WORKSHOP REPORT

A Strategic Vision for Incoherent Scatter Radar

FACILITIES FOR THE 21ST CENTURY

April 26–28, 2021

http://landau.geo.cornell.edu/workshop.pdf

Contents

Executive summary

A virtual workshop was held April 26–28, 2021, to consider the future of the geospace facilities program. The workshop was designed to identify priority science questions and investigations that would compel investment in one or more new incoherent scatter radar (ISR-class) facilities. Ten science priorities spanning different geophysical regimes in geospace were identified and are described in this report:

1. Cross-scale coupling
2. Data assimilation
3. Space weather
4. Neutral/plasma coupling
5. Mesospheric and lower thermospheric instabilities and mesoscale dynamics
6. Meteor science
7. Energetics, dynamics, transport
8. Planetary radar
9. Plasmaspheric radar
10. Solar echoes

Three cross-cutting themes also arose throughout the workshop. The themes pertain to the importance of (1) exploiting emerging technologies in facility design, (2) involving and leveraging knowledge from adjacent science communities, and (3) incorporating workforce training and development, along with international collaboration, in any new facility undertaking.

Two findings that are closely related to these themes emerged from the workshop and the science priorities that came forward:

1 The community should undertake the development of a new geospace facility, a geospace radar, following in the footsteps of contemporary, worldwide developments in radio astronomy and radar techniques.

11 It is imperative to train the next generation of scientists and engineers to take over ISR research and technology as an integral part of any next-generation facility.

The findings will be conveyed to the next Decadal Survey in Solar and Space Physics, along with the outlines of a NSF midscale mission concept inspired by them.

Background

Representatives of the AGS geospace facilities were charged by Carrie Black, then NSF program director for the facilities, to convene a workshop to help plan the future of the program in December 2018. A committee was formed at that time, including Anthea Coster and Philip Erickson (MIT Haystack Observatory), David Hysell (Cornell University), Elizabeth Kendall (University of Central Florida), and Roger Varney (SRI International), and workshop planning commenced. The original idea was to hold an in-person workshop at Cornell University in Ithaca, NY, in March 2020. A program was assembled, speakers and audience members were invited, and all the logistical arrangements for the workshop were made. Regrettably, that workshop had to be cancelled due to the COVID 19 crisis, which was just emerging. While the committee continued to seek opportunities for an in-person workshop, ultimately a virtual workshop was planned and conducted from April 26–28, 2021. The workshop was advertised widely using community mailing lists, and final workshop planning was conducted with input from the AGS section head and facilities director. Workshop attendance was consistently above 100 persons throughout the event. A total of 186 people attended the workshop from 79 institutions.

The workshop program can be found at http://landau.geo.cornell.edu/workshop.pdf.

Following the workshop, this report was written by the organizing committee and reviewed and vetted by the ten workshop session leads, who also helped with workshop coordination and moderation. The session leads are named in the workshop program linked above, which is part of this report.

Workshop charge

The committee was charged with organizing and holding a community-wide workshop to address the future of the AGS Geospace Facilities Program. Specifically, the committee was charged with identifying and prioritizing science questions that compel new investment in the geospace facilities. The emphasis of the workshop was to be on scientific questions rather than on new technologies and methods, although some discussion of the latter was seen as being inevitable. The intent of the workshop was not to entertain proposals for specific facilities or locations.

The workshop was designed to produce three products. The first is this report, which will be delivered to the Geospace Section leadership. The second is a whitepaper to be delivered to the NASEM Decadal Survey. The whitepaper will recommend investments in the Geospace Facilities Program consistent with the findings of the workshop report, along with additional community input sought by the committee. Finally, it is expected that one or more proposals to the National Science Foundation and other agencies for support to develop and ultimately actualize a facilities concept will be forthcoming from the community.

Audience

This report was written by the workshop organizers and lead speakers who assisted with workshop coordination. The intended audience is the workshop participants, the broader geospace science community, and the leadership in the Geospace Section of the AGS Division of the National Science Foundation, who commissioned the report and the workshop. The report’s findings will be conveyed to the next Decadal Survey in Solar and Space Physics and should be used to inform subsequent proposals for the creation of new facilities.

Science priorities

In this section are the science priorities that arose from the workshop discussions. These are not specific to any one geophysical region or phenomenon but instead apply to multiple lines of investigation spanning all latitudes and altitudes in geospace. Many of these priorities are couched in terms of the present-day capabilities of the geospace facilities and the limitations they pose on our understanding. Progress in these areas will be contingent on the development of better research tools, including facility-level instruments.

1. Cross-scale coupling

The ionosphere exhibits phenomena across orders of magnitudes of different scales in space and time, and the understanding of couplings between processes at different scales remains a major imperative for the community. The science discussions at the workshop repeatedly emphasized the potential for radar facilities to probe a wide variety of processes operating at different scales. For the purposes of this description, we will divide the phenomena between global scales (1,000–10,000 km), mesoscales (100–1,000 km), small scales (1–100 km), scintillation scales (100 m – 1 km), fine scales (10–100 m), and microscales (10 cm–10 m). No physics-based model can describe processes across all of these scales, and development of sub-grid parameterizations is required to model the real ionosphere. IS radars have a significant history of major contributions to studies of different scales, and facilities of the future could transform understanding of cross-scale coupling.

