Non-cooperative Transmitter Selections for Space-Surface Bistatic SAR

Rui Zuo, R.Saini, M. Cherniakov
Electronic, Electrical and Computer Engineering
University of Birmingham, Edgbaston, Birmingham. B15 2TT

Abstract

This paper presents a comparison study of potential candidates of non-cooperative transmitters for SS-BSAR. The comparison is made on the basis of three parameters: transmitter availability, resolution and power budget. Four different types of satellite trasmitters are considered. They are: GALILEO, ASTRA, Inmarsat 3 and Iridium.

Keywords: bistatic synthetic aperture radar, space-surface radar, non-cooperative transmitter,

Introduction

The SS-BSAR consists of a spaceborne transmitter and a receiver mounted on or near the earth's surface, see Figure 1. The receiver could be airborne, mounted on a ground vehicle, onboard a ship, or even in a stationary position on the ground. For the stationary receiver a non-geostationary satellite should be used to provide aperture synthesis. The core of SS-BSAR systems is their essentially asymmetric topology [1]. This is in contrast to a more usual BSAR configuration where the transmitter and receiver are moving along collinear trajectories. The basic operation of SS-BSAR systems is much the same as the operation of other BSAR systems, the differences being introduced mainly as a consequence of the geometry employed.

SS-BSAR can be operated using either a co-operative transmitter or a non-cooperative transmitter. The co-operative radar means that the transmitter and receiver are specially designed to work together and have built-in means of synchronisation. The radar specifications (such as power, waveform, coverage, processing etc) are also chosen to suit a particular application. The non-cooperative radar, on the other hand, employs a radar receiver to 'hitchhike' off another source of illumination. The other sources can be another radar, transmissions from audio-video broadcasting, navigation and communication satellites. This mode of operation is termed as non-cooperative since the illuminator is not specifically built to support the radar operation.

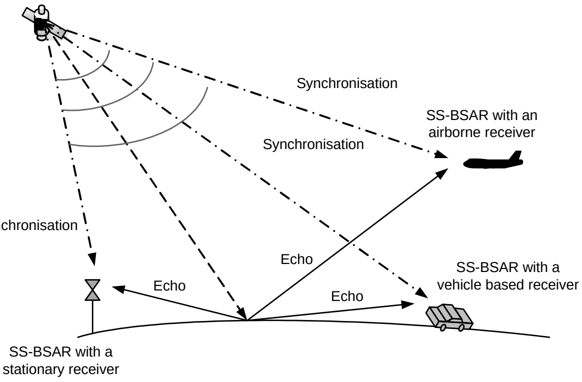

Figure 1 *SS-BSAR topology*

Over the last decade SS-BSAR with non-cooperative transmitters has generated a lot of interest [2-4]. An attractive feature of this system is that the receiver is passive and the transmitter, placed in space, is out of range of conventional air defence systems. In addition, there is no need to build transmitters, which are usually power

consuming and essentially influence the radar's weight, dimension and cost.
The very basic requirement for SS-BSAR with non-cooperative transmitter is the transmitter availability. Transmitters should not be deliberately switched off without appropriate preliminary discussions and/or authorisation. Ideally the system should have the non-cooperative trasmitters diversity. This increases the system reliability and the bi (multi) static system architecture can be properly organised. The second vitally important parameters are the transmitters radiating power and signal bandwidth. They must be big enough for targets detection with reasonable range resolution.

The aim of this paper is to compare potential candidates of non-cooperative transmitters on the basis of three important radar requirements: transmitter availability, resolution and power budget. Four different types of satellite transmitters are considered. They are: 1) GALILEO, the forthcoming European navigation satellites. 2) ASTRA, a geo-stationary satellite system, which provides direct-to-home transmission of TV, radio and multimedia services. 3) Inmarsat-3, also geo-stationary satellites that provide world-wide telephony and data services. 4) Iridium, active LEO communication satellites allowing worldwide voice and data communications.

Transmitter Availability

As mentioned earlier, the key problem of SS-BSAR with non-cooperative transmitter is the transmitter's availability. Table 1 summarises the availability of the considered satellite transmitters in terms of coverage, number, and visibility.

When GALILEO is fully operational, there will be 30 new satellites in Medium Earth Orbit (MEO) providing a global coverage. Each satellite will take about 14 hours to orbit the earth. Typically, at any point on the earth's surface, 4 to 10 GALILEO satellites will be simultaneously visible above the horizon. As a result, a particular satellite in the best (or at least suitable) position can be selected and there is no need for a very specific aircraft trajectory to allow the observation of an area. Potentially, signals from more than one satellite could be used to provide radiogrammetric 3-D surface mapping. Another advantage is a relatively simple synchronisation of GALILEO signals. This follows from the fact that navigation signals are designed to be optimal for remote synchronisation.

