

The background is a deep blue gradient with a subtle pattern of white dots, resembling a starry sky. Overlaid on the left side are several concentric circles and arcs in a lighter blue color. A prominent circular scale with degree markings from 140 to 260 is visible. Other smaller circles and arcs are scattered across the left half of the image, some with arrows indicating direction.

SENSOR “CENSUS”

NASEM ROUNDTABLE

FOCUS OF THE SENSOR “CENSUS”

- Existing near surface observations (ground-based, airborne, or buoys)
- US-owned and/or maintained sensors and networks
- Priority to sensors identified by the PROSWIFT Act
- Priority to sensors with potential for use in space weather operations

TYPES OF SENSORS, AS DESIGNATED BY PROSWIFT

The PROSWIFT Act states that "... ground-based observations provide crucial data necessary to understand, forecast, and prepare for space weather phenomena" ...

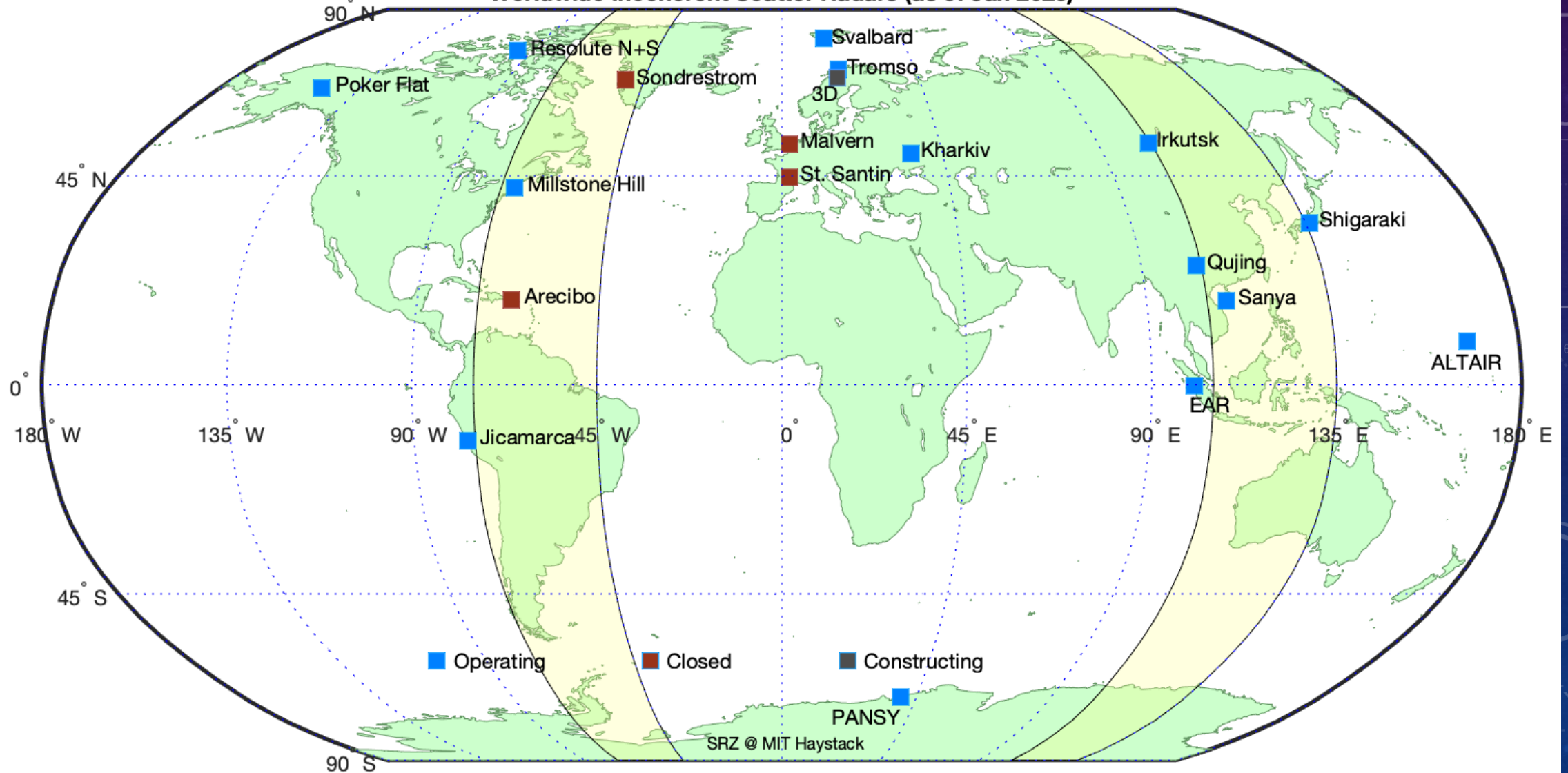
... which it defines as "radars, lidars, magnetometers, neutron monitors, radio receivers, aurora and airglow imagers, spectrometers, interferometers, and solar observatories."

	SpaceWx application(s)	Sensors/networks	Funding source	Operational capability
Incoherent Scatter Radars	Satellite drag	RISR-N	NSF	Data available through Madrigal
		Poker Flat		
		Millstone Hill		
		Jicamarca	Partially NSF-funded	
Magnetometers	Power grid (GIC), Satellites (Radiation belts), Navigation	UCLA - SMART	NSF	Near real-time
		MagStar	NSF	Real-time and MADRIGAL access
Neutron Monitors	Aviation, Radiation monitoring	Simpson Neutron Monitor Network	NSF	8 in real-time, through NMDB
GPS/GNSS Receivers	Navigation, Aviation (TEC, ionosphere)	NOAA CORS	Multi-agency	
		Orion Space Solutions network		Real-time
Interferometers and Imagers	Power grid (auroral boundary), Satellite navigation and drag	MANGO Array	NSF	Near real-time (Imagers) and 1-day latency (FPIs)
		Kerr-CPI Array	Partially NSF-funded	MADRIGAL access
Solar Observatories	Power grid, Navigation, Aviation, Satellites	GONG	NSF and NOAA	1-4 day forecast using WSA-Enlil model
		SEON	Air Force	Near real-time

INCOHERENT SCATTER RADARS

RISR-N/RISR-C, POKER FLAT ISR, MILLSTONE HILL ISR, JICAMARCA ISR, SUPERDARN

Worldwide Incoherent Scatter Radars (as of Jan 2023)



RISR-N and RISR-C

Deployment Info: 2015

Years Operational: 8 years

Funded through: NSF (RISR-N) and Canada (RISR-C)

The Advanced Modular Incoherent Scatter Radar (AMISR) design was created in 2000 by SRI International and funded in 2003 by NSF as a relocatable incoherent scatter class radar, becoming the first IS radar system purpose-built for basic ionospheric research. AMISR was designed as a UHF phased-array, solid-state incoherent scatter radar with modular and reconfigurable features for easy dismantling and relocation.

Poker Flat Incoherent Scatter Radar (PFISR)

Deployment Info: 2007

Years Operational: 16 years

Funding Source: NSF

The first radar face of AMISR became operational in Poker Flat, Alaska (PFISR) in 2007, with the remaining two faces operational in Resolute Bay (RISR-N) in 2009 and Nunavut, Canada (RISR-C, operated by Canada) in 2015. PFISR provides subauroral and auroral zone ionospheric measurements and also supports rocket launch activities at the NASA Poker Flat Rocket Range in Alaska. The system has enabled many important studies, including 3D studies of traveling ionospheric disturbances [103], volumetric imaging of the auroral ionosphere [104], electron density during pulsating aurora [105], nightside ionospheric electrodynamics associated with substorms [106], fine scale auroral ion temperature dynamics [107], and intense ion upflows in near-cusp regions associated with storm enhanced density plume transport [108].

