The EISCAT_3D Arbitrary Waveform Exciter and Polyphase Constant Amplitude Codes for EISCAT VHF and ESR D/E Layer Experiments

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Abstract

The performance specifications for the EISCAT_3D third-generation phased-array incoherent-scatter (IS) radar mandate a transmitter subsystem with full arbitrary-waveform capabilities and a power bandwidth of more than 5 MHz. An exciter meeting these requirements, based on the AD9957 digital up-converter chip, is currently under development at the Swedish Institute of Space Physics. An overview of the 3D exciter system and the AD9957 and its capabilities, with emphasis on its performance in an IS system, is given. To verify the capabilities of the AD9957 in a real radar environment, two polyphase codes with good D- and E-layer performance have been developed, viz. a QPSK-coded eight-element set of complementary [A, B] sequences and a complementary-coded set of 71-baud Chu sequences. Features of the two codes are described; results from on-the-air tests will be shown.

1. Introduction

From May 1, 2005 to April 30, 2009, a consortium of five parties led by the EISCAT Scientific Association carried out the EU-supported EISCAT_3D Design Study for an incoherent-scatter radar system with 3-D imaging capabilities [1]. The aims of this project were essentially twofold, viz. 1) to study the feasibility of constructing a third-generation incoherent-scatter radar to replace the existing EISCAT VHF and UHF systems, using cutting-edge technology throughout and providing an order-of magnitude improvement in temporal and spatial resolution, and 2) to produce a detailed, costed design for such a system. Extensive consultation with the scientific user community demonstrated that only *a multi-static phased array system with multi-beaming capabilities on both transmit and receive* could reach or approach the performance demanded by present and future users. Tentative system specifications were collected in a Design Specification Document [2], which then served as the target for all subsequent design work. The specifications for beam pointing were particularly demanding: it should be possible to point the beams to any arbitrary position in the array field-of-view in < 500 μs, and to do so non-dispersively over a 30 MHz bandwidth centred on 235 MHz while receiving and over at least 5 MHz while transmitting, thus *requiring true time-delay beam steering both in the transmit signal path and in the receive path.* At the same time, the transmitter system had to be future-proof, i.e. allow the seamless introduction of new modulations, including arbitrary combinations of amplitude and phase modulation, without any hardware modifications.

2. The EISCAT_3D transmitter system

In the system design which eventually evolved (an overview can be found in [1]), the transmitting side beam-steering/arbitrary-waveform requirements are met by providing each antenna array element with a self-contained transmitter subsystem, comprising a digital arbitrary waveform generator (AWG) and a linear (class-AB) RF 300-W power amplifier unit with an instantaneous –1 dB power bandwidth ≥5 MHz. This subsystem is capable of generating arbitrary waveforms with essentially flat power spectral distributions over the allocated band (230.0-236.7 MHz), while at the same time implementing both time-delay beam-steering and array aperture tapering on transmit, if desired, by FIR filtering the baseband waveform data in software and/or firmware before feeding it into the AWG. This also allows the application of tailored spectrum masks to all transmissions, something which might turn out to be required at all times in order to reduce adjacent-channel emissions in the T-DAB channels above and below the 3D spectrum slot (actively used for regional broadcasting in northern Norway) to harmless levels.

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Clearly, for this scheme to be practically and economically feasible, arbitrary-waveform generators must be available as low-cost building blocks, as thousands of them will be required. At the beginning of the Design Study in late 2005, a limited number of digital up-converter ASICs designed for the cellphone base station market and incorporating the desired AWG functionality were available, but at that time none of these devices was fast enough to generate the 235-MHz EISCAT_3D transmitter carrier frequency directly. Meanwhile, steady progress towards higher clock frequencies has been made and now at least one silicon subsystem providing the required performance is available. This device, the AD9957 by Analog Devices, Inc., is currently being evaluated at IRF with the aim of eventually applying it as the core building block of a future EISCAT_3D exciter system.

2.1 The AD9957-based EISCAT_3D exciter

The AD9957 [3] is a 1-GHz universal I/Q modulator and frequency-agile upconverter. It is available off-the-shelf and relatively inexpensive; current pricing is around USD 25 in 1000+ quantities. Evaluation boards with matching Windows-compatible driver software are also available [4]. In the AD9957, a direct digital synthesiser (DDS) generates a numerical quadrature carrier signal with 32-bit frequency resolution. The carrier is multiplied by an upsampled replica of the user-supplied 18-bit baseband I/Q data stream in a digital quadrature mixer. The chip accepts baseband I/Q data at up to 250 MHz data rate, but in the 3_D application it will probably be set up to run at 20 MHz, corresponding to 10 MHz maximum modulation bandwidth.The mixer output data stream drives a 14-bit D/A converter which generates the analogue RF output signal. With a 1-GHz maximum internal clock rate, the chip can generate output signals up to 400 MHz and is therefore easily capable of generating the 235-MHz EISCAT_3D carrier frequency directly. The component also comprises a PLL clock generator with programmable clock multiplier circuitry, multi-chip synchronisation logic and a number of other housekeeping functions, making it a promising candidate for the EISCAT_3D exciter system, where individual AWGs must be phase-locked to a common high-stability clock and operated in strict synchronism. In the EISCAT_3D exciter, an FPGA–based control system will buffer the baseband data to be transmitted and stream it through a set of all-pass time delay FIR filters to the individual AD9957 chips in real-time. In the prototype now under development, one FPGA will handle three AD9957s; in the target system a single FPGA may handle up to 14 AD9957s.

