l'Observatoire de Paris SYRTE

Systèmes de Référence Temps-Espace

VLBI Fundamentals I

AVN Training School 2019, HartRAO

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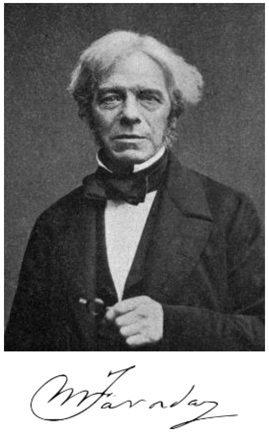
SYRTE, Observatoire de Paris

History of VLBI

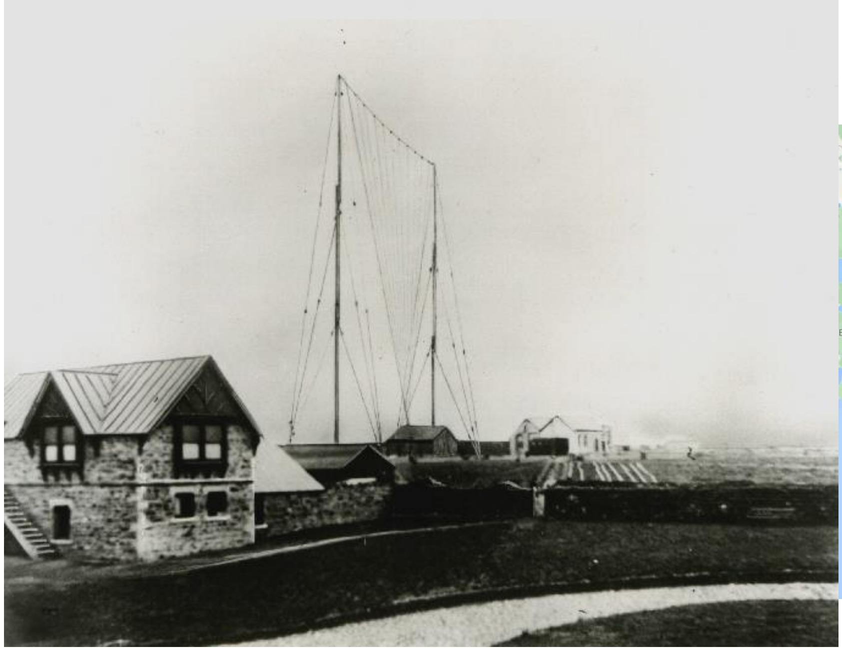
- Faraday (1791-1867) and Volta (1745-1827) performed experiments with electricity and magnetism



- James Clerk Maxwell (1831-1879) developed
  - the theory of electricity and magnetism by the coherent integration of four equations: relate both as two aspects of the same force
  - predicted that there is a form of radiation involved (soon known as electro magnetic waves)

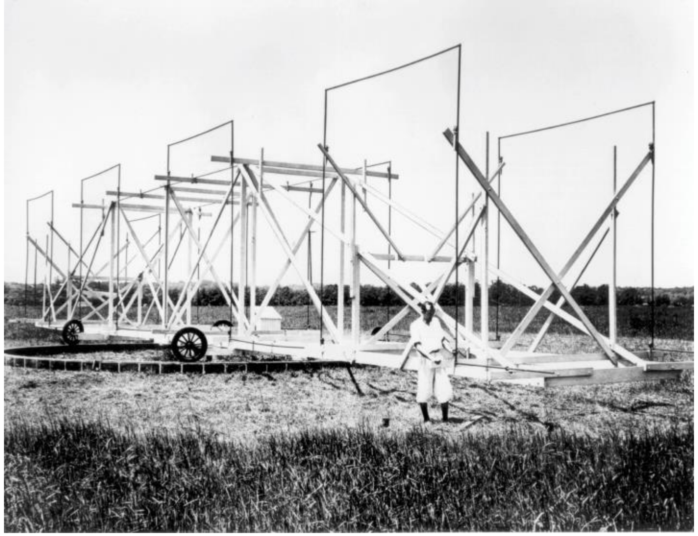
History of VLBI

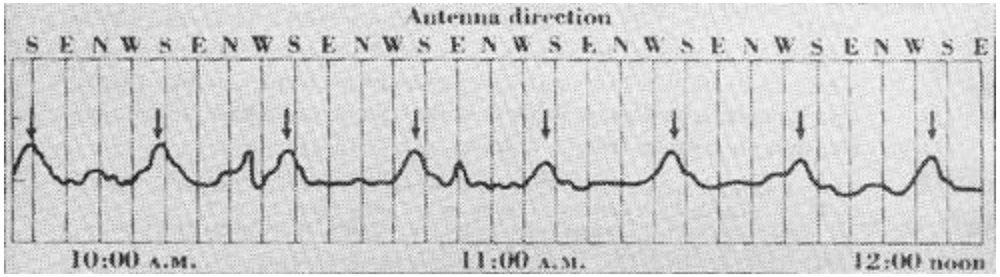
- Dawn of Telecomunication
  - In 1901 Guglielmo Marconi (1874-1937) was the first to send and receive signals across an ocean from Newfoundland to Cornwall.



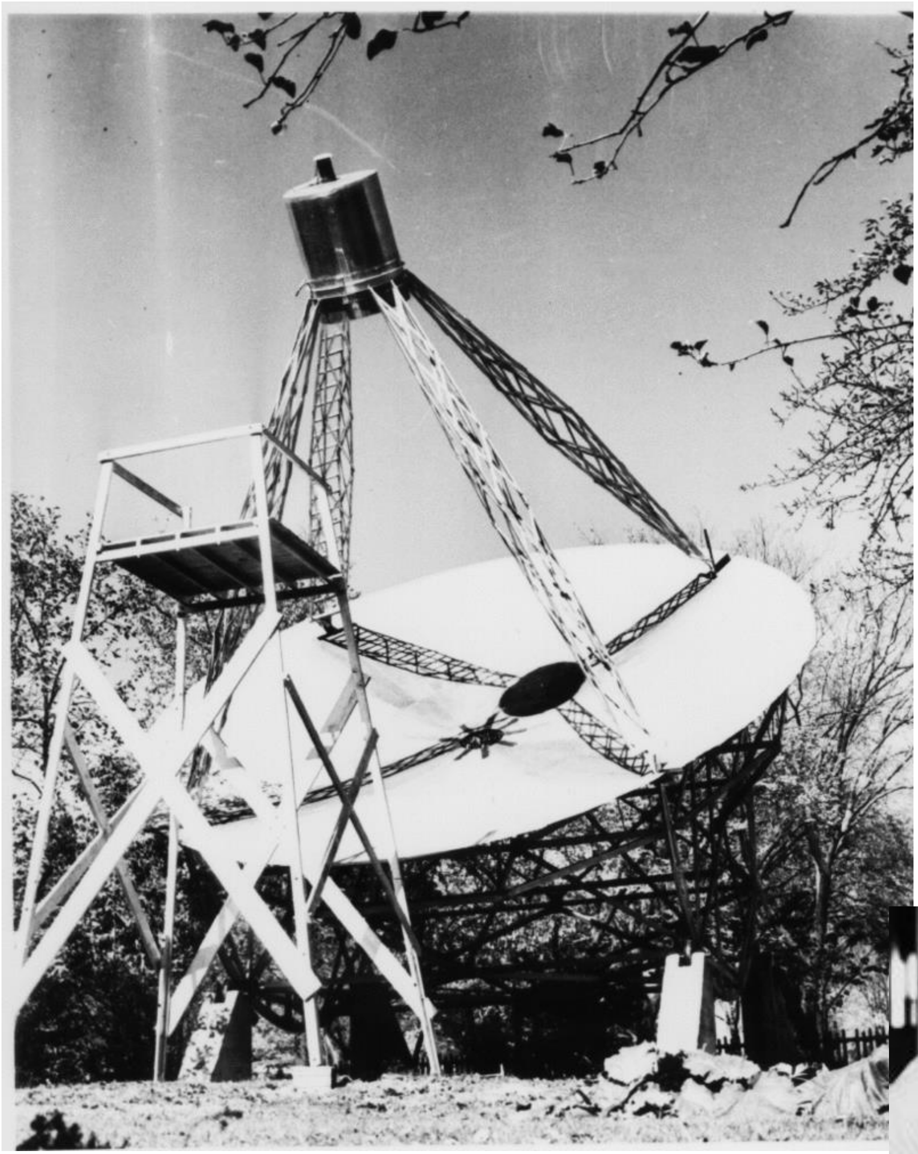
History of VLBI

- 1930s: Bell Telephone Company was having trouble with the functioning of their transatlantic service, due to static of some sort. The company asked the physicist Karl Jansky (1905-1950) to find the source of such interference.
- “Jansky’s merry-go-round”: antenna designed to receive radio waves at a frequency of 20.5MHz, and with its rotation ability it was able to locate the direction of any radio signal.
  - three different types: first two originated from nearby and distant thunderstorms.
  - 3rd: signal repeated every 23 hours and 56 seconds. Jansky concluded that the radiation came from the constellation Sagittarius in the Milky Way Galaxy.

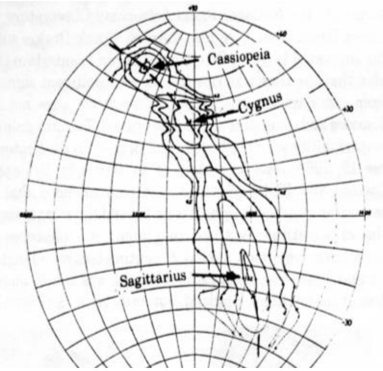




History of VLBI



- Grote Reber (1911-2002) wanted verify if the waves were in fact coming from the Milky Way or other celestial objects.
- Great Depression, Bell Labs were not hiring at that time → back yard
- 1937 he constructed a telescope that had a 9 m parabolic dish reflector and 3 receivers: 3300MHz, 900MHz and 160MHz.
- A year later, in 1938, the last receiver mentioned gave him what he was looking for, galactic radio waves.



The quest for higher resolution

The quest for higher resolution

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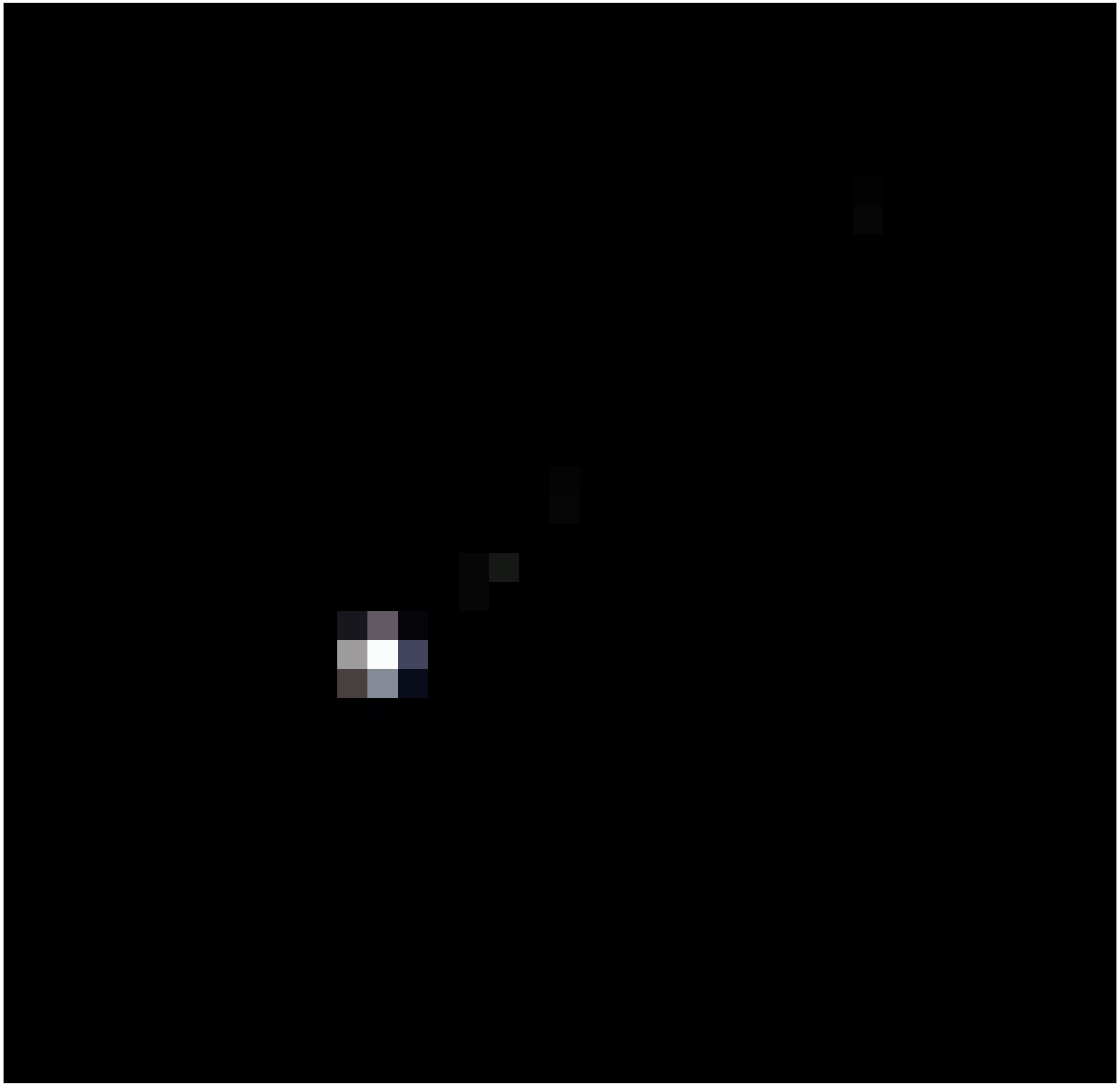
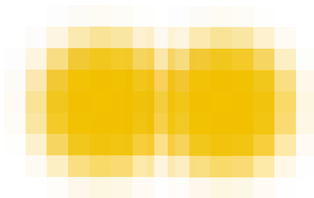
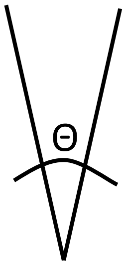


