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Key Points:
- Comparison between the OIS, the ITU Rec533 HF prediction model, and the VIS of a transequatorial link
- The channel is studied in terms of frequency availability as function of time

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Vertical and oblique ionospheric soundings over the long haul HF link between Antarctica and Spain

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Abstract This paper presents a comparative study between the oblique sounding results, the International Telecommunication Union Rec533 HF prediction model, and the vertical sounding results of a transequatorial long haul link. The long haul link is a 12,760 km link between the Spanish Antarctic Station, SAS, located in the Livingston Island and the Ebro Observatory (OE) in Spain. The data were collected during three consecutive surveys (2009/2010, 2010/2011, and 2011/2012). The ionospheric channel from the SAS to the OE is studied in terms of frequency availability as function of time using the measurements of an oblique incidence sounder (OIS) and measurements of several vertical incidence sounding stations (VIS) placed near the estimated radiopropagation path. The results obtained show promising correlations between VIS and OIS measurements and led us to think that the frequency of largest availability for this particular long haul radio link can be estimated from the VIS sounding measurements.

1. Introduction

The Research Group in Electronics and Telecommunications Systems has been involved for more than 10 years in a project whose goal is the design of a high-frequency (HF) transequatorial radio link from the Spanish Antarctic Station, SAS, in Livingston Island (62.6°S, 60.4°W) to Ebro Observatory, OE, in Spain (40.8°N, 0.5°E) [*Torta et al.*, 2010; *Pijoan et al.*, 2014]. The distance between both stations is around 12,700 km; therefore, a minimum of four ionospheric reflections are expected in the wave propagation [*Perkiomaki*, 2013] (see Figure 1).

Nowadays, several works related with new oblique soundings [*Jackson-Booth et al.*, 2012] from HF radio links can be found, but most of them are one-hop analysis [*Warrington et al.*, 2000]. Results of oblique incidence sounder (OIS) have a complex interpretation in terms of ionospheric physics but usually provide valuable information about ionospheric propagation. Certainly, they will help the HF modem design by providing the prediction of the best transmission frequencies [*Angling et al.*, 1998].

Our goal in this work is to establish a prediction method for the frequency availability in the 12,700 km long haul radio link [*Vilella et al.*, 2008; *Ads et al.*, 2012], by means of vertical incidence sounding, VIS, measurements. To validate this method, their results are compared to the oblique incidence sounding, OIS, measurements. Consequently, frequency transmission would be changed according to VIS outcomes and higher time efficiency in the use of the channel would be achieved. Other prediction environments have been found in the literature for both midlatitude links [*Shukla and Cannon*, 1994] and for high latitudes [*Jodalen et al.*, 2001], but a long haul link needs several VIS stations near the radio path and a combination of their measurements would help to reach to an accurate prediction of the frequency management of the long haul radio link.

In *Vilella et al.* [2009] a first approach to the analysis of the 12,700 km radio link was performed and comparisons with data recorded at VIS stations along the path were performed. The constraints of that work were the few number of available transmission frequencies, and a consequent limited time of tests measurements. In the work presented in this paper, we have extended the range of transmission frequencies to the whole HF band (2–30 MHz) making possible the OIS measurements 24 h/d. Moreover, we have also analyzed a larger number of VIS stations located along the radio path, as well as increased the performance of the transmitter and the receiver.

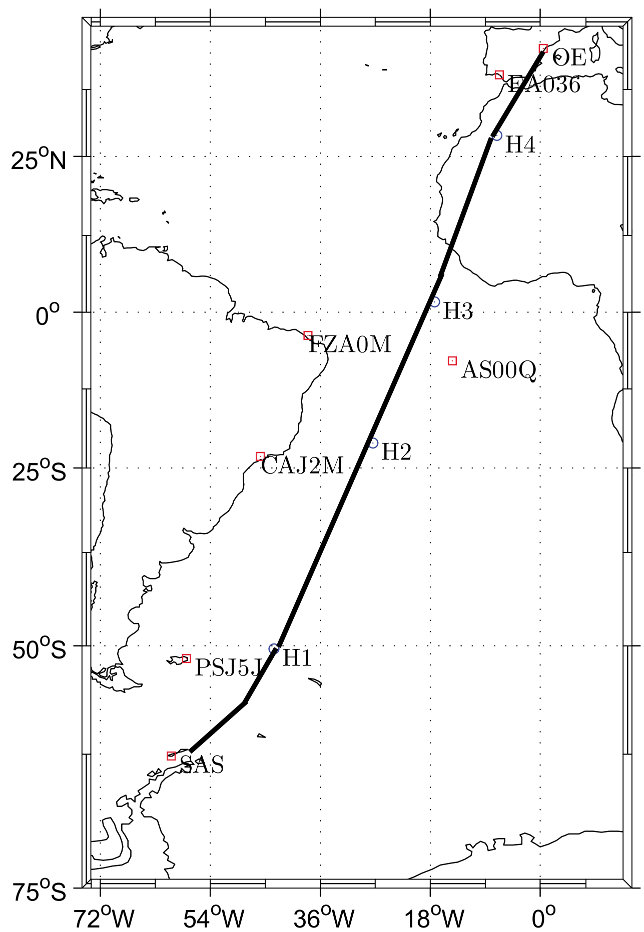

Figure 1. The locations of the VIS stations and the reflection points along the link path.

In this paper we present the results of the data analysis of OIS and VIS measurements gathered throughout three surveys (2009/2010, 2010/2011, and 2011/2012). We compare the experimental OIS and VIS data with the estimated MUF(*D*) values, the maximum usable frequency obtained by the Rec533 for different levels of solar activity. The MUF(*D*) is defined as the highest frequency for which an ionospheric communication path is predicted on 50% of the days of the month [*International Telecommunication Union Recommendation (ITU-R)*, 2012]. These three surveys have been conducted with a wider range of transmission frequencies and with the VIS and OIS systems working 24 h/d, so complete frequency diagrams can be found in the results section compared to previous results obtained by *Vilella et al.* [2009]. The communication availability of this remote system is often low; however, we analyze all the HF frequency range to improve the results using the best frequency at each hour. This information will be used to support frequency allocation in the 12,700 km channel HF system design.

Section 2 gives details of the description of both sounding systems, OIS and VIS, its measurements, and the influence of the solar activity in the measurements. Section 3 presents the results of the time variation of MUF(3000)F_2, obtained from VIS, and the frequency of largest availability (FLA), obtained from OIS measurements. MUF(3000)F_2 is the maximum usable frequency for a single hop transmission at 3000 km reflected at the F_2 layer, which is measured from VIS ionograms. Section 4 compares the results of the time variation of the FLA with that of the MUF(3000)F_2. Finally, in section 5, the conclusions and the feasibility of frequency forecast are discussed.

2. Description of the Sounding System

In this section we introduce the OIS and the VIS systems, and we briefly detail the solar activity during the three consecutive surveys studied in this paper. In Table 1 we can find the first and the last days of the gathered data, and the total number of days sounded per survey.

Table 1. The Starting Date, the Final Date, and the Number of Days per Survey

Survey	Starting Date	Final Date	No. of Days
2009/2010	1/1/2010	2/2/2010	33
2010/2011	22/1/2011	26/2/2011	35
2011/2012	30/12/2011	9/1/2012	17

2.1. Oblique Incidence Sounding

The OIS system has been working since 2003 [*Pijoan et al.*, 2014], analyzing the channel by means of narrowband and wideband signals.

