VLBI Fundamentals

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Madrid Deep Space Communications Complex
NASA/INTA

AVN Training School

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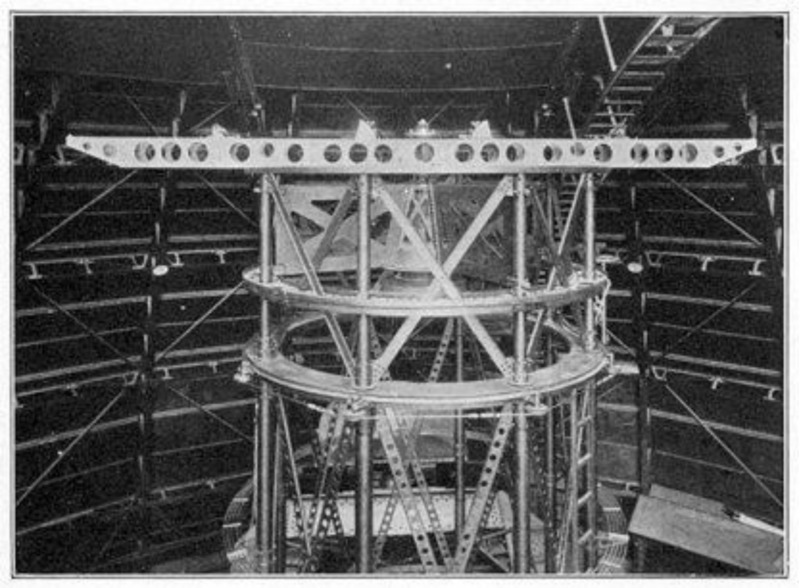
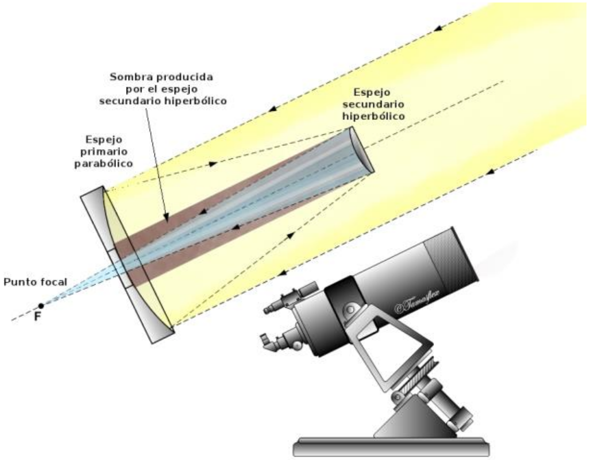
VLBI Fundamentals

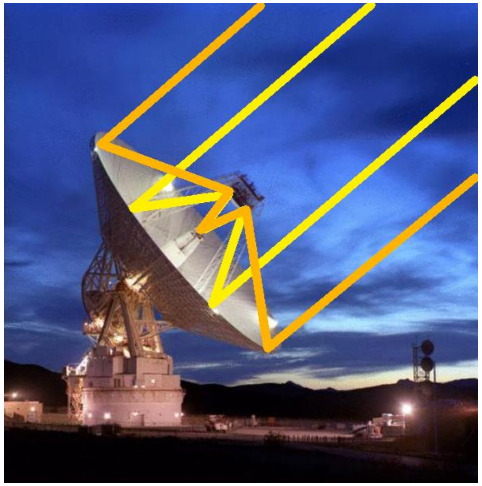


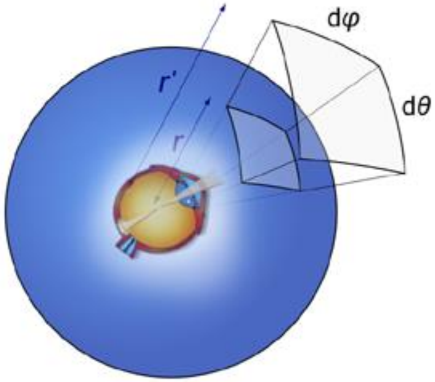
Short history of VLBI
Connected versus VLBI
VLBI networks
VLBI data acquisition terminals
VLBI correlation

Short history of VLBI: why?
QUEST FOR RESOLUTION

OPTICAL vs RADIO:







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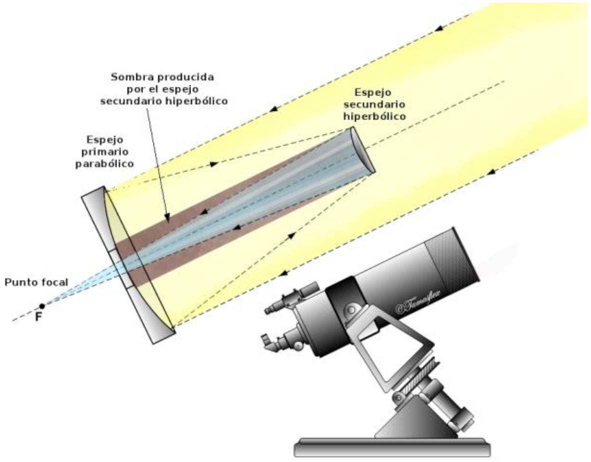

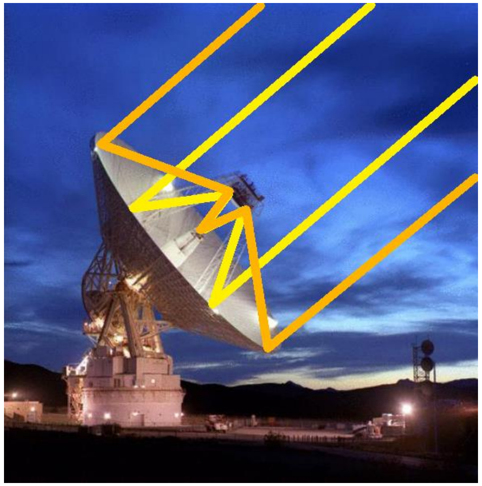

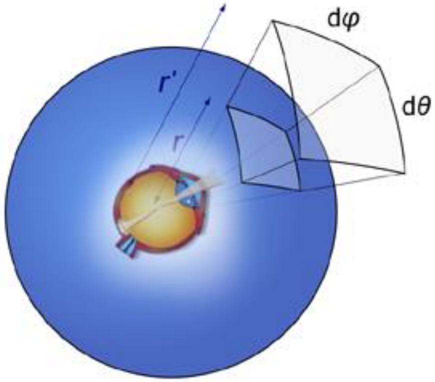

Diffraction-limited instruments

Short history of VLBI: why?
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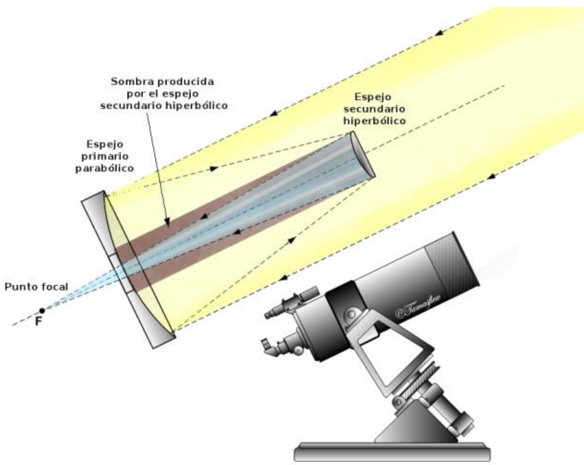
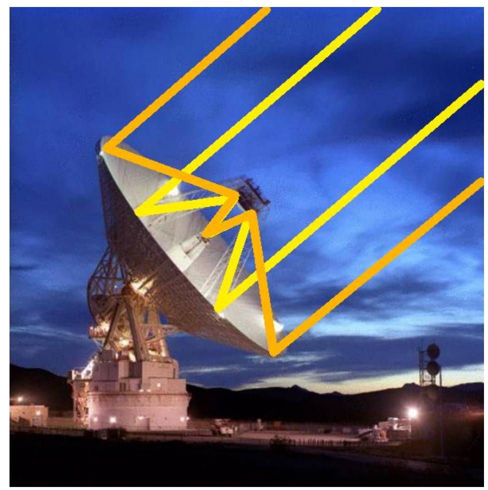
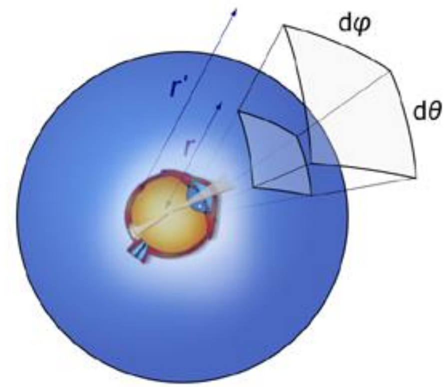
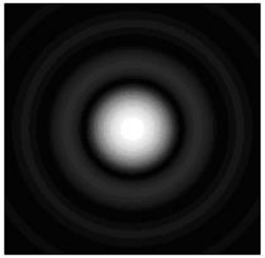






Diffraction-limited instruments

Single dish resolution (arcsec): $$\theta = \frac{2.1\ 10^5\ \lambda}{D}$$



Airy disc or perfect PSF

Short history of VLBI: why?
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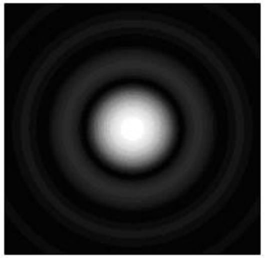

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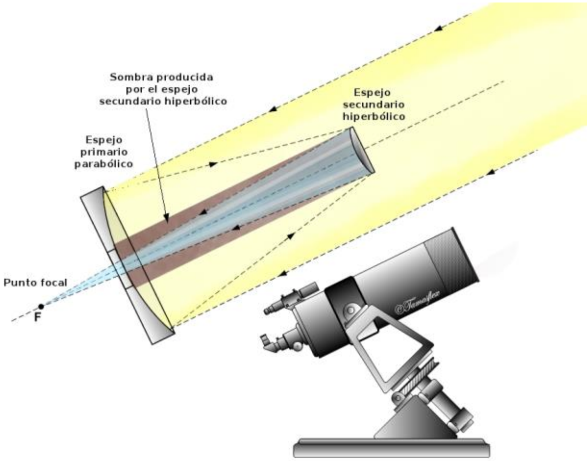
OPTICAL vs RADIO resolution:



8-m telescope in yellow
light 550nm: **14 mas**

Short history of VLBI: why?
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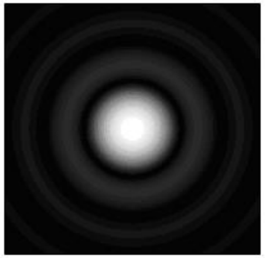

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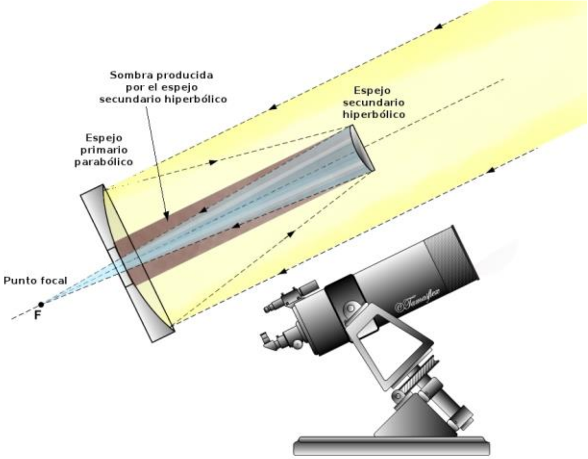

8-m telescope in yellow light 550nm: **14 mas**

70-m telescope in
1.3cm (22GHz): **39 arcsec**
18cm (1.6GHz):
540 arcsec = 9 arcmin

Short history of VLBI: why?
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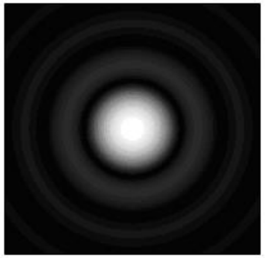

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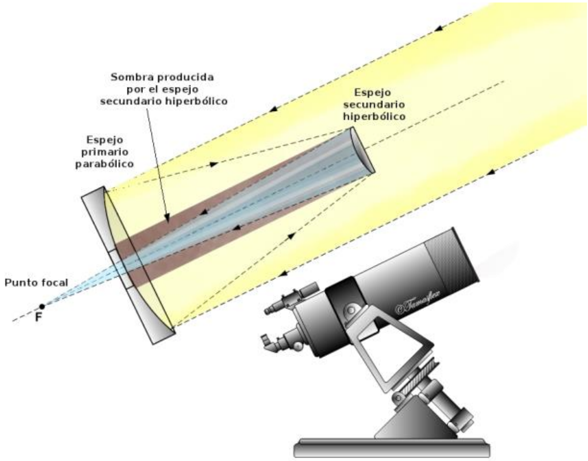

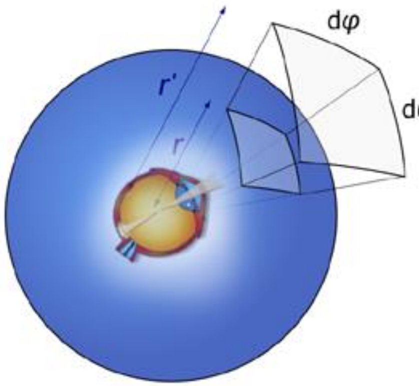

8-m telescope in yellow light 550nm: **14 mas**

70-m telescope in 1.3cm (22GHz): **39 arcsec**
18cm (1.6GHz):
540 arcsec=9 arcmin

Naked eye (7mm pupil) in yellow light 550nm:
(**16.5 arcsec** theoretical)
1 arcmin effective

Short history of VLBI: why?
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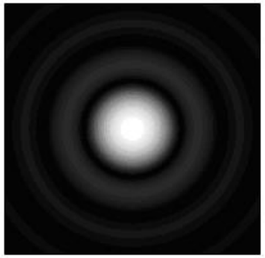
Single dish resolution (arcsec): $\theta = \frac{2.1\ 10^5\ \lambda}{D}$



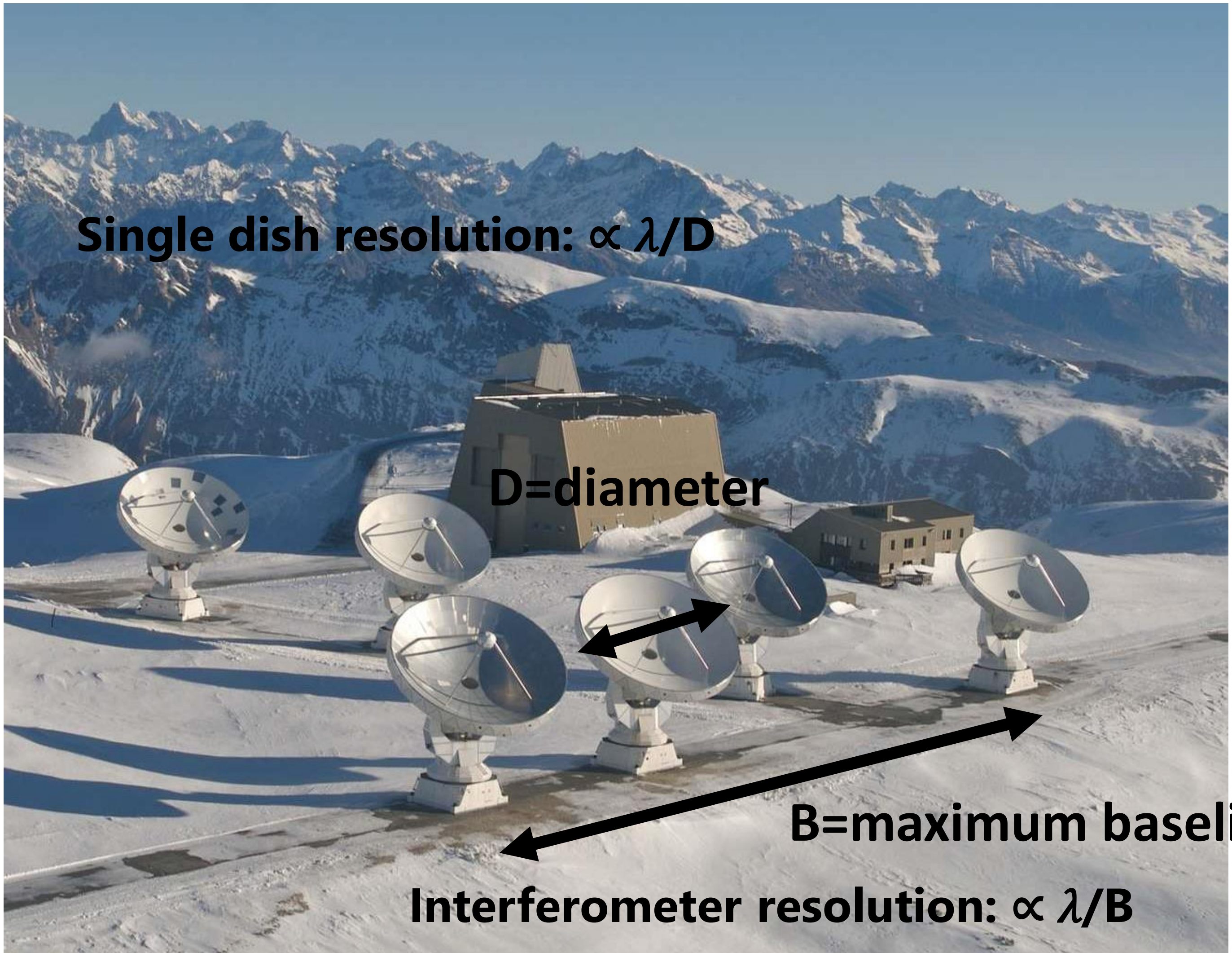
Airy disc or perfect PSF

OPTICAL vs RADIO resolution:

radio waves 10^3-10^7 longer than light waves…

radio telescopes x 10^3-10^7 larger than optical ones for same resolution!!

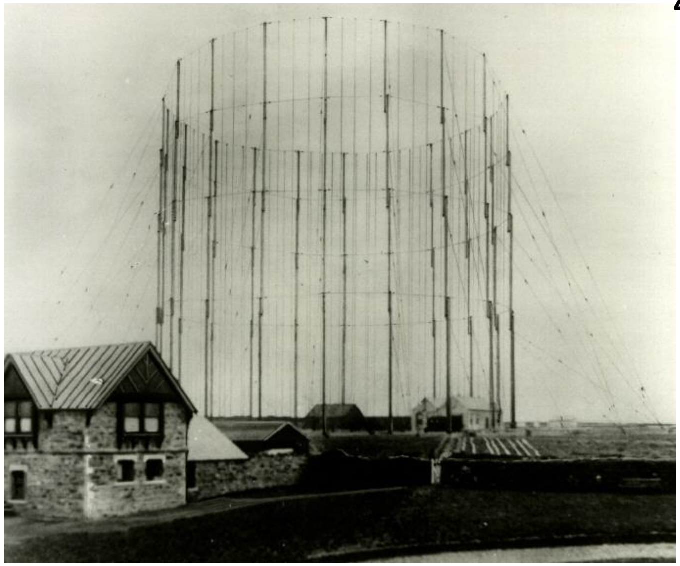
Short history of VLBI: why?
QUEST FOR RESOLUTION



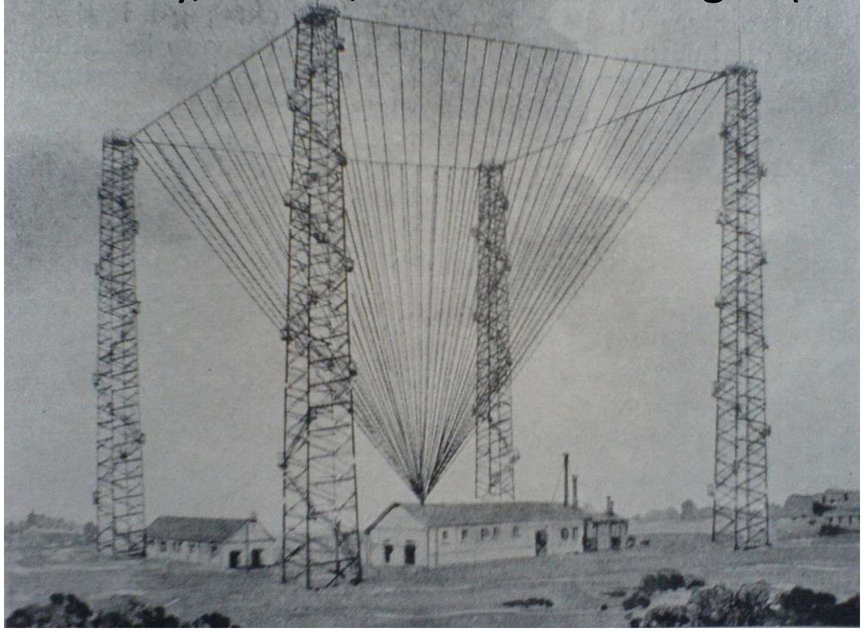
Short history of VLBI

G. Marconi monopole antenna array in Poldhu, Cornwall (1900):

First transatlantic transmission on 12 December 1901 to his temporary receiving station on Signal Hill, St. John's, Newfoundland.

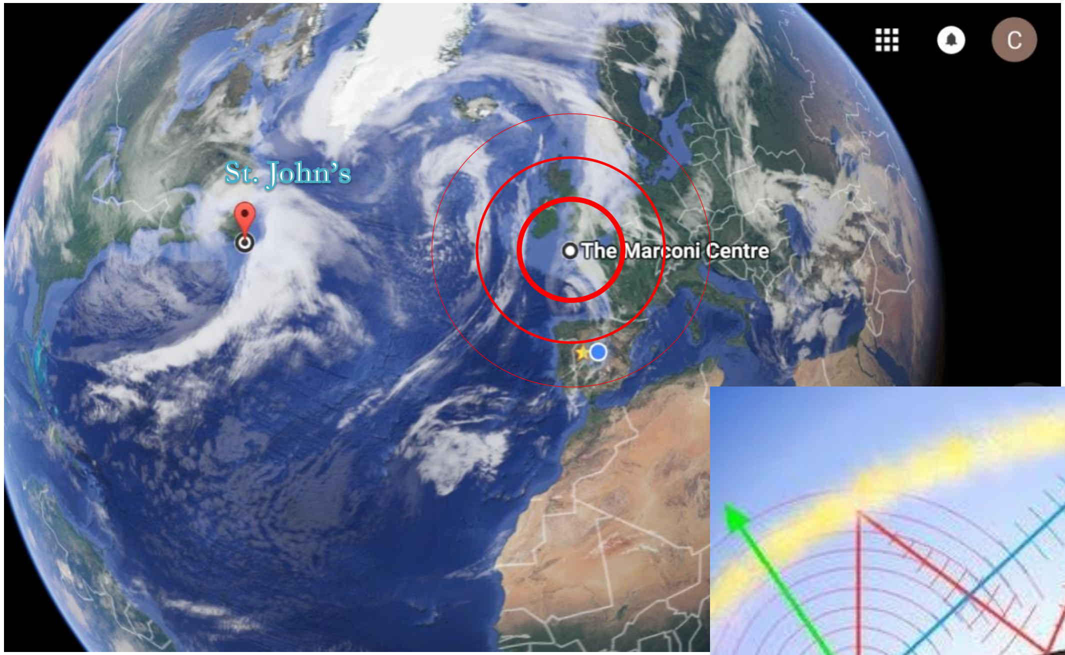


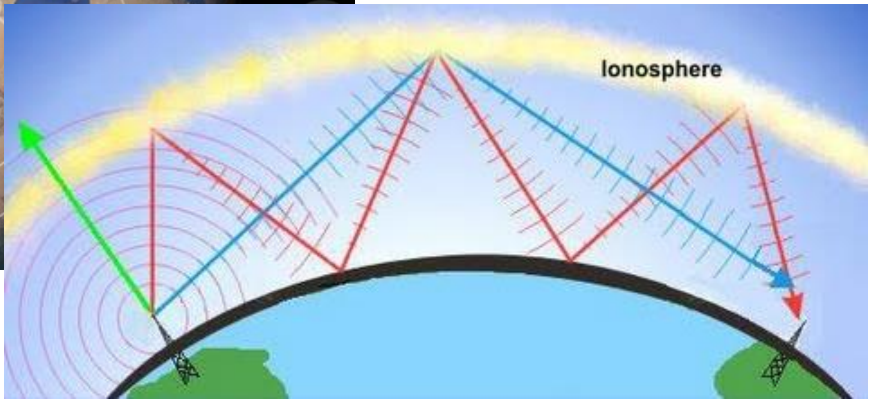
4 tower array, 12 kW, 366 m wavelength (820 kHz)



