

New Architectures: Magnetosphere-Ionosphere-Thermosphere Panel

Key Questions:

- 1) What are the novel observational/model architectures/technologies that we are not utilizing as yet?
- 2) What do we need to build a fluently operating architecture from the multi-source / multi-organization observational base we have
- 3) What are the government/private resources (data/platforms) that we could utilize but are not doing so right now?

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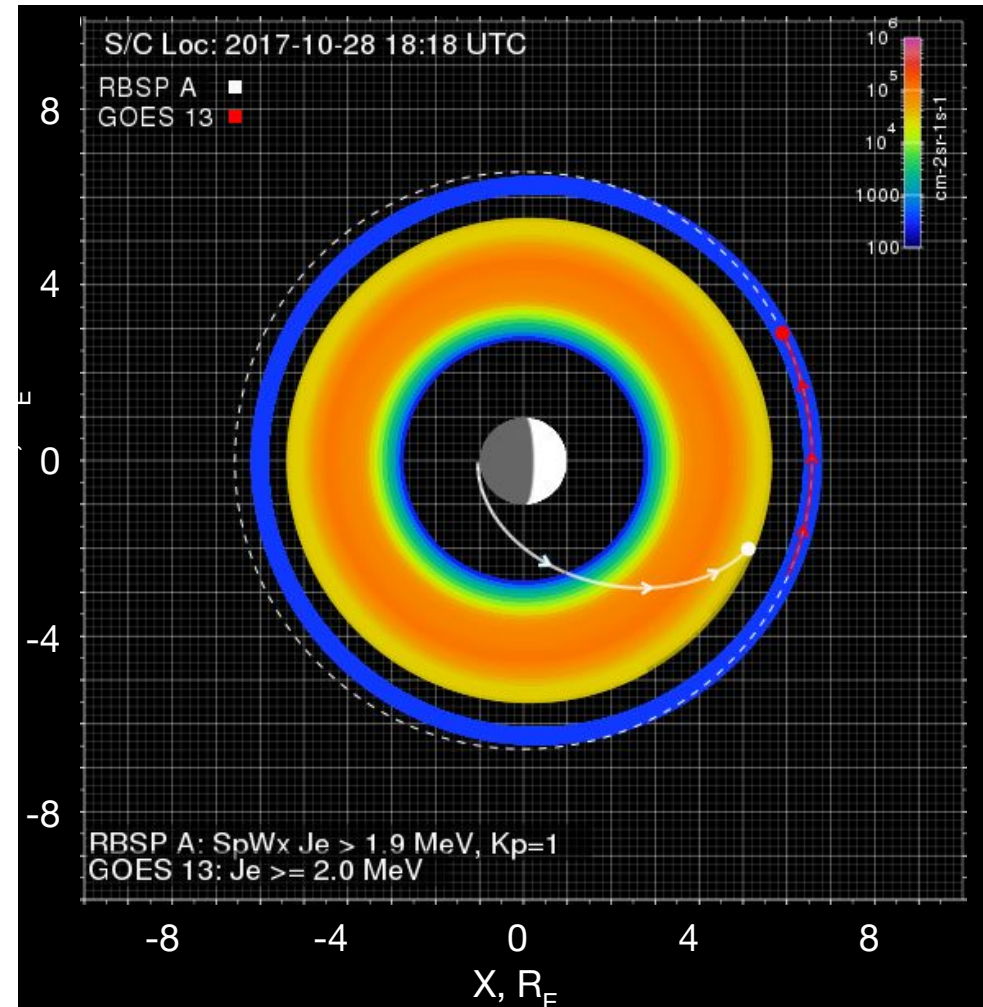
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MIT Haystack Observatory

Space Weather Operations and Research Infrastructure Workshop: Phase II, Wednesday, April 14, 2022, 1145 ET

