The transponder data recorder: Implementation and first results

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INTRODUCTION

The secondary surveillance radar (SSR), that is an evolution of the military identification friend-or-foe systems, is widely used by air traffic control service providers to localize and identify co-operating aircraft equipped with a standard transponder [1]. The ground SSR installation transmits interrogations, from a rotating, narrow azimuthal beam antenna. The airborne transponders, once they have received an interrogation, transmit at a 1,090-MHz carrier a reply signal containing the requested data, i.e., identity (*mode A* reply) or flight level (*mode C* reply). Azimuth and range of the aircraft are measured by the interrogator, based on the delay of the reply and on the antenna pointing angle. The current SSR standard is based on the use of selective interrogations and replies and is called mode S: to reduce the interferences, the mode S protocol is based on a message format that includes the unique address of the aircraft. The airborne segment of the SSR is composed of the transponder and a pair of antennas on top and on the bottom of the fuselage. As the aircraft antennas are omnidirectional, many ground stations can receive the replies. This allowed the development of multilateration (MLAT) systems for the aircraft localization based on 1,090-MHz signals [2]. A typical MLAT system is composed of a distributed network of 1,090-MHz sensors, an interconnecting facility, and a central processor for the fusion of the sensor data. The data fusion relies on the estimation of the signals arrival time at the different stations and on hyperbolic localization. To identify the emitters, the processing is done with mode A replies or mode S replies that contain the emitter identity. A transponder with mode S capability can also transmit a particular downlink format message, called *squitter*, containing the aircraft's unique address and other information. The *squitter* signals are not elicited by the SSR interrogation, but they are spontaneously emitted at pseudoperiodical intervals. They are the basis of the automatic dependent surveillance-broadcast (ADS-B) concept [3]: the ADS-B OUT function periodically transmits information (identity, position, state, etc.) about the aircraft, and the ADS-B IN function receives the messages from nearby traffic. On the airborne side, the ADS-B OUT broadcasts data with onboard equipment using the *squitter* signals. The airborne ADS-B IN equipment provides to the pilot the traffic scenario, receiving the messages from ground and nearby aircraft ADS-B OUT. Moreover, the ADS-B IN can receive other ground services: the traffic information services-broadcast (TIS-B) and the flight information services-broadcast (FIS-B) [3]. Airport vehicles can be equipped with an ADS-B OUT, a simplified, nonflyable device transmitting 1,090-MHz *squitter* signals containing the identity and the position. As a matter of fact, there are various users of the 1,090-MHz channel: 1) SSR transponder replies (modes A, C, S); 2) ADS-B OUT messages; 3) MLAT systems with interrogation capability; and 4) TIS-B.

The terminal area around a large airport can be characterized by the presence of a large amount of transponders and vehicular *squitter* beacons. Considering also the presence of a TIS-B station, there is likely to be high traffic load on the 1,090-MHz radio channel. It has been shown by different studies that in a high-density traffic scenario, the probability that 1,090-MHz signals interfere with each other is not negligible [4]–[7]. The SSR with a narrow beam antenna and perhaps using the selective mode can limit interference, but in a receiver using a wide-beam antenna (such as MLAT or ADS-B IN), the interference problem is much more severe. In fact, a signal can be overlapped by others arriving from any direction, and the consequent cor-