Short history of VLBI

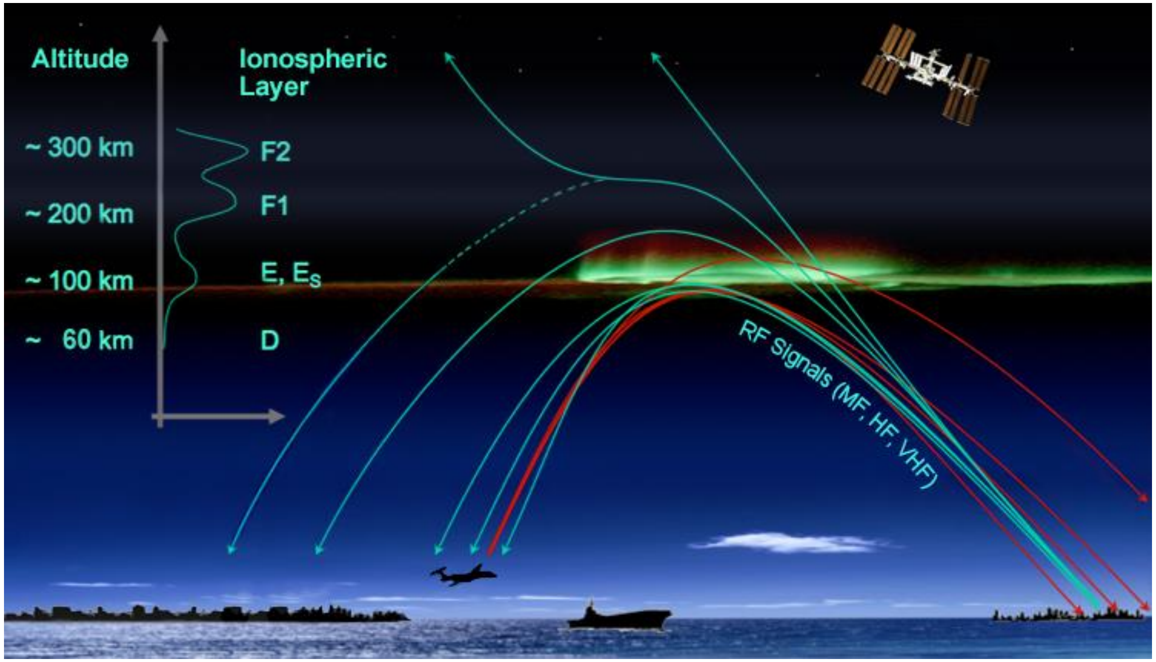
Marconi's transatlantic transmission
required multiple reflections off the ionosphere

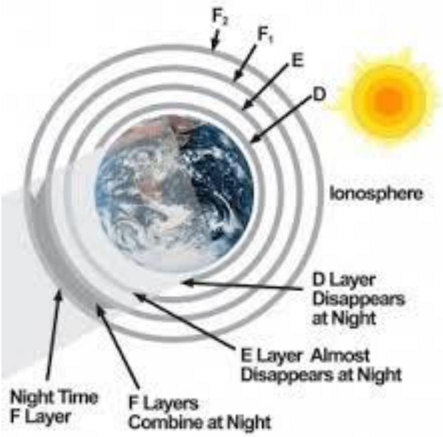




Short history of VLBI

Discovery of the ionosphere and its reflective and refractive properties

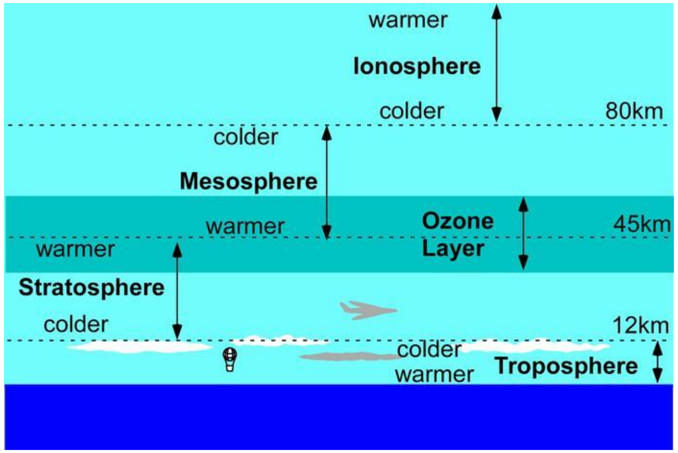


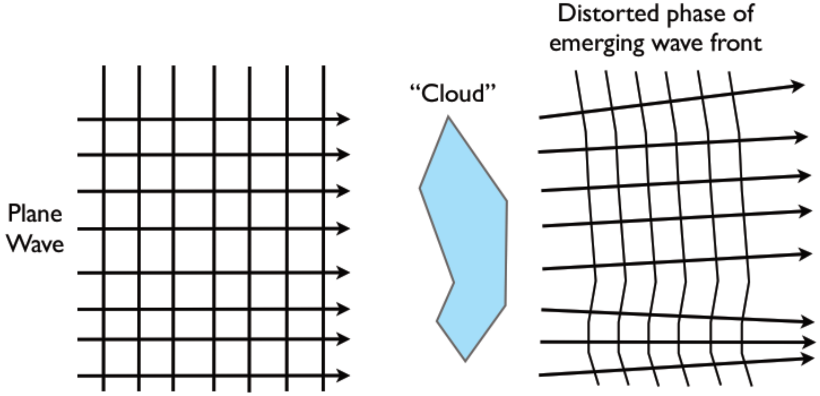


Solar radiation is the main ionizing source, ionosphere height changes diurnally

Short history of VLBI

Help from the atmosphere: much better behavior for radio wavelengths than for optical





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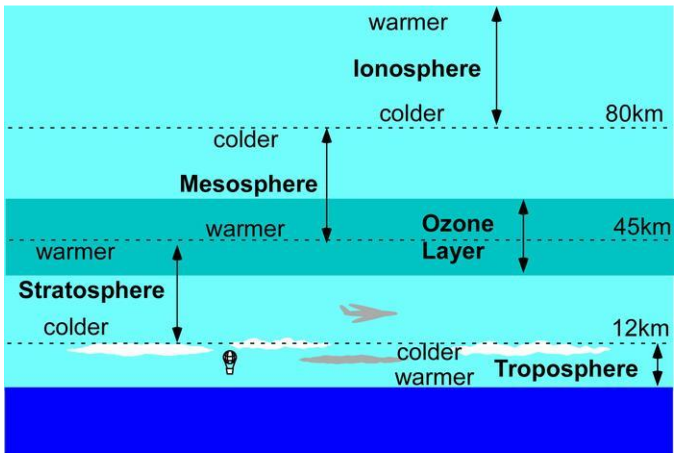
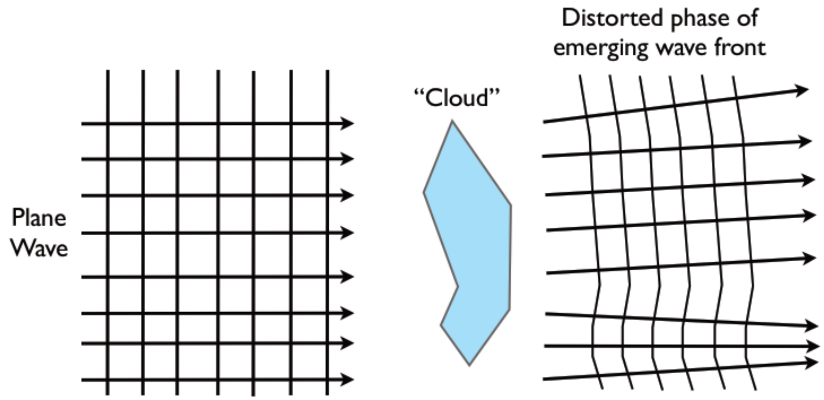




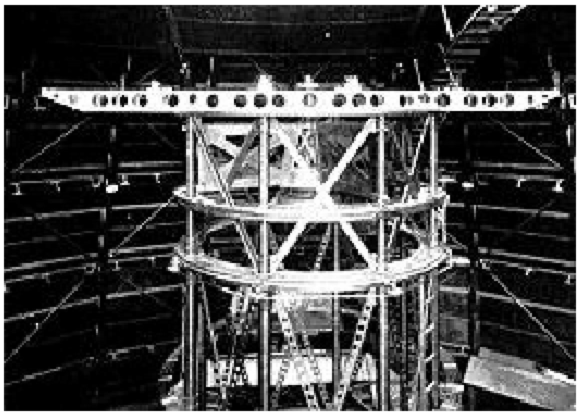
Coherence time: phase change 1 rad in incoming wavefront,
3 cm (0.5 10^{-6} m) vs. 600 m (1 cm)
ms vs. min

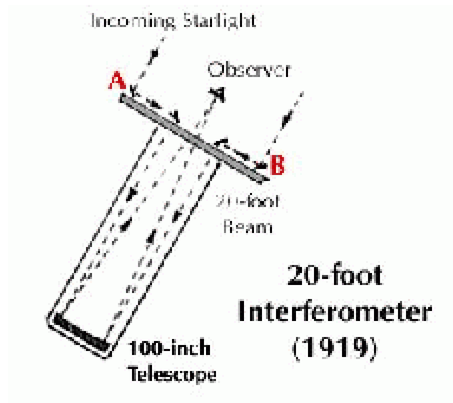
Typical coherence times:

Freq	**Good**	**Bad**
151 MHz	3 min	15 sec
480 MHz	10 min	45 sec
2 GHz	45 min	3 min
5 GHz	40 min	10 min
22 GHz	3 min	10 secs
200 GHz	0.5 min	1 sec

Short history of VLBI

Michelson Interferometer (1919): 20-ft stellar interferometer mounted atop the 100-inch Mount Wilson telescope → twice its actual size!





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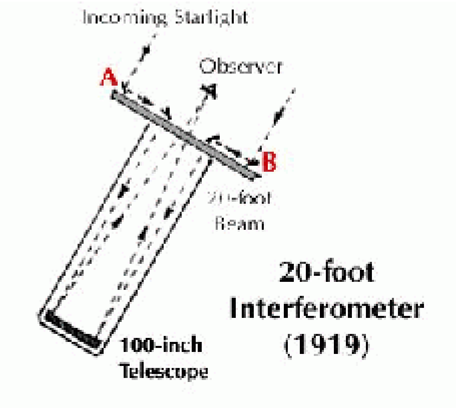
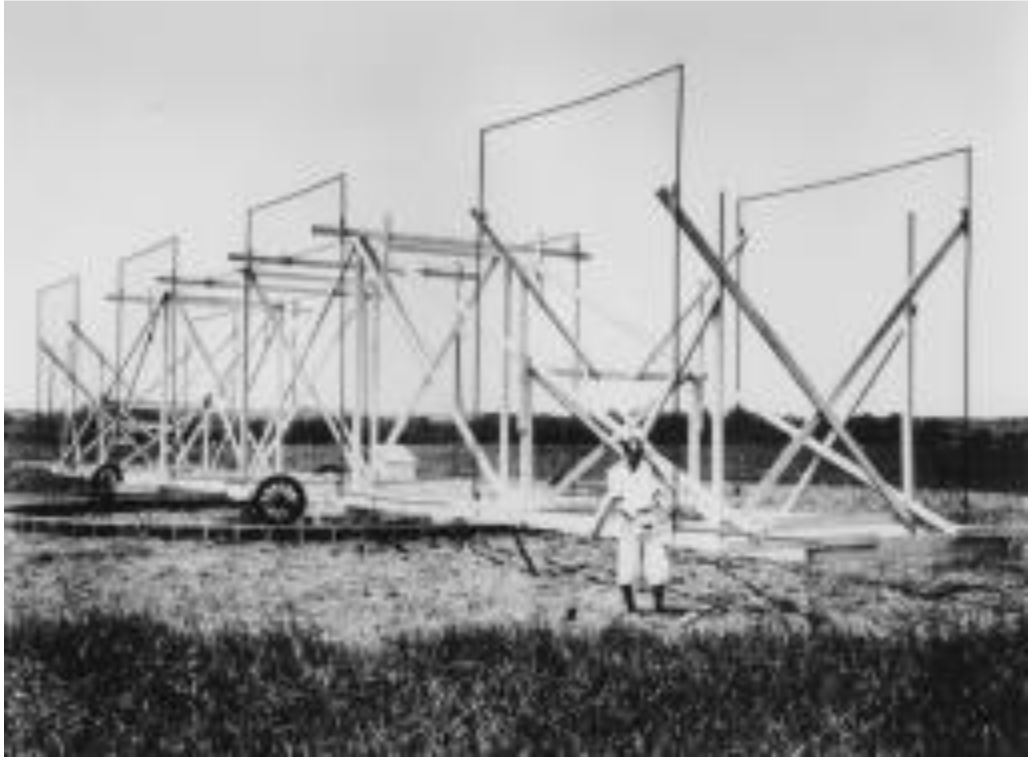


Measure the diameter of the stars for first time!

Short history of VLBI:

Karl Jansky (1933) : Discovery of cosmic radio waves from the galactic center using a Bruce-type antenna array about 2λ in extent.
Angular resolution only 30 deg…



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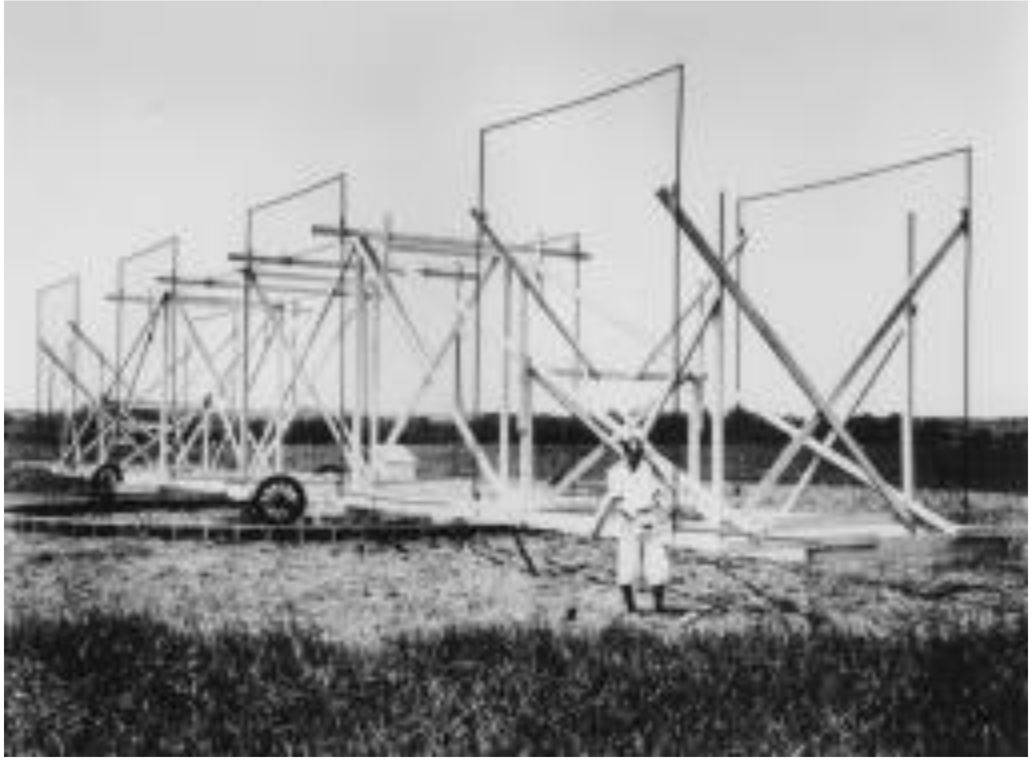
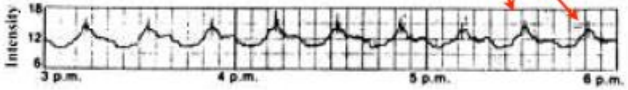


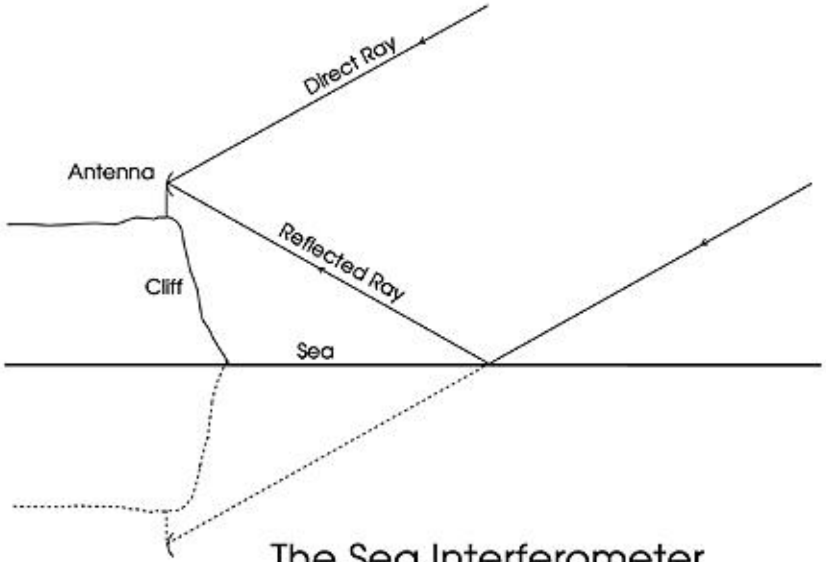
Galactic centre

20.5 MHz Recording 16 Sept 1932

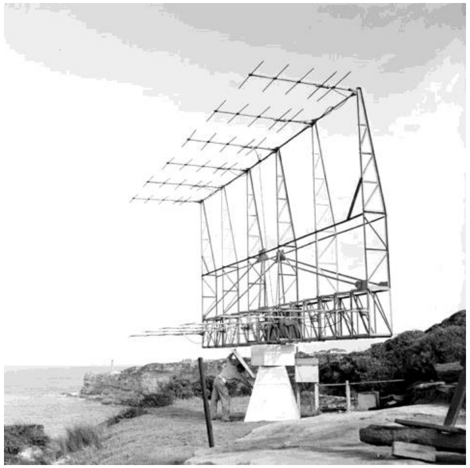


Short history of VLBI

Sea-Cliff interferometer (1946) in Australia:
first interferometric observations in radio astronomy



The Sea Interferometer



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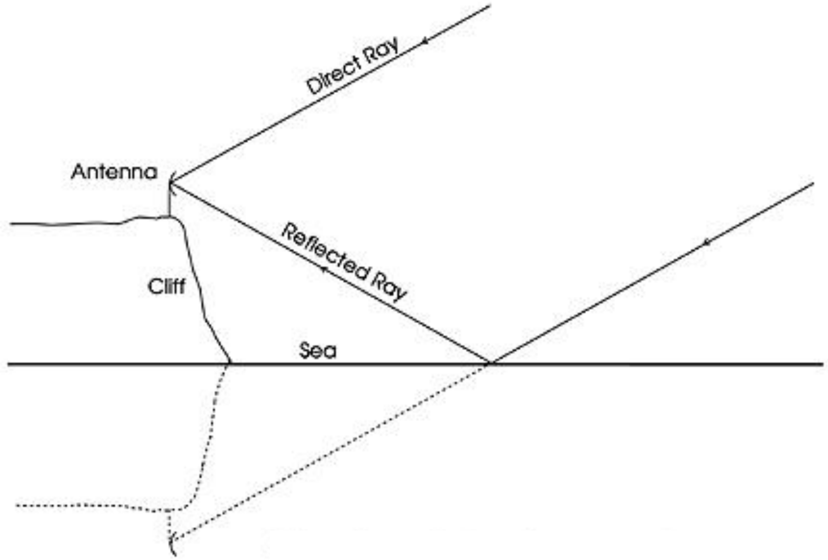
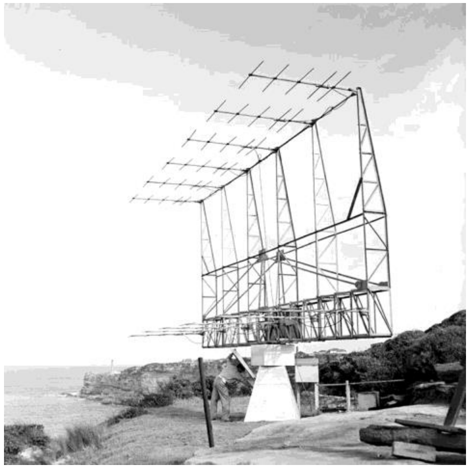
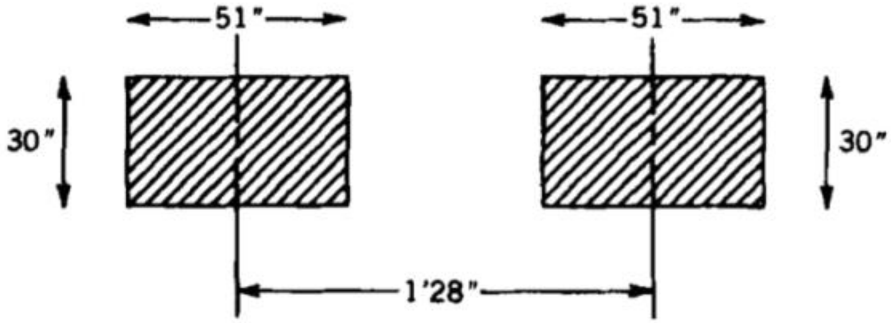




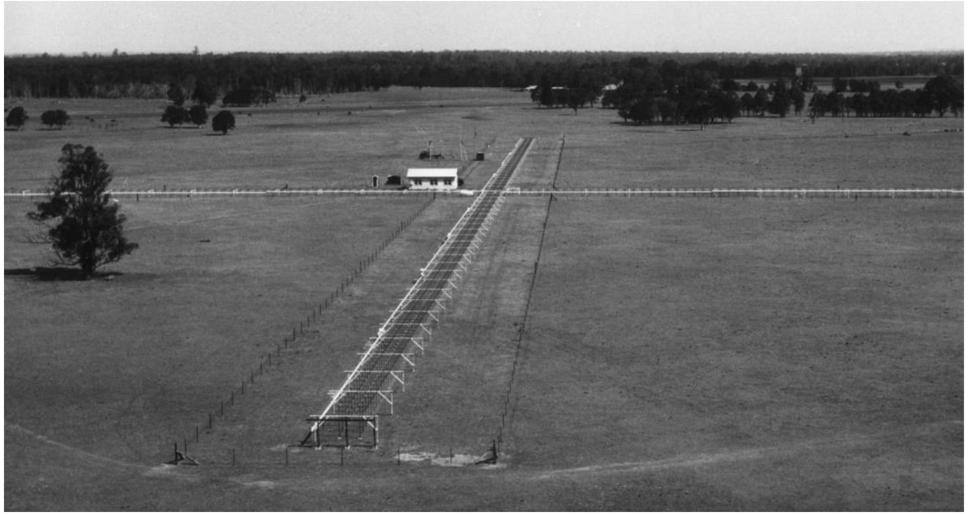
First image of a radio source: **Cygnus A**

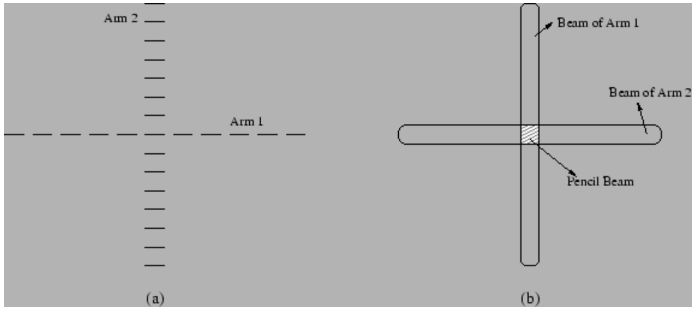


Jennison & Das Gupta (1953)

Short history of VLBI

Mills Cross-type radio telescopes (1953): two-dimensional cross array, at 3.5 m (86 MHz) 1 deg resolution.





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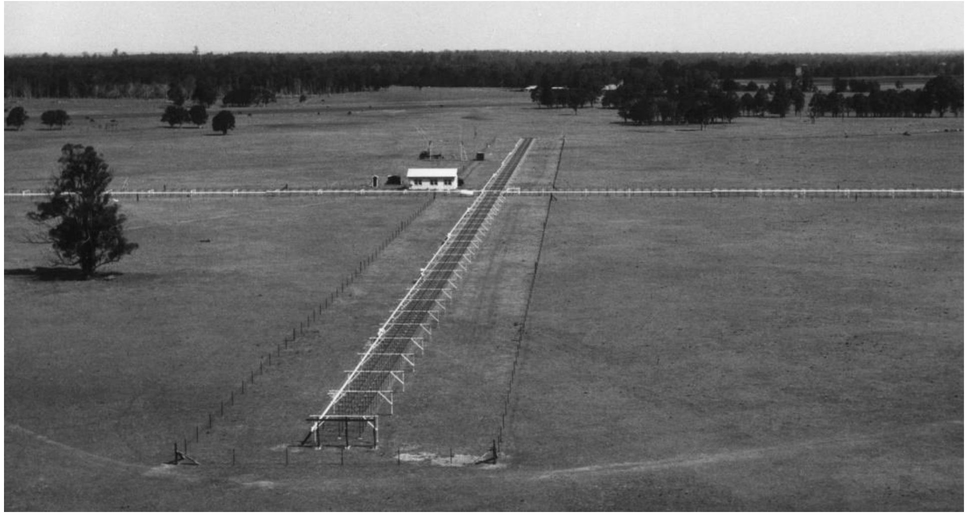
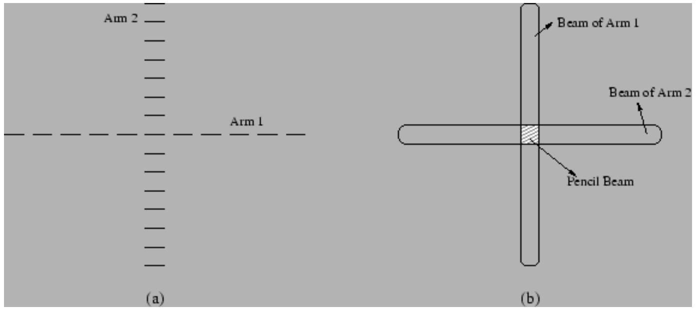
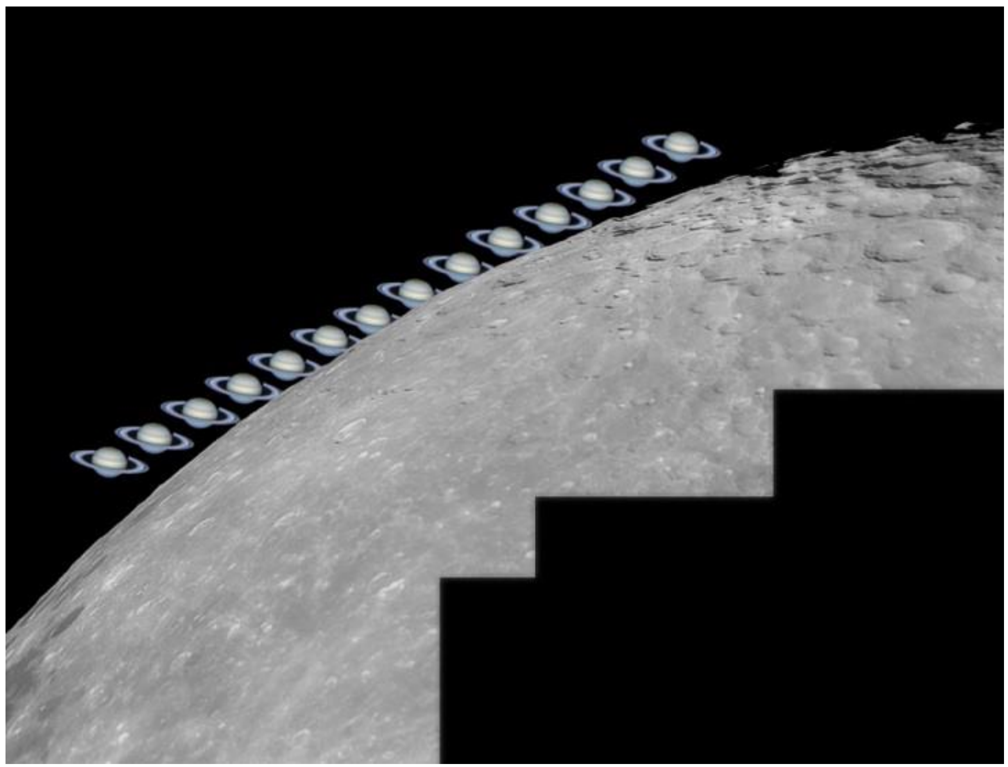




Improved version worked at 73 cm (408 MHz) with 2.8 arcmin resolution. East-west arm used as a full earth-rotation synthesis instrument at 36 cm (843 MHz) with 43 arcsec resolution.

