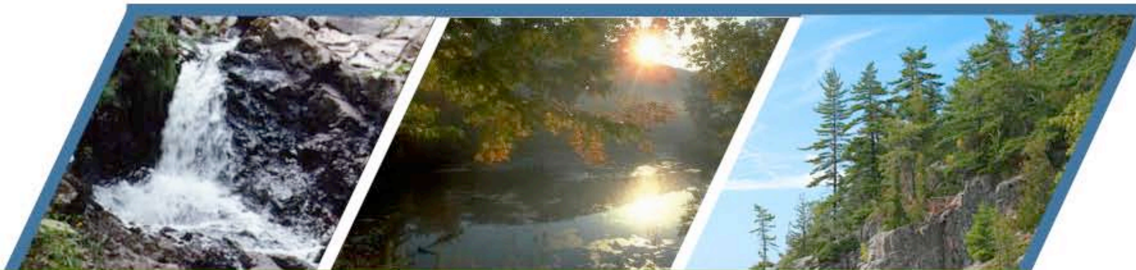
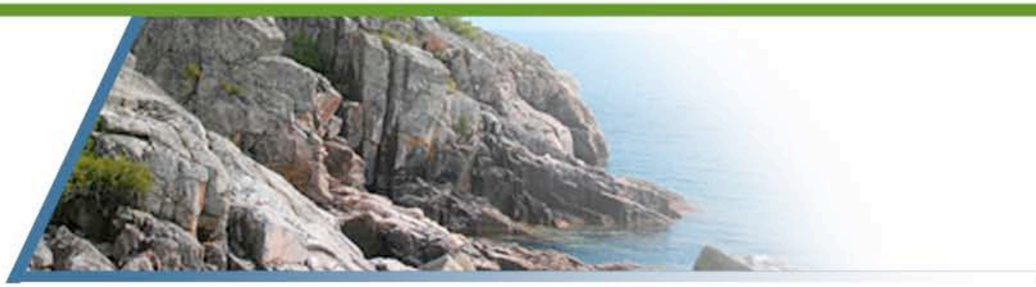


Using Quasars to Measure the Earth

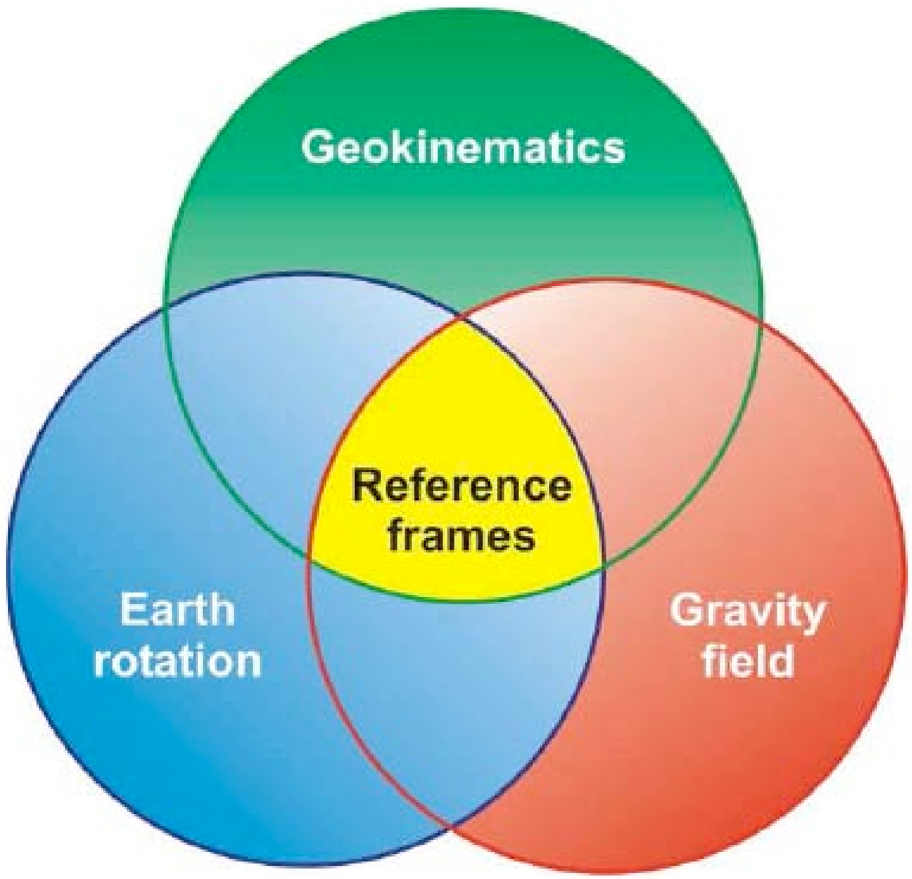
Bill Petrachenko, Nov 5, 2007, University of New Brunswick



Natural Resources Canada Ressources naturelles Canada

Canada

The Three Pillars of Geodesy



What is a geodetic reference system?

- It is an idea, a set of rules used to assign coordinates to points
- In general, it includes:
  - Location of an origin
  - Orientation of axes
  - Definition of scale
- In practice, it also requires:
  - Definition of physical constants
  - Definition of physical models
- A simple example is a 2-d Cartesian system.

What is a geodetic reference frame?

- It is a realization, in other words, it is the way we gain *access* to a reference *system*
- In practice, it is the coordinates of a set of points determined from specific observations analyzed with appropriate models.

Historical Progression

- Historically, reference systems progressed from:
  - local -> regional -> national -> continental
- Since classical surveying requires line of sight measurements the continents couldn’t be connected
- As a result, each continent eventually had a separate reference frame with different:
  - Ellipticity, origin, and orientation
- The oceans could only be bridged using less precise positional astronomy

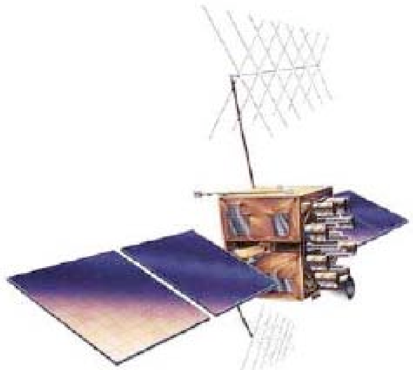
Launch of Sputnik I, the Dawn of the Space Age

- On Oct 4 1957, the USSR launched the first ever man-made object into orbit, Sputnik I.
- Although not intended for geodesy, the new orbital capability allowed the continents to be connected through the mutual observation of satellites
- This heralded the era of *space geodesy,* and as a result, globally consistent geodetic reference systems could now be envisioned!
- Geos-A was launched in 1965.

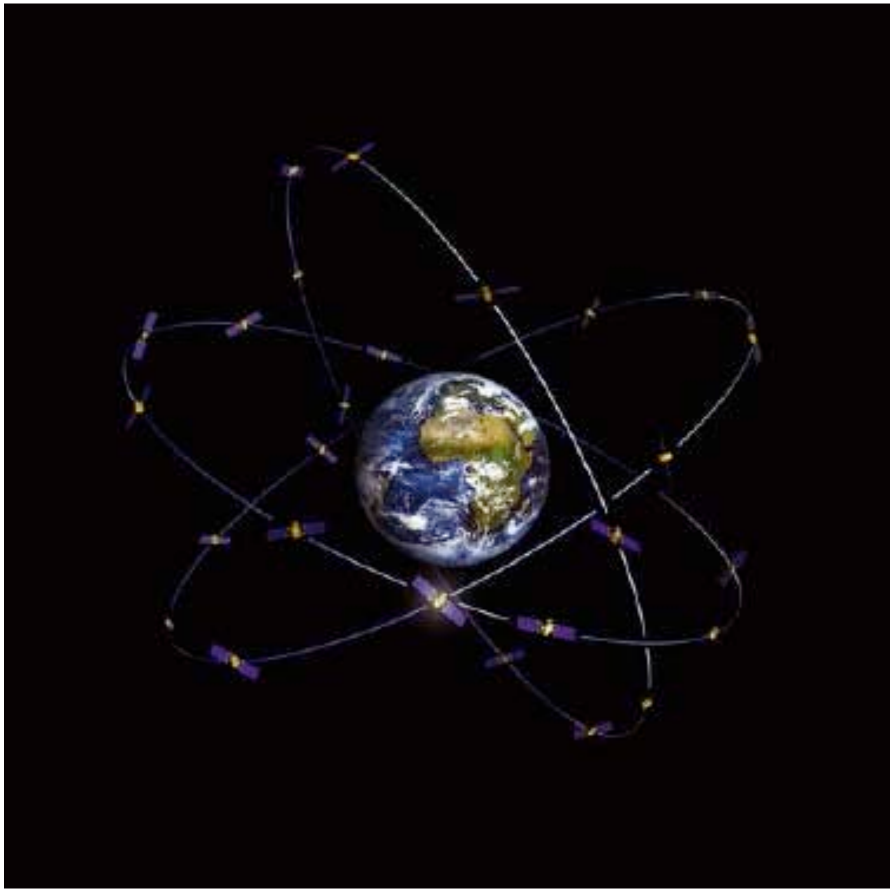
Space Geodesy Techniques

- The four main space geodesy measurement techniques (not including those related to gravity) are:
  - Global Navigation Satellite Systems (GNSS)
  - Satellite and Lunar Laser Ranging (SLR and LLR)
  - Very Long Baseline Radio Interferometry (VLBI)
  - DORIS

Microwave Satellite Systems (GNSS)



