Space-Based Passive Radar: experimental results

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Abstract—In this paper we investigate the possibility to develop a passive radar system using, as illuminator of opportunity, a high EIRP level geostationary broadcast transmitter. The possibility to resort to a quasi-stationary transmitter is shown to highly simplify the signal processing required by the passive radar system. A preliminary evaluation of the achievable SNR is conducted, showing that mid-range target detection can be achieved with reliable performance. In addition, a analysis of the Doppler frequency contributions due to the motion between target and transmitter is conducted. Finally, preliminary measurement on the received signal are reported.

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1.INTRODUCTION

This paper presents some preliminary results obtained in the framework of the research project “Study on Space-based Passive Radar” by Selex-Galileo and the INFOCOM Dept. of University of Rome “La Sapienza”. The main aim of the project is to develop a prototypal ground-based passive radar for air target detection exploiting space-based transmitters as illuminators of opportunity.

It is well known that existing broadcast transmitters can be used as illuminators of opportunity for passive radar systems. Ground-based broadcast transmitters used for FM radio, analog and digital TV, WiFi-local network, have been largely exploited with success, see for example [1]-[3]. The possible use of space-based (in lieu of ground-based) illuminators, has been considered only in a limited number of studies. In fact, space-based broadcast transmitters have typical level of Equivalent Isotropic Radiated Power (EIRP) in the range of 40-50 dBW and high orbits, yielding a low level e.m. field close to the Earth’s surface.

When considering broadcast transmitters in Geostationary Earth Orbits (GEO), very long integration times (order of many minutes/hours) are required to yield an acceptable Signal to Noise Ratio (SNR). This allows to make images of the Earth’s surface (also by exploiting a limited satellite motion relative to the Earth) [4], but not to detect aircrafts using the short integration times compatible with their typical motion (order of seconds).

The possibility to detect air targets (i.e. short integration times) can be considered using transmitters on Low Earth Orbit (LEO), [5], due to the reduced range of these sources. In this case, a full constellation (e.g. Globastar or Iridium) is necessary to guarantee a continuous coverage of a specific region and continuous satellite tracking is necessary. However, the available constellations are devoted to personal communications, so that the effective presence of signals in the air largely depends on the number of actual users and on the time-division multiplexing characteristics.

As a more promising alternative, we consider the passive radar exploiting a new generation of space-based illuminators, based on GEO satellites, but operating with sensibly higher EIRP and adequate bandwidth. These are being introduced recently for Satellite Mobile Digital TV broadcast purpose, and are designed to allow mobile users to receive satellite TV without large antennas. These signals are especially suitable for passive radar not only for their power level, but also for: (1) waveform characteristics; (2) area coverage (size of covered air space) and (3) simplicity of operation (not requiring tracking satellite position and changing Doppler frequency).

This paper is organized as follows. In Section 2 a brief overview of existing space-based illuminators is presented. In Section 3 a preliminary SNR analysis is conducted to evaluate the feasibility of a passive radar system based on spaceborne transmitters of opportunity. Sections 4 reports a Doppler analysis, while in the section 5 there are the preliminary measurements obtained by DVB-SH signal of W2A satellite. Finally, in Section 6 we draw some conclusions.

2.SPACE-BASED TRANSMITTERS

Among the enormous set of orbiting systems transmitting signals down to Earth, we have focused on systems suitable for usage as transmitters of opportunity in passive radar. Specifically, Figure 1 reports the set of transmitters considered in the following analysis in terms of EIRP and height orbit together with information regarding the received signal power density on the Earth surface (Prx). The main characteristics taken into account are:

(1) high EIRP level;

(2) wide area coverage;

(3) reliability of the transmission;

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(4) existing information on signal characteristics.

The two first characteristics refer to common requirements for any radar transmitter. In addition, to be suitable for passive radar system design, an illuminator has to guarantee a continuous signal availability in a given area sorrounding a fixed position over the Earth surface. This requirement is not always met when space-based illuminators are considered, for two main reasons. The former is that the availability of the signal might be subject to an effective on-going transmission, as it happens for mobile communication systems (e.g. Globastar, Iridium). The latter is that the satellite is orbiting around the Earth. Hence the selection of illuminators of opportunity is restricted only to GEO satellites or to constellation of LEO/MEO satellites.

