Low Cost Digital Radio Arrays, the Geospace Array, and Ethiopia

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[sunrise over lake Tana, biker tony]
Enabling Technologies for Radio Science Instrumentation

- Exponential increase in network, storage, computational systems
- Wide-area networking - allows unified data transport / assimilation
- Global Positioning Systems – Wide Area Coherence
- Software Radio – Unified Multi-role Instrumentation Platforms
  - Unlike Communications Applications, Latency Can Be Tolerated
Radio Astronomy Arrays

- Global Array Radio Telescope Efforts
- Astronomical Science Targets
  - Significant Space Weather and Geospace Capabilities
    - Passive techniques (radio star position, satellite beacons, passive radar, etc...)
- Significant Technology Development Efforts
- Rapidly Getting Easier to Build Digital Radio Arrays
Low Frequency Astronomical Radio Arrays (HF to UHF)

MIT Haystack Deuterium Array
24 Stations / 24 crossed dipoles each
326 MHz narrow band (1152 RF ports; $300 / RF channel)

Cambridge SKA Lo Prototype Antenna
70 to 450 MHz (extensible to 50 MHz)
(target price is ~$100 USD / antenna dual polarization with 30K LNA pair)

The Astronomy Community has invested heavily in Low Frequency Radio Array Technology Development

Just Add a Transmitter...

Astron LOFAR Station (1 of 24)
High Band (110 to 240 MHz / 96 per site)
Low Band (15 to 80 MHz / 48 per site)
~ $300 / RF channel

MWA (Western Australia)
16 dual polarization dipoles / tile
80 to 300 MHz
(128 Tile Final System; ~ $150 / RF channel)

Long Wavelength Array
10 to 88 MHz
Dual polarization active dipoles
$625 / RF channel
Example Array Antenna Elements

MWA Dipole (80 to 300 MHz)

LOFAR High Band Antenna (110 to 240 MHz)

LOFAR Low Band (15 to 80 MHz)

LOFAR High Band Radome (foam + cover)

Note: The FM band (80 to 110 MHz) is great for Geospace!
327 MHz All Digital – 576 antennas, 1152 channels

Note: Receiver provides 24 channels per polarization so that one corner element is not used.
Murchison Widefield Array

128 Tiles (16 antennas per tile)
Focused and Science Driven
Large N Design (FOV)
Realtime Calibration and Processing
Preserve Data Into Processing Pipeline

32 kHz Spectral Resolution
8 Second Integration Cadence
Full Sky Imaging Capability
16 Dual Polarization Voltage Beams
The CASPER Project as a Model:
Center for Astronomical Signal Processing and Radio Electronics

- Share engineering costs
- Rapid development
- Generic technology for multiple instruments
- Open-source and collaborative
- Reusable Hardware, Firmware, and Software
- Tools Accessible for Graduate Students
- Industry standard communication protocols
- Use network switches for interconnect

Custom Hardware is Obsolete by the Time it is Deployed
How Can You Deploy Hardware at the Last Minute?
Open Source Software and Hardware

Open Source is a Strategy

Collectively Build and Maintain Valuable Technology
Peer Review and Collaboration Applied to Technical Development
Helps to mitigate “not invented here” syndrome

Many Highly Useful Open Source Tools are Available
Not Universally Applicable or a Panacea for Complexity
You Still Need People with Time and Resources to Contribute

Why I Like and Use Open Source as a Strategy:

<table>
<thead>
<tr>
<th>Longevity</th>
<th>Not Being Tied to a Single Company or Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evolution</td>
<td>Darwinian development complete with a fossil record!</td>
</tr>
<tr>
<td>Knowledge</td>
<td>The Details are There to Understand if Necessary</td>
</tr>
<tr>
<td>Time</td>
<td>Many Problems Already Have Solutions</td>
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</tbody>
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Next Generation Radio Science

- **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 costs**
  - Interleaved missions on a fine scale – adaptive response to conditions

<table>
<thead>
<tr>
<th>Modern Digital Array Radar</th>
<th>Advanced Geospace Radar</th>
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</thead>
<tbody>
<tr>
<td>Narrowband</td>
<td>Broadband – Distributed</td>
</tr>
<tr>
<td>Single Aperture</td>
<td>All Digital Elements</td>
</tr>
<tr>
<td>Planar geometry</td>
<td>Adaptive beams : TX and RX</td>
</tr>
<tr>
<td>100 to 200 RX beams</td>
<td>Simultaneous TX / RX - 1000 beams</td>
</tr>
<tr>
<td>Element, brick, sub-array, array</td>
<td>Deep per element data buffers</td>
</tr>
<tr>
<td></td>
<td>Moderate power - high aperture</td>
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</tbody>
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**Key enabling technologies**

- RF MCM (multichip module)
- RF MEMS
- Software Radar
- Supercomputing

A challenge to reach the limits enabled by existing technology
Achieve a flexible, shared, and widely capable instrument
Greater science output for smaller operating costs
Astronomical Science

Galactic Evolution and Large Scale Structures
The First Black Holes and Stars
Astronomical Tests of Gravitation
Understanding Cosmic Magnetic Fields
The Formation of Planetary Systems
Transient Astronomical Events

