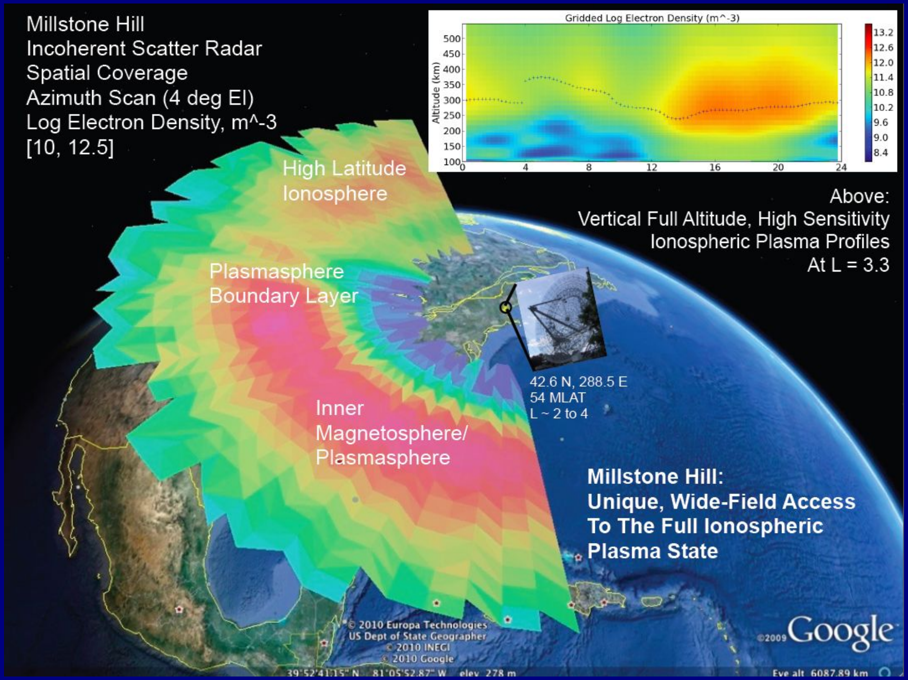
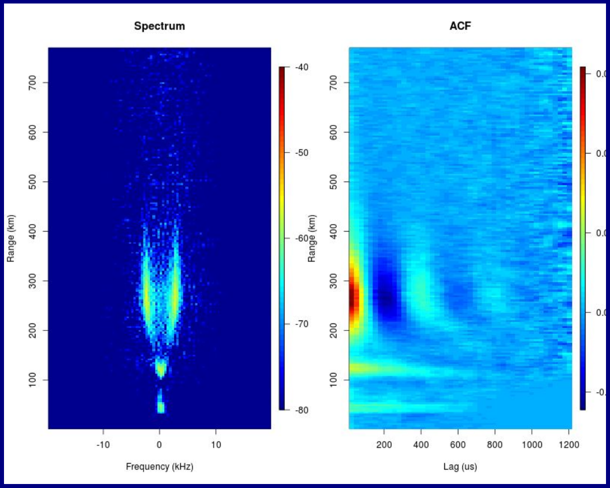
Geospace Radar Design Considerations

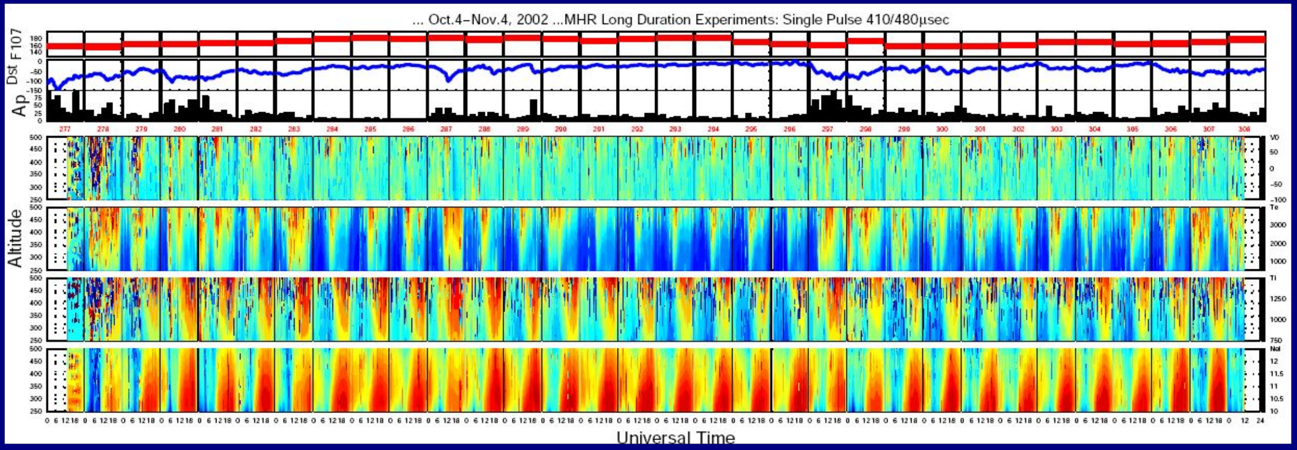
Philip J. Erickson[1], Frank D. Lind[1], John Swoboda[1]

(1) MIT Haystack Observatory, Westford, MA, USA





[McKay-Bukowski, et al., 2014]

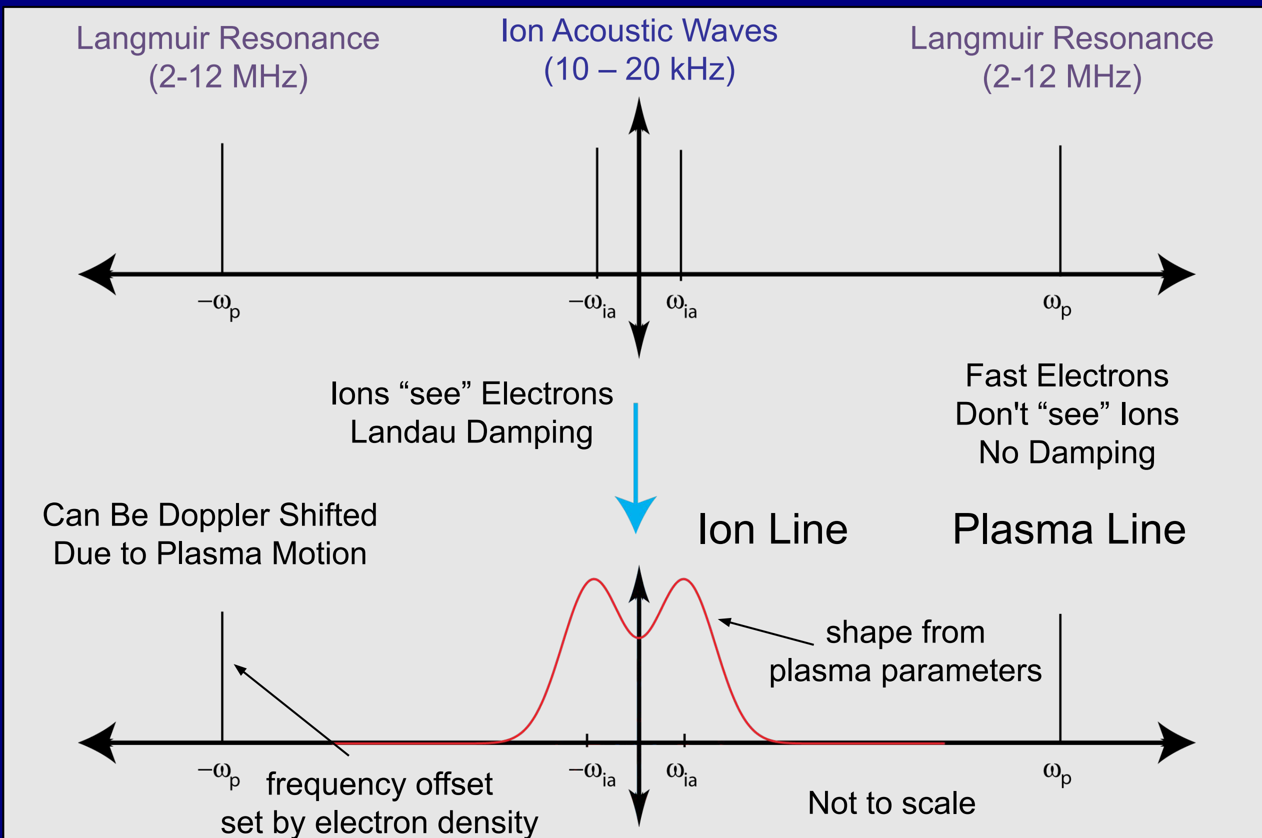


contact info :

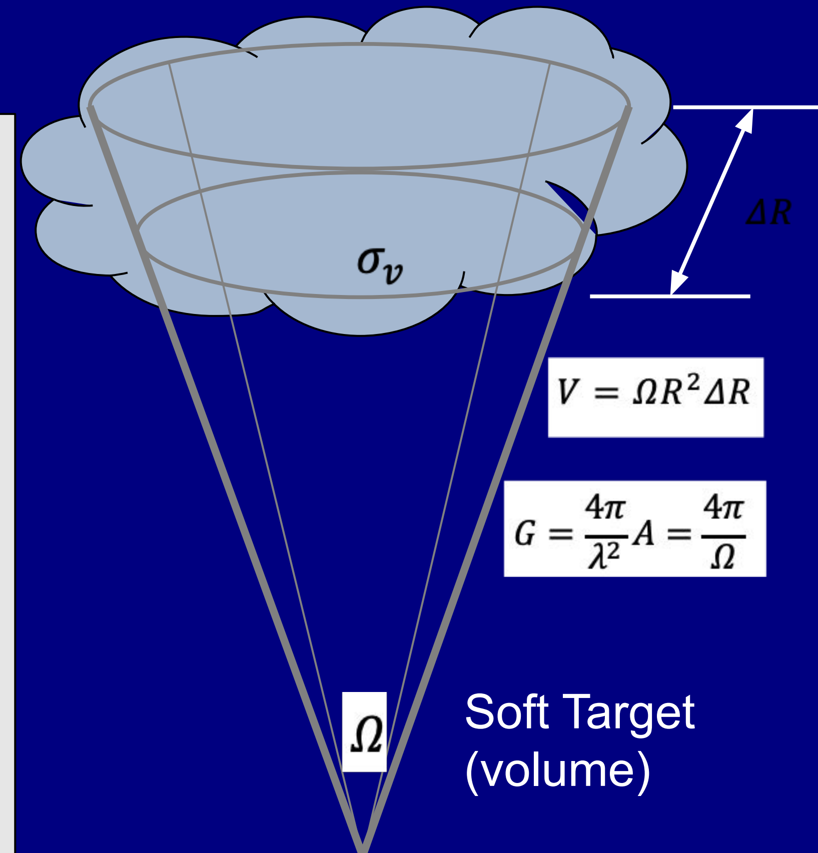
Dr. Frank D. Lind
MIT Haystack Observatory
Route 40
Westford MA, 01886
email - flind@haystack.mit.edu

Incoherent / Collective Thomson Scatter Radar

A Comprehensive Plasma Remote Sensing Technique



Requires a large Power-Aperture per unit Temperature



$$V = \Omega R^2 \Delta R$$

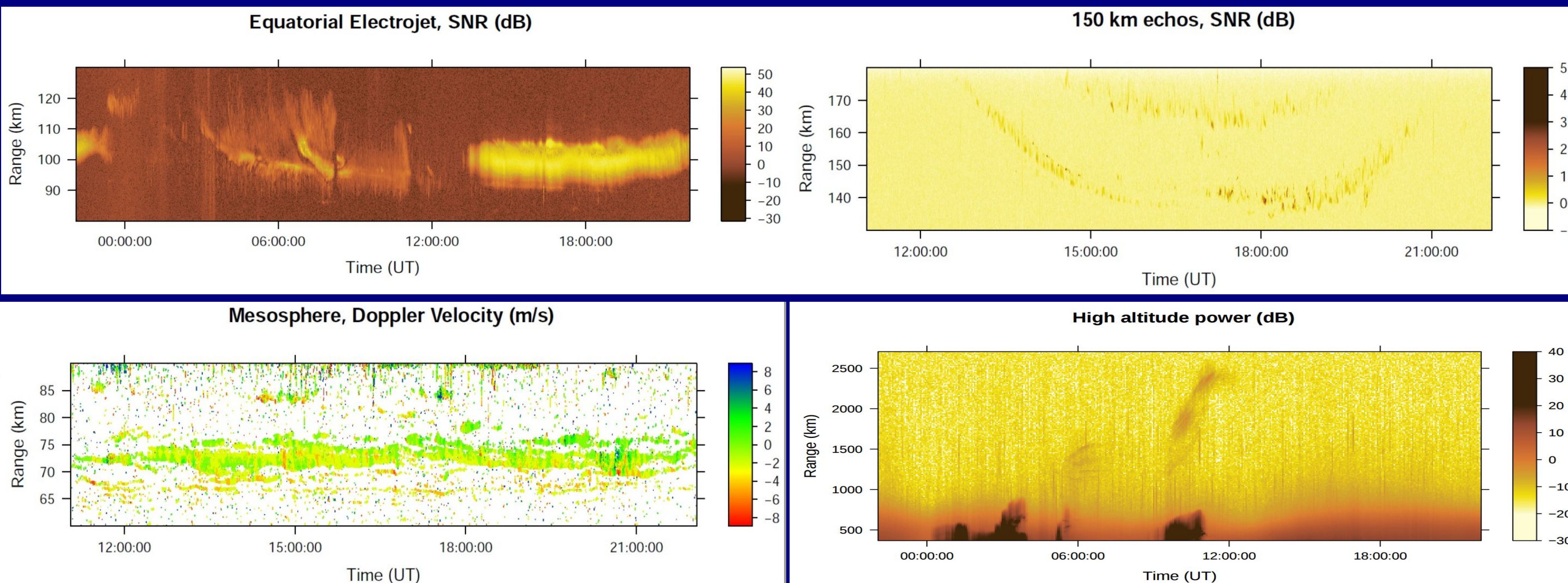
$$G = \frac{4\pi}{\lambda^2} A = \frac{4\pi}{\Omega}$$

$$SNR = \frac{P_{rx}}{kTB} = \frac{P_{tx} A \sigma_v \Delta R}{4\pi R^2 kTB}$$

Noise like signal received → Gaussian Random Variable → Statistical Target
Very Weak return (~10s of femtoWatts for a Megawatt class illuminating pulse)
Hi

Next Generation Geospace Radar

Technological advances enable multiple instrument applications
Measurements can span from the lower atmosphere to heliosphere
Active and passive measurements, frequency diverse, polarimetric
Geospace Radar is relevant for a much wider community of users!

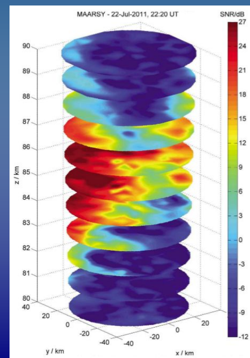


Jicamarca All Altitude Experiment (J. Vierinen 2012)

Geospace Radar: The Most Science for the Aperture

Lower Atmosphere / MST

Neutral Winds, Tides,
Turbulence, Dynamics
Coupling, PMSE



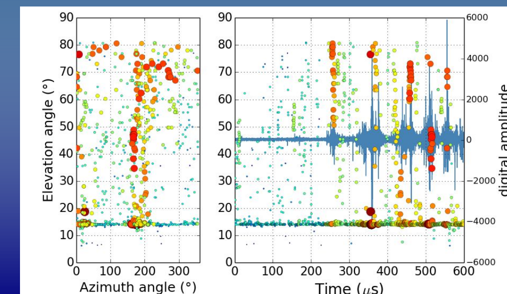
[MAARSY PMSE Latteck et al., 2012]

(HF, VHF, UHF)

Lightning Radio Imaging

[RAPID 2017: VHF Lightning Image J. Tilles / N. Liu / F. Lind]

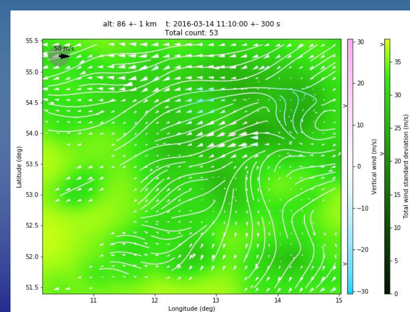
Lightning Dynamics,
Discharge Physics,
Storm Electrification



(HF, VHF, UHF)

Meteor Trails + Wind Fields

E-region Neutral Winds,
Tides, Dynamics,
Temperature, Coupling



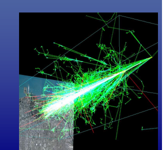
(HF, VHF, UHF)

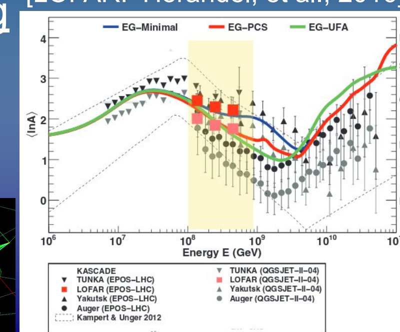
[HF MIMO Meteor Radar ; Volz et al. 2018]

Astroparticle Radio Imaging

[LOFAR: Horandel, et al., 2016]

Particle Energy and Mass
Arrival Angles
Air Shower Extent

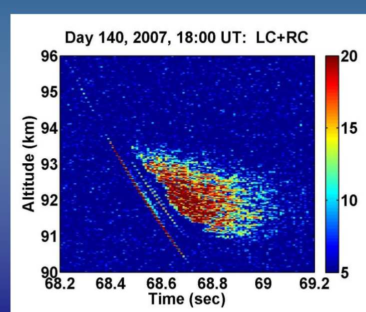




(HF, VHF, UHF)