2.1.1. OIS Hardware Description

The last OIS system update took place during the 2009/2010 survey, along with the results presented in *Ads et al.* [2012]. The updated system overcame the system described in *Vilella et al.* [2009]; the main differences between the two systems are as follows: (i) the frequency range turned from [4, 18] MHz to the entire HF band [2, 30] MHz; (ii) the new system is able to operate 24 h a day; (iii) higher-frequency synchronization accuracy, using an oven controlled crystal oscillator; and (iv) a new GPS unit with a pulse per second signal that increases the time synchronization accuracy (1 μs).

The current transmitter and receiver are software defined radio devices digitalizing the whole HF band (2–30 MHz) with high-speed analog to digital converters and D/A converters. The antennas used in the transmitter and in the receiver are two 7.5 m rugged monopoles, equipped with an antenna tuner that can adapt the whole band. In the Antarctica the monopole was located on the top of a small hill with a clear view to the northeast direction (to the receiver). At the receiver, the antenna was installed on a clear grassland. The transmission power has been limited to 250 W due to power consumption restrictions at the SAS. More details about the core of the system can be found in *Ads et al.* [2012].

2.1.2. OIS Test Design

The designed transmitted signals are organized in a frame as shown in Figure 2, once every hour per day and using frequencies in the range of [2, 30] MHz in 0.5 MHz steps. The waiting intervals are defined as W in Figure 2. After the antenna tuning period, a full power tone is transmitted during 10 s for narrowband sounding. This period is used for channel availability estimation and for computing the signal-to-noise ratio (SNR) statistics. After a 4 s waiting period, a pseudorandom noise sequence (m-sequence) [*Proakis*, 2000] of variable length and with good autocorrelation properties, as discussed by *Parsons* [2000], is transmitted during 10 s for wideband sounding. The wideband channel parameters to be measured are wideband SNR, multipath spread, Doppler spread, propagation time, and Doppler shift [*Ads et al.*, 2012].

Narrowband analysis focuses on channel availability and SNR computation. The channel availability means the probability of a link to reach a minimum SNR value and hence achieve a certain quality of service as defined by *Goodman et al.* [1997]. According to *Vilella et al.* [2008], a minimum SNR value of 6 dB has been specified to estimate the channel availability in a bandwidth of 10 Hz. In this paper, we have improved the narrowband detection method by measuring the variation of the SNR along the received signal power profile. This is done by windowing and time framing the received signal in the time domain, as explained below. Such techniques improve significantly the reliability of the detection system against noise and interference [*Ads et al.*, 2012].

SNR is computed by comparing the received power P_s measured during the tone interval (see Figure 3) to the noise power P_n measured during the waiting periods. The problem that we have faced is the false detection produced by interference signals present during the signal interval.

2.2. Vertical Incidence Sounding

The VIS parameters can be used to predict a propagation model for short distance sky wave paths. However, by applying some geometrical factors to the ionograms, some OIS properties for longer paths can be obtained. This is the aim of this work, i.e., to compare the information about the OIS system to the VIS system analysis, in order to settle the working frequencies and thus avoiding the oblique incidence sounding.

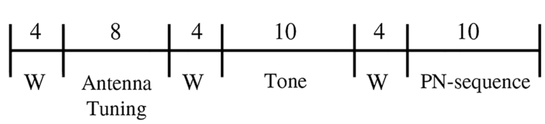

Figure 2. A sounding transmission frame structure.

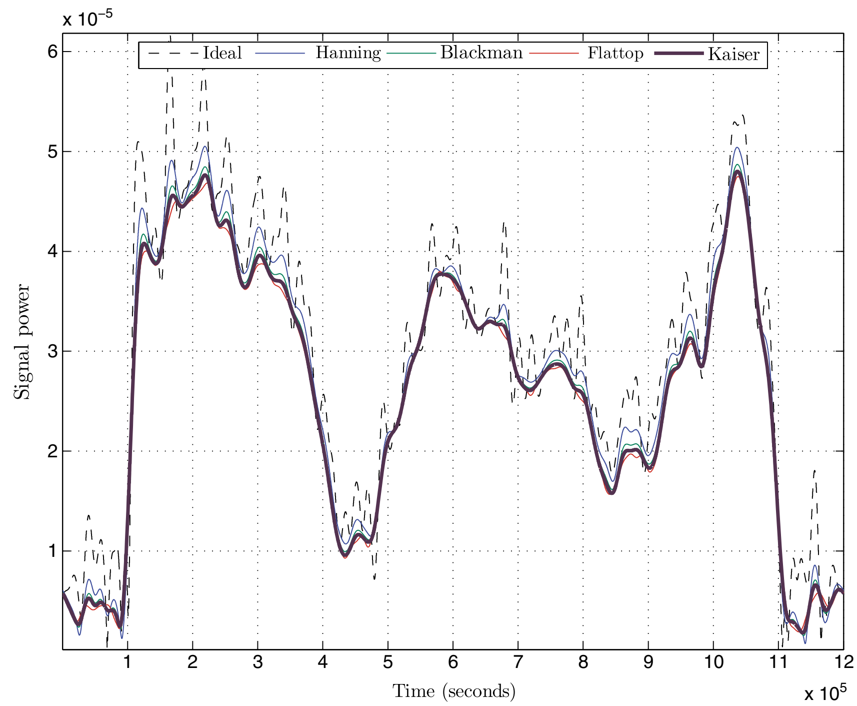

Figure 3. Narrowband signal filtered using several windows with a carrier frequency of 15.5 MHz at 10:00 UTC, where P_s is measured — 8 January 2010.

The reliability of these parameters depends on how much the OIS reflection points are close to the VIS station, as already mentioned by *Vilella et al.* [2009]. *McNamara and Wilkinson* [1984] already discussed how the observation on one point could clarify the ionospheric conditions in another point. Therefore, measurements from different VIS stations near the path of the radio link (see Figure 1 and Table 2) were chosen and compared to the OIS measurements gathered in the 12,700 km long haul link to be used in the future frequency availability estimations.

The analysis of the VIS records focus on the measurement of MUF(3000)F_2 for the purpose of our study. The results of this analysis are compared to the availability of the entire channel and to the estimated MUF(*D*). Although the VIS stations collect data by means of different equipment (see Table 2), all of them are Lowell Digisondes [*Lowell Digisonde International*, 2014], and their similar performance evaluation allows us to compare results from all of them.

Table 2. The Location of the VIS Stations, the Reflection Hops, and the Equipment of the VIS Stations [*Lowell Digisonde International*, 2014][a]

Station	Latitude	Longitude	URSI Code	VIS Station Equipment
Port Stanley	51.6°S	57.9°W	PSJ5J	DPS1 Lowell Digisonde
H1	50.4°S	43.6°W		
Cachoeira Paulista	22.7°S	44.2°W	CAJ2M	D256 Lowell Digisonde
H2	21.1°S	27.4°W		
Fortaleza	3.9°S	38.4°W	FZA0M	DPS4 Lowell Digisonde
Ascension Island	7.95°S	14.4°W	AS00Q	D256 Lowell Digisonde
H3	1.3°N	17.3°W		
El Arenosillo	37.1°N	6.7°W	EA036	D256 Lowell Digisonde
H4	28.2°N	7.1°W		

[a]URSI: Union Radio Scientifique Internationale.