Both LEO and MEO satellites, due to their high orbiting velocities, do not represent a favourable solution. In fact, a tracking capability of the satellite might be required to keep the reference antenna pointed towards the transmitter during the acquisition time. Moreover, the fast motion of the satellite leads to fast-varying Doppler frequencies, which may complicate the subsequent processing. Finally, the selection of a constellation of LEO/MEO satellites, needed to ensure continuous system operability, might require hand-over capability from a satellite to another. This is the case of the Iridium constellation, [9]. In fact, despite of the lower EIRP level, a reduced signal attenuation is experienced due to the lower distance to Earth, thus leading to adequate SNR values. However, being Iridium a constellation of LEO satellites for mobile communication, it suffers of the drawbacks mentioned above and, therefore, it has been excluded for further analysis.

It is worth noticing that also satellites for remote sensing such as TerraSAR-X, Radarsat-2, and Cosmo-SkyMed [6,7,8] are able to provide very high EIRP values and appealing signal waveforms. However, they are mounted on LEO platforms and present burst signal transmissions, not making them suitable for a reliable air target detection.

Among the remaining transmitters, adequate transmission power requirements can be guaranteed by systems like Sirius-Xm, Eutelsat W2A, and Inmarsat I-4 EMEA. Sirius-Xm is a GEO system for Digital Audio Broadcast services which transmits only over North America. Therefore, since no signal reception from Europe is possible, Sirius-Xm has been excluded as well for further analysis.

Eutelsat W2A, [10]-[11], and Inmarsat I-4 EMEA, [12], represent a new generation of satellites for mobile communications. They are intended to transmit signals over central and southern Europe, thus representing an appealing solution to develop a prototypal passive radar in Italy.

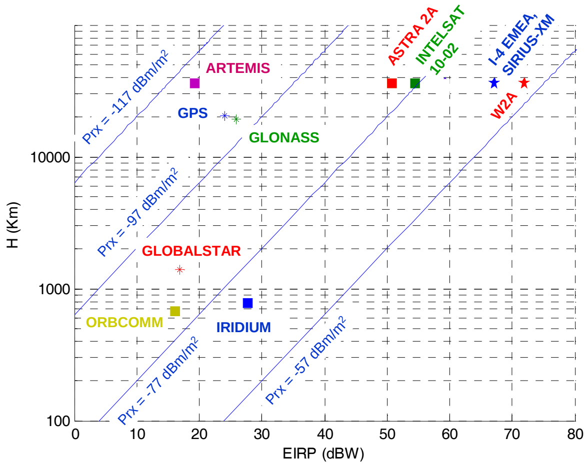

Figure 1- Overview of space-based transmitters

Table 1 - Eutelsat W2A main characteristics

Latitude/Longitude	0.01° N / 10.05 ° E
Height	35840 Km
EIRP	72 dBW (nominal) (59 dBW reduced value used during test campaign)
Carrier frequency	2.17 GHz
Signal Bandwidth	5 MHz
Coverage	Europe

Table 2 - Inmarsat I-4 EMEA main characteristics

Latitude/Longitude	0° / 25.12° E
Height	35800 Km
EIRP	67 dBW
Carrier frequency	1.5 GHz
Signal Bandwidth	200 KHz
Coverage	Europe – Africa – Middle Asia

In particular, Eutelsat W2A is intended to broadcast DVB-SH (Digital Video Broadcast-Satellite Handheld) services for mobile terminals (i.e. smartphones, PDA), equipped with quasi-omnidirectional antennas. On the other hand, Inmarsat I-4 EMEA, has been developed to increase the performance of the BGAN (Broadband Global Area Network) service, providing voice and data links for mobile users all over the world. In Table 1 and Table 2 the main characteristics of the two selected space-based illuminators are reported.

3. PRELIMINARY SNR EVALUATION

The receiver is considered equipped with two different antennas, one pointing directly to the transmitter aiming at collecting the direct signal (reference antenna), while the second antenna is intended to collect echoes reflected from air targets (surveillance antenna). Signals received by the two antennas are separately down-converted and digitized for direct signal removal and 2D-CCF evaluation, [1]. In this preliminary analysis we have neglected losses due to not perfect synchronization between the two channels. Main parameters are sketched in Table 3.