ISR descriptions taken from:

***Science and Discovery Through Incoherent Scatter Radar:
Brief History, Development, and Future Directions, A. J.
Coster, P. J. Erickson, Published in
https://ursi.org/Publications/URSI100/URSI100_book.pdf***

<http://cedar.openmadrigal.org>

Millstone Hill ISR

Deployment Info: 1961

Years Operational: 60 years

Funded through: NSF

The first experimental configuration of the Millstone Hill Incoherent Scatter Radar occurred in 1961 on the campus of MIT Haystack Observatory in eastern Massachusetts, when an existing UHF satellite tracking radar with a 26 meter class antenna was tasked for occasional incoherent scatter measurements by Dr. J. V. Evans and colleagues. The available 26 m satellite tracking antenna was not ideally suited for incoherent scatter work, and its aperture could only achieve marginal performance at the radar's 440 MHz center frequency. Nevertheless, it did allow Millstone to be the first to publish IS observations using a full incoherent scatter radar system [24]. In 1962, the 26 m satellite tracking radar was converted to L-band, freeing the UHF transmitter for other purposes. In 1962-63, Evans had a 68 m diameter fixed zenith pointing antenna built specifically for use in incoherent scatter measurements and the now spare megawatt class UHF transmitter was attached, forming the first dedicated Millstone Hill IS radar. In 1978, a 46 m fully-steerable antenna (MISA) and rapid transmit antenna switch was added to the radar configuration, providing ionospheric measurements over a wide spatial field encompassing the eastern US, Canadian border, and into the Caribbean. The MISA antenna was originally designed by SRI and moved from the Sagamore Hill Air Force facility where it was originally installed. Millstone Hill's key studies include storm enhanced density (SED) [25] and sub-auroral polarization stream (SAPS) [26] velocity flows driven by strong magnetosphere-ionosphere coupling in the mid-latitude and subauroral ionosphere, empirical models of subauroral and high latitude electric fields [27], optimal full altitude signal processing [28], software radar approaches [29], ionosphere-thermosphere coupling [30], and mid-latitude E and F region electrodynamic coupling through Farley-Buneman two-stream instability diagnostics [31]. Millstone Hill has continued uninterrupted incoherent scatter radar observations of the mid-latitude and sub-auroral ionosphere for more than 60 years under NSF support, and is operated for the community as part of the multi-disciplinary Millstone Hill Geospace Facility.

<http://cedar.openmadrigal.org>

Jicamarca

Deployment Info: 1960/1961

Years Operational: 60 years

Funded through: partially supported by NSF

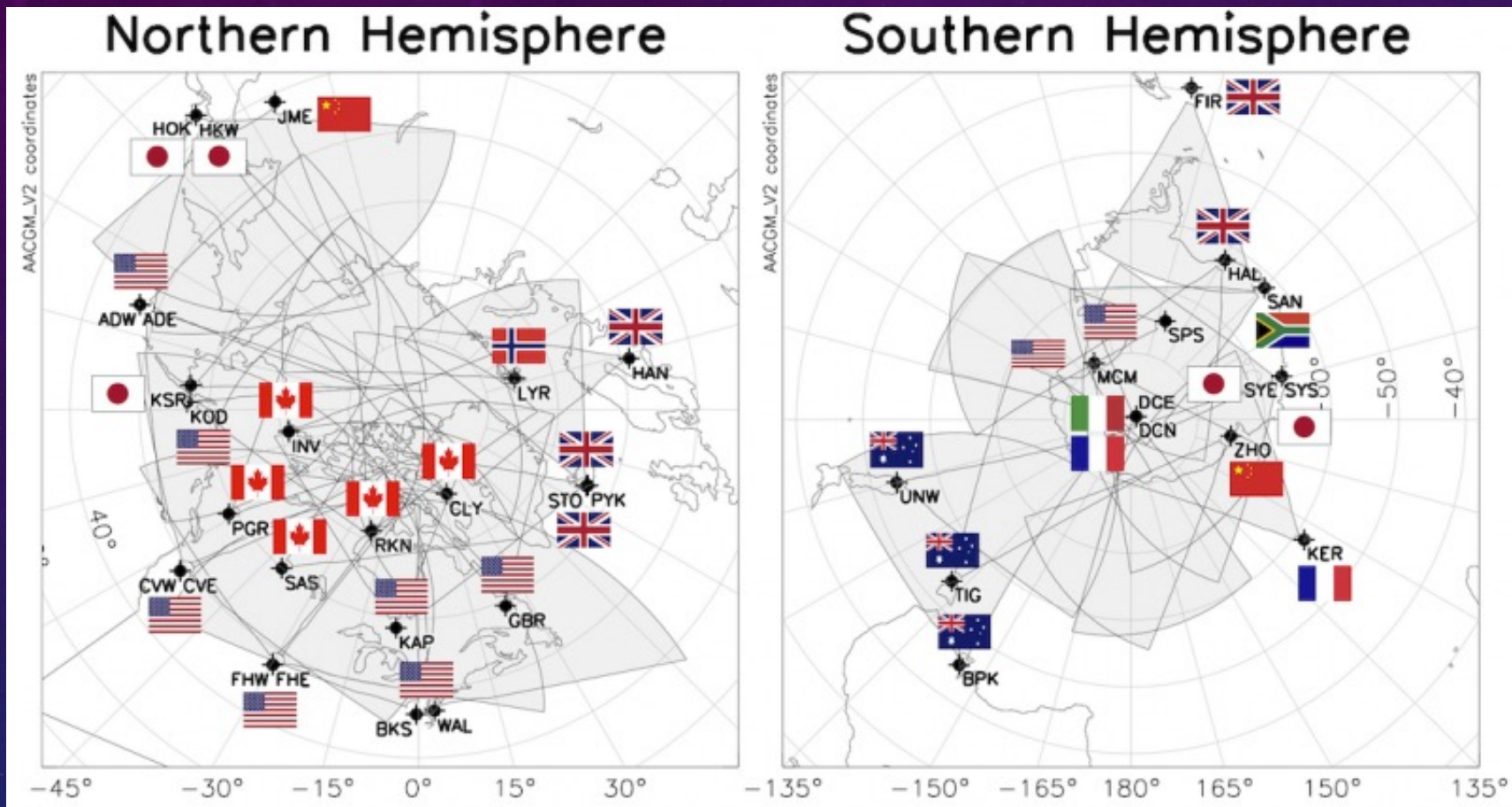
The 50 MHz incoherent scatter radar at the Jicamarca Radio Observatory near Lima, Perú was constructed beginning in 1960 through 1961 by K. L. Bowles, B. Balsley, G. Ochs, G. Miller, and J. Green of the National Bureau of Standards (NBS), soon after the 1957 International Geophysical Year (IGY) [13]. . This lab later became part of the Environmental Science Service Administration (ESSA) and then the National Oceanic and Atmospheric Administration (NOAA). In 1969, the Observatory was turned over to the Instituto Geofísico del Perú (IGP) which had been cooperating with CRPL during the International Geophysical Year (IGY) in 1957–58 and had been intimately involved with all aspects of the construction and operation of Jicamarca. ESSA and then NOAA continued to provide some support to the operations for several years after 1969, in major part due to the efforts of the informal group called “Jicamarca Amigos” led by Prof. William E. Gordon. Prof. Gordon invented the incoherent scatter radar technique in 1958.

A few years later the National Science Foundation began partially supporting the operation of Jicamarca, first through NOAA, and since 1979 through Cornell University via Cooperative Agreements. In 1991, a nonprofit Peruvian organization—called Ciencia Internacional (CI)—was created to hire most observatory staff members and to provide services and goods to the IGP to run the Observatory.

