Ground-based infrastructure for improved space weather specification at low latitudes

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Synopsis

A notional deployment of a heterogeneous network of ground-based instrumentation is proposed. The scientific rationale for the deployment is to gain a comprehensive suite of measurements pertinent to improving our understanding of the longitudinal variability in the equatorial and low-latitude ionosphere/thermosphere system and the irregularities that can exist, therein. By pursuing a distributed ground-based deployment strategy, measurements over a large spatial region at sufficiently high temporal cadence can be achieved. The types of instruments proposed in the notional deployment are well-proven and reliable. It is suggested that significant effort in capacity building and operations would be required to successfully deploy and run such a network.

Background

Much of what is known about equatorial ionospheric physics is based on observations of the incoherent scatter and the MST/coherent radar (JULIA) at Jicamarca, Peru [e.g., *Chau et al.*, 2012]. Jicamarca is located in the American sector, where there is a fairly large excursion between the geomagnetic and geodetic equator due to the dip of the geomagnetic equator. However, equatorial ionospheric phenomena, such as equatorial spread F/equatorial plasma bubbles (EPBs), the equatorial electrojet, the strength of the pre-reversal enhancement (PRE), the dynamo efficiency, and the behavior of thermospheric winds and tides, are all in some way influenced by the regional geomagnetic field, its declination, and the proximity of the magnetic to the geographic equator, all of which vary as a function of longitude.

LEO satellite observations, such as those currently being provided by ICON [e.g., *Immel et al., 2018*), COSMIC-2 [e.g., *Pedatella and Anderson*, 2022], TIMED [e.g., *Christensen et al*, 2003] and Swarm [e.g. Zakharenkova etal, 2016] have been critical in increasing our understanding of equatorial ionospheric dynamics. Through providing global coverage, these observations clearly show that there are large longitudinal differences in ionospheric dynamics and irregularity formation. GEO satellite observations, such as those currently being provided by GOLD [e.g., *Eastes et al.*, 2017], can provide more routine observations of the state of a specific region of the ionosphere, but are limited in the pertinent parameters they can provide. Due to these limitations, satellite observations cannot provide sufficient temporal resolution to fully understand ionospheric dynamics and its potential drivers.

Understanding the physics behind the global distribution of equatorial ionospheric irregularities is becoming critical to our technological systems. In fact, our communication and navigation technologies depend on understanding, modeling, and