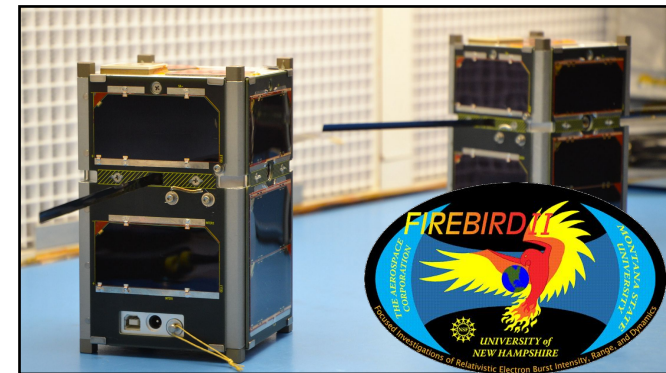
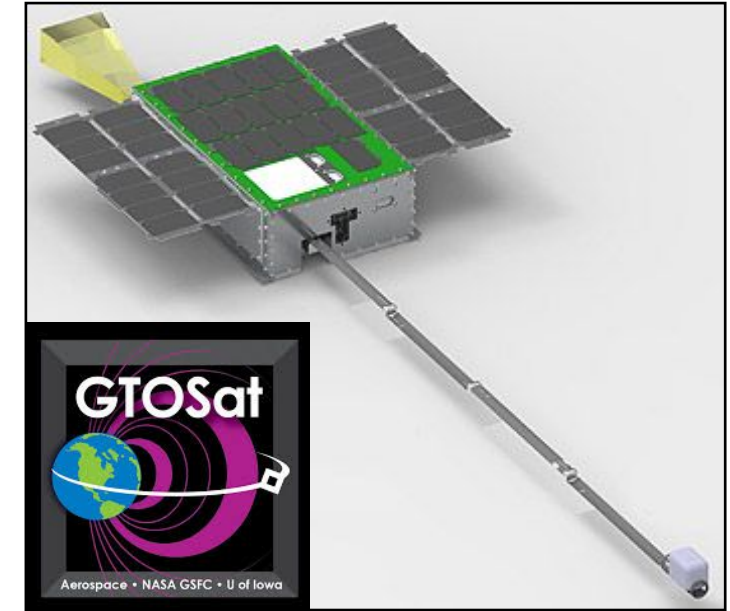
Case Study: Radiation Belt Environment

- Ever-increasing number of our Nation's space assets encounter the heart of the RB
 - GPS, weather, communications satellites, LEO-GEO transit, etc.
- Radiation enhancements can be localized ($\sim R_E$) or extend across the system ($\sim 10R_E$)
- Largest radiation enhancements occur inside GEO and above LEO orbits
- Currently gap in measurements for both science and operational use.
 - Van Allen Probes mission ended in 2019
 - We do not yet have the understanding required for prediction
 - Operational mostly data limited to GEO and LEO



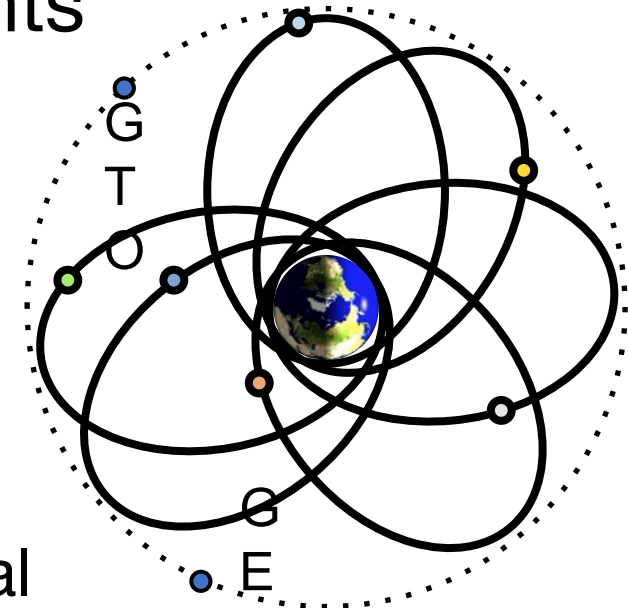
Ongoing Efforts to Leverage Opportunities

- Real-time space weather beacons
 - Demonstration by Van Allen Probes
 - Successful NASA/NOAA/international collaboration
 - Requires substantial effort, planning, resources
- Leveraging SmallSat technologies for science
 - Numerous LEO CubeSats (NSF and NASA)
 - GTOSat (June 2022) demo in heart of radiation belts
 - COSPAR international smallsat constellation effort
- LEO hosted payloads
 - REACH (Responsive Environmental Assessment Commercially Hosted) Constellation
 - 32 hosted sensors on Iridium NEXT
 - U.S. Air Force, The Aerospace Corporation, JHU APL, Iridium Communications and Harris Corporation.
 - unprecedented capability to monitor Earth's radiation environment in low Earth orbit.



