On the estimate and assessment of the ionospheric effects affecting low frequency radio astronomy measurements

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Abstract

The development of the LOw Frequency telescopes ARray (LOFAR) has posed a serious issue on the calibration of those measurements in the presence of the Earth's ionosphere. The purpose of measuring at radio frequencies as low as VHF exposes LOFAR to a number of ionospheric phenomena, capable of deteriorating the accuracy of the measurements and subsequently of the sky imaging. The ionosphere is normally treated at signal processing level, where various efforts attempt to remove possible errors introduced by it. Here, a close look at particular ionospheric features and their possible consequence to radio astronomy measurements is given from a point of view of the ionospheric radio wave propagation. It seems the radio astronomy and ionosphere communities will need to work closely together in order to achieve a satisfactory solution to the problem.

1 Introduction

In radio astronomy experiments the ionosphere is usually treated as a simple refracting layer introducing an error (i.e., a phase advance). This problem is particularly relevant for LOFAR measurements (as well as for the future Square Kimolometre Array) which extends towards low (i.e., VHF) radio frequencies. Because of the typical values for the plasma frequency, those radio wavelengths are particularly sensitive to propagation through the Earth's ionosphere.

The effects of the ionosphere on low frequency radio astronomy measurements can be summarised as (1) an extra phase delay and (2) a Faraday rotation (rotation of the polarisation vector).

At present, the ionospheric calibration of LOFAR measurements (concerning point 1) is attempted by means of numerical methods which take place at signal processing level. The most notable effort is probably the so called "source peeling" and "self-cal" methods [1-2]. This is an iterative method based on bright calibrator sources present in the sky and on a pure phase screen approximating the ionosphere [2]. At this stage, the possibility of uncorrelated ionospheric structures over different telescopes within an array seems to lead astronomers to a refinement of this method (as well as other similar methods), for instance by considering multiple phase screens.

Point 2 is claimed to be solved at signal processing level, by manipulating the measurement equation in a suitable way [3]. This exercise was elegantly solved within a quaternions formalism [3].

Unfortunately, the assumptions relative to the ionosphere are close to trivial and their validity is then strongly limited. This seriously affects low frequency measurements in radio astronomy. It has to be noticed that:

- the ionosphere is not a single/multiple phase screen extremely variable. It is rather a 3-d dynamic medium containing both temporal and spatial inhomogeneities.
- The ionospheric behaviour shows a significant day-to-day variability.
- The ionospheric behaviour strongly depends on the combination of the magnetic and solar activities.
- The ionosphere shows different features at magnetic low, middle and high latitudes.
- The ionospheric behaviour shows a significant asymmetry between local night and day.

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The relevance of the ionospheric calibration also arises from the accuracy needed in low frequency measurements for radio astronomy.

Reasonably, the accuracy of LOFAR measurements will need to be quite accurate (of the order of $10^{-2}TECU$). On average, independent standard ionospheric measurements are accurate usually within few TECU.

Very simple examples about the complexity of the ionospheric medium and its effects on the propagation of radio waves will be given below. The hope is to stimulate a fruitful discussion and cooperation with the astronomers in such a common field.

2 Examples of ionospheric features as measured by means of GPS signals

Previous studies have demonstrated part of the complexity of the ionospheric problem by using GPS signals [4-5]. Those studies essentially showed what is expected from the point of view of radio waves propagating through the ionosphere. It was indeed argued on the overall additional phase advance to be expected at day and night from a given direction in the sky as well as on the asymmetry of the ionospheric error through a large baseline of observations [4-5]. However, those studies contained a strong limitation, lying on the use of TEC computed from GPS signals. The estimate of (slant and, more importantly, vertical) TEC through the use of GPS signals is affected by a calibration problem depending on satellites and receivers biases.

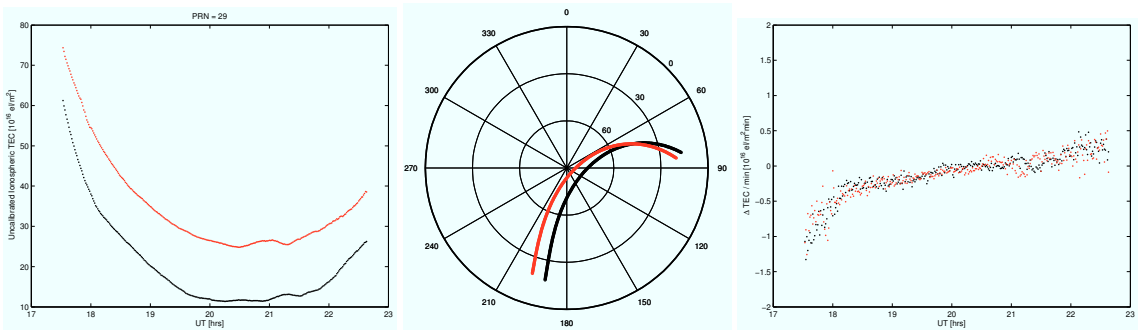
Figure 1a shows an example of TEC calculated by using the same GPS signal (i.e., from the same PRN29) as received from two different stations (in this case, Nottingham and Dourbes) at the same time. The red marker refers to the measurement from Nottingham, while the red marker to those from Dourbes. They refer to a magnetically quiet day (28 June 2008, $K_p \leq 2$). It is not attempted to level the two measurements because different calibrations will be needed for the two (contrary to what is shown in [4-5]). Nevertheless, attention to the relative behaviour of the two curves should be paid. It may be noticed as the two measurements seem to show a somehow parallel behaviour, though a little oscillation appears at an earlier time over Nottingham and at a later time over Dourbes (quite probably a signature of a medium scale travelling ionospheric disturbance, or TID). The two measurements both refer to a satellite at its highest elevation (elevation angles between $60°$ and $90°$, see Figure 1b). Figure 1c shows the behaviour of the temporal fluctuations in the TEC over the two stations which, in this particular case, has small deviation around its average value at zero.