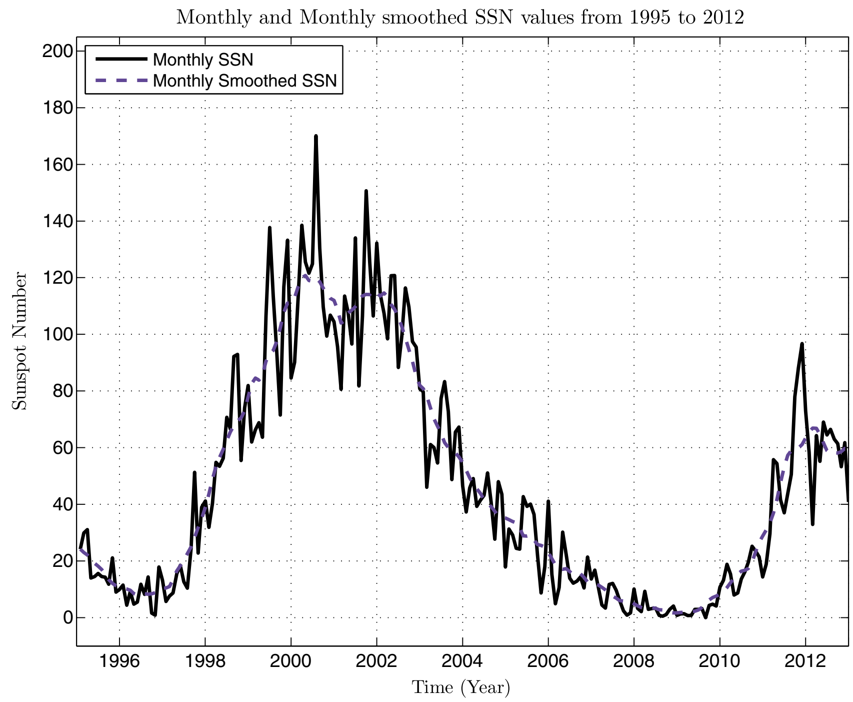

Figure 4. SSN values, with 4 month average from 1995 to 2012.

2.3. Solar Activity During 2009–2012 Campaigns

HF ionospheric propagation is deeply dependent on solar activity, among other circumstances. The high propagation condition associated with the daytime is largely supported by the high ionization conditions and the F_2 layer existence as well. The layer complete absence during the night leads to high propagation conditions at low HF range. However, frequencies lower than 10 MHz do not propagate during the daytime because the existence of the *D* layer [*Davies*, 1990].

Furthermore, a brief overview of the solar activity during the three surveys studied can lead us to some conclusions in terms of propagation analysis. Figure 4 shows an overview of the smoothed sunspot number (SSN) value from 1995 to 2012, both the value through the year and the average during the period of the campaign. In addition to the SSN value, the solar activity can be monitored by the solar flux. The larger the solar flux is, the greater is the Sun influence on ionospheric propagation. The values of the solar activity in the three studied campaigns are shown in Table 3. Since the Sun represents the ionization source of the ionosphere, Figures 5 and 6 show the sunrise and the sunset times during the austral summer at the VIS stations along the link path and at the geographical positions where the four hops are expected to be [*Perkiomaki*, 2013].

3. OIS and VIS Sounding Results Comparison

In this section, both OIS and VIS sounding results are shown for the three campaigns tested (see Table 1).

3.1. Survey Results and Comparison

Channel availability, FLA measured as in *Vilella et al.* [2009] and *Ads et al.* [2012] and obtained from the OIS soundings, and VIS soundings MUF(*D*) predicted by the Rec533 model [*ITU-R*, 2012] during the three surveys have been evaluated and compared.

Table 3. The SSN and Solar Flux Values Measured Throughout the Three Consecutive Surveys, During the Period of the Campaign

Survey	Averaged SSN	Solar Flux
2009/2010	11.72	79
2010/2011	29.9	86
2011/2012	64.2	134

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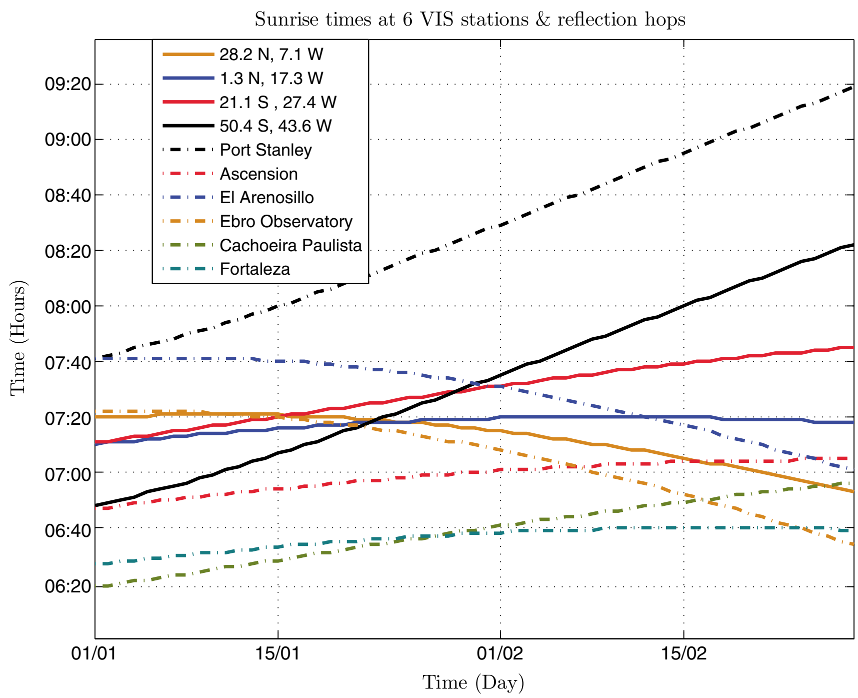

Figure 5. The sunrise time at OIS receiver, four reflection hops, and the VIS stations along the path.

3.1.1. 2009/2010 Survey

As depicted in Figure 7, frequencies higher than 23.5 MHz did not propagate throughout the whole 2009/2010 survey. Generally, the FLA is about 5 MHz below the MUF(*D*) as depicted in Figure 7. The difference between FLA and MUF(*D*) reaches its maximum (7 MHz) at midnight (00:00 UTC). Also, the MUF(*D*) is approximately limiting the channel availability, especially during the period from 00:00 UTC to 16:00 UTC. However, significant availability of the channel is recorded above MUF(*D*) from 16:00 to 24:00 UTC.

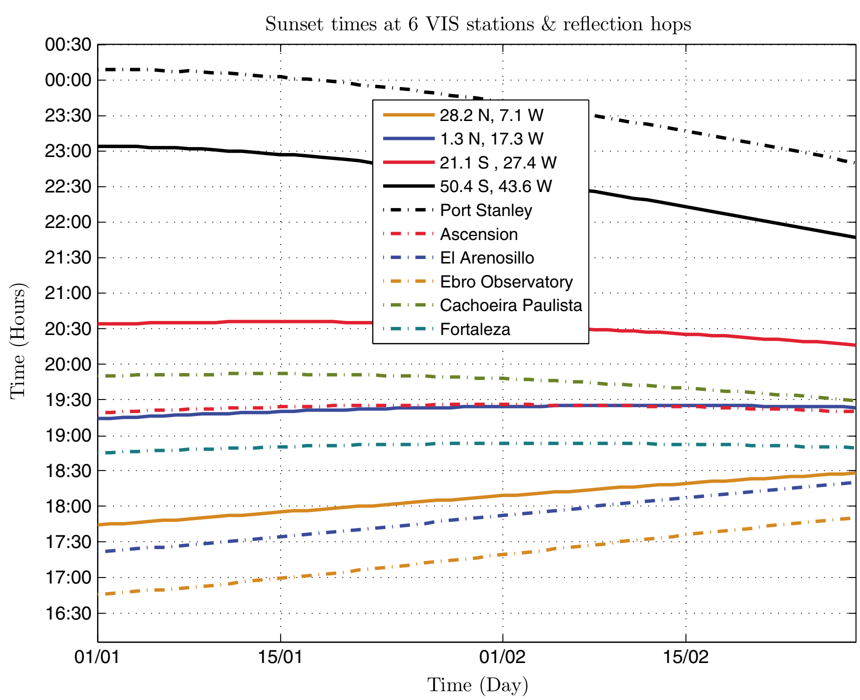

Figure 6. The sunset time at OIS receiver, four reflection hops, and the VIS stations along the path.

