MIT
HAYSTACK
OBSERVATORY

The upcoming VGOS station at Kokee Park, Hawaii, and updates from the Westford-GGAO VGOS baseline prototype

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Working in close association with the Haystack Team led by
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SGP VLBI Principal Investigator
Chester Ruszczyk
SGP VLBI SC Project Manager &
SGP VLBI SC System Engineer

Follow us on http://space-geodesy.nasa.gov/blogs/KPGO/index.html

Path to MIT Haystack Observatory

- 1978-2001 @ Raman Research Institute, Bangalore *(10.4m Millimeterwave Observatory)*
  - 1990-94 Guest Researcher at Chalmers *(InP LNAs, Receivers)*
- 2001-2012 @ Cornell University's Arecibo Observatory *(Cryogenic Receivers 327MHz-10 GHz)*
- 2012-2015 @Cornell Ithaca Campus CCAT- Cerro Chajnantor Atacama Telescope *(CCAT Readout Electronics)*
- 2015 mid-September @ MIT Haystack Observatory *(Kokee Park Geophysical Observatory)*

Overview

- InterTronic 12m Antenna
- Frontend (FE)
  - Block Diagram
  - RF Design
  - Mechanical Design
  - Integration & Testing
- Backend (BE)
  - Block Diagram
  - Equipment Rack Layout
  - VGOS UDC w/ baseband output
  - RDBE-G v3.0
  - Integration & Testing
- Signal Chain Calibration Subsystem
- Monitor/Control VLBI Data AcQuisition (VDAQ) Module
- Schedule

Frontend – Antenna

InterTronic Antennas

High accuracy, high slew speed, full motion 12m Antenna System

- Main reflector surface comprises 100 precision adjustable stretch formed aluminum panels,
- Carbon fiber composite sub-reflector with optional high accuracy hexapod adjustment mechanism
- Precision zero backlash torque biased mechanisms based on COTS motors and controllers
- Extensively galvanized and painted to assist with corrosion protection, galvanic protection built in by design
- Meets **all** the VLBI2010 specifications
- Suitable for array applications
- Passed CDR in July 2014
- Passed SAT in September 2015

http://space-geodesy.nasa.gov/blogs/KPGO/index.html

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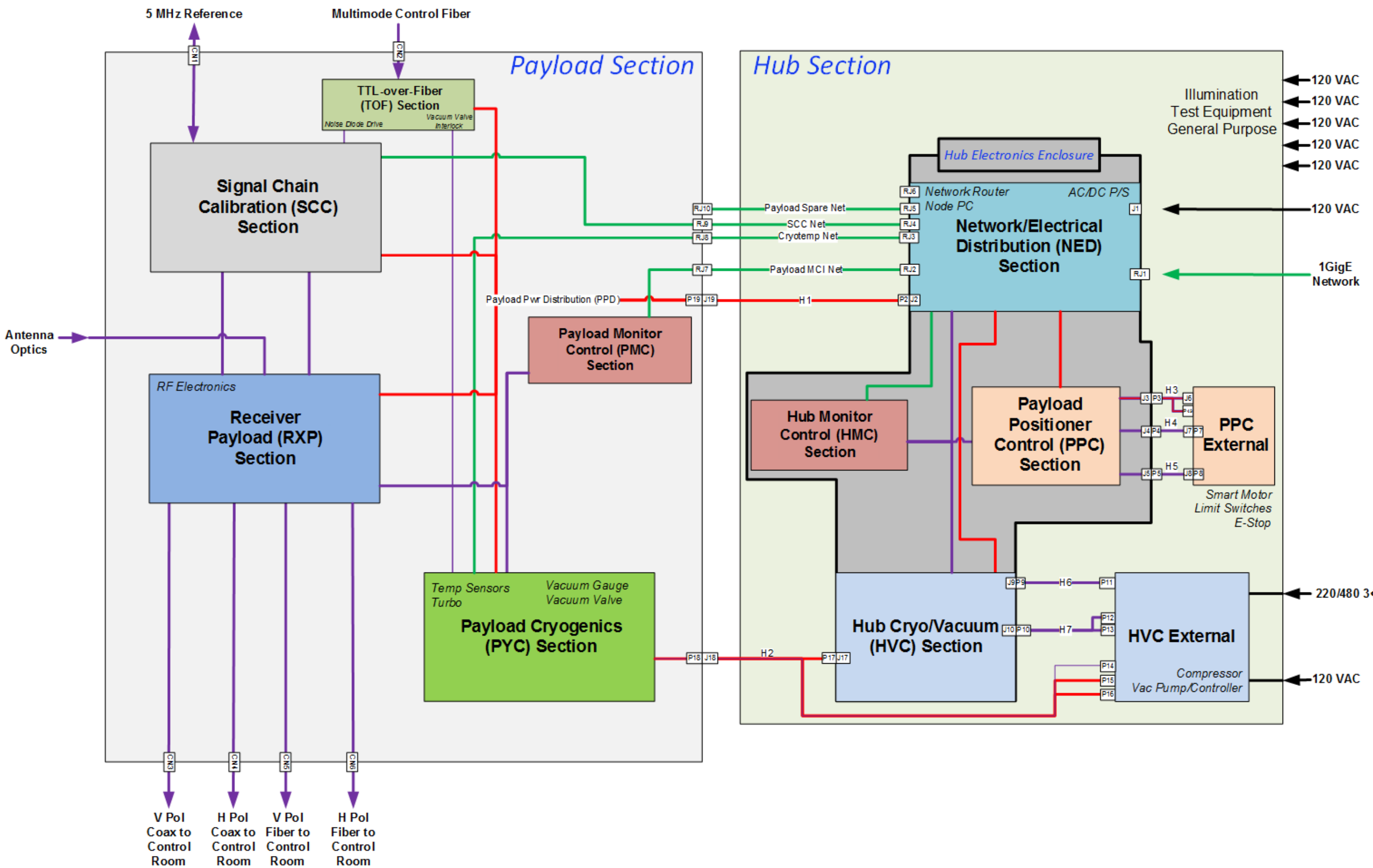
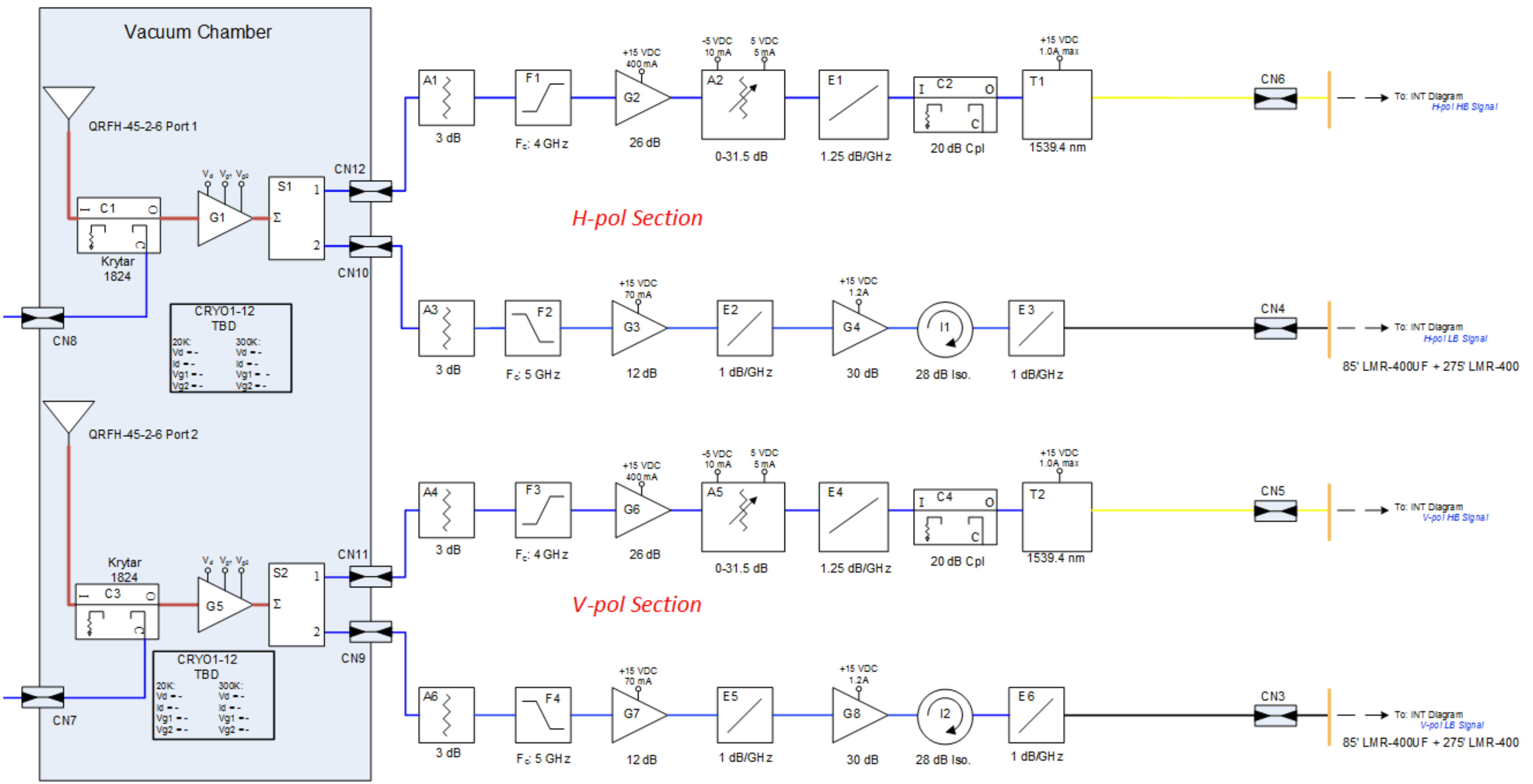
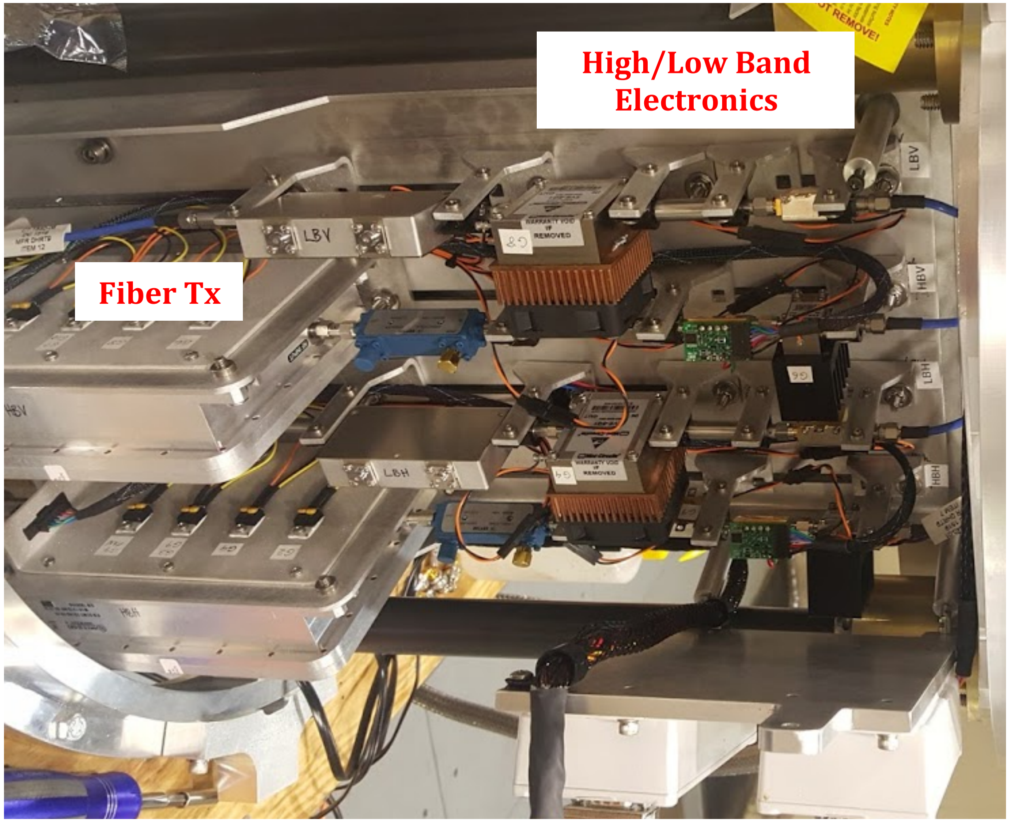
Frontend – Block Diagram