<http://cedar.openmadrigal.org>

SuperDarn

All information below taken from <http://vt.superdarn.org/>



US-operated installations:

(Northern Hemisphere)

- Adak Islands East/West
- Blackstone
- Christmas Valley East/West
- Fort Hays East/West
- Goose Bay
- Kapuskasing
- Kodiak
- Wallops Island

(Southern Hemisphere)

- McMurdo
- South Pole Station

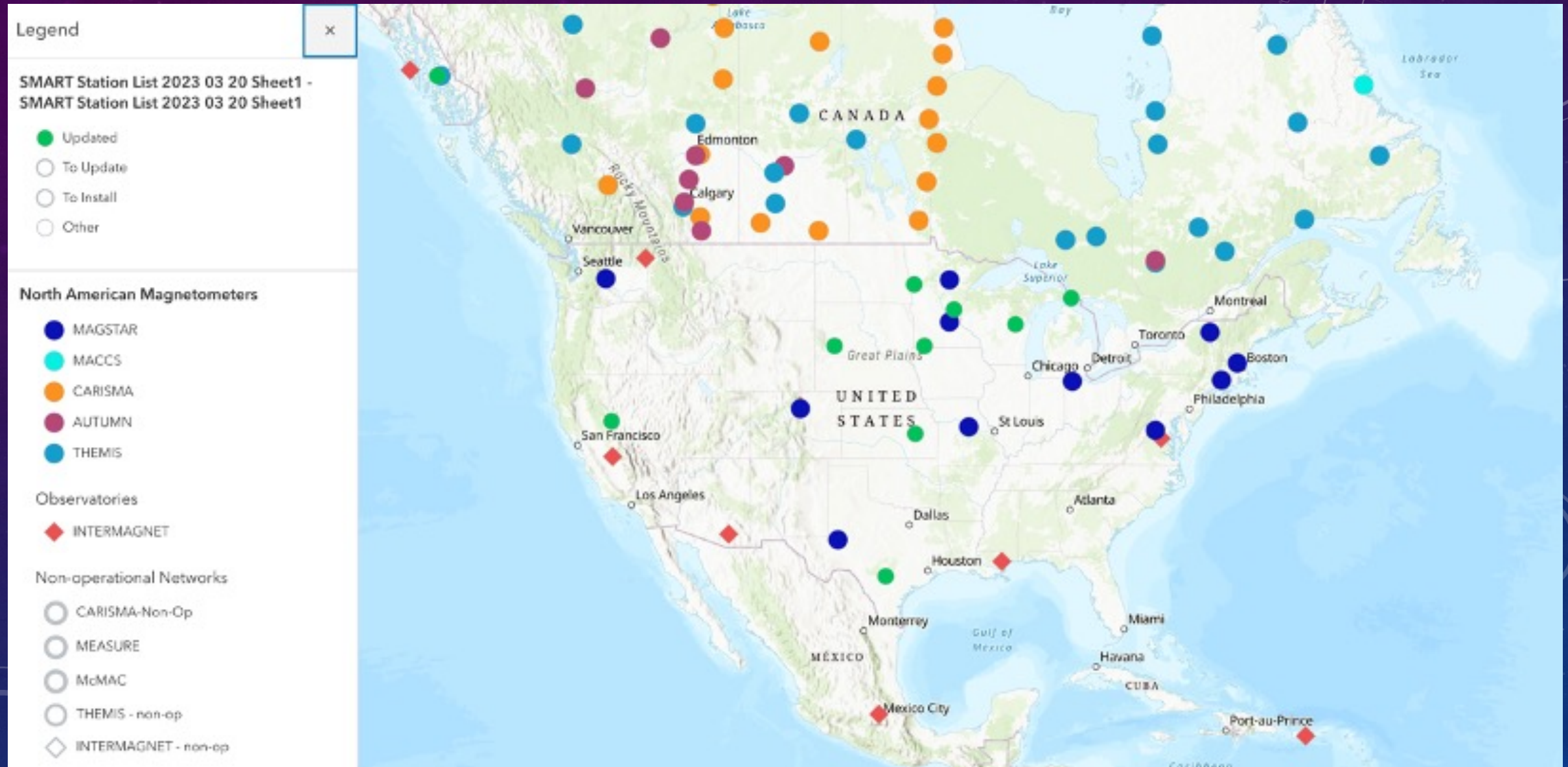
"This is a list of all SuperDARN radars. It includes radars which are currently not operational, such as the Falkland Islands Radar." More information is available through the superdarn webpage.

MAGNETOMETERS

UCLA SMART ARRAY, MAGSTAR ARRAY



Magnetometers in North America



UCLA SMART Array

Award Abstract # 2012202

Ground-based Magnetoseismic Observations with Surface Magnetic Assessment in Real Time (SMART) Network

"This project reorganizes and enhances the UCLA ground-based magnetometers in the United States, forming a network of fourteen Surface Magnetic Assessment in Real Time (SMART) stations. The SMART network will be used to answer unsolved questions about the plasmasphere."

<https://www.smartmagnet.net/data>

Station Code	Site	Geogr. Lat.	Geogr. Long.	Status
AMER	Americus, KS	38.5	-96.3	Updated
BENN	Bennington, NE	41.4	-96.2	To Update
BMLS	Bay Mills, WI	46.2	-84.3	Updated
CCNV	Carson City, NV	39.2	-119.8	Updated
DSNY	Poinciana, FL	28.1	-81.4	To Install
DRBY	Derby, VT	45	-72.1	To Update
GLYN	Glyndon, MN	46.9	-96.4	Updated
HRIS	Harris, MN	45.6	-93.3	Updated
HOTS	Hot Springs, MT	47.6	-114.7	To Update
LREL	Laurel, MD	39.2	-76.9	To Update
PTRS	Petersburg, AK	56.8	-133.2	Updated
RMUS	Remus, MI	43.6	-102.6	Updated
SATX	San Antonio, TX	29.4	-98.6	Updated
TBLE	Table Mt, CA	34.4	-117.7	To Update
SWNO	Shawano, WI	44.8	-88.6	Updated
UKIA	Ukiah, OR	45.1	-88.6	To Update
WRTH	Worthington, MN	43.6	-95.6	Updated
PLMR	Palmer, Antarctica	-64.8	-64.1	To Update



MagStar Array

MagStar was funded under the initial DASI solicitation to deploy real-time, operational magnetometers in observational gaps across the contiguous US. The data is 1 Hz, low-noise, and is provided to NOAA SWPC, several power utilities and ISOs, and other entities through an API, and to the scientific community through real-time API access and the NSF Madrigal repository.

Deployment Info: 13 installations in the Contiguous US
Data: <1 second latency, 1Hz data

<http://cedar.openmadrigal.org>

NEUTRON MONITORS

SIMPSON NEUTRON MONITOR NETWORK



Simpson Neutron Monitor Network (SNMN)

In 2021, the Simpson Neutron Monitor Network (SNMN) was created. It consists of neutron monitors owned and operated by US institutions. One of the priorities of the SNMN is to address these issues by securing, maintaining, and extending the NM observations for the coming decades.