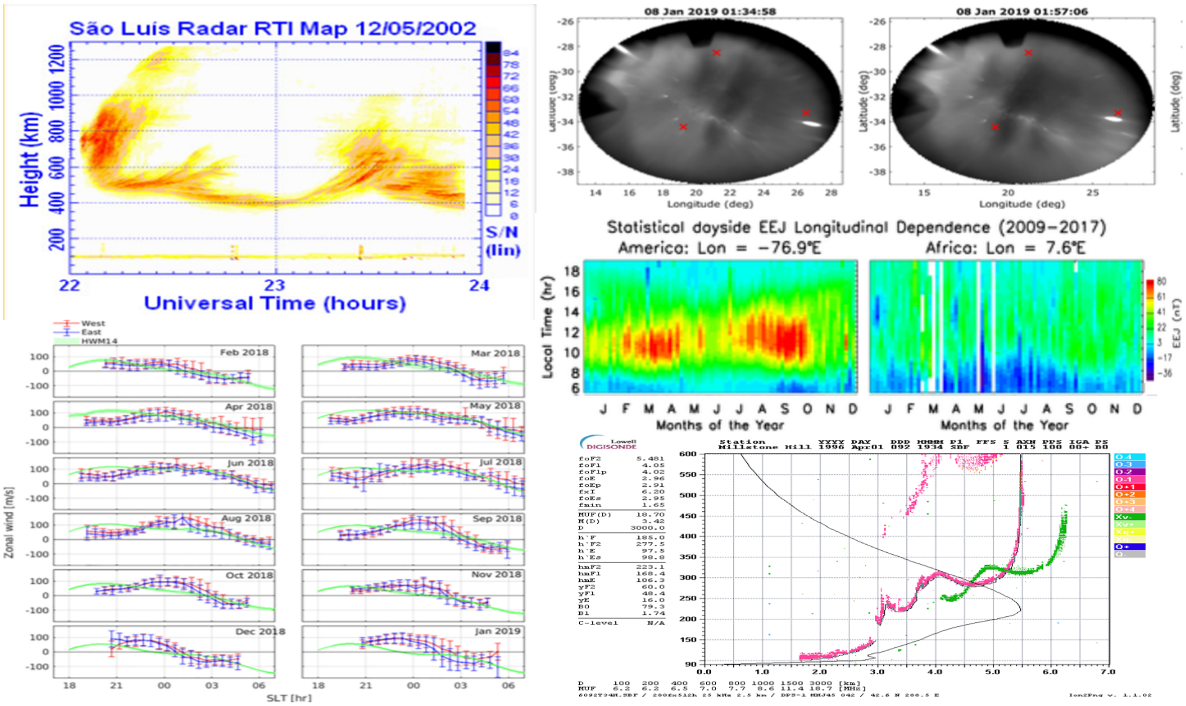

Figure 1. *Typical observation of VHF radar (top left), FPI (bottom left), ASI (top right), Magnetometer (middle right), and ionosonde (bottom right).*

mitigating the effects of these irregularities [*e.g., Doherty et al.*, 2004]. Progress has been hampered by an inability to quantify the necessary physical parameters with the needed temporal resolution over the large spatial-scales at play. ***Addressing this limitation requires a comprehensive, longitudinally-distributed network of ground-based instruments at different longitudes resulting in a greatly enhanced understanding of the global equatorial space weather impacts on our technological systems***.

The equatorial region has the largest tropical landmass area in the world, suitable for deployment of a comprehensive network of instruments capable of improving our understanding of the local time and longitudinal variation of key parameters for space weather applications (winds, plasma density, electrojet/ionospheric currents, scintillations, and gravity wave/traveling ionospheric disturbances). Such a deployment is now possible using a suite of well-established and proven instruments (Fabry-Perot interferometers, ionosondes/ digisondes, high-rate GNSS receivers, magnetometers, 50-MHz VHF radars, and wide-angle imaging systems). The aeronomy community has also developed significant expertise in the deployment and operation of smaller networks of heterogeneous instrumentation, which can be leveraged while expanding to the continental-scale deployment required here to close the gap in existing low-latitude observational capacity. Success of such an endeavor requires, in addition to a significant investment in instrumentation, a commitment to augmenting the community's data infrastructure allowing for wide access to the collected data and ability for it to be ingested into assimilative models. Additionally, it must be recognized that the continued operation of such a network is commensurate with a traditional facility, albeit a distributed one that has the added complexity of needing investments in sustainable international partnerships and capacity building.

The individual instruments described below all provide measurements of certain aspects of equatorial dynamics and irregularity formation, some examples of which are shown in **Figure 1**. The overwhelming advantage of the heterogeneous network approach is that these individual strengths combine to provide a more complete picture of the physics at play, reducing the number of assumptions and/or reliance on models (physics-based, empirical, or otherwise) to provide background parameters (e.g., winds, drifts) during conditions that might be outside of their applicable range (e.g., irregularity formation).

Notional instrument types

Fabry Perot Interferometers (FPI)

Thermospheric winds are a key parameter for understanding the ionosphere. In the equatorial region, the thermospheric zonal wind dynamo is responsible for the pre-reversal enhancement (PRE) [*Heelis et al.*, 2012] as well as the Rayleigh-Taylor (R-T) instability linked to the occurrence of equatorial plasma bubbles (EPBs) [*e.g., Sultan*, 1996]. Plasma bubbles can be very disruptive to critical communication and navigation systems at low latitudes. Hence, understanding the conditions conducive to their occurrence to the point of being able to provide forecasting capabilities is of great importance for space weather research. Because of the strong link between the winds and bubble development, wind observations can provide clues to the longitudinal and seasonal variation of EPBs. While satellite observations can cover all longitudes, they are limited in local time coverage. Ground-based FPI instruments, while individually limited in spatial coverage, can provide extended nightly local time coverage with high temporal resolution.

The difficulty is that FPIs are available only in limited longitudinal sectors (America, Asia, and Africa). A network of FPIs with 1000-km spacing will provide ability to resolve longitudinal variation in the winds due to known non-migrating tides, planetary waves, and beyond.

Ionosondes

The ionosonde remains one of the most reliable and cost-effective instruments to provide bottom side ionosphere information especially in the E and F regions. Some of the most important parameters provided by ionosondes include maximum electron density of the F2 layer along with the corresponding altitude, both of which are useful for HF communication purposes. Thus, ionosonde data is relevant for both real-time space weather monitoring of ionospheric parameters such as critical frequencies of different ionospheric layers [e.g., *Galkin et al., 2022*) as well as contributing to studies of atmospheric gravity waves (AGWs) [e.g., *Klausner et al., 2009*] and data assimilation approaches [e.g., *Galkin et al., 2012, Lin et al., 2015*]. It also remains relevant for empirical specification of the ionosphere ranging from modeling of parameters in different layers [e.g., *Bilitza, 2001*; *Radicella and Leitinger*, 2001] contributing towards electron density specification in three-dimensions when combined with other data sources such as LEO satellites data [e.g., *Gowtam et al., 2019*].

