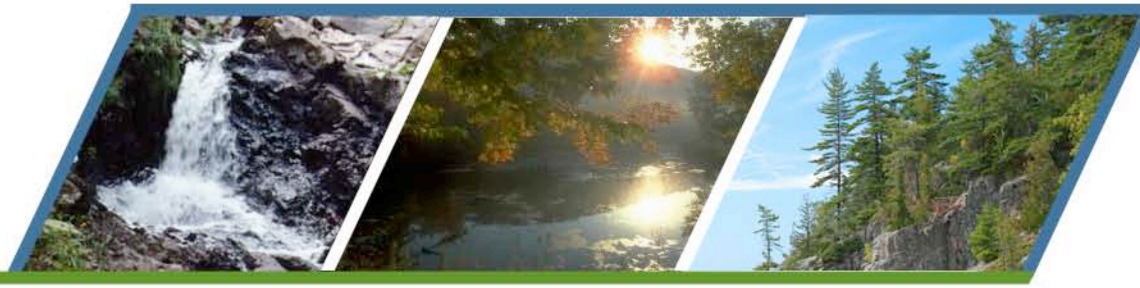
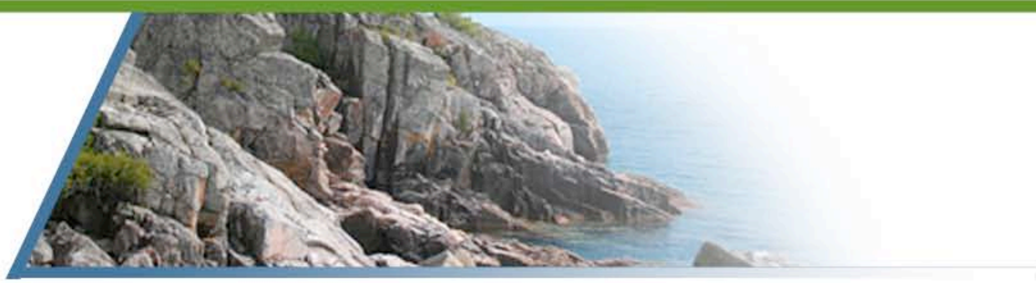


VLBI2010: In search of Sub-mm Accuracy

Bill Petrachenko, Nov 6, 2007, University of New Brunswick



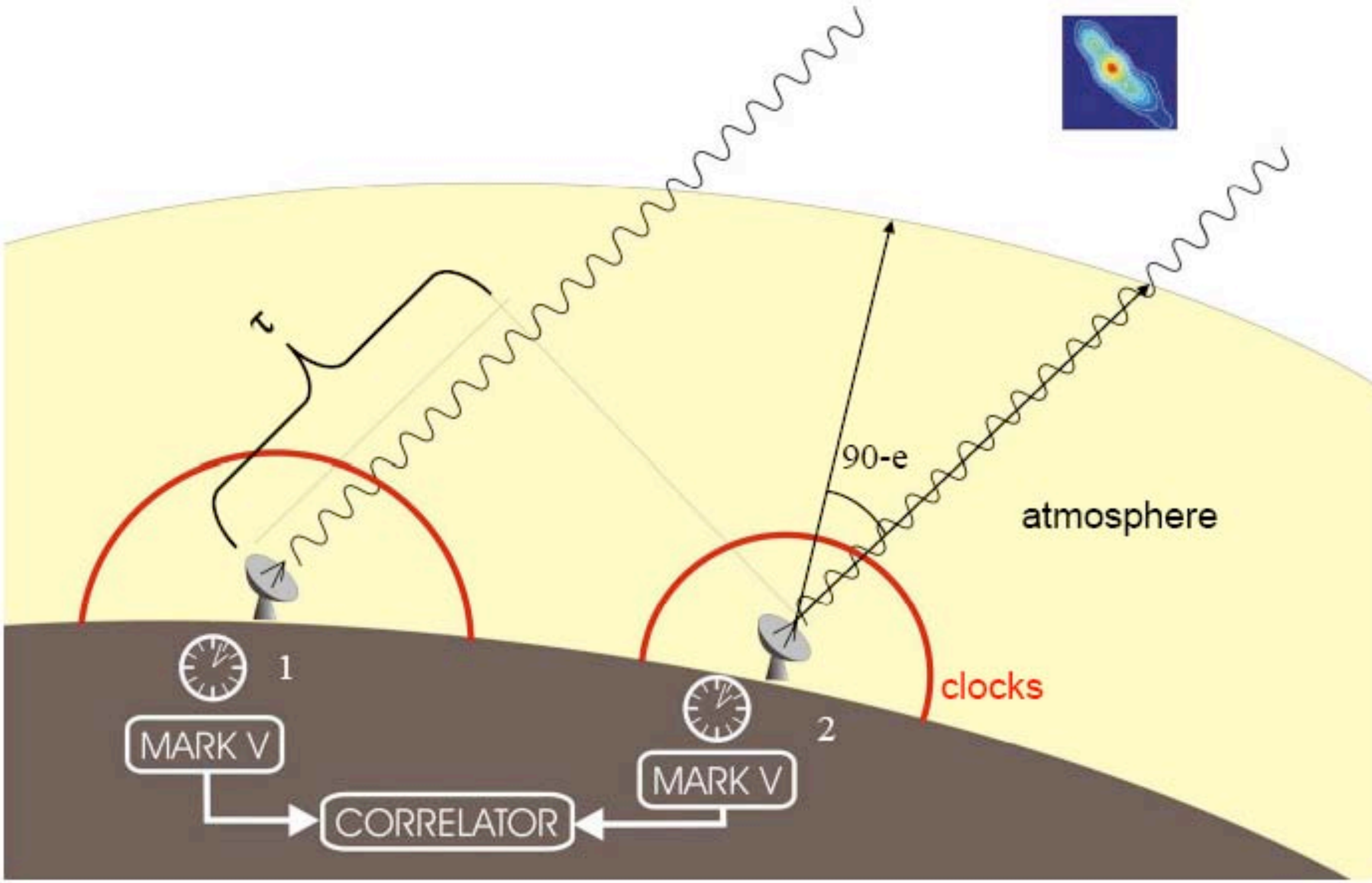
What is VLBI2010?

- VLBI2010 is an effort by the International VLBI Service for Geodesy and Astrometry (IVS) to define by 2010 a next generation system for VLBI
- It began with a working group in 2003
- It has continued since 2006 through the work of the VLBI2010 committee (V2C)
- This talk will report on the progress of the VLBI2010 committee to date with particular emphasis on the quest to achieve 1 mm position accuracy.

Review: What is VLBI and how does it work for geodesy?

- VLBI is a radio astronomy technique invented by Canadians in 1967
- Noise signals are received from quasars simultaneously at multiple antennas
- The difference in time of arrival at pairs of the antennas is determined through correlation
- This time difference is scaled by c to get the component of the baseline in the direction of the source
- Multiple sources provide the full vector baseline

How does VLBI work for geodesy (cont'd)?



What is VLBI’s role in space geodesy?

- Definition of the Celestial Reference Frame (ICRF)
  - 212 Quasars
- Determines all Earth Orientation Parameters (EOP)
  - Unique for UT1 and nutation
- Definition of the Terrestrial Reference Frame
  - Especially Scale

What applications depend on VLBI?

- Spacecraft navigation
  - Dynamical equations require knowledge of the orientation of the Earth in space
- Climate change
  - Measuring sea level rise requires stable scale
- Geohazards, e.g. earthquakes
  - Measuring long term strain buildup requires stable scale
- Properties and interaction of geophysical fluids, e.g.
  - UT1 is correlated with Zonal winds
  - Nutation gives information of the Earth’s deep interior

Why modernize VLBI [1]? Limitations of the Current System

- Current VLBI systems are decades old and are becoming obsolete
- Antennas are old and move slowly, hence can't achieve full sky coverage
- RFI is a growing problem
- Network distribution is not ideal, many gaps, problems in the southern hemisphere
- Cost of manned operations is high
- Long lag times for initial products

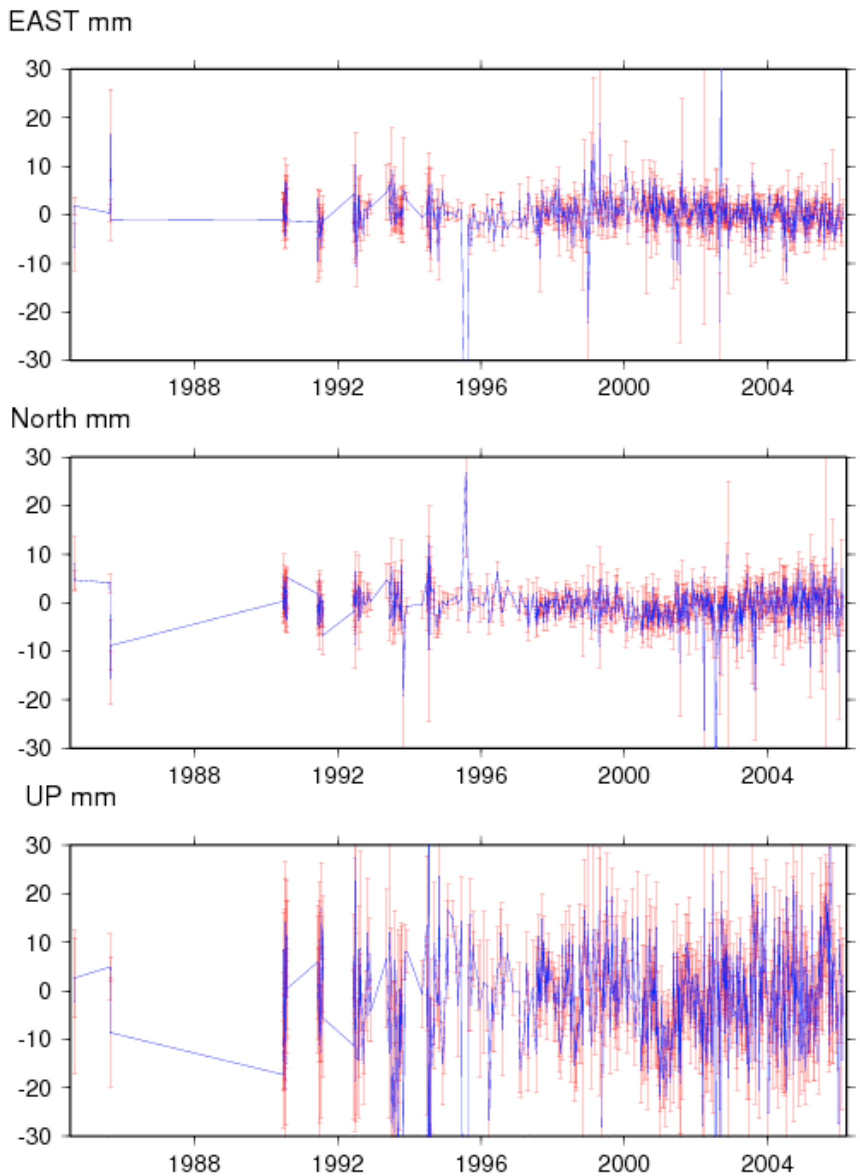
Why modernize VLBI [2]? New technology is available

- Lower cost moderate size antennas are now available, e.g. ATA, SKA, DSNA
- Higher disk data rates and capacities are availiable at reasonable cost
- Global optical-fibre Networks are now in place
- High speed digital signal processing is now available at reasonable cost
- Broadband receivers for radio astronomy have been developed for astronomy

Why modernize VLBI [3]?
New Requirements

- Support measurements of sea level rise and earthquake strain fields related to tectonics requires
  - ~1 mm position accuracy.
- Understanding earth dynamics through EOP requires
  - Continuous data records
- Supporting operational users of UT1 requires
  - Shorter time to initial products