- TRANET
- GPS
- GLONASS
- GALILEO
- DORIS

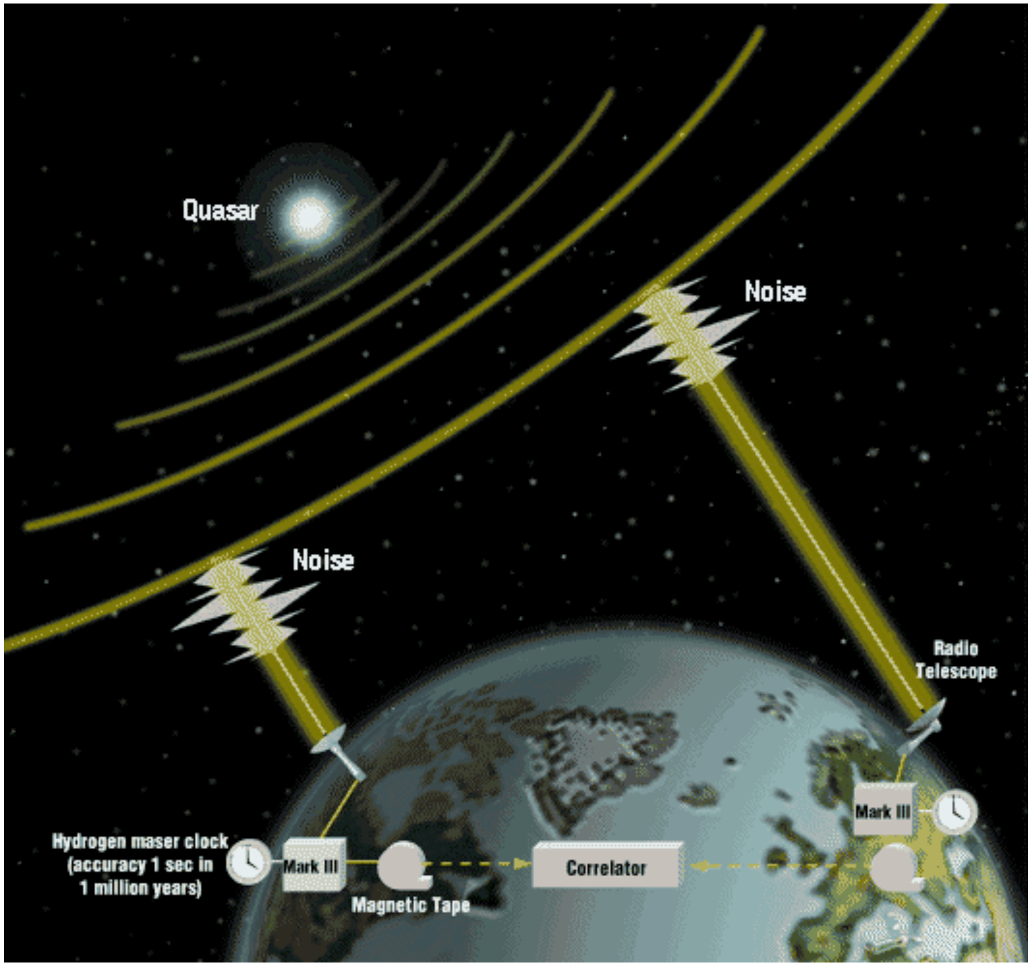


Laser Ranging

- Satellite Laser Ranging (1976)
- Lunar Laser Ranging (1969)

Very Long Baseline Interferometry (VLBI)

- Invented by Canadian Astronomers in 1967
- Required the invention of:
  - Atomic clocks
  - Broadband tape recorders.



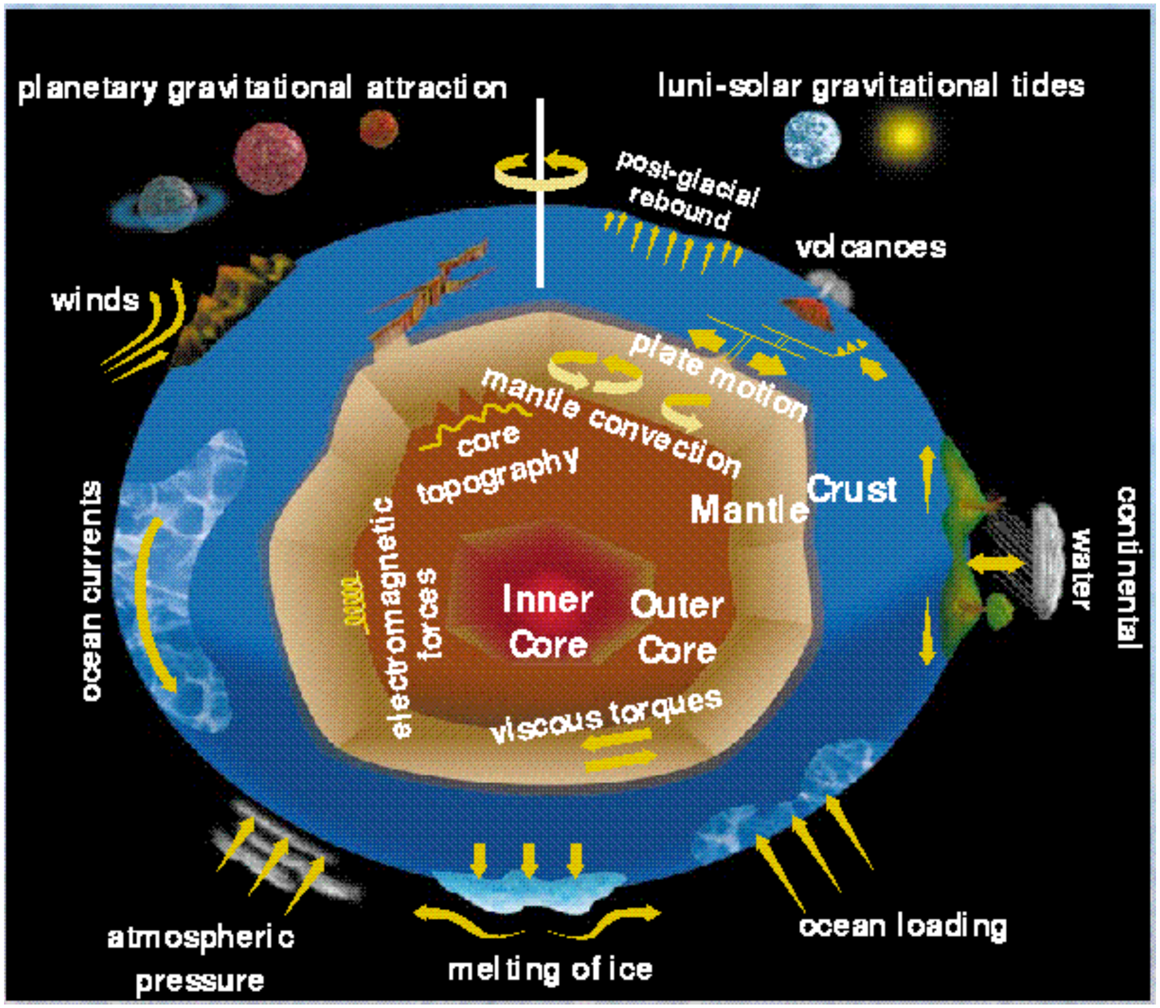
Reference Frames

- On the global level, space geodesy (not including gravity) has three main components:
  - International Terrestrial Reference Frame (ITRF)
  - International Celestial Reference Frame (ICRF)
  - Earth Orientation Parameters (EOP)

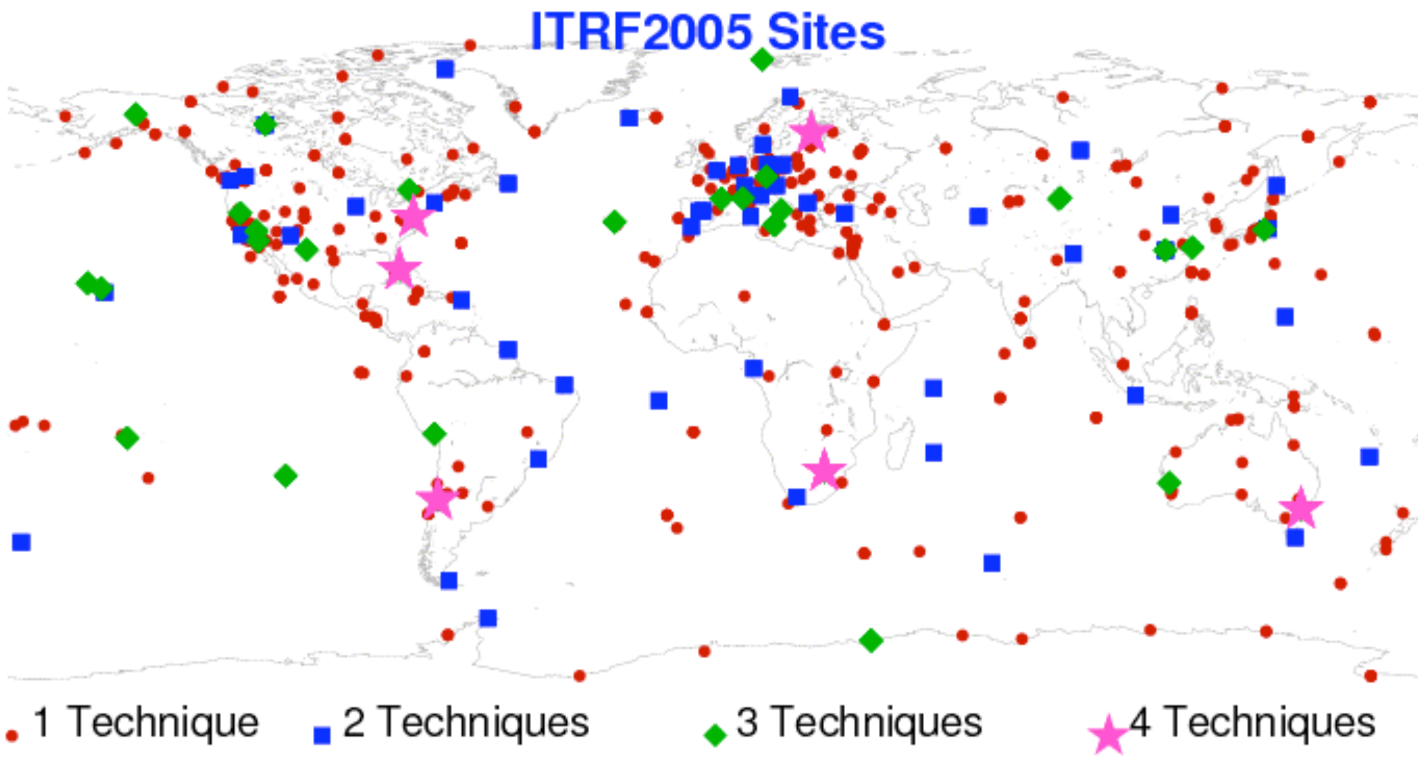
International Terrestrial Reference System (ITRS)

- Origin -> Centre of mass of the whole earth
  - Determined by satellite systems only, mainly SLR
- Orientation -> Equatorial system, given by the BIH orientation at 1984.0
- Scale -> Unit of length, metres
  - Determined by VLBI, SLR?
- Time evolution
  - No-net-rotation
  - Geophysical models