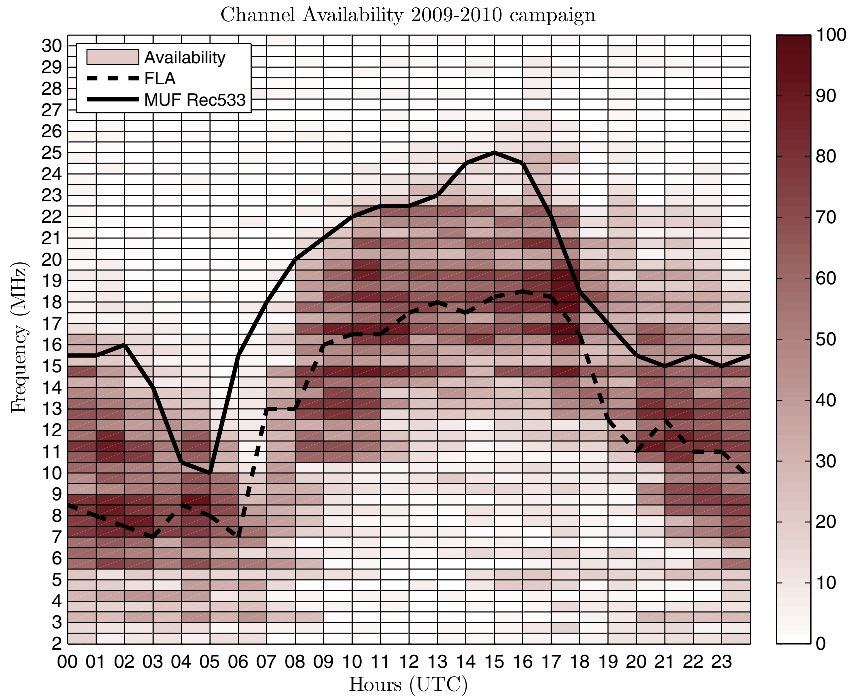

Figure 7. Comparison of interday variation of FLA, MUF(*D*), and channel availability during 2009/2010 survey.

3.1.2. 2010/2011 Survey

During the 2010/2011 survey (Figure 8) 25.5 MHz is the upper bound during daytime region and 18 MHz during the nighttime. As occurred in the 2009/2010 survey, MUF(*D*) values are bounding the channel availability approximately throughout the 24 h of the day. However, significant availability of the channel is recorded above MUF(*D*) from 14:00 to 22:00 UTC.

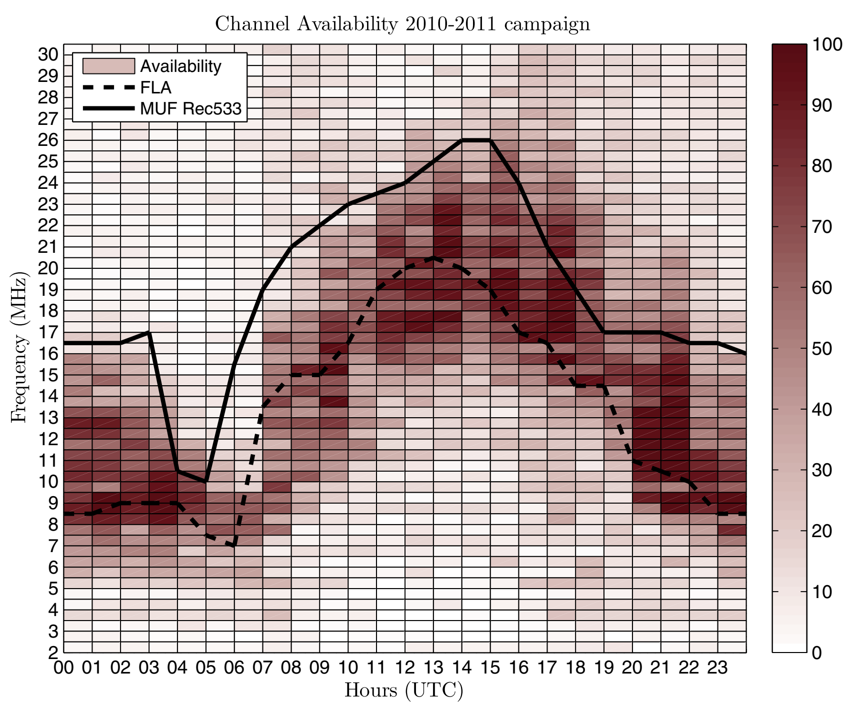

Figure 8. Comparison of interday variation of FLA, MUF(*D*), and channel availability during 2010/2011 survey.

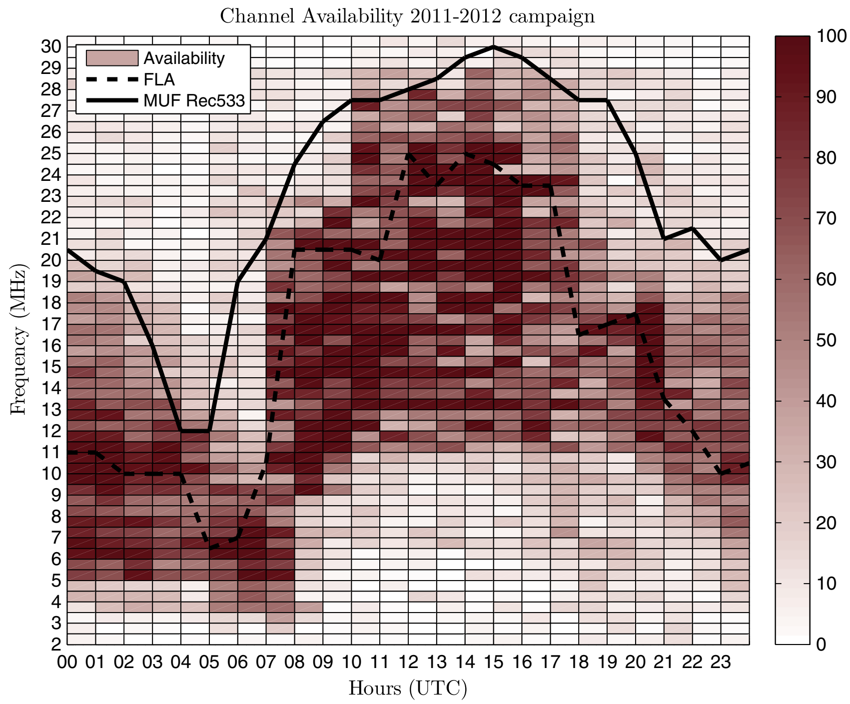

Figure 9. Comparison of interday variation of FLA, MUF Rec533, and channel availability during 2011/2012 survey.