Table 3 – Main parameters for SNR evaluation

Target RCS (σ)	13 dB
Receiver noise figure (F)	5 dB
Receiver antenna gain (G_{RX})	21 dB
Integration time (τ)	1 sec

The direct path SNR is considered as the SNR measured on the reference channel before integration, with the reference antenna pointing in the direction of the transmitter. The SNR measured on the direct path is calculated all over Italy, with contour plots reported in Figure 2, and Figure 3 for the two transmitters under analysis.. The SNR variations in the maps are mainly due to the antenna transmitting beam pattern, due to the long distance Satellite-Earth surface.

As it is apparent, direct signal SNR values are slightly higher for I-4 EMEA, even if this system transmits a lower EIRP. This is due to the different signal bandwidths of W2A and I-4 EMEA (see Table 1 and
Table 2), which results in different receiver noise powers.

The reflected path SNR is measured on the surveillance channel after 1 second of integration (see Table 3), for a target inside the surveillance antenna beam. Obtained results are reported in Figure 4 as a function of the target-RX distance, for a receiver located in Rome, Italy.

By fixing a minimum SNR value of about 8 dB to guarantee reliable target detection, a maximum target distance of about 50 km and 90 km is derived for I-4 EMEA and W2A, respectively. Therefore, from a preliminary SNR analysis, a mid-range passive radar system for air target detection based on space-based transmitters seems to be feasible.

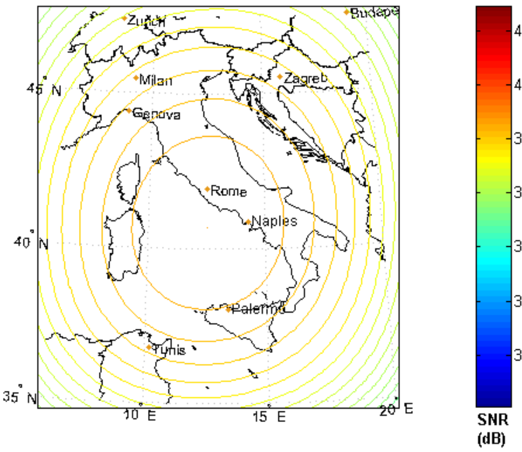

Figure 2 – W2A direct path SNR (nominal EIRP)

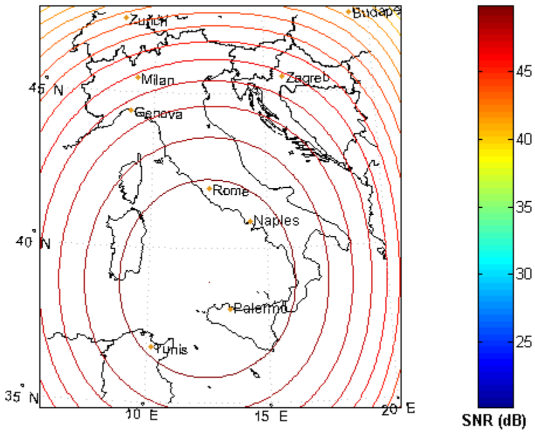

Figure 3 – I-4 EMEA direct path SNR

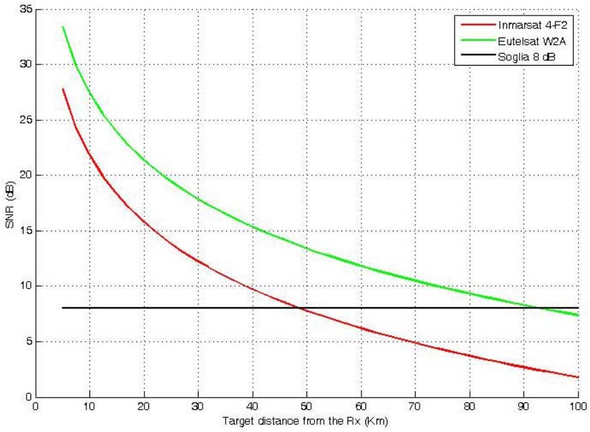

Figure 4 – SNR on reflected path

4.DOPPLER FREQUENCY ANALYSIS

The analysis of the Doppler frequency is of a particular interest for the considered geometry. The overall bistatic Doppler frequency can be expressed as:

$$f_d = \frac{1}{\lambda}\left(V_{TX} + V_{RX}\right), \tag{1}$$

where V_{TX} represents the target velocity vector projection along the target-transmitter (TX) direction, while V_{RX} represents the target velocity vector projection along the target-receiver (RX) direction. In general, these projections both depend on the 3D target velocity vector orientation, and on the relative positions of target, TX, and RX.

