



VLBI Fundamentals

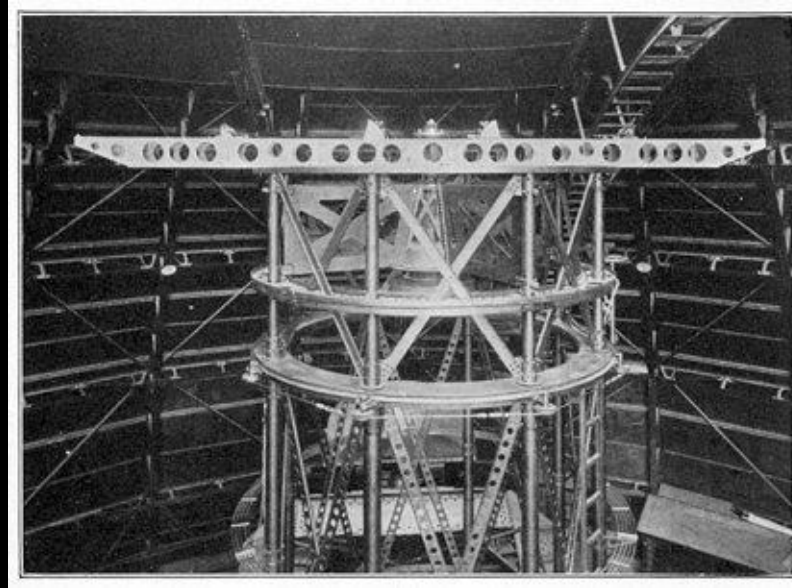


Cristina García Miró

Madrid Deep Space Communications Complex
NASA/INTA

AVN Training School
HartRAO, March 2017

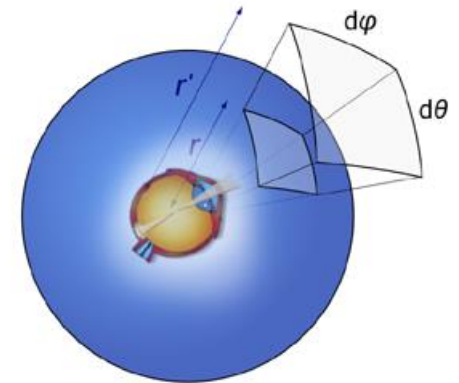
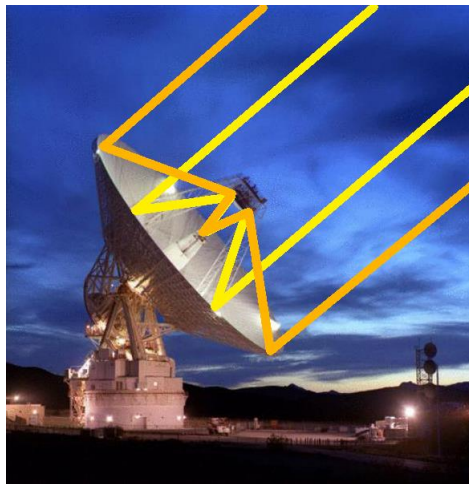
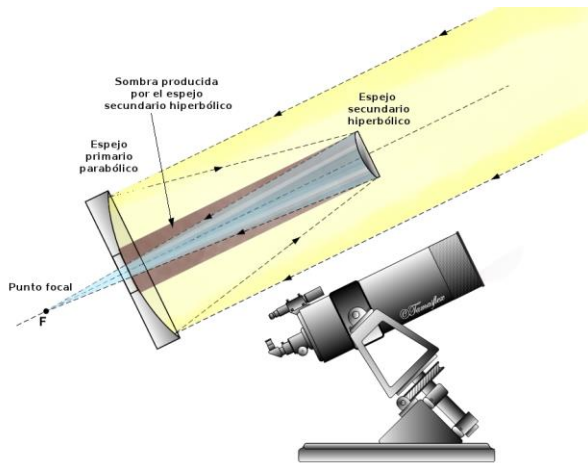
VLBI Fundamentals



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

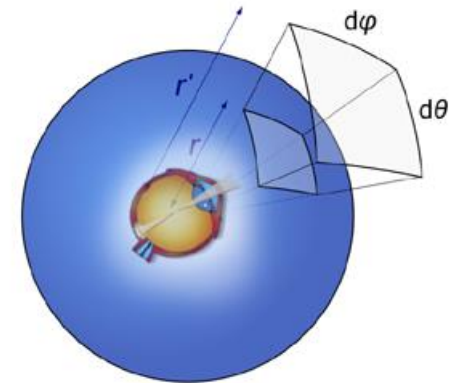
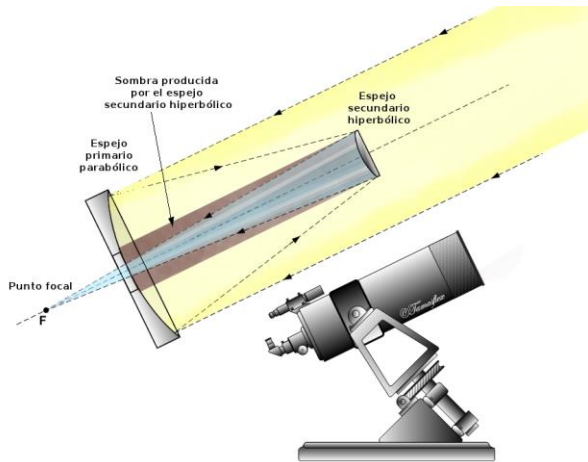
Short history of VLBI: why? QUEST FOR RESOLUTION

OPTICAL vs RADIO:



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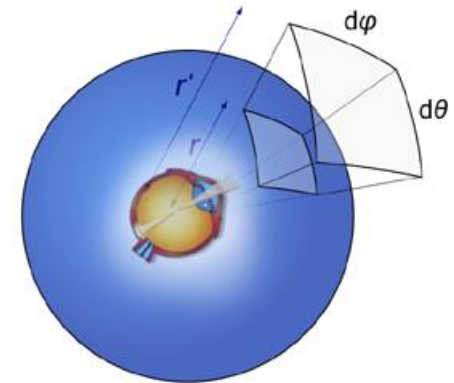
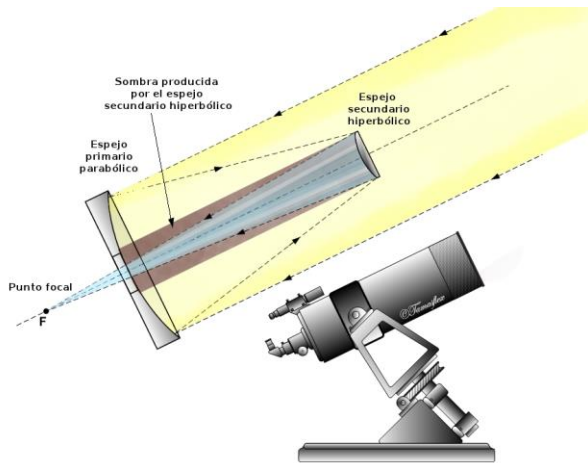
OPTICAL vs RADIO:



Diffraction-limited instruments

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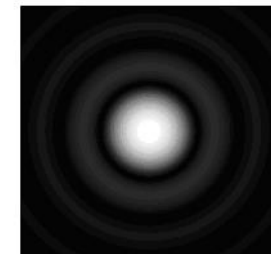
OPTICAL vs RADIO:



Diffraction-limited instruments

Single dish resolution (arcsec):

$$\theta = \frac{2.1 \cdot 10^5 \lambda}{D}$$

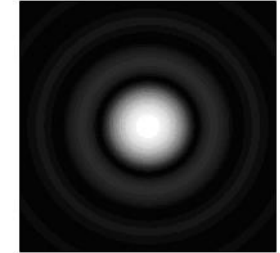


Airy disc or perfect PSF

Short history of VLBI: why? QUEST FOR RESOLUTION

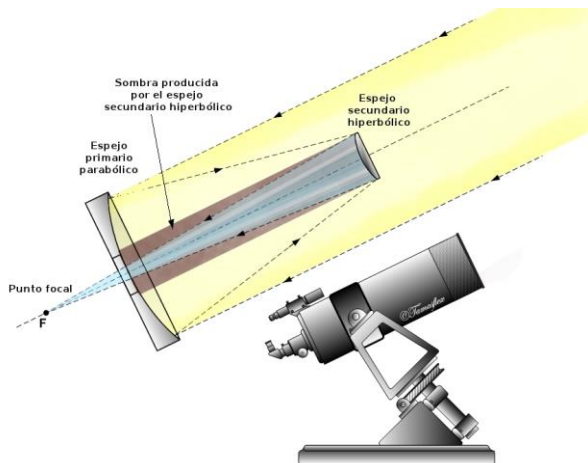
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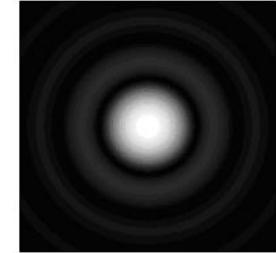


8-m telescope in yellow
light 550nm: **14 mas**

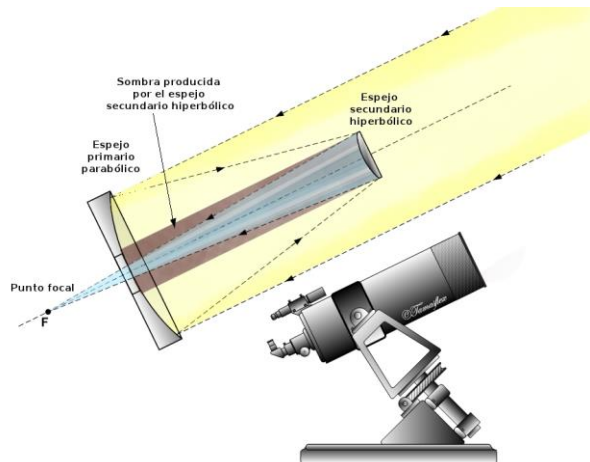
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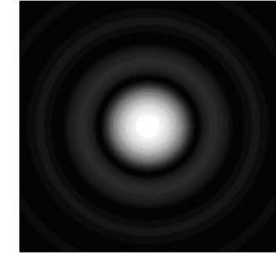
8-m telescope in yellow
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70-m telescope in
1.3cm (22GHz): **39 arcsec**
18cm (1.6GHz):
540 arcsec = 9 arcmin

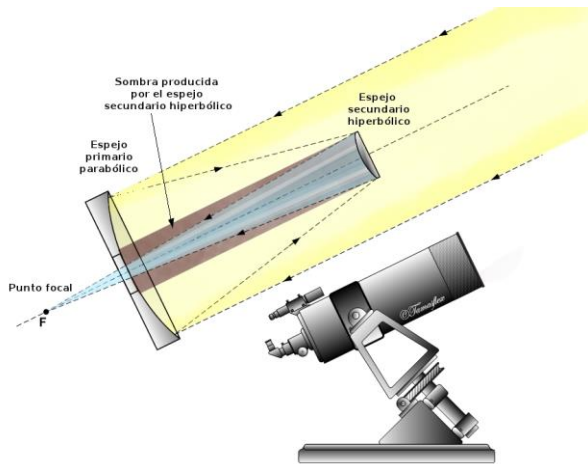
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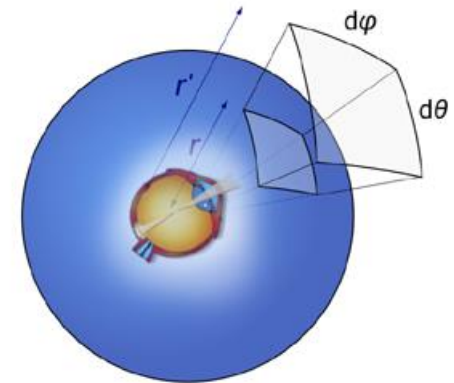
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OPTICAL vs RADIO resolution:



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



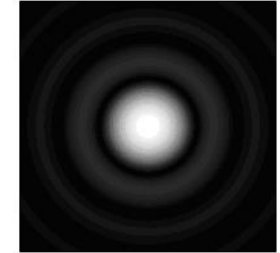
70-m telescope in
1.3cm (22GHz): **39 arcsec**
18cm (1.6GHz):
540 arcsec=9 arcmin

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

Short history of VLBI: why? QUEST FOR RESOLUTION

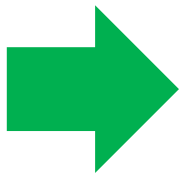
Single dish resolution (arcsec):

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OPTICAL vs RADIO resolution:

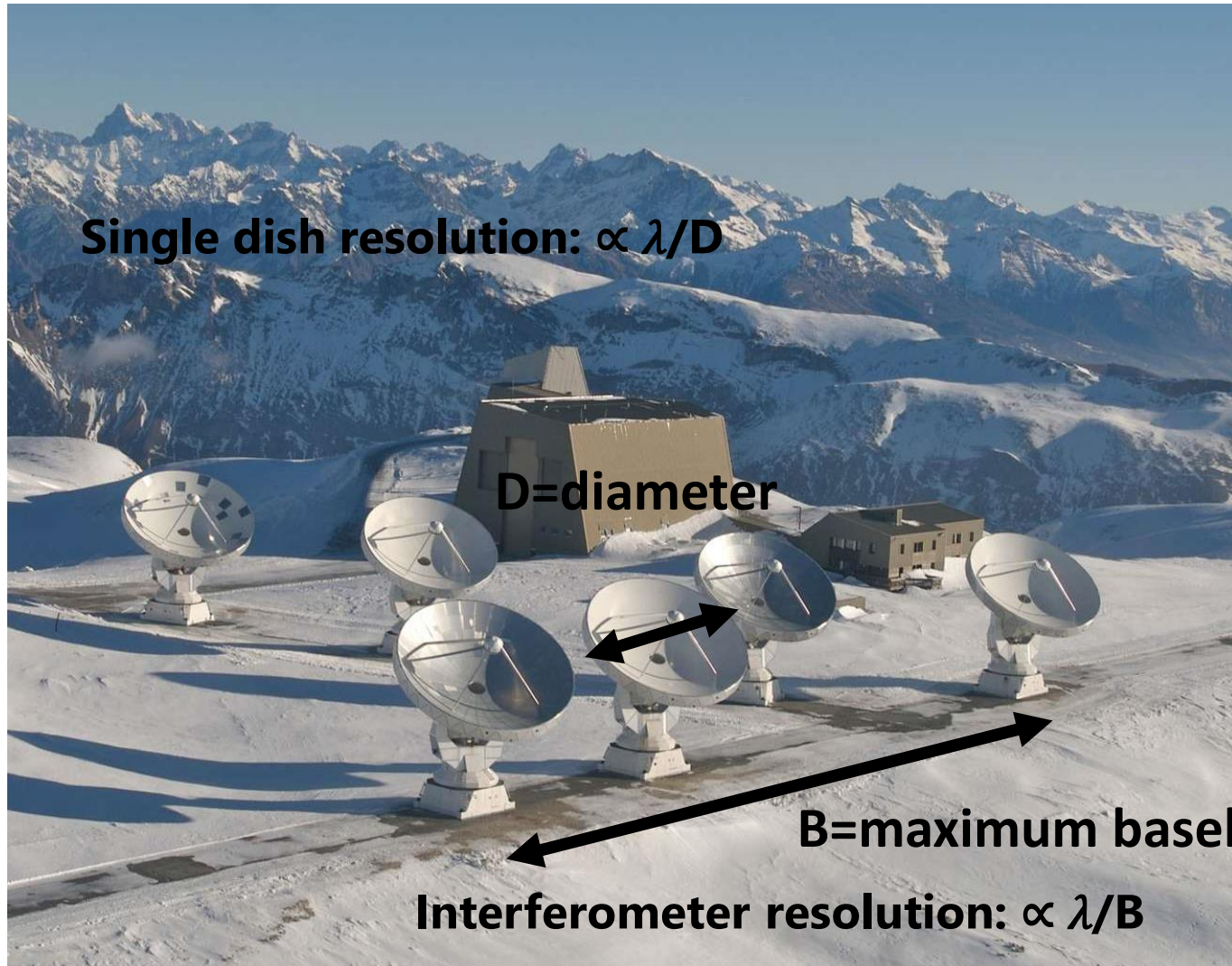
Airy disc or perfect PSF



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

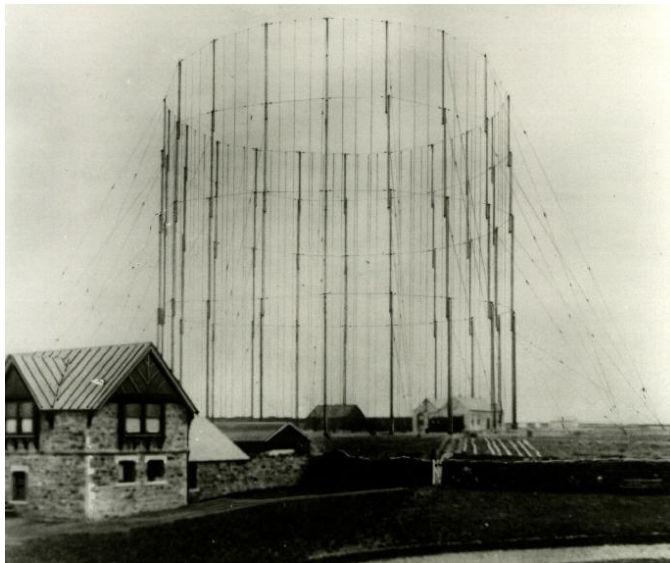


Short history of VLBI

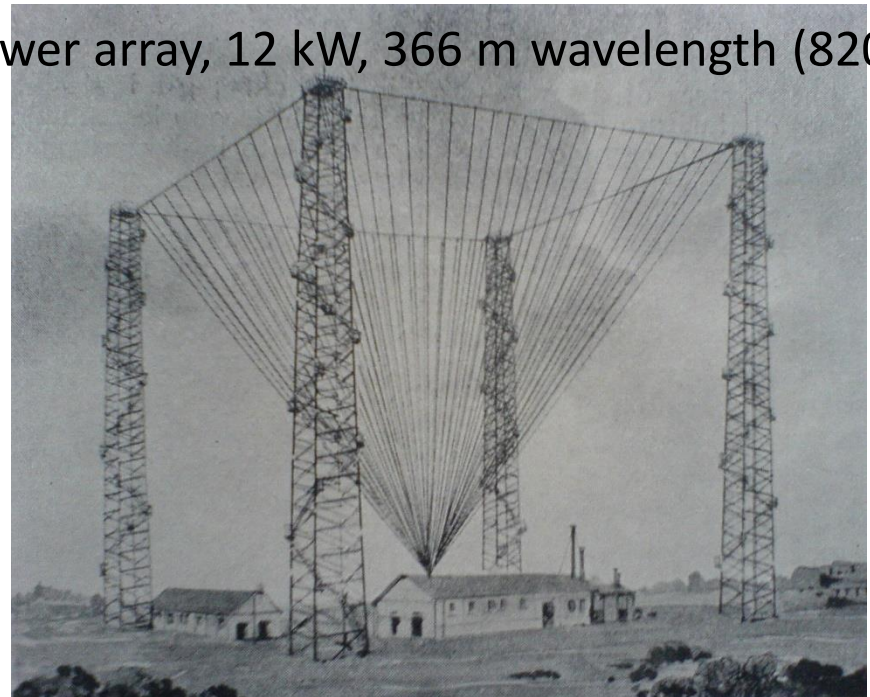


G. Marconi monopole antenna array in Poldhu, Cornwall (1900):

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

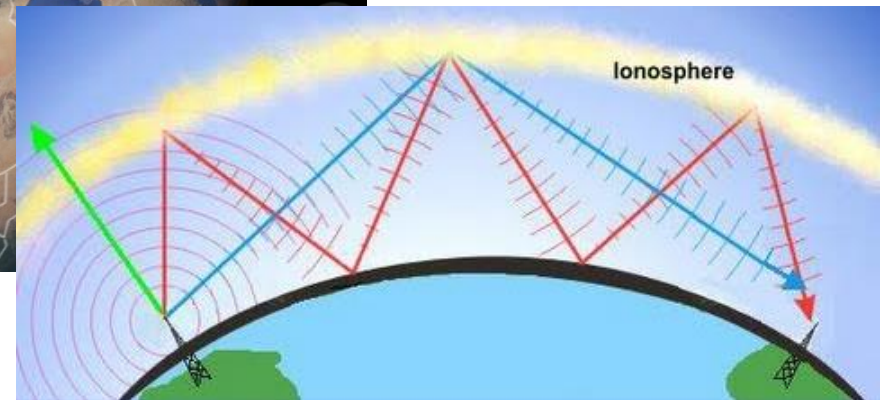
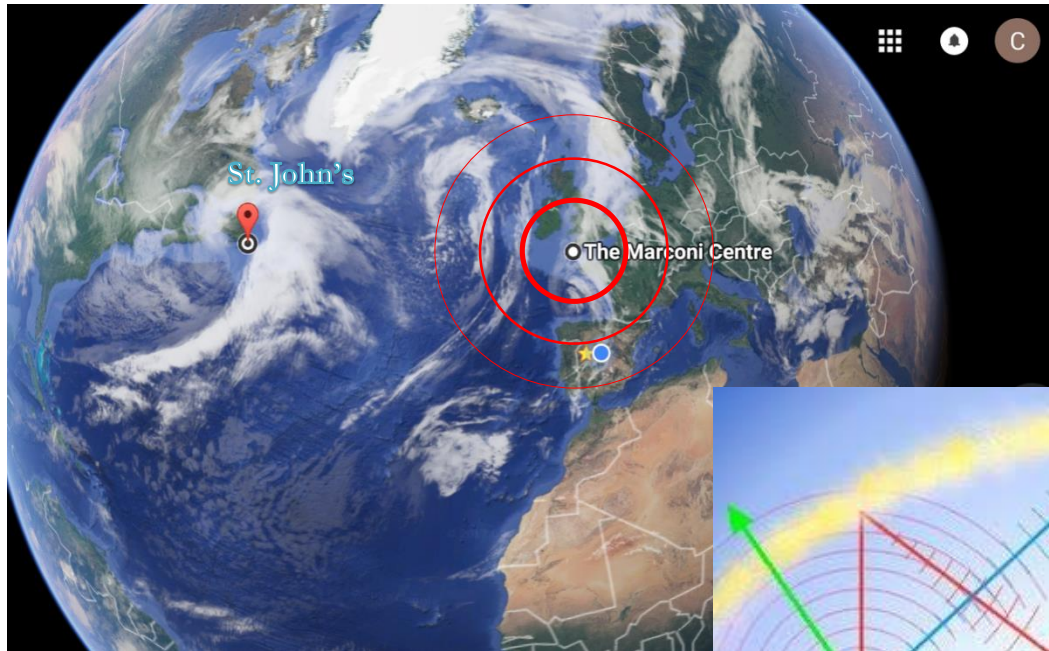


4 tower array, 12 kW, 366 m wavelength (820 kHz)



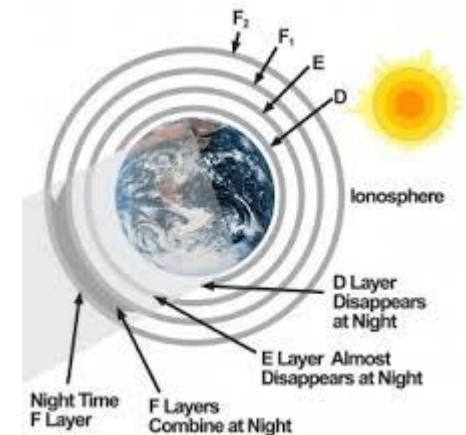
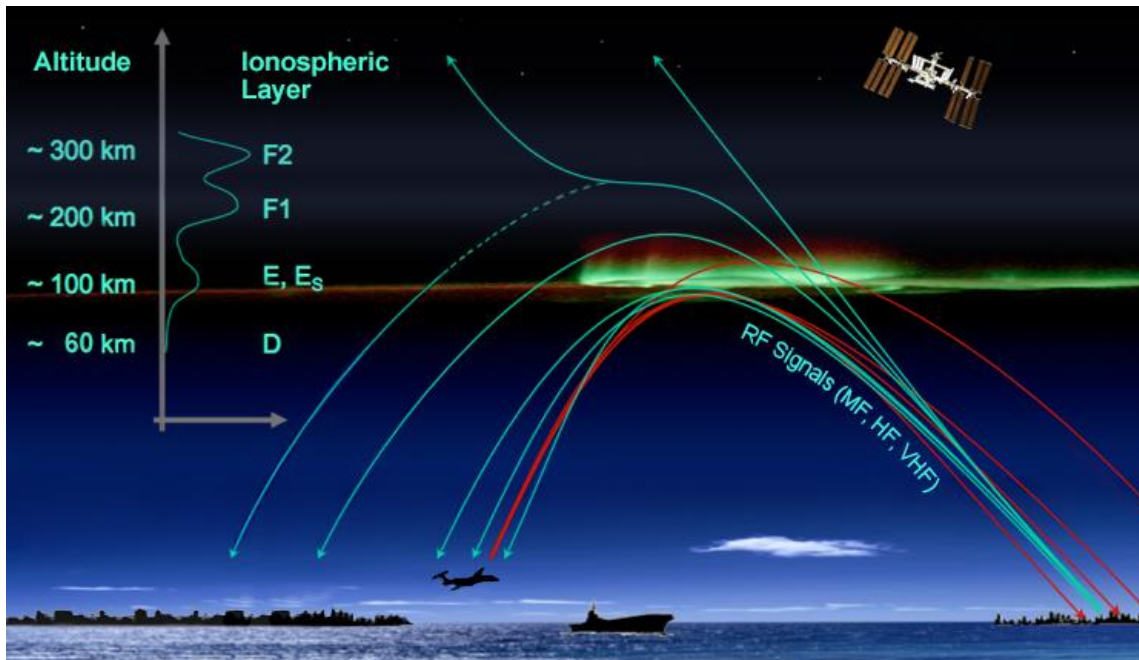
Short history of VLBI

