Sun Corona Electron Densities Derived from VLBI Sessions in 2011/2012

B. Soja, J. Sun, R. Heinkelmann, H. Schuh, J. Böhm

Abstract Twelve IVS R&D sessions in 2011/2012 primarily aimed to increase the sensitivity of VLBI to relativistic phenomena by including observations closer than 15 degrees to the heliocenter. These observations are also affected by the plasma of the Sun corona, a dispersive medium which is the target of our research presented here. Starting with the ionospheric delay corrections derived from two-frequency VLBI measurements, Sun corona electron densities were estimated together with other dispersive effects like instrumental biases and the Earth ionosphere. The results for the R&D sessions were analysed and compared with external information like Sunspot numbers and solar flux indices. The estimated electron densities show good agreement with previous models of the Sun corona obtained by various spacecraft missions.

Keywords Sun corona, Ionosphere, VLBI

1 Introduction

The Sun corona is part of the atmosphere of the Sun, located between the chromosphere and interplanetary medium. It consists of fully ionized gas (i.e. plasma) and is primarily affected by the magnetic field of the Sun. The magnetic field is responsible for temperatures over 1 million K (the exact mechanism being the topic of current research) and the existence of diverse and timely-variable regions. The climatology of the corona follows the 11-year solar cycle (Aschwanden, 2004).

One of the most important characteristics of the corona is its electron density N_e. In the undisturbed case, it can be described as decreasing with distance from the Sun, following a power law:

$$N_e(r) = N_0 \cdot r^{-\beta} \quad (1)$$

with r as the distance from the heliocentre in solar radii, N_0 as the (theoretical) electron density at the surface of the Sun and the radial fall-off parameter β.

Depending on the distance from the Sun the model of electron density can also include terms of higher order (Tyler et al., 1977).

Electron density models following (1) have been successfully estimated from measurements of space missions during superior solar conjunctions in the past 45 years (Bird et al., 2012). Here we show the first determination of such a model from VLBI data.

2 Methods

The Sun corona is a dispersive medium for electromagnetic waves. For VLBI observations close to the Sun the effects of the corona need to be taken into account (Shapiro et al., 1977). Other dispersive phenomena affecting VLBI observations are the delays due to the Earth ionosphere and receiver hardware (Kondo, 1991). For the total dispersive contribution to group delay observations in X-band (usually called "ionospheric delay" τ'_{igx}) the following observation equation is applied:

$$\tau'_{igx} = \frac{40.3}{cf_x^2}\left(\varDelta STEC_{corona} + \varDelta STEC_{iono}\right) + \varDelta\tau_{inst} \; . \quad (2)$$

Most of all, the delay is dependent on the slant total electron content (STEC) of the Earth ionosphere and the Sun corona. The effective frequency f_x of the X-band and the dispersive instrumental delays τ_{inst} are

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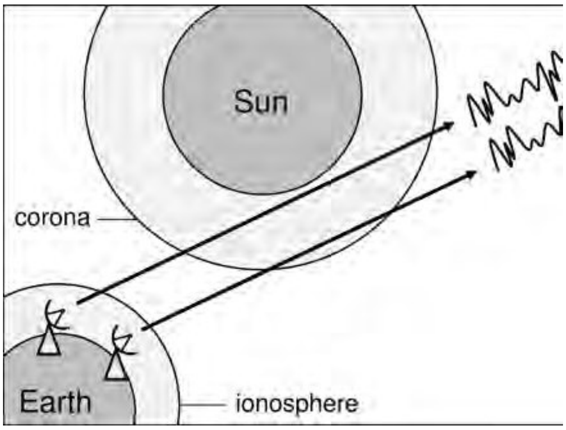

Fig. 1 The ray paths of the two radio telescopes pass through different regions of the Earth ionosphere and the Sun corona.

assumed to stay constant over each 24 hour VLBI experiment. The constant c is the vacuum speed of light and Δ indicates that for the respective quantities the difference between the two radio telescopes is taken. The basic observation configuration is shown in Fig. 1.

