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NLR-TP-2015-518 | December 2015

High Accuracy Measurements of Ionospheric Parameters by Combining Radio-Astronomical and GNSS Observations

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EXECUTIVE SUMMARY

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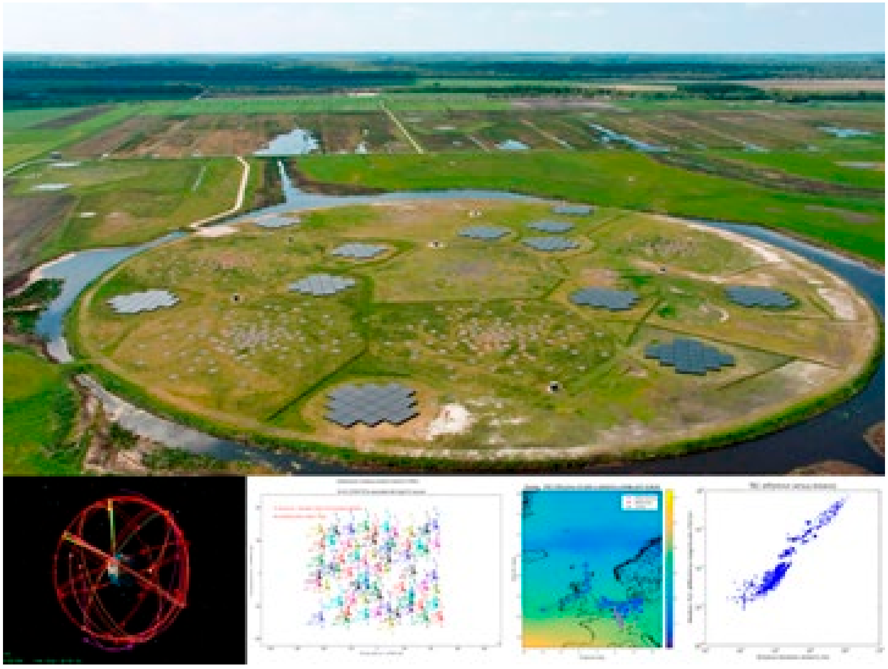
High Accuracy Measurements of Ionospheric Parameters by Combining Radio-Astronomical and GNSS Observations



Problem area

The ionosphere has a significant impact on low frequency radio astronomy observations and also on Global Navigation Satellite System (GNSS) observations. This is the motivation for a comparison between radio astronomy observations of the ionosphere, in parallel to GNSS based measurements.

Description of work

NLR and ASTRON have performed a parallel experiment, observing ionospheric total electron content (TEC) with the LOw Frequency ARray (LOFAR) radio telescope and a pair of dual frequency GNSS receivers.

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LOFAR is used to observe astronomical radio sources in the direction of a passing GNSS satellite, leading to parallel observations of the same ionosphere. The results of the experiment are analysed to estimate the quality of LOFAR ionospheric TEC observations. The applicability of the LOFAR observations for ionospheric error corrections in GNSS is analysed, likewise, the potential benefits from GNSS on LOFAR are analysed.

Results and conclusions

GNSS observations of ionospheric TEC achieved an absolute accuracy of approximately 1 – 4 TECU, largely depending on the absolute accuracy of the method used for bias correction. LOFAR observations of TEC achieved a relative accuracy of at least 0.1 TECU, with noise levels that are much lower (< 0.01 TECU). This strongly suggests that LOFAR can indeed measure with a very high relative accuracy and a high spatial density (varying from hundreds of meters to tens of kilometres). These results are very promising and suggest that LOFAR can be used to improve GNSS ionospheric corrections.

Applicability

This paper serves as the executive summary for the final project report NLR-CR-2015-329 for the project EGEP ID 89.08, “Real-time high accuracy measurements of ionospheric parameters using LOFAR and GNSS”. In addition to the material discussed here, the final report also provides a study of the applicability of the results: a potential ionospheric correction service is evaluated, as well as the potential for improving the LOFAR calibration process for astronomic imaging using GNSS receivers.

