A Transportable Hybrid Antenna-Transmitter System for the Generation of Elliptically Polarized Waves for NVIS Propagation Research

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***Abstract*—For empirical research on Near Vertical Incidence Skywave (NVIS) characteristic wave propagation, a beacon transmitter system is needed that can be programmed to emit precisely defined elliptically and circularly polarized waves at high elevation angles. This paper proposes a novel hybrid antenna-transmitter system, a combination of a synchronous dual channel transmitter and a turnstile antenna. The polarization emitted by the turnstile antenna is defined by the power ratio and phase difference of the outputs of the transmitter. Operating frequency is between 3 to 10 MHz. An automated and transportable solution is described, which can be fed by battery or solar power. Power consumption is 5.7 W.**

Keywords—antenna, circular polarization; characteristic wave; elliptical polarization; ionosphere; measurement; Near Vertical Incidence Skywave; NVIS; radio wave propagation.

I. Introduction

Communication via ionospheric radio wave propagation can be used for the coordination of relief efforts after natural disasters [1, p.82-83; 2-4] and for communication for humanitarian projects in remote areas [5, 6]. The Near Vertical Incidence Skywave (NVIS) propagation mechanism provides coverage of a continuous surface of approximately 200 km radius, by means of waves transmitted nearly vertically at frequencies below the equivalent vertical frequency [7, pp. 157-158], typically between 3 and 10 MHz.

Previous empirical research using circularly polarized antennas [8] has demonstrated substantial isolation (>25 dB) between the ordinary and extraordinary wave [9] traveling through the ionosphere in NVIS propagation. So, simultaneous reception of these characteristic waves using antennas with matched polarization can be used to nearly double channel capacity [10-12] or reduce channel fading by 8-11 dB [13]. The characteristic wave isolation measurements in [8] and [12] were performed over one path in The Netherlands (midpoint at 52.7ºN, 6.5ºE), and more tests are needed to verify the independence of azimuth and distance. This can be done by repeating the measurements on multiple paths with different azimuth angles and distances. Also the influence of the vertical angle of the earth magnetic field [14] has to be evaluated, requiring additional measurements. This 'dip angle' changes with latitude. Ideally, multiple paths are measured simultaneously, so that the effect of short term and day-to-day variation of the ionosphere is essentially the same on all paths, and the effect of azimuth and distance variation can be observed. This can be realized by the deployment of multiple beacon transmitters in a semi-random way around one measurement receiver, as depicted in Fig. 1. The proposed experiment is first performed in The Netherlands (52.1ºN, 5.4ºE), and then repeated in North East Spain (41.7ºN, 1.5ºE), so that the influence of the magnetic dip angle can be studied.

The experiment has two objectives: (i) to measure the isolation between both characteristic waves, and (ii) to measure the polarization of the downward characteristic waves. The latter is important for further (dynamic or static) optimization of antenna polarization, to increase the isolation between the characteristic wave channels. For both measurements the polarization of the upward waves has to be kept within tight tolerances. To achieve this, a novel antenna-transmitter hybrid system consisting of a turnstile antenna [15] and a dual channel beacon transmitter is proposed, capable of producing precisely defined elliptical or circular polarization of which the parameters are programmable. The realization of an easily transportable system is described.

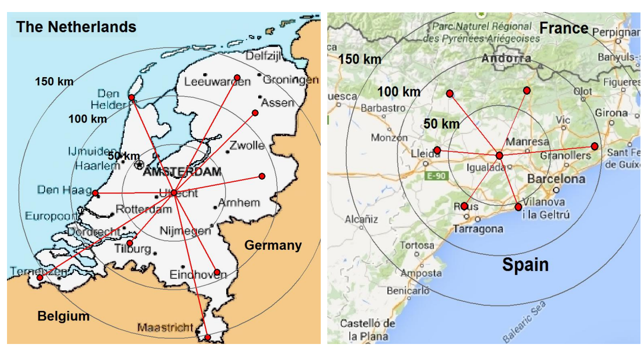

Fig. 1. Simultaneous measurements over multiple NVIS propagation paths with 9 beacons and 1 receiver in The Netherlands, and 6 beacons and 1 receiver in Spain.

The development of the hybrid antenna-transmitter system is sponsored by the University of Twente. The measurements in Spain are sponsored by the European Association on Antennas and Propagation (EurAAP).

This paper is structured as follows: in Section II the necessity for improvement of the beacon transmitter and antenna system for generation of elliptically polarized waves is discussed. This is followed by the design of a novel hybrid antenna-transmitter system described in Section III. Practical realization and solutions that improve cross-polarization and decrease installation time are discussed in Section IV. The document concludes with measured performance of the system and ideas for possible further development in Section V.