3.1.3. 2011/2012 Survey

The 2011/2012 survey results are shown in Figure 9. The highest propagated frequency observed is around 28 MHz during daytime and 19 MHz at nighttime.

3.1.4. Survey Results Comparison

Finally, a comparison between the interday FLA variation measured during the three surveys is depicted in Figure 10. Generally, the average FLA measurements of 2009/2010 are similar to 2010/2011 surveys.

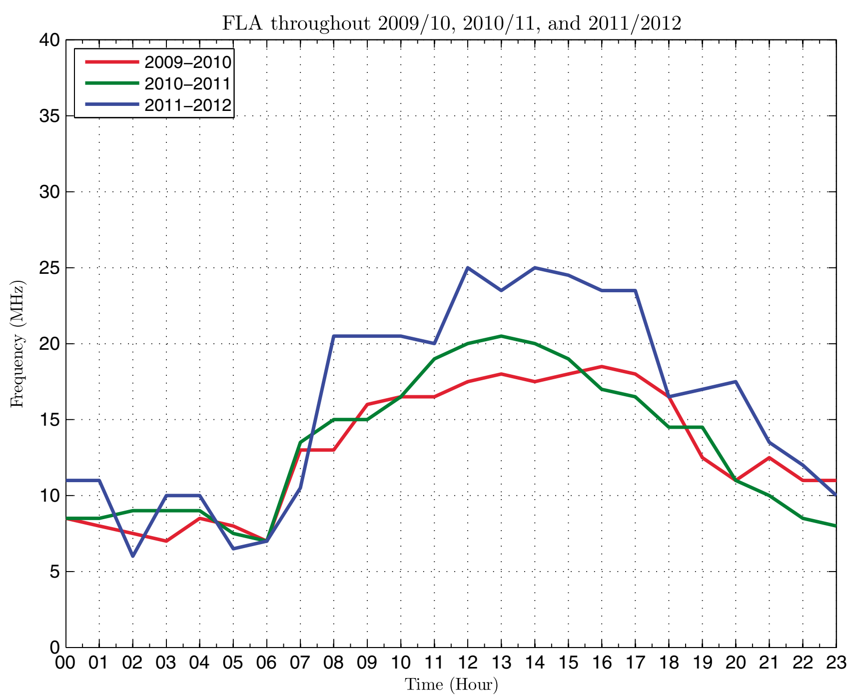

Figure 10. The FLA interday variation during 2009/2010, 2010/2011, and 2011/2012 surveys.

Table 4. Frequencies of Maximum Channel Availability During the Three Surveys Segmented Into Daytime and Nighttime Regions

	Daytime		Nighttime		Unit
Survey	08:00 to 17:00	00:00 to 04:00	05:00 to 07:00	18:00 to 23:00	(UTC)
2009/2010	10 to 23.5	5.5 to 14	10 to 17	10.5 to 17.5	(MHz)
2010/2011	12 to 25.5	6.5 to 15	8 to 17.5	8.5 to 16.5	(MHz)
2011/2012	10 to 28	5 to 18	3.5 to 21	11 to 18	(MHz)

However, during the 2011/2012 survey, the FLA is approximately 20% higher, 23% during the day and 15% during the night. The propagated signal frequency reaches the maximum value, i.e., 18.5 MHz at 16:00 UTC during 2009/2010, 20.5 MHz at 13:00 UTC during the 2010/2011, and 25 MHz at midday during 2011/2012 survey. During the afternoon period, the propagated signal frequency begins to decrease due to the lack of electron density. Therefore, the SSN annual increment (11.6, 21, and 65.4) and the solar flux (79, 86, and 134) strongly affect the ionospheric channel availability by raising the FLA. Consequently, the FLA outcomes grow proportionally to solar activity. The availability results are summarized in Table 4.

3.2. Vertical Incidence Sounding Results

In order to find the relationship between OIS parameters and VIS parameters such as MUF(3000)F_2, we analyze in this section the recorded interday variations of MUF(3000)F_2 at the VIS stations under study.

The solar activity influence on the ionospheric F_2 layer characteristics, as MUF(3000)F_2, is related to latitude as mentioned in *Sethi et al.* [2002] and to solar activity history [*Triskova and Chum*, 1996]. The MUF(3000)F_2 interday variation essentially differs during years of minimum and maximum solar activity. Herein there is an investigation of the effect of the solar activity, based on the SSN proxy, on MUF(3000)F_2 interday variation during three consecutive surveys.

The interday variation of MUF(3000)F_2 recorded at VIS stations is illustrated in Figures 11–15. Each one shows the series of results during the three surveys analyzed.

Figure 11 shows how the MUF(3000)F_2 interday variation recorded at Port Stanley station decreased from around 23 MHz at midnight to 16 MHz at dawn. It increases to around 25 MHz throughout the rest of the day.

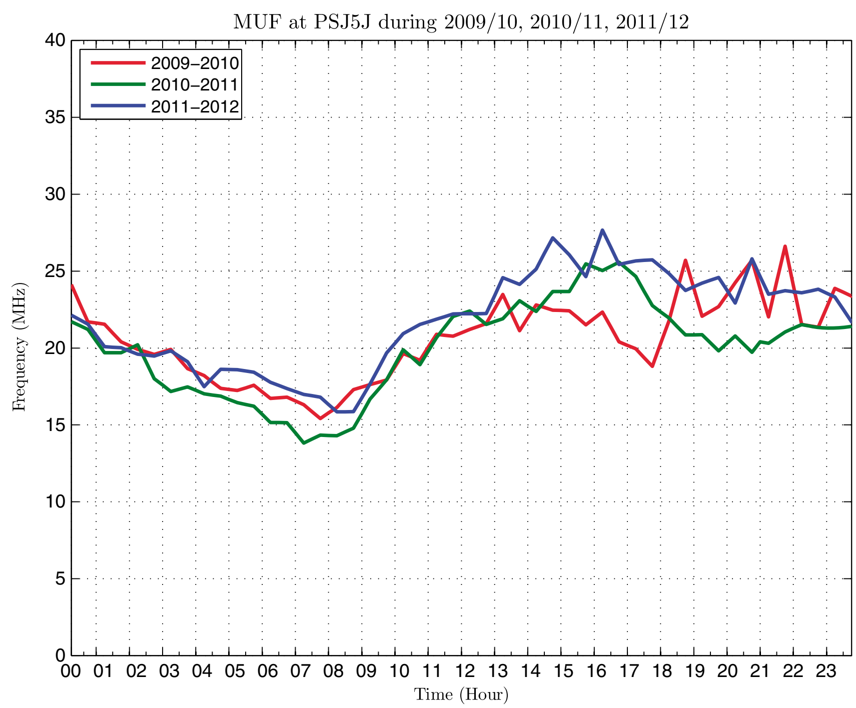

Figure 11. Interday variation of MUF(3000)F_2 at Port Stanley station during the surveys 2009/2010, 2010/2011, and 2011/2012.