GENERAL NOTE

This report is based on a presentation held at the 5th International colloquium on Scientific and Fundamental aspects of the Galileo Programme, Braunschweig, 27 October 2015

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High Accuracy Measurements of Ionospheric Parameters by Combining Radio-Astronomical and GNSS Observations

CUSTOMER: European Space Agency

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HIGH ACCURACY MEASUREMENTS OF IONOSPHERIC PARAMETERS BY COMBINING RADIO-ASTRONOMICAL AND GNSS OBSERVATIONS

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ABSTRACT

The ionosphere has a significant impact on low frequency radio astronomy observations and also on Global Navigation Satellite System (GNSS) observations. This is the motivation for a comparison between radio astronomy observations of the ionosphere, in parallel to GNSS based measurements. A parallel experiment is performed, observing ionospheric total electron content (TEC) with the LOw Frequency ARray (LOFAR) radio telescope and a pair of dual frequency GNSS receivers. LOFAR is used to observe astronomical radio sources in the direction of a passing GNSS satellite, leading to parallel observations of the same ionosphere. The results of the experiment are analysed to estimate the quality of LOFAR ionospheric TEC observations. The applicability of the LOFAR observations for ionospheric error corrections in GNSS is analysed, likewise, the potential benefits from GNSS on LOFAR are analysed.

1. INTRODUCTION

The dispersive nature of the ionosphere introduces a group delay and a phase advance both in low frequency radio astronomy observations and in global navigation satellite system (GNSS) signals. In each case, the ionosphere is an error source for the target observation parameters (range for GNSS and radio emissions from astronomical sources for radio telescopes). This is the motivation for a comparison between radio astronomy observations of the ionosphere, in parallel to GNSS based measurements. Both fields have developed methods to estimate the contribution of the ionosphere and to compensate for its effects, each with its own strengths and weaknesses. The aim of this study is to see if ionospheric total electron content (TEC) observations made with a radio telescope can be used to improve GNSS observations.

LOFAR (LOw Frequency Array) [1] [2] is the largest low frequency radio-telescope currently operational in the world. Its array of antennas is spread out over a large part of North-western Europe, with the core of the telescope located in the Netherlands. ASTRON is the Netherlands Institute for Radio Astronomy and operates LOFAR. The LOFAR telescope is a so-called phased array antenna: it consists of many small antennas, which are combined in order to form a large synthetic aperture. LOFAR consists of 71 antenna stations, distributed over north-western Europe ranging from Sweden to the UK and Germany. The LOFAR core, located in the north of the Netherlands, contains the highest concentration of stations. Each station consists of an antenna field containing a large number of small antennas, divided in low band antennas (LBA) and high band antennas (HBA). The frequency bands LOFAR is designed to receive are 10-90 MHz (LBA) and 110-250 MHz (HBA). The frequency bands are sampled in small sub-bands of 0.195 MHz.

The principle behind LOFAR is interferometry: a signal from a single source arrives at each antenna element with a slightly different delay, depending on the viewing direction (elevation, azimuth) of the source. By correlating the signals from all antennas, taking into account the relative delays, the telescope can form a digital “beam” to detect signals from a specific direction. This principle is used to create detailed maps of the radio sky with very high dynamic range.

Ionospheric free electrons along the space-to-ground path induce a group delay proportional to the inverse of the frequency squared (and a phase advance, with different sign due to dispersive nature of the ionosphere). The total electron content (TEC) is the integrated electrons density along the ionosphere path along a cross section of 1 square meter. If all antennas were to experience the same ionospheric phase delay, LOFAR observations would be insensitive to the effect. However, when the ionosphere has local gradients, each station experiences a slightly different phase delay. LOFAR detects these small phase variations with very high accuracy.

In normal imaging operations, the ionospheric phase delays are compensated for. This is done by observing a well-known, strong radio source. The theoretical phase delays to be observed by each station can now be computed. By taking the difference between the observed delays and the predicted delays, a map is created of the phase delays caused by the ionospheric TEC and any remaining errors, mainly consisting of station clock errors. An accurate estimate of the actual ionospheric TEC can now be made by removing the clock error contribution and converting the phase delays to TEC values. The relation between ionospheric TEC and ionospheric group delay d can be approximated by

$$d = 40.3 \times \frac{TEC}{f^2} \qquad (1)$$

where TEC is given in 10^{16} electrons per m^2 and f is the frequency in Hz. LOFAR can typically measure relative phase delays between two antenna stations with an accuracy of 0.1 radians. Using LBA antennas at 75 MHz (4 m wavelength), this translates to a relative accuracy of approximately 0.001 TECU or better using equation (1) above. For the HBA antennas used in this experiment (120-240 MHz) the accuracy is approximately 0.002 TECU.