40104S001 7282 Residuals



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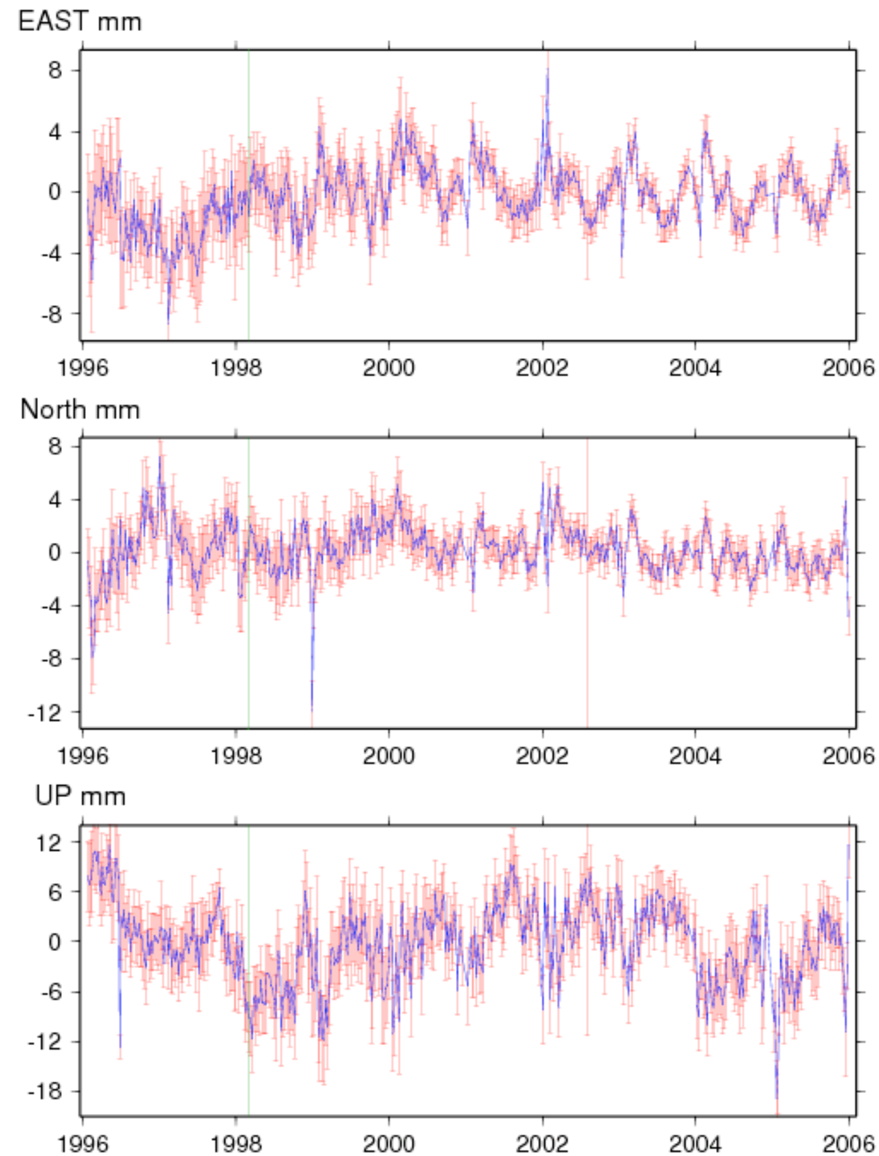
ITRF2005 Residuals analysis

40104M002 ALGO Residuals



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ITRF2005 Residuals analysis

Goals of Next generation VLBI System (VLBI2010)

- 1mm and 0.1mm/y accuracy for position and its rate, interpreted as:
  - Median of rms position error (3-D) of 1 mm over the entire network
  - Assuming a 24 hour observation
- Continuous observations.
- Short turnaround (<24 h) between observations and initial results.

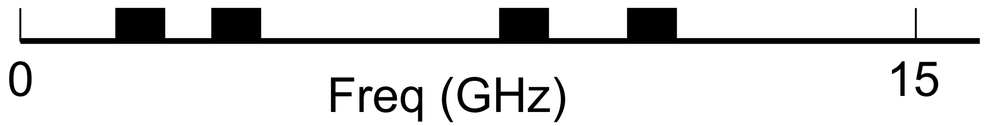
7 strategies to achieve 1 mm accuracy target

- Minimize effect of random components of error
  - Measurement error, clocks and atmosphere
- Increase number of observations per session
- Reduce systematic errors
  - Geological stability, antenna deformations, electronics and source structure
- Increase number and distribution of stations
- Reduce the impact of RFI
- Develop new observing strategies
- Improve data analysis, e.g.
  - Models, reliability, integrated solutions, automation
  - Fast gradients and/or spherical harmonics for the atmosphere

Main thrusts of the VLBI2010 Committee

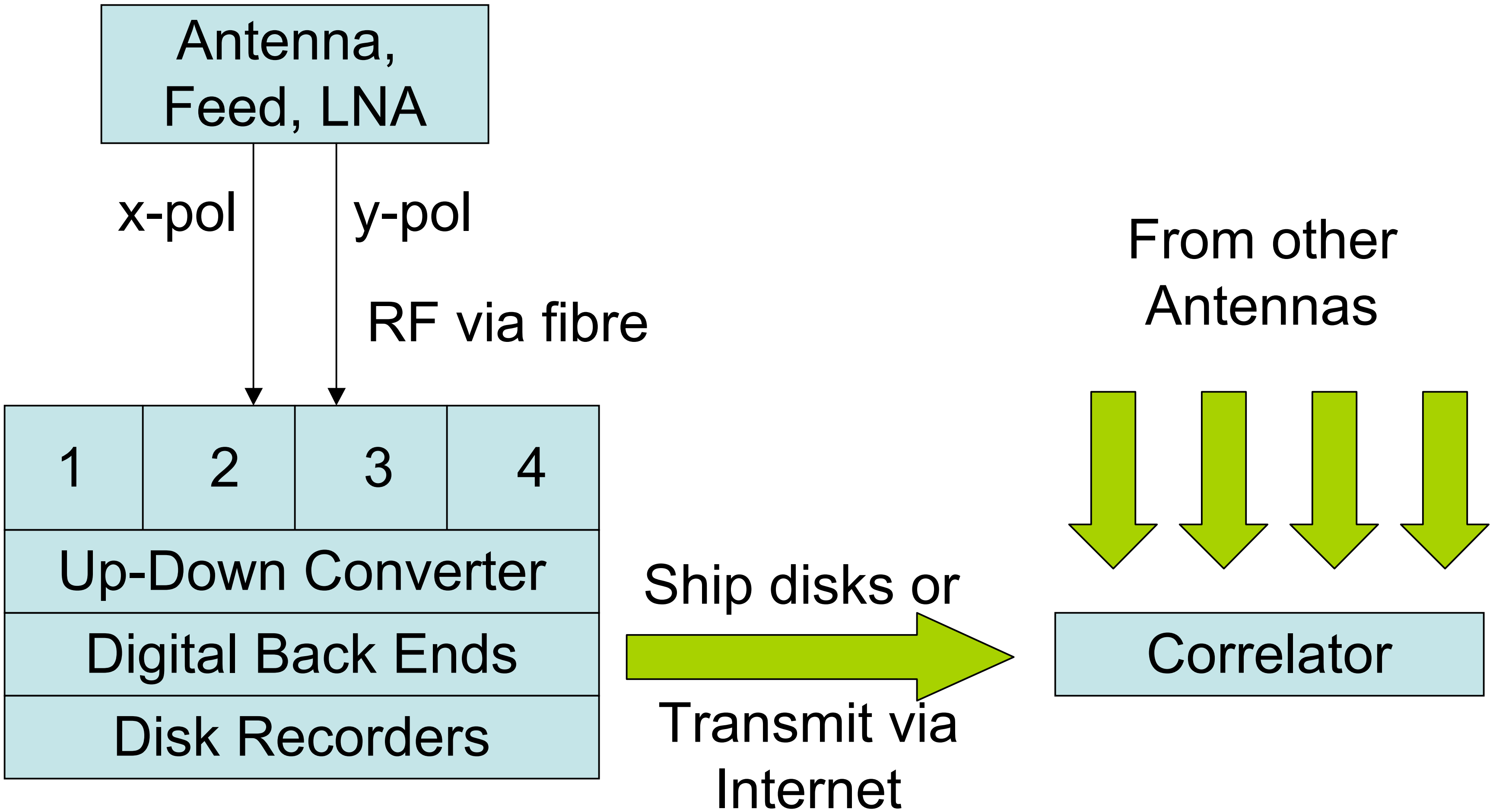
- Develop Monte Carlo simulators to:
  - Predict performance of the VLBI2010 system
  - Study the impact of strategies, system parameters, specs, etc
  - Understand error processes
- Prototyping effort (supported by NASA):
  - Test “broadband delay” concept
    - Many bands (~4) to help resolve phase delay at low SNR
  - Gain real world experience with next generation VLBI subsystems

What is broadband delay and why are we interested?

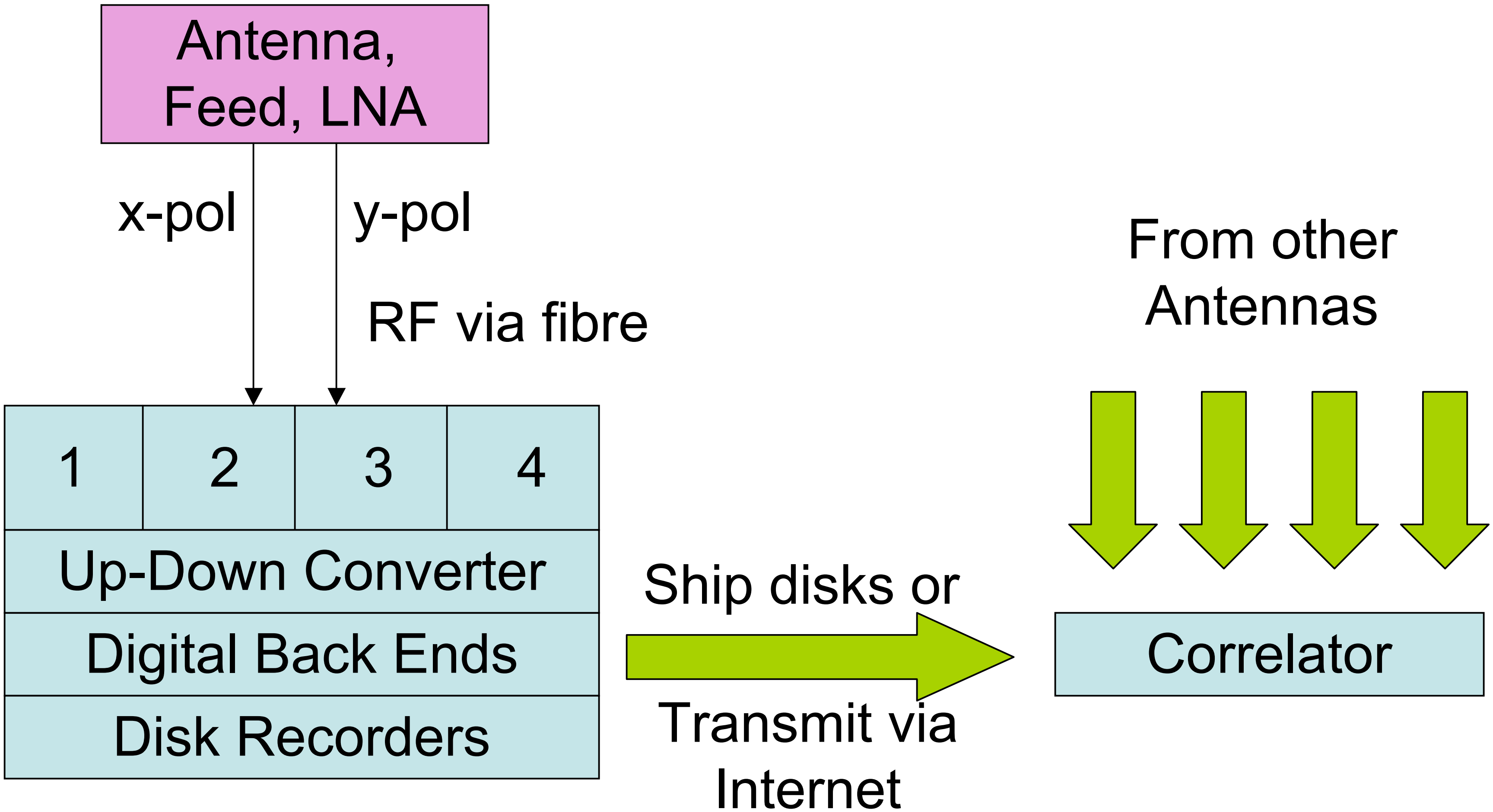


- Broadband delay is a process for resolving the VLBI RF phase at low SNR (~7 in each band)
- It involves the use of a broadband (2-15 GHz) feed to a acquire a large number (~4) of arbitrary frequency bands.
- The group delays (which are what we use today) can then be used to resolve the phase differences between bands, and these phase differences can be used to resolve the RF phase in each band.
- The RF phase delay (~3 ps) is about an order of magnitude more precise than the group delays (~30 ps)

Compenents of a VLBI2010 system



Compenents of a VLBI2010 system



Antenna Subsystem Characteristics

- As small as 12 m diameter
- Fast slew motors, e.g.
  - 6 deg/s azimuth
  - 2 deg/s elevation
- Fully automated
- Robust
- Easy to maintain

12m Antenna Installed at JPL

Composite antennas at DRAO for SKA Pathfinder

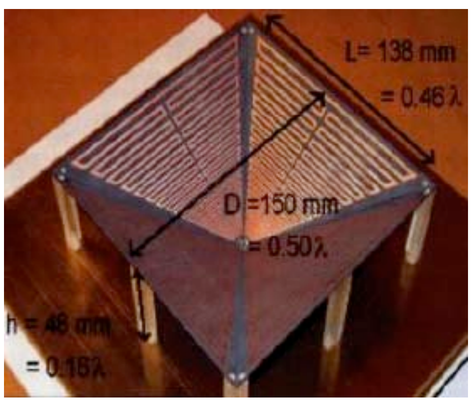
- Kevlar design
- 15% of the weight of an aluminum antenna
- Inexpensive
- Low thermal coefficient
- Stiff to gravity and the wind