Critical Need: Distributed Measurements

- Multi-point measurements for Science
 - Improved empirical models
 - Studies to assess where and when we need measurements
 - Improved understanding => better physics-based models
- Real-time monitoring for Operations
 - Inputs to forecasting and nowcasting models
- Coordination: agencies, commercial, academia, international
 - What policies, programs, incentives are needed to increase opportunities to use commercial platforms for hosted instruments or data-buy?
 - What are the barriers for international cooperation (regulatory, timing of funding, launch opportunities)?
- Getting the most from distributed measurements
 - What are the best infrastructure models to get the data down & useable?
 - benefits of onboard processing, AI
 - distributed ground stations & operations centers, data pipelines
 - How do we efficiently combine data from different platforms (including ground-based and simulations)?



Commercial data acquisition for space weather

- USG procurement is generally slower than commercial development.
 - Difficult to incorporate space weather instrumentation designs and accommodation into commercial implementation: Commercial design/development moves fast.
 - Use what is already designed or implemented for other purposes. Ideal parameters may not be available: need to adapt, e.g. magnetic field at low ~ 30 nT resolution vs plasma drift.
 - Effort for science/space weather becomes post-acquisition assessment/calibration.
 - Opportunities to include custom instruments on replacement satellites may be one avenue to deploy targeted sensors.
- There are no guarantees of performance vis-à-vis requirements.
 - Parameters, sensitivity, noise, resolution, sampling cadence all set/chosen by commercial provider.
 - Assessment of suitability for science/space weather may be labor intensive: develop new validation/calibration methods and processing techniques. Decision re. utility may not be possible until substantial effort is invested. May involve significant participation from vendor – esp. vehicle supporting data to investigate noise/contamination/calibration.
 - Customizing acquisition may not be possible, i.e. sampling region or rate, attitude/pointing ...
- Buy-in from commercial provider as a product development effort may be required.
 - Note that USG engineering contracts (e.g. NASA missions) can require compliance with federal acquisition requirements – which some commercial entities will not do.
 - Once the product is developed a data-buy model can be used ... but it may not be possible to explicitly fund the development effort on the commercial side.
- LEO is very well populated and getting more-so.
 - Iridium and/or Globalstar were impressive constellations wrt number of satellites up until a few years ago (Iridium still is for the unique/specific capabilities it offers).
 - Starlink, Planet Lab, and others have/will have 100s to 1000s of satellites with continual refresh.
 - Magnetometers are one of the most common instruments included on cubesat class platforms because they provide attitude backup: whether these data are sufficient to meet space weather needs is not yet known.