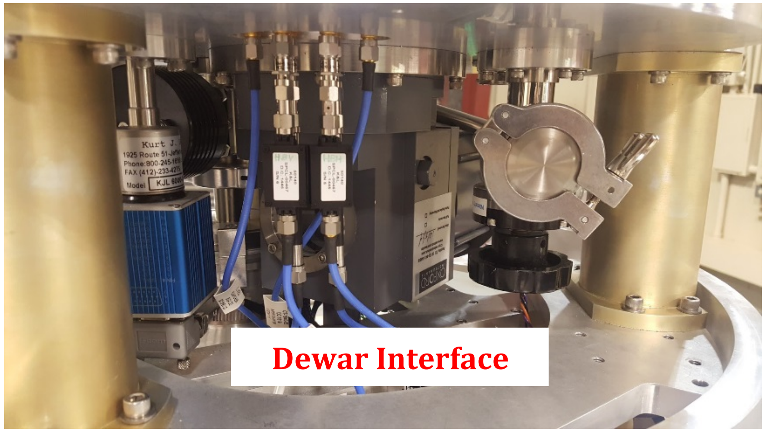


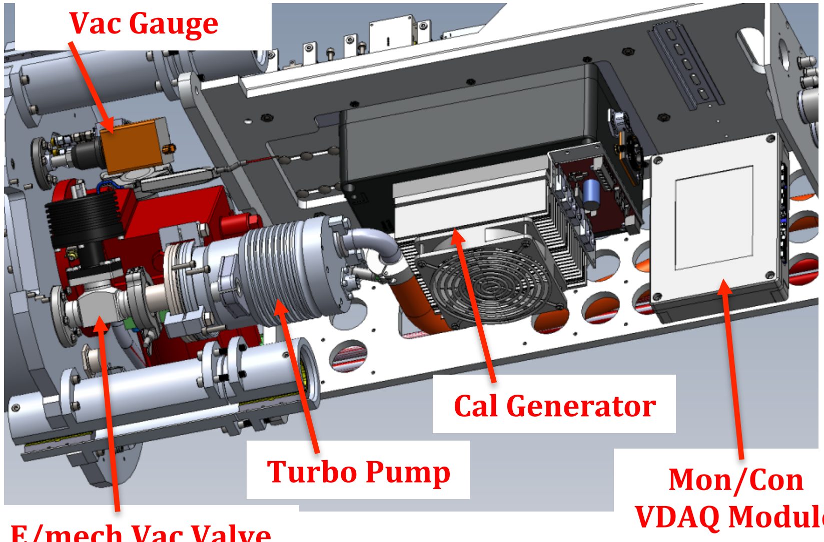
Frontend – RF Design



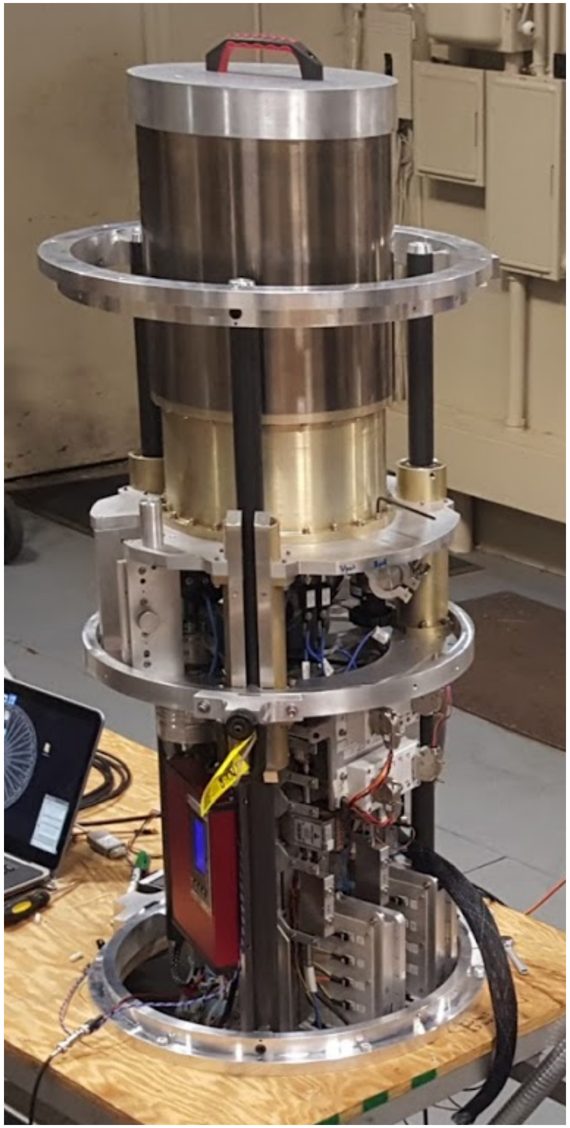
Frontend – Mechanical Design

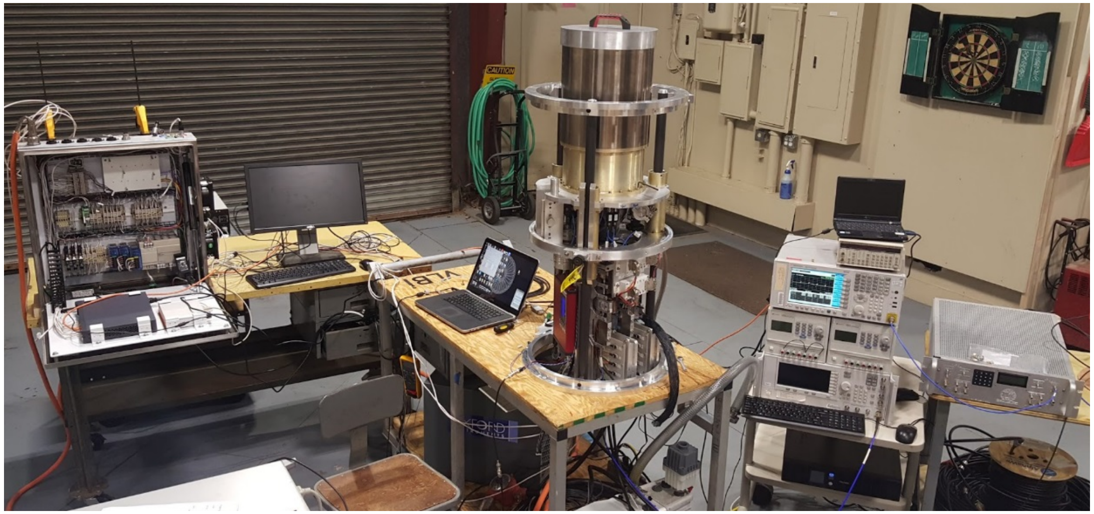




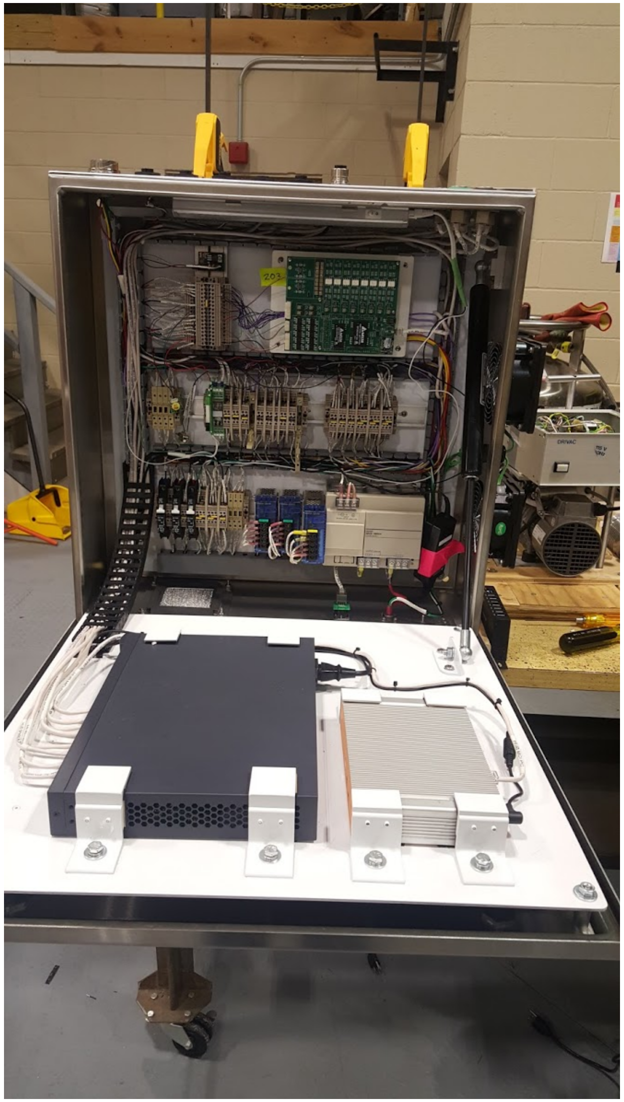


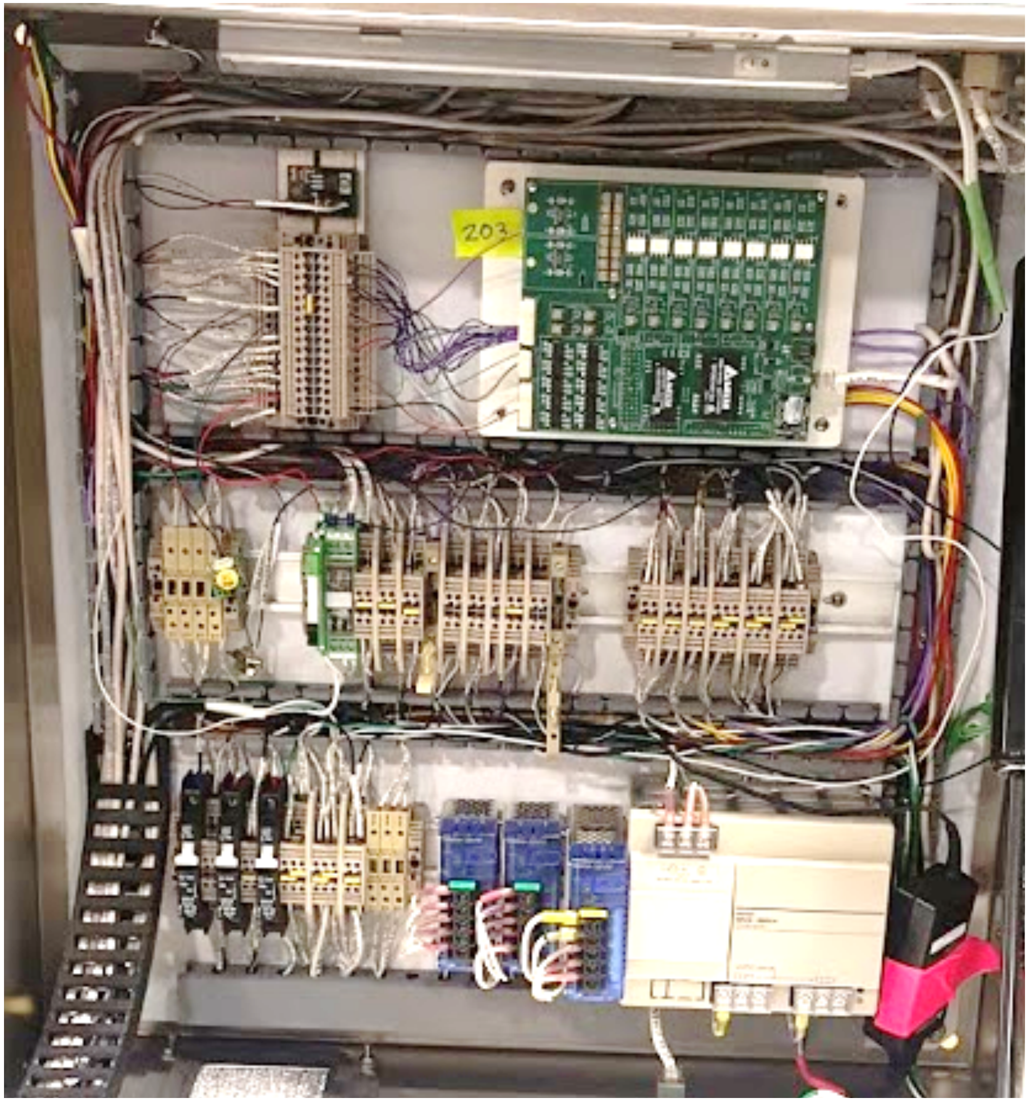
