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TIME OF FLIGHT MEASUREMENTS OVER A RADIO LINK FROM UPPSALA TO BRUNTINGTHORPE AND THEIR APPLICATION FOR TESTING PREDICTIONS METHODS THAT APPROXIMATE THE RAY TRACING TECHNIQUE

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1 INTRODUCTION

Time of flight measurements (TOF) as well as azimuthal angle of arrival measurements (AOA), on the Uppsala (Tx: 59°.9' N, 17°.6' E) - Bruntingthorpe (Rx: 52°.5', 1°.1' W) radio link have been performed every 2 minutes at 6 frequencies (4.637 Mhz, 6.954 Mhz, 8.008 Mhz, 10.391 Mhz, 11.118 Mhz, and 14.364 Mhz) during the period November 2006-January 2008. Accurate predictions of the main parameters characterizing the HF ionospheric channel require a detailed knowledge of the ionospheric conditions that only numerical ray tracing technique (such as Jones and Stephenson, 1975 and Norman et al., 1994) or analytic ray tracing techniques (Norman and Cannon, 1997, 1999) can provide. In this work three different predictions methods IRI-95, SIRM&BR_D and ICEPAC that approximate the ray tracing techniques were tested. In order to verify the validity of the methods approximating the ray tracing technique in real propagation conditions, comparisons between the predictions provided by IRI-95, SIRM&BR_D and ICEPAC and the TOF median measurements for the one hop propagation modes 1E and 1F were carried out for different frequencies and seasons.

2 DESCRIPTION OF THE METHODS THAT APPROXIMATE THE RAY TRACING TECHNIQUE

The IRI-95 prediction method uses the hourly monthly median electron density profiles predicted by IRI-95 version (Bilitza, 1990; Bilitza, 2001). The SIRM&BR_D prediction method utilizes the monthly median predictions of the ionospheric characteristic, foF2 and M(3000)F2, provided by SIRM (Zolesi et al., 1993; Zolesi et al., 1996) applied in conjunction with the Bradley-Dudeney model (Bradley and Dudeney, 1973) to calculate hourly monthly median electron density profiles. For developing IRI-95 and SIRM&BR_D predictions methods the following procedure has been adopted. The monthly median electron density profiles $N = N(h)$ provided by IRI-95 and SIRM&BR_D have been used to calculate the vertical plasma frequency profiles $f_v = f_v(h)$ at the mid-point of the Uppsala (Tx) - Bruntingthorpe (Rx) radio link. As the effect of Earth curvature is important for ground ranges greater than 500 km, the curvature of the Earth and the known ground range (D=1411 km) of the radio link, have been taken into account for calculating the secant of the angle of incidence φ of the ray at the base of the ionosphere as a function of R, D, and h (R being the radius of the Earth) (Davies, 1990). The values of $\sec\varphi = f(R,D,h)$ have been calculated assuming a very simple geometry based on ionospheric reflections taking place from a simple horizontal mirror at the appropriate height h (figure 1). Subsequently, the secant law (McNamara, 1991) was applied to calculate the oblique transmission frequency $f_{ob} = f_v \sec\varphi$. The length of the oblique ray path $P = f(R, D, \sec\varphi)$, its corresponding TOF and take off angle $\Delta = f(R, \sec\varphi)$ have been calculated from simple mathematical relationships deduced from the geometry sketched in figure 1. The software package ICEPAC is a full system performance model for HF radio communications circuits (Stewart, undated) . It utilizes the monthly median electron density profiles (Haydon and Lucas, 1968) at the mid-point of the radio link derived from CCIR foF2 and M(3000)F2 coefficient (CCIR, 1966), and, from these, provides for a given oblique transmission frequency and hour, predictions of the main propagation parameters characterizing a given radio link such as elevation angle, TOF, virtual height, etc.