Doppler component due to target-TX relative motion

In our particular geometry, characterized by a space-based transmitter and a ground-based receiver, the behaviour of the two Doppler contributions is quite different. In fact, due to the very long distance between target and TX, the projection of the target velocity along the transmitter-target direction can be assumed, in good approximation, locally constant over the coverage area. In other words, the relative positions of target and TX do not vary significantly over the area of interest, hence the target-TX Doppler frequency contribution only depends on the orientation of the target velocity vector in the 3D space.

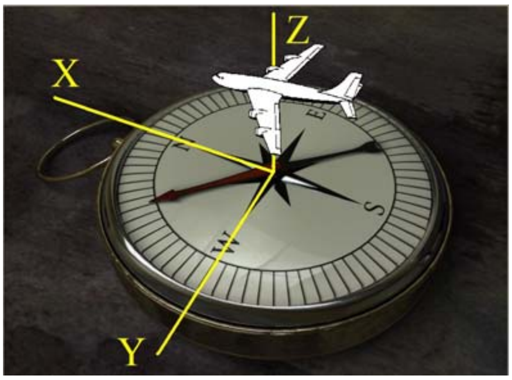

Figure 5 – Reference system

By fixing a specific target trajectory, variations of the V_{TX} component can be appreciated only over a very wide area. To this end, we have evaluated the V_{TX} component for a target flying at a height of 30000 feet with a velocity of 220 m/s, varying its position over the Earth surface. The analysis has been conducted without loss of generality, by considering W2A as transmitter. A reference system centered in the target position has been considered, with x-axis pointing to the North, y-axis pointing to the West, and with z-axis normal to the (x,y)-plane forming a right-handed reference system, as sketched in Figure 5.

The V_{TX} term can be projected along the three axes, leading to the maps of Doppler components $V_{TX}^{(x)}$, $V_{TX}^{(y)}$, and $V_{TX}^{(z)}$ reported in Figure 6, Figure 7, and Figure 8, respectively. The satellite is considered visible if it is seen at least 5° over the horizon, thus leading to a windowing of the maps. Moreover, the transmitter coverage beam pattern is also approximately super-imposed to the maps with a circle.

By fixing a position for the ground-based receiver over the Earth surface (e.g. central Italy in our case study), the decomposition of the Doppler component related to V_{TX} into the three contributions (i.e. $V_{TX}^{(x)}$, $V_{TX}^{(y)}$, and $V_{TX}^{(z)}$) is fixed all over the area coverage.

Doppler component due to target-RX relative motion

Differently from the analysis conducted above, the Doppler component due to the relative motion between target and RX (i.e. V_{RX}), is highly variable over the coverage area in the most general case. This is due to the relatively small target-RX distance. The Doppler analysis of air target detection with a ground-based receiver has been deeply analyzed in past literature [13], and, hence, it is here omitted.