Frontend – Integration and Test



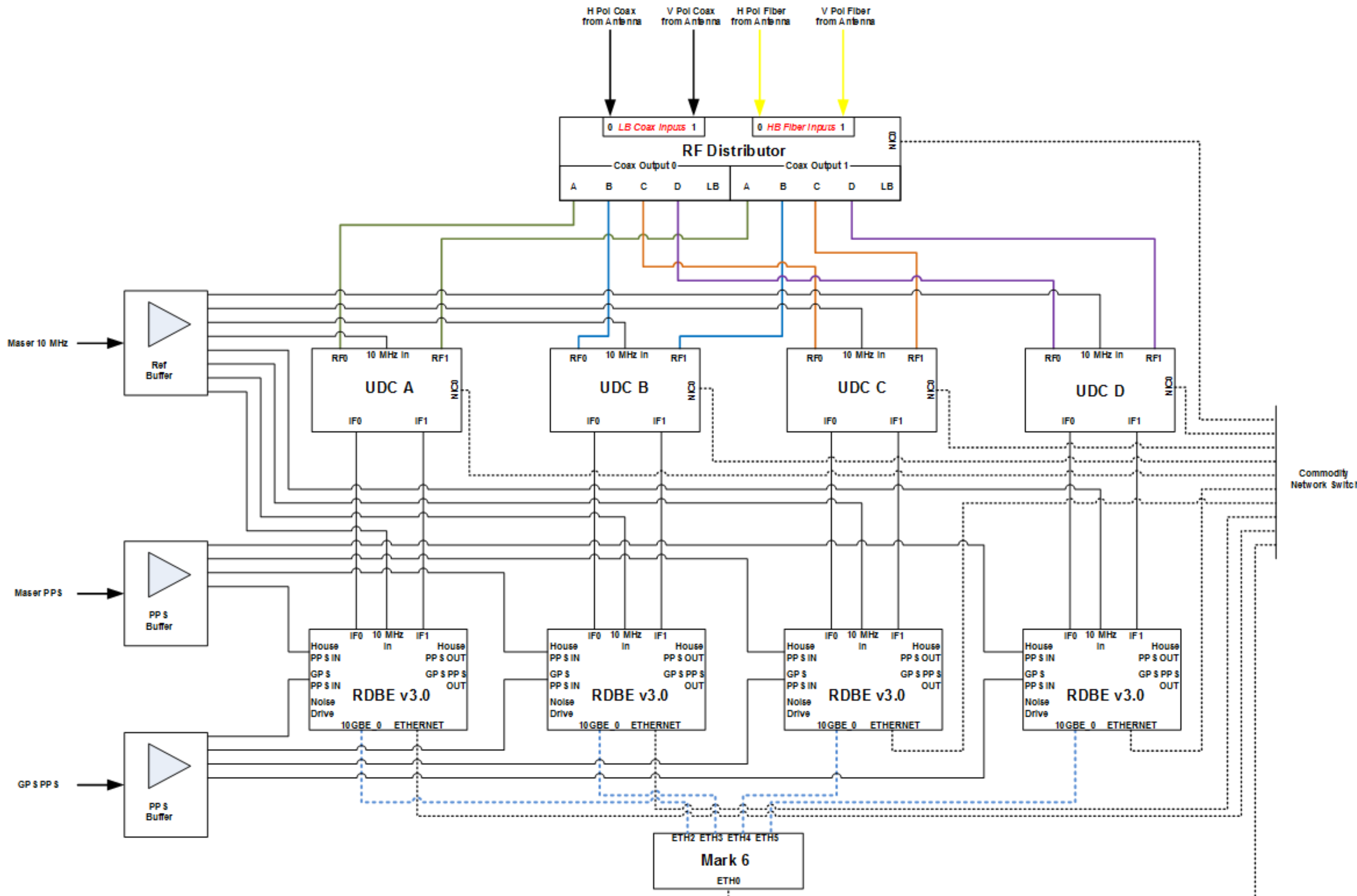


Frontend – Hub Electronics Enclosure

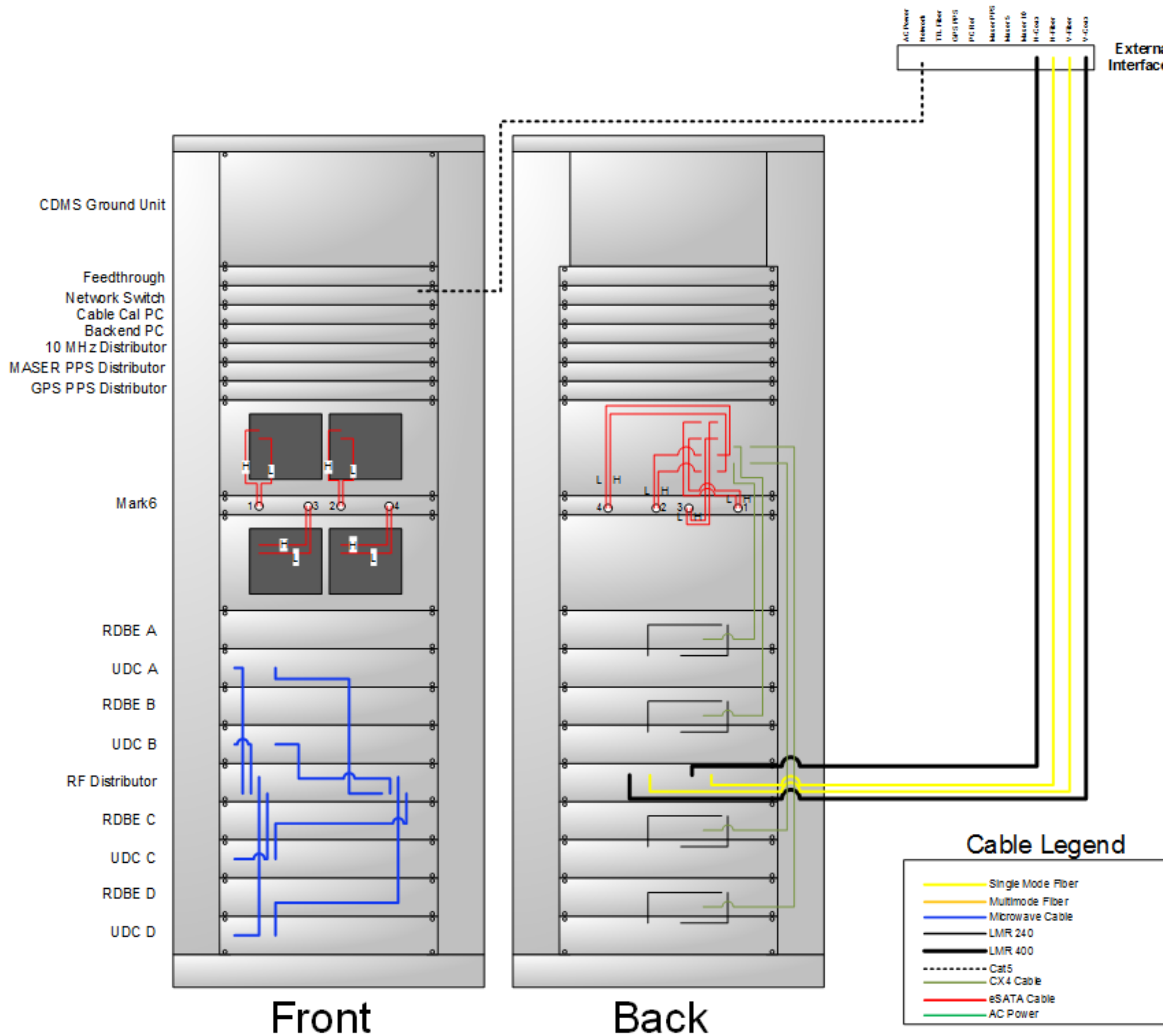




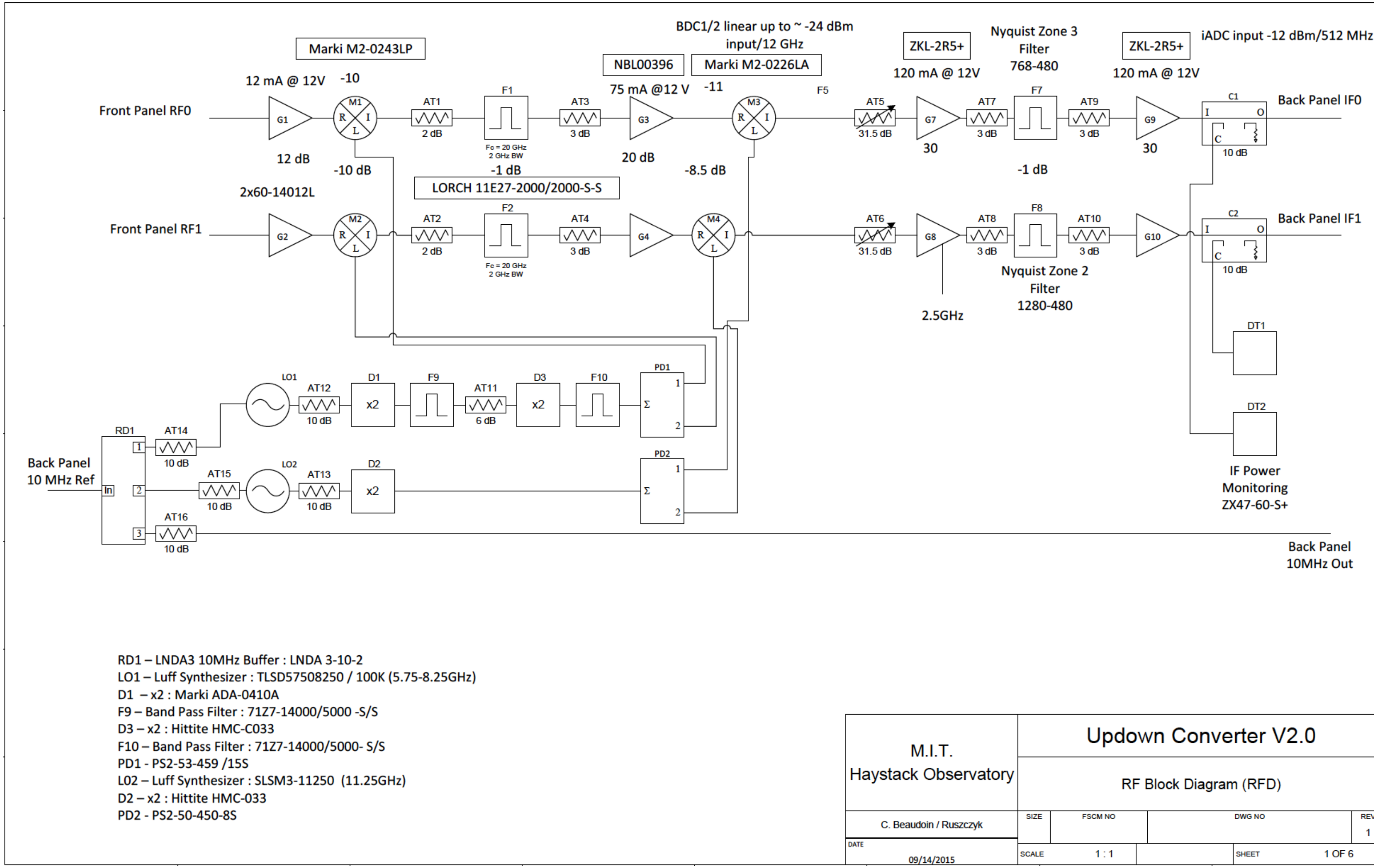
Backend – Block Diagram



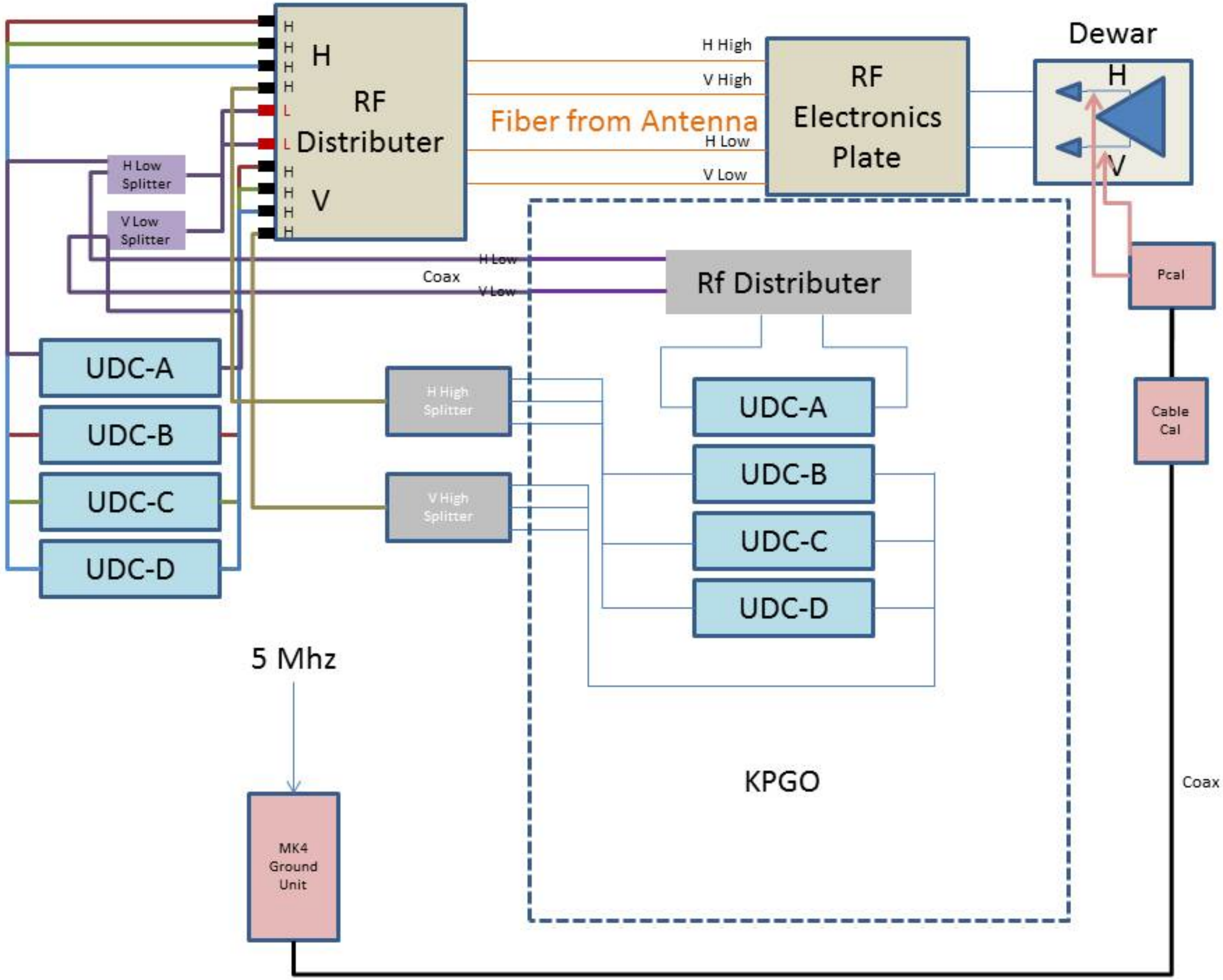
Backend – Equipment Rack Layout



