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IAR's 60th anniversary: Prospects for low-frequency radio astronomy in South America (November 15-18, 2022)
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TOWARD A GLOBAL NETWORK OF RADIO TELESCOPES FOR IONOSPHERIC SCIENCE

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RESUMEN

Este manuscrito describe el desarrollo y la proliferación de un radiotelescopio interferométrico de coste relativamente bajo optimizado para la teledetección ionosférica. Denominado Deployable Low-band Ionosphere and Transient Experiment (DLITE), el sistema se basa en la tecnología de antena desarrollada para el Long Wavelength Array (LWA) y en métodos de análisis probados inicialmente con el sistema de banda baja del Very Large Array (VLA). Al tratarse de un conjunto de cuatro elementos, DLITE es asequible/desplegable y ha demostrado su capacidad para caracterizar perturbaciones ionosféricas a escalas de ∼50–150 km e irregularidades a escalas de ∼1 km. En este artículo se describen las mediciones que pueden realizarse con DLITE y el estado actual de la incipiente red, que consta de tres telescopios y en la que se están buscando oportunidades para varios más.

ABSTRACT

This manuscript describes the development and proliferation of a relatively low-cost interferometric radio telescope optimized for ionospheric remote sensing. Called the Deployable Low-band Ionosphere and Transient Experiment (DLITE), the system is based on antenna technology developed for the Long Wavelength Array (LWA) and analysis methods initially tested with the Very Large Array (VLA) low-band system. As a four-element array, DLITE is affordable/deployable and has been demonstrated to be adept at characterizing ionospheric disturbances on scales of ∼50–150 km and irregularities on scales of ∼1 km. This paper describes the measurements that can be made with DLITE and the current state of the fledgling network, which consists of three telescopes with opportunities for several more being pursued.

Key Words: atmospheric effects — instrumentation: interferometers — techniques: interferometric

1. INTRODUCTION

Density fluctuations within Earth's ionosphere complicate radio-frequency astronomical observations, especially at low frequencies (<500 MHz). In particular, synthesis-imaging interferometers with baselines longer than a few km can lose coherence and be unable to image sources within this frequency regime. Conversely, these corrupted observations can serve as extremely precise probes of ionospheric structure on spatial scales from kilometers to ∼100 km and on time scales on the order of seconds to hours. It is not surprising then that in the past few decades, several unique investigations of ionospheric disturbances have been undertaken using telescopes such as the Very Large Array (VLA; Cohen and Röttgering 2009), the Long Wavelength Array (LWA; Helmboldt and Taylor 2020), the Low Frequency Array (LOFAR; Fallows et al. 2020), the Murchison Widefield Array (MWA; Loi et al. 2015a), and the Giant Metrewave Radio Telescope (GMRT; Mangla and Datta 2022).

While these pioneering efforts have quite successfully elucidated several unique aspects of ionospheric structure, they suffer from a common shortcoming: portability. Establishing a network of similar telescopes to enable global studies of ionospheric disturbances/irregularities is not economically feasible. Here, we describe efforts to develop a Deployable Low-band Ionosphere and Transient Experiment (DLITE) to address this. The DLITE system is an interferometer consisting of four LWA inverted vee dipole antennas spread out over baselines of 200–500 m. The backend uses commercial off-the-shelf parts, including software-defined radios with the real-time correlator at its heart written with GNURadio (`https://www.gnuradio.org`). DLITE operates in a nominal band of 30–40 MHz, using time difference of arrival (TDOA) methods and nonlinear fitting techniques to isolate bright cosmic sources on the sky.