Restless Planet



International Terrestrial Reference *Frame* (ITRF) – coordinates and rates



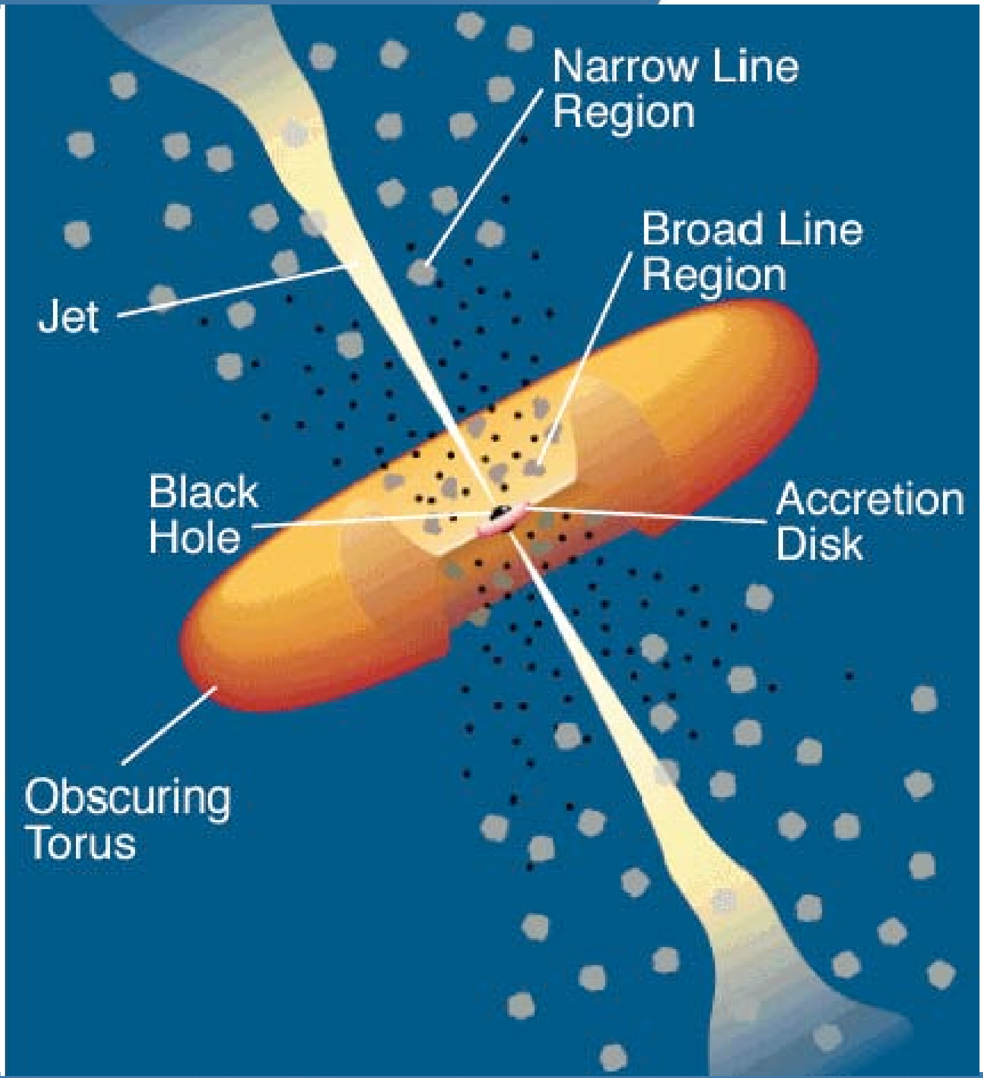
Precision of best sites: 1-3 mm position; 0.1-0.3 mm/yr
Most recent ITRF produced in 2005

International Celestial Reference System (ICRS)

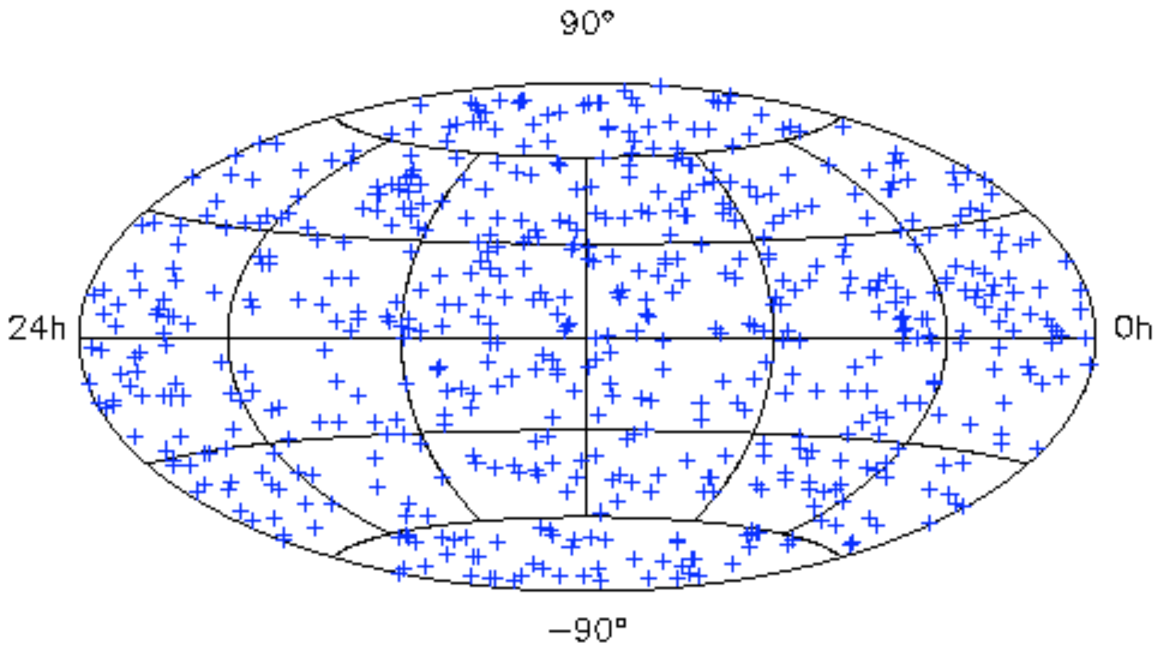
- Origin -> Solar System Barycentre
- Orientation -> Equatorial system, given by
  - Mean equator of J2000.0
  - Origin at dynamical equinox of J2000.0
- Time evolution?
  - Required regular monitoring

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.



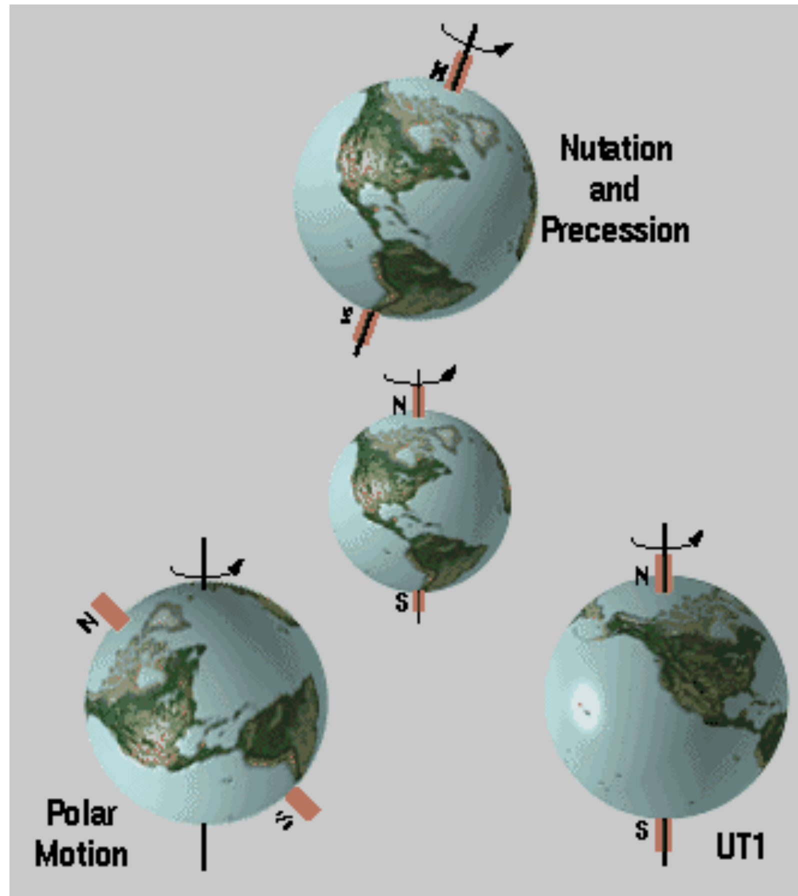
International Celestial Reference *Frame* (ICRF)