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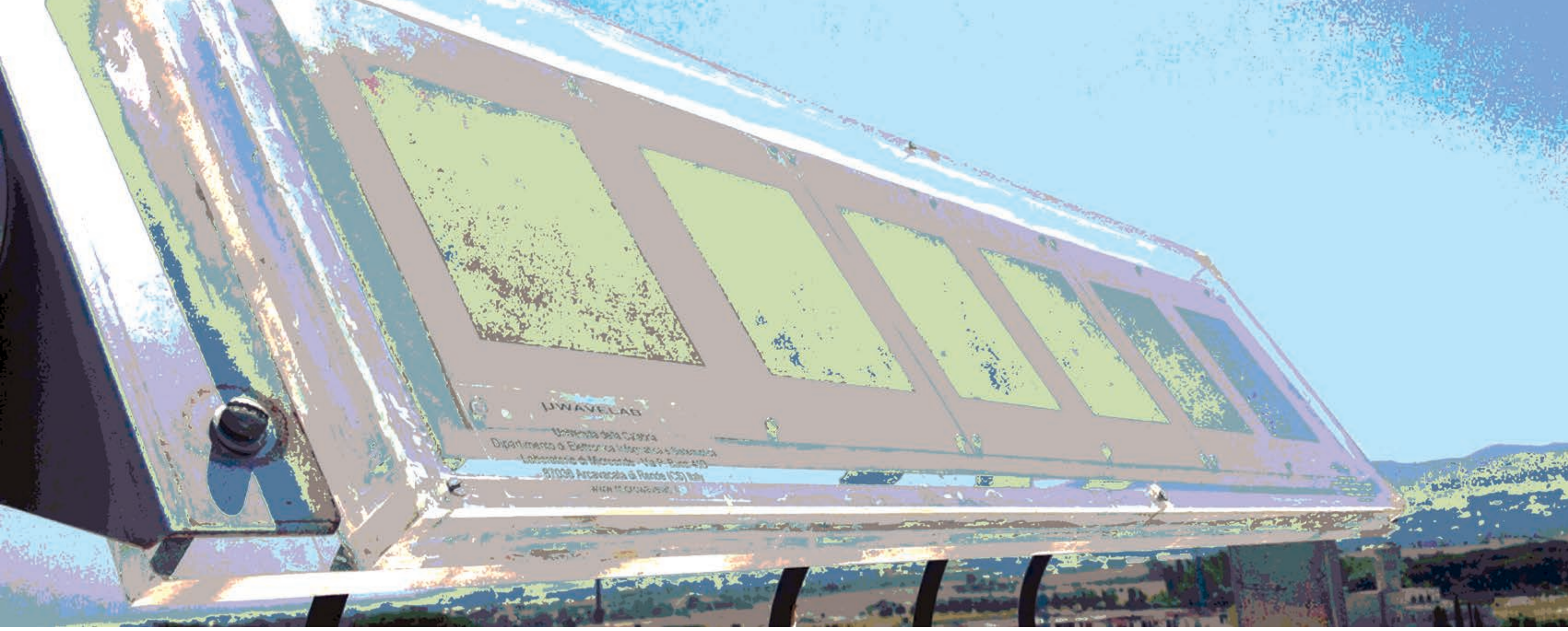

ruption of this signal is likely to lead to the loss of the transmitted information.

To mitigate the problems related to 1,090-MHz signal interference, a research programme concerning algorithmic methods has been carried out in an international collaboration led by Delft University, Delft, The Netherlands, and Tor Vergata University, Rome, Italy. The algorithms that have been developed are used to detect interferences between two or more signals and to apply a blind source separation delivering unmixed 1,090-MHz signals to the decoder section, resulting in an increased channel capacity. Alternative methods, also based on array signal processing, have been developed [8], [9], [10].

In this context, it is useful to have a signal receiver and recorder that provides some 1,090-MHz channel live traffic to be used as test data for the algorithms. Therefore, a receiver for the 1,090-Mhz band was designed and developed. It is named Transponder Data Recorder (TDR); it is a multichannel receiver, designed, and realized at the Radar and Navigation Laboratory of Tor Vergata University, with the collaboration of University of Calabria (antenna design and realization), and Delft University/University of Reims (analog front-end design and signal processing algorithms). The TDR system allows the reception, recording, and application of different signal processing techniques to the 1,090-MHz traffic. It is also possible to analyze the channel load and its characteristics and to test and evaluate the algorithms under development.

TDR SYSTEM DESIGN AND IMPLEMENTATION

The TDR is a multichannel receiver composed of four independent linear channels and one logarithmic channel. Each receiving channel is connected to an array element. This layout permits the use of array processing techniques with the linear channels but also the use of TDR as a monochannel receiver. The logarithmic channel, which provides a baseband signal, is used in those applications that are based on signal amplitude and also as a signal detector. The system is deployed by the engineering faculty of Tor Vergata University in Rome, Italy. The antenna system, which is an array of six patch elements, is placed on the building roof. Figure 1 shows a photo of the experimental setup.

The system has been designed to receive 1,090-MHz signals from airborne transponders at ranges from 100 m up to 200 km and from vehicular transponders from 5 m up to 5 km. The Tor Vergata University RadarLab owns and

Figure 1.
Photo of the antenna installation (shown in dashed circle).

uses two operational SQUID vehicular transponders provided by ERA [14]. The sensitivity, the dynamic range, and the receiver bandwidth necessary to attain the specifications have driven the design for the analog front end. The digital section of the system samples, digitizes, and records the signals to allow offline signal processing after recording. The chosen digital section is an integrated commercial solution, with three acquisition cards, each one with two input channels (National Instruments PXI-5122), with a sampling rate up to 100 Msamples/s, able to acquire the linear channels directly at the intermediate frequency (21.5 MHz). This digital acquisition system provides a software development environment, useful to implement the receiving and decoding routines. It is usable not only as a TDR component but also for other applications. Figure 2 shows the overall block diagram of the TDR system.

