Technical Challenges of VLBI2010 Broadband Observations

Bill Petrachenko
Natural Resources Canada (NRCan)
Bill.petrachenko@nrcan-rncan.gc.ca

1st International VLBI Technical Workshop,
Haystack Observatory, Groton, MA
Oct. 22-24, 2012
Geodetic VLBI: How does it work?

A network of antennas observes a Quasar

The delay between times of arrival of a signal is measured

Using the speed of light, the delay is interpreted as a distance

The distance is the component of the baseline toward the source

By observing many sources, all components of the baseline can be determined.
VLBI2010: Why do we need a next generation geodetic VLBI system?

**Aging systems (now >30 years old):**
- Old antennas
- Obsolete electronics
- Costly operations
- RFI

**New requirements:**
- Sea level rise
- Earthquake processes
- 1-mm accuracy
- GGOS

**New Technology:**
- Fast cheap antennas
- Digital electronics
- Hi-speed networks
- Automation

**New system**
Goals of the next generation system

1-mm position accuracy \( (based \ on \ a \ 24\text{-hour \ observation}) \)
- Unprecedented, needs research

Continuous measurements of station position and EOP
- Update processes and increase automation

Turnaround time to initial products < 24-hrs
- Use eVLBI
Strategy for VLBI2010 Goal #1: 1-mm accuracy

Reduce Random Errors:
- Atmosphere
- Clocks
- Delay Measurement

Reduce Systematic Errors:
- Antenna Deformations
- Source Structure
- Electronics

Remedy:
- Careful design
- Calibration

Remedy:
- Reduce Source Switching Interval
  - Faster slewing antennas
  - Shorter “on-source” time
Need faster slewing antennas
Smaller diameter: ~12-m
12°/s azimuth rate; 6°/s elevation rate

Pictured here:
Twin Telescopes Wettzell (Vertex)

Other antennas meeting spec include:
• MT Mechatronics - RAEGE project (Spain & Portugal)
• Intertronics
Need short on-source times

Use extremely high data and record rates

“Burst Mode”

- Acquire data at 32 Gbps while on-source
- Record data at 8 Gbps while slewing between sources

Use Broadband Delay (BBD)

- **NEW**
- Resolve phase delay at modest SNR

Broadband feeds 2-14 GHz

Four 1-GHz bands across 2-14 GHz
VLBI2010 System Block Diagram

Complete redesign relative to legacy S/X system
Haystack Approach

- Cryostat
- LNA
- V-pol
- H-pol
- PCAL Generator
- Stable cable
- LMR-400
- UDC
  - 2-12 GHz
  - BW=512MHz
  - HV-pol
- RDBE
  - BW=512MHz
  - HV-pol
- MK6/Mk5C
- H-maser

DBBC Approach

- Cryostat
- LNA
- V-pol
- H-pol
- DBBC3
  - 28 Gsps
  - 8-bit
- Digital over fibre
- Stable cable
- LMR-400
- DBBC VLBI 2010
- MK6/Mk5C
- H-maser
### Broadband feeds: several already exist, e.g.

- **ATA log periodic 0.5-14 GHz feed**
- **Lindgren open quadridge 2-18 GHz feed**

**Problem with most:** location for maximum efficiency depends on frequency

- Hence, no single focus position simultaneously achieves maximum efficiency at all frequencies
  - e.g. for ATA feed, at best compromise position, efficiency can vary by ~30% across full frequency range

**VLBI2010 feed challenge:**

- Find feeds having high efficiency at all frequencies
  - while at a single focus position
- Two solutions: Eleven Feed and QRFH
Eleven Feed: Chalmers University, Sweden

- Phase centre is by design always in the ground plane

- Feed performance is very good at all frequencies

- Challenge:
  - Convert 8 outputs from 4 petals into a single output for each polarization V-pol and H-pol
A number of combining networks are possible