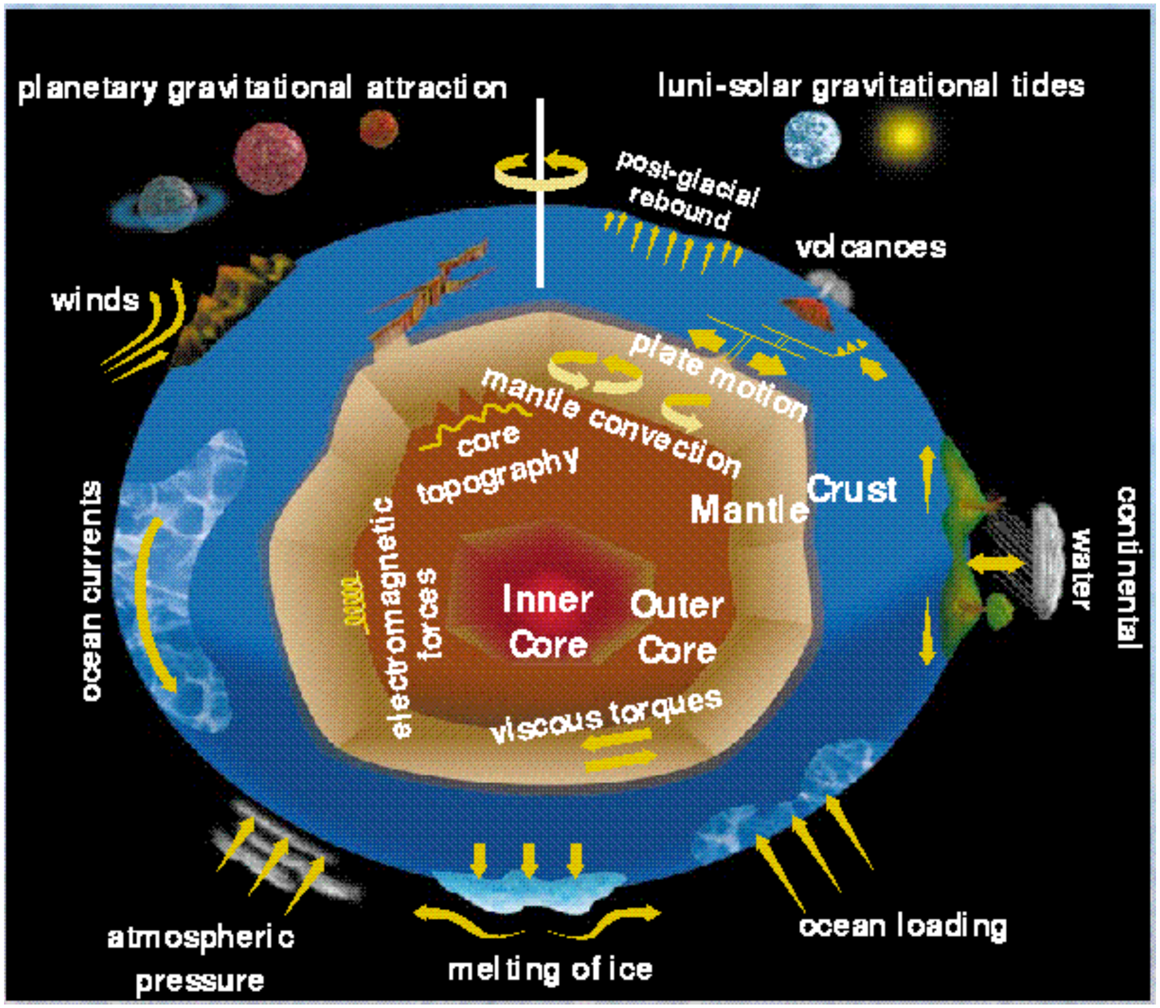
- Over 700 sources, 212 of them are defining sources
- New ICRF expected in 2009

Earth Orientation Parameters

- Why do we care?
  - Dynamical equations expressed in a non-rotating frame
- UT1, rotation angle
  - VLBI only
- Precession and nutation, orientation in space
  - VLBI
- Pole position, geographic location
  - All techniques



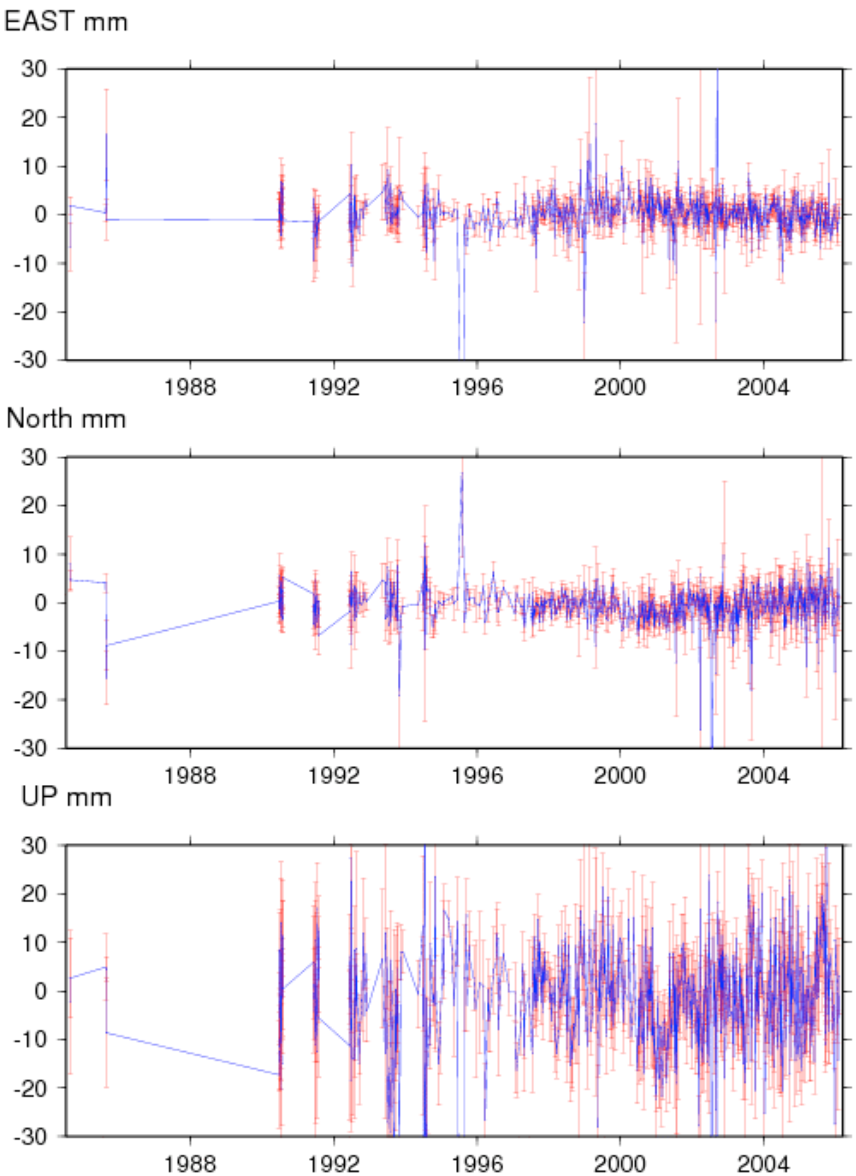
Restless Planet



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

40104S001 7282 Residuals



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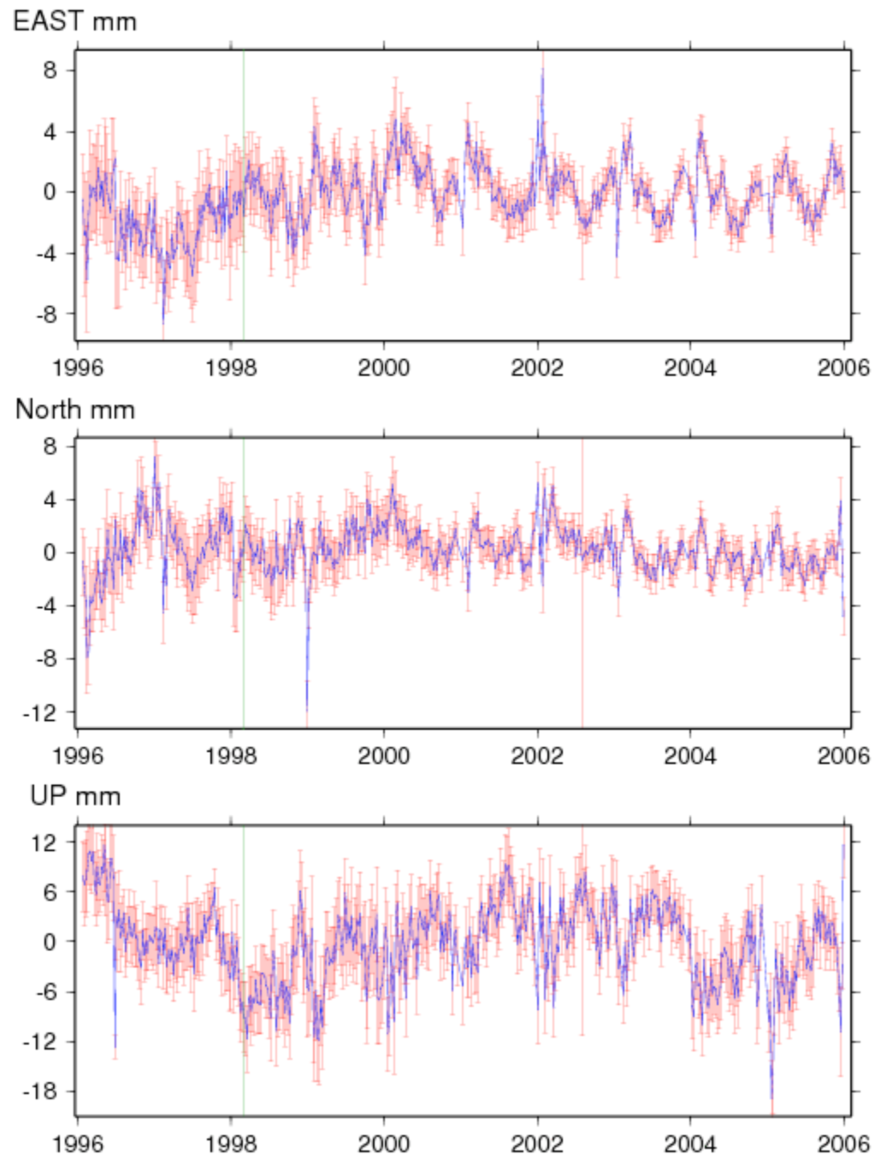
ITRF2005 Residuals analysis

40104M002 ALGO Residuals



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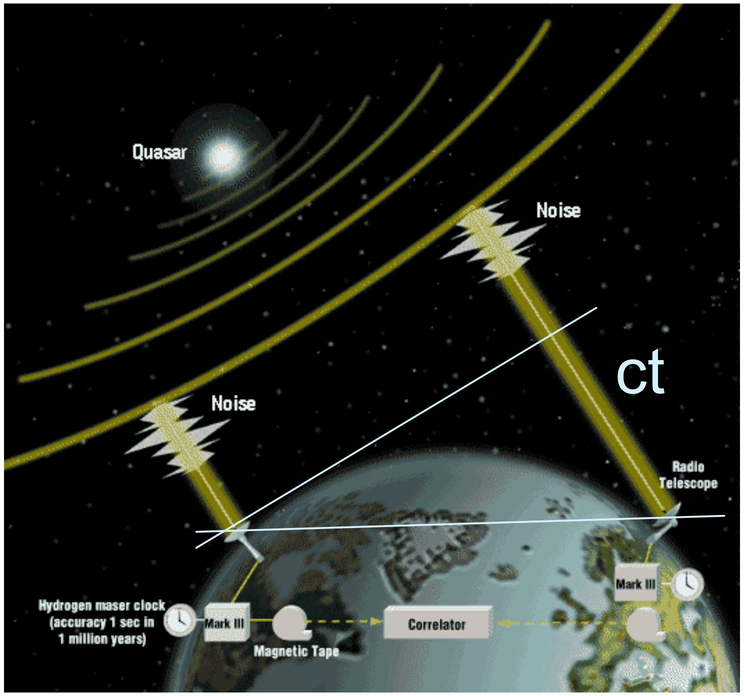
ITRF2005 Residuals analysis

