Digital Signal Processing 56 (2016) 24–34

Contents lists available at ScienceDirect

Digital Signal Processing

www.elsevier.com/locate/dsp

# Radar detection of high-energy cosmic rays in non-Gaussian background using a time-frequency technique

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ARTICLE INFO

*Article history:*
Available online 27 May 2016

*Keywords:*
Cosmic rays
Chirp detection
Bistatic radar
Hough transform
Non-Gaussian noise
Low SNR

ABSTRACT

Cosmic rays are the highest-energy observable particles in the universe. Their study opens a new frontier for scientists to better understand the nature of the universe. This paper reports our study of a bistatic radar approach that is being developed for remote sensing of cosmic-ray induced air showers. In this context, we propose a robust detection technique based on time-frequency domain for the received radar echoes. These echoes are modeled as linear-downward chirp signals, characterized by very short sweep periods, low energies, and corrupted by non-stationary and non-Gaussian background noise. In addition, the related parameters of the received echoes are variable within some expected ranges, determined by the physical parameters of the air showers. In this paper, we explore the performance of the proposed detection method through an extensive theoretical analysis. We derive formulae for probability of the correct detection, as well as false-alarm rate. Numerical simulations and experimental results that corroborate our analysis are also presented.

## 1. Introduction

Chirp signals are ubiquitous in nature. They can be observed in various areas, such as echolocation (bats) [1], geophysics [2], underwater explorations [3], and gravitational waves in astrophysics [4]. Also, they are frequently encountered in various areas of signal processing, such as sonar [5], radar [6], and spread spectrum communications [7,8]. Some of these applications rely on chirp signal transmission as in the case of sonar [5], while others model the received signal after Doppler spread as chirp signals, e.g., in synthetic aperture radars (SARs) [9], and heart sound signals [10]. In this paper, we study the detection of chirp signals that are encountered in a bistatic radar which we are developing for remote sensing of cosmic ray induced air showers. Next, we discuss the background and motivation behind the presented work in this paper.

### *1.1. Background and motivation*

High energy cosmic rays (HECR) have been a subject to study for many years. Their study is considered to be a major step forward in understanding the fundamental nature of the universe [11]. HECR define high energetic particles, much higher than the energy produced by terrestrial particle accelerators, of extraterrestrial origin. The origin and composition of the highest energy cosmic rays is currently unknown. When cosmic rays experience collisions with atoms of the upper atmosphere (about 10 km above the ground), they generate cascades of secondary particles known as extensive air showers (EAS) that propagate through the atmosphere towards the Earth's surface. EAS resulting from cosmic rays produce ionization columns which are detected by such conventional observatories as ground surface-detector arrays and fluorescence detectors. Currently, the Telescope Array (TA) detector, which has been operating in Utah since 2007, employs two detection mechanisms: three fluorescence detectors (FDs) that record the ultraviolet light (UV) emitted from EAS, and a grid of scintillation detectors (SDs) that measures the flux of secondary charged particles arriving at the surface [12]. Fluorescence detection is costly and has a low duty cycle (about 10%), since the observations can only be made on clear moonless nights. Scintillation detectors operate with 100% duty cycle, but must cover hundreds or thousands of square kilometers in order to obtain reasonable detection rates. Therefore, a clear motivation exists for moving towards a simpler and more efficient technique such as radar. Our research group, the Telescope Array RAdar (TARA) project, is working on a novel approach based on bistatic radar technology [13]. This technique is promising. It will allow the next generation of cosmic-ray observatories to be built at a fraction of the cost required by current technologies. An additional point to note is that our system setup

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http://dx.doi.org/10.1016/j.dsp.2016.05.010

is co-located with the TA detector, hence allows us to validate the accuracy of the radar system that we are developing.

### 1.2. The research problem

Radar detection of EAS is expected to be a workable solution because of the large ionization densities, at the core of the air shower, which can reflect radio frequencies that lie in the low VHF band. The choice of low VHF band returns to the corresponding plasma frequency which is of order 50 MHz in which range reflection will occur [14]. In a sufficiently radio-quiet environment, EAS ionization is detectable using radar techniques to capture reflected RF radiation. Research studies have shown that the radar cross section is greatest in the forward scattering direction [15] and hence, bistatic or two-station radar is perfect choice in detecting weak returning echoes. Based on the physical characteristics of cosmic ray air showers, radar echoes are expected to be characterized by a rapid phase modulation-induced frequency shift, covering several tens of MHz in a period of 10–15 μs. These signals sweep linearly from a high to low frequency, hence, can be modeled as linear-downward chirps. However, the related parameters of the received echoes are nondeterministic, since they are tied to the physical parameters of the air showers. Thus, unlike most of the existing chirp applications, we are interested in the detection of chirp echoes of variable parameters, center frequencies and frequency rates, within a relatively wide range. In addition, our detection threshold is required to be set as low as possible in order to enhance the ability of detecting signals with signal-to-noise ratio (SNR) in the negative dB range.