Marconi's transatlantic transmission
required multiple reflections off the ionosphere



Short history of VLBI

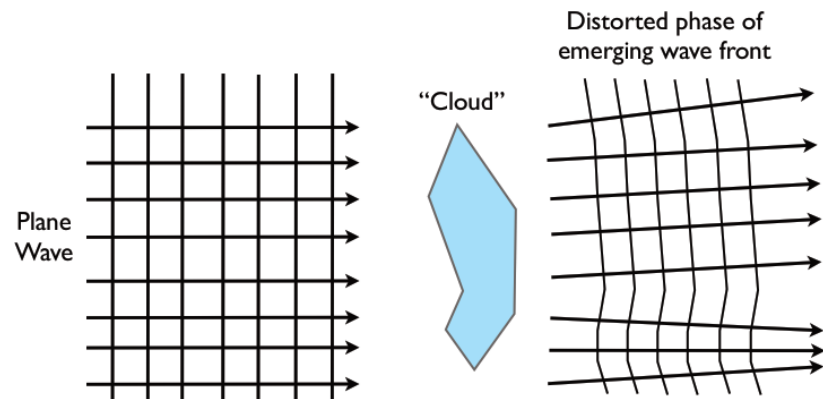
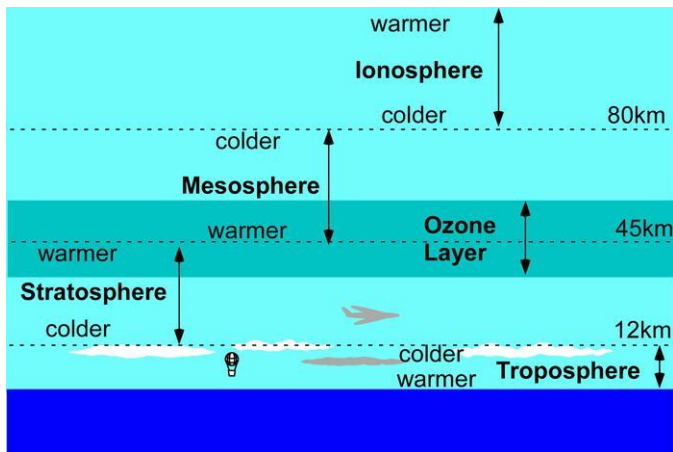
Discovery of the ionosphere and its reflective and refractive properties



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

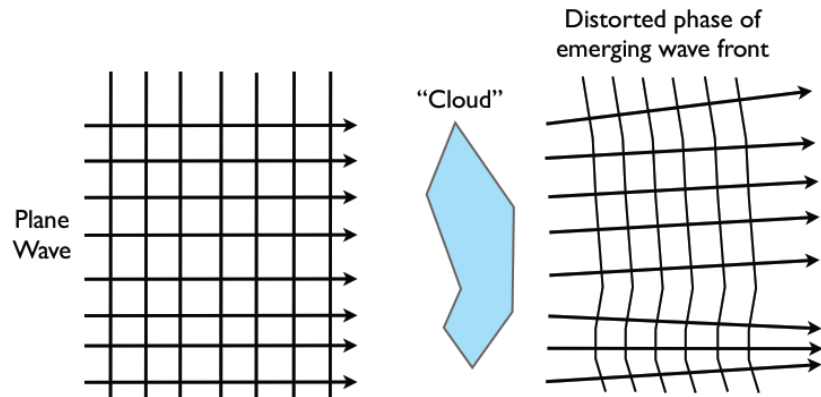
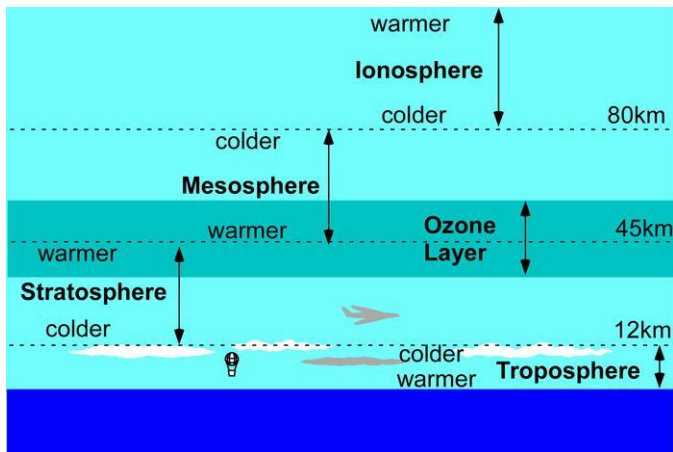
Short history of VLBI

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



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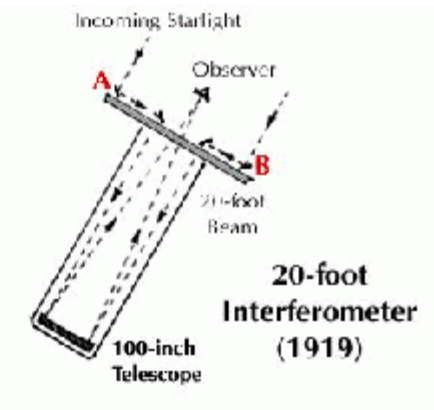
Coherence time: phase change
1 rad in incoming wavefront,
3 cm ($0.5 \cdot 10^{-6}$ m) vs. 600 m (1 cm)
ms vs. min

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

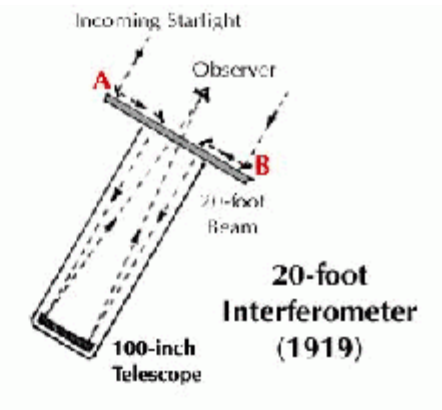
Short history of VLBI

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



Short history of VLBI

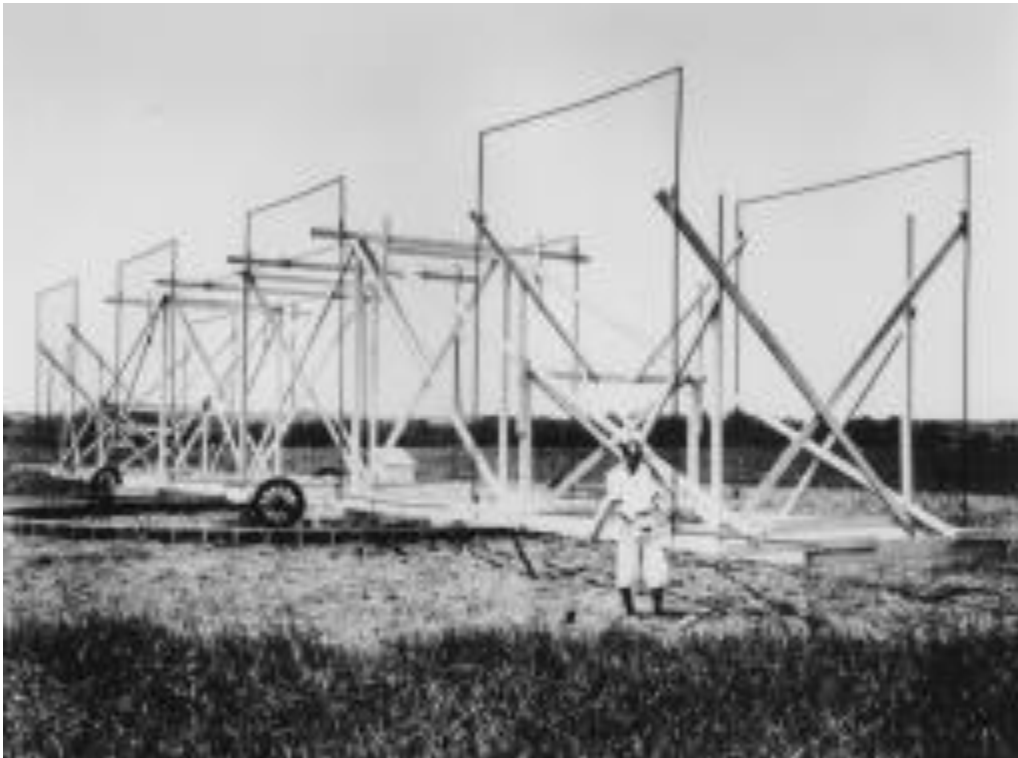
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Measure the diameter of the stars for first time!

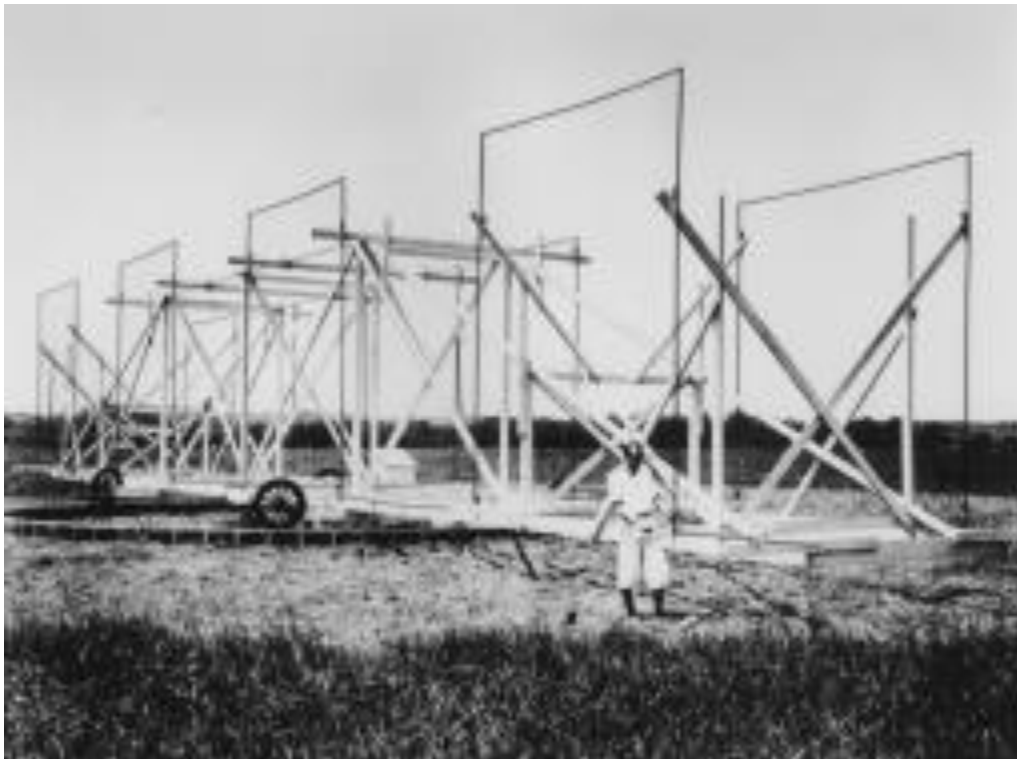
Short history of VLBI:

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...**

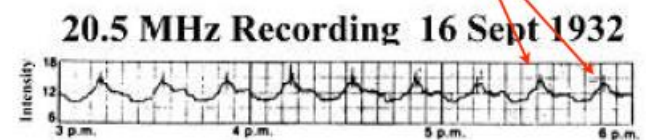


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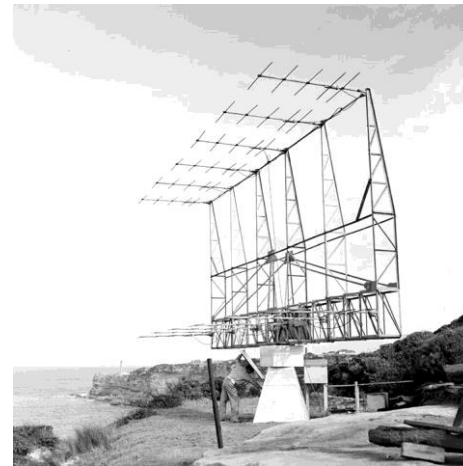
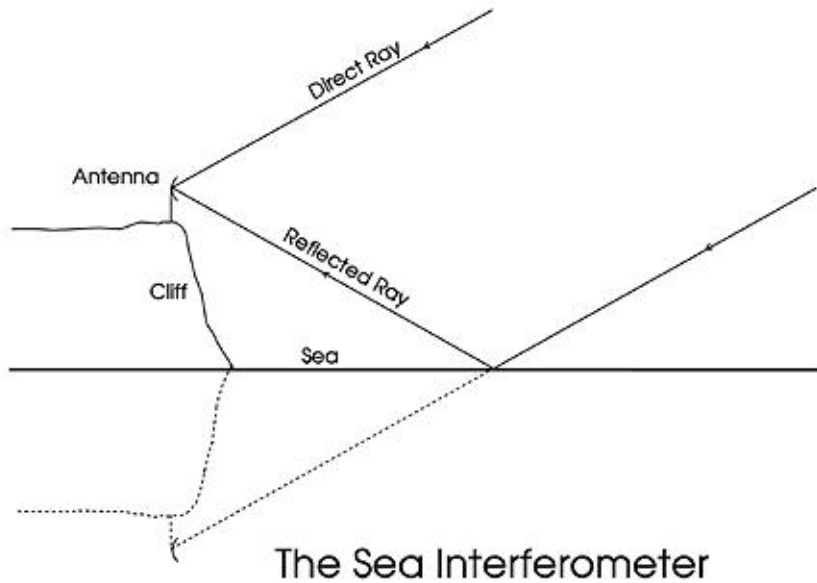


Galactic centre



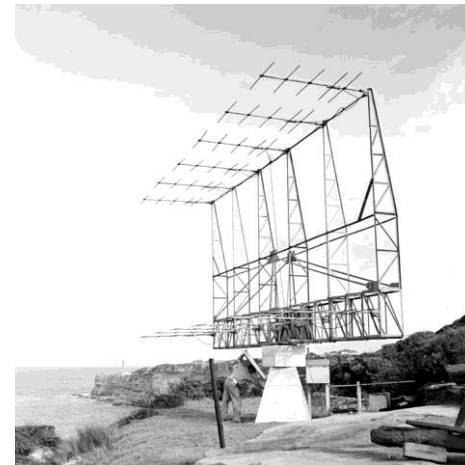
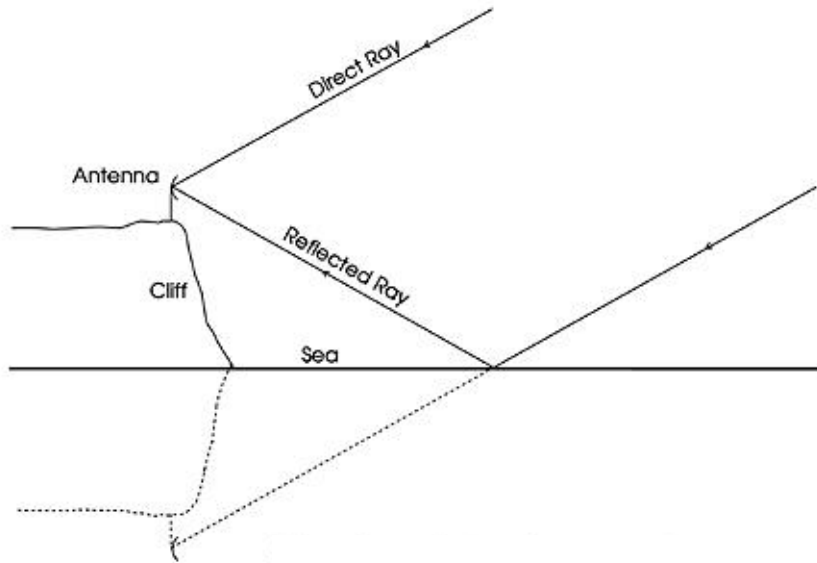
Short history of VLBI

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

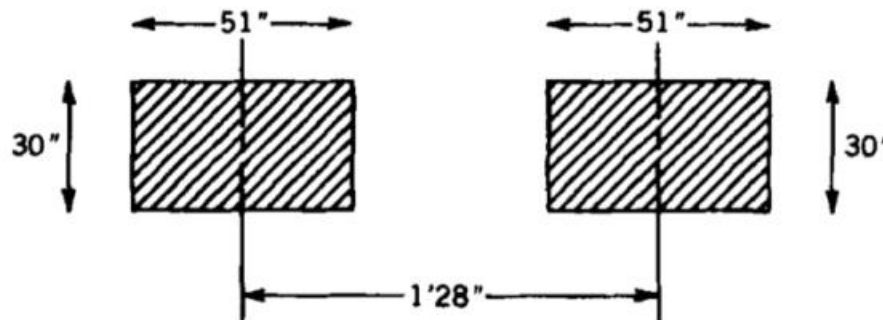


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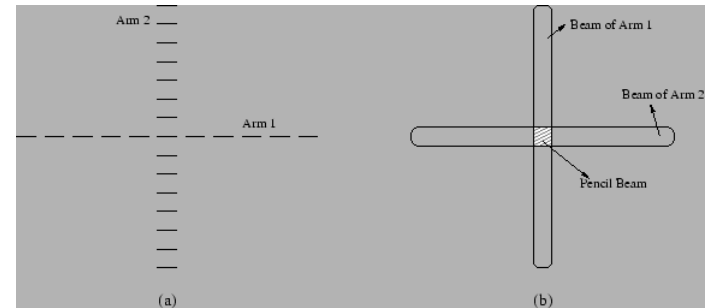
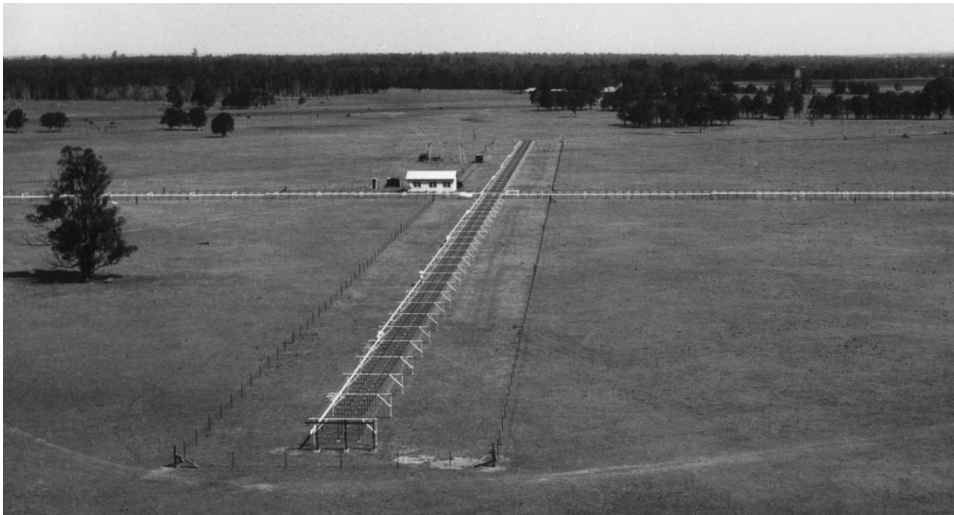
First image of a
radio source:
Cygnus A



Jennison & Das Gupta
(1953)

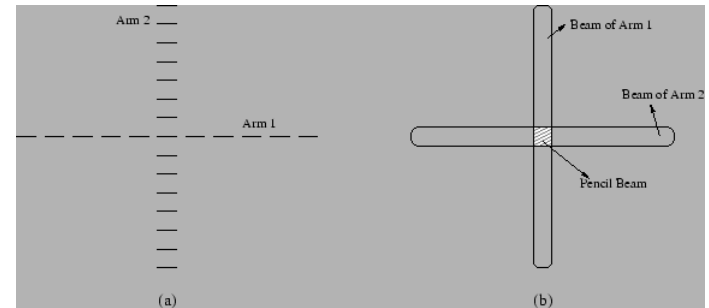
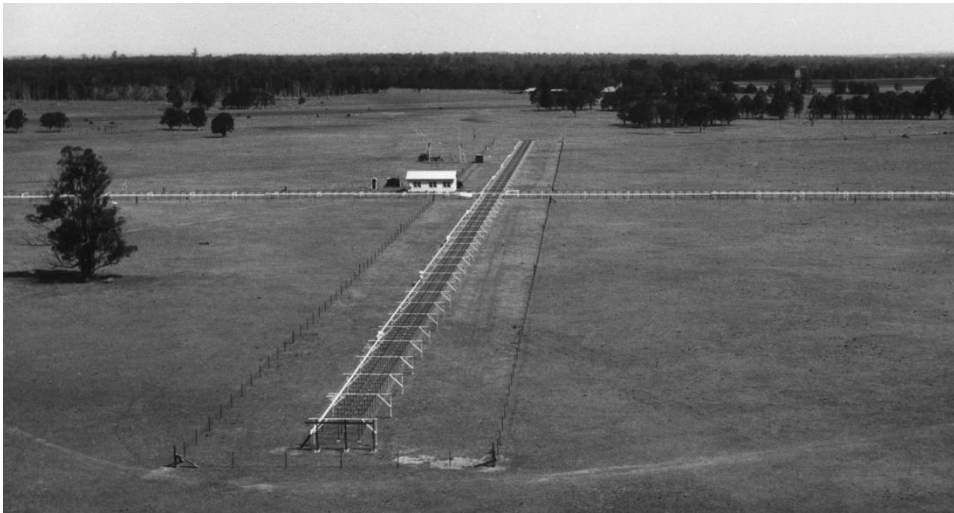
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Mills Cross-type radio telescopes (1953): two-dimensional cross array, at 3.5 m (86 MHz) **1 deg resolution.**



Short history of VLBI

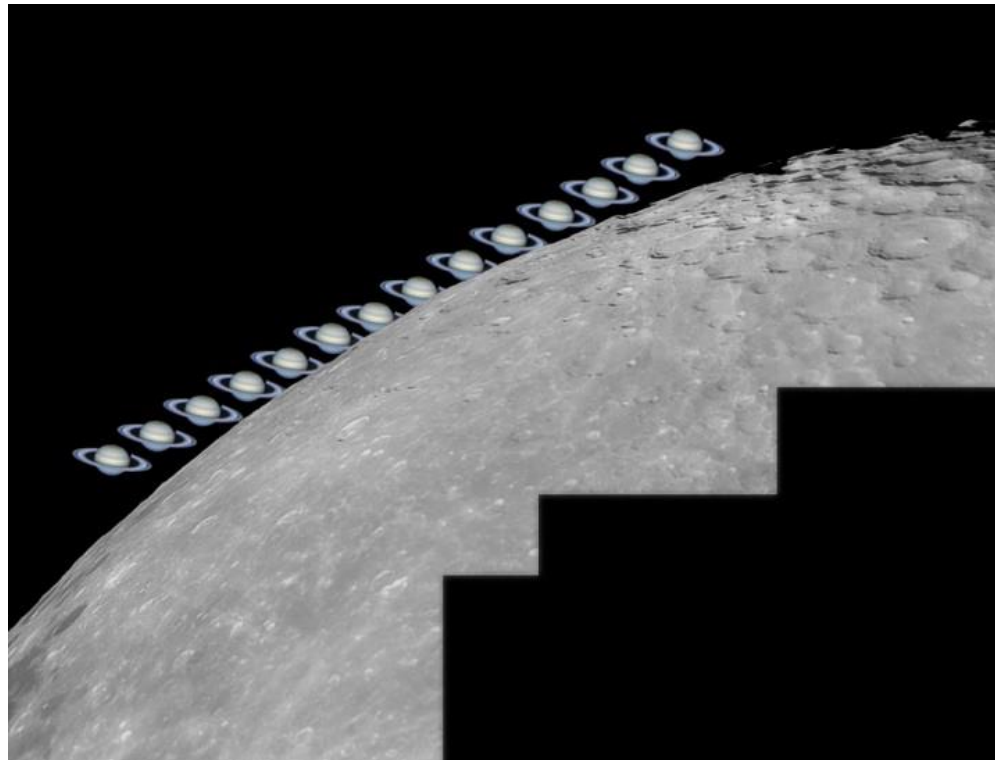
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Improved version worked at 73 cm (408 MHz) with **2.8 arcmin resolution.**
East-west arm used as a full earth-rotation synthesis instrument at 36 cm (843 MHz) with **43 arcsec resolution.**