University of Delaware / Bartol

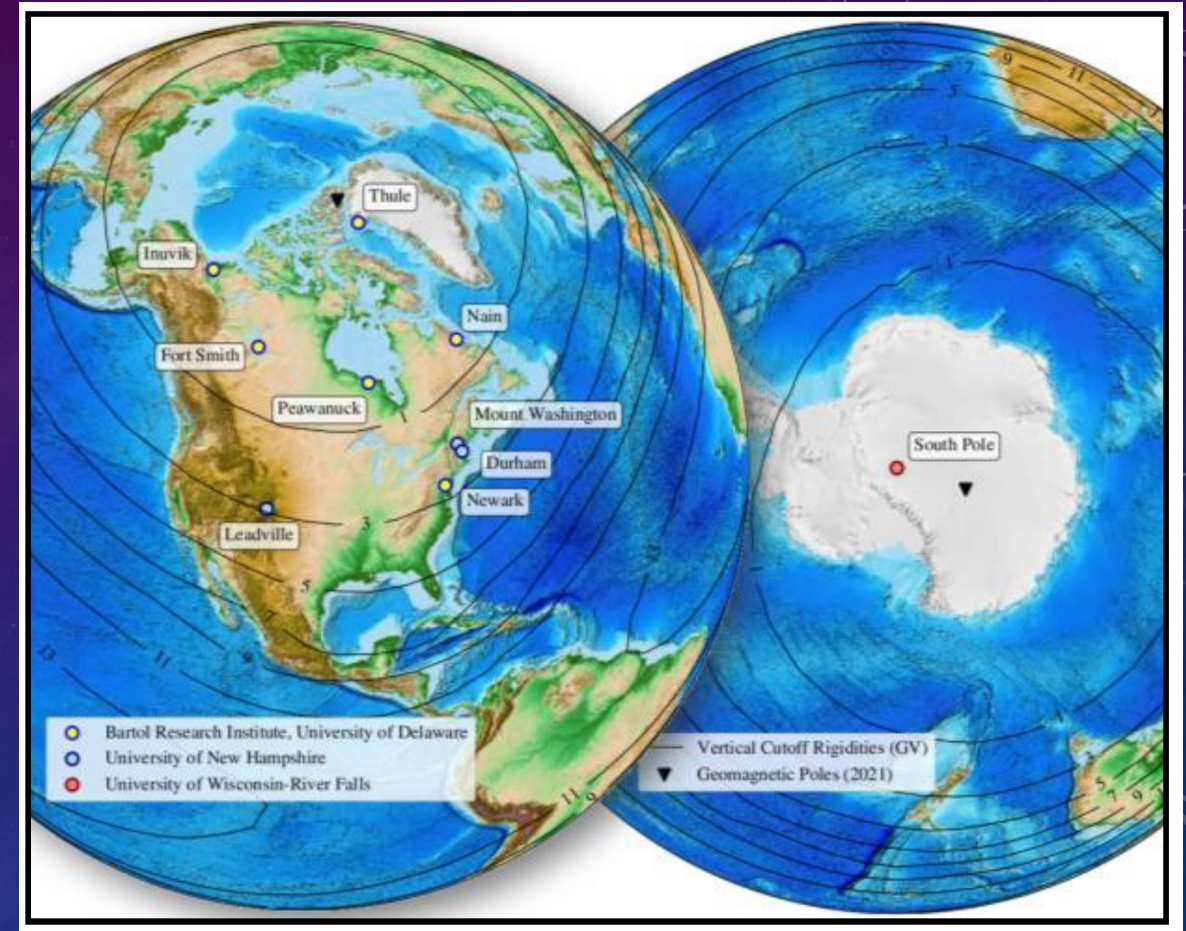
Bartol operates 9 neutron monitors in the United States, Canada, Greenland and Antarctica. Seven of these are part of SpaceShip Earth: Fort Smith, Inuvik, Nain, Newark, Peawanuck, South Pole Bare, South Pole Thule

University of New Hampshire / UNH

UNH has operated up to 6 neutron monitors: Durham, Huancayo, Leadville, Mount Washington

University of Wisconsin / UW

UW took over the operation of the South Pole NMs from Bartol: South Pole Bare, South Pole



Neutron Monitor Database (NMDB: <https://www.nmdb.eu>)

GPS/GNSS RECEIVERS

NOAA CONTINUOUSLY OPERATING REFERENCE STATIONS NETWORK (CORS), ORION SPACE SOLUTIONS NETWORK, CHAIN, UNAVCO,

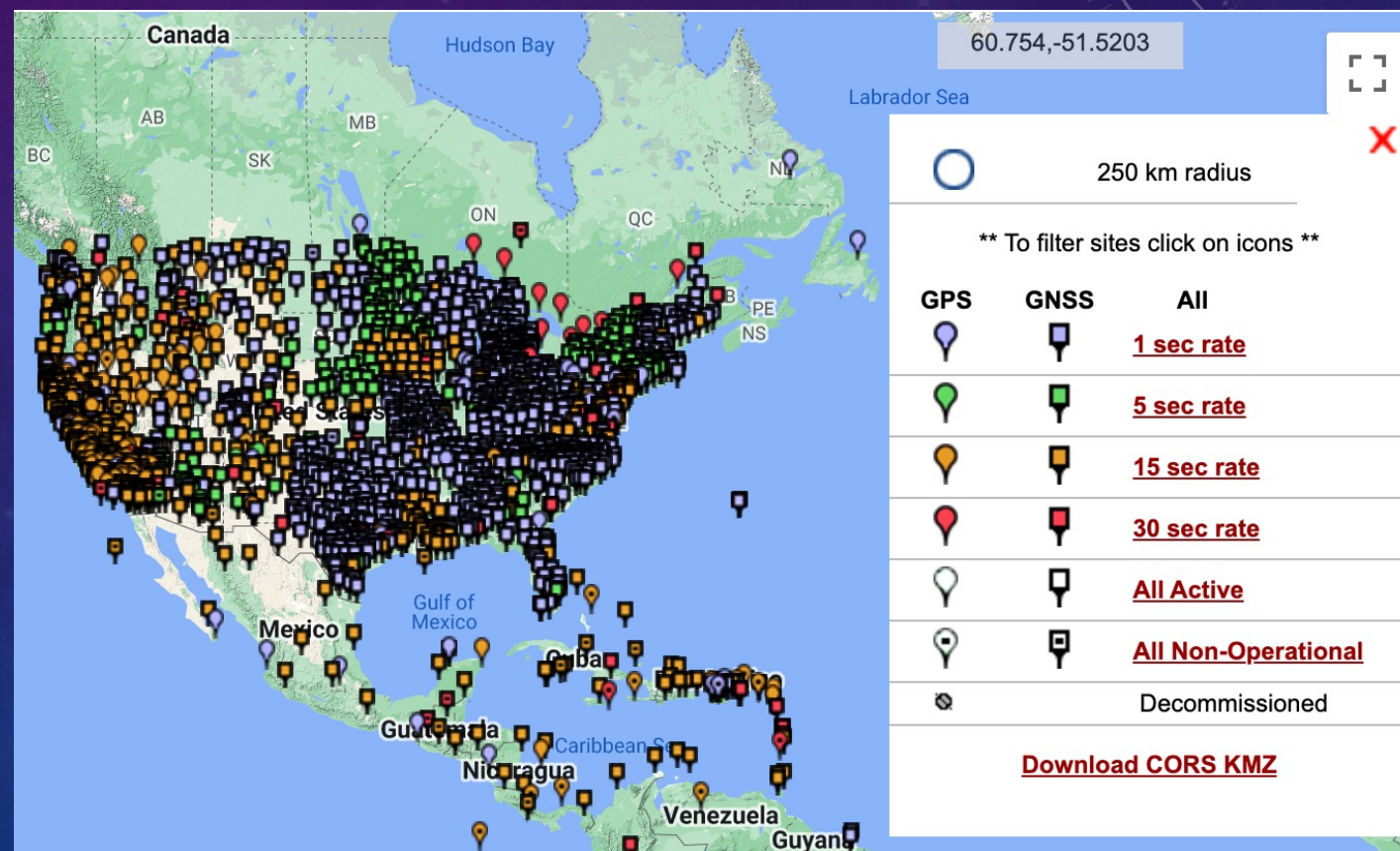
NOAA Continuously Operating Reference Stations (CORS) Network (NCN)

NCN is 2,866 stations operated by 242 partners. NOAA sets the standards, serves the data, and funds and operates 36 of the stations as federally owned to ensure longevity and quality.