The quest for higher resolution

- **„angular“** resolution
  - $\Theta = \lambda / \mathcal{D}$
  - $\lambda = c / f$





Jupiter and Io as seen from Earth

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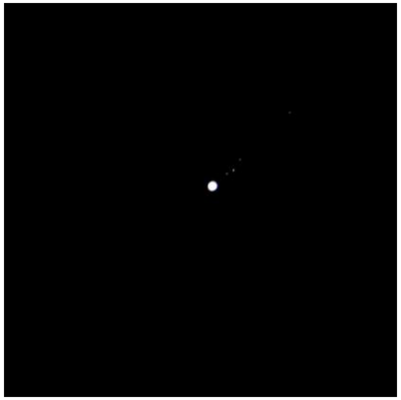

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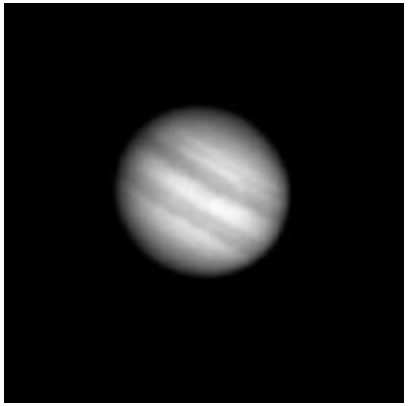

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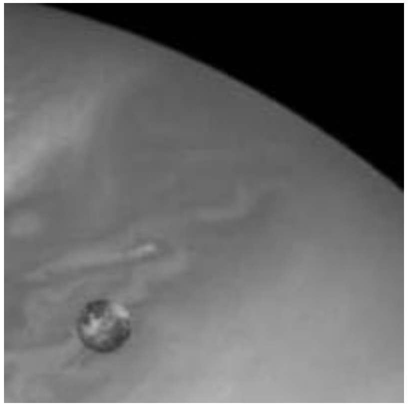

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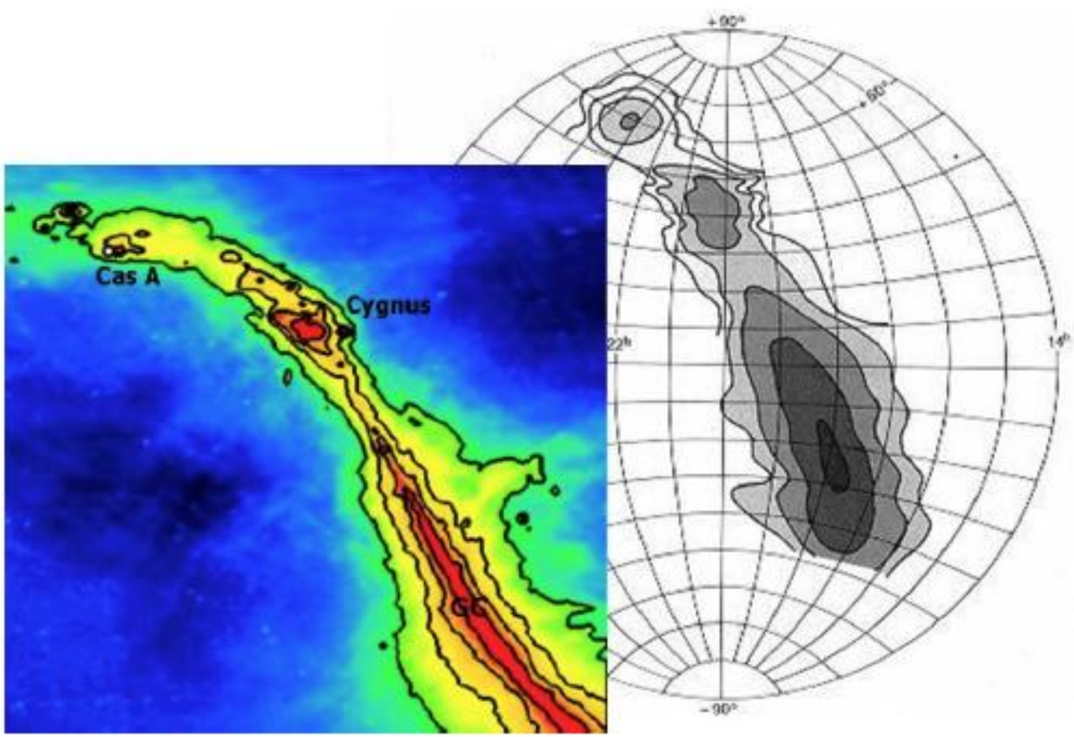
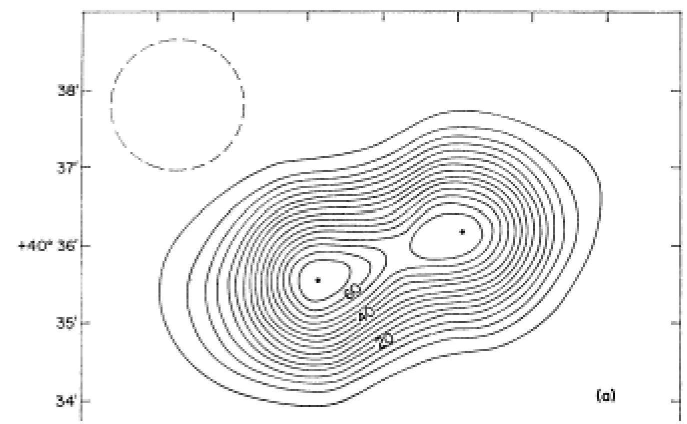
The quest for higher resolution

- Jupiter is close (588*10^9 m = 3,943 AU)
- Radio sources are millions of light years away
  - 1 ly= 9.46x10^15m= 63.235 AU
  - 1 pc= 3,26156 ly = 206.265 AU
- Cygnus A (3C 405) is a radio galaxy, and one of the strongest radio sources in the sky. Discovered by Grote Reber in 1939.
  - Distance: 232 Mpc (756 million ly)

The quest for higher resolution



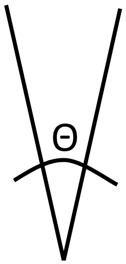
Grote 1938, λ = 1.9m, D=9m



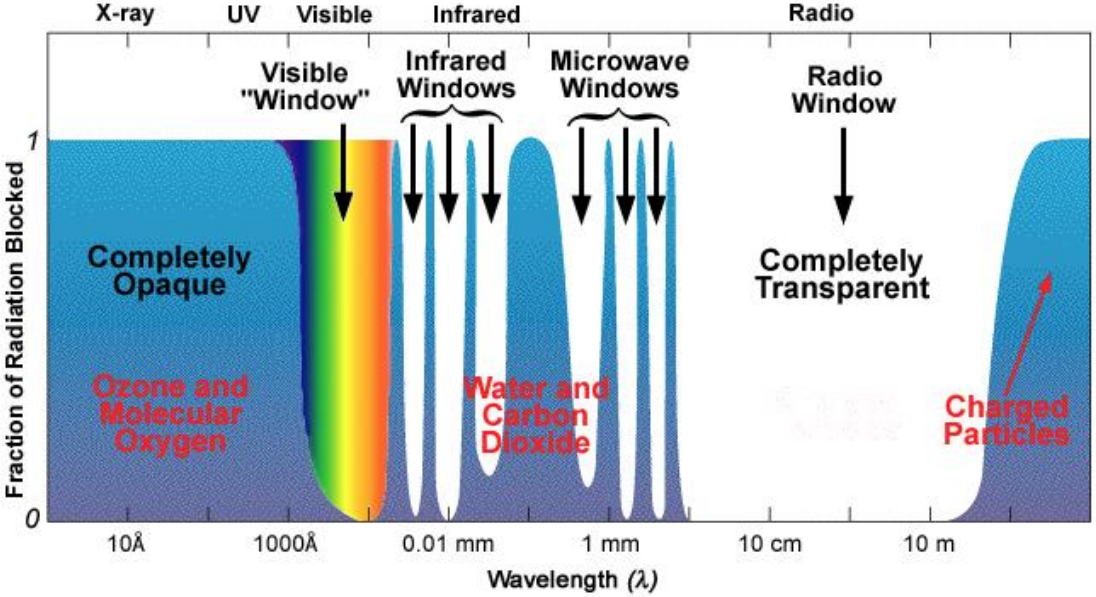
Meyer et al, 1968, λ =1.55cm, D=42.7m

The quest for higher resolution

- **„angular“** resolution
  - $\Theta = \lambda / \mathcal{D}$
  - $\lambda = c / f$

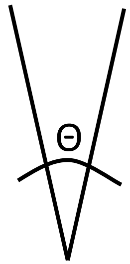


- Increase **frequency**
  - Limited by atmosphere



The quest for higher resolution

- **„angular“** resolution
  - $\Theta = \lambda / D$
  - $\lambda = c / f$



- Increase **frequency**
  - Limited by atmosphere

- Increase **diameter**
  - **Limited by gravity**

The quest for higher resolution

- Effelsberg, 100 m, Θ = 9,4 arcmin @ L-Band (λ =21 cm/ f~1-2GHz)
- Aperture Spherical Radio Telescope (FAST), 500m, Θ =2,8 arcmin @ L-Band

The quest for higher resolution

„angular“ resolution

$\Theta = \lambda / D$

$\lambda = c / f$

- Increase **frequency**
  - Limited by atmosphere

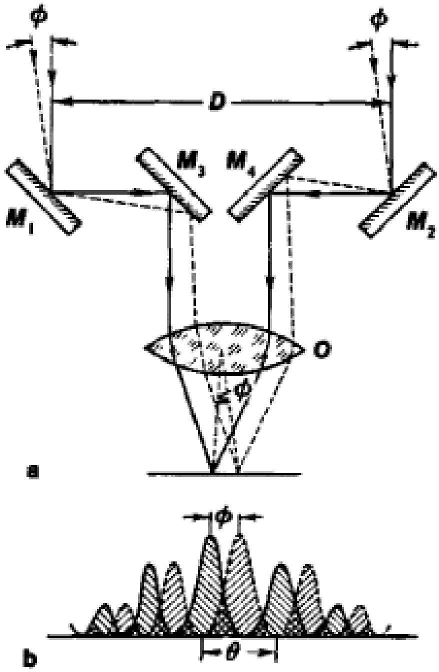
- Increase **diameter**
  - Limited by gravity

Connect several small antennas!

→ **Build an interferometer!**

History of VLBI: Interferometry ?

- An interferometer is a device for measuring the spatial coherence function’ (Clark 1999)
- Concept: the spatial intensity distribution of an electromagnetic radiation produced by an astronomical object at a particular frequency I, can be reconstructed from the spatial coherence function measured at two points with the interferometer elements V.
- Albert Abraham Michelson (1852-1931) was the first to use interferometers to obtain higher angular resolution.



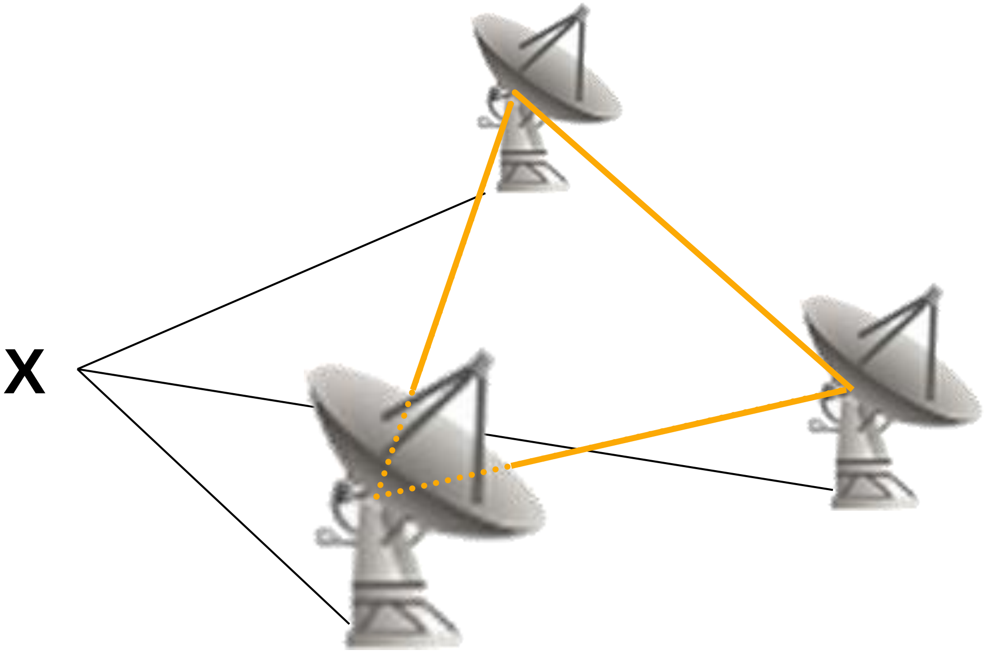
Interferometry

„angular“ resolution

$\Theta = \lambda / b$

$\lambda = c / f$

- **Limitation: lengh of cable**



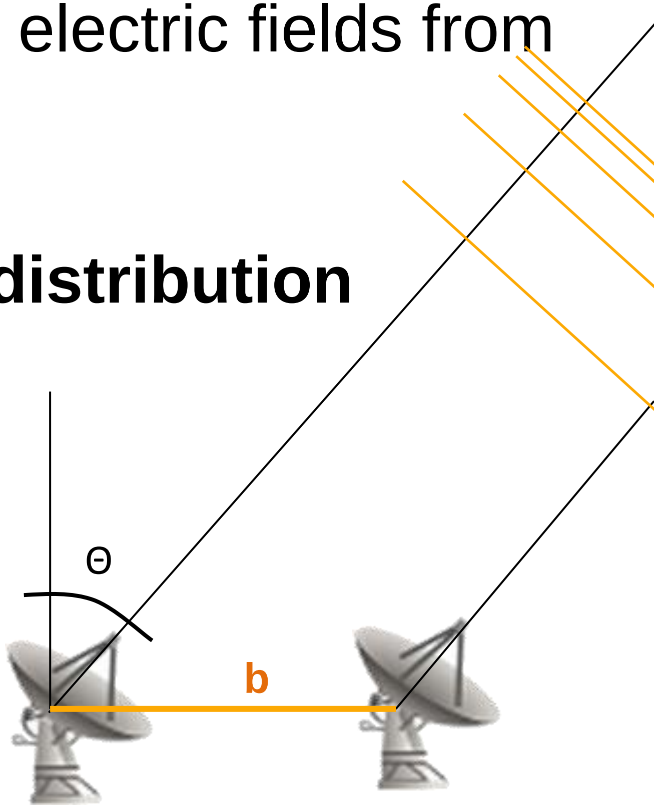
Interferometry

- The basic idea of an interferometer is that the spatial intensity distribution of electromagnetic radiation produced by an astronomical object at a particular frequency **I** , can be reconstructed from the spatial coherence function measured at two points with the interferometer elements **V**.
- Interferometer measures the product of electric fields from two receptors, i.e**.** visibility:

$$\mathcal{V}_{ij}=<\mathcal{E}_i\mathcal{E}_j{}^*>$$

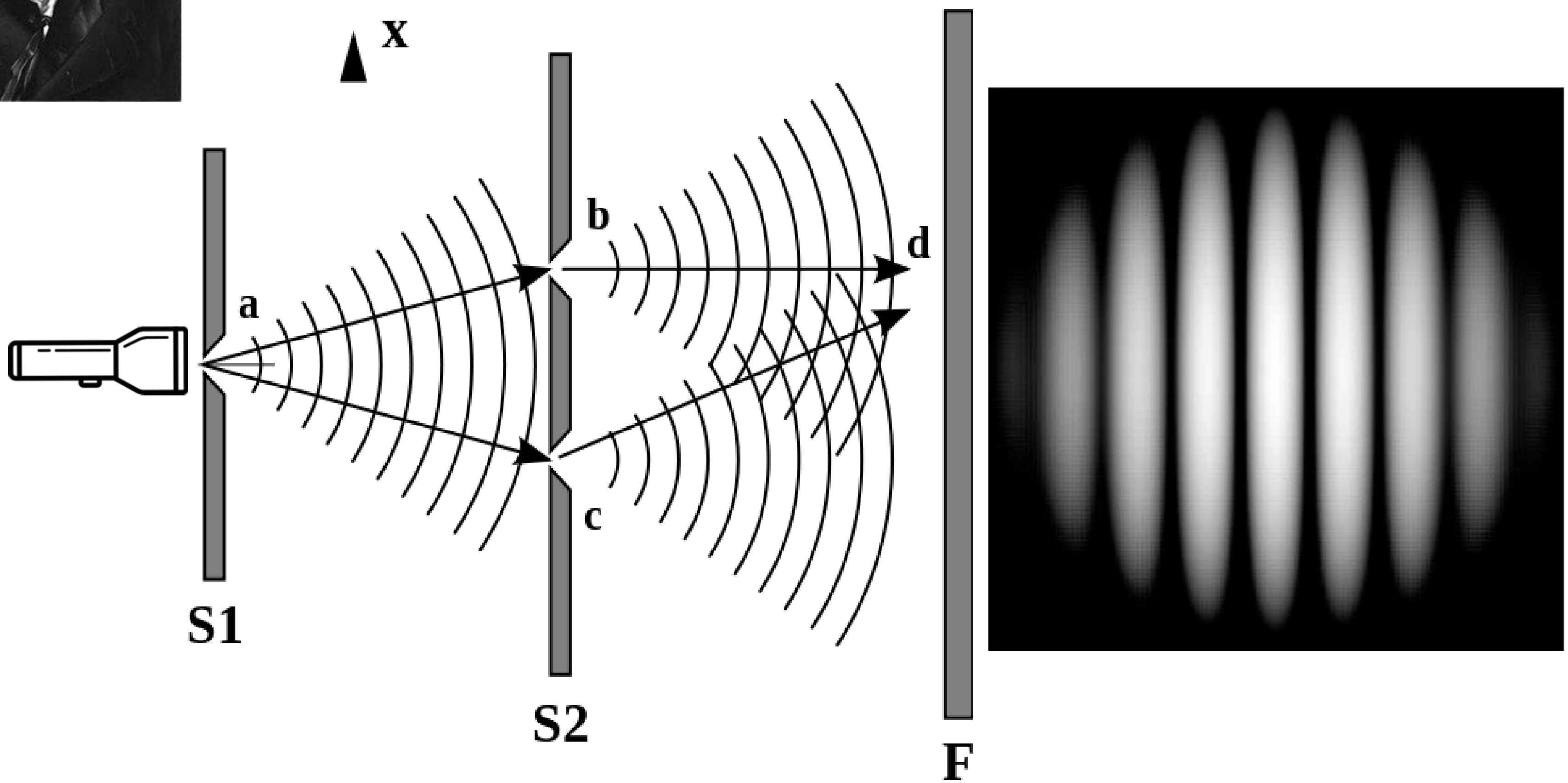
- **Visibility** is related to **sky brightness distribution** (complex):

$$\mathcal{V}_{ij} = \mathcal{I}(\Theta)$$

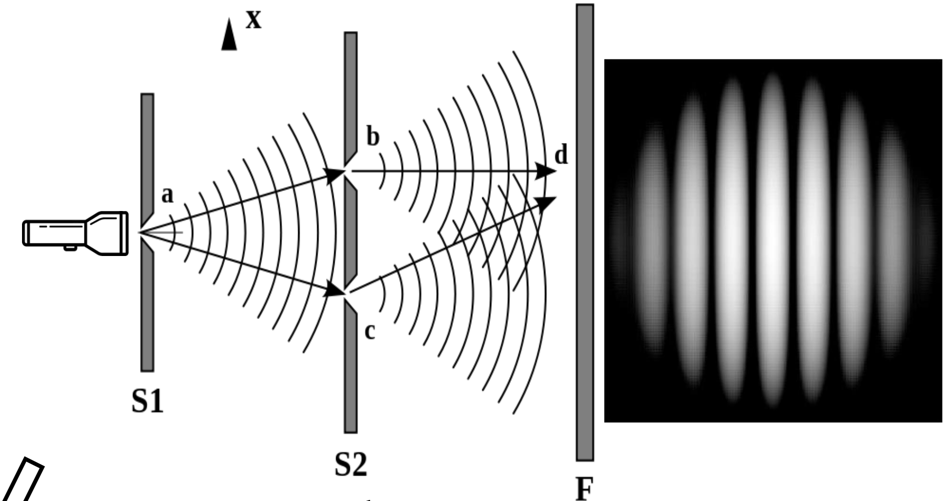


Interferometry

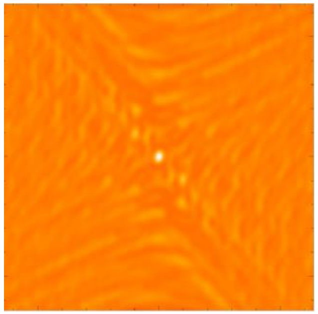
Young's experiment (1803)