The ASTRA is Europe's leading Direct-to-Home satellite system, providing digital TV, radio and multimedia services. The ASTRA satellite fleet currently comprises 13 geo-stationary satellites. In spite of transmitting 10 dB more power flux density near the earth surface in comparison with GALILEO (see Table 3), the drawback of using a geo-stationary satellite is that only one satellite is visible at any point on the earth. This requires a specific aircraft trajectory for mapping a particular area and, in many or even most situations, a vital loss in ground resolution may take place.

Inmarsat 3 is a group of five geo-stationary satellites that provides telephony and data services. There are two types of coverage provided by each Inmarsat 3 satellite. Each satellite is equipped with a single global beam that covers up to one-third of the Earth's surface, apart from the poles. In general, global beam coverage extends from latitudes of −78 to +78 degrees regardless of longitude. It also has wide spot beam coverage which is optimised for covering most areas of interest and is thus somewhat limited in comparison to global beam coverage.

The Iridium system has 66 active satellites allowing worldwide voice and data communications. These satellites are in low earth orbit. At one stage there was a threat that the Iridium satellites would have to be de-orbited, however they did remain in situ and operational, and their services were re-established in 2001 by the newly founded Iridium Satellite LLC.

Table 1 *Satellite Availability*

	Galileo	ASTRA	Inmarsat 3	Iridium
Number of Satellites	30	13	5	66
Coverage	Global	Europe	Global (Except poles)	Global
Number of simultaneously visible satellites	4-10	1	1	1 or 2
Satellite visibility time	360 m	All the time	All the time	11 m

Resolution

Table 2 shows the potential range resolution of the four different satellite systems. The stated resolution is for quasi-monostatic configuration. It should be noted that the aggregated bandwidth of each satellite is a result of combining multiple channels. This combining of multiple channels is a subject of future study. Our forthcoming publication will consider the GALILEO E5 signal. It is expected that there is a potential of achieving a 3-8 m resolution (50 -20 MHz bandwidth) if the entire E5 (combining E5a and E5b) signal is used.

Table 2 *Range Resolution*

Transmitter	Signal bandwidth (MHz)	Aggregated Bandwidth* (MHz)	Quasi- monostatic Range Resolution (m)
GALILEO E5a/b	10.23	-	15
GALILEO E5 (E5a+E5b)	20-50	20-50	3-8
ASTRA	2	2×10=20	7.5
Inmarsat 3	2	2×10=20	7.5
Iridium	0.04	0.04×240= 10	15

* signal bandwidth achieved by combining multiple channels (signal bandwidth× number of channels)

In SS-BSAR, the spatial resolution is dependent upon the geometry of the system, i.e. satellite-receiver-target positions relative to each other. The effect of the system's geometry on the resolution is comprehensively discussed in [5]. As an example, Figure 2 shows the degradation of range resolution as a function of bistatic angle. It is seen that for large bistatic angles there will be a huge loss in range resolution. The key advantage of using a GALILEO satellites compared to other satellites is that the user can choose the desired bistatic topology (i.e. with low bistatic angle). This is due to the fact that 4 to 10 satellites will be simultaneously visible at any point on the earth.

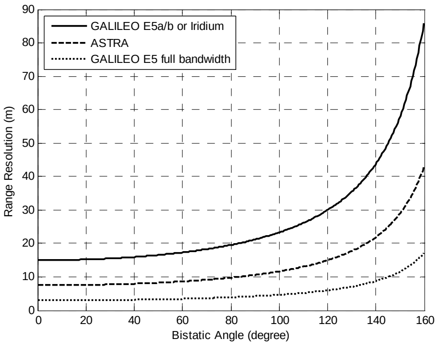

Figure 2 *Degradation of range resolution as a function of bistatic angle*

Power Budget

Table 3 shows the power density of the different satellites. It is seen that iridium generates the strongest power density on the earth's surface compared to other satellites, whereas GALILEO has at least 10 dB lower power density against the other candidates. For Inmarsat 3 its spot beam provides around 9 dB higher power than its global beam.