For equation (2) the influences of the interplanetary, interstellar and intergalactic media are neglected. This is admissible since in these regions the gradients in electron density are usually negligible in scales of typical baseline lengths (Hobiger et al., 2006). For observations in S- and X-band the higher order terms of the dispersive delay can be neglected (Hawarey et al., 2006).

The STEC can be determined by numerical integration of an electron density model along the ray path:

$$STEC = \int_S N_e ds \approx \sum_S N_e \Delta s \ . \tag{3}$$

In the case of the Sun corona, a power law (Eq. 1) is applied for modelling N_e. For the ionosphere it is assumed that all the free electrons are concentrated in a thin-layer at about the height of the F2 layer. This allows the conversion of the STEC into the vertical total electron content (VTEC) at the ionospheric pierce point (IPP) using a mapping function (Ros et al., 2011):

$$STEC = mf \cdot VTEC' \ . \tag{4}$$

The VTEC at the IPP (geographic coordinates λ', ϕ') can be related to the $VTEC$ above the station by (Hobiger, 2006):

$$VTEC'(\lambda', \phi', t') = (1 + G_{ns} \Delta\phi) \cdot VTEC(\lambda, \phi, t) \ . \tag{5}$$

The difference in latitude is considered by estimating one or two north-south gradients. For our studies we apply two gradients as recommended by Dettmering et al. (2011). Assuming that the ionospheric VTEC distribution co-rotates with the apparent movement of the Sun (360° per day) and that it is invariable during the parameter time interval of about 45 min., differences in longitude can be related to differences in time (Hobiger et al., 2006):

$$t - t' = (\lambda - \lambda')/15 \tag{6}$$

with t in hours and λ in degrees. Referring the observations to time t instead of t' the VTEC above the station can be estimated. In order to achieve redundancy, $VTEC(t)$ is parametrized by piece-wise linear functions. The intervals are chosen in a way that a certain number of observations (n_{obs}) falls in each interval. For our studies a value of $n_{obs} = 15$ is applied yielding a temporal resolution of VTEC of roughly 45 min.

Another possibility would be to use ionosphere VTEC data in terms of global ionospheric maps from GNSS. At the moment, the precision (2–8 TECU) and temporal resolution of two hours (Ros et al., 2011) are inferior to those of estimating station VTECs with VLBI (about 1 TECU, minimal temporal resolution 30 min., according to Hobiger (2006)).

The left hand side of (2) is the result of a linear combination of the observed group delays in X- and S-band, while the right hand side describes the theoretical delay depending on the unknown parameters. The latter are solved for by minimizing the difference "observed minus computed" in a least-squares sense. The stochastic model is obtained by weighting the observations based on their formal errors, which are provided in NGS files of the International VLBI Service for Geodesy & Astrometry (Schuh and Behrend, 2012).

3 Data

To study the Sun corona with VLBI, observations close to the Sun are necessary. Such observations are sparse before 2002 and non-existing afterwards due to a change of the elongation cut-off angle to 15 degrees introduced within the IVS (cf. Heinkelmann and Schuh, 2009). However, close observations to the Sun are valuable, e.g. for relativistic studies, so the IVS decided to dedicate twelve R&D-sessions in 2011 and 2012 to particularly observing close to the Sun.

The 24 hour sessions were observed by global networks of up to eight telescopes. The scheduling was done similar to the standard R1/R4 sessions, but with the addition of observations closer than 15° elongation. The last seven of these R&D sessions were scheduled

Table 1 The IVS R&D sessions in 2011 and 2012 which include observations close to the Sun. For each session, the minimum Sun elongation, the number of successful observations closer than 15 degrees and the estimated electron densities (1σ) are shown.

