Infrastructure needs on latitudinal and longitudinal chains of co-located ground-based observations

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Synopsis

The generation, propagation, and dissipation of atmospheric planetary waves (PW), tides, and gravity waves (GW) constitute the primary mechanism that transfers energy and momentum from the atmosphere to space. While single-location ground-based observations have been making successful measurements of such waves over the past decades, NSF funded ground-based observations are not yet systematically distributed at the same latitude or the same longitude, despite the importance of latitudinal and longitudinal dependence of dynamical processes like large scale wave propagation, interaction, and dissipation. This white paper discusses the significance and potential of coordinating a chain of ground-based instruments with the current large facilities to extend the latitudinal and longitudinal observational coverage in the American sector (both South and North America). We further discuss the benefits of co-locating heterogeneous instruments with different techniques and different temporal/spatial resolution/coverage, for instance, radio instruments (e.g., ISR, HF radar, meteor radar), optical instruments (e.g., FPI, lidar, airglow imager), magnetometers, ionosondes, sounding rockets and so on.

Key points

1. **Build west-east dual hemisphere observational capability that connects the North American, European, and Asian longitudinal sectors.**
2. **Build north-south dual hemisphere observational capability from the north pole to the south pole in the American longitudinal sector.**
3. **Develop and deploy the next-generation ground-based instruments, and co-locate heterogeneous small instruments with large facilities.**

1. Scientific Motivations and Challenges

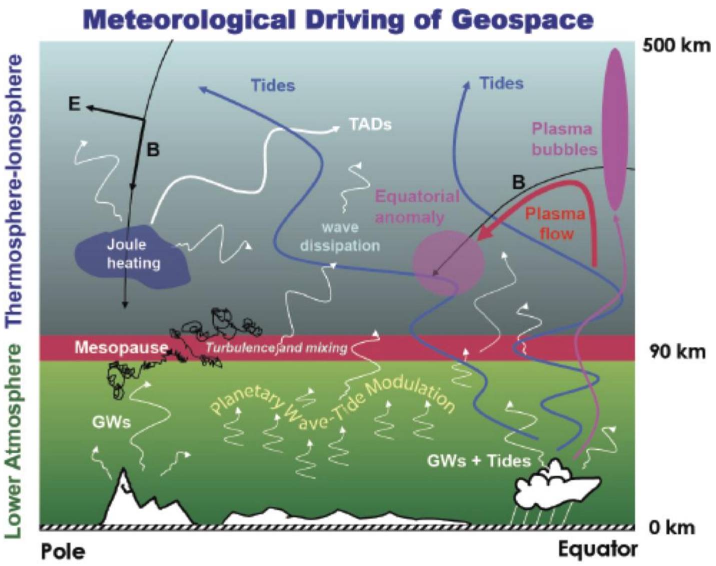

Figure 1. Schematic of the various mechanisms through which lower-atmosphere processes influence the ionosphere and thermosphere. Courtesy: Jeffrey M. Forbes, University of Colorado, Boulder, and David Fritts, GATS/Boulder. (Heliophysics Decadal Survey, 2013, Figure 8.10)

As a transition region between the stratosphere and space, the mesosphere and lower thermosphere (MLT) region links terrestrial weather and space weather. Wave activities play critical roles in energy and momentum transfer from the atmosphere to space, and cause considerable geospace irregularities at this region, as shown in Figure 1. Local measurements of MLT waves have been successfully made by single-location ground-based instruments over the past decades. However, it is critical to further understand the latitudinal and longitudinal dependence of wave activities. A chain of instruments distributed at the same latitude or longitude can provide continuous observations of physical processes across all scales, not only local but also regional and global scales. With the advancement of modern technology and commercialization of next-generation techniques and instruments, it is now feasible to deploy a chain of instruments that connect the (South and North) American longitudinal sector from the south pole to the north pole, as well as connect the North American, European, and Asian longitudinal sectors at the same latitude.