NOAA CORS Network (NCN) Today:

- **Preliminary:** 5 stations (0.17%)
- **Operational:** 1778 stations (62.04%), including:
 - 173 **GPS-only** stations (6.04%)
 - 1605 **GNSS** stations (56.00%)
- **Non-Operational:** 132 stations (4.61%)
- **Suspended:** 6 stations (0.21%)
- **Decommissioned:** 945 stations (32.97%)

<https://geodesy.noaa.gov/CORS/about/contributors.shtml>



https://geodesy.noaa.gov/CORS_Map/

Other GPS/GNSS Arrays – CHAIN, GAGE, IGS, ORION Space Solutions



CHAIN

CHAIN has 25 GNSS Ionospheric Scintillation and TEC Monitors (GISTM) located throughout the Canadian Arctic.

GAGE

GAGE handles data management tasks for GPS/GNSS data and products for 2493 globally distributed permanent stations

Orion Network

Orion Space Solutions has deployed 10-15 ionospheric monitoring stations that use GPS signals to measure Total Electron Content and ionospheric scintillation.

Using these data Orion is able to map the electron density and irregularities over Alaska. These data are all real-time.

Orion has also been operating 2 instruments to monitor TEC and Scintillation in the middle of the Pacific Ocean, which have been hosted on NOAA TAO Buoys.

(Image courtesy of Jade Morton)

Orion Network

Orion Space Solutions builds and has deployed numerous ionospheric monitoring stations that use GPS signals to measure Total Electron Content (TEC) and ionospheric scintillation in the ionosphere.

In Alaska, Orion leverages this data to map the Total Electron Content (TEC), electron density profile, and scintillation (irregularities) in real time. These density profiles and irregularities have numerous applications.

In the middle of the Pacific Ocean, hosted on NOAA TAO Buoys, Orion also operates two ionospheric monitoring stations measuring TEC and scintillation .

In Boulder, CO an Orion receiver has operated for over 10 years collecting TEC and scintillation data.

Orion Arctic Ionospheric Monitoring using GNSS

Site Location (see map)

Poker Flat Research Range, AK
Barrow, AK
Gakona (HARP site), AK
Toolik Field Station, AK
Thule AB, Greenland
Ft. Yukon, AK
Kaktovik, AK
Eagle, AK

Orion Middle and Low Latitude GNSS Sensors

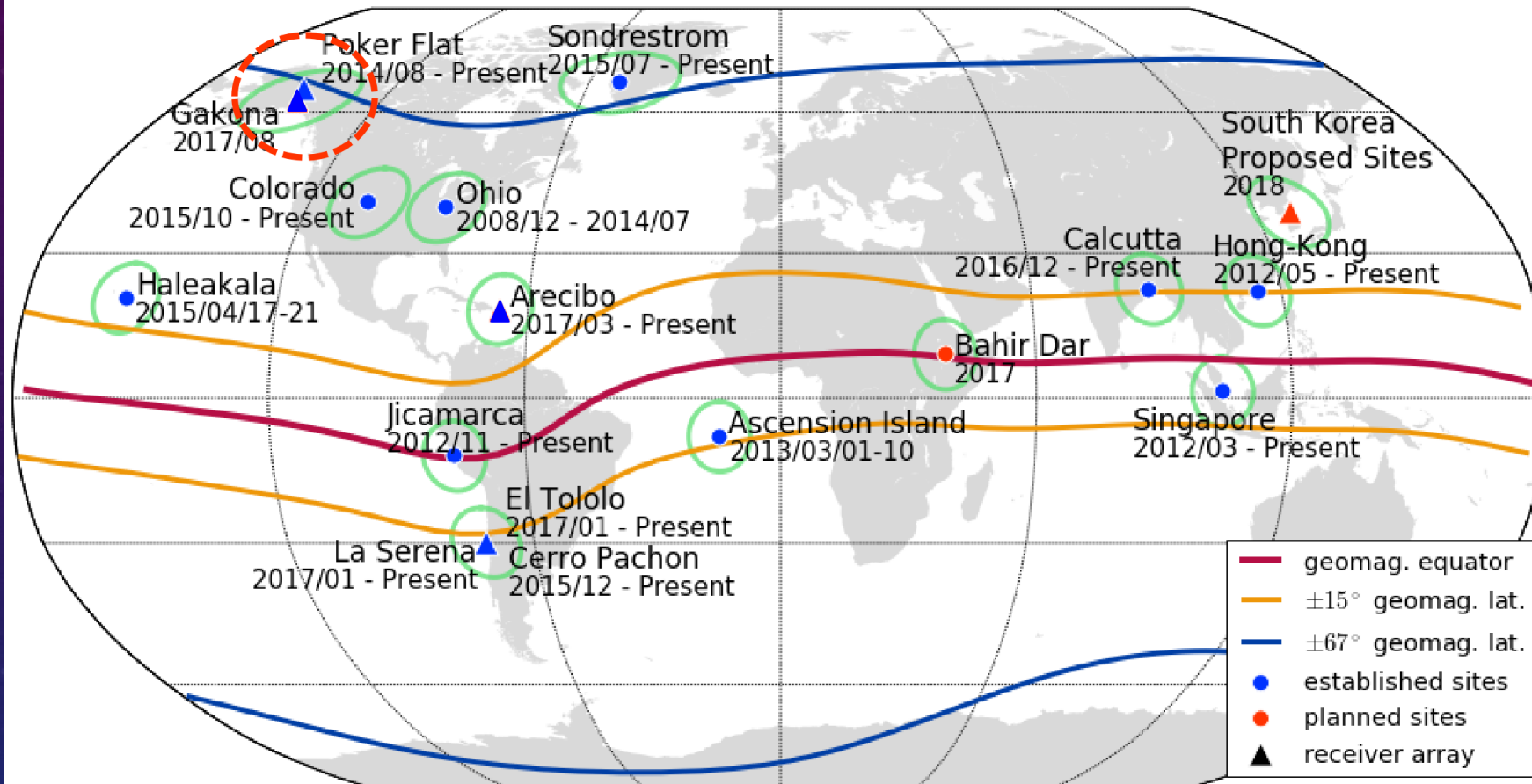
Boulder, CO
Western Pacific Ocean (on two NOAA TAO buoys)