The dynamical and electrodynamical changes in longitude are significant in low latitude regions [*e.g., Yizengaw and Groves, 2018*]. A deployment of ionosondes along the magnetic equator, with spacing of approximately 2000km would allow for characterization of this longitudinal variability throughout the day and night, measuring key parameters needed to understand the development of the PRE and EPBs while also measuring the spreading effect these irregularities have on radio waves.

High-rate GNSS receivers

GNSS measurements are well established for operational monitoring of the Total Electron Content (TEC) of all layers of the ionosphere and the plasmasphere [e.g., *Jakowski*, 2017]. TEC measurements provide valuable information on the dynamics of the ionospheric electron density during storms and can be used to monitor or create models that help mitigate range errors in single frequency GNSS applications. Small-scale ionospheric irregularities at low latitudes associated with EPBs and often related to the Rayleigh-Taylor instability may even cause loss of lock of GNSS signals. Measurements of small-scale irregularities require special high-rate GNSS receivers with sampling frequencies of 50-100 Hz. Required is a systematic deployment of such high-rate GNSS receivers in a coordinated fashion, e.g., together with ionosondes, to utilize the complementary view on ionospheric processes and to derive the equivalent slab thickness of the ionosphere that provides additional information on the shape of electron density profiles [e.g., *Jakowski et al.*, 2017]. A systematic deployment of high-rate GNSS receivers as it has been realized in the MONITOR project in Africa [*Beniguel*, 2019] in recent years is able to contribute to studies of latitudinal/longitudinal and seasonal occurrence of radio scintillations in relation to underlying ionospheric physics [e.g., *Mersha et al.*, 2021], plasma bubble detection [e.g., *Mersha et al.,* 2020] and drifts [e.g., *Kriegel et al.*, 2017]. Deployments should be done with at least three receivers, separated by ~1 km, deployed at a given site to enable EPB drift measurements. An alternative, lower-cost approach to measure drifts with improved sensitivity and accuracy, would be to co-locate dual-channel VHF geostationary beacon receivers with spaced antennas with a single GNSS system [*Wernik, et al*., 1983]. In either case, a broad deployment of high-rate GNSS receivers at low latitudes in the vicinity of the geomagnetic equator would be very effective to better understand ionospheric processes, particularly when coordinated with other ground and space-based facilities.

Magnetometers

Both in-situ and ground-based observations show the global plasma distribution is non-uniform and sometimes exhibits different dynamics at different longitudes. One of the potential reasons for such longitudinal dependence is plasma transport due to vertical drifts that are stronger at the geomagnetic equator and vary as a function of longitude. The lack of observations of the temporally-evolving equatorial vertical drift at multiple longitudes makes it difficult to characterize the global plasma density distribution as a function of local time and longitude. In order to address this, measurements of vertical drift as a function of local time at different longitudes is essential. A reasonably inexpensive technique to determine vertical drift on the dayside as a function of local time and longitudes is through equatorial electrojet (EEJ) estimation using a pair of magnetometers [*Anderson et al.*, 2004], one on the magnetic equator, and one approximately 6-10 degrees off of the magnetic equator.

Augmenting the measurements provided by ionosondes with EEJ measurements from magnetometer pairs spaced approximately 1000-km in longitude will not only provide the longitudinal dependence but also the temporal evolution of the daytime drift. Such a magnetometer networks at the equator can also be utilized to detect the magnetopause origin and solar wind driven ultra-low-frequency (ULF) waves in the Pc5 range that penetrates to the equator [*e.g., Engebretson et al.*, 1988]. This allows the community to characterize the impacts of ULF waves at the low-latitude ionosphere, which is not well understood due to the lack of instrumentation in the region.

VHF radars

In-situ satellite observations show that the equatorial ionospheric irregularities/-bubbles exhibit different depth, strength, duration, and occurrence rate at different longitudes. The lack of observations of the temporal and longitudinal variability of these irregularities hinders the modeling community's ability to fairly capture and predict the global ionospheric dynamics. For example, in-situ observations from different altitudes have shown that EPBs rise to higher altitudes more often than those in the other longitudinal sectors [e.g., *Hei et al.*, 2005].

