Probing the solar corona with very long baseline interferometry

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Understanding and monitoring the solar corona and solar wind is important for many applications like telecommunications or geomagnetic studies. Coronal electron density models have been derived by various techniques over the last 45 years, principally by analysing the effect of the corona on spacecraft tracking. Here we show that recent observational data from very long baseline interferometry (VLBI), a radio technique crucial for astrophysics and geodesy, could be used to develop electron density models of the Sun's corona. The VLBI results agree well with previous models from spacecraft measurements. They also show that the simple spherical electron density model is violated by regional density variations and that on average the electron density in active regions is about three times that of low-density regions. Unlike spacecraft tracking, a VLBI campaign would be possible on a regular basis and would provide highly resolved spatial-temporal samplings over a complete solar cycle.

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For electromagnetic waves, the Sun’s corona is a dispersive medium. This results in the deflection of ray paths and correspondingly in slower group velocities. The dispersive contribution to the group delay is proportional to the total electron content (TEC) along the ray path. Thus, by conducting two-frequency radio observations through the Sun’s corona, the TEC can be derived and electron density models can be developed. In its simplest form, such a model is radial-symmetric and usually follows a power law depending on the distance \( r \) (in solar radii) from the heliocenter:
\[
N_e(r) = N_0 \times r^{-\beta}.
\]
\( N_0 \) is the fictitious electron density at the surface of the Sun and \( \beta \) is the roughly quadratic falloff exponent. For heliocentric distances of less than four solar radii, additional terms of higher order are necessary. Some models have included a heliographic latitude dependence factor to account for the equatorial structure of the corona in times of low solar activity. For the data used in this work, the single-term model is sufficient.

In the past, several techniques have been used to assess the electron density of the solar corona, for example, polarized brightness inversions from white-light coronagraph data, pulsar time delay measurements, emission lines observations, radio interferometry on short baselines or spacecraft tracking measurements during superior conjunctions. A different technique, also capable of observing targets (in this case cosmic radio sources) with small heliocentric elongation angles, is very long baseline interferometry (VLBI). VLBI measures the differences in arrival times (that is, differential group delays) of signals emitted by these radio sources at several radio telescopes belonging to a global terrestrial network. The signals are recorded at two frequencies in the S and X bands (centre frequencies: 2.3 and 8.4 GHz, respectively). This allows the determination of the differential dispersive effects, predominantly caused by the Sun’s corona, the Earth’s ionosphere and receiver hardware. In contrast to absolute measurements of electron content (for example, in the case of spacecraft ranging), the differential ionospheric contributions to VLBI group delays are larger than those caused by the corona. This challenge, and the techniques we developed to overcome it, are presented in detail in the Methods section.

Spacecraft measurements allow for a very precise determination of the coronal TEC, but can only probe the corona at the line-of-sight to the spacecraft during a conjunction. These observations are well complemented by coronagraph images that provide the context but are more difficult to calibrate. Compared with spacecraft tracking, VLBI has the advantage of a larger number of potential targets, which in principle enables a continuous monitoring of the corona. This is illustrated in Fig. 1a,b, which shows the apparent annual motion of the Sun with respect to the International Celestial Reference Frame 2 (ICRF2) radio sources. If only defining ICRF2 sources (that is, radio sources of highest astrometric quality) are considered, the average minimum solar elongation would be 5°. Scheduling also other ICRF2 radio sources, this angle would be decreased to 1.5° (Fig. 1c). Furthermore, usually several natural radio sources have lines-of-sight in the vicinity of the Sun at the same time, whereas opportunities to simultaneously probe the corona by observing two or more spacecraft are rare.

In this work we show that VLBI data can be used to create electron density models of the solar corona. Comparisons to models obtained by spacecraft tracking are conducted and show promising results. By analysing the geometry of the observations with respect to coronagraph images, the sensitivity of VLBI to non-spherical variations in electron density becomes evident. Finally, the potential of VLBI in monitoring the solar corona is discussed.

![Figure 1 | ICRF2 radio sources and minimum elongation angles.](image)

**Results**

**VLBI data acquisition.** Observations close to the Sun are necessary to study the effects of the corona. However, such observations are often of lower quality because of signal perturbations due to the corona. The risk of losing observations increases for lines-of-sight close to the Sun. Also, for elongation angles less than one degree, the receiver hardware of the telescopes may get even damaged. These considerations have led to the introduction of a rather conservative cutoff elongation angle of roughly 15° in mid of 2002 (compared with 5° before 2002; ref. 21) for the International VLBI Service for Geodesy and Astrometry (IVS) observing schedules.