Research vs real-time: large effort difference

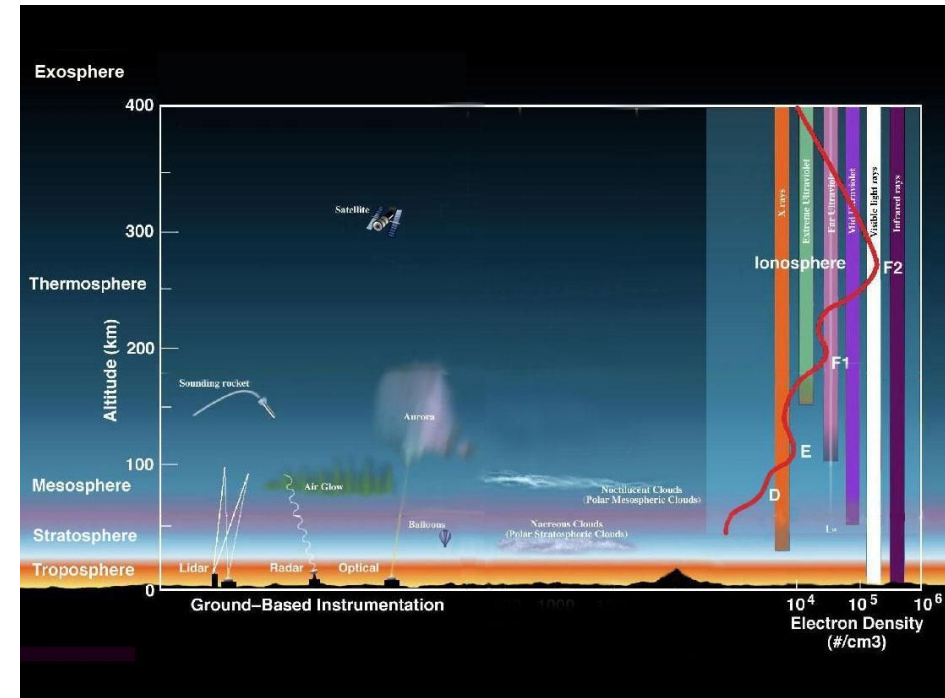
- Data acquisition for research can be economical.
 - Non-interference with commercial mission – nice to have – best effort basis. Constellation operation and primary mission objectives take priority: continuous data is not assured.
 - Transmission of some data to ground in real-time from LEO is not guaranteed although it is no longer unusual.
 - Receipt of all required data (e.g. not just sensor – but supporting data), pre-processing, calibration analysis, and product generation are generally delayed relative to acquisition time.
 - System and staffing stability are not major issues because there are no hard deadlines.
 - Delays related to system/software updates, power outages or hardware failures and uneven staffing due to competing commitments, weekends, holidays, absences, and turnover.
- Real-time acquisition and operation is resource intensive.
 - Benefit to commercial provider needs to be sufficient to bring space weather data priority on par with primary mission.
 - Transmission of ALL required data in real-time, pre-processing, and accessions must be done in real-time. Substantial development upgrade likely relative to science support.
 - Operations requires robust, dedicated computer systems and backup capabilities at both data provider and science processing center in case of computer malfunction, power outages, etc.
 - Staffing plan must include at least a 24/7 on-call component for both data acquisition and product processing.
 - Constellations are robust technically to individual satellite data drop-outs, but are also subject to a wide variety of surprises in types of non-nominal behavior that affect processing, e.g. relative timing of different data streams that might break the product generation. Anticipating all the ways the system might break is very complex.

Handling heterogeneous data: disparate quality, parameters, distribution, cadence

- Distribution of observations though 'global' is dynamic and uneven.
 - LEO is by far the most densely sampled region. Even there, irregularity in the observation distribution and re-sampling cadence must be accommodated in derivations of products.
 - Largely use what is already implemented designed.
 - Development effort focuses the post-acquisition assessment/calibration effort.
- Handling varying accuracies and noise.
 - Accuracies and noise vary even between 'identical' vehicles in the same constellation.
 - Different sources of data will have very different qualities.
 - Need to quantify errors/uncertainties of each data source and use covariance verification to cast this information in useful form for assimilation analyses.
- Multi-parameter assimilation is key.
 - Assimilation in the classic tropospheric weather use via transport equations may be challenging for the multi-scale M-I-T system.
 - The ionosphere may be amenable to assimilation using equations of electrostatics as a means to infer electrodynamic state from disparate parameter sets. e.g. long history of KRM, AMIE, and modern developments such as AmGEO.
 - Validation of models/simulations at ionospheric projection should be a powerful technique to validate models/simulations in real-time. Most important for intense/unusual events.

What is needed to build a fluently operating architecture from the multi-source / multi-organization observational base we presently have?

- To Make Progress on Open Science Questions, Heterogenous Data Sets Will Be Used
- Multi-source / multi-organization observational base
 - Ground-based & Space-based
 - Government, Industry, Research/Academia



Leveraging Heterogeneous Data Requires *Excellent* CVV Of Each Instrument

Calibration, Validation, & Verification

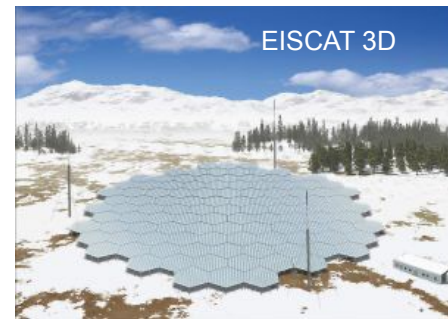
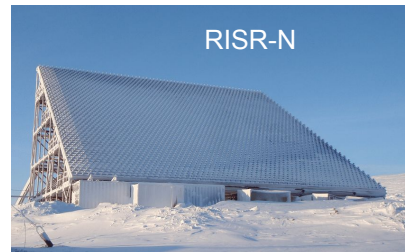
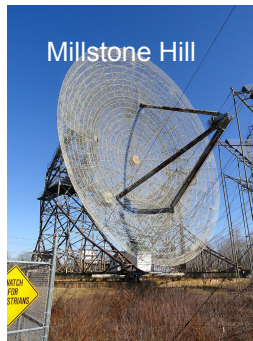
- Mission concept, Pre-launch, Early on-orbit check-out, Intensive Cal/Val, Long term monitoring
- Cross-platform, Cross-instrument
 - Satellite constellations, ground-based
- Data Assimilations
 - Require uncertainties, error covariances