Short history of VLBI

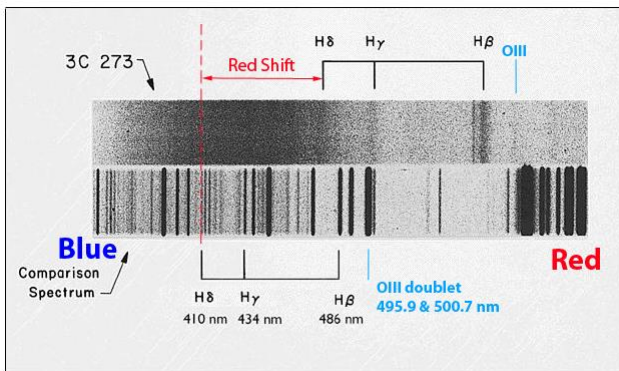
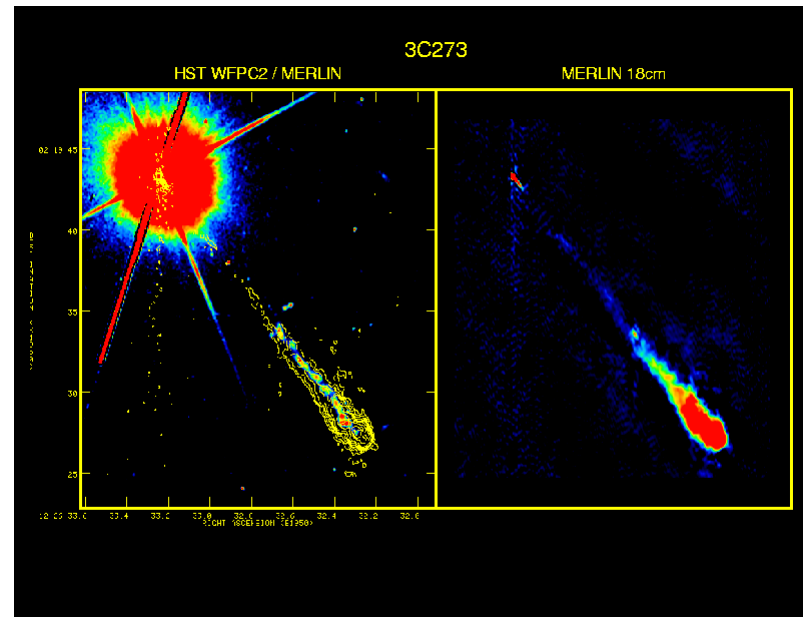
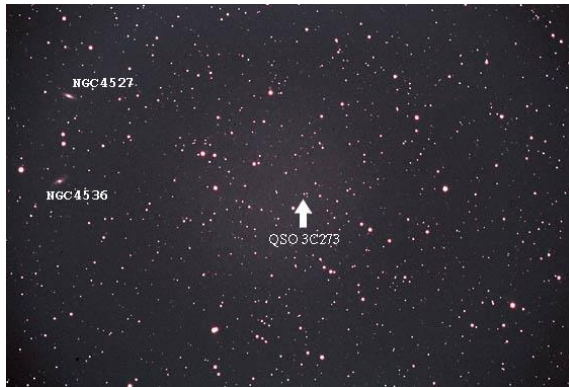
Lunar Occultations (1939): occultations of stars to measure their angular sizes and positions. The effect of diffraction can be precisely removed so that the angular resolution is limited only by the telescope sensitivity, **up to 5 mas at 0.5 μm .**



Short history of VLBI

Lunar Occultations (1939):

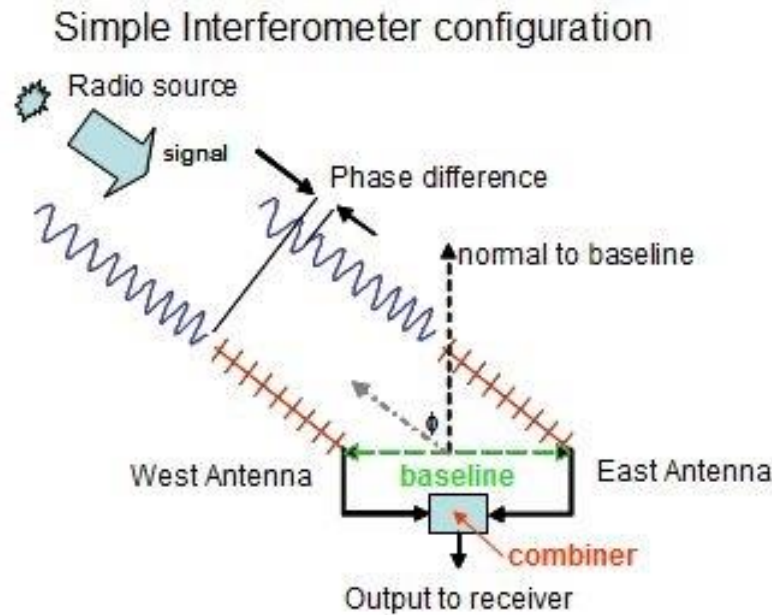
Optical identification of 3C273 and discovery of quasars with Parkes 210-ft radio telescope
(Schmidt 1963)



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.

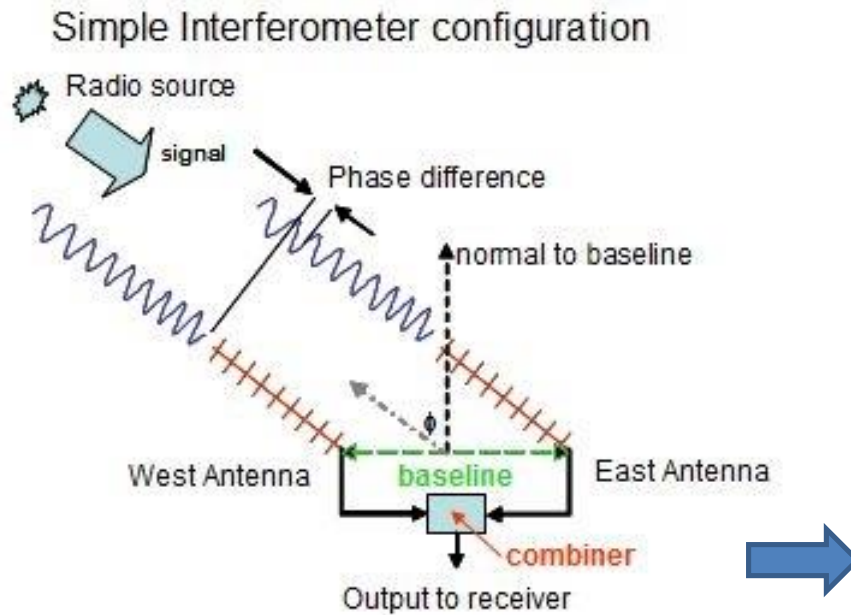


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Cambridge interferometric sky surveys (IC surveys).
Up to 6 arcmin

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.**

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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:

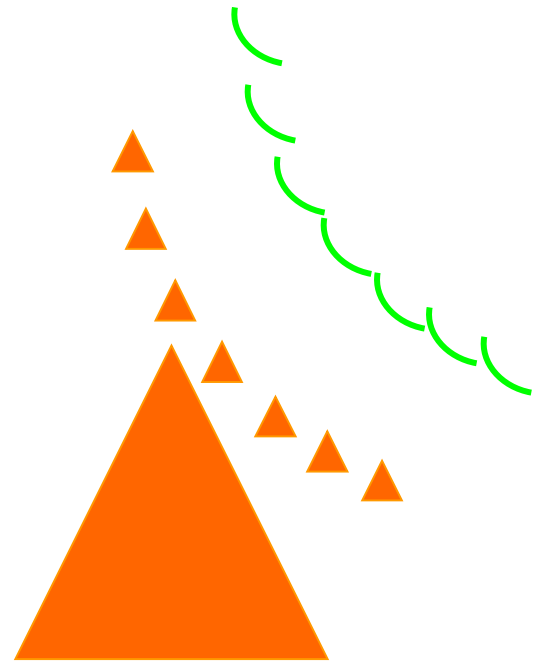
MERLIN Multi-Element-Radio-Link-Interferometer-Network (1980):

7 antennas, with up to **10 mas**

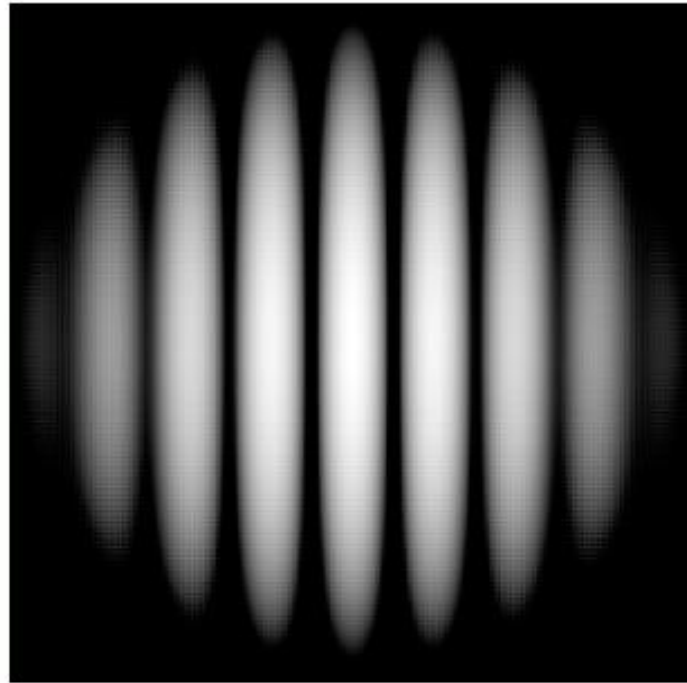
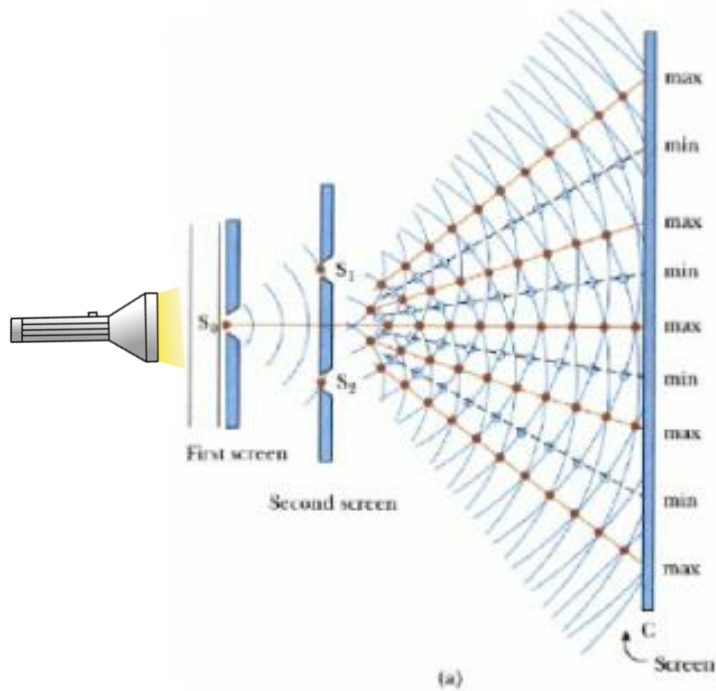


Connected arrays: Aperture Synthesis

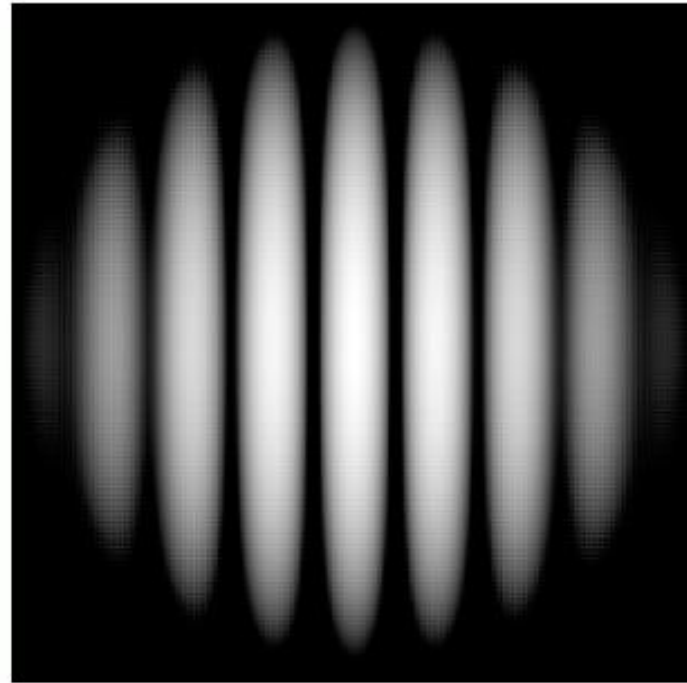
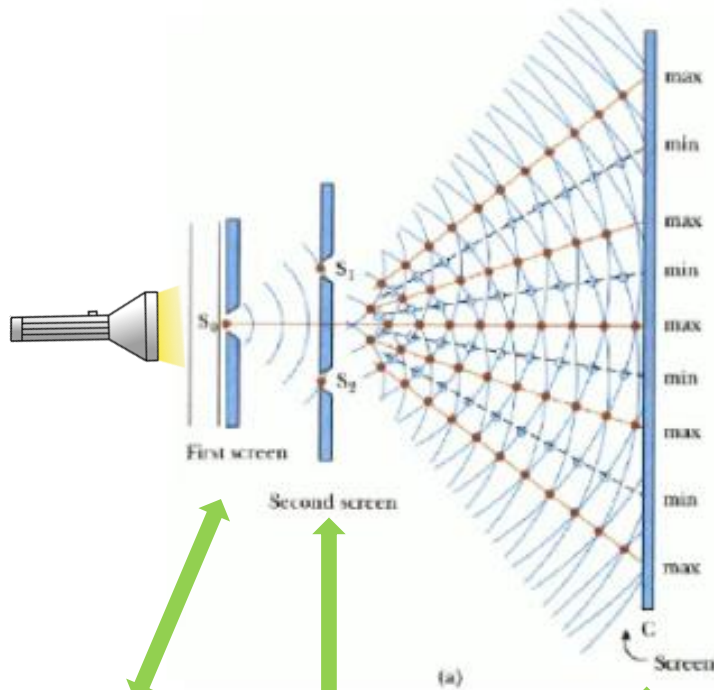
Aperture synthesis: interferometry of a collection of antennas to synthesize an instrument with the size (= resolution) of the entire network.



(Young double-slit experiment)



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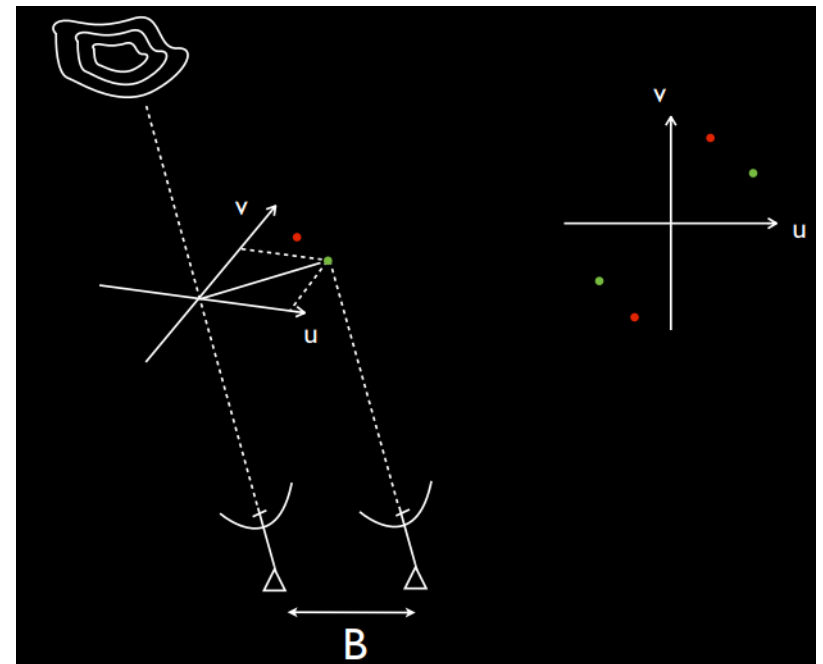
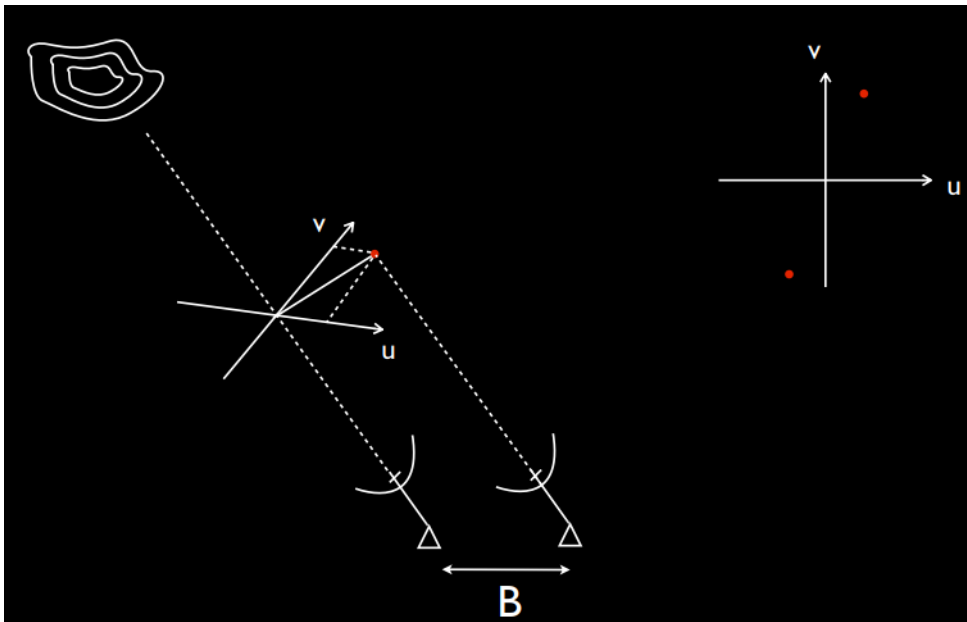
Complex visibility function = interference pattern in screen

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

galaxy = torch

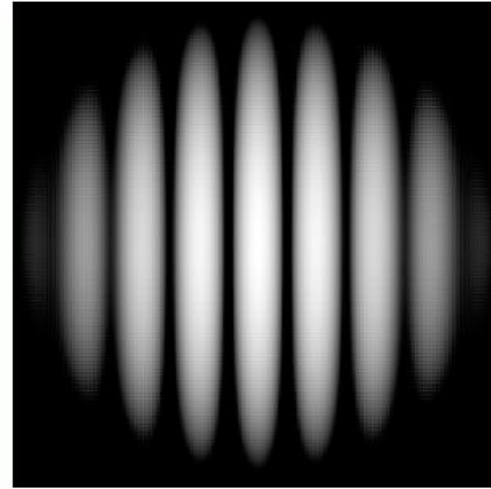
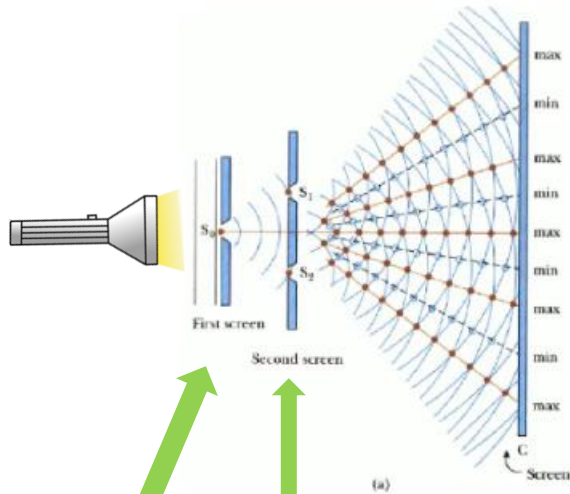
interferometer = double slit

(Visibility or UV plane)



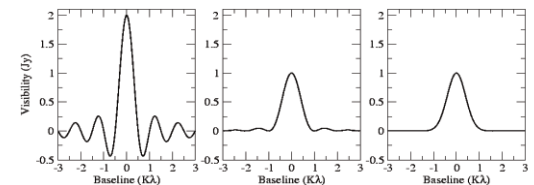
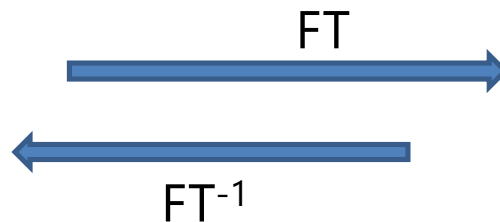
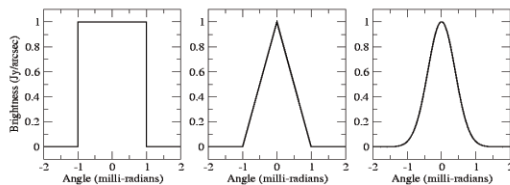
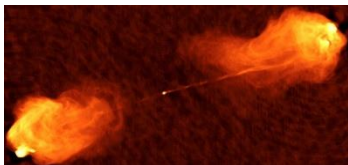
Plane perpendicular to the source direction, where the visibility function is measured during the observation

(Young double-slit experiment)

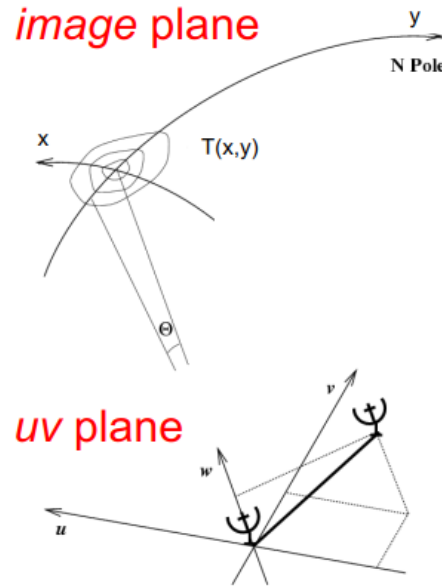
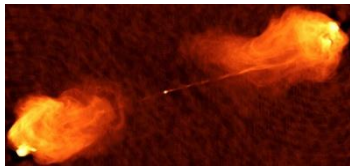


Complex visibility function

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

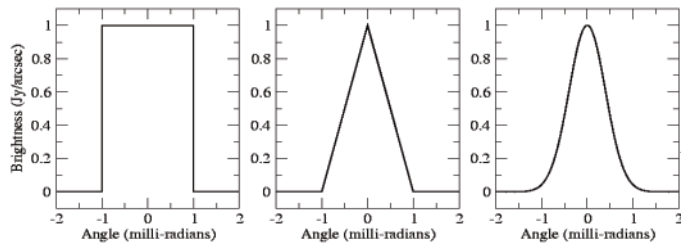


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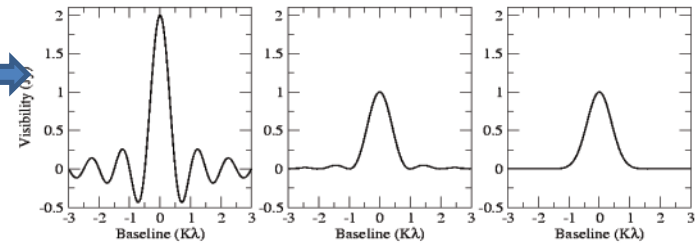