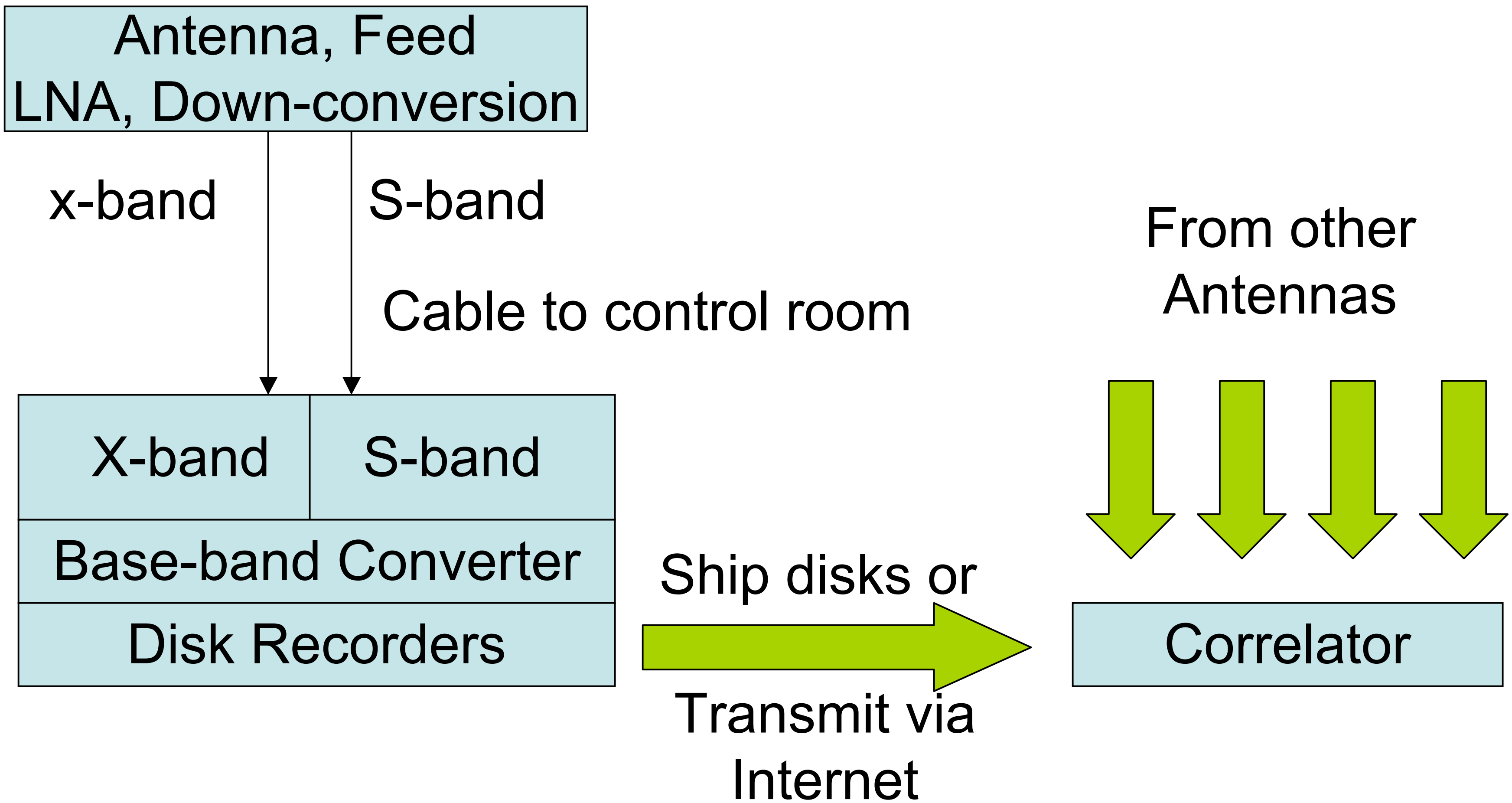
How does VLBI work?

- The delay between the time of arrival of a signal at two antennas is measured
- Using the speed of light, c, this can be interpreted as a distance.
- That distance is the component of the baseline in the direction of the source
- If many sources are observed, the full 3-D vector baseline can be determined

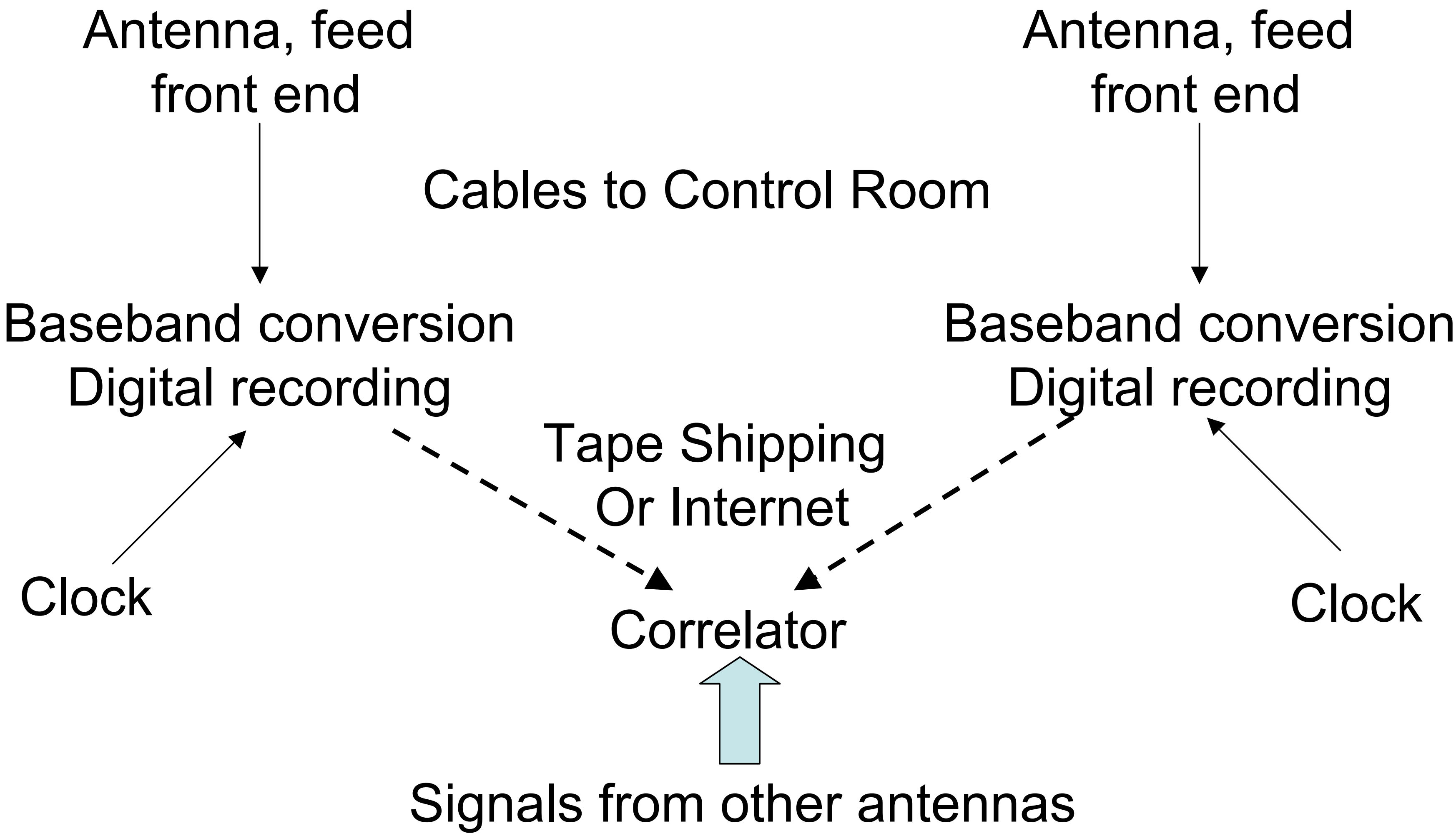


$$\tau = \frac{\vec{b} \cdot \hat{s}}{c} + \Delta\tau_c + \Delta\tau_I + \Delta\tau_{atm}$$

Components of a VLBI system



Basic VLBI System



Antenna, Feed, Front End

- Antenna collects and focuses weak signals from Quasars
- Feed converts EM waves to electrical signals in wires.
- Front end amplifies the signal and reduces its frequency
- Photo: Antenna at Algonquin Park