Besides studying the corona, observations relatively close to the Sun are important for relativistic investigations, in particular for
the estimation of the parameter $\gamma$ (from the parameterized post-
Newtonian formalism) and the investigation of higher order relativistic effects. Lambert and Poncin-Lafitte\(^2\)\(^3\) presented reasons for the re-introduction of such observations into VLBI schedules, which would lead to a more precise determination of $\gamma$. The IVS decided in 2011 to dedicate 12 VLBI R&D (research and development) sessions to foster relativistic and Sun-related investigations.

The 12 experiments took place between November 2011 and December 2012. Each lasted for 24 h and featured a global network of up to nine VLBI radio telescopes (Table 1). The baseline lengths were between 920 km (Onsala, Sweden–Wettzell, Germany) and 12,400 km (Tsukuba, Japan–Concepción, Chile). The scheduling of observations followed the standard procedure for IVS VLBI sessions, but additionally included observations closer than 15° solar elongation. To avoid correlations between the parameters of the Sun’s corona, the Earth’s ionosphere and the instrumental delays in the least-squares adjustment, also observations further away from the Sun were scheduled and considered in the analysis. This way, the correlations between the coronal electron density parameter $N_0$ and the other parameters estimated in the adjustment were <5% for all VLBI experiments.

The radio sources with ray paths closest to the Sun were preferentially observed because these observations are more sensitive to the effects of the coronal plasma. Another feature to be considered when scheduling observations is the astrometric quality of the sources, for example, indicated by their position error in the ICRF2, by their flux density and by their structure index.\(^2\)\(^4\) Observations were preferentially scheduled to radio sources of higher quality (low position error, high flux density and compact structure, that is, small structure index). The duration of each individual observation (‘coherent integration time’) was chosen in a way that a certain signal-to-noise ratio (20 for X band, 15 for S band) was achieved and thus was different for every observation, depending on the baseline and radio source. On average, the integration time (scan length) for the R&D sessions was ~5 min.

During the R&D sessions, between four (RD1106, RD1107, RD1201, RD1210) and eight radio sources (RD1206) closer than 15° were successfully observed during the 24-h sessions (Table 1). The number of observations within 15° varies significantly between the sessions, depending on the pursued strategies and the numbers of available radio telescopes (cf. Tables 1 and 2). The first five sessions did not focus as much on close observations compared with the later ones. Starting with session RD1204, scans of the radio sources closest to the Sun were scheduled on a regular interval. The low number of observations during session RD1204 was due to two radio telescopes being unavailable (Westford and Kokee Park) and the radio telescope in Tsukuba having to pause because of a passing typhoon. As an example of a typical VLBI network used in the R&D sessions as well as of the corresponding space segment, Fig. 2 shows the geometry of stations and radio sources for session RD1206. The minimum heliocentric distance at which observations could be scheduled depended on the availability of high quality radio sources and is given in Table 2. For almost all sessions, observations between 4° and 6° elongation were successfully carried out. An exception is session RD1203 with no appropriate radio source closer than 10°.

The signals recorded at the radio telescopes during the R&D experiments were collected and correlated at the MIT Haystack Correlator (co-sponsored by NASA Goddard Space Flight Center). The resulting differential group delays (that is, the delays between the two stations of a baseline) for S and X band have been made available through the IVS. More information on the observables is given in the Methods section.