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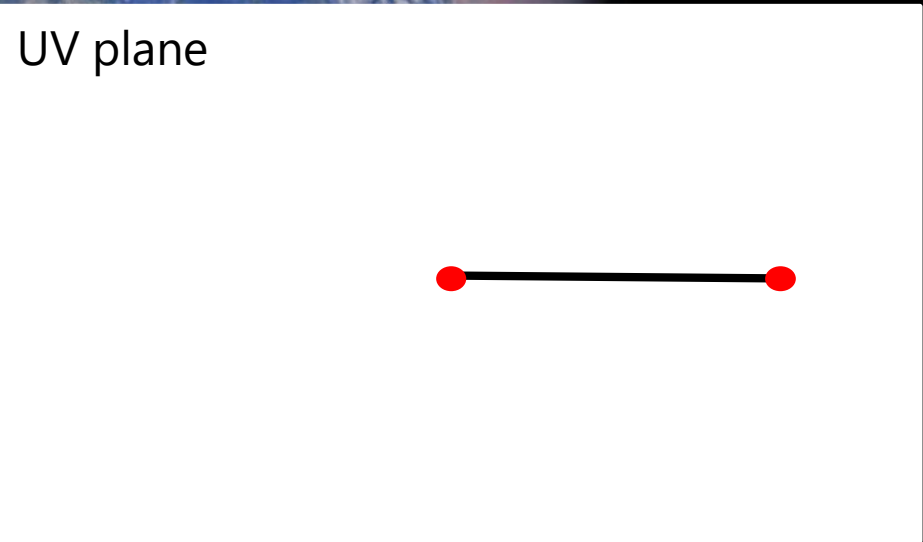
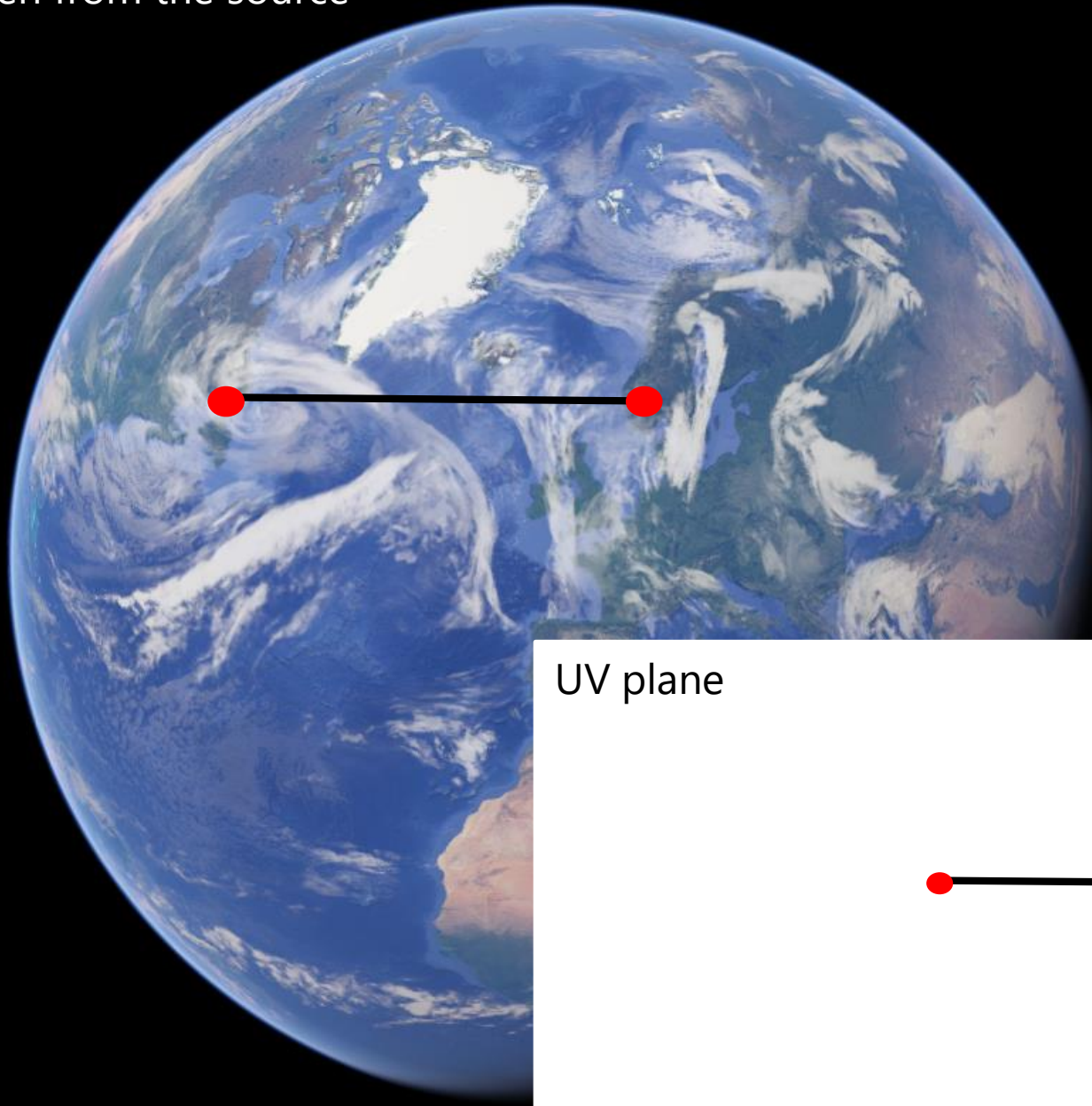
FT
FT⁻¹



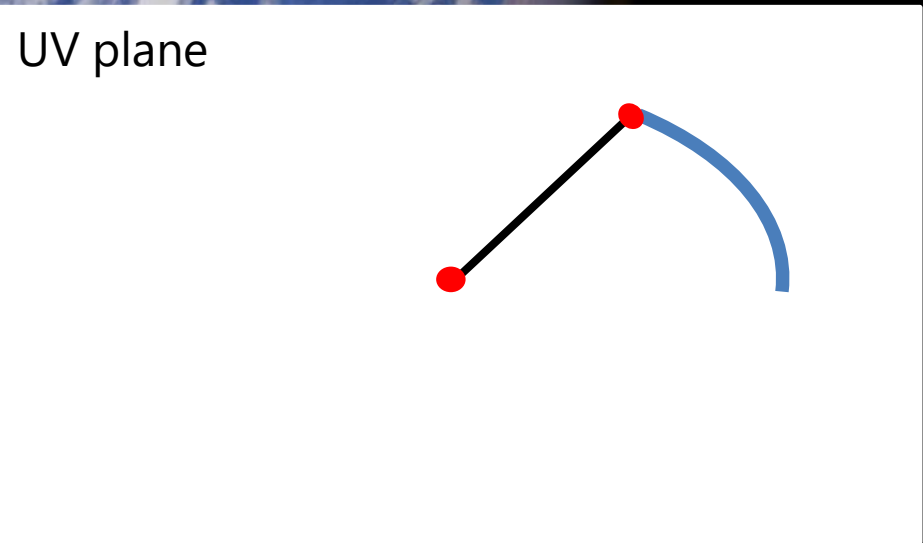
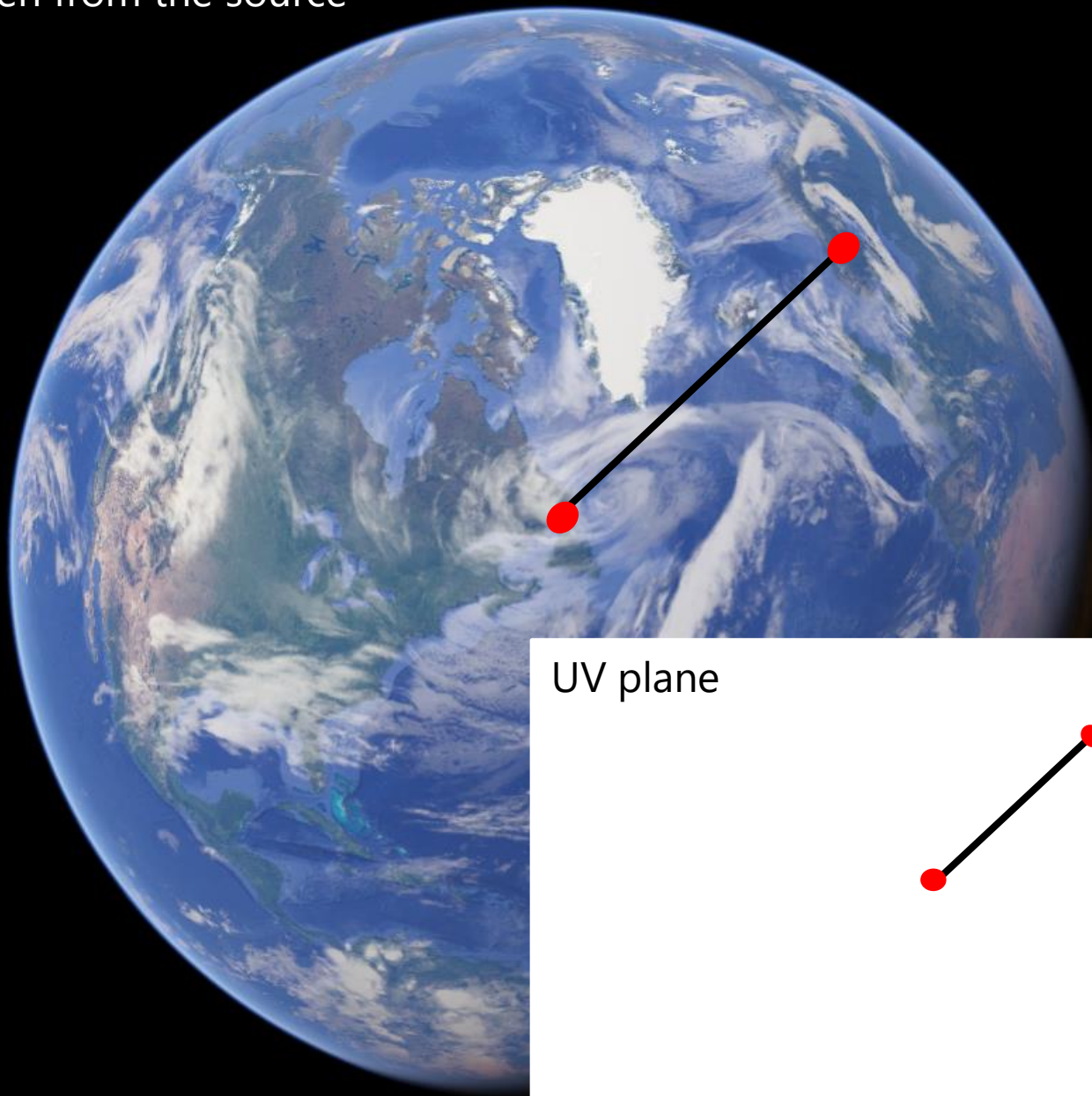
$$I(x, y) = \iint V(u, v) e^{-2\pi i(ux+vy)} du dv$$

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

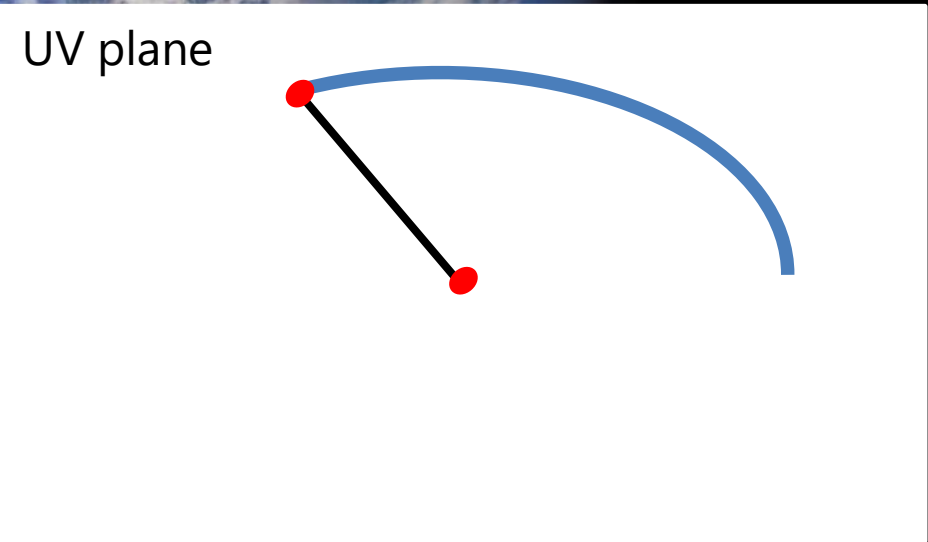
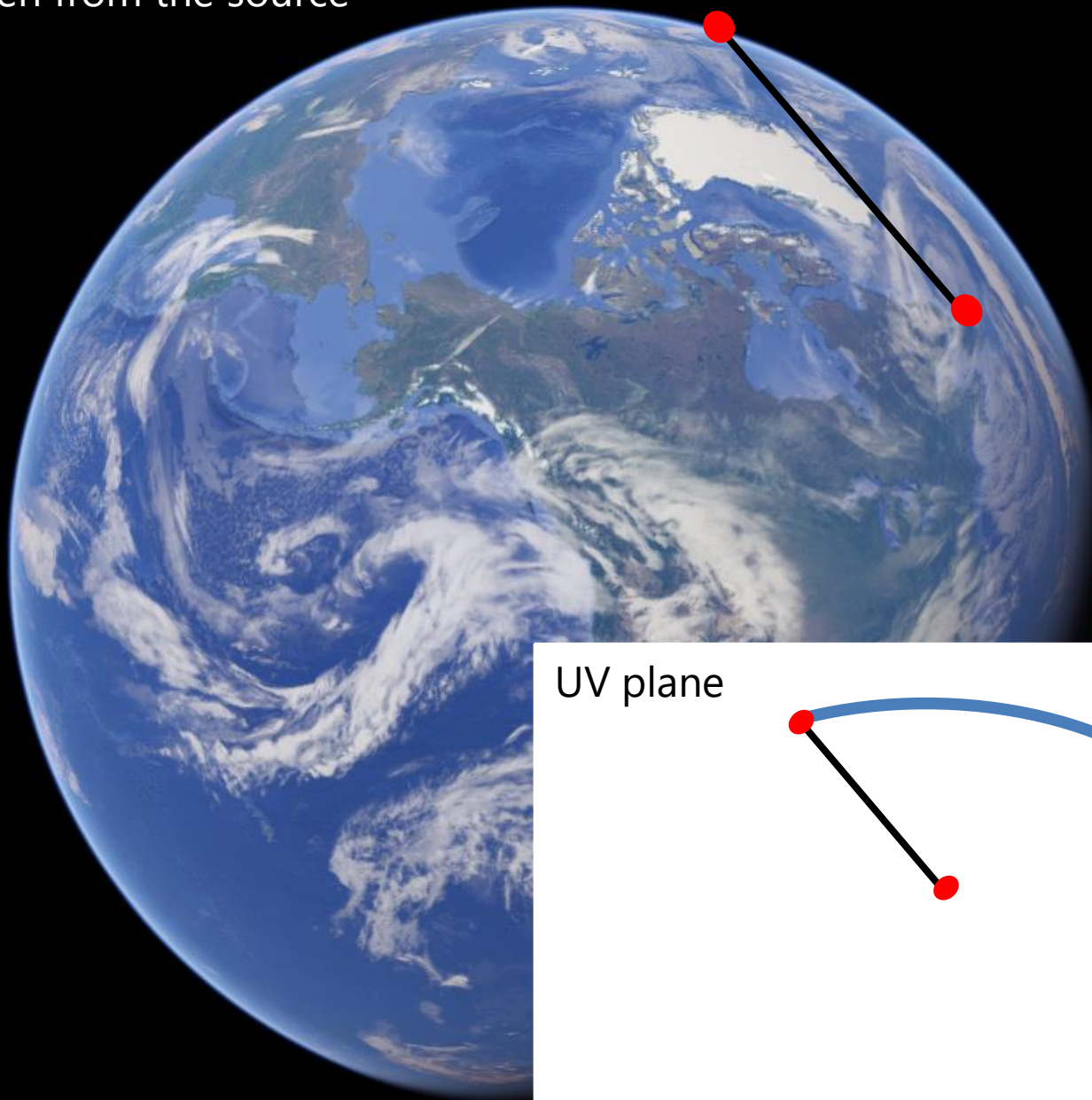
Earth seen from the source



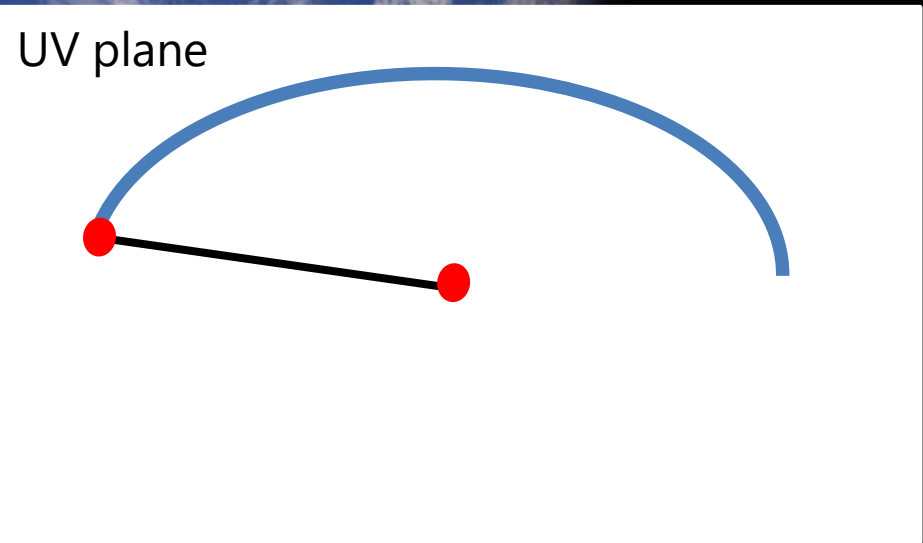
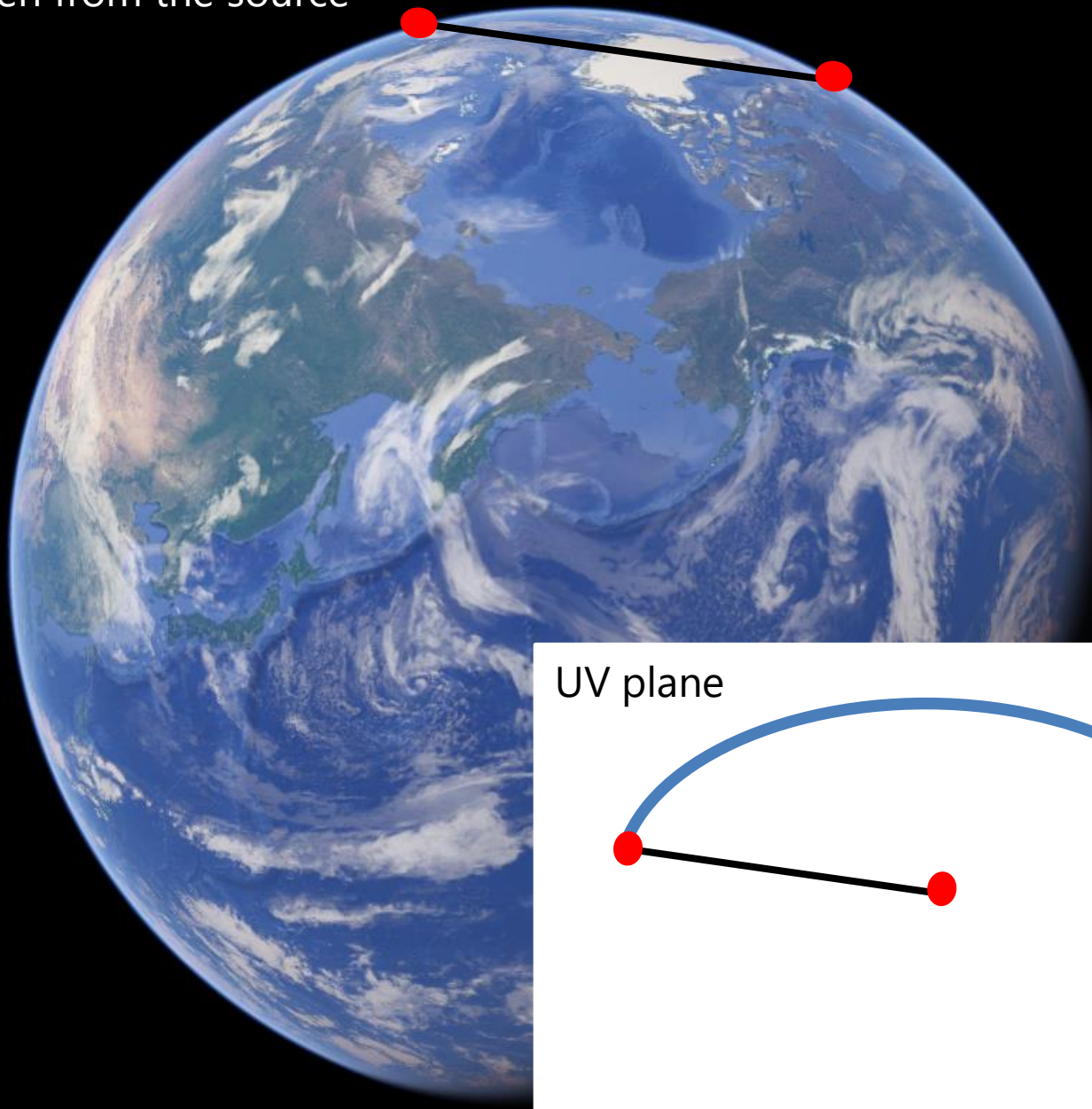
Earth seen from the source



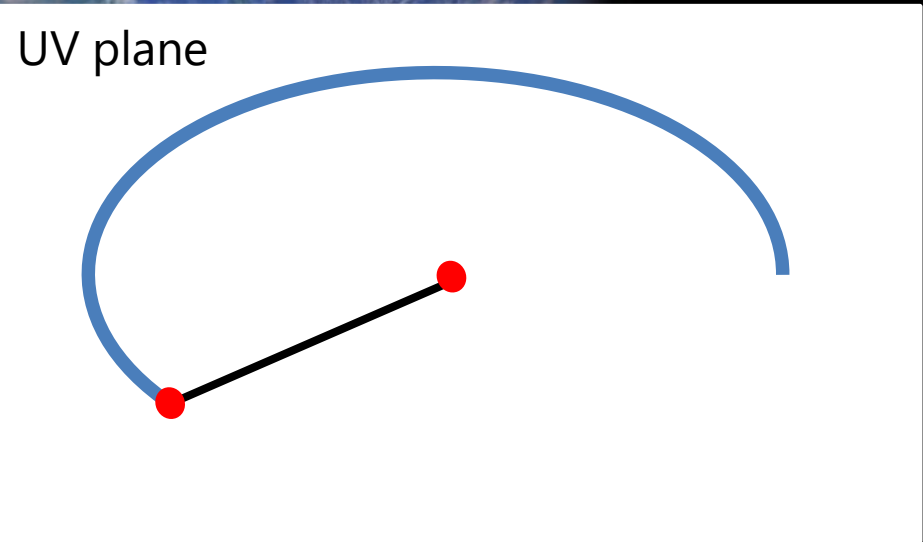
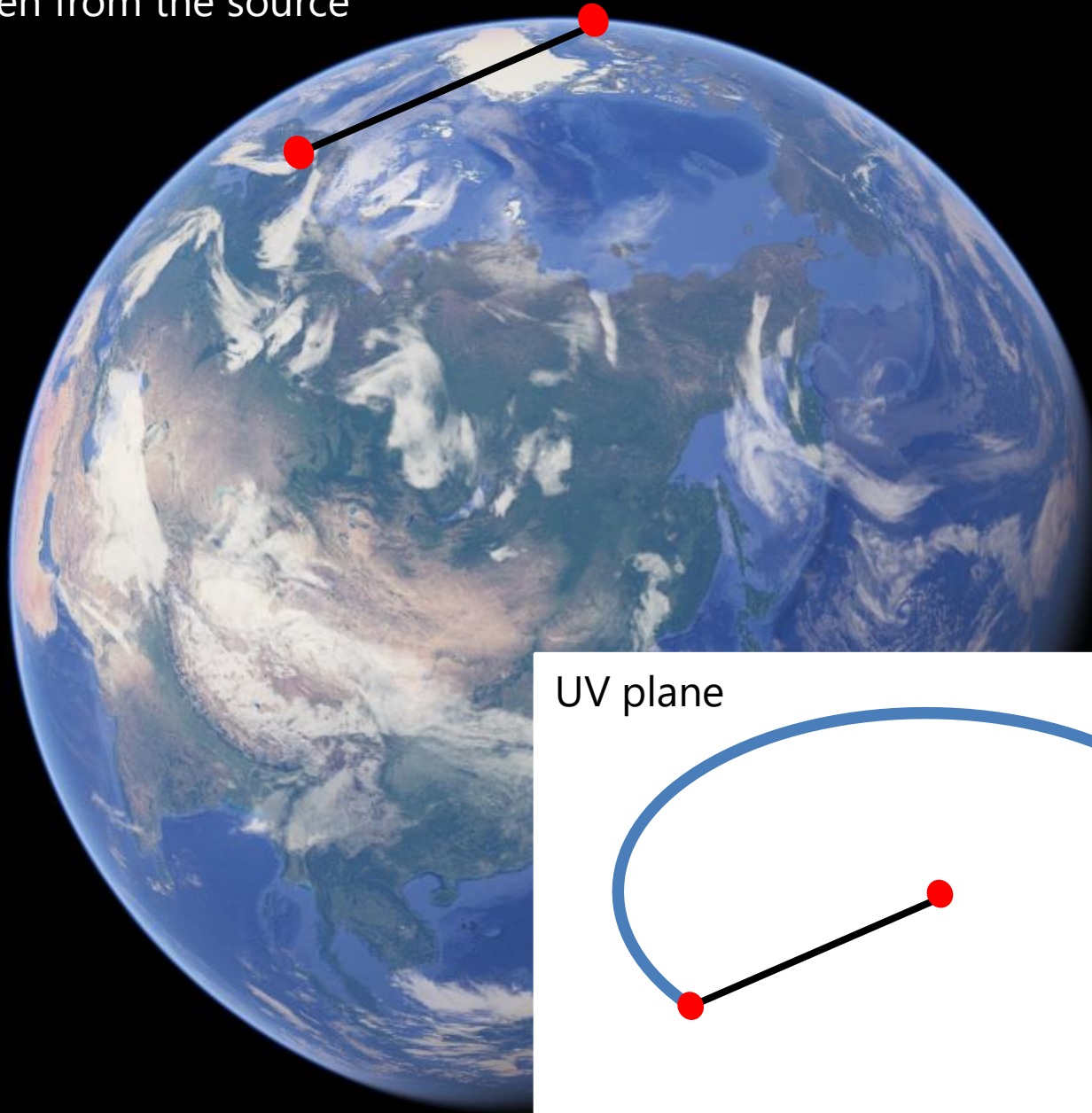
Earth seen from the source