Meteor Head Echoes

Meteoroid Flux, Mass, Velocity
Winds, Instability Physics,
Ablation Physics

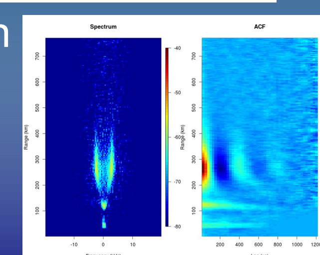


(HF, VHF, UHF, L-band, S-band)

[S. Close et al., 2007]

Ionosphere via Coherent and Incoherent Scatter

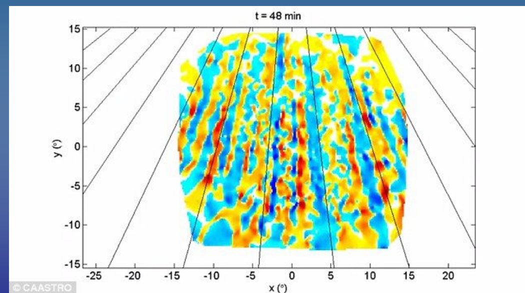
Structure, Dynamics, Composition
[McKay-Bukowski, et al., 2014]
Instability Physics, MI Coupling,
Neutral Coupling, Winds, Tides,
Waves / TIDs, Propagation, etc.
(HF, VHF, UHF, L-band, S-band)



Geospace Radar: The Most Science for the Aperture

Magnetospheric

Plasma Structures
Plasma Parameters
via radar

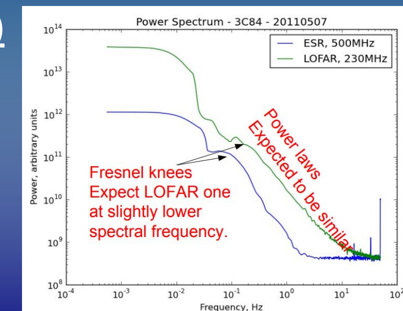


[MWA Magnetospheric Flux Tubes, Cleo Loi, 2015]

(HF, VHF)

Solar Wind Density (via IPS)

3D Solar Wind Density
Solar Wind Speed
Dynamics and Evolution

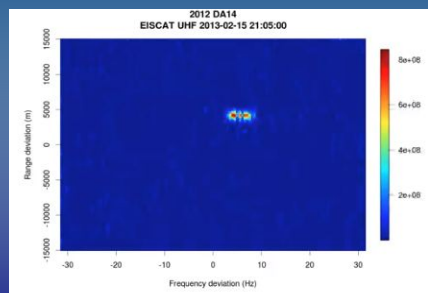


(HF, VHF, UHF)

[LOFAR and ESR, R. Fallows, 2011]

Near Earth Object Radar

Orbital Parameters
Shape and Rotation
Surface Structure



[EISCAT UHF: J. Vierinen et al. 2012]

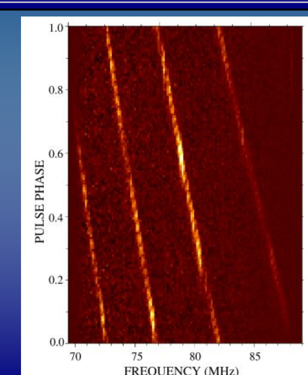
(HF to S-band and up)

Solar Wind B-Field (via Faraday Rotation)

B-Field Orientation (TBD)
CME Density (TBD)

[LWA-1 Pulsar / CME Howard, et. al. 2016]

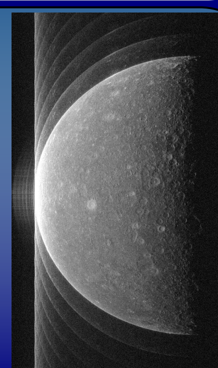
(HF, VHF, UHF)



Planetary Imaging Radar

[Millstone UHF Lunar Image J. Vierinen 2015]

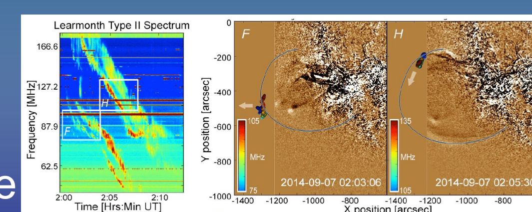
Doppler Motions
Surface Structure and Details
Change Detection



(HF, VHF, UHF, L-band, S-band, higher)

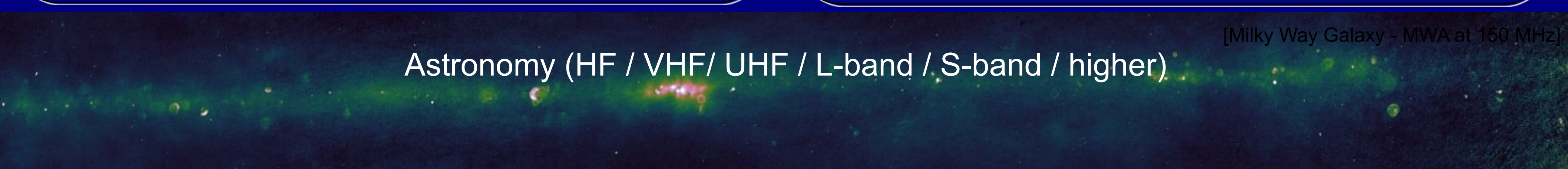
Solar System Radio Imaging and Spot Mapping

Solar Plasma Physics
Space Weather
Jovian Magnetosphere



[MWA Divya Oberoi and Colin Lonsdale 2016]

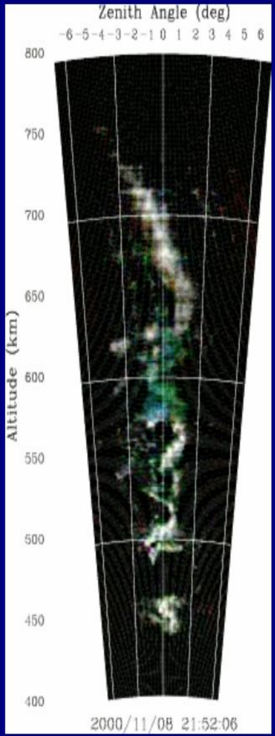
(HF, VHF, UHF, L-band)

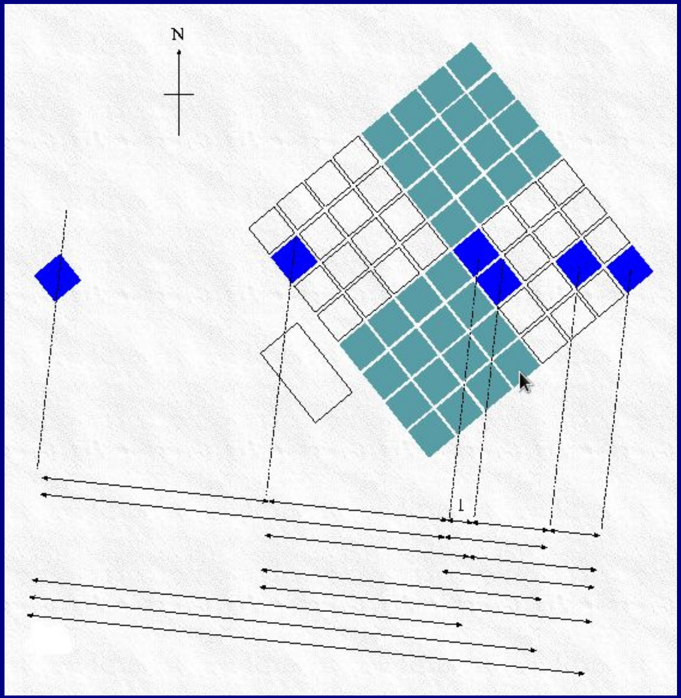


[Milky Way Galaxy - MWA at 150 MHz]

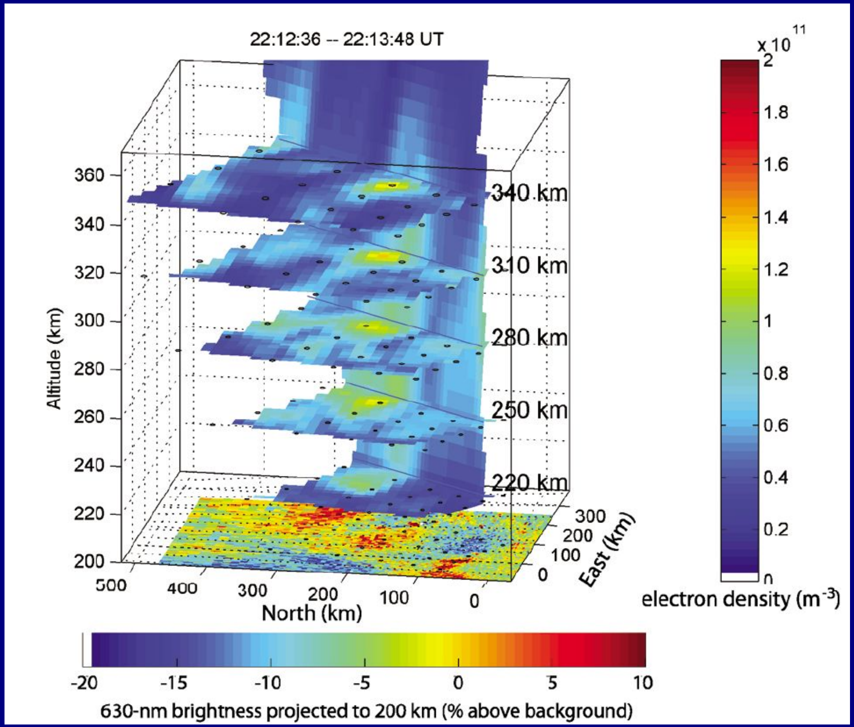
Astronomy (HF / VHF/ UHF / L-band / S-band / higher)

Radar Interferometry and Imaging

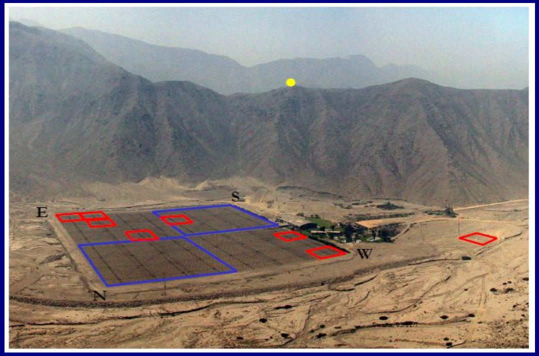




multiple unique baselines



[RISR-N Interleaved Beam Imaging, Dahlgren et al. 2012]

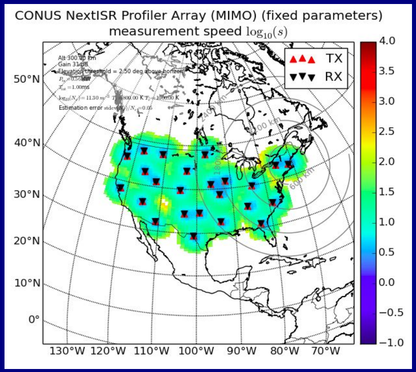


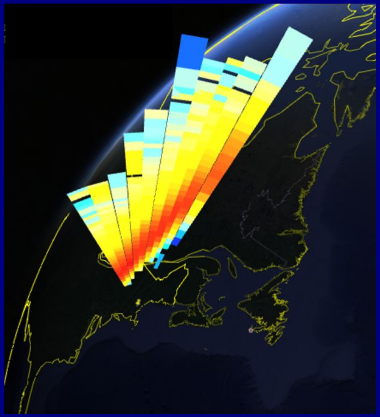
[Jicamarca Inverse Imaging of Coherent Scatter, Hysell and Chau 2006]

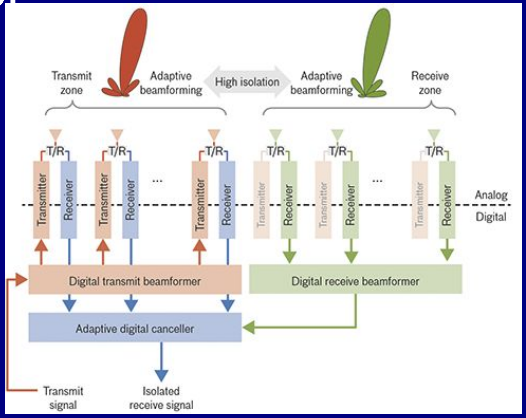
Apertures capable of incoherent scatter are also capable of detailed volumetric / interferometric observations.. with the right antenna and receiving flexibility along with good processing techniques (radio astronomy)

Design Space is Complex but Rich

- Antenna Type
  - Dish vs Array
- Radar Geometry (Monostatic / Multistatic)
- Illuminating and Receiving Frequency
  - Geophysics, Licensing considerations
- Spatial Coverage
  - Single Antenna vs Array
- TX Peak, Average RF Power
  - Final amplifier (single vs phased array)
  - Solid state modulators
  - Sometimes a big win to scale <u>aperture</u> instead of power
  - Solid state MW class is now commercial
- Monostatic systems: avoid the T/R switch
  - Simultaneous Transmit and Receive (STAR) systems
  - Or avoid the problem with separate TX, RX arrays
- More..



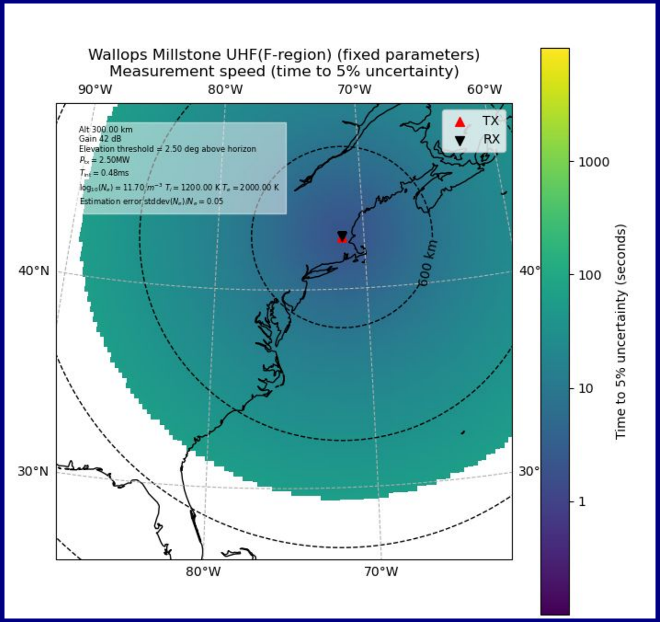




Design Tools / Simulators Are Necessary

MIT ISR Performance Simulator (MIPS)

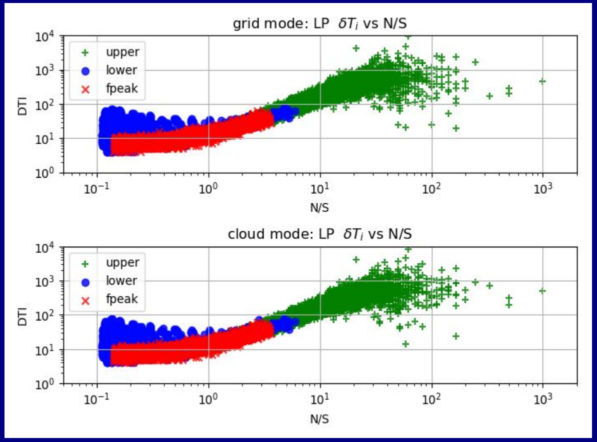
- Statistical performance given radar equation, Debye length, IS forward model, geometry, etc.
- Multistatic capable
- How long to observe in given geophysical and observing conditions to achieve a specific uncertainty?
- Allows tradeoffs (range resolution vs. performance, power aperture vs. performance, etc.)



MIPS example:
Wallops Flight Facility ISR performance study

SimISR: Simulate IS Radar Data [Swoboda]

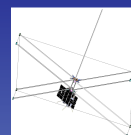
- Simulates voltage level data given plasma parameters, radar configuration
- Summation of shaped noise processes
- Simulate detailed radar performance
- Signal processing and analysis validation
- Potential for use in future guided Geospace Radar design



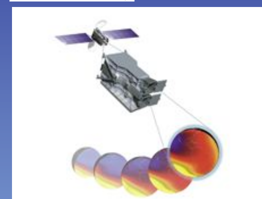
SimISR example:
Uncertainty in ion temperature vs S/N ratio

Instrumentation Cost and Scope

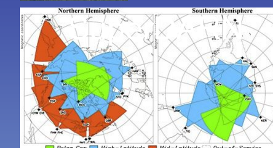
Cost	NASA	NSF
$ 1M	(e.g. MatISSE)	MRI (small)
$ 5M	HTides	MRI (large)
$15M	UNEX	Midscale
$65M	MO	Large Midscale
$120M	SMEX	MREFC
$200M	MIDEX	MREFC
$1 to 10 B	FLAGSHIP	(Congress)

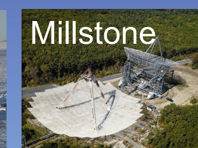


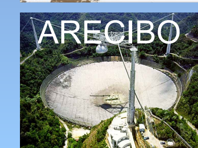
AERO-VISTA



Coherent Scatter Radar







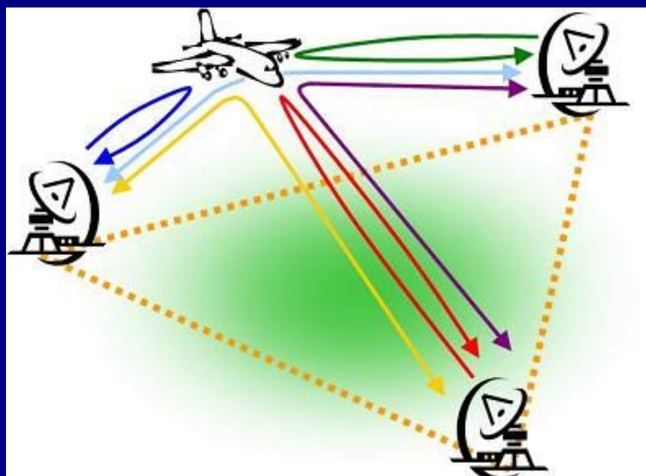
Incoherent Scatter Radar

Instruments can have long lifetimes!

