Cover Page

Title: Ground-based assets to support the GDC mission

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Synopsis:

The synergistic relationship between the in-situ and ground-based measurements of our geospace system has provided great advances in heliophysics. In the next decade several multi-spacecraft missions are expected to become part of our Heliophysics System Observatory. The Geospace Dynamic Constellation (GDC) is one of the most anticipated of these future missions. A key element for the success of GDC is the preparation and coordination of our ground-base assets. While our ground-based instruments have been highly successful and scientifically prolific, the heliophysics community does not have a clear path or pipeline for the continuous support of these instruments and arrays, nor their expansion and improvement. In this white paper we present an overview of some of these ground-based capabilities and pose the recommendation for a clear path to continuously support our ground-based assets, namely that the space physics community**: 1) maintains the pipeline for the continuous support and maintenance of our existing ground-based assets, 2) increases coverage of inexpensive proven technologies, and 3) improves support for the testing and implementation of new remote sensing technologies**.

<u>Recommendations:</u> Support space-based observations with ground-based instrumentation by: 1) maintaining the pipeline for the continuous support and maintenance of our existing ground-based assets, 2) increase coverage of inexpensive proven technologies, and 3) improve support for the testing and implementation of new remote sensing technologies.

Introduction

The space exploration era was marked by the development of in-situ satellite measurements of the near-Earth space environment, the geospace. As part of these developments, the heliophysics community has benefited enormously from past and existing missions that encompass the Heliophysics System Observatory. Joining these efforts, the Geospace Dynamic Constellation (GDC) will address crucial scientific processes that take place in Earth's Magnetosphere-Ionosphere-Thermosphere (MIT) system. GDC, in conjunction with the Dynamical Neutral Atmosphere-Ionosphere Coupling (DYNAMIC) mission, will revolutionize our understanding of the MIT system. However, even with multipoint global spacecraft observations (such as GDC) and the combined efforts among these in-situ observations, only a limited area of our geospace can be sampled. For this reason, our satellite missions rely on ground-based assets to provide context for these measurements. Both space- and ground-based instrumentation require this synergistic operation.

With GDC's expected launch at the end of the decade, we need to ensure that our available ground-based assets are prepared and sufficient for these coordinated efforts. This white paper serves as an overview of some existing ground-based instrumentation and provides recommendations to help the heliophysics community plan for the continuous support, maintenance, and improvement of our ground-based assets for the next 10-20 years. In particular:

1. Maintain the funding pipeline by the national agencies for the continuous support and maintenance of our existing ground-based assets
2. Increase coverage of inexpensive proven technologies
3. Increase support for the testing and implementation of new technologies that could help our current and future instruments' lifetime

This white paper predominantly focuses on GDC, given that it is an upcoming mission, but can easily be applied to other upcoming in-situ missions and instrumentation (e.g. rocket missions). In the next three sections, we target the recommendations mentioned above.

(a) Maintaining the Funding Pipelines for Continued Support and Maintenance

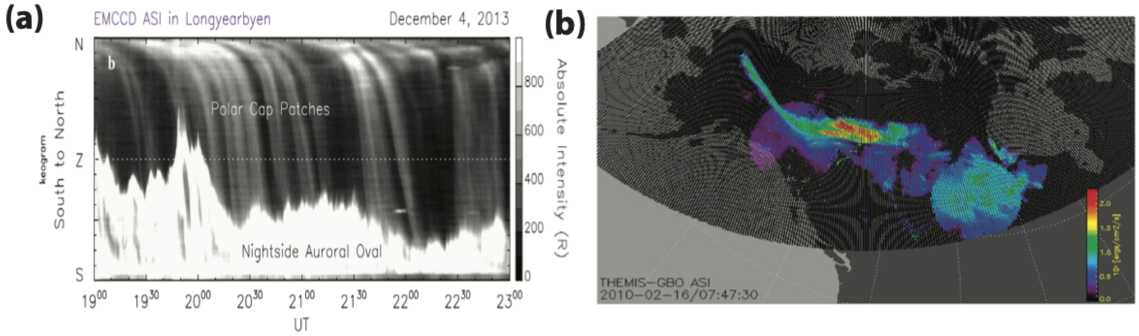
Large-scale ground-based instrumentation requires funding to be built, but also requires funding to be maintained. Two highly prolific examples of this in space physics are Incoherent Scatter Radars (ISRs) and Super Dual Auroral Radar Network (SuperDARN) radars. Both ISRs and SuperDARN systems are able to examine multiple directions within a relatively wide region. Furthermore, Advanced Modular ISR systems can even explore multiple directions simultaneously, providing a volumetric "snapshot" of the ionosphere. ISRs probe ionospheric plasma properties, such as the ion and electron temperatures, plasma density, and line-of-sight velocity, from the radar backscatter. They do this by measuring the Doppler spectrum that is Thomson scattered off the ionosphere and applying spectral fitting routines to the measured backscatter. These observations can further be used to infer ion-neutral coupling through neutral winds (Heiselman and Nicolls et al., 2008), and precipitation (Kirkwood and Osepian, 1995; Kaeppler et al., 2020), both of which are priorities for the GDC mission.

