Status report on observations with the GGAO-Westford VGOS systems

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MIT Haystack Observatory

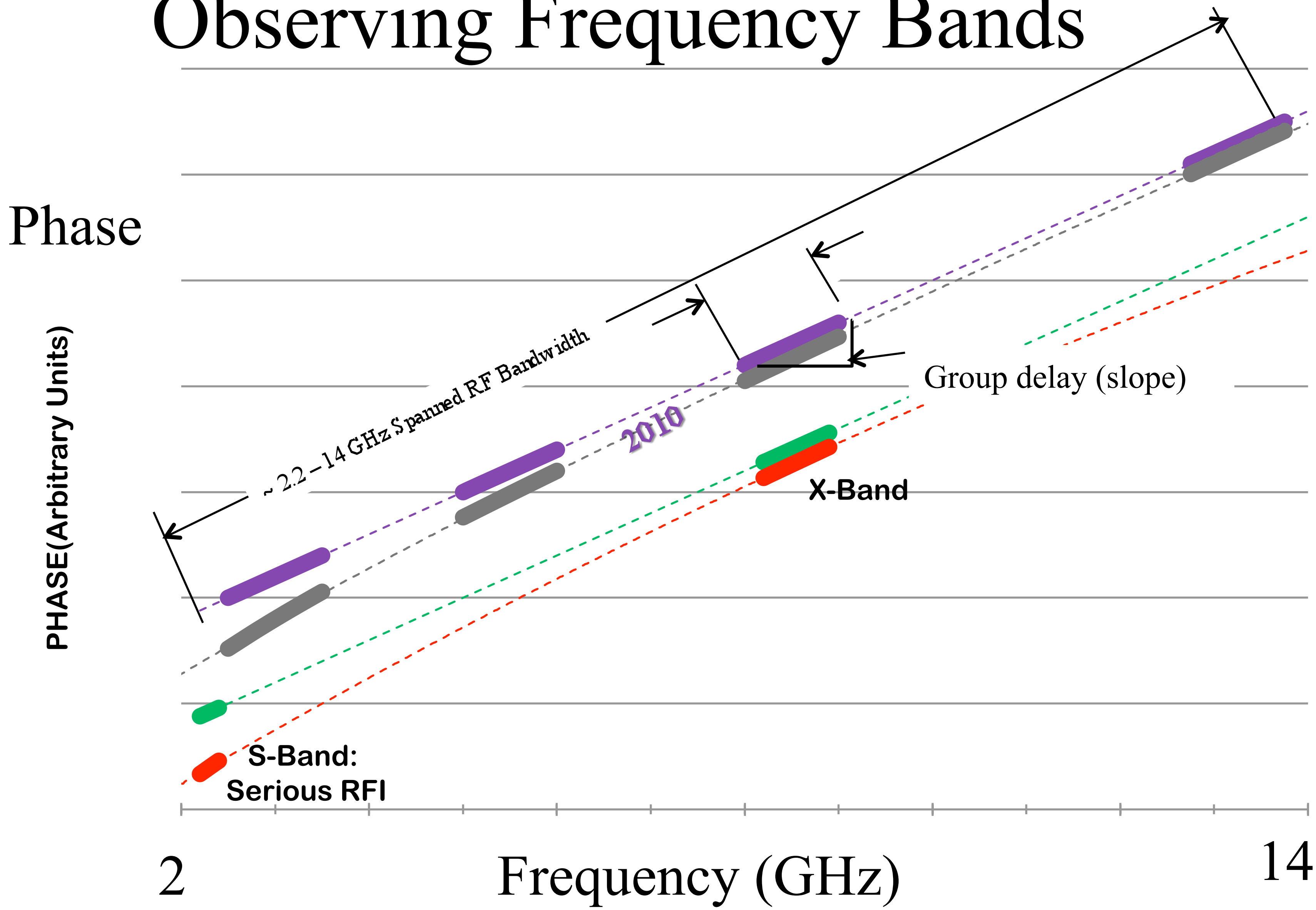
Outline

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

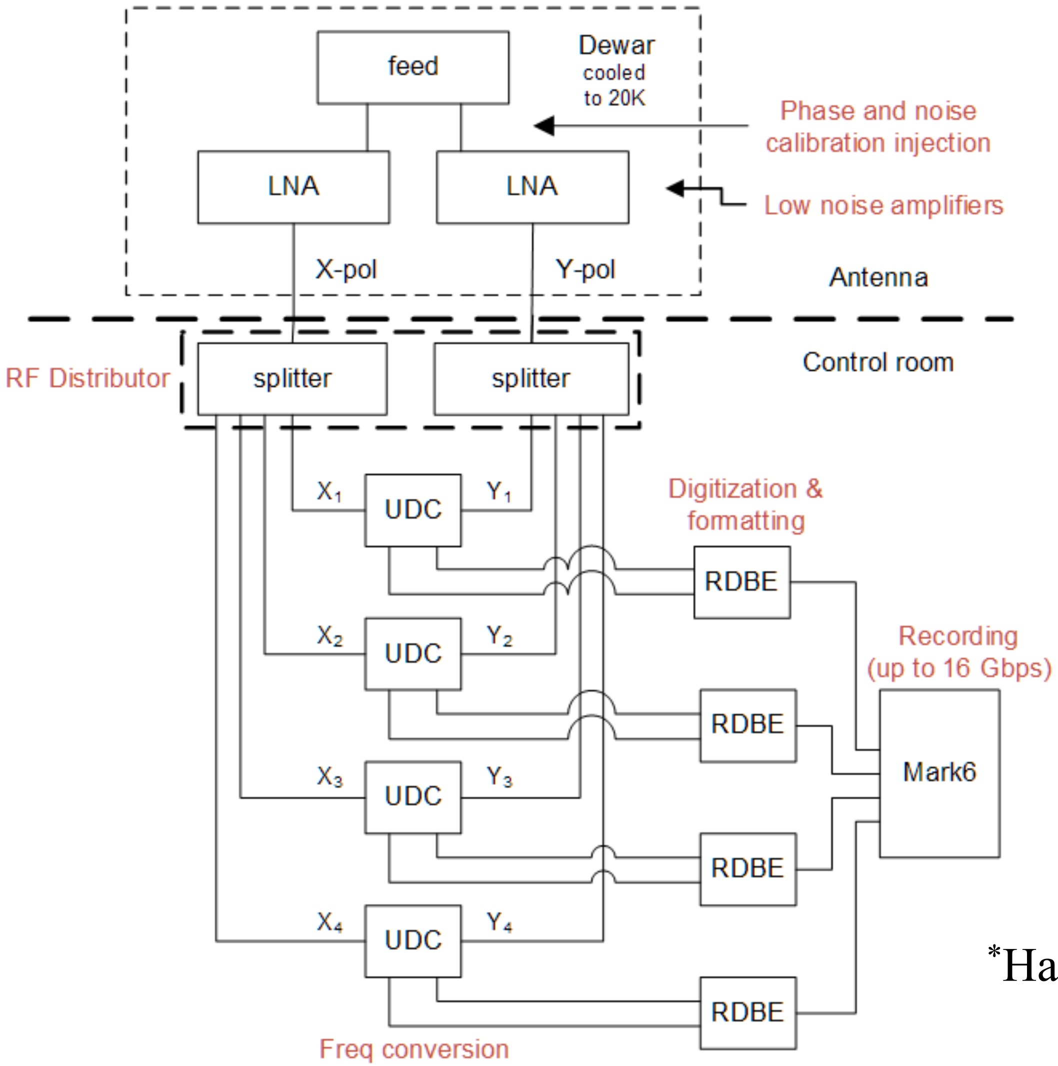
Special thanks

- Chris Beaudoin, Chris Eckert, Mark Derome – Broadband signal chain design and implementation
- 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 System Diagram*