3. Polyphase constant-amplitude codes for EISCAT VHF and ESR D/E work

An important element of the EISCAT_3D exciter development project is to verify the ability of the AD9957 to reliably generate arbitrary codes while driving a high-power transmitter. To that end, two constant-amplitude polyphase codes with good D and D/E region properties have been developed and will be tested in real experiments with the EISCAT VHF and ESR systems, with the prototype 3D exciter generating the phase-modulated carrier.

Incoherent scatter observations of the ionospheric D- and E-regions are very demanding. The electron density at 90-100 km altitude in the E-region can exceed 10^{12} m^{-3} during sporadic-E events. In the D-region a few kilometres lower down the electron density is typically less than 10^{10} m^{-3}, the correlation time of the medium is in the order of tens of milliseconds and scale heights are in the order of a few hundred metres or less. During the PMSE season, quasi-coherent scattering from the mesopause can produce radar echoes 30 – 50 dB above the quiescent level. To resolve both regions correctly at the same time requires a modulation which is essentially free of range sidelobes, which delivers both intra-pulse lags and pulse-to-pulse lags and which suppresses most or all returns from the first ambiguous range (which is typically right in the densest part of the F-layer). So far all D/E region work at EISCAT has used BPSK codes, as this is the only phase modulation that the old transmitter exciters can generate. It is not easy to find good low-sidelobe codes as long as one is limited to one binary degree of freedom; a noteworthy effort in this direction is the random-code based experiment by Turunen, Westman, Häggström and Wannberg [5].

Polyphase codes have been extensively studied since the early 1960s and the work has generated a vast body of litterature. Many code families with extremely well-behaved auto- and crosscorrelations have been found, e.g. [6-9]. On paper, the excellent performance exhibited by these and other polyphase codes make them attractive candidates for improved D/E region experiments, but mainly due to the difficulty of generating the required large number of unevenly spaced phase steps with analogue phase modulators they have so far not been serious alternatives to BPSK. However, with the advent of the AD9957 and similar digital upconverter devices that particular practical obstacle can now be easily removed.

The two examples described below are both *constant-amplitude* polyphase codes, which can be effectively used also on the nonlinear EISCAT VHF and ESR transmitters. The first code (a) is a QPSK-coded eight-element group of complementary sequences. It is essentially a direct application of the theory for polyphase complementary codes presented in [9]. Two binary sequences A and B forming the complementary pair [A B] are first BPSK coded and then transmitted alternately, but with the start phases shifted by integer multiples of $\pi/2$ according to the sequence

$$\phi_{start} = \pi/2 \cdot \begin{bmatrix} 0 & -1 & 0 & +1 & +2 & -1 & -2 & +1 \end{bmatrix} \tag{1}$$

Decoding the radar returns by cross-correlating with the respective rotated codes, the resulting response is free from range sidelobes in the primary range interval after summing over the eight transmit/receive cycles forming the group. But in addition *all contributions from the first ambiguous range that are phase-coherent on the interpulse time scale cancel exactly*, such that the D-region pulse-to-pulse autocorrelation is not biased by them.

Chu sequences [7] are families of complex-valued sequences defined on the unit circle, whose cyclic autocorrelation functions are identically zero at all nonzero lags. For every sequence length N there exist a family of N-1 codes of length N whose cross-correlations are all well-behaved [10]. For N prime, the sequences are periodic with period N. Chu codes have recently seen use as spreading and synchronization codes in cellphone protocols [11]. Our second test code (b) is constructed from the first 64 members of the set of 71-baud Chu sequences CS

$$CS(u,n) = \exp\left(-i\,\frac{\pi\, u\, n\,(n+1)}{N}\right) \quad ; N = 71,\ n = 0,2,...,70,\ u = 1,2,...,64 \tag{2}$$

by multiplying each *CS(u)* with a sign coefficient *sgn(u)* taken from the binary complementary sequence [A_{32} B_{32}]. The resulting code set $sgn(u) \cdot CS(u,n)$, $u = 1,2,\ldots,64$ is then transmitted either as one code per pulse for a pure D-layer experiment, or as sixteen groups of four concatenated codes for a combined D/E layer experiment. In both cases the returns are decoded by cyclic autocorrelation with the transmitted sequences and a pulse-to-pulse autocorrelation function for the D region is computed from the decoded zero-lag responses.