Short history of VLBI

Lunar Occultations (1939): occultations of stars to measure their angular sizes and positions. The effect of diffraction can be precisely removed so that the angular resolution is limited only by the telescope sensitivity, up to 5 mas at 0.5 μm.

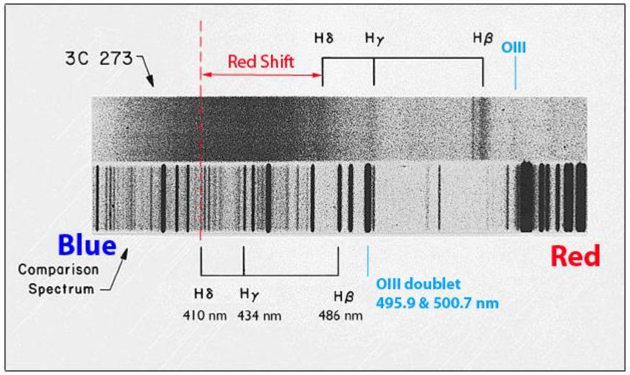


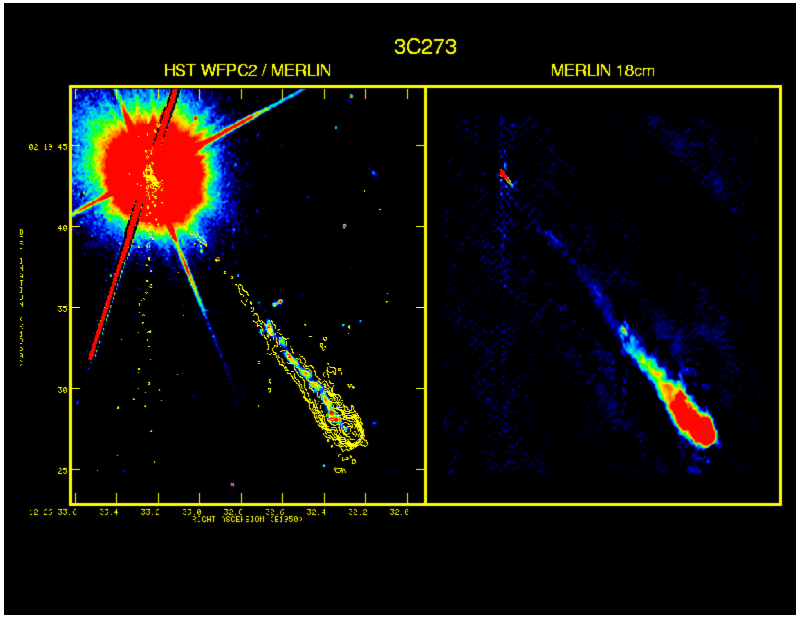
Short history of VLBI

Lunar Occultations (1939):

Optical identification of 3C273 and discovery of quasars with Parkes 210-ft radio telescope

(Schmidt 1963)

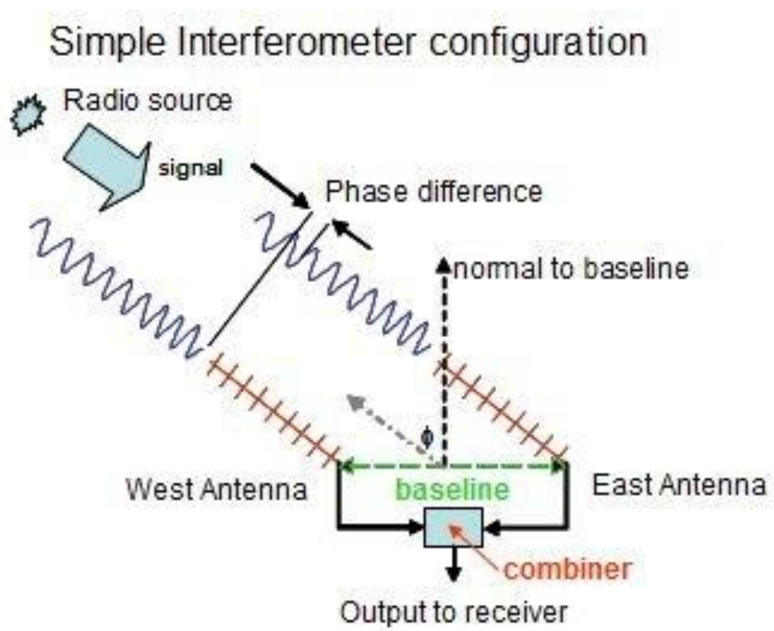




Short history of VLBI

Michelson Interferometers (Ryle & Vonberg 1946):
First radio analog of the optical interferometer: two-element radio interferometer with a maximum spacing 0.5 Km.

Signals from 2 antennas are added, squared and averaged.



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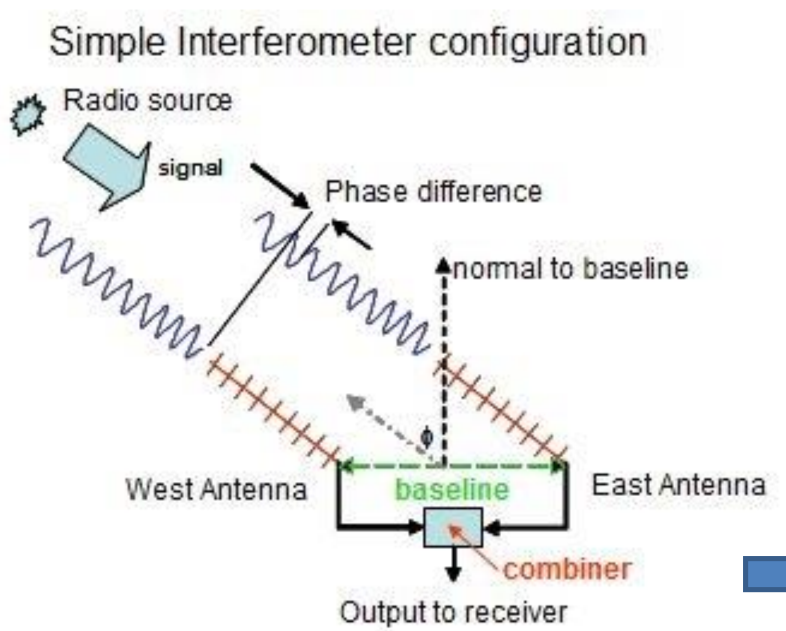

Cambridge interferometric sky surveys (IC surveys).
Up to 6 arcmin

Let's VLBI begin… Not quite

Radio link interferometers: extend radio interferometers to larger distances, distribute the local oscillator phase reference and to return the intermediate frequency, 10 Km at 3 m (101 MHz) with 1 arcmin res.

Let's VLBI begin… Not quite

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1 km connected interferometer and a radio link to join a portable antenna, up to 20 Km, upper limit of diameters 12 arcsec (3Cxxx)

Up to 134 Km at 73 cm with 0.4 arcsec resolution

Later developments up to 0.05 arcsec

Let's VLBI begin… Not quite

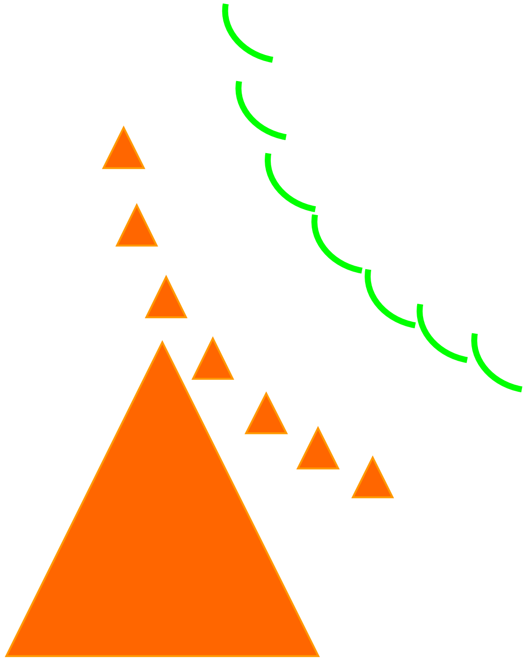
Radio link interferometers:

MERLIN Multi-Element-Radio-Link-Interferometer-Network (1980):

7 antennas, with up to 10 mas

Connected arrays: Aperture Synthesis

Aperture synthesis: interferometry of a collection of antennas to synthesize an instrument with the size (= resolution) of the entire network.



Connected arrays: Aperture Synthesis

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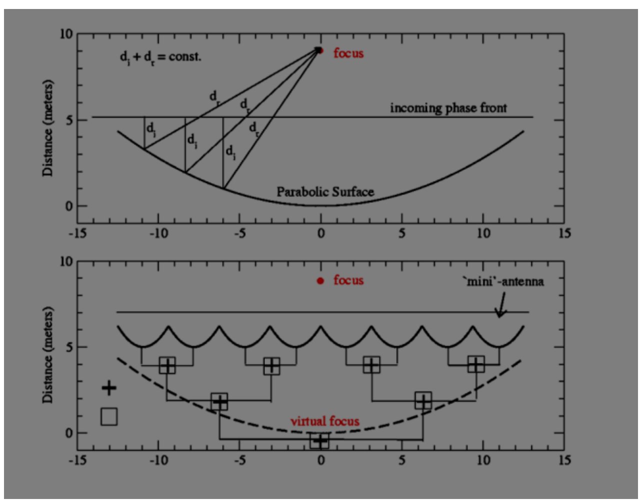
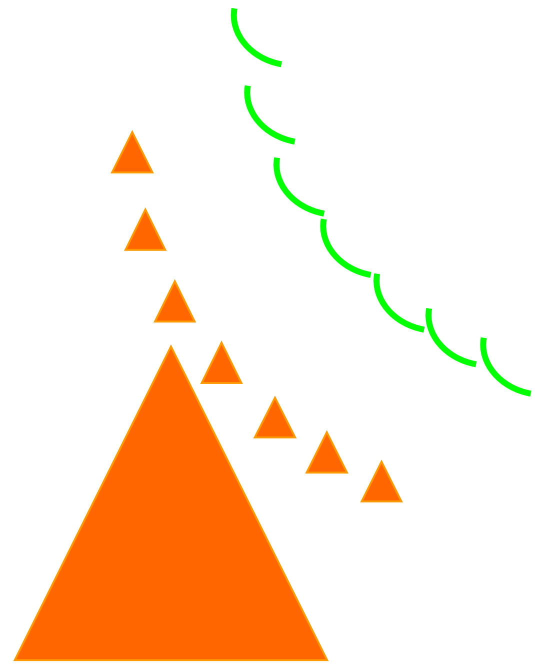
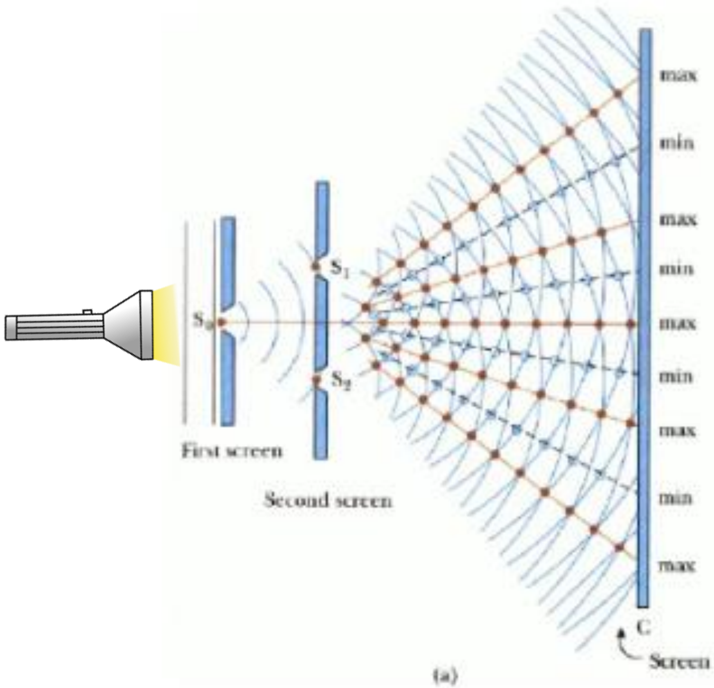
In order to produce a high quality image, a large number of different separations between different telescopes are required:

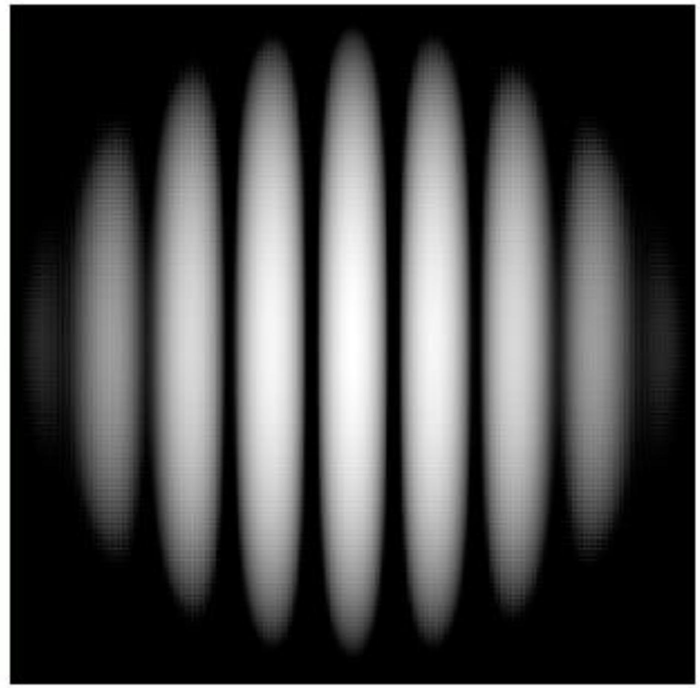
- **artificial rotation of the interferometer**
- **or Earth rotation.**





(Young double-slit experiment)





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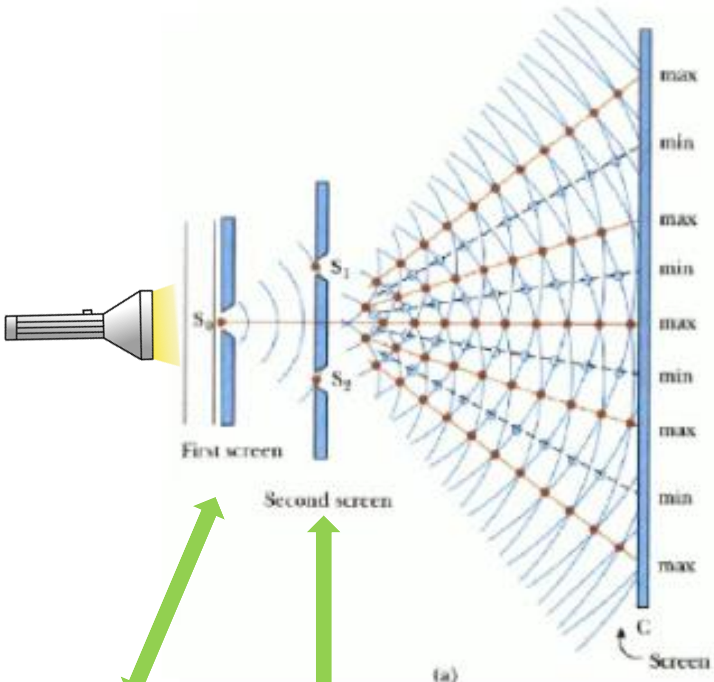
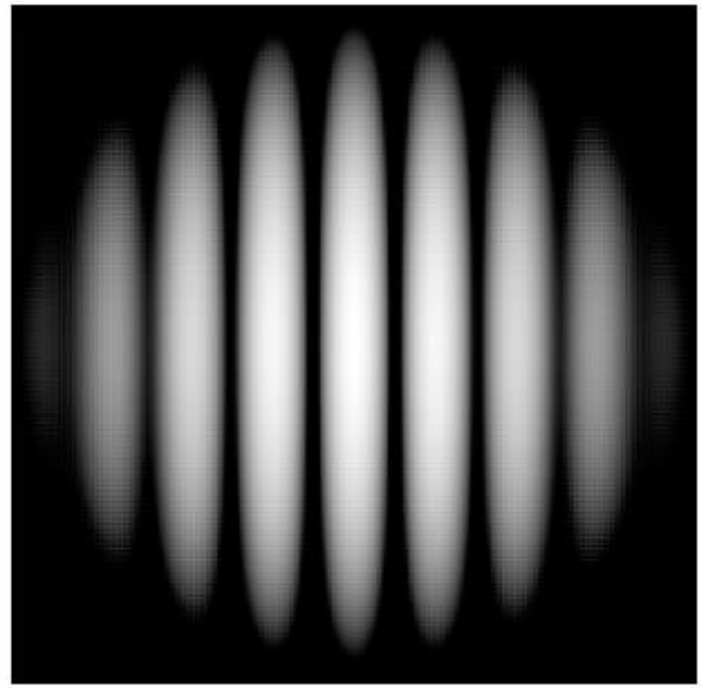
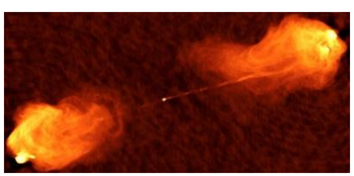






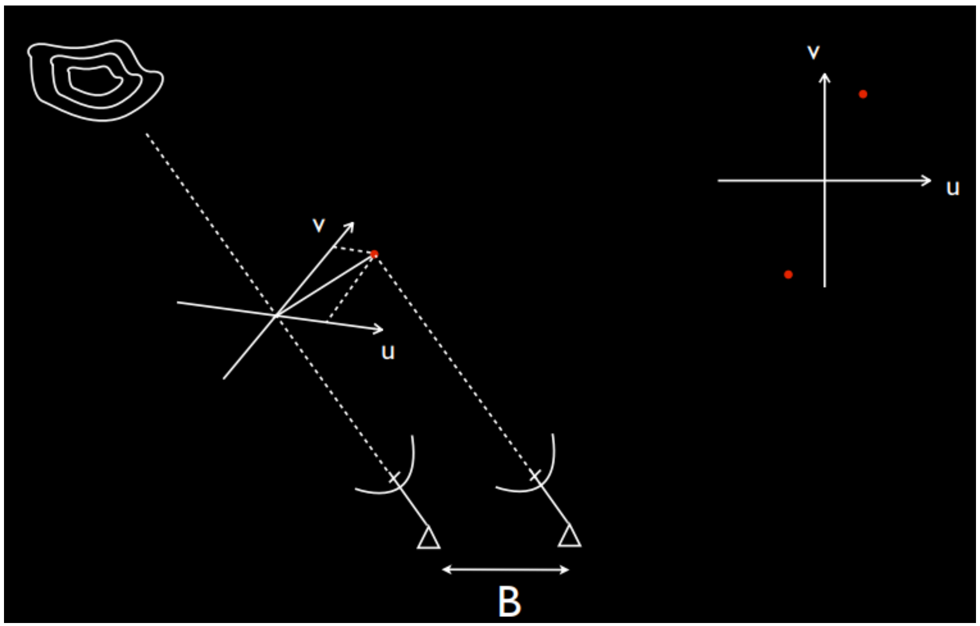
galaxy = torch

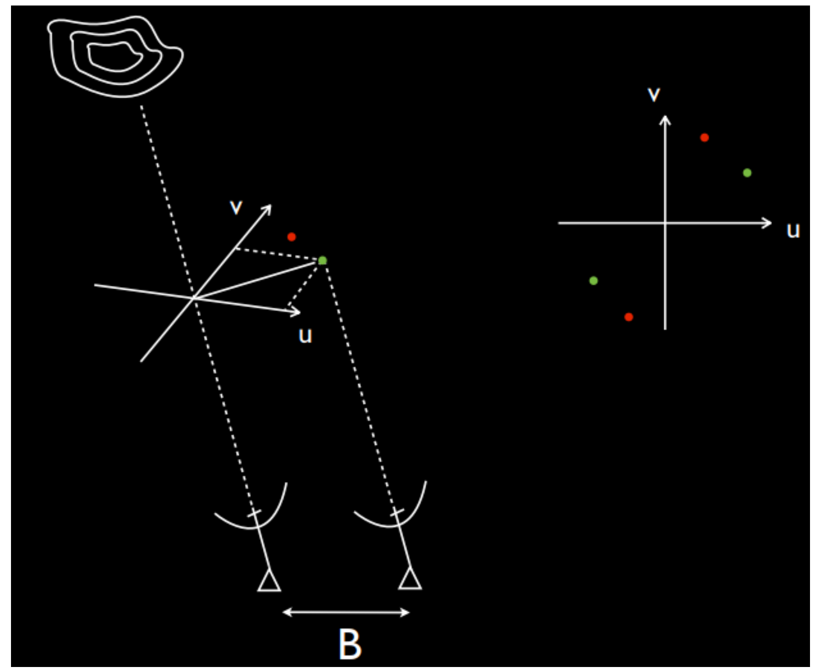
interferometer = double slit

Complex visibility function = interference pattern in screen

$$V = |V|e^{i\phi} \qquad |V| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

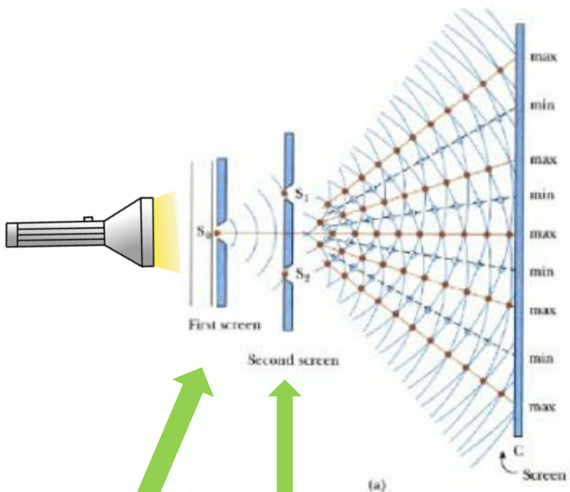
(Visibility or UV plane)

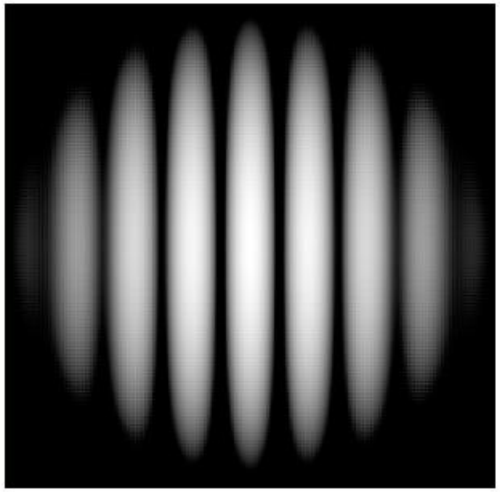




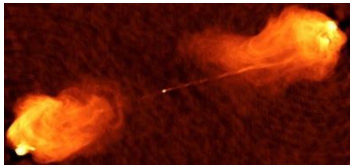
Plane perpendicular to the source direction, where the visibility function is measured during the observation

(Young double-slit experiment)

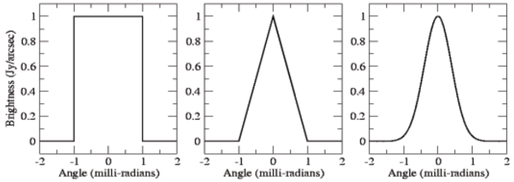




Complex visibility function

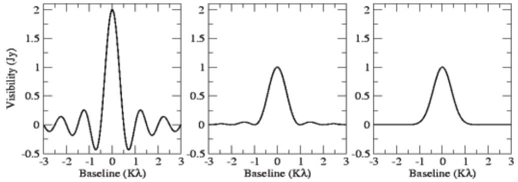


$$V = |V|e^{i\phi} \qquad |V| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