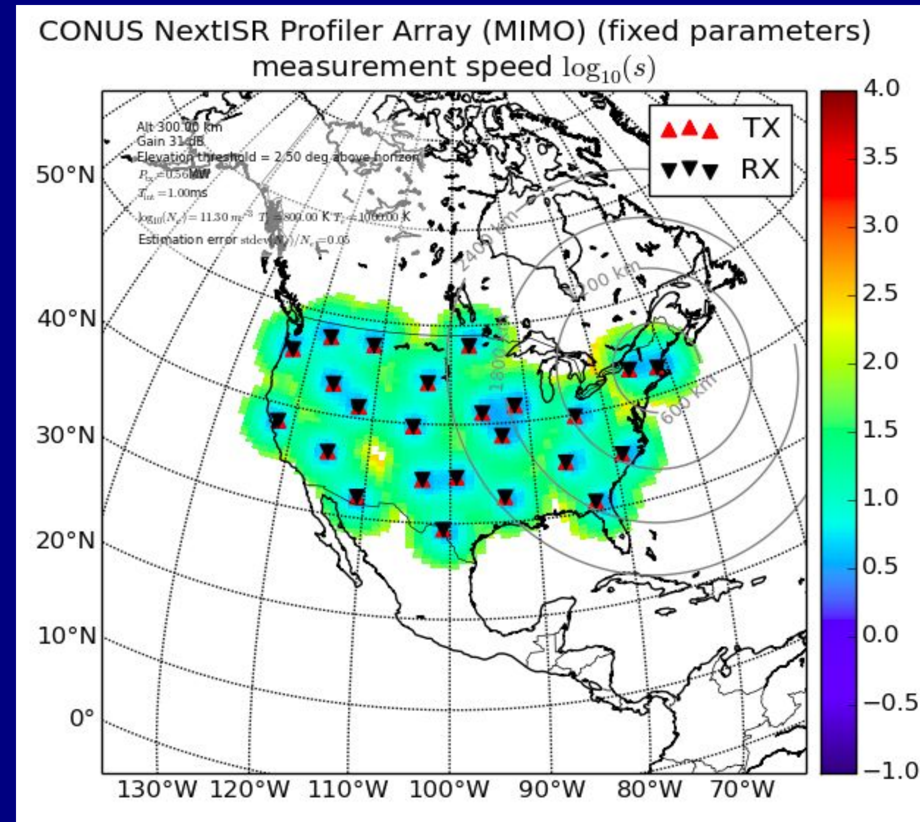
Key considerations:
Calibration/validation; Reasonable operating costs; Recapitalization time frames

Workforce → Goals → Instruments → Data → Analysis → Science → Applications

Geospace Radar Networks



MIMO (Multi-In Multi-Out)



Example: Complete CONUS Plasma Profiling Coverage

Wide Spatial Coverage via Networks of Geospace Radars

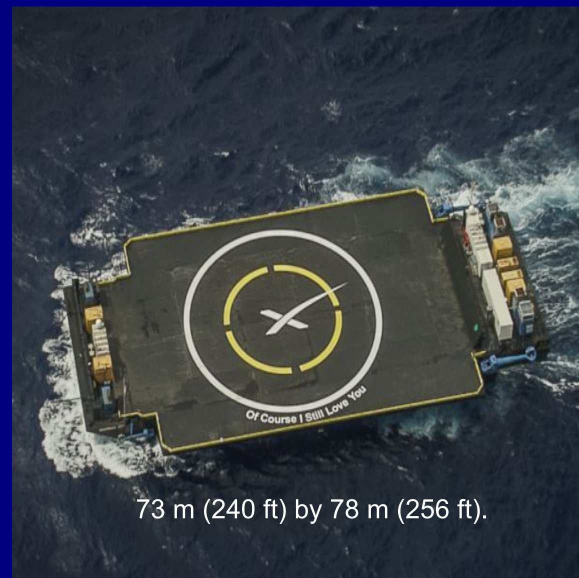
Multi-static (multiple RX) or MIMO (multiple RX and TX)

- True vector measurements with fast measurement speeds!
- RX Arrays are less expensive than TX arrays → More RX than TX in networks

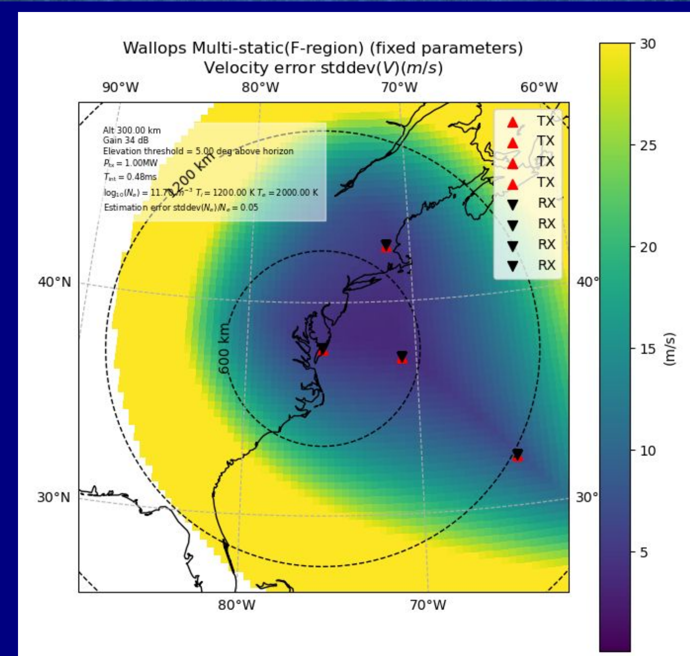
Many possible configurations to explore…

Future 1: Geospace Radar on Ocean Platforms

$500M new, SpaceX got 2 for $3.5M
<u>used</u> + Refurb cost?



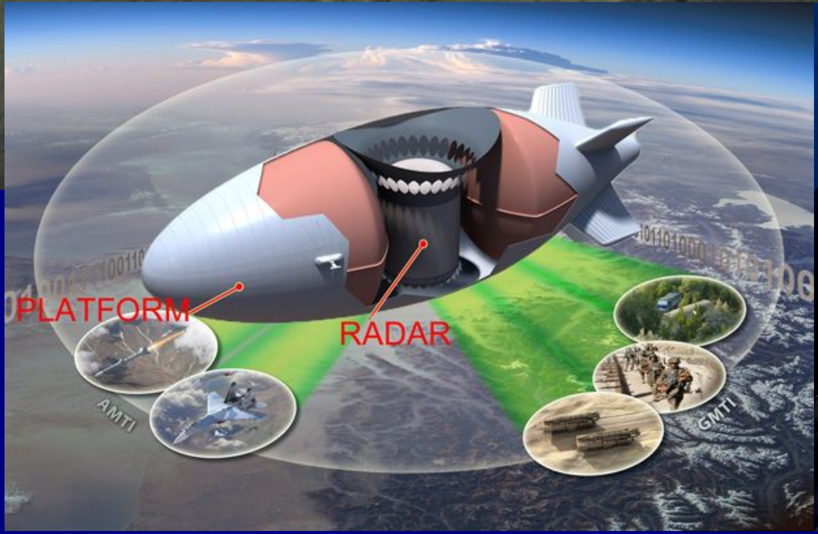
- Solar + wind + wave power + flow batteries
- Large aperture with low power per element
- Compensation for platform motion
- Secondary instruments via containers
- Platforms are too expensive when new...



Future 2: Airship Based Geospace Radar

Science:

Campaign Focused
ST/ MST / Lightning
Meteor Trails
Meteor Head Echoes
Plasma Instabilities
Ionospheric Regions
Radio Astronomy

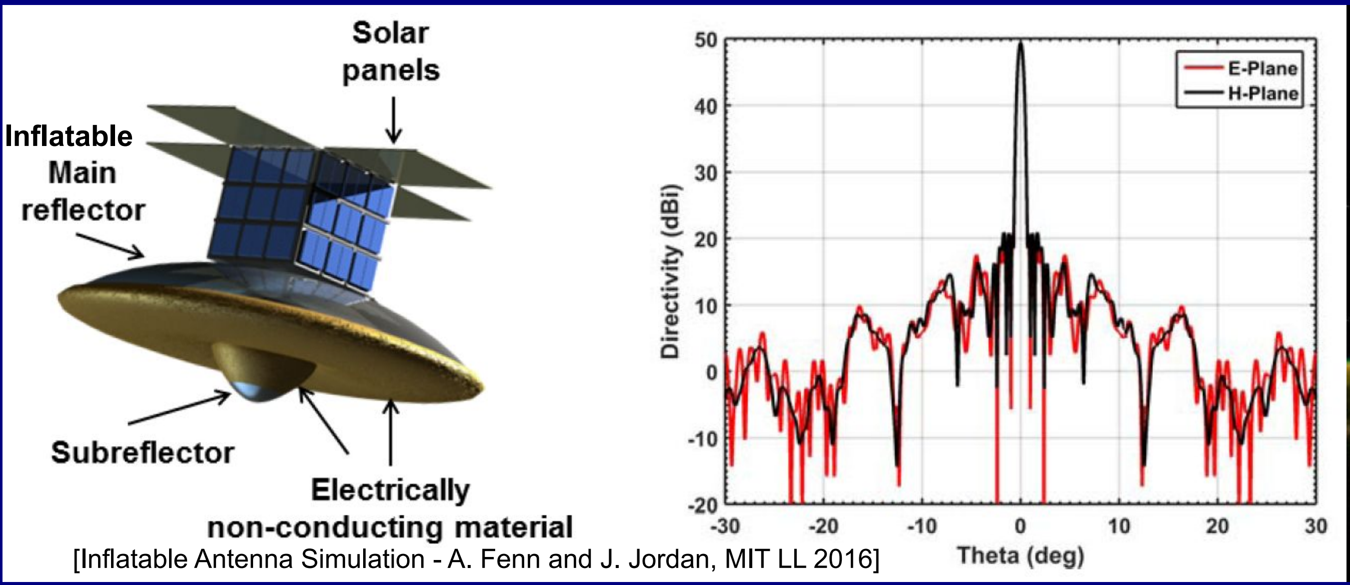


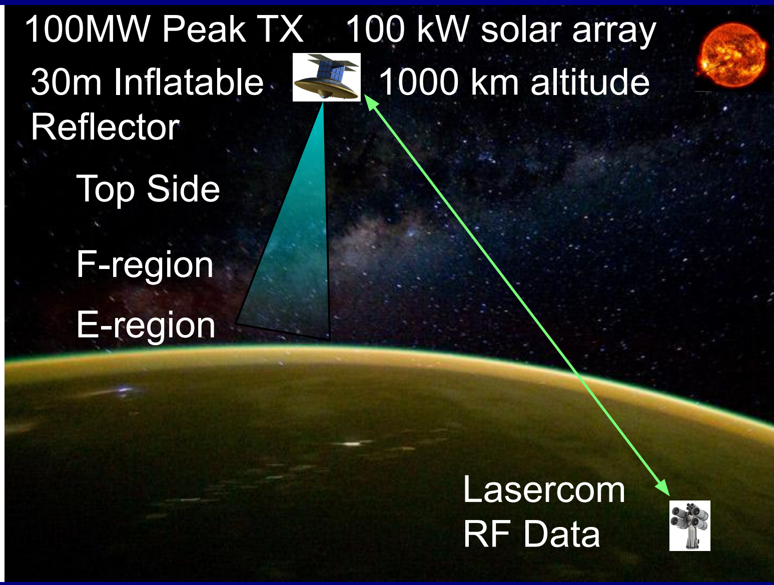
Hybrid Airship Geospace Radar

Example : DARPA Integrated Sensor Is Structure

Low average power per element and probable compromises on performance / field of view
Global Mobility with medium term persistence, conformal aperture → wide fields of view
Future high speed satcom (v-band) to uplink data for remote processing

Future 3: Space Based Geospace Radar



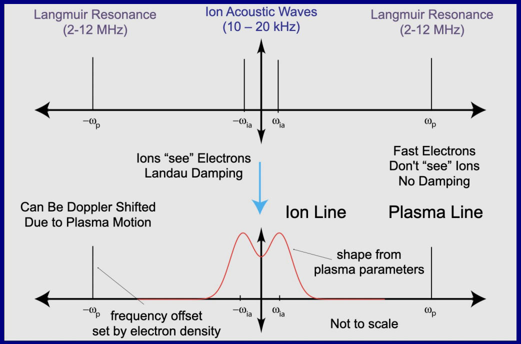


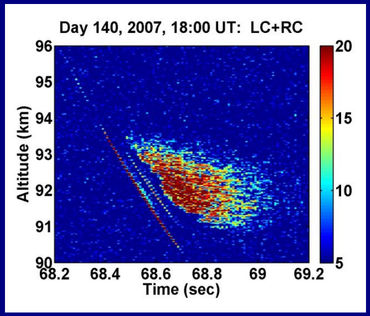
Geospace Radar from Orbit (Earth, Venus, Mars, Jupiter, Saturn, Solar?)

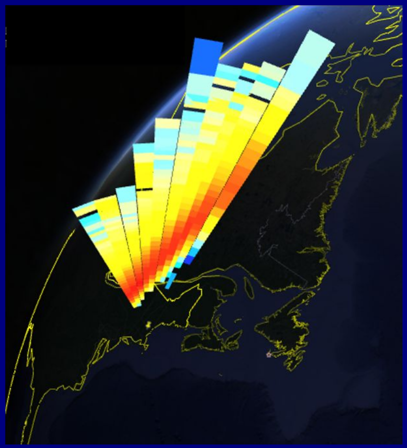
Challenges: Power, size / mass, reliability, wide bandwidth, ground clutter

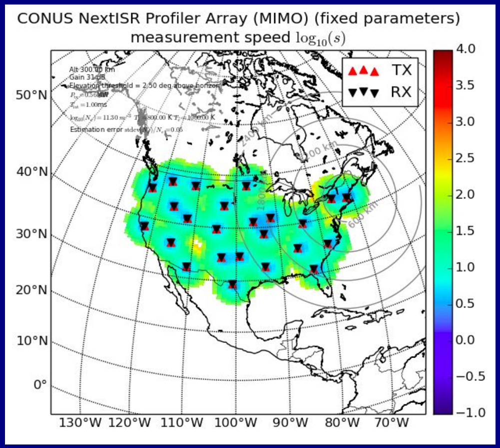
- Ultra high peak power (i.e. 100 MW) → Swath measurement
- Very low duty cycle → Manageable average power levels (~ 100 kW / e.g. ISS)
- Lasercom for raw data to ground or V-band satellite to satellite data (Earth)
- Secondary applications in SAR, iSAR, Surface Penetrating Radar

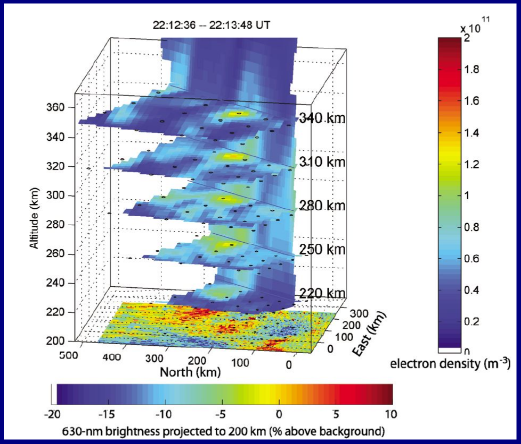
Summary

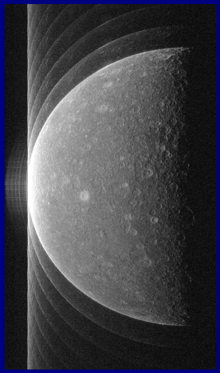


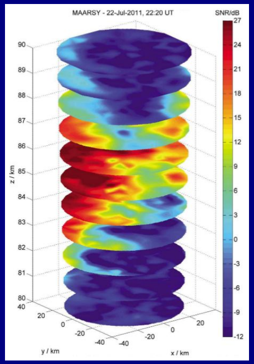


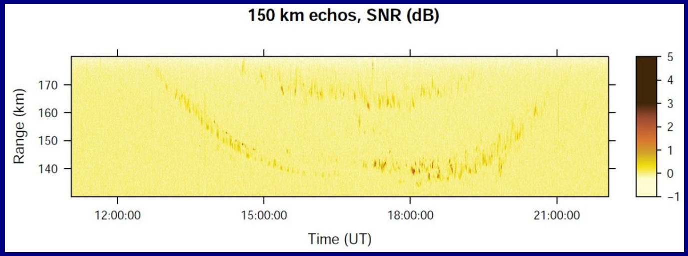








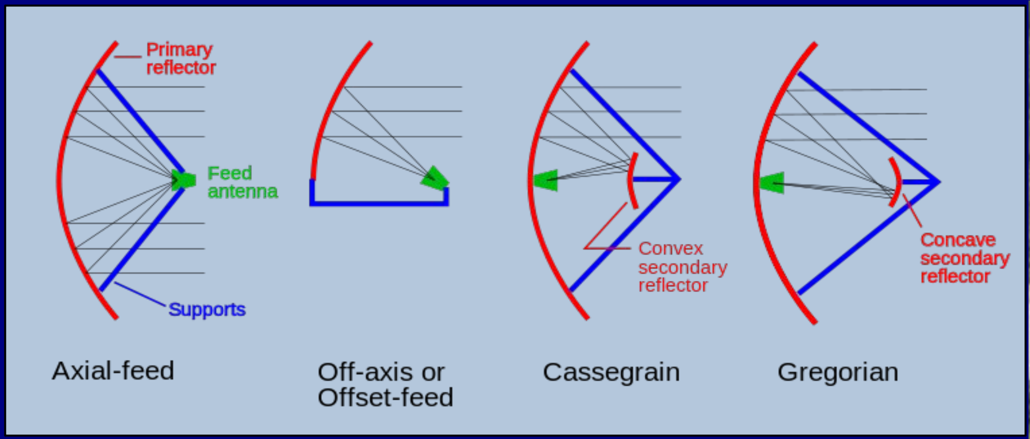


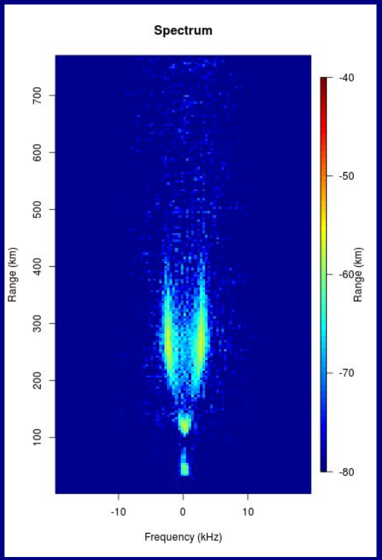


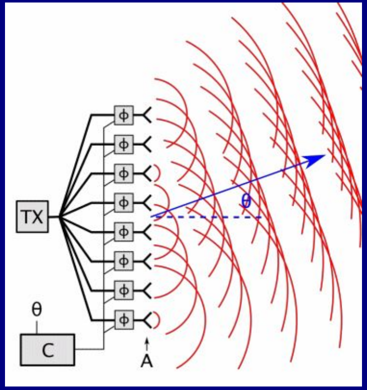
- Geospace radar provides the most science for the aperture
- Design space is complex and large, but very rich in possibilities
- Design tools are available
- Technology for both receive and transmit continues to open new avenues
- Concerted community effort can realize a 21st century discovery class Geospace Radar

Backup Slides

What Type of Antenna do you want?

