MEASURING SPACE DEBRIS WITH PHASE CODED APERIODIC TRANSMISSION SEQUENCES

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ABSTRACT

We describe a radar transmission scheme with long phase coded pulses and non-uniform inter-pulse periods (IPPs) that gives a full range coverage while maintaining high radar duty cycle. In this scheme, the range ambiguity is mitigated using a combination of phase coding and non-uniform inter-pulse periods. To demonstrate the concept, we show initial results from a recent 21-hour EISCAT UHF measurement conducted soon after the Iridium-Kosmos collision. We also discuss the possibility of using the tri-static EISCAT UHF system for measuring the orbital elements of debris.

Key words: Radar, Aperiodic transmission sequence.

1. INTRODUCTION

Previous space debris work at EISCAT has been done by Markkanen et.al. [1]. These measurements are usually performed as a secondary analysis of routine ionospheric experiments. Due to the high duty cycle and uniform IPPs typically used by EISCAT, most of the space debris experiments have missing ranges. Depending on the case, 20-60% of the ranges are missing because the echos cannot be received during transmission and ground clutter. One way to overcome this is to use non-uniform IPPs, so that the transmission and ground clutter bite-out doesn't always block echos from the same ranges.

The use of non-uniform IPPs has been widely studied. Some of the first plasma autocorrelation measurements were in fact made with short unevenly placed transmission pulses, so called *multi-pulse codes* [2]. Uppala [3, 4] investigated two types of multi-pulse sequences, *simple difference covers* [5], and *aperiodic transmission sequences*, which have recently been used e.g., at Jicamarca [6] for measuring equatorial spread-F echos. Simple difference covers have also been used for weather radar to solve the range-Doppler dilemma [7]. Recently, we have investigated the use of simple difference covers together with long coded pulses [8] for measuring the plasma backscatter autocorrelation in the 50 to 1000 km range.

In this study, we will describe a new experiment with non-uniform IPPs that allows observation of echos at all ranges. This experiment is also suitable for ionospheric measurements at the same time. To demonstrate the method, we show results from a recent EISCAT unusual program run that was conducted to measure the Iridium-Kosmos debris soon after the collision. The ionospheric plasma parameter estimates and space debris detection results for this experiment are promising.

2. NON-UNIFORM IPPS

Simple difference covers are in a sense perfect timings as, when used correctly, they provide each lag and a flat radar efficiency as a function of range [8]. However, the large variability in the IPP lengths makes simple difference covers less attractive for space debris use. Other timings with slightly more variable radar efficiency can also provide much larger range coverage, which is essential in space debris measurements.

Arithmetic modulus coding sequences discussed by Uppala [3, 4] have the desirable property of being able to cover all ranges, while maintaining relatively uniform IPPs. Arithmetic modulus codes are defined as

$$\begin{aligned}\mathrm{IPP} = \{a, a+k \mod p, a+(2k \mod p)\cdots,\\ a+((N-1)k \mod p)\},\end{aligned} \tag{1}$$

where $p \in \mathbb{N}$ is the number of IPPs, p is also a prime. Optimal parameters $a \in \mathbb{N}$ and $k \in \mathbb{N}$ are then found exhaustively. Uppala performed a search for codes that are as uniform as possible, to satisfy transmitter requirements and to make it possible to use estimation algorithms that assume uniform IPPs. The downside of the near-uniformity for high duty-cycle long coded pulse measurements is the the large variation in received echos from different ranges, as shown in Fig. 1.

Another scheme that has less variability than simple difference covers is a simple ramped timing scheme, where

