Next-Generation Instruments for Geospace Science

John Foster
MIT Haystack Observatory

CEDAR Student Workshop
June 2009
Geospace is a System
Individual Features and Instruments
Reveal Parts of the Complex Geospace System

Understanding the System poses many Questions
How do ionospheric outflows impact magnetosphere-ionosphere system dynamics? [Lotko et al., 2007]

electrodynamic–inertial linkage

coupling and feedback

global modeling

mass transport

superthermal outflow

thermal outflow

flux

TEM

V

V||

12

12

12

12

TEC

Alfvénic

EM power flows
What Will the Future Look Like?

- **Improved Instruments** to push the envelope of what can be measured.
- **Minaturization**: cost-effective instruments in large quantities
- **Distributed Arrays**: interconnected regional and global multi-user instrument arrays
- **Integrated space and ground-based observing capabilities**
Thought-Provoking
Radio Arrays
What is a Modern Radio Instrument?  (Frank Lind)

- All Digital RF Technology enables extensive capabilities
  - Combine array radar and array radio telescope approaches
  - Broadband, adaptable, all digital electromagnetic interface
  - Transform applications through applied computing power
  - Array must be affordable -> Low per element cost
  - Interleaved missions on a fine scale – adaptive response to conditions

Modern Digital Array Radar
- Narrowband
- Single Aperture
- Planar geometry
- 100 to 200 RX beams
- Element, brick, sub-array, array

RF MCM (multichip module)
RF MEMS
Software Radar
Supercomputing

Advanced Digital Radar System
- Broadband – Distributed
- All Digital Elements
- Adaptive beams : TX and RX
- Simultaneous TX / RX - 1000 beams
- Deep per element data buffers
- Moderate power - high aperture

Key enabling technologies
Advanced Modular ISR (AMISR)

- New NSF ISRs
- Modular/Transportable/Reconfigurable
- Phased array / rapid steering
- Solid state / No warmup
AMISR Coverage – Global Context

ISRs
SuperDARN
Allsky Imagers
Satellites

Employ Instruments in Unison
EISCAT_3D will give accurate, large-scale, three dimensional measurements of the ionosphere and atmosphere for the first time.

EISCAT_3D will give unprecedented temporal and spatial information about the plasma environment – essential to understanding crucial and societally relevant problems in the geospace environment, in space weather, and in the global energy budget and related climate change.
MIDAS-Mobile Coherent Software Radio System

- Advanced digital receivers
  - ECDR-GC314FS
- Six analog inputs (2 cards)
- Up to 24 simultaneous RF channels

- Ultra stable GPS locked oscillators
- Wide area coherence
- Absolute alignment of data to UTC
  - 1 part in 1E11, 20 nsec alignment
- Low phase noise

- High integration UHF Radar Tuners
- DC to 1500 MHz (with external filters)
- 30 MHz down-converted bandwidth

- Fully remote Internet based operation
- Realtime web based visualization
- Grid Computing
- Remote power control

**MIDAS-M : Latest Millstone Data System**
- Millstone UHF Radar and ISIS Array

**Software Radar Architecture : Raw Voltage Based Processing**
- Realtime signal processing, analysis, database, and visualization
- Production quality IS radar ion line processing
- Active and Passive Radar, Monostatic/Multistatic, Satellite Beacons, Spectral Monitoring
ISIS
Distributed Software Radio Array

- Radar Using Intercepted Signals as the Transmitter Source
- Coherent Scatter from Ionospheric Irregularities and Meteors
- Dynamic Range From Multistatic Architectures
- Precise Synchronization Using GPS Signals
- Transmitter and Scattered Signal Coherent Digitization
- Wide Area Network Transport of Raw RF Data
- Numerically Intensive Data Processing
Rockets for Tomorrow’s Sub-Orbital Program
(What Will They Be Like?)
Optical Sensors
Ground Based
(But New Ground to Break)
Images of Geospace Optics, GPS TEC & IS Radar

Equatorial Uplift Destabilizes Plasma

Spread F (Bubbles) in Enhanced TEC Region

(Courtesy: J. Makela)
Future Directions (Jon Makela)

- We are studying a global system
  - Land masses are becoming increasingly well instrumented
  - What about the oceans?
- Multiple-instrument clusters provide more comprehensive measurements than individual instruments
  - Can we assemble a “menu” of instruments that a PI setting up a site can choose from?
  - Is it time to deploy a community-driven/supported array? This is a large logistical undertaking
- To not be constrained by where we can plug in our instruments, we need to be able to deploy off grid
  - Requires development of lower-powered (but not less-capable) instruments
  - Requires cellular/satellite communications to get data back
Technologies for Remote Deployment
System Science

System Science is an approach to understanding the natural and physical world that recognizes how various phenomena are interconnected.

