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Key Points:

- Examine the feasibility of applying polarization diversity to a 12,760 km ionospheric link
- Polarization diversity could be used to increase SNR and performance through smart combination of receiving signals
- There is a marked difference between signals at vertical and horizontal polarized antennas, depending on the hour and the frequency

Correspondence to:

R. M. Alsina-Pagès,
ralsina@salle.url.edu

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Polarization diversity in a long-haul transequatorial HF link from Antarctica to Spain

Pau Bergadà¹ , Rosa Ma Alsina-Pagès² , and Marcos Hervás²
¹Wavecontrol, Barcelona, Spain, ²GTM-Grup de Recerca en Tecnologies Mèdia, La Salle-Universitat Ramon Llull, Barcelona, Spain

Abstract This paper describes a set of experiments which examine the feasibility of applying polarization diversity to a 12,760 km ionospheric link from Livingston Island (62.6°S, 60.4°W), South Shetlands, to Cambrils (41.0°N, 1.0°E), Spain. A transmitting monopole and both a monopole and a dipole (inverted-V) at reception are the antennas used in this measurement campaign. Receiving antennas are orthogonal polarized to check whether wave polarization rotation causes differences between simultaneous signals. The results gathered in the paper indicate that there is a marked difference between simultaneous signals at vertical and horizontal polarized antennas, which depends on the hour of the day and the signal frequency. In this low-throughput HF data link, polarization diversity could be used to increase SNR and performance through smart combination of receiving signals, due to the low cross-correlation factor between them.

1. Introduction

The transmission of data from sensors placed in very remote areas is difficult due to weak satellite coverage and scarce power supply. La Salle has been working for 11 years on the design of a long-haul ionospheric data link [Pijoan *et al.*, 2014]. Communications through the ionosphere have persisted, although the use of artificial repeaters, such as satellites, has provided more reliable means of communication. Despite being random, noisy, and susceptible to be interfered, ionospheric transmission still has encouraging characteristics (e.g., low cost equipment, worldwide coverage, and invulnerability) that appeal to current communications engineering.

Several physical layer transmission schemes for this long-haul HF link have been studied, using both narrowband and wideband soundings [Hervás *et al.*, 2015], as well as through data transmitted using several modulation techniques [Bergadà *et al.*, 2014; Hervás *et al.*, 2016]. The main goal of these works has been to study the highest possible bit rate with minimum bit error rate (BER). Once the transmission system has already taken advantage of frequency and time diversity by means of the optimum modulation technique, coding scheme, and time frame [Alsina-Pagès *et al.*, 2016], the research focus has switched to a polarization diversity scenario to increase the SNR at the receiver. In this study we discarded the use of spatial diversity since long distances between antennas should be guaranteed throughout the whole HF band. In addition, some research works conclude that antenna diversity is more effective than spatial diversity in order to reduce cross correlation of received signals [Gunashakar *et al.*, 2010]. The transmitter equipment, which uses a 7.5 m rugged monopole, is placed on Livingston Island, and the receiver, which uses both a monopole and a dipole (inverted-V antenna), is placed at Cambrils. The monopole is a vertical polarized antenna whereas the dipole is a horizontal polarized antenna. Both antennas allow polarization diversity tests throughout the whole HF band, by means of an antenna tuner (monopole) and a balun (dipole).

This paper is structured as follows. Section 2 details several polarization diversity studies found in HF literature, while section 3 focuses on ordinary and extraordinary waves. Section 4 explains the setup used in the tests, section 5 details the tests, and section 6 evaluates the results of these tests. Finally, in section 7, the conclusions of the tests are given and future work is set out.

2. Polarization Diversity in HF Literature

Several polarization diversity studies applied to HF ionospheric channels can be found in HF literature. These works are either focused on decreasing the BER for a given data throughput or on increasing the throughput for a certain BER.

First, in *Serinken et al.* [1996] the authors quantified the potential advantage of polarization diversity applied to a 2.4 kbps HF data system. They reduced the BER up to 3 orders of magnitude by using two orthogonal antennas at the receiver. Both studies, *Ndao et al.* [2010] and *Ndao et al.* [2011], worked to increase the bit rate from 30 kbps to 80 kbps in a 9 kHz bandwidth for a standard quality of service quantified by a BER of 10^{-3} . This goal was achieved by using a multiple-input multiple-output (MIMO 2x2) solution and by generating two complementary circular polarization waves at the transmitter end.