From a GNSS point of view, the ionospheric TEC is routinely observed with dual frequency GNSS receivers. Equation (1) shows that the signal delay is directly proportional to TEC and inversely proportional to the frequency squared. This means that a signal in the L1 band is delayed more than a signal in the L2 band. By measuring pseudo-ranges on both frequencies in parallel, a fairly accurate estimate can be made of the ionospheric TEC that affected the signals between the satellite and the receiver. Using carrier-phase observations the accuracy that can be achieved is quite high. However, inter-frequency instrument biases and other error components give rise to a potentially large, unknown bias in the TEC estimate. This means that even using state of the art receivers and algorithms, ionospheric TEC estimates from dual frequency receivers are limited to an accuracy of above 1.0 TECU.

Although LOFAR observes relative TEC between stations and not absolute TEC, its accuracy promises to be (much) better than what can be achieved with modern GNSS receivers. In addition, LOFAR can provide observations with a high spatial resolution. This is the primary motivation for this study. We will investigate if, and if so how, LOFAR can be used to improve current practices of estimating TEC with the purpose of error corrections in GNSS receivers.

2. EXPERIMENT

An experiment was designed to determine the quality and usability of LOFAR TEC observations for use in GNSS ionospheric error corrections. The primary purpose of the experiment is to obtain TEC estimates from LOFAR and GNSS satellites in parallel, to be able to compare both measurements and possibly combine the two for an improved accuracy. The results will also be compared to existing alternatives (Klobuchar [4], NeQuick [5] and EGNOS [6]). External global ionospheric maps (GIMs) were used for aligning dual-frequency ionospheric TEC estimations, or as a “truth” reference for validation. In particular the ESA/Monitor TOMION maps with 15 minute update frequency from UPC-lonSat [7] and the two-layer GIMs from gAGE-UPC [8] were used.

A dual frequency GNSS receiver is installed near the LOFAR core in Exloo, the Netherlands. A second GNSS receiver is installed at a LOFAR station near Steenwijk, the Netherlands, approximately 50 km from the first station. Using this setup, LOFAR and GNSS observations can be compared for the same baseline. Parallel observations can now be performed. LOFAR estimates ionospheric slant TEC by observing a radio source which is close in viewing direction to a passing

GNSS satellite. In parallel, the GNSS receivers track the satellite, estimating the ionospheric slant TEC using dual frequency carrier phase and pseudo-range observations. The difference in observed TEC between the two GNSS receivers can be directly compared with the relative TEC observed by LOFAR for these two stations. Figure 1 shows the layout of the LOFAR stations in the Netherlands and the two observation sites.

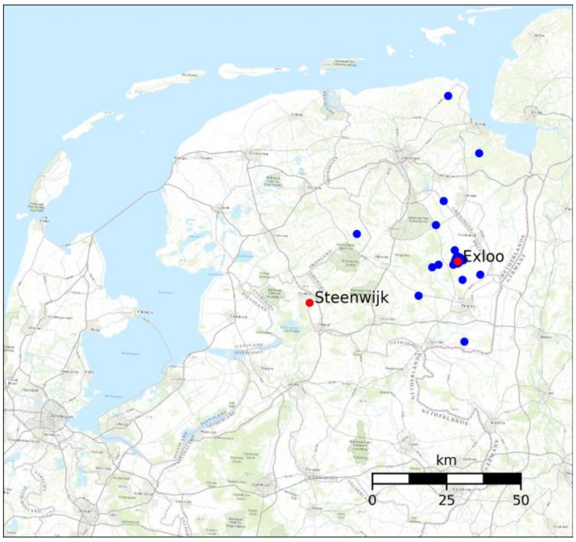

Figure 1: The LOFAR stations in the north of the Netherlands used for the experiment. The two stations with GNSS receivers are marked in red (LOFAR core near Exloo and Steenwijk).