New antennas for VLBI2010

- Australia (3) 12 m antennas
- New Zealand (1) 12 m antenna
- Germany, twin telescopes (pair) 12 m antennas
- Korea (1) fast slewing 22 m antenna plus (3) 21 m antennas for astronomy
- India, (1-4) 12 m antennas
- Yebes, (1) fast 40 m antenna

Broadband Feed Characteristics

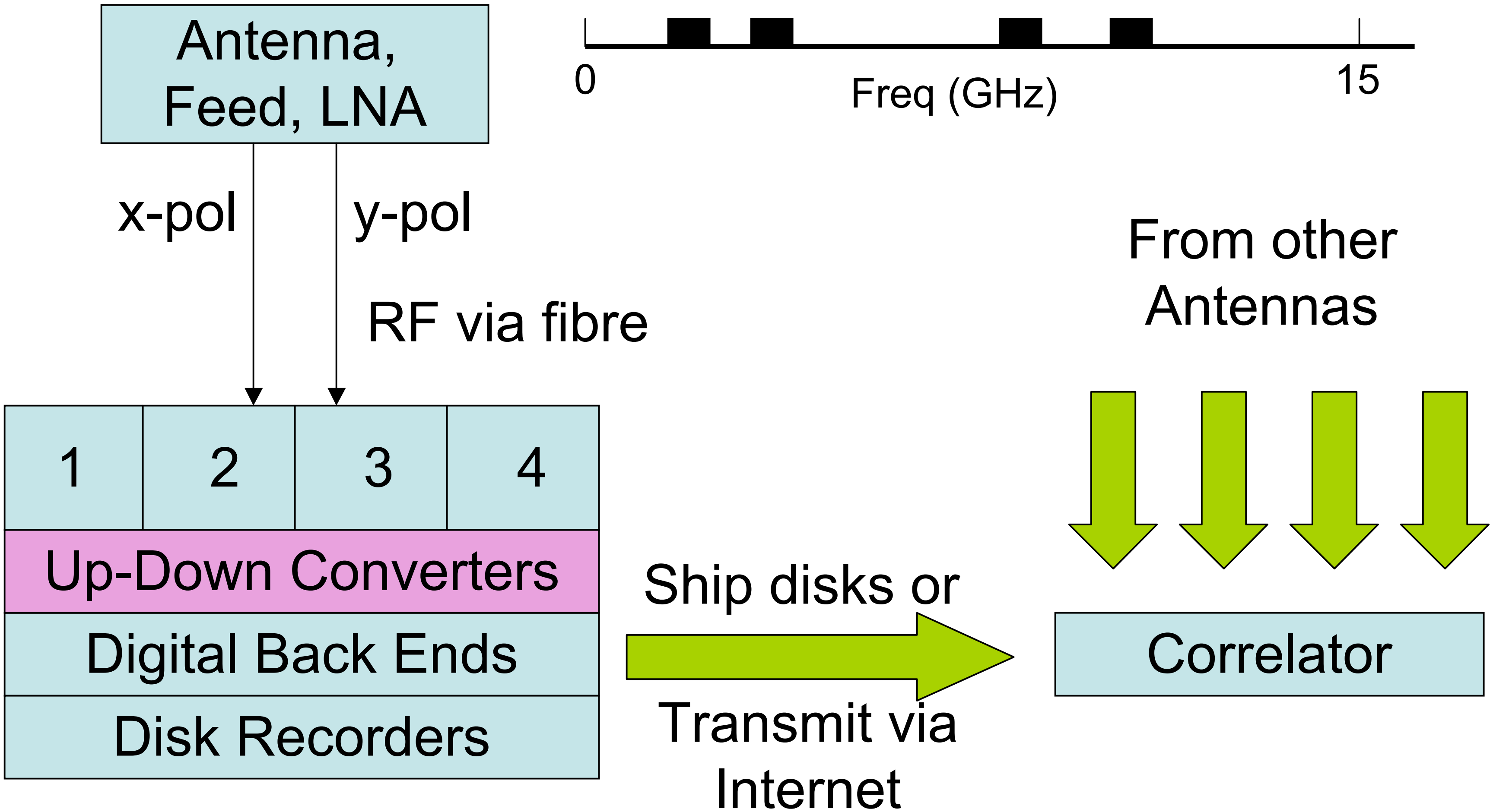
- Frequency coverage, 2-15 GHz
- Fixed phase centre with frequency
- Fixed spreading angle with frequency
- Challenges, must be cooled to minimize losses, and uses dual linear polarization



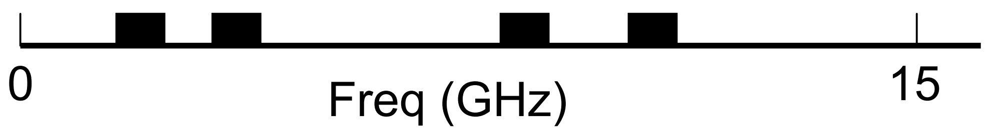
•Kildal feed, Chalmers U.
•Best but needs development

•ETS Lingren Feed
•Commercially available

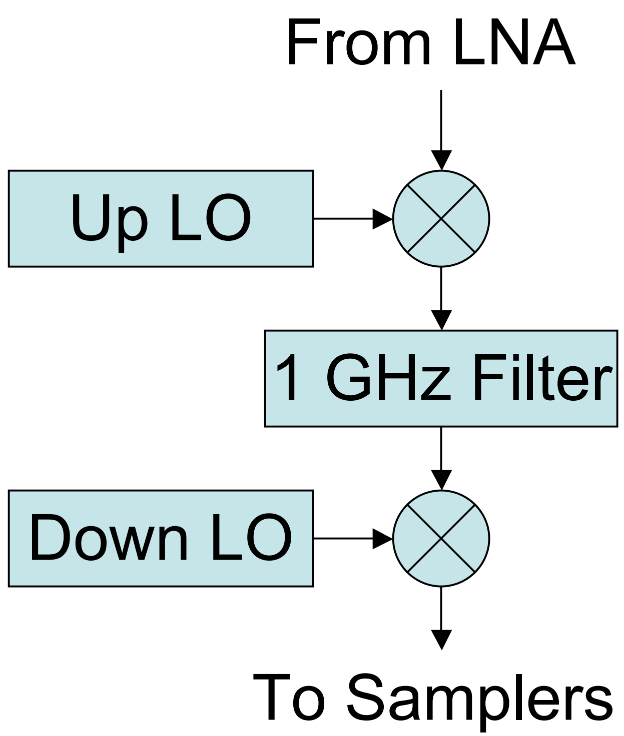
Compenents of a VLBI2010 system



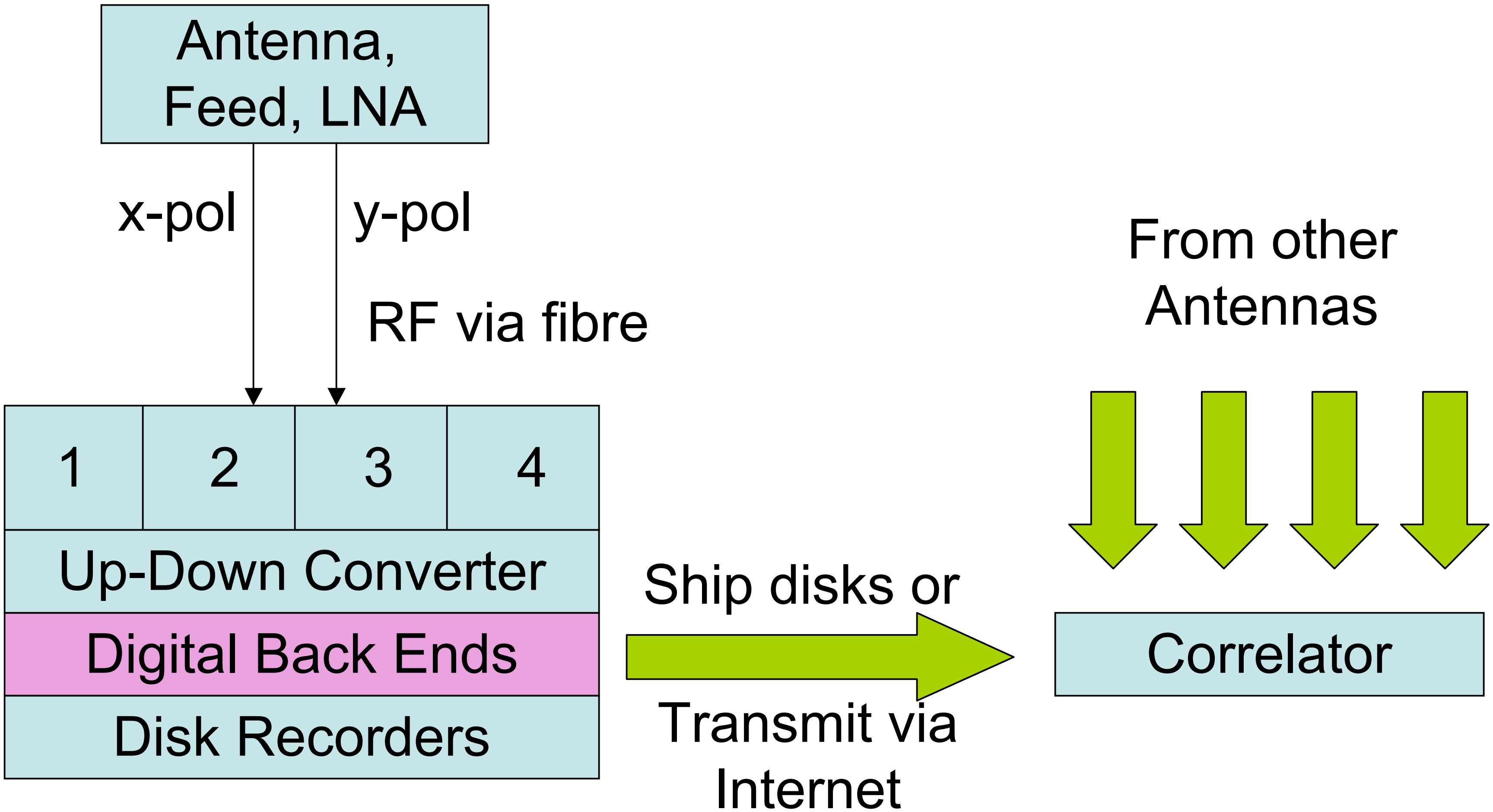
Up-Down Converter Characteristics



- Replaces S/X receiver
- Must be able to select an arbitrary frequency from the entire RF range, 2-15 GHz
- Up conversion with a programmable LO
- Filter with antialias bandwidth filter
- Down conversion with fixed LO