Backend – VGOS UDC



Westford Zero Baseline & Standalone Tests



KPGO BE under test at Westford

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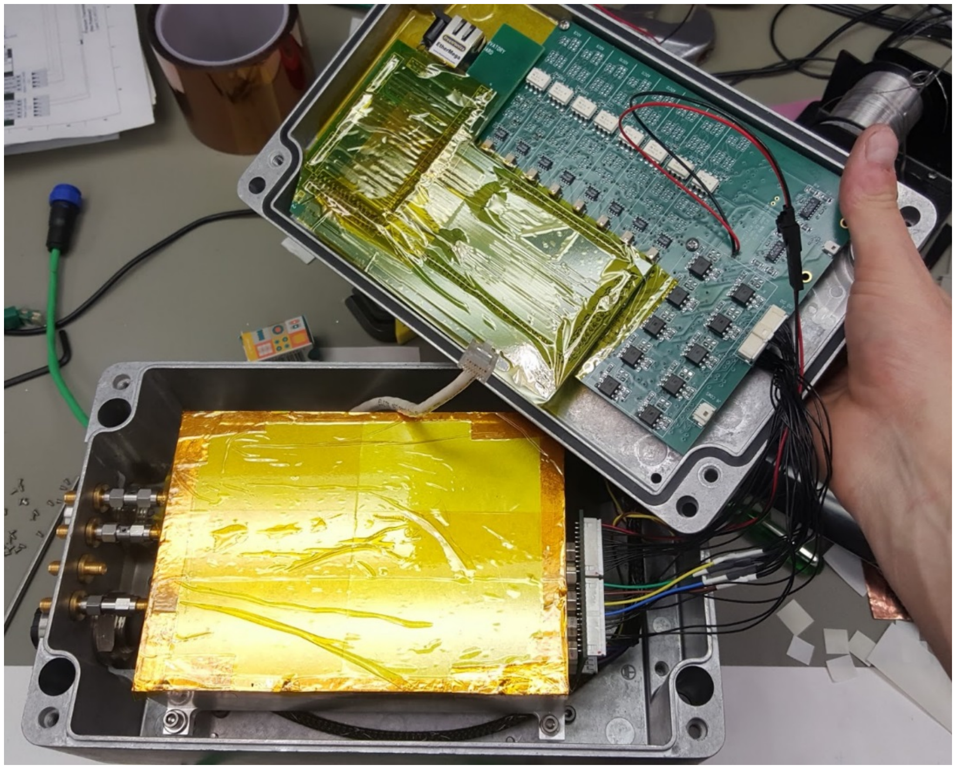
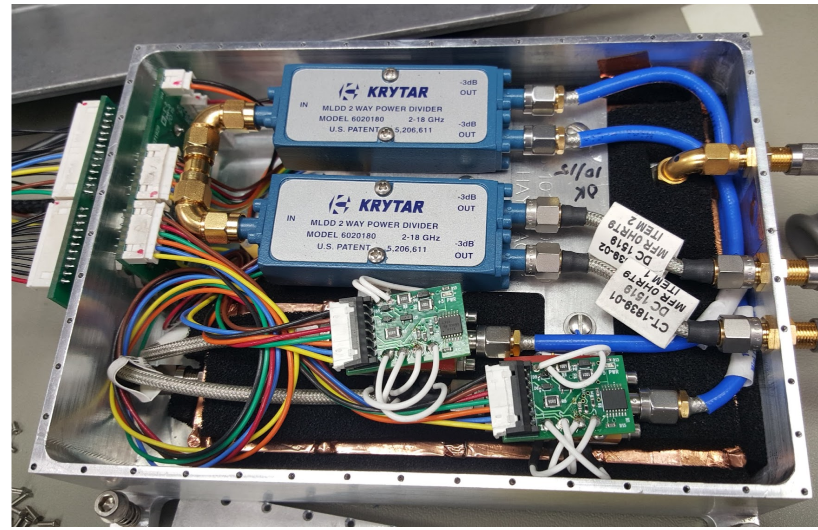
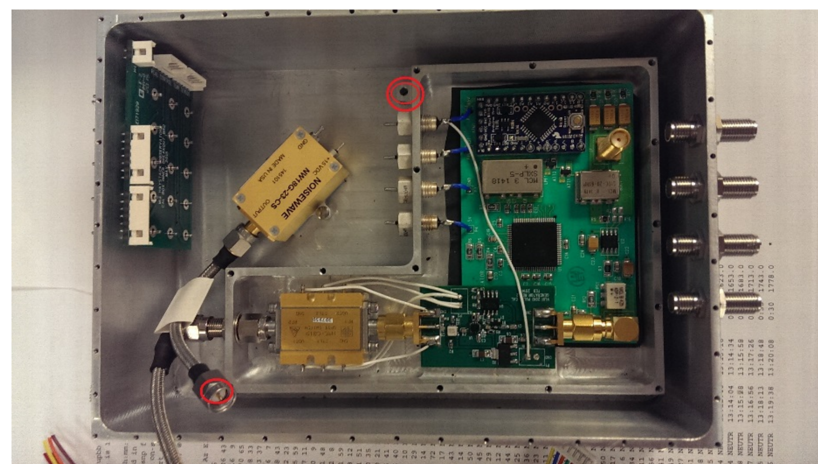