Global scales

IS radars have allowed us to monitor the coupled M-I-T system with high temporal and altitude resolutions that cannot be provided by space-based observations. Regarding remote sensing of geospace dynamics, highlighted topics of intense community interest included global magnetospheric and ionospheric convection driven by reconnection, viscous interaction, boundary layer diffusion, ring current dynamics, Birkeland region 1 and region 2 field-aligned current drivers of convection electric field, conductivity spatial variations, synoptic electric field mapping between the ionosphere and magnetosphere, and heavy, cold ion outflows providing significant mass loading of the magnetosphere. IS radars are singularly capable diagnostic tools for all of these subjects, with spatial location distinguishing the topics that can be addressed.

IS radar observations in the dayside subauroral zone target storm enhanced density (SED) formation and thermodynamics, interactions between plasma flows and thermospheric wind, and ring current electrodynamic feedback creating such features as sub-auroral polarization streams (SAPS) [Foster and Burke, 2002; Aa et al., 2020], intense narrow subauroral ion drifts (SAID) with rapid temporal lifetimes [Erickson et al., 2002], and MSTID/LSTIDs [Zhang et al., 2019]. For example, Millstone Hill has shown the importance of severe neutral wind intensification and vortex initiation at mid latitudes under strong forcing from ~km/s SAPS flows [Zhang et al., 2015; Guo et al., 2018], but it is not yet clear what the relevant strength of ion drag and Coriolis forcing is [Guo et al., 2018; Ferdousi et al., 2019]. Strong correlations between SAPS and TIDs have been identified with ISR and GNSS TEC [Zhang et al., 2019]; however, mechanisms for observed direct midlatitude MSTID alteration of equatorward LSTID propagation are not understood, yet are important scientifically and for space weather progress. IS radar profiles also are powerful tools for investigations of magnetic conjugacy efficiency and interhemispheric asymmetries in mid-latitude response at a wide range of scale sizes.

Cusp region IS radar observations directly address ionospheric response to solar wind shock compression including ion upflow, Joule heating, rapid flow variations, and two-way ionosphere-magnetosphere feedback. Examples include PFISR measurements which employed altitude and spatial diagnostics to study enhanced ionization with NOAA POES electron and proton flux quantification, localizing substorms within the overall geospace system [Zou et al., 2009]. Studies of upflow and mass transport out of the ionosphere into the magnetosphere also rely on IS radar's altitude-dependent parameter information in order to quantify upflow dynamics. For example, EISCAT Svalbard has provided statistical pictures of cusp mass flux [Ogawa et al., 2003], and PFISR has been used to statistically reveal the ion upflow and downflow characteristics in the subauroral and auroral zone controlled by solar and geomagnetic activities [Ren et al., 2020]. Even transient ion upflow excited by interplanetary shock can be captured by ISR [Zou et al., 2017].

Direct probing of inner magnetospheric boundaries (where cold plasma populations interact with energetic particles), specifically within the turbulent plasmasphere boundary layer [Carpenter and Lemaire, 2004] tightly coupled to ionospheric SED regions [Foster et al., 2002], is possible with sufficiently large IS radar systems at a range of low to mid latitudes. This would allow plasmasphere characterization to occur in unique and highly complementary ways to in-situ probes.

Mesoscales

The coupling between global-scale phenomena and mesoscale processes has been a highly active area of research, with studies on the roles of mesoscale flows [Lyons et al., 2016; Gabrielse et al., 2018], polar cap patches [Ren et al., 2018], storm-enhanced density structures [Zou et al., 2014], and traveling ionospheric disturbances [Nicolls et al., 2004]. The existing AMISR systems can reasonably image structures between 50 and 300 km, which has allowed detailed studies of critical structures, such as Harang reversal [Zou et al., 2009], flow channels [Lyons et al., 2011], and polar cap patches [Dahlgren et al., 2012]. Furthermore, the combined fields of view of the RISR-N and RISR-C radars allows tracking polar cap patches from their creation in the cusp to the polar cap [Nishimura et al., 2021]. Nonetheless, the discussion in the workshop highlighted a coverage gap in scales above 300 km and below the scales sampled by missions with global coverage (e.g. the longitudinal spacing of AMPERE is ~3000 km). The workshop discussion suggested that imaging areas as large as 1000 x 1000 km or larger could have a transformational impact on our understanding of the processes mediated by mesoscale features. 1000 km is the typical latitudinal width of the auroral oval, so imaging an area this large would allow detailed studies of processes connecting the poleward and equatorward edges of the oval and thus remotely sensing the magnetotail dynamics from the distant tail to the inner magnetosphere region. 1000 x 1000 km is also comparable to the field of view of an all-sky imager, which would allow much more close use of optical and radar techniques together. By comparison, PFISR only covers a fraction of the field of view of the Poker Flat all-sky imager. The workshop also highlighted the value of being able to track the evolution of structures in the Lagrangian frame of reference moving with the plasma, and a larger field of view is needed to observe a significant portion of the evolution. For example, typical timescales for the acceleration of ion upflow are on the order of 5–15 minutes, during which time a flux tube convecting at 500–1000 m/s will move 150–900 km horizontally.