Based on collected data from conventional cosmic-ray observatories, chirp-echoes that correspond to high-energy cosmic rays are expected to be rare, at the level of few events per week, and thus, background noise reception is the case most of the time. That makes our radar problem unique and more challenging. Based on our radar environment, background noise is punctuated with persistent single-frequency tones that might originate from different sources around the receiver unit including the radar carrier signal 54.1 MHz. These deceptive tones are powerful, hence may lead to positive false-alarms. The other major source of false-alarm is the sudden noise spikes that cover wide frequency bands. These spurious signals cause an erroneous radar detection decision by exceeding the detection threshold. In this research, we address these issues by proposing a robust signal processing technique for detecting the radar echoes and dealing with existing system challenges.

### 1.3. Review of literature

In a radar problem, the transmitted signal will be subject to a phase shift induced by the distance and relative motion between the target and the receiver. Thus, a chirp signal may be observed. The phase angle of the chirp reflects the related parameters of the radar target including the speed and range. The estimation of parameters is part of our planned research and thus will be reported in our future publications. In the current phase of our radar application, our main interest lies in the detection of the received chirp echoes produced by cosmic-ray induced air showers.

Different techniques have been developed for the detection of linear chirp signals. The developed methods may target the detection problem in different domains: time-domain or frequency-domain or joint time-frequency domain.

The time domain methods include several adaptive algorithms that approach the detection problem as a recursive least squares (RLS) algorithm [16], or a least mean square (LMS) algorithm [17], and a multiple frequency tracker [18]. However, these adaptive techniques suffer performance degradation under low-SNR conditions [19]. Furthermore, matched filters are one of the most commonly used time-domain methods in radar systems. If the parameters of the radar chirp echoes are known, the optimal detector in stationary white Gaussian noise is proven to be a matched filter followed by a threshold comparison [20]. Passing the chirp echo through its corresponding matched filter will result in a high peak at the output of the filter. This output is known as the chirp autocorrelation function which is well studied in many contexts, e.g., [20]. Neyman–Pearson criterion, or likelihood ratio test, is commonly used in evaluating the detection performance of the matched filter for the case of deterministic chirp signal [21]. In the case of multiple deterministic chirp signals, generalized likelihood ratio test (GLRT) detector is considered where a bank of matched filters are used [21]. A mismatch of chirp rates between the received signal and the matched filter will result in phase error and thus, a loss in the output peak value. In our application, as mentioned before, we lack the knowledge of received signal parameters and thus, mismatch of the chirp rate between the received chirp signal and the matched filter(s) at the receiver is unavoidable. The assumption of white Gaussian noise is frequently used in the study of radar and communication systems to greatly simplify their analysis. For various applications, the Gaussian noise assumption is justified, e.g., in microwave terrestrial or satellite links; however, in other cases, including ours, background noise turns to be impulsive and thus of a non-Gaussian nature. These challenges lead us to consider different approaches.

Discrete Fourier transform (DFT) is considered as a standard, as well as useful, tool for spectrum analysis in the area of digital signal processing, typically implemented in efficient way using Fast Fourier Transform (FFT). Fourier transform provides the corresponding magnitude and phase of the signal spectral content. However, it does not provide a time distribution of the spectral components which we would need for linear chirp signals to look at the change of frequency versus time and exploit the hidden features of chirp signals. In the past, joint time-frequency domain (TFD) techniques have been developed for that purpose. These methods apply a transformation such as the short-time Fourier transform (STFT) or the Wigner–Ville Distribution (WVD) to obtain the time-frequency information. Among these techniques, Page's test [22], the expectation-maximization (EM) algorithm [23], and Hough transform (HT) [24] are more broadly used. Other two-dimensional techniques include Radon transform [25] and Radon–Fourier transform [26]. These approaches are more robust than time-domain methods in detecting non-deterministic chirps and overcoming the limitations of matched filters.

### 1.4. Paper contributions

In this paper, we focus our attention to the detection of linear chirp signals using a Hough-transform based technique and propose a strategy for detection of chirp signals with non-deterministic parameters (center-frequencies and chirp-rates). We introduce additions to the proposed detector that optimize the detection performance and greatly reduce the computational complexity. Without loss of generality, we consider the bistatic radar application which we are developing for remote sensing of cosmic-ray induced air showers as a good example in evaluating the performance of our proposed technique. For the case where background noise is additive, white, and Gaussian, we develop analytical expressions for the probability of false-alarm and the probability of correct detection of chirp signals. We illustrate the validity of the white Gaussian noise assumption by showing how our proposed technique efficiently filters the existing non-Gaussian components.