signal with a fractional bandwidth of more than 0.25 (so that it could be considered as a carrier-free signal), or any signal with a bandwidth exceeding 500 MHz [10]. In UWB FSR, depending on the radar application we can expect utilisation of both kinds of UWB signals.

UWB FSR block diagram. UWB FSR assumes utilisation of a UWB waveform as the ranging signal. A simplified block diagram of a UWB FSR with a short pulse waveform is shown in Fig. 2. The shortest path between the transmitter and the receiver corresponds to the baseline itself and the corresponding signal is synchronised at the receiver, to be used as the correlators' reference signal (heterodyne) in the delayed channels. The elementary delay in the multi-channel correlators, i.e. matched receiver, is approximately equal to the transmitting pulse length.

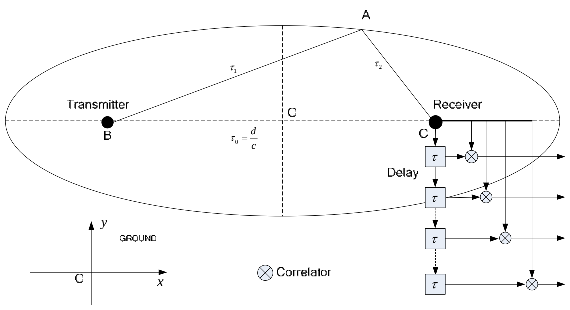


Figure 2 *UWB FSR block diagram*

Coverage area and resolution. Using this approach, for a given time delay the target could be located anywhere on the three-dimensional space formed by the boundaries of two confocal ellipsoids with a semi-major axes delay difference of $\tau/2$. We will refer to this shape as a resolution *shell* (shown in Fig. 3 as shaded areas) by analogy to the resolution *cell*. The boundaries of these ellipsoids can be presented as:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{b^2}=1 \quad a=\frac{d+n\cdot c\tau}{2} \quad b=\sqrt{a^2-\left(\frac{d}{2}\right)^2}$$

where a and b are the semi-major and semi-minor axes of the iso-range ellipses. For the 2-D case (shown in Fig. 3):

$$x^2/a^2+y^2/b^2=1$$

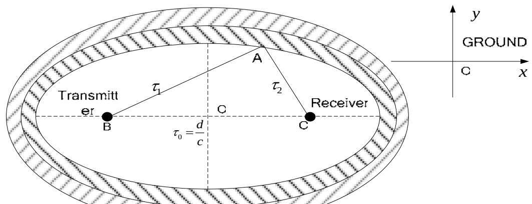


Figure 3 *Resolution shells in UWB FSR*

It is important to mention that in Fig. 3 all scales are distorted for better visualization; the area outside approximately $\pm 10-20°$ from the transmitting and the receiving antennas does not introduce strong FS reflections. So, the resolution in UWB FSR is specified by the resolution shells. At the correlators' outputs only signals and clutter originating from inside the appropriate volumes will be received. We will refer to the whole volume enclosed by the first ellipsoid as the main resolution shell; the resolution shell immediately after is shell number 1 and so on. The maximal thickness of the shells occurs along the ellipses' semi-minor axes. In Fig. 4-a this is plotted (as an example) against the shell number for a 2km baseline and pulse durations of 2, 1, 0.5 and 0.25 ns.

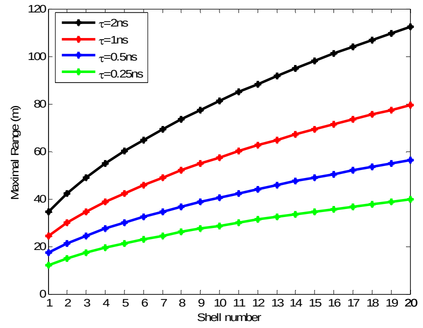


Figure 4-a) *Resolution shells* maximal *thickness*

The maximal distance from the baseline to the resolution shells boundaries at x=0 is shown in Fig. 4-b.

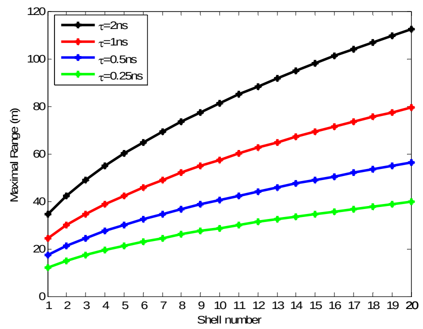


Figure 4-b) *Maximal deviation from the base line*

Examples of UWB FSR applications

<u>Air target detection</u>. Three benefits of UWB signal utilization in FSR for air targets detection are seen. The first being the resolution of targets which are flying in different formations; the system topology is conceptually shown in Fig. 5.

