VLBI2010: A New VLBI System for Geodesy and Astrometry
(In Search of the Millimeter)

W. Petrachenko (1)
D. Behrend (2) J. Boehm (3)
P. Charlot (4) A. Collioud (4)
T. Clark (2) B. Corey (5)
J. Gipson (2) R. Haas (6)
Y. Koyama (7) D. MacMillan (2)
Z. Malkin (8) A. Niell (5)
T. Nilsson (6) A. Pany (3)
A. Rogers (5) A. Searle (1)
G. Tuccari (9) J. Wresnik (3)

(1) NRCan, (2) NVI/GSFC, (3) IGG/TUWien, (4) Bordeaux Obs.,
(5) MIT/Haystack Obs, (6) Onsala Obs, Chalmers U, (7) NICT,
(8) Pulkovo Obs, (9) INAF
This talk is not directly about the impact of VLBI errors on Reference Frames.

It is about an effort in the IVS to reduce VLBI errors and hence minimize their impact.
Motivation for a next generation VLBI system

• Limitations of the current VLBI system:
  – Obsolete electronics, old slow antennas, high cost of operations, gaps in geographic coverage, RFI problems, etc

• New technology:
  – Lower cost antennas, broadband (1-11 GHz) receiving systems, cheap large disks, global fibre optic networks, high speed digital processing, etc

• Enhanced Requirements (both science & operations)
  – Need more accuracy to measure sea level change, monitor strain fields related to tectonics, support spacecraft tracking, etc
Goals for VLBI2010

• *1 mm accuracy for site position*
• Continuous observations for EOP.
• Short turnaround (<24 h) between observations and initial results.
Major VLBI error sources

• Random/stochastic error
  – Atmosphere variability
  – Thermal delay measurement error
  – Clock drifts

• Systematic error
  – Source structure
  – Instrumentation
  – Antenna deformations
  – Site stability
Major VLBI error sources

- **Random/stochastic error**
  - Atmosphere variability
  - Thermal delay measurement error
  - Clock drifts

- **Systematic error**
  - Source structure
  - Instrumentation
  - Antenna deformations
  - Site stability
Strategies for reducing the random/stochastic error component

- Use many more observations per session
- Use much more precise delay observables
- Improve analysis strategies
- Improve scheduling strategies
- Use external measurements
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Method for evaluating the strategies: Monte Carlo Simulators

- **How do they work?**
  - Sets of simulated data are generated based on realistic models.
  - The simulated data is analyzed as if it were real.
  - The process is repeated several (25) times and statistics are done on the analysis products.

- **Noise models to simulate VLBI2010 data:**
  - *Wet troposphere:* Turbulent moving screen (Lanyi & Treuhaft) and implemented by Tobias Nilsson.
    - Latitude dependent Cn’s and h’s. Winds from NWM’s.
  - *Clocks:* Random walk plus integrated random walk with Alan Standard Deviation = 1.e-14 @ 50 min.
  - *Delay measurement error:* 4 ps based on expected phase delay performance.
Test of the Monte Carlo Simulators using CONT05 Data (OCCAM KF)
Monte Carlo Simulators can be used to study many things

- Impact of using many more observations per session
- Impact of using much more precise delay observables
- Impact of improved clock performance
- Impact of increasing network size
- Impact of analysis strategies
- Impact of scheduling strategies
- Comparison of analysis packages
- Comparison of Kalman Filter vs Least Squares
Monte Carlo Simulators can be used to study many things

- Impact of using many more observations per session
- Impact of using much more precise delay observables
- Impact of improved clock performance
- Impact of increasing network size
- Impact of analysis strategies
- Impact of scheduling strategies
- Comparison and validation of analysis packages
- Comparison of Kalman Filter vs Least Squares
Test schedules were generated with uniform sky coverage and uniform source switching interval.

Sky coverage at Wettzell for a representative 9 min interval.