Small scales, scintillation scales, and plasma instabilities

The ionosphere is prone to a variety of plasma instabilities, and the irregularities created by these instabilities have significant impacts on radio propagation. Of particular operational interest are the Fresnel scales of L-band signals used for GNSS, which are on the order of 100 m. GNSS systems are impacted by variable refraction of the signal associated with small-scale (1–100 km) gradients in electron density, as well as diffraction of the signal by the Fresnel scale structures. Modern multi-frequency GNSS receivers can compensate for many of the refractive effects, but the diffractive effects remain extremely challenging for receivers to mitigate [e.g., McCaffrey and Jayachandran, 2019]. The Fresnel-scale structures are associated with instabilities that cascade from larger scales. The largest uncertainties with the numerical simulations of these instabilities are the initial gradients and shears at ~10 km scales (e.g., Deshpande and Zettergren, 2019; Spicher et al., 2020). If radar facilities of the future could provide more information on small scales (1 - 100 km), that could transform the understanding of the cascades from small scales to the scintillation scales. Theoretical studies also suggest that additional physical processes become important for instability dynamics at the smallest scales (e.g., Gondarenko et al., 1999). For example, simulations including ion inertia suggest that inertial effects can be safely neglected above 1 km scales, but they significantly impact the evolution of plasma irregularities below 1 km scales. Experimental techniques that can directly probe these scales, such as using interferometric imaging within the radar beam, could test theories of the physics in these regimes that are fundamentally different from the larger scales.

Fine scales and microscales

Kinetic instabilities in the ionosphere mediate a variety of plasma waves at fine scales and microscales, and the large-scale ramifications of the energy dissipation at these very small scales is poorly understood. Radars can observe the effects of unstable plasma waves indirectly through their electron heating. This is particularly true for the Farley-Buneman instability, where IS radars routinely observe E-region electron temperature enhancements associated with the instability [Makarevich et al., 2013; St. Maurice and Goodwin, 2021]. Both the anomalous mobilities and heating effects on recombination in these heated layers are thought to have nonlinear effects on E-region conductivity, and therefore consequences for the global-scale magnetosphere-ionosphere coupling [Oppenheim and Dimant, 2013; Liu et al., 2016]. Radars can also directly observe unstable plasma waves directly by Bragg scattering from the waves. Bragg scattering is highly sensitive to the radar's look direction and wavelength, so radars of the future that can explore larger regions of k-space have potential for the discovery of new plasma waves and instabilities. Past work with equatorial radars looking perpendicular to B have observed a wide variety of ionospheric plasma waves and have even recently discovered new unstable waves in the plasmasphere [Derghazarian et al., 2021]. Most of the current high-latitude radars operate at UHF frequencies where they are sensitive to 10s of cm scales, but even at these microscales they observe a wide variety of phenomena, including Langmuir cavitons [Akbari et al., 2013] and naturally enhanced ion acoustic lines [Michell and Samara, 2013]. The workshop discussion highlighted how new high-latitude radars operating at lower frequencies could discover whole new classes of plasma instabilities at meter scales. Radars also observe enhanced Bragg scatter from electron-scale plasma waves in the form of enhanced plasma lines and gyro lines, and the details of these electron-scale features have provided very careful tests of plasma kinetic theory [Bhatt et al., 2008; Hysell et al., 2017; Longley et al., 2021]. Many of these studies were performed at Arecibo precisely because of the need for sensitivity to detect these electron-scale waves. A major unsolved problem in ionospheric kinetic theory is how electron-scale plasma waves can couple to ion-scale plasma waves. Such nonlinear wave-wave couplings are thought to be needed to explain the connections between photoelectrons, unstable upper-hybrid waves, and 150-km echoes [Oppenheim and Dimant, 2016]. Coupling between electron-scales and ion scales are also needed to explain anomalous ion line spectra observed alongside Langmuir cavitons [Akbari et al., 2013].

2. Data assimilation

To address science topics at global to regional scale, the workshop discussion highlighted data assimilation techniques as a method for rapid progress on some of the most intractable problems at the frontier of understanding. In other fields such as meteorology, assimilation techniques have long been essential for routine ~km-scale system data ingestion into convective models, particularly wind and temperature (e.g., Tsuyuki et al., 2007; Bocquet et al., 2015). Analysis relies on a robust, well-parameterized forward model that maps physical system variables into observables. Incoherent scatter radar techniques have a robust first-principles-forward model developed over more than 50 years (physical plasma state to spectral response) that—if made widely available to the community in an open source format—can be profitably integrated into standard techniques including inverse methods [Rodgers, 2000] to achieve efficient assimilation. Great potentials for breakthroughs in cross-scale energy and momentum transfer currently exist. Careful attention must be paid in these applications to spatial and temporal scale mismatch issues between data and model resolution. A recommended approach is to start efforts at regional data assimilation matching a typical IS radar facility's field of view, relating the sub-grid realization to global boundaries such as the plasmapause and the high-latitude convection edge. Additionally, mitigation techniques for inevitable nonlinearities injected by the approach may be necessary (e.g., EnKF variations; Shokri et al., 2019), along with Fisher information matrix considerations within the hypercube formed by IS radar observations.

