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LOFAR as an ionospheric probe☆

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Abstract

At the Low-Frequency Array (LOFAR)(Planet. Space Sci. (2004) these proceedings) frequencies (HF/VHF), extraterrestrial radiation experiences substantial propagation delay as it passes through the ionosphere. The adaptive calibration technique to be employed by LOFAR will use signals from many known bright radio sources in the sky to estimate and remove the effects of this delay. This technique will operate along many simultaneous lines of sight for each of the stations. Measurements will be made on time scales of seconds or shorter, and with accuracies corresponding to path length variations of 1 cm or less. Tomographic techniques can be used to invert the thousands of changing and independent total electron content (TEC) measurements produced by LOFAR into three-dimensional electron density specifications above the array. These specifications will measure spatial and time scales significantly smaller and faster than anything currently available. These specifications will be used to investigate small-scale ionospheric irregularities, equatorial plasma structures, and ionospheric waves. In addition, LOFAR will improve the understanding of the solar drivers of the ionosphere by simultaneously measuring the solar radio bursts and the TEC. Finally, LOFAR, which will be situated to observed the galactic plane, will make continuous, high-resolution observations of the low-latitude ionosphere, an important but under-observed region. This paper will look at LOFAR as an ionospheric probe including comparisons to other ionospheric probes as well as possible methods of operation to optimize ionospheric measurements.

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1. Introduction

Low Frequency Array (LOFAR) will be the first in a new generation of radio telescopes, utilizing advanced technologies to provide unsurpassed observational capabilities and explore innovative operational modes. It will in effect open a new window on the universe and permit research ranging from cosmology and galactic astrophysics to space physics and aeronomy. LOFAR (Kassim, 2004) is designed to achieve arc-second angular resolution, high dynamic range and wide-field imaging in the HF/VHF band. In order to do this, radio distortion caused by the ionosphere must be removed.

Removing this radio distortion will provide a measurement of the total electron content (TEC) along the line of sight of each LOFAR antenna. Since LOFAR will operate passively, it will provide near-continuous measurements in volumes never seen before. In addition to providing regional maps of the TEC and phase distortion, LOFAR data can be combined by tomographic (Austen et al., 1988; Bust et al., 1994) and objective analysis (Pi et al., 2003; Bust et al., 2003) techniques to create a three-dimensional electron(3D) density specification. These specifications will have higher spatial and temporal resolutions than are routinely available by other techniques. In addition, the LOFAR frequency band covers the range of radio bursts that are associated with solar flares. Because of

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these properties, LOFAR measurements will be useful for studies of small-scale ionospheric irregularities, equatorial electron density structures, ionospheric wave propagation, and ionospheric response to solar flares. In addition, LOFAR observations will be useful for operational space weather monitoring. Thus, LOFAR will be a new and exciting ionospheric observatory.

2. LOFAR properties as an ionospheric observatory

LOFAR will be a revolutionary ionospheric observatory. While the technical details of LOFAR are fully discussed elsewhere in this volume, several LOFAR characteristics that will be useful for ionospheric studies include:

- a site designed for viewing the galactic center and hence the equatorial ionosphere,
- an observational base line of ~ 400 km,
- an adaptive calibration that provides continuous ionospheric measurements with a data cadence in seconds,
- radio observations in the 10–90 and 110–240 MHz frequency bands,
- independent measurements from each of 10,000–15,000 antennas,
- a multi-arm log-spiral geometry that provides a well filled U,V plane,
- individual "pencil" beams that can be digitally steered independently.

Adaptive calibration is fundamental in many areas of research (Cornwell, 1995). LOFAR will utilize this technique to remove the noise-induced decorrelations on the observed phase caused by atmospheric and dominated by ionospheric effects. Adaptive calibration continuously updates the instrument calibration and provides real-time calibration information. Standard self-calibration has been used on the 74 MHz system at the Very Large Array (VLA) radio telescope to remove ionospheric effects (Kassim et al., 1993). The first order correction delivers only a single, angle-invariant ionospheric phase correction for each antenna as a function of time (Lazio et al., 1999). While the first generation of ionospheric compensation algorithms used have difficulties with the finite size of the ionospheric isoplanatic (constant beam plane) patch viewed by VLA, innovative algorithms are being developed to provide an angle variant self-calibration method for LOFAR.