Signal Chain Calibration – Antenna Unit







VLBI Data Acquisition Module

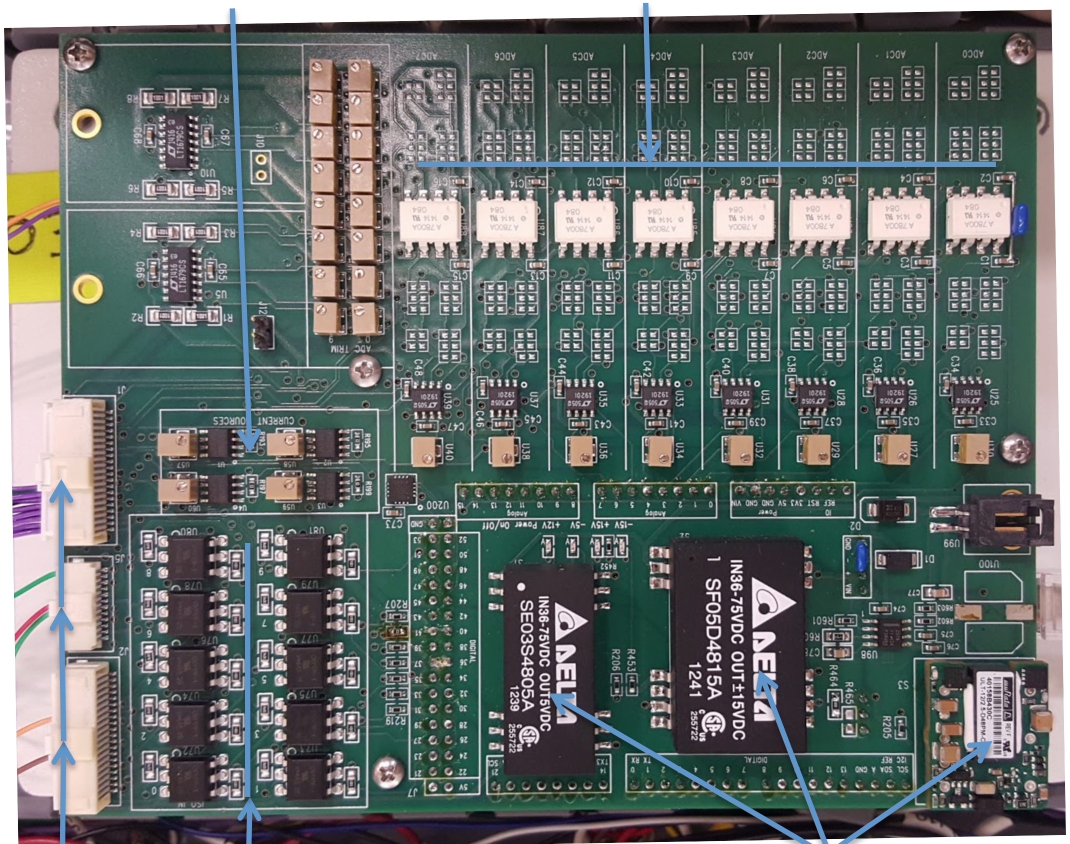
- VLBI Data AcQuisition (VDAQ) module
  - Open-source hardware development
  - Hot-Swappable
  - Deployable Temperature, Pressure, Humidity Sensing
  - On-board temperature sensor
  - Logging to SD card