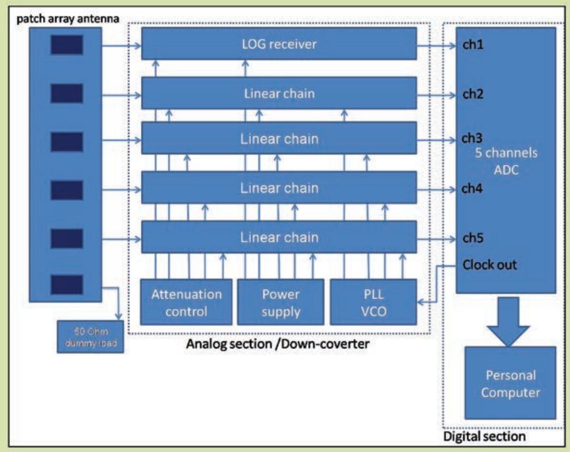

Figure 2.
Overall structure of the TDR.

THE ANTENNA

The antenna is an array of six patch elements, placed at a half wavelength distance over a metallic ground plane. It was designed and implemented by the Microwave Lab at Università della Calabria. The return loss of each patch element immersed into the array has been experimentally characterized, and the radiation patterns provided by the various array elements have been measured. Figure 3 shows a photo of the antenna.

Each patch element is placed on a stratified dielectric support, and it is excited by a coaxial probe. The design and implementation provides a return loss greater than −10 dB in a band wider than 40 MHz centered at 1,090 MHz, to maintain signals fidelity for TDR purposes. Figure 4 shows the experimental radiation patterns of each element, according to the measurements developed in the anechoic chamber at Università della Calabria [11]. The radiation pattern has a useful wide pattern in both directions and is able, by setting a proper tilt, to cover both air and surface traffic.

Figure 5 shows the antenna location, in Rome, close to Ciampino Airport and about 30 km away from the Rome International Airport Fiumicino, Leonardo da Vinci. The dotted line highlights the boresight pointing between both airports.

The antenna can be tilted from 0° to 90°. For air traffic recording sessions, the tilt is set at 45°, and for vehicular recording sessions, it is set at 90°.

The four central elements of the array are connected to four linear channels, the side elements smooth the side discontinuity effect for the inner array, and one side patch is connected to the logarithmic receiver, while the other is connected to a 50-ohm dummy load. Finally, the implemented antenna has shown full compliance with the requirements, in terms of passband and coverage. Using the antenna with a ADS-B receiver (the AirNav Systems RadarBox [12]), it was possible to characterize the general antenna behavior in azimuth by plotting the position of the aircraft equipped with ADS transponders. Figure 6 shows the results of this recording session, highlighting the compliance of the measured

Figure 3.
Photo of the six-element antenna.

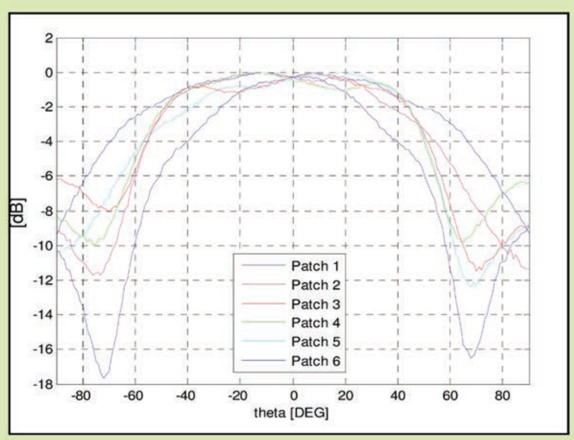

Figure 4.
Radiation pattern of each array element [11].

Figure 5.
TDR antenna location.