In conjunction with the spaceborne observations, particularly the ongoing GOLD and ICON missions and the upcoming AWE, GDC, and DYNAMIC missions, ground-based instrument chains/networks provide complementary global observational capabilities. For example, the existence of large-scale GW features (e.g., concentric rings) at the airglow layer have been reported by satellite observations but the fast temporal evolution (on the order of a few minutes to tens of minutes) of such waves was not captured. A ground-based airglow imager network with adjacent coverage areas is the only approach to observe such features and their evolution over time. On the other hand, heterogeneous small instruments co-located with large facilities (e.g., ISRs) contribute to provide a comprehensive vertical coverage of multiple parameters that is critical for further advances in geospace research. A chain of ground-based observations would also provide important cross references for spaceborne observations, with an emphasis on long-term temporal coverage and high temporal resolution of the MLT/IT measurements.

In order to improve the capability of monitoring and forecasting space weather phenomena using the state-of-the-art general circulation models (GCMs), global observational data are needed for data assimilation to constrain the model state observationally. For example, NAVGEM-HA assimilates MLT wind inputs observed by meteor radars. Such observational constraint is critical for accurately representing the MLT dynamics, which subsequently influence the ionosphere (McDonald et al., 2015; Sassi et al, 2021). In addition, Aa et al. (2022) indicates that three-dimensional storm-enhanced electron density features could be reproduced after GNSS, COSMIC, Jason and Millstone Hill ISR observations are assimilated in a self-consistent manner. However, there is often a problem when comparing the state-of-the-art ground-based observations with the GCMs due to the very different spatial resolutions between GCM outputs and ground-based observational data. A chain of observations consisting of several locations at the same latitude or longitude will help to solve the resolution gap problem, by simply matching more geographic grid points on GCM simulations, as well as making the observational uncertainties more consistent and robust.

It is scientifically important to develop a chain of instrumentations that co-locates instruments across different infrastructure categories. Large facilities (e.g., ISRs, current and proposed) and distributed networks (i.e., current networks like SuperDARN, SuperMAG, and MANGO; proposed chains/networks of next-generation maintenance-free meteor radars, airglow imagers, resonance lidars, etc.) provide observational datasets of highly complementary physical parameters (temperature, wind, density, ion motion, airglow emission, etc.) with different spatial coverages and vertical resolutions, which in combination provide valuable observational insights into atmosphere-ionosphere vertical coupling processes. For example, the connection between the formation/suppression of ionospheric irregularities and the generation/suppression of the equatorial ionization anomaly (EIA) is probably related to the enhancement of quasi-stationary planetary waves. However, simultaneous observations that capture the whole coupling process from the stratosphere to ionosphere are required to confirm this connection and to investigate the coupling mechanisms (Goncharenko et al., 2011, White Paper for Heliophysics Decadal Survey).

2. Example of a Chain of Observations, Proposed Chain of Observations and Anticipated Outcomes

2.1 Example of a Chain of Observations

One successful example of chains of observations is the Chinese Meridian Project (CMP), which consists of a ground-based instrument array (with four chains) monitoring the space weather environment and constructed in two phases. After Phase I, 15 observation stations were located along 120°E longitude and 30°N latitude (two yellow chains shown in Figure 2(a)). Phase II will additionally deploy 16 stations, with two more chains (red bands shown in Figure 2(a)) established along 100°E longitude and 40°N latitude, forming a double-cross network configuration (Wang et al., 2020; Liu et al., 2021).

Such chains of observations were fundamental components leading to successful international collaborations to address scientific questions like PW propagation. For example, He et al. (2018, 2019, 2021) analyzed data from paired meteor radars (two stations located at the same latitude) to diagnose zonal structures of tides and Rossby planetary waves. Such pairs of meteor radars used in those studies, particularly the midlatitude pair at Juliusruh (Germany, 54.6ºN, 13.4ºE) and Mohe (China, 53.5ºN, 122.5ºE), could possibly be extended to the North American longitudinal sector (e.g., in Saskatchewan, CA, 53.5ºN) and provide east-west dual hemispheric observational coverage. Similarly, by adding ground-based observations along the 30ºN or 40ºN latitude chain in the US (e.g., Boulder, CO or State College, PA at 40ºN chain; Gainesville, FL or San Antonio, TX at 30ºN chain), dual hemisphere observational capability could also be provided as a combination with the CMP double-cross network configuration.