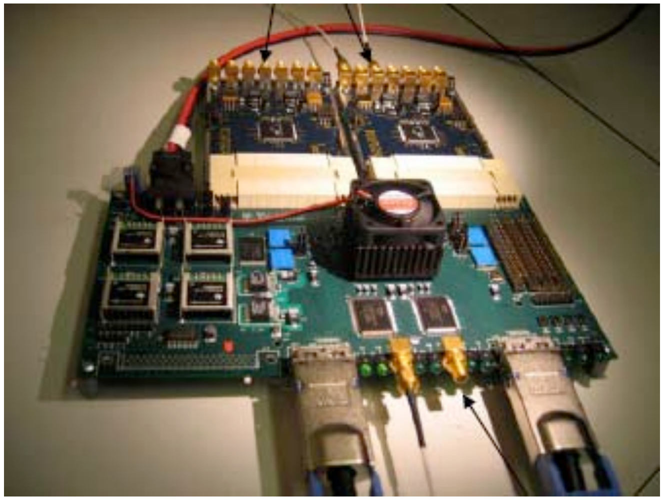


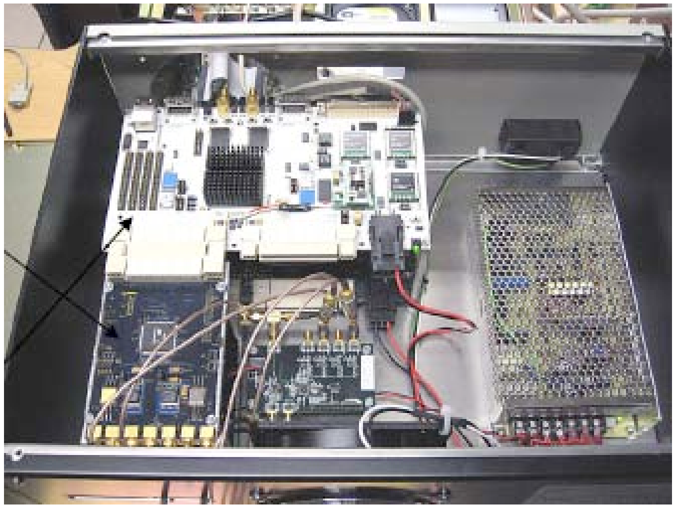
Compenents of a VLBI2010 system



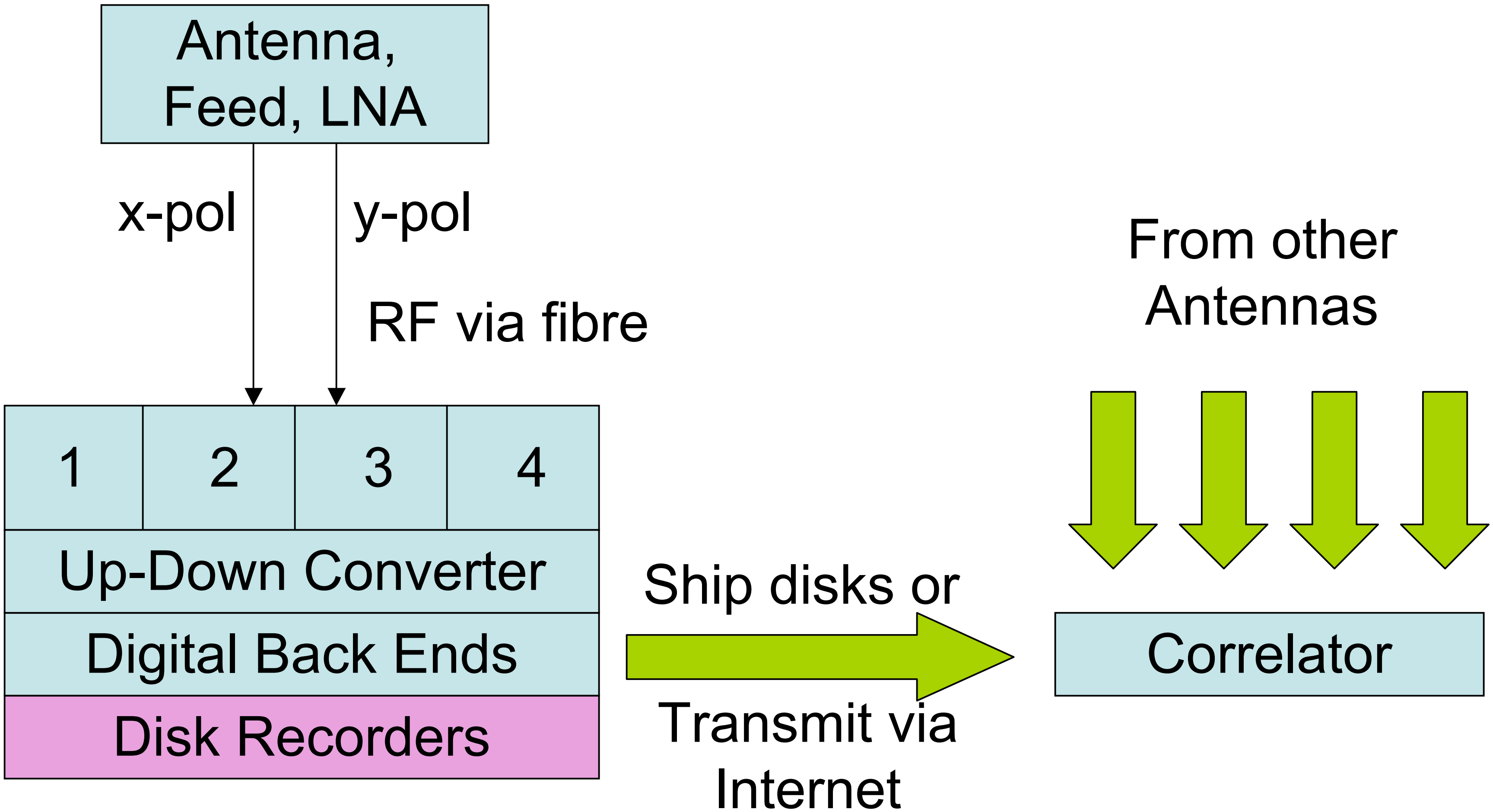
Digital Back End Characteristics

- Replaces entire Mk3 Rack
- 10% of the cost of Mk3 Rack but need 4 of them
- Separates signal into channels
- Prepares data for recording
- Includes data quality analysis
  - Phase Cal (PCAL)
  - Autocorrelation
  - Total Power radiometry
- Includes RFI protection



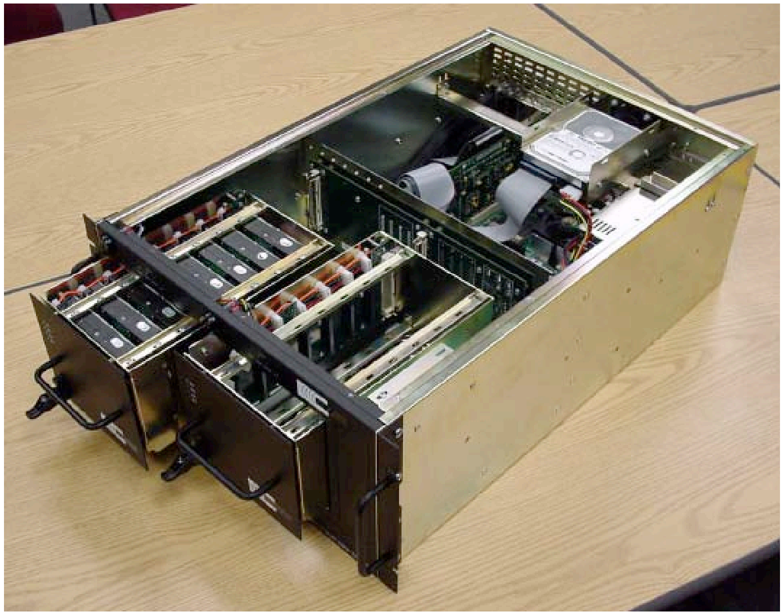


Compenents of a VLBI2010 system



Mk5 Disk Recorders

- Replaces tape recorders
- 10% of the cost of a Mk3/4 recorder but need 4 of them
- Mk5B+ handles 2 Gbps
- 1 Gbps continuous recording for 24 hrs
- Mk5C under development at 4 Gbps
- 8 Gbps required for VLBI2010
- Potentially large shipping costs for continuous observations



eVLBI (Data Transmission by Internet)

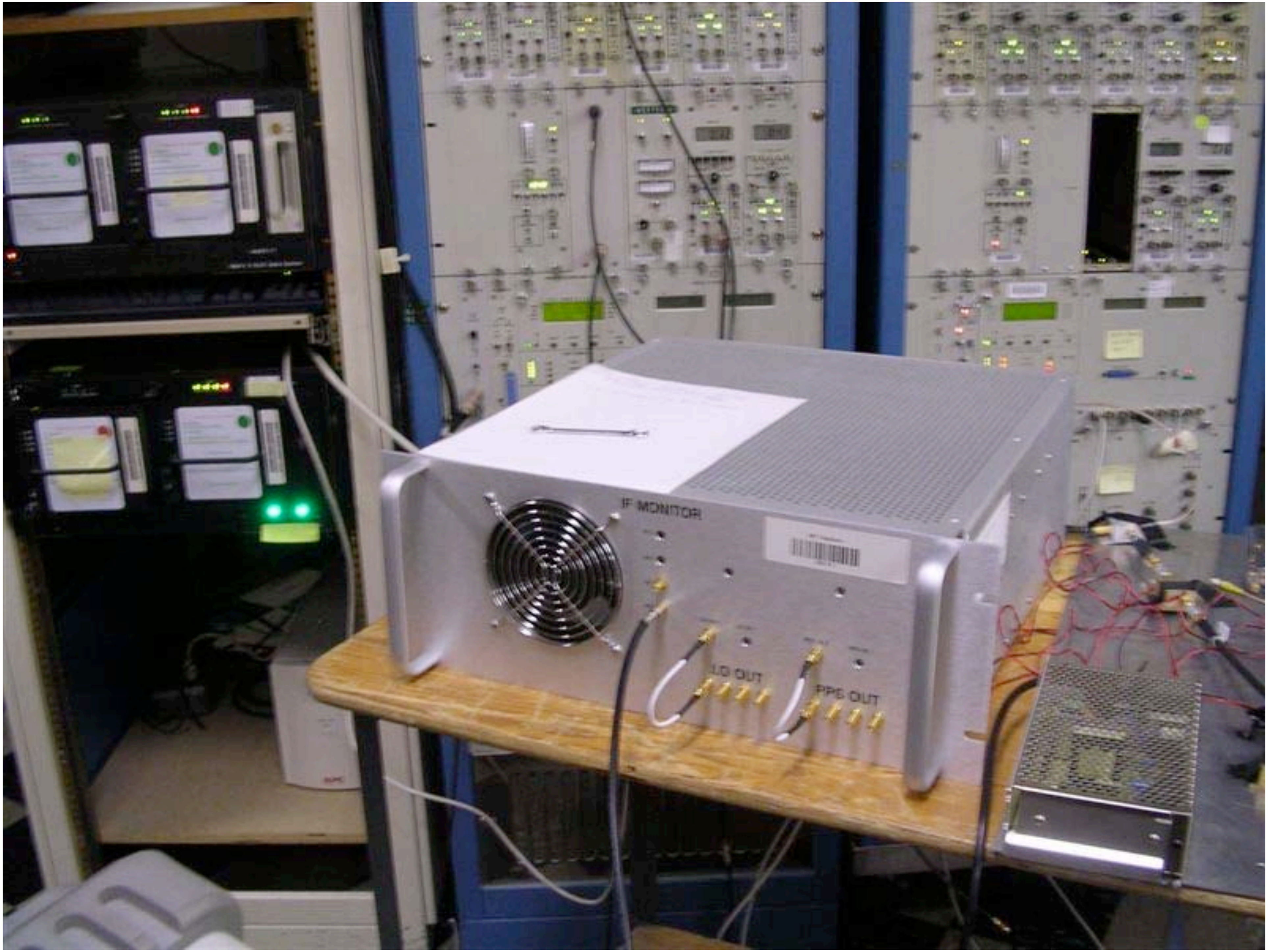
- Required for quick turnaround to initial products
- Last km to antennas solved for many sites
- Sustained data rates near 1 Gbps achieved, but require vigilant monitoring of the light pathways
- 10 gige infrastructure expected to be widely available in the mid future -> achieves 8 Gbps VLBI2010 rates
- Risks
  - Cost and availability of research networks not known and definitely not guaranteed

Many Electrical Engineering Challenges

- Broadband feed design
- Handling of linear polarized data in post-processing
- High speed sampler design
- High speed (8 Gbps) global data transmission on optical fibres
- Digital back ends
  - High speed signal processing algorithms in Field Programmable Gate Arrays (FPGA’s)
- Correlator
  - High speed signal processing algorithms in FPGA’s
- Handling Radio Frequency Interference (RFI)

NASA Proof of Concept test

- Test the broadband delay concept
- 20+ m antenna at Westford, MA
- 5 m antenna at GGAO, Wash, DC
- Single band tests underway
- 4-band test expected early in new year

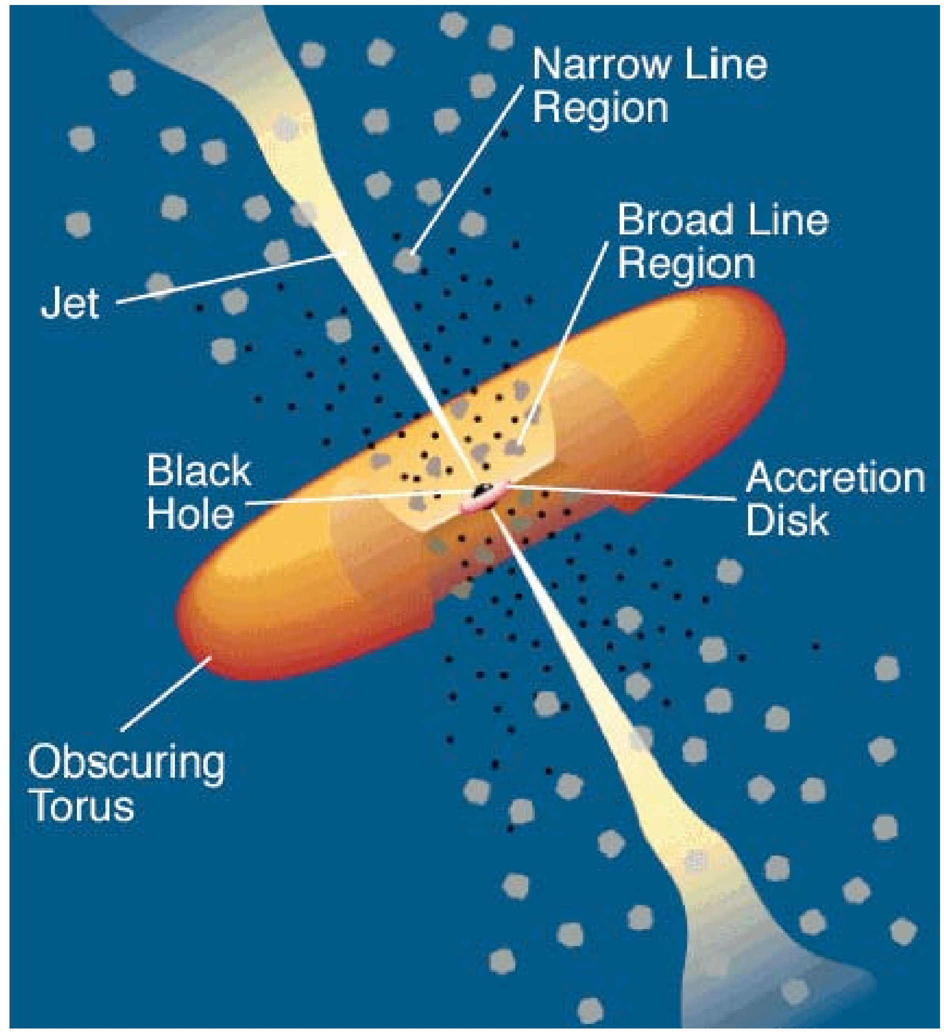

IF MONITOR
LO OUT
PPS OUT

Risk Factors

- Availability of the Kildal feed
- Ability to handle linear polarized feeds
- Cost and availability of research networks for eVLBI
- Shipping costs -> will Moore's Law continue to hold
- Ability to control systematic effects
  - Geological instability, antenna deformations, uncalibrated instrumental drifts
- Phase wander across the band due to source structure
  - Problems with broadband delay and systematic delay error