Session	Date	Min. Elongation	Obs. < 15°	N_0 $[10^{12}\ \mathrm{m}^{-3}]$
RD1106	Nov 29	3.9°	33	0.5 ± 0.4
RD1107	Dez 06	4.0°	59	1.1 ± 0.4
RD1201	Jan 24	4.8°	21	2.9 ± 1.0
RD1202	Apr 03	5.8°	39	1.3 ± 0.4
RD1203	May 30	10.5°	52	6.1 ± 1.5
RD1204	Jun 19	4.4°	32	1.3 ± 0.7
RD1205	Jul 10	6.1°	186	0.7 ± 0.3
RD1206	Aug 28	3.9° (1.8°)	193	0.5 ± 0.1
RD1207	Sep 25	6.1°	120	0.2 ± 0.7
RD1208	Oct 02	3.9°	103	0.5 ± 0.3
RD1209	Nov 27	4.2°	57	0.1 ± 0.3
RD1210	Dez 11	4.7°	80	2.2 ± 0.5
Weighted mean over all R&D sessions				0.63 ± 0.17

using the Vienna VLBI Software (Sun et al., 2011). For the other sessions the scheduling software SKED was used. Table 1 shows the characteristics of each of the sessions, including the elongation of the closest observation and the number of observations which are closer than 15° elongation.

In session RD1206 a radio source with 1.8° elongation was scheduled for observation. Unfortunately, for all scans to this particular source the correlation in S-band failed, making it impossible to derive dispersive corrections. Nevertheless, in the session many observations to another source at 3.9° were successful.

4 Results

For the distances from the heliocentre at which successful VLBI observations to radio sources are available (i.e. $\geq 3.9°$elongation), the parameters N_0 and β are highly correlated, making it impossible to estimate both at the same time. Previous models found a value for β between 1.9 and 2.5. For our purposes the parameter was fixed to $\beta = 2$, what equals the theoretical value for constant solar wind velocity (Bird et al., 1994). An outlier test based on the residuals v was applied: all observations with $v/\sigma_v > 5$ were excluded to get more reliable results. Table 1 shows the estimated electron densities N_0 together with their 1σ standard deviations. The largest uncertainty is found for session RD1203. During this session no sources closer than 10 degrees were observed.

During times of high solar activity, higher Sun corona temperature, turbulence and electron density are expected (Bird et al., 1994). The estimated electron densities are therefore compared to indicators for the solar activity. Fig. 2 shows daily relative Sunspot numbers (SSN) together with the electron densities estimated from the twelve R&D sessions. Some sessions show a good temporal agreement, while others diverge. Similar results are obtained when comparing the electron densities to solar flux indices, e.g. the F10.7 index (not shown here).

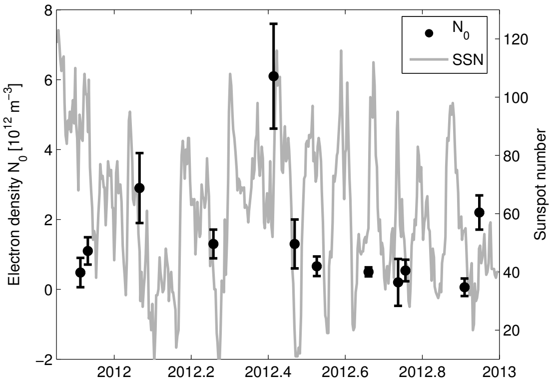

Fig. 2 Electron densities from VLBI compared to daily Sunspot numbers.

The differences might be explained by deviations of the Sun corona from a simplified axial model. Sessions with unexpected high or low electron density are analysed in greater detail using images of the Sun, provided e.g. by the X-ray telescope (XRT) on the Hinode spacecraft[1]. For instance, in the case of session RD1106, three sources closer than 15° were observed, one at 4° (1622-253) and the others farther away (11°, 13°). The source 1622-253 was most sensitive for the effects of the Sun corona and the estimated electron density mostly depended on the observations to this source. In Fig. 3 the positions of the sources together with the variable and quiet regions of the Sun are plotted. 1622-253 is located above a region of low solar activity and most likely lower electron density compared to the active regions. This might explain the low value of the estimated electron density in contrast to the high Sunspot number or solar flux.

Effects due to different observation geometries or deficiencies in the model are assumed to have a random impact and are reduced by computing the weighted mean over all available VLBI sessions. The resulting value for N_0 is $(0.63 \pm 0.17)\ 10^{12}\ \mathrm{m}^{-3}$ coming from data obtained during the 14 months in 2011 and 2012. The average solar activity during this time was medium.