Deploying 50-MHz backscatter radars at different longitudes (at ~4,000-km spacing in longitude) will provide the height-resolved extension of the bubbles [e.g., *Costa et al.*, 2011] as a function of local time and longitudes as well as other measurements

Table 1: Notional tabulation of instruments needed to provide the necessary data coverage to address the outstanding questions about the local time and longitudinal variability of thermospheric and ionospheric parameters. **Figure 2** shows a notional distribution of this instrumentation. Estimated costs are also provided, totaling approximately $18M. Existing infrastructure could be leveraged to reduce the number of instruments that would be needed to provide the necessary coverage to address the science goals.

	FPI	**GNSS**	**Ionosonde**	**Magnetometer**	**50 MHz VHF Radar**	**Wide-angle imaging**
Africa *(# of instrument / estimated value)*	22 $2.75M	42 $420K	3 $1.05M	10 $200K	2 $600K	77 green; 22 red $2.5M
S. America *(# of instrument / estimated value)*	16 $2.0M	30 $300K	2 $700K	6 $120K	2 $600K	58 green; 16 red $1.85M
Ocean Coverage *(# of instrument / estimated value)*	20 $2.5M		3 $1.05M		2 $600K	20 green; 20 red $1.0M

that will allow the physics of irregularity development and evolution to be better understood. They would also provide observations of the EEJ and 150-km echos on the dayside.

Wide-Angle Imagers

One key parameter potentially contributing to the longitudinal variability of the thermosphere/ionosphere system is the distribution of gravity waves [*e.g., Hecht et al.*, 2009]. These waves can transport energy and momentum both vertically and horizontally and are thought to be a potential seed enhancing the RT growth rate [e.g., *Krall et al.,* 2013] for equatorial irregularities as well as structures occurring at low/mid-latitudes such as medium-scale traveling ionospheric disturbances (MSTIDs) [e.g., *Fukushima et al.*, 2012]. While upcoming satellite missions such as AWE [*Taylor et al.*, 2017] are primed to provide a global view of these waves, a continuous-in-time and broad-spatial specification of wave parameters is required to fully understand their effect on upper atmospheric variability. Observing the same naturally occurring airglow emissions as the FPIs, wind-angle imaging systems can provide local horizon-to-horizon observations of structures in the mesosphere (e.g., gravity waves) and thermosphere (e.g., equatorial plasma bubbles related to scintillations, MSTIDs). Deployments such as THEMIS [*e.g., Nishimura et al.*, 2010], those by the Boston University imaging group [e.g., *Martinis et al.*, 2020], and the MANGO network [e.g., *Kendall and Bhatt*, 2019] all demonstrate the feasibility and strength of deployments of multiple imaging systems leading to enhanced understanding to spatial-temporal variability in the upper atmosphere over large regions.

The fields-of-view of the mesospheric observations are smaller than those in the thermosphere, due to the altitude of the emissions. Thus, to provide full coverage, imagers observing the mesospheric greenline emission require a 500-km spacing while those observing the thermospheric redline emission can be spaced on the order of 1000-km.

Notional Estimated Costs & Schedule

Estimated Costs

To provide the necessary measurements to address the science goals stated above, a nested network of instruments is required. Notional instrument types, costs, and spacing is summarized as:

1) FPI - $125K each needed on a 1000-km grid.
2) Ionosonde - $350K each needed along the magnetic equator at 2000-km spacing.

3) High-rate GNSS receivers - $10K each. Suggested is a triple deployment in a triangle with spacings of a few kilometers, located at stations on and 1000-km off the magnetic equator. Alternately, a VHF beacon system could be co-located with a single GNSS receiver.
4) Magnetometer - $20K each with equatorial/off-equatorial pairs spaced 1000-km spacing in longitude.
5) 50-MHz VHF radar - $300K each with a 4000-km separation in longitude along the magnetic equator.
6) Wide-angle imaging - $25K each (single filter systems) needed on a 500-km (greenline) or 1000-km (redline) grid.

Both Africa and South America provide large landmasses at the magnetic equator, making them prime candidates for instrumentation. Furthermore, the relationship between geomagnetic and geodetic equators are significantly different in these two regions, allowing for studying the importance of competing influences tied to the plasma and neutrals.