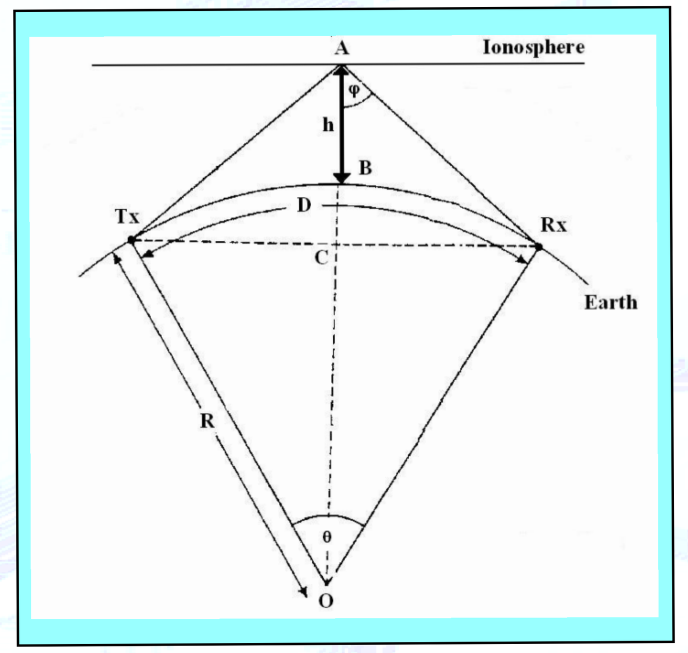

Figure 1.
Geometry of reflection from a simple horizontal mirror.

3 DATA ANALYSIS

Systematic observations of parameters TOF and DOA (both azimuth and elevation) were performed from November 2006 to January 2008 over the radio link Uppsala - Bruntingthorpe every 2 minutes at 6 frequencies (4.637 Mhz, 6.954 Mhz, 8.008 Mhz, 10.391 Mhz, 11.118 Mhz, and 14.364 Mhz). Some example observations are presented in figures 2 - 3.