ORION'S ALASKA CURRENT (8) OPERATIONAL REAL-TIME GNSS RECEIVERS



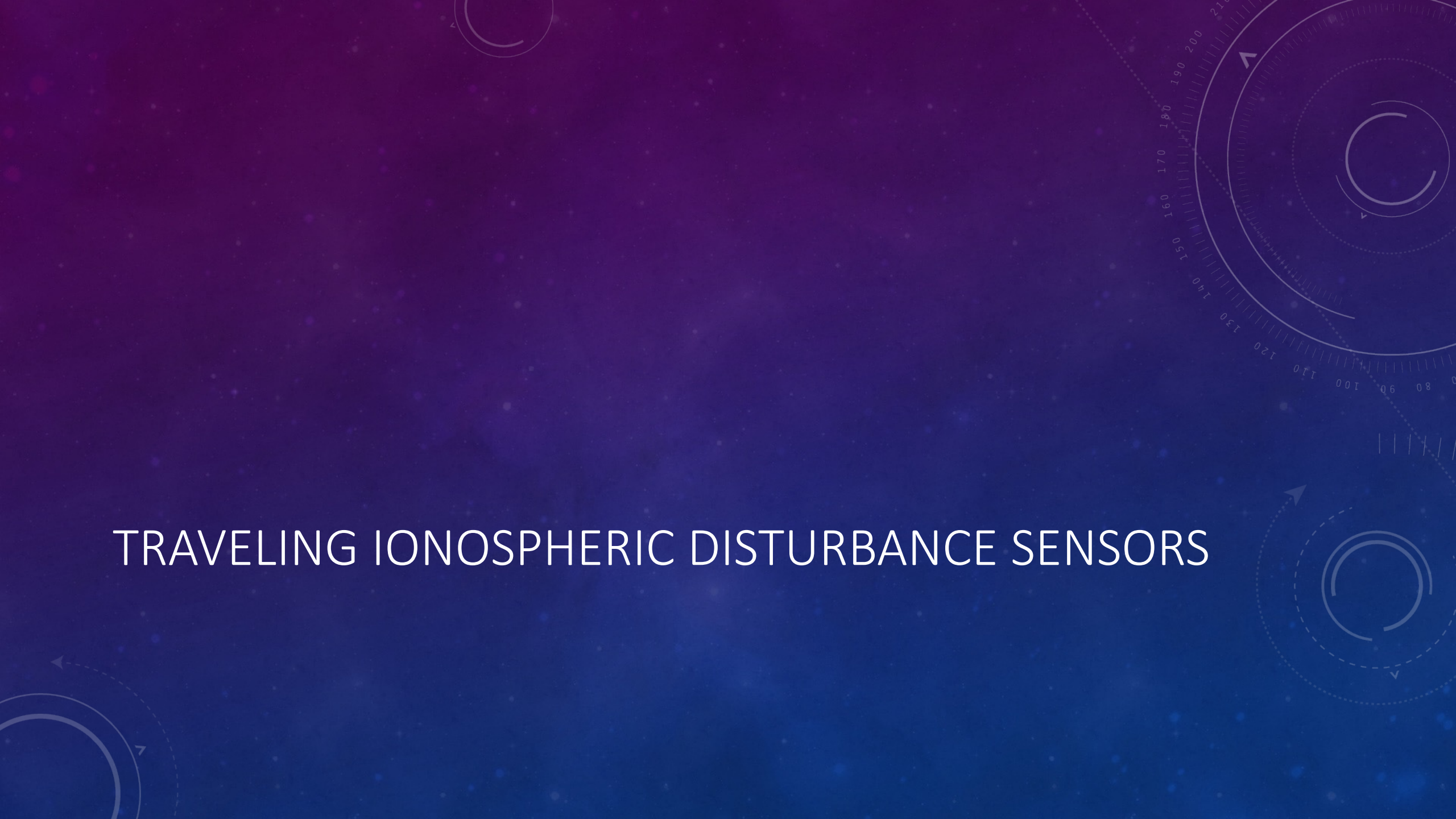
CSU GNSS Network

~350TB and growing



Morton, Y., Y. Jiao, and S. Taylor, "High-latitude and equatorial ionospheric scintillation based on an event-driven multi-GNSS data collection system," *Proc. Ionospheric Effects Sym.*, Alexandria, VA, May 2015.

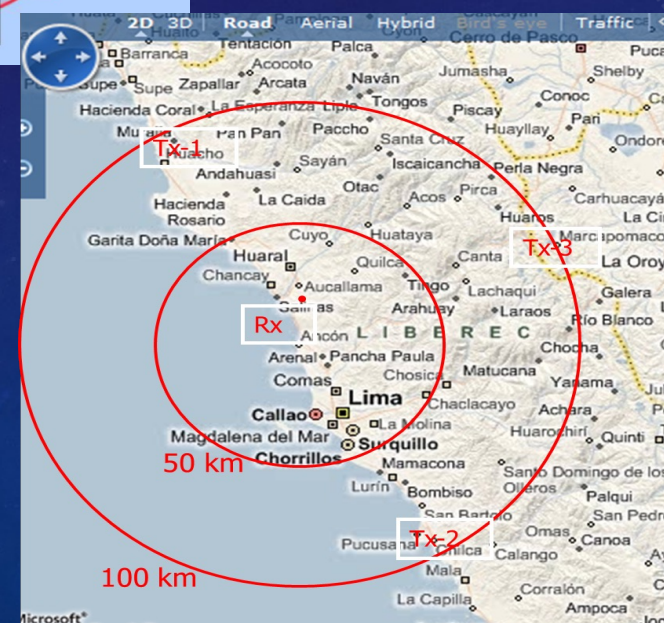
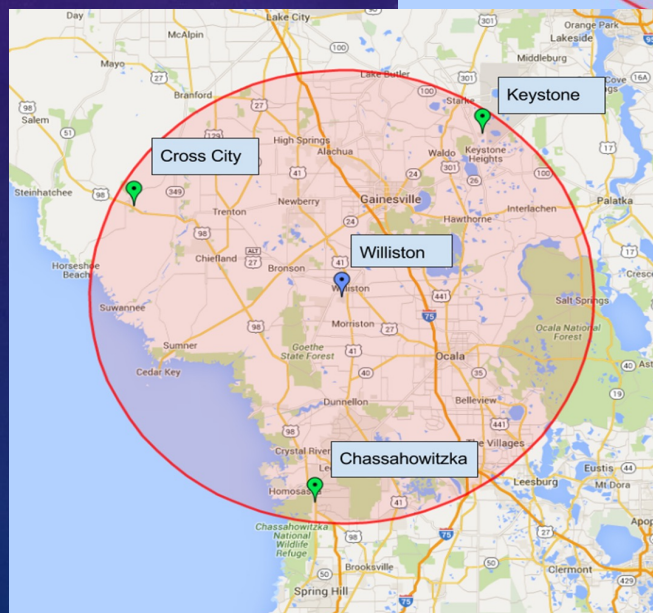
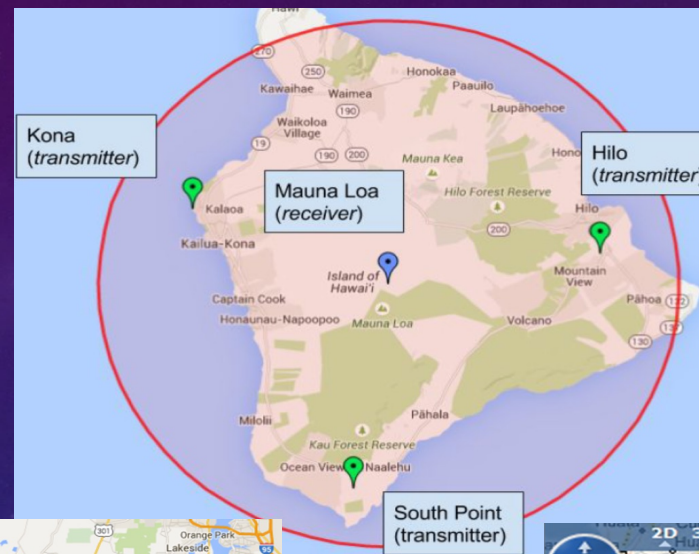
TRAVELING IONOSPHERIC DISTURBANCE SENSORS



Characterizes travelling -ionospheric disturbances (TID) using reflected HF radio signals from multiple transmitters and a central receiver. Provides TID wave amplitude and wave velocity as a function of wave frequency across the entire acoustic and gravity wave spectrum

Orion operates the only operational sensor measuring TIDs in 3 locations, Hawaii, Florida and Peru. Previously a TIDDBIT system was located at Wallops Island to support rocket launch analysis from that location

The detection of TIDs has been correlated to ocean waves, weather phenomena (thunder storms and hurricanes), aurora, tsunamis, rocket launches, and explosive detonations.