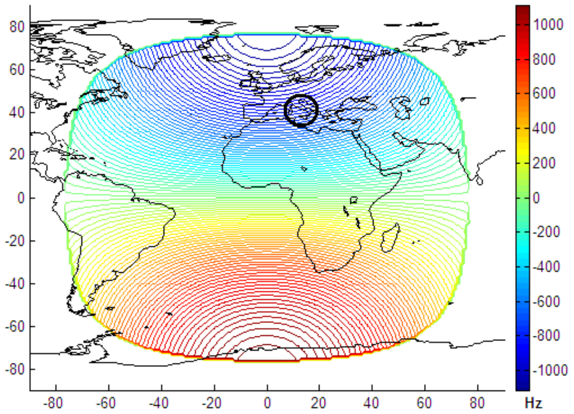

Figure 6 – Map of Doppler contribution due to $V_{TX}^{(x)}$

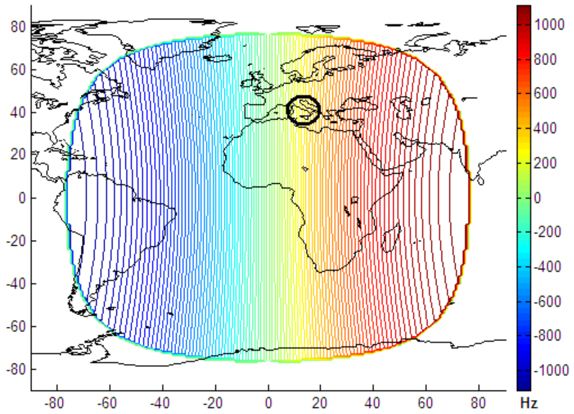

Figure 7 – Map of Doppler contribution due to $V_{TX}^{(y)}$

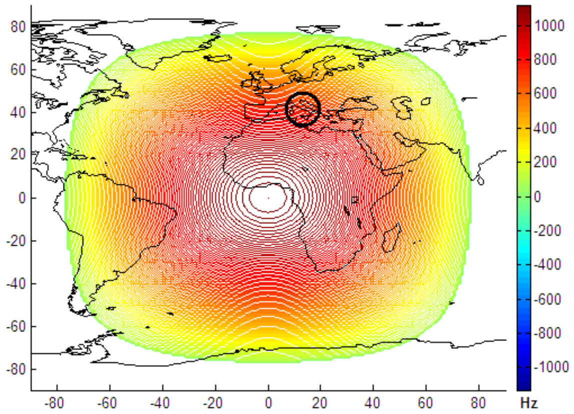

Figure 8 – Map of Doppler contribution due to $V_{TX}^{(z)}$

5.PRELIMINARY EXPERIMENTAL MEASUREMENT

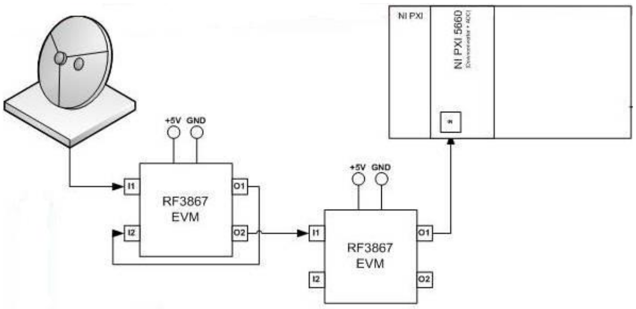

Figure 9 – Block diagram of the experimental setup

In Figure 9 the block diagram of the preliminary receiver is sketched. The receiver is composed by an antenna, a Low Noise Amplifier (LNA). Then, we have to use a NI-PXI-5600 to obtain the sampled signal.

Our antenna has the following characteristics:

- Frequency: 1500 ÷ 2200 MHz;
- Gain: 21 dB;
- Main lobe (-3 dB): 8° ÷ 12°;

The antenna feed is a Short Back Fire Antenna (SBFA) composed by two different reflectors of 0,3λ÷0,7λ and 1,5λ÷2,5λ meters (where λ indicates the wave length).

The LNA stage is composed by two amplifier RF3867; each amplifier RF3867 is composed by two different channel on single evaluation board and it has a useful range frequency from 700 to 3800 MHz.

The NI PXI-5600 permits to obtain the single fully coherent down conversion stage and a high quality ADC conversion with wide dynamic range (software selectable), controlled by an external stable and tunable oscillator.

In Matlab environment the baseband signal is obtained.

In the following, we report the results obtained by considering only W2A as transmitter of opportunity. The same analysis on the Inmarsat-4F2 system has been conducted.

Power level measurements

The theoretical value of the direct power signal can be expressed as:

$$Ps = \frac{EIRP_{TX} \cdot \lambda^2 G_{RX}}{(4\pi z)^2 L} \qquad (2)$$

Where

- $EIRP_{TX}$ indicates the level of Equivalent Isotropic Radiated Power of W2A satellite;
- λ is the wavelength;
- G_{RX} represents the antenna gain of the receiver;
- L is the loss due to the connector etc.
- z represents the distance between transmitter and receiver.