Source Jet Model

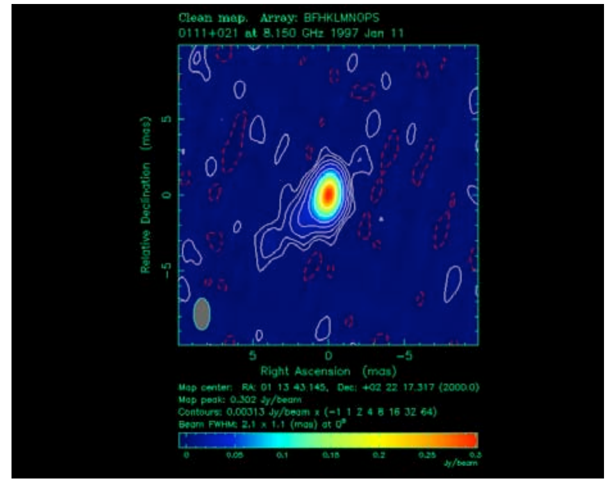
- Positionally stable point is the dense Black hole at the core
- Only the jets are visible to VLBI
- Unfortunately for geodesy, the jets are dynamic.

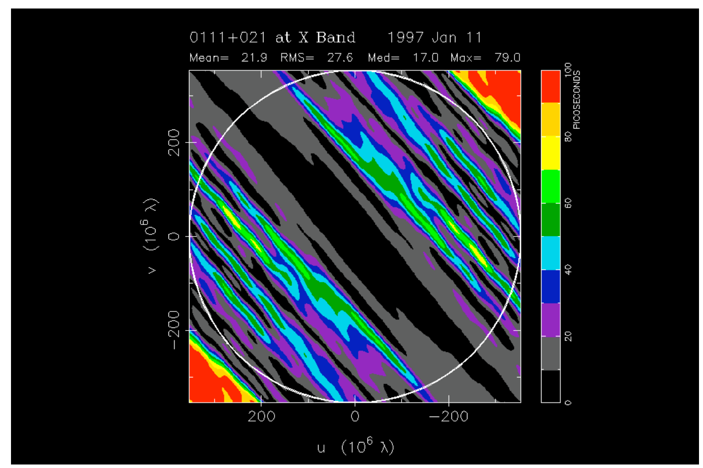


Source Structure Errors

- At the level of precision of VLBI2010 sources can no longer be considered points
- Better lists of sources with low structure have been generated.
- Perhaps source structure corrections will be possible

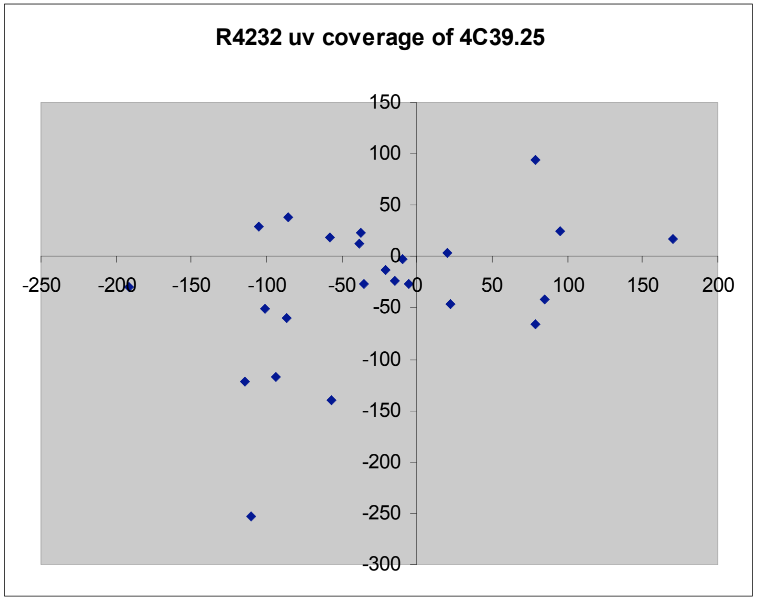
- Source with structure index 3
- 30% of ICRF has this index

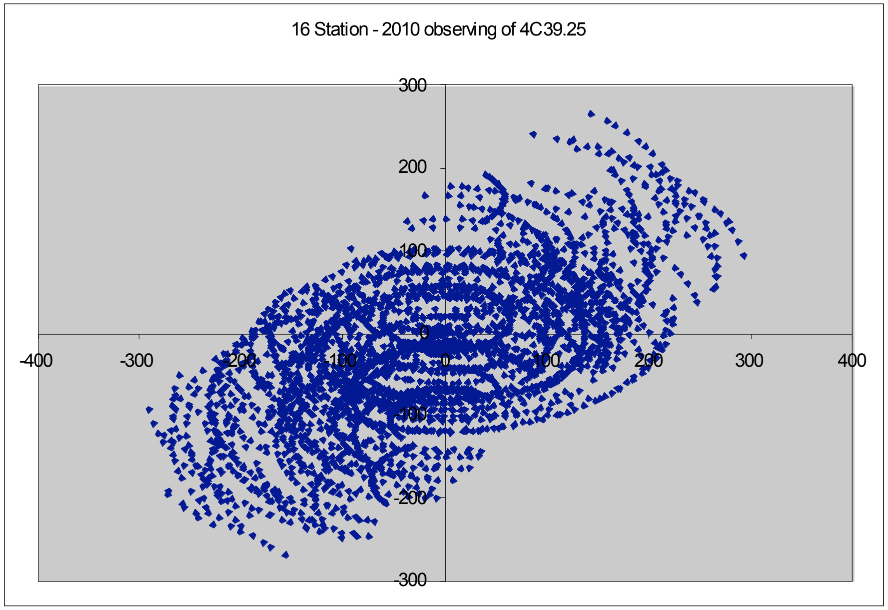


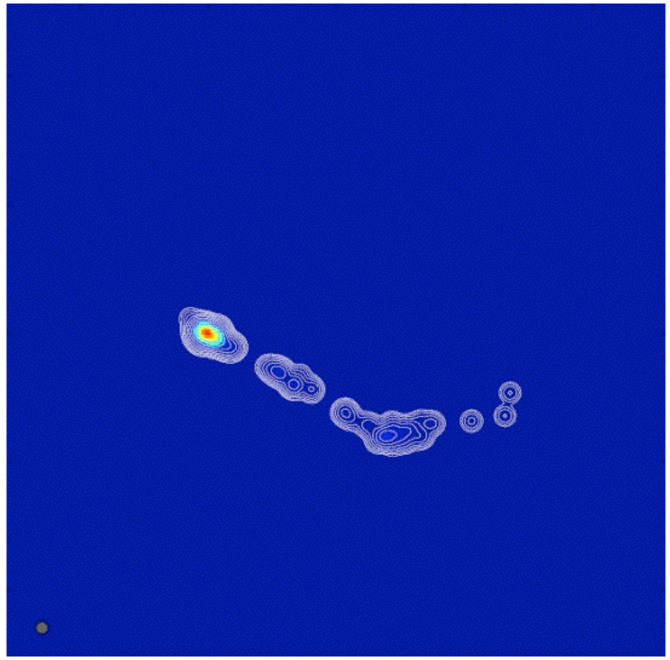


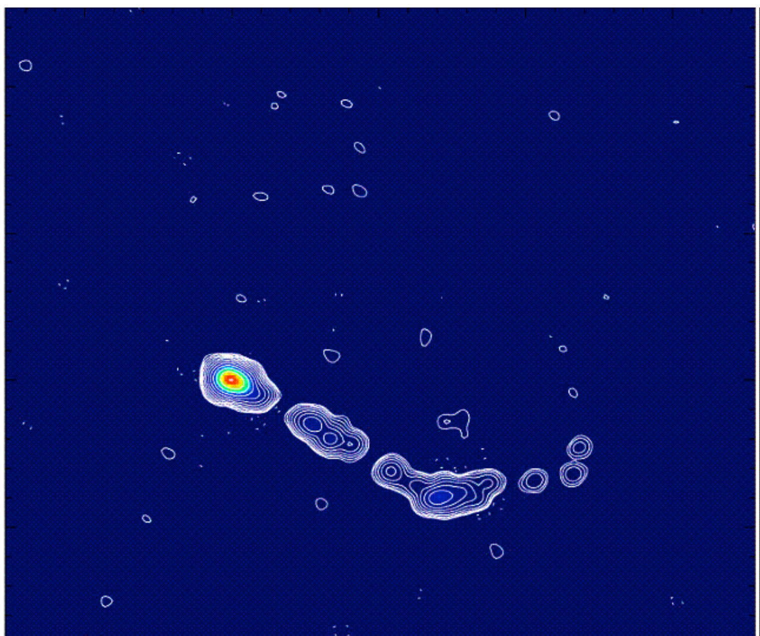
Generate Structure Corrections Directly from VLBI Data

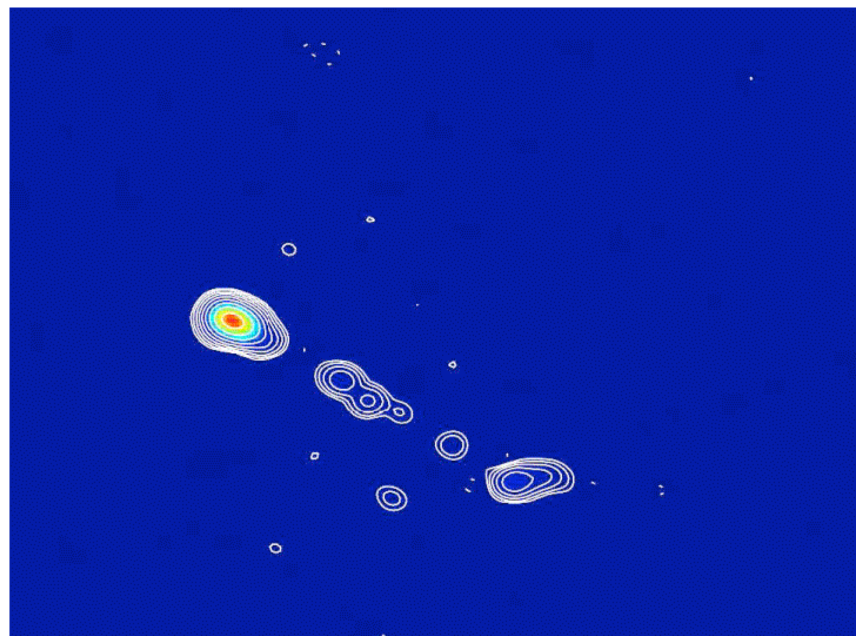
- With old schedules uv coverage, i.e. the number of different geometries for a source, was not enough for good mapping
- With the VLBI2010 improvement to faster slewing antennas, higher data rates and larger networks quality source maps will be possible enabling effect source structure corrections