*Haystack implementation

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

Recent observations - 1

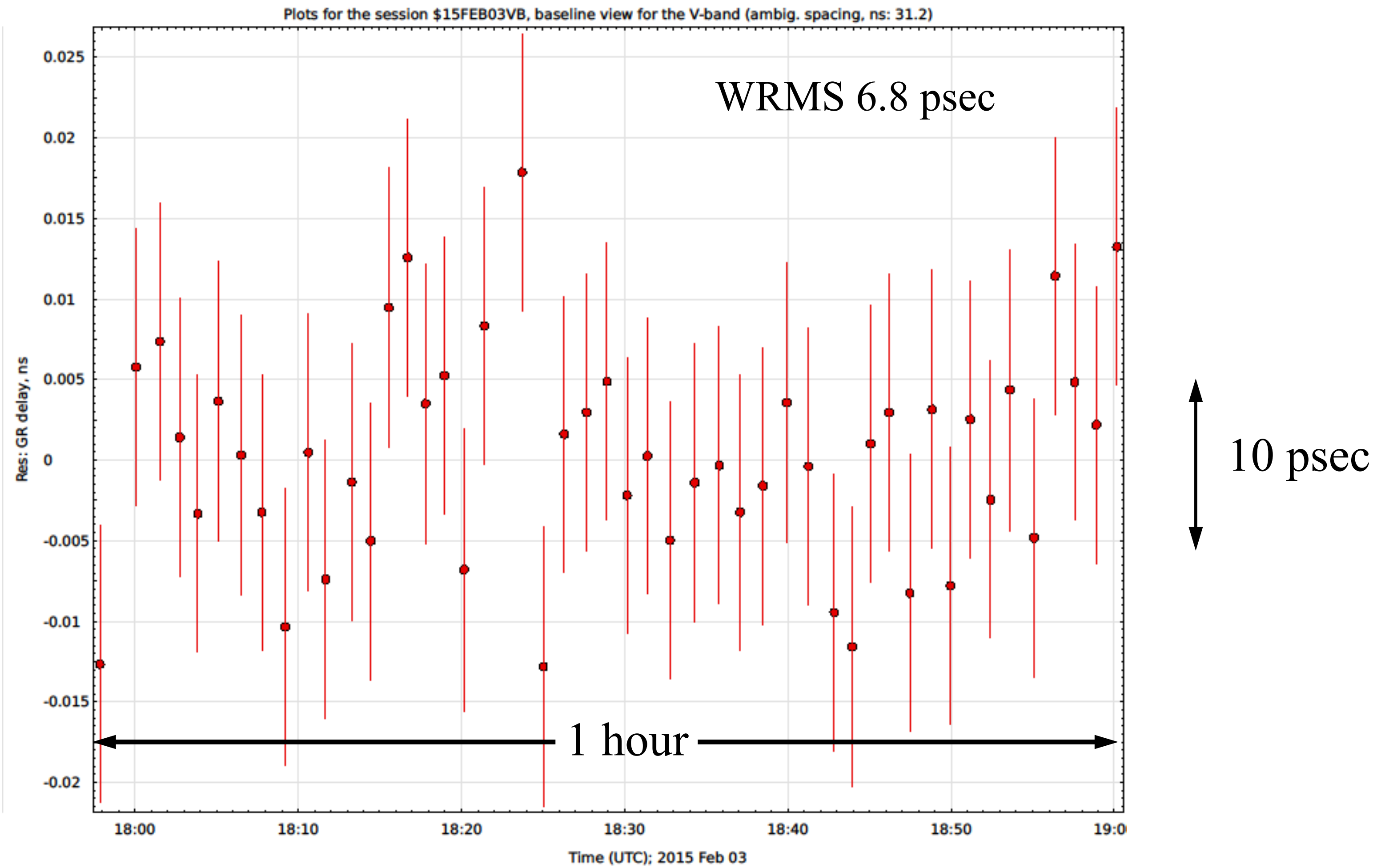
- **VGOS Data Series**
  - Work towards operational broadband observing.
  - Have observed one hour sessions about every two weeks since 2014 December (9 successful sessions).
  - The most recent sessions have been run under Field System control, including UDCs, RDBEs, and Mark6.
  - Center frequencies for the four bands:

    3.3 GHz   5.5 GHz   6.6 GHz   10.5 GHz

Recent observations - 2

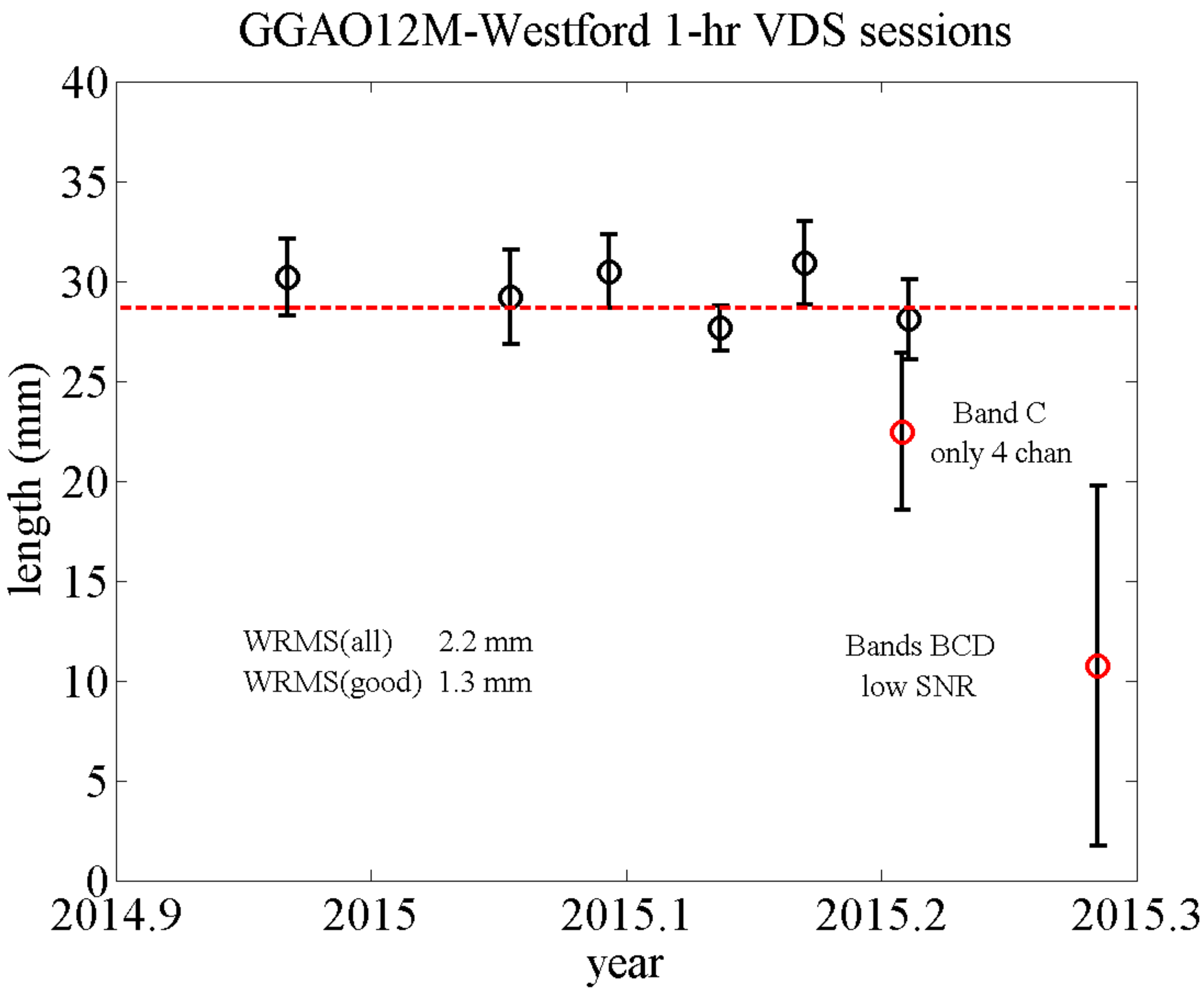
- **VGOS Data Series (cont'd)**
  - Median delay uncertainty per scan is ~1 psec.
  - Correction for phase variation across the bands and with time would raise this to a few psec (see previous 64-channel *fourfit* figure).
  - With re-weighting by additive delay to the geodetic estimation, the WRMS post-fit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