However, even now there are clear issues with combining ISR and GDC operations. For example, by the time GDC launches the radars at Resolute Bay (RISR-North and -Canada) will not be operational without significant maintenance investments (of ~10s of millions of dollars). Given the unique geophysical location of each current ISRs (e.g. RISR-North and -Canada, Poker Flat ISR, Millstone Hill, and Jicamarca), and the global scope of GDC, all ISRs will be critical for addressing cutting edge science topics in combination with GDC observations and validating GDC's measurements. Arguably European instrumentation and datasets, such as European Incoherent Scatter Scientific Association 3D (EISCAT3D) can provide assistance, but we need to establish international partnering to accomplish this goal. Since the closure of Sondrestrom, the EISCAT Svalbard Radar (ESR) is the only ISR near the usual location of the cusp, a critical region for energy deposition that is highly relevant to GDC's mission. EISCAT estimates that their current supply of obsolete klystron transmitters will be sufficient for operations until 2030 (L. Baddeley, private communication, 2022), after which point ESR will need to close or be replaced by a new radar using new technology. The US and European communities should work together to plan for the future of cusp observational facilities; however, the US needs to also establish and maintain its own instruments' data sovereignty.

Meanwhile, SuperDARN are radars that infer from the backscatter the line-of-sight ion velocity of ionospheric plasma, the backscatter power, and the spectral width (Greenwald et al., 1995). Although individually they are not able to infer as many plasma properties as ISRs, their overlapping observations allow them to resolve large-scale dynamics and convection. Given that ionospheric convection is inherently tied to the magnetosphere, SuperDARN data infers Magnetospheric-Ionospheric coupled dynamics. Examining this on a finer-scale is one of the goals of GDC, which makes these HF radar systems ideal for validation purposes and future conjugate studies. However, much like ISRs, these instruments need constant maintenance and support to be operational. Furthermore, given that these operate most successfully as a network, funding is needed to develop more of these systems.

ISRs and SuperDARN represent two large-scale operations (in terms of funding and maintenance) that require more dedicated funding lines, but they certainly are not the only two. Optical instruments have provided key insights to understand the coupled magnetosphere-ionosphere-thermosphere system. At equatorial and low-latitudes, for example, zonal plasma drift observations have uncovered important information of the nighttime low-latitude E and F region plasma (e.g., Martinis et al., 2003). In addition, ground-based observations at high-latitudes have been instrumental to understanding auroral and subauroral processes (e.g., Zesta et al., 2000; Donovan et al., 2006; Kepko et al., 2009; Nishimura et al., 2010; MacDonald et al., 2018; Gallardo-Lacourt et al., 2018; Martinis et al., 2021). In the past decades, spectrographic observations, combined with satellite measurements, at auroral latitudes helped us understand important physical processes in the magnetosphere-ionosphere system, such as the emission lines produced by particle precipitation (e.g., Chamberlain, 1966; Solomon et al., 1988). More recently, two dimensional all-sky imagers have uncovered the dynamics of optical structures in the polar cap, auroral, and sub-auroral regions (e.g., Hosokawa et al., 2020; Hosokawa et al., 2016; Forsyth et al., 2020; Gallardo-Lacourt et al., 2021).