The hardware used in the experiment consists of two identical GNSS dual frequency receivers of type Septentrio AsteRx3, with a Maxtena M1227HCT-A antenna. The receivers are capable of tracking GPS (L1, L2), Galileo (E1, E5), GLONASS and Beidou satellites. For the experiment, only GPS and Galileo are used. EGNOS ionospheric corrections are recorded for reference.

The measurement campaign was performed on March 25, 2015. Table 1 summarizes the measurements that were taken. Figure 2 shows how the LOFAR telescope alternates its beam between satellites. In each direction 6 consecutive observations of 10 seconds are taken, followed by a 1 minute switching interval to re-point the telescope. The GNSS receivers record all satellites in view at 1 Hz. The ionosphere was relatively calm on the day of the experiment, with no recorded ionospheric disturbances.

Table 1: Parallel data collection experiment

Date / Time	25 March 2015, 13:30–23:00 UTC
Stations (GNSS)	LOFAR core, Steenwijk
Stations (LOFAR)	55 (all in the Netherlands)
GNSS satellites tracked	19 GPS, 2 Galileo
LOFAR pointings	285
GNSS variables recorded	Pseudo range (L1,L2,E1,E5) Ionospheric TEC Position solution
LOFAR variables recorded	HBA antennas Relative phase errors
Parallel satellite observations	7 – 9, interleaved

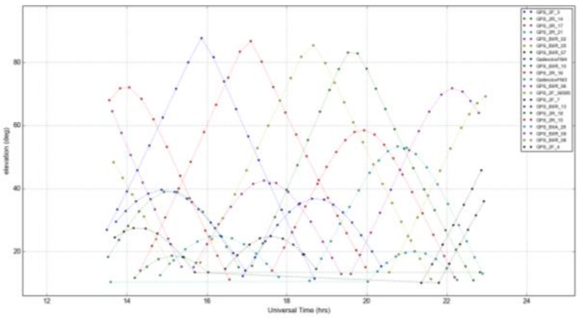

Figure 2: LOFAR observed radio sources in the same direction as a passing GNSS satellite. Each LOFAR observation ("pointing") lasted for 1 minute, with a 1 minute switching time. Observations alternated between satellites in time.

LOFAR target selection is performed by generating a list of visible satellites during the experiment for each station. The satellite coordinates are matched with a database of strong, well-known radio sources from the Multi-frequency Snapshot Sky Survey (MSSS) [3]. These radio sources are normally used for LOFAR calibration, in our case as a radio source for ionosphere TEC observations. It was established that for each 1 minute observation, a suitable calibrator source can be found within a 2^0 angular distance from the GNSS satellite.

The MSSS sky survey was created with station baselines of less than 3 km, which means that the model validity for baselines of 50 km such as used in our experiment is uncertain. For the present experiment this is not a problem however: the model is only incorrect for sources that are not point-like, and to first order an extended source introduces only an amplitude error. Only strongly asymmetric sources introduce phase errors.

3. RESULTS

The GNSS observations (carrier-phase pseudo-range) are processed to obtain the best estimate of the ionospheric delay using equation 2

$$I_{L1} = \frac{f_{L2}^2}{(f_{L1}^2 - f_{L2}^2)} [\lambda_{L1}(\phi_{L1} - N_{L1}) - \lambda_{L2}(\phi_{L2} - N_{L2})] \quad (2)$$

where I is the phase advance, λ is the wave length, ϕ is the carrier phase and N is an unknown integer ambiguity. Subscripts $_{L1}$ and $_{L2}$ denote the carrier frequency. Satellite elevations lower than 10 degrees are discarded. The resulting contiguous time series of slant TEC are of high quality with very low noise levels, but they contain an unknown bias. The bias is caused mainly by the inter-frequency instrument biases, and by the integer ambiguity in carrier phase processing.

To remove the unknown bias, the ionosphere STEC values are computed using dual-frequency carrier-phase observables from the stations, using GIMs to level the geometry-free combination of carrier phases as indicated in [9]. In our case the ESA/Monitor TOMION GIMs are used [7]. This is a single-layer model with a 5 degree spatial resolution and a 15 minute time step. Figure 3 shows a sample result for GPS satellite G02.