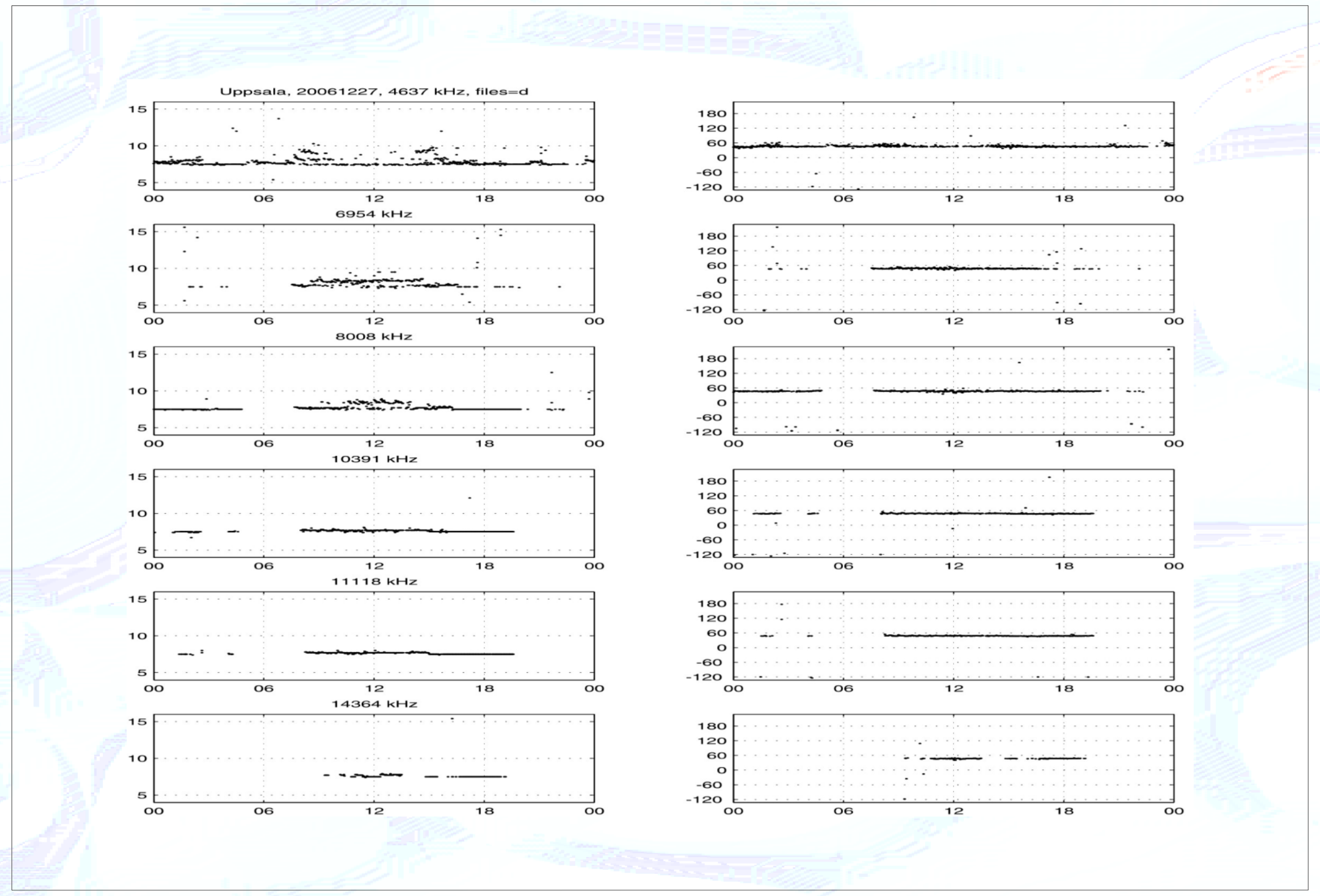

Figure 2. Observations of TOF (on the left) and AOA (on the right) at Uppsala on 27 December 2006 for the transmitting frequencies 4.637, 6.954, 8.008, 10.391, 11.118, and 14.364 MHz; in particular, note the small variations in TOF at around 14.00 U.T. at the frequencies 10.391 and 11.118 Mhz indicating a change from 1F to 1E propagation mode.