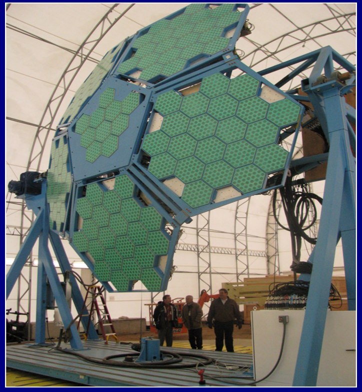






Dish Antenna

Full Sky Coverage
Broadband in frequency
Mechanical Steering
Maintenance



AFSCN
Geodesic Dome
Phased Array
Antenna
Advanced
Technology
Demonstration
(S-band)

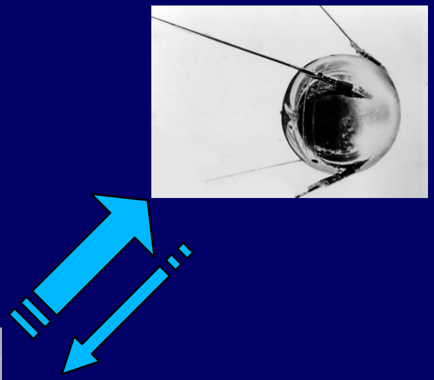
Array Antenna

Phased Array and/or Sparse Array
Limited Steering Angles (+/- 40 to 60 max)
Full sky coverage very expensive
Imaging Capabilities
HF / VHF Systems

What Radar Geometry do you Want?

Descriptions of Radar Geometry

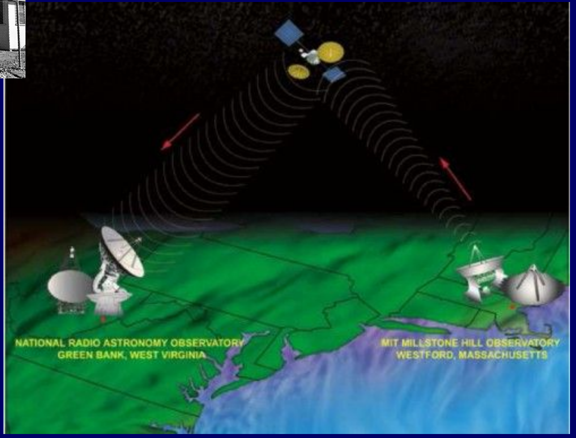
Monostatic – one site both TX & RX
Multisite – Multiple monostatic radars
Bistatic – one TX site, one RX site
Multistatic – one or more TX, one or more RX
- Joint processing
- MIMO – Multiple In Multiple Out
- SIMO – Single In Multiple Out



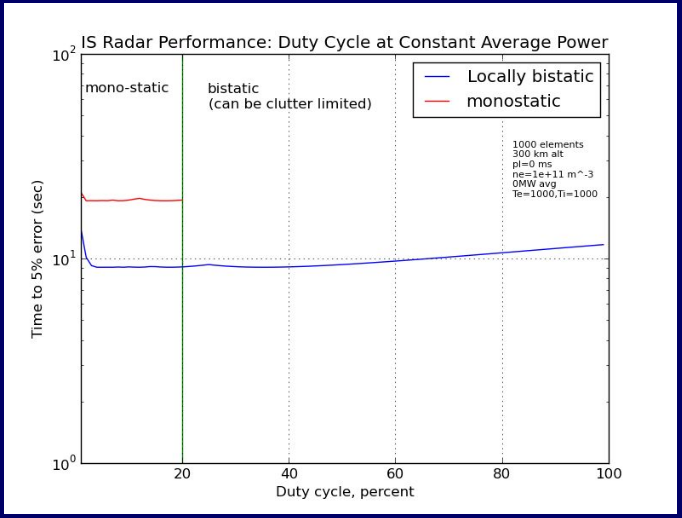
Monostatic

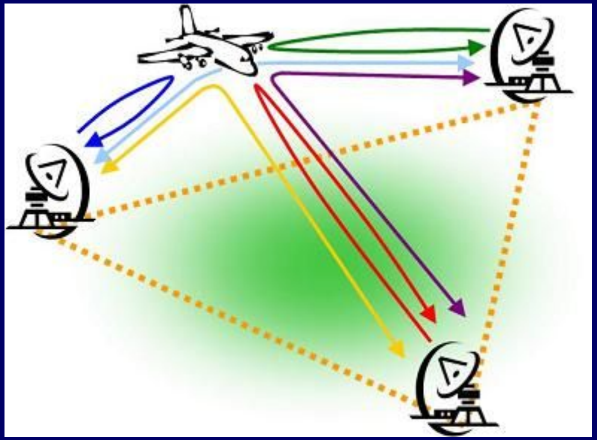
Why do this?

Scattering Geometry
Target Measurements
- Vector estimates, improved statistics, target properties
Spatial Coverage



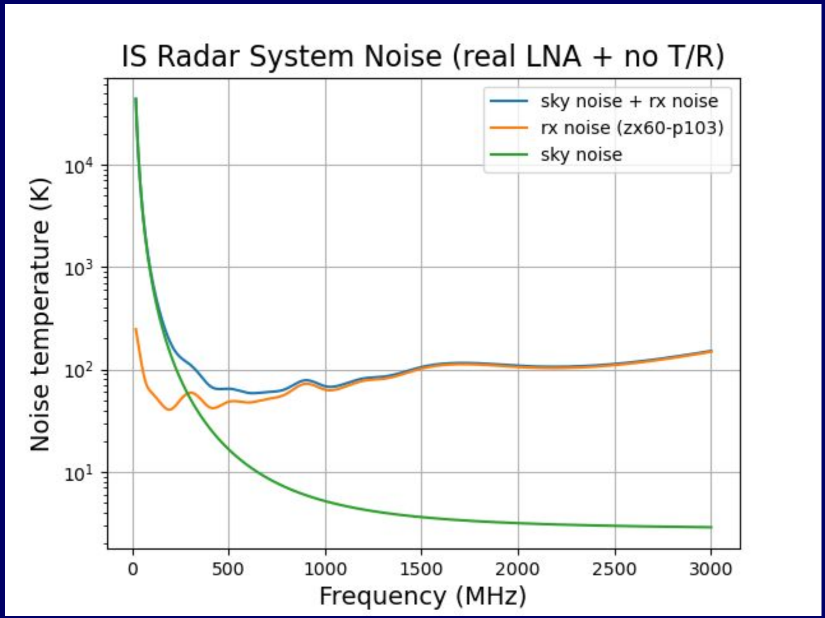
Bistatic

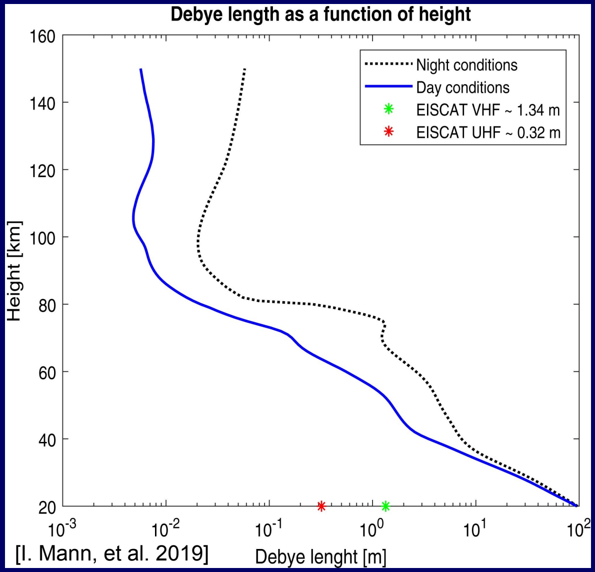


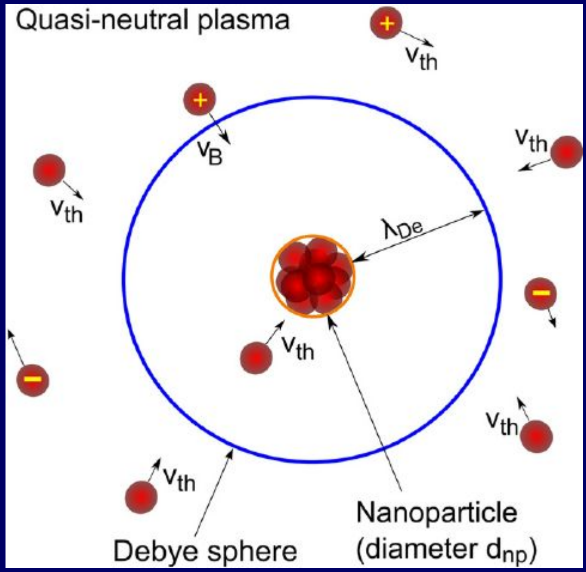


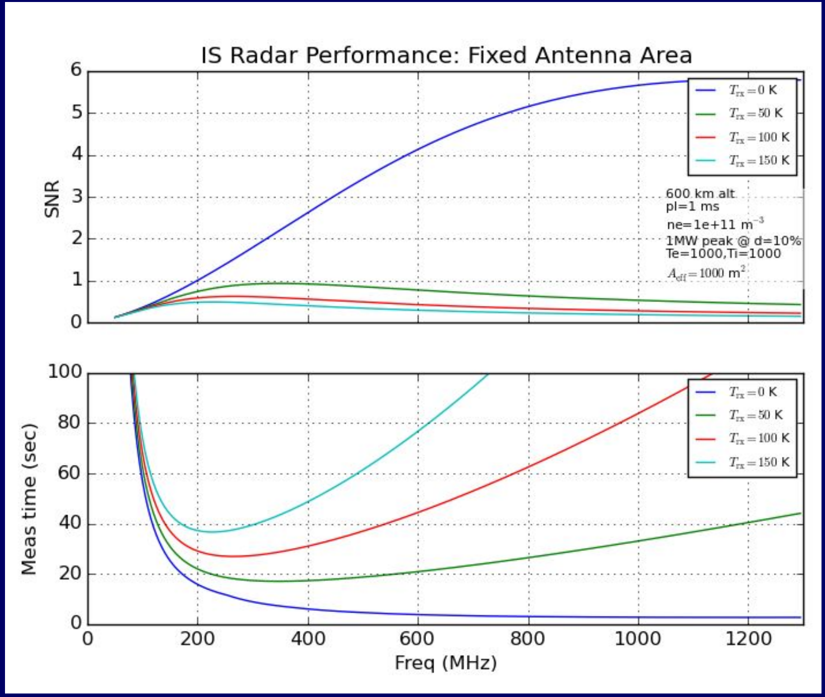
Multistatic

What Frequency do you Want?









Sky temperature dominates at low frequencies
RX temperature important as frequency increases

LNA Technology has gotten very good (GaN, SiGe, InP)
< ~ 100K uncooled at VHF to S-band (InP < 15K)!

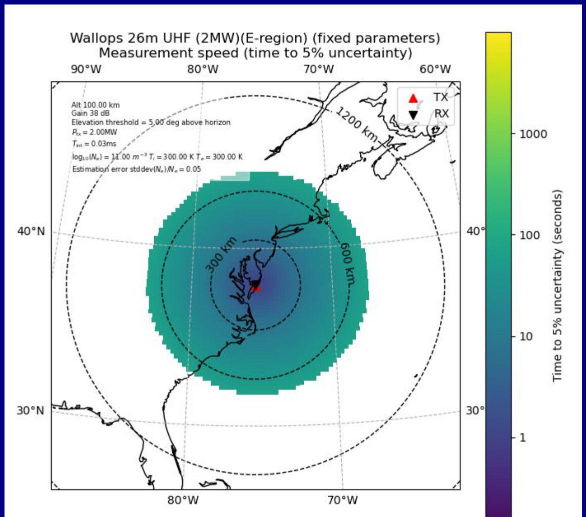
T/R Switches have a big impact
Dish : 10 to 30K versus Array : 50 to 500K

Bi-static and Multi-static systems can
always out perform a mono-static system in Tsys!

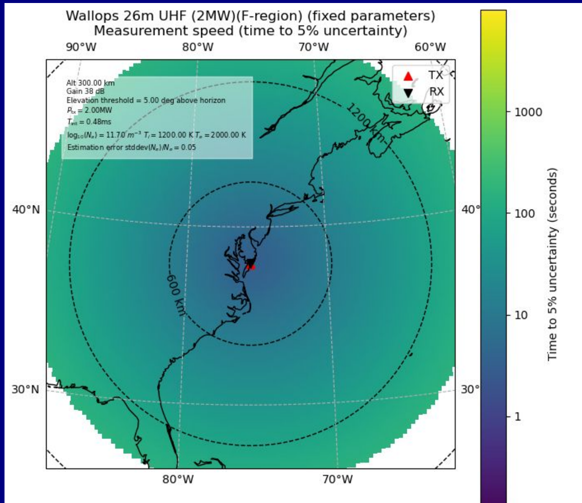
Licensing limits : Radar bands are UHF, L-band, S-band
Special authorization required for HF, VHF

Spatial Coverage

Dish Antenna

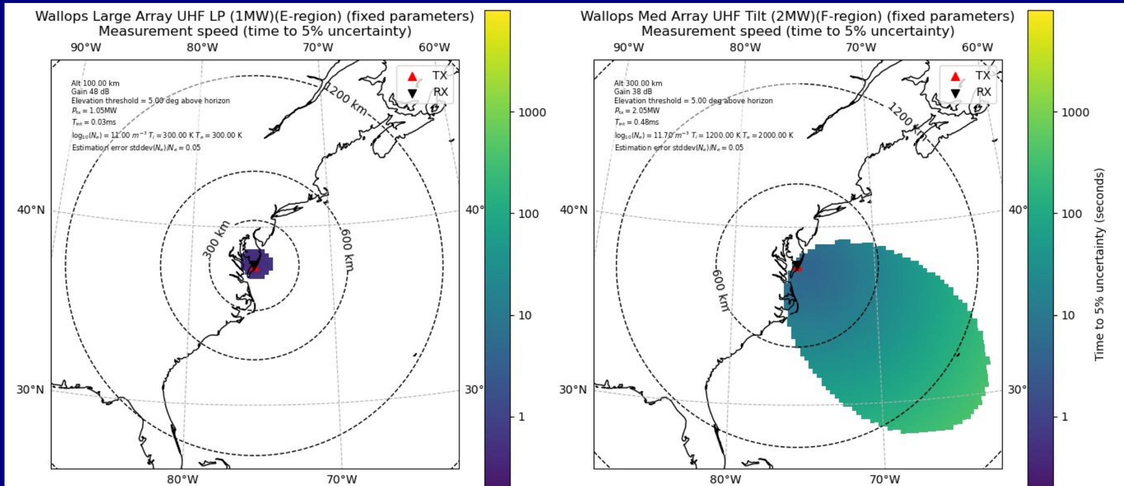


E-region coverage (5 deg cut-off)



F-region coverage (5 deg cut-off)

Array Antenna



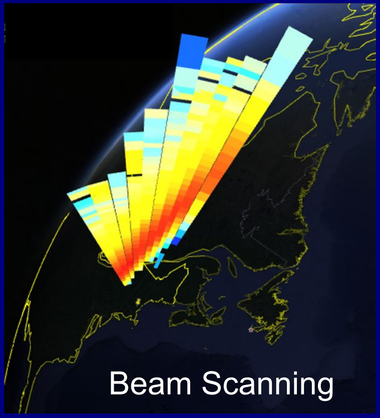
E-region coverage (vertical +/-45 deg) **F-region (130Az, 50 deg tilt +/-45 deg)**