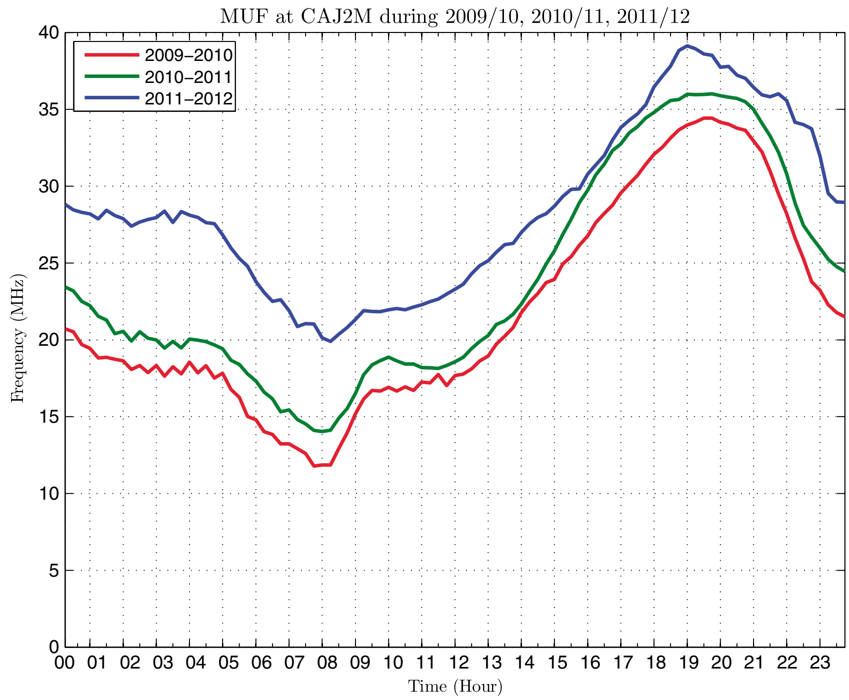

Figure 12. Interday variation of MUF(3000)F_2 at Cachoeira Paulista station during the surveys 2009/2010, 2010/2011, and 2011/2012.

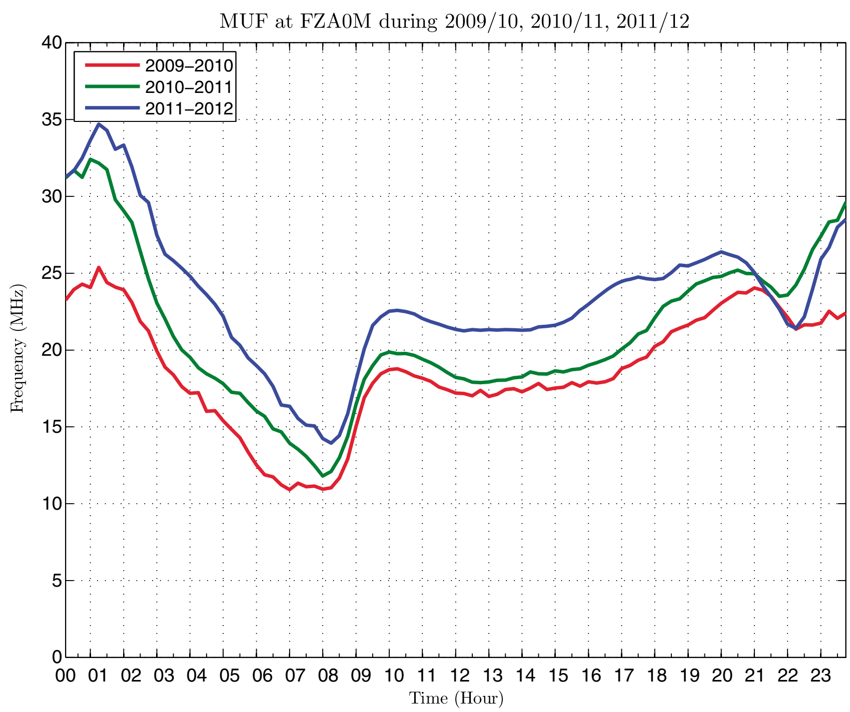

Figure 13. Interday variation of MUF(3000)F_2 at Fortaleza station during the surveys 2009/2010, 2010/2011, and 2011/2012.

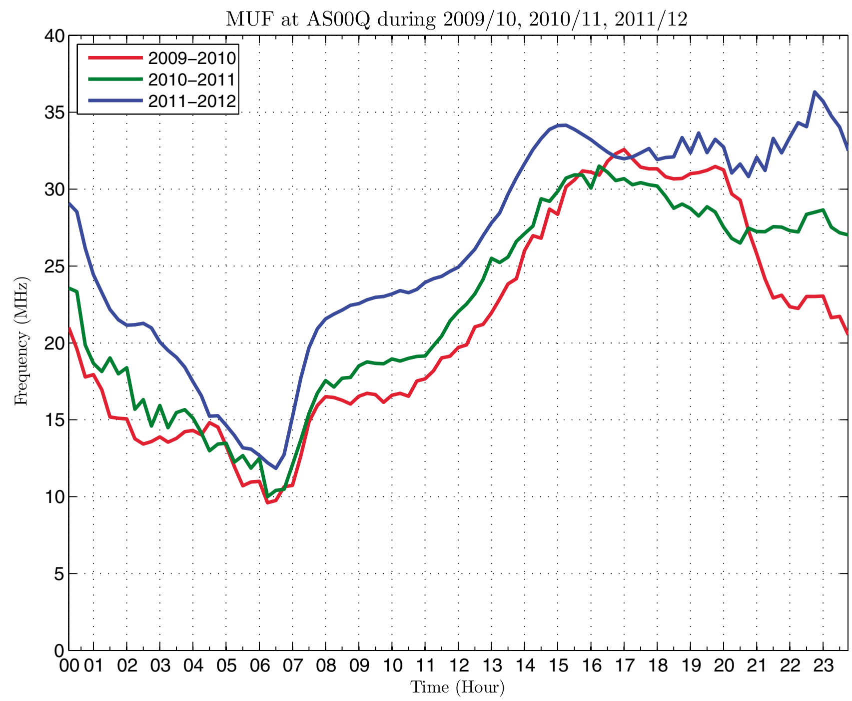

Figure 14. Interday variation of MUF(3000)F_2 at Ascension Island station during the surveys 2009/2010, 2010/2011, and 2011/2012.

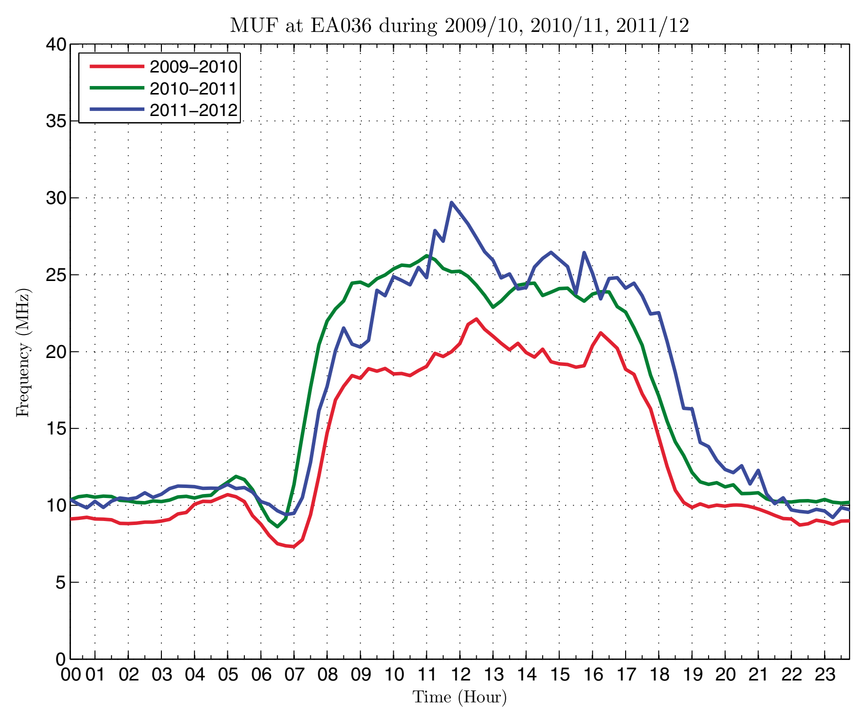

Figure 15. Interday variation of MUF(3000)F_2 at El Arenosillo station during the three surveys 2009/2010, 2010/2011, and 2011/2012.