Adopting another approach, *Perrine et al.* [2004] reached up to 20 kbps in a 6 kHz bandwidth using a heterogeneous circular array of four loop antennas, instead of the standard 4.8 kbps in a 3 kHz bandwidth. They maintained a BER of around 10^{-3} , which is considered acceptable for an HF modem. In *Abbasi et al.*, 2009] and *Gunashekar et al.*, 2009] the authors increased the channel capacity using MIMO due to the low cross correlation of signals transmitted and received by different antennas. They concluded that to achieve a lower cross-correlation factor, the homogeneous arrays should be replaced by collocated antennas and heterogeneous arrays.

All previous works analyze the performance of polarization diversity in one hop HF links, with a maximum channel length of 1800 km, and most of them applied to even shorter links (e.g., 700 km or even 250 km). Some of them use spatial diversity techniques to minimize the cross-correlation factor of signals, and others use different types of polarized antennas to guarantee minimum cross correlation.

In our case, spatial diversity cannot be an option due to the range of frequencies we are using (the entire HF band, from 2 MHz to 30 MHz). The analysis has been conducted over the data received from two different antennas: a 7.5 m rugged monopole and an inverted-V dipole. Another singular characteristic of our channel analysis is the length of the ionospheric link, which is 12,760 km long, with around 4 hops from Livingston Island to Cambrils. This transequatorial link strongly limits transmission performance due to high attenuation and to ionospheric variability [*Ads et al.*, 2015]. Therefore, the study on the cross-correlation factor between signals received simultaneously by the monopole and the dipole is a challenging task due to the scarce availability of the link and hence the unusual simultaneous high SNR at both receiving antennas.

3. The Ordinary and Extraordinary Waves

The ionosphere consists of plasma ionized by the solar activity superposed with the Earth's magnetic field. These two factors make it an anisotropic medium. As soon as an incident radio wave impacts the ionosphere, it splits into ordinary and extraordinary components due to the magnetic field [*Davies*, 1990].

These modes are differently affected by the external magnetic field. The index of refraction in the ionosphere is defined by the Appleton formula [*Ratcliffe*, 1962], which provides different results for ordinary and extraordinary waves. In fact, according to this formula, only these two modes can propagate in this medium.

The ordinary and extraordinary modes propagate on different paths and velocity due to their distinct refractive index. Consequently, these waves are reflected back at different heights reaching the receiver with different delays. Moreover, the amplitude and the maximum reflected frequency are also different. In fact, the maximum reflected frequency in the F_2 layer for the ordinary (f_oF_2) is usually lower than that for the extraordinary (f_xF_2).

Ordinary and extraordinary waves have elliptical polarization, and the axial ratio of these elliptical polarization might be different. For this reason, a monopole and an inverted-V antenna, with vertical and horizontal linear polarization, respectively, can be used to maximize the signal power received.

4. System Design

The following subsections explain the transmitter and the receiver setup. Both block diagrams are depicted in Figures 1 and 2, respectively.

4.1. Transmitter Details

The transmitter is placed on Livingston Island (62.6°S, 60.4°W), in the South Shetlands archipelago and consists of a software-defined radio platform (see Figure 1) in a compact weather resistant design box, installed near the antenna at the top of a hill near the Spanish Antarctic Station-Juan Carlos I (SAS-JCI) (see Figure 3). The core of the transmission system is a Virtex-4 XtremeDSP development platform from Xilinx, with three FPGA performing all signal processing, including the up and the down direct conversion. A GPS unit with a pulse

Figure 1. Transmitter Block Diagram at Livingston Island (Antarctica).

per second (PPS) signal increases the synchronization accuracy (up to 1 μ s), which even allows for the measurement of wave propagation time. In order to improve the frequency synchronization accuracy, a 100 MHz Oven-Controlled Crystal Oscillator (OCXO) is working at both the transmitter and the receiver. A wattmeter that controls the forward and the reverse transmitted power can switch off the transmitter power amplifier in case of severe impedance mismatch. Due to power restrictions at the SAS-JCI, the transmitted power is upper bounded at 250 W.