This electron density model, representative for the VLBI observations, is compared to previous models derived by measurements to spacecraft during superior

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[1] http://www.isas.jaxa.jp/e/enterp/missions/hinode/

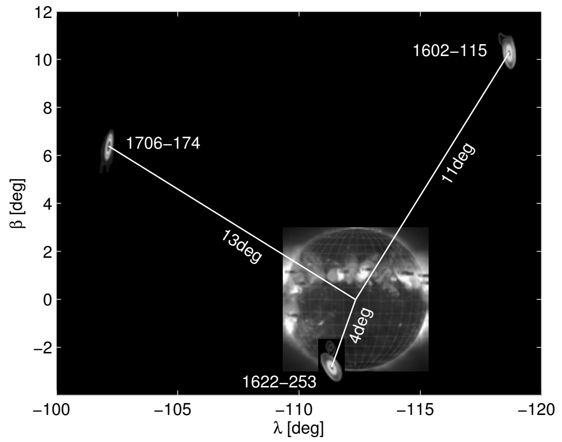

Fig. 3 Source geometry of session RD1106 w.r.t. an out of scale XRT image of the Sun.

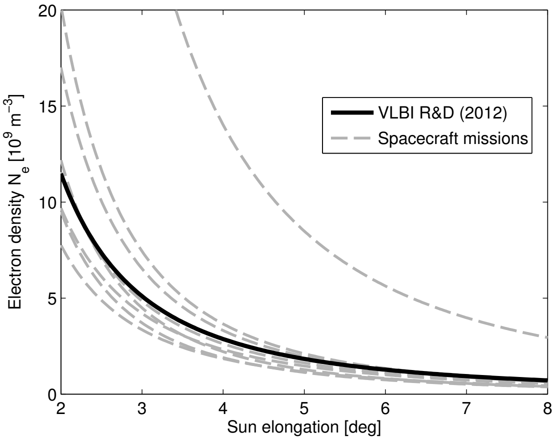

Fig. 4 Comparison between the electron density models from VLBI and various spacecraft missions.

solar conjunctions. Fig. 4 shows the VLBI model along with the models derived from various space probes, such as Mariner 6/7, Viking 1/2, Voyager 2, Ulysses, Mars Express and Rosetta with data collected between 1970 and 2008. The various spacecraft models are from periods of different solar activity. For example the Ulysses conjunctions in 1991 happened during a solar maximum, while the one with Mars Express in 2008 was during very low activity (Bird et al., 2012). The electron density models were accordingly higher and lower, respectively. The VLBI model agrees well with the previous models, especially with those when the data were obtained during medium solar activity.

5 Conclusions and Outlook

For the first time, the electron density of the plasma of the solar corona has been estimated utilising VLBI observations. Good agreement is found when comparing the VLBI model with previous models derived from measurements to spacecraft. The latter have the advantage that they include observations much closer to the Sun (up to 0.8 degrees elongation) and are therefore able to estimate both parameters N_0 and β. The strength of VLBI compared to spacecraft missions is that radio sources are more often in the vicinity of the Sun.

At 11 out of 12 R&D sessions, observations between 4 and 6 degrees elongation were possible. This shows that VLBI could monitor the Sun corona on a daily basis. It should be mentioned that no problems at all (technical problems, extensive loss of signals) occured for observations as close as 4 degrees to the Sun.

In the future, when improved global ionospheric maps will be available, it is planned to test different approaches of separating the effects of the Earth ionosphere and the Sun corona to get more reliable corona electron densities. VLBI2010 will bring interesting new options, such as observations of phase scintillations, which could be used to investigate the turbulence in the Sun corona. The precision and reliability of the dispersive delays determined with VLBI2010 are expected to be significantly higher due to the foreseen broadband delay approach. Thus, we expect a positive impact on the quality of the derived parameters of the Earth ionosphere and Sun corona once VLBI2010 will be in place.

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