In this topology, Fig. 6 demonstrates the variation in the aircraft's angular position (α) and the resolution shell's thickness Δ_H with the aircraft's altitude (*H*) and the shell number, assuming that: the baseline is 30 km, the antennas' elevation is 30m and the pulse duration is 2ns (i.e. a 500 MHz bandwidth).

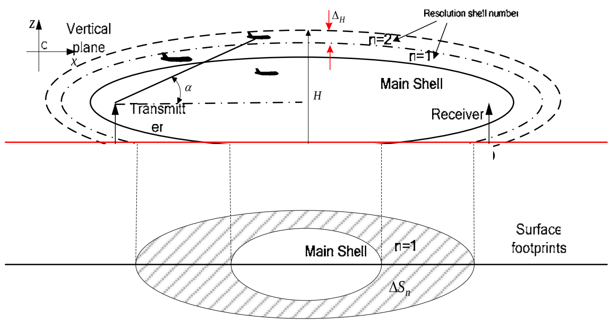
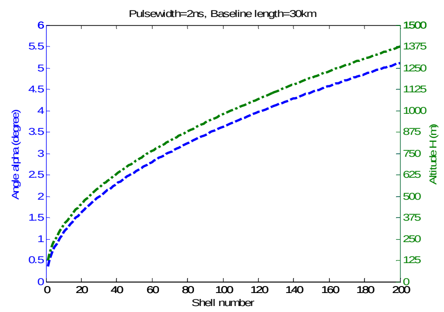
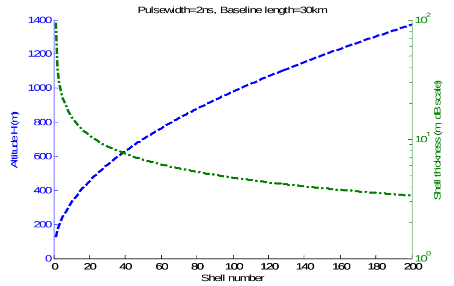


Figure 5 *UWB FSR topology (vertical cross section)*



a) Aircraft altitude and view angles



b) Aircraft altitude and Shell thickness

Figure 6 *Parameters of UWB FSR example for air targets*

The second benefit is in the ground clutter reduction. Comparing the clutter level between NB and UWB FSR, the improvement factor is $\gamma = InF_{NB} / InF_{UWB}$, where the NB clutter level (InF_{NB}) is evaluated as:

$$InF_{NB} = \int_S \frac{dS}{R_t^2 R_r^2}$$

$$= 2 \times \int_{h\cot(\theta)-\frac{d}{2}}^{0} \int_{-h\sqrt{\frac{(x+d/2)^2}{(h\cot(\theta))^2}-1}}^{h\sqrt{\frac{(x+d/2)^2}{(h\cot(\theta))^2}-1}} \frac{dydx}{R_t^2(x,y)\,R_r^2(x,y)}$$

and the UWB clutter level (InF_{UWB}) is evaluated as:

$$InF_{UWB} = 2\times\int_{x_C}^{x_E}\int_{b_1\sqrt{1-\frac{x^2}{a_1^2}}}^{h\sqrt{\frac{(x+d/2)^2}{(h\cot(\theta))^2}-1}} \frac{dydx}{R_t^2(x,y)R_r^2(x,y)} +$$
$$2\times\int_{x_E}^{x_F}\int_{b_1\sqrt{1-\frac{x^2}{a_1^2}}}^{b_2\sqrt{1-\frac{x^2}{a_2^2}}} \frac{dydx}{R_t^2(x,y)R_r^2(x,y)} +$$
$$2\times\int_{x_F}^{x_D}\int_{b_1\sqrt{1-\frac{x^2}{a_1^2}}}^{h\sqrt{\frac{(x-d/2)^2}{(h\cot(\theta))^2}-1}} \frac{dydx}{R_t^2(x,y)R_r^2(x,y)}$$

The improvement factor for different pulse durations is shown in Fig. 7. As one can see, for practical applications we are expecting at least 20-25 dB improvement in signal-to-clutter ratio in UWB FSR.