**But to avoid degradation:**
- LNA’s are required *before* the combining network

**Challenges:**
- Requires 8 cooled LNA’s instead of 2
- LNA’s must be matched in gain and phase
- Must inject calibration signals directly into the feed – but reflections may be a problem
Quadruple-ridge flared horn (QRFH): Caltech

- Phase centre location varies with frequency
  - *But* phase efficiency is still high, i.e. the antenna efficiency with the feed at the best compromise focal position is high at all frequencies

- No combining network required
  - Only one LNA required per polarization output
  - No LNA balancing required
  - Easy to insert PCAL couplers
The Eleven Feed and QRFH are linearly polarized

As seen from above, the linear polarization orientation for alt/az antennas varies with geographic location.

For parallel orientations, correlated signal is found in the co-pol products, e.g. $v_1*v_2$ and $h_1*h_2$

For orthogonal orientations, correlated signal shifts to the cross-pol products, e.g. $v_1*h_2$ and $h_1*v_2$

To avoid this, VLBI traditionally uses circular polarization, where amplitude is independent of orientation.

Although unprecedented, VLBI2010 uses linear polarizations directly. All four polarization products are correlated and combined to generate a total intensity (I) observable post-correlation. [Circular polarization could be generated electronically using 90°-hybrids but LNA imbalances are a problem.]
Post-correlation determination of Total Intensity

\[ I = \left( \langle v_1 \cdot v_2^* \rangle + \langle h_1 \cdot h_2^* \rangle \right) \cdot \cos \Delta + \left( \langle v_1 \cdot h_2^* \rangle - \langle h_1 \cdot v_2^* \rangle \right) \cdot \sin \Delta \]

\( \Delta \sim \) differential antenna polarization angle, i.e. \( \Delta = \phi_2 - \phi_1 \)

Need to know \( G \) and \( D \) terms
- can be determined by observing a strong unpolarized point source
- \( G \) terms can be tracked using noise and phase cal signals
Broadband Delay requires separation of dispersive and non-dispersive delay 

**during** (not after) fringe detection

\[
\phi = f \cdot \tau \\
\phi = f \cdot \left( \tau_g + \tau_{clk} + \tau_{atm} + \ldots \right)
\]

**Non-dispersive delay.** Delay is independent of frequency (phase is linear wrt frequency)

\[
\phi_{ion} = \frac{K}{f} \quad \tau_{ion} = -\frac{K}{f^2}
\]

**Dispersive delay.** Delay varies with frequency. Variation is due to the Ionosphere.
Level 1 Solution: Group Delay only

With SNR=10 per band and a group delay only solution, $\Delta T \approx 32$ ps ($\approx 1$ cm).
Level 2 solution: Using the group delay solution, connect the phase between bands

Need to resolve integer cycles of phase between bands

For SNR=10 per band and phase resolved between all bands, $\Delta \tau = \sim 5\text{-ps} \sim 2\text{ mm}$. 
Level 3 solution: Using the connected phase solution, resolve the phase offset.

For SNR=10 and the phase offset resolved, $\Delta\tau = \sim 1.3\, ps \, (\sim 0.5\, mm)$. 
In practice, a search algorithm is used to determine $\mathcal{T}$ and $K$

Search to find values of $\mathcal{T}$ and $K$ that flatten the observed delay (when subtracted) and hence maximize the coherent sum

- **Non-dispersive**: $\phi = f \cdot \tau$
- **Dispersive**: $\phi = \frac{K}{f}$
Sources of RFI (2-14 GHz)

Entire band is already fully allocated by international agreement

Sources internal to VLBI and co-located space geodetic techniques (e.g. SLR, DORIS, GNSS)
- Local oscillators, clocks, PCAL pulses, circuits
- DORIS beacon at ~2 GHz
- SLR aircraft avoidance radar at ~9.4 GHz

Terrestrial Sources
- General communications, fixed and mobile – land, sea, air
- Personal communications cell phones, wifi
- Broadcast
- Military
- Navigation
- Weather
- Emergency

Space Sources
- Communications
- Broadcast (C-, Ka-band; in Clarke belt at ±8° dec)
- Military
- Exploration
- Navigation
- Weather
- Emergency
How does RFI enter the receiver chain?