### Table 1 | Station networks and observations close to the Sun.

| Session | VLBI telescopes | Radio sources within 15° (no. of observations) |
|---------|----------------|-----------------------------------------------|
| RD1106  | HhKkMaNyOnTvWiWz| 1519 – 273 (9), 1602 – 115 (5), 1622 – 253 (13), 1706 – 174 (6) |
| RD1107  | KkMaNyOnShTvWiWz| 1622 – 253 (24), 1657 – 261 (2), 1706 – 174 (3), NRAO530 (30) |
| RD1201  | HhKkMaNyOnTvWiWz| 1920 – 211 (16), 1936 – 155 (4), 1958 – 179 (7), 2008 – 159 (4) |
| RD1202  | HhKkNyOnTvWiWz  | 0019 + 058 (10), 0055 – 059 (2), 0111 + 021 (9), 0119 + 041 (3), 0119 + 115 (12), IIIZW2 (3) |
| RD1203  | FtKkMaNyOnTvWz  | 0342 + 147 (2), 0406 + 121 (2), 0440 + 345 (12), 0446 + 112 (29), 0506 + 101 (3), 0515 + 208 (4) |
| RD1204  | FtMaNyOnTvWz     | 0515 + 208 (8), 0528 + 134 (13), 0536 + 145 (2), 0544 + 273 (2), 0600 + 177 (6), 0611 + 131 (1) |
| RD1205  | FtHkMaNyOnTvWz   | 0657 + 172 (65), 0743 + 277 (3), 0745 + 241 (18), 0748 + 126 (98), 0759 + 183 (2) |
| RD1206  | HhKkNyOnTvWiWz   | 1012 – 232 (34), 1013 + 054 (14), 1015 + 057 (25), 1022 + 194 (6), 1023 + 131 (35), 1049 + 215 (7), 1055 + 018 (43), 1111 + 149 (29) |
| RD1207  | HhKkNyOnTvWiWz   | 1130 + 009 (11), 1145 – 071 (1), 1149 – 084 (19), 1219 + 044 (18), 1236 + 077 (20), 1243 – 072 (15), 3C274 (36) |
| RD1208  | HhKkNyOnTvWiWz   | 1145 – 071 (1), 1149 – 084 (14), 1213 – 172 (16), 1219 + 044 (17), 1236 + 077 (31), 1243 – 072 (21) |
| RD1209  | HhKkMaNyOnTvWiWz | 1519 – 273 (9), 1602 – 115 (9), 1622 – 253 (25), 1657 – 261 (5), 1706 – 174 (9) |
| RD1210  | HhKkMaNyOnTvWiWz | 1622 – 253 (19), 1657 – 261 (12), 1706 – 174 (15), NRAO530 (34) |

The VLBI stations are specified by their two-character IVS codes that can be found at http://ivsc.gsfc.nasa.gov/about/org/components/ns-list.html. For each radio source with elongation angle <15°, the number of successful observations is given. During each session, many other ICRF2 radio sources were observed for a better sky coverage, not included in this table.
Table 2 | Characteristics of the VLBI experiments.

| Session | Date       | Minimum elongation | No. of observations within 15° | Total no. of observations |
|---------|------------|--------------------|-------------------------------|---------------------------|
| RD1106  | 29 Nov 2011| 3.9°               | 33                            | 3,695                     |
| RD1107  | 06 Dec 2011| 4.0°               | 59                            | 4,242                     |
| RD1201  | 24 Jan 2012| 4.8°               | 31                            | 3,482                     |
| RD1202  | 03 Apr 2012| 5.8°               | 39                            | 2,776                     |
| RD1203  | 30 May 2012| 10.5°              | 52                            | 2,099                     |
| RD1204  | 19 Jun 2012| 4.4°               | 32                            | 828                       |
| RD1205  | 10 Jul 2012| 6.1°               | 186                           | 2,953                     |
| RD1206  | 28 Aug 2012| 3.9°               | 193                           | 1,558                     |
| RD1207  | 25 Sep 2012| 6.1°               | 120                           | 1,727                     |
| RD1208  | 02 Oct 2012| 3.9°               | 103                           | 1,918                     |
| RD1209  | 27 Nov 2012| 4.2°               | 57                            | 2,731                     |
| RD1210  | 11 Dec 2012| 4.7°               | 80                            | 3,540                     |

The IVS R&D sessions in 2011 and 2012, which include observations close to the Sun starting at either 17:30 or 18:00 UT on the day given in the second column and lasting 24 h. For each VLBI session, the minimum Sun elongation and the number of successful observations in total as well as closer than 15° are shown.