The adaptive calibration will produce ionospheric measurements as a by-product. At a given frequency, the adaptive method will use a known radio source to correct for ionospheric phase distortion on each receiving element. This phase correction is the observed phase due to the interaction of the electromagnetic wave with the ionospheric plasma. The observed phase corrections will be used in studies of ionospheric irregularities. They can also be converted into TEC measurements. The spatial resolution of these measurements is limited by:

- diffraction scale size for the frequency of interest,
- number of sources which have been cataloged,
- number of receive antennas on the ground and
- processing power which is available for the adaptive calibration.

Since each receiving element will obtain an ionospheric irregularity phase map across the entire visible sky with a sampling frequency of ~ 1 Hz, and a spatial resolution of 10–100 m, LOFAR will generate enormous volumes of irregularity data.

2.1. Current ionospheric probes and LOFAR

LOFAR will fill an important niche in ionospheric observations. Table 1 compares the data resolution and cadence for many of the commonly available ionospheric measurements.

These measurements include:

- GPS ground and occultation—the dual frequency beacons from the GPS satellites are measured by either a ground based or space based GPS receiver. The relative phase shift of the signal from the two frequencies gives a measure of the integrated total electron content (TEC) between the GPS satellite and the receiver. These types of measurements are continuous, and globally distributed in large numbers. However, GPS ground receivers are heavily clustered in the North America and Europe. LOFAR will have advantages over GPS in accuracy as well as resolution both spatially and temporally. The main advantage of the GPS measurements is that they can be made at any place with a relatively low-cost dual frequency GPS receiver.
- Low Earth Orbiting (LEO) radio beacons and Computerized Ionospheric Tomography (CIT)—the dual frequency beacons aboard LEO satellites (e.g. Navy Ionospheric Monitoring Satellites (NIMS)) can provide TEC measurements in the same way GPS systems do. The differences between LEO measurements and GPS measurements are the number of beacons in the field of view (seldom more than one for LEO and typically eight for GPS), the height of the integration (~ 800 km for LEO and $\sim 20,000$ km for GPS) and the satellite transit time across the field of view (~ 20 min for LEO and ~ 8 h for GPS). Because of this rapid transit time, LEO receivers can be deployed in arrays of multiple receivers to allow CIT to process these data into 2D electron density specifications. CIT specifications provide detailed maps of the large scale horizontal structures with

Table 1
The table outlines several current methods of measuring the ionosphere along with estimates for LOFAR

Type	Time	δT	Field of view	Spatial resolution	Coverage
GPS	Continuous	30 s	100 km	100 km	Global
CIT	Intermittent	20 min	1000 km	10 km	Regional
Beacon	Intermittent	1 ms	1000 km	Integrated point	Regional
Sounder	Continuous	15 min	100 km	100 km horiz. 1 km vert.	Local
In situ	Continuous	4 s	Point	Point	Global
ISR	Intermittent	1 s	1000 km	10 m	Regional
LOFAR	Continuous	1 s	1000 km	10–100 m	Regional

The table compares the type of measurements in a number of different categories. The numbers are meant for comparative purposes only and in some cases refer to typically reported parameters as opposed to the highest possible resolution of the instrument.

good spatial resolution. LOFAR will have excellent spatial resolution with the ability to point in any direction at any time unlike LEO satellites.