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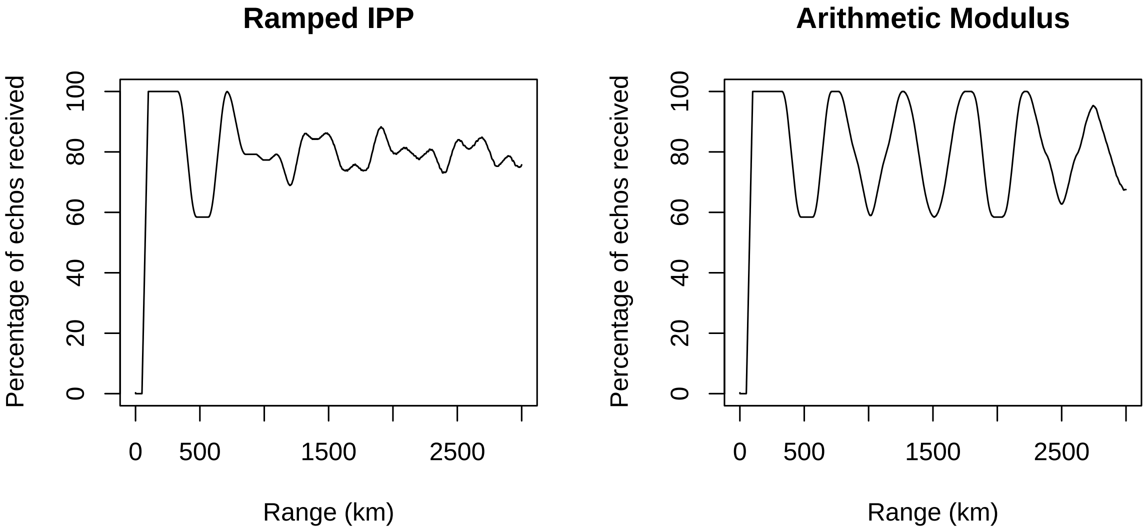
Ramped IPP

Arithmetic Modulus

Figure 1. A comparison of ramped IPP ($N = 53$, $a = 84 \times 30$, $k = 30$), and arithmetic modulus coding ($p = 53$, $a = 84 \times 30$, $k = 14 \times 30$) radar efficency per range. Both experiments have the same duty-cycle and transmission length. The ramped IPPs show less variation in radar efficiency than the arithmetic modulus coding above 1000 km.

we simply gradually increase the IPP during the cycle. This scheme allows high duty-cycle coded long pulse measurements and has less variation in radar efficiency per range than the arithmetic modulus method. The IPPs of the ramped method are defined as

$$\mathrm{IPP} = \{a, a + k, a + 2k \cdots , a + (N - 1)k\}. \qquad (2)$$

A comparison of a ramped and arithmetic modulus IPP radar efficiency as a function of range is shown in Fig. 1. Both have the same number of IPPs and the same transmission pulse length of 330 μs. In addition to this, we assume that another 330 μs are lost due to ground clutter.

Optimal IPP selection for long coded pulse high duty-cycle measurements is still a relatively unexplored topic. Currently the ramped IPP seems promising, but maybe a compromise solution would be possible, with more uniform IPPs than the ramped scheme, and smaller variation in the echo count per range measure.

3. THE SPADE09 EXPERIMENT

In our experiment, we used ramped IPPs with parameters $N = 53$, $a = 84 \times 30$ μs, and $k = 30$ μs. As codes we used 159 random 22-bit codes with a 15 μs baud length. The code cycle length gives sufficient range coverage for space debris and at the same time the experiment is well suited for ionospheric measurements, which is the primary goal of EISCAT.

3.1. Results

As the software for coherent integration doesn't yet support non-uniform IPP experiments, we used a simple power domain detection algorithm. We expect to find more weak events when the raw voltage data is re-analyzed using coherent integration with the FMF [1] method.

The initial goal was to perform a 24-hour run, but due to technical difficulties we only managed to do a 21-hour run. We observed 482 debris events during a 21-hour run, this is approximately 20 events per hour. The Iridium-Cosmos collision debris seems to be visible in the data. The results are shown in Fig. 3.

Visual inspection of echo amplitude envelopes shows that approximately $\frac{1}{3}$ of the objects have an asymmetric shape and can be seen rotation rotating at 10-150 revolutions per second. Exact rotation period could be used for target identification and classification. Also, the ratio of the minimum and maximum radar cross-section could be used as a first order indication of target shape or albedo. One practical case would be to determine the fraction of spherical NaK droplets within other, mostly irregularly shaped objects. An example of the raw echo power from a rotating object is shown in Fig. 2.

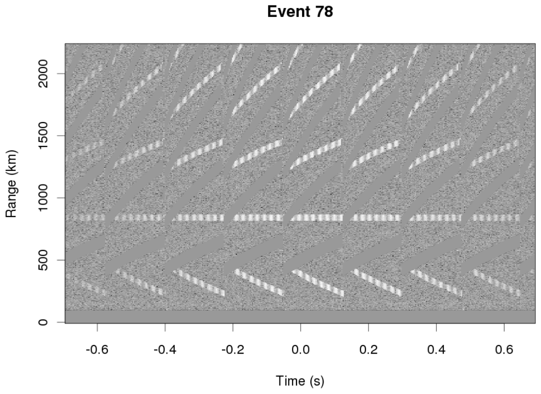

Figure 2. The raw zero-lag echos from a single event at around 800 km. The gray uniformly colored regions are transmission slots from which we do not get echos. However, due to the non-uniform nature of the IPPs, we get some echos from each range during one 0.17 s IPP cycle. The ambiguous echos are ones that fan out around the correct echo. The backscatter cross-section is also fluctuating in a regular manner, most likely caused by an irregularly shaped object that is rotating.