Several topic areas can benefit from advanced data assimilation of IS radar observations. A highlighted area was high-latitude ionosphere and thermosphere response, as community understanding requires a unified global and local perspective on ionospheric electrodynamics to understand cross-scale magnetosphere-ionosphere coupling processes. The approach has known merits even today, since Poker Flat ISR data (for example) routinely contains dynamic features that are almost invariably at sub-model spatial and/or temporal grid scales for current tools (e.g., Semeter et al., 2009). Fusion approaches are potent here, combining IS radars with other sets including, for example, global AMPERE-based Birkeland current measurements, SuperDARN convective flows, SuperMAG derived currents, and particle precipitation energy information (e.g., DMSP / SSUSI, THEMIS, and Van Allen Probes electron energy flux). In particular, altitude-resolved descriptions, a hallmark of IS radar capabilities, are essential to understand fundamental features such as ionospheric current closure, neutral wind dynamo and flywheel effects, Joule heating by small- to medium-scale structures, and critically important conductivity effects. Boundary condition problems for these studies can be tackled through physical constraints on volume elements from 3D radar data while making sure that first-principles constraints correctly apply on volumetric surfaces. Realistic initialization of models can be assisted by IS radar determination of mesoscale and convective-scale atmospheric state variables.

Whole atmosphere coupling—in particular, lower–upper atmosphere feedback and interchange—was also highlighted as a rich area for future IS radar model-data fusion applications. The community continues to need a fundamental, multi-scale description of gravity wave dissipation in the lower thermosphere [Vadas and Nicolls, 2008], as this has outsize impact on large extant problems such as global ionospheric structure, exospheric temperature, and atmospheric escape. Of particular importance is vertical eddy diffusion, which today is heuristically tuned to match observations (e.g., Qian et al., 2009, 2013; Pilinski and Crowley, 2015). With the right IS radar data, this could instead move toward a more fundamental physics understanding. IS radar altitude profiles, coupled with data assimilation, can also target important variability issues such as neutral wind altitude variation from observed ion velocity dynamics, and drivers of spatially dependent day-to-day electron density variability.

3. Space weather

The Promoting Research and Observations of Space Weather to Improve the Forecasting of Tomorrow Act (PROSWIFT) was signed into law on October 21, 2020. This law reflects the increasing concern on a governmental level of potential consequences of space weather effects on critical infrastructure. The incoherent scatter radar technique is capable of providing critical data to both space weather prediction and now-casting, in addition to providing a long-term historical database for modelers to use for validation and verification. Incoherent scatter directly and uniquely measures full altitude profiles of the most fundamental ionospheric parameters including electron density, electron temperature, ion temperature, plasma velocity, and ion composition. These basic state variables, with varying assumptions, then allow further derivation of such key quantities as electric field strength, conductivity, electric currents, neutral temperature, and neutral wind velocity. Many of these measurements can be provided in real time to the community. In addition, the capability to produce volumetric images of ionospheric plasma parameters using aperture synthesis radar imaging will allow for three-dimensional images detailing the movements of different ionospheric constituents, and information about the temperature, the intensity of electric fields, and the density of different atmospheric species. Additional forecast information might ultimately come from radio sounding of the plasmasphere and solar corona (see sections 9, 10.)

Space weather includes effects due to ionospheric phenomena that disturb radio wave propagation through refraction and diffraction. The technology primarily impacted is involved with communication (comm), and positioning, navigation, and timing (PNT). For example, HF propagation and communications, have become very important for transpolar civil aviation and over the horizon radars (OTHR). To predict HF propagation, the bottomside ionosphere—and its variability—needs to be specified. Current models fall short, especially in the D region. HF-comm outages rely on prediction of D-region absorption, and again the D-region is not classically well characterized. Predicting feasible OTHR operating parameters also relies on better specification of ionospheric parameters. GNSS applications in PNT extend across multiple domains, for example in precision farming, autonomous navigation, timing. Ionospheric variability, induced by ionospheric gradients of all scale sizes have a profound influence on GNSS systems.

In the auroral region, small-scale gradients, such as those generated by irregular precipitation of energetic electrons at altitudes from 100 km and above (associated with the Northern/Southern Lights) can generate scintillation effects leading to loss of signal lock [Semeter et al., 2017]. These effects are not fully addressed by “conventional” studies (e.g., classifying events via scintillation indices). In the high latitudes, structured depletions and enhancements of electron density are observed again leading to scintillation effects and/or positioning errors. Medium-scale irregularities (20–200 km in wavelength) are present. During periods of increased ionospheric activity, degraded DGPS positioning accuracies are common. For navigating restricted waterways, horizontal positioning accuracy of 2–5 m (95%) are required. In the mid-latitudes, large-scale gradients, such as the Storm-Enhanced Density feature that form during geomagnetic storms, can lead to significant positioning errors. Finally, space weather effects are strongest in the low latitude region. The equatorial ionospheric region is an extremely complex region that hosts numerous plasma instabilities and many unresolved problems. Examples of ionospheric dynamics in the equatorial region include the variability of: the Equatorial Ionospheric Anomaly (EIA); the presence of equatorial irregularities; the dynamo efficiency; the equatorial electrojet; the enhanced post-sunset vertical drift (pre-reversal enhancement); and the thermospheric winds due to lower atmospheric forcing (tidal, planetary, and gravity waves) and their vertical shears.

For all of the above purposes, better specification of the ionosphere and its irregularities are needed. In some cases, it is possible to reduce ionospheric effects for precise positioning purposes by using stochastic modeling techniques and/or a regional GPS network approach. However, data assimilation can be helpful and much can be learned from practices such as multi-scale and multi-instrument ISR, Swarm, and GNSS phase analysis. There are outstanding questions, such as:

- Can the drivers and mechanisms of these diffraction effects be identified?
- Can benchmarks/thresholds be established?