The transmitter antenna is a simple 7.5 m rugged monopole with an antenna tuner, which adapts the impedance of the antenna to the power amplifier reaching a voltage standing wave ratio lower than 2.0. The tuner enables the monopole to work throughout the entire HF band, although it is not a wideband antenna. Since the radiation pattern is highly dependent on the quality of the ground plane, a set of 32 radials were connected to the antenna ground to improve the performance of the effective radiated power in almost the whole band.

4.2. Receiver Details

The receiver is placed at Cambrils (41.0°N, 1.0°E), Spain, and consists of two synchronized software-defined radio platforms that allow simultaneous reception at a 7.5 m rugged monopole and at an inverted-V antenna (see Figures 2 and 4). Both, despite not being wideband antennas, allow polarization diversity tests in the entire HF band. The receiving monopole is connected to a tuner, as the transmitter monopole, and the inverted-V antenna uses a balun to couple the balanced dipole to the unbalanced receiver and matches both impedance. The receiving monopole ground is also connected to 32 radials, similarly as the transmitter monopole ground. The two receiving antennas are 25 m apart. The inverted-V antenna is E-W oriented, both wings are 30 m long, and two lateral masts are mounted around the central mast of the dipole to align the V-wings and arrange them in an angle of 30°.

5. Test Design

In a low-SNR scenario, as for the HF link described in previous sections, polarization diversity can increase reliability in a single-input multiple-output (SIMO) link by combining signals gathered at different antennas. However, an increase of SNR can only be achieved if simultaneous signals are suitably decorrelated (i.e., their cross-correlation factor is lower than 0.7) [Jakes, 1974]. The main goal of this study is to compute the

Figure 2. Receiver Block Diagram at Cambrils (Spain).

Figure 3. Transmitter antenna in Livingston Island (Antarctica).

cross-correlation factor of narrowband signals recorded at nearby antennas which are sensible to orthogonal polarization. Moreover, 10 kHz bandwidth pseudonoise (PN) sequences are transmitted as well, in order to compare the channel impulse response seen at the two receiving antennas.

Throughout a campaign that began on 22 January 2011 and ended on 26 February 2011, the system sounded the channel 24 h/d along the whole HF band, from 2.050 kHz to 30.050 kHz in frequency steps of 500 kHz (i.e., a set of 56 different carrier frequencies). The system transmitted a 10 s nonmodulated wave each minute at a different carrier frequency from Antarctica. These nonmodulated carrier signals were received at Spain and simultaneously recorded using two orthogonal polarization antennas. After each nonmodulated signal, a set of 255-chip 10 kHz maximum length sequences was transmitted for 10 s to allow the computation of

Figure 4. Receiver antenna in Cambrils (Spain).

Figure 5. The signal is divided in 10 slots of 1 s each. The two preceding and following slots of noise are used to compute SNR.

the channel impulse response and the scattering function. The delay and Doppler spread were finally derived from the channel scattering function.

Once narrowband signals from the two receivers were recorded, we proceed to low-pass filter each of them by means of a Kaiser window [Ads *et al.*, 2013]. To reduce high-frequency components, the filter had very narrow bandwidth (i.e., 10 Hz). Furthermore, to minimize spurious transients from impulsive interference, in the time domain, a high beta factor was chosen (i.e., 8); for a broader explanation, please see Hervás *et al.* [2015]. Right after low-pass filtering the signals, we segmented the recorded files into 10 slots of 1 s of duration (see Figure 5). Although the transmitted narrowband signal is 10 s long, the receiver appends 2 s of noise and interference at the beginning and end of each signal file, which results in a 14 s long file. We then computed the signal to interference plus noise ratio (SINR) as the ratio of the power on every signal slot over the power measured at each noise slot, as