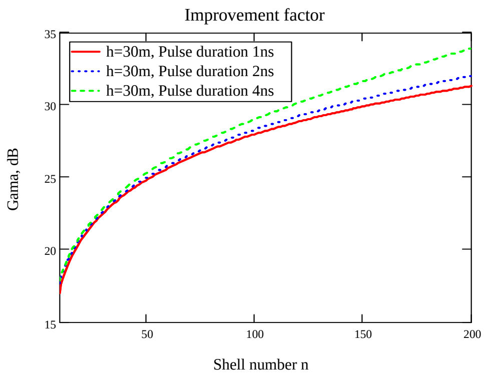


Figure 7 *The improvement factor γ vs Shell number n (30km baseline)*

The third benefit follows from the fact that using a monopulse receiving antenna, the target's position could be roughly estimated in real time (Fig. 8).

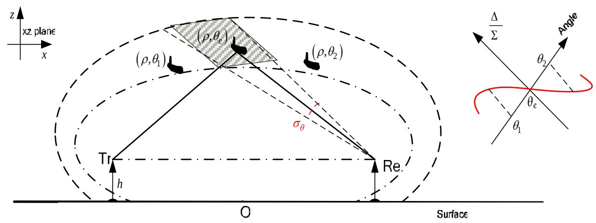


Figure 8 *Using a monopulse receiving antenna to extract target position*

An example of the potentially achievable accuracy (σ_z) for the targets' direct altitude estimation (using the topology of Fig. 8) is shown, for different transmitted pulse durations, in Fig. 9.

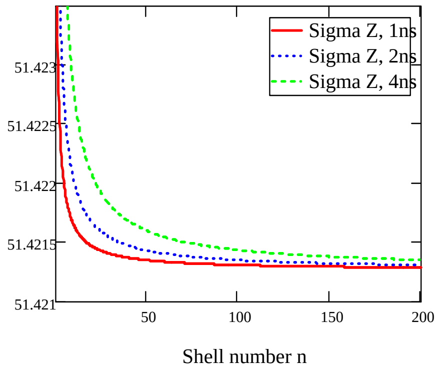


Figure 9 σ_z *vs shell number n (SNR=30dB, 30km baseline)*

Maritime target detection. The key problem for maritime targets detection in FSR is the clutter level reduction. It is a known fact that within the FSR operational area the sea surface clutter could reach 10 dBm^2 [2]; UWB signal utilisation in FSR may essentially reduce this clutter level. The system topology is shown in Fig. 10.

In contrast to air targets, maritime targets are directly crossing the baseline and the main resolution shell should be observed for target detection. To introduce the UWB FSR advantage over its narrowband counterpart we will consider some calculation examples - assuming that the radar operates in X band.

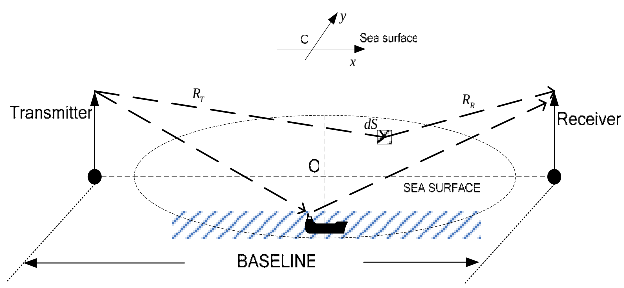


Figure 10 *UWB FSR for maritime target detection*

First of all, depending on the antennas' elevation and separation, the main resolution shell may not touch the surface at all. The dependence of the pulse duration vs the baseline for two different antenna elevations (3 and 6 meters), assuming that the main shell does not touch the sea surface, are shown in Fig. 11. As one can see, for an antenna elevation of 6 meters and a pulse duration of 0.1 ns (or 10 GHz bandwidth), surface clutter will not be picked up over a distance of about 3 km. Of course, this is an idealisation as sea waves will cross this resolution shell, but even in this situation we can expect a dramatic clutter reduction.