CVV Will Continue to Depend on Both Ground-Based & Space-Based Instruments

- Requires Resources & Agency Coordination
 - Will certain instruments be available when needed?
 - Are there alternatives?
 - What resources are needed to keep these world-class instruments operational when needed for CVV? What resources are needed for operators to support CVV activities?
- Are CVV activities rewarded in the scientific community?
 - What are the incentives to do this work?



Ground based instruments: Considerations for usable space weather data

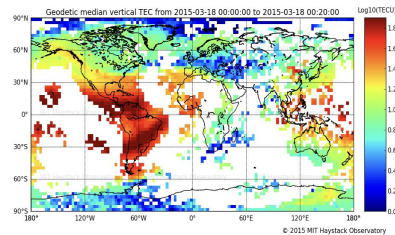


“Odd vs. even pulses”

- **Vast difference** between research / flexible grade and production grade approach
 - Harder (but not impossible) after the fact
 - Not likely to occur ad-hoc
 - Do both: e.g. “Even pulses” = always same mode for SW, “odd pulses” = research/dev
 - Instrument design must keep multiple analysis/operation pathways viable
- SW feeds must be properly and separately resourced in both people and materials
- Ideally, designed for SW production from the start, not a post-construction addition
- Follow spacecraft methods: define SW requirements up front
 - Time cadence? Measurement fidelity?
 - VETTED UNCERTAINTIES? (mandatory for any forecast use!)
 - Basic [Level 1] vs derived products [Level 2+]? The latter take resources. Which are “community vital”?

Future SW instrumentation *will be* network-centric

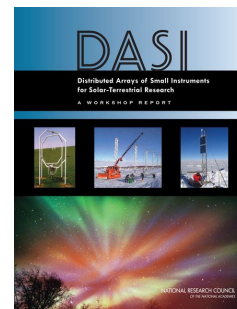
GNSS TEC



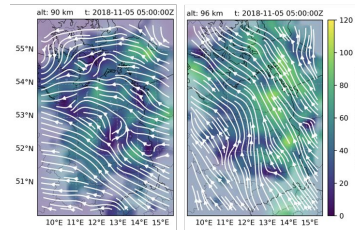
- Meta-instruments [e.g. GNSS TEC]: the networked data IS the instrument and exists only in the processor, not the sensor level
 - Design metadata flow to enable the meta-instrument
 - Try to anticipate metadata for future uses [this is hard work!]
 - REALTIME flow important, vs retrospective analysis (most of I-T-M science): what latency is too large for effective SW work?
 - *Where and when* are measurements useful?
- Space weather advances demand **multiscale** observations
- If networks are the future, you need a tech toolkit that efficiently uses them (look to *radio astronomy* for array design practices, for example)
- But data assimilation is harder in a multiscale system - community must be ready (e.g. how to deal with simulation artifacts that are generated at smaller scales)
- Observational structural design: use OSSE to simulate optimal sensor designs; these also define your critical requirements
- Again: **intentional space weather design practices from the start**, rather than ad-hoc later after the fact

Erickson/MIT Haystack

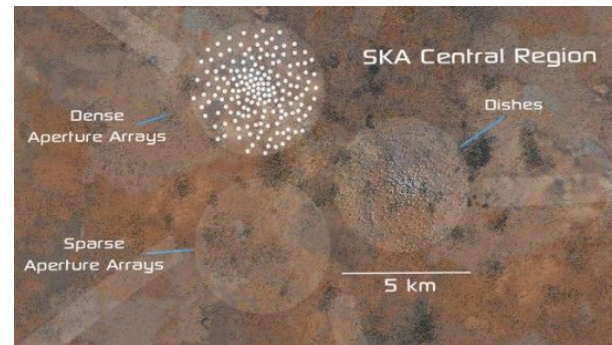
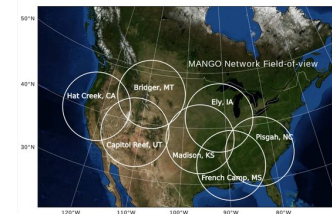
NASEM I-T-M New Architectures