Post-fit delay residuals V15034 2014FEB03 48/50 obs retained



Recent observations - 3

- **VGOS Data Series (cont'd)**
  - Baseline length is 601 km.
  - For six (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-hr VDS sessions
length (mm)
year
40
35
30
25
20
15
10
5
0
2014.9
2015
2015.1
2015.2
2015.3
Band C
only 4 chan
WRMS(all) 2.2 mm
WRMS(good) 1.3 mm
Bands BCD
low SNR

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?

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
  - Modify input parameters to compensate for high data rate in each band
  - Use S-band and X-band flux densities but 3GHz and 10GHz system characteristics to calculate minimum scan lengths

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
      - Layout for 16*32MHz recording
      - Minimum redundancy frequence per band

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

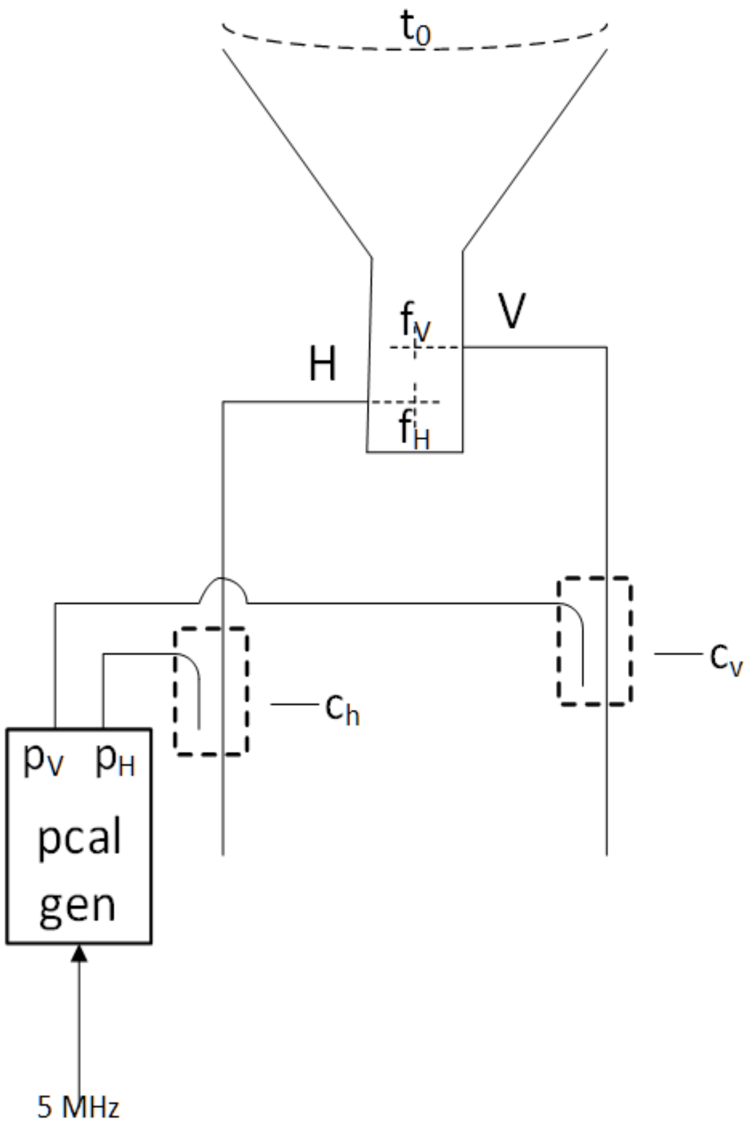
Broadband correlation - 2

- **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).
- **Uncalibrated delay and phase offsets between polarizations**
  - Correct for RF path length through the feed and before phase cal injection.