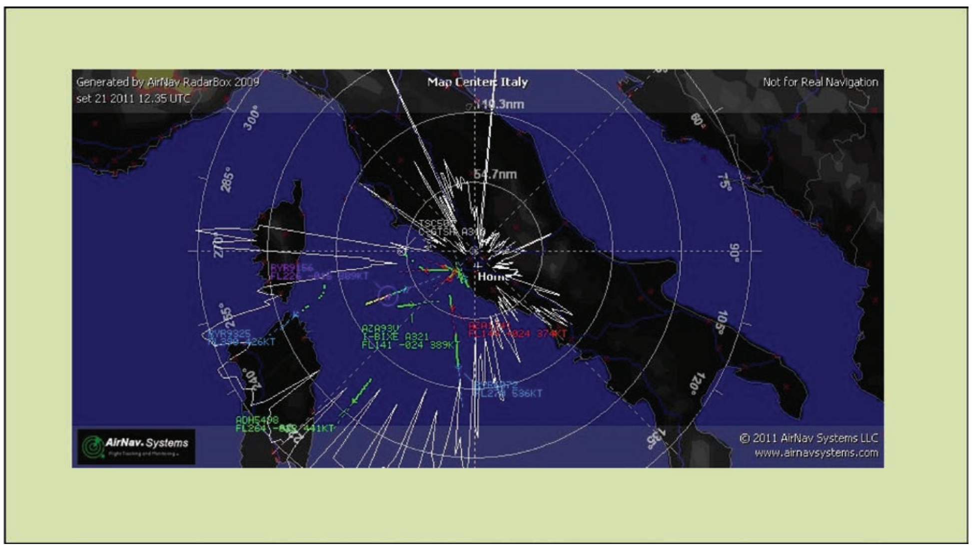

Figure 6.
TDR antenna coverage pattern.

antenna pattern with the typical azimuth beam of a patch, including the secondary lobes.

THE ANALOG FRONT-END

The design of the analog front end for the linear channels and for the logarithmic receiver was driven by the requirements on minimum and maximum targets range. Considering an airborne transponder transmitting between 21 dBW and 27 dBW (International Civil Aviation Organization standard, [13]) and a vehicular nontransponder device emitting between 10 dBW and 13 dBW, and setting the requirements on the maximum/minimum target range (5 km/5 m for vehicles and 200 km/100 m for aircraft), the required dynamic range and sensitivity have been derived: from −94 dBm to −1 dBm for aircraft and from −70 dBm to +1.8 dBm for vehicles.

To be in compliance with the requirements, it was decided to fix the nominal gain of the chain and to shift the dynamic range of the receiver using a variable attenuation, to use the receiver in a "near-airport area," where the closeness of the sources may saturate the receiver, and in an "en route area," where more sensitivity is required. The necessary gain of the chain is demanded to two amplifiers among, which is placed the supplementary attenuation. It is possible to change the attenuation of the logarithmic channel independently from the linear channels.

A linear channel is composed of the radio frequency (RF) section, from the antenna cable to the mixer, and the intermediate frequency (IF) section, from the mixer to the channel output. The RF section is composed by power limiter, a first bandpass filter, the first low-noise amplifier, the variable attenuator, the second low-noise amplifier and the second filter, then the mixer. The IF section is composed by a bandpass filter and a direct current (DC) block. The RF signal is downconverted to the intermediate frequency of 21.5 MHz. This value of the IF permits the use of commercial components for the IF bandpass filter and also permits the direct sampling at 50 Msamples/s as well as at 100 Msamples/s. The local oscillator provides a reference at 1,068.50 MHz; it is composed of a quartz oscillator at 10 MHz and a phase-locked loop (PLL). There is only one PLL in the TDR, and its reference signal is split into four signals to feed each mixer on the four linear chains, then each linear channel uses the same phase reference for the downconversion. Figure 7 shows the block diagram of a linear channel.

The bandpass filters of the RF section are of the surface acoustic wave (SAW) type, characterized by a low insertion loss (2.3 dB) and a good rejection at 1030 MHz (40 dB). The passband at 3 dB is 30 MHz. The low-noise amplifier is characterized by a low-noise figure (0.8 dB) and a nominal gain of 30 dB with a gain flatness of ±0.5 dB in the band. After the