By monitoring "A-Team" sources (Cygnus A,

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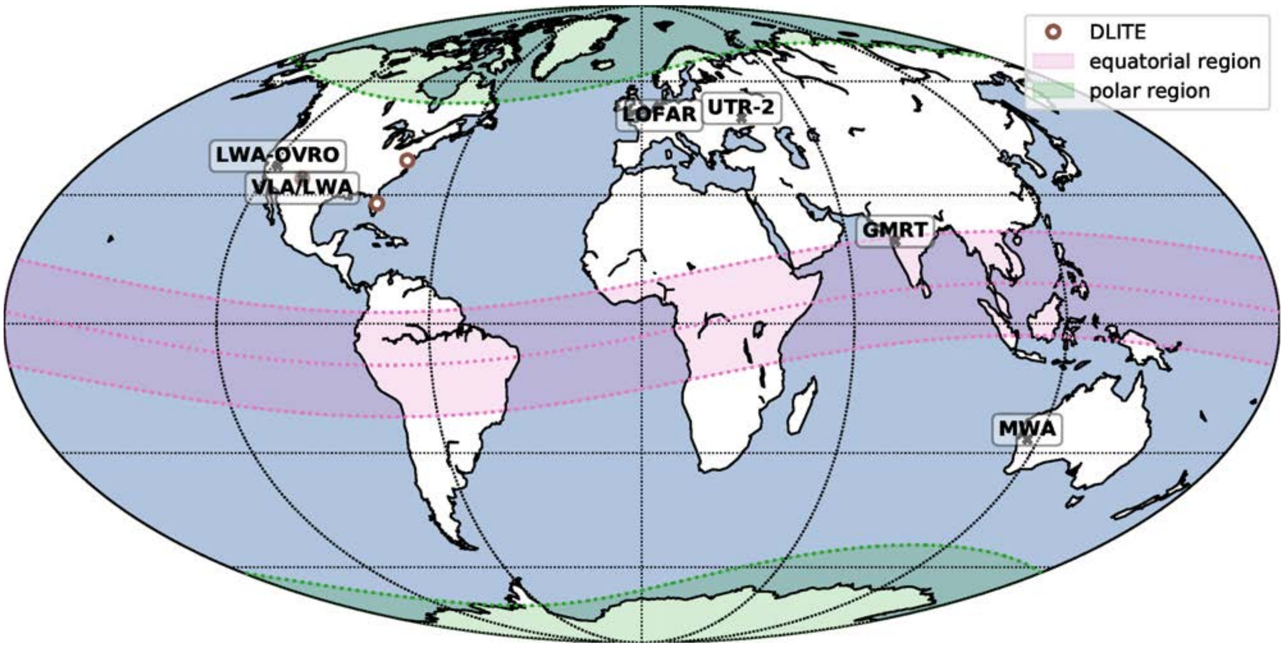

Fig. 1. A map of locations of current major low frequency telescopes relative to the equatorial (pink) and polar (green) ionospheric regions. Locations of existing DLITE arrays are indicated with brown circles.

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Cassiopeia A, Virgo A, Taurus A, Hercules A, Hydra A, and Centaurus A) with a relatively wide bandwidth, the array can detect intensity and phase fluctuations from irregularities with strength parameters as small as $C_kL \approx 10^{27}$. This is several orders of magnitude below what can be measured with methods based on Global Positioning System (GPS) satellite data (Carrano et al. 2019). Additionally, by using DLITE to track the apparent motions of these sources, transverse gradients in the line-of-sight total electron content (TEC) can be measured with a precision $\sim 10^{-4}$–10^{-3} TECU km^{-1} (1 TECU= 10^{16} m^{-2}). More details can be found within the DLITE system paper (Helmboldt et al. 2021).

Within this paper, we will discuss the current state of the network, which consists of three arrays in Maryland, New Mexico, and Florida; recent science results; and plans/opportunities for future deployments.

2. IONOSPHERIC SCIENCE WITH LOW-FREQUENCY RADIO TELESCOPES

To achieve an angular resolution of an arcminute or better, low-frequency radio telescopes need to be quite large, on the order of tens of km or more. This necessitates the use of interferometers for high angular resolution synthesis imaging. Since phase errors due to ionospheric structure are proportional to the observing wavelength, if structures comparable in size to the telescope array exist, they can be especially problematic at these frequencies. Indeed, such structures were the chief limiting factor to the size of low-frequency interferometers for several decades.

The advent of self-calibration methods (Cornwell and Formalont 1999) offered a potential solution to this issue. This led directly to the first sub-arcminute resolution images below 100 MHz obtained using self-calibration with the VLA 74 MHz system (Kassim et al. 1993). Almost from the beginning, this new ionospheric calibration method was used to study ionospheric disturbances with investigations conducted by Jacobson and Erickson (1992a, 1992b, 1993) with the VLA 330 MHz system revealing a plethora of wavelike phenomena, including a newly discovered class of plasmaspheric irregularities. It has since been used to study traveling ionospheric disturbances (TIDs) and turbulence-like small-scale disturbances with the VLA (Helmboldt et al. 2012a), LOFAR (Mevius et al. 2016), and GMRT (Mangla and Datta 2022).