- Interface
  - Ethernet Communications
  - Powered over Ethernet
    - Isolated DC Power Sources
  - 16 Analog Monitors
    - Single-ended or Differential
    - Isolated or Non-Isolated
    - Configurable signal conditioning
  - 40 Digital Monitors or Controls
    - 10 Isolated Monitors
    - 10 Isolated Controls
    - 20 Non-isolated Monitors and/or Controls
  - RS232 and I^2C Communications

VDAQ- VLBI Data Acquisition Module

Currunt Sources

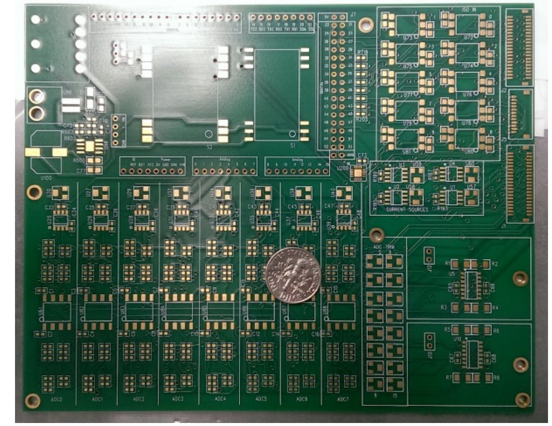
Analog Input Channels



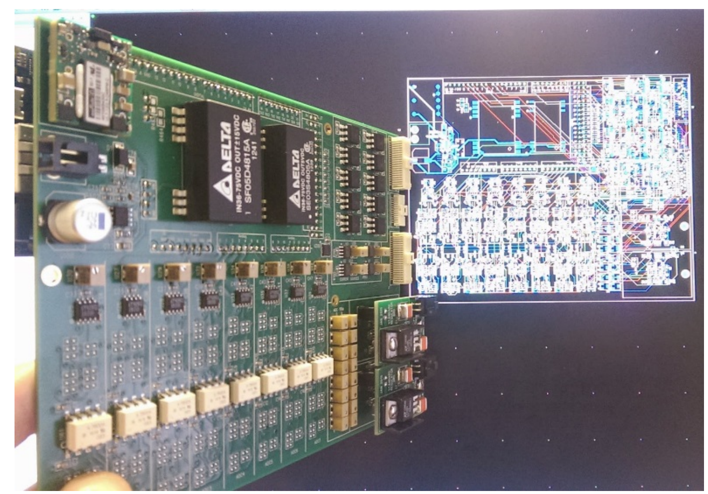
Isolated Digital in/out

Power Supplies

Monitor/Control Signal Interface



Prototype PCB



Layout Design and Assembled VDAQ

Schedule

- November 2015: Calibration Subsystem Fab Complete
- October 2015: Frontend/Backend Subsystems Fab Complete
- November 2015: MCI and Integration Complete
- October-November 2015: Integrated Testing at Haystack
- December 15-16: SIR & PSR at Haystack
- December 2015: Ship to KPGO
- January – February 2016: Installation/Testing
- February 2016: Complete System Test
- February-May 2016: Commissioning
- June 2016 and beyond: IVS Integration

Acknowledgements

- Chris Beaudoin (now at Umass, Lowell), Alan Whitney, Arthur Niell, Brian Corey, Chris Eckert, Mark Derome, Russ McWhirter, Jason SooHoo, Mike Titus, Alan Rogers, Peter Bolis, Roger Cappallo, Jon Byford & many others - ***MIT Haystack Observatory***
- Chopo Ma, Larry Hilliard, Tom Clark **– *NASA GSFC***
- Ed Himwich **– *GSFC/NVI***
- Bill Petrachenko **– *Natural Resources Canada***
- ***And, NASA SGP team***
  - ***Stephen Merkowitz, SGP Project Manager***
  - ***Jamie Esper, SGP Project Engineer***
  - ***Darryl Lakins, SGP Systems Engineer***
  - ***Carol Hamilton, SGP Chief Safety Officer***

Status report on observations with the GGAO-Westford VGOS systems

Ganesh Rajagopalan
and Arthur Niell
MIT Haystack Observatory

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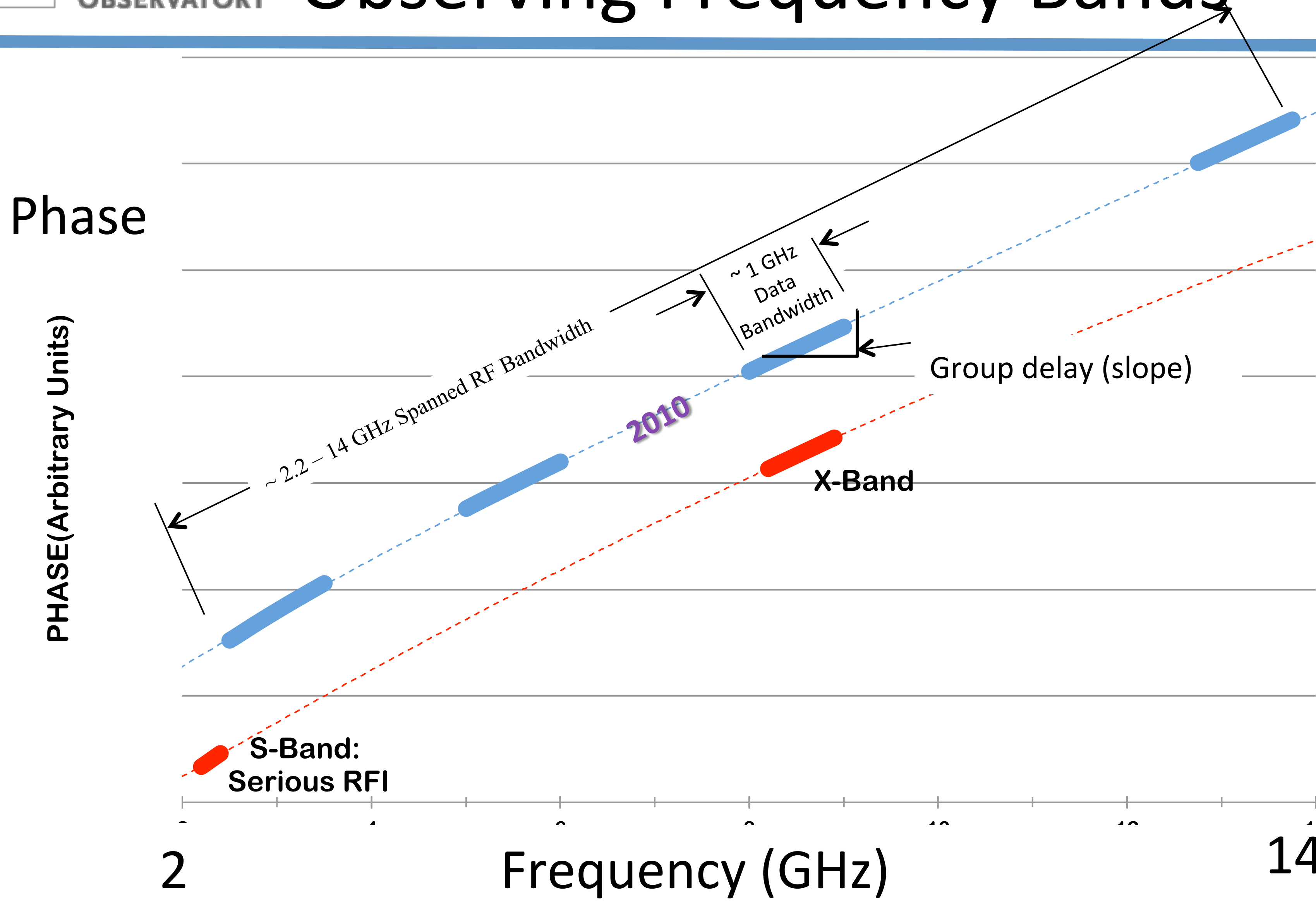
Outline

- Implementation of Broadband Signal Chain on GGAO12M and Westford
- Results
- Plans
- Observation, correlation, and analysis

Special thanks

- Chris Beaudoin, Chris Eckert, Mark Derome – Broadband signal chain design and implementation on GGAO12M and Westford
- Chet Ruszczyk, Jason Soohoo, Mike Poirier, Katie Pazamikas, Jay Redmond, Russ McWhirter – observing session setup and operation
- Ed Himwich – antenna checkout for GGAO12M and Westford and Field Station modification for Broadband
- John Gipson – *sked* modification
- Mike Titus – correlation (understatement of effort!)
- Brian Corey – station performance analysis and amplitude calibration
- Roger Cappallo – *difx* and *fourfit* modifications
- David Gordon – data base modification and creation
- Sergei Bolotin – *nuSolve* creation and processing
- Bill Petrachenko – brilliant ideas, continued encouragement
- Chopo Ma and John Labrecque for funding the Proof of Concept development and the GGAO-Westford systems
- And others!