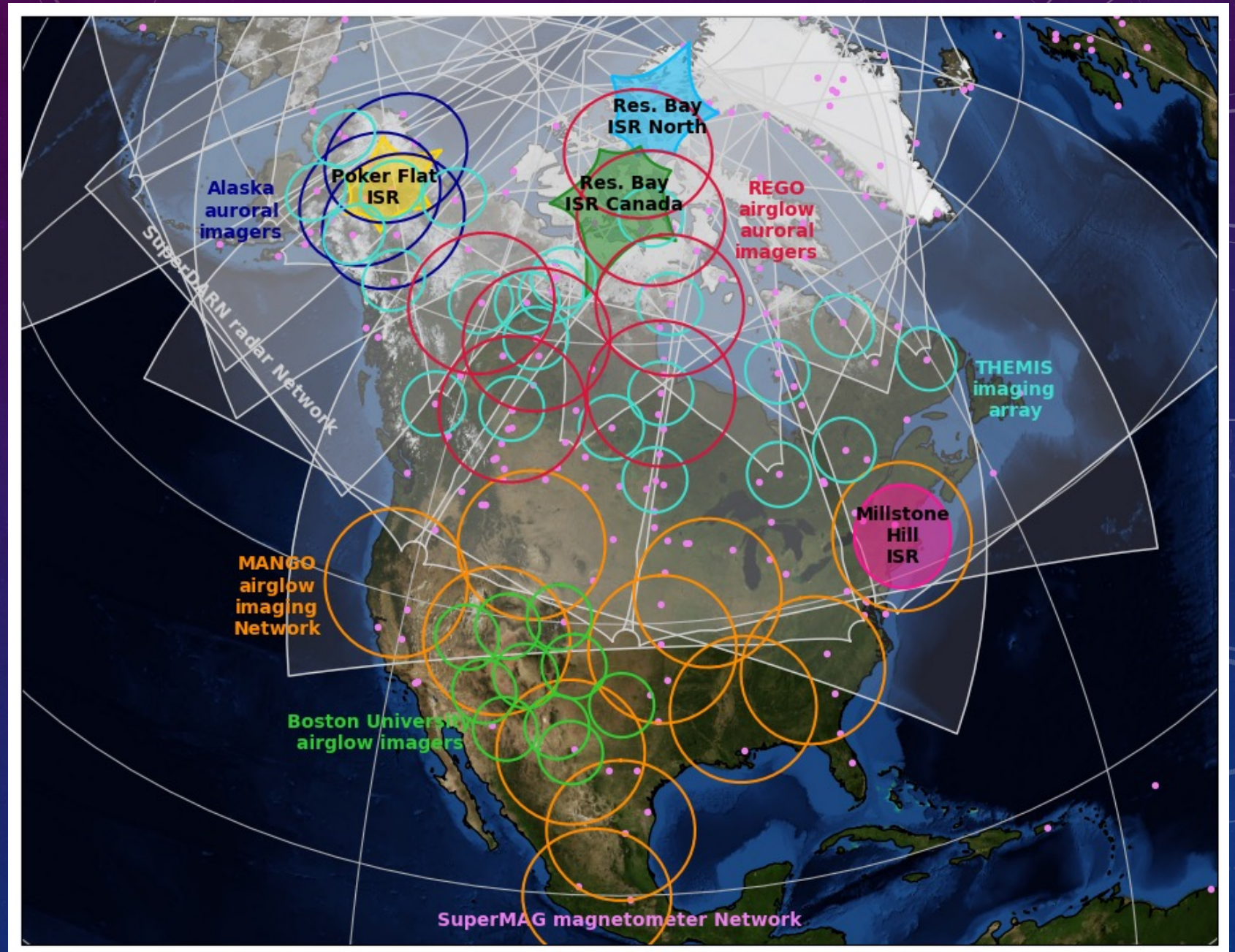


OPTICAL INSTRUMENTS (AURORAL AND AIRGLOW IMAGERS, INTERFEROMETERS)

MANGO ARRAY, CPI IMAGERS AND FPIS

A broad view of existing and planned networks of homogeneous instruments across North America along with ISRs. The figure is generated by Leslie Lamarche.

(<https://github.com/ljlamarche/infrastructure-maps>) (taken from Bhatt et al. White Paper)



Site name and code	Geographic Location	Instrument(s)		FPI		Operation time period
		Imager		Red	Green	
Christmas Valley, OR (CVO)	43.27° N -120.35° E	✓	✓	✓	✓	Dec 2021 – Now
Capitol Reef Field Station, UT (CFS)	38.15° N -111.18° E	✓	✓			May 2014 – Now
Bear Lake Observatory, UT (BLO)	41.6° N -111.6° E		✓	✓	✓	Aug 2021 – Now
Lowell Observatory, AZ (LOW)	35.20° N -111.66° E		✓	✓	✓	Aug 2021 – Now
Eastern Iowa Observatory, IA (EIO)	41.88° N -91.50° E	✓				Nov 2015 – Now
Madison, KS (MDK)	38.11° N -96.09° E	✓				July 2016 – Now
French Camp Observatory, MS (FCO)	33.29° N -89.38° E	✓				July 2016 – Mar 2018
Pisgah Astronomical Research Institute, NC (PAR)	35.20° N -82.87° E	✓				Sep 2016 – Jun 2018
Hat Creek Observatory, CA (HCO)	40.8° N -121.46° E	✓				Feb 2014 – Apr 2020
Bridger, MT (BMT)	45.34° N -108.91° E	✓				Nov 2015 – Dec 2017
Urbana Atmospheric Observatory, IL (UAO)	40.16° N -88.16° E			✓	✓	2012 – Now
Magdalena Ridge Observatory, NM (MRO)	33.96° N -107.18° E		✓			Nov 2022 – Now
Big Dog Ranch, TX (BDR)	31.23° N -98.3° E		✓			Nov 2022 – Now
Martens Observatory, ND (MTO)	48.15° N -97.66° E	✓				Feb 2023 – Now

MANGO Array

Funding source: NSF (both current and historical) and various/internal funding for early deployment of two of the imagers and one of the FPIs.

Data: The imager data produce continuously streaming nightly all-sky images showing the wave field every 2-4 minutes depending on the wavelength (green line - 2min, red line - 4min). The images are available to view and download in near real time though we produce quicklook movies the next morning that gives a better overview of the previous night. The higher level data products are available with a day's latency.

The FPI provides horizontal neutral winds and temperatures. The cadence varies between approximately 30 seconds and 10 minutes per measurement. Latency for processed data availability is about 1 day, typically.

Funded through: The MANGO network (with both imagers and FPIs) is funded through August 2023. An instrument O&M proposal has been submitted to the NSF CEDAR program this year to continue the work of maintaining the hardware and producing the data for the broader user community.

CPI Imagers and FPIs

CPI designed FPIs

Site	Lat.°	Long.°	¹ dec.°	² Incl.°	1 st light	Owner
<u>Cachoeira Paulista</u>	22.7 S	45.0 W	22.5 W	-40.4	07/2019	INPE
Santarém	2.7 S	54.5 W	18.9 W	-0.5	12/2022	INPE
Culebra	18.3 N	65.3 W	13.8 W	41.5	08/2019	NSF
Arecibo red-line	18.3 N	66.8 W	13.2 W	42.2	05/2012 ³	NSF/CPI
Arecibo green-line					05/2012	NSF/CPI
Arecibo NIR					02/2011	CPI
Arecibo H-alpha					01/2011	CPI
Millstone Hill red-line	42.6 N	71.5 W	14.1 W	66.8	11/2009 ⁴	CPI
Millstone Hill green-line					06/2012	
Easton, Maine	46.7 N	67.9 W	16.3 W	69.2	7/2023 ?	CPI

¹magnetic declination per the World Magnetic Model (WMM) 2020.