4. Neutral/plasma coupling

The dynamic interaction between plasma and neutrals in the upper atmosphere impacts how the ionosphere responds to changes in thermospheric dynamics, composition, and energetics and how the thermospheric dynamics and thermal structure are in turn affected by plasma electrodynamics. Neutral winds can both reconfigure the ionosphere so as to destabilize it and drive currents that can be further destabilizing (ionospheric wind dynamo) (e.g., Richmond, 1995). Neutral forcing in the MLT region can moreover induce ionospheric structure directly [Goncharenko and Zhang, 2008, Goncharenko et al., 2010]. Particle, Joule, and wave heating can heat the neutral gas and set it in motion. The motion can persist after magnetospheric forcing diminishes and continue to drive the ionospheric wind dynamo (flywheel effect; e.g., Deng et al., 1991; Ferdousi et al., 2019). One of the unsolved questions involves, at a given space and time, the relative roles in driving the electric currents/fields between magnetospheric forcing vs. neutral wind dynamo, and in particular, do these roles change in relative importance during geomagnetically active conditions (e.g., Maruyama et al., 2005; 2007; 2011). Neutral waves launched in the auroral zone, referred to as thermospheric atmospheric disturbances (TAD), can carry energy and momentum to middle and low latitudes (e.g., Richmond and Matsushita., 1975). TADs and changes in global circulation and neutral composition generate disturbance dynamo (e.g., Blanc and Richmond, 1980), and affect ionospheric stability there. TADs can also generate so-called large-scale traveling ionospheric disturbances (LSTIDs), further impacting ionospheric stability (e.g., Nicolls et al., 2004). In contrast, TIDs with smaller-scale sizes are understood to be generated by atmospheric gravity waves (AGWs) propagating from the lower atmosphere.

A critical component of these ionosphere-thermosphere (IT) interactions is a variety of ion-neutral coupling processes. For example, coupling across interfaces is especially strong in the presence of magnetic fields. At these interfaces, mass, momentum, and energy transfer are highly efficient. Where ions are magnetized, ion-neutral collisions may be the dominant way to convert fast ordered motion into heat, likely a major source of heating for the ionosphere and thermosphere.

Significant gaps exist in our understanding of how ion-neutral coupling forms ionospheric features such as the equatorial anomalies of the neutral density, temperature, and wind (e.g., Maruyama et al., 2003; Lei, 2021). Storm-time processes producing the neutral upwelling caused by energy deposition in the thermosphere are also not fully understood, although its effect on the global storm-time IT perturbation has been observed. In all of the above examples, how the exchange of material, momentum, and energy occurs is the area that more progress is needed.

5. Mesospheric and lower thermospheric instabilities and mesoscale dynamics

High temporal and spatial resolution measurements of mesosphere and lower thermosphere (MLT) dynamics are needed to understand the interplay of gravity waves and stratified turbulence at these altitudes and their importance in mean and tidal flows and in vertical coupling processes (e.g., Marino et al., 2015). During summer months at high latitudes, strong mesospheric echoes governed by ice-particles, electron density, and turbulence, have been used as tracers to explore kilometer-scale dynamics associated to mesospheric instabilities, like Kelvin-Helmholtz instability (KHI) [Chau et al., 2020] and mesospheric bores with extreme vertical velocities [Chau et al., 2021]. These dynamics are expected to occur at different latitudes and seasons. Examples of Jicamarca KHI and layering without discriminating spatio-temporal features can be found in Lehmacher et al. [2007] and Lee et al. [2019]. A modern geospace radar operating in the low VHF band with power-aperture more than one order of magnitude greater than Jicamarca would enable observing this kind of dynamics interplay during different seasons and at different latitudes. Moreover, the dynamics of the so-called “radar gap,” between 30 and 50 km (e.g., Maekawa et al., 1993), could be explored. Unambiguous, volumetric velocity estimates could be obtained through a combination of multistatic and spaced-receiver methods.

High vertical resolution MLT wind profiles comparable to rocket-derived winds from chemical releases can be obtained from non-specular meteor echoes, also called range-spread trail echoes (RSTE) [Oppenheim et al., 2009]. Jicamarca wind profiles have been obtained from relatively long trail echoes using interferometry, that is, tracking how the trail echoes evolve in space as a function of time. Multi-static observations of RSTE would allow velocity and spatial measurements with more precision, and from trails lasting for shorter times, allowing more measurements. The latter would be possible since line-of-sight velocities from at least three different projections could be obtained.

We can go further and point out that capturing neutral and plasma dynamics at any scale through remote sensing demands the incorporation of spaced antenna methods, multistatic (multi-k) methods, or both for unambiguous determination of the vector flow in three dimensions and the higher-order flow characteristics (divergence, vorticity, energy dissipation rate, etc.) the need for such characteristics in a next-generation geospace radar was a recurring theme in the workshop.

6. Meteor science

Besides the use of meteor echoes to study MLT dynamics, their study with high-power larger-aperture radar is interesting in different fields—for example, meteoroid orbits and origin (e.g., Chau et al., 2007) and meteoroid masses (e.g., Schult et al., 2017). Estimating the total meteoroid mass deposited in the Earth's atmosphere is not trivial. Plasma physics, meteoroid composition, atmospheric chemistry, and meteoroid fragmentation (e.g., Sugar et al., 2019; Kero et al., 2019), are among the most important aspects controlling the meteoroid mass estimation from meteor-head echoes. A modern geospace radar with interferometry, and multi-static and high-power large-aperture features will contribute to improve meteoroid mass estimation.