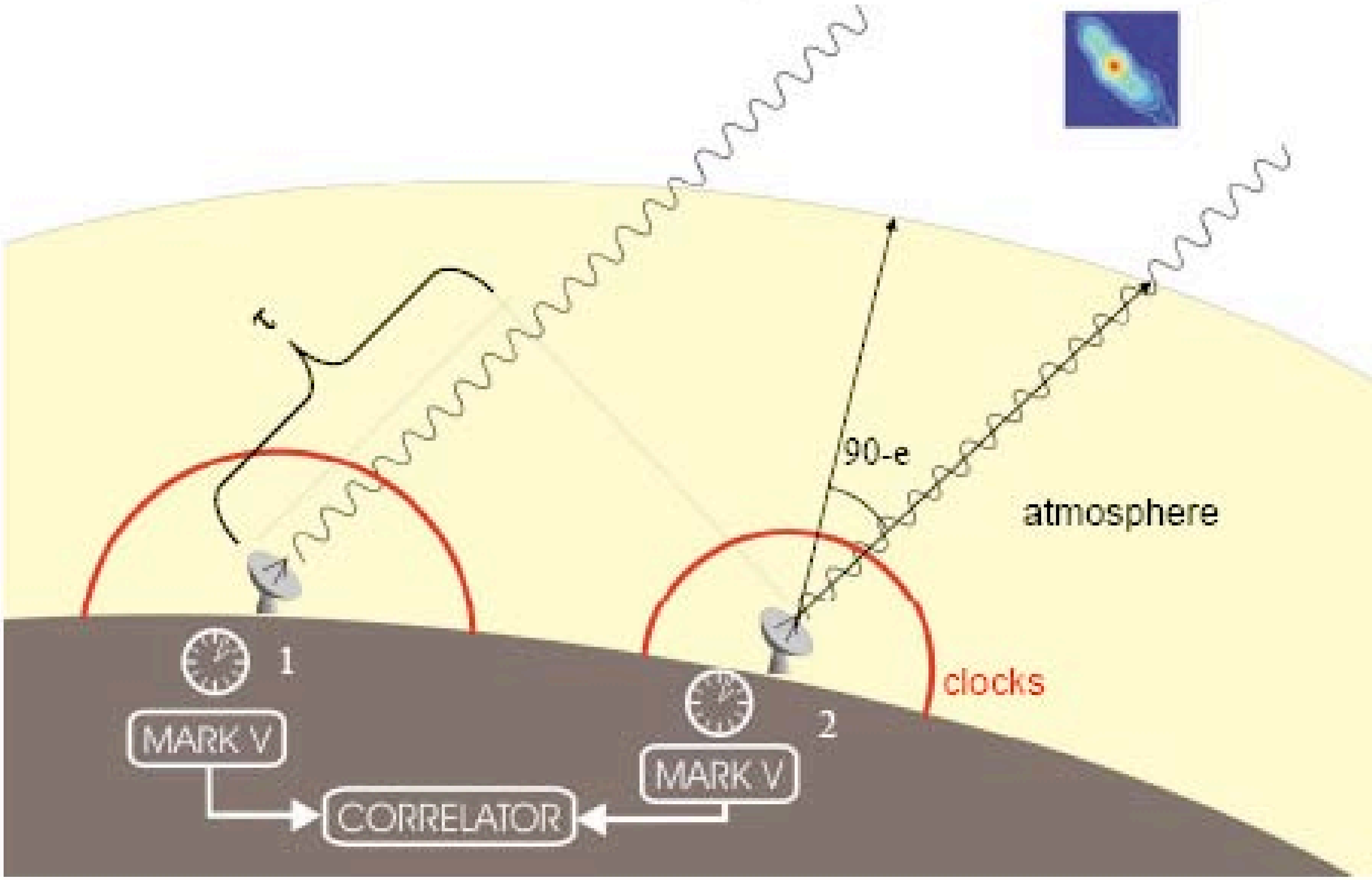


Monte Carlo Simulations: What are they?

- A Monte Carlo simulator involves the generation of fake data using realistic models
- The fake data is then analysed as if it were real data
- Several sets of data are generated and analysed and their outputs are studied statistically
- The advantages of Monte Carlo simulators are:
  - We know the input values for later comparison
  - No need to know complex input correlations
- However, Monte Carlo simulators are only as realistic as the models used for the fake data

Monte Carlo simulation

wzd & clocks are stochastic processes → simulate for station 1 and 2



Phenomena to study with Monte Carlo Simulations

- Impact of more observations per session
- Impact of higher precision observables
- Impact of different clock performances
- Impact of network size
- Impact of analysis strategies, e.g.
  - Including input data correlations into the analysis
  - Impact of shorter atmosphere intervals
  - Impact of adding spatial structure to atmosphere
- Impact of scheduling strategies
- Comparison and validation of analysis packages
- Comparison of Kalman Filter and Least Squares

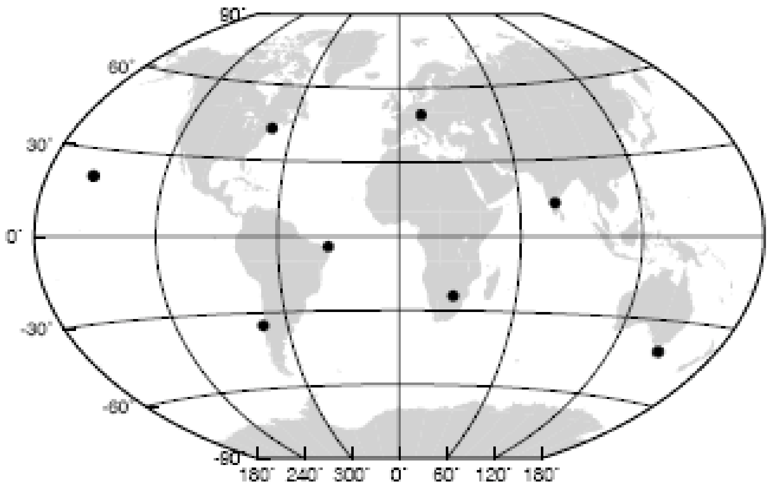
Noise Models for the Monte Carlo Simulators

- Atmosphere: turbulent moving screen as described by Truehaft and Lanyi (1987) and implemented by Tobias Nilsson.
  - Latitude dependence of structure constant
  - Winds from numerical weather models
- Clock: random walk plus integrated random walk
  - Constrained by single Alan Variance value, e.g. 2.e-15 @ 50 min
- Measurement error: Gaussian random variable

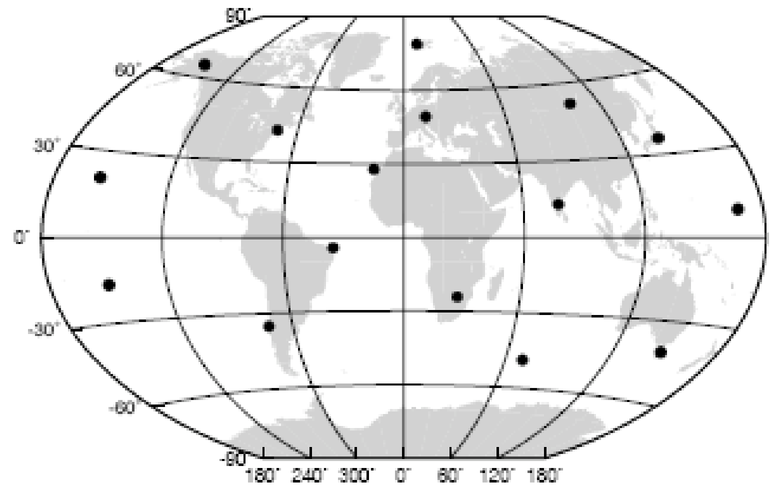
Collocated VLBI/SLR Simulation Networks

(Close to VLBI2010 Simulation Networks)