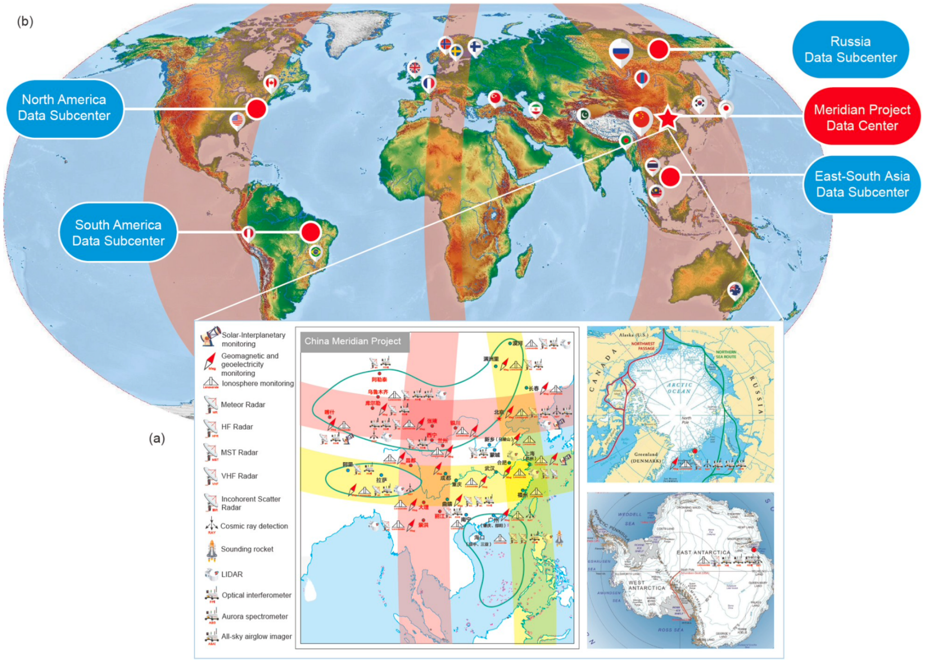

Figure 2. Schematic illustrating the Chinese Meridian Project (CMP) (Liu et al., 2021). (a) CMP as a combination of low-cost instrument arrays and facility-class instruments; (b) the world-wide network of IMCP instruments along the two optimal great circles identified from the Science Case.

2.2 Proposed Chain of Observations

Two major steps are required for a successful development of the proposed chain of observations: 1) upgrade of current facilities, and 2) development/deployment of the next generation ground-based instruments along the same latitude/longitude with the existing facilities. Feasibility of deploying a chain of observations is advanced. Benefited by the development of modern technology, more scientific goals can be achieved with less cost and uncertainty. For instance, various practical techniques of next-generation instruments are now available, and the cost could be potentially limited by the commercialization of certain hardwares (e.g., CMOS cameras), or commercial companies (e.g., meteor radar companies). Some examples of the solutions are listed as below:

a. Upgrade current facilities & develop the next-generation ISR facilities: Currently existing ISR systems represent a significant long-term investment that is the most complex and expensive component of ground-based research infrastructure. These radars provide observations of multiple ionospheric parameters in a large range of altitudes, enabling unique studies of lower to upper atmosphere coupling. Every radar site also includes a cluster of instruments (ionosondes, FPIs, magnetometers), multiplying its diagnostic power for a variety of research topics. Each radar site is located in a unique geophysical location (Jicamarca, Millstone Hill, PFISR, RISR, EISCAT), which is crucial to understanding the ionosphere in a system science context. We recommend further investments in incoherent scatter radar capabilities and infrastructure with the goal to modernize, improve sensitivity, and enable operations of instruments for longer periods of time to address a wider variety of cutting-edge scientific topics.