Discussion

Our results comprise the first solar corona electron density model successfully developed from VLBI group delays and provide a measure of the potential of VLBI for probing the solar corona. Compared with spacecraft measurements, a disadvantage of VLBI is the low signal strength of cosmic radio sources, which makes successful dispersive group delay measurements unlikely at elongation angles of <2°. For instance, observations of the radio
The VLBI sessions discussed here took place during a period of medium solar activity. However, for times of low solar activity, two-frequency group delays at just above 2° have been successfully observed21. One strength of VLBI is that observations are possible on a regular basis and do not depend on the coincidence of a spacecraft’s position with radio sources in the vicinity of the Sun. The sessions RD1205 and RD1206 had the largest number of observations within 15° elongation obtained in the least-squares adjustment are shown. The residuals (‘observed minus computed’) are plotted against the solar distance and stay within ±10 cm, corresponding to ±0.3 ns. Above each plot the names of the observed radio sources are given. The turquoise or red colours indicate that the ray paths passed through low or high density regions of the corona, respectively.

The coronal electron density distribution is expected to be correlated with the solar activity cycle. However, indicators for solar activity (for example, sunspot numbers or solar flux indices) describe the integrated activity of the Sun, whereas the VLBI delays are only affected by the coronal structure in the vicinity of the ray path. This is shown in Fig. 4. Here, as an example, the source positions during two VLBI experiments are compared with images from the Large Angle and Spectrometric Coronal Image Telescope (LASCO)28 C3 coronagraph onboard the Solar and Heliospheric Observatory (SOHO) spacecraft. During VLBI session RD1206, the radio sources were located in regions of low white-light intensity and we obtained a lower electron density than the mean VLBI model. For RD1208 it was the opposite: sources were found in high density (streamer) regions and the value of $N_0$ was higher. The animated LASCO images for the duration of the VLBI observations during session RD1206 and RD1208 are provided as Supplementary Movies 1 and 2, respectively. For sessions with the radio sources spread over diverse regions, the resulting electron densities were closer to the average model (for example, RD1205). Thus, these violations of the assumption of a spherical electron density distribution explain some of the scatter found in the $N_0$ values in Table 3.

The variations in precision of the estimated $N_0$ values are to some extent dependent on the number of observations close to the Sun. The sessions RD1205 and RD1206 had the largest numbers of observations within 15° elongation (186 and 193, respectively) and consequently the electron density models could be derived with the highest precision ($\pm 0.1$ and $\pm 0.3 \times 10^{12}$ m$^{-3}$, respectively). Sessions RD1201 and RD1204 with 31 and 32 observations, respectively, obtained less precise results ($\pm 1.3$ and $\pm 1.0 \times 10^{12}$ m$^{-3}$). Session RD1203 shows that also the minimal observed elongation angle affects the precision: with no sources closer than 10° elongation available, the precision drops considerably ($\pm 1.8 \times 10^{12}$ m$^{-3}$).

At the time of some of the VLBI experiments, coronal mass ejections (CME) took place. During the last few hours of session RD1201, a CME reached the lines-of-sight to radio sources 1958 – 179 and 2008 – 159 (Supplementary Movie 3). The additional plasma from the CME affected also the estimate of $N_0$ which is larger than for other sessions. RD1205 features a strong CME (Supplementary Movie 4), but the VLBI experiment ends before it can reach the ray paths to radio sources 0743 + 277 and 0745 + 241. During RD1208, a minor CME passes the lines-of-sight of radio source 1243 – 072 and the estimated electron density during this session is larger than average.

The assumption of spherical symmetry limits the accuracy of the electron density models derived by VLBI. Therefore, for the

### Table 3 | Electron density models and statistical measures.

| Session       | Reduced $\chi^2$ | $\Delta$AIC | Relative likelihood | $N_0$ (10$^{12}$ m$^{-3}$) |
|---------------|------------------|-------------|---------------------|----------------------------|
| RD1106        | 1.1              | –5.1        | 0.08                | 0.0 ± 0.4                  |
| RD1107        | 1.1              | –49.5       | 0.00                | 1.7 ± 0.4                  |
| RD1201        | 1.7              | –8.4        | 0.02                | 3.3 ± 1.3                  |
| RD1202        | 1.2              | –0.3        | 0.85                | 0.9 ± 0.4                  |
| RD1203        | 1.2              | –2.2        | 0.33                | 2.2 ± 1.8                  |
| RD1204        | 0.8              | –6.4        | 0.04                | 1.2 ± 1.0                  |
| RD1205        | 0.8              | –4.1        | 0.13                | 0.5 ± 0.3                  |
| RD1206        | 0.5              | –8.4        | 0.02                | 0.3 ± 0.1                  |
| RD1207        | 2.4              | 0.9         | 0.65                | 0.6 ± 0.8                  |
| RD1208        | 2.0              | –64.2       | 0.00                | 1.5 ± 0.4                  |
| RD1209        | 0.6              | –2.8        | 0.25                | 0.1 ± 0.3                  |
| RD1210        | 0.6              | –16.8       | 0.00                | 2.5 ± 0.6                  |