Table 3 *Transmitter's Parameters*

Transmitter	EIRP (dBW)	Orbit Altitude (km)	Power density (dBW/m^2)
GALILEO	32	23222	-126*
ASTRA	51	35786	-111
Inmarsat 3	39	35786	-123 (global beam)
	48		-114 (spot beam)
Iridium	21	785	-108

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[*] This is the guaranteed minimum power received from the GALILEO satellite when it is near the horizon. Potentially, one can expect 6 dB increase from the min. power when the satellite is at an elevation of 45°

The receiving part of the SS-BSAR in general case consists of two channels: the radar channel used for receiving reflected signal from the target and the heterodyne channel (pointed directly towards the satellite) is used for synchronisation. In the following we discuss the power budget of the two channels.

Power Budget of Heterodyne channel: Usually in a radar signal processor, the range compression consists of a correlation (or match filtering) of the radar channel signal with the heterodyne channel signal delayed for each range resolution cell. Certainly the performance of the matched filter depends on the quality of the heterodyne channel signal. Ideally, one would like the signal to be as clean as possible, i.e. as free from corruption. Unfortunately, the heterodyne signal will be spoiled by factors, which may include receiver noise, propagation distortions, multipath, clutter, and interference. At best, however, one might get a heterodyne signal from a line-of-sight direct path relatively free from interference, multipath and clutter. In this case, only the noise in the heterodyne channel corrupts the signal. Thomas [6] has comprehensively investigated the effect of an imperfect heterodyne signal on synchronisation. He showed that match filtering losses are negligible for the heterodyne channel signal having reasonably high SNR. As an example, Figure 3 shows the loss in matched filtering as a function of noisy heterodyne channel. From the figure we assume a SNR of 10 dB in the heterodyne channel for negligible loss in match filtering.

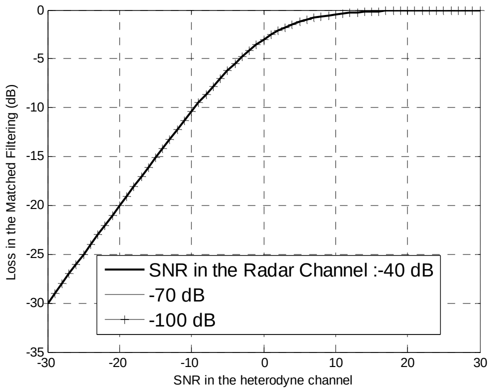

Figure 3 *Matched filtering losses as a function of noisy heterodyne channel*

The signal-to-noise ratio at the output of the heterodyne channel can be approximated by:

$$\frac{S}{N} = \frac{\rho A_e}{K T_s B_n} \tag{5}$$

where ρ is the received signal's power density on the earth's surface, A_e is the effective area of the receiving heterodyne channel antenna, T_s is the system noise temperature, assumed to be 410K, B_n is the bandwidth of the receiver, assumed to be equal to the radar signal bandwidth.

Using transmitter parameters of Table 2, 3 Equation (5), Table 4 shows the required SNR at the heterodyne channel as a function of antenna size. For GALILEO, the noiseless reference signal can be locally generated as the signal structure and the spreading codes are fully known. However this locally generated signal needs to be synchronised (in delay and Doppler) with the satellite signal received at the heterodyne channel. A typical synchronisation algorithm (tracking loops) requires a minimum of 10 to13 dB SNR at the output of its correlator (or discriminator). The E5a or/and E5b components of GALILEO signal (10 MHz bandwidth) could be used for synchronisation. For 10 dB SNR at the output of the correlator (1 msec integration time[†]) requires a minimum of -30 dB SNR at the heterodyne channel.

Table 4 *SNR in heterodyne channel*

Transmitter	A_e (m^2)	Required SNR (dB)
GALILEO	0.001	-30
ASTRA	0.15	10
Inmarsat 3	0.3	10
Iridium	0.04	10

The principle of signal synchronisation and range compression has been fully verified experimentally using GLONASS navigation satellite in our previous publication [7].

For other satellites (ASTRA, Inmarsat 3, Iridium), the reference signal cannot be generated locally. This is due to the random nature of the transmitted information. In this case, the minimum required SNR at the heterodyne channel is ≥ 10 dB (see Figure 3) for low match filtering loss. As seen from Table 4 this is achieved at the expense of increased antenna size. It should be noted that the calculations shown in Table 4 does not take in to account a number of practical problem such as propagation and receiver losses. In real situation we can expect a further increase in the antenna size. Also, if one needs to further increase the range resolution by increasing the aggregate bandwidth (combining multiple channels), this will lead to decrease in the SNR. The only way to compensate this reduction in SNR is increasing the antenna size.