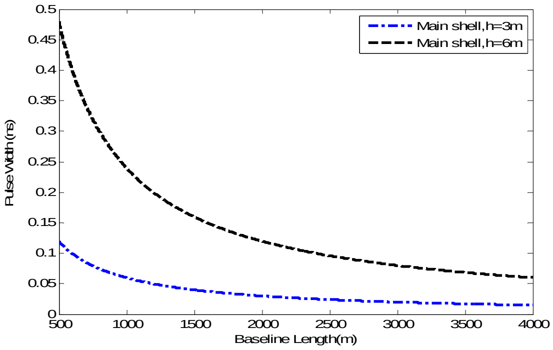
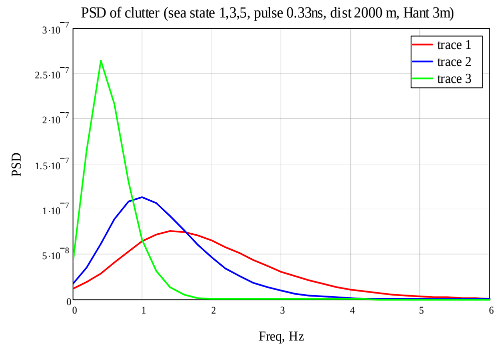


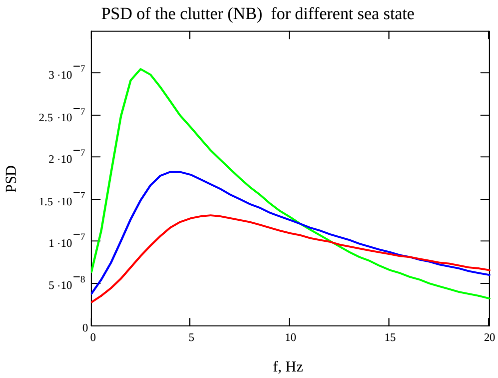
Figure 11 *Pulse durations for "clutter free" case*

Further signal to clutter ratio improvement could be achieved by separating the sea clutter power spectrum from that of the target. Assuming that an area element of the sea surface has a Gaussian spectrum [11] with a mean value and standard deviation both approximately equal to 1/8 of the sea waves' speed, the clutter power spectrum density (PSD) within the main resolution shell was calculated (see Fig. 12) for: sea states 1, 2, 3; antennas elevation 3 m; baseline 2000 m and pulse duration 0.33 ns (cross-wind case).

Any moving target has a Doppler spectrum which depends on the component of its speed normal to the baseline. It is seen from the figure that the highest PSD values occur at very low spectral components. This follows from the fact that the closer the object (the sea wave in our case) is to the baseline, the less its absolute Doppler component will be. Consequently, by removing the low frequency part of the spectrum, we can further improve the signal-to-clutter ratio. Target detection in this case is available from ranges starting near the main shell boundary (where the Doppler component increases).



a)



b)

Figure 12 *Clutter power spectrum in the main resolution shell of a) UWB FSR, b)NB FSR.*

An example of the signal-to-clutter improvement versus the baseline distance (horizontal axis), for targets with different speeds (vertical axis) is shown in Fig. 13. Our calculations were made for a sea state 1 (3 m/s wind speed) and an UWB pulse duration of 0.33 ns. We can see in the figure that to improve signal-to-clutter ratio by 30 dB, for a radar with 3000 m baseline, the target should have a speed of approximately 6 m/s.

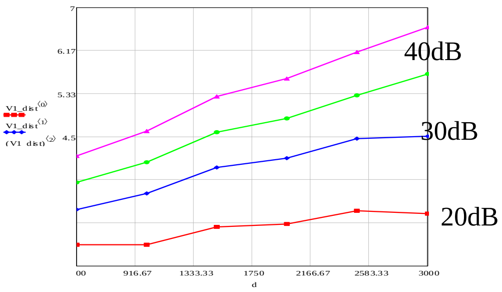


Figure 13 *Signal to clutter ratio improvement in frequency domain in UWB FSR for different target speeds*

Conclusion

In this paper we have considered some features of a newly introduced remote sensing system, the Ultra Wideband Forward Scattering Radar. This paper is mainly based on a rather general analysis and a set of examples, a detailed study of UWB FSR is yet to be done. Nevertheless, the early stage of the system's study clearly indicates some unique system properties that can make it a prospective and innovative tool for numerous practical applications.

Some major features of the UWB FSR are:

1. Essential reduction of surface clutter, thus making the system applicable in maritime scenario - narrowband FSR cannot generally operate over the sea surface.
2. Some degree of target resolution and essential reduction in surface clutter for air targets detection.
3. High immunity to multipath - a key benefit for situation awareness in urban areas or similar. This point was not discussed in the main text but it directly follows from extensive research in UWB communications [12].
4. UWB FSR allows covert operation as the average transmitting power density per Hz is very low and therefore it is hard for it to be detected.

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