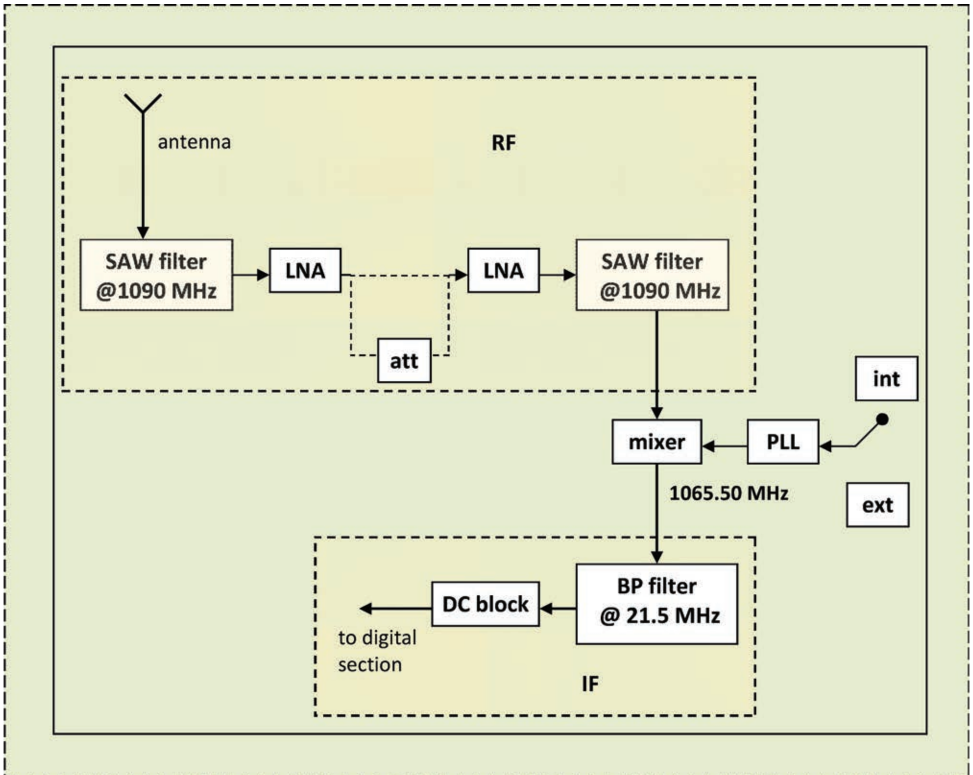

Figure 7.
Scheme of the analog linear channel.

mixer, the signal is converted to IF (21.5 MHz) and filtered followed by a DC block component. The nominal gain of the linear channel is 40 dB. The logarithmic channel is quite similar, with the output of the second SAW filter being connected with the logarithmic receiver, having the RF input linear dynamic range of 60 dB, from −65 dBm to −5 dBm.

All the components chosen to realize the analog linear and logarithmic channels are discrete to avoid the costs of developing a printed circuit board. This means that greater space is needed, and there is greater attenuation due to connectors and cables. Moreover, this choice permits an easy change of the components. The analog section of the TDR (linear channels, logarithmic channel, PLL, and power supply devices) is contained in three rack frames; see Figure 8.

THE DIGITAL SECTION

The digital section samples the channels with a common clock, with potential for high sampling rate (up to 100 Msamples/s) to perform a precise reconstruction of the signals from the various channels. To acquire the linear channel directly at IF, the sampling frequency can be set to 50 or 100 Msamples/s, while for the logarithmic channel, a lower value can be 10 MHz. The core of the digital section is based on the NI PXI 1082 controller. There are three acquisition cards (NI PXI 5122), with two analog input channels each. Figure 8 shows a photo of the analog and digital sections of the TDR, and Figure 9 shows a screen shot of the acquisition software developed in the NI programming environment. On the bottom right it is visible, on the control display, a received mode S signal envelope.

THE TDR RESEARCH FRAME

The TDR system is currently operating at Tor Vergata University, with the antenna boresight that may be aimed at two airports that are 6 km and 30 km away (Figure 5). This area is characterized by a fairly high air traffic density. The TDR is involved in 1,090-MHz signal processing methods, in particular, the study and development of algorithms to avoid the problems of signal interference. As stated before, several air and airport surveillance systems are based on airborne and vehicular transponders. Considering the source emissions as asynchronous (transponders with squitter capability), the probability of interferences between signals from different sources are not negligible, especially in area with high-density traffic or when using an omnidirectional receiving antenna. As shown in Figure 10, the correct reception (no interference) probability for an extended squitter (ES) could decrease dramatically as the false replies unsynchronized in time (FRUIT) rate, that is representative of the traffic load, increases.