II. NEEDED TRANSMITTER AND ANTENNA IMPROVEMENT

In previous NVIS research, circularly polarized waves were generated with a 300 W beacon transmitter followed by a turnstile antenna [15]. The antenna incorporated an analog phasing network, as depicted in Fig. 2. At NVIS elevation angles, typically between 70º and 90º, the polarization of the emitted waves depends on the attenuation and phase shift of both branches of this network. With equal power and 90º degrees phase difference, circular polarized waves are emitted. The sense of rotation is determined by a positive or negative phase difference (leading or lagging phase). Elliptical polarization can be generated with other power ratios and/or phase differences. An example is given in Fig. 3. The axial ratio (AR), the ratio between the maximum and the minimum field strength on the polarization ellipse, can be calculated as:

$$\mathrm{AR} = \sqrt{\frac{1 + \delta\mathrm{P} + \sqrt{1 + \delta\mathrm{P}^2 + 2\delta\mathrm{P}\cos(2\Delta\varphi)}}{1 + \delta\mathrm{P} - \sqrt{1 + \delta\mathrm{P}^2 + 2\delta\mathrm{P}\cos(2\Delta\varphi)}}}\,, \qquad (1)$$

where δP is the power ratio and Δφ is the phase difference. In the previous design each change of frequency or change of polarization required modification and calibration of the phasing network. The calibration tolerances are tight: to achieve circular polarization with 25 dB cross-polarization, the power difference must be < 0.3 dB and the phase error must be < 2.5º [8]. At the same time more flexibility in dynamic polarization switching and a higher calibration precision is desired.

As shown in Fig. 1, 9 beacon transmitter locations are selected for the experiment in The Netherlands. To measure all 9 beacons simultaneously a frequency separation of 100 Hz between the beacons is chosen, so that 9 beacons can be received within a 1 kHz receiver bandwidth, after which they can be separated using digital filtering. This imposes a maximum frequency drift of < 20 Hz in 48 hours, to keep the signals sufficiently separated.

The transmitters and antenna systems have to be installed in 9 locations that are far apart, therefore quick and easy installation is desirable. As the supervision of 9 transmitters would require more personnel than is available, automation is desired. And with 9 beacon transmitters, the transmitter design and realization cost and the phase network calibration time are also multiplied. A new approach is needed.

III. POWER REDUCTION

To reduce cost and to simplify design, the RF output power of the beacons was reduced from the previous 300 W to 2 W. Results from previous measurements [8] suggest that this power will yield a signal-to-noise ratio (SNR) of 40 to 50 dB in a 30 Hz receiver bandwidth, which is sufficient for our measurements. This lower transmit power brings four practical advantages:

- The transmitter can be housed in a small box at the top of the mast, directly connected to the antenna.
- The transmitter can be fed from battery or solar power, making installation in remote locations possible. The battery can be installed on the ground below the mast.
- Buried feed lines and power lines are no longer necessary, significantly reducing installation time.
- The transmit power is low enough to allow unmanned operation.

However, even at low power, the necessity to perform very precise amplitude balance and phase difference in the dipole antenna elements of the turnstile antenna remains a bottleneck. If a power splitter and coaxial phasing lines are used, 9 of these have to be built and calibrated at the operating frequency for the desired polarization.

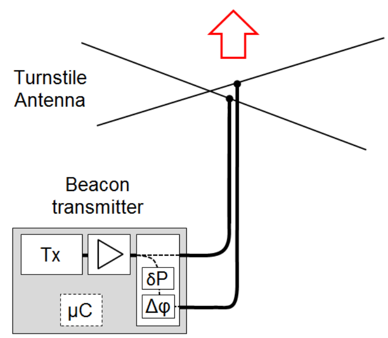

Fig. 2. The beacon transmitter and turnstile antenna used in previous measurements incorporated a precisely calibrated analog phasing network. The polarization of the emitted waves depends on the attenuation (δP) and phase shift (Δφ) of both branches of this network. A microcontroller (μC) controls the transmitter (Tx) and the switching between 2 polarizations.

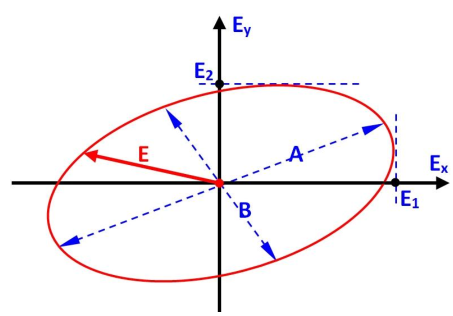

Fig. 3. Elliptical polarization of the electric field (E), defined by the power ratio (δP) and phase difference (Δφ) of the output ports of the phasing network of Fig. 2. Example shown is for δP = -2 dB and Δφ = 70º. The axial ratio (the ratio of A and B) is 1.5.