$$\text{SINR}_{ij} = \frac{S_j + I_j + N_j}{I_i + N_i}, \quad (1)$$

$$\text{SINR} = \frac{1}{KL} \sum_{i=0}^{K-1} \sum_{j=0}^{L-1} \text{SINR}_{ij}, \quad (2)$$

where S_j , I_j , and N_j are the powers of the desired signal, interference, and noise, respectively, at slot j , I_i and N_i are the powers of interference and noise, respectively, at slot i , L is the maximum number of signal slots (i.e., 10) and K is the maximum number of noise slots (i.e., 4). In such a high interfered scenario it is mandatory to know whether the desired signal has been jammed by an interfering signal (with higher power than the desired signal); hence, equation (1) would be equal to 1; otherwise, we would get the SNR in a 10 Hz bandwidth. In order to increase the reliability of the availability algorithm against short high-power interference signals, we established a condition to improve availability estimation: SINR_{ij} should be higher than a certain lower bound (SINR_{LB}), $\forall i, j$. The SINR_{LB} can be modified based on previous studies of occurrence of narrowband interfering signals in this channel [Ads *et al.*, 2013], to get a more robust availability factor. Therefore, the availability factor was computed as

$$\text{Availability} = \frac{\sum (\text{SINR}_{ij} \geq \text{SINR}_{LB})}{K \cdot L}. \quad (3)$$

We also used the availability criteria (see (3)) to decide on which files we computed the cross-correlation algorithm. In this case we limited the receptions to be considered to those with an availability factor higher than 0.5, which means that at least 50% of the SINR_{ij} were higher than SINR_{LB} . Then, right after low-pass filtering the signal, SINR, and availability computation, we cross correlated simultaneous signals gathered at both antennas as

$$\rho = \frac{\langle s_m, s_d \rangle - [\bar{s}_m \cdot \bar{s}_d]}{\sqrt{\sigma_{s_m}^2 \cdot \sigma_{s_d}^2}}, \quad (4)$$

where s_m is the signal gathered at the monopole, s_d is the signal gathered at the dipole, $\langle \cdot, \cdot \rangle$ is the inner product of both signals, and $\bar{(\cdot)}$ and $\sigma^2(\cdot)$ are the mean and variance operator, respectively, of a signal $(\cdot)$.

Figures 6 and 7 show the time amplitude fluctuation suffered by nonmodulated signals gathered simultaneously at both antennas. Channel fading makes the amplitude of the received signal decrease by more than 20 dB several times within the 10 s receiving interval. As these figures depict, fading at both antennas does not always occur at the same time, which could be attributed to the existence of more than one mode of propagation in this HF link. Moreover, it appears that the prevalence of this phenomena depends on the frequency

Figure 6. Amplitude fluctuation of two narrowband signals gathered simultaneously at the monopole and dipole on 22 of January 2011 at 20 UTC at 10.05 MHz (cross-correlation factor = 0.20).

of the signal and the time of the day, as shown in the examples of Figures 6 and 7. The results presented in the following section summarize the performance of the cross-correlation factor between two narrowband signals gathered at orthogonal polarized antennas and its variation along day and night and throughout the whole HF band. In addition, some preliminary comparisons between wideband characteristics of the channel seen from both antennas are provided. The aim is to obtain some kind of coincidence between narrowband and wideband studies, which may show higher confidence in the results of this work.

Figure 7. Amplitude fluctuation of two narrowband signals gathered simultaneously at the monopole and dipole on 22 January 2011 at 16 UTC at 17.00 MHz (cross-correlation factor = 0.80).

Figure 8. Probability (in %) of finding a cross-correlation factor below 0.7 between two narrowband tones at two orthogonal polarized antennas as a function of time.

6. Test Results

In this section we present the results computed, as explained in the previous section, from the data gathered at the receiver site throughout 36 days during the 2010/2011 Antarctic campaign. The outcomes of cross correlation between narrowband signals simultaneously received at orthogonal polarization antennas are shown together as a function of time and frequency for better comparison and comprehension.