Flexible Apertures with Large Potential Collecting Area
Wide Field Imaging and High Available Receive Beam Counts
Deep Burst and Delay Buffering for Transient Events

158.72 MHz
BW 1.28 MHz
5 m integration
26 x16 dipoles

MWA data
simulation

L. Greenhill
Heliosphere Science and Space Weather

Solar Radio Bursts
Interplanetary Scintillation Technique
Coronal Mass Ejections
Ionospheric TEC Fluctuations
Input for Space Weather Models

Realtime / Always On Operations
High Available Receive Beam Count
Deep Burst and Delay Buffering for Critical Events
Data Quality and Uniformity Have Been Greatly Improved
Array Radar Has Enabled Gap Free Observation
Multiple Application Experiments Demonstrated
Lower Atmosphere Science

Energy Coupling from Lower to Upper Atmosphere
Tides and Atmospheric Gravity Waves
Mesosphere / Stratosphere/ Troposphere Imaging
Lower Atmosphere Scattering Physics
Microphysics Investigations

Frequency coverage from VHF to S-band
Full Sky 3D Radar Imaging
Interleaved Lower and Upper Atmosphere Observations
Full Polarization Diversity

Boston NEXRAD (S-band 3 GHz)
[NOAA, 2008]

Amherst Imaging Radar (UHF 915 MHz)
[Palmer et. al, 2005]

EISCAT PMSE (VHF 224 MHz)
[Fernandez, et al, 2005]
Geospace Array Radar Architecture

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

Narrow Band TX at Multiple Frequencies and Sites

Low TX Power per Element (Scale to Measurement Requirements)

Large Aperture, Distributed, All Digital, Broadband Receive Arrays

Centrally Dense Aperiodic RX Array Layout

Rapid Realtime Calibration and Validation

Get Rid of Everything Possible

Focus on Lowering Per Element Costs

TX/ RX in Arctic :
Moderate Per Element Costs

RX Only in Desert :
Low Per Element Costs

How Low is Possible?
$100 USD per element?
deployed?
and operational?
Signal Processing Concept

Digital Receiver Array Group

Deep Solid State Ring Buffer

User Programming To FPGA Level When Desired

End User via Web Interface

Real Time or Batch Signal Chains

Parallel
- Initialize
- FFT
- FD Filter
- Tracking
- Hilbert
- Time Domain Filter
- Mix Preparation
- Mixer
- Descimate

CPU + Disk

GPU

Multicast FEC Accelerator

Deep Solid State Memory Buffer

Map Reduce Cloud Distributed File System

Peta-bps Mesh Switch Interconnect

100 Gbps / link

100 Gbps / link
A next generation Software Radar architecture coupled to global cloud computing can process signals from a global Geospace Radar array.

The Instruments are Realized Dynamically in the Computing Cloud
Geospace is a Global Environment

The Space Environment of the Earth
Ionosphere, Plasmasphere, Magnetosphere
Neutral Atmosphere Below, Heliosphere Above
Incoherent Scatter Radars Around the World

Global Network of High Power Radars

Measure Physical Properties of the Space Environment

Electron density, electron temperature, ion temperature, plasma velocity, and more...
Incoherent Scatter Radars Around the World

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Concept of Geospace Array Operations

Build a large and involved user community

Geospace Science
Atmospheric Science
Astronomy
Space Weather
Education and Outreach

Goals
Ideas
Operations
Software

Scientific Progress
Global Needs
Sponsor Requirements

Data
Capabilities

Goals and Questions

Communities:
- Community of Science
- Community of Education
- Community of Application
  - Experiments
  - Signal Processing
  - Analysis Techniques
  - Search and Identification
  - Science as a Service

Mathematics

Geospace Array

End User Implemented Techniques
- Web based design and development
- End to end framework
- Avoid infrastructure re-development
- Quick prototyping and live testing
- Auto-validation, calibration, classification
- Production quality results

Broadband
Always On
Burst on Demand
Deep Reanalysis
Live Search
Scalable Computing
Flexible Scheduling
Intelligent Application
Simultaneous Use

Production quality results
EISCAT 3D: The Next Big Step

Volumetric All Digital Radar Array
The Most Science for the Aperture

International Effort to Develop a “Best in Class” Instrument

F. Lind - EISCAT 3D Technical Coordinator

NSF Support now in place for US / EISCAT Collaboration

e-Infrastructure Collaboration Opportunities

EISCAT 3D is not the end, it is the beginning
Low Cost Digital Array Radar → Global Deployments
Build to Last, Inspire, and Teach
Ethiopia and the Geospace Array

Development of a Low Cost Digital Array Radar
Enables global deployments at a reasonable cost

The Geospace Science Community Needs African Partners!

Must Have Complementary Technical and Scientific Interests

Enable the Growth of Human Capacity...
To solve problems using advanced technology
To explore and study the natural world
To enable a culture of learning, understanding, and achievement
"If you want to build a ship, don’t drum up the people to gather wood, divide the work, and give orders. Instead, teach them to yearn for the vast and endless sea." -- Antoine De Saint-Exupery

Thanks for your attention!