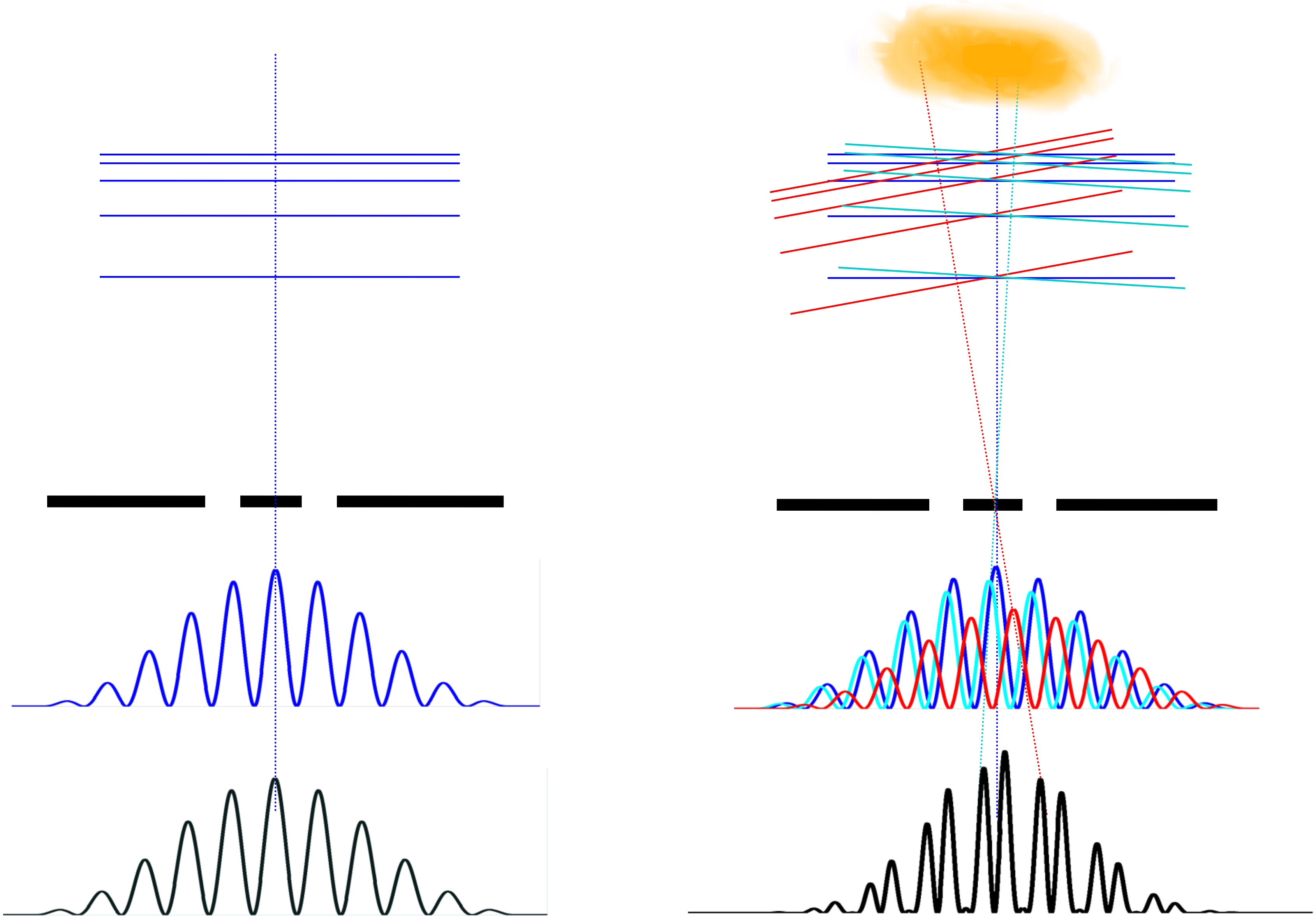
Interferometry



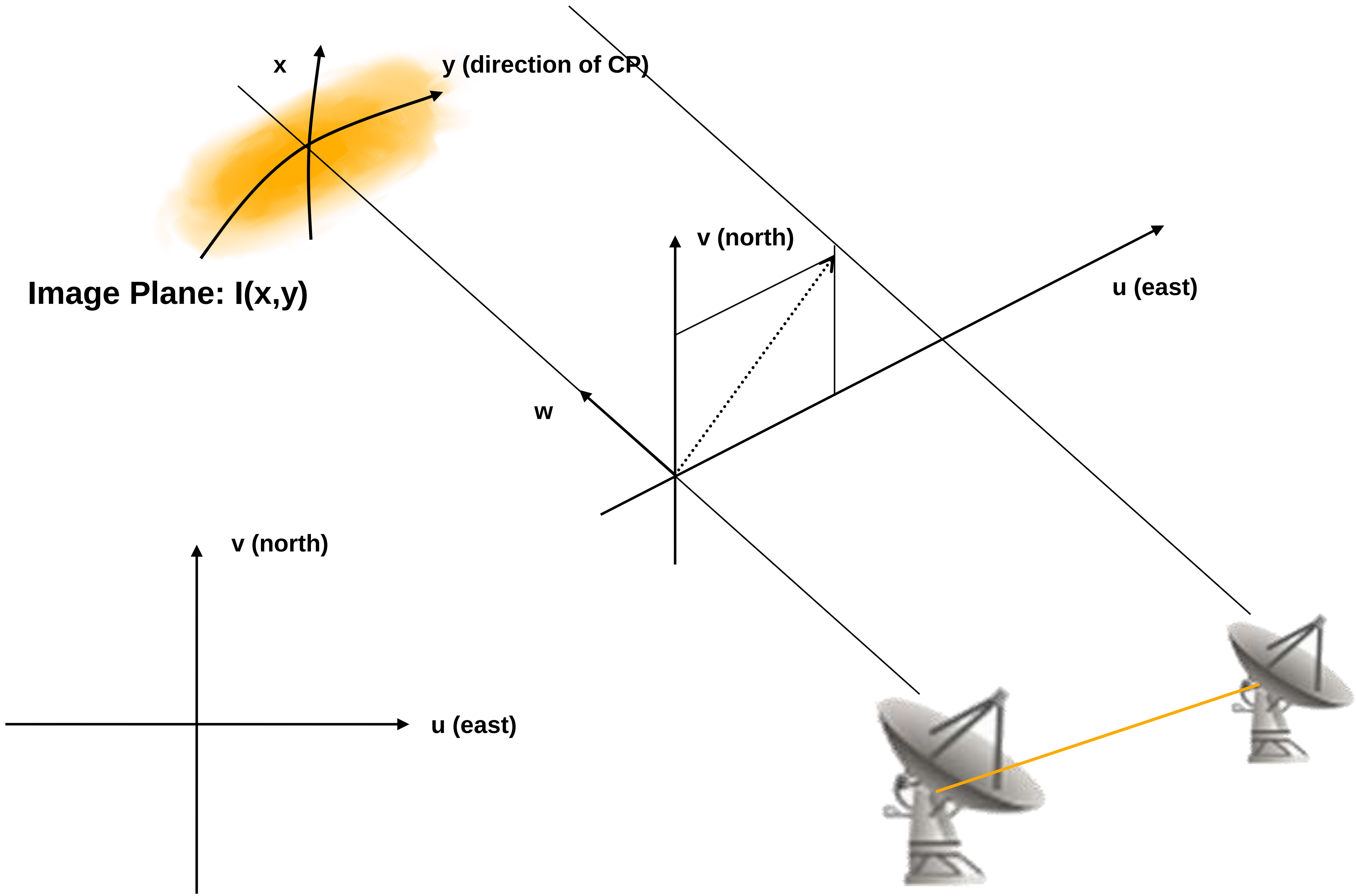
X



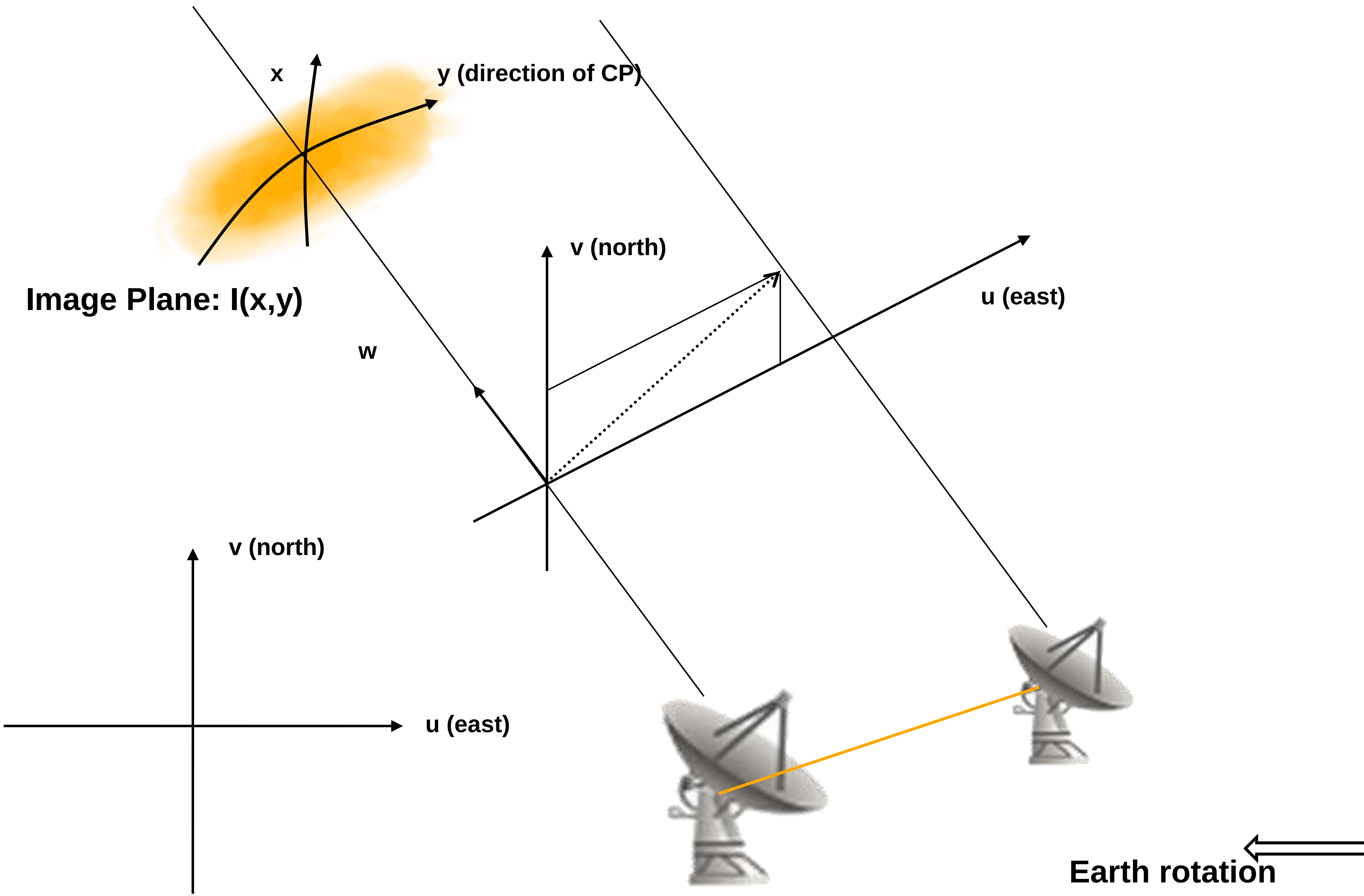
Interferometry 1D



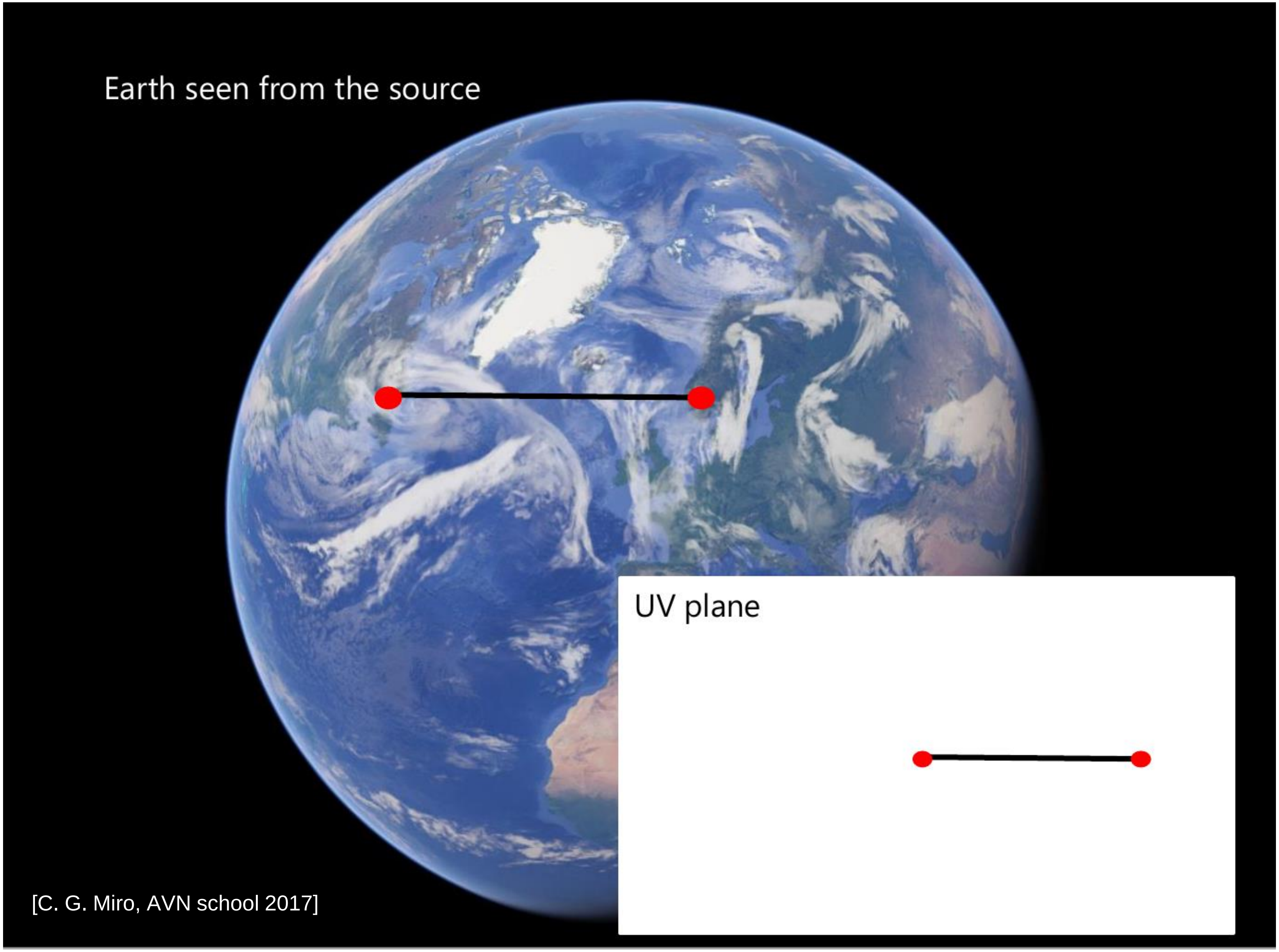
Interferometry – 2D



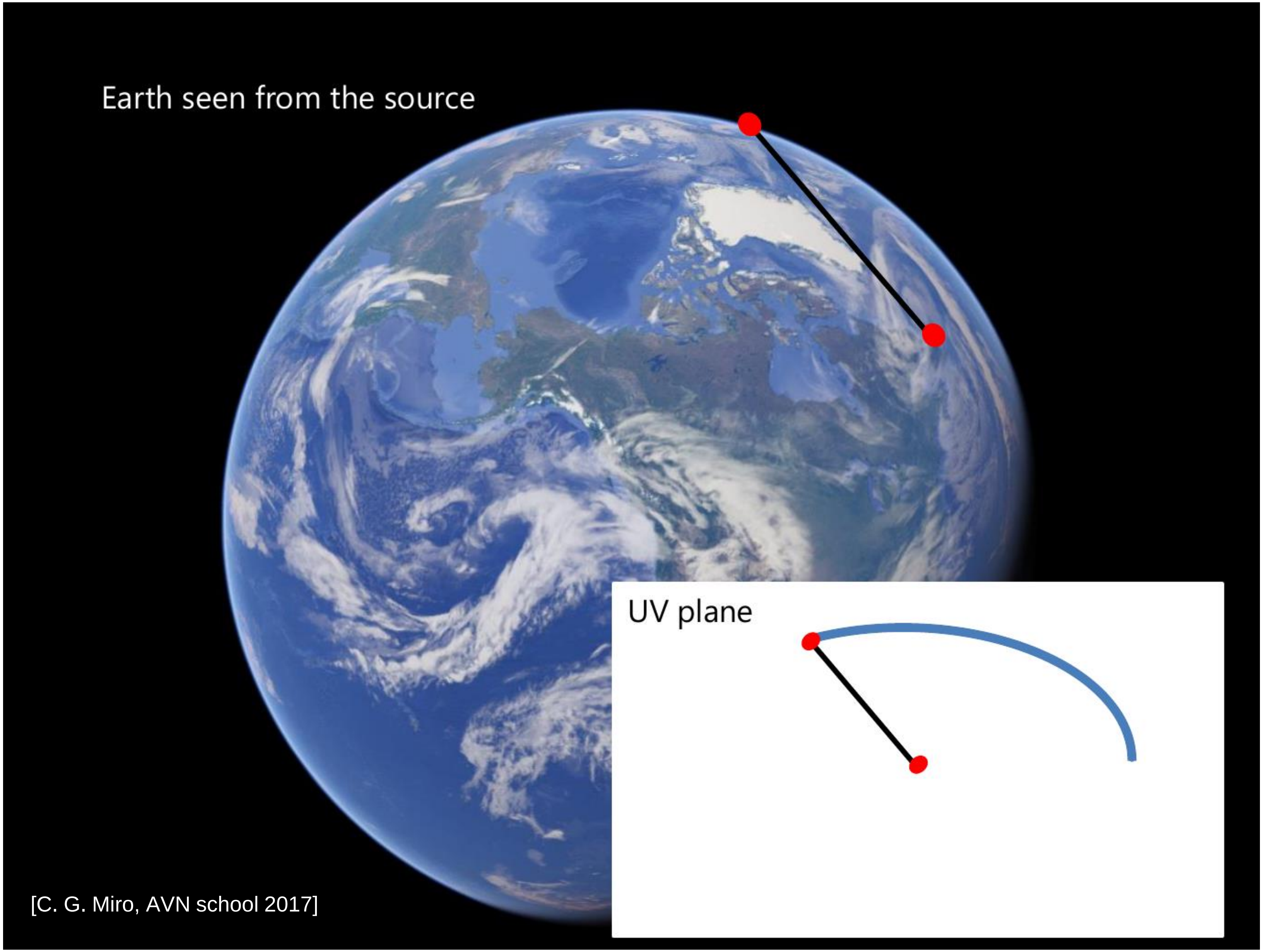
Interferometry – 2D



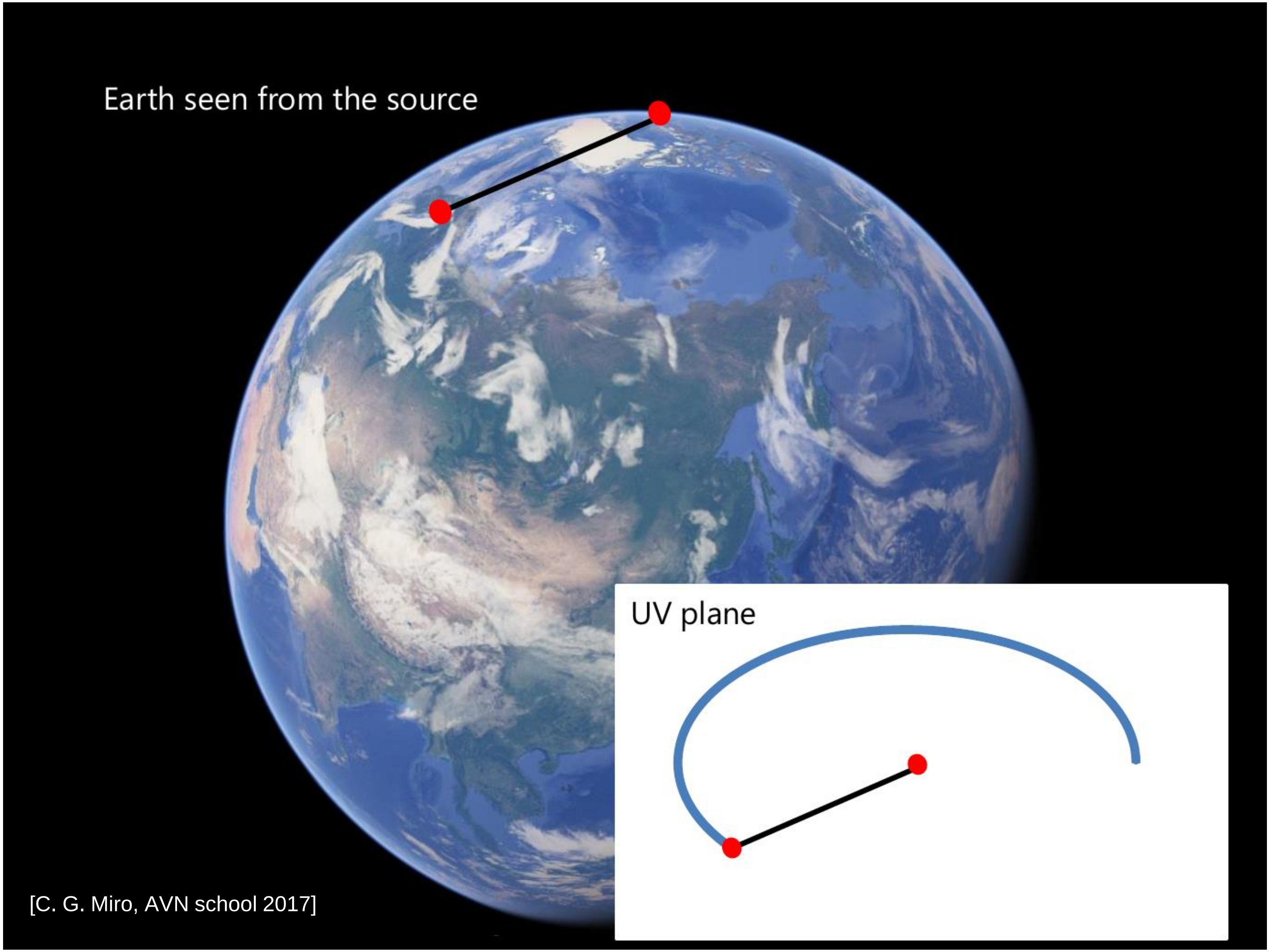
Interferometry – 2D



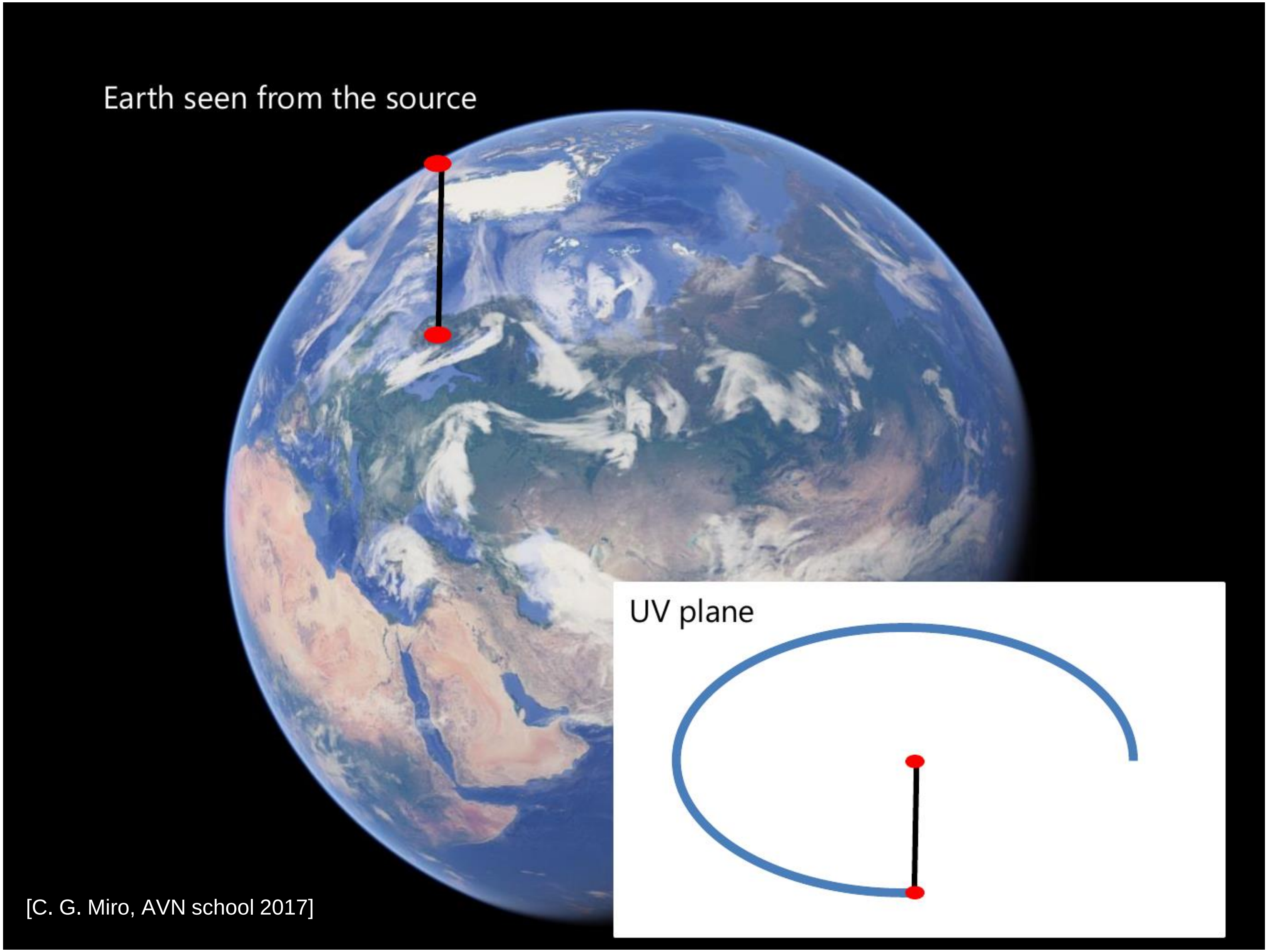
Interferometry – 2D



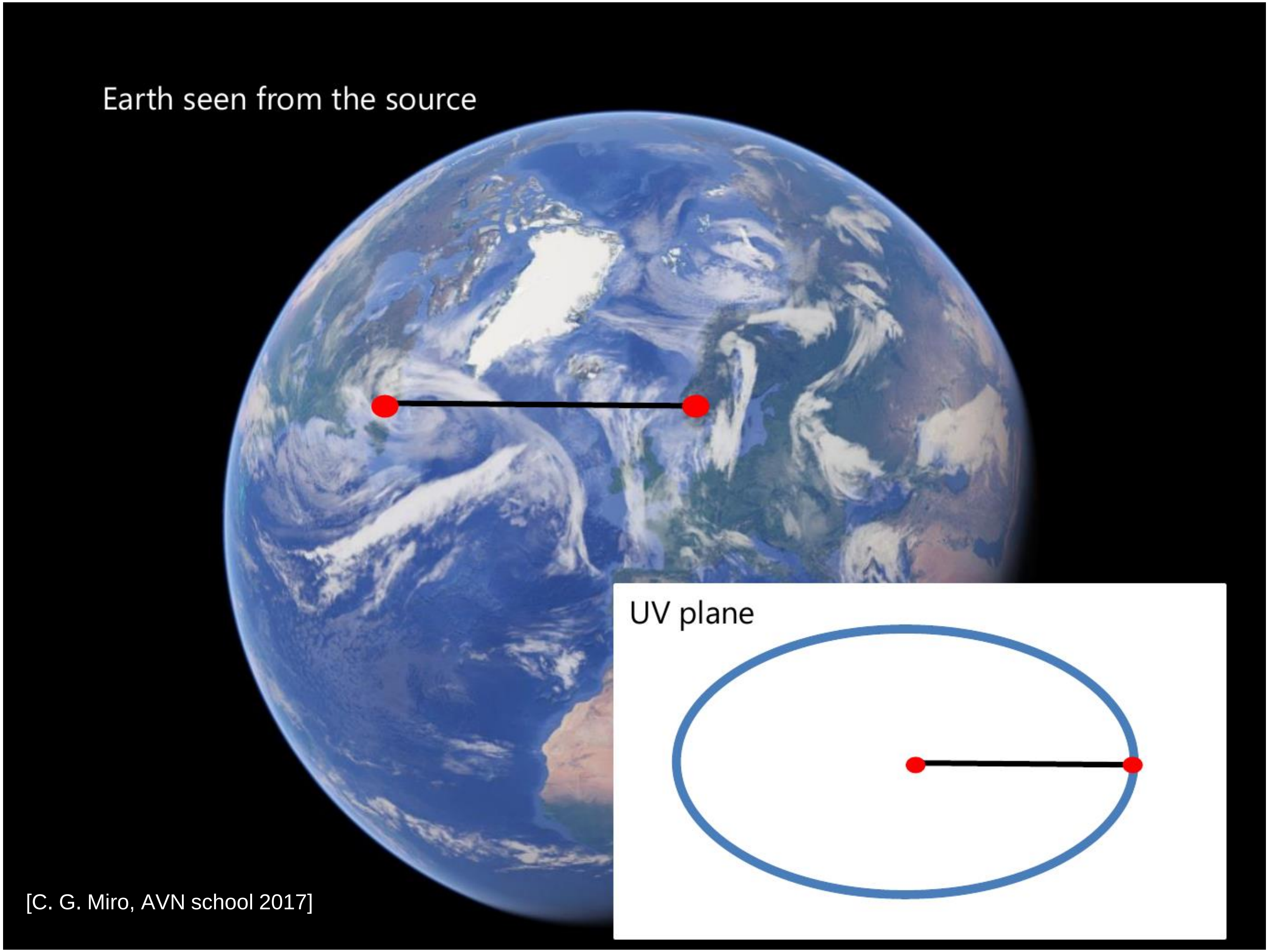
Interferometry – 2D



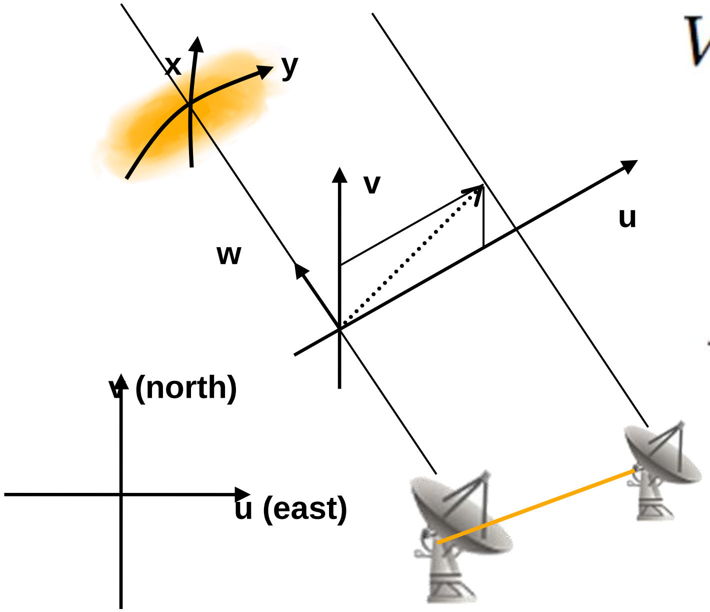