- Sounders–ground based radio transmitters which sweep a frequency band typically from 1 to 20 MHz. The relative time delay of the reflected signal is related to the electron density directly above the sounder. They are excellent instruments for determining bottom-side ionospheric characteristics including the profile and peak densities.
- In situ spacecraft instruments—measurements are made of the electron density at a point in space. Since these measurements are actually direct local measurements rather than remote measurements, they are considered to be more accurate, but lack the spatial diversity of a remote sensing technique.
- Incoherent Scatter Radar (ISR)—a radar system which measures several ionospheric parameters from the backscattered power along the beam path. As an active system, ISR make excellent measurements of electron density and can steer the beam to cover a large area. Due to high construction and operating costs, ISR data is both spatially and temporally limited.

The overall temporal coverage is shown in the first column titled "Time". The δT column considers the typical time resolution. The "field of view" is the horizontal extent of the instrument coverage. Finally, "Coverage" refers to both the spatial distribution and the density of the measurement set. Thus, GPS and sounders have a global network of instruments, but only the GPS network is considered "global" since the GPS network is dense enough to have overlapping fields of view. Similarly, in situ instruments are considered global measurements since typical satellite orbits cross all lines of longitude eventually.

2.2. Summary of LOFAR capabilities

The LOFAR telescope will have the ability to make high-resolution measurements of the ionosphere. Table 2 summarizes the relevant characteristics of the instrument.

Table 2
Summary of the capabilities for the LOFAR instrument

Characteristic	LOFAR
Horizontal resolution	2 m
Vertical resolution	2 m
Temporal resolution	1 s
Relative accuracy	<0.001 TECU

3. LOFAR modes for ionospheric observation

While LOFAR will primarily be an astronomy observatory, there will be times when it can be used as a dedicated ionospheric observatory. Thus in addition to the astronomical data modes for LOFAR, it will be possible to define ionospheric and other data modes. The default mode will take TEC measurements as simple by-products of the astronomical measurements. The other modes are specifically dedicated to ionospheric research. Since LOFAR will have multiple beams available it may be that both the ionospheric and astronomical measurements can occur simultaneously. In addition, there are likely to be periods when more delicate astronomical research will not be possible at the lowest frequencies because of the ionospheric disturbances. Since these conditions occur because of intense ionospheric irregularities, the ionospheric modes should not interfere significantly with astronomical viewing modes and should be complementary to other viewing modes such as the air shower mode. This co-utilization of the array assures that the maximum amount of science possible is performed with LOFAR without regard to geomagnetic conditions.

3.1. Ionospheric shell mode

This default mode will observe a 2D ionospheric shell. The TEC observed by each antenna will be collected into a horizontal TEC map over LOFAR. This mode will be necessary for the adaptive calibration and can be generated from an astronomical measurement. In this technique the LOFAR measurements can be used to quickly specify the electron density distribution for astronomical measurements. This method would have minimal ionospheric information beyond what is needed for accurate astronomical corrections, but it could be processed very quickly to provide that correction.

3.2. Three dimension mode

Since primarily LOFAR will be employed in astronomical observations, real-time ionospheric irregularity observations may be limited to 2D electron content information. However, a fully 3D analysis of these irregularities can be achieved through a special processing technique along with the possibility of specialized ionospheric observational modes. If the pencil beams from different stations are steered so that they cross one another, then the LOFAR measurements can be utilized by tomographic or data assimilation techniques to specify the 3D electron density distribution with a high spatial resolution.

More refined 3D electron density specifications can be produced by utilizing a dedicated observational mode in which the beams move quickly between a number of different calibration sources. Since these calibration sources will be relatively bright, it is expected that the beam would only have to stare at a particular source for several seconds. This mode would also be optimized to have the beams from different stations crossing as much as possible.

3.3. Sounder mode

In this mode, the ionosphere will be assumed to be a simple uniform profile. The profile could be determined by employing an Ionosonde-like technique in which the array is used to receive an active transmission. Alternately, an ionosonde could be deployed near the central core to measure the bottom-side ionosphere profile. This mode would allow for an accurate specification of the bottom-side profile of the ionosphere.