1. Multipath off objects and antenna structure
2. Spillover direct into the feed
3. Antenna sidelobes
4. Direct coupling into cables and circuits
Negative Impacts of RFI

Small RFI appears as added noise
- Reduces performance of the system
- Only impacts frequencies where RFI occurs
- Undesirable but can be tolerated within limits

Larger RFI can saturate the signal chain
- Impacts entire band, not just frequencies where RFI occurs
- Must be avoided (observation is lost)

Even larger RFI can damage the VLBI receiver
- Typically LNA is most vulnerable
- Must be protected against (leads to expense and down time)
RFI Mitigation Strategies

Avoidance mask
Do not observe below the dotted line

Physical barrier as attenuator

Design improvements
- Diode protection for LNA`s
- Higher dynamic range components
- Lower antenna sidelobes

Time windowing for pulsed signals
Do not observe at these times

Frequency reject filters
- Frequency selective feeds or cryogenic IF filters are technically challenging and expensive
- Less flexible
- IF filters are technically easier and less expensive
- More flexible
Amp and phase vary with uv-coordinates

Amp and phase vary with frequency

Complicates broadband phase resolution

Amp and phase vary with time

Solution #1
Use sources with minimum structure and stable position

Solution #2
Observe at higher frequency e.g. X/Ka used by JPL/DSN

Solution #3
Apply source structure corrections

Core shifts

Sub-beam structure
Based on Charlot and Fey S/X Gaussian component models (1999), Arthur Niell generated 2-14 GHz structure phase models.

- **0014+813, SI=(1,1)**
- **0149_218, SI=(2,2)**
- **0202+149, SI=(2,2)**
- **2143-156, SI=(2,2)**
- **0113-118, SI=(2,3)**
- **0248-156, SI=(2,4)**
Source structure corrections

Step #1
Generate an image (or model) for each frequency band using the VLBI2010 data
- Depending on schedules, VLBI2010 observations could generate 500 or more UV points per day
- Many VLBI2010 sources will be observed day after day
- SNR per UV point typically low, e.g. ~7.

Step #2
Align images (or models) between the four bands
- Use the highest frequency image as reference
- Complicated by “core-shifts” and sub-beam structure

Step #3
Select a feature in the highest frequency map as the reference point
- Hopefully close to the dense positionally stable black hole
Source structure corrections

Image alignment between frequencies can be a problem

0149+218, SI=3.3

This slide has made use of the Bordeaux Image Database
Cross frequency image alignment problems

- Enough information in raw data (but not phase closure data) to align images
  - but map offsets are confused by correlation with the ionosphere
Summary:
- General intro to VLBI2010
- VLBI2010 system description
- Feed issues
- Dealing with linear polarization
- Fringe detection in the presence of the ionosphere
- 2-14 GHz RFI
- Source structure
Thank you for your attention!

Questions?
Dynamic Range (DR) Example

- Astronomical Signal -110-dBm
- Tssys Noise 50°K = -80-dBm
- Max linear power -50-dBm
- IN1dB
- IP3

10-dB/division

- 1% Noise add
- 20-dB DR
- 30-dB DR

Follow-on stage

- Max range of sampler
- 12-dB
- 18-dB DR
- 3% Noise add

Gain

8-bit sampler ~18-dB DR
10-bit sampler ~25-dB DR

Sampler

12-dB

ENOB

Gain

Prefer 10-bit sampler

18-dB DR

1% Noise add

Max range of sampler

IN1dB

LNA

18-dB DR

1% Noise add

Max range of sampler
red->phase delay; green->bbd; blue->phase bbd

Nap=10   SNR=28

delay(ps)
time after start of scan(s)
Structure phase complicates phase resolution across frequency

* VLBI2010 bands (BW=1-GHz) shown in blue
Role of VLBI in Space Geodesy

Celestial Reference Frame (CRF)