After this ionospheric barrier was broken, an additional ionospheric issue needed to be dealt with. Whether parabolic antennas (e.g., the VLA) or phased arrays (e.g., LOFAR) are used for the elements of an interferometer, the width of the field of view (FoV) is proportional to wavelength. If the FoV is larger than the isoplanatic patch associated with ionospheric structure, a single set of antenna-based phase corrections is not sufficient. Two meth-

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ods have been developed and used, sometimes in tandem, to address this problem.

To first order, gradients in TEC due to ionospheric structure cause a source's position to appear to shift in the direction of the gradient. For a relatively wide FoV, several moderately bright sources can be monitored with a series of "snapshots," images with integration times of ∼1–2 minutes. A set of basis functions (e.g., Zernike polynomials) can be fit to these sources' position shifts to correct aberrations over the entire FoV before averaging the snapshots together for a deeper image. For the VLA 74 MHz system, this could be done with around 20–30 calibration sources within the ∼13° wide FoV (Kassim et al. 2007). For the MWA, which has an FoV as wide as ∼30°, hundreds of sources are used to map ionospheric distortions. Like self-calibration, this method has been used to study ionospheric structure from New Mexico (Cohen & Röttgering 2009; Helmboldt et al. 2012b) and Australia (Loi et al. 2015b) with a notable discovery of plasma ducts in the topside ionosphere using MWA data (Loi et al. 2015a).

A second method, referred to as "peeling," iteratively employs the self-calibration process on a source-by-source basis. Starting with the brightest detected source, antenna-based calibrations are solved for in the direction of one source after which it is subtracted from the visibilities using a model corrupted by the inverse of the ionospheric corrections. After this, the algorithm moves on to the next brightest source, and so on (see, e.g., Intema et al. 2009). This is sometimes used in tandem with the position shift method to mitigate the impact of extremely bright sources on the data. Helmboldt and Intema (2012) employed the peeling and position shift methods together with an observation of the bright source Vir A with the VLA 74 and 330 MHz systems. These were used to simultaneously detect plasmaspheric disturbances with the Vir A self-calibration data and TIDs with the position shifts measured for other sources within the FoV.

These results not withstanding, radio telescopes largely remain a novel category of ionospheric remote sensing instrument. This is not entirely surprising since these are typically multi-million dollar instruments funded for astronomy and astrophysics and not to study the ionosphere. Because of this, the temporal coverage of data that is usable for detailed ionospheric analysis is extremely sparse. Even with the introduction of the VLA Low-band Ionosphere and Transient Experiment (VLITE), which continuously collects data using 18 of the VLA's antennas at 320–384 MHz, this issue is only partially alleviated since only about 10% of these data are useful for ionospheric analysis (Helmboldt et al. 2019).

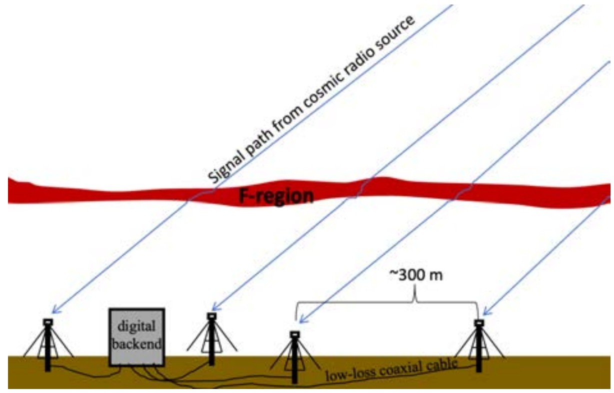

Fig. 2. A schematic (not to scale) of the DLITE system.

Even though low-frequency telescopes can be found around the world (see Fig. 1), because of the dedication to their primary astronomy-focussed missions, there is no coordination of joint efforts for global ionospheric analysis. In addition, to maximize performance, these telescopes tend to be clustered at mid-latitudes where ionospheric disturbances are typically quite mild when compared with the equatorial and polar regions (see Fig. 1). Only the GMRT is located close to the equatorial anomaly, which often has a severely negative impact on performance, especially near sunset.

To realize the potential of radio telescopes for high-precision, passive remote sensing of ionospheric structure, a new type of radio telescope must be designed, one that is optimized for portability and economical enough to facilitate many deployments around the world. This was the impetus for the development of the DLITE system.