4. DISCUSSION

We introduced a new type of ramped IPP timing suitable for high duty-cycle long phase coded pulses. This kind of a spacing allows fairly uniform radar efficiency as a function of range. There are also obvious benefits for using this kind of an experiment also for incoherent scatter, so we hope to eventually migrate EISCAT routine experiments to ones that allow ionospheric and space debris determination at all ranges.

We have performed a 21-hour trial run of this new type of an experiment with promising results. We were able to successfully make a spade debris and ionospheric measurement with the same experiment. The ionospheric analysis, which was produced using lag-profile inversion [9], is shown in Fig. 4.

The tri-static nature of EISCAT makes it possible to determine orbital elements of objects in the tri-static common volume. We have now installed samplers on all remote stations and planning planning a tri-static campaign this year. One advantage of EISCAT for determining orbital elements is the fact that EISCAT also measures the ionosphere, which can be used to correct ionospheric propagation.

However, EISCAT tri-static operations are possibly ending soon, as the frequency used by the UHF system is going to be reallocated to GSM operators at the remote sites during 2009. A change of frequency would be needed in order to continue tri-static operations in the future.

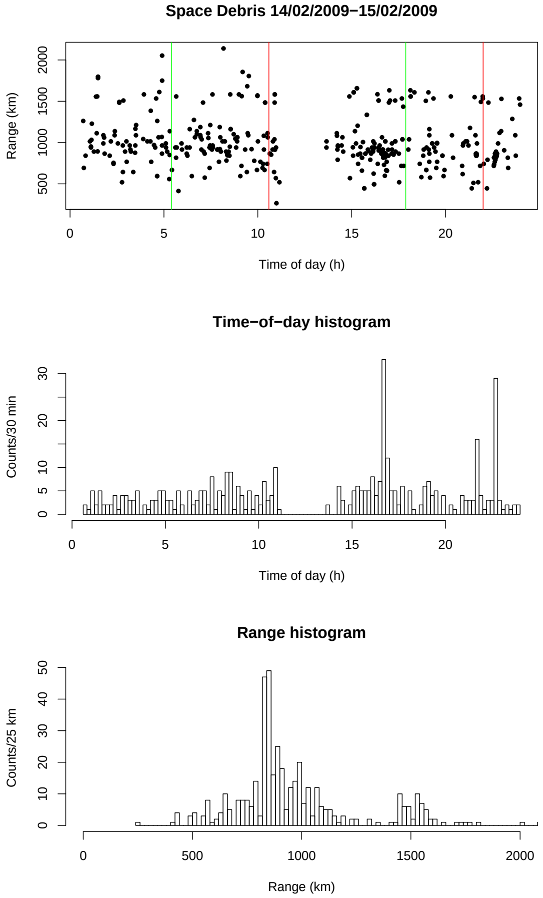

Figure 3. Results for a 21-hour EISCAT Unusual Program run that was conducted soon after the Cosmos-Iridium collision to measure resulting debris. Unfortunately the experiment was not run for a full 24-hours due to technical difficulties.

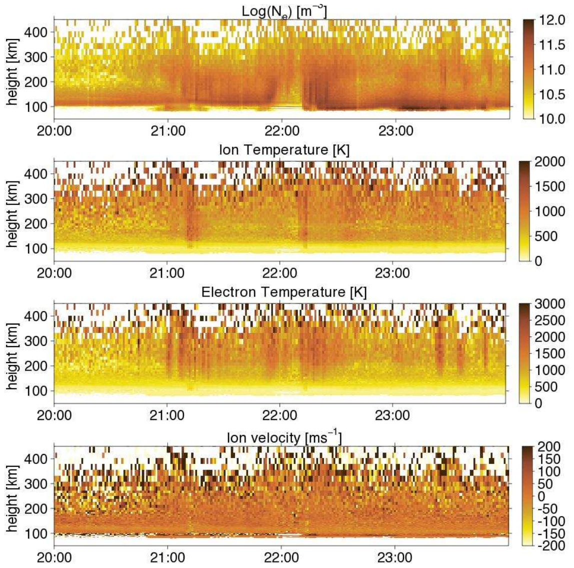

Figure 4. The ionospheric plasma parameters determined from the Spade09 experiment run using lag-profile inversion.

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