In order to make advances in the study of micrometeoroids entering the Earth's atmosphere, three observational improvements should be pursued:

- Multi-static time of flight observations for obtaining a significant improvement of trajectory measurements: at least a tri-static configuration would be needed for the technique.
- Multi-k observation capability to allow comparison of meteor head echo models with observations [Sugar et al., 2019]: this can be achieved with a combination of multi-static observing geometry and use of multiple transmit frequencies.
- Full-trajectory observation capability: the most useful measurements of meteors would include observations of the full path of the meteor (as long as ~100 km) from the point where ablation starts to the point where ablation ends. This would provide valuable measurements of atmospheric deceleration and evolution of the radar-cross-section as a function of height and velocity. This would require a radar capable of reacting fast to newly discovered meteors, or a radar that conducts fast scans of a sufficiently large observation volume. The multiple-in multiple-out (MIMO) technique may also provide a technical solution here.

Not only would these improvements enable studies of atmospheric interaction, they would also allow a proper investigation of interstellar meteoroids to be done. While there are several papers about these kinds of meteors, no widely accepted observations exist that conclusively show an interstellar trajectory for a meteor. Studies of dust outside the solar system would greatly benefit from these data.

7. Energetics, dynamics, transport (aeronomy)

IS radars have multiple capabilities that make them uniquely useful for diagnosing energy transport in the ionosphere. IS radars can directly measure ion and electron temperatures of the cold plasma, which gives them direct information on the ion and electron heating. Measurements along multiple look directions can also provide information about the ion velocity distribution functions, which can become anisotropic, toroidal, or otherwise highly distorted during times of intense frictional heating [Akbari et al., 2017].

IS radars can also measure altitude profiles of densities and temperatures as well as derivatives of those profiles. The field-aligned derivatives of the temperatures give direct information on the heat fluxes, and this is particularly interesting to investigate in mid-latitude regions that are directly influenced by heat flow from the ring current in the inner magnetosphere [David et al., 2011; Zhu et al., 2016]. Correctly assessing heat flow and temperature is essential not only for modeling of plasmaspheric density profiles, but also to understanding of electron heating variability effects on O+ ionospheric outflow populating the warm plasma cloak [Chappell et al., 2008]. These latter processes have been identified as critical drivers of magnetospheric configuration, circulation, ring current dynamics, and particle energization dynamics [Glocer et al., 2009; Welling et al., 2011]. IS radars have also been used to discover new regions of heat flow between the magnetosphere and ionosphere, such as the significant heat flows associated with pulsating auroras [Liang et al., 2018]. Derivatives of the densities and temperatures can also be used to calculate pressure gradients and ambipolar electric fields, which are critical for understanding ion upflow and mass transport along field lines.

Furthermore, understanding particle precipitation is critical for understanding the loss of energetic particles from the magnetosphere, understanding ionospheric conductivity, and understanding middle atmospheric chemistry. Altitude profiles of E-region density can be inverted into properties of precipitating particles using energetic electron transport models and ion chemistry models [Semeter and Kamalabadi, 2005]. In addition to auroral electron precipitation, ring current proton precipitation can cause ionization bands below 150 km under the auroral electron oval, and these effects, along with mid-latitude SAPS ion-neutral interactions, cause significant ionospheric electron heating that is best quantified with altitude profiles from IS radars.

Furthermore, EISCAT VHF radar was used to detect the impact of the precipitating relativistic electrons during Pulsating aurorae (PsA) on the electron density in the D-region ionosphere, leading to catalytic ozone depletion at the mesospheric altitude [Miyoshi et al., 2021].

8. Planetary radar

We recently lost the most capable planetary radar in the world: the Arecibo Observatory S-band radar. While most of the planetary work was conducted with this system, Arecibo was also used for 7.5-meter and 70-cm studies of the Moon. A low VHF frequency radar cannot replace the lost capability, but it would open up a possibility to study the composition and structure of the Moon at long wavelengths, which are still relatively unexplored. Only a few such studies exist [Thompson 1978; Vierinen et al., 2017]. A combination of modern ionospheric calibration and an interferometric and polarimetric phased array radar system at a mid-latitude location would be able to do a significantly better job at making this observation. The advantage with longer wavelengths is that they penetrate deeper into the subsurface, allowing us to, for example, peer back further into the geological history of the Moon. Longer wavelengths also study the roughness of the Moon on larger scales. Perhaps the most active topic of research related to the Moon currently is the search for deposits of water ice within the polar regions (see Patterson et.al., [2017] and references therein), as this would greatly aid the long-term goal of establishing a permanently occupied base on the Moon. Of great interest is also the mineral composition and geological history of the Moon, including the timeline of lunar volcanism [Hartmann et al., 1986]. The use of longer wavelengths with high-quality polarimetry would greatly aid with both of these research topics.

An ideal system would allow focused synthetic aperture radar (SAR) maps of the Moon to be done across a range of frequencies between 30 and 400 MHz, with the low end of the frequency range being more scientifically interesting than the high end. The measurements would need to be done ideally with a dual-polarization transmit and receive capability and with high polarization purity. Sophisticated interferometry techniques would allow better dynamic range to be obtained in disambiguation of the Doppler North-South ambiguity inherent in the SAR technique for planetary bodies.