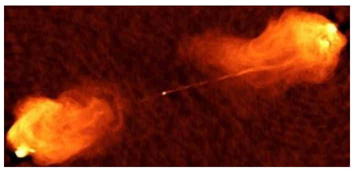


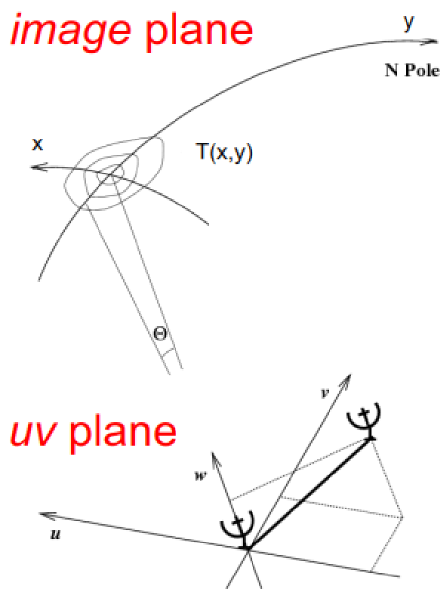
FT

FT^{-1}



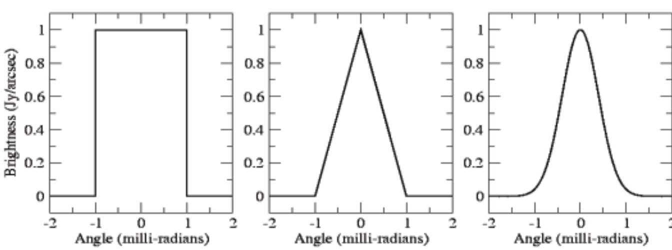
(Young double-slit experiment)





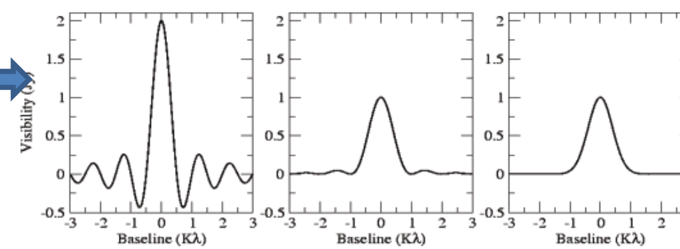
Complex visibility function

$$V = |V|e^{i\phi} \qquad |V| = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$



FT

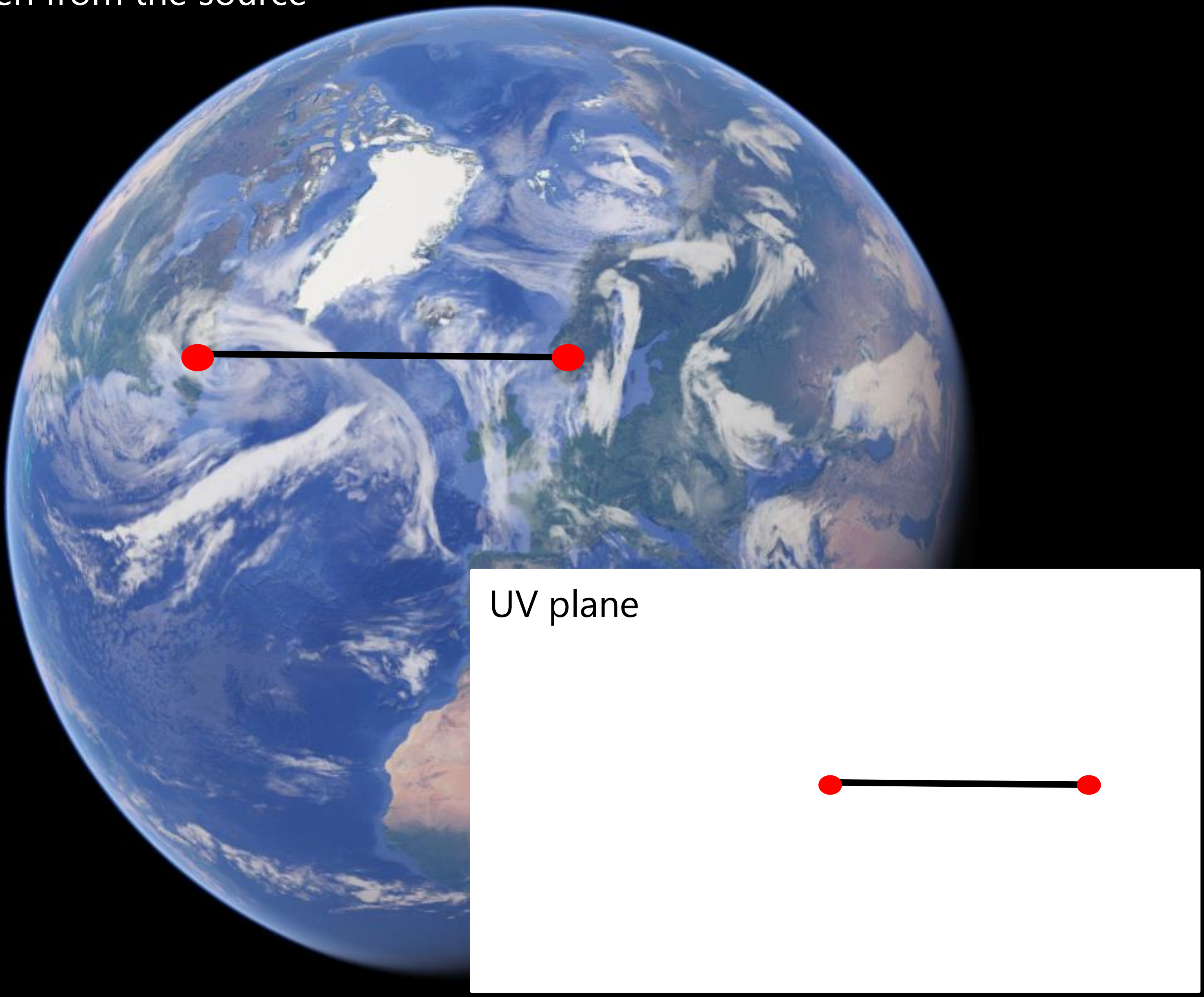
FT^{-1}



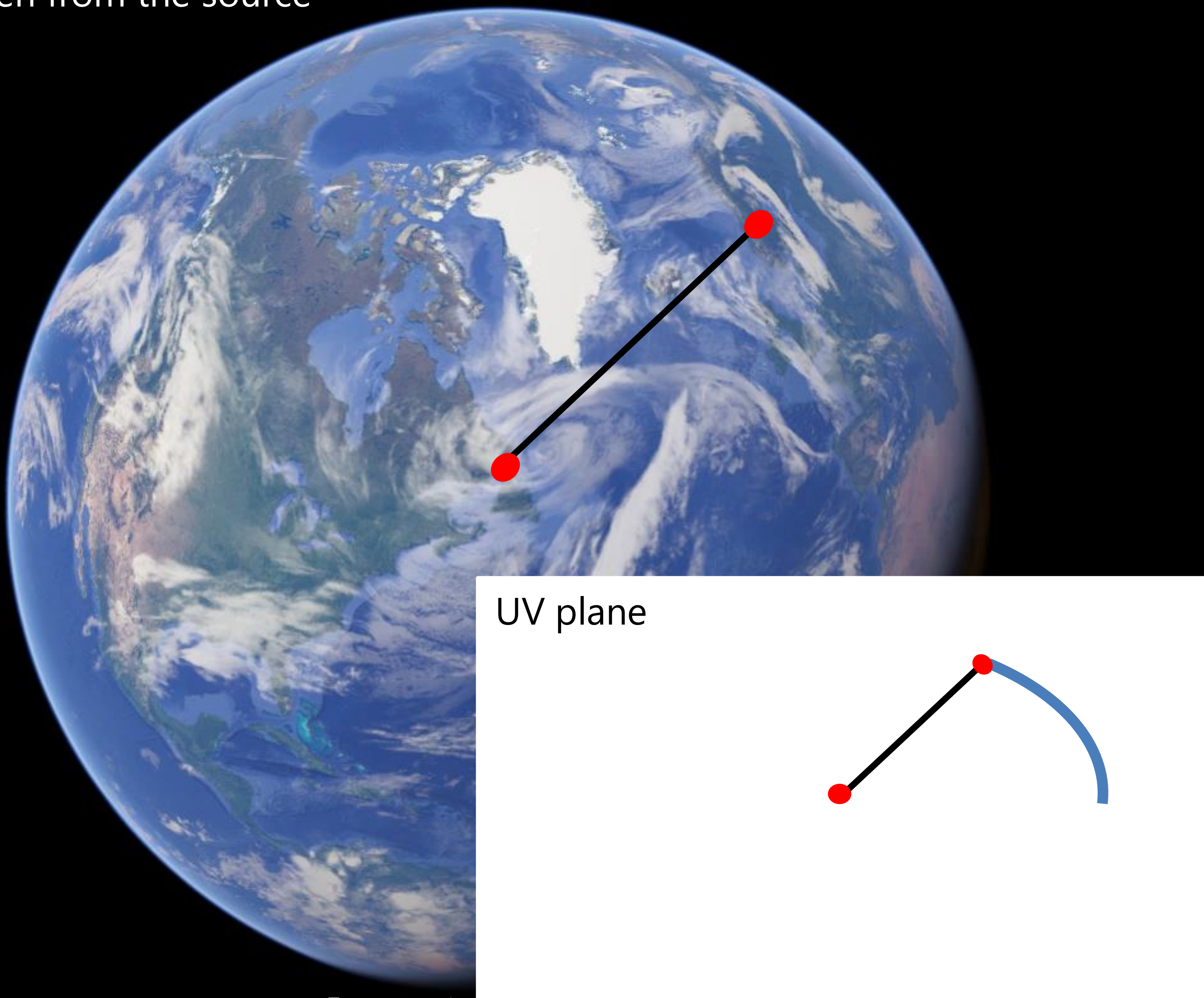
$$I(x,y) = \iint V(u,v)\, e^{-2\pi i(ux+vy)}\, du dv$$

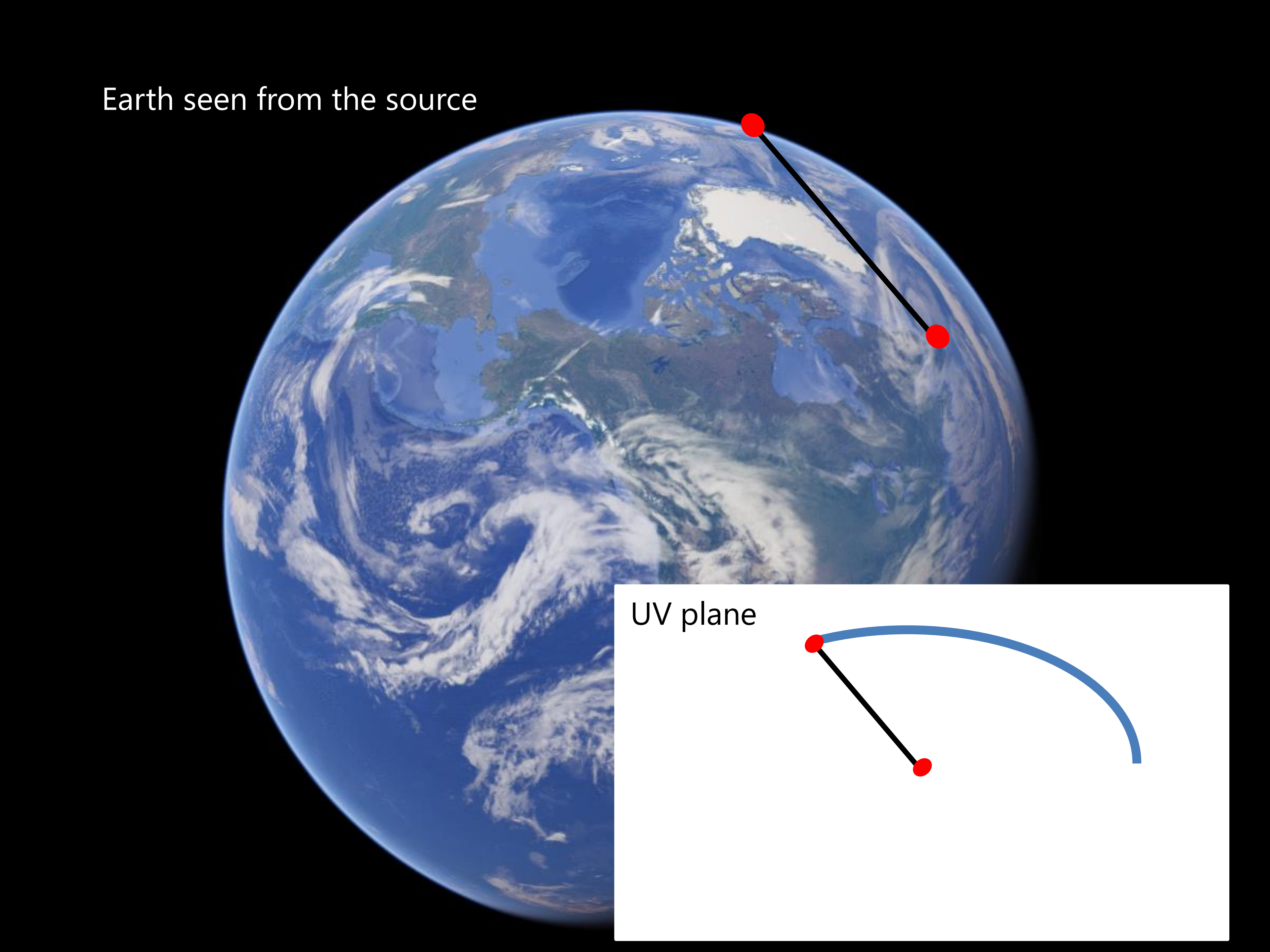
$$V(u,v) = \iint I(x,y)\, e^{2\pi i(ux+vy)}\, dx dy$$