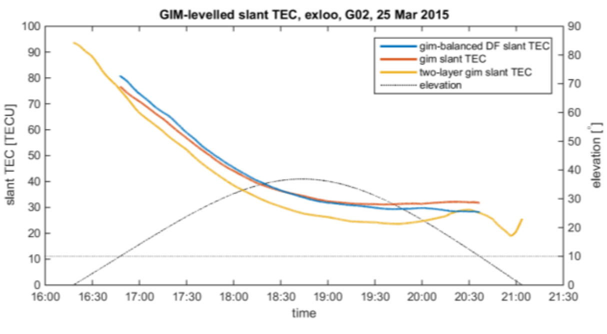

Figure 3: slant TEC estimates for GPS satellite G02. The blue line shows the observed, bias-corrected results. The red line is the external GIM used for the bias correction. The yellow line is the independent, two-layer GIM used for validation. The black line shows the satellite elevation with a cut-off at 10 degrees.

The resulting slant TEC estimate is compared to the external GIM used for bias-removal. A second, two-layer GIM [8] is used as an independent reference truth for validation purposes.

The LOFAR relative phase observations are converted to a set of relative TEC values, one value per station. There is again an unknown bias in the TEC estimates; however the relative TEC values *between* the stations are correct. The LOFAR observations are subjected to a careful review to verify that the observed phase errors are actually due to ionospheric TEC (instead of other error sources such as clock errors). By looking at the spatial dependency of relative TEC observations, it was determined that the observations have good internal consistency with low noise. Compared to the external GIM, the relative LOFAR observations show the expected spatial slope in TEC. Also, as shown in Figure 4, the magnitude of the TEC variations shows a clear spatial dependency. Other sources of phase error are not expected to be spatially dependent. Compared to the GNSS observations, the LOFAR observations show the expected variations in time. The conclusion is that the LOFAR observations indeed represent relative slant TEC as experienced by each LOFAR stations.

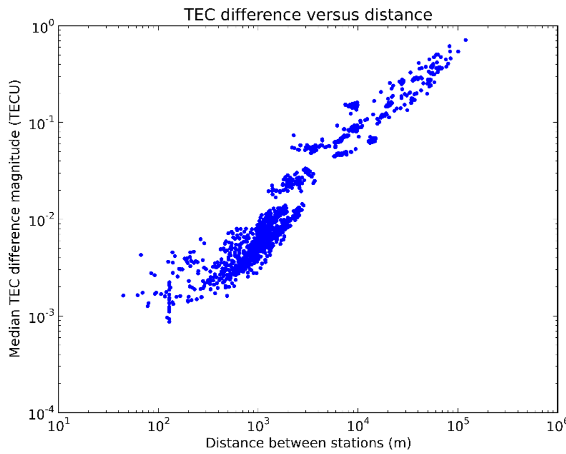

Figure 4: The median of the magnitude of the TEC difference between pairs of stations, plotted as a function of their distance. A clear trend is visible from a few hundred meters up to 100 km. Below these distances, the ionospheric fluctuations are below the noise floor of a few mTECU.

The LOFAR results can now be compared directly to the GNSS results. The difference in observed slant TEC between the two GNSS receivers is computed. This difference is directly compared against the relative TEC observed by the two LOFAR stations. Figure 5 shows the results of the comparison for GPS satellites 12 and 24.