Quasars

Orientation of the Earth in Space

Terrestrial Ref Frame (TRF) Scale
Science:
Astrometry & Astrophysics

Celestial Reference Frame (CRF)

Science:
Earth mass Exchanges

Orientation of Earth In Space

Quasars

VLBI Antenna:
Stable structure
Stable phase centre
No multipath

Science:
Deep Space Tracking

Precise Orbit Determination

UT1

Science:
Solar System Exploration

Science:
GNSS apps
LEOS apps

Science:
Sea level change

Roles of VLBI
History and Organization of VLBI2010

**IVS Directing Board**
- 2003
- 2006

**Working Group 3:**
- Set VLBI2010 goals
- Did system outline

**VLBI2010 Committee:**
- Carries out studies
- Did system definition
- Doing prototyping

**VLBI2010 Project Executive Group:**
- Provides strategic leadership
- Promotes network expansion
Goals of the next generation system

VLBI2010 Goals

1-mm position accuracy \((based\ on\ a\ 24\text{-}hour\ observation)\)

Continuous measurements of station position and EOP

Turnaround time to initial products \(<\ 24\text{-}hrs\)
NASA Broadband Delay Proof-of-concept Development Project

• **Purpose:**
  – Prove that Broadband Delay can be used operationally to resolve phase delay.
  – Develop the first generation of VLBI2010 electronics.
  – Gain experience with new VLBI2010 subsystems.

• **Status**
  – Proof-of-concept tests are ongoing
  – Final prototypes are in development
VLBI2010 System Block Diagram

VLBI2010 Specifications

Antenna diameter >= 12-m.
Antenna slew rate
  - azimuth=12°/s az; elevation=4°/s
Frequency range = 2-14 GHz
Polarization = dual linear
# of bands = 4
Bandwidth/band = 1-GHz
Total data rate = 32-Gbps
Record/xmit rate = 8-Gbps
Back end = digital
Correlator = Software
Planned or proposal in preparation
Proposal submitted
Funded
Under construction
Operational

Planned ~17
Proposed ~5
Funded ~9
Construction ~9
Total ~40

Locations not decided

Twin telescope
More stations needed in the Southern Hemisphere
More stations needed below 15°N latitude
**Gravitational deformation**

At the zenith, the dish opens a small amount and the focus draws nearer to the surface.

The opposite happens at the horizon.

This results in an elevation dependent delay which appears as a height bias.

**Thermal deformation**

The antenna reference point moves up and down due to thermal expansion and contraction of the antenna tower.

If there is no correction at the epoch of the site tie, the height is biased.
VLBI2010 approaches to antenna deformations

VLBI2010 antennas are smaller
→ deformations will be smaller

Thermal offsets are monitored in real time
(COLD MAGICS project and others)

In a few cases accurate and complete gravitational models have been developed
Another approach for antenna deformations and site ties

Use *connected element interferometry* to a small nearby antenna to measure the "*effective*” reference point of the VLBI2010 antenna.

Observe *GNSS satellites* with the same small antenna and measure the “*effective*” reference point of the GNSS antenna.

The intersection of axes of the small antenna becomes the reference point for both VLBI & GPS and ties the techniques.
VLBI2010 Status

- Faster slewing antennas are being designed and built 😊
- BBD systems have been built and are being tested 😊
- Network is growing 😊
- Systematic errors are being tackled 😊
- eVLBI is expanding 😐
- Automation and remote-control of sites progressing 😊
- Updated analysis packages are under development 😊
- Initial operating scenarios are under development 😊
Conclusions

- VLBI2010 will perform significantly better than current geodetic VLBI
- VLBI2010 will be a key technique within GGOS
Need faster slewing antennas
Smaller diameter: ~12-m
12°/s azimuth rate; 6°/s elevation rate

Twin Telescopes Wettzell (Vertex Antennas)
Auscope - Hobart (Patriot antenna)

New model meets VLBI2010 spec

RAEGE project (Spain & Portugal): MT Mechatronics