Observing Frequency Bands



Broadband observing - 1

- **Geodetic VLBI session procedures**
  - Schedule (*sked*)
  - Observe
  - Correlate
  - *fourfit*
  - *calc/nuSolve*
- Highlight differences for Broadband

Broadband observing - 2

- Schedule (*sked*)
  - New broadband section added to allow for Mark6 recording
    - 8 Gbps onto single module
    - Buffering time of about scan length required
  - Use S-band and X-band flux densities but 3GHz and 10GHz system characteristics to calculate minimum scan lengths

Broadband correlation - 1

- **Correlation procedures**
  - *gather* Mark6 data from raw format to linux files
  - Correlate all four bands simultaneously (or each band separately and then *fourmer* into one file)
  - Correlate HH/VV/HV/VH within each band for all four bands

Broadband correlation - 2

- **Correlation procedures (cont'd)**
  - Extract all phase cal tones for every channel in both polarizations
    - Six or seven tones for each channel
    - Use all non-corrupted tones for multitone phase cal **delay and phase** for each channel (exclude tones with spurious signals)
  - Run *difx2mk4* on correlator output files to allow additional processing with the standard HOPS package (as used for S/X geodesy)

fourfit: differences between broadband and S/X

- **Phase cal**
  - Apply multitone pcal to align the four bands.
  - Input *a priori* cable delay for each station (maser-antenna-DBE) to provide resolution of multitone delay ambiguity (1/4 * 200 nsec for 5 MHz spacing).
- **Correct for uncalibrated delay and phase offsets between polarizations**
  - Correct for RF path length through the feed and before phase cal injection.
- **Estimate ionosphere dTEC with group delay**

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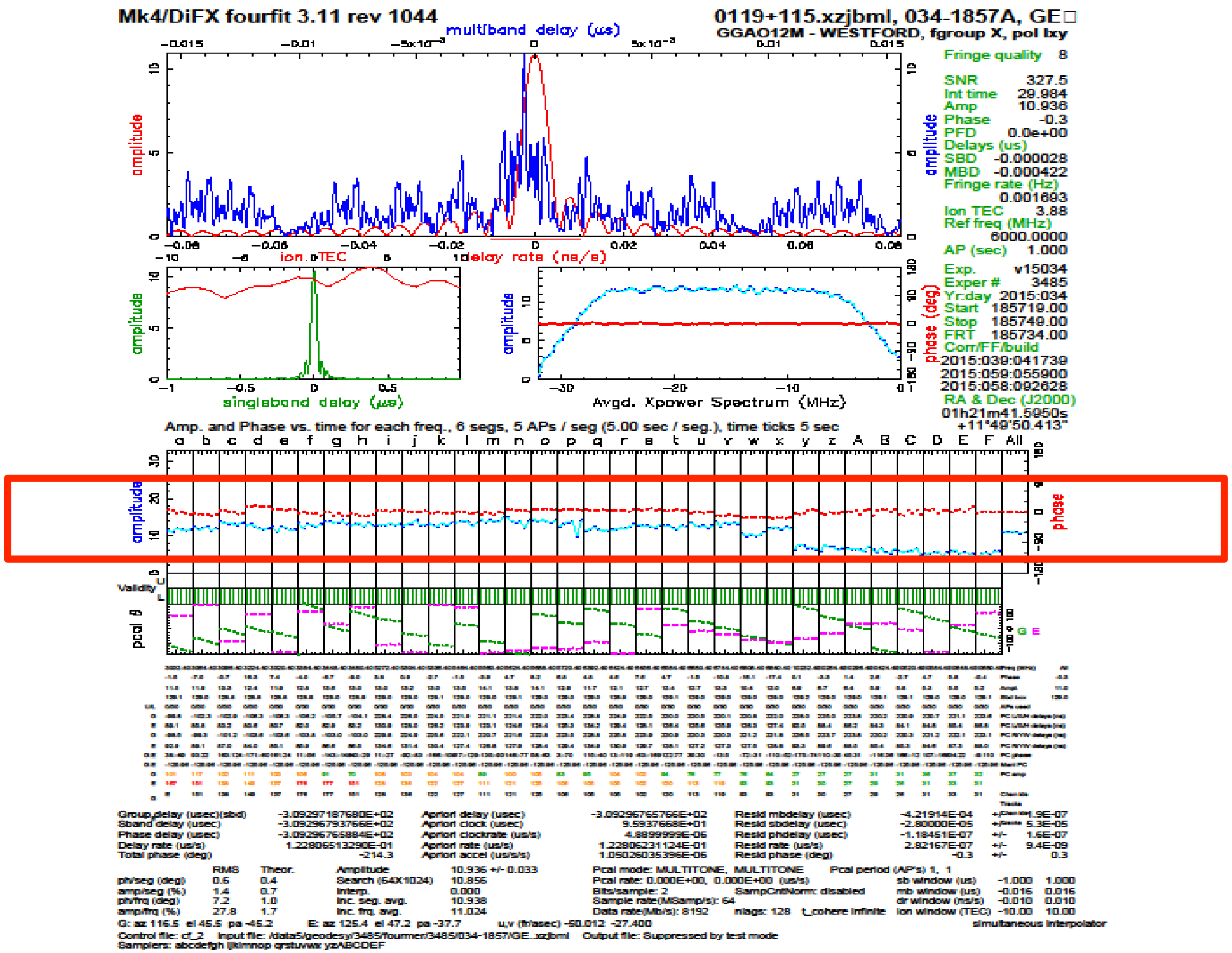
Combined polarization data



phase

RMS 7.2°

Post-correlation analysis

- ***fourfit* (assume 64-ch correlation)**
  - Use all four polarization products to determine delay and phase differences between polarizations for each antenna
- ***calc/nuSolve***
  - Create database (required modification of dbedit)
  - (Currently) use nuSolve for preliminary analysis
    - Use single time interval for the full session
    - Estimate pos'n and clock for GGAO, ZWD at one site, and troposphere gradients

Recent observations - 1

- **VGOS Demonstration Series (VDS)**
  - Work towards operational broadband observing.
  - Observed one-hour sessions about every two weeks from 2014 December to 2015 June.
  - The most recent sessions have been run under Field System control, including UDCs, RDBEs, and Mark6.
  - Center frequencies for the four bands:

    3.3 GHz 5.5 GHz 6.6 GHz 10.5 GHz

Recent observations - 2

- **VDS (cont'd)**
  - Median delay uncertainty per scan is ~1 psec.
  - Correction for phase variation across the bands and with time would raise this to a few psec (see previous 64-channel *fourfit* figure).
  - With re-weighting by additive delay to the geodetic estimation, the WRMS post-fit delay residual is typically 6 psec (compared to a few times 10 psec for current S/X sessions using ~20-meter antennas).