While optical instruments have been essential to uncover important geospace properties, the heliophysics community does not have a tangible plan for continuous support and maintenance of our optical ground-based assets. A good example are the THEMIS (Time History of Events and Macroscale Interactions during Substorms) All-Sky Imagers (ASI), one of the most scientifically prolific optical instruments in our community, that has been continuously capturing the night sky at auroral latitudes with its 20 cameras operating for more than 15 years. Despite their highly productive scientific research, THEMIS ASI does not have a clear support pipeline to ensure that our instruments are well maintained to keep thriving for the next 15 years. While individual group support (such as UC Berkeley and U. of Calgary) has been fundamental to maintain, expand, and complement our ground-based optical instruments, expansions that include, for example, the Redline Emission Geospace Observatory (REGO, UCalgary) and Transition Region Explorer (TREx) arrays ; they need support from the entire heliophysics community to guarantee their successful future operations. Similarly, mid-latitude optical networks such as the Midlatitude All sky-imaging Network for GeoSpace Observations (MANGO), and the Boston University red and green line imager networks are producing data towards discovery science (e.g. Martinis et al, 2021), but without a proper roadmap these resources may not last.



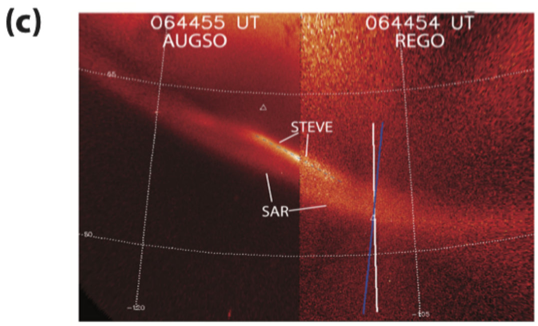


Figure 1:Illustration of optical data capabilities. (a) Polar cap patches observations adapted from Hosokawa et al., 2019. (b) Energy flux calculations at auroral latitudes derived from THEMIS ASI data, by Gabrielse et al., 2021. (c) Subauroral structures observed with multiple optical instruments, adapted from Liang et al., 2019.

One of the instruments with the largest coverage in the heliophysics community are ground-based magnetometers. Providing extensive latitudinal and longitudinal coverage, particularly over North-America (e.g., Gjerloev, 2012), magnetometers are relatively inexpensive and versatile instruments. Apart from measuring magnetic fields and their variations, ground-based magnetometers can be used to obtain ionospheric currents, waves, and other phenomena (e.g., Amm, 2001; Weyhand et al., 2011; Weimer and Edwards, 2020). The ground-based magnetometer data and the coverage available now is the best it has ever been. In addition, there are already many existing tools for providing data products that will be directly relevant to the GDC mission science, therefore ground magnetometers must be considered as a critical ground-based asset for the GDC mission as a whole. Recent coordination between US ground magnetometer arrays will benefit the GDC mission (Engebretson and Zesta, 2017): the formation of an advisory board to periodically evaluate the operations and effectiveness of all U.S.-funded ground magnetometer arrays and prioritize magnetometer locations (in consultation with USGS and international community/ULTIMA), efforts to better coordinate operation of ground magnetometer arrays operated by different investigators, community support for SuperMAG to continue collecting data and generating higher level data products relevant to GDC (e.g., equivalent currents), preparing data in standard formats, improving data collection and transmission systems, and generating new higher level data products with input from GDC. These community coordination efforts present a real strategy for coordinating and preparing our existing ground-based assets efficiently in preparation for GDC.

(b) Increased Usage and Coverage of Smaller-Scale Instruments

Large-scale ground-based systems are beneficial, and it is important to not underestimate the importance of systems that are comparatively inexpensive and more portable. For example, one of the few ground-based instruments that are able to resolve neutral dynamics are Fabry-Perot Interferometers (FPIs) (Vaughan, 2017), and they are relatively cheap (typically costing 100s of thousands). From interferometry, these systems are able to infer within a given column of space the neutral temperature, bulk flow, and relative chemical composition. Filter wheels allow for different altitudes to be examined, similar to all-sky imagers. The comparison of these measurements with plasma observations gives important insights into ion-neutral coupling, a core focus of the GDC mission. These systems can be relocated to increase GDC science returns. However, they are also greatly underutilized; in the continental US (there are currently only six: Oregon, Bear Lake, Urbana, Lowell Observatory, Jenny Jump, and Millstone Hill).