For the first time, scientists have easy access to massive amounts of information by which to study the interconnectedness of diverse phenomena.

**The system itself is a frontier** – we must identify and understand its characteristics and components.
Class I Facilities – Old and New

EISCAT, Svalbard 1996

EISCAT, Tromsø, Norway 1981, 1985

Sondrestrom, Greenland (Chatanika, Alaska 1971)

AMISR, Poker Flat, Alaska 2007
UAF Geospace Observatories Probe the Boundaries of Geospace

### UAF Geospace Observatories
- RISR
- PFISR Sondrestrom
- Millstone Hill
- Arecibo
- Jicamarca

### ITM Regions
- Polar Cap
- Auroral
- Sub-Auroral
- Mid-Latitude
- Equatorial

### Magnetospheric Regions
- Solar Wind
- Magnetosheath
- Outer Magnetosphere
- PBL
- Inner Magnetosphere
- Ion/Neutral Boundary
UAF Geospace Observatories

- **Span altitudes** across the ion-neutral transition
  - Earth’s threshold to space
- **Span latitudes** mapping all regions of geospace
- Positioned at **major boundary layer (BL) locations**
  - observe universal BL processes
- Ground-based: **continuous/repeatable coverage**
- Coordinated observations: **snapshots of geospace**
  - interconnectivity of processes

- Magnetopause BL /cusp: RISR, Sondrestrom
- Open/Closed B-field BL: RISR, Sondrestrom, PFISR
- Plasmasphere BL (PBL): Millstone Hill
- Ion-Neutral BL: Jicamarca, Arecibo, high-lat ISRs
Jicamarca Radio Observatory, near Lima, Peru
18,432 dipoles, 50 MHz, 1961
System Science Requires Global Coordinated Observations

The latitude and altitude regions of the upper atmosphere are coupled in complex ways and behave as a dynamic system.

Meso-scale (1000-km) features associated with the redistribution of thermal plasma from the low-latitude ionosphere to the auroral and polar regions and its outflow and acceleration into the magnetosphere provide a striking example of coupled-system interactions. Solar disturbances driving prompt penetration electric fields impact the state of the ionosphere from the poles to the equator, intermingling the effects of neutral-ion coupling with magnetosphere dynamics over the planet-wide upper atmosphere on short (10-min) time scales.

Such complex behavior requires distributed system-wide observations to address the processes involved in both regional and larger-scale effects. Individual observing techniques and facilities (e.g. the SuperDARN radars or the ISRs) provide only a portion of the needed coverage. Coordinated observations among instrument types and with good spatial distribution are needed to view, diagnose, and understand the overall global system.
DASI: A Framework for Community Collaborative Research

- Geospace is a System
- System Science: Distributed Realtime Observations Needed
- Insufficient Data: New Instruments
- Multi-Instrument Collaboration provides New Views of Geospace
- Time to Get Started!
Regional DASI to address System Science
SuperDARN (Polar, Auroral, Mid-Latitude), ISR, THEMIS GBO, ISIS, etc.
Next-Generation Instrument: Regional DASI

- Combine existing distributed arrays and Class I instrument clusters
- North American arrays span polar, auroral, sub-auroral, and mid latitudes
- Multi-technique facilities: Magnetometers, Imagers, ISRrs, HF Radars, Rockets
- Communications infrastructure is in place
Ground-Based Instrumentation in North America

UC Berkeley
U Calgary
U Saskatchewan
EISCAT
U Tromso
FMI
DMI
SRI
Astronomy North
Lancaster U
- Class I Facilities Anchor North American Array
- Key Locations for System Science

Arecibo, Puerto Pico

Mid-Latitude Large Dish ISRs

Millstone Hill, Mass.
Millstone Hill ISR Mid-Latitude Field of View
Direct Observation of Velocity and Flux by Millstone Hill ISR

Ground-Based GPS Maps TEC Plume

[Foster et al., GRL 2002]

Radar & GPS TEC Arrays Map Ionospheric Structure & Dynamics
Monitoring the Ionosphere: SuperDaRN Radar Arrays
Ground and Space-Based Arrays for Geospace Studies
Next-Generation Instruments

Our next-generation instruments will evolve from our current capabilities, taking advantage of technological developments to improve their sensitivity, capability, and operational efficiency.

The breakthrough will come in our ability combine the output of the available instruments in ways which address the processes and characteristics of the Geospace System taken as a whole.