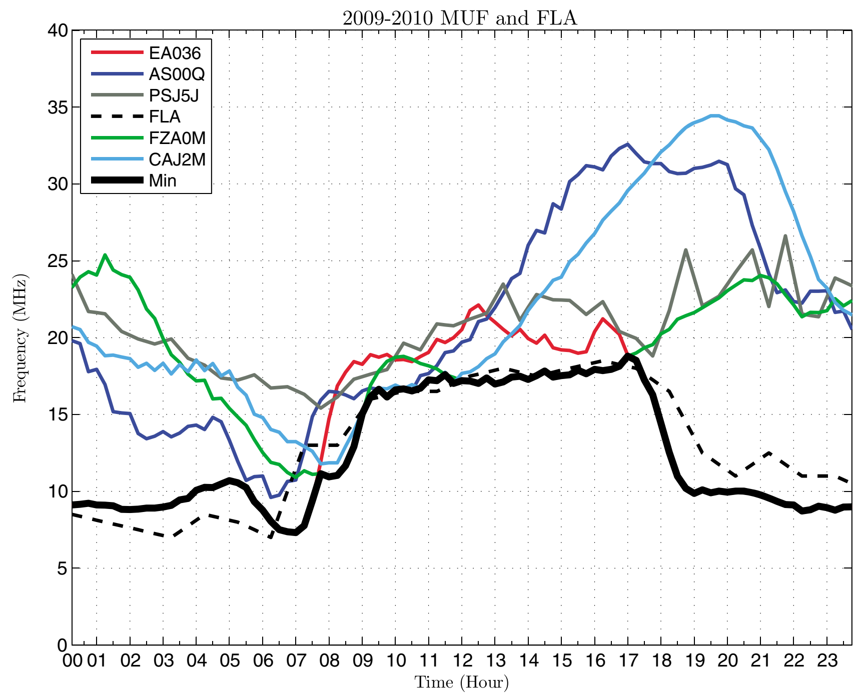

Figure 16. MUF(3000)F_2, FLA, and the minimum MUF(3000)F_2 among the VIS stations during 2009/2010 survey.

Cachoeira Paulista (see Figure 12) reaches the maximum MUF(3000)F_2 value at sunset (around 37 MHz), and the minimum at sunrise (around 12 MHz). In this case, 2011/2012 survey reaches significantly higher frequency values of MUF(3000)F_2, with a maximum difference of 7 MHz, than the other two surveys.

Fortaleza (see Figure 13) reaches the maximum MUF(3000)F_2 value at midnight (01:00 UTC), with a value around 35 MHz, and the minimum value at sunrise (08:00 UTC) around 10 MHz.

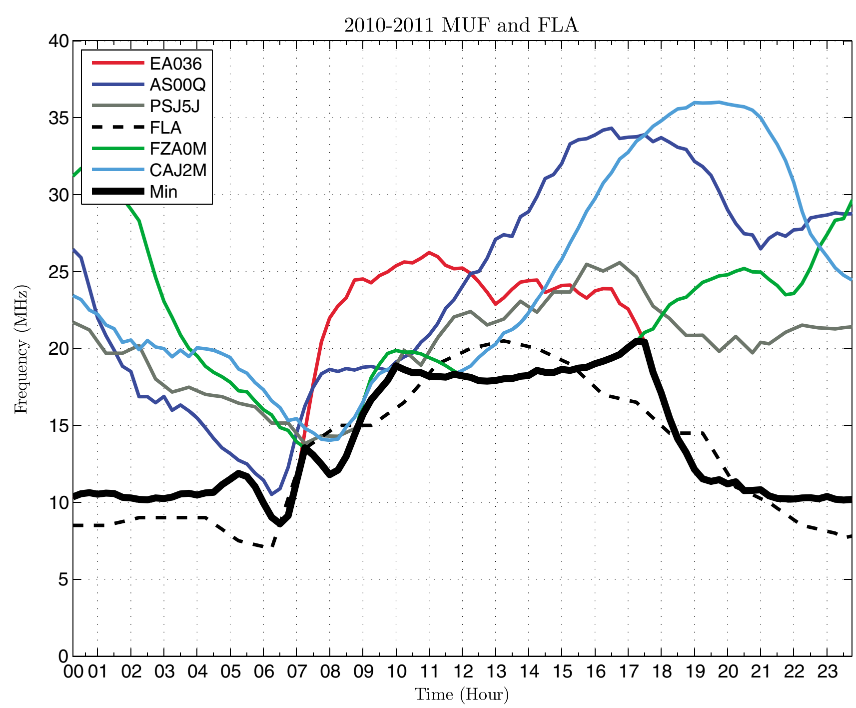

Figure 17. MUF(3000)F_2, FLA, and the minimum MUF(3000)F_2 among the VIS stations during 2010/2011 survey.

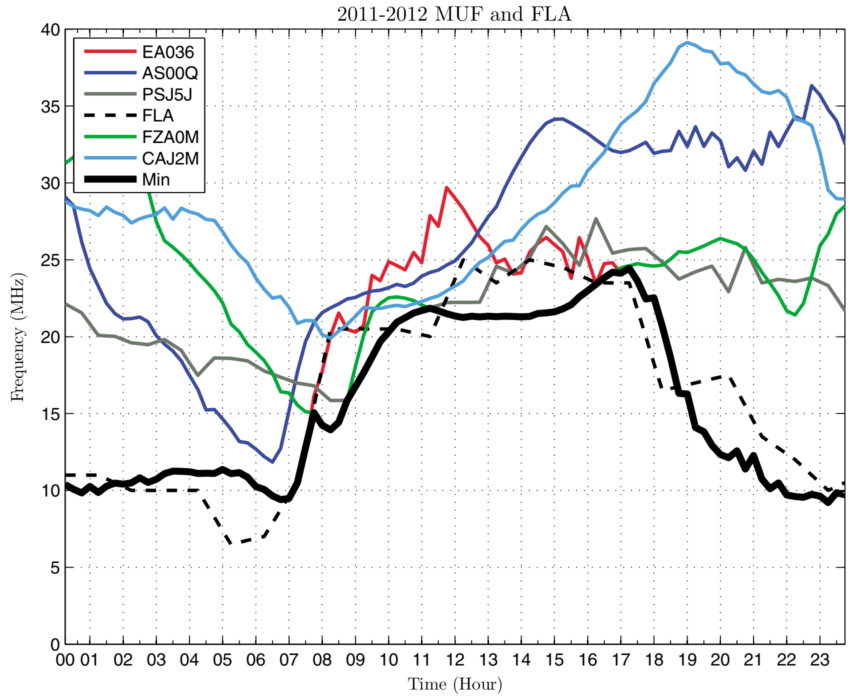

Figure 18. MUF(3000)F_2, FLA, and the minimum MUF(3000)F_2 among the VIS stations during 2011/2012 survey.