GGAO antenna at GSFC

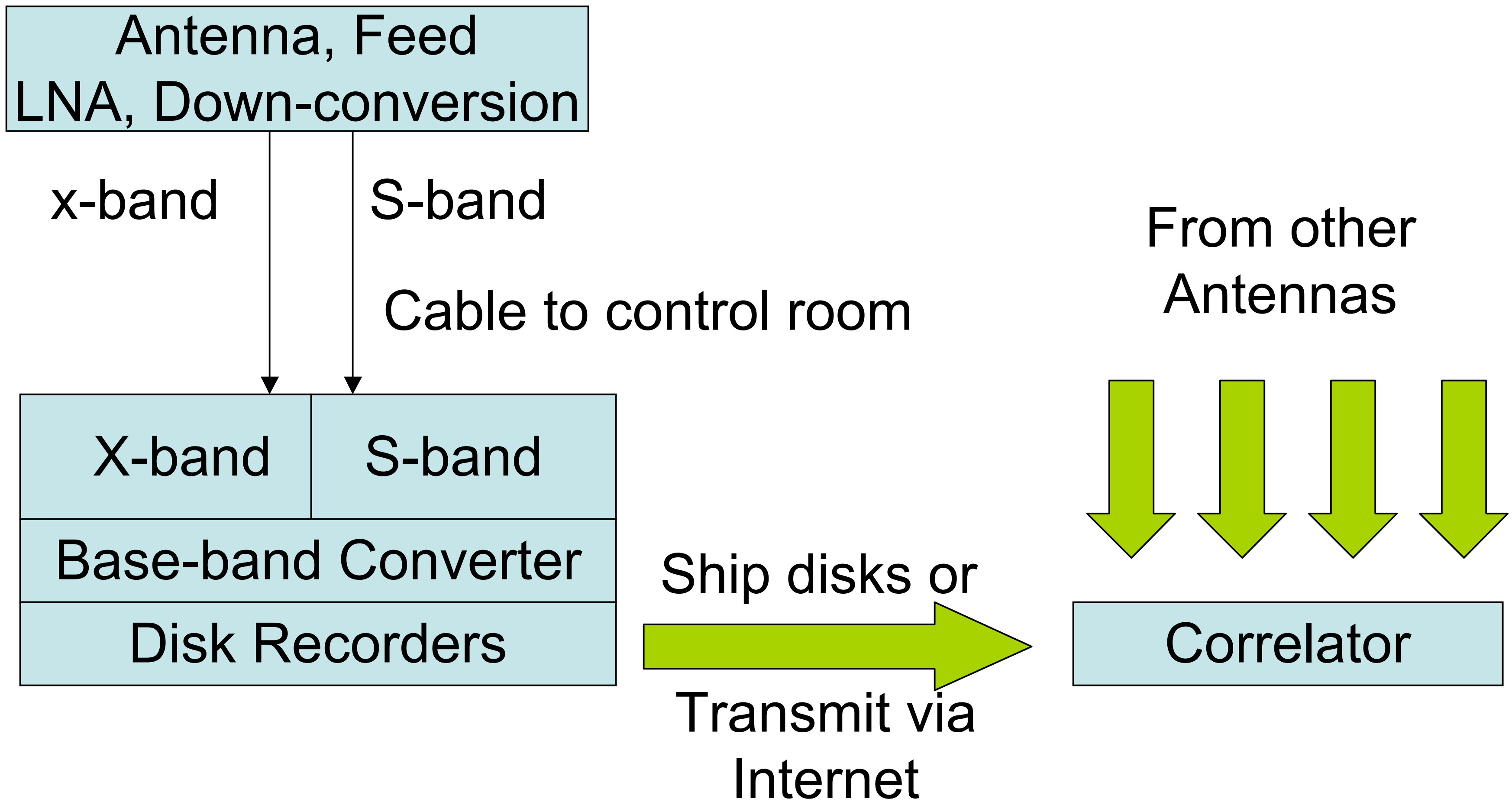
Composite antenna

- Approximately 15% of the weight of an equal size and stiffness Patriot antenna
- Kevlar and carbon fibre composites are about 10 times more thermally stable than steel and 30 times more thermally stable than aluminum.


DODGE


National Research
Council Canada
Canada

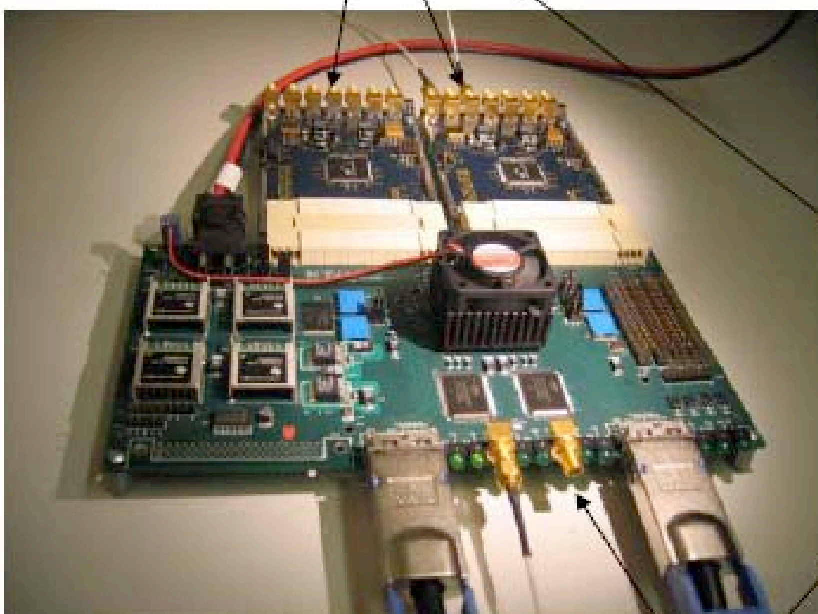
Components of a VLBI system

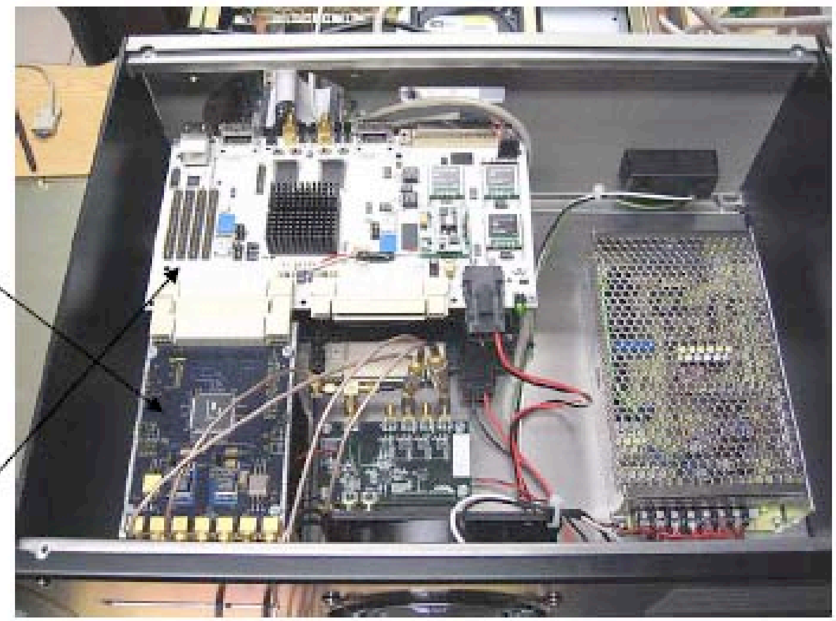


Digital Back End – digitizer, baseband converter

iBob/DBE1

Sampler boards



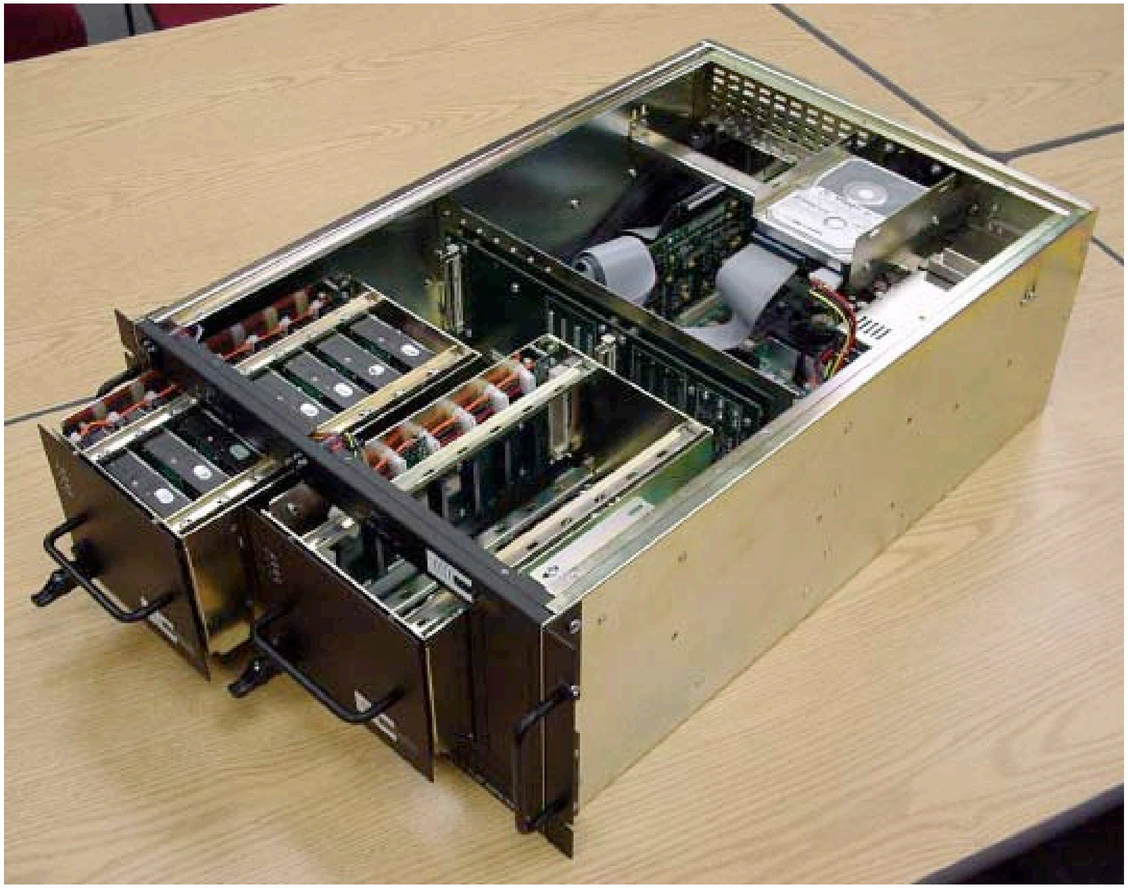


(two iBOB bds per chassis)