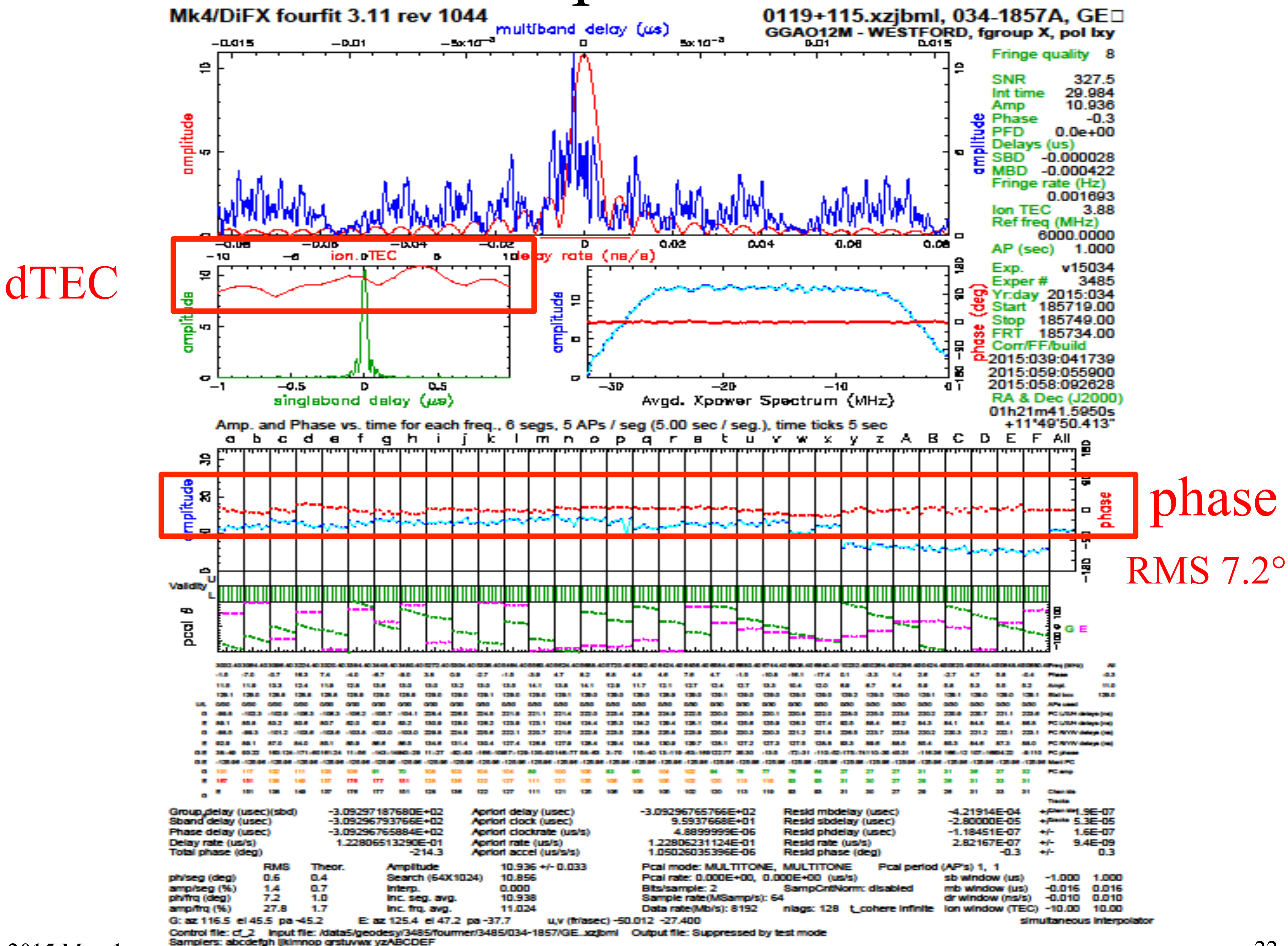
Polarization delay offset



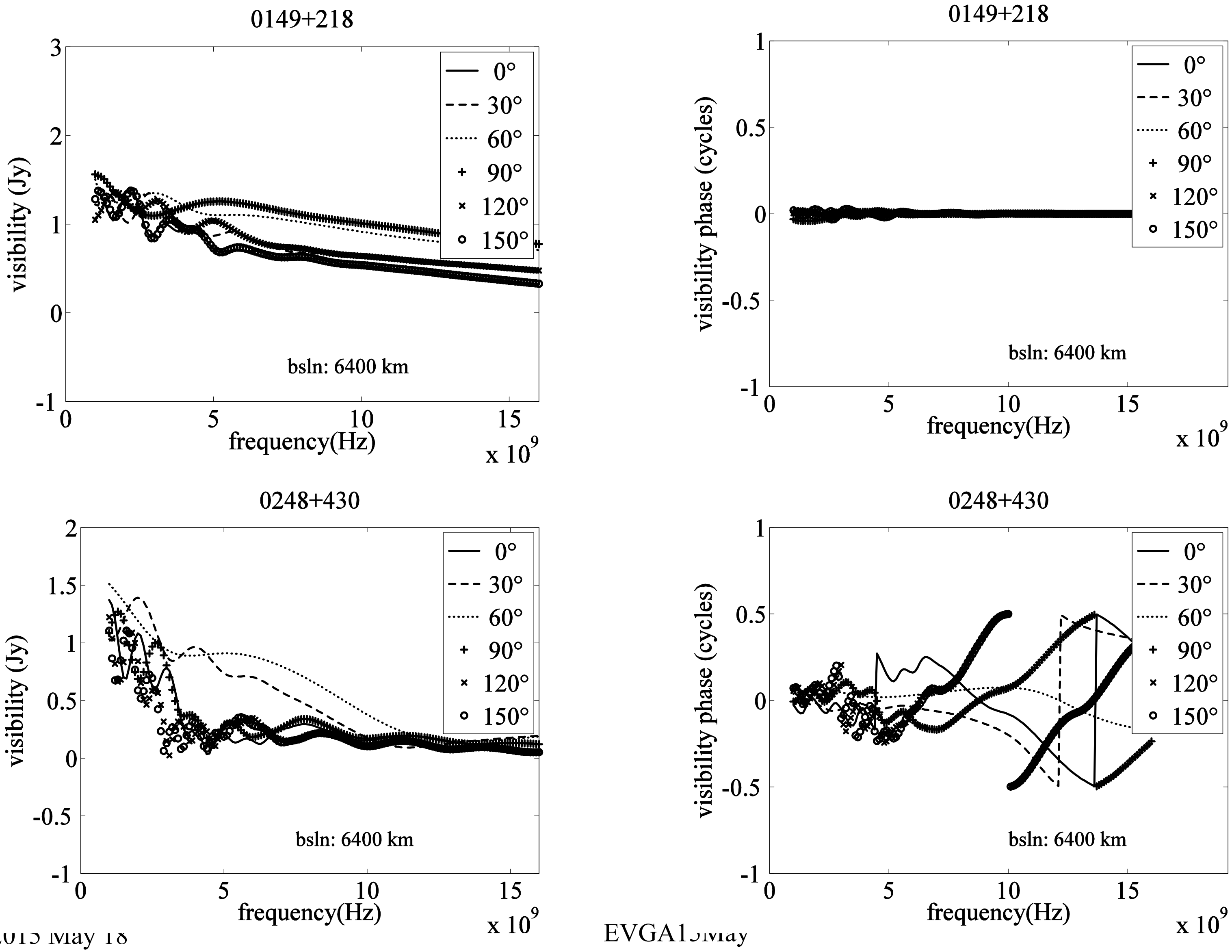
Post-correlation analysis - 1

- ***fourfit*** **(assume 64-ch correlation)**
  - Use all four polarization products to determine delay and phase differences between polarizations for each antenna
    - *fourfit* one or more strong sources for HH and VV to determine dTEC (for S/X determined from S and X)
    - *fourfit* HV and VH at that dTEC to get delay and phase differences between polarizations for each antenna
    - *fourfit* all 128 channels (4 bands * 8 channels * 4 pol'n products) to estimate group delay and consistent total electron content difference (dTEC) between the sites
  - Example *fourfit* plot in next slide