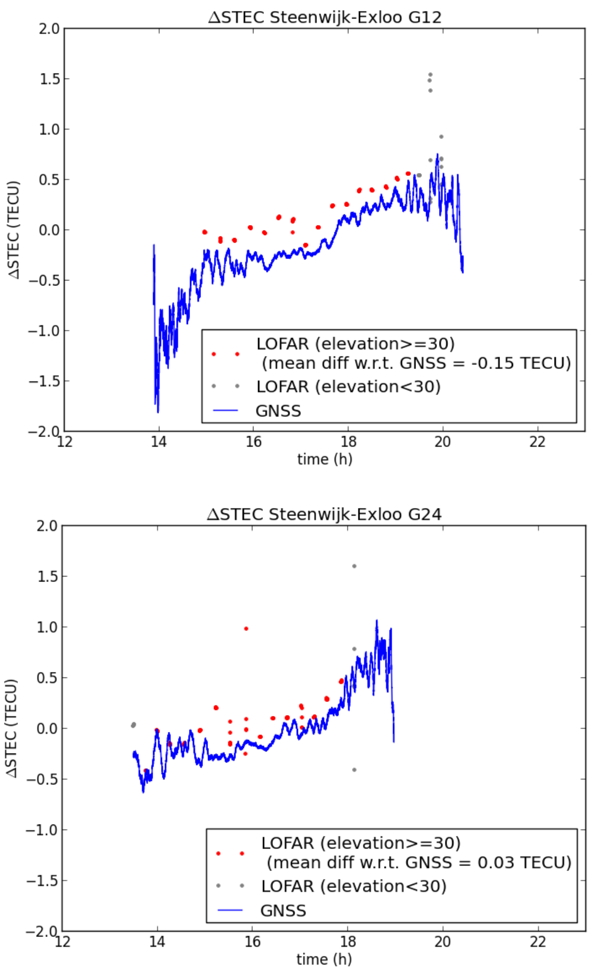

Figure 5: TEC difference between stations Exloo and Steenwijk as observed by GNSS (blue line) and LOFAR (red dots). Top panel: satellite GPS 12, bottom panel: satellite GPS 24.

In general there is a good match between the LOFAR and GNSS observations, but there are a few outliers. These results prove that the spatial TEC gradient between the two stations, and its variations in time, is accurately captured by LOFAR. Obviously some of the gradient between the two GNSS receivers is introduced by the bias correction process: on average the GNSS gradient will report the spatial gradient of the GIM map used for calibration. However, the fluctuations in time in the observed gradients are real. The very good average match (0.15 and 0.03 TECU) between the LOFAR and GNSS data suggests that LOFAR can indeed accurately measure relative TEC.

The remaining differences between LOFAR and GNSS are further analysed. As the satellite travels through the LOFAR field of view during a 1 minute observation period, the direction of the GNSS observations varies (slightly) from the direction of the LOFAR observations. The angular distance between the two observations is known exactly, shown in Figure 6.

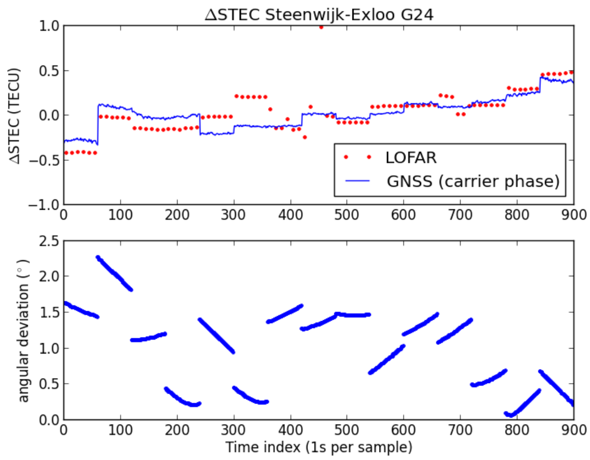

Figure 6: LOFAR slant TEC observations (blue line, top panel) compared to GNSS (red dots). The bottom panel shows the angular deviation between the two observations. It is clear that during a 1 minute observation window the angular distances changes slowly, up to 2 degrees. Note that all observations for a single satellite are shown “compressed in time” on the horizontal axis.

The distance varies slowly over the course of the observation window. If the angular distance is cause for an error in the slant TEC estimate, we expect to see a relation between the distance and the difference between LOFAR and GNSS observations. Figure 7 shows the resulting comparison. The data is clearly clustered, but there is no clear trend, indicating that in this case the angular deviation between GNSS and LOFAR observations can likely be safely ignored. Other satellites show similar behaviour.

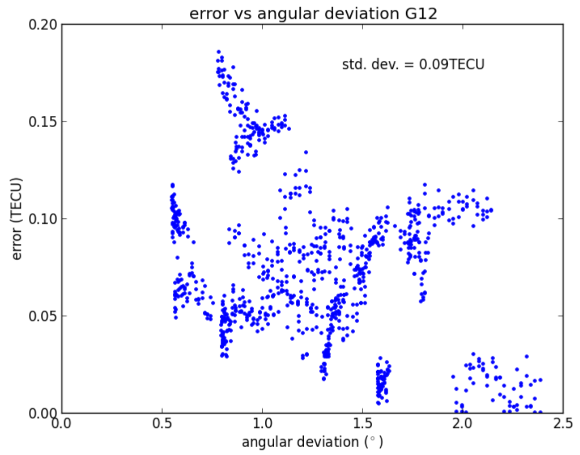

Figure 7: The relation between angular deviation slant TEC estimate errors. The horizontal axis shows the angular deviation between the LOFAR and GNSS observations. The vertical axis shows the difference in the estimated slant TEC gradient (Exloo – Steenwijk). Although the data is clustered, no clear trend can be discerned.