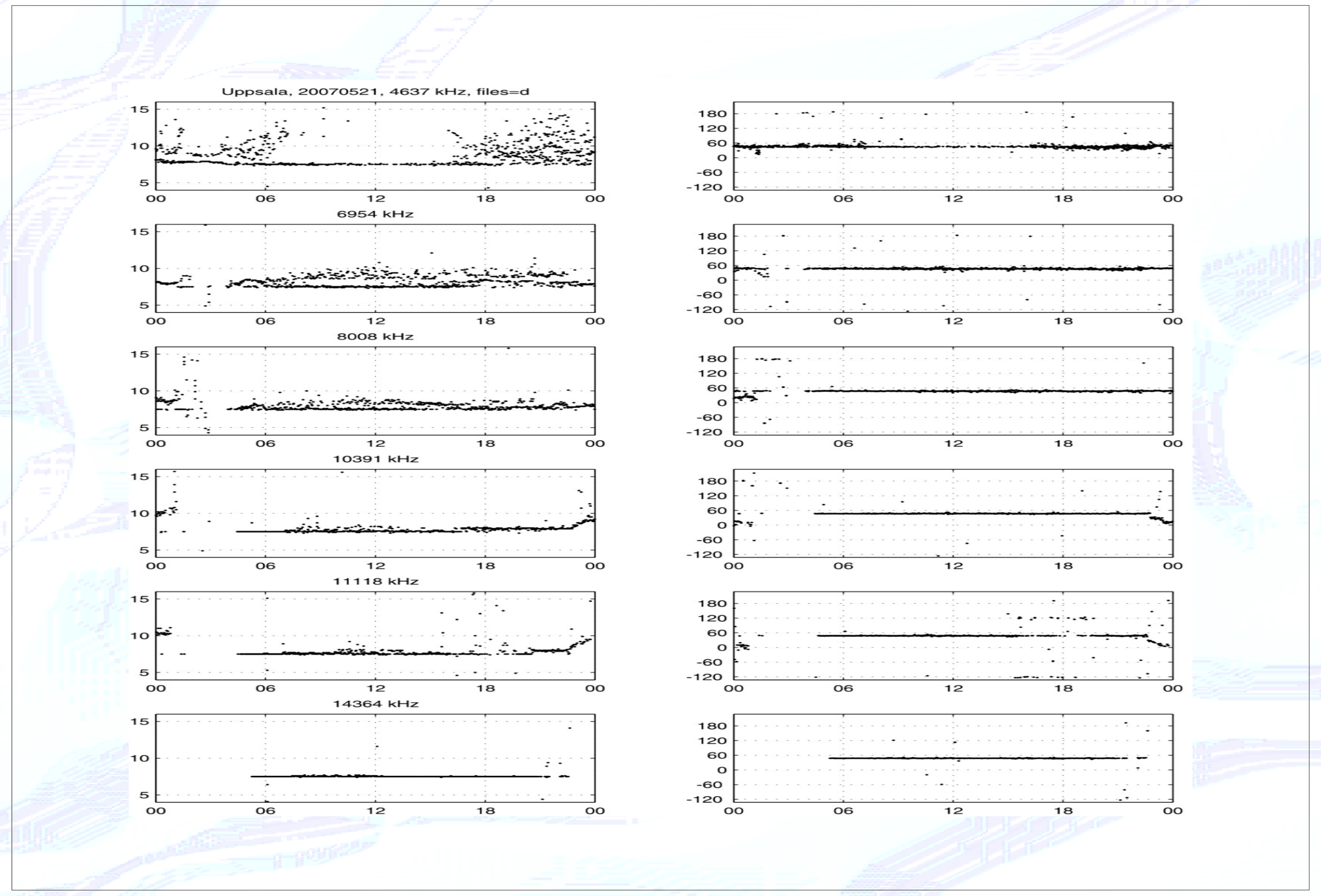

Figure 3. Observations of TOF (on the left) and AOA (on the right) at Uppsala on 21 May 2007 for the transmitting frequencies 4.637, 6.954, 8.008, 10.391, 11.118, and 14.364 MHz; in particular, note the change of the signal AOA by several tens of degrees to the north and the corresponding increase in the TOF occurring towards the end of the day at the frequencies 10.391 and 11.118 MHz. These AOA and TOF variations show the presence of non conventional (i. e. off great circle) propagation modes in the ionosphere.

A preliminary analysis was carried out in order to detect the TOF values associated with off great circle propagation. The AOA measurements were used as a filter to determine wheter the signal has travelled via a conventional propagation modes, i.e. along the great circle path or by another mechanism(e. g. deviations due to scattering from irregularities in the auroral oval, Siddle at al. 2004 a, b) that results in the signal being displaced significantly from the great circle direction. With this in mind, as the azimuth angle between Uppsala and Bruntingthorpe is approximately 47°, all TOF measurements corresponding to AOA measurements which values differed significantly from 47° were disregarded. In such a way, TOF measurements associated with off great circle propagation modes, interfering signals, or with an array side lobe have been excluded from the analysis and only TOF measurements related to conventional propagation modes were selected. Moreover such measurements were "cleaned up" from the calibration offset (2.7± 0.1 ms) due to the time it takes for the signal to pass through the filters in the transmitter and receiver. Subsequently TOF measurements associated with conventional one hop propagation modes around each hour (hr) were considered to extract TOF measurements for 1E ($TOF_{1E,hr}$) and 1F ($TOF_{1F,hr}$) propagation modes at a given hour . From $TOF_{1E,hr}$ and $TOF_{1F,hr}$ data, TOF median measurements for 1E ($TOF_{1E,hr,med}$) and 1F ($TOF_{1F,hr,med}$) propagation modes were calculated for each hour, month and frequency.

4 RESULTS

A few comparisons between TOF monthly median measurements and TOF monthly median predictions provided by IRI-95, SIRM&BR_D and ICEPAC are shown in figures 4-8 for different seasons and frequencies for the one hop propagation modes 1E and 1F.