Ascension station (see Figure 14) reaches the minimum value at sunrise (06:00 UTC) around 10 MHz, and the maximum value at sunset, around 33 MHz.

Finally, Figure 15 illustrates the interday variation of MUF(3000)F_2 recorded at El Arenosillo station during the three surveys. The maximum value of 30 MHz is measured at noontime (12:00 UTC) throughout the 2011/2012 survey.

As a summary of Figure 15, during the nighttime of the three surveys an average value of around 10 MHz is observed, which starts increasing after dawn to around 20 MHz at 2009/2010 and 25 MHz through the 2010/2011 and 2011/2012 surveys. In hours near sunset, the MUF(3000)F_2 decreased to around 10 MHz at 19:00 UTC during the 2009/2010 survey, at 19:30 UTC during the 2010/2011 survey and at 20:00 UTC throughout the 2011/2012 survey. Also, an extension of the daytime propagation region of 2 h is observed from 2009/2010 survey to 2011/2012 survey, related to the higher solar activity values.

4. OIS and VIS Analysis Comparison

In this section we compare the MUF(3000)F_2 value recorded at the VIS stations close to the oblique link with the FLA obtained from the OIS system. Figures 16–18 illustrate the MUF(3000)F_2 recorded at the five stations along with the FLA of the OIS system. The minimum MUF(3000)F_2 gathered at the VIS stations is also shown. In order to easily compare the figures, we divide them into three intervals: from 00:00 UTC to 07:00 UTC, from 07:00 UTC to 18:00 UTC, and finally, from 18:00 UTC to 24:00 UTC.

In the three consecutive surveys it can be observed, see Figures 16–18, that the first time interval (00:00 UTC to 07:00 UTC) restricts the FLA of the link, confirming the results mentioned by *Vilella et al.* [2009]. This result is given by El Arenosillo values in the three figures.

In the 2009/2010 and 2010/2011 surveys, the second interval (07:00 UTC to 18:00 UTC) is limited by the minimum MUF(3000)F_2 values represented mostly by Cachoeira Paulista at the beginning of the day, until 12:00 UTC approximately, and Fortaleza just afterward and until 18:00 UTC. This same interval but for 2011/2012 survey is strictly limited by the MUF(3000)F_2 value obtained at Fortaleza; in this case the value at Cachoeira Paulista is higher. But at the end of the second interval, it appears a limit due to El Arenosillo, from 16:00 UTC to 18:00 UTC, approximately.

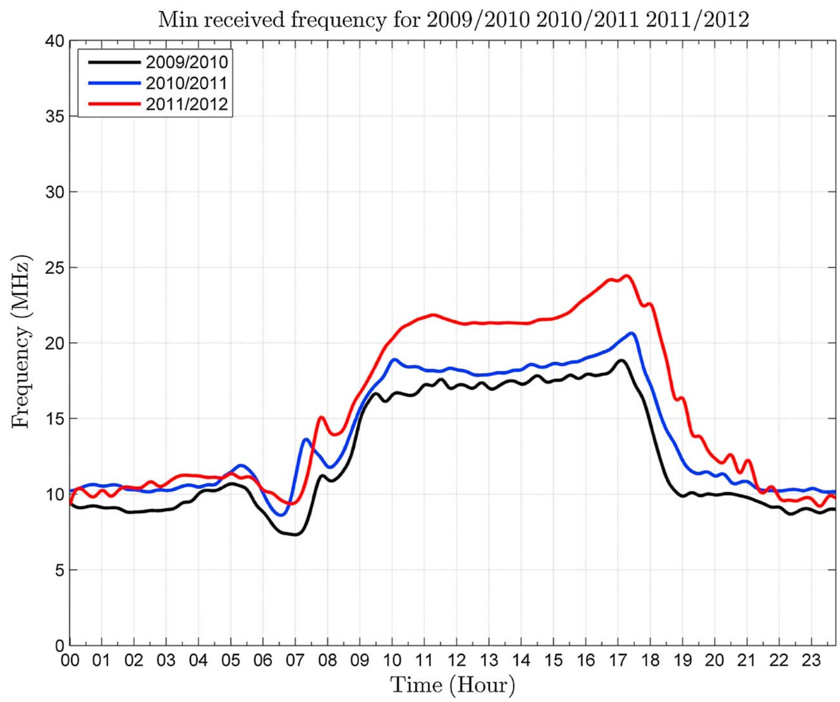

Figure 19. Minimum propagated frequency comparison throughout the 2009/2010, 2010/2011, and 2011/2012 surveys.

The third interval (from 18:00 UTC to 24:00 UTC) is lower bounded for the minimum MUF(3000)F_2 in that interval, which corresponds for three surveys to the results of El Arenosillo.

Finally, in Figure 19, the minimum of MUF(3000)F_2 evolution in the three consecutive surveys is shown. The first time interval shows no substantial increment in the MUF(3000)F_2. The second time interval (from 07:00 UTC to 18:00 UTC) illustrates that the maximum propagated frequency increased gradually year after year to near 25 MHz at 17:00 UTC in survey 2011/2012. And it progressively decreased to less than 10 MHz. Remarkably, the maximum propagated frequency during the daytime propagation region increased by around 1 h from the first to the last survey. That is highly related to the increasing of the SSN and solar flux from 12 to 65 and from 79 to 134 solar flux unit (sfu), respectively. Then, according to the previous results, the lowest MUF(3000)F_2 recorded at the VIS stations, which are strategically located close to the link, correlates with the FLA value at a specific time and it seems to limit.

5. Conclusions

The aim of this work was to find a prediction method for the best frequency transmissions of a long haul 12,700 km over-the-horizon link between Livingston Island to Spain without the need of oblique sounding. Due to this purpose, an oblique sounding of the channel was performed and its results were compared to the propagation results of five VIS stations along the path. The comparison between MUF(3000)F_2 obtained by the VIS stations and FLA obtained by the oblique sounding gives us a promising result in terms of prediction: in the three analyzed campaigns, there is clear dependency between the minimum MUF(3000)F_2 obtained by the VIS stations and the FLA computed by the oblique sounding. Despite the VIS stations are not equally separated from the path, we conclude that during the night (00:00 UTC to 07:00 UTC and from 18:00 UTC to 24:00 UTC) the nearest station to the receiver is the most limiting one (El Arenosillo), while during the day (from 07:00 UTC to 18:00 UTC) three stations have the lower MUF(D): Fortaleza, Cachoeira Paulista, and Ascension, with this order of appearance. It sounds like the ionospheric conditions recorded at Port Stanley seem to not affect the radio link for these three campaigns. These results led us to the conclusion that the optimum transmission frequency for this ionospheric channel can be predicted with enough accuracy using the data analyzed from these four stations (El Arenosillo, Fortaleza, Cachoeira Paulista, and Ascension). Port Stanley data could be avoided regarding the analysis we have just presented.

Remarkably, the minimum propagated frequency during the daytime propagation region increased by around 1 h from the first to the last survey. This is highly related to the increasing of the SSN and solar flux from 12 to 65 and from 79 to 134 sfu, respectively. Therefore, according to the previous results, the lowest MUF(3000)F_2 recorded at the VIS stations which are located strategically close to the link is similar to the FLA values at a given time.

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