4. APPLICATION

We conclude that the LOFAR observations of relative slant TEC are indeed in good agreement and can be used in ionospheric estimation for GNSS receivers. The next question is how the data could be used for such an application. Ideally, a LOFAR-like telescope would cover the complete area of interest of a GNSS user. The telescope could support the generation of a map of ionospheric TEC over the area of interest. The telescope would have to observe the full sky over the coverage area. The refresh rate of the observations must be fairly rapid: it should match the relevant rate of change of the ionospheric TEC for a GNSS user. An initial estimate would be a full update every 15 minutes or better.

Based on the above demands, a coverage analysis can be performed. The LOFAR stations in the Netherlands as used in the present experiment cover an area of approximately 60×60 km, which creates a “footprint” on the ionosphere of approximately the same size. The first question is whether sufficient radio sources are available to “scan” the entire sky. Figure 8 shows that this is the case: if only the strongest (“3C”) radio sources are selected, complete sky coverage for the selected 500×300 km area can be achieved with overlap between individual LOFAR observations. This overlap is required (both in space and in time) to combine individual LOFAR observations into a single ionospheric model.

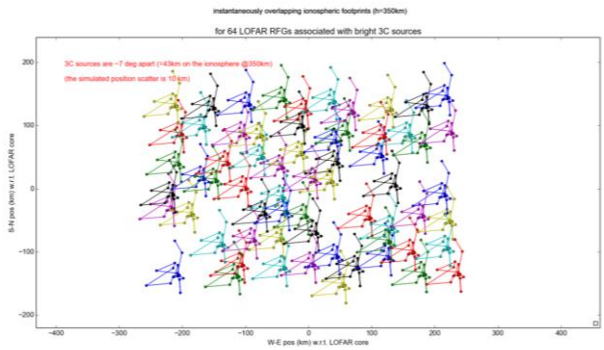

Figure 8: coverage analysis for a hypothetical ionospheric estimation system based on the LOFAR stations used in the present study. For the selected coverage area sufficient strong radio sources (3C) are available to create a complete scan of the sky with spatial overlap between LOFAR observations.

To achieve the above coverage in practice, a telescope must be designed that can quickly scan the sky and take repeated “snapshots”. An initial suggestion would be a dedicated array of small LOFAR-like stations, with a size of between 5×5 m and 10×10 m and spacing between stations of 10 km — 30 km. The reduced sensitivity of such small stations (current LOFAR stations are much larger) is compensated by using only brighter (3C) radio sources. To provide continuous observations of all visible 3C sources, each station should be able to form 50-100 independent beams on the sky. This is deemed feasible with the present technology used in LOFAR stations. A solution with less beams or non-continuous coverage (for example alternating between different sources in time) may already be adequate.

The advantage of the system described above, in comparison to current GNSS-based ionospheric maps, would be an increased spatial resolution. Such increased detail should allow the detection of ionospheric gradients and anomalies on smaller spatial and temporal scales than is currently possible. The proposed spatial resolution of 10 km may not be practical, but even a coarser resolution of 100 km would be a major improvement. The current alternatives (global ionospheric maps) have a spatial resolution of approximately 5 degrees between grid points or stations.

A remaining issue is the relative nature of LOFAR TEC observations. Even if all observations are balanced and combined into a single ionospheric model, the absolute TEC cannot be estimated by LOFAR itself. This means that additional measurements from GNSS receivers will be required in order to align into absolute TEC values. The most promising solution therefore appears to be to assimilate the LOFAR observations into an ionospheric model (such as the models used in processing 2D / 3D GIMs in the IGS centres), *together* with all available observations from fixed GNSS reference stations. In this way the maximum benefit can be gained from the high spatial density of the LOFAR observations, and the high temporal resolution and absolute accuracy of GNSS TEC observations.