The plot is obtained from the Poisson distribution $p(n) = e^{-\lambda T} (\lambda T)^n / n!$, which gives the probability of no interference

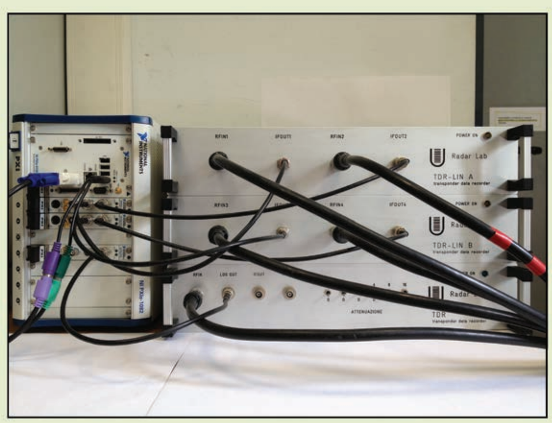

Figure 8.
Digital (on the left) and analog sections of the TDR.

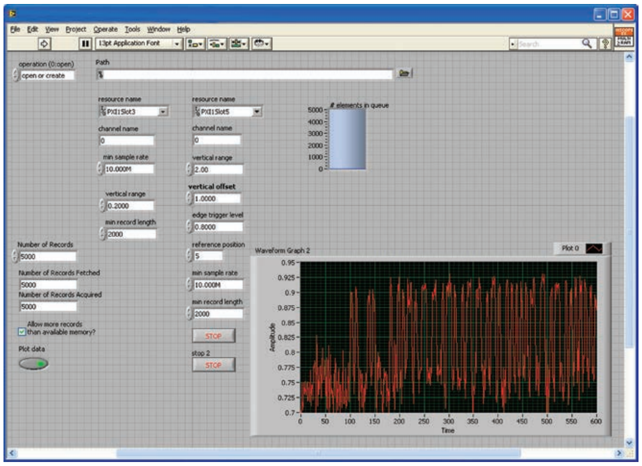

Figure 9.
Screenshot of the developed acquisition software for TDR.

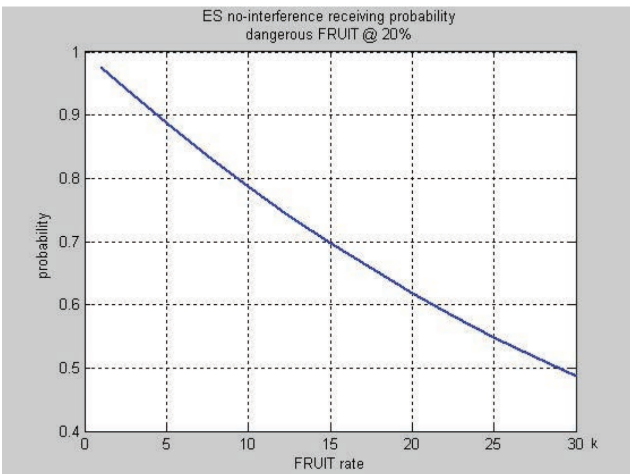

Figure 10.
ES probability of no-interference versus the FRUIT rate.

($n = 0$) in the time support of an ES ($T = 120$ µs) and varying λ (FRUIT rate) from 10^3 s^{-1} to $30 \cdot 10^3$ s^{-1}. Moreover, λ was weighted with the constant 0.2 to take into account that only 20% of the FRUIT emitters are in a range such that their messages could have an amplitude to be considered as interfering.

In this context, one research activity is focused on the study of blind source separation signal processing algorithms useful to detect and solve interference event. The usage of the TDR consists of 1) the recording and signals detection, using the logarithmic channel to analyze the traffic characteristics and obtain statistical indicators to implement an air traffic model; 2) the acquisition and recording of signals by the linear channels to be used as live signals database for the signal processing algorithms tests; 3) acquisition and recording session using the ERA SQUID [14] vehicular squitter beacon; and 4) implementing a software for signals detection and decoding, capable to extract the sources, to evaluate the system performance for vehicular localization. The following three subparagraphs present the mentioned activities.

CHANNEL TRAFFIC MODEL

Using the logarithmic channel of the TDR, it is possible to record the data stream to perform a channel traffic analysis. The analysis of the received signal powers, considering the receiving chain gain, the antenna gain, and the assumed transponder power, allows us to estimate the range distribution of aircraft that transmitted the received signals. The detection and decoding of 1,090-MHz signals allows us to measure the traffic load and its characteristics, including interference rates. The FRUIT rate in the area around the actual TDR installation is low, but the probability of receiving mode S signals with interference is not negligible (about 8% over all the received mode S signals) [9]. A complete air traffic model is useful for the evaluation of the effectiveness of the implemented algorithms.