iBOB

Disk Record Unit – Mk5B

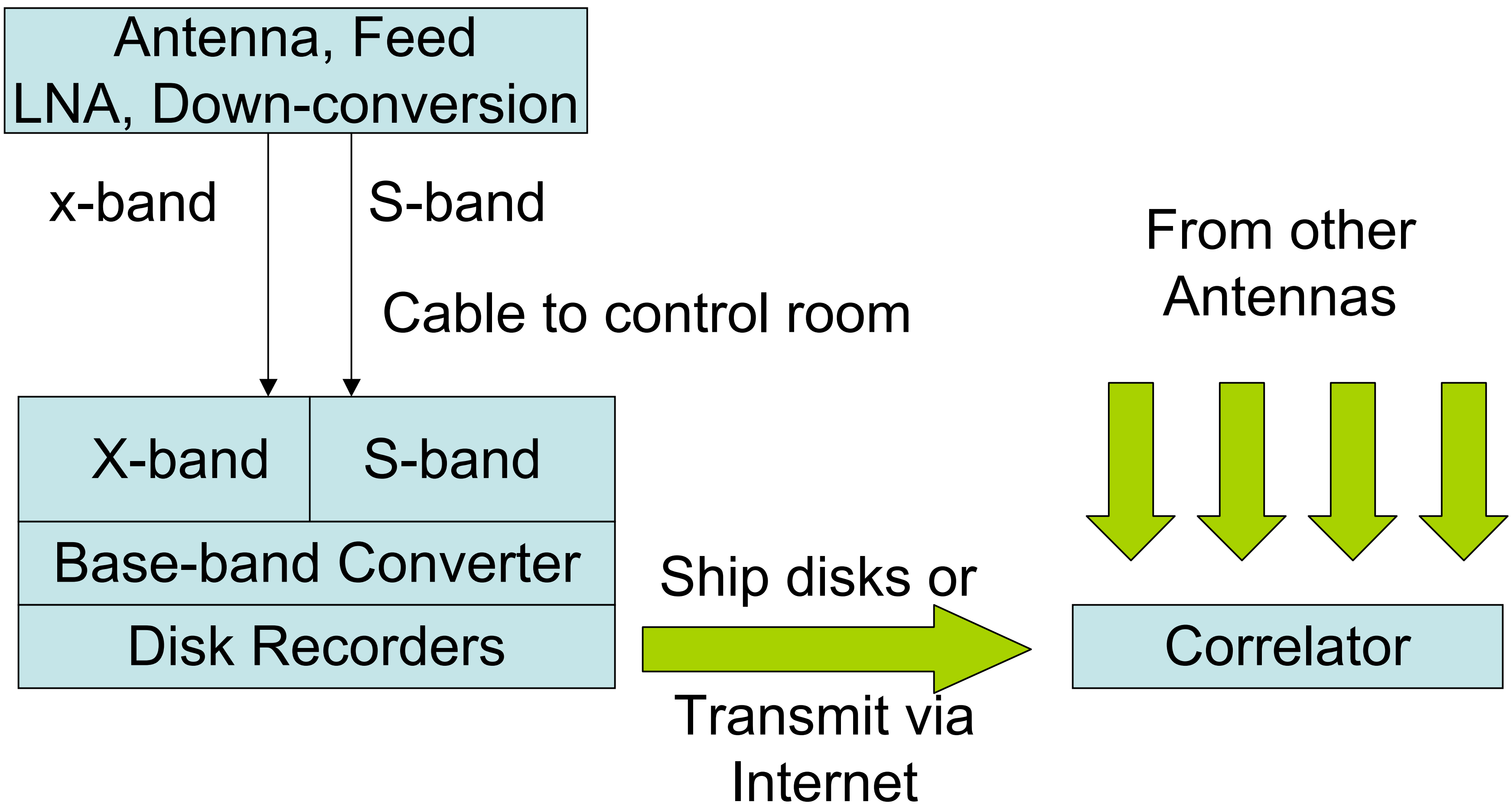
- Can record 1 Gbps data continuously for 24 h
- Mk5C is in design and will record at 4 Gbps
- Data rate has increased by nearly an order of magnitude per decade since 1967,



eVLBI (Data Transmission by Internet)

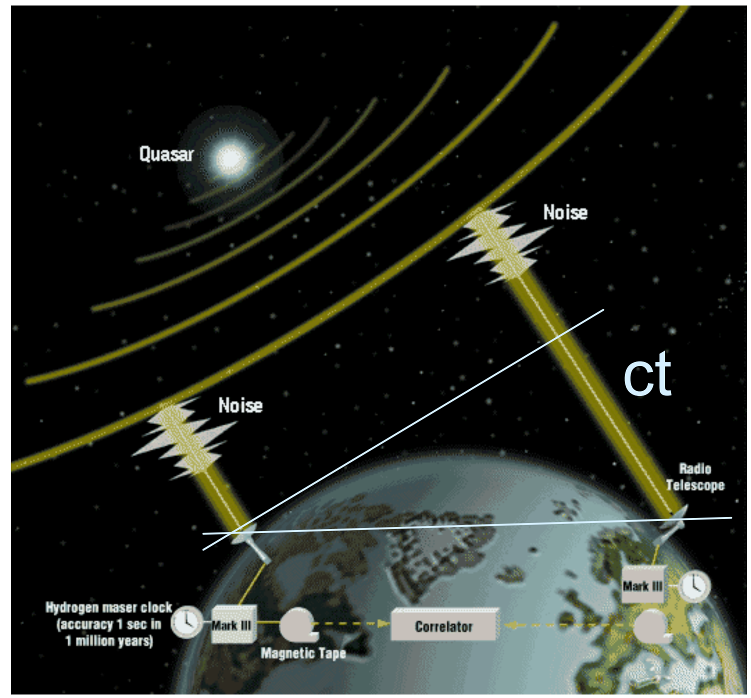
- Required for quick turnaround to initial products
- Last km to antennas solved for many sites
- Sustained data rates near 1 Gbps achieved, but require vigilant monitoring of the light pathways
- 10 gige infrastructure expected to be widely available in the mid future -> achieves 8 Gbps VLBI2010 rates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

Components of a VLBI system

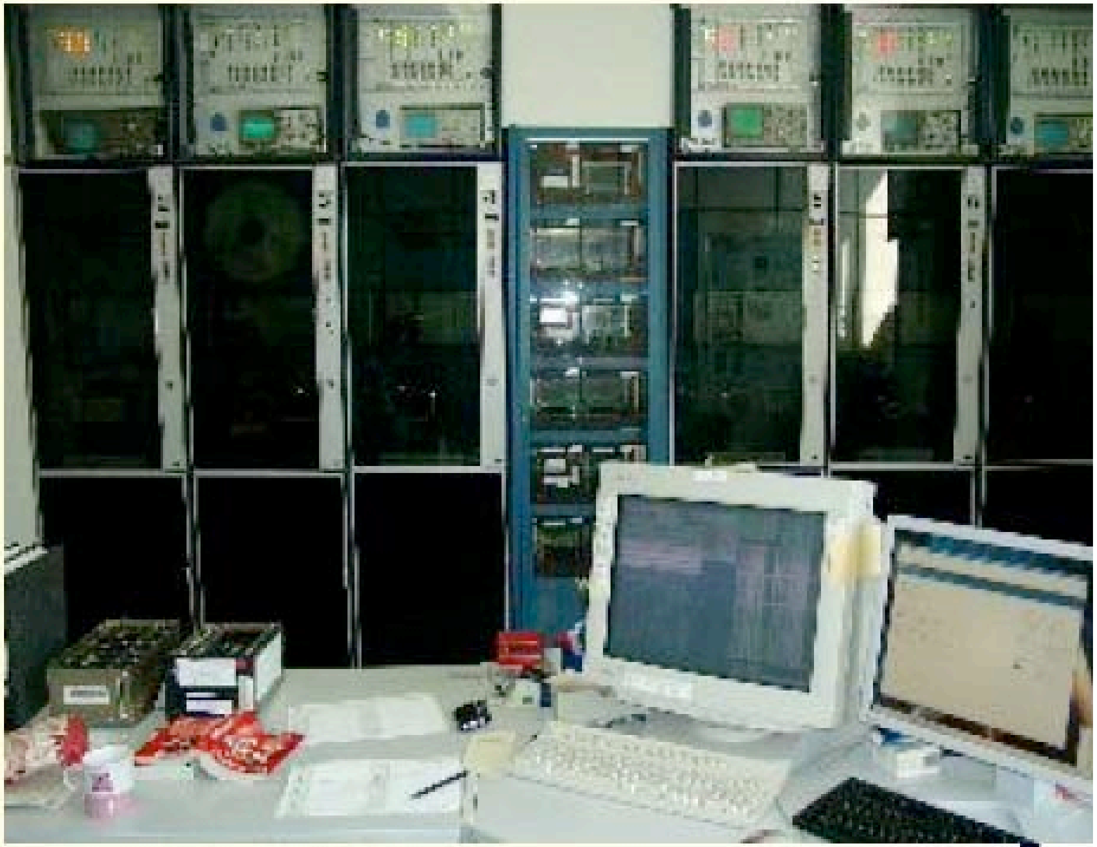


How does a VLBI correlator work?

- Signals are offset by a model delay to account for the interferometer geometry
- Signals are multiplied and accumulated (correlated) at different sample delays
- Positive correlation occurs when the two noise signals are aligned
- The offset of maximum correlation is added to the model delay to produce the output delay observable.



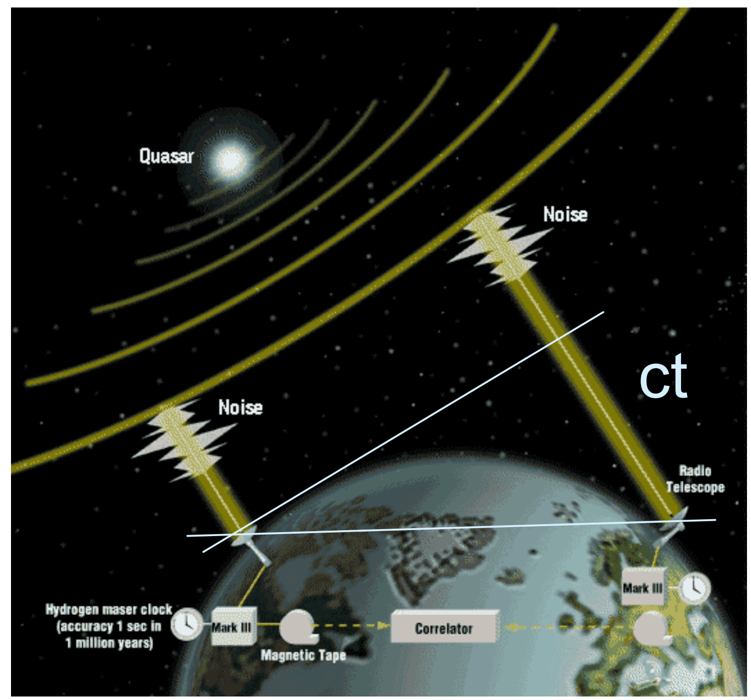
Mk4 Correlator in Bonn Germany



The VLBI Delay Observable

$$\tau_{\vec{b},\hat{s}}(t,f) = \frac{\vec{b}(t)\cdot\hat{s}}{c} + \Delta\tau_c + \Delta\tau_{Inst} + \Delta\tau_{atm} + \frac{K_{ion}}{f^2} + \Delta\tau_{\hat{s}}$$