IV. A NOVEL HYBRID TRANSMITTER-ANTENNA SYSTEM

As a solution, a hybrid system composed of a turnstile antenna and a dual channel transmitter is proposed. The transmitter has two synchronous output ports with controllable phase and amplitude difference. The turnstile antenna consists of two orthogonal half wave dipole antennas. Each dipole antenna element of the turnstile is fed separately by one of these ports, as depicted in Fig. 4, thereby creating an active turnstile transmit antenna. The polarization of the transmitted waves is controlled by changing the power ratio and phase difference between the transmitter ports.

When the dual channel transmitter is realized using Direct Digital Synthesis (DDS), high stability and control over frequency, amplitude and phase difference is possible. Phase and amplitude errors in the power amplifiers and low pass filters can be compensated by complementary fixed offsets in the DDS, making calibration quick and easy. As the crosstalk between the two orthogonal dipole elements is < -25 dB, the power from one transmit port coupling into the other is sufficiently low to enable independent operation.

V. PRACTICAL REALIZATION

A. The turnstile antenna

A portable turnstile antenna is constructed around a single tubular telescoping aluminum mast with a height of 6.3 m. Four copper wires slope down from the top of this mast in 4 directions, as depicted in Fig. 5. The sloping wires are the antenna elements; the mast only keeps the wires in the air. At the top, the wires are connected to two Reisert-Guanella [16] balance-unbalance transformers (baluns) to form two perpendicular half wave dipole antennas. Each dipole antenna is fed by one port of the dual channel transmitter. The wire length is tuned to the operating frequency. In our application, at a frequency of approximately 7 MHz, the length of each wire is 10.1 m long.

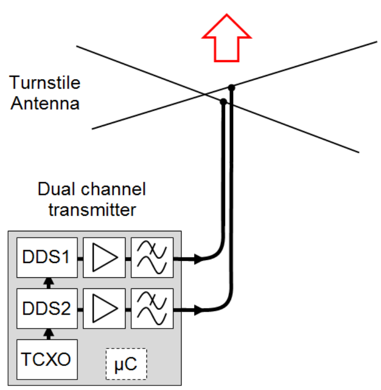

Fig. 4. A novel transmitter-antenna hybrid composed of a turnstile antenna and a dual channel transmitter. The polarization of the transmitted waves is controlled by changing the power ratio and phase difference of the two synchronized Direct Digital Synthesizer (DDS1 and DDS2) outputs. Both DDS are followed by a 1 W amplifier and a low pass filter. The beacon transmitter is controlled by a microcontroller (μC).

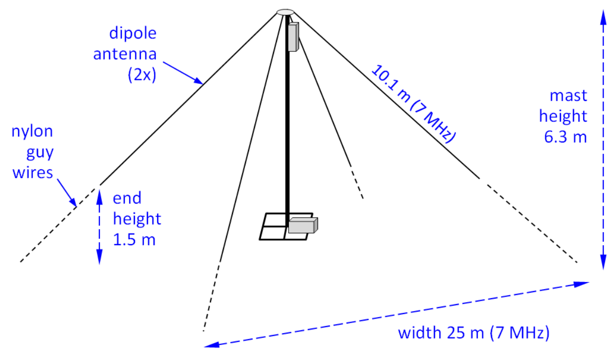

Fig. 5. Turnstile antenna, consisting of 4 wires sloping down from a single lightweight telescoping mast.

B. Dual channel transmitter

A block diagram of the dual channel transmitter is shown in Fig. 6. An Analog Devices AD9958 dual channel direct digital synthesizer (DDS) generates two synchronized RF carrier signals. The transmit frequency is derived from a 25 MHz temperature compensated crystal oscillator (TCXO). The dual channel DDS is followed by two 1 Watt class C power amplifiers (PA). To suppress harmonic emissions both amplifiers are followed by 7-pole low pass filters (LPF). Measurements show that all harmonic signals are < -63 dBc. Spectrum regulation requires spurious and harmonic emissions to be < -50 dBc.

The transmitter is controlled by an Atmel ATmega324p microcontroller (μC) that can be programmed via universal serial bus (USB). The controller software as well as calibration settings are retained in its 32 kB non-volatile memory. A real time clock (RTC) provides the μC with absolute time information, which is used to switch on the beacons at a preprogrammed date and time to allow for unmanned operation.