Figure 8 shows the probability of cross correlation between simultaneous signals at orthogonal polarization antennas to be lower than 0.7, which is the value to distinguish correlated signals from noncorrelated ones [Jakes, 1974]. This probability is depicted in Figure 8 as a function of the time of the day. On this plot, as well as on the plot of Figure 10, we have considered all the receptions throughout the whole campaign with a medium robust availability factor (i.e., $\text{SINR}_{LB} = 3$ dB) in at least 50% of the slots (i.e., an availability factor higher than 0.5), which is a trade-off between robustness against interferences and sensitivity.

Figure 9 (top) shows the amount of samples used in each hour to compute the cross-correlation factor depicted in Figure 8, which depends on the availability factor of the received signal. The amount of samples ranges from 30 or 50 samples, for low available hours (i.e., 05 UTC, 06 UTC, and 16 UTC), to more than 100 samples, for high available hours (i.e., from 00 UTC to 03 UTC, from 07 UTC to 09 UTC, 21 UTC, and 22 UTC). Figure 9 (bottom) shows the mean and variance of the availability factor of those signals used in Figure 9 (top) to compute the cross-correlation factor.

Figure 10 shows the same concept as Figure 8, but the probability of cross correlation is depicted now as a function of the frequency. Figure 11 (top) shows the amount of samples used in each frequency to compute the cross-correlation factor depicted in Figure 10, which depends on the availability factor of the received signal. The amount of samples ranges from below 25 samples, for low available frequencies (i.e., lower than 7.0 MHz, from 17.5 MHz to 19.0 MHz, 20.0 MHz, and higher than 23.5 MHz), to a number of samples between 40 and 100, for high available hours (i.e., from 7.0 MHz to 17 MHz with some exceptions). Figure 11 (bottom) shows the mean and variance of the availability factor of those signals used in the upper subplot to compute the cross-correlation factor.

Again, the amount of samples computed in each frequency depends on the availability factor and ranges from 60 samples for low available frequencies (i.e., higher than 23 MHz and lower than 4 MHz), to 120 samples for high available frequencies (i.e., between 5 MHz and 22 MHz).

Figure 9. Number of signals used to compute the cross-correlation factor (CF) as a function of (top) the hour of the day and (bottom) the mean and variance of the availability factor of these signals.

Figure 10. Probability (in %) of finding a cross-correlation factor below 0.7 between two narrowband tones at two orthogonal polarized antennas as a function of frequency.

Figure 11. Number of signals used to compute the cross-correlation factor (CF) as a function of (top) frequency and the (bottom) mean and variance of the availability factor of these signals.

Figure 8 shows that from 00 UTC to 08 UTC the probability of finding a cross-correlation factor lower than 0.7 is always higher than 80%, as well as from 18 UTC to 23 UTC where this probability never falls below 85%. However, from 09 UTC to 17 UTC the probability of finding a cross-correlation factor lower than 0.7 is always lower than 80%. A lower bound happens at 15 UTC when this probability reaches a value of 44%. There is a noticeable sharp change between 15 UTC and 16 UTC, when the probability varies from 44% to 75%. It is worth remarking that at this very moment the sunset begins at some points of this HF link [Ads et al., 2015].

Figure 12. Scattering channel function gathered at monopole recorded on 3 February 2011 at 14:32 UTC at 17.450 MHz.

Figure 13. Scattering channel function gathered at dipole recorded on 3 February 2011 at 14:32 UTC at 17.450 MHz.

Figure 10 shows that below 7 MHz the cross correlation oscillates abruptly along the whole probability range. This behavior could be attributed to a poor performance of the antenna tuner used by both the transmitter and the receiver monopole, at this low frequency range. From 7 MHz to 13.50 MHz the cross correlation is always lower than 0.7 with a probability higher than 87%. Whereas, from 14 MHz to 20 MHz this probability ranges from 68% to 88%. Beyond 20 MHz the probability of getting a cross-correlation factor lower than 0.7 is almost always upper bounded at 70%, with a minimum at 23 MHz with a probability of just 20%.