Interferometry – 2D



Interferometry – 2D



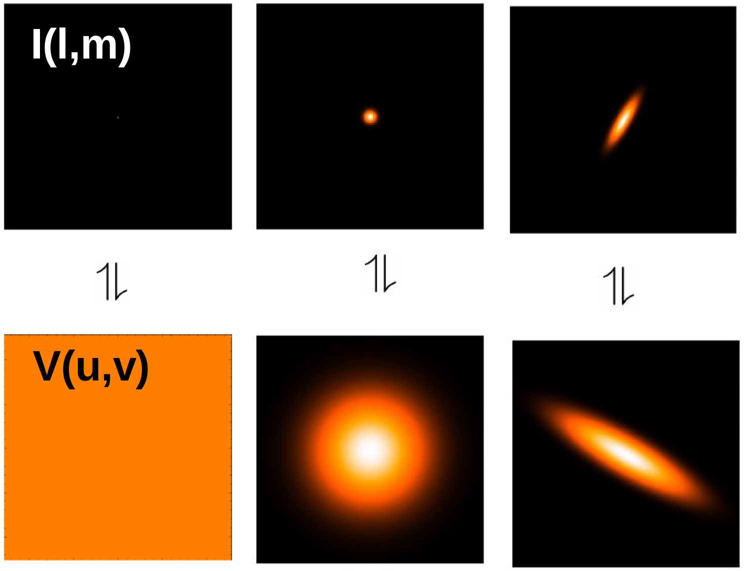
van Cittert - Zernike relation



$$V(u,v) = \int\int I(l,m) e^{-2\pi i (ul+vm)} dl dm$$

FT^{-1} ⇓ ⇑ FT

$$I(l,m) = \int\int V(u,v) e^{2\pi i (ul+vm)} du dv$$



By measuring the visibility function **V(u,v)** we can, through a Fourier transform, derive the brightness distribution **I(l,m)**.

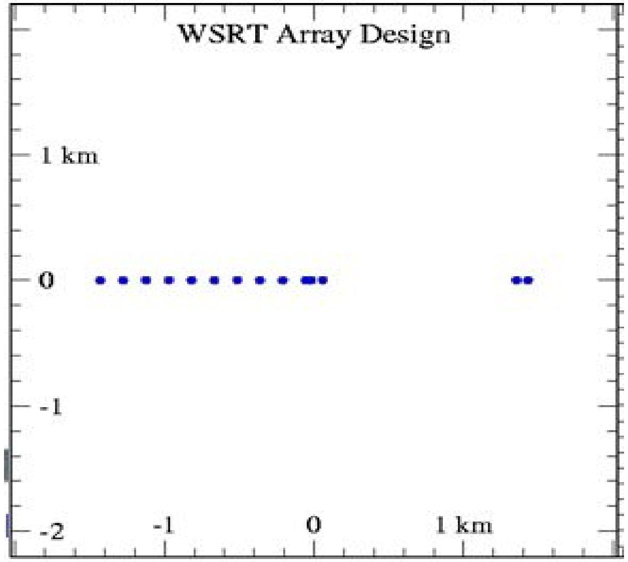
The more u,v samples we measure the more complete our knowledge of the source structure.