Another example of underused technologies is ionosondes. Using radio chirps, these instruments infer the bottom-side vertical plasma density profile along a line-of-sight. The return signal also provides the plasma density of the F2 peak (nmF2), the altitude of the F2 peak (hmF2), and flows. The only other instrument that can resolve this information are ISR systems, which are vastly more expensive and less portable. Ionosondes have paltry coverage globally, particularly in North America. These instruments would significantly enhance the science return of GDC by providing bottom-side vertical plasma density profiles giving context to GDC's plasma density measurements, for example. Despite this flexibility, and how inexpensive and portable ionosondes are, these systems are underutilized.

The technologies accessible to citizen scientists also vastly improve space physics data coverage at a low cost. One well-known example of this is amatuer aurora photographers, such as the Alberta Aurora Chasers, who have been able to provide images of the rare optical phenomenon Strong Thermal Emission Velocity Enhancement (STEVE) and emphasized the need for more full color images of the upper atmospheric phenomenon. Another important citizen science effort is HamSCI, which is a collaboration of Ham radio enthusiasts (both scientists and citizen scientists) who utilize radio waves to better understand long distance communication and ionospheric irregularities. Additionally, HamSCI is developing a personal space weather station that will be distributed widely to citizens. Each system is modular and includes a Grape Low-Cost Personal Space Weather Station (WWV Doppler Monitor), a TangerineSDR (High-performance Software Defined Radio), a ground magnetometer module, and a Very Low Frequency Receiver. Regardless, investing in citizen science will improve data coverage and the scientific returns of spacecraft missions, such as GDC.

(c) Increase support for the testing and implementation of new technologies

The previously discussed recommendations focus on optimizing the systems and instrumentation that is currently in place or available to us. However, given that GDC will launch closer to the end of the current decade, and will run for a long time once it is in orbit, it is not unrealistic to imagine and develop new technology to coordinate with this mission during its lifetime. Already, instruments such as EISCAT3D have improved upon the capabilities of ISR systems to provide an increased resolution. It is therefore worth highlighting that having funding lines to research and develop improved ground-based instrumentation would benefit GDC science returns.

Summary

The goal of this white paper is to outline several key ground-based instruments that will vastly improve the science returns of spacecraft missions, as well as provide recommendations. Although there are many possible ways to improve the scientific returns of spacecraft missions through ground-based observations, this paper recommends that: **1) we maintain the pipeline for the continuous support and maintenance of our existing ground-based assets, 2) we increase the coverage of inexpensive and proven technologies, and 3) we increase support for the testing and implementation of new technologies**. While these recommendations will be beneficial for any spacecraft mission, advancing these recommendations is critical for the success of the GDC mission, and they need to be addressed prior to the launch of GDC.

References

Chamberlain, J. W., Physics of the Aurora and Airglow, Academic, San Hays, P. B., and C. D. Anger, Influence of ground scattering on satellite Diego, Cald., 1961

Donovan, E., et al. (2006), The azimuthal evolution of the substorm expansive phase onset aurora, in *Proceedings of ICS-8*, edited by M. Syrjäsuo and E. Donovan, pp. 55– 60, Univ. of Calgary, Calgary, Alberta, Canada.

Engebretson, M., and E. Zesta (2017), The future of ground magnetometer arrays in support of space weather monitoring and research, Space Weather, pp. n/a–n/a, doi: 10.1002/2017SW001718, 2017SW001718.

Forsyth, C., Sergeev, V.A., Henderson, M.G. et al. Physical Processes of Meso-Scale, Dynamic Auroral Forms. Space Sci Rev 216, 46 (2020). https://doi.org/10.1007/s11214-020-00665-y

Gallardo-Lacourt, B., Liang, J., Nishimura, Y., & Donovan, E. (2018). On the origin of STEVE: Particle precipitation or ionospheric skyglow? *Geophysical Research Letters*, 45, 7968– 7973. https://doi.org/10.1029/2018GL078509

Gallardo-Lacourt, B., Frey, H.U. & Martinis, C. Proton Aurora and Optical Emissions in the Subauroral Region. *Space Sci Rev* 217, 10 (2021). https://doi.org/10.1007/s11214-020-00776-6

Gabrielse C, Nishimura T, Chen M, Hecht JH, Kaeppler SR, Gillies DM, Reimer AS, Lyons LR, Deng Y, Donovan E and Evans JS (2021) Estimating Precipitating Energy Flux, Average Energy, and Hall Auroral Conductance From THEMIS All-Sky-Imagers With Focus on Mesoscales. Front. Phys. 9:744298. doi: 10.3389/fphy.2021.744298

Gjerloev, J. W. (2012), The SuperMAG data processing technique, J. Geophys. Res., 117, A09213, doi:10.1029/2012JA017683.