BLIND SOURCE SEPARATION ALGORITHMS FOR 1,090-MHZ SIGNALS

Receiving superimposed signals from different sources often results in the complete loss of the received signals, especially with a standard decoder in compliance with Appendix I of [3], as shown in [8]. In fact, interfering signals, although emitted by different sources, have nominally the same central frequency and the same spectral occupancy. Proposed new methods are a single channel blind source separation (BSS) algorithm [9] and space-time algorithms that need a multichannel receiver and an antenna array [8]. What is useful for our scope is the *sparsity* property of the sources. Other methods have been proposed, see, for instance [15], exploiting the array angular response and the measurement of the direction of arrival of 1,090 MHz. Such methods call for array calibration, a rather complicated task in real-time and field applications. Conversely, our methods do not require any calibration, as they exploit the signals diversity in terms of different impinging directions at the array. The sparsity property permits the use of time supports in which only one source is present to derive the beamformers, as described in the following: consider the matrix of the received channels, $\mathbf{X}=\mathbf{MS}+\mathbf{N}$, where $\mathbf{M}$ is the mixing matrix, $\mathbf{S}$ is the source matrix to be estimated and $\mathbf{N}$ is the noise matrix. From $\mathbf{X}$, it is possible to extract two submatrices, $\mathbf{X}_1$ and $\mathbf{X}_2$, containing only the first source and only the second source, respectively. The columns of matrix $\mathbf{M}$, $\mathbf{m}_1$, and $\mathbf{m}_2$, are estimated with a singular-value decomposition of $\mathbf{X}_1$ and $\mathbf{X}_2$. The beamformers, $\mathbf{w}_1$ and $\mathbf{w}_2$, are then derived by the Moore-Penrose pseudoinverse of the estimated $\mathbf{M}$: $\mathbf{w}_1$ is orthogonal to $\mathbf{m}_2$ and $\mathbf{w}_2$ is orthogonal to $\mathbf{m}_1$. In a two-dimensional space representation, $\mathbf{w}_i$ can be interpreted as the orthogonal projection of $\mathbf{m}_i$ on $\mathbf{m}_j$, with $i \neq j$. These methods belong to the *projection family* [8]. In this case, the TDR is useful to extend the records for the algorithms trials. TDR will play an important role also for the study and implementation of other BSS methods belong-

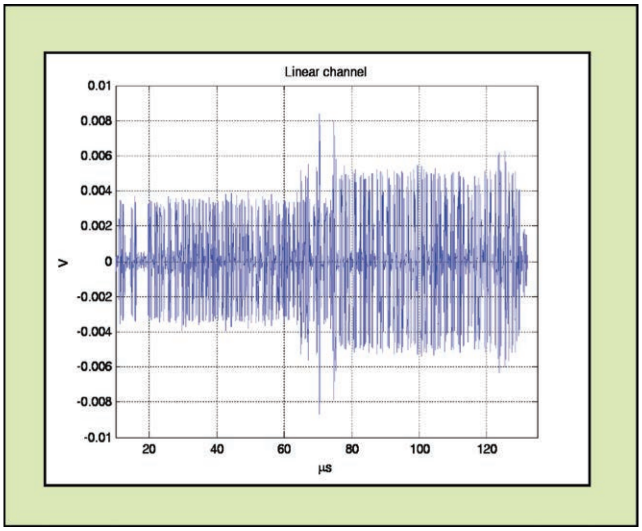

Figure 11.
Two overlapping mode S signals—linear channel.

ing to the *geometric family* [10]. The single-channel method, which is based on joint exploiting of sparsity of sources and their diversity in terms of frequency shift, is under study to complete the evaluation phase. In this case, the TDR is used as a monochannel receiver, acquiring only one linear channel. The single-channel algorithm, named projection algorithm for single antenna (PASA) as illustrated in [9] and [16], separates overlapping sources by exploiting the signals diversity due to the tolerance of the transponder central frequency. PASA is based on a signal vector reshaping that reorganize the acquired signal samples into a matrix. The last results obtained using single-channel signals recorded with the TDR shows a success rate of 93.5% for the leading reply and 64.2% for the trailing reply. These results are obtained over a set of 109 signals composed by two overlapping mode S replies, and a success event is defined when the algorithm application the reply is detectable and decodable without errors. Figure 11 shows one linear channel at IF, where a signal is composed by two overlapping mode S replies. The normalized envelopes shown in Figure 12 are obtained by PASA processing applied to the signal of Figure 11. The planned work on PASA consists of extended tests with more signals and the correlation between the overlapping signals characteristics (frequency shift, time delay, and amplitude ratio) and the algorithm performance.