Recipes for uv-plane coverage

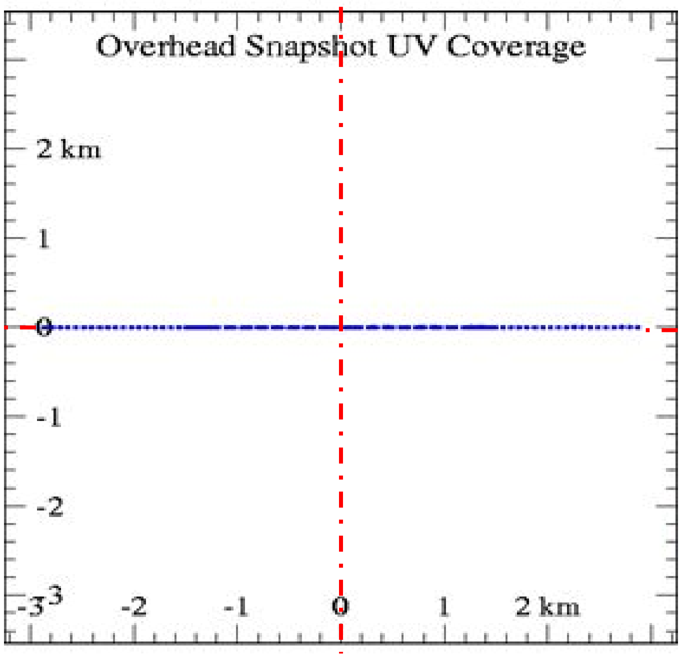
- Importance of a good uv-plane:
  - A well-filled uv-plane is crucial for good calibration and imaging.
  - Any ‘holes’ that remain in the uv-coverage will lead to side-lobes.
- Use a large number of (reconfigurable) elements: both costly & time consuming: fex. VLA, ALMA.
- Use the rotation of the earth to fill the uv-plane, f.ex.: WSRT
- Use a wide range of frequencies, i.e. bandwidth synthesis : WSRT, SKA (?).

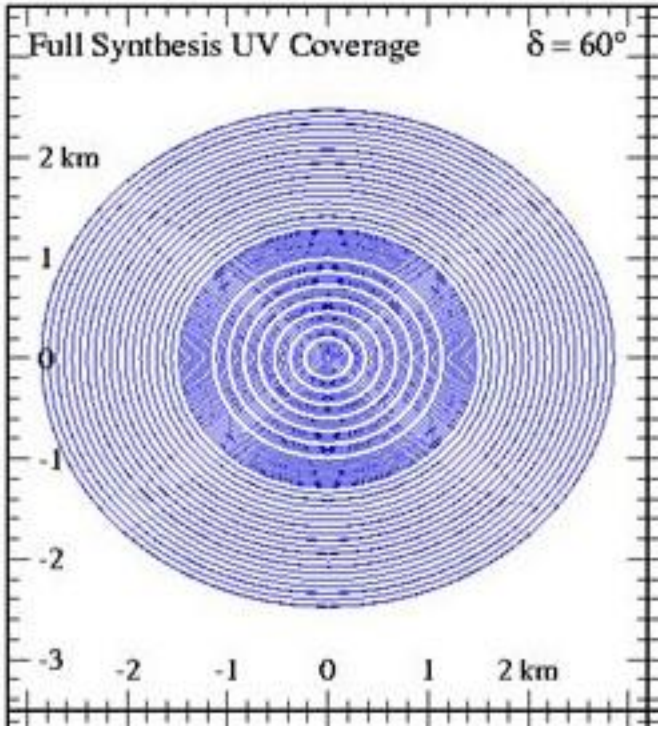
Visibility & UV-Planes

Westerbork Synthesis Radio Telescope

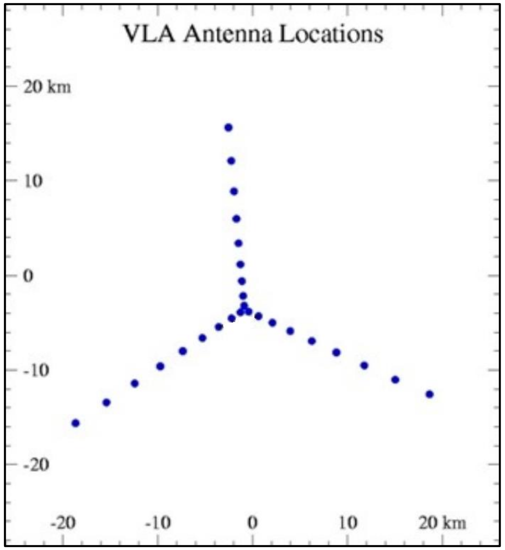


[A. Cohen]



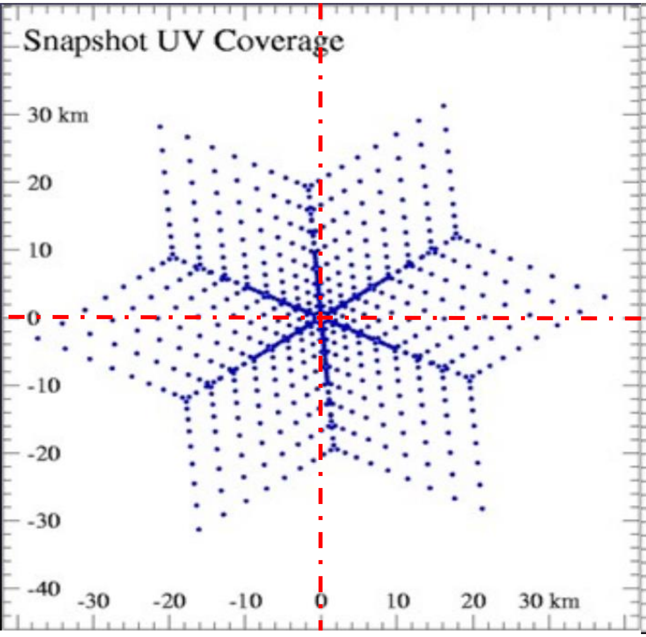


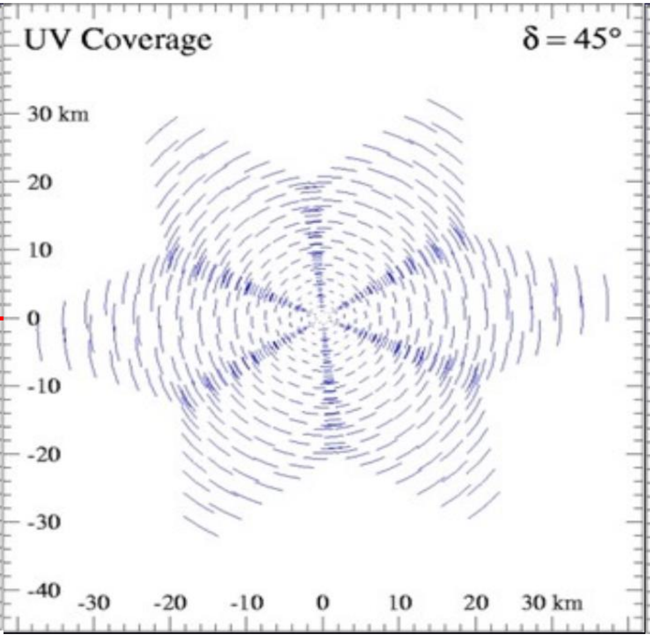
Visibility & UV-Planes

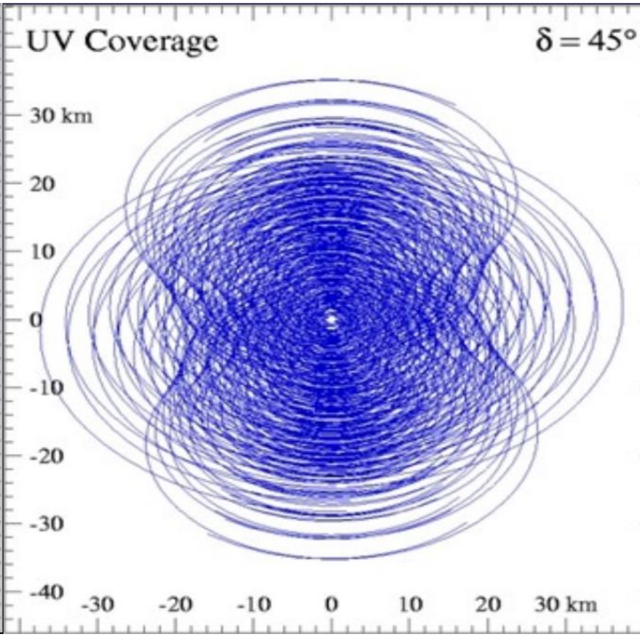


Very Large Array

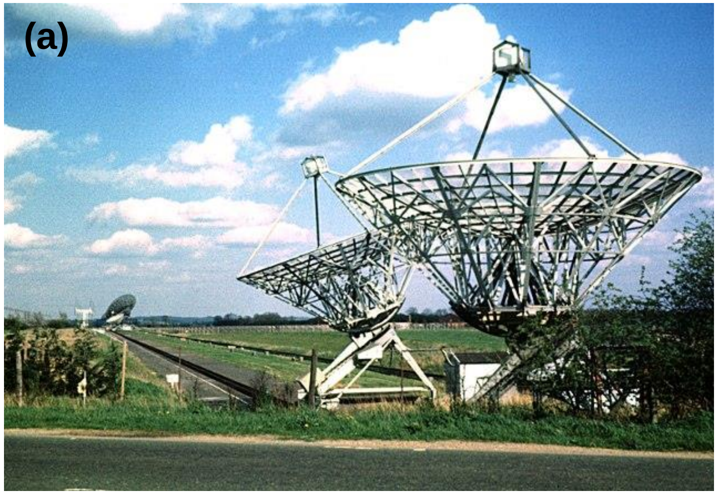
[A. Cohen]

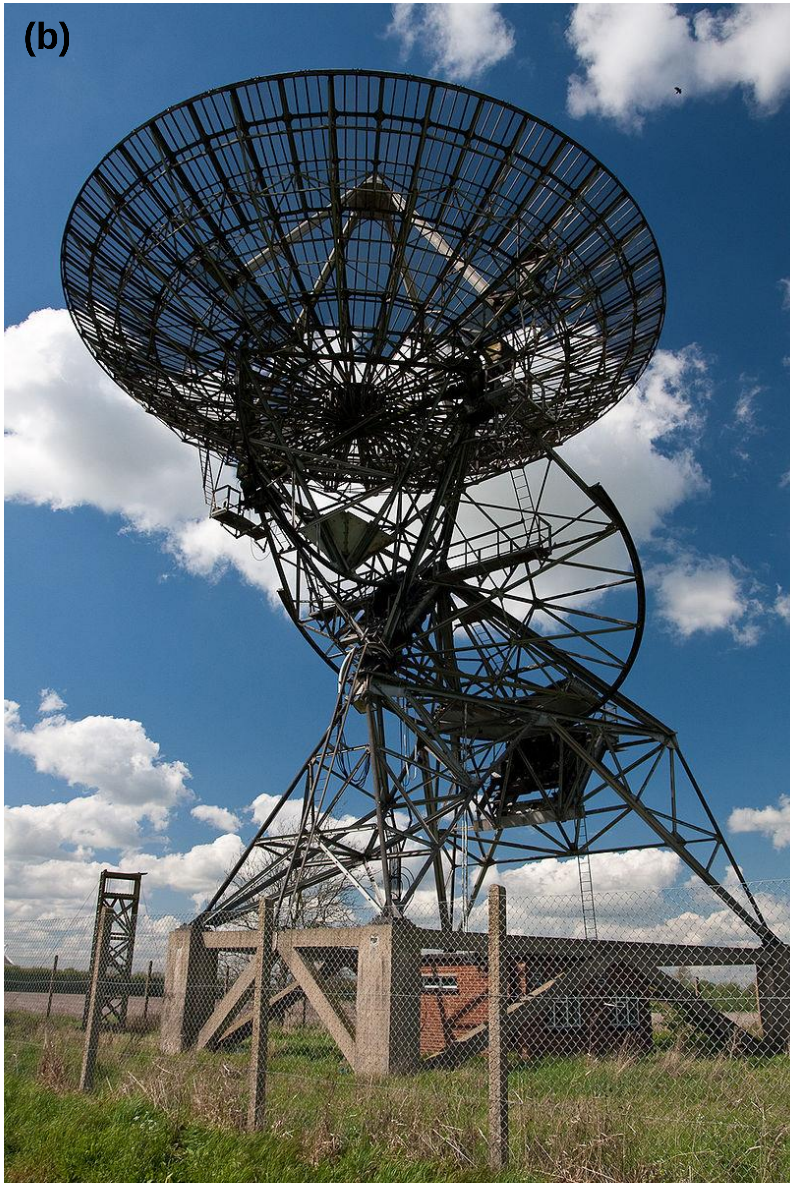






Mullard Radio Astronomy Observatory, UK



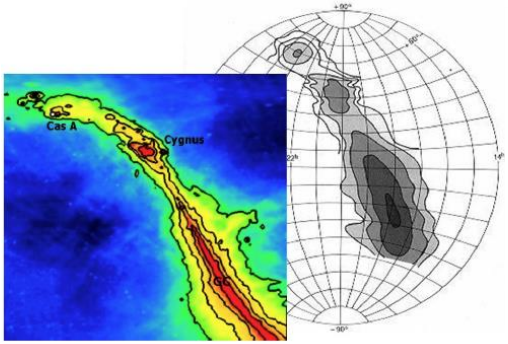


a) Cambridge Half-Mile Telescope (3)

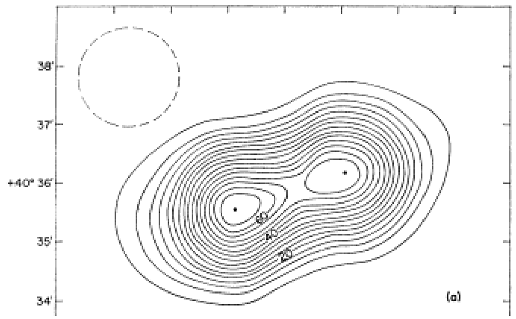
b) Cambridge One-Mile Telescope (3)

c) Cambridge Five-Kilometre Radio Telescope (8)