Weighted mean over all R&D sessions 0.57 ± 0.18

For each of the IVS R&D sessions in 2011 and 2012, a least-squares adjustment was performed estimating the parameters of the Sun’s corona, the Earth’s ionosphere and instrumental delays. The goodness of fit is indicated by the reduced $\chi^2$. Another adjustment without estimating the electron density parameter $N_0$ was performed for all four sessions, the Akiike Information Criterion (AIC) was computed. The difference $\Delta$AIC = AIC$\text{corona–ionosphere–instruments} - \text{AICwithout}$ is given as well as the relative likelihood $\exp(\Delta$AIC/2). The model excluding the solar corona with respect to the one which takes the corona into account (vice versa for RD1207). Furthermore, the estimated parameters $N_0$ of the electron density model and their 1 s.e. from the least-squares adjustment (obtained from the a posteriori variance-covariance matrix) assuming $\beta = 2$ are listed.
two sessions with the largest number of observations close to the Sun (that is, RD1205 and RD1206) a different parameterization was tested. With the aid of the LASCO C3 images, the observations within 15° elongation were separated in two groups depending on whether the lines-of-sight pass through low or high-density regions. As the position of the Sun changes with respect to the radio sources during the 24 h duration of the sessions and the coronal electron density has temporal variations, this categorization is sometimes ambiguous. Furthermore, for the observations outside the field-of-view of the C3 coronagraph, the visual information has to be extrapolated. Figure 5 shows for the start of session RD1205 all radio sources with ray paths within 15° elongation together with the LASCO C3 image. The 116 observations of radio sources 0745 + 241 and 0748 + 126 are mostly in the low-density corona, the other 70 observations in high-density regions. The categorization of the radio sources is also indicated in Fig. 3. For each set of observations $N_0$ was determined: $\langle 0.2 \pm 0.4 \rangle \times 10^{12}$ m$^{-3}$ (low density) and $\langle 0.7 \pm 0.4 \rangle \times 10^{12}$ m$^{-3}$ (high density). For comparison, the overall value for $N_0$ for this session is $\langle 0.5 \pm 0.3 \rangle \times 10^{12}$ m$^{-3}$ (Table 3).

During session RD1206, only 1049 + 215 and 1055 + 018 were located behind coronal plasma of higher density. These two radio sources, both at solar elongations larger than 10°, were observed 50 times. The six radio sources with ray paths in low density regions accumulated 143 observations. Three of these radio sources are seen in Fig. 4a. The resulting $N_0$ value for the low-density regions is $\langle 0.3 \pm 0.1 \rangle \times 10^{12}$ m$^{-3}$, which corresponds to the overall value for the session. The observations in higher density regions had a low impact on the overall value because of the larger angular distance from the Sun and the lower number of observations. Still, it was possible to derive an individual $N_0$ value from these observations, although less precise: $\langle 1.0 \pm 0.6 \rangle \times 10^{12}$ m$^{-3}$. Similar to session RD1205, the electron density is larger by a factor of about three.

In the case of the mean electron density model $N_0 = (0.57 \pm 0.18) \times 10^{12}$ m$^{-3}$, the effects of different observation geometries and transient events are, to some extent, averaged out. Figure 6 shows the comparisons of the model created from VLBI data to previous models developed from spacecraft tracking measurements during superior solar conjunctions. The models obtained from spacecraft data were determined at various periods of different solar activity. For instance, during the Ulysses conjunction in 1991, a solar maximum took place^6. The Mars Express conjunction in 2008 happened during very low activity^27. The models, therefore, cover a range of realistic electron densities of the Sun’s corona. The model from VLBI agrees very well with the results from the spacecraft missions, especially when considering that the VLBI data, on average, were acquired during a period of medium solar activity (between Nov 2011 and Dec 2012). The data from the 1988 conjunction with Voyager 2 (uppermost curve in Fig. 6) stands out as most ranges were recorded when the signal ray path was passing a dense coronal streamer^6. Evidently, the electron density models from spacecraft tracking are affected by regional coronal structures to a similar extent as the individual VLBI models in Table 3.