All current ISR facilities operate in a narrow range of transmit and receive frequencies, which means they are only capable of probing the plasma with a small range of k-vectors. Since the shape of the ISR spectrum is different at different k-vectors, it would be useful for the next-generation ISR facility to have the capability to probe the plasma with large k-vector diversity. Such a facility would enable us to unambiguously measure the ion-neutral collision frequency and make independent observations of electron temperature using plasma lines. It would also likely help us better study nonlinear plasma processes (Ashton Reimer, 2021, ISR tutorial at CEDAR student workshop).

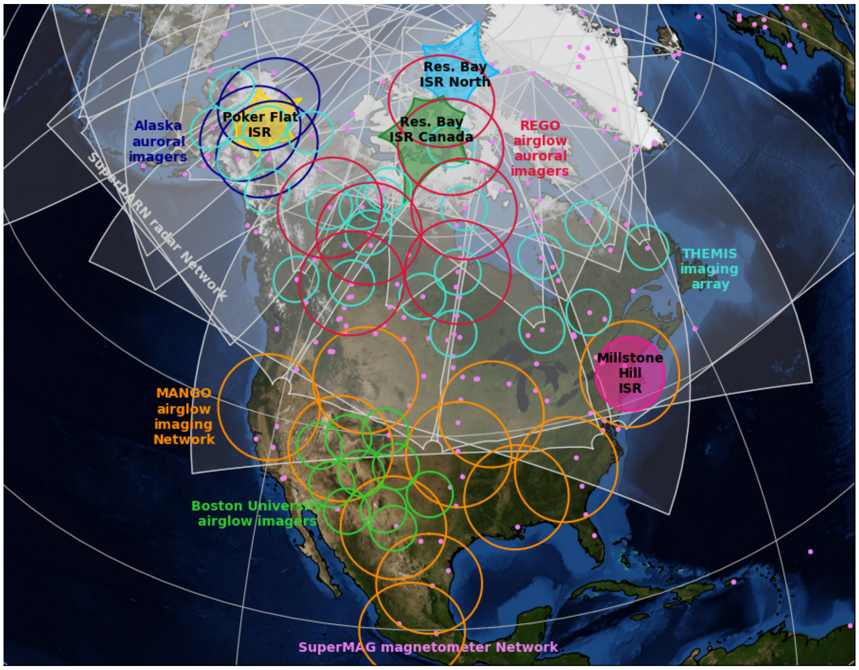

Figure 3. A map showing fields-of-view of currently operational diverse ground-based geospace instruments in North America supported by NSF. These instruments measure ionospheric irregularities, airglow and auroral emissions, and precise ionospheric parameters like electron density and temperature. Courtesy: Leslie Lamarche, SRI International, USA.

b. Deploy a chain of the next-generation meteor radars: Modern multistatic specular meteor radars (e.g., MMRIA-Norway, 70ºN; MMRIA-Germany, 50ºN; SIMONe-Peru, 6ºS, 12ºS; CONDOR, Chile, 30ºS; SIMONe-Argentina, 50ºS) contribute to studies of the mesoscale dynamics using not only the first-order dynamics (i.e., wind fields) but also the second-order dynamics (e.g., correlation or structure functions) (e.g., Stober and Chau, 2015, Chau et al., 2019, Volz et al., 2021, Vierinen et al., 2019).

Specifically, state-of-the-art commercial meteor radar networks such as CONDOR, the Nordic Meteor Radar Cluster, or the Patagonia Antarctica meteor radar cluster enable investigations of the spatial and temporal patterns in wind by applying tomographic algorithms such as the 3DVAR or 3DVAR+DIV (Stober et al., 2018, Stober et al., 2021, Stober et al., 2022). Furthermore, with a combination of typical meteor radars, these radar clusters provide valuable insights about the large scale spatial variability of momentum fluxes and gravity wave variances (sometimes termed second order statistics), the propagation of large-scale waves, the latitudinal dependence of atmospheric tides, and the atmospheric vertical coupling events such as sudden stratospheric warmings (e.g., De Wit et al., 2016 de Wit et al., 2017, He et al., 2021, Stober et al., 2021b, Liu et al., 2020, Liu et al., 2022). Nevertheless, such studies would be further advanced by deploying more meteor radars at the same latitude/longitude chain. Commercial companies such as ATRAD Ltd. (Holdsworth et al., 2004) and Genesis Ltd. (Hocking et al., 2001) could contribute to the successful deployment of such modern meteor radar networks.