Combined polarization data



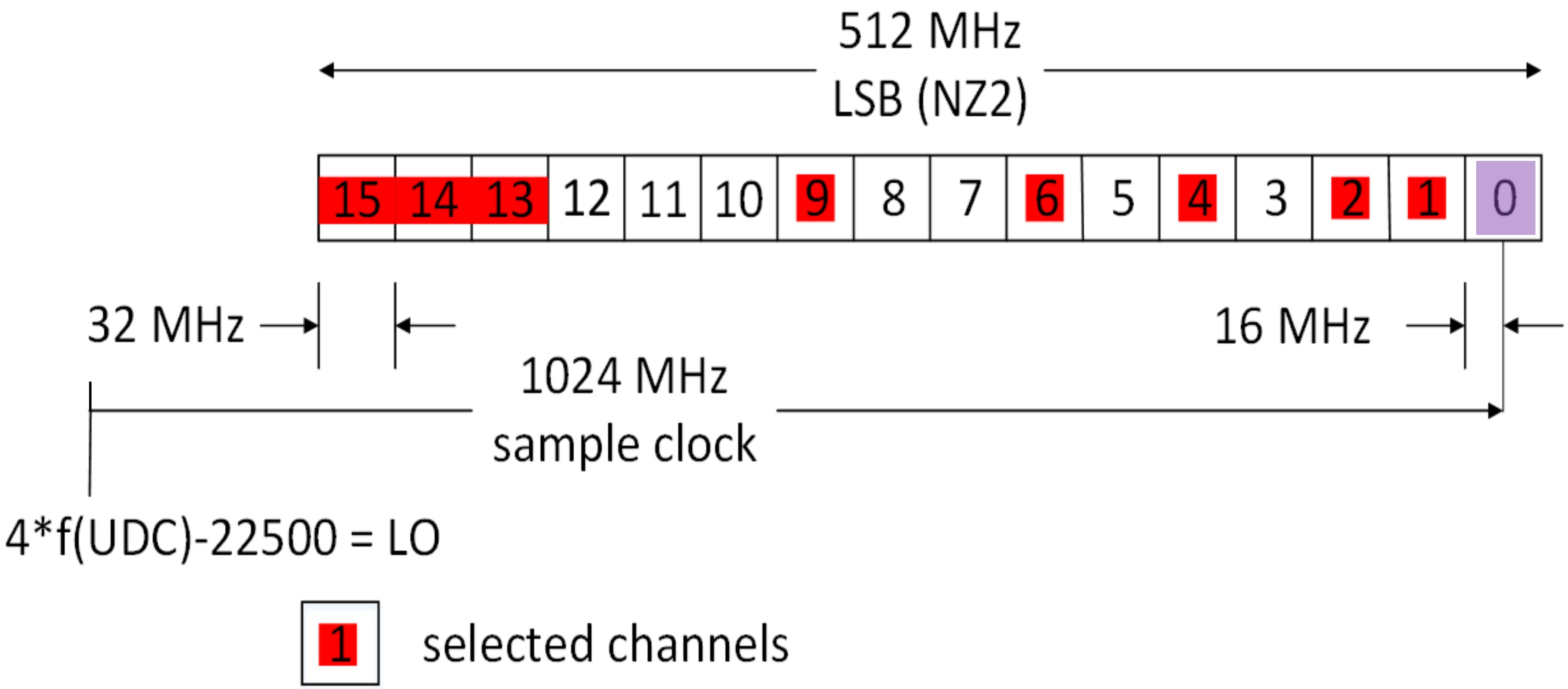
Source structure phase



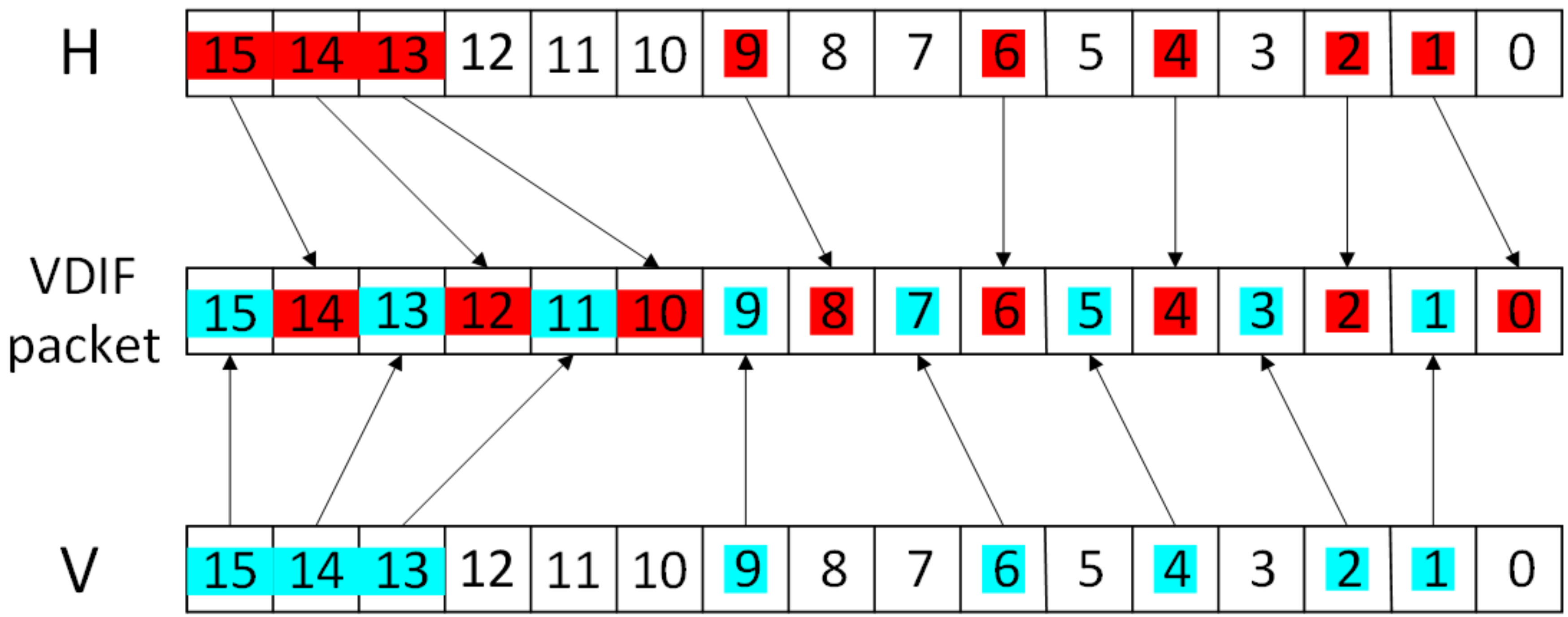
Post-correlation analysis - 2

- ***calc/nuSolve***
  - Create database (required modification of dbedit)
  - (Currently) use nuSolve for preliminary analysis
    - Use single time interval for the full session