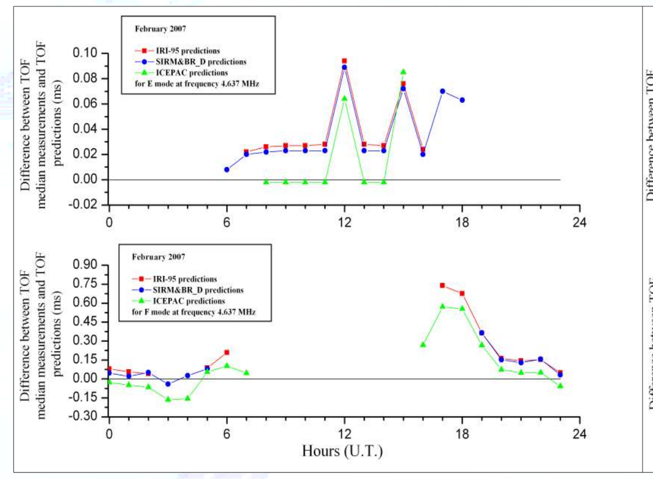

Figure 4. For 1E propagation mode, ICEPAC's performance is slightly better (r.m.s. = 0.038 ms) than that provided by IRI-95 (r.m.s. = 0.045 ms) and by SIRM&BR_D (r.m.s. = 0.045 ms). For the 1F propagation mode, the performances provided by IRI-95,SIRM&BR_D and ICEPAC in terms of r.m.s are equal to 0.325 ms,0.139 ms, and 0.232 ms, respectively.

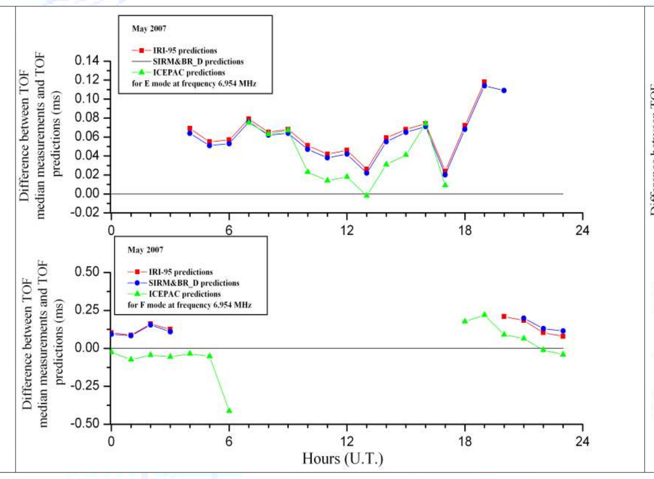

Figure 5. For 1E propagation mode, ICEPAC's performance is slightly better (r.m.s. = 0.046 ms) than that provided by IRI-95 (r.m.s. = 0.064 ms) and by SIRM&BR_D (r.m.s. = 0.065 ms). For the 1F propagation mode, the performances provided by IRI-95, SIRM&BR_D and ICEPAC in terms of r.m.s are equal to 0.139 ms,0.131 ms, and 0.147 ms, respectively.

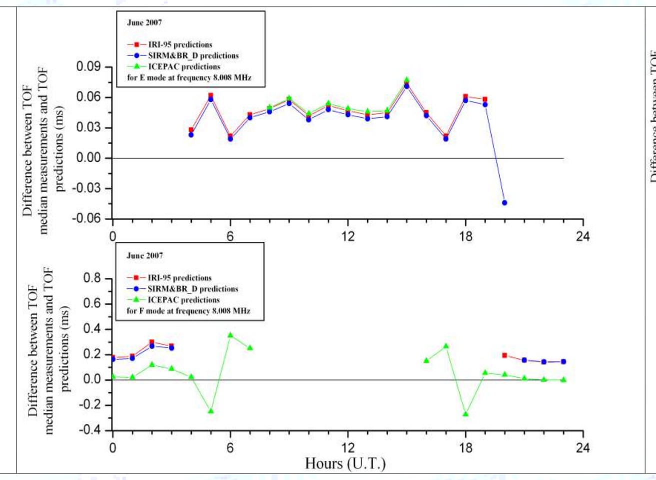

Figure 6. For 1E propagation mode, ICEPAC's performance is slightly worst (r.m.s. = 0.054 ms) than that provided by IRI-95 (r.m.s.= 0.049 ms) and by SIRM&BR_D (r.m.s. = 0.045 ms). For the 1F propagation mode, the performances provided by IRI-95, SIRM&BR_D and ICEPAC in terms of r.m.s are equal to 0.204 ms,0.192 ms, and 0.167, ms, respectively