c. Deploy a network of **cost-efficient** OH airglow imager (peaks at ~87 km): As shown in Figure 3, networks of auroral airglow imager have been deployed for auroral, streamers, and substorms studies at polar region: THEMIS whitelight imaging array, REGO imaging system, and Alaska auroral imagers observes the aurora over the Northern American continent from Canada to Alaska, which contributes to determine the auroral substorm onset (Donovan et al., 2006; Mende et al., 2009; Liang et al, 2016). In addition, networks of 630 nm redline atomic oxygen airglow imagers (peaks at ~250-300 km) have been deployed by MANGO and the Boston University airglow imagers (Martinis et al., 2018). Besides, a network of 557.7 nm greenline atomic oxygen airglow imagers (peaks at ~97km) is included in MANGO's deployment plan.

   While the networks of whitelight auroral substorm imagers and greenline/redline atomic oxygen airglow imagers have been deployed or scheduled, a network of infrared OH airglow imagers (peaks at ~87 km) is still lacking. The OH airglow layer which peaks around the mesopause region features the MLT response of various atmospheric disturbances, for example, the gravity waves induced by thunderstorms and typhoons (e.g., Xu et al., 2021; Suzuki et al., 2013(b)). Since the FOV of all-sky imagers is smaller at the lower latitude, a large number of OH imagers is required to cover the entire contiguous US, which made it cost-concerned for deploying a network of traditional OH imagers (cost estimate $100K for one set). However, benefited by the broad application and popularity of commercial astrophotography cameras, studies have indicated that a network of 700 nm-900 nm broadband OH airglow imagers could be deployed at a very low cost (e.g., Suzuki et al., 2013(b)), compared to the usage of traditional scientific cameras (e.g., the expensive Hamamatsu CCD camera). For example, the cost estimate of one compact set of OH imager hardware is lower than $2,000, with the ZWO ASI180MM Pro CMOS camera ($800), fast fisheye lens ($500), IR highpass filter ($100), Raspberry Pi computer assuring autorun and remote access ($200), and some other utilities. Thus, roughly 107 imagers could combine to form a network that covers the entire contiguous US while using the central region of the FOV (120º) to control the circular distortion at the edges, as shown in Figure 4 (b) (not including Hawaii and Alaska), and the whole cost estimate is less than $2 million.

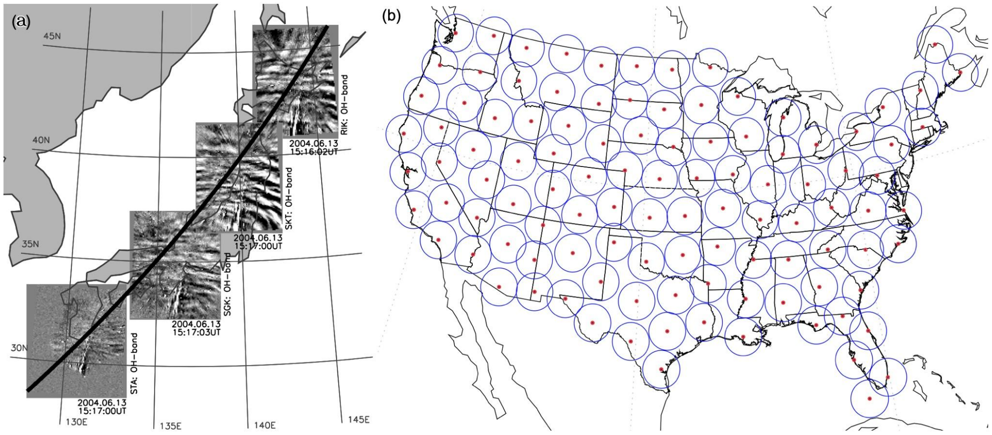

Figure 4. (a) Japanese low-cost OH airglow imager network. From Suzuki et al. (2013 b), Figure 2(a); (b) Illustration of the distribution of low-cost OH airglow imager network at 120º FOV that covers the US.