The μC also controls the transmit sequence composed of 5 time intervals of 12 s each, as depicted in Fig. 7. The 1st, 2nd and 4th intervals are for transmission in preprogrammed polarizations, in this example right-hand circular polarization (RHCP), left-hand circular polarization (LHCP) and linear polarization (LIN). The 3rd interval is for identification. The 5th interval is without transmission, and is used to synchronize the (remote) measurement system. To simplify receiver synchronization, the duration of the 5 intervals is derived from the TCXO, so that the time error is less than 9 ms per hour.

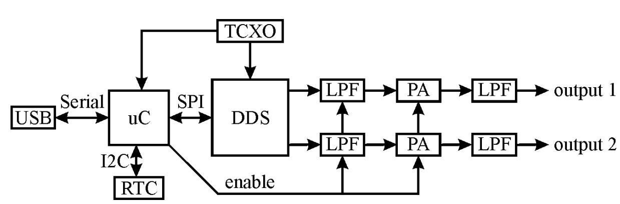

Fig 6: Block diagram of the dual channel transmitter. Explanation of the functional blocks (and of the abbreviations) given in Section V, subsection B.

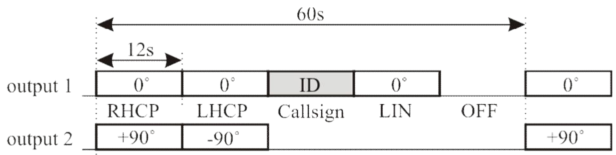

Fig 7: Transmit sequence composed of 5 time intervals. 1st, 2nd and 4th intervals are for transmission in preprogrammed polarizations, here left-hand circular polarization (LHCP), right-hand circular polarization (RHCP) and linear polarization (LIN). The 3rd interval is for identification (ID). The 5th interval without transmission (OFF) is for measurement synchronization.

The transmit frequency can be set with a 0.1 Hz resolution by programming the frequency register of the DDS. The TCXO has a long-term frequency stability of 2.5 ppm, which corresponds which corresponds with 17.5 Hz at a transmit frequency of 7 MHz. The systematic frequency error of the 25 MHz TCXO is compensated in the µC software of each beacon.

The phase difference and amplitude ratio between both output ports can be programmed with a resolution of 0.02 degrees and 0.01 dB, by setting the appropriate registers of the DDS. The measured phase and power error of the exciter is <0.2 dB and < 0.5º. The phase and power errors added by the subsequent PA and LPF are much larger, < 4.7º and < 1.5 dB. The phase error is compensated in the µC software, the power error is compensated by adjusting the PA gain and fine tuning in the µC software. The measured phase and power error after calibration is < 0.05 dB and < 0.1º. Parameter drift mainly occurs in the PA and LPF under influence of temperature changes, and estimated overall phase and power accuracy is < 0.2 dB and < 0.5º, which is within the limits of 0.3 dB and 2.5º specified in Section II. DC input power of the system is 5.7 W.

C. System Integration

The beacon transmitter is mounted in a box of 23 * 8 * 8 cm in which the beacon transmitter is housed, shown in Fig. 8, is attached to the top section of the mast. The beacon transmitter is powered from a battery that is located at the foot of the mast. A picture of the completed beacon system with turnstile antenna, dual channel transmitter, antenna mast and battery housing is shown in Fig. 9. The system can be divided into smaller components that can be easily transported, as can be seen in Fig. 10. Total weight of the hybrid antenna-transmitter system is 15.5 kg, without battery or solar panel. The 40 Ah battery selected for our application weighs 14 kg.

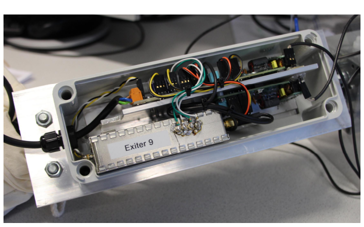

Fig. 8. The dual channel exciter, followed by 1 W power amplifiers for each channel, mounted in a box of 23 * 8 * 8 cm, which is attached to the top section of the antenna mast.