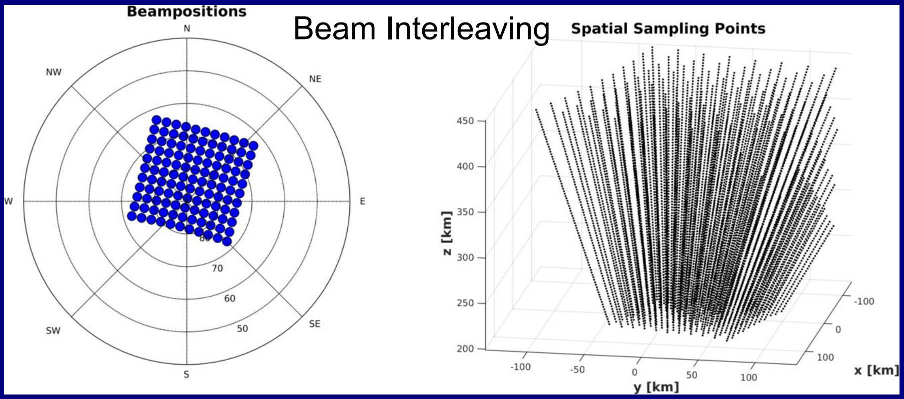
Dish antennas provide full sky coverage

Multiple array antennas or geodesic geometries ($$$$)

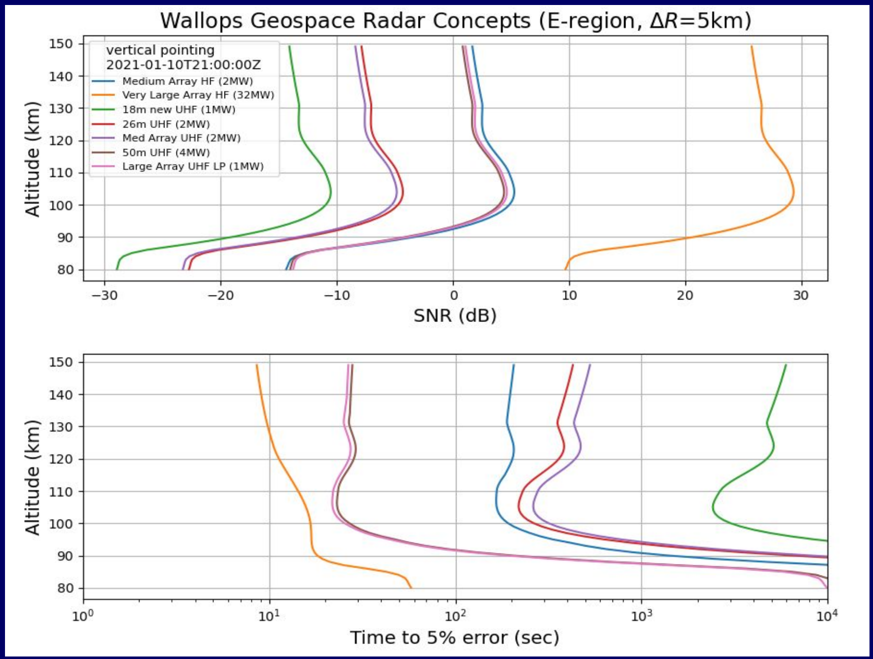
Arrays provide flexibility of beam pointing and interleaving

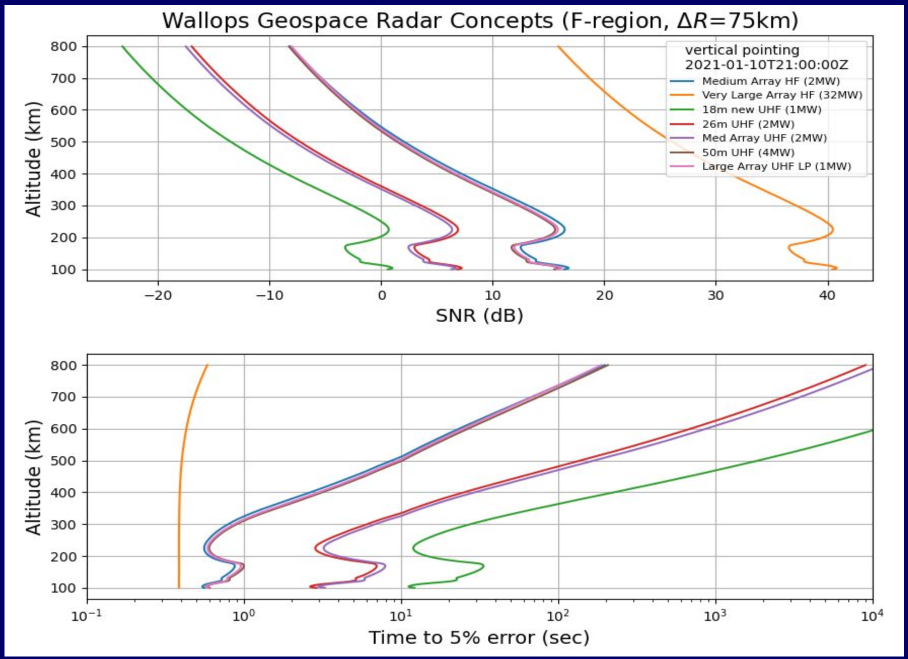
Reduced aliasing, needs big radar for volume imaging

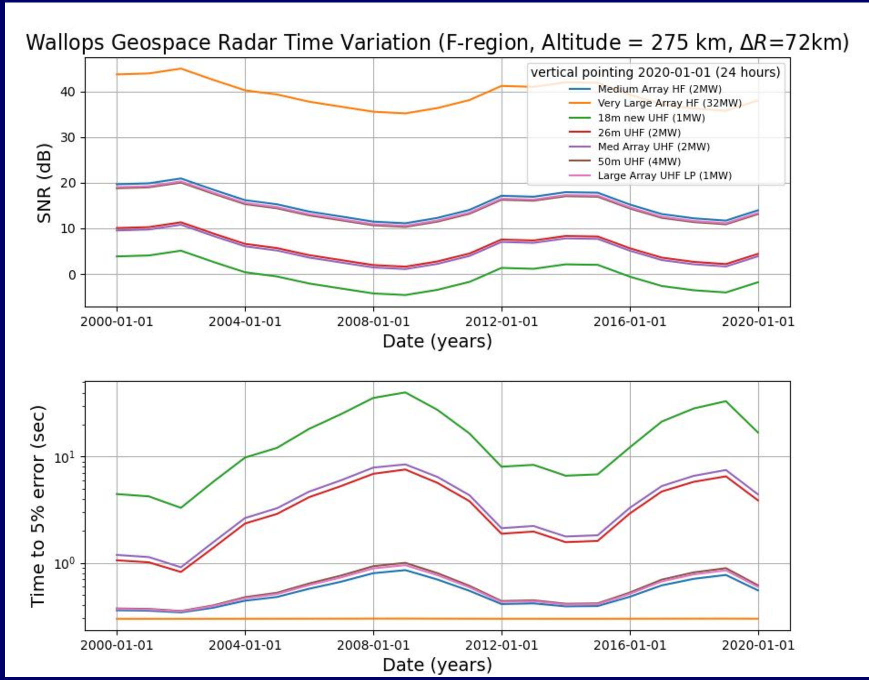


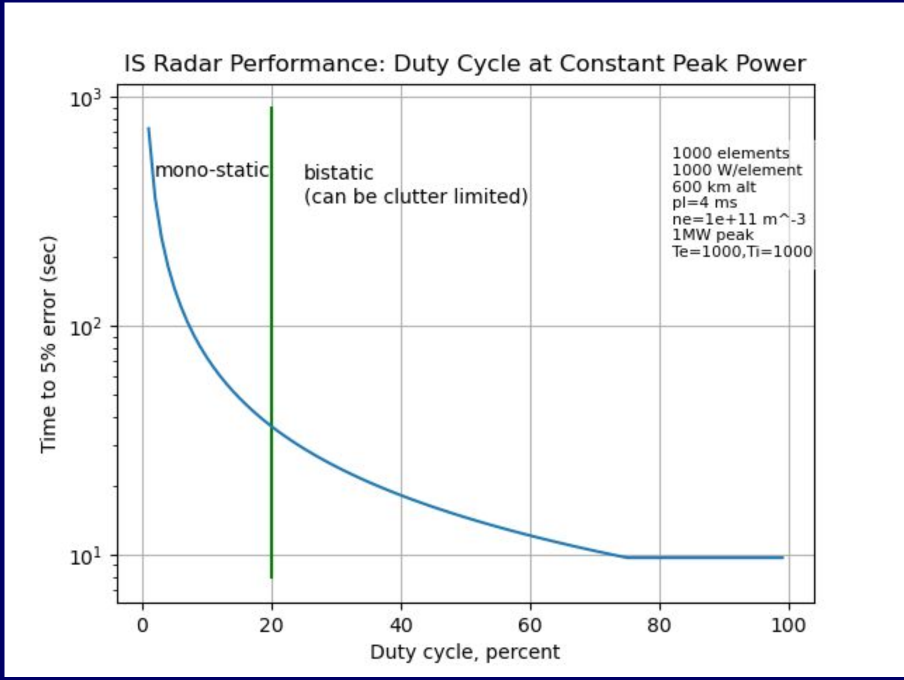


How much RF Power do you want?

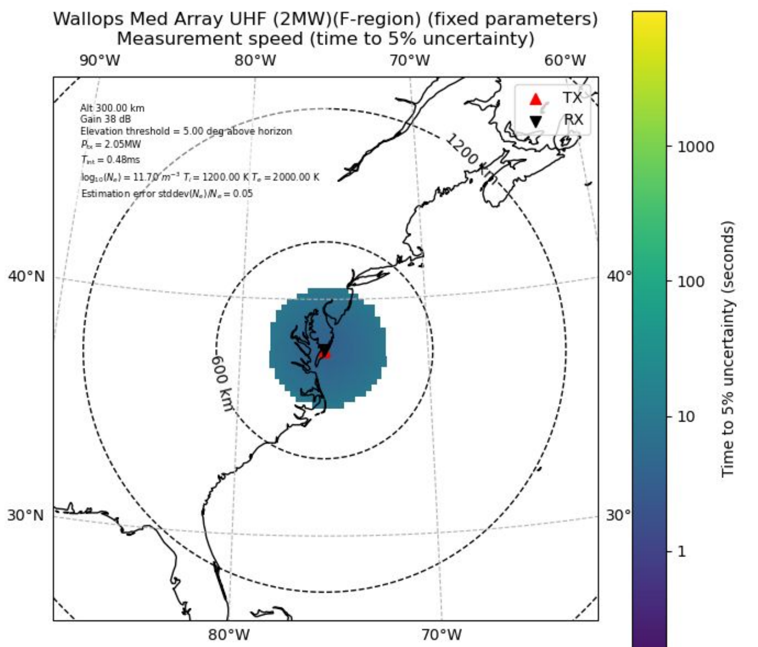




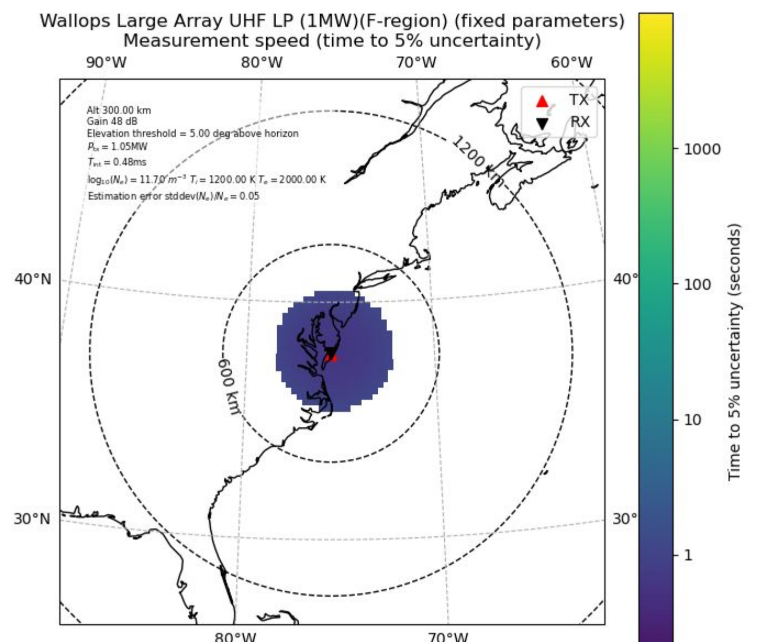




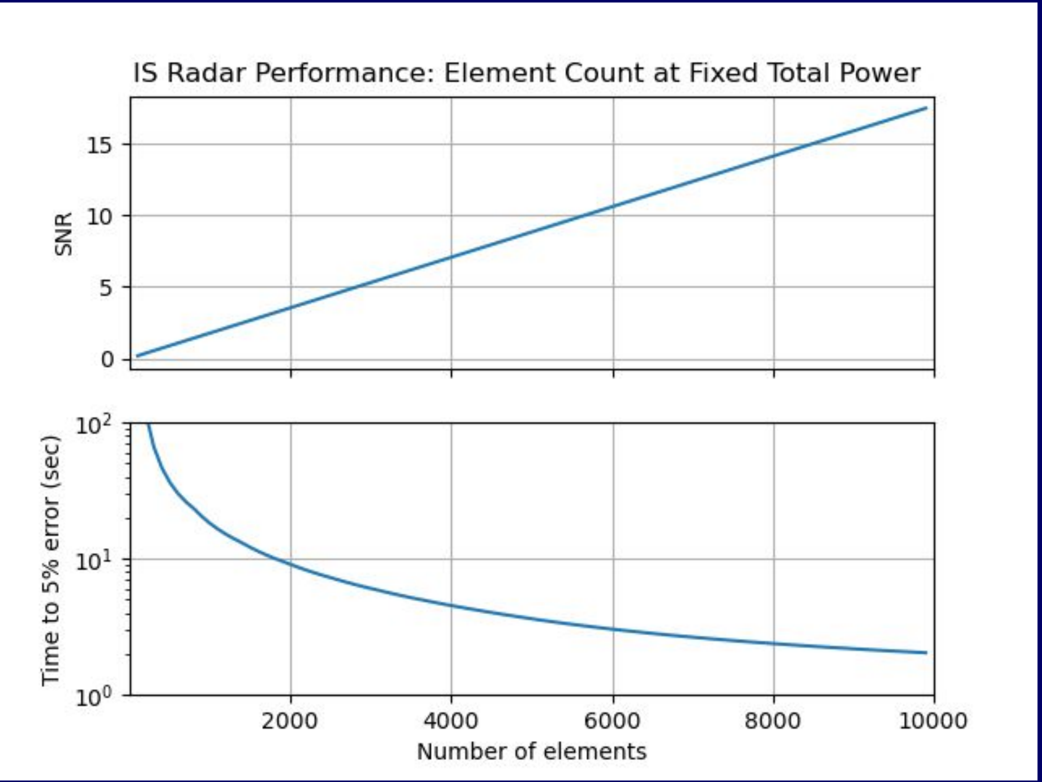
Scale Aperture instead of Power



2048 Elements @ 1 kW / element



32768 Elements @ 32 W / element

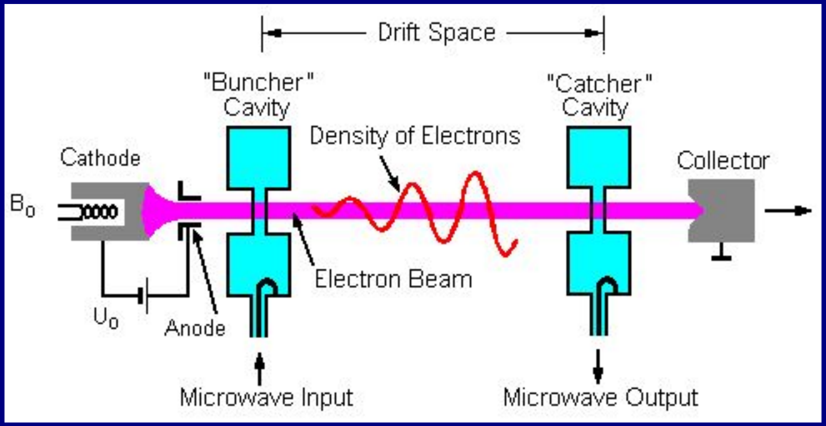


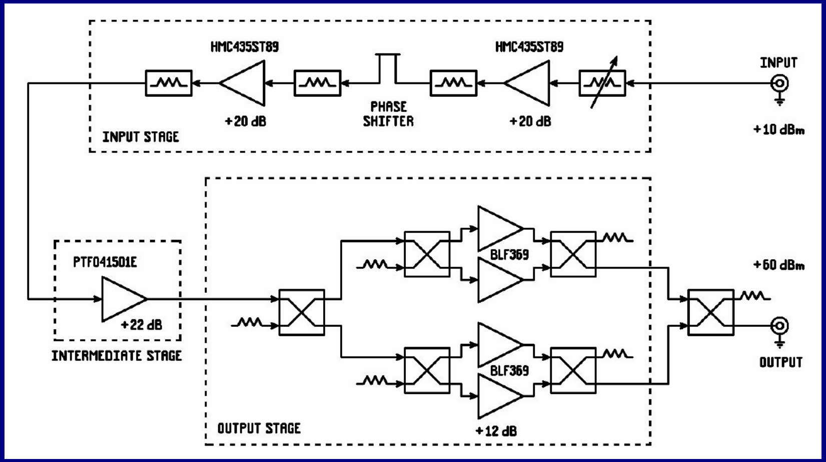
Scaling aperture can be a big win
- Zenith pointed arrays work particularly well
- Hard to do a big tilted array, dishes get very big

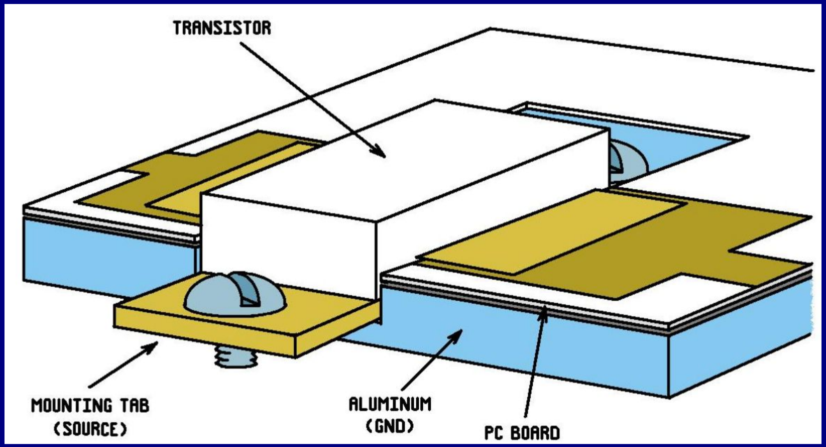
Possible to lower average power for same performance
- Ops cost savings for same power aperture

Large and capable receive system

What Kind of Amplifier do you Want?