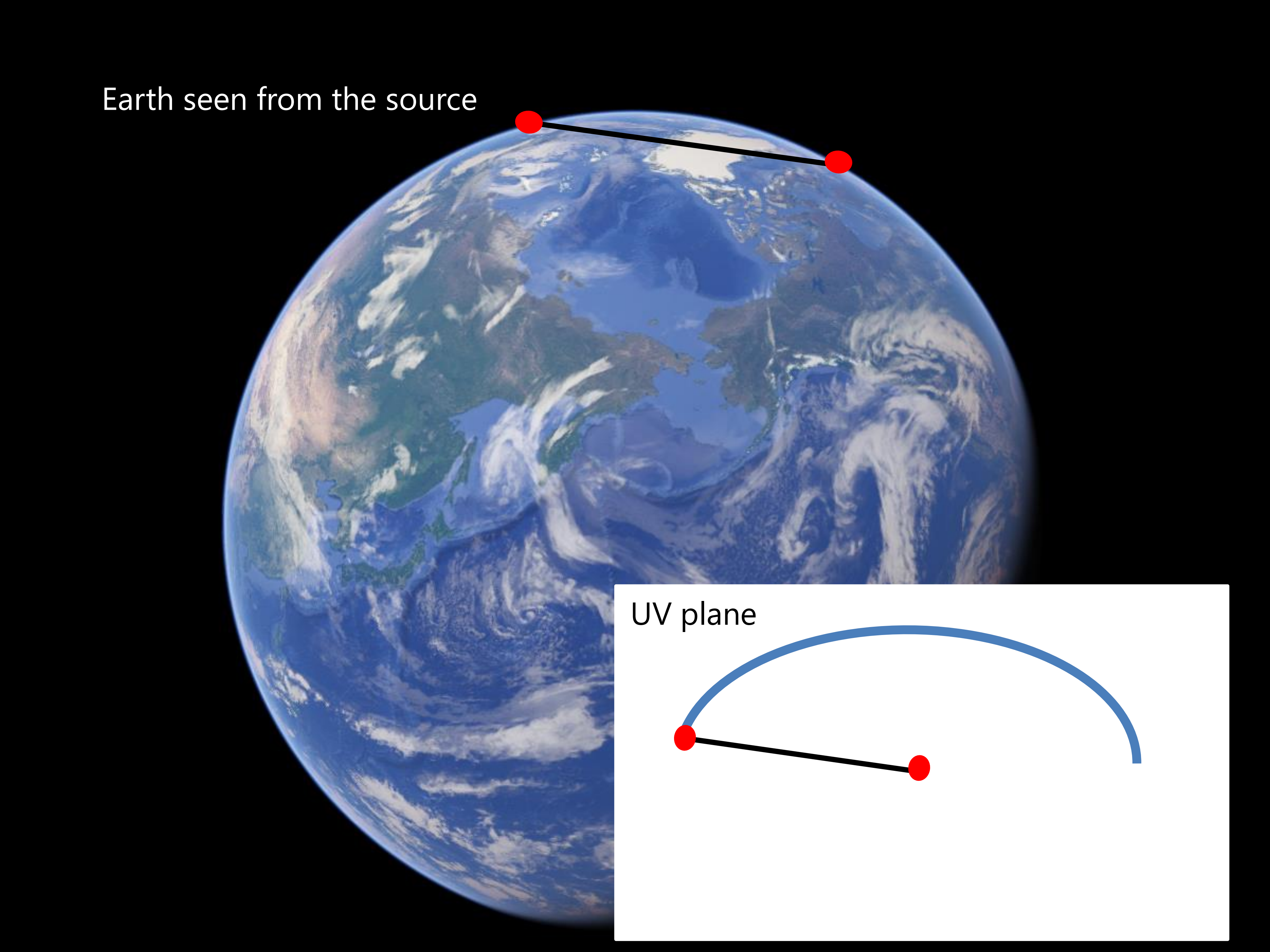
Earth seen from the source

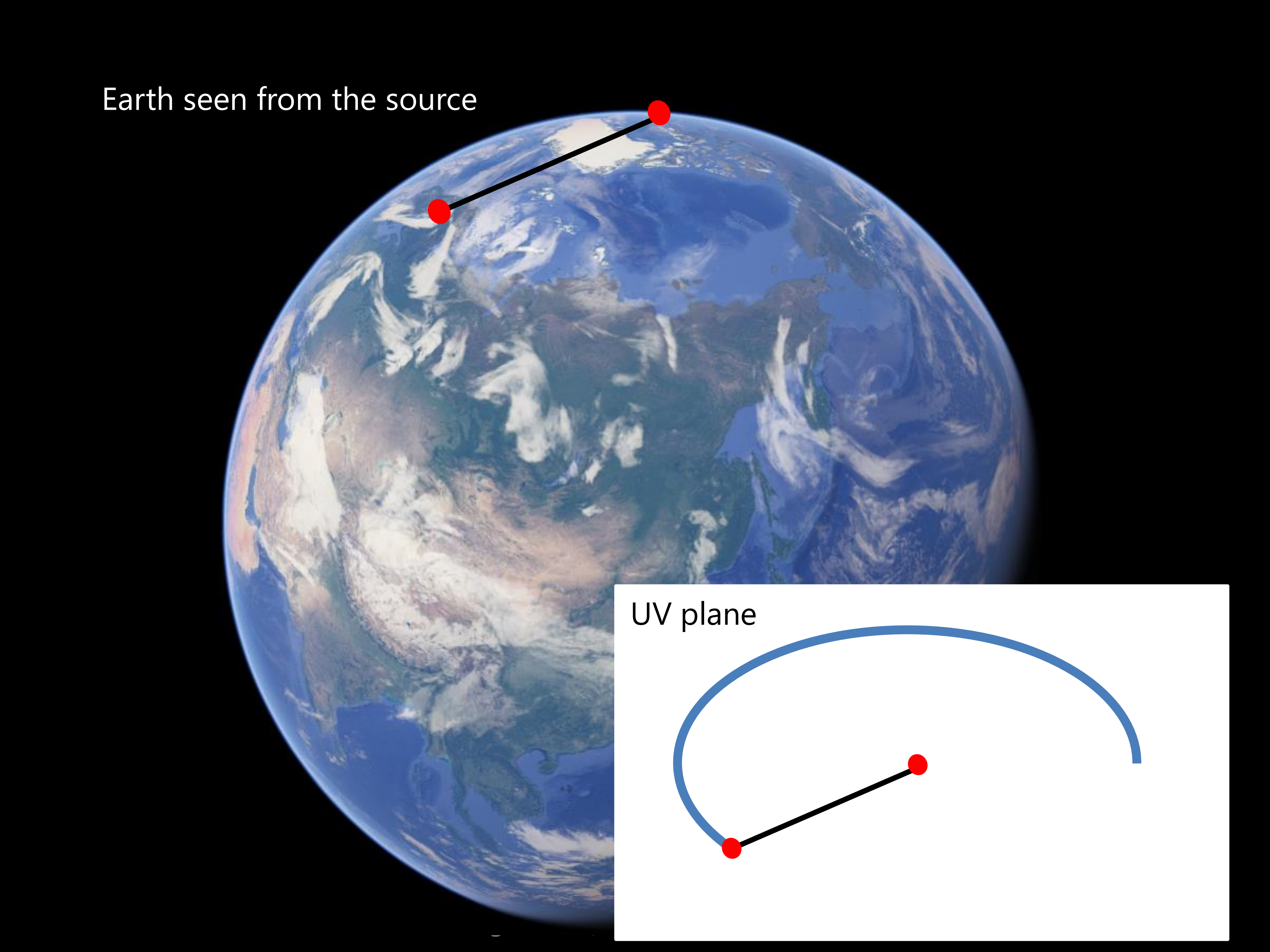


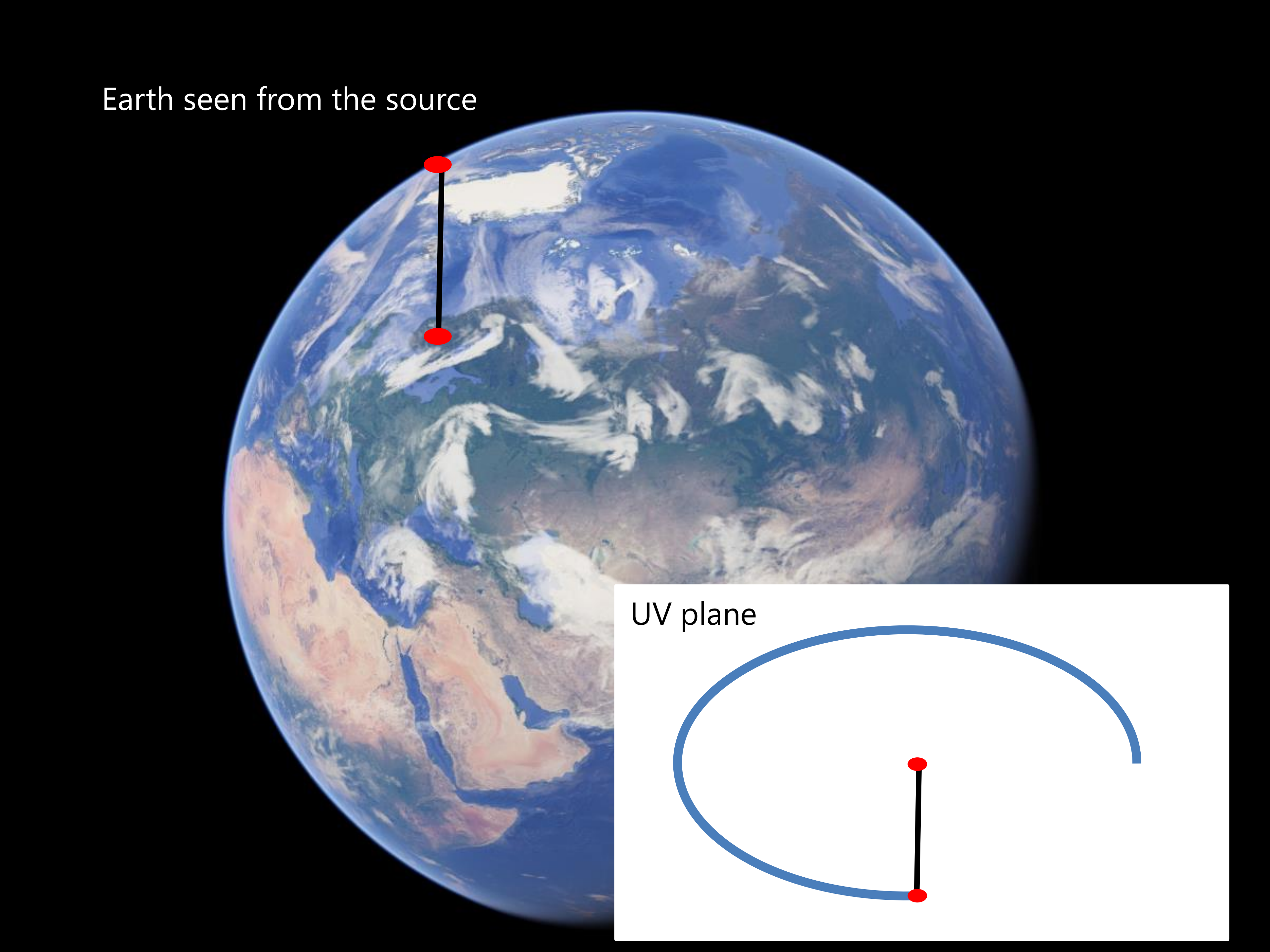
Earth seen from the source

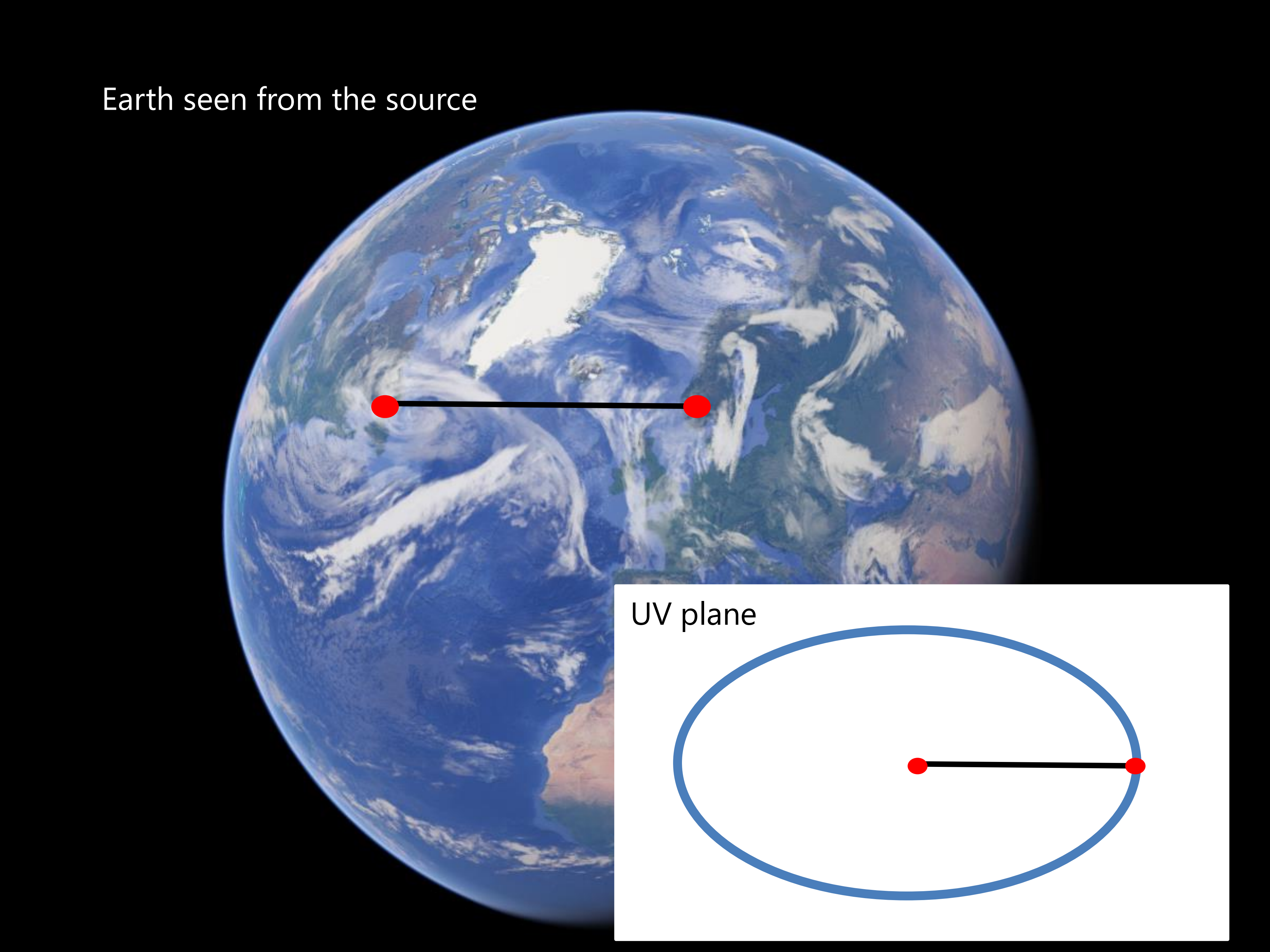



Earth seen from the source
UV plane


Earth seen from the source
UV plane

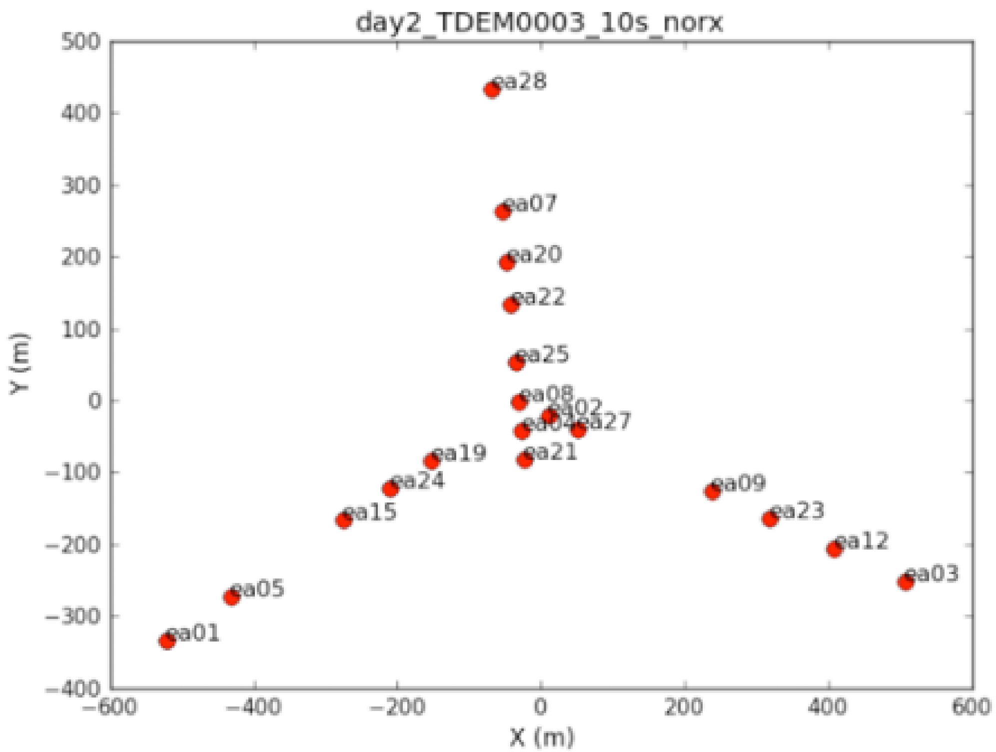

Earth seen from the source
UV plane

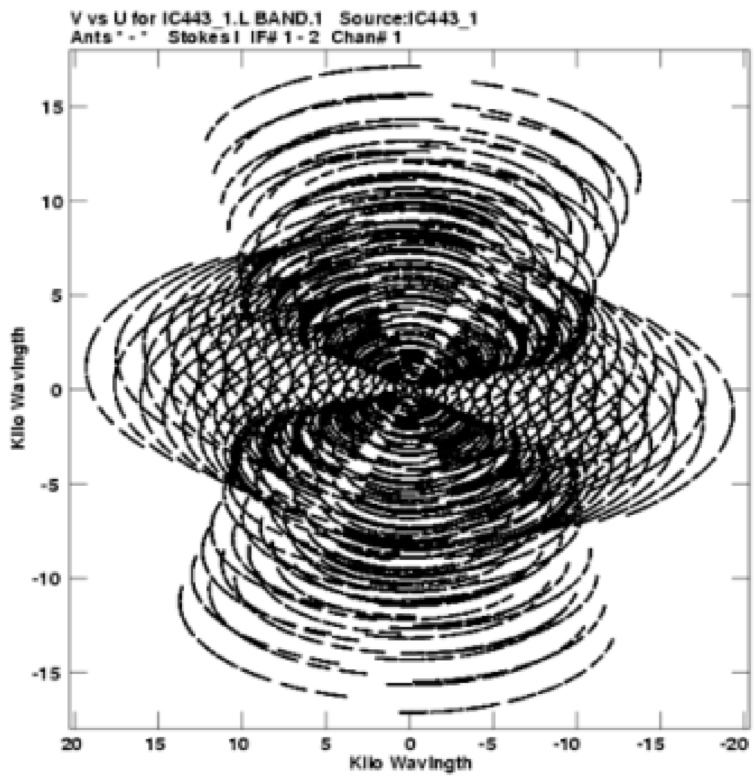

Earth seen from the source
UV plane


Earth seen from the source
UV plane

(Visibility or UV plane)

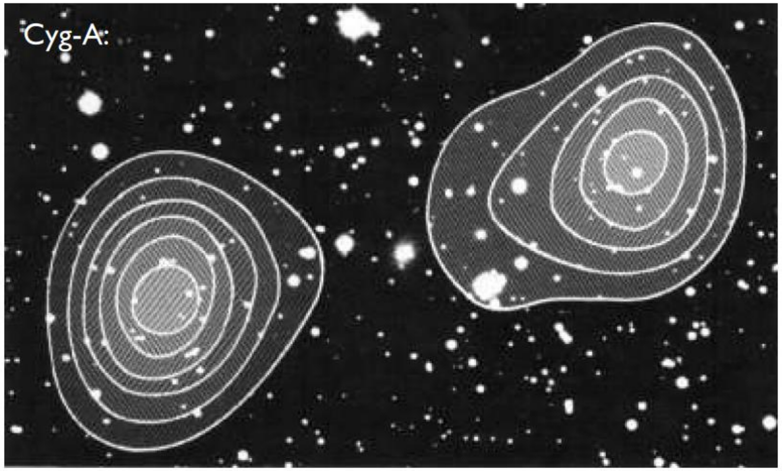
Plane perpendicular to the source direction, where the Visibility function is measured





Connected arrays: Aperture Synthesis

Cambridge one-mile (Ryle 62) and 5 Km radio telescopes (Ryle 72) up to 1 arcsec: first radio telescope at Cambridge designed to study structure of individual sources



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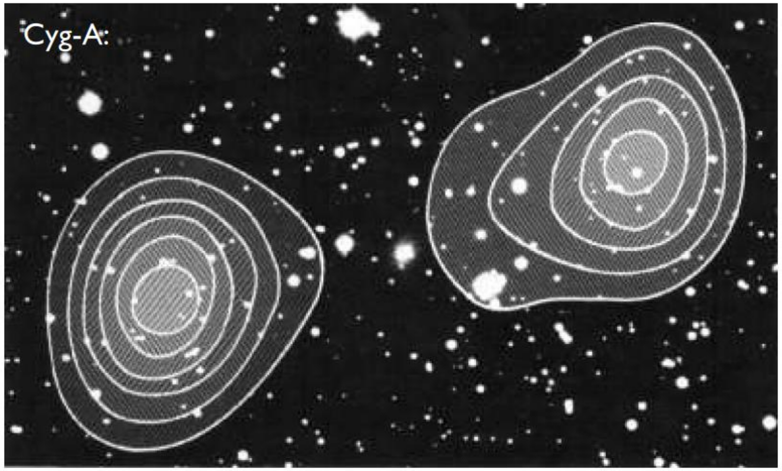

Aperture synthesis more powerful than cross-type interferometer

Need 1 arcsec resolution = optical

Connected arrays: Self-calibration

Manchester group shown: 3 elements give the phases without need for calibration!!

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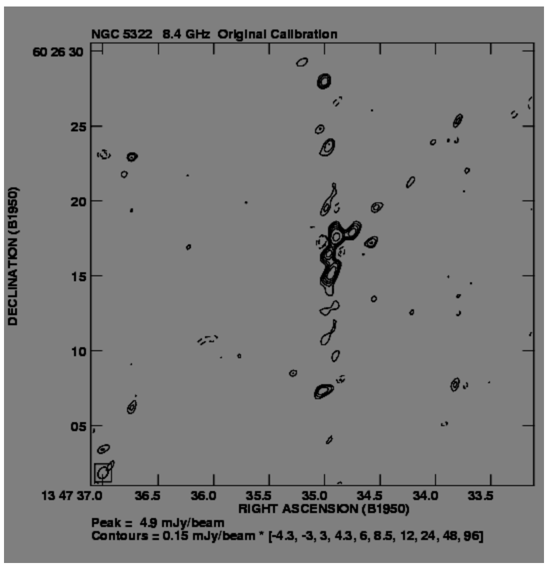
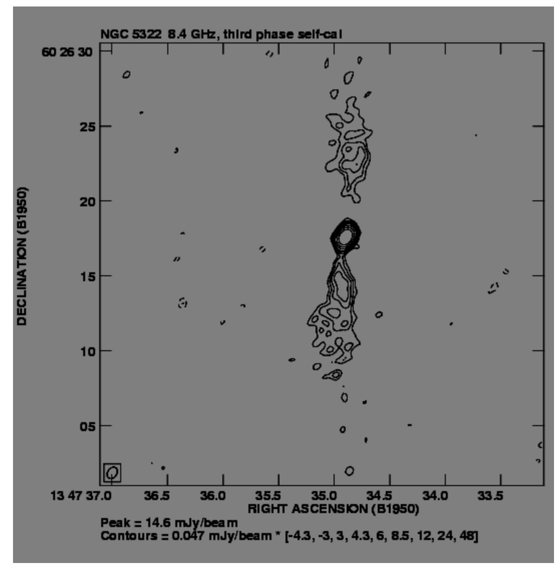


Initial image



Final image

Connected arrays: Self-calibration

Fundamental calibration equation

$$V_{ij}(t) = g_i(t)g_j^*(t)V^{true}(t) + \varepsilon_{ij}(t)$$

$V_{ij}(t)$	Visibility measured between antennas i and j
$g_i(t)$	Complex gain of antenna i
$V^{true}(t)$	True visibility
$\varepsilon_{ij}(t)$	Additive noise

Connected arrays: Self-calibration

Self-calibration preserves the ***Closure Phase*** which is a good observable even in the presence of antenna-based phase errors:

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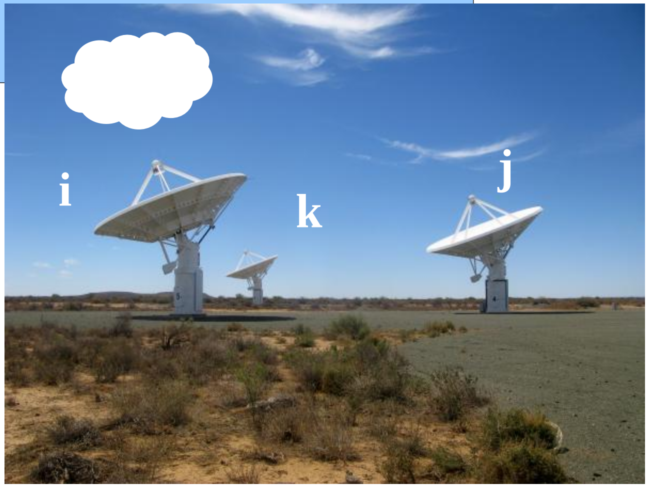
Self-calibration preserves the ***Closure Phase*** which is a good observable even in the presence of antenna-based phase errors:

$$\begin{aligned}\Phi_{ijk} &= \theta_{ij} + \theta_{jk} + \theta_{ki} \\ &= \theta_{ij}^{\text{true}} + \left(\phi_i - \phi_j\right) + \theta_{jk}^{\text{true}} + \left(\phi_j - \phi_k\right) + \theta_{ki}^{\text{true}} + \left(\phi_k - \phi_i\right) \\ &= \theta_{ij}^{\text{true}} + \theta_{jk}^{\text{true}} + \theta_{ki}^{\text{true}}\end{aligned}$$

Closure Phase cancels out contribution from atmosphere, electronics, etc.



Connected arrays:
The Westerbork Synthesis Radio Telescope

East-west array of 10 fixed and 2 movable 25-m dishes with baselines up to 1 mile (1970),
21 cm with 23 arcsec.
Upgrade with 2 more movable antennas, up to 3 Km baselines, new instrumentation: improved resolution and sensitivity: 2 arcsec at 3.6 cm
Redundant spacings: improves robustness of self-calibration leading to images with enhanced dynamic range

Connected arrays:
The Very Large Array – VLA (1980)

27 antennas of 25-m diameter
4 configurations (0.6-36 Km)
1.3-20 cm
Up to 0.1 arcsec resolution

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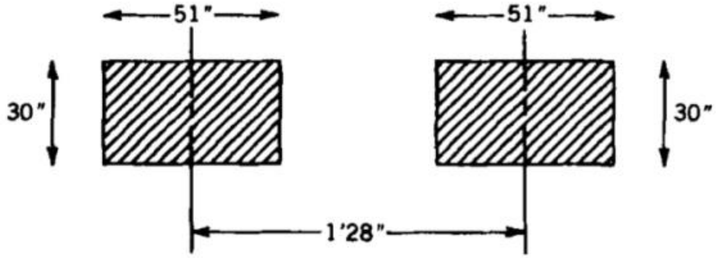

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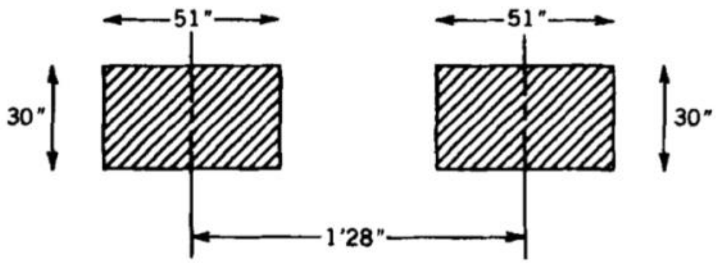
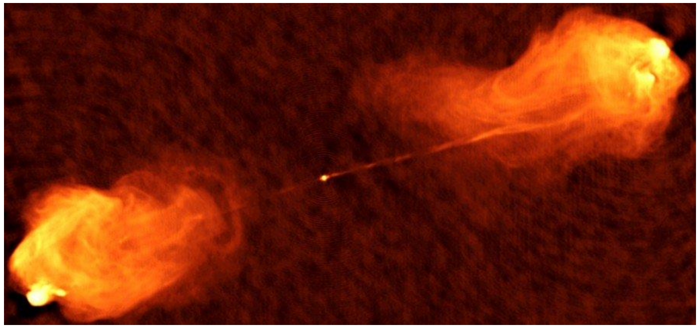




Let’s VLBI begin…

“FATHERS OF VLBI” AT IAU164, 1997

Jim Moran Marshall Cohen Bernard Burke

Dave Jauncey Ken Kellermann Barry Clark

Let's VLBI begin…

Let’s VLBI begin…

First intercontinental in SH between DSS-51 (HartRAO) and DSS-41 (Woomera), Nicolson 1970.

Let's VLBI begin…

Aperture synthesis & Self-calibration

Let’s VLBI begin…

Aperture synthesis & Self-calibration

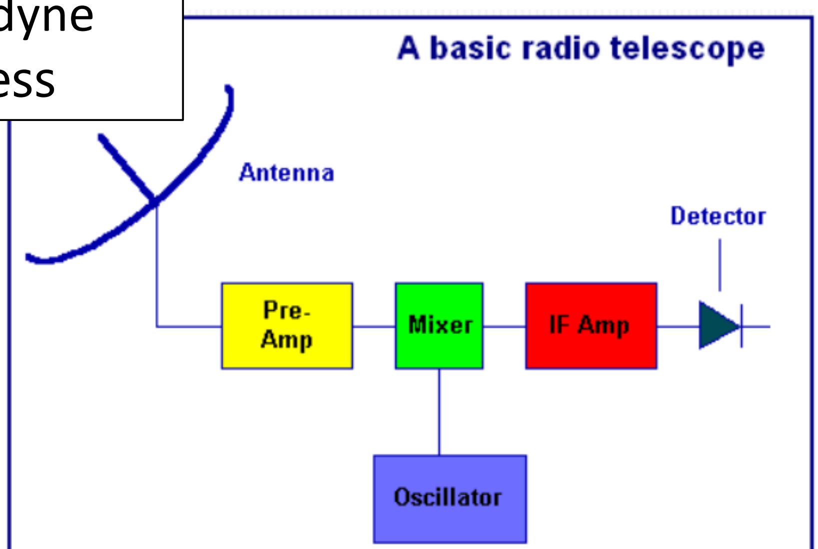
+

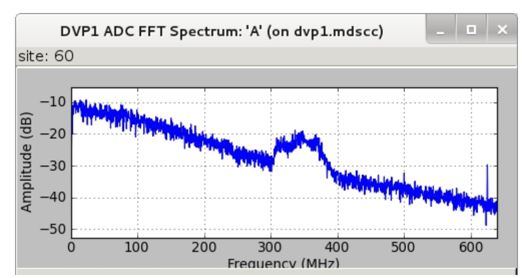
Heterodyne receivers
Atomic clocks
(CLEAN algorithm)

VLBI: Heterodyne Receivers

Both the amplitude and the phase of the incoming signal are measured by each telescope. Signal is converted to an intermediate frequency and sampled:

Heterodyne process



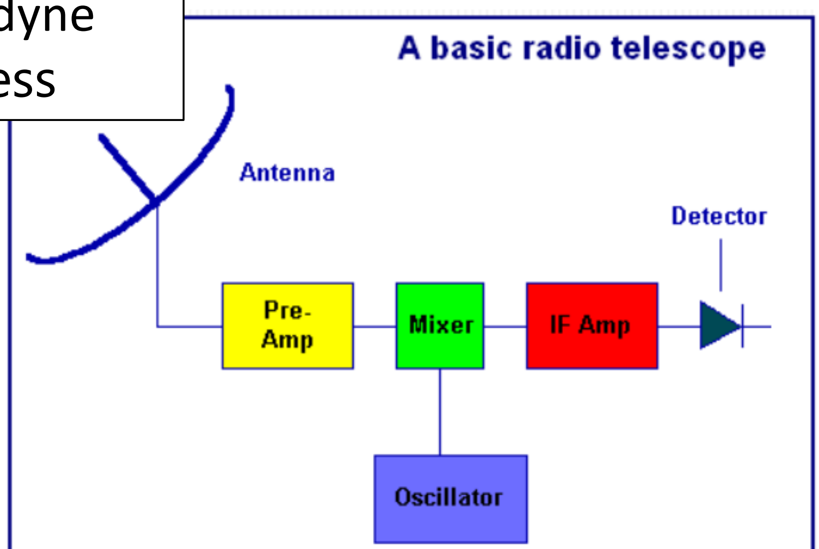


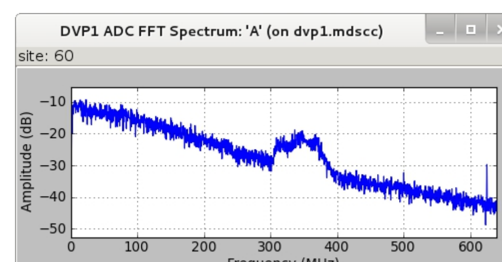
VLBI: Heterodyne Receivers

Both the amplitude and the phase of the incoming signal are measured by each telescope. Signal is converted to an intermediate frequency and sampled:

- **Pros:** Nyquist sampling rate much lower than for sky frequencies (2 orders of magnitude smaller).
- **Pros:** Allows post-processing of the signal: spectroscopy and non real-time interferometry → **VLBI has born!**
- **Cons:** Less sensitive tan bolometric receivers with smaller bandwidths (few GHz) but high spectral resolution.

Heterodyne process





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Both the amplitude and the phase of the incoming signal are measured by each telescope. Signal is converted to an intermediate frequency and sampled:

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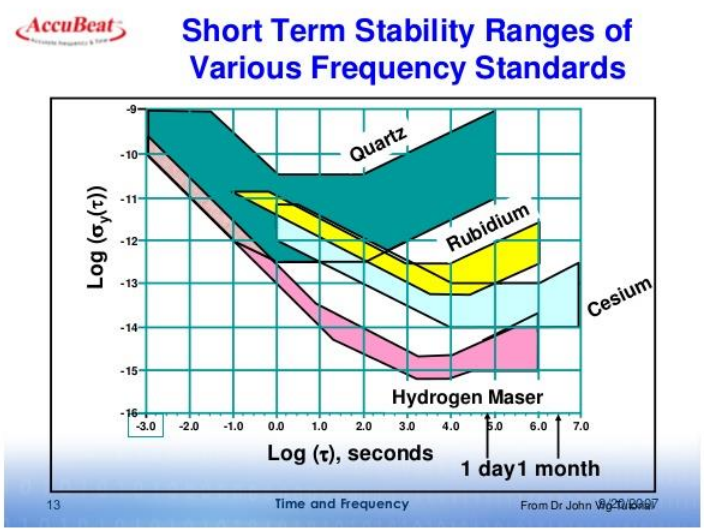
- **Pros:** Allows post-processing of the signal: spectroscopy and non real-time interferometry → **VLBI has born!**
- **Cons:** Less sensitive tan bolometric receivers with smaller bandwidths (few GHz) but high spectral resolution.

B5 receiver (Chalmers Univ., Sweden) implemented for ALMA (JAO, Chile)

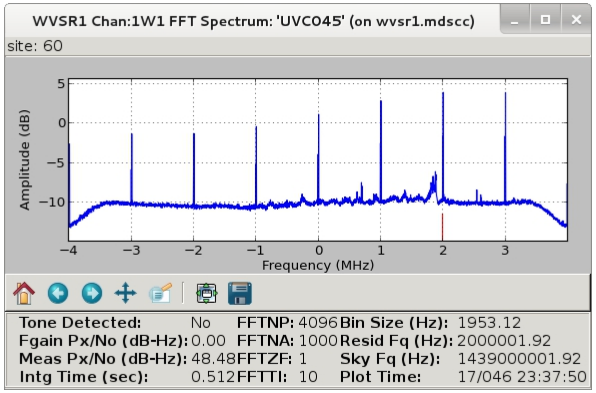
VLBI: Atomic Clocks

Atomic clocks are the **most accurate time and frequency standards** known, and are used as primary standards.
They use the emission from different atomic transitions: HI, cesium-133 (second definition by International System of Units), rubidium-87, etc.
Hydrogen masers superior short-term stability, but lower long-term accuracy.



VLBI: Phase Calibration Signal

Tones generated by injecting a pulse once per μsec ("comb" of very narrow, weak spectral lines every MHz)
Use to **correct for instrumental delays and phase shifts** (diurnal phase shift in cables due to temperature, electronics, etc.) between baseband converters.