3.4. Vertical profile mode (VPM)

The VPM is a specialized version of the 3D mode in which the objective is to make a high-precision vertical measurement of the ionosphere. This mode would provide very high vertical resolution ($\sim 2\,\text{m}$). This additional resolution would assist in the study of vertical correlations especially to determine how this correlation varies as a function of time, date and geomagnetic conditions. Correlation measurements are important for data assimilative techniques. It would be possible to consider creating several VPM-type beams over the extent of the LOFAR array. This would allow us to make measurements of the correlation in the horizontal plane. Similarly, a horizontal scan mode (HSM) can be defined to examine the horizontal correlation lengths and times.

3.5. Bistatic mode

Bistatic measurements are radio signals from an unseen transmitter that reflect off of an airborne object. These measurements can be useful in a couple of ways. First, they can validate an ionospheric specification; if the transmitter and reflector can be uniquely identified and located. Alternately, if the electron distribution and transmitter location are known, then the location of the reflector can be determined (Sahr and Lind, 1997).

3.6. Diffraction tomography

The precision of the LOFAR array will allow the testing of a theoretical type of ionospheric tomography called 3D diffraction tomography (Devaney, 1984; Kunitsyn et al., 1994). This will require LOFAR to track the 150 MHz signal from beacon satellites. The LOFAR data will be ideal for diffraction tomography since the signals at each antenna will be measured and correlated allowing the measurement of small-scale phase shifts between the antennas.

3.7. Air shower mode

In this mode the LOFAR will be utilized as a detector for high TeV muon showers (Huege and Falcke, 2003). This method will measure the extensive air showers (EAS) from high-energy muons and the allow for a back trace along the pair production pathways. The method allows for the use of the upper atmosphere as a type of Cerenkov detector. As such it may need to be "triggered" by the use of additional detectors. This trigger event would then allow for the processing of the RF wavefront to allow for the reconstruction of the event.

4. Potential ionospheric studies with LOFAR

While it is impossible to fully anticipate the ionospheric phenomena that can be investigated by LOFAR, the initial ionospheric investigations will focus upon five important issues in ionospheric physics and space weather: continuous 3D electron density specification, small-scale ionospheric irregularities, ionospheric waves, the ionospheric response to solar radio bursts, and equatorial ionospheric variations. While LOFAR ionospheric studies will focus on these areas, there are other interesting studies that can be conducted with LOFAR.

4.1. Specification of electron density of the ionosphere

The LOFAR's main ionospheric science objective will be continuous specification of the current state of the ionosphere in the LOFAR field of view. These specifications will be used to investigate the local morphology, large scale ionospheric structures (e.g. TIDS), and correlation lengths and times. While LOFAR measurements are regional, they will be useful for both global data assimilation algorithms and the validation of theoretical global ionospheric models because the observations are continuous and occur across an approximately 400 km baseline.

4.2. Investigation of small-scale structure

LOFAR will be an exciting instrument for studying ionospheric small-scale structures. The array size and sensitivity (better than 0.001 TECU) will provide new opportunities to investigate small-scale electron density irregularities. In particular, LOFAR will be able to observe small-scale (<100 m) ionospheric features, which are difficult to measure with more traditional ionospheric instruments. In the CIT mode, LOFAR measurements will be collected into very high-resolution electron density distributions. These specifications will be available in a rapid cadence over extended periods of time. These specifications will be used to investigate such small- and mid-scale structures as equatorial plumes, sporadic E and spread F. These structures are known to be highly dynamic and will be well suited to LOFAR-type measurements. Mid-latitude irregularities will also be investigated in order to determine the internal structure of the mid-latitude ionosphere. This can include such things as measurement of Sporadic E and the mid-latitude irregularities observed at Arecibo by Kelley et al. (2000), Bust et al. (2000) and others.