MANGO all-sky imager network



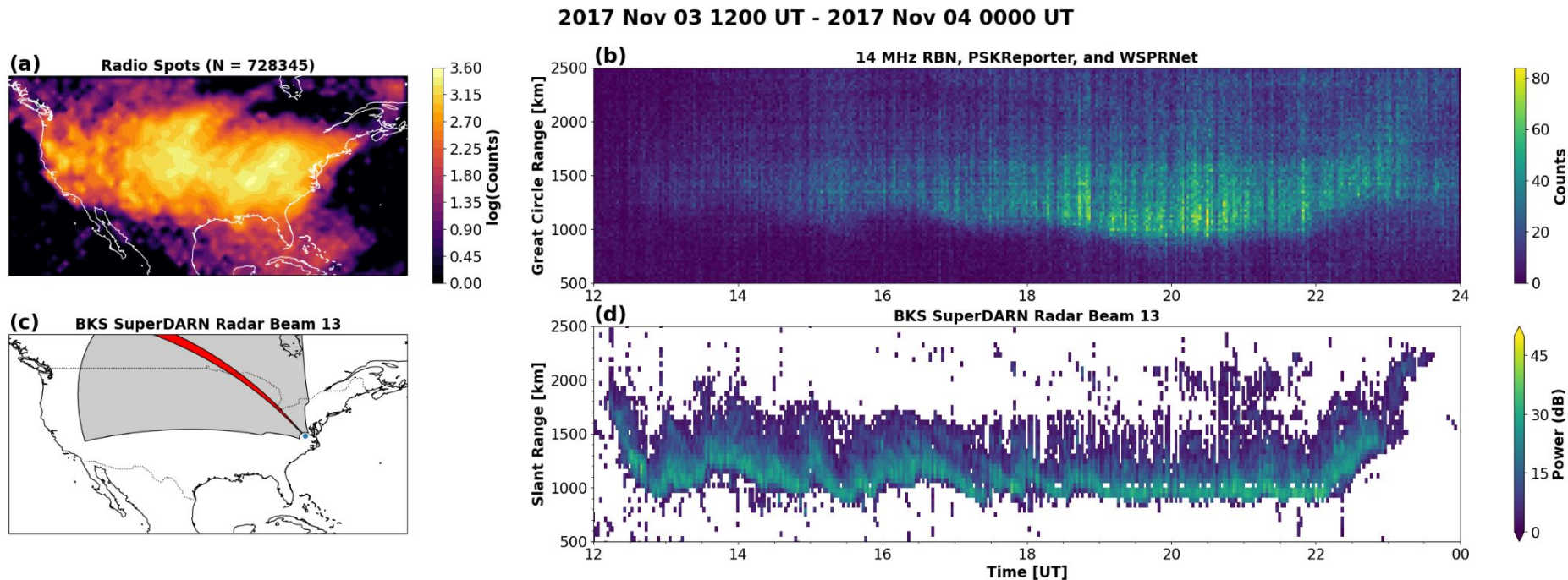
MIMO Meteor Wind Radar



SKA (Radio Astronomy sparse aperture)

2022-04-14

Innovate from Non-traditional Data Sources with Unique Sampling



Bottomside TIDs observed with crowd-sourced ad-hoc Amateur Radio comms (top)
Vetted against SuperDARN Blackstone HF Radar simultaneous observations
Frissell et al 2022 <https://doi.org/10.1029/2022GL097879>

Can we resource this properly as a SW tool?
Unique Spatiotemporal Sampling...

Consider the Diverse Palette of “Agency DNA”

- NSF, NASA are science question driven
 - Advances the knowledge frontier
 - Studies are often retrospective driven (data already exists)
 - Resources not always driven towards production of reliable, calibrated/validated, always-on data streams: Agency buy-in
- NOAA is operationally driven
 - Closer to space weather network needs
 - Forecast/prediction focus
 - But requires a rigorous approach to production-level system requirements that is not always easy for discovery science mode
- SWO2R, R2O efforts are attempting to weld these two approaches together
 - Requires dedicated inter-agency cooperation
 - Requires *liberal, free access* to both realtime and retrospective data streams - how can the commercial connection support this?
 - Workforce: train community to better define the production level requirements of space weather systems (not often taught in academic settings)