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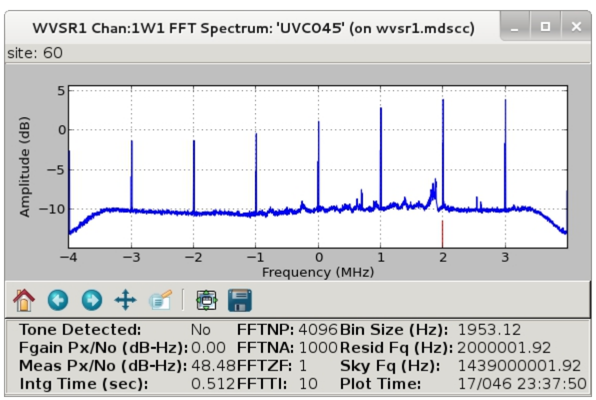
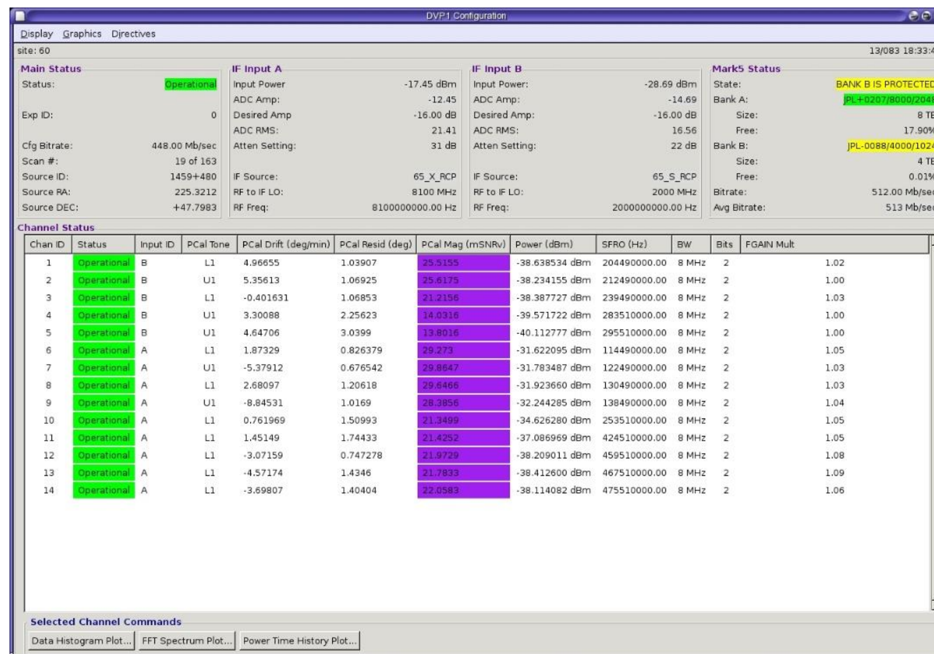
The phases of one or more of these lines are measured by the detector in real-time, logged as a function of time, and delivered in a log or table.

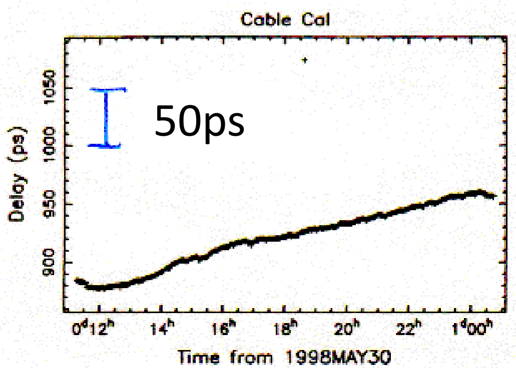
Also extracted at the correlator.





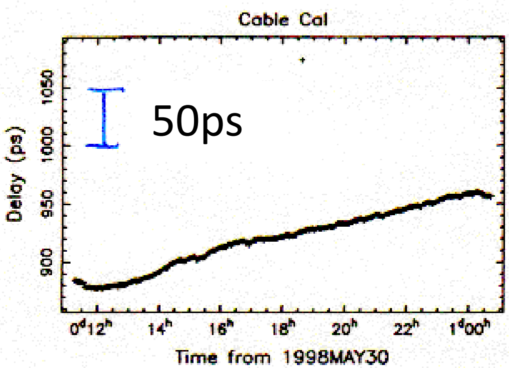
VLBI: Phase Calibration Signal

Cable Cal

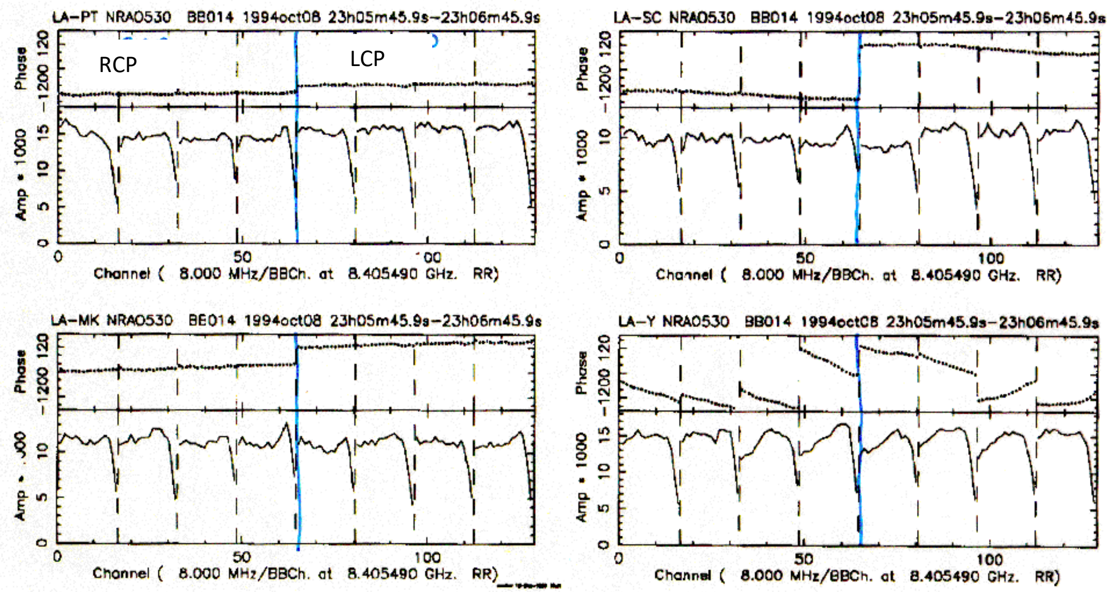


VLBI: Phase Calibration Signal

Cable Cal



Data Aligned with Pulse Cal



No PCAL at VLA

Shows unaligned phases

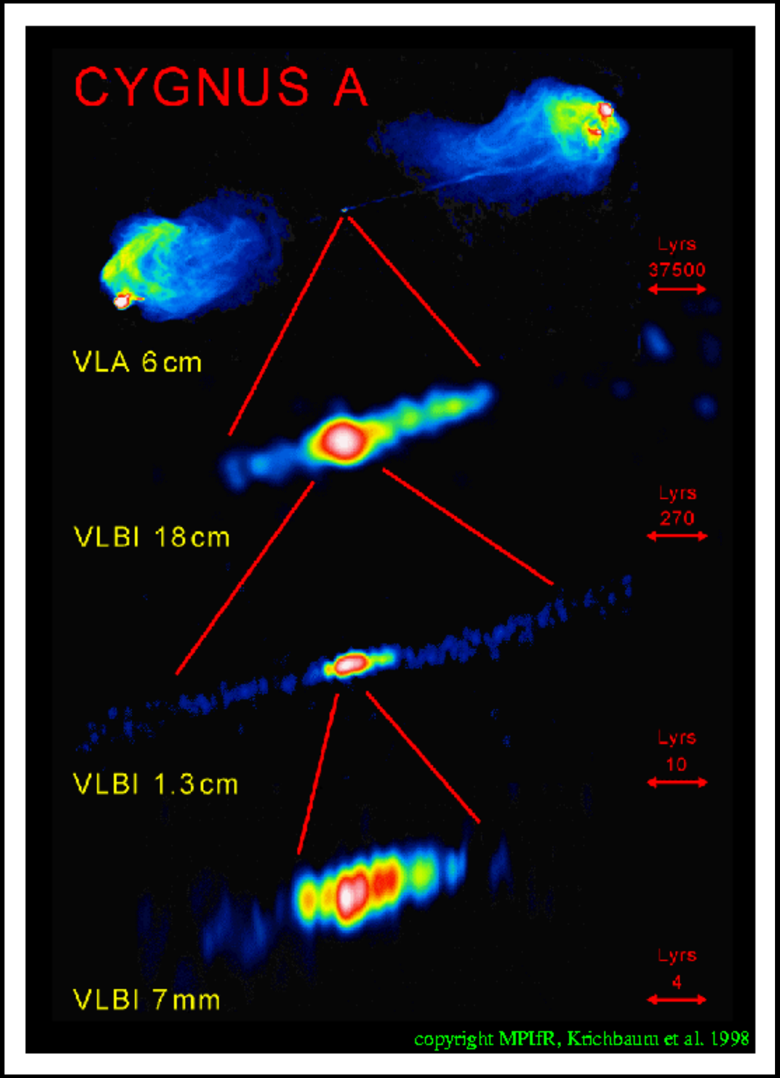
VLBI Networks

Very Long Baseline Array

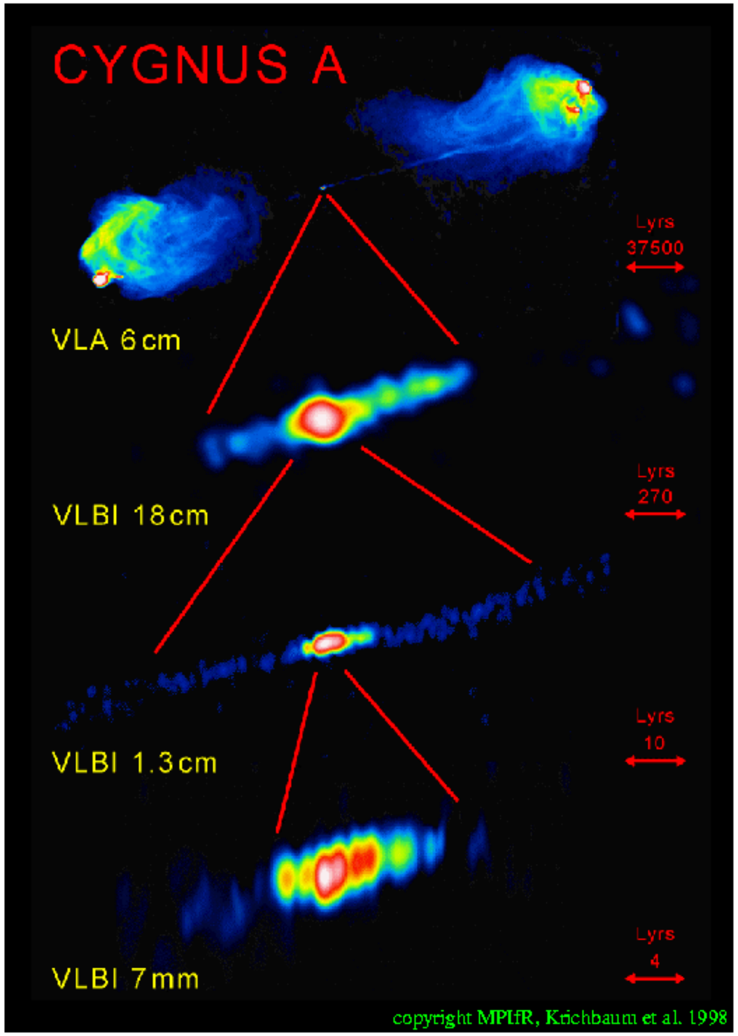
European VLBI Network

VLBI Networks: Deep Space Network

VLBI Networks



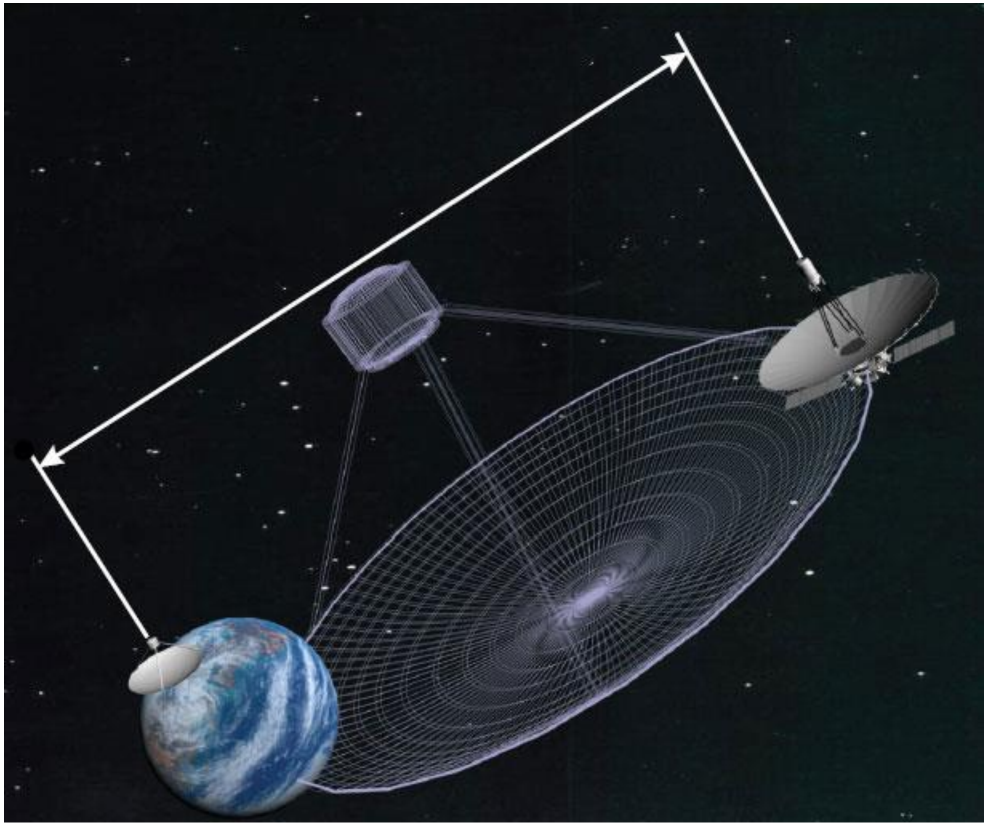
VLBI Networks



VLBI thanks to...

Better behavior of the atmosphere
Electromagnetic waves behavior:
Interference
Aperture Synthesis
Self-calibration (and CLEAN)
Atomic Clocks
Heterodyne receivers
Digitization techniques
Phase calibration tones

Space VLBI: RadioAstron



Max baseline 350000 Km

151 MHz - 24 GHz

40 μas angular resolution

VLBI: Data Acquisition Terminal - DAT

Functions of DAT:

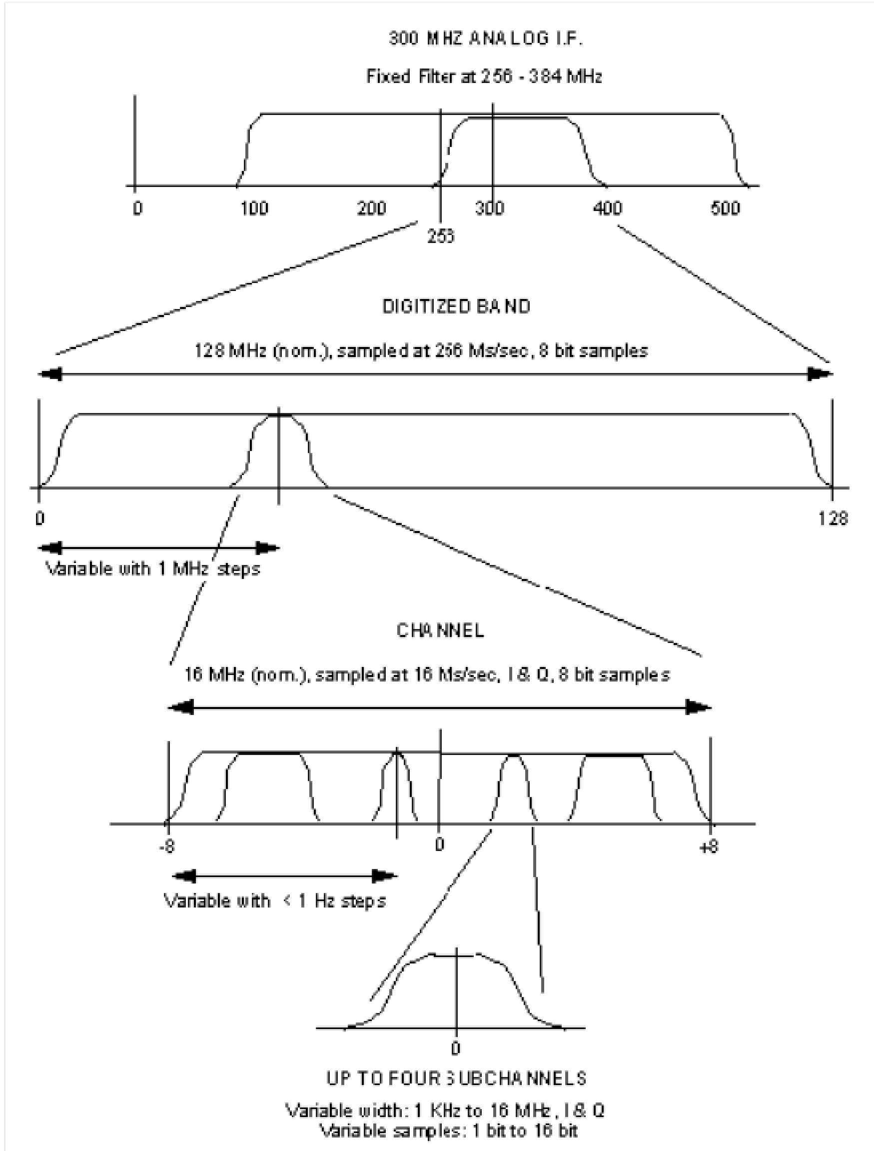
- IF signal selection
- Conditioning of the signal: amplification & attenuation
- Channelization and baseband conversion
- Formatting: digitization and time tag
- Recording
- Transport of data to correlator

Configuration & Control:

- Field System

VLBI: Baseband conversion

IF



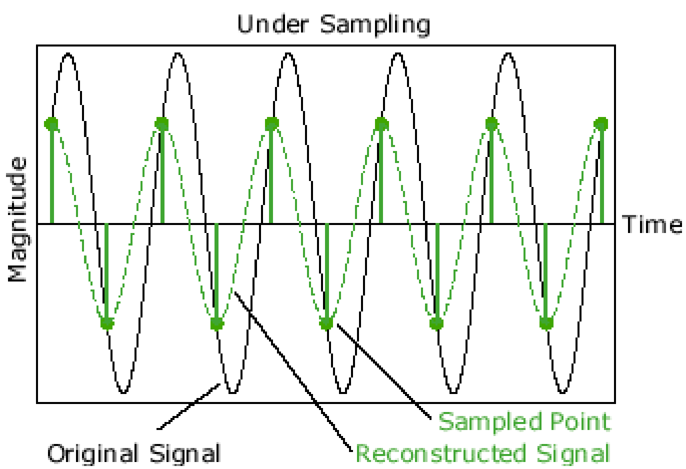
BB

VLBI: Digitization

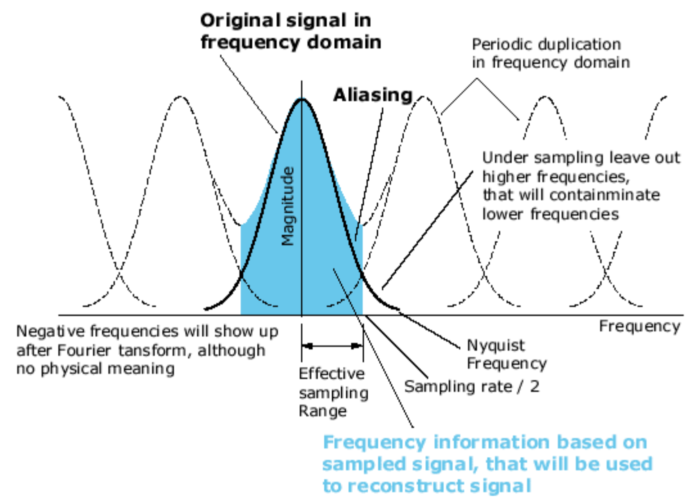
NYQUIST SAMPLING THEOREM (1933)

An analog signal waveform may be uniquely reconstructed without error from samples taken at equal time intervals. Sampling rate must be equal, or greater than, twice the highest frequency component in the analog signal.

SAMPLE RATE < ⇨ UNDER SAMPLING



Original signal cannot be reconstructed



Under sampling causes aliasing: frequency components that are higher than half of the sampling frequency

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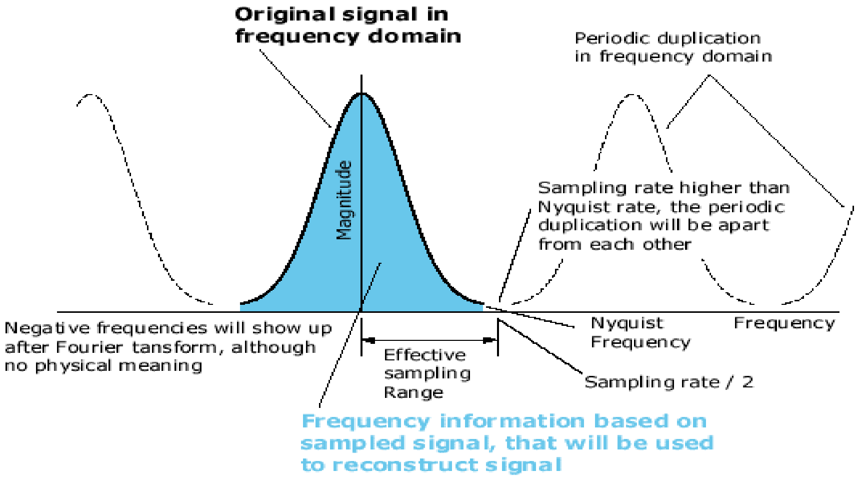
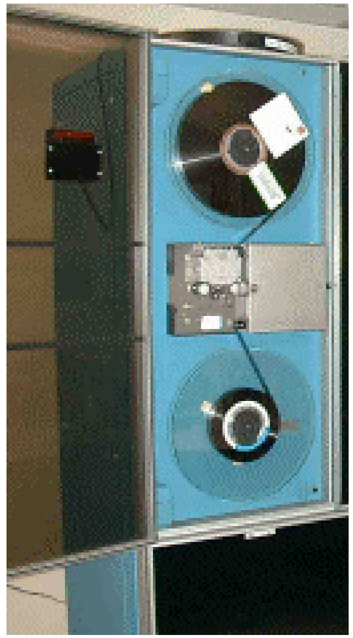
SAMPLE RATE **>** ⇨ OVER SAMPLING



Original signal can be reconstructed

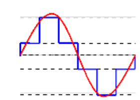
Increasing sampling rate SNR increases but more bits will be recorded

VLBI: MarkIV and VLBA DAT



Baseband conversion: analog filtering and down conversion, upper and lower side bands, 14 maximum video converters, bandwidth ≤ 16 MHz

Formatter or digitizer: Samples 28 channels, 2 bits, with time code, parity bit and sync word

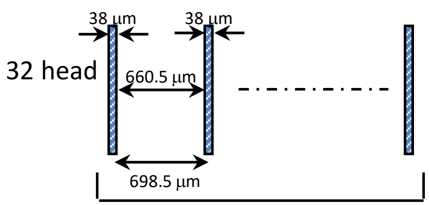


IF signal selection: 2 IF outputs, high and low filters

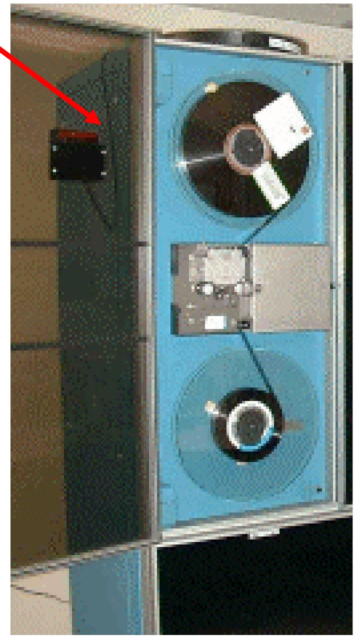
IF signal conditioning: Amplification + attenuation

VLBI: MarkIV and VLBA DAT

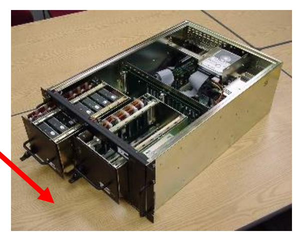
Recording:
Honeywell/Metrum magnetic recorder/reproducer
thick (8820 ft, 33333 bpi)
thin (17600 ft, 56250 bpi)
14 passes → 448 tracks
8 Mbps/head, 1Gbps



2 x Headstack



Recording:
Mark5A recorder/reproducer
Up to 1024Mbps
8-pack disk modules



Transport of data to correlator

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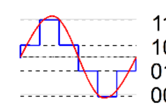