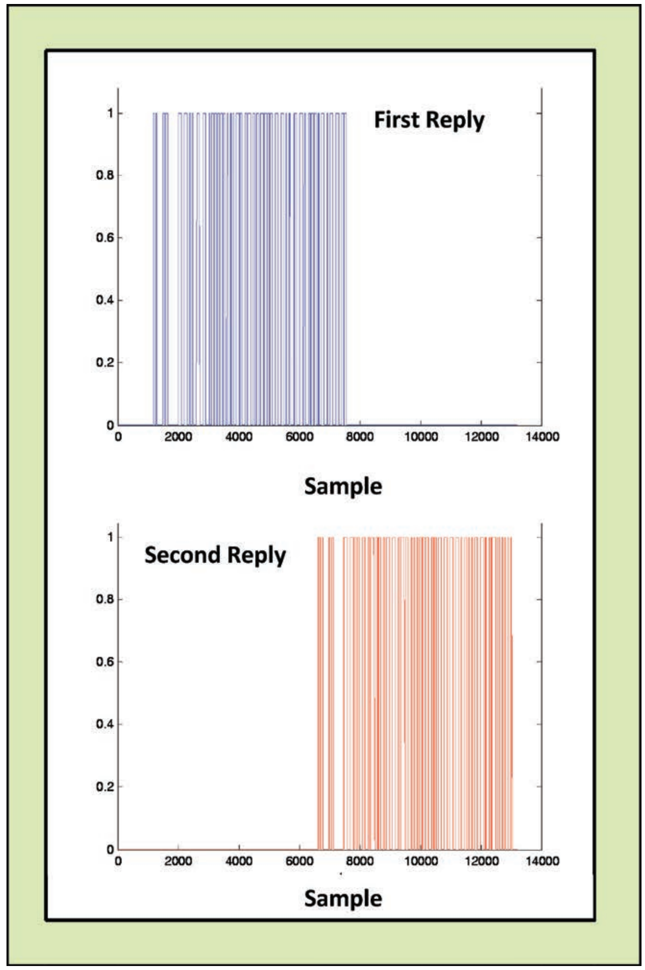

Figure 12.
Source signals degarbled (reconstructed signal envelope) by PASA.

VEHICULAR SQUITTER BEACON TEST

The TDR is also involved in a study devoted to implement enhanced techniques for ground surveillance using a vehicular *squitter* beacon in a complex area such as an airport. The scope is to develop a system and signal processing techniques useful for improving the probability of detection of vehicles and aircraft on the ground. The project, that is at preliminary phase, includes experimental surveillance using a SQUID [14] provided by ERA. Figure 13 shows the SQUID track acquired during a trial. The figure is composed using Google Earth centered on the TDR antenna position. The plots are represented with white squares, and the dotted line is the direction of the antenna boresight.

To complete the project a real time decoding and plot extracting software is needed. The experimental sessions will be useful also to evaluate whether an antenna configuration for rejecting the air traffic signals is necessary. Finally, because ERA supplied two SQUIDS, it will also be possible to analyze signals interferences between two ground sources.

CONCLUSIONS

We have designed, implemented, and tested a flexible receiving and processing multichannel system for signals in the 1,090-MHz band with significant air traffic management applications in surveillance and communication. Thanks to a wide bandwidth and a large dynamic range, with four linear channels plus a logarithmic channel, this TDR allows us to record the signals of interest with minimal distortion, from sources whose distance from the antenna sys-

Figure 13.
Vehicular surveillance test.

tem ranges from a few tens of meters up to hundreds of kilometers. From the recorded signals, it is possible: 1) to characterize the traffic in the 1,090-MHz band, and 2) to test the effectiveness of different source separation algorithms, either based on space diversity or based on frequency diversity. The system permits a higher degree of automation and higher quantity of data acquisition than some previous experimental systems. ◆

ACKNOWLEDGMENT

The authors are grateful to ERA who supplied the two SQUID devices used for the measurements.

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