The considered values to calculate the power signal are report in the Table 4.

Table 4 – Theoretical power evaluation of the signal

	Eutelsat W2A	**Mean value of Direct power signal measured on different acquisition**
$EIRP_{TX}$ [dBW]	59	**-47,60 dBm**
Antenna Gain [dB]	21	
Loss [dB]	5	
Height	GEO Orbit	
Carrier frequency	ISM Band	
Direct power signal [dBm]	**-47,30**	

In Table 4, the mean value of the direct power signal measurements to different acquisition are also reported. As it is apparent, this value is comparable with the theoretical value obtained by the Equation (2).

Signal Bandwidth

In the Table 1, the nominal bandwidth of the transmitted signal from W2A satellite is reported. In the DVB-SH standard a band guard for useful data is foreseen so the theoretical bandwidth signal is less of the nominal value of 5 MHz; in this specific case, according to DVB standard, we can evaluate the bandwidth signal as $BW_{useful} \cong 4.75$ MHz.

In Figure 10 we show the density power spectrum of a signal acquisition. As it is apparent, the bandwidth signal obtained is comparable with the theoretical results. Moreover, the error between the measurement and the theoretical value is less of 160 Hz; this value represents the step frequency used to estimate the density power spectrum.

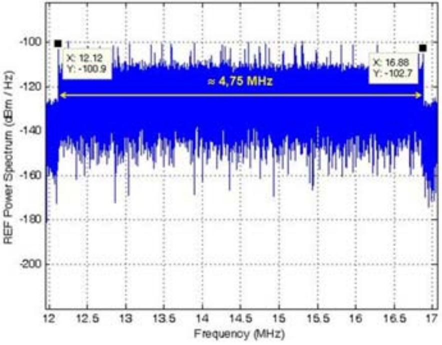

Figure 10 – Density power spectrum of the signal

Demodulation of the signal

The DVB standard allows three different constellations to modulate the data, QPSK, 16-QAM and 64-QAM respectively. The modulation of the data is normalized to achieve E{zz*}=1 (z indicates the generic symbol of the constellation).

The demodulation of the data, which are inside of OFDM symbol, can be achieve after the synchronization and coarse channel estimation steps.

In the following we report the results obtained only in a generic acquisition signal, without loss of generality. The synchronization algorithms have been applied to dataset, yielding the results shown in the Table 5.

Figure 11 and Figure 12 show the results obtained without or with an coarse channel estimation respectively.

The channel estimation is achieved exploiting only the information and the position of continual pilots inside the OFDM symbol. As expected, the channel contribution does not permit a correct evaluation of symbols.

Table 5 – Synchronization results

		Value
ML Estimator	Delay estimate (ms)	0.018
	Frequency offset estimate (Hz)	135.00
Fine Synchronization	Integer frequency offset estimate (KHz)	0
	Sampling frequency offset estimate	1.83 10^{-6}
	Fractional frequency offset estimate (Hz)	0.02