4.3. Ionospheric waves

In addition to investigating electron density, LOFAR will provide unique observations of ionospheric waves. Because of its high spatial and temporal resolution coupled with continuous observations, LOFAR will expand the observable spectrum of ionospheric waves, and will better observe the propagation of waves. While large interferometers (such as VLA) have been used to study TIDs (Perley and Bust, 2002; Sakurai and Spangler, 1994), the short baselines of these arrays have prevented the determination of such basic parameters as the direction of wave propagation. LOFAR's much larger baseline will enable a direction-finding capability. It is also hoped that the dissipation of ionospheric waves will be observed. Future LOFAR observations of ionospheric waves will expand our knowledge of these phenomena.

4.4. Solar drivers of ionospheric physics

LOFAR will be able to observe meter-wave solar radio bursts. These radio bursts have been separated into five types based upon their frequency spectrum. The most common radio bursts are Type III bursts. About one-third of these bursts are associated with solar flare eruptions, which produces hard X-rays (Barron et al., 1985). These hard X-rays are a significant ionization source for the D-region. Because LOFAR will be able to simultaneously observe the radio signature of a solar flare and the ionospheric reaction to the flare, it will be useful in studies of impact of solar flares upon the Earth's space weather.

4.5. Equatorial ionospheric space weather

Since one of the primary interests of LOFAR will be to observe objects in the galactic center, LOFAR is likely to be placed in a location from which it can image the equatorial ionosphere, one of the least understood and dynamic regions of the ionosphere. Through continuous, passive observations, LOFAR will generate an enormous data set of the equatorial ionospheric conditions. The specification of the electron density distribution of the equatorial ionosphere is a major goal of the National Space Weather (NSW) program. Since LOFAR will continuously monitor the ionospheric conditions, it will be an invaluable asset in observing the space weather.

4.6. Other potential studies

LOFAR's main ionospheric focus will be to investigate these phenomena, but there are other possible ionospheric studies for which LOFAR will be useful. Two additional studies that should be possible are electron density measurements above the ionosphere and investigations of meteor scatter.

4.6.1. Interstellar electron density using dual frequency sources

LOFAR-only measurements of the electron density will be unlikely to decouple the effects of the Earth's ionosphere and the non-ionospheric electron density. It is possible by including ionospheric information from satellites to decouple the two contributions. It should be possible to make measurements of the non-ionospheric electron density by subtracting off ionospheric electron density or content measurements from different instruments. The remaining density is due to the magnetosphere and beyond.

4.6.2. Meteor scatter measurements

Meteor scatter is a commonly observed bistatic measurement. Meteor scatter has been observed by active radar systems such as the ALTAIR system at Kwajelen (Close et al., 2002). LOFAR coupled with a coherent transmitter will be able to track meteors as they enter the Earth's atmosphere. These meteors produce ionization trails which briefly open up communication channels which allow for non-line-of-sight communications in the 30–110 MHz frequency range. Because the meteor trails act as a noise source for astronomical measurements, they must be accurately measured and understood.

5. Summary

In addition to being a revolutionary astronomical observatory, LOFAR will be an exciting ionospheric observatory. LOFAR's adaptive calibration will allow for continuous measurements of the total electron content (TEC) along the line of sight of each of the 10,000–15,000 antennas. These antennas are distributed along a multi-arm log-spiral geometry with a $\sim 400\,\mathrm{km}$ baseline. In addition, each antenna will be digitally steered independently. Because of these properties, LOFAR TEC measurements can be combined through tomographic and data assimilative techniques into high-resolution three-dimensional electron density specifications.

While it is impossible to fully outline the potential scientific studies for which these specifications will be used, four areas of studies immediately come to mind. First, LOFAR specifications will show the electron density distribution over roughly a 3.5° circle of the ionosphere making these specifications useful for space weather monitoring and comparisons with theoretical aeronomy models. Second, the LOFAR specifications will have meters resolution, which will allow detailed studies of small-scale ionospheric irregularities. Similarly, LOFAR's high cadence and long baseline will be useful in observing the propagation of ionospheric waves. In addition, LOFAR's adaptive calibration technique and high HF/VHF resolution will enable LOFAR to make simultaneous measurements of solar radio bursts and the ionospheric response. Finally, LOFAR's site location will provide an excellent view of the equatorial ionosphere. LOFAR's measurements will enhance are understanding of the equatorial ionosphere, which is scientifically interesting and operationally important.