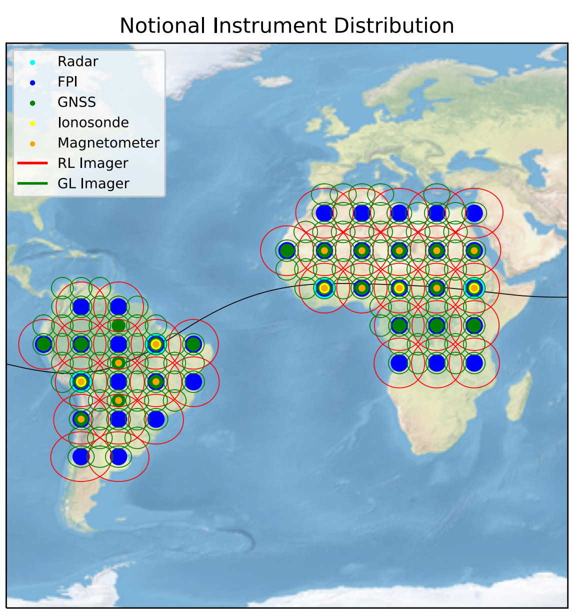

Figure 2: *Notional distribution of instruments on the South American and African continents. Additional instrumentation would be deployed to cover ocean regions.*

For coverage of the oceans, island deployment will not reach the spatial resolution as on land, but will greatly narrow the gap in current coverage and make measurements more evenly distributed. This will help future analysis of tides and planetary systems by reducing aliasing. **Table 1** shows the number of each instrument type that would need to be deployed in a notional configuration, as shown in **Figure 2**, which concentrates on the South American and African continent.

As multiple instrument types can be deployed at individual sites, the total number of sites that would be required is on the order of 80 in Africa and 60 in South America, driven by the number of greenline imagers needed. The ocean deployment is limited by available islands, although deployment in India and Asia/Oceanic region would provide larger landmasses to populate. Existing instrumentation and the realities of finding host locations would be taken into account in any actual deployment.

Robust and low-maintenance imaging systems exist from multiple groups. Similarly, robust and reliable FPI instrument designs exist from multiple groups and can be operated with little intervention for considerable periods of time. However, the inclusion of moving parts (e.g., steerable mirror systems required to point the instrument's field of view in different directions) induces the need for occasional maintenance. Magnetometers exist from several vendors/research groups and have been shown to be relatively easily maintained with a little bit of training.

In contrast, the 50-MHz VHF radars and ionosondes both require significant infrastructure and support, including a larger power-budget, the need to acquire licensing to support the ability to transmit, and the regular support of a local technician to operate and maintain the instrument.

Deployment costs (e.g., shipping, insurance) would be considerable, but significantly less costly than other means of gaining coverage over large spatial distances (e.g., satellite launches).

Estimated Schedule

Highly-capable examples of the types of instruments that would need to be deployed are well-established through multiple groups within the aeronomy community. Thus, minimal instrumentation development would need to be undertaken. However, the instruments still do not consist entirely of off-the-shelf parts, and procurement of several components, especially at the scale required to accomplish the deployment goals of an ambitious project such as this, is expected to take on the order of two years. Integration and testing of each instrument is generally well understood and not expected to add significantly to a deployment schedule.

Operation of such an extensive network in many countries around the world would necessitate significant capacity building, requiring investment at the onset of the project to identify potential collaborators and hosts for instruments. Although there are existing partnerships that can be leveraged, many new ones will need to be forged. A successful project of this magnitude would significantly benefit from agency to agency international collaboration (e.g., between agencies such as NSF and NASA and their counterparts around the world) and the involvement of international organizations such as the United Nations, as was begun over ten years ago through the International Space Weather Initiative (ISWI). The involvement of local agencies from an early stage is also important for reducing the complexities and cost of importation of equipment.

A schedule for deployment must include not only the time to build the individual instruments and get them in the field, but the time to develop and train collaborators. The Aeronomy and Space Weather communities have extensive experience in running summer schools (e.g., the NSF-sponsored Incoherent Radar Summer schools organized by MIT and SRI) and other capacity-building workshops (e.g., those run under the auspices of the United Nations Basic Space Science Initiative and ISWI), typically undertaken in partnership with local government institutions and universities, which could be run in parallel to instrument building.

One of the challenges that has been faced in previous deployments of similar instrumentation is the longevity of local support for operations, and consideration needs to be given for permanent/long-term staffing to maintain operations. A potential model would involve developing and supporting regional hubs of technicians that can support the operational and maintenance needs of multiple sites, including both instrumentation and data infrastructure needs. Operational costs would therefore involve support for this technical staff in addition to the infrastructural support (electricity, data transport, maintenance, repair/replacement costs) typical of single-PI driven deployments.

Technology Development Needs

Two anticipated challenges that would need to be addressed are the ability to power the deployed instruments and reliably transport the data back for processing, integration into modeling efforts, and distribution to the wider community through existing data repositories. Outside of the active RF instruments (50-MHz radar and ionosondes), the other instruments are low power and could likely be run using a solar/battery system. Data transport through cellular or satellite (e.g., Starlink) networks is feasible, if local infrastructure can support it.

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