IF signal selection:
2 IF outputs,
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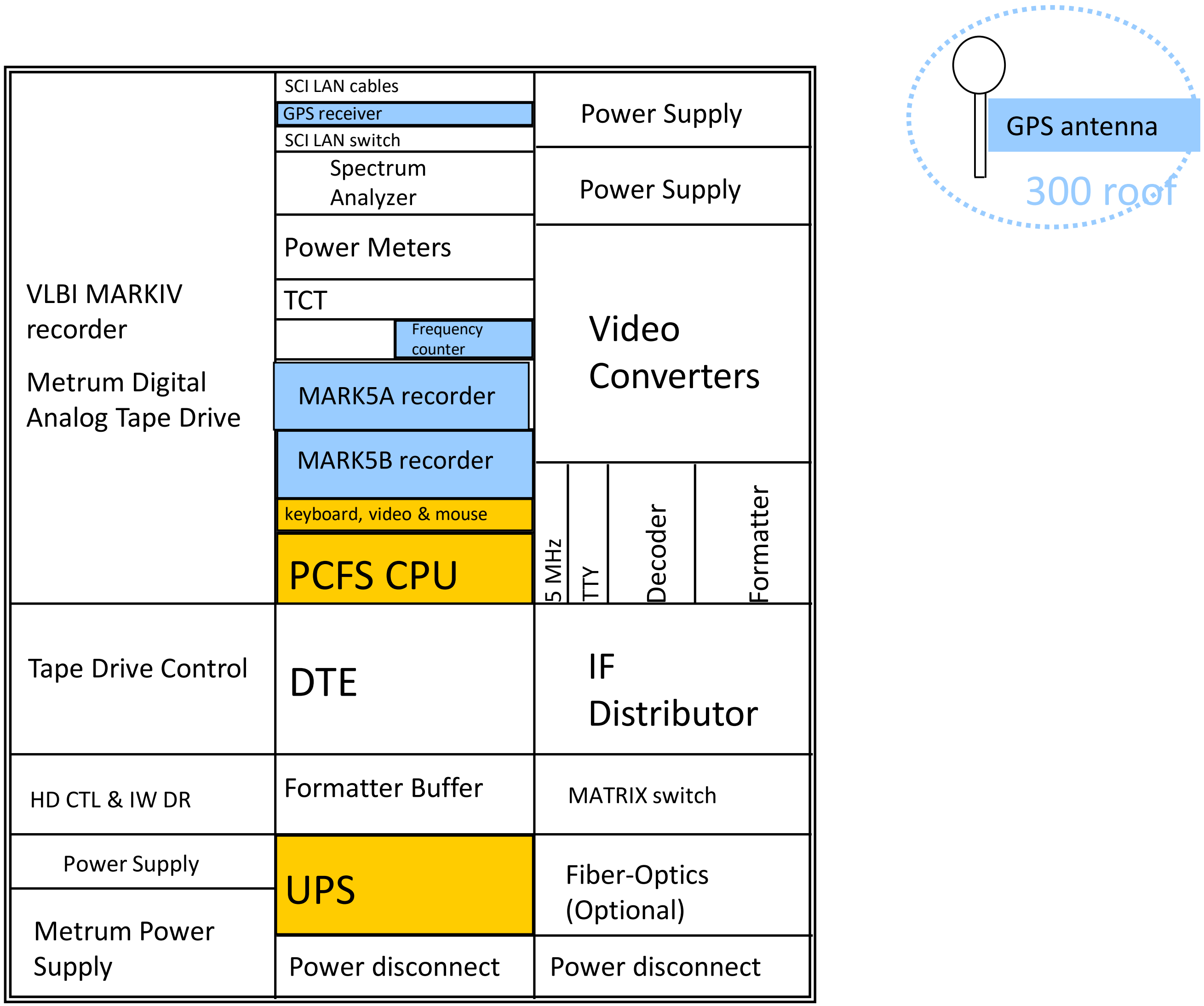
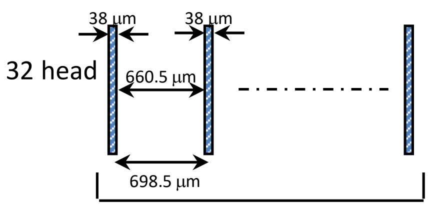
Amplification + attenuation

VLBI: MarkIV and VLBA DAT

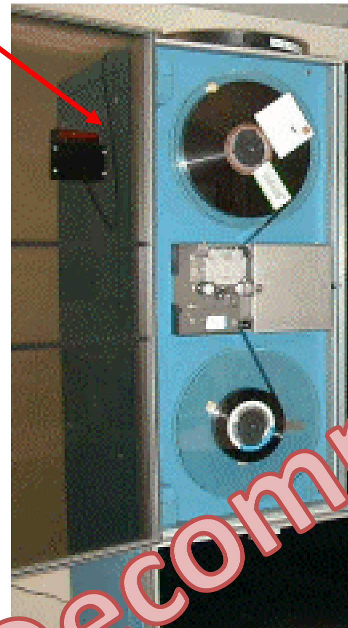


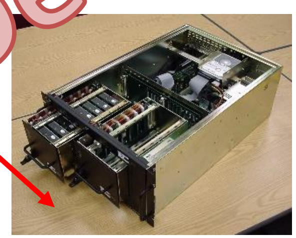
VLBI: MarkIV and VLBA DAT

Recording:
Honeywell/Metrum magnetic recorder/reproducer
thick (8820 ft, 33333 bpi)
thin (17600 ft, 56250 bpi)
14 passes → 448 tracks
8 Mbps/head, 1Gbps



2 x Headstack

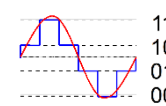




Decommisioned

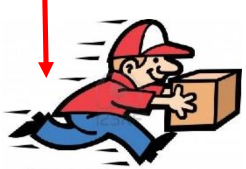
Baseband conversion: analog filtering and down conversion, upper and lower side bands, 14 maximum video converters, bandwidth ≤ 16 MHz

Formatter or digitizer:
Samples 28 channels, 2 bits, with time code, parity bit and sync word



Recording:
Mark5A recorder/reproducer
Up to 1024Mbps
8-pack disk modules

Transport of data to correlator

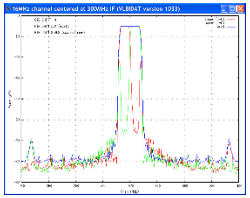


IF signal conditioning:
Amplification + attenuation

IF signal selection:
2 IF outputs,
high and low filters

VLBI: DSN VLBI Processor - DVP

Baseband conversion:
channelization and sub-band filtering with ROACH/CASPER board
JPL interface module to ROACH

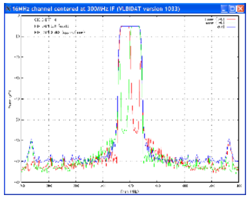


Digitizer: JPL IF digitizer module
100-600MHz
8bits @ 1280MHz sampling rate
Digitally controlled built-in attenuator
Reduced spurious signals below 97dB

IF signal selection: COTS switch
12 inputs, 2 outputs

VLBI: DSN VLBI Processor - DVP

Baseband conversion:
channelization and sub-band filtering
with ROACH/CASPER board
JPL interface module to ROACH



Recording: Mark5C recorder
(2Gbps limited by DSN s/w)
VDIF format

Digitizer: JPL IF digitizer module
100-600MHz
8bits @ 1280MHz sampling rate
Digitally controlled built-in attenuator
Reduced spurious signals below 97dB

**Transport of data
to correlator**

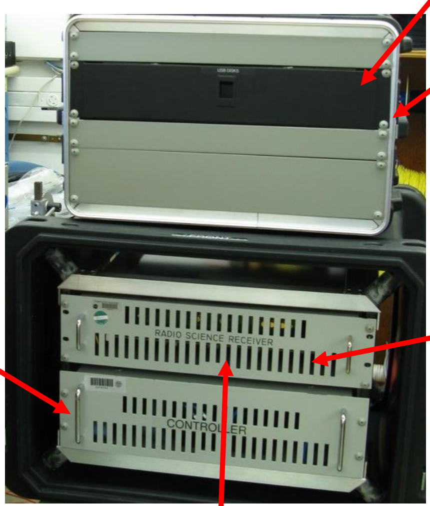
IF signal selection: COTS switch
12 inputs, 2 outputs

VLBI: DSN Portable Radio Science Receiver

IF signal selection: manual
1 IF input

IF signal conditioning:
Amplification + attenuation

Recording: hard disk in DSN format



Digitizer: JPL IF digitizer module
100-600MHz
8bits @ 1280MHz sampling rate
Digitally controlled built-in attenuator
Reduced spurious signals below 97dB

Transport of data to correlator

Baseband conversion:
channelization and sub-band filtering with FPGA board

VLBI:
DSN Portable Radio Science Receiver

IF signal selection: manual
IF input

signal conditioning:
mplification + attenuation

Recording: hard disk
format

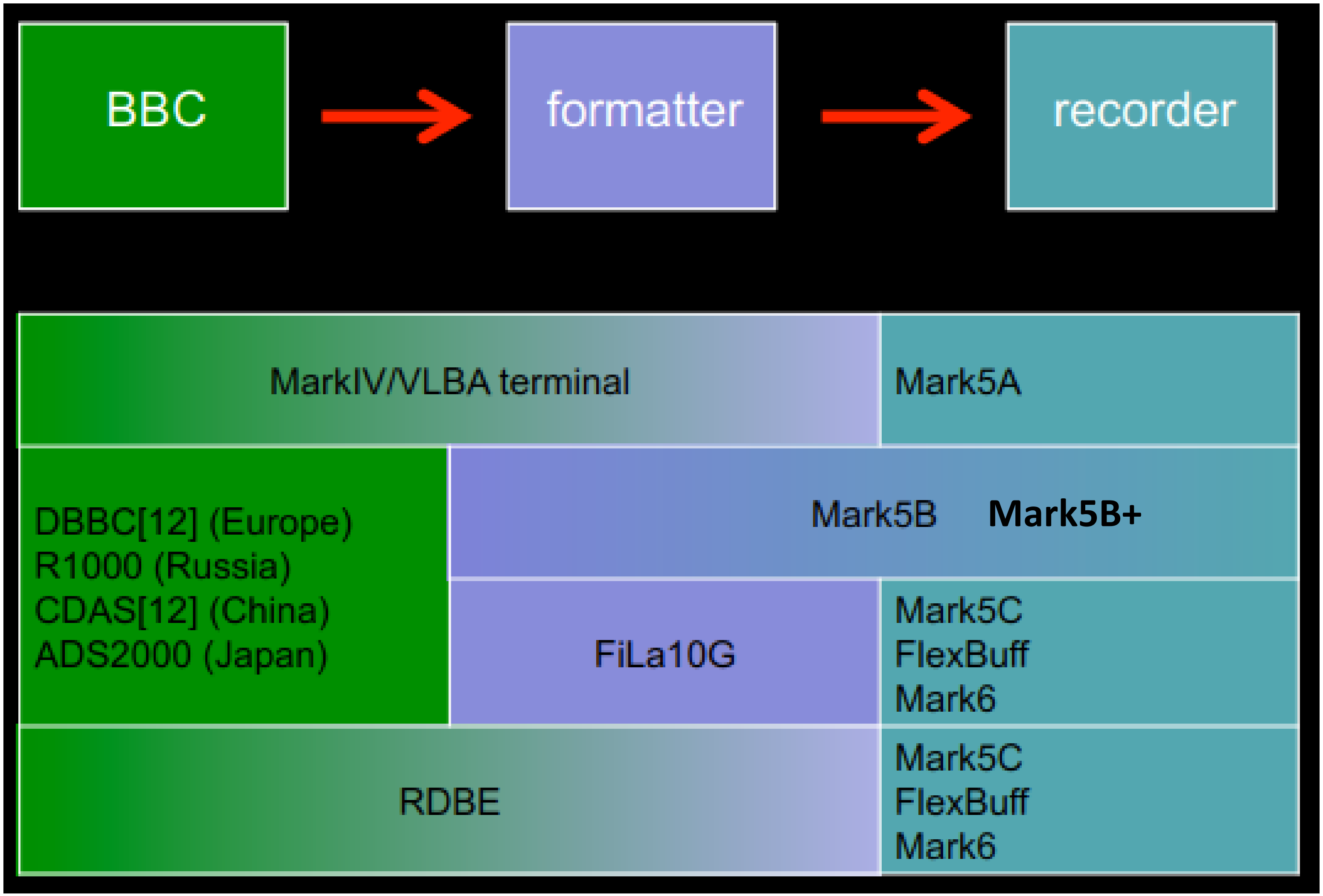
izer: JPL IF digitizer module
00MHz
@ 1280MHz sampling rate
lly controlled built-in attenuator
ed spurious signals below 97dB

ing

with FPGA board

Transport of data to correlator

VLBI: Data Acquisition Terminals - DAT



VLBI: data formats

formatter	format
MarkIV, VLBA	MarkIV, VLBA
Mark5B	Mark5B
FiLa10G	Mark5B, VDIF
RDBE	Mark5B, VDIF

VLBI: data formats

formatter	format
MarkIV, VLBA	MarkIV, VLBA
Mark5B	Mark5B
FiLa10G	Mark5B, VDIF
RDBE	Mark5B, VDIF

MarkIV & VLBA (& Mark5A):

header (sync word + time code) + data + aux (staid)

Full header per bit stream

Bit streams from each channel fanned-out to 2 or 4 recording heads (tracks) with barrel rolling

Frame length depends on number of recorded channels

Parity bit after every 8-bit byte: check validity of data in tape (Mark5A strips parity bit out)

VLBI: data formats

formatter	format
MarkIV, VLBA	MarkIV, VLBA
Mark5B	Mark5B
FiLa10G	Mark5B, VDIF
RDBE	Mark5B, VDIF

MarkIV & VLBA (& Mark5A):
header (sync word + time code) + data + aux (staid)
Full header per bit stream
Bit streams from each channel fanned-out to 2 or 4 recording heads (tracks) with barrel rolling
Frame length depends on number of recorded channels
Parity bit after every 8-bit byte: check validity of data in tape (Mark5A strips parity bit out)

Mark5B:
16 byte header (time code, frame# within second) + data
One header for all bit streams
Number of channels/stream must be 2^n
Fix frame length 10016 bytes > max Ethernet frame = 9000 bytes
Placement of sign, magnitude bits not fixed
Maximum 2048Mbps

VLBI: data formats

formatter	format
MarkIV, VLBA	MarkIV, VLBA
Mark5B	Mark5B
FiLa10G	Mark5B, VDIF
RDBE	Mark5B, VDIF

MarkIV & VLBA (& Mark5A):
header (sync word + time code) + data + aux (staid)
Full header per bit stream
Bit streams from each channel fanned-out to 2 or 4 recording heads (tracks) with barrel rolling
Frame length depends on number of recorded channels
Parity bit after every 8-bit byte: check validity of data in tape (Mark5A strips parity bit out)

Mark5B:
16 byte header (time code, frame# within second) + data
One header for all bit streams
Number of channels/stream must be 2^n
Fix frame length 10016 bytes > max
Ethernet frame = 9000 bytes
Placement of sign, magnitude bits not fixed
Maximum 2048Mbps

VDIF - VLBI Data Interchange Format:
32-byte header (frame# within second, staid, thread id) + data
Layout of data and order of bits standardized:
- Single data threads carrying multi-channels data frames
- Single channel format

Allows very high data rates (128 Gbps)

VLBI: Data Acquisition Terminal DBBC

Digital Base Band Converter (Istituto di Radioastronomia in Italy and Max Planck Institute fuer Radioastronomie in Germany):

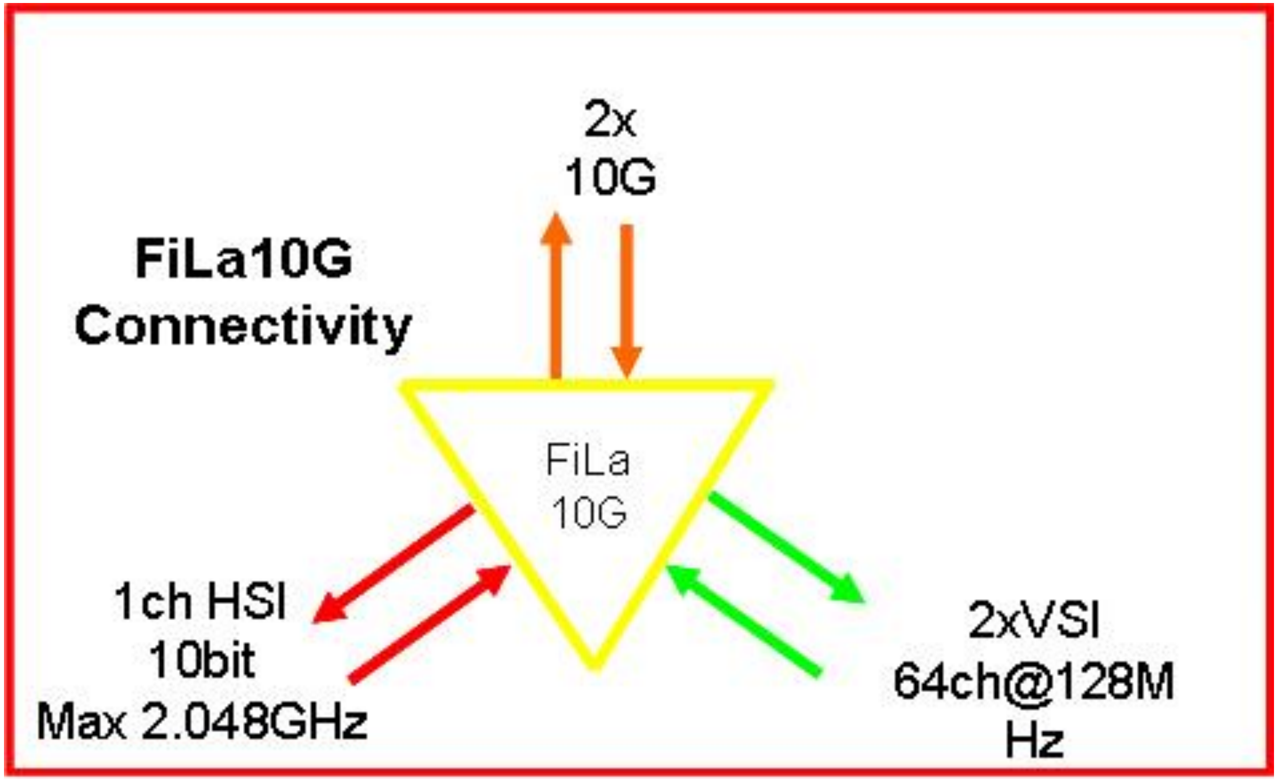
- Replace MarkIV VLBI terminal with a complete and compact system to be used with any VSI compliant recorder or data transport
- Flexible architecture, composed by **one or more FPGA boards as computation elements**, placed in a mixed cascaded/parallel structure

VLBI: Data Acquisition Terminal DBBC

- Four RF/IF Input in a range up to 2.2 GHz.
- 1024 MHz sampling clock frequency.
- Channel bandwidth ranging between 500 KHz and 16 MHz, U&L, some wider channel bandwidth: 32 and 512 MHz, I&Q
- Tuning step less than 1 Hz
- Maximum output bandwidth of 8.192 Gbps per core module.
- Field System support is used to configure the different modules and allow standard settings, and still getting total power measurements of the converted channel.

VLBI: FiLa10G

Double port 10G VLBI-Ethernet Interface: add 10G connectivity



VLBI: Data Acquisition Terminal RDBE

Roach Digital Backend (VLBA):

2 analog IF signals, applies an anti-alias filter that passes 512 to 1024 MHz, sets the power levels, samples the signals at a 1024 MHz sample rate (8 bit samples at this stage), digitally filters the data to the final basebands, resamples the data to 2 bits, and formats it for recording.

2 RDBE per VLBA antenna (4 IF)

RDBE supports multiple personalities:

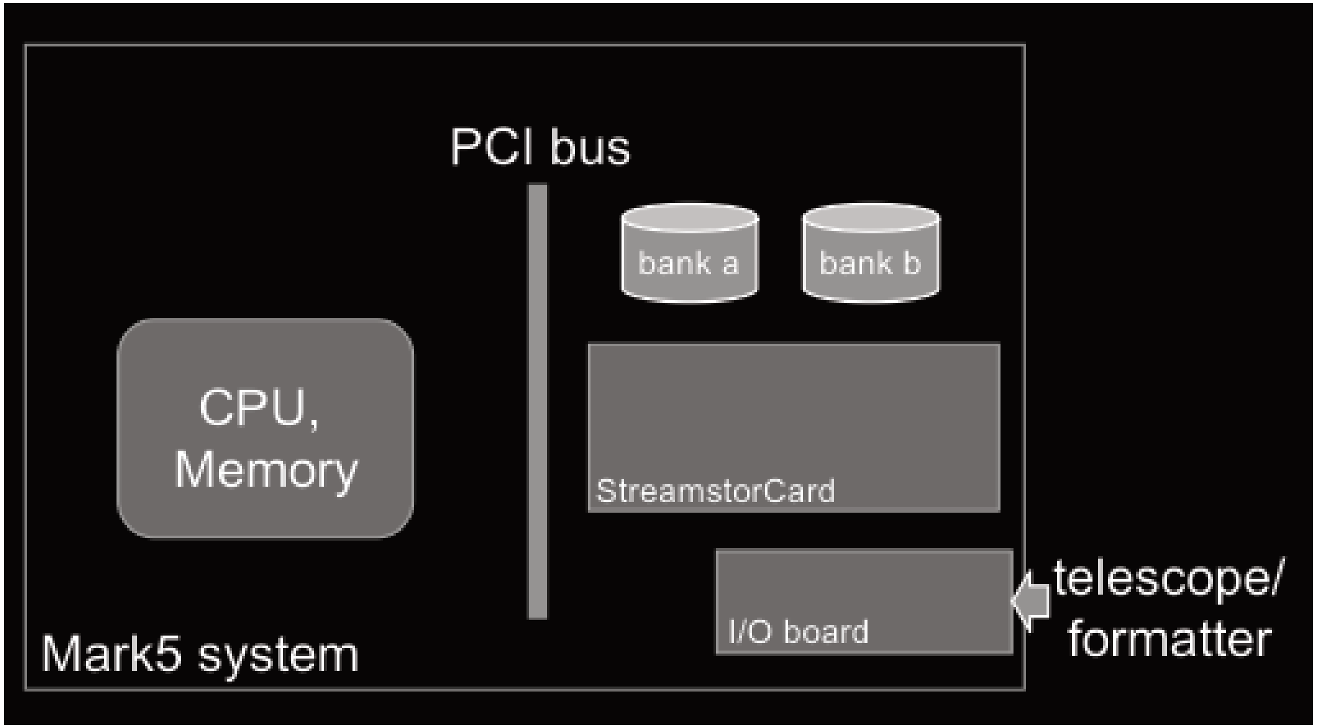
- **PFB personality** that uses a polyphase filter to break each of the two 512 MHz IFs into 16 basebands of 32 MHz each, all lower sideband.
- **Digital Down Converter personality** provide a few 4 (possibly 8 later) filters per RDBE that can provide arbitrary offset frequencies and can provide any bandwidth at the factor of 2 steps between 1 and 64 MHz.