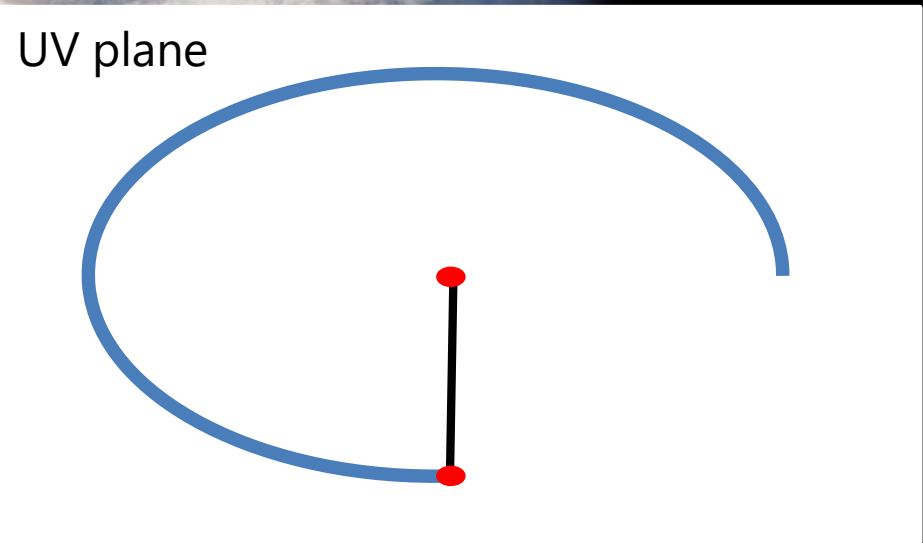
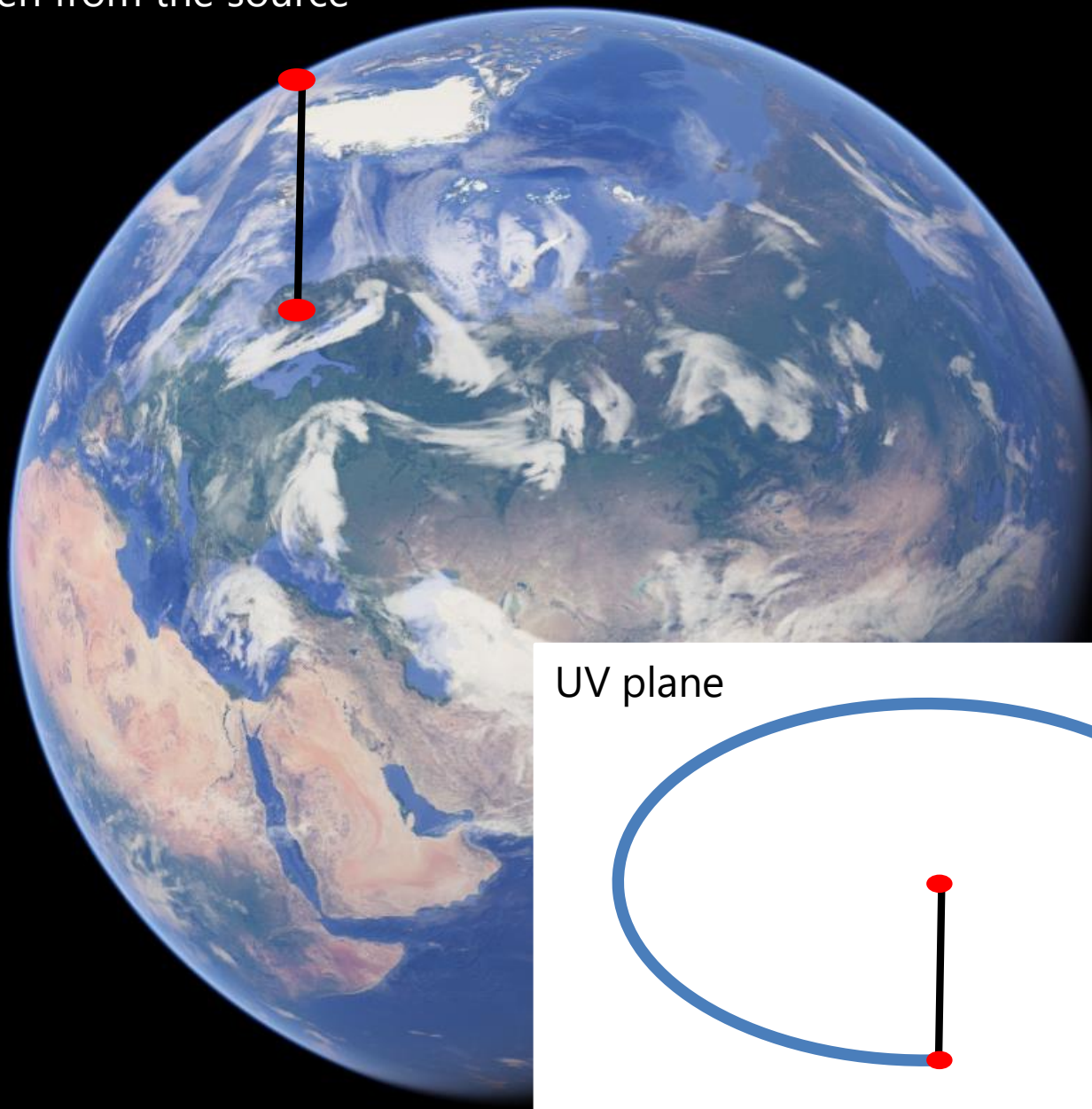
Earth seen from the source



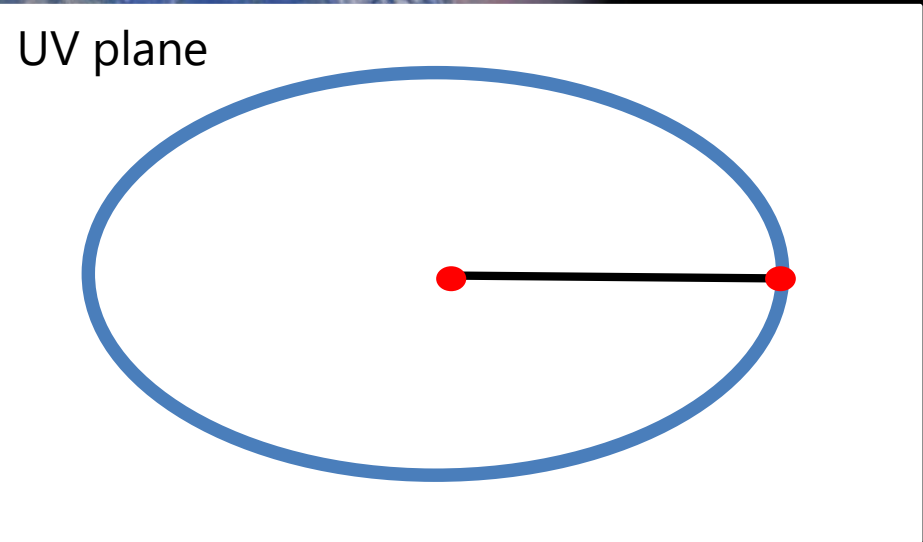
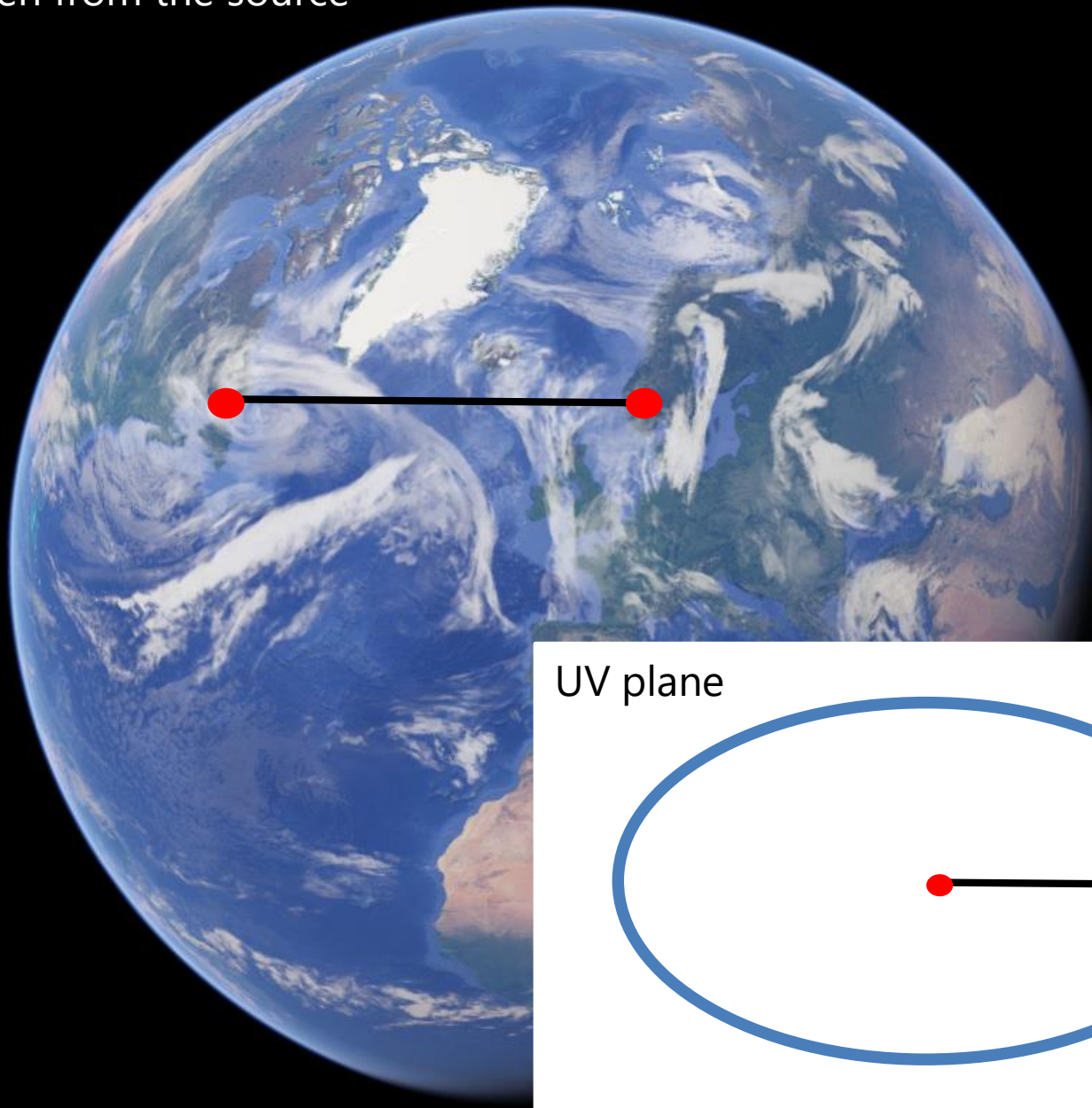
Earth seen from the source



Earth seen from the source

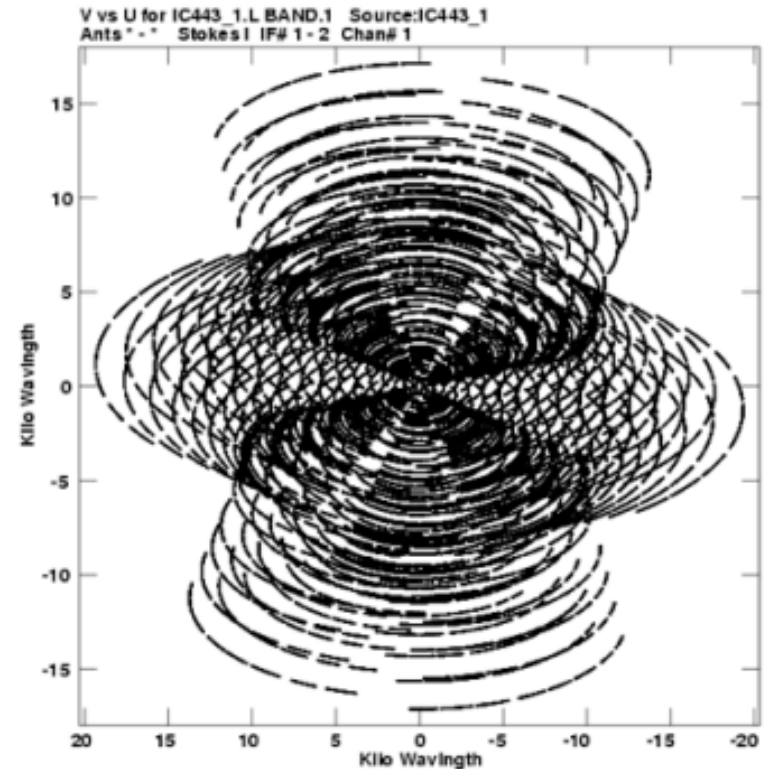
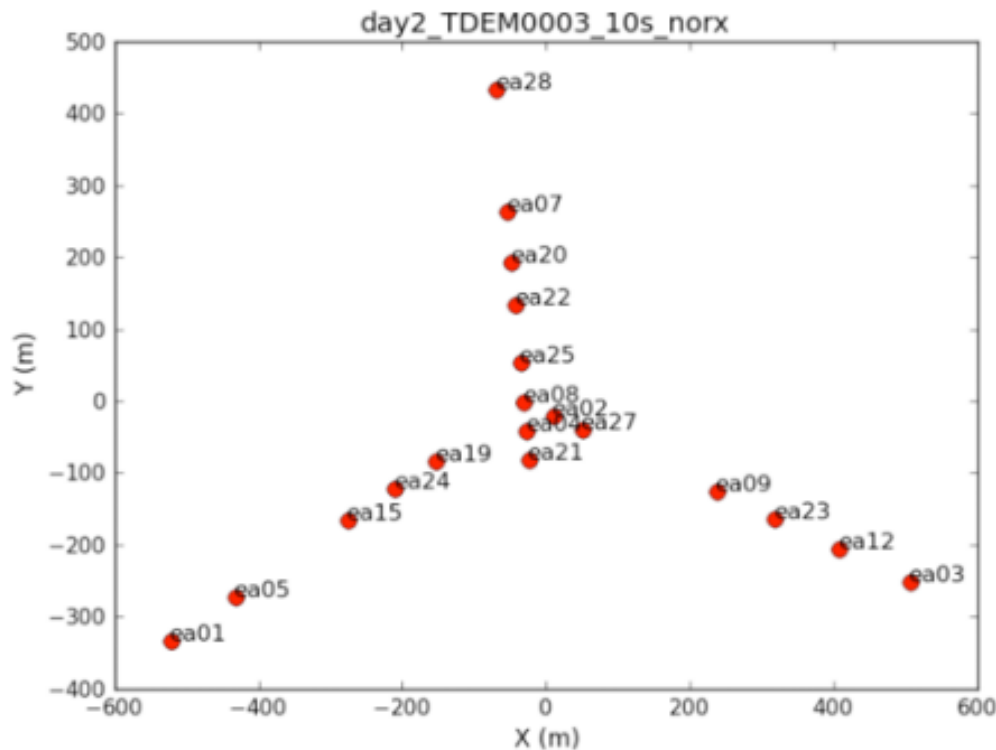


Earth seen from the source



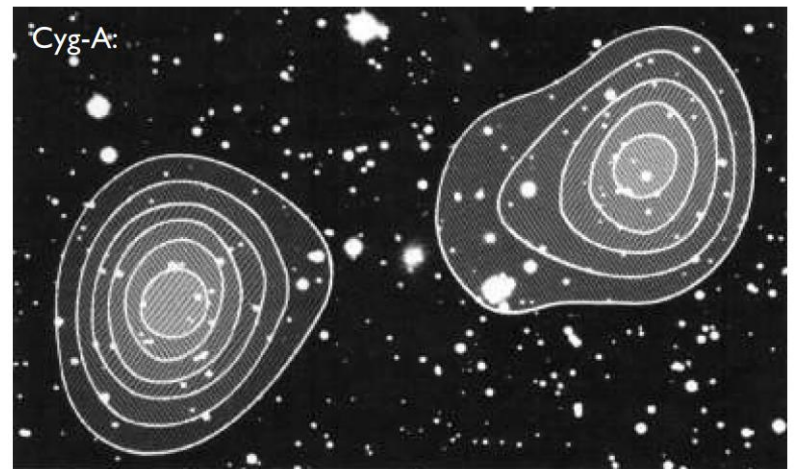
(Visibility or UV plane)

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



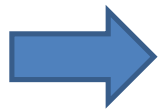
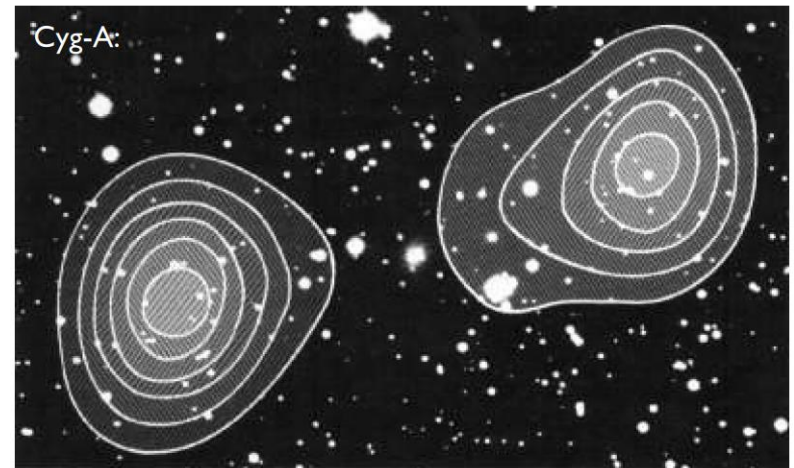
Connected arrays: Aperture Synthesis

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



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



Aperture synthesis more powerful than cross-type interferometer

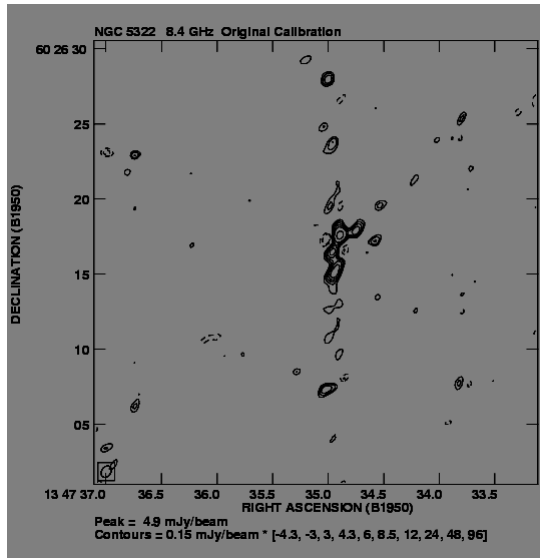
Need 1 arcsec resolution = optical

Connected arrays: Self-calibration

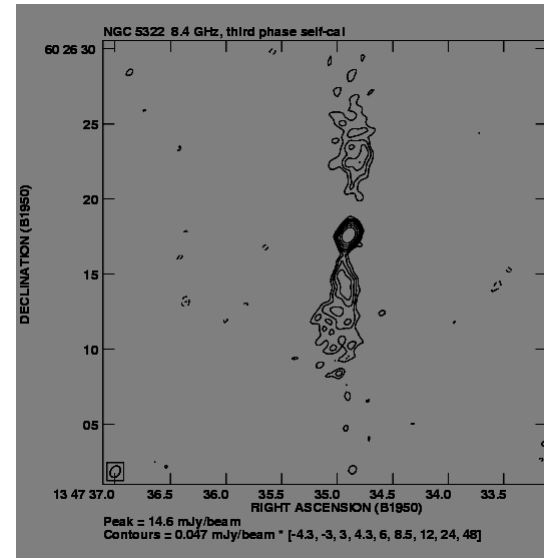
Manchester group shown: 3 elements give the phases without need for calibration!!

Connected arrays: Self-calibration

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



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

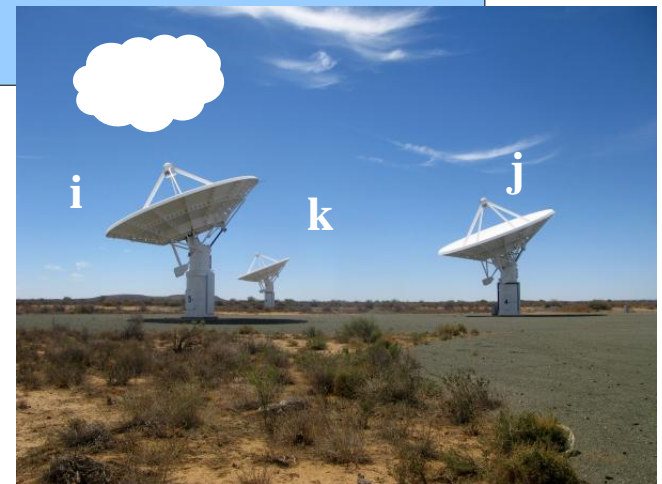
Self-calibration preserves the **Closure Phase** which is a good observable even in the presence of antenna-based phase errors:

Connected arrays: Self-calibration

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

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

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)

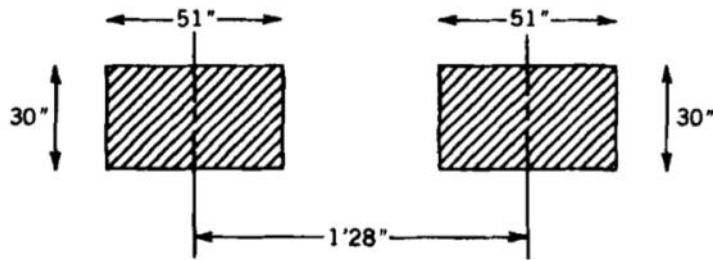


27 antennas of 25-m diameter
4 configurations (0.6-36 Km)
1.3-20 cm
Up to **0.1 arcsec** resolution

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



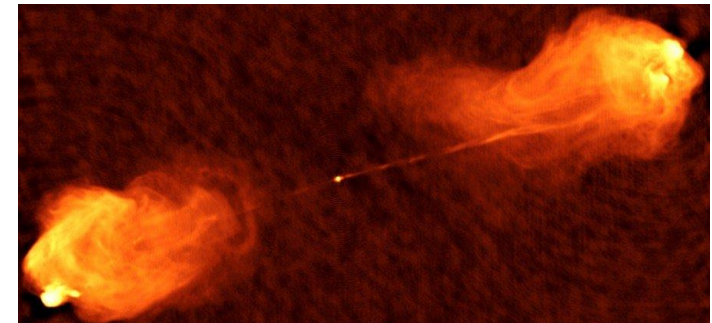
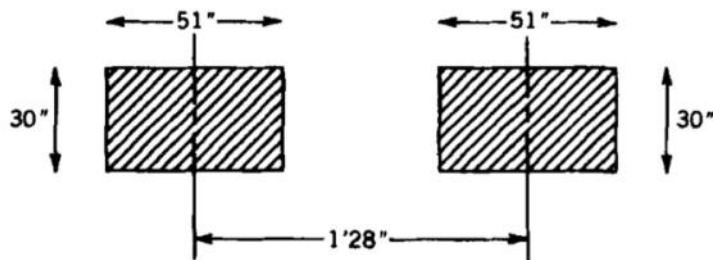
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Connected arrays: The Very Large Array – VLA (1980)



27 antennas of 25-m diameter
4 configurations (0.6-36Km)
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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...

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Dave Jauncey Ken Kellermann Barry Clark

Let's VLBI begin...

“FATHERS OF VLBI” AT IAU164, 1997



y Clark

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...