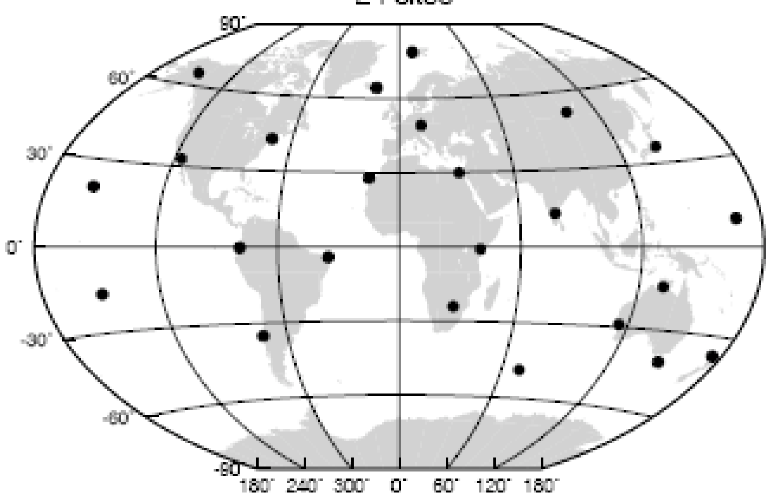
8 sites



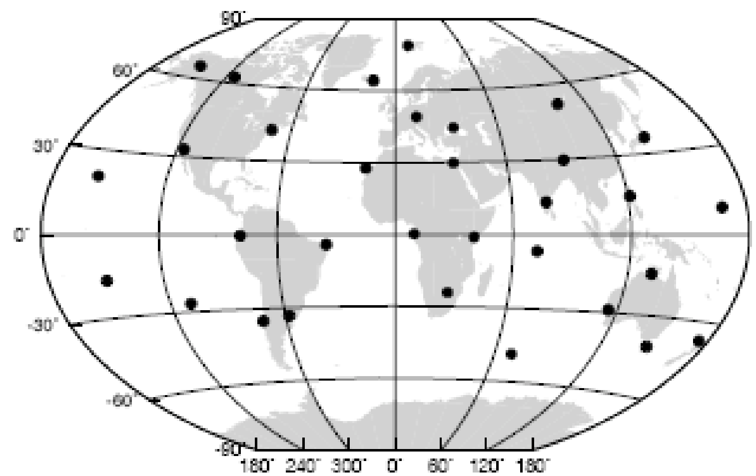
16 sites



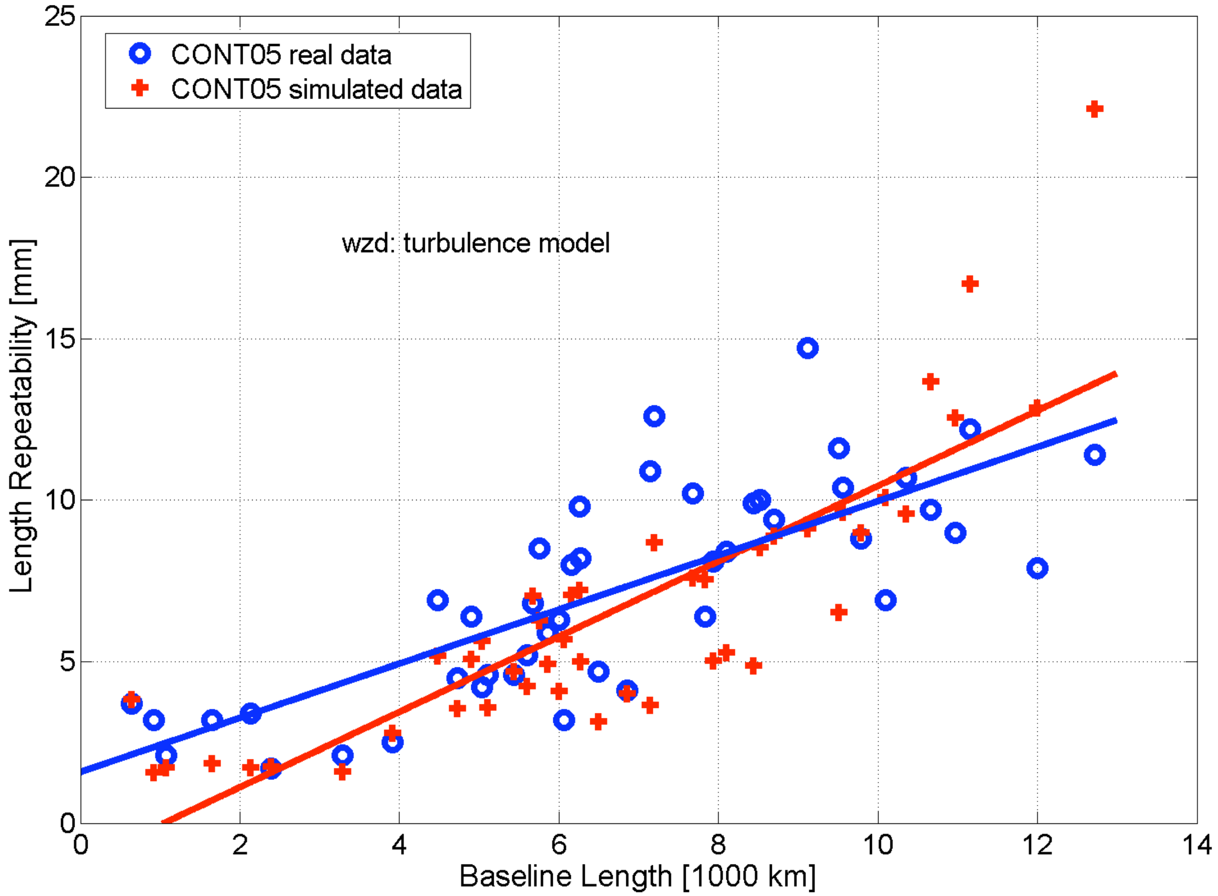
24 sites



32 sites

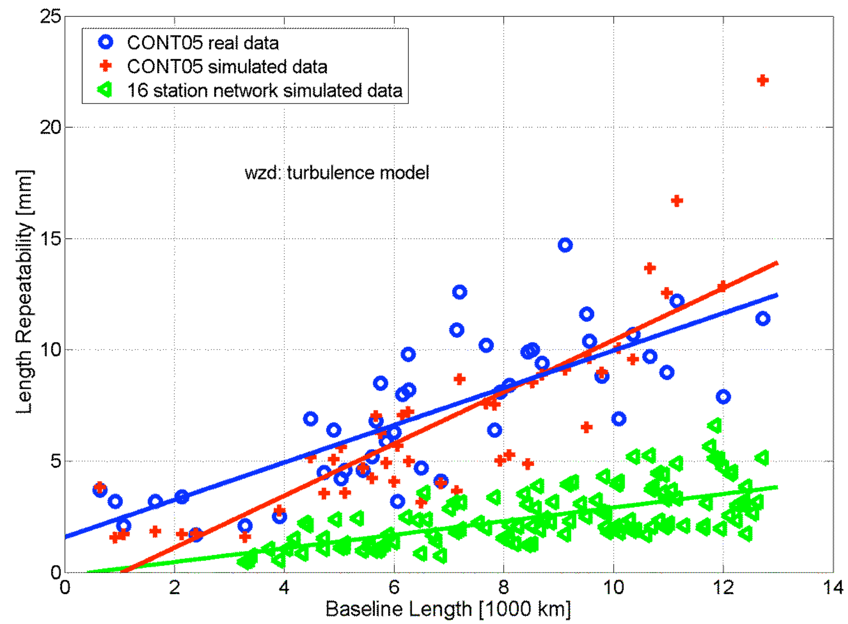


CONT05 Simulation Comparison

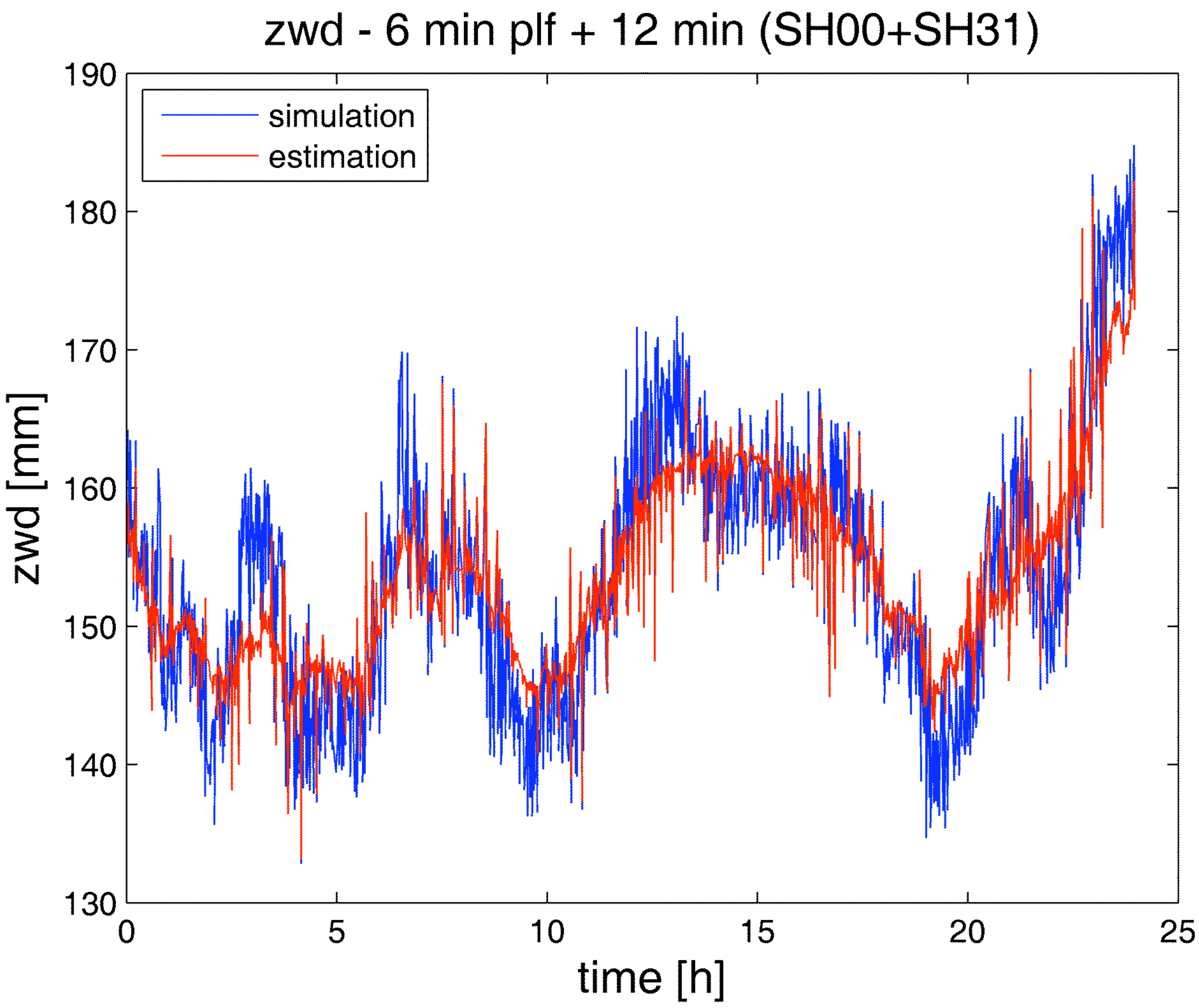


CONT05 Simulations compared with VLBI2010 Simulation

- VLBI2010 improvements include:
  - More observations per day
  - More precise observations
  - Larger networks