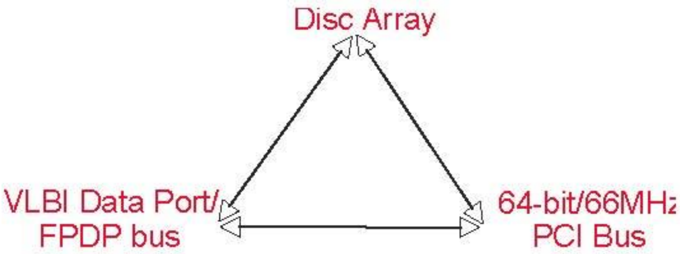
VLBI: Mark5 Recorders

Developed by Haystack obs. (MIT):

- First high-data-rate VLBI recorder based on magnetic-disk technology
- Recording/playback/real-time data transfer
- *StreamStor* disk interface card that is specially designed for high-speed real-time data-collection and playback
- Mark5 A/B/C and Mark6
- Record removable disk packs PATA/SATA
- Dual bank recording and switching
- From 1024 Mbps to 4096 Mbps
- Controlled from Field System using MIT software or EVN jive5ab

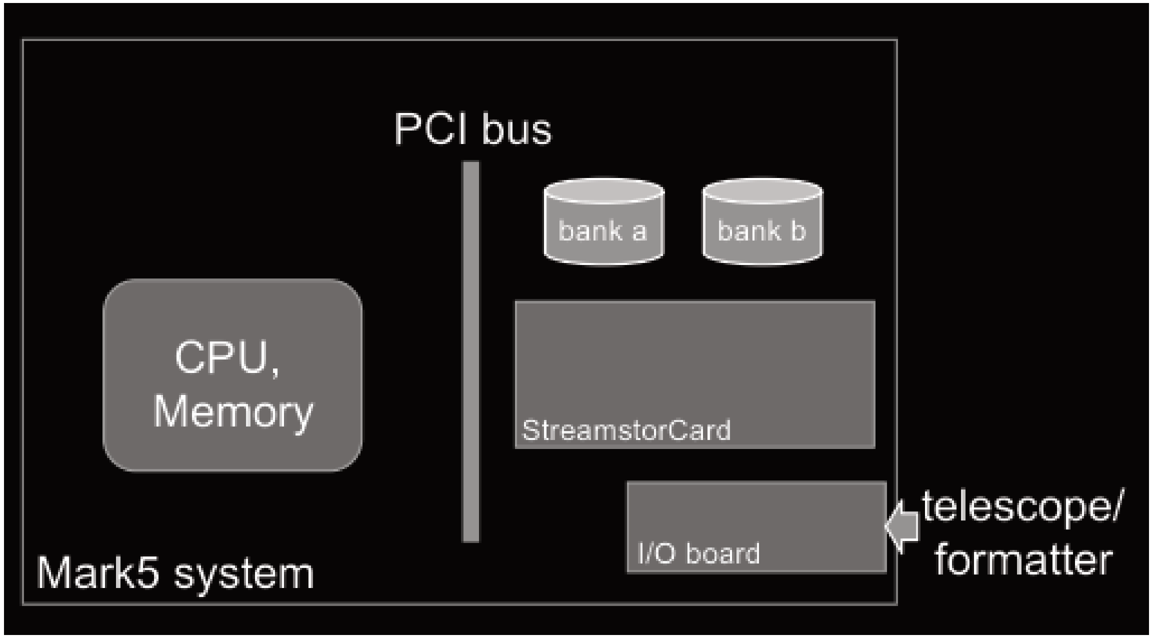
VLBI: Recorders Mark5A/B/C and Mark6

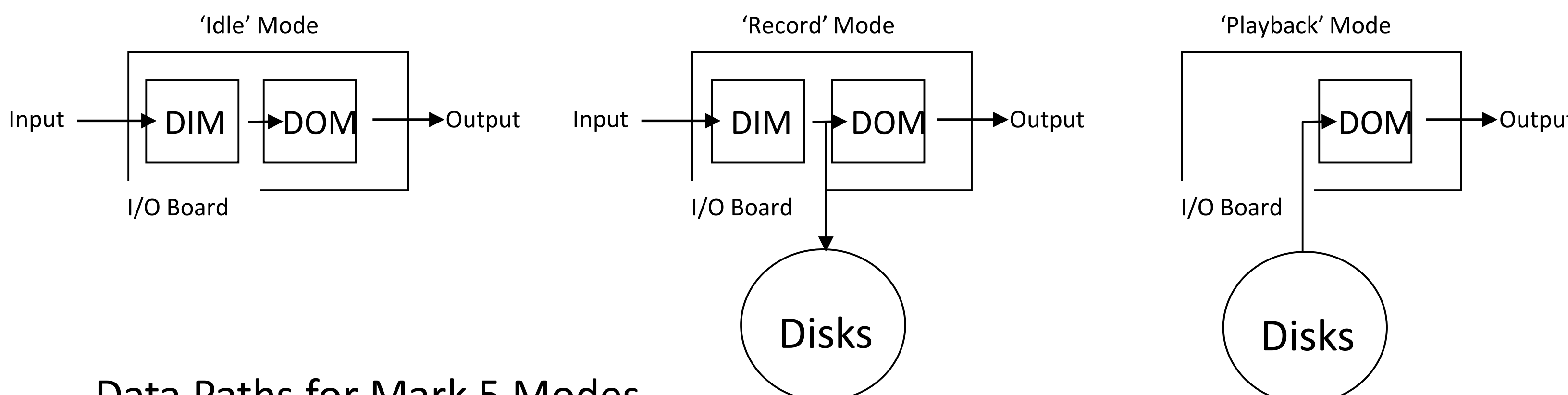




'Triangle of connectivity' of StreamStor interface card

VLBI: Recorders Mark5A/B/C and Mark6





Data Paths for Mark 5 Modes

VLBI: Recorders Mark5A/B/C and Mark6

Mark5A (decommissioned):

- Direct replacement of MarkIV magnetic recorders with same data format (VLBA tape-format).
- up to 1024Mbps

Mark5B (decommissioned) and 5B+:

- VSI-H compliant
- up to 1024Mbps or 2048Mbps
- No external formatter needed.

Mark5C:

- 10GigE interface
- Format-less packet recorder, supports VDIF format
- up to 4096Mbps, limited to 1Gbps for e-VLBI

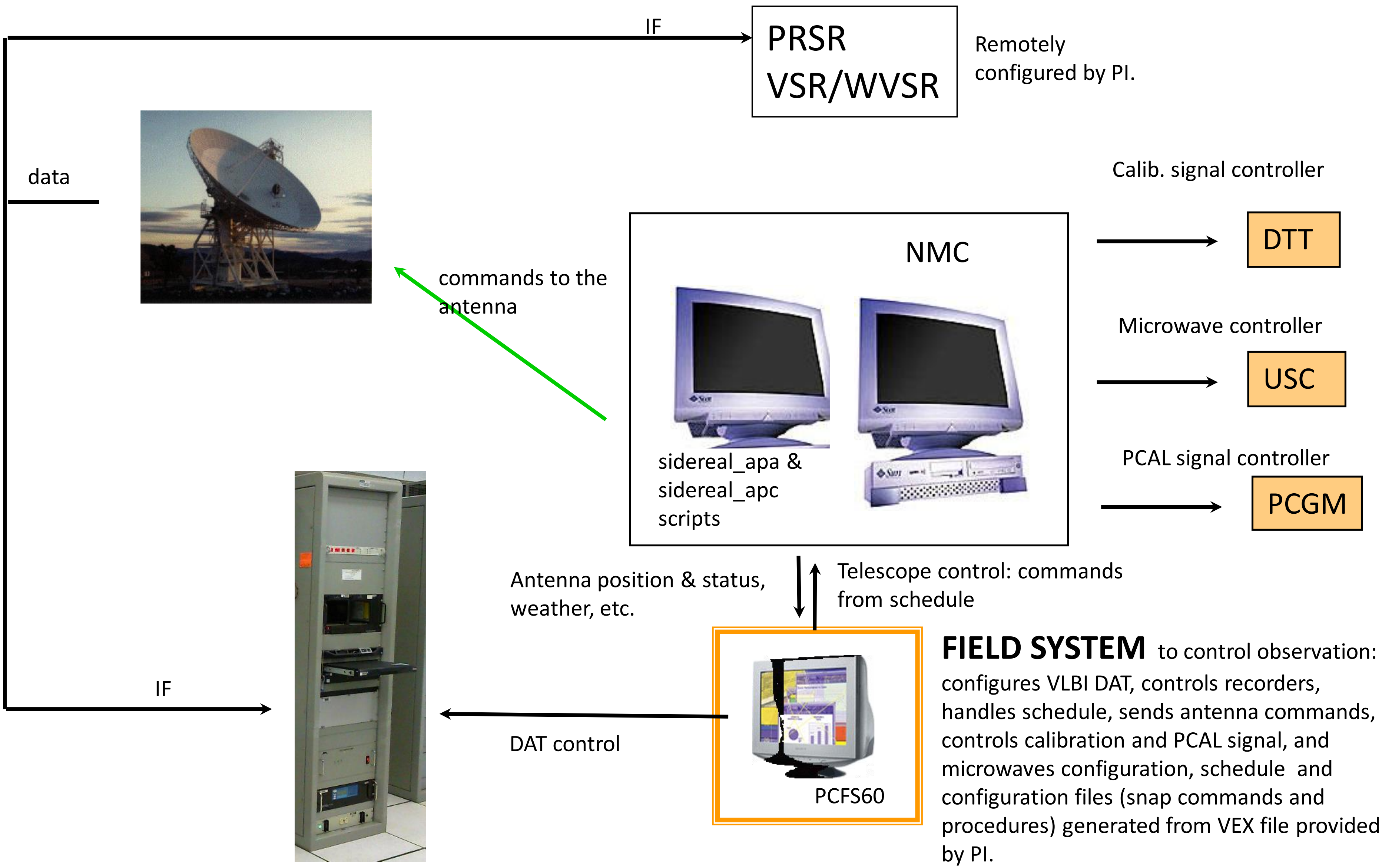
Mark6:

- 10GigE interface
- Supports all common VLBI data formats
- up to 16Gbps (4 disk modules)

VLBI: Recorder FlexBuff

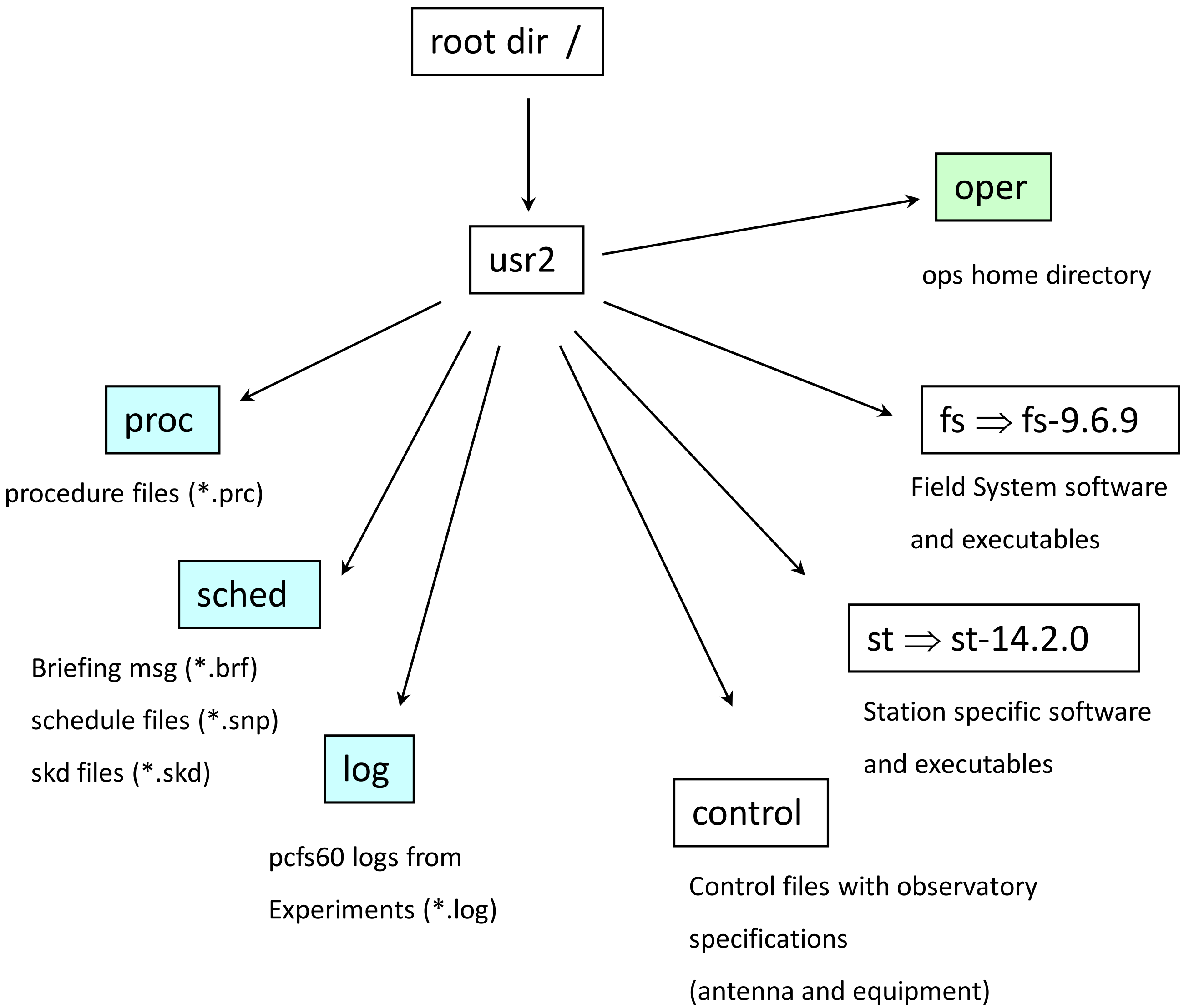
Metsähovi Observatory development (2010):
Stripe data over lots of disks
In regular files
Sustained 16 Gbps, 210 TB per unit
Recorded data transferred via internet or e-VLBI mode.
Controlled from Field System using EVN jive5ab

VLBI: Field System



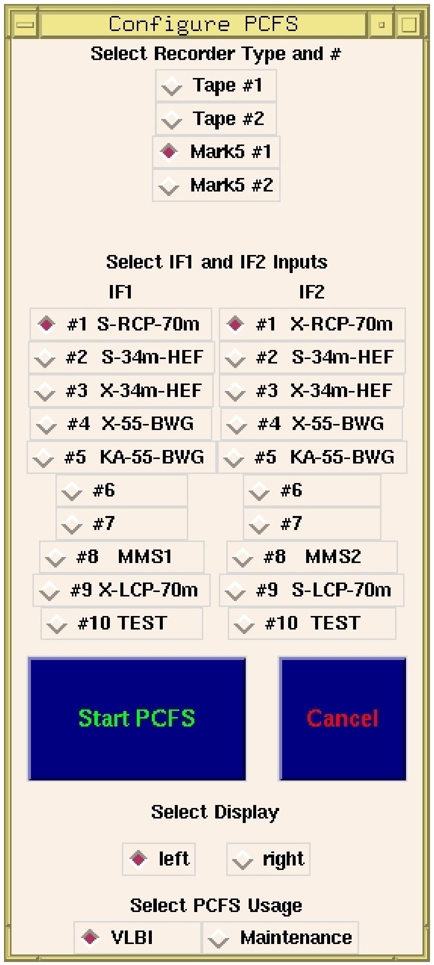
VLBI: Field System

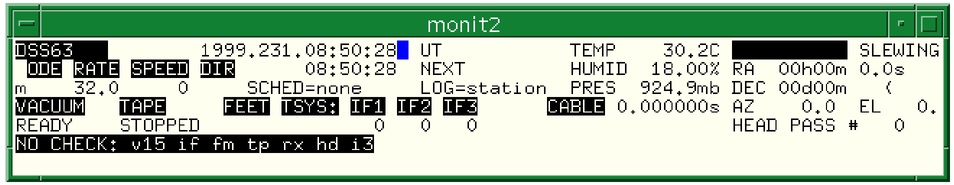
PCFS directory structure:

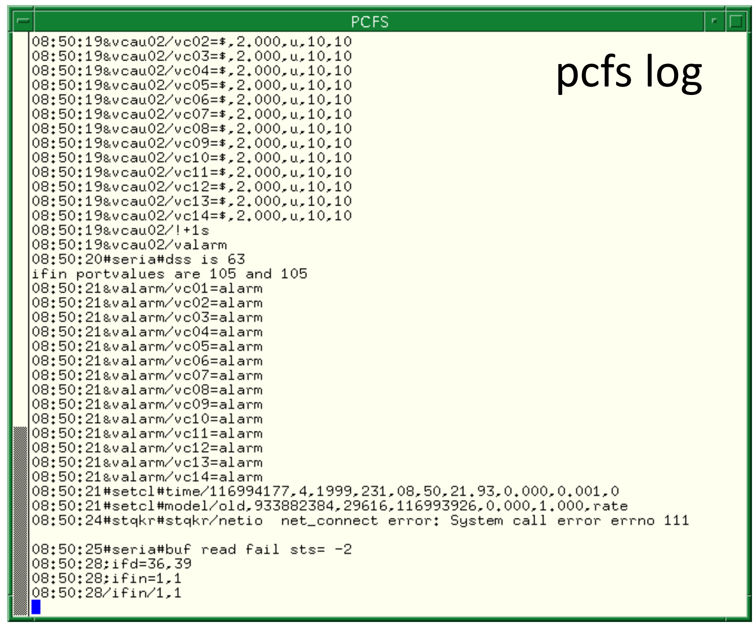


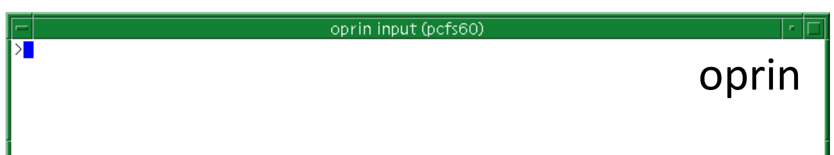
VLBI: Field System

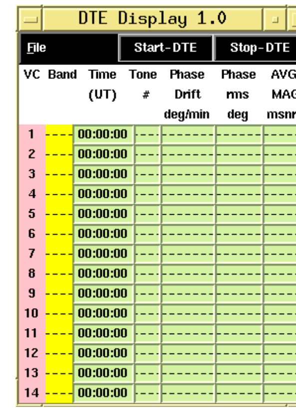
PCFS windows:

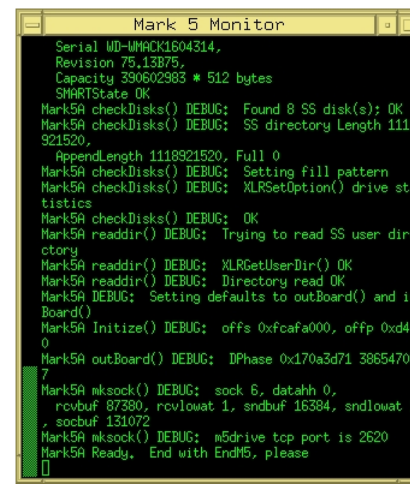












/usr2/st/scripts/pcfsa &

VLBI: Correlation

VLBI: hardware correlators

VLBI: software correlators

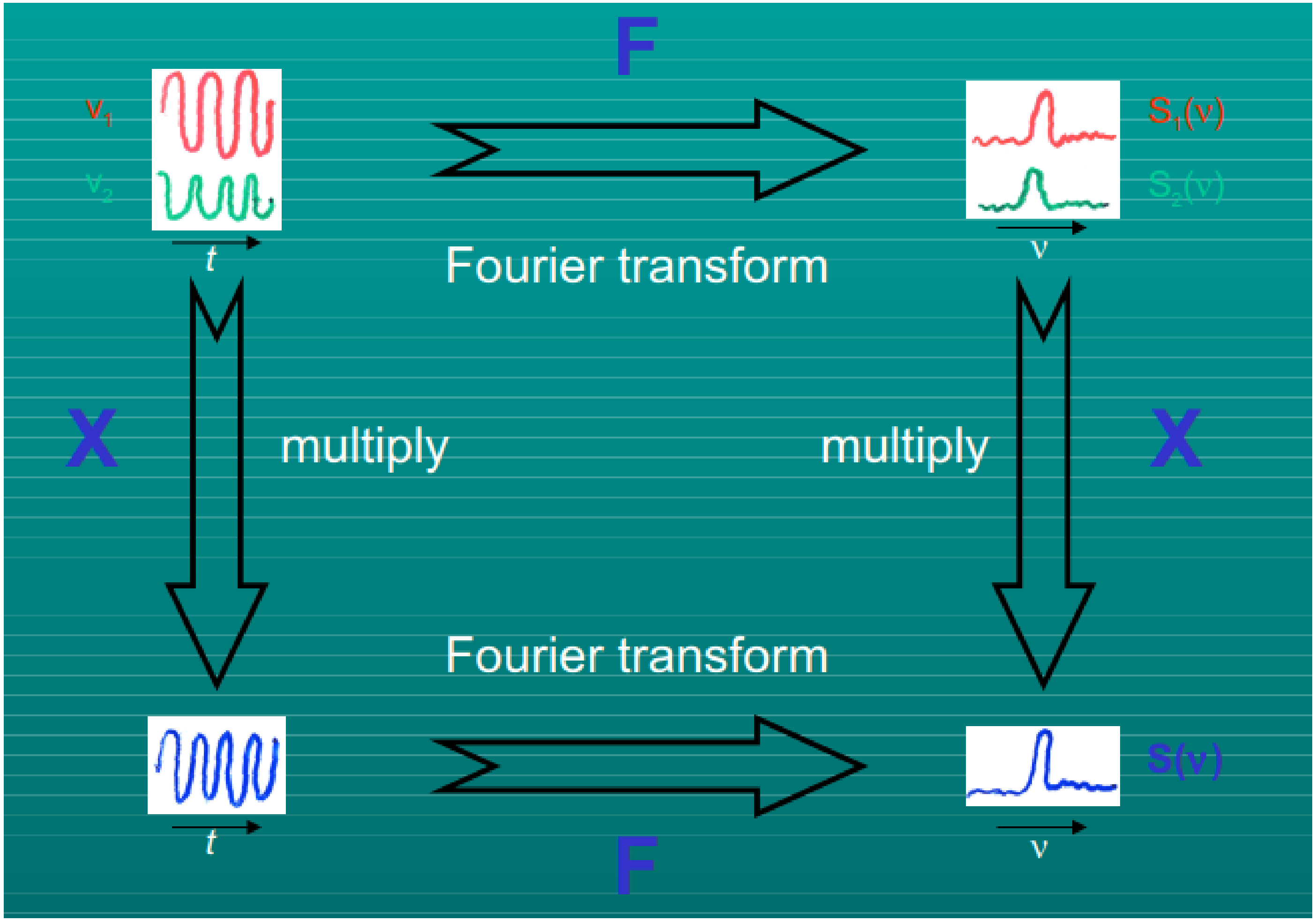
VLBI: Correlation

- Read Mark5 disk modules or receives e-VLBI data via internet using FlexBuff.
- Synchronize data.
- Apply geometrical delay model.
- Correct for known Doppler shifts (mainly from Earth rotation)
- **FX type:** FFT then cross multiply spectra (VLBA, DiFX and EVN SFXC s/w correlators)
- **Lag or XF type:** cross multiply lags, FFT later (JIVE, Haystack, VLA, SoftC JPL s/w correlator):

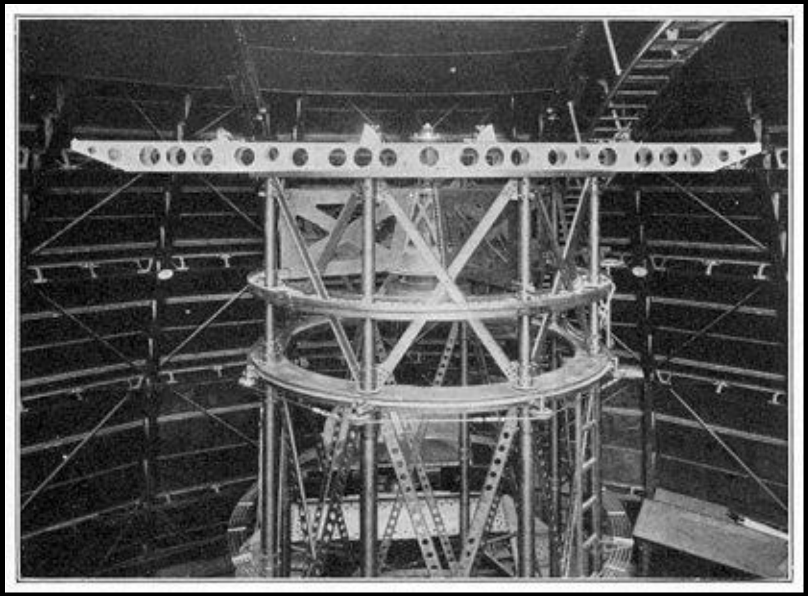
  $x(t_i)$ correlated with { … $y(t_{i-2})$, $y(t_{i-1})$, $y(t_i)$, $y(t_{i+1})$, $y(t_{i+2})$, $y(t_{i+3})$,…}
- Phase calibration extraction, continuous calibration extraction.
- RFI mitigation.
- Fringe finder in selectable search time window.
- Accumulate (integration time from msec to sec) and write data to archive in FITS format.
- Pipeline: automatic post-processing.

VLBI: Correlation

FX vs. XF correlator:



VLBI Fundamentals



Short history of VLBI
Connected versus VLBI
VLBI networks
VLBI data acquisition terminals
VLBI correlation

VLBI Fundamentals

MANY THANKS!!

Cristina García Miró
Madrid Deep Space Communications Complex
NASA/INTA

AVN Training School
HartRAO, March 2017

Short history of VLBI

Phase-switched interferometer (Ryle 1952): a 180deg phase shift periodically introduced in one arm of the interferometer. The resulting synchronously detected signal retained only the cross-product of the signals from the antennas, improving the effective sensitivity.

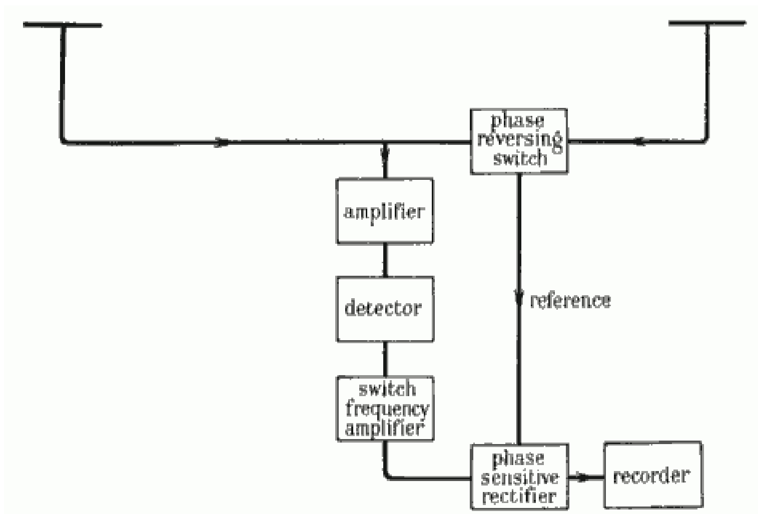
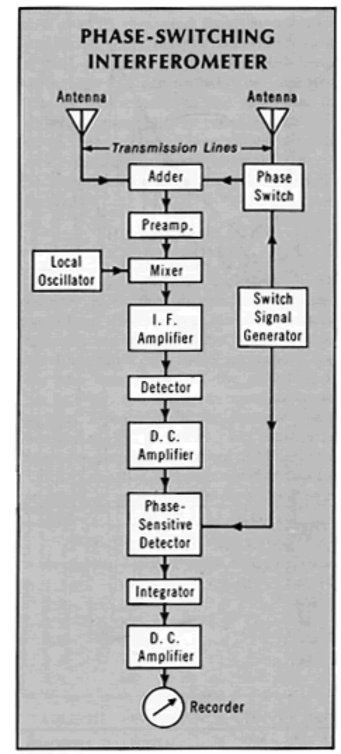


FIGURE 2. Block diagram of the phase-switching system.



Up to 6arcmin!!!!

VLBI: Data Acquisition Terminal - DAT

RS422	MarkIV VLBA	**512 Mbps**
VSI/H	DBBC[2] R1002 CDAS ADS[123]000	**2048 Mbps**
Ethernet	DBBC[2]+FiLa10G R[2]DBE CDAS2 BRAS	**8192 Mbps**