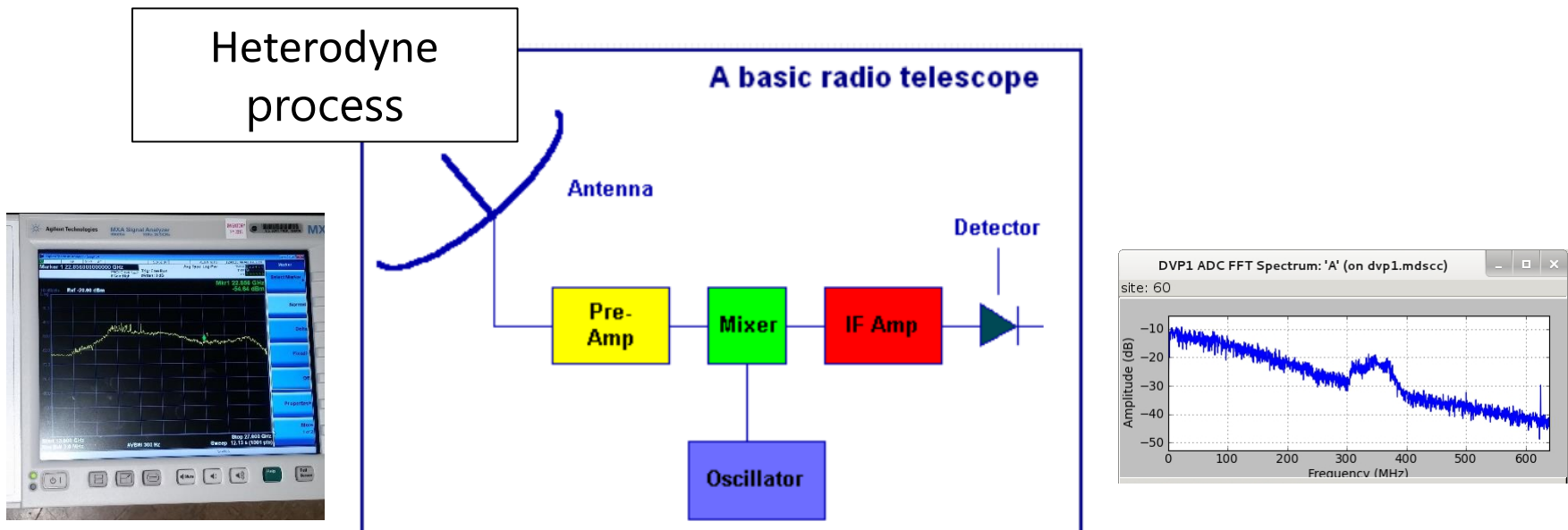
Aperture synthesis & Self-calibration

+

**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:

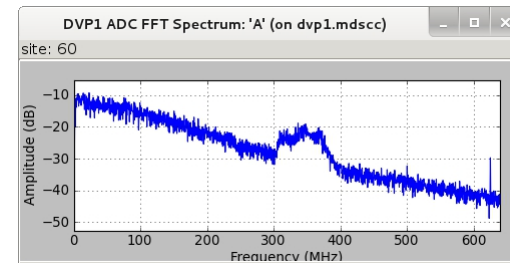
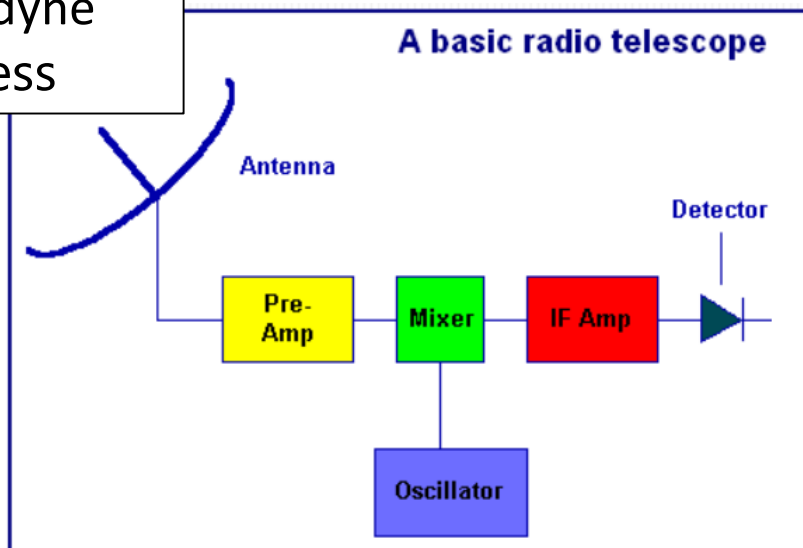


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- **Pros:** Nyquist sampling rate much lower than for sky frequencies (2 orders of magnitude smaller).
- **Pros:** Allows post-processing of the signal: spectroscopy and non real-time interferometry → **VLBI has born!**
- **Cons:** Less sensitive than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

Heterodyne process

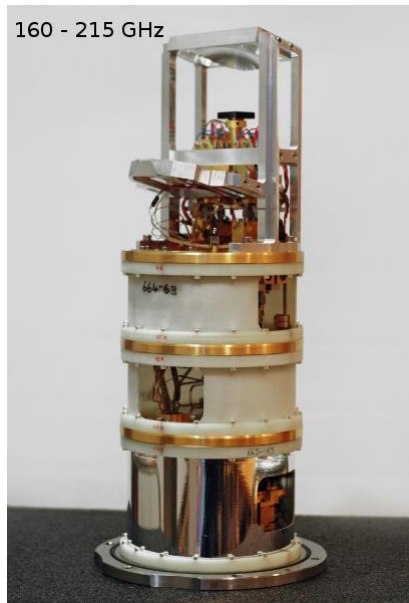


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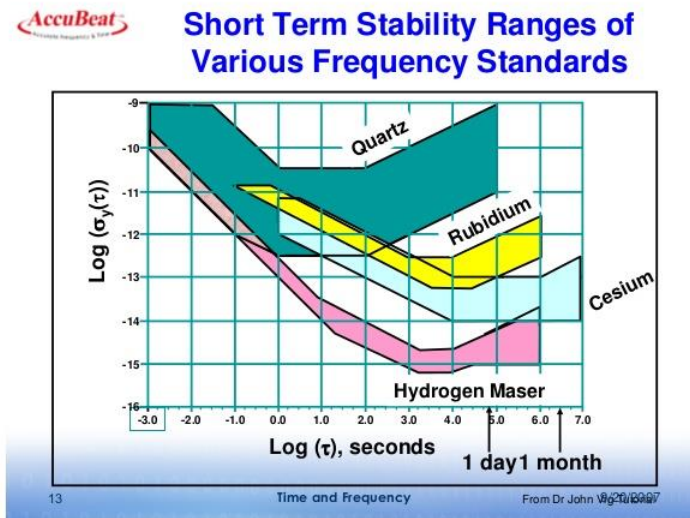
B5 receiver
(Chalmers Univ.,
Sweden)
implemented for
ALMA (JAO, Chile)



VLBI: Atomic Clocks

Atomic clocks are the **most accurate time and frequency standards** known, and are used as primary standards.

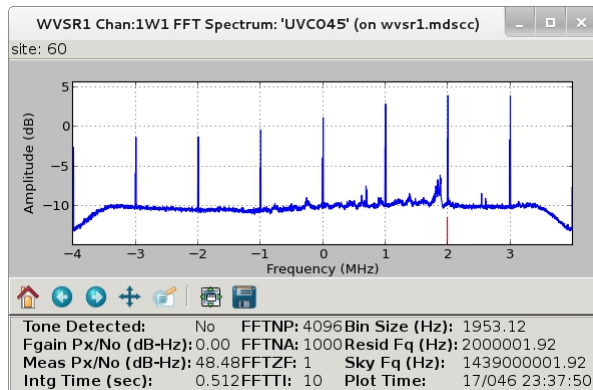
They use the emission from different atomic transitions: H1, cesium-133 (second definition by International System of Units), rubidium-87, etc. Hydrogen masers superior short-term stability, but lower long-term accuracy.



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.

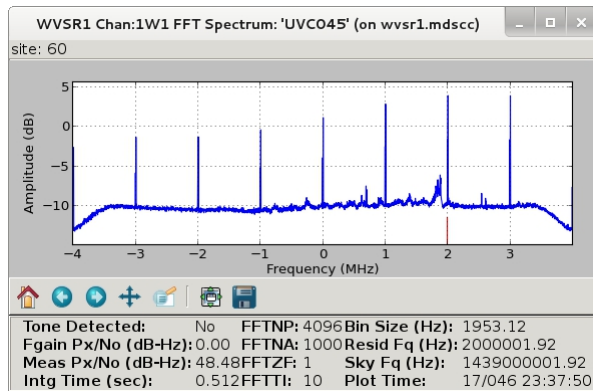


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The phases of one or more of these lines are measured by the detector in real-time, logged as a function of time, and delivered in a log or table. Also extracted at the correlator.



DVP1 Configuration

site: 60

Main Status

Status: **Operational**

IF Input A

Input Power: -17.45 dBm

ADC Amp: -12.45

Desired Amp: -16.00 dB

ADC RMS: 21.41

Atten Setting: 31 dB

IF Source: 65_X_RCP

RF to IF LO: 8100 MHz

RF Freq: 8100000000.00 Hz

IF Input B

Input Power: -28.69 dBm

ADC Amp: -14.69

Desired Amp: -16.00 dB

ADC RMS: 16.56

Atten Setting: 22 dB

IF Source: 65_S_RCP

RF to IF LO: 2000 MHz

RF Freq: 2000000000.00 Hz

Mark's Status

State: **BANK B IS PROTECTED**

Bank A: **PL-0307/8000/2048**

Size: 8 TB

Free: 17.90%

Bank B: **PL-0088/4000/1024**

Size: 4 TB

Free: 0.01%

Bitrate: 512.00 Mb/sec

Avg Bitrate: 513 Mb/sec

Channel Status

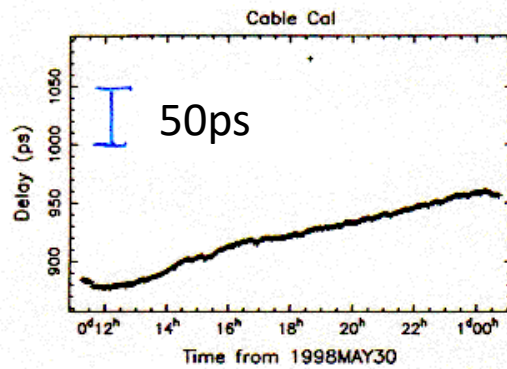
Chan ID	Status	Input ID	PCal Tone	PCal Drift (deg/min)	PCal Resid (deg)	PCal Mag (mSNRv)	Power (dBm)	SFRO (Hz)	BW	Bits	FGAIN Mult
1	Operational	B	L1	4.96655	1.03907	25.5155	-38.638534 dBm	204490000.00	8 MHz	2	1.02
2	Operational	B	U1	5.35613	1.06925	25.6175	-38.234155 dBm	212490000.00	8 MHz	2	1.00
3	Operational	B	L1	-0.401631	1.06853	21.2136	-38.387727 dBm	239490000.00	8 MHz	2	1.03
4	Operational	B	U1	3.30088	2.25623	14.0316	-39.571722 dBm	283510000.00	8 MHz	2	1.00
5	Operational	B	U1	4.64706	3.0399	15.8036	-40.112777 dBm	295510000.00	8 MHz	2	1.00
6	Operational	A	L1	1.87329	0.826379	25.273	-31.622059 dBm	114490000.00	8 MHz	2	1.05
7	Operational	A	U1	-5.37912	0.676542	25.8647	-31.783487 dBm	122490000.00	8 MHz	2	1.03
8	Operational	A	L1	2.68097	1.20618	25.6485	-31.923660 dBm	130490000.00	8 MHz	2	1.03
9	Operational	A	U1	-8.84531	1.0169	26.3856	-32.244285 dBm	138490000.00	8 MHz	2	1.04
10	Operational	A	L1	0.761969	1.50993	21.3499	-34.626280 dBm	253510000.00	8 MHz	2	1.05
11	Operational	A	L1	1.45149	1.74433	21.4252	-37.086969 dBm	424510000.00	8 MHz	2	1.05
12	Operational	A	L1	-3.07159	0.747278	21.9779	-38.209011 dBm	459510000.00	8 MHz	2	1.08
13	Operational	A	L1	-4.57174	1.4346	21.7833	-38.412600 dBm	467510000.00	8 MHz	2	1.09
14	Operational	A	L1	-3.69807	1.40404	22.0583	-38.114082 dBm	475510000.00	8 MHz	2	1.06

Selected Channel Commands

Data Histogram Plot... FFT Spectrum Plot... Power Time History Plot...

VLBI: Phase Calibration Signal

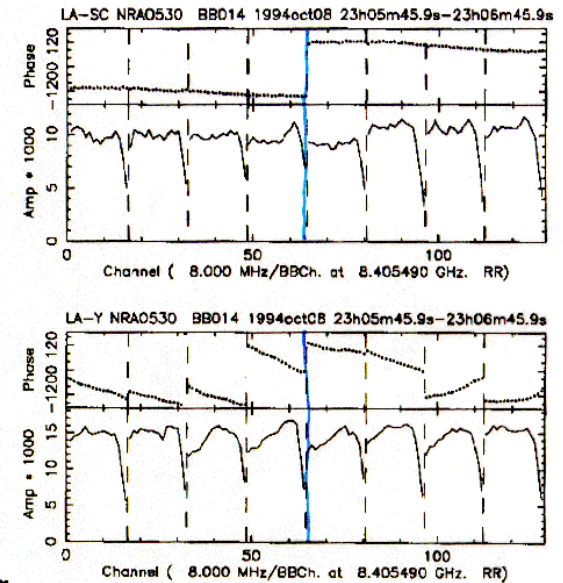
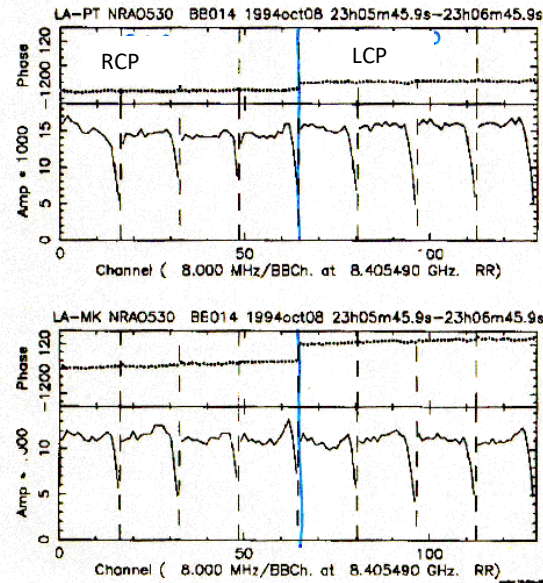
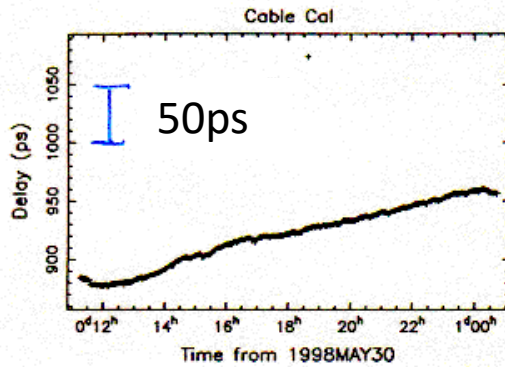
Cable Cal



VLBI: Phase Calibration Signal

Data Aligned with Pulse Cal

Cable Cal



No PCAL at VLA

Shows unaligned phases

VLBI Networks



Very Long Baseline Array



European VLBI Network

VLBI Networks: Deep Space Network



Goldstone Complex
California

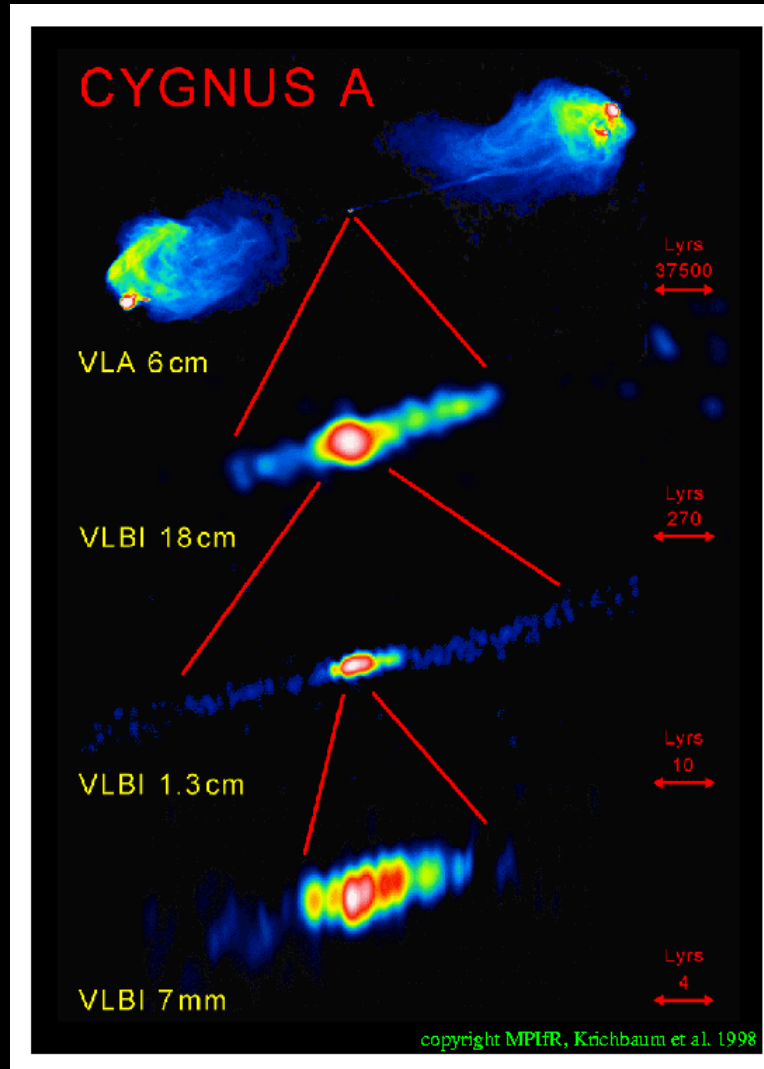


Canberra Complex
Australia

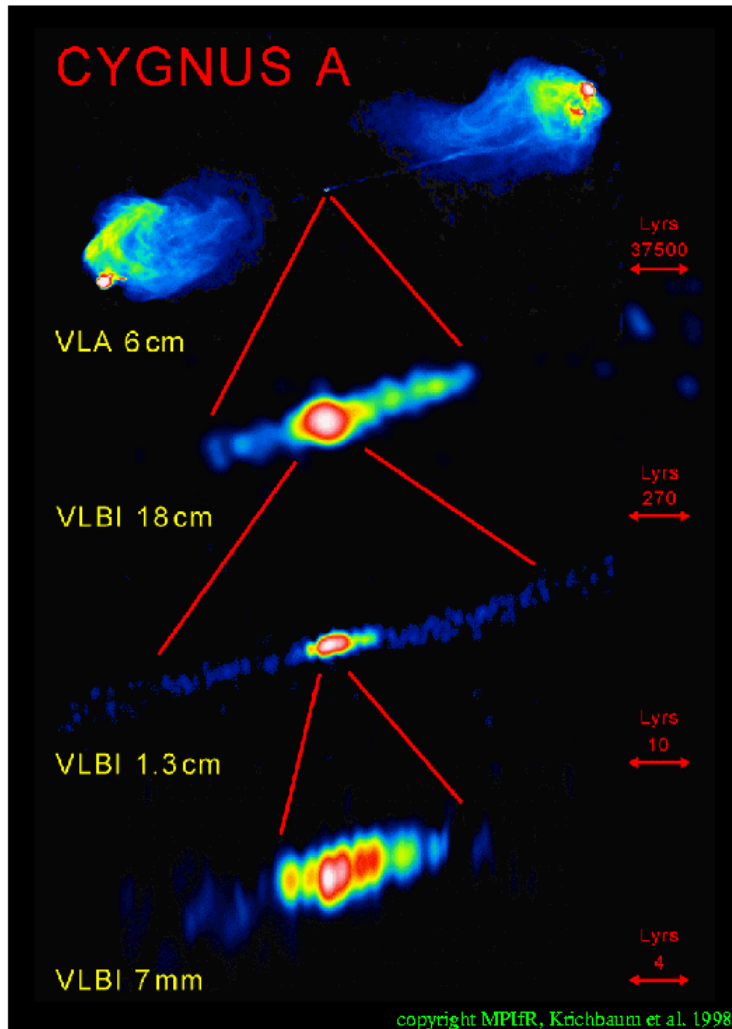


Madrid Complex
Spain

VLBI Networks



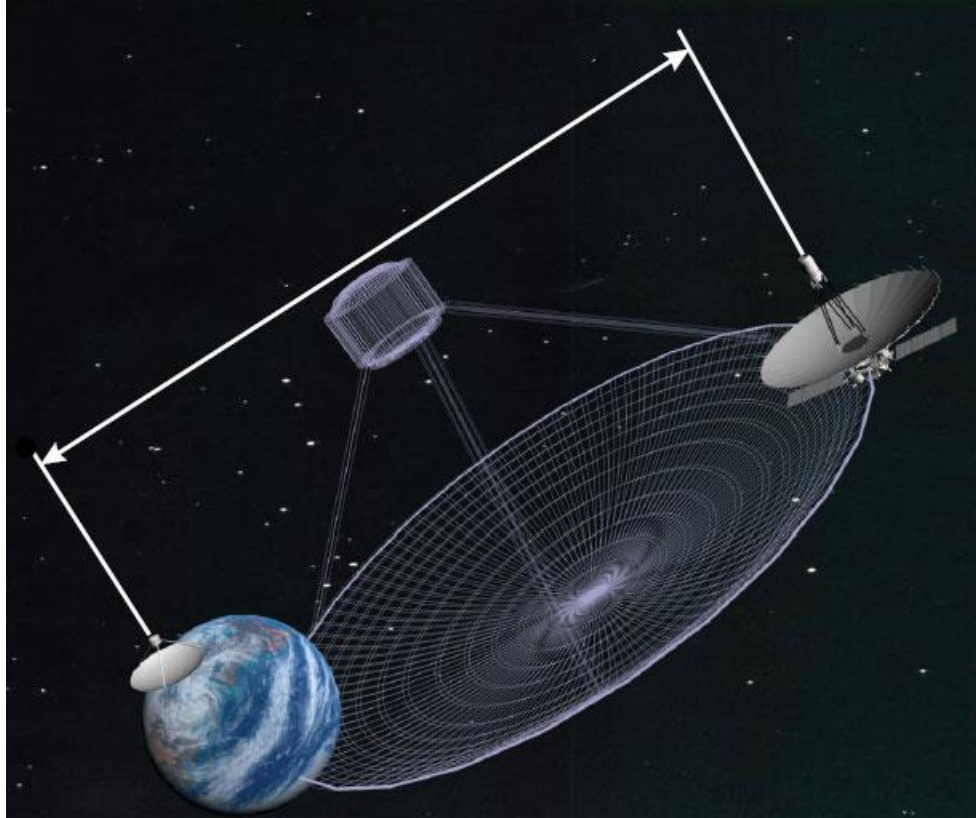
VLBI Networks



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 μ as angular resolution

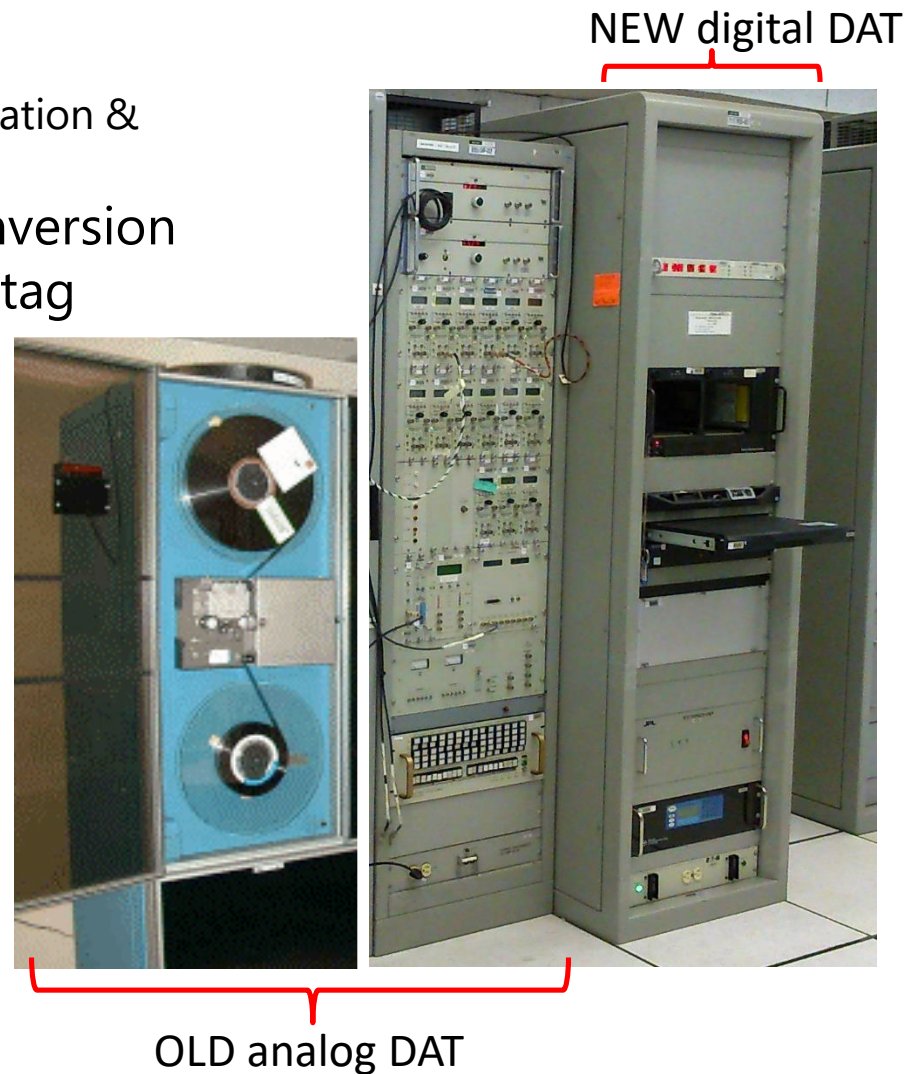
VLBI: Data Acquisition Terminal - DAT

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

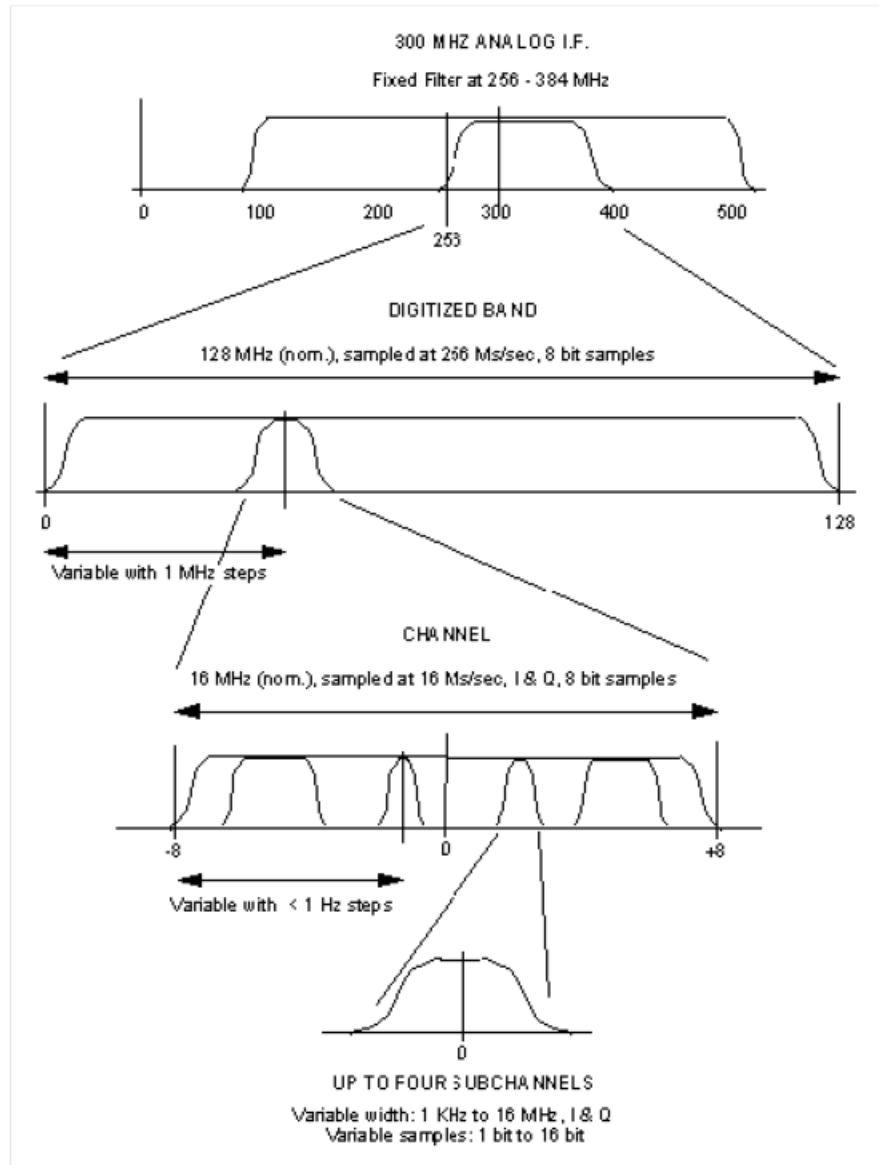
Configuration & Control:

- Field System



VLBI: Baseband conversion

IF



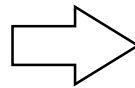
BB

VLBI: Digitization

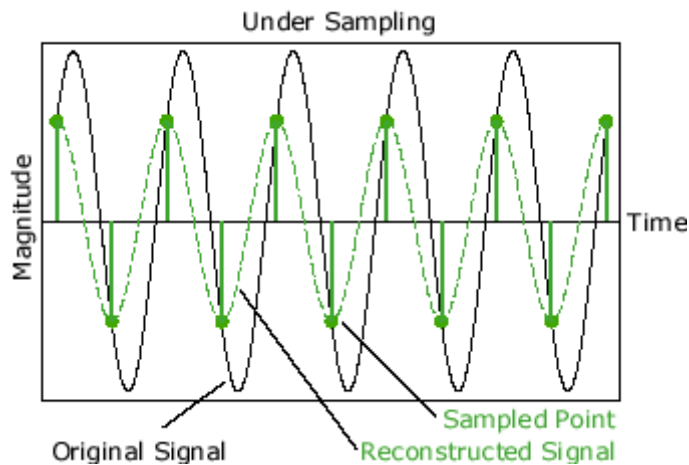
NYQUIST SAMPLING THEOREM (1933)

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.

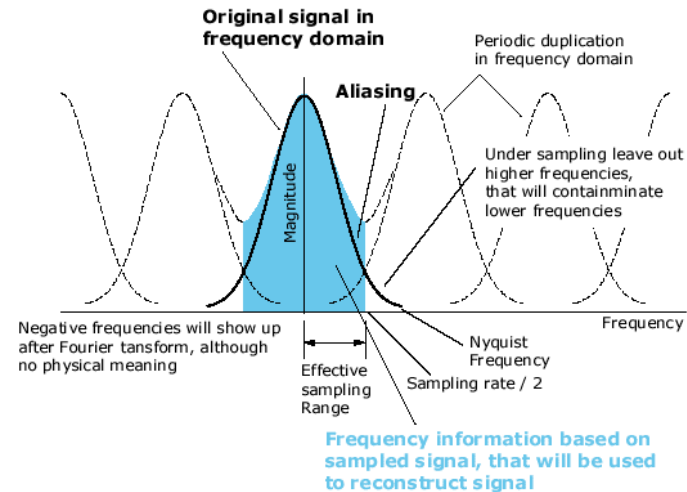
SAMPLE RATE <



UNDER SAMPLING



Original signal cannot be reconstructed

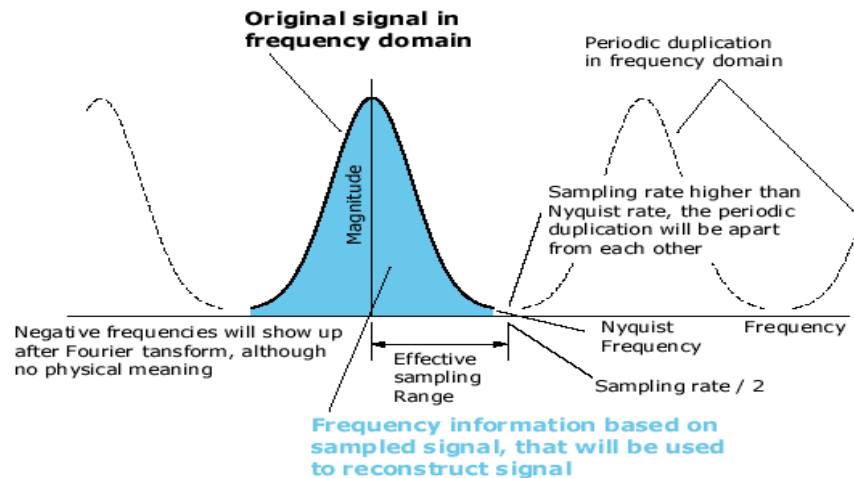
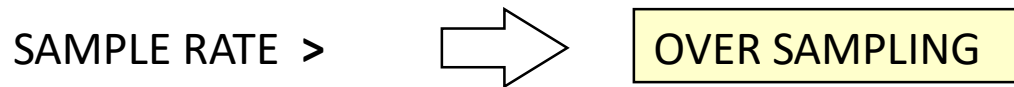


Under sampling causes aliasing: frequency components that are higher than half of the sampling frequency

VLBI: Digitization

NYQUIST SAMPLING THEOREM (1933)

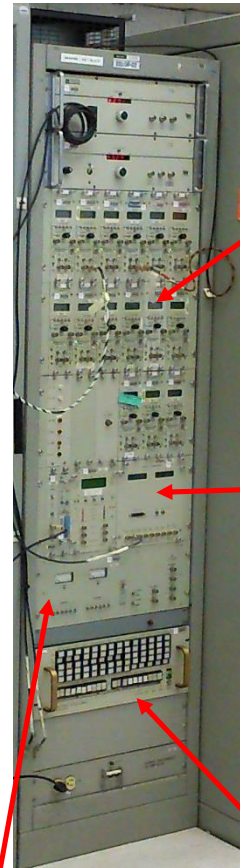
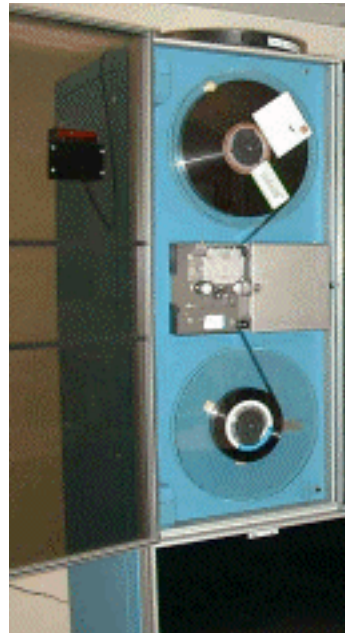
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Original signal can be reconstructed

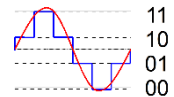
Increasing sampling rate SNR increases but more bits will be recorded

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



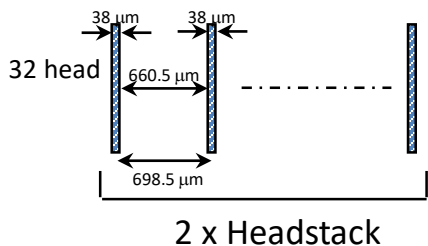
IF signal conditioning:
Amplification + attenuation

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

VLBI: MarkIV and VLBA DAT

Recording:

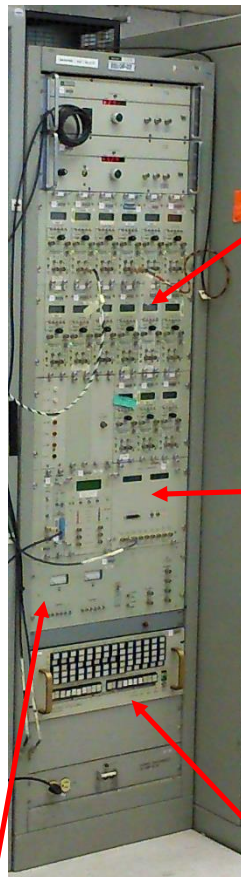
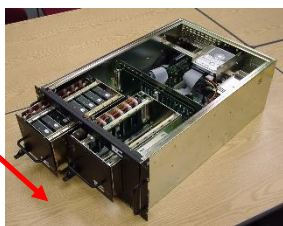
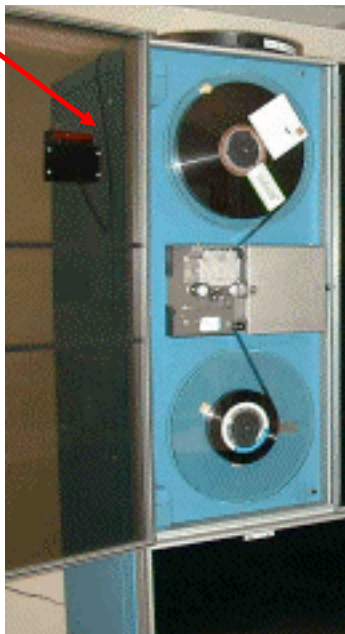
Honeywell/Metrum magnetic recorder/reproducer
thick (8820 ft, 33333 bpi)
thin (17600 ft, 56250 bpi)
14 passes → 448 tracks
8 Mbps/head, 1Gbps



Recording:

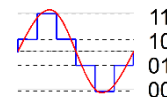
Mark5A recorder/reproducer
Up to 1024Mbps
8-pack disk modules

Transport of data to correlator



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

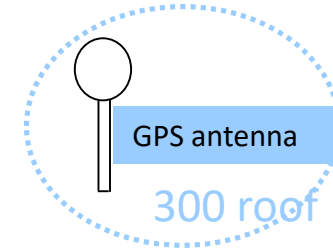


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Amplification + attenuation

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VLBI: MarkIV and VLBA DAT

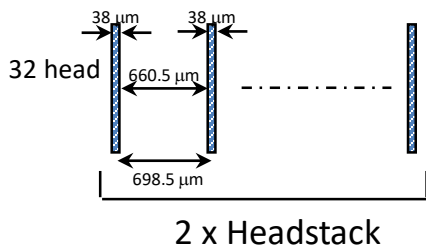
VLBI MARKIV recorder Metrum Digital Analog Tape Drive	SCI LAN cables	Power Supply				
	GPS receiver					
	SCI LAN switch					
	Spectrum Analyzer	Power Supply				
	Power Meters	Video Converters				
	TCT					
	Frequency counter					
	MARK5A recorder					
	MARK5B recorder					
	keyboard, video & mouse					
PCFS CPU	5 MHz	TTY	Decoder	Formatter		
Tape Drive Control	DTE	IF Distributor				
HD CTL & IW DR	Formatter Buffer	MATRIX switch				
Power Supply	UPS	Fiber-Optics (Optional)				
Metrum Power Supply		Power disconnect	Power disconnect			



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



Recording:

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

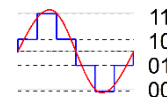
Transport of data to correlator



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

Formatter or digitizer:

Samples 28 channels, 2 bits, with time code, parity bit and sync word



IF signal conditioning:
Amplification + attenuation

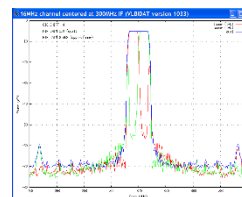
IF signal selection:

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

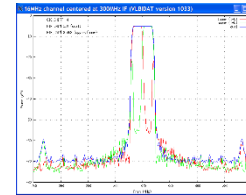
VLBI: DSN VLBI Processor - DVP

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



Baseband conversion:

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



Transport of data to correlator



Digitizer: JPL IF digitizer module

100-600MHz
8bits @ 1280MHz sampling rate
Digitally controlled built-in attenuator
Reduced spurious signals below 97dB

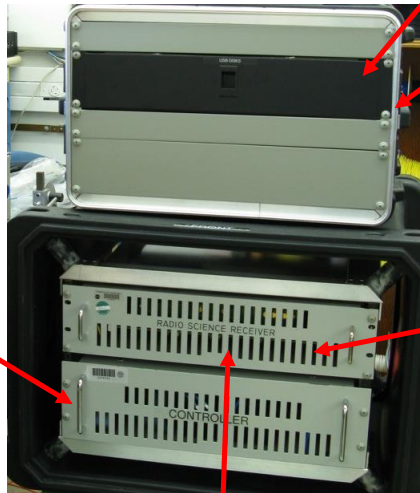


IF signal selection: COTS switch
12 inputs, 2 outputs

VLBI: DSN Portable Radio Science Receiver

Recording: hard disk in DSN format

Transport of data to correlator



IF signal selection: manual
1 IF input

IF signal conditioning:
Amplification + attenuation

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

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

VLBI: DSN Portable Radio Science Receiver

Recording: hard disk
format

**Transport of data
to correlator**



IF signal selection: manual
IF input

IF signal conditioning:
amplification + attenuation

Digitizer: JPL IF digitizer module
100MHz
@ 1280MHz sampling rate
Automatically controlled built-in attenuator
Rejects spurious signals below 97dB

ing

with FPGA board

VLBI: Data Acquisition Terminals - DAT



MarkIV/VLBA terminal	Mark5A
DBBC[12] (Europe) R1000 (Russia) CDAS[12] (China) ADS2000 (Japan)	Mark5B Mark5B+
	Mark5C FlexBuff Mark6
RDBE	Mark5C FlexBuff Mark6

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

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

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

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

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Placement of sign, magnitude bits not fixed

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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)

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



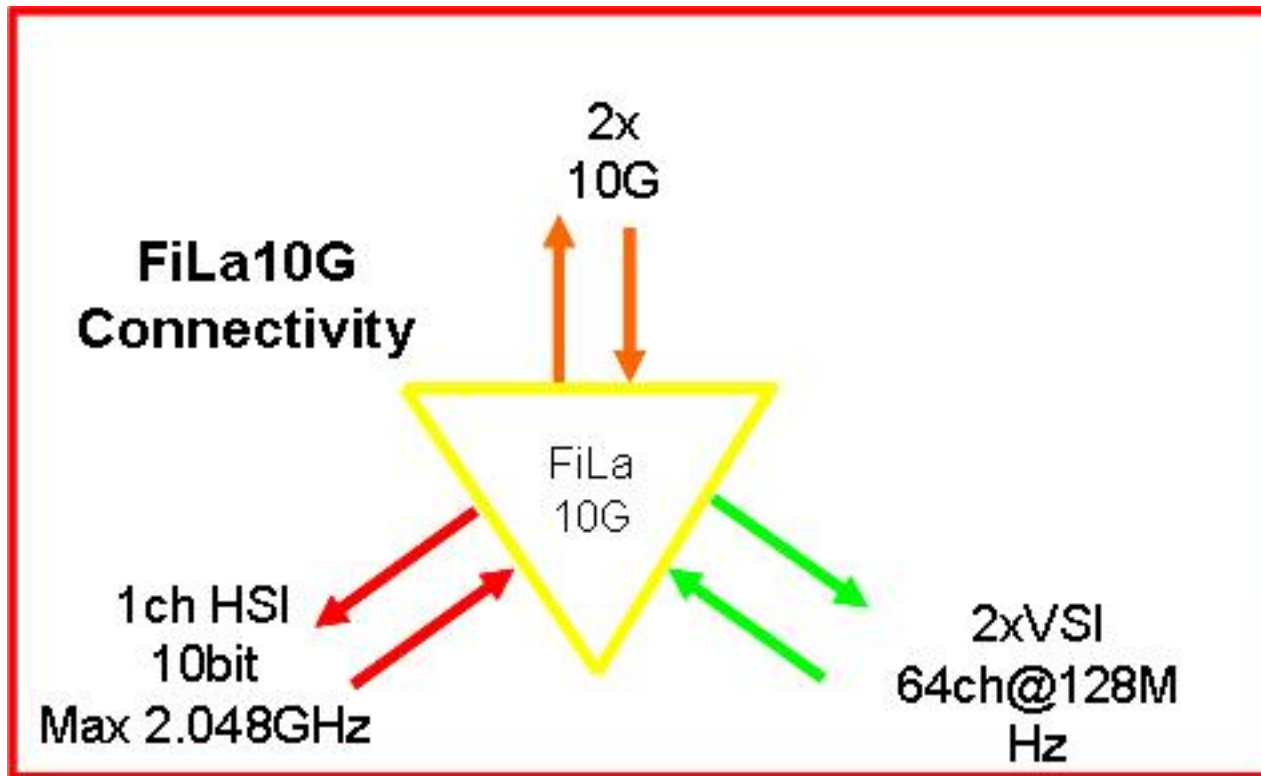
VLBI: Data Acquisition Terminal DBBC

- 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:

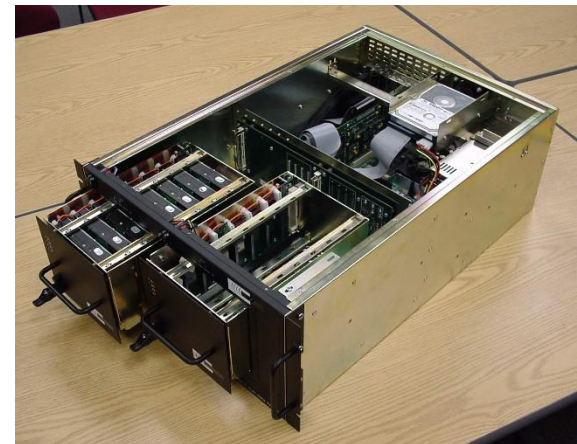
- **PFB personality** that uses a polyphase filter to break each of the two 512 MHz IFs into 16 basebands of 32 MHz each, all lower sideband.
- **Digital Down Converter personality** provide a few 4 (possibly 8 later) filters per RDBE that can provide arbitrary offset frequencies and can provide any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



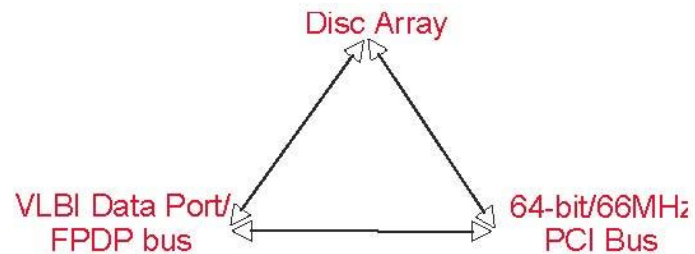
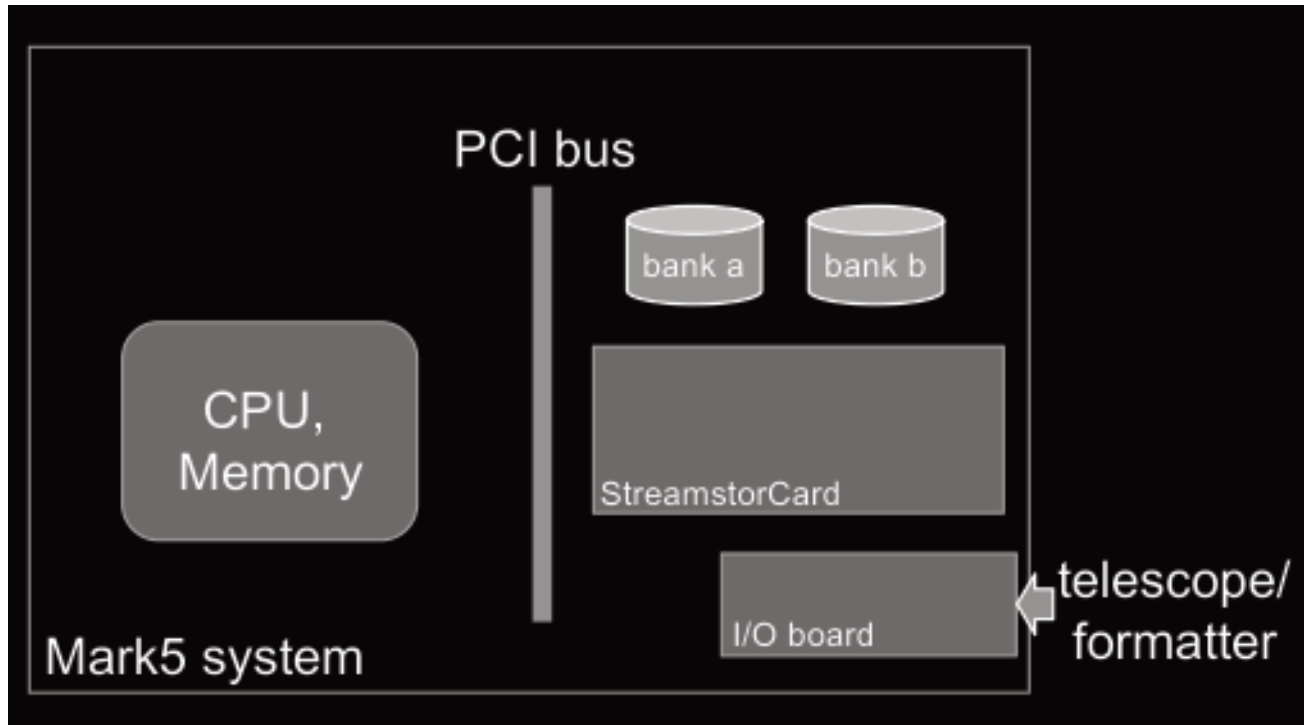
VLBI: Mark5 Recorders