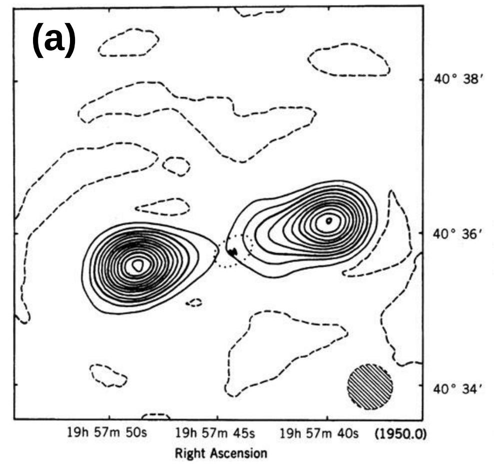
The quest for higher resolution



Grote 1938, 160 MHz, D=9m

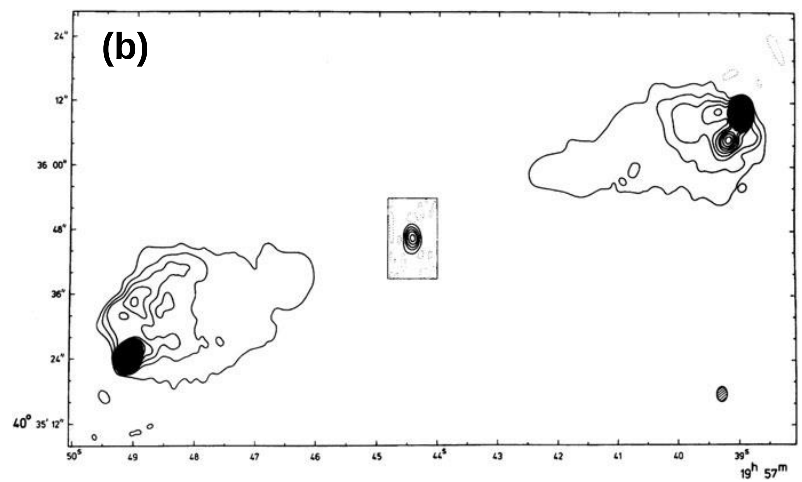


Meyer et al, 1968, 20 GHz, D=42.7m



(a) Cambridge One-Mile Telescope @ 1.4 GHz (Ryle et al. 1965)

(b) Cambridge Five-Kilometre Radio Telescope @ 5 GHz (Hargrave and Ryle, 1974)



Westerbork Synthesis Radio Telescope

- 14 antennas with a diameter of 25 metres arranged on a 2.7 km East-West line
- operate at several frequencies between 120 MHz and 8.3 GHz

Australia Telescope Compact Array

- 6 mobile antennas with a diameter of 22 m arranged on a 2.9 km East-West line
- Operates at 2100 MHz

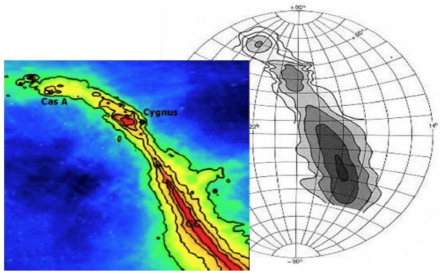
Atacama Large Millimeter Array

- 66 mobile antennas with mostly 12m diameter
- operates at wavelengths of 9.6 to 0.3 millimeters (31 to 1000 GHz)
- max BL = 16 km

Karl G. Jansky Very Large Array

- 27 antennas with a diameter of 25 meters deployed in a Y-shaped array.
- frequency coverage: 74 MHz to 50 GHz
- Max. BL=36km

The quest for higher resolution



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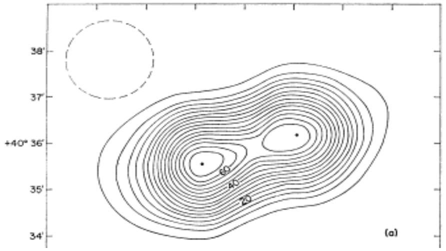
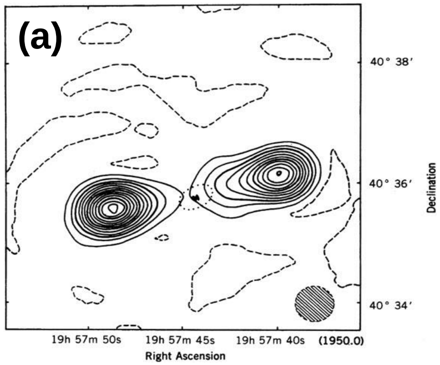


Meyer et al, 1968, 20 GHz, D=42.7m



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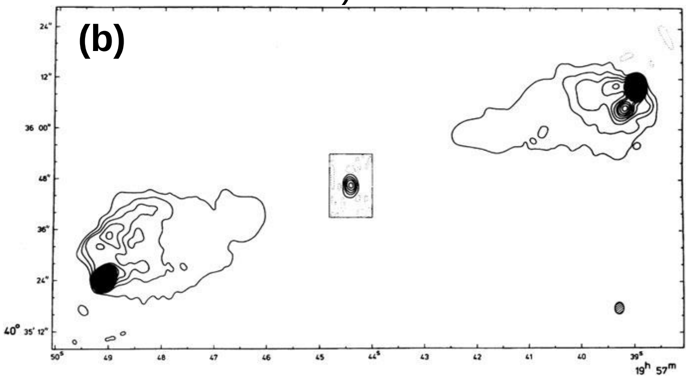
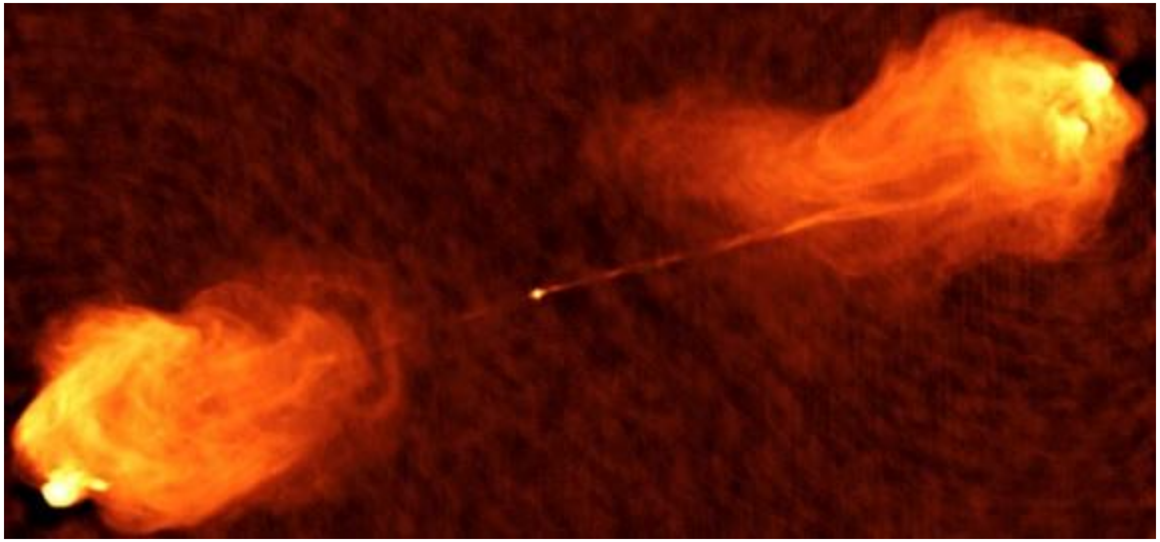




VLA, Perley et al., 1983, 4.8 GHz

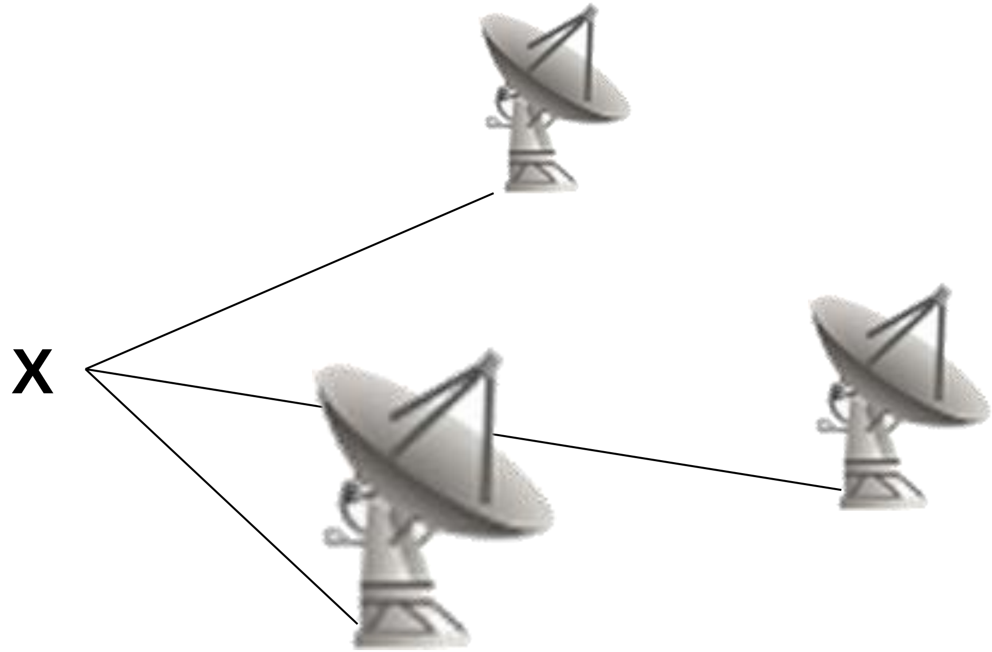
Interferometry

„angular“ resolution

$\Theta = \lambda / \mathbf{b}$

$\lambda = c / \mathbf{f}$

- Limitation: lengh of cable



Iterferometry

„angular“ resolution

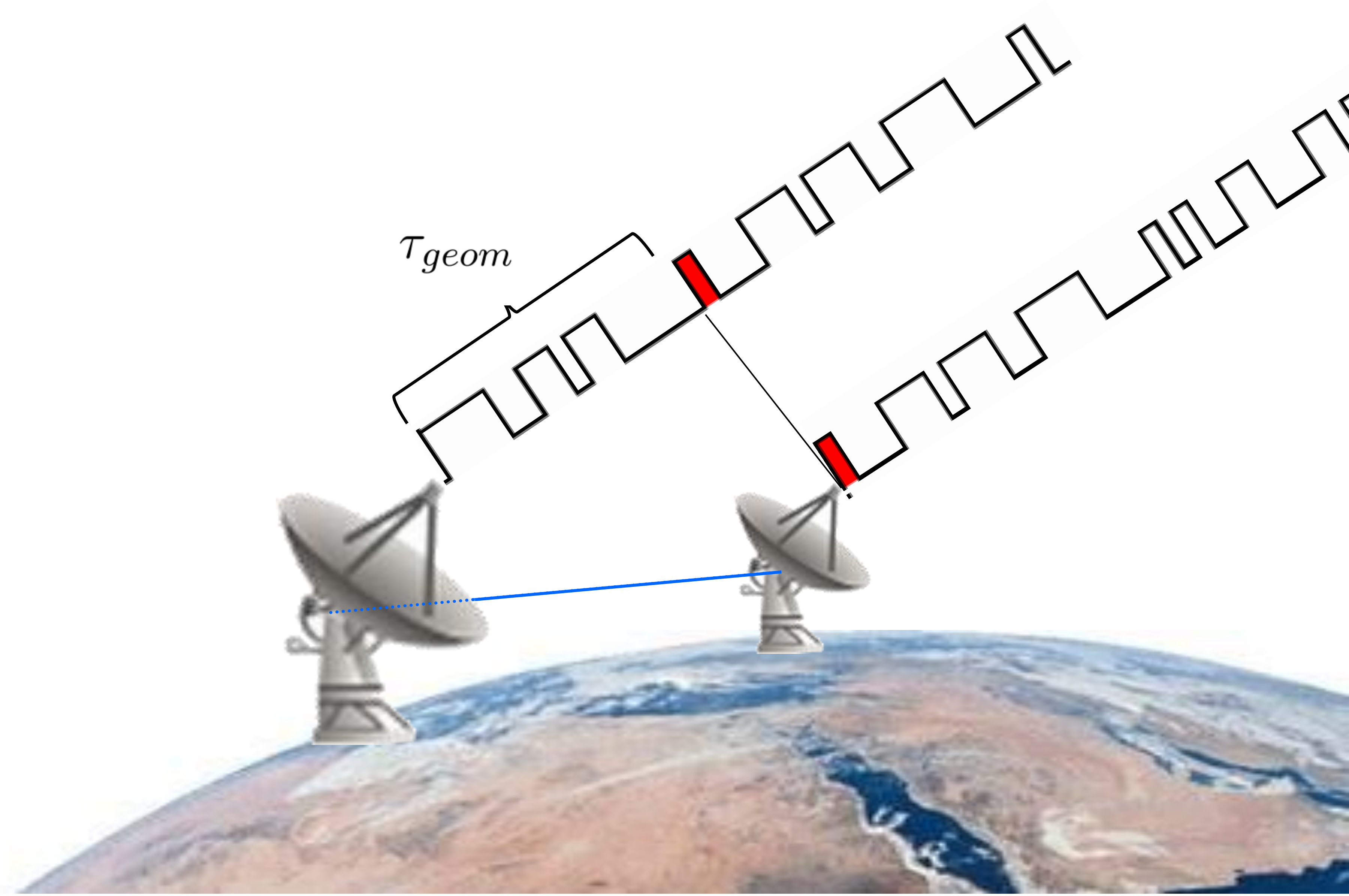
$\Theta = \lambda / \mathbf{b}$

$\lambda = c / \mathbf{f}$

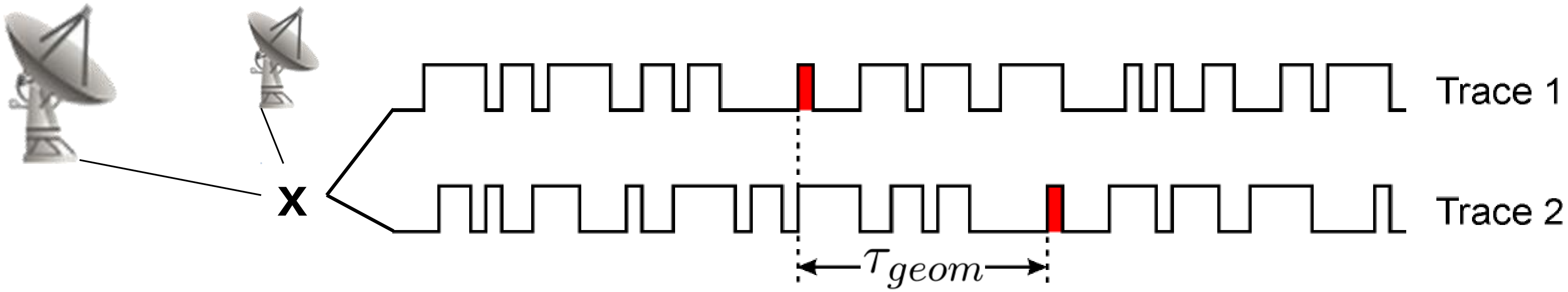
- Limitation: diameter of Earth
- Problem: we loose coherence!