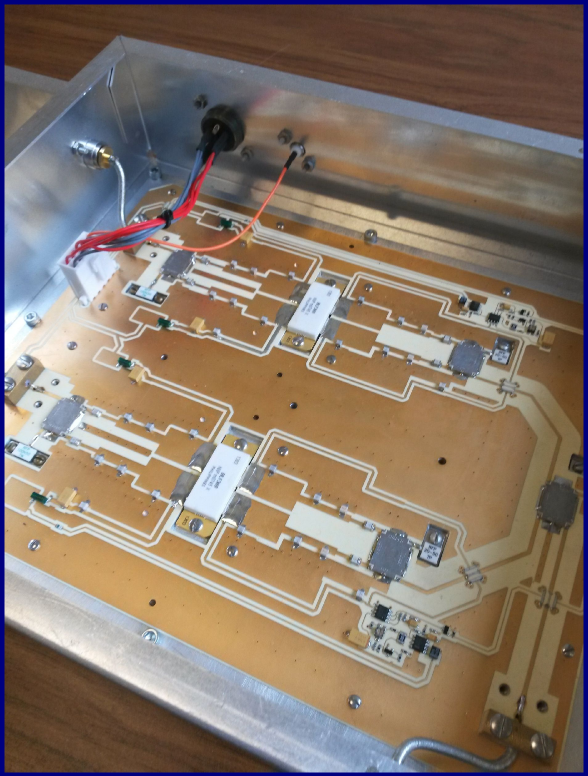




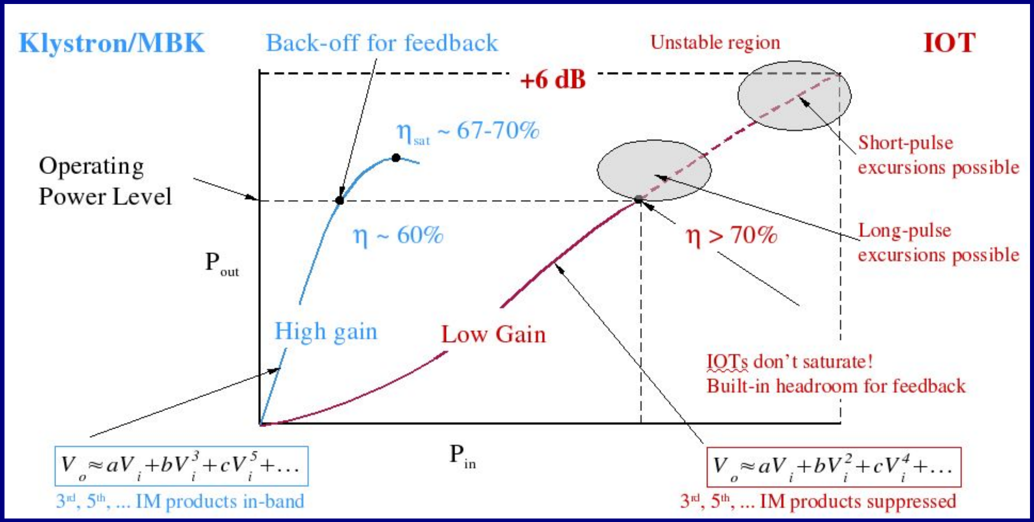
Need high power RF for many applications

Tubes enable very high peak power levels
- 40 to 70% efficiency (i.e. plug to RF)

Solid state amplifiers use RF transistors (mostly)
- LDMOS and GaN, ~ 25 to 40% efficiencies
- Combiner networks are lossy! → Phased Arrays

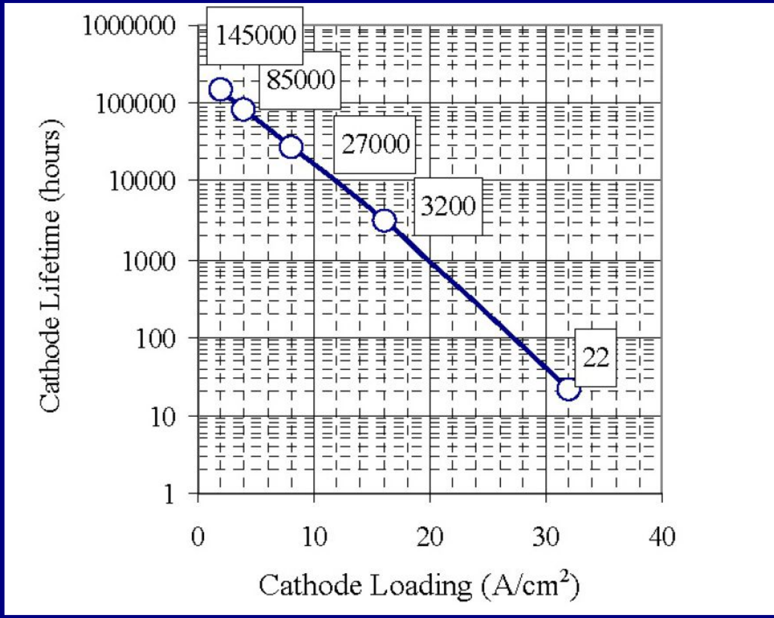


Klystron Tubes



Klystron

- High gain (35-50 dB) and energy density RF tube
- Production tubes are semi-custom designs
- Limited suppliers
- 30,000 to 50,000 hour lifetimes
- Efficiency ~ 60% at full RF power level
- 4 MHz RF bandwidth typical for a modern unit

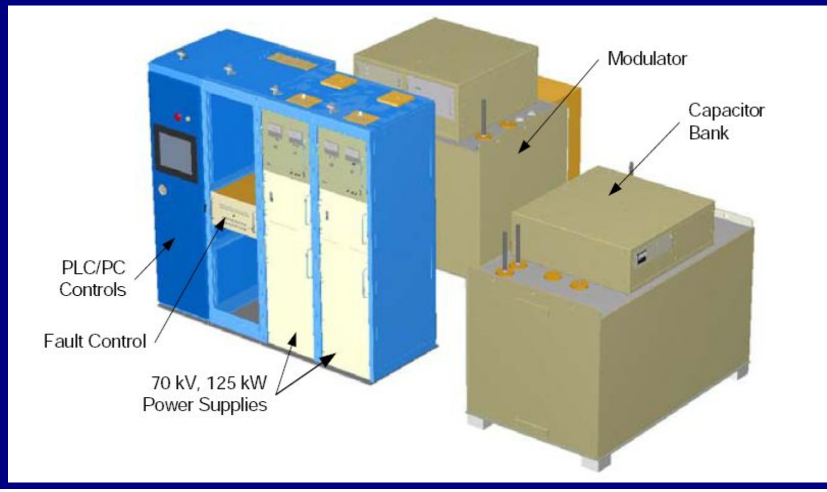


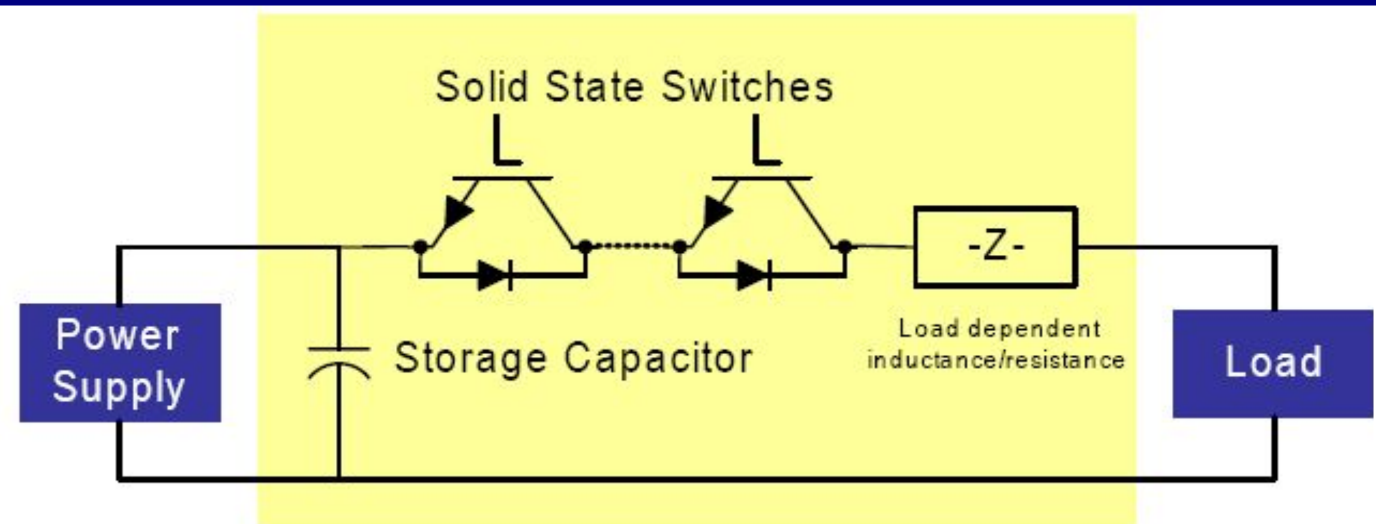
Empirical Tube Cathode Lifetime [Chin 2008]

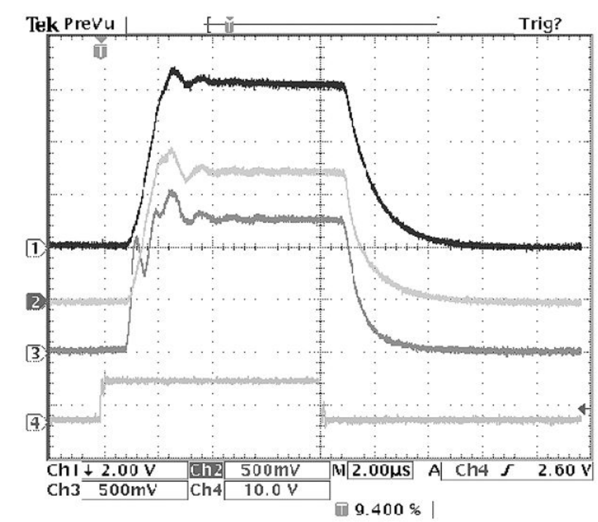
CPI UHF Klystron

- Tube recently developed for Chinese
- Retuned easily to 420-450 MHz band
- 2 MW peak, 10% duty cycle, 4 MHz RF bandwidth
- A single tube for 2MW peak, or dual tube for 4 MW peak
- Potential for a simple single tube transmitter and lower tube burn rate
- High unit costs but moderate NRE, relatively low risk
- Single supplier and low production quantities

Modern Transmitters: Solid State Modulation



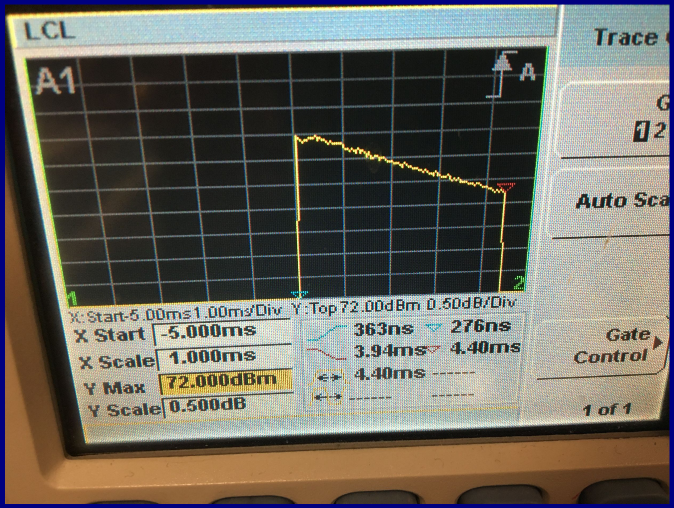




Transmitters with Solid State Modulation for High Reliability

- Solid state IGBT transistor based modulator
- Fast **direct** modulation of high voltage (scalable up to 200 kV @ 5000 A)
- In use at Sondrestrom site since 2005 with good results
- Tube arcs suppressed in < 1 usec, next pulse goes out without a problem
- MTBF ~ 350,000 hours
- Hardware costs roughly linear with tube count plus combiner network

Solid State Transmitters

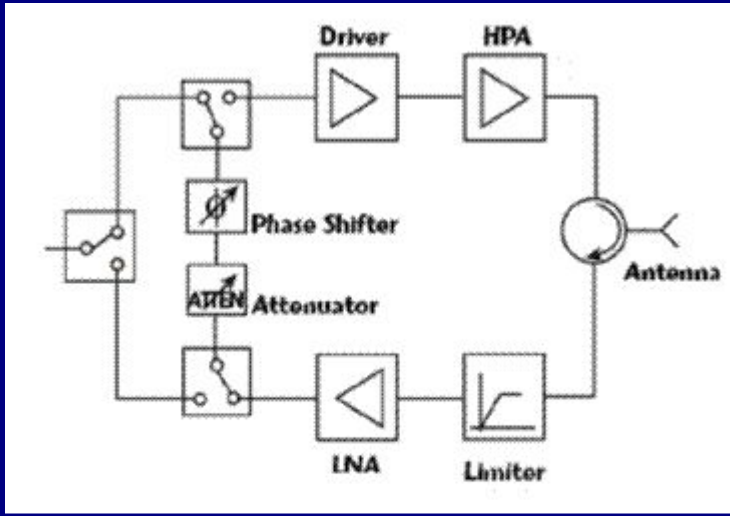


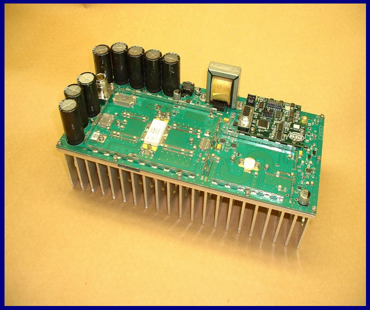
HF through X-band
GaN or LDMOS in rack modules with hot swap
High RF bandwidth compared to tubes
Plug to RF efficiency of 25% is typical
Liquid cooling + large combiner network
~ 100 kW peak per rack → 1MW = 10 racks + combiners
10 to 20% duty cycle
No high voltage (i.e. 208 or 480V 3-phase)

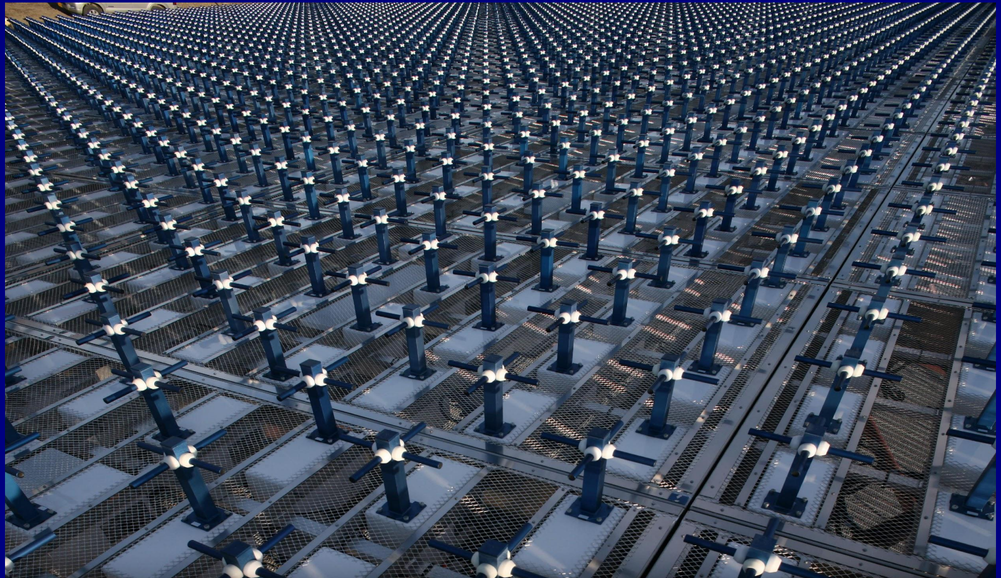
More exotic cavity combiner approaches exist

- Often as "tube" replacements
- Increase overall efficiency but lower TRL

Phased Array Radars / Transmit Receive Microwave Modules

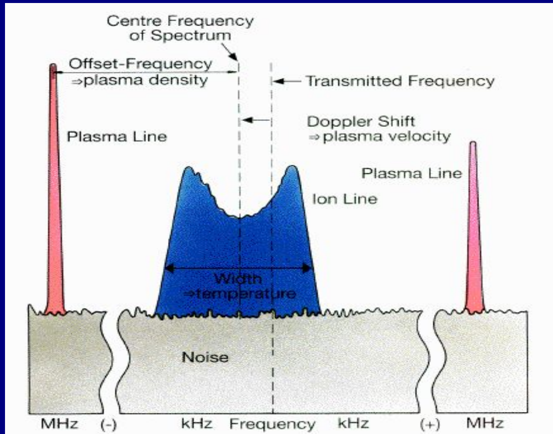


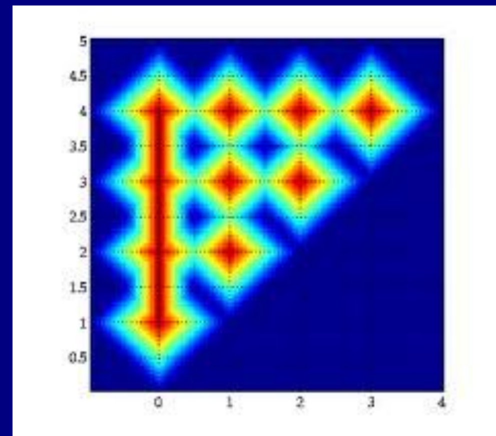


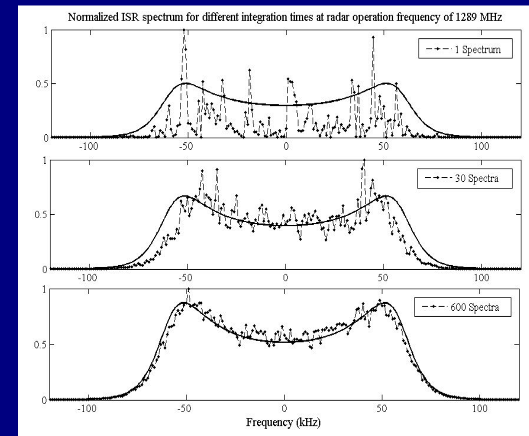


Electronic Steering and Beam Forming
Larger for same sensitivity as dish (in general)
Spatial coverage takes multiple arrays / faces
Module reliability is key to longevity
Flexibility in operation (e.g. low duty cycle)
Large radar needed for effective imaging (e.g. EISCAT_3D)

Signal Processing and Analysis Flow







Voltage Level Data
30 MHz @ 16 bits IQ max
Ion Line : 100 kHz nominal
Plasma Line : 4 MHz nominal

~ 100 Gbytes / day
(max raw rate 10 Tbytes / day)

Archive Here for Maximum Flexibility!