- Major error sources are:
  - Neutral Atmosphere
  - Ionosphere
  - Instrumentation
  - Clocks
  - Source structure



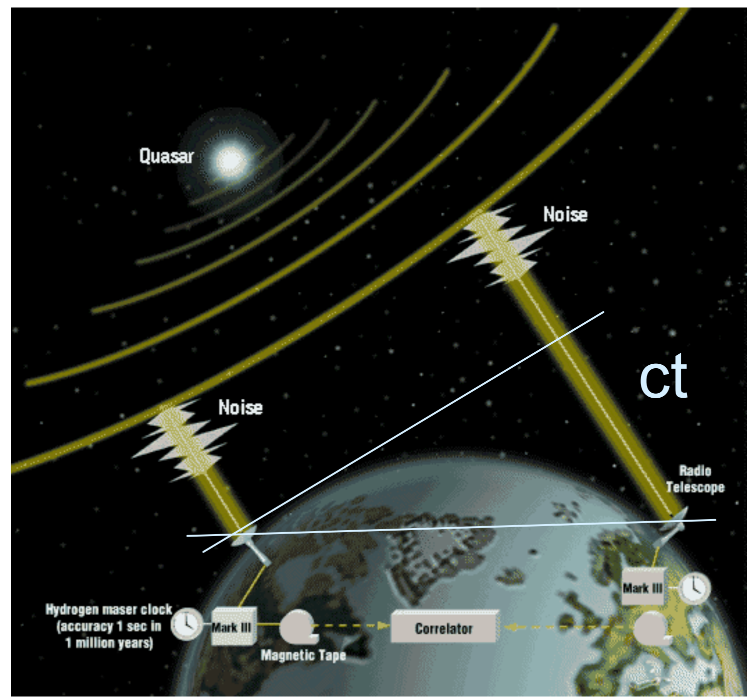
Error Source: Ionosphere

- Since the ionosphere is dispersive, i.e. changes with frequency, it can be calibrated by observing at two widely space frequencies, e.g. S-band (2.3 GHz) and X-band (8.5 GHz)
- K is proportional to total line-of-sight electron content

$$\frac{K_{ion}}{f^2}$$

$$\hat{\tau}_S = \tau_{non} + K \big/ f_S^2 \qquad \hat{\tau}_X = \tau_{non} + K \big/ f_X^2$$

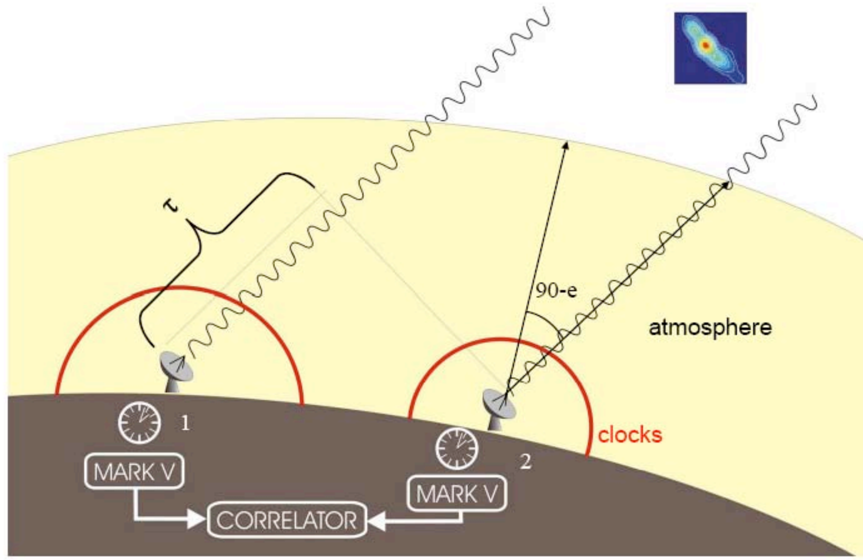
$$\tau_{non} = \frac{\hat{\tau}_X \cdot f_X^2 - \hat{\tau}_S \cdot f_S^2}{f_X^2 - f_S^2}$$



Error Source: Neutral Atmosphere and Clocks

- Neutral Atmosphere has two components:
  - Dry atmosphere
  - Wet atmosphere
- The dry atmosphere is corrected using:
  - Accurate dry mapping function
  - The use of numerical weather data
  - On-site pressure measurements
- The wet atmosphere
  - Water vapour radiometers

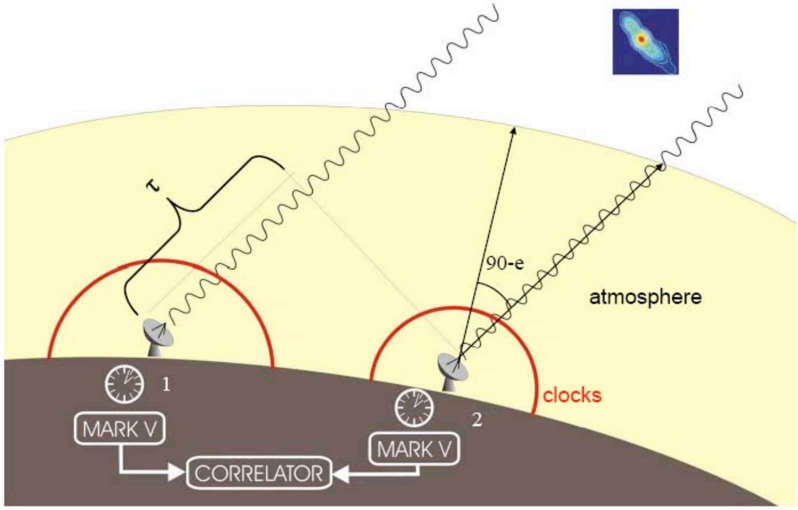
$$\Delta\tau_{atm}^{D} + \Delta\tau_{atm}^{W}$$



Error Source: Neutral Atmosphere and Clocks

- The wet atmosphere is handled by estimating it from the VLBI delay data itself. This requires:
  - Accurate wet mapping functions
  - Clever scheduling to make the error sources separable, i.e.:
    - Geometry changes abruptly as the source changes
    - Atmosphere changes as elevation angle changes
    - Clocks change smoothly and continuously
    - Schedules switch rapidly between sources to vary geometry and elevation angle, making parameters seperable.

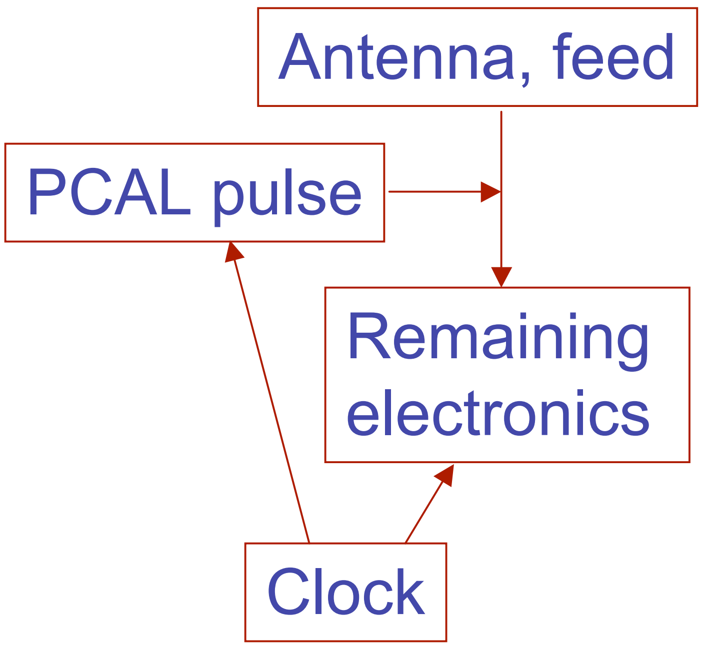
$$\frac{\vec{b}(t)\cdot\hat{s}}{c}+\Delta\tau_c+\Delta\tau_{atm}^{W}$$



Error Source: Instrumentation

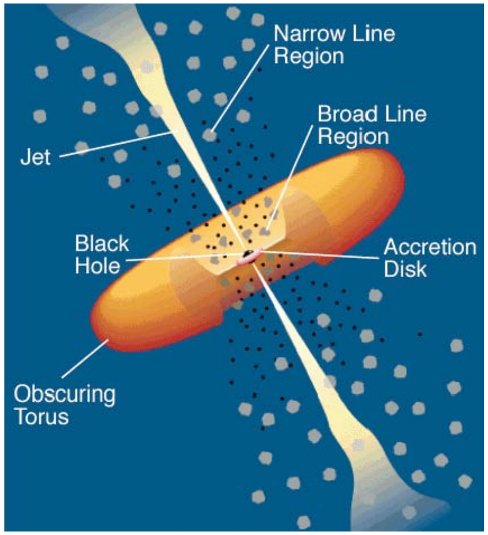
- Instrumental errors are handled through phase calibration:
  - A very short pulse is injected early into the signal path
  - Since the pulse follows the same path as the signal, the delay of the signal through the electronics can be calibrated.
  - The limitations are:
    - It is only as stable as the calibration pulse
    - Not all of the system is calibrated

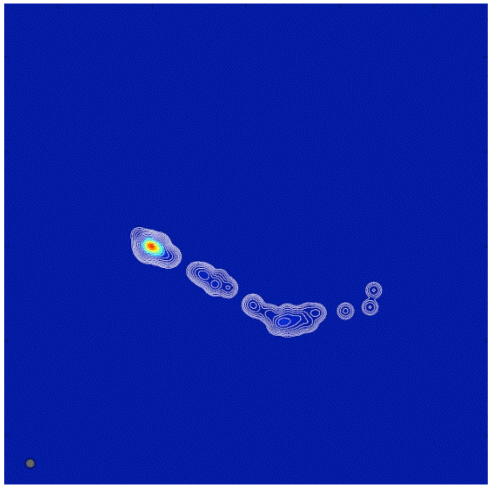
Phase Calibration



Error Source: Source Structure

- Sources are not in general points.
- To make matters worse, their structure changes with time.
- Lists have been carefully made of the best, most point-like and stable, sources
- If enough observations could be made, source structure could be corrected for.





- Thanks for being interested in VLBI and Geodesy!!!

- Questions?

- Please come to my talk tomorrow at 10:30 on the future directions of VLBI