Scientific Measurements of Near-Earth Space:
Effective RF Data Strategies Using Software-Defined Radio Architectures

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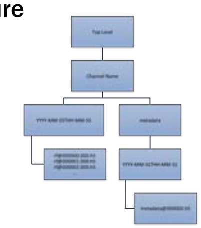
Introduction

Since the 1990s, MIT Haystack Observatory has leveraged **software-defined radio architectures for scientific measurements of near-Earth space**. These have involved diverse systems including large-aperture, high-power radars (megawatt-acres) and include characterization of variations in the planet's ionosphere and its interactions with the neutral atmosphere. Effective execution of these scientific measurements requires precision measurements of very weak received signals that are in some cases at or below the thermal noise floor, along with **effective and complete metadata recording** in order to provide proper interpretation and extraction of physical information contained in the signals. In some cases, analysis of these signals along with their metadata may take place years or even decades after their collection, requiring long-term stable knowledge of their characteristics.

To achieve these scientific goals, it is useful to have a **common software toolkit** efficiently implementing quick, time-tagged access to RF voltage–level data with accompanying metadata. MIT Haystack has created an **open source product, Digital RF**, that addresses these needs. Digital RF allows for the recording and storage of RF voltage data with O(1) retrieval speed. With a companion **Digital Metadata format and applications program interface (API)**, use of this highly configurable software stack considerably speeds the software development process for radio science applications.

RF container: Digital RF and Digital Metadata architecture

- Block-oriented format and namespace
  - Time → Channel → Subchannel → Samples
  - Indexed by number of samples from Unix epoch (Jan. 1, 1970)
  - Data saved within HDF5 files for long-term portability
  - File structure is optimized for quick API retrieval of specific RF samples
- Metadata is saved along with RF
  - Digital metadata is saved synchronously with each RF voltage file
  - HDF5 format ensures long term portability and metadata retrieval
  - Tree structure of time-indexed data objects



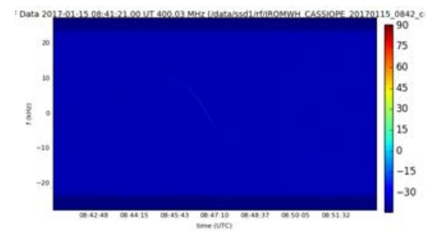
Digital RF/Metadata file structure

Features

- C and Python bindings (read/write), MATLAB (read)
- GNU Radio Sink and Source blocks
- Tested extensively with Ettus SDRs (N200, X300, B200 series) but other radios also possible
- Samples indexed by absolute UTC time using number of samples since epoch

Ettus N210, X310, and B210mini

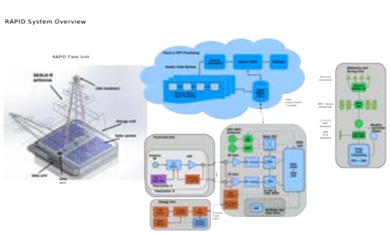
- Self-documenting for data archival
- O(1) sample lookup for quickly reading any segment of data
- Numerous software tools and examples included with package:
  - Easy-to-use command-line program for data recording: the Haystack Observatory Recorder (thor)
  - Snapshot and ring buffer tools
  - Plotting tools built in for easy debugging and for RF quick-look spectrograms
  - Geophysical measurement examples
    - Satellite beacon receiver
    - Ionospheric sounder



Example spectrogram from satellite flyover

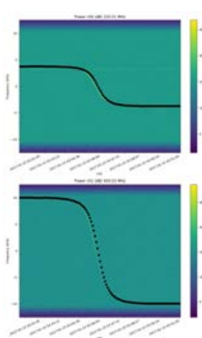
Example radio science applications

- Radio Array of Portable Interferometric Detectors (RAPID)
  - Deployable radio interferometer for geospace science and astronomy
  - Solar and battery powered software radio raw data acquisition
- RF antenna pattern measurement; antenna pattern characterization using UAS (drone) platforms
- Geospace radar: physical measurement of earth's ionosphere via incoherent scatter radar

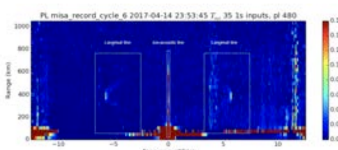


UAV drone used for antenna pattern measurement

Jicamarca Radio Observatory (JRO), Peru, (top); RAPID Field deployment at JRO (bottom)



Dual-channel beacon satellite flyover with expected frequency derived from two-line element

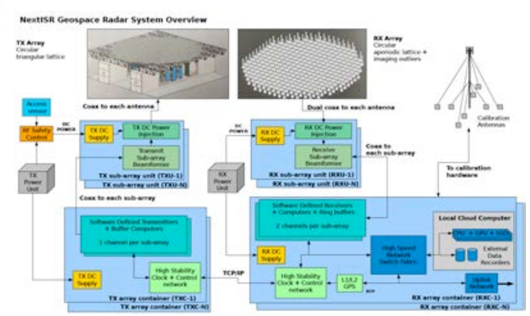


Incoherent scatter radar frequency content along range

Millstone Hill atmospheric radar

Future

- Formal open source release of package through GitHub and other sources
- Next-generation geospace radar



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