The situation in Figure 1, though with some problems arising from spatial and temporal asymmetries, is not always the case. Figures 2 and 3 show additional cases. Figure 2 refers to the baseline Nottingham - Dourbes (PRN26, 27 March 2008, $K_p \leq 6$) and shows how structures may become apparent in an asymmetric way over the two measurements, thus limiting the accuracy of interferometric observations due to a spatial decorrelation of effects. Figure 3 refers to the baseline Nottingham - Nova Gorica (PRN3, 20 December 2010, $K_p \lesssim 3$) where the behaviour is quite asymmetric.

3 Conclusion

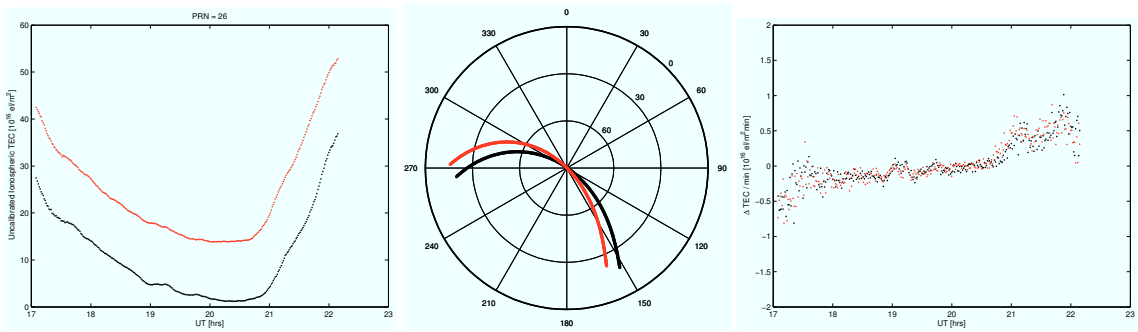
The simple examples shown here are intended to draw the attention on the complexity of the ionosphere and the evaluation of its effects on low frequency measurements in radio astronomy. It seems evident that methods based on signal processing only may not be adequate to address the problem. Also,independent estimates of ionospheric refraction (such as through the use of GPS signals) may be quite limited in accuracy.

The ionosphere is not a simple phase screen but a complex 3-d medium with inhomogeneities in both space and time. Its behaviour strongly depends on the combination of the magnetic and solar activities and its day-to-day variability exhibits different patterns at different magnetic locations in view of different processes taking place there.



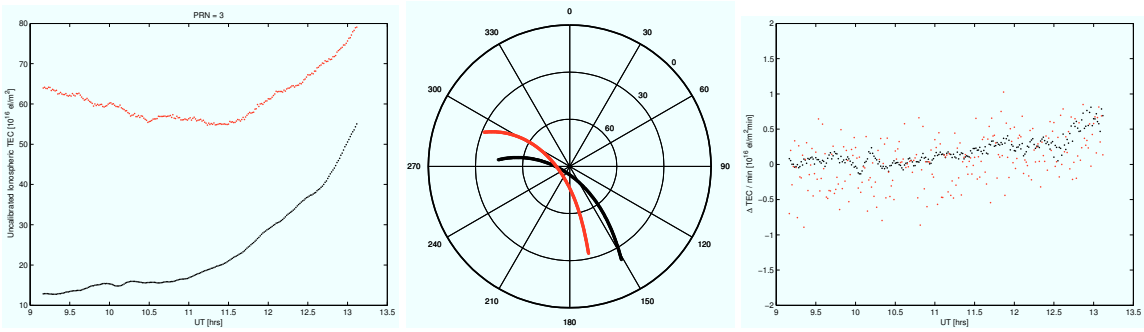
(a) (b) (c)

Figure 1: Baseline Nottingham-Dourbes relative to day 28 June 2008, for PRN29: (a) TEC, (b) azimuth and elevation, (c) temporal fluctuations in TEC.



(a) (b) (c)

Figure 2: Baseline Nottingham-Dourbes relative to day 27 March 2008, for PRN26: (a) TEC, (b) azimuth and elevation, (c) temporal fluctuations in TEC.



(a) (b) (c)

Figure 3: Baseline Nottingham-Nova Gorica relative to day 20 December 2010, for PRN03: (a) TEC, (b) azimuth and elevation, (c) temporal fluctuations in TEC.

A final remark must be made about independent estimates of the ionospheric TEC. It was proposed by different authors [3-5] to possibly include TEC estimates or maps calculated by GPS signals. It turns out that GPS based ionospheric TEC estimates are affected by a non-trivial calibration error (amounting to few TECU). However, next to this problem, there is the additional ionisation effect of the plasmasphere which inherently limits GPS based TEC estimates.

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5 References

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