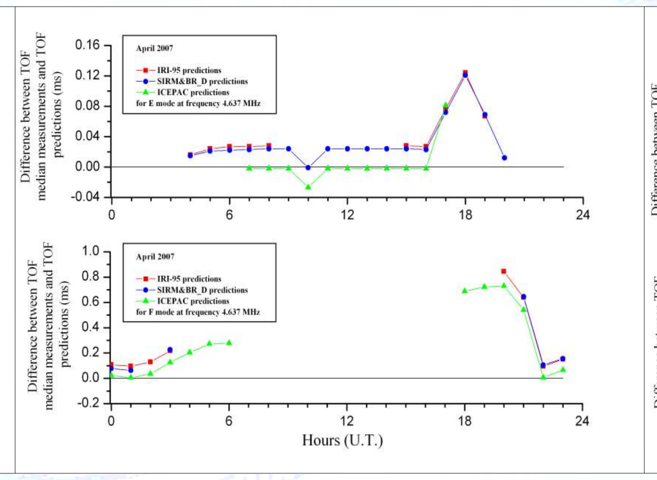

Figure 7. For 1E propagation mode, ICEPAC's performance shows a remarkable improvement (r.m.s. = 0.026 ms) compared to that provided by IRI-95 (r.m.s. = 0.055 ms) and by SIRM&BR_D (r.m.s. = 0.043 ms). For the 1F propagation mode, the performances provided by IRI-95, SIRM&BR_D and ICEPAC in terms of r.m.s are equal to 0.393 ms,0.292 ms, and 0.396 ms, respectively.

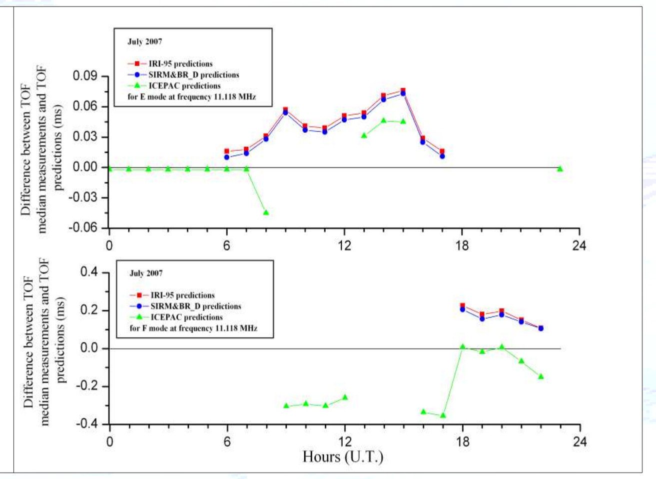

Figure 8. For 1E propagation mode, ICEPAC's performance shows a remarkable improvement (r.m.s. = 0.023 ms) compared to that provided by IRI-95 (r.m.s. = 0.046 ms) and by SIRM&BR_D (r.m.s. = 0.043 ms). For the 1F propagation mode, the performances provided by IRI-95, SIRM&BR_D and ICEPAC in terms of r.m.s are equal to 0.177 ms,0.161 ms, and 0.234 ms, respectively.

1E propagation mode	Winter months $r.m.s_{min} - r.m.s._{max}$ (ms)	Equinoctial months $r.m.s_{min} - r.m.s._{max}$ (ms)	Summer months $r.m.s_{min} - r.m.s._{max}$ (ms)
IRI-95	0.038 – 0.099	0.044 – 0.085	0.013 – 0.093
SIRM&BR_D	0.045 – 0.099	0.043 – 0.084	0.008 – 0.072
ICEPAC	0.002 – 0.048	0.022 – 0.062	0.002 – 0.082

Table 1. The minimum and maximum value of the r.m.s. error are shown taking into account all the frequencies which arrive at the receiver following the 1E on great circle propagation modes.