    - Estimate:
      - Position of GGAO (Westford fixed)
      - Clock offset at GGAO (plus second order polyn)
      - ZWD at one site (since baseline is so short)
      - Troposphere gradients at both sites

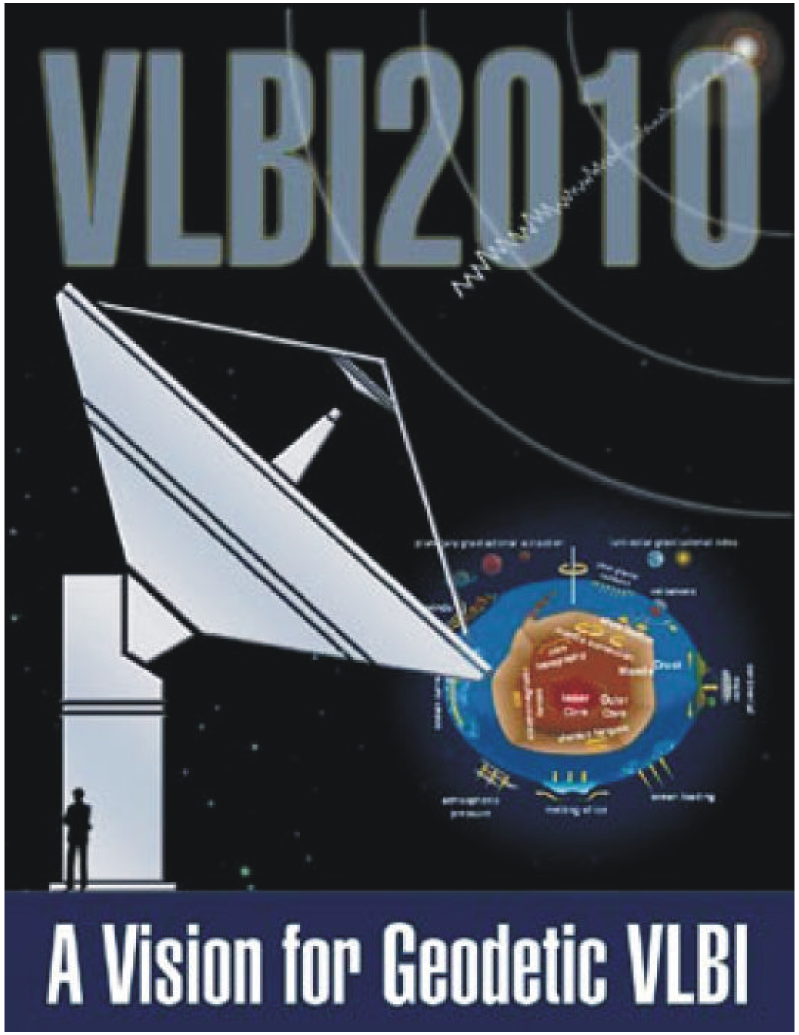
Frequence
(frequency sequence)



Channels in packet



Better late than never!



Patriot 12M Antenna @ GGAO