Greenwald, R. A., Baker, K. B., Dudeney, J. R., Pinnock, M., Jones, T. B., Thomas, E. C., ... & Yamagishi, H. (1995). Darn/superdarn. Space Science Reviews, 71(1), 761-796.

Heinselman, C. J., & Nicolls, M. J. (2008). A Bayesian approach to electric field and E-region neutral wind estimation with the Poker Flat Advanced Modular Incoherent Scatter Radar. Radio Science, 43(05), 1-15.

Hosokawa, K., Ogawa, Y. & Taguchi, S. Imaging of polar cap patches with a low-cost airglow camera: pilot observations in Svalbard, Norway. Earth Planets Space 71, 115 (2019). https://doi.org/10.1186/s40623-019-1094-7

Hosokawa, K., Taguchi, S., & Ogawa, Y. (2016). Edge of polar cap patches. Journal of Geophysical Research: Space Physics, 121(4), 3410-3420.

Hosokawa, K., Kullen, A., Milan, S. et al. Aurora in the Polar Cap: A Review. Space Sci Rev 216, 15 (2020). https://doi.org/10.1007/s11214-020-0637-3

Kaeppler, S. R., Sanchez, E., Varney, R. H., Irvin, R. J., Marshall, R. A., Bortnik, J., ... & Reyes, P. M. (2020). Incoherent scatter radar observations of 10–100 keV precipitation: Review and outlook. The Dynamic Loss of Earth's Radiation Belts, 145-197.

Kepko, L., Spanswick, E., Angelopoulos, V., Donovan, E., McFadden, J., Glassmeier, K.-H., Raeder, J., and Singer, H. J. (2009), Equatorward moving auroral signatures of a flow burst observed prior to auroral onset, *Geophys. Res. Lett.*, 36, L24104, doi:10.1029/2009GL041476.

Kirkwood, S., & Osepian, A. (1995). Quantitative studies of energetic particle precipitation using incoherent scatter radar. Journal of geomagnetism and geoelectricity, 47(8), 783-799.

Liang, J., Donovan, E., Connors, M., Gillies, D., St-Maurice, J. P., Jackel, B., et al. (2019). Optical spectra and emission altitudes of double-layer STEVE: A case study. Geophysical Research Letters, 46, 13630– 13639. https://doi.org/10.1029/2019GL085639

Solomon, S. C., Hays, P. B., and Abreu, V. J. (1988), The auroral 6300 Å emission: Observations and modeling, J. Geophys. Res., 93(A9), 9867– 9882, doi:10.1029/JA093iA09p09867.

MacDonald, E. A., Donovan, E., Nishimura, Y., Case, N., Gillies, D. M., Gallardo-Lacourt, B., et al. (2018). New science in plain sight: Citizen scientists lead to the discovery of optical structure in the upper atmosphere. *Science Advances*, 4(3), eaaq0030. https://doi.org/10.1126/sciadv.aaq0030

Martinis, C., Eccles, J. V., Baumgardner, J., Manzano, J., and Mendillo, M. (2003), Latitude dependence of zonal plasma drifts obtained from dual-site airglow observations, J. Geophys. Res., 108, 1129, doi:10.1029/2002JA009462, A3.

Martinis, C., Nishimura, Y., Wroten, J., Bhatt, A., Dyer, A., Baumgardner, J., & Gallardo-Lacourt, B. (2021). First simultaneous observation of STEVE and SAR arc combining data from citizen scientists, 630.0 nm all-sky images, and satellites. Geophysical Research Letters, 48, e2020GL092169. https://doi.org/10.1029/2020GL092169.

Nishimura, Y., L. Lyons, S. Zou, V. Angelopoulos, and S. Mende (2010), Substorm triggering by new plasma intrusion: THEMIS all-sky imager observations, *J. Geophys. Res.*, 115, A07222, doi:10.1029/2009JA015166.

Vaughan, J. M. (2017). The Fabry–Perot interferometer: history, theory, practice and applications. Routledge.

Zesta, E., Lyons, L., & Donovan, E. (2000). The auroral signature of Earthward flow bursts observed in the magnetotail. *Geophysical Research Letters*, 27(20), 3241– 3244. https://doi.org/10.1029/2000gl000027