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

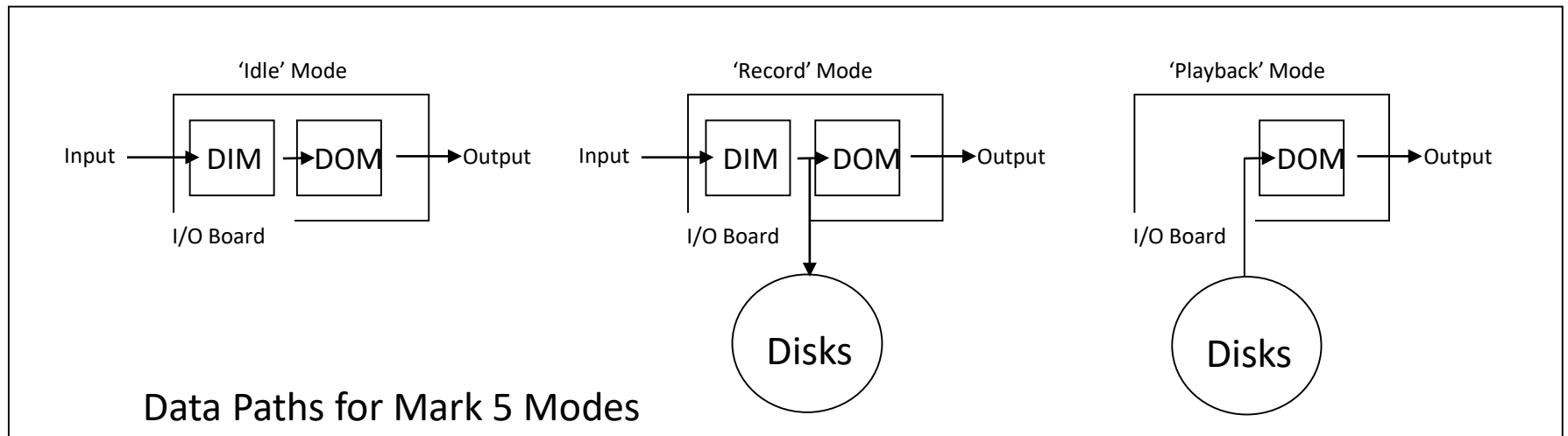
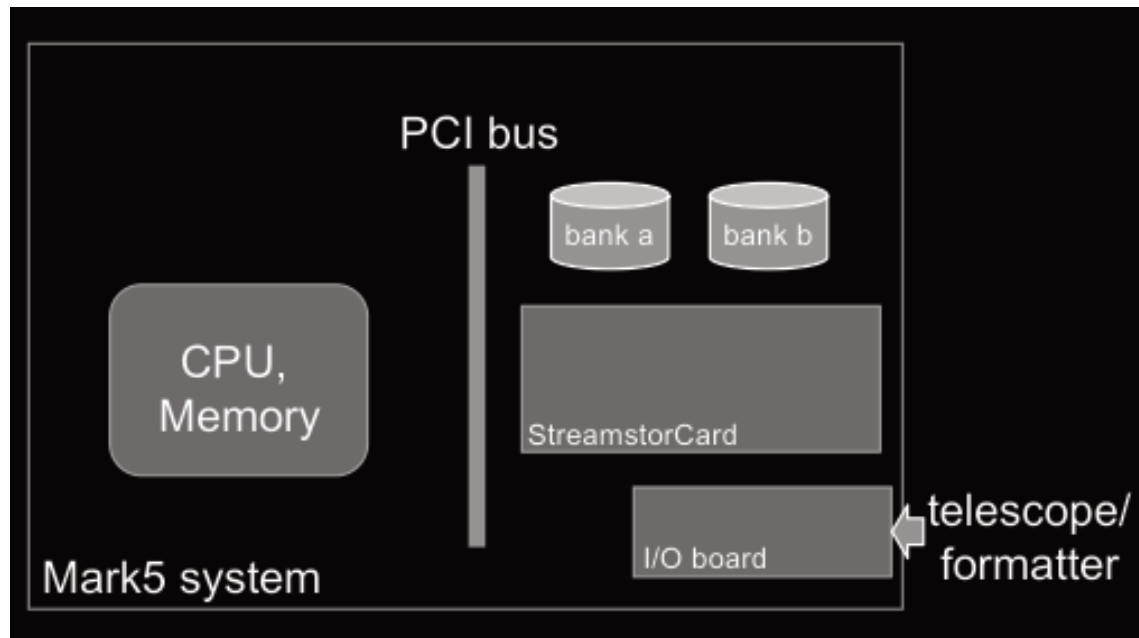


VLBI: Recorders Mark5A/B/C and Mark6



'Triangle of connectivity' of StreamStor interface card

VLBI: Recorders Mark5A/B/C and Mark6



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



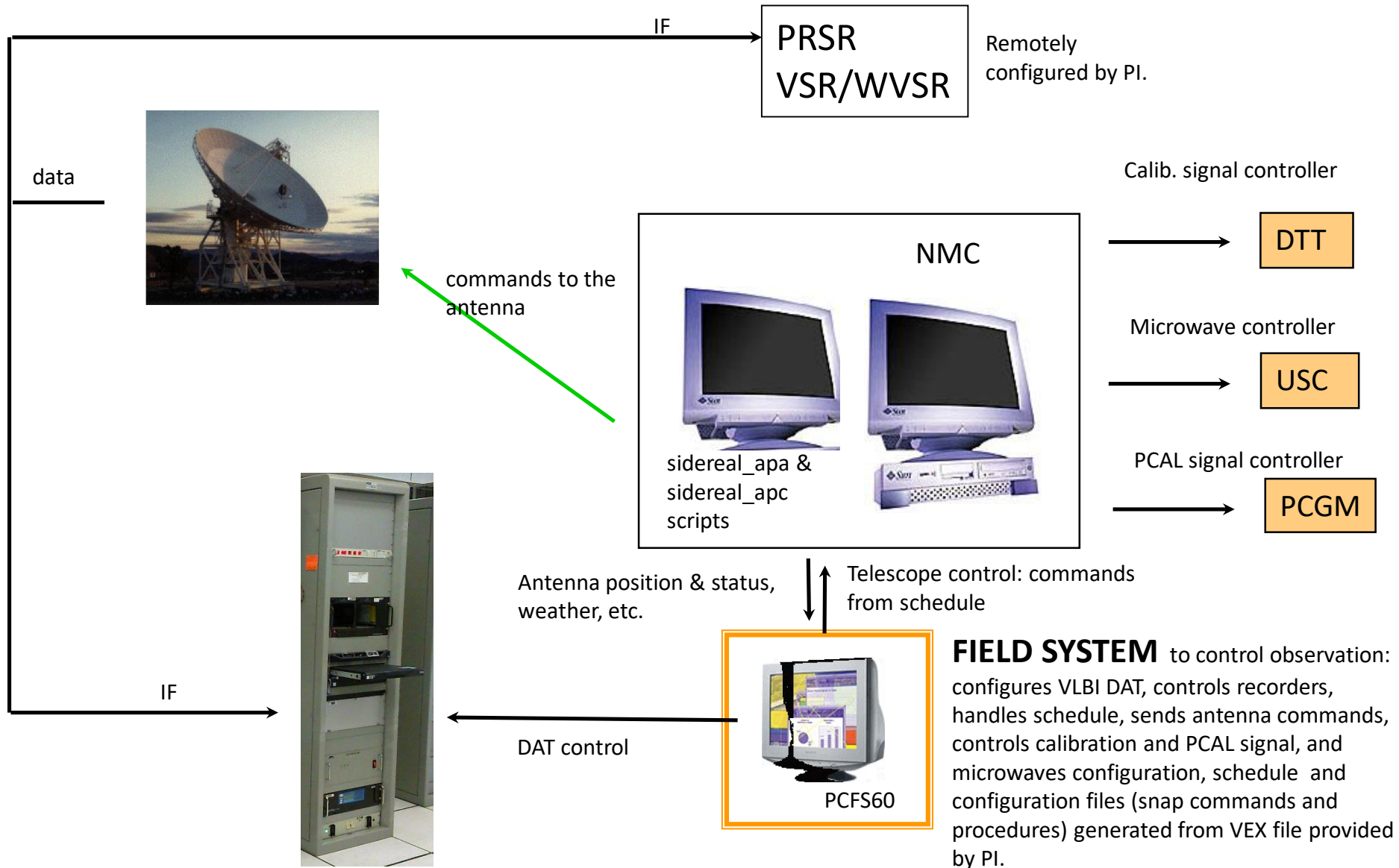
Metsähovi Observatory development (2010):

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.

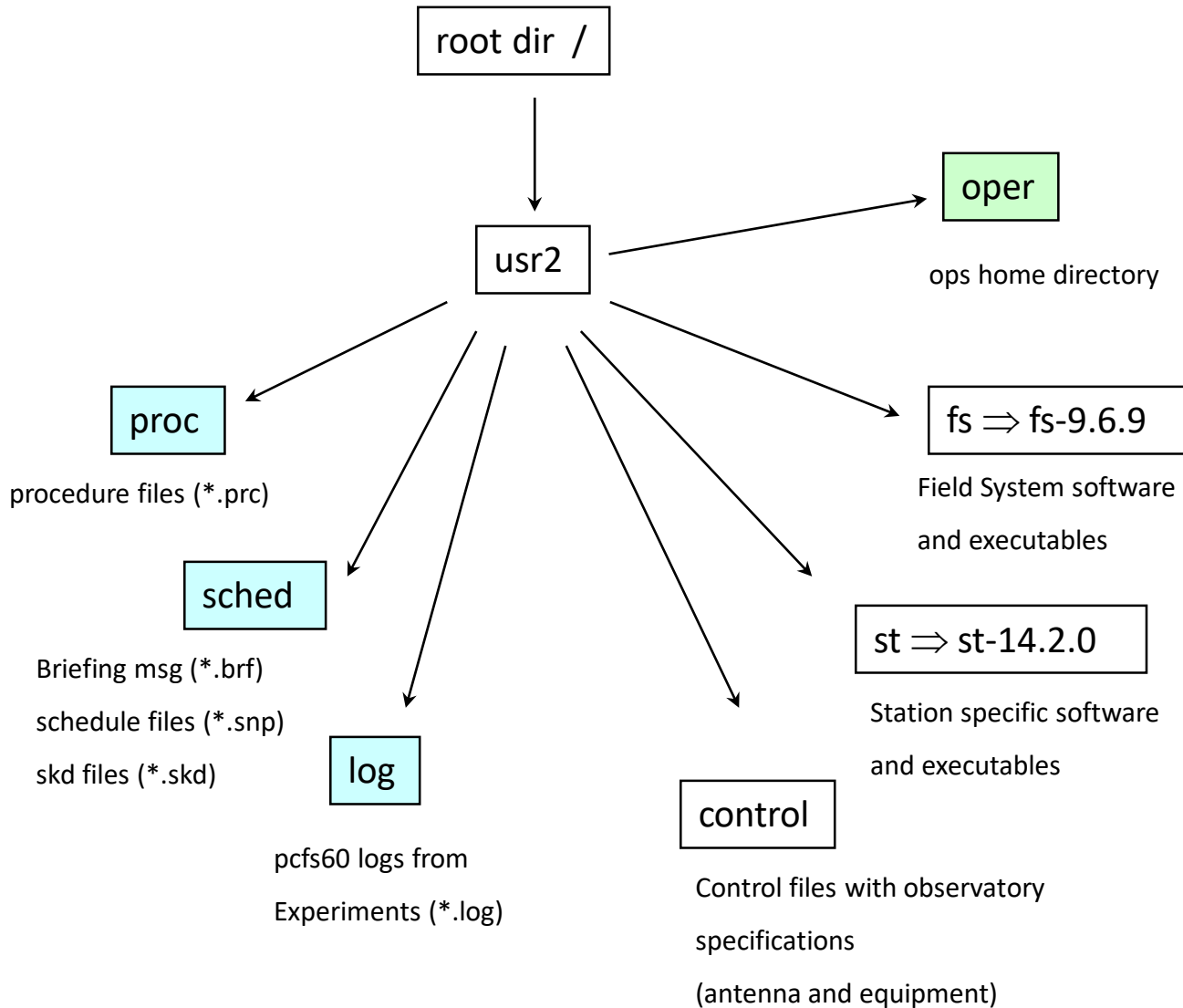
Controlled from Field System using
EVN jive5ab

VLBI: Field System



VLBI: Field System

PCFS directory structure:



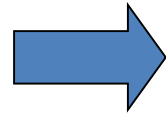
VLBI: Field System

PCFS windows:

```

monit2
DSS63          1999,231,08:50:28 UT          TEMP 30.2C          SLEWING
ODE RATE SPEED DIR          08:50:28 NEXT          HUMID 18.00% RA 00h00m 0.0s
m 32.0 0          SCHED=none LOG=station PRES 924.9mb DEC 00d00m (
VACUUM TAPE FEET TSYS: IF1 IF2 IF3          CABLE 0.000000s AZ 0.0 EL 0.
READY STOPPED 0 0 0          HEAD PASS # 0
NO CHECK; v15 if fm tp rx hd i3
    
```

File	Start-DTE	Stop-DTE	AVG	
VC Band	Time	Tone	Phase	
(UT)	#	Drift	rms	
		deg/min	deg	
			MAG	
			msnrV	
1	00:00:00			
2	00:00:00			
3	00:00:00			
4	00:00:00			
5	00:00:00			
6	00:00:00			
7	00:00:00			
8	00:00:00			
9	00:00:00			
10	00:00:00			
11	00:00:00			
12	00:00:00			
13	00:00:00			
14	00:00:00			



Configure PCFS

Select Recorder Type and #

Tape #1
 Tape #2
 Mark5 #1
 Mark5 #2

Select IF1 and IF2 Inputs

IF1	IF2
<input checked="" type="checkbox"/> #1 S-RCP-70m	<input checked="" type="checkbox"/> #1 X-RCP-70m
<input type="checkbox"/> #2 S-34m-HEF	<input type="checkbox"/> #2 S-34m-HEF
<input type="checkbox"/> #3 X-34m-HEF	<input type="checkbox"/> #3 X-34m-HEF
<input type="checkbox"/> #4 X-55-BWG	<input type="checkbox"/> #4 X-55-BWG
<input type="checkbox"/> #5 KA-55-BWG	<input type="checkbox"/> #5 KA-55-BWG
<input type="checkbox"/> #6	<input type="checkbox"/> #6
<input type="checkbox"/> #7	<input type="checkbox"/> #7
<input type="checkbox"/> #8 MMS1	<input type="checkbox"/> #8 MMS2
<input type="checkbox"/> #9 X-LCP-70m	<input type="checkbox"/> #9 S-LCP-70m
<input type="checkbox"/> #10 TEST	<input type="checkbox"/> #10 TEST

Select Display

left
 right

Select PCFS Usage

VLBI
 Maintenance

```

PCFS
08:50:19&vc02/vc02=#,2,000,u,10,10
08:50:19&vc02/vc03=#,2,000,u,10,10
08:50:19&vc02/vc04=#,2,000,u,10,10
08:50:19&vc02/vc05=#,2,000,u,10,10
08:50:19&vc02/vc06=#,2,000,u,10,10
08:50:19&vc02/vc07=#,2,000,u,10,10
08:50:19&vc02/vc08=#,2,000,u,10,10
08:50:19&vc02/vc09=#,2,000,u,10,10
08:50:19&vc02/vc10=#,2,000,u,10,10
08:50:19&vc02/vc11=#,2,000,u,10,10
08:50:19&vc02/vc12=#,2,000,u,10,10
08:50:19&vc02/vc13=#,2,000,u,10,10
08:50:19&vc02/vc14=#,2,000,u,10,10
08:50:19&vc02/1+1s
08:50:19&vc02/valarm
08:50:20#seria#dss is 63
ifin portvalues are 105 and 105
08:50:21&valarm/vc01=alarm
08:50:21&valarm/vc02=alarm
08:50:21&valarm/vc03=alarm
08:50:21&valarm/vc04=alarm
08:50:21&valarm/vc05=alarm
08:50:21&valarm/vc06=alarm
08:50:21&valarm/vc07=alarm
08:50:21&valarm/vc08=alarm
08:50:21&valarm/vc09=alarm
08:50:21&valarm/vc10=alarm
08:50:21&valarm/vc11=alarm
08:50:21&valarm/vc12=alarm
08:50:21&valarm/vc13=alarm
08:50:21&valarm/vc14=alarm
08:50:21#setcl#time/116994177.4,1999,231,08,50,21,93,0,000,0,001,0
08:50:21#setcl#model/old,933882384,29616,116993926,0,000,1,000,rate
08:50:24#stqkr#stqkr/netio net_connect error: System call error errno 111
08:50:25#seria#buf read fail sts= -2
08:50:28:1fd=36.39
08:50:28:1fin=1.1
08:50:28:1fin/1.1
    
```

pcfs log

```

oprin input (pcfs60)
>
    
```

oprin

```

Mark 5 Monitor
Serial MD-WMACKL604314,
Revision 75,13B75,
Capacity 390602383 * 512 bytes
SMARTState OK
Mark5A checkDisks() DEBUG: Found 8 SS disk(s): OK
Mark5A checkDisks() DEBUG: SS directory Length 1118
924520,
AppendLength 1118921520, Full 0
Mark5A checkDisks() DEBUG: Setting fill pattern
Mark5A checkDisks() DEBUG: XLRSetOption() drive sta
tistics
Mark5A checkDisks() DEBUG: OK
Mark5A readdir() DEBUG: Trying to read SS user dire
ctory
Mark5A readdir() DEBUG: XLRGetUserDir() OK
Mark5A readdir() DEBUG: Directory read OK
Mark5A DEBUG: Setting defaults to outBoard() and in
Board()
Mark5A Initize() DEBUG: offs 0xfcafa000, offp 0xd40
0
Mark5A outBoard() DEBUG: IPhase 0x170a3d71 38654705
7
Mark5A mksock() DEBUG: sock 6, datah 0,
rcvbuf 87380, rcvlowat 1, sndbuf 16384, sndlowat 1
, socbuf 131072
Mark5A mksock() DEBUG: n5drive tcp port is 2620
Mark5A Ready, End with EndM5, please
    
```

/usr2/st/scripts/pcfsa &

VLBI: Correlation



VLBI: hardware correlators



VLBI: software correlators

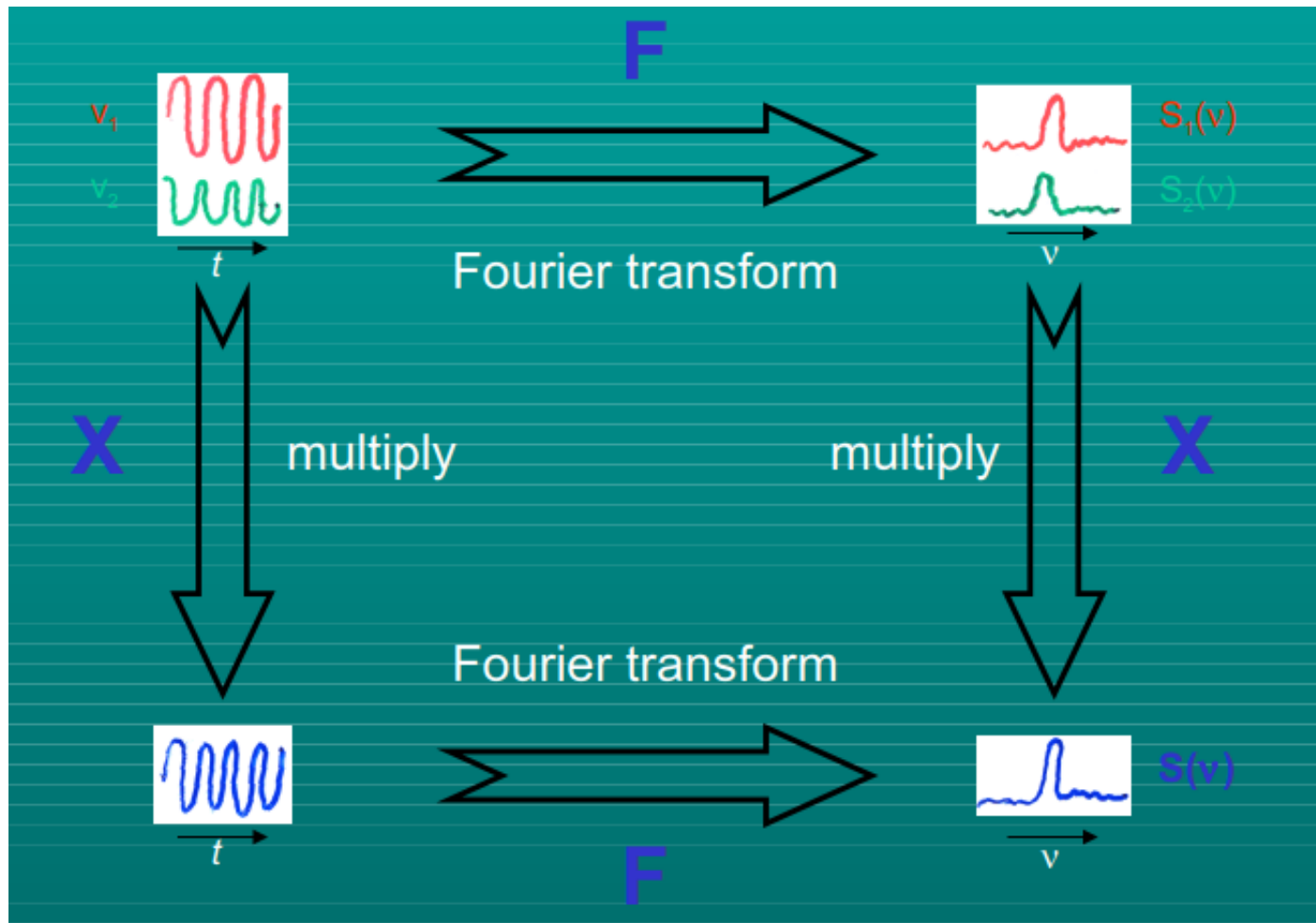


VLBI: Correlation

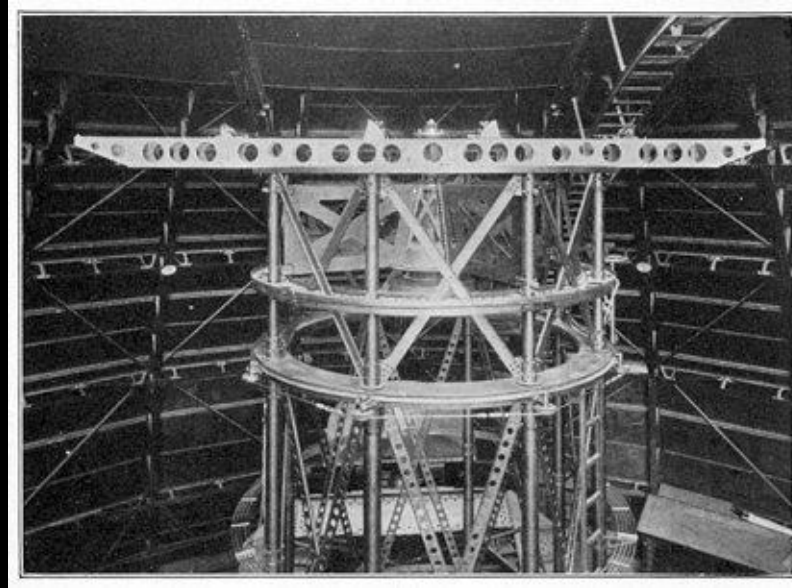
- Read Mark5 disk modules or receives e-VLBI data via internet using FlexBuff.
- Synchronize data.
- Apply geometrical delay model.
- Correct for known Doppler shifts (mainly from Earth rotation)
- **FX type:** FFT then cross multiply spectra (VLBA, DiFX and EVN SFXC s/w correlators)
- **Lag or XF type:** cross multiply lags, FFT later (JIVE, Haystack, VLA, SoftC JPL s/w correlator):
 - $x(t_i)$ correlated with $\{ \dots y(t_{i-2}), y(t_{i-1}), y(t_i), y(t_{i+1}), y(t_{i+2}), y(t_{i+3}), \dots \}$
- 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.

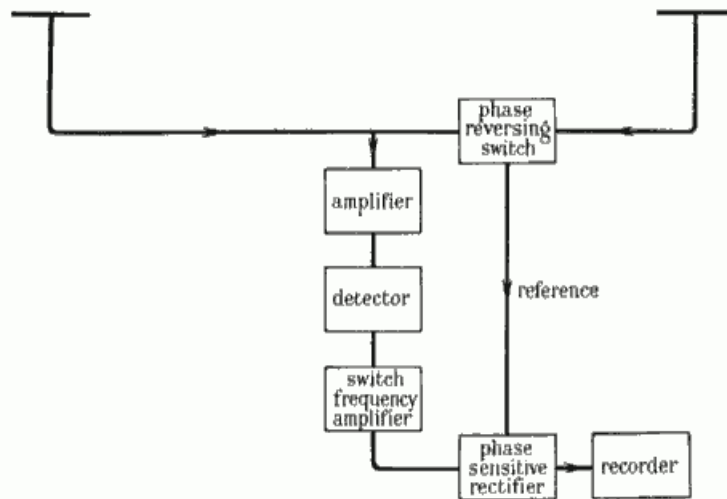
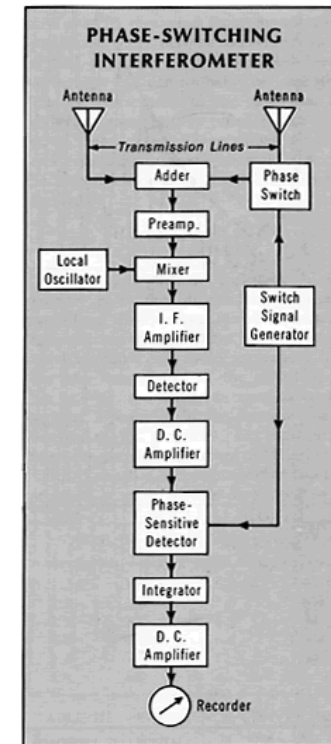


FIGURE 2. Block diagram of the phase-switching system.



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