d. Consider adding multiple next-generation instruments at the poles: Next-generation radiometers such as TEMPERA and TEMPERA-C could provide continuous and nearly weather-independent temperature soundings up to the MLT; the WIRA instrument observes stratospheric and mesospheric winds; and the next-generation ozone and water vapor observations assess the strength of the upwelling and downwelling within the polar vortex (e.g., Krochin et al., 2022a, Hagen et al., 2018, Schranz et al., 2019). Furthermore, the new TEMPERA-C radiometer is going to measure changes in the mesospheric magnetic field leveraging the Zeeman effect (Krochin et al., 2022b). These instruments advance studies such as the characterization of the mesospheric polar vortex (Harvey et al., 2022, White Paper for Heliophysics Decadal Survey).

In summary, we recommend building dual hemisphere observational capabilities: from East to West, from North to South

- Build a latitudinal chain connecting the North American sector to the European and the Asian Sectors, with a scientific motivation on investigating longitudinal dependence of MLT/IT variations.
- Build a longitudinal chain connecting the North American sector to the South America sector, with an emphasis on connecting current facilities and networks to poles for characterizing the mesospheric polex vortex (Harvey et al., 2022, White Paper for Heliophysics Decadal Survey).

2.3 Anticipated Outcomes

The global coverage enabled by a chain of observations will not only contribute to atmospheric and ionospheric vertical and interhemispheric coupling studies by providing observational insights across a broad latitude and longitude range (e.g., Lieberman et al., 2021; Heale et al., 2019; Martinis et al., 2010; Harvey et al., 2022 White Paper), but also offer valuable datasets for data assimilation and cross references for GCM simulations and satellite observations. By deploying latitudinal and longitudinal chains of ground-based observations in the American Sector, a database of MLT winds and temperature for climatological means, as well as the day-to-day variability due to atmospheric waves could be provided for validation of GCMs, as well for data assimilation. Accessibility to long-term climatological observations enables the further investigations on the MLT long-term trend, climate change, and space weather impact on the earth's AIM system over solar cycles. These questions could be better understood by comparing observations with long-term runs of GCMs or climate models. Ground-based stations in conjunction with satellites, especially with the upcoming AWE, GDC, and DYNAMIC missions, will provide important cross references of observations with much longer and stable temporal coverage, which benefits challenging studies like large scale fast wave evaluations.

Tremendous training and job opportunities for the future generation of scientists and engineers could be provided by the development and deployment of next-generation instruments. By involving in the hands-on work of deploying a chain of instrumentation, monitoring, and data management, undergraduate and graduate students could easily step into the field and integrate their work into scientific projects, following the path of instrument deployment, data acquisition and processing, and scientific goal achievement. These STEM skills are highly transferable to either academic or industry environments, and the development of ground-based instrumentations needs to be seen as a practical and highly scalable component of training future STEM workforce. Some small maintenance-free instruments could even be distributed in local high schools (e.g., distribution of OH airglow imagers shown in Figure 4(b)), for the purpose of inspiring and advocating scientific interests among high school students, and enriching the general public awareness of space sciences. Meanwhile, several conditions provided by high schools including but not limited to the robust electric and internet access as well as the relatively low light pollution in the nighttime bring a win-win solution for the compact low-cost optical instruments. Nevertheless, training and job opportunities including both short-term programs (for example, ISR summer schools, future chains of observation workshops) and longer-term early career opportunities (for example, post-bachelor 'gap year' employment opportunities, specifically designated graduate student grants, focused post-doc opportunities, etc.) could be provided by the deployment of chains of observations.

3. Recommendations

It is recommended that the report of the Decadal Survey includes language that:

a. Solicits instrumentation proposals to deploy chains of observations that crosses east-west or south-north dual hemispheres.
b. Encourages international collaboration to build dual hemispheric observational capabilities.
c. Solicits studies on (i) understanding AIM interhemispheric dynamics, atmospheric vertical coupling processes, etc; (ii) data assimilation and cross references for GCM simulations and satellite observations using ground-based chains of observations.

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