From the results depicted in Figures 8 and 10 we can say that in this HF channel there is a range of hours (i.e., from 09 UTC to 17 UTC) and signal frequency (i.e., above 20 MHz) in which the probability to get a low correlation between signals are the lowest. This phenomenon might indicate that both antennas are receiving signals coming from the same mode (ordinary mode or extraordinary mode), and the other one is fading (it is worth noting that we have only computed the correlation factor of those signals with an availability factor higher than 0.5 at both antennas). To better understand the phenomenon happening in this channel, vertical ionograms would be useful. However, we would need ionograms of the whole HF band (as the oblique sounding is spread over the whole HF band), 24 h/d and all along the link. Hence, a new full study will be

Figure 14. Scattering channel function gathered at monopole on 1 February 2011 at 09:30 UTC at 16.50 MHz.

Figure 15. Scattering channel function gathered at dipole recorded on 1 February 2011 at 09:30 UTC at 16.50 MHz.

worth considering the comparison between vertical ionograms at some point near the link and the correlation between signals gathered at the receiver of the oblique link by means of orthogonal polarized antennas.

Although we can only show some preliminary results regarding the wideband sounding of the channel, we have found some points that may corroborate the outcomes shown in the narrowband study. As an example, Figures 12 and 13 and Figures 14 and 15 depict two couples of scattering functions of the channel simultaneously gathered at both antennas at similar frequency (i.e., 17.45 MHz, at top, and 16.50 MHz, at bottom). Figures 12 and 13 are recorded at 14:32 UTC, and Figures 14 and 15 are recorded at 09:30 UTC. Figures 12 and 13

Figure 16. Mean difference between delay and Doppler spread, accumulated throughout the whole campaign, gathered at orthogonal polarized antennas as a function of time.

appear to be quite similar, in terms of delay and Doppler spread, whereas Figures 14 and 15 show a different number of paths and hence different delay spread. Doppler spread appears to be particularly similar in both cases.

In order to give a more general view of this phenomenon, we computed the scattering function from the received wideband PN signals at the whole HF band from 00 UTC to 23 UTC. From these scattering functions we derived the delay and Doppler spread of the channel. In Figure 16 we summarize the mean difference observed between both antennas regarding delay spread (at top) and Doppler spread (at bottom), as a function of the time of the day. Regarding delay spread, there is a minimum difference from 21 UTC to 02 UTC and from 11 UTC to 14 UTC, while there is a great difference between 16 UTC and 20 UTC. This results partially coincide with those shown in Figure 8, where a minimum of probability of low cross correlation occurs between 11 UTC and 15 UTC. At 16 UTC there is a sharp change in the mean difference between delay spread that goes from the minimum value (i.e., 0.1 ms) to almost the maximum value (i.e., 4.5 ms). A sharp change can also be observed at the same time with regard to cross-correlation probability of occurrence (see Figure 8). Regarding the mean Doppler spread difference, it takes its minimum value (i.e., lower than 0.5 Hz) between 13 UTC and 16 UTC, at 03 UTC and at 10 UTC and its maximum value (i.e., higher than 1.5 Hz) from 17 UTC to 20 UTC and at 22 UTC, 23 UTC, and 04 UTC.

7. Conclusions and Future Work

In this work we have studied the cross-correlation factor between narrowband signals on a long-haul HF channel gathered at nearby orthogonal polarized antennas. Similarly, we have also compared wideband signal characteristics. The main goal we pursue is the feasibility of using polarization diversity to increase SINR in such an adverse channel by means of a single-input multiple-output setup.

Results show that simultaneous signals at both antennas are not equal and that diversity depends on the frequency of the signal as well as on the time of the day. Highest decorrelated signal frequencies range from 7 MHz to 18 MHz. From 16 UTC to 09 UTC of the following day we can also find the lowest cross-correlation factor.

Wideband results show some coincidences with narrowband cross-correlation results, in the sense that when the difference between scattering functions of both antennas is minimum (approximately between 10 UTC and 15 UTC) the cross-correlation factor is the highest during the whole day. Whereas when the delay spread shows its maximum difference between antennas (between 16 UTC and 20 UTC) the cross correlation is lower than 0.7 with a probability higher than 80%.

The outcomes presented in this paper are preliminary and should be supported by the analysis of other campaigns. Nevertheless, these results encourage the study of diversity techniques (e.g., maximum ratio combining, equal gain combining, and switching combining) at the receiver to increase the SNIR of this HF link.

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