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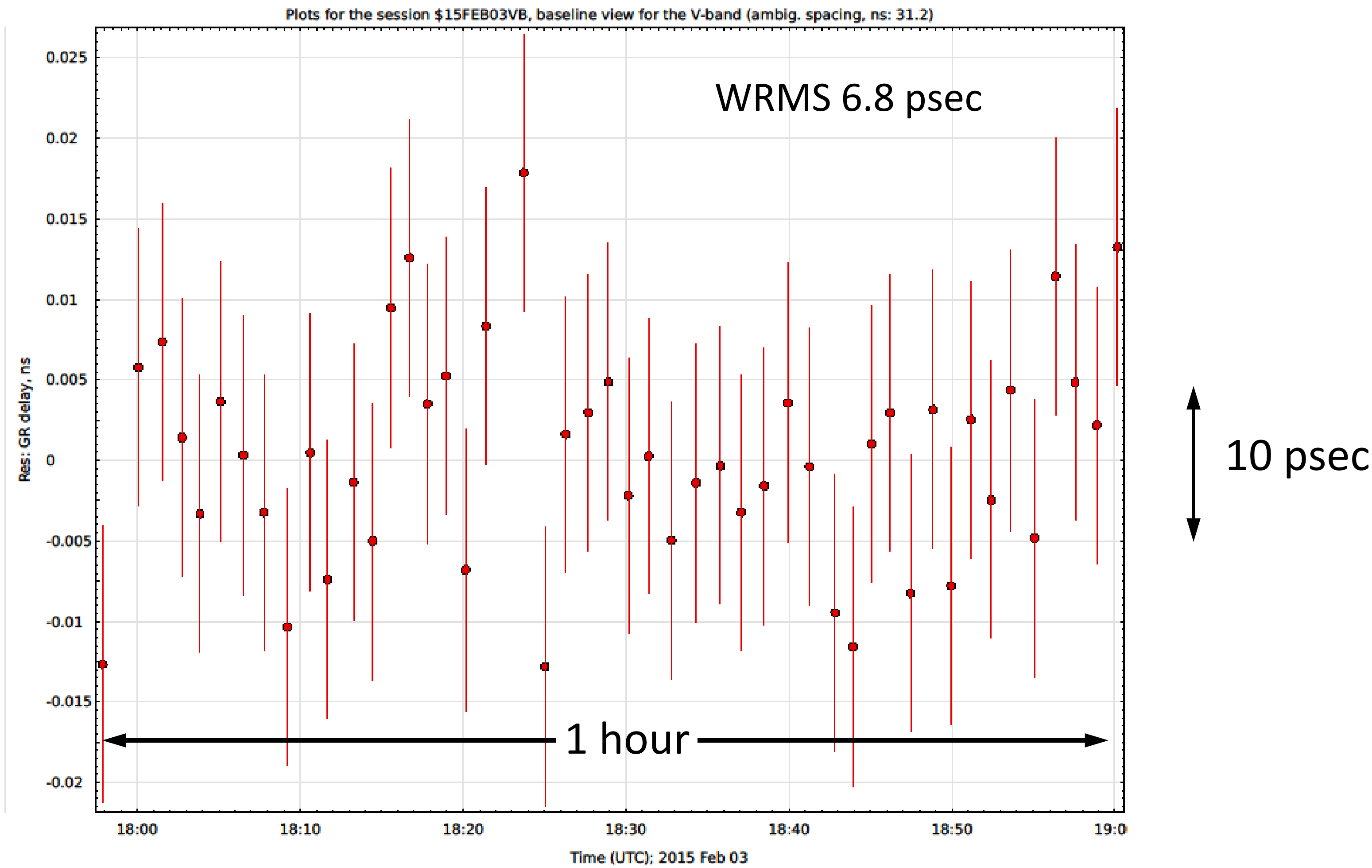
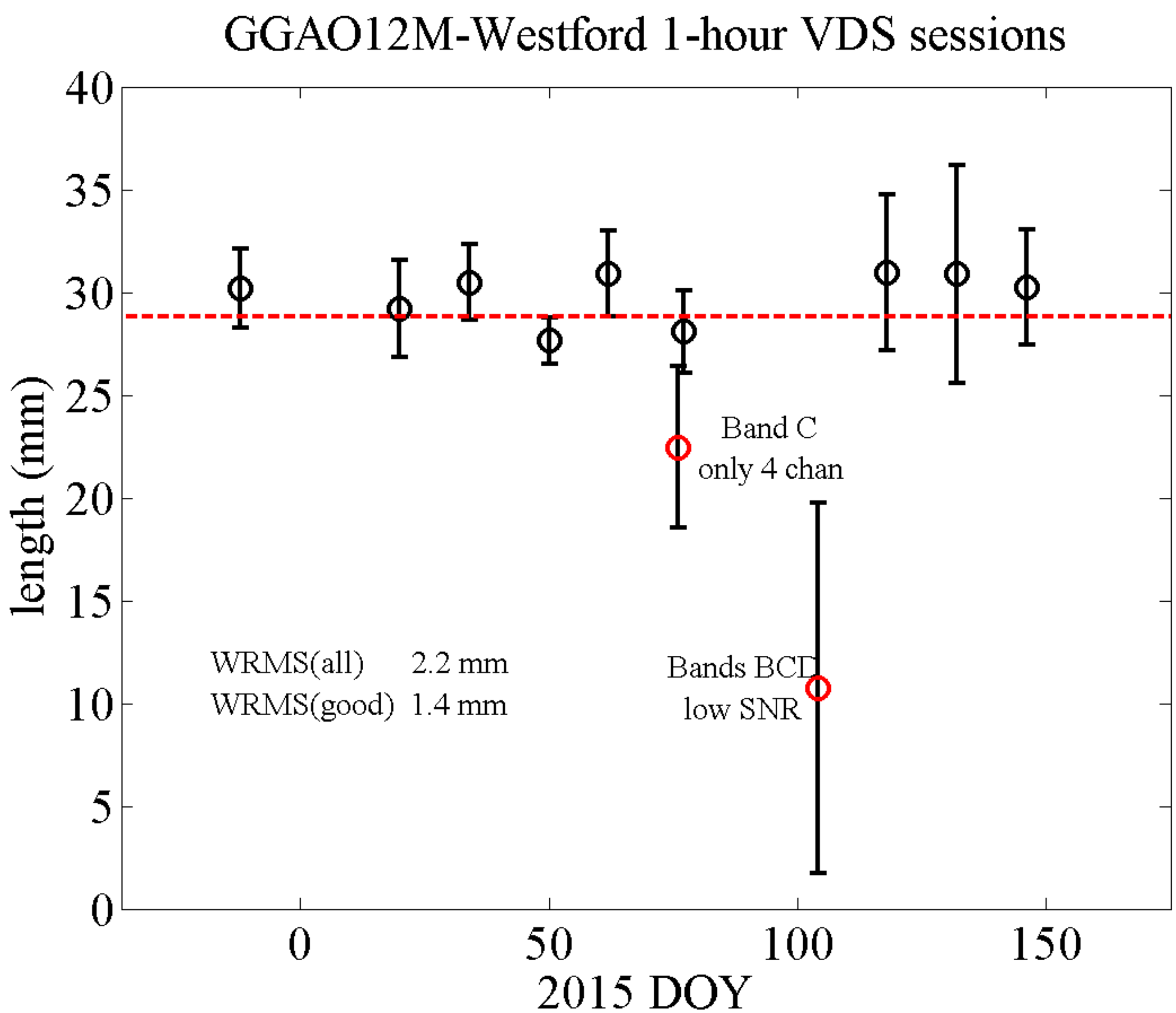
Post-fit delay residuals V15034 2015FEB03 48/50 obs retained



Recent observations - 3

- **VGOS Data Series (cont'd)**
  - Baseline length is 601 km.
  - For nine (good) sessions, the position uncertainties for GGAO with 1 to 1.5 hours of data are:
    - Up/East/North (UEN): 3-7 mm, 1-2 mm, 1-2 mm
    - Length: 1-2 mm
  - The RMS scatters in components and length are approximately :
    - UEN: 4 mm, 2 mm, 2 mm
    - Length: 1 mm


GGAO12M-Westford 1-hour VDS sessions
40
35
30
25
20
15
10
5
0
length (mm)
0
50
100
150
2015 DOY
Band C
only 4 chan
Bands BCD
low SNR
WRMS(all) 2.2 mm
WRMS(good) 1.4 mm

Plans

- **VGOS Demonstration Series (VDS)**
  - Continue bi-weekly 1-hour sessions till VGOS operations are 'routine'.
  - Enhance operations software (*sked*/FieldSystem/correlator-related) to accommodate Broadband VGOS systems.
  - Increase duration of sessions.
  - Include other VGOS-capable antennas in test sessions.
  - Migrate to regularly scheduled 24-hour sessions.

Yet to do or understand (partial)

- **Instrumentation**
  - Add cable delay measurement systems.
  - Upgrade UDCs to Kokee version.
  - What causes freq. dependent phase distortion?
- **Analysis/understanding**
  - How should the broadband delay uncertainty be determined for input to estimation?
  - How can sky coverage be improved in scheduling programs?
  - What is the best way to determine the polarization delay and phase offsets?

Qusetions to Arthur ?

Patriot 12M Antenna @ GGAO

Backup Slides from Arthur

MIT Haystack / NASA Implementation

- Prototype systems
  - 12-meter Patriot antenna at GGAO and 18-meter Westford antenna at Haystack
    - QRFH feed and two LNAs from Caltech
    - Separate low- and high-band RF downlinks for each polarization (need phasecal)
    - Four RDBE-G digital backends
    - One Mark6 recorder

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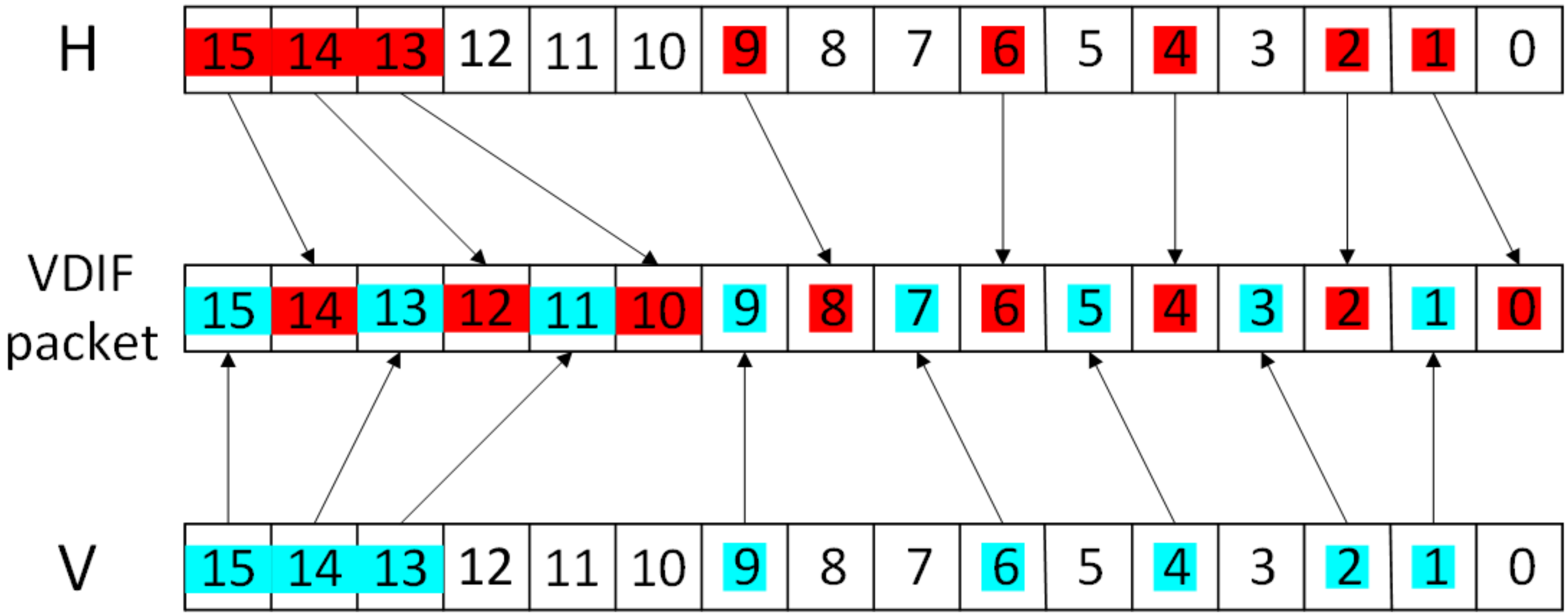
Broadband observing - 3

- **Data acquisition format**
  - Four bands with two polarizations each band
    - Total data rate 2 Gbps per band (1 Gbps per polarization)
    - Only 15 good channels per pol'n for polyphase filter bank (PFB) but get 16 channels per band using half of the channels in each band.
    - See next figure
      - Minimum redundancy array per band
      - Layout for 16*32MHz recording

Channels in packet



Polarization delay offset