Interest in a planetary mission was one of the more progressive aspects of the workshop, given resurgent interests in space exploration and growing commercial interests in the Moon and other non-planetary solar system bodies.

9. Plasmaspheric radar

Frequency diversity and k-space exploration were recurring themes throughout the workshop because of the variety of science investigations they could support. One advantage of using a low VHF frequency for incoherent scatter radar is immunity from finite Debye length effects that render the technique unusable when the plasma is rarefied. The 50 MHz Jicamarca radar is able to detect incoherent scatter at altitudes up to about 10,000 km and can therefore be used to probe the plasmasphere, although the integration time required for usable results at Jicamarca is of the order of hours [Farley, 1991; Hysell et al., 2017]. This requirement could be greatly reduced if the power aperture product were increased. Studies of plasmaspheric erosion and refilling and energy transfer from hot to cold particle populations in the PBL region could thereby be conducted practically from the ground. This technique would also provide an additional method to investigate the formation of plasmaspheric ducts that would be complementary to passive radio measurements of ducts [Loi et al., 2015a].

In addition to incoherent scatter, the plasmasphere is home to electrostatic waves and instabilities that can be detected readily through coherent scatter. This is an emerging area of research that could be opened with a new geospace facility capable of operations in the low VHF band. For example, electrostatic plasma waves at altitudes near 2000 km were recently detected over Jicamarca [Derghazarian et al., 2021]. The echoes appear after sunset and persist until dawn in patchy, slowly drifting layers. They appear to occur during intervals of low solar flux. Most remarkably, the echoes have strong sidebands at the lower hybrid frequency. Lower hybrid solitary structures were discovered in the auroral zone but are now known to occur at the equator [Berthelier et al., 2008]. The free energy for the irregularities appears to be VLF radiation from lightning. It is not yet known whether the equatorial layers are intrinsically unstable.

10. Solar echoes

Solar radar is another important application for high-power, larger-aperture low-frequency VHF radar. The idea of obtaining radar reflections from the solar corona dates to the earliest days of planetary radar, and several attempts have been made to detect them. Success was reported by Eshleman [1960] at Stanford using a very modest 25.6 MHz system, but the results could not be repeated. A much more substantial, purpose-built 38.25 MHz radar was deployed by MIT in El Campo, Texas, where solar echoes were reportedly observed throughout a ten-year effort [James, 1964; 1970]. Solar-radar experiments were also carried out at Arecibo using a 40 MHz feed [Parrish, 1968; D. Campbell, 2016, personal communication]. Solar echoes were reportedly observed, but the results were not documented or disseminated extensively due to a perceived lack of novelty at the time. More recently, a series of solar-radar experiments using the 50 MHz main radar at Jicamarca was performed and carefully documented [Coles et al., 2006]. This time, to the surprise of the investigators, echoes could not be detected despite multiple attempts using a number of experimental refinements. The upper limit on the radar cross-section for coronal echoes was subsequently downgraded from the El Campo estimate, and the discrepancy remains a quandary.

A geospace radar, operating in the low VHF band with a power-aperture product an order of magnitude greater than that of Jicamarca, could be used to resume solar radar research. Such a project could resolve the decades-old mystery concerning the challenging but seemingly straightforward problem of receiving soundings from a distant ball of plasma. (The problem is evidently not so straightforward, and some possible complications rooted in coronal physics were discussed by Coles et al. [2006].) The detection of solar echoes would have immense impact across the geospace sciences and would capture the public imagination. A solar-radar capability would represent an important new diagnostic method for radio science and solar physics to complement next-generation optical observations from DKIST and CLST. Such a capability would also be a decisive tool for operational space weather forecasting.

Cross-cutting themes and workshop findings

Three cross-cutting themes spanned the workshop discussions. The first concerned emerging technologies that we can use to pursue the aforementioned science priorities. The second was the benefit of involving and exploiting developments in adjacent science communities as we proceed. The third was the importance of workforce development and international relationships. Each of these themes is expanded in the following sections. From these themes emerged the report's two main findings, which are also highlighted.

I. Utilize emerging technology

The science behind the evolution of the universe and that of the upper atmosphere are very different, but the instruments we use to study them today are quite similar. In the early days of radio observatories in the 1960s, there was a parallel development of instruments such as the Jicamarca Radio Observatory and the Cambridge Interferometer, since differences in objectives (such as the need for radar or high angular resolution) pushed for different designs. Use of these instruments by researchers from outside the supporting field were minimal. Common ground was found with the Arecibo Observatory, which was jointly supported by both the Astronomy and the Atmospheric and Geospace Sciences divisions at NSF for 50 years. Over the past two decades, a number of rewarding astronomical topics have emerged at low frequencies including the study of Cosmic Dawn when the first stars and galaxies lit up the universe, a new type of variable source known as Fast Radio Bursts (FRBs), and the discovery of self-generated emission from large meteors known as Meteor Radio Afterglows (MRAs). These and other discoveries have led to a new suite of radio telescopes operating below 300 MHz that take advantage of advances in digital signal processing to explore wide fields of view with high angular and temporal resolution.