Schedules were generated with 15, 30, 45, 60 and 120 s source switching intervals.

Current skeds use switching intervals ~300s.
3-D RMS Position Error for each station

median: 1.294
Median 3-D position error vs switching interval

- **Source Switching Interval (s)**
  - 0
  - 30
  - 60
  - 90
  - 120

- **3-D Position accuracy (mm)**
  - 0
  - 1
  - 2
  - 3
  - 4
Median position error vs source switching interval

3-D Position accuracy (mm)

Source Switching Interval (s)

1 antenna with 5 deg/s azimuth slew rate
Median position error vs source switching interval

3-D Position accuracy (mm)

Source Switching Interval (s)

1 antenna with 5 deg/s azimuth slew rate

2 antennas, 5 deg/s
Strategies for reducing the random/stochastic error component

- Use many more observations per session
- Use much more precise delay observables
- Improve analysis strategies
- Improve scheduling strategies
- Use external measurements
How do we get much better delay precision?

Use the *broadband delay* technique to resolve the RF phase.
How does broadband delay work?

- It uses a broadband (2-12 GHz) feed to acquire a large number (~4) of wide bandwidth (~1 GHz) optimally spaced frequency bands.
- Group delays are used to resolve the phase differences between bands and the phase differences are used to resolve the RF phase.
- **Precision.** The resolved RF phase delay has a precision of ~3ps at SNR=10/band. This is about an order of magnitude improvement over current group delays.
- **Proof.** Since the broadband delay has not yet been demonstrated, NASA sponsored a proof-of-concept development project to evaluate the broadband delay technique.
Purposes of the NASA Broadband delay Proof-of-concept development project

• Prove that broadband delay can be used operationally to resolve phase delay.
• Gain experience with new VLBI2010 subsystems
Status of *Broadband* tests

- To date, one complete VLBI2010 band has been constructed.
- Fringes were detected between the new VLBI2010 hardware at GGAO antenna (near Washington, DC) and standard geodetic X-band hardware at Westford antenna (near Boston)
- Sufficient VLBI2010 hardware is currently under construction for two complete stations.
- Phase resolution using full broadband delay mode (e.g. 4 bands) will be tested this summer
VLBI2010 Broadband Tests

Feed

Digital Back End
Reduce VLBI Systematic Errors: Source Structure

- At the level of precision of VLBI2010, sources can no longer be considered points, e.g. 0111+021
- In this structure index 3 source, there are delay errors as large as 70 ps (23 mm) at some baseline orientation
- Although better lists of sources (with structure index 1 and 2 only) now exist, source structure is still a significant error.

(Bordeaux VLBI Image Database)
With VLBI2010, structure corrections can be generated directly from the data

- With old schedules, uv coverage, i.e. the number of different geometries for observing a source, was not good enough for mapping
- With the VLBI2010 improvement to faster slewing antennas, higher data rates and larger networks, quality imaging will be possible enabling effective source structure corrections
Antenna deformations and site ties

• A novel approach has been propose (Koyama-san et al) to use connected element interferometry to a local small mechanically well understood antenna to develop thermal and gravitational antenna models.

• This approach also has obvious application to site ties.

• VLBI2010 observations of GPS satellites is also being considered.
  – Determine GPS orbits directly in the context of the ICRF
  – Establish more generalized site ties using a small collocated directional GPS antenna.
Summary

• The IVS has initiated a modernization program with an ambitious goal to achieve 1 mm accuracy for position.
• Monte Carlo studies are underway to discover means of improving performance toward the 1 mm goal. Results are promising.
• A NASA proof-of-concept effort is underway to test the broadband delay technique to resolve RF phase and hence improve delay precision by an order of magnitude.
• At the same time, novel approaches are being considered to reduce systematic errors.
• VLBI2010 antennas are already being requisitioned, e.g. a pair of super antennas for Wettzell, 3 in Australia, 1 in New Zealand, and proposals exist in India and Korea.