In the future, the determination of the Sun’s corona electron densities using the VLBI technique could be optimized in a variety of ways. The next release of the ICRF29, probably in 2018, will include even more radio sources than the current one. Thus, the number of candidate radio sources for Sun-related investigations is very likely to increase significantly. Also, from a technological point of view, significant improvements are expected with the new-generation VLBI system VLBI2010 (refs 4,30) and its future network of VLBI stations, the VLBI Global Observing System (VGOS). Instead of group delays, phase delays will be observed that will be of great benefit to future investigations of the solar corona.
The dispersion delays are due to the intergalactic and interstellar media, as well as the Earth’s ionosphere, receiver hardware, and, in the case of observations close to the Sun, the corona. As VLBI is a differential method and the baseline lengths are shorter than the diameter of the Earth, the effects of media with small gradients in electron density are negligible. Thus, following Hobiger et al., we assume that the effects of the intergalactic and interstellar media can be neglected. At the heliocentric distances the VLBI data were observed, the effects of path separation due to different propagation of the S and X band signals in the coronal plasma can be considered negligible. The instrumental dispersive delays arise due to different propagation of the S and X band signals in the receivers’ feeds. Effects in turbulent plasmas like angular broadening or spectral broadening can lead to less precise observations or even non-detections during the correlation of the signals. Density irregularities on longer time scales cause some of the scatter seen in the VLBI data. Therefore, without knowledge about the ionospheric TEC it is not possible to create meaningful electron density models of the solar corona using VLBI data. To overcome this problem, we parameterize the ionospheric TEC in a way enabling us to estimate it together with the unknown parameters of the corona and the instrumental biases in a least-squares adjustment, as described in the next section.

### Methods

#### Differential dispersive group delays observed by VLBI

The basic geodetic VLBI observable is the differential group delay \( \tau \), which is the arrival time of radio signals at two-radio telescopes. It is obtained by cross-correlating the signals recorded at both stations. Group velocities of electromagnetic waves in dispersive media are slower compared with the propagation in vacuum, causing an additional dispersive contribution \( \tau_{\text{disp}} \) (ref. 33). This delay depends on the frequency \( f \) of the radio wave and thus can be observed by observing at two frequencies at the same time. For this reason, VLBI observations are routinely performed in the S band (2.2–2.4 GHz) and the X band (8.2–8.95 GHz). The corresponding frequency-dependent delays between the two stations are given by \( \tau_f = \tau_2 - \tau_1 \), with \( f \) denoting either S or X band. At these frequencies, the dependence of the delay on the frequency may be assumed to be proportional to \( f^{-2} \) and no higher order terms have to be included. By forming a linear combination of the observed group delays in the S and X bands, the dispersive contribution in the X band can be determined:

\[
\tau_{\text{disp},X} = -\frac{f_2^2}{f_2^2 - f_1^2} (\tau_1 - \tau_2). \tag{1}
\]

### Absolute and differential measurements of TEC

For this study, the electron density \( N_e \) in the Sun’s corona is of interest. Simplified, it can be described by a radial power law in the form of:

\[
N_e(r) = N_0 \times r^{-\beta}
\]

with \( N_0 \) the electron density at the surface of the Sun \( R_0 \), the distance from the heliocenter \( r \) in solar radii \( (R) \) and the radial falloff parameter \( \beta \) (ref. 7). The coronal TEC included in Equation (2) can be assessed by numerically integrating the power-law model from Equation (3) along the ray path:

\[
\text{TEC} = \int_N e_0(r) \, dr.
\]

Compared with the electron density \( N_e \) that falls off approximately as \( r^{-2} \) (ref. 6), the TEC, directly detected by spacecraft tracking, decreases roughly as \( p^{-1} \) (p is the impact parameter, the smallest distance between the ray path and the Sun). Observations at low elevations, the TEC is larger, for example at an elevation of \( 5^\circ \) the factor is ~2.7 (ref. 38). For stations at mid or high geographic latitudes the ionospheric TEC is smaller, usually not exceeding 50 TECU in zenith direction. The coronal TEC for a single ray with an impact parameter \( p \) of 15 R_S (ref. 27). Thus, in the case of absolute TEC measurements the contribution of the Earth’s ionosphere is minor and can be neglected.