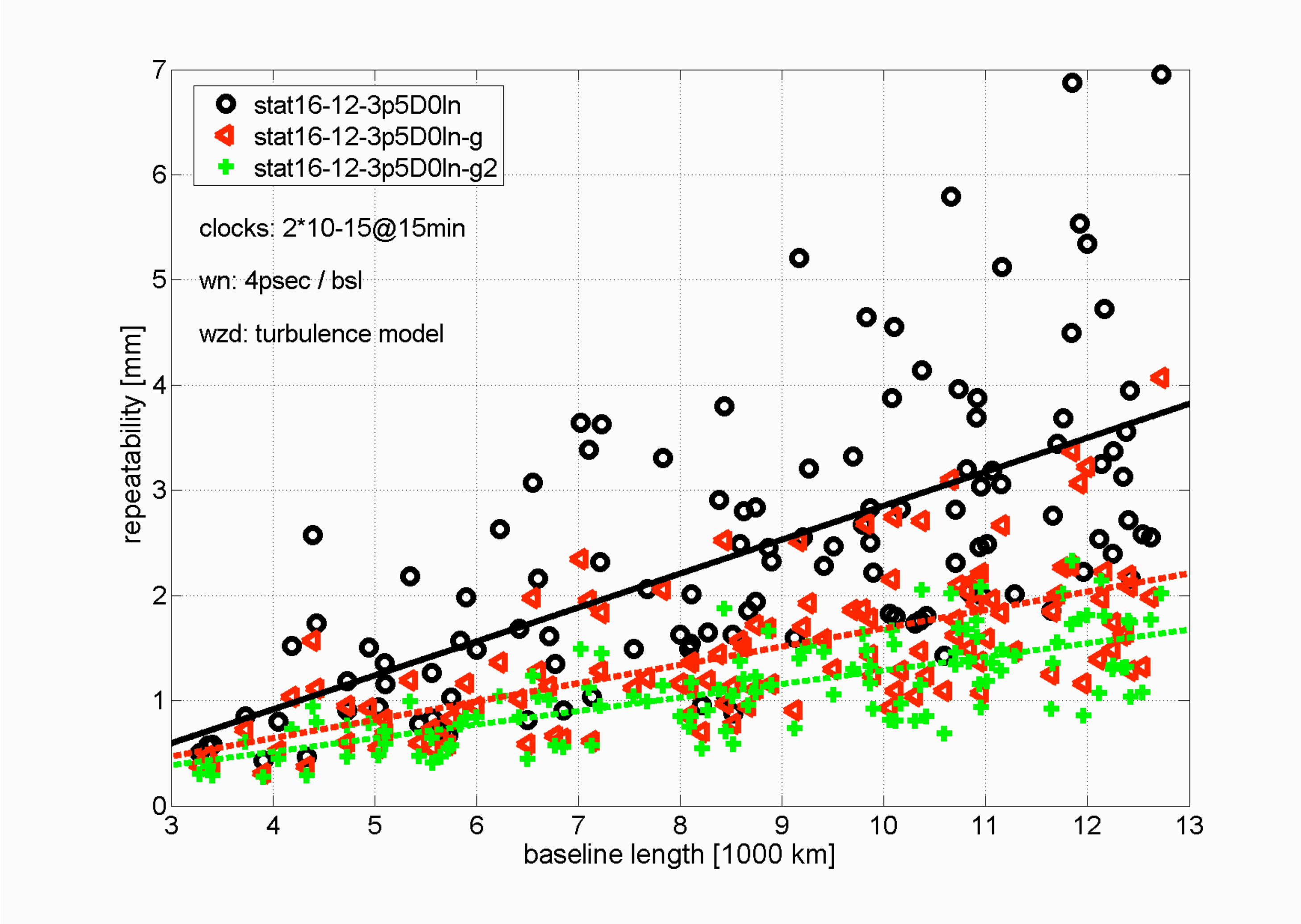
Atmosphere Estimation Errors

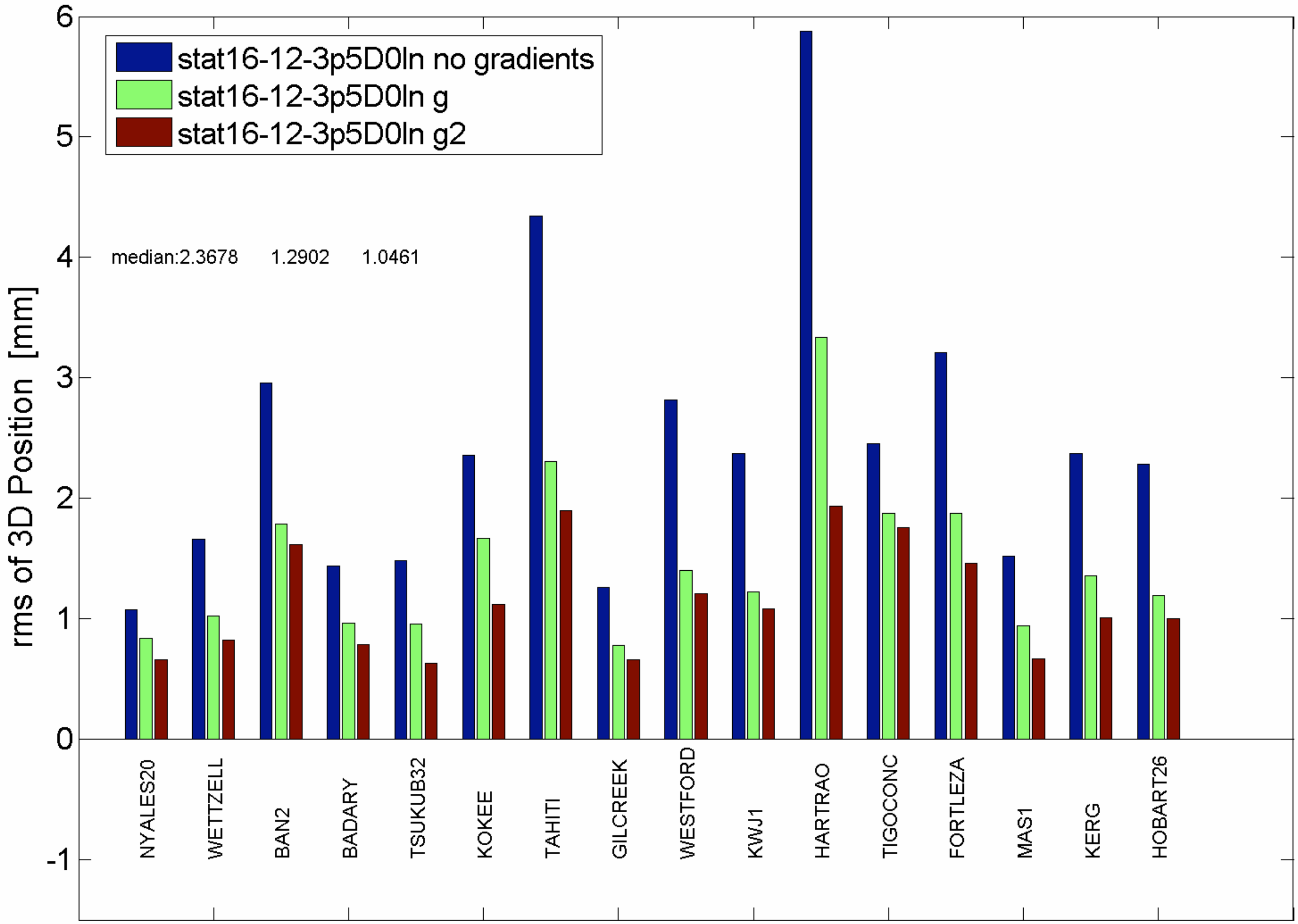


Other Estimation Strategies

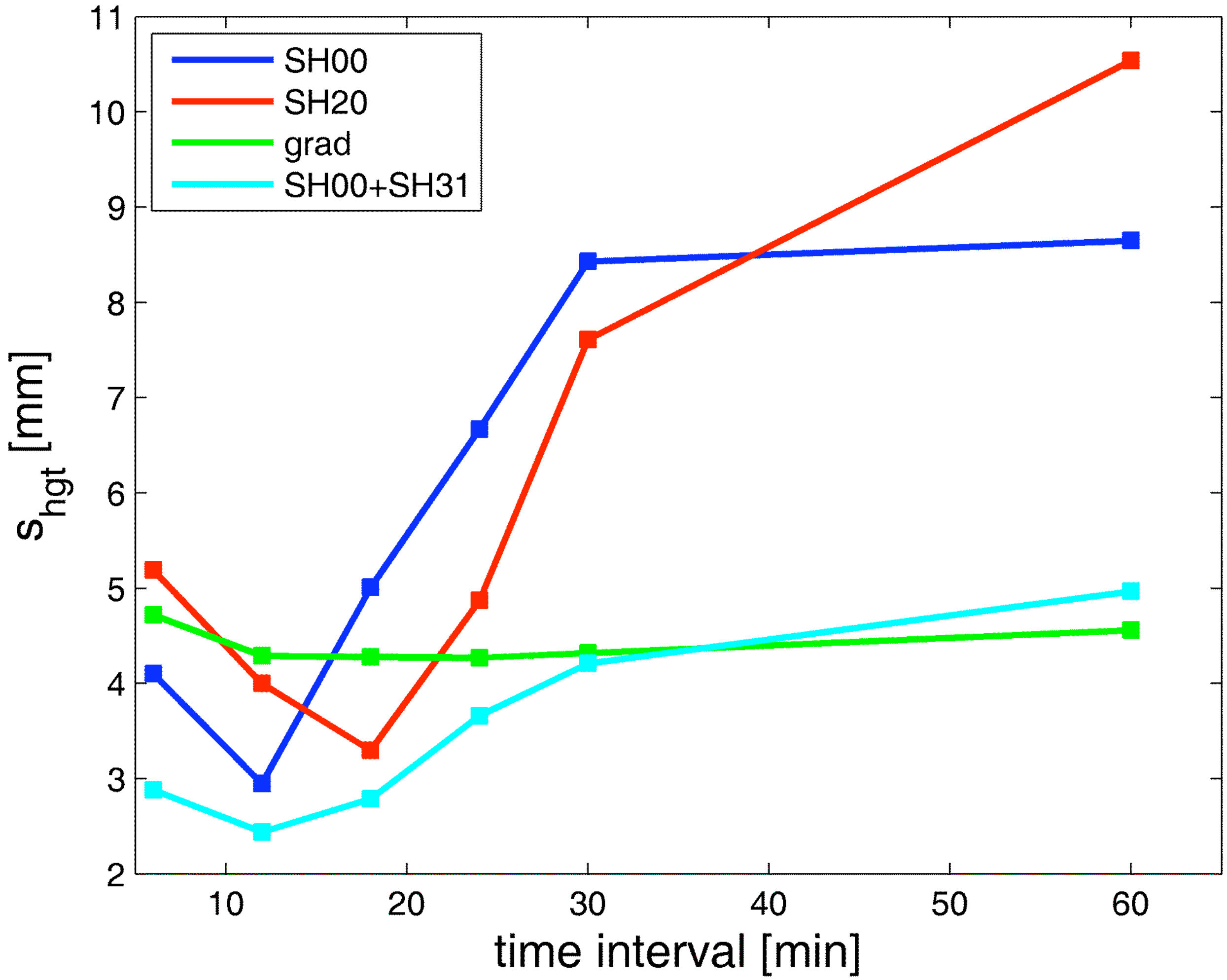
- Include elevation angle dependence
- Include elevation angle cut-off
- Include input data correlations, e.g.
  - Between baselines
  - Lanyi Treuhaft atmosphere correlations
- Include gradients
- Estimate atmosphere and gradient more frequently
- Loosen constraints on atmosphere and gradient estimates
- Experiment with spherical harmonics

Experimentation with Rapid Gradients




stat16-12-3p5D0ln no gradients
stat16-12-3p5D0ln g
stat16-12-3p5D0ln g2
median:2.3678 1.2902 1.0461
rms of 3D Position [mm]
6
5
4
3
2
1
0
-1
NYALES20
WETTZELL
BAN2
BADARY
TSUKUB32
KOKEE
TAHITI
GILCREEK
WESTFORD
KWJ1
HARTRAO
TIGOCONC
FORTLEZA
MAS1
KERG
HOBART26

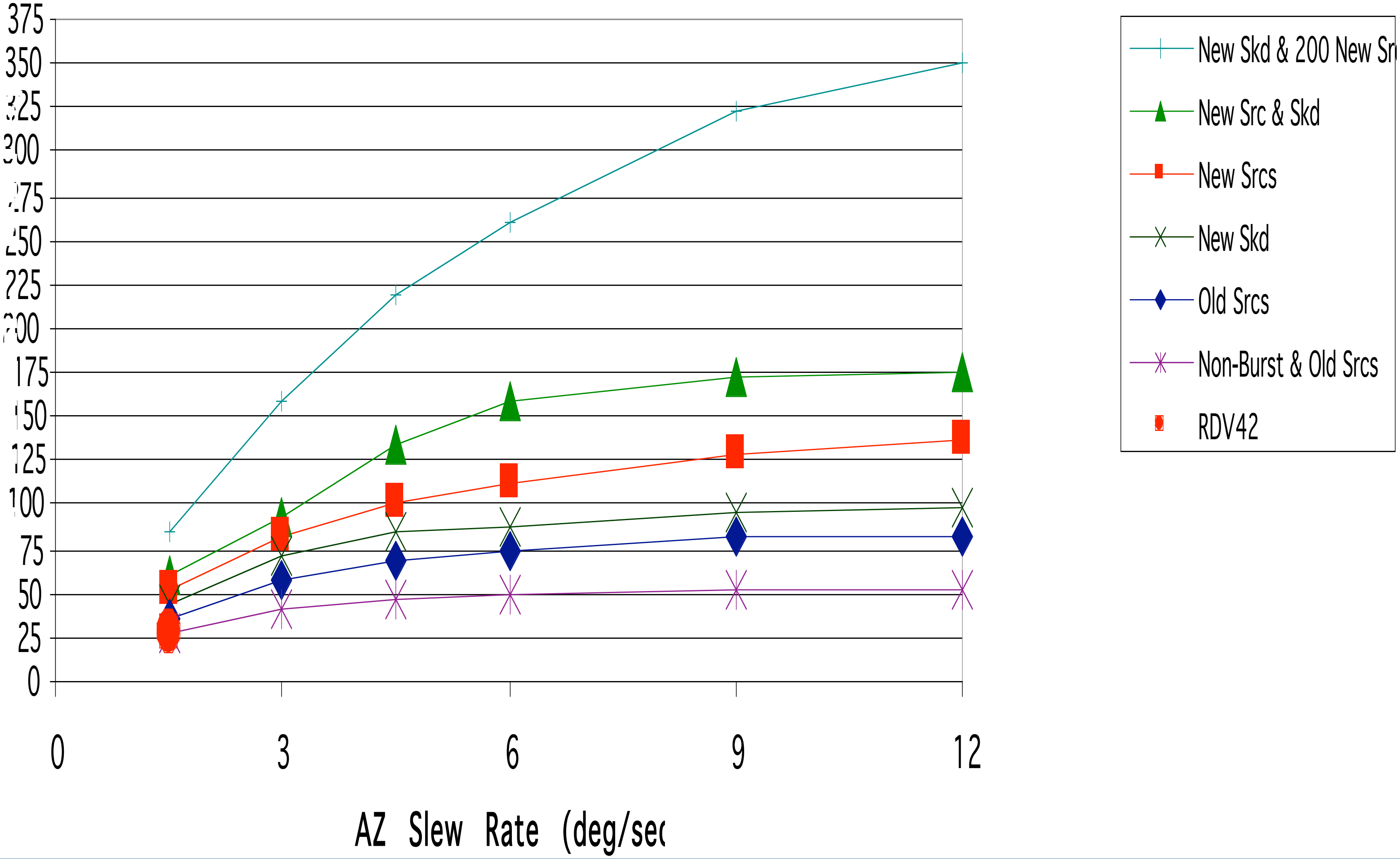
Spherical Harmonic Model



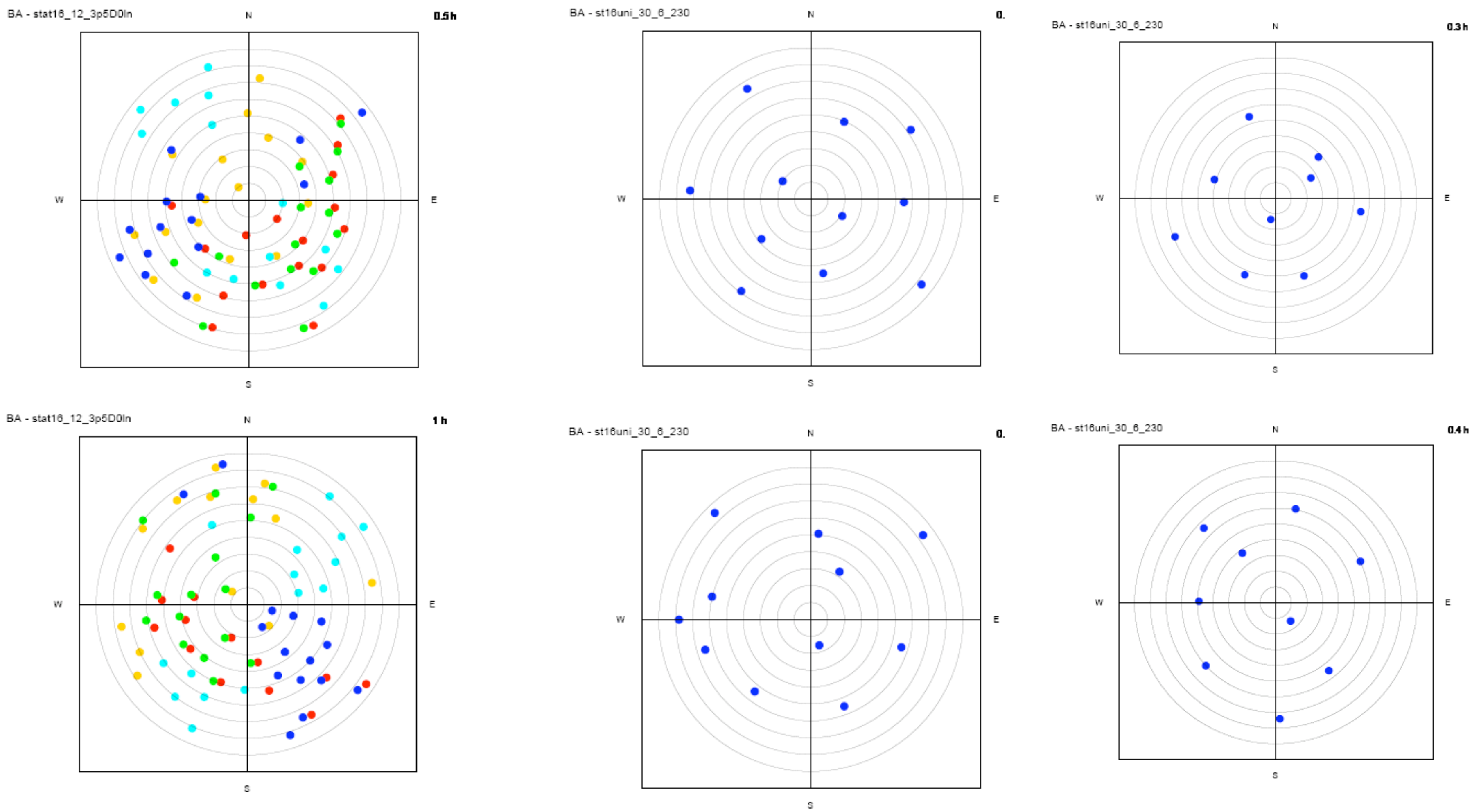
stat16_12_3p5D0
HartRAO

SH00
SH20
gradients
SH00+SH31

Schedules with Large Numbers of Observations per Day



Uniform sky Schedules



Thank you for your interest in the Future of VLBI!

- Questions?