²field line inclination per WMM-2020.

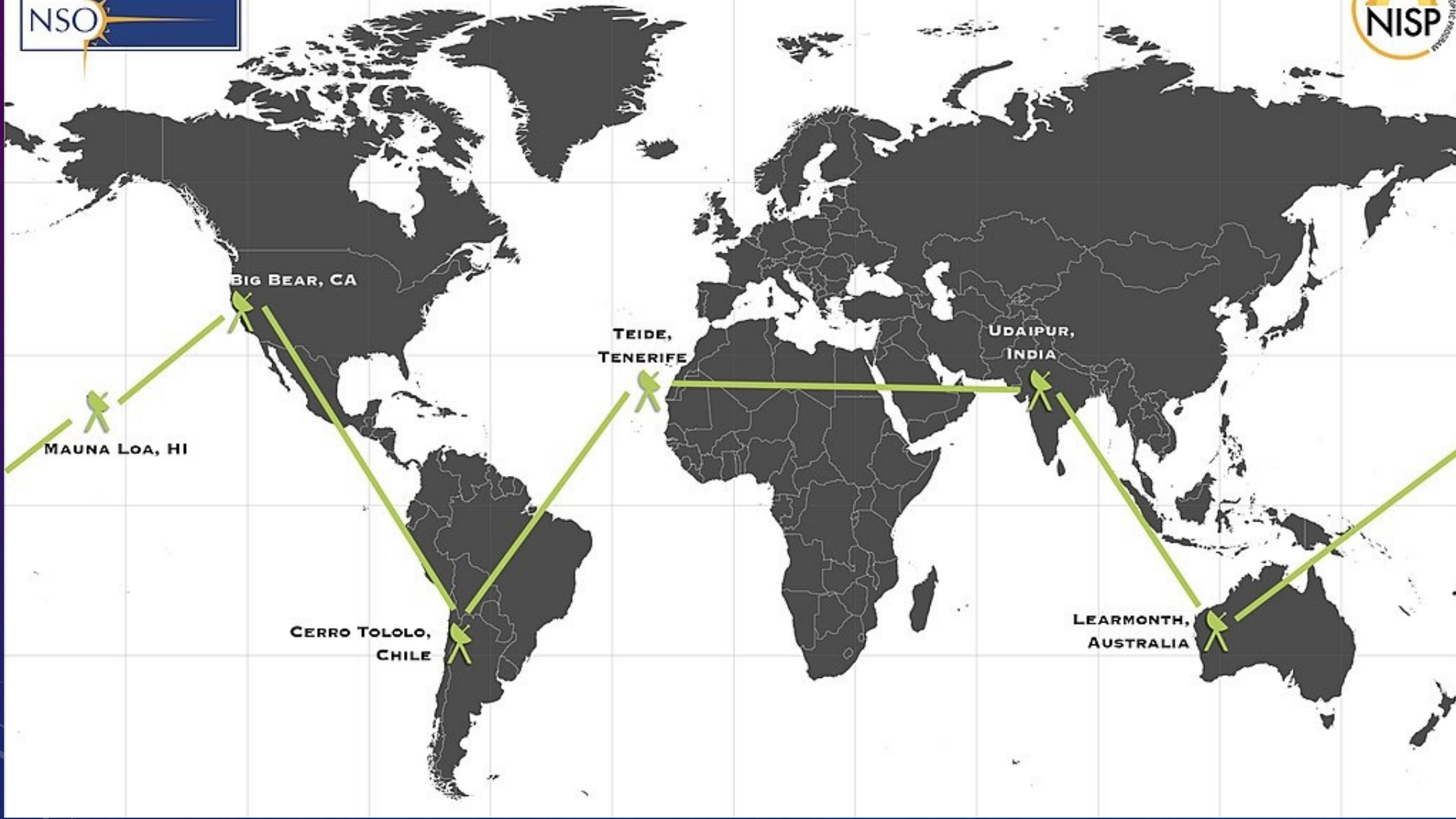
³An earlier pressure-scanning FPI provided wind/temperature data at Arecibo from 1980 to 2009.

⁴An earlier pressure-scanning FPI provided data at Millstone Hill from 1989 to 2002.

SOLAR OBSERVATORIES

SOLAR DOPPLER-MAGNETOGRAM NETWORK (GONG), SOLAR ELECTRO-OPTICAL NETWORK (SEON)

[MAP OF SOLAR OBSERVATORIES](#)



Solar Doppler-Magnetogram Network (GONG)

- <https://www.spaceweather.gov/products/wsa-enlil-solar-wind-prediction>

“To provide one- to four-day advanced warning of [geomagnetic] storms, NOAA SWPC continuously operates the Wang-Sheeley-Arge-Enlil background solar wind model, with coronal mass ejections from the Sun simulated with the “cone” model, based on white-light coronagraph observations. An essential observational input to the model are global maps of the Sun’s surface magnetic field. These maps are created by the National Solar Observatory’s (NSO) Global Oscillation Network Group (GONG), a network of six observatories situated around the globe to provide continuous observations of the Sun. GONG was originally built in 1995 for helioseismology research. It is an aging network, and its operation beyond 2030 is considered problematic, and the ability to continue operations beyond 2032 is unlikely. There are no presently available data sources that can replace GONG with longer expected lifetimes. The planned successor to GONG, the next generation Ground-based solar Observing Network (ngGONG), has been discussed for years. An ngGONG proposal was submitted and reviewed under NSF’s Mid-Scale Research Infrastructure Program in 2021. It was not selected for funding. The lack of a tangible commitment from an operational agency was perceived to be a major impediment to selection. NSO is submitting a new proposal for the design phase to the NSF Mid-scale R-1 program in May 2023. As the design and construction of ngGONG is expected to take eight years (three years design, five years construction) at minimum, it is imperative that the design phase begin as soon as possible. We recommend that NOAA/NWS financially support the design phase for ngGONG, to insure the initiation of the project.”

Excerpt from the “Environmental Information Services Working Group (EISWG) Statement on GONG and its Successor Data Source for SpaceWeather Operations Submitted to the NOAA Science Advisory Board (SAB), 2022

Solar Electro-Optical Network (SEON)

As part of the Solar Electro-Optical Network (SEON), the Radio Solar Telescope Network (RSTN) observatories provide timely, accurate solar alerts and analyses of the Sun's radio emission 24/7, 365 days a year. Solar Analysts monitor the Radio Interference Measurement Set (RIMS) and Solar Radio Spectrograph (SRS). Stations serving USAF RSTN-1 second data Palehua, Hawaii; Sagamore Hill, New York; San Vito, Italy; Learmonth, Australia.

As part of the Solar Electro-Optical Network (SEON), the SOON system provides the capability to observe, analyze, and report visible solar phenomena such as solar flares, sunspots, magnetic fields, and disk and limb activity. Solar flares can trigger high velocity Coronal Mass Ejections (CMEs) that can interact with the Earth's magnetosphere to create geomagnetic storms. Current stations serving SOON data: Learmonth, Australia, Holloman AFB, New Mexico, San Vito, Italy

<https://www.ncei.noaa.gov/products/space-weather/legacy-data/solar-electro-optical-network>