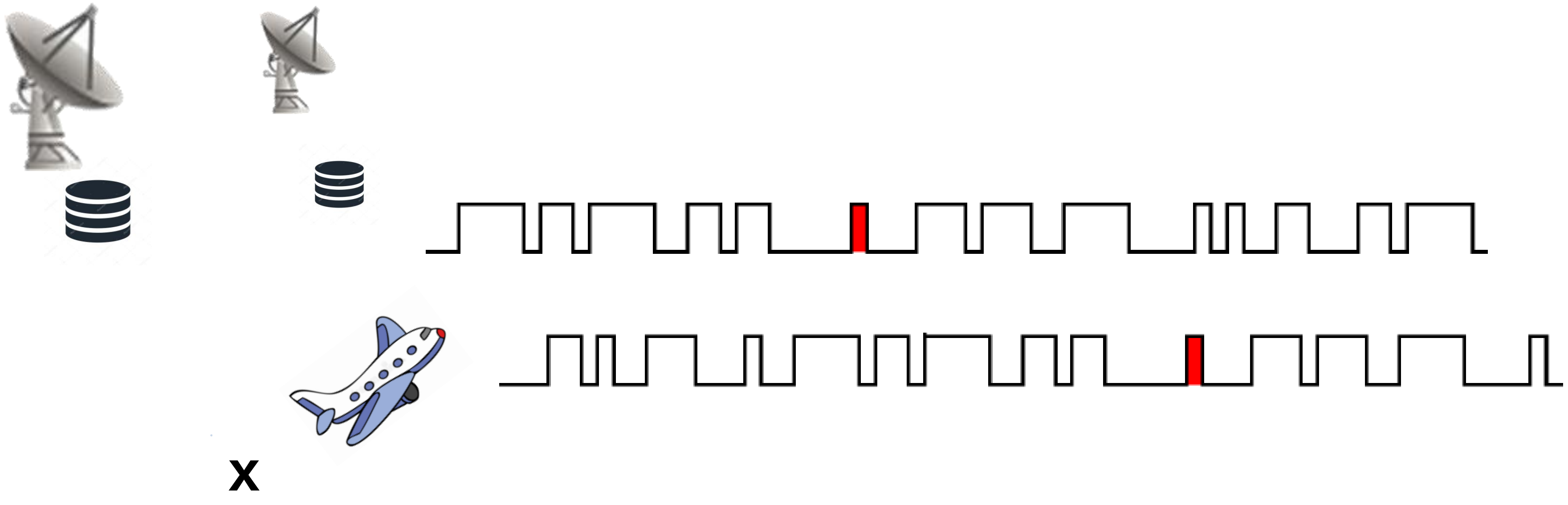
X

Iterferometry



Iterferometry





Iterferometry

„angular“ resolution

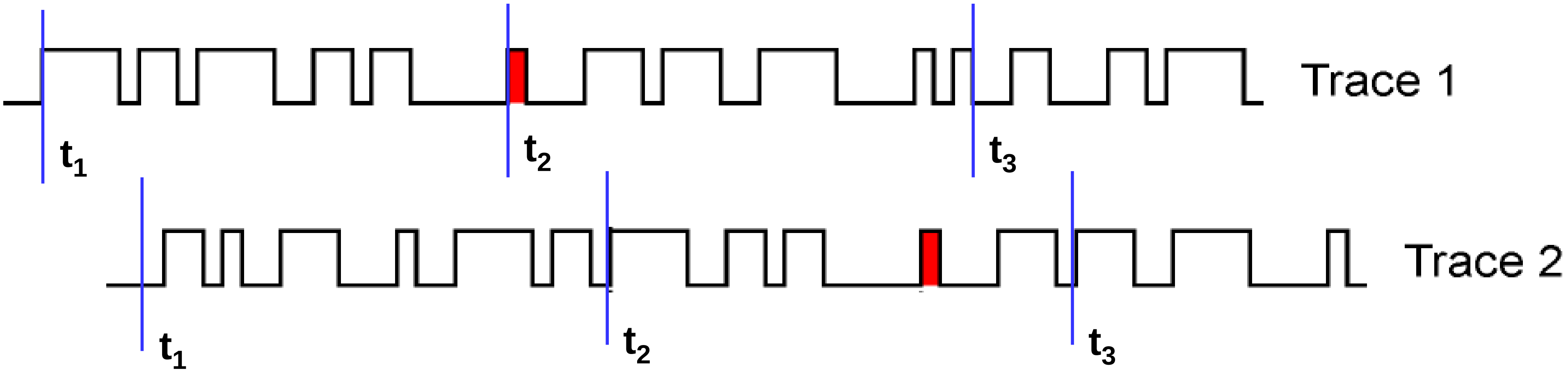
$\Theta = \lambda$ / **b**

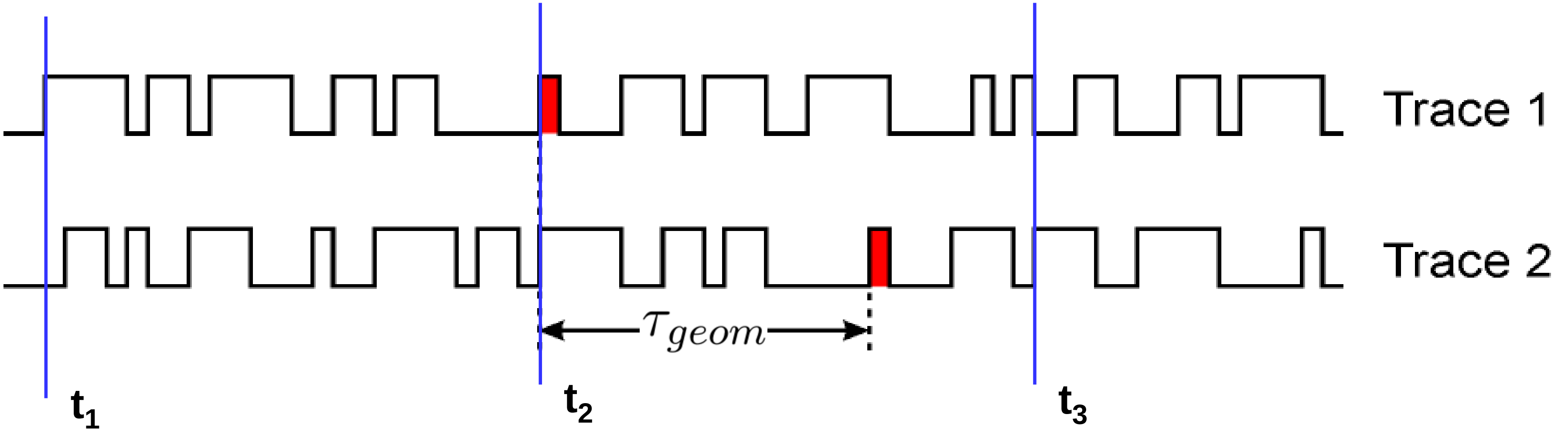
$\lambda = c$ / **f**

- Limitation: diameter of Earth
- Problem: we loose coherence!
- Solution: Time stamps

X

Iterferometry



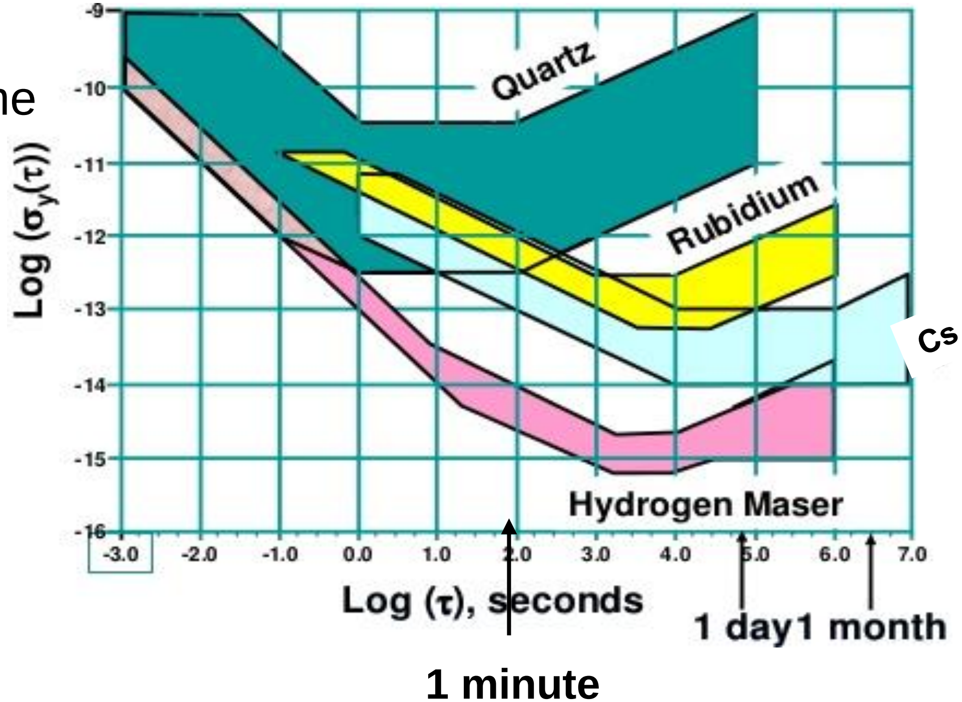


Local oscillators

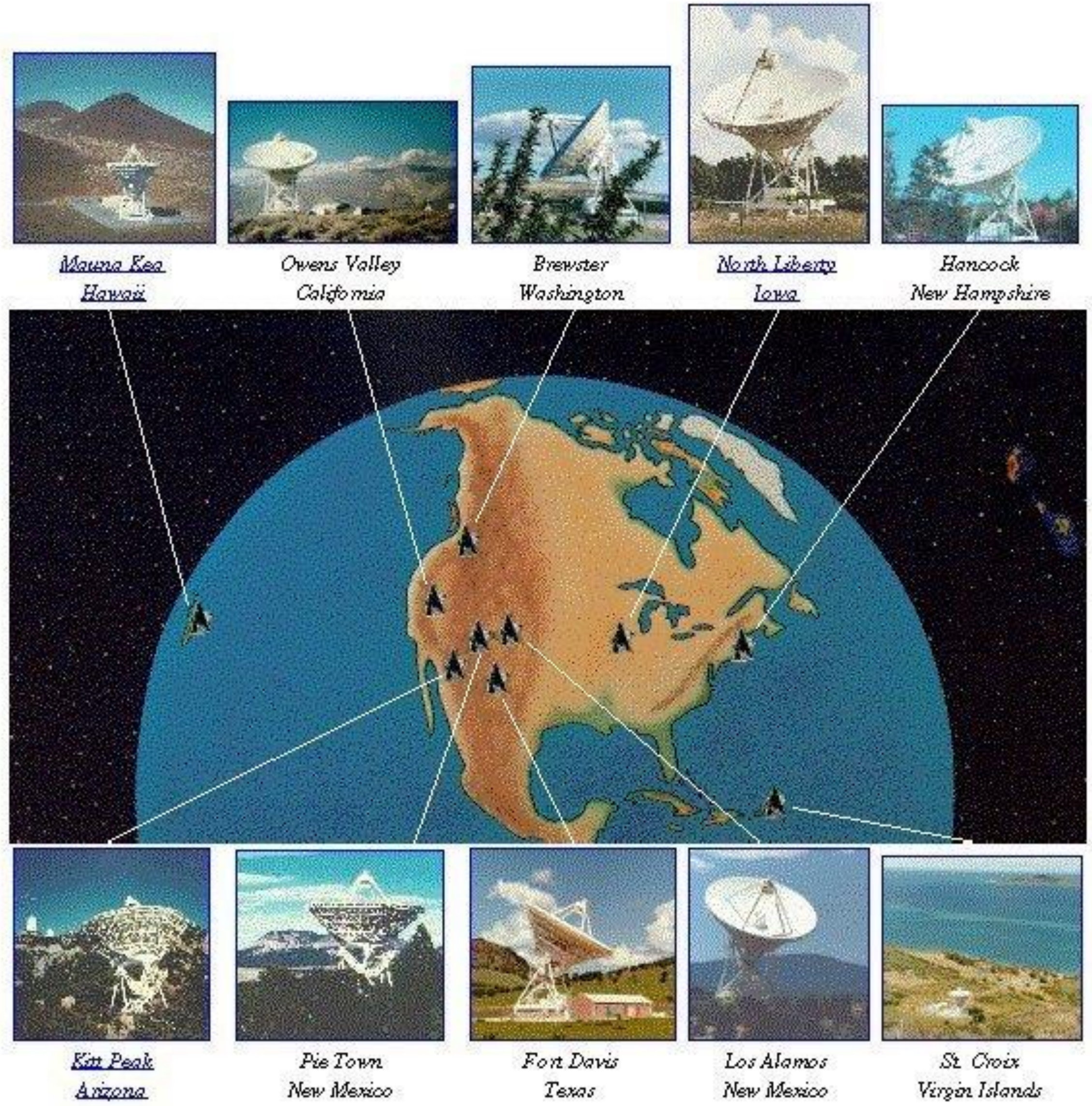
Job of the H-maser:

- keep the time
- need to play back signals synchronised
- required accuracy: coherence time
- coherence time ~ 1/ bandwidth
- keep synchronisation over observation

- Atomic clocks are the most accurate time and frequency standards
- used as primary standards
- Hydrogen masers superior short-term stability, but lower long-term accuracy.



VLBI….finally