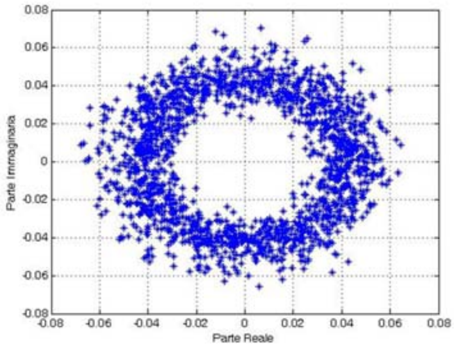

Figure 11 – Constellation obtained before the coarse channel estimation

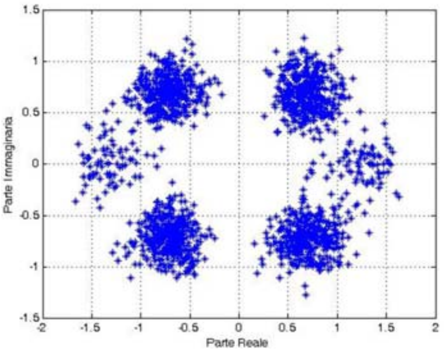

Figure 12 – Constellation obtained after the coarse channel estimation

6.CONCLUSIONS

In this paper, the possibility to design a passive radar system for mid range air traffic control based on spaceborne illuminators has been evaluated. Among different existing orbiting satellites, a new generation of high-EIRP GEO transmitters has been identified. The possibility to resort to a quasi-stationary transmitter highly simplifies the signal processing required by the passive radar system. Moreover, no tracking of the orbiting satellites is required. The high transmitted power level, together with the simplified geometry due to geostationary orbits makes feasible, at least from a simulated point of view, such a space-based passive radar system. A preliminary evaluation of the achievable SNR has been conducted, showing that mid-range target detection can be guaranteed with reliable performance. In addition, a analysis of the Doppler frequency contributions due to the relative motion between target and transmitter has been conducted. Finally, a preliminary experimental measurement in term of power level, bandwidth signal and demodulation of the signal have been reported.

7.REFERENCES

[1] Griffiths, H.D.; Baker, C.J.; “Passive coherent location radar systems. Part 1: performance prediction”, IEE Proc. on RSN, June 2005.

[2] Colone, F.; O'Hagan, D. W.; Lombardo, P.; Baker, C. J.; "A multistage processing algorithm for disturbance removal and target detection in Passive Bistatic Radar", IEEE Trans. on AES, April 2009.

[3] Colone, F.; Cardinali, R.; Lombardo, P.; et alii “Space-Time CMA for multipath removal on the reference signal exploited by Passive Bistatic Radar”, IET Proc. on RSN, June 2009.

[4] European Telecommunications Standard Institute, “Digital video broadcasting (DVB); framing structure, channel coding and modulation for digital terrestrial television”, EN 300 744, V1.1.2, 1997.

[5] Saini, R.; Cherniakov, M.; “DTV signal ambiguity function analysis for radar application”, IEE Proc. on RSN, June 2005.

[7] Ali, Z.; Kroupnik, G.; Matharu, G.; Graham, J.; Barnard, I.; Fox, P.; Raimondo, G.; "RADARSAT-2 space segment design and its enhanced capabilities with respect to RADARSAT-1", Canadian Journal of Remote Sensing Volume 30 No. 3, June 2004, pp 235-245.

[8] Impagnatiello, F.; Bertoni, R.; Caltagirone, F.; "The SkyMed/COSMO system: SAR payload characteristics", IGARSS '98, vol.2, no., pp.689-691, 6-10 Jul 1998.

[9] Fossa, C.E.; Raines, R.A.; Gunsch, G.H.; Temple, M.A., "An overview of the IRIDIUM low Earth orbit (LEO) satellite system," Aerospace and Electronics Conference (NAECON) 1998 Proc., pp.152-159, 13-17 Jul 1998.

[10] Arcidiacono; Finocchiaro; et alii; “S-Band: A New Age in Mobile Satellite Services”, 4th Advanced Satellite Mobile Systems 2008, pp. 128-133, 26-28 Aug. 2008.

[11] Chuberre, N.; Courseille, O.; Bodevin, F.; “Digital video broadcast to handheld via hybrid satellite /terrestrial network”, Alcatel Telecom. Review.

[12] Guy, R.F.E.; et alii; “Synthesis of the Inmarsat 4 multibeam mobile antenna”, Bae System, Astrium.

[13] Willis, N. J.; “Bistatic radar”, Scitech Publ. Inc., 1995.

[14] Langellotti, D.; Colone, F.; Bongioanni, C.; Lombardo, P.; "Comparative study of Ambiguity Function evaluation algorithms for Passive Radar ", Proc. of IRS 2009, Hamburg, Germany, pp. 325-329.

[15] D. Cristallini, M. Caruso, P. Falcone, D. Langellotti, C. Bongioanni, F. Colone, S. Scafè, P. Lombardo, “Space-Based Passive Radar Enabled by the New Generation of Geostationary Broadcast Satellites”, 2010 IEEE Aerospace Conference, March 6-13, 2010, Big Sky, Montana (USA).

[16] D. Langellotti, C. Bongioanni, F. Colone, P. Lombardo, “Impact of Synchronization on the Ambiguity Function shape for PBR based on DVB-T signals”, 11th International Radar Symposium IRS-2010, June 16-18, 2010, Vilnius, Lithuania.