Power Budget of Radar Channel: The signal-to-noise ratio of the radar channel is calculated for the time of aperture synthesis, considering only targets that have RCS independent of frequency and angle. Indicating that the expression for SNR after range and azimuth compression, for an active bistatic SAR, it can be written as [8]

$$\frac{S}{N} = \frac{\rho A_e \sigma \lambda \eta}{4\pi R_{rt} K T_s V_a \Delta_{az}} \qquad (6)$$

where λ is the wavelength, η is a general loss factor, σ is the radar cross-section of the target, Δ_{az} is the azimuth resolution, R_{rt} is the receiver-target range, V_a is the aircraft's velocity.

Using the parameters in Table 3, 5 and considering the rest of the parameters in Equation 6 as variables, the final equation can be written as:

$$\frac{S}{N} = k \times \frac{\sigma}{R_{rt} V_a} \qquad (7)$$

$$k = \frac{\rho A_e \lambda \eta}{4\pi K T_s \Delta_{az}} \qquad (8)$$

The effective length of the array is determined by the distance along the flight line over which a particular target is in the beam of the real antenna. This is given by:

$$L_a = V_a T_c = R_{rt} \theta_B = R_{rt} \frac{\lambda}{D} \qquad (9)$$

where T_c is the integration time, θ_B is the beamwidth of a real antenna, D is the antenna width. From Equation (9) it is seen that the effective length of the array is a function of target range, being longer for more distant targets. The cross-range resolution for the focused bistatic SAR is given by:

$$\Delta_{az} = \frac{\lambda}{L_a} R_{rt} = \mathrm{D} \qquad (10)$$

which is independent of the range.

Table 5 *Parameters for Calculation*

Transmitter	λ (cm)	V_a m/s	η	A_e (m^2)	Δ_{az} (m)	T_s (K)
GALILEO	25.2	200	0.5	0.5	1	410
ASTRA	2.8					
Inmarsat 3	18.3					
Iridium	18.5					

Figure 4 shows the potential range of SS-BSAR for different satellites. If considering 14 dB SNR as the radar detection threshold, targets with 50 m^2 RCS can be detected at the range of approximately 3 km (or 12 km when the satellite is at an elevation of 45°)

[†] The integration time can potentially go up to 100 msec or more for GALILEO E5$a_{/b}$ pilot signal. However this depends upon the dynamics of the delay/Doppler variation. In this case the minimum required SNR at the output of the heterodyne channel is -50 dB.

using GALILEO, 4 km using Inmarsat 3 (global beam), 10 km using ASTRA and more than 80 km if Iridium is used.

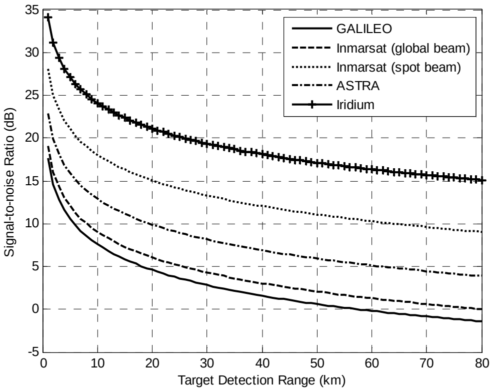

Figure 4 *Detection range of SS-BSAR for different satellites with 50 m^2 RCS target*

Conclusions

This paper compared the potential candidates of non-cooperative transmitter for SS-BSAR. The comparison is made on the basis of three important parameters: availability of transmitters, resolution and power budget. Four different types of satellite transmitters were considered. They are: GALILEO, ASTRA, Inmarsat, and Iridium.

It was highlighted that the GALILEO satellite transmits more than 10 dB less power compared to other satellites. However it has an advantage of satellite diversity when compared with other considered satellite systems. Therefore using GALILEO one can choose the desired bistatic topology for low resolution loss.

It was also pointed out that for low match filtering loss, the heterodyne channel should have reasonably high SNR. It was shown that for communication/ broadcasting satellites this is achieved at the expense of increased antenna size and potentially the antenna may be impractical to be mounted on an aircraft. However for GALILEO one can locally generate the reference signal but it needs to be synchronised with the satellite transmitter. The synchronisation requires very low SNR (-30 to -50 dB) at the output of heterodyne channel. This makes it a good candidate for SS-BSAR with airborne receiver.

Finally, it is concluded that overall GALILEO satellite is the best candidate for SS-BSAR. It provides a reasonable range resolution of ~ 3-8 m, allows satellite diversity and a target detection range of ~ 3-12 km for 50 m^2 targets. However, the final choice depends upon a particular application.

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