5. SUMMARY AND CONCLUSIONS

A parallel experiment was performed, observing ionospheric TEC with the LOFAR radio telescope and dual frequency GNS S receivers. Two GNSS receivers were installed at LOFAR stations (a total of 55 LOFAR stations in the Netherlands were used). LOFAR has observed radio sources in the direction of a passing GNSS satellite, leading to parallel observations of the same ionosphere.

LOFAR observed phase differences between different stations which were converted to slant TEC differences. The GNSS receivers observed pseudo ranges (carrier phase tracking) on two frequencies, which were used to estimate the total slant TEC. An external global ionospheric map was used to remove any remaining unknown biases (mainly inter-frequency instrument biases) from the GNSS observations.

The resulting GNSS time series have an absolute accuracy of approximately 1 – 4 TECU compared to the independent global ionospheric map. Note that this accuracy depends mainly on the absolute accuracy of the method used for bias estimation. The relative accuracy of the GNSS time series cannot be validated independently as no truth data exists with adequate spatial and temporal resolution. However, a relative accuracy of approximately 0.1 TECU was estimated derived from the difference in observed TEC between two stations separated by 50 km.

The LOFAR telescope claims to achieve a relative spatial accuracy of 0.1 radians in phase difference (equivalent to 0.001 TECU) between stations. A comparison with GNSS observations suggests that LOFAR achieved a relative TEC accuracy of at least 0.1 TECU, with noise levels that are much lower (< 0.01 TECU). This strongly suggests that LOFAR can indeed measure with a very high relative accuracy and a high spatial density (varying from hundreds of meters to tens of kilometres). These results are very promising and suggest that LOFAR can be used to improve GNSS ionospheric corrections.

The results of the experiment were used as input for an initial feasibility study for a future ionospheric estimation method based on the technology used in LOFAR. The analysis shows that it would be feasible to create a TEC observation system with much higher spatial resolution than the currently used GNSS networks, with a high temporal update frequency (every 10 minutes). Assimilation of LOFAR observations of relative TEC, together with GNSS observations into an ionospheric model promises to be the best way forward in order to obtain absolute values

The potential benefits of using GNSS for LOFAR has been analysed but is not described in this paper. The most promising ideas are related to image calibration, in particular increasing the spatial resolution near outer LOFAR stations using GNSS receivers. However, the accuracy required by LOFAR for the ionospheric estimation is very high (in the order of 0.1 TECU 1-sigma absolute), therefore the demonstration is beyond the scope of this paper.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. M.P. van Haarlem et al., LOFAR: The LOw-Frequency ARray, *Astronomy & Astrophysics* 556,A2 (2013), DOI: 10.1051/0004-6361/201220873

2. LOFAR web site: http://www.lofar.org

3. LOFAR MSSS, https://www.astron.nl/radio-observatory/lofar-msss/lofar-msss

4. Klobuchar, J., 1987. Ionospheric Time-Delay Algorithms for Single-Frequency GPS Users. *IEEE Transactions on Aerospace and Electronic Systems* (3), pp. 325-331.

5. European Union, 2015. ‘Ionospheric Correction Algorithm for Galileo Single Frequency Users’. Issue. 1.1.

6. RTCA,2006. Minimal Operational Performance Standards for GPS/WAAS Airborne Equipment. *Report* P.2145. RTCA.

7. Hernandez-Pajares, M. et al. ‘MONITOR ionospheric monitoring system: analysis of perturbed days affecting SBAS performance’. *Proceedings of the ION 2015 Pacific PNT Meeting*. Honolulu, Hawaii, pp. 970–978.

8. Rovira-Garcia, A., J. Juan, J. Sanz and G. Gonzalez-Casado 2015. ‘A Worldwide Ionospheric Model for Fast Precise Point Positioning’. *IEEE Transactions on Geoscience and Remote Sensing* 53.8, pp. 4596–4604. issn: 0196-2892.

9. Prieto-Cerdeira, R., R. Orus-Perez, E. Breeuwer, R. Lucas-Rodrguez and M. Falcone, 2014. ‘Performance of the Galileo Single-Frequency Ionospheric Correction During In-Orbit Validation’. *GPSworld* 25.6, pp. 53–58.

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