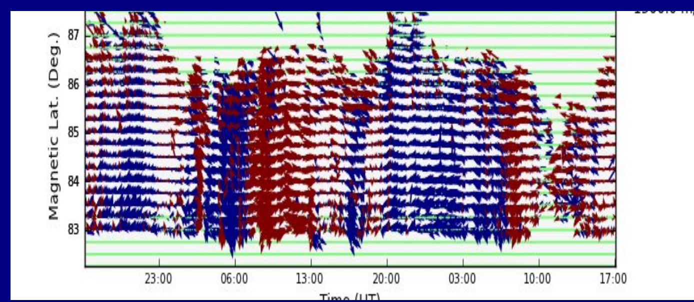
Raw Lag Product Data
Correlator Output
sub-integrations (seconds)
Ranges x Lags

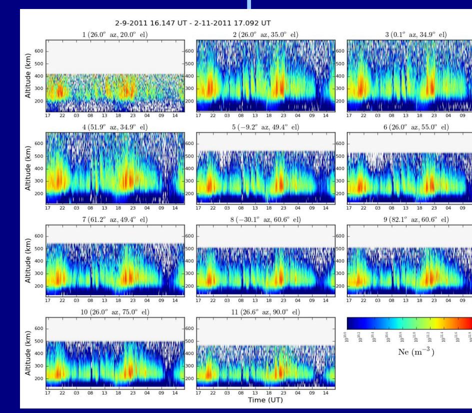
~ 100 Gbytes / day

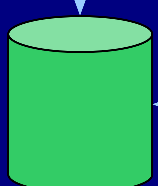
Integrated Spectra / ACF
Integrate in Time (minutes)
Ranges (filtered) x Lags (filtered)

~ 1 Gbytes / day

Radar Control / Feedback
Adaptive Response
Optimized Measurement
Cognitive Radar







Data Management System
Data Archive, Search
Post Analysis, Visualization

Derived Data Products
Model Inversion of Parameters
Vector Fields
Gridded Measurements

~ 1 Gbytes / day

Fitted Data Products
Inversion Output (minutes)
Parameters x Ranges
Error Covariances

~ 1 Gbytes / day

Low Cost Radars for Space Weather

Separate Transmit and Receive Arrays (i.e. locally bi-static / multi-static)

Narrow Band TX at High Power Per Element (no T/R switch!)

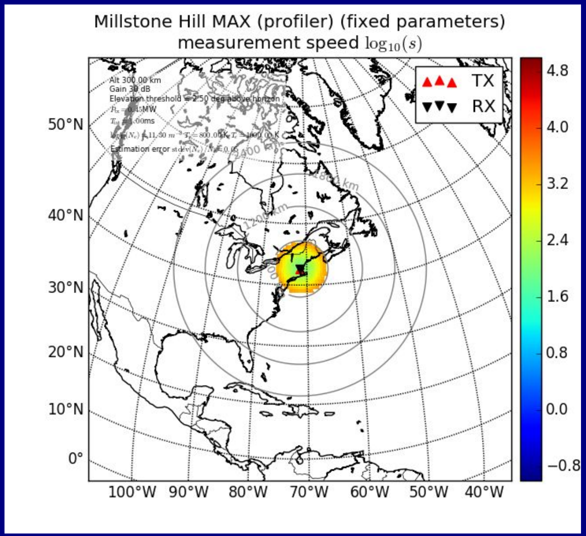
Flexible Transmitter Duty Cycle and Bandwidth (to 100% with STAR)

Large Aperture, Distributed, Digital, Broadband Receive Arrays

Centrally Dense Aperiodic RX Array Layout with GaN LNA + low Tsys

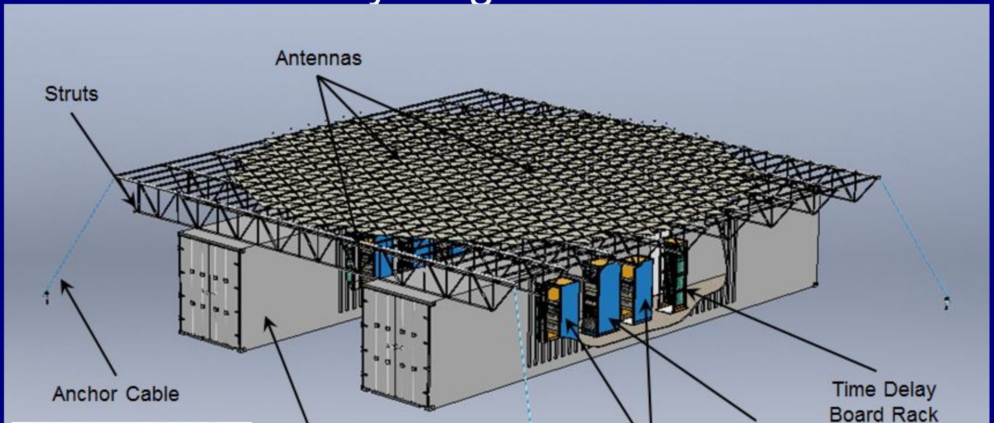
Digital RX / TX (per element) + Cloud Based Software Signal Processing

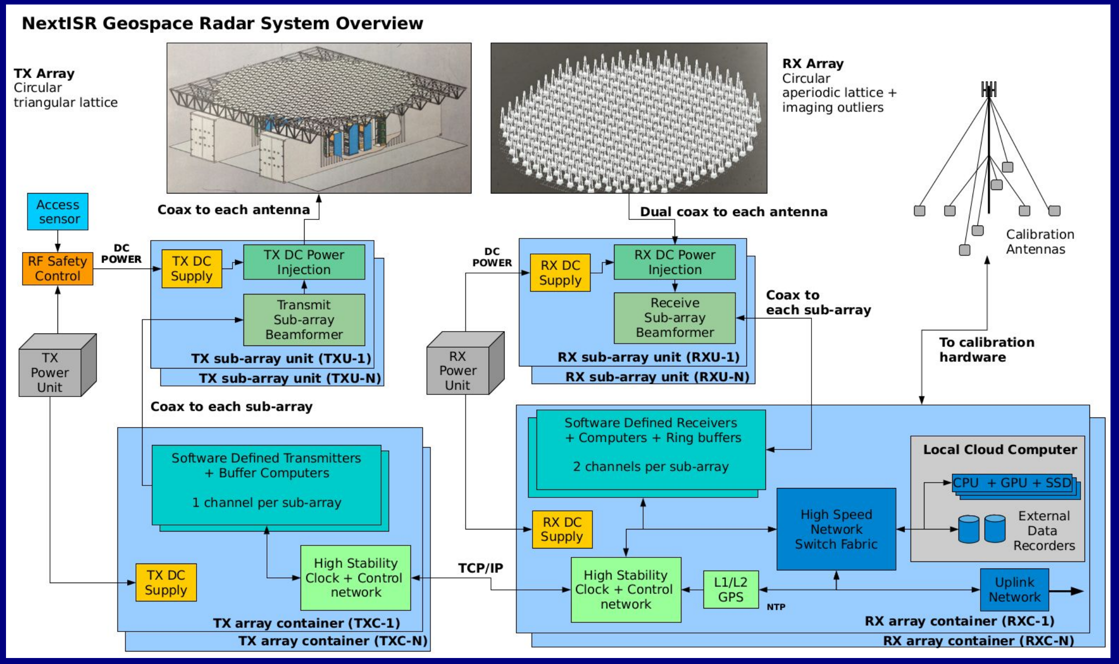
Get Rid of Everything Else Possible → Lower Per Element Costs



The NextISR System

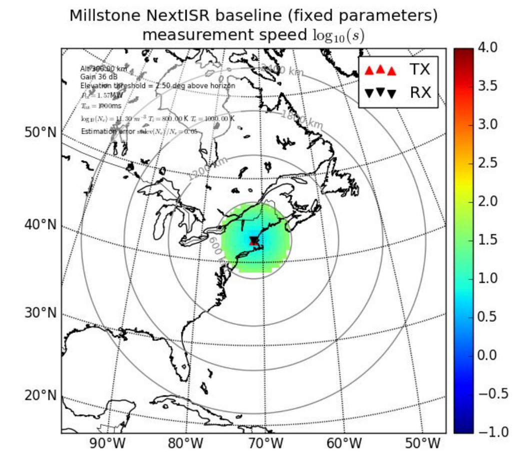
In partnership with:



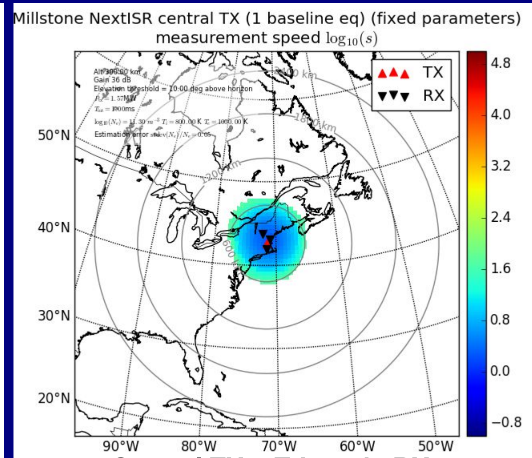


(MIT and DTI Proprietary)

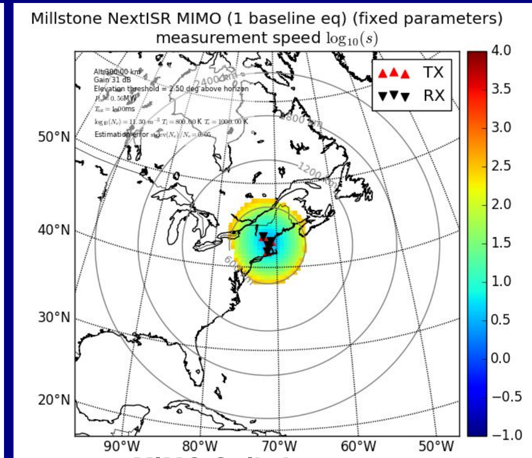
Geospace Radar Networks



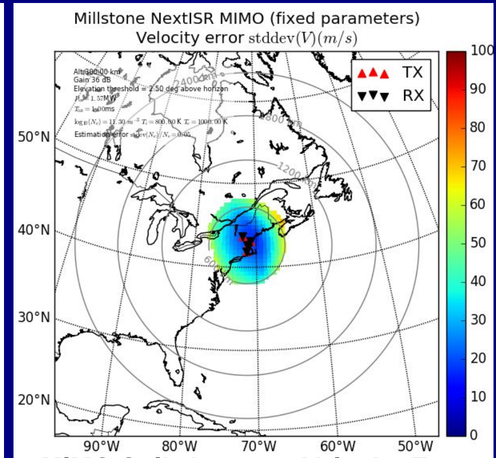
Locally Bi-static



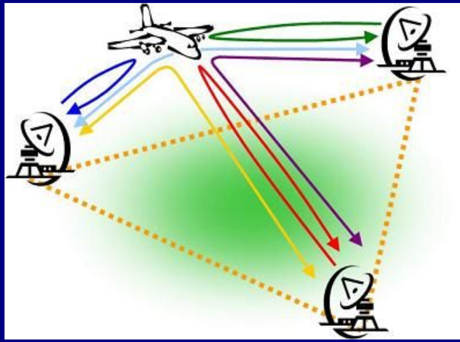
Central TX + Tri-static RX



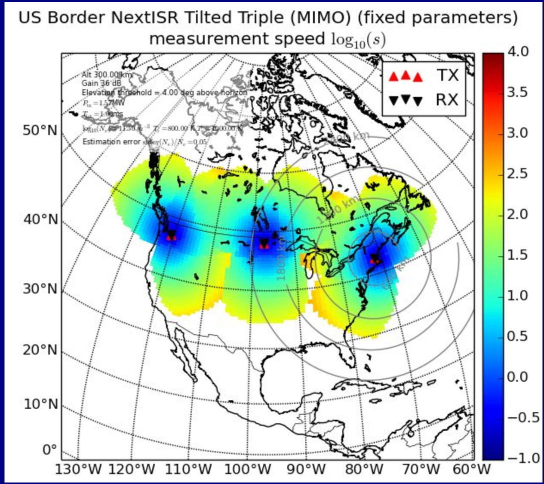
MIMO Split Aperture

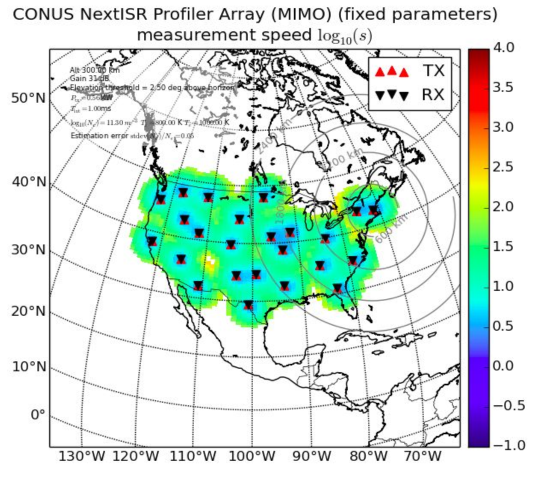


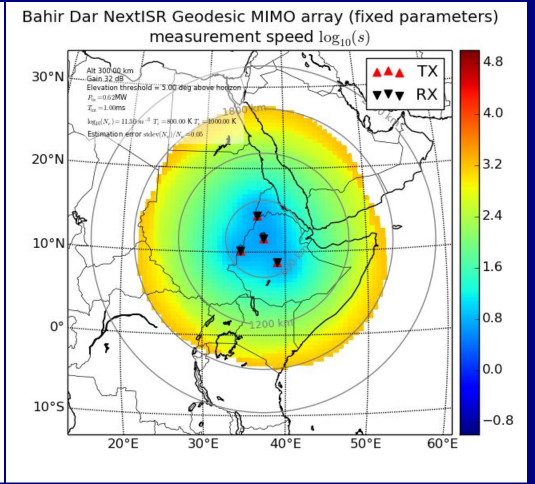
MIMO Split Aperture Velocity Error



MIMO (Multi-In Multi-Out)







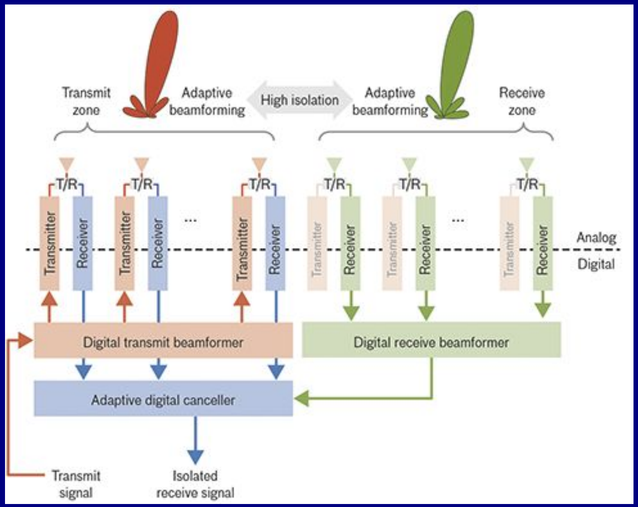
Wide Spatial Coverage via Networks of Geospace Radars

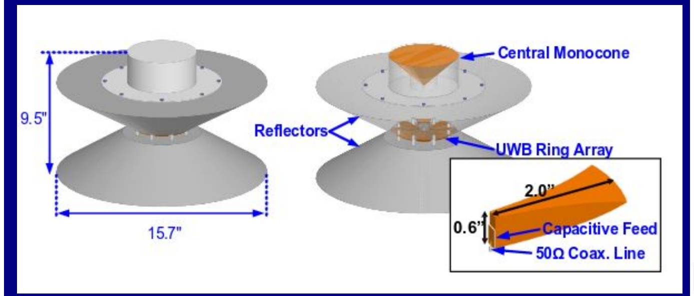
Multi-static (multiple RX) or MIMO (multiple RX and TX)

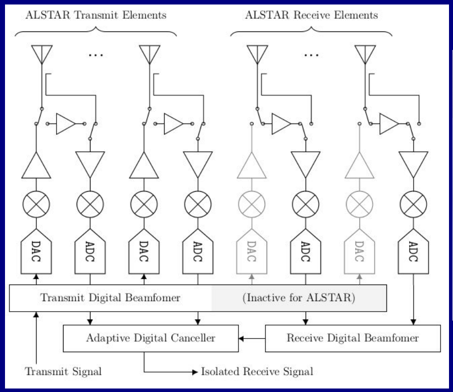
- True vector measurements with fast measurement speeds!
- RX Arrays are less expensive than TX arrays → More RX than TX in networks