For differential observations on a global scale (that is, baselines longer than a few thousand kilometres as in the case of VLBI), the ionosphere can cause a differential delay of up to 3 ns (corresponding to a distance of ~1 m) in X band. The effect of the Sun’s corona is smaller: Assuming a global baseline, X band observations at a distance of 10 R_S, and the electron density model from the DMS Telecommunications Link Design Handbook (ref. 5), the coronal differential delay is <1.5 ns. For most observations, the effect of the corona is significantly smaller.

Therefore, without knowledge about the ionospheric TEC it is not possible to create meaningful electron density models of the solar corona using VLBI data. To overcome this problem, we parameterize the ionospheric TEC in a way enabling us to estimate it together with the unknown parameters of the corona and the instrumental biases in a least-squares adjustment, as described in the next section.
Estimating the ionospheric TEC from VLBI data. The task of estimating the ionospheric TEC from VLBI data is achieved by relating the ionospheric TEC (from here denoted as slant TEC, STEC) for each observation to the vertical TEC (VTEC) above the VLBI antennas. To convert the STEC to the station-based VTEC we follow a method first proposed by Kondo and later developed by Hobiger et al. The first assumption is that all charged particles of the ionosphere are compressed into a thin layer at the height of the F2 layer (under normal condition this is the height of the largest electron density, Venusz 34)). Using an ionospheric mapping function \( m_f \), the STEC can be converted to the VTEC at the point of intersection between the ray path and the thin layer (that is, the ionospheric pierce point, IPP), denoted by a prime: \[ \text{VTEC} = m_f \times \text{STEC}. \] (5)

The modified single-layer model mapping function \( m_f \) is used with the scaling factor \( z = 0.9782 \) for zenith distances \( \zeta \), the height \( h = 506.7 \) km of the thin-layer ionosphere and the Earth radius \( R_e = 6,371 \text{ km} \). \[ m_f(\zeta) = \frac{1}{\sqrt{1 - \left( \frac{\zeta}{R_e \sin \zeta} \right)^2}}. \] (6)

The factor \( z \) is introduced to approximate the mapping function of a Chapman profile (which would require numerical integration) to \( z < 1 \% \) (ref. 38). The horizontal distance between the radio telescope (geographic coordinates \( \lambda, \phi \) ) and the IPP \( (\lambda', \phi') \) can be up to \( 2,000 \text{ km} \) for low elevation angles (assuming an zenith distances of up to \( 85^\circ \)). To assess the VTEC at the station, further simplifications are necessary, leading to the following equation:

\[ \text{VTEC} = (1 + G_{z whipping.}

The difference in the Earth's gravitational constant \( G_m \) from introducing a linear north-south north-south G_m. Further improvement can be achieved by using two gradients, one for observations with azimuths between \( -90 \) and 90 degrees (north gradient) and one for those between 90 and 270 degrees (south gradient). We apply this two-gradient approach as recommended by Dettmering et al. Assuming that the ionospheric VTEC distribution correlates with the apparent movement of the Sun (360° per day) for durations below 1 hour, it is possible to relate the difference in longitude (unit: degrees) to a difference in time (unit: minutes):

\[ t' - t = (\lambda - \lambda') / 15. \] (8)

Generally, this method of estimating station-based VTEC from VLBI observations works best if the coordinates are first transformed to a geocentric coordinate system. The errors due to the various assumptions increase with growing zenith distances, making it necessary to down-weight low elevation observations in the least-squares adjustment.

To reach redundancy in the adjustment, we parameterize the VTEC using piece-wise linear functions with adaptive interval lengths. The interval borders are determined in a way that every interval contains the same amount of observations. The advantage is that during periods with many observations, the temporal resolution of the estimated VTEC is higher. For times of lower observation density, less intervals are necessary, thus reducing computation time.

Assuming that the ionospheric VTEC distribution correlates with the apparent movement of the Sun (360° per day) for durations below 1 hour, it is possible to relate the difference in longitude (unit: degrees) to a difference in time (unit: minutes):
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Author contributions
B.S. developed the methodology with inputs from all authors, performed the data analysis and wrote the manuscript. All authors reviewed the manuscript.

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