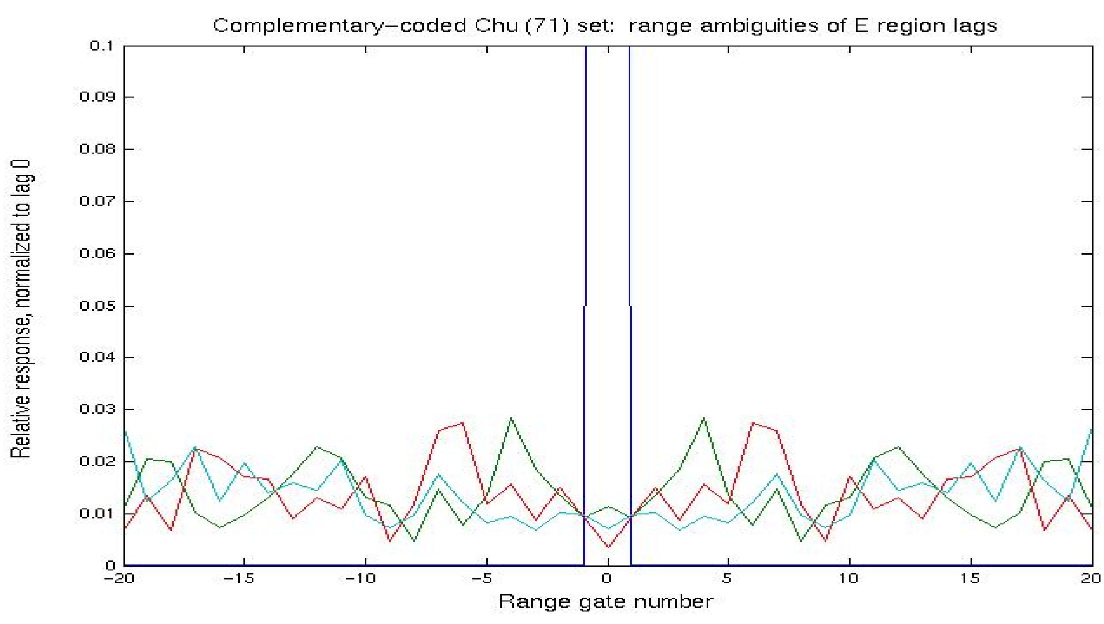

Figure 1: Range ambiguities of the zero lag and the three intra-pulse E-region lags generated by the complementary-coded, 71-baud Chu sequence D/E layer experiment. Blue = lag 0, green = lag 1, red = lag 2, cyan = lag 3. The ambiguities out to +/– 70 range gates behave in the same general manner, never exceeding the 3 % level.

Since the individual codes are sidelobe-free, the shortest pulse-to-pulse lag in the pure D-layer version of the experiment becomes equal to the interpulse period, i.e. a twofold improvement in lag resolution over conventional complementary codes. In the combined D/E region version, three intra-pulse "E-layer" lags at respectively one, two and three times the duration of the individual code (i.e. 71 times the baud-length) are computed by multiplying the four time-shifted zero-lag responses from each transmission with each other. After summing over all codes, the ambiguous-range responses of both intra-pulse and pulse-to-pulse lags are evenly distributed at about the 1.5 % level as shown in Figure 1. In this case the second-level complementary coding is vital to the overall performance; with it, the leakage into the zero lag from the neighbouring and/or ambiguous-range codes is < 1%, but without it the leakage increases to almost 12 %.

The instruction words of the EISCAT VHF, UHF and ESR radar controllers contain a presently uncommitted six-bit field. An interface mapping this bit field to an AD9957 evaluation board is now being constructed. Five of the six bits can be used to generate 2s-complement I and Q data, which will allow the generation of both QPSK and 8-PSK constant-amplitude codes. Our code (a) will soon be used for D-region and PMSE observations with the VHF system using this setup and with the AD9957 driving the klystron transmitter. Results will be presented at the GA.

4. Summary

A mass-produced fast digital up-converter, the AD9957, has been found to possess most of the qualities required to implement the beam-steering and arbitrary waveform capabilities of the EISCAT_3D radar system. As an integral part of the EI_3D exciter development programme, a number of constant-amplitude phase codes have been investigated and two experiments with excellent D- and E-region properties developed. At least one of these will be implemented and tested on the existing EISCAT radars during the 2011 PMSE season and results and conclusions will be reported at the GA.

5. References

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