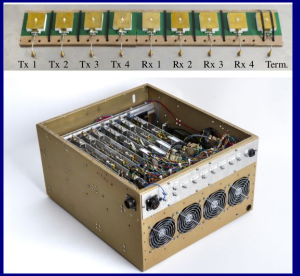
Many possible configurations to explore…

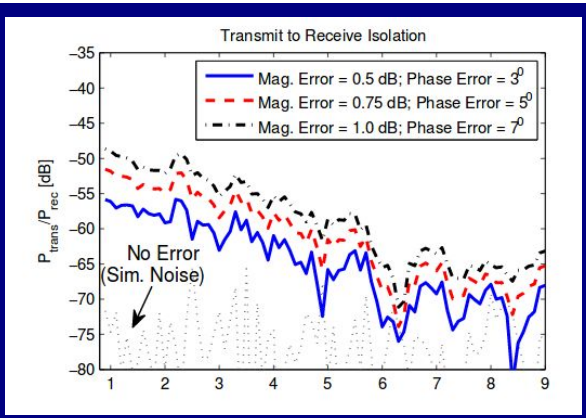
Simultaneous Transmit and Receive (STAR)

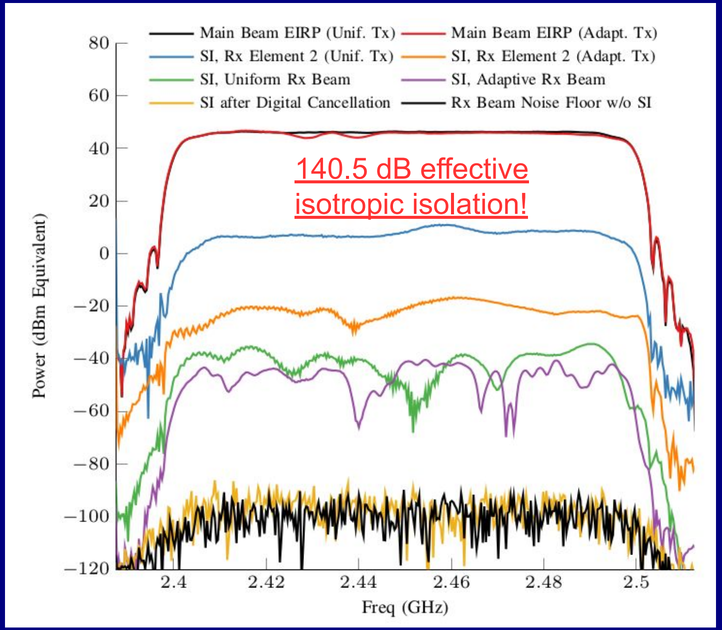


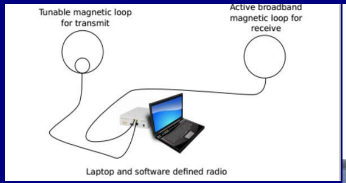


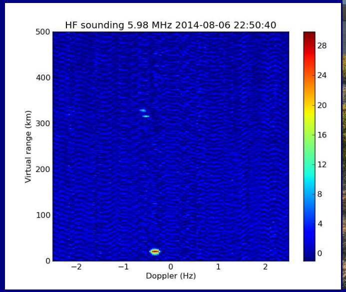












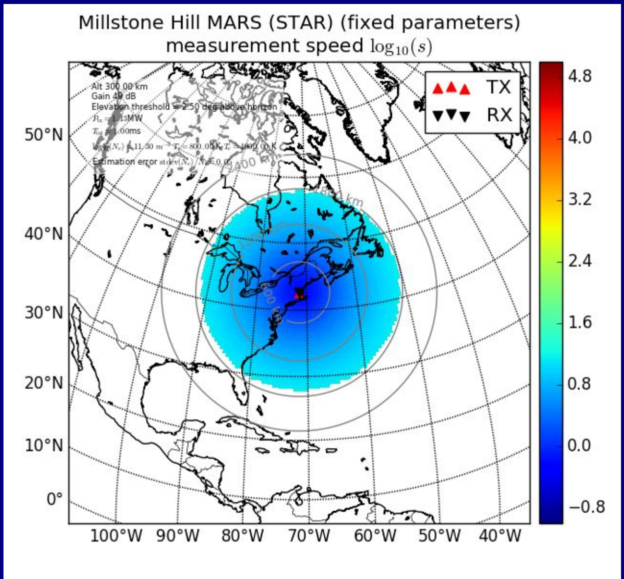
Wideband Antenna Array for Simultaneous Transmit and Receive (STAR) Applications, William F. Moulder, Bradley T. Perry and Jeffrey S. Herd. MIT Lincoln Laboratory, Massachusetts Institute of Technology

Simultaneous Transmit and Receive Performance of an 8-channel Digital Phased Array, Jonathan P. Doane, Kenneth E. Kolodziej, Bradley T. Perry, MIT Lincoln Laboratory

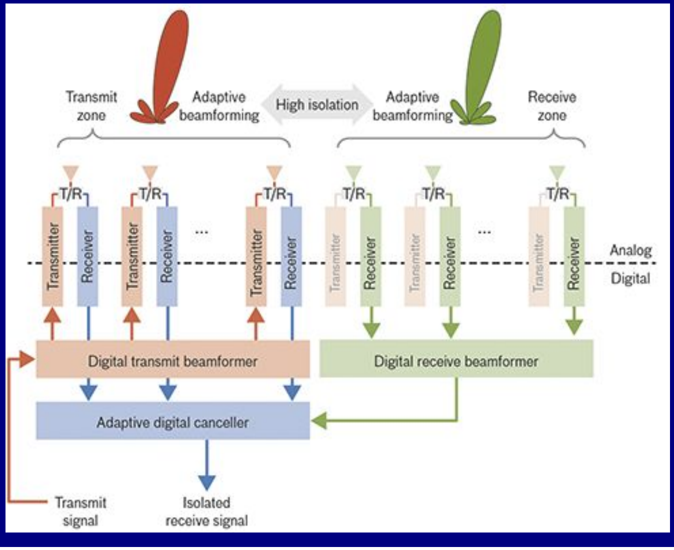
Transmit at 100% duty cycle → Don't saturate the receivers!
Create TX to RX dynamic range via : element design, array layout, TX and RX beamforming, TX digitization + adaptive filtering

Low power per element and high element count apertures
How close to thermal noise limited performance can be achieved?

Example: Geospace Radar for Scientific Discovery



Simultaneous Transmit and Receive (STAR)

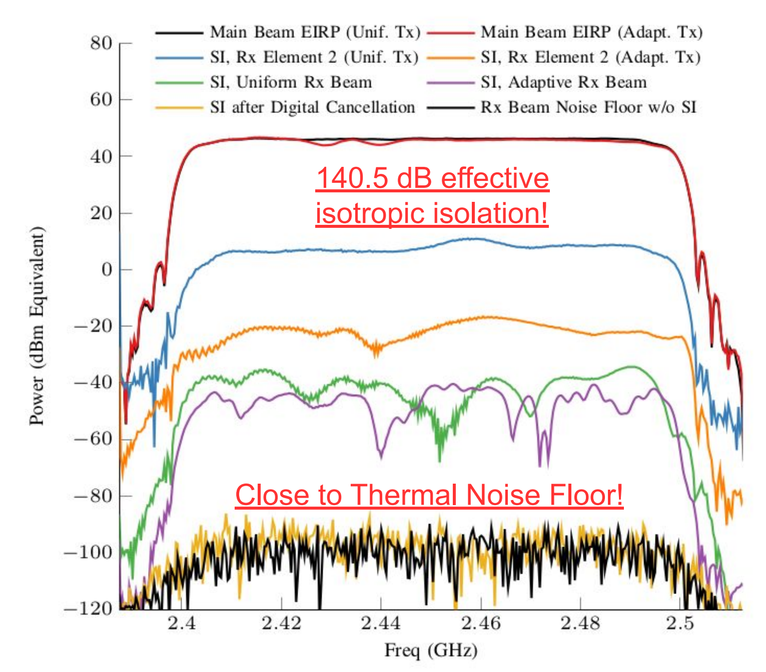


The Millstone Advanced Radar System (concept)
- Recapitalization of the Millstone Site
  - Geospace Radar, Astronomy
  - Near Earth Objects, Space Surveillance

Conformal STAR Aperture (100% duty cycle)
- Full sky coverage, multi-role aperture
- Multiple spatial ‘beams’ and snapshot imaging
- Frequency, polarization, and temporal multiplexing

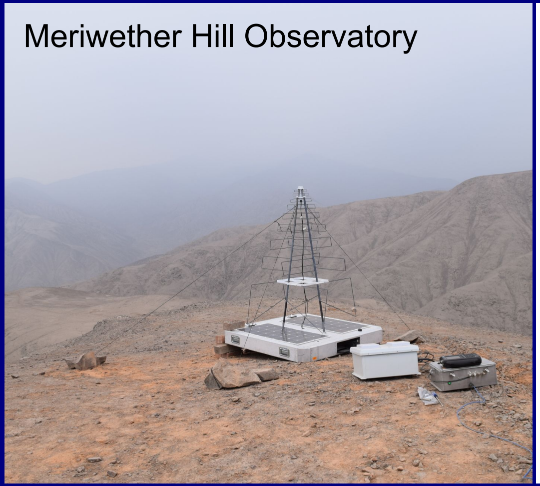
Narrowband TX (e.g. UHF, L-band, S-band)
Broadband RX (e.g. VHF to S-band)

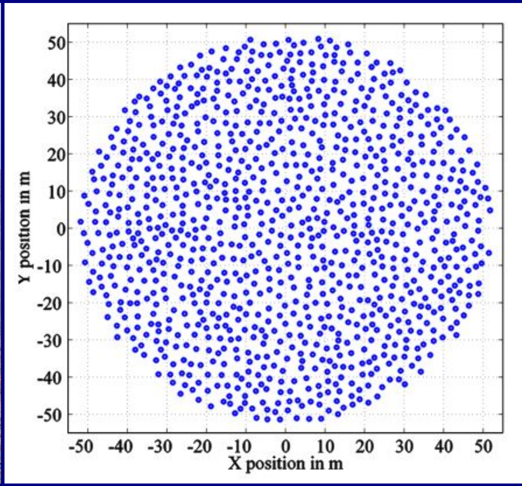
Low Power per Element and Geodesic Geometry

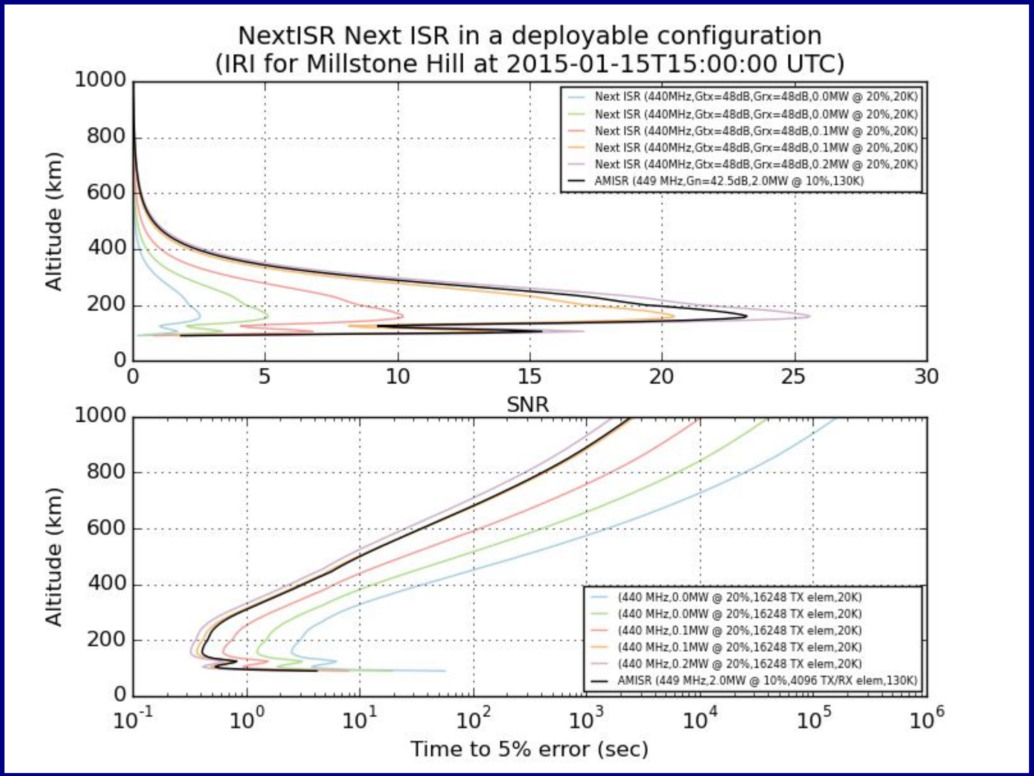


Simultaneous Transmit and Receive Performance of an 8-channel Digital Phased Array, Jonathan P. Doane, Kenneth E. Kolodziej, Bradley T. Perry, MIT Lincoln Laboratory

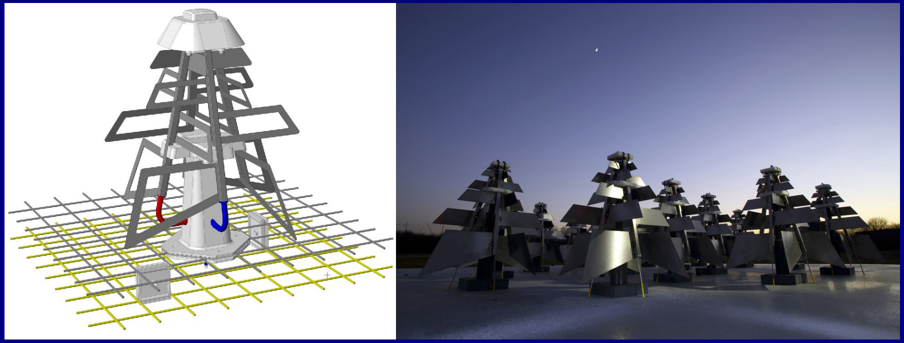
Deployable Geospace Radar Arrays







1W, 2W, 4W, 8W, 10W RF peak per element (20% duty cycle)



SKA MFAA Courtesy Eloy de Lera-Acedo (Cambridge University)

RAPID (Radio Array of Portable Interferometric Detectors)

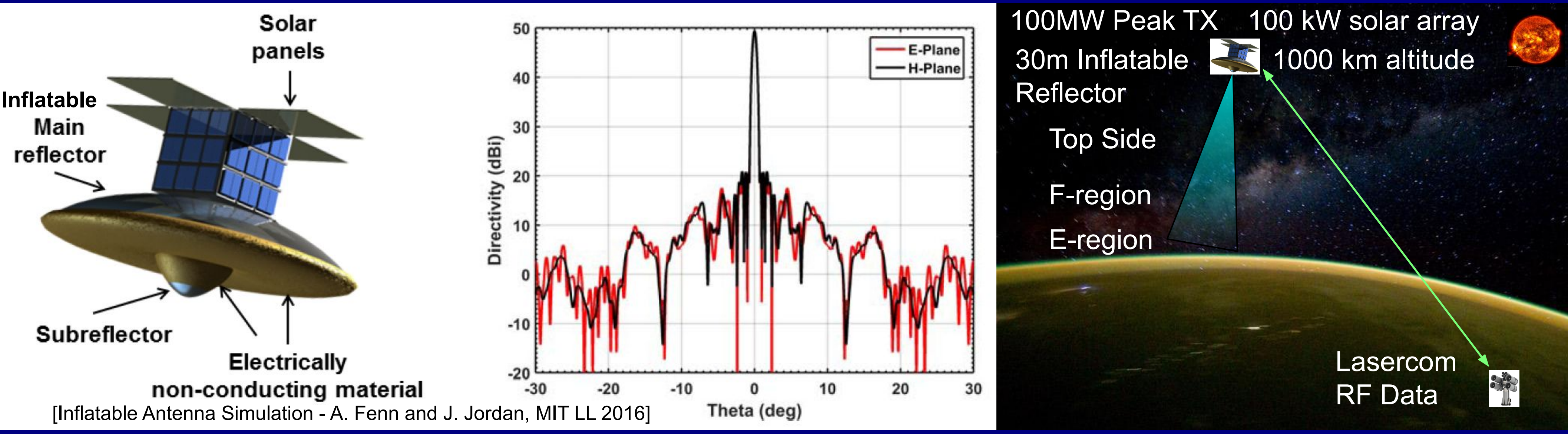
- RAPID x-Series (Xilinx RFSoC with RX <u>and TX</u> at multi-GSPS / 16 channels)
- Add a low power transmitter and combine with SKA MFAA antenna (or a more shippable one)
- Needs a big aperture (16K elements) → Tile for efficient sub-array level deployment

Solar and Battery Powered Incoherent Scatter Radar

Low average power per element and probable compromises on performance / coverage

Future high speed satcom (v-band) to uplink data for remote processing?

Space Based Geospace Radar



Geospace Radar from Orbit (Earth, Venus, Mars, Jupiter, Saturn, Solar?)

Challenges: Power, size / mass, reliability, wide bandwidth, ground clutter

Ultra high peak power (i.e. 100 MW) → NLTL transmitters → Swath measurement
L-band? + Inflatable Dish TX / RX (~ 30 meters) → Size depends on peak power
Use SNR to improve measurement speed → Single pulse parameter estimates
Need to get sufficient correlation function samples → Aperiodic pulse patterns?
Very low duty cycle → Manageable average power levels (~ 100 kW / e.g. ISS)
Lasercom for raw data to ground or V-band satellite to satellite data (Earth)
Secondary applications in SAR, iSAR, Surface Penetrating Radar