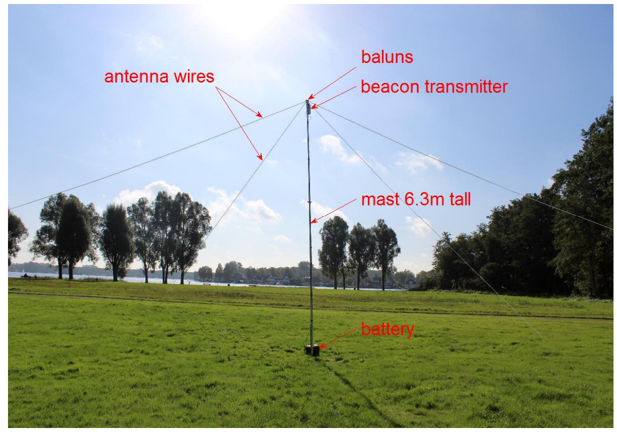

Fig. 9. The novel hybrid antenna-transmitter system in a typical Dutch landscape. The dual channel beacon transmitter is housed in a small box attached to the top section of the supporting mast. The beacon is fed from a battery located at the foot of the mast.

Fig. 10. The hybrid antenna-transmitter system can be made light and transportable. First author holds the top section of the mast with attached beacon transmitter (left) and the telescoping antenna mast (right). Mast foot and battery are shown at the bottom left of the picture.

VI. MEASURED PERFORMANCE

The DDS uses an internal clock operating at 400 MHz to generate the sinewave output and produces an extremely clean transmit spectrum: measured in a 10 Hz bandwidth the noise level is -85 dBc at 70 Hz from the carrier. However, the abrupt transitions from one polarization to another produce unwanted spectral artefacts that can be heard as 'clicks' in receivers tuned to nearby frequencies. The same is true for the amplitude transitions during the identification of each beacon transmitter in Morse code, using on-off-keying. These artefacts are commonly indicated as 'key clicks'.

To reduce this interference, more gradual transitions are programmed, as depicted in Fig. 11. As the digital exciter is followed by a class C power amplifier, which is inherently non-linear, the amplitude transitions of the exciter are programmed in such a way that that DDS and power amplifier together produce the desired soft transitions. This dramatically improves the spectral bandwidth of the beacon during identification, as can be seen in Fig. 12.

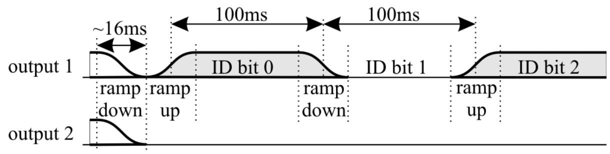

Fig 11: The beacon identifier (ID) is transmit in Morse code using on-off keying. Pulse shaping is applied to reduce occupied bandwidth.

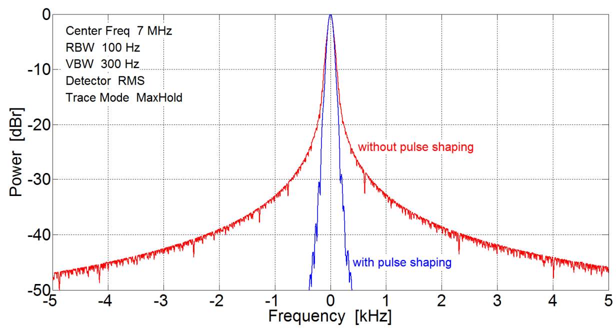

Fig 12: Output spectrum of the beacon transmitter while sending the identification with (red) and without (blue) pulse shaping.

A transition time of 16 ms provides a good compromise between spectral bandwidth and readability of the identification code. The transition is realized using small amplitude steps, at a rate of 1 step / 62.5 µs. This introduces unintended amplitude modulation with a frequency of 16 kHz, but of small relative amplitude. As the spurious emission limit is -50 dBc according to European regulations, the pulse shaping is optimized to reduce the key clicks below that level at 400 Hz from the carrier.

VII. CONCLUSIONS AND FURTHER DEVELOPMENT

A light weight (15.5 kg), low power (5 W), transportable hybrid antenna-transmitter system is realized, which will be used as beacon signal source for Near Vertical Incidence Skywave propagation measurements. It uses a combination of a dual channel synchronous transmitter and a turnstile antenna to generate circularly or elliptically polarized radio waves.

Power ratio and phase difference between the dipole elements in the turnstile antenna can be controlled within approximately 0.2 dB and 0.5º. With this precision, the cross polarization is expected to be < -25 dB [8] when circular polarization is generated, which was the targeted goal. Control of frequency, phase difference and power ratio is realized by an embedded microcontroller. Sequences of different polarizations can be programmed, as well as timer activation using a real-time clock as reference. Nine of these hybrid antenna-transmitter systems where realized. They will be used in empirical Near Vertical Incidence Skywave propagation research in Spain and The Netherlands.

Further attempts to increase the power efficiency and spectral purity of the dual channel beacon transmitter may lead to a system based on envelope elimination and restoration (EER) [17], possibly with class E amplifiers [18].

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