References

Austen, J.R., Franke, S.J., Liu, C.H., 1988. Ionospheric imaging using computerized tomography. Radio Sci. 23, 299.

Barron, W.R., Cliver, E.W., Cronin, J.P., Guidice, D.A., 1985. Solar radio emission. In: Adolph S. Jursa (Ed.), Handbook of Geophysics and the Solar Environment. Air Force Geophys. Lab., Hanscom AFB, MA.

Bust, G.S., Cook, J.A., Kronschnabl, G.R., Vasicek, C.J., Ward, S.B., 1994. Application of ionospheric tomography to single-site location range estimation. Int. J. Imag. Systems Technol. 5, 160.

Bust, G.S., Coco, D., Makela, J.J., 2000. Combined ionospheric campaign 1: Ionospheric tomography and GPS total electron count (TEC) depletions. Geophys. Res. Lett. 27 (18), 2849.

Bust, G.S., Garner, T.W., Gaussiran, T.L., II, 2003. Ionospheric data assimilation three dimensional (IDA3D): a new global, multi-sensor, three dimensional electron density specification algorithm. Radio Sci., submitted for publication.

Close, S., Hunt, S.M., McKeen, F.M., Minardi, M.J., 2002. Characterization of Leonid meteor head echo data collected using the VHF-UHF advanced research projects agency long-range tracking and instrumentation radar (ALTAIR). Radio Sci. 37 (1).

Cornwell, T., 1995. Imaging concepts, ASP Conference Series 82: Very Long Baseline Interferometry and the VLBA.

Devaney, A.J., 1984. Geophysical diffraction tomography. IEEE Trans. Geosci. Remote Sensing 22, 3.

Huege, T., Falcke, H., 2003. Radio emission from cosmic ray air showers: coherent geosynchrontron radiation. Astron. Astrophys. 412, 19.

Kassim, N., 2004. Planet. Space Sci., these proceedings.

Kassim, N.E., Perley, R.A., Erickson, W.C., Dwarakanath, K.S., 1993. Subarcminute resolution imaging of radio sources at 74 MHz with the very large array. Astron. J. 106 (6), 2218.

Kelley, M.C., Makela, J.J., Swartz, W.E., Collins, S.C., Thonnard, S., Aponte, N., Tepley, C.A., 2000. Caribbean ionosphere campaign, year one: airglow and plasma observations during two intense mid-latitude spread-F events. Geophys. Res. Lett. 27, 2825.

Kunitsyn, V.E., Andreeva, E.S., Tereshcehenko, E.D., Khudukon, B.Z., Nygren, T., 1994. Investigation of the ionosphere by satellite radiotomography. Int. J. Imag. Systems Technol. 5 (2), 112.

Lazio, T.J.W., Kassim, N.E., Weiler, K., Gross, C.A., 1999. The Low Frequency Array (LOFAR). Bull. Am. Astron. Soc. 31, 1498.

Perley, R., Bust, G.S., 2002. Probing the ionosphere with the Very Large Array. USRI General Assembly, Maastrich, The Netherlands.

Pi, X., Wang, C., Hajj, G.A., Rosen, G., Wilson, B.D., Bailey, G.J., 2003. Estimation of $E\times B$ drift using a global assimilative ionospheric model: an observation system simulation experiment. J. Geophys. Res. 108 (A2), 1075.

Sahr, J.D., Lind, F.D., 1997. The Manastash Ridge radar: a passive bistatic radar for upper atmospheric radio science. Radio Sci. 32, 2345.

Sakurai, T., Spangler, S.R., 1994. Use of the Very Large Array for measurement of time variable Faraday rotation. Radio Sci. 29 (3), 635.