The breadth of science, and synergies between astronomy, aeronomy, and space weather, are now so prevalent that when a group of instrument directors (all astronomers) started an annual conference, the name selected for it was "Science at Low Frequencies" (SALF; http://salfconference.org/). There have been seven of these to date, with a steadily growing number of participants. Talks on ionospheric physics and meteors have been a staple at the meetings. However, there is still much room for additional collaboration. For astronomers, the ionosphere is a nuisance whose effects must be removed from the data to achieve scientific objectives. For aeronomers, understanding the ionosphere is part of their science and worthy of study in its own right. Clearly, these two groups can help each other, and communication between the two is vital.

For the past decade, the University of New Mexico has been operating the Long Wavelength Array (LWA) consisting of two dipole arrays with 256 elements each in New Mexico, with two additional stations under construction in New Mexico and California. Support for the telescope has come from NSF/AST, NSF/GEO, AFRL, NRL, NASA, DARPA, and DTRA. This is in contrast with other radio telescopes (LOFAR, VLA, GBT) that typically have just one main sponsor. The broad base of support for the LWA is the result of the diverse uses of the telescope.

II. Leverage knowledge and resources from other communities

The radio astronomy community has reached a point where their instruments are able to simultaneously observe the whole lower VHF band. This is because many of the key science goals (epoch of reionization, fast radio bursts, pulsars) are inherently broadband phenomena.

Because many of the geospace phenomena are also highly frequency dependent in terms of scattering, propagation, and emission of electromagnetic waves, low frequency astronomical telescopes are well suited for studies of various plasma physical phenomena occurring in Earth's near space.

The main low frequency astronomy projects are LOFAR (Europe), LWA (US), and the Murchison Widefield Array (MWA). These projects also have geospace research themes as well. LOFAR hardware has been used to study the frequency dependence of ionospheric scintillation and absorption [McKay-Bukowski et al., 2014]. It has also been used to demonstrate the feasibility of making bi-static incoherent scatter radar, MST radar and meteor radar observations [McKay-Bukowski et al., 2014]. Similarly, LWA has been used to study broad band emissions from meteors [Obenberger et al., 2016] and to make ionogram measurements using broadband short pulses of emission originating from current structures within terrestrial lightning [Malins et al., 2019]. MWA has studied plasmasphere ducting structures [Loi et al., 2015a], power spectra of ionospheric fluctuations [Loi et al., 2015b], and ionospheric electron density gradients [Arora et al., 2016].

One logical way to go forward in geospace research instrumentation is to pair the already existing technical capability of wideband all-digital phased-array radio telescope hardware with a frequency-agile transmit capability. This will allow studies of the relatively unexplored frequency dimension of scattering of various geospace phenomena, such as incoherent scattering from ionospheric plasma, neutral turbulence, and meteor head echoes. The use of general purpose wideband radio telescope hardware would enable serendipitous discovery in the field of geospace, as already demonstrated by the LWA, LOFAR, and MWA projects.

These two themes form the basis for one finding of the report: that **we should undertake the development of a new geospace facility, a geospace radar, following in the footsteps of contemporary, worldwide developments in radio astronomy and radar techniques.**

III. Develop workforce and establish international collaborations

The second major finding of this report pertains to the crucial role of workforce development for sustaining and expanding the impact of geospace research, including its broader impact, which was also the third cross-cutting workshop theme. **It is imperative to train the next generation of scientists and engineers to take over ISR research and technology as an integral part of any next-generation facility.** The workshop also highlighted the need to develop a diverse and inclusive workforce and to ensure equitable access to the facility science programs by removing as many barriers to entry as possible. While programs like the ISR Summer School do provide training for users of ISR data, there are few opportunities for the training the ISR theory and engineering necessary to run facilities.

One path forward could be stronger collaboration with international programs. For example, the UNIS program in Svalbard trains 12–16 students per year. As the EISCAT_3D project unfolds, both the need and the demand for international programs like this one will undoubtedly grow, and the community needs to provide commensurate support. Another possibility would be to partner with engineering departments at universities and create three-week classes where students travel to a facility for in-depth training on a particular aspect of ISR. These three-week classes are found between semesters at some universities and could be an easier entry point to the university system than hiring a dedicated faculty member who would teach semester-long courses. In addition, physically visiting a radar facility motivates discussion and knowledge acquisition in a way often not possible through textbooks and remote learning. Another possibility is to create nuggets of ISR topics that could be embedded within current popular courses in electromagnetics and signal processing. The ISR field is rich with both physics and engineering applications. Having these nuggets available for instruction, perhaps in the form of on-line tutorials and/or Jupyter notebooks with examples, would be another way for a professor to include the content without developing an entire course focused on ISR.

Beyond workforce development, international collaboration is also key to making global measurements of upper-atmospheric properties and processes through instrument chains, such as the Meridian Chain being proposed. Instruments could be distributed along a meridian, in clusters on a continent, or scattered strategically around the Earth. The international community needs to work collaboratively together on global scale phenomena such as CO_2 impact and variability in the Earth's magnetic field. Measurements are needed on different scale sizes, different longitudes, and different hemispheres. We could take advantage of other instruments being proposed, such as the SKA in Africa, for atmospheric measurements. EISCAT_3D by itself will be a powerful engine, driving new developments in signal processing and analysis techniques, and partnerships with that and other ISR projects worldwide will accelerate progress on the science objectives laid out in this report. Creating these international partnerships will be nontrivial, but it will be essential to forge and maintain strong relationships with colleagues in countries around the world.

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