Table 2. The minimum and maximum value of the r.m.s. error are shown taking into account all the frequencies which arrive at the receiver following the 1F on great circle propagation modes.

1F propagation mode	Winter months $r.m.s_{min} - r.m.s._{max}$ (ms)	Equinoctial months $r.m.s_{min} - r.m.s._{max}$ (ms)	Summer months $r.m.s_{min} - r.m.s._{max}$ (ms)
IRI-95	0.071- 0.325	0.072 – 0.393	0.111 – 0.572
SIRM&BR_D	0.097– 0.139	0.070 – 0.254	0.108 – 0.340
ICEPAC	0.025 – 0.325	0.093 -0.396	0.095 – 0.432

5 DISCUSSION OF THE RESULTS AND CONCLUSIONS

Taking into account all the signals at frequencies that arrive at the receiver via the 1E on great circle propagation modes in winter, equinoctial and summer months, the comparisons between IRI-95 and SIRM&BR_D do not show significant differences in terms of r.m.s. deviations. As expected, both the models are able to predict the TOF of 1E on great circle propagation modes during daylight hours. The behaviour of ICEPAC is different because it is also able to predict TOF of 1Es propagation modes both during the night time and day time. ICEPAC's performance in general is better than that provided by the IRI-95 and SIRM&BR_D models as shown in figures 4-5, but some exceptions are present (see figure 6). In particular the performance of ICEPAC shows a remarkable improvement compared with the performance provided by IRI-95 and SIRM&BR_D when the E sporadic layer is present as shown in figures 7-8. As can be noted from the results presented in tables 1-2, IRI-95 , SIRM&BR_D and ICEPAC give better TOF predictions when 1E propagation modes are considered. Nevertheless IRI-95, SIRM&BR_D and ICEPAC could be used only to give a rough estimate of the time delay during daylight hours, in that the values of the r.m.s. for the 1E modes, correspond to differences of some tens of kilometres in the reflection height. ICEPAC could be used to predict TOF of 1Es propagation modes with a good accuracy both during daytime and night time as can be seen in figures 7-8. Taking into account all the signals at frequencies that arrive at the receiver via 1F on great circle propagation modes the results provided by the three methods are not satisfactory as can be seen in table 2. This means that IRI-95, SIRM&BR_D and ICEPAC are completely inadequate for the prediction of the time delay of 1F modes. When a radio signal reflects from the E region, the oblique ray path is affected by the ionosphere for a relatively short time, consequently the model assuming ionospheric reflections taking place from a simple horizontal mirror is a good approximation . This probably explains why IRI-95 , and SIRM&BR_D can provide a rough estimate of the TOF concerning the 1E on great circle propagation modes. When the propagation is via the F region, the ionospheric plasma affects the oblique ray path for a longer time, and consequently the model adopted is not a good approximation. In this case the prediction methods investigated here fail and a precise estimate of the time delay can not be provided. This happens because we have tried to characterize the HF ionospheric channel in a very simple way, assuming a geometry based on ionospheric reflections taking place from an horizontal mirror, and using a modelled electron density profile N = N(h) only in the middle point of the radio link, while accurate electron density profiles at all points along the whole path between the transmitter and receiver should be considered for describing with a good accuracy the HF communication link.The results obtained in this work show that, in spite of the relative speed of application of the three prediction methods (no ray tracing is required), it is necessary to adopt a different procedure that is able to include a more appropriate knowledge of the ionospheric conditions. Therefore only a ray tracing technique, either analytical or numerical, could be expected to provide better TOF predictions. A ray tracing technique with magnetic field, coupled with modelled monthly median electron density profiles in a 2D - 3D ionosphere or better with electron.
density profiles updated by real time measurements could provide large improvements.

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