3. THE DLITE SYSTEM AND NETWORKING PROSPECTS

The DLITE system is described in extensive detail by Helmboldt et al. (2021); a simple schematic of the system is shown in Fig. 2. Briefly, it is an interferometer of four LWA antennas, nominally operating in a 30–40 MHz band. The optimum configuration has three antennas at the vertices of an equilateral triangle that is at least 350 m long on each side with the fourth antenna in the middle. In practice, site constraints can make this difficult, and alternate configurations are possible. The key is to make sure the minimum baseline length is ∼200 m such that A-Team sources can be adequately resolved from one another using TDOA and a bandwidth of ∼8–10 MHz. It is also important to max-

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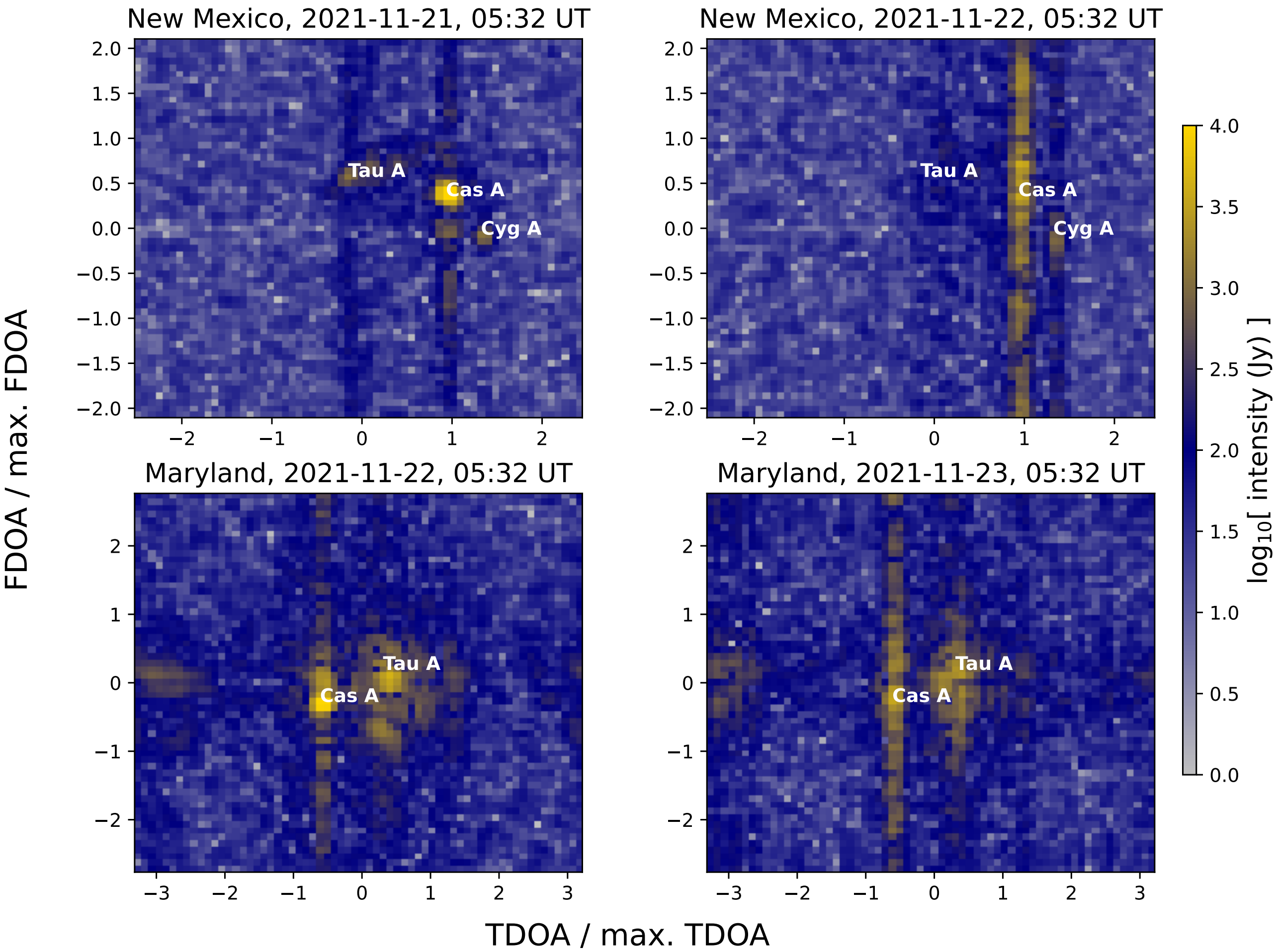

Fig. 3. Example TDOA / FDOA images from a ∼420-m east/west baseline in New Mexico (upper panels) and from a ∼350-m north/south baseline in Maryland (lower panels) from Nov. 2020. Visible A-Team sources are labeled. The strong vertical bar associated with Cas A in the upper right panel is due to a relatively extreme mid-latitude scintillation event ($\log_{10} C_k L \simeq 32$) that occurred over New Mexico on 22 Nov. A similarly strong event was observed from Maryland the next day (lower right panel). Extended structure near FDOA=0 from Maryland is primarily due to broadband interference from a nearby power line/utility pole.

imize the variety of baseline orientations to ensure that any two A-Team sources will be resolvable in TDOA with as many baselines as possible. Thus, while the array has a relatively large footprint, the actual elements take up little space.

With such a configuration, A-Team sources can be isolated and tracked on the sky to measure line of sight TEC gradients toward each. Due to their extreme brightness, Cyg A, Cas A, and Vir A provide the best TEC gradient measurements with precisions $\sim 10^{-4}$–$\sim 10^{-3}$ TECU km^{-1}, which rivals what is achievable with the VLA with typical calibration sources. Scintillations due to irregularities comparable to the Fresnel scale (∼1-2 km at 35 MHz) are characterized by forming TDOA and frequency difference of arrival (FDOA) images (i.e., delay and fringe rate) with each baseline using roughly one hour of data. Intensity variations due to scintillations form a plateau-like artifact in the FDOA direction on these images that is larger in amplitude than the background noise.

The ratio of this plateau to the measure intensity of each source provides a means to estimate the S_4 index, which is the ratio of the standard deviation of the intensity to the mean intensity. This can be converted to the $C_k L$ irregularity index, which is independent of observing geometry and frequency and is proportional to the vertically integrated electron density variance. At low latitudes, $C_k L$ can reach as high as 10^{36} and is measurable with GPS data for which the noise floor corresponds to $\sim 10^{33}$ (Carrano et al. 2019). At mid-latitudes, however, $C_k L$ is

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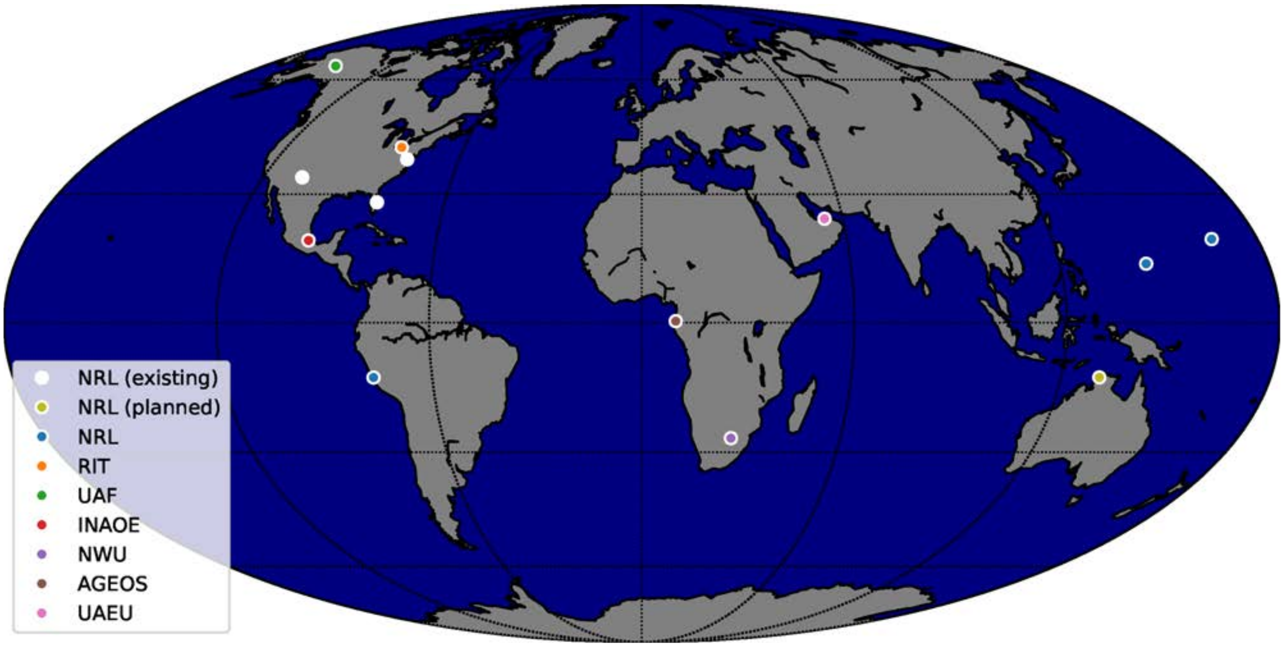

Fig. 4. Locations of DLITE arrays for which funding is being pursued, color-coded by the institutions leading each effort. Within the legend, NRL is the U.S. Naval Research Laboratory; RIT is the Rochester Institute of Technology; UAF is the University of Alaska Fairbanks; INOAE is Mexico's National Institute of Astrophysics, Optics, and Electronics; NWU is the North-West University in South Africa; AGEOS is the Gabonese Agency for Space Studies and Observations; and UAEU is the United Arab Emirates University.

rarely as high as 10^{33}, and the impact of irregularities at these latitudes barely registers within GPS data. DLITE, on the other hand, can measure C_kL as low as around 10^{27} due to the fact that it operates at a much lower frequency (35 MHz versus ∼1500 MHz for GPS).

Examples of this imaging-based analysis are shown in Fig. 3 with images from New Mexico using a ∼420-m east/west baseline shown in the upper panels for 21–22 Nov. 2020 and results from a ∼350-m baseline in Maryland from 22–23 Nov. in the lower panels. The image in the upper right panel shows a relatively strong scintillation event (for mid-latitudes) with $\log_{10} C_kL \simeq 32$ that rendered Cas A completely temporally incoherent as evidence by a very prominent artifact. This is in contrast with the image in the upper left from the day before that shows a very well defined source in the same location. From Maryland, a similarly strong scintillation event was observed the next day on 23 Nov., as can be seen within the lower right panel. Preliminary analysis of GPS-based TEC data and meteorological data imply that these events are related to TIDs that were initiated in the lower/middle atmosphere by a strong distortion in the jet stream, which was near New Mexico on 22 Nov. and which moved to the eastern U.S. by 23 Nov.

The DLITE digital backend consists of software defined radios (SDRs) that are synched to a common reference clock. Each of the four SDRs has two inputs, one for each linear polarization, and are run as a single eight-channel receiver within software written with GNURadio. This software streams complex voltages from the SDRs, channelizes them with fast Fourier transforms (FFTs; nominally with 512 channels), multiplies the results from each of the six baselines together, then averages over a set integration time (nominally ∼1 s). Additional processing is performed per 24 hour data set that flags spurious data from interference that is narrow in time and/or frequency before averaging the data down to one-minute sampling and 64 frequency channels. These visibilities are then analyzed separately for position shifts/TEC gradients and scintillations as described above.

The remaining components of the system are the control/processing computer and a DC power supply and bias-t that supplies power to the antennas' active baluns. The power consumption of the system is a few hundred Watts and is driven almost entirely by the computer. Thus, it can potentially be run with a portable power system such as a solar generator, although this has not been explicitly tested. The current cost of materials is approximately $45k; the labor cost for installation is comparable to this but may vary significantly base on deployment location. These factors imply that DLITE systems can be acquired and deployed by institutions of modest size with relatively small funding grants/commitments. Consequently, as of this writing, research and educational institutions are independently pursing funding for deployments in several locations around the world, summarized in Fig. 4.

4. SUMMARY

We have demonstrated that while low-frequency radio telescopes have produced compelling and unique ionospheric research, the temporal and spatial coverage offered by these systems is limited by several practical concerns. Fortunately, if one focuses on the brightest sources on the sky, a large telescope with dozens if not hundreds of antennas is not needed for high-precision ionospheric measurements. This has been effectively established by the use of the DLITE system for investigations of both km-scale irregularities and medium-scale (∼50–150 km) TIDs (Helmboldt and Zabotin 2022). With this four-dipole interferometer design, an affordable low-frequency telescope can be procured by modestly sized organizations for basic research an education, similar to small optical telescopes the domes of which are visible on may college and even secondary school campuses. Indeed, as Fig. 4 indicates, several such organizations have expressed interest and are actively pursuing funding. As the DLITE user community grows, the ionospheric data products from the network of telescopes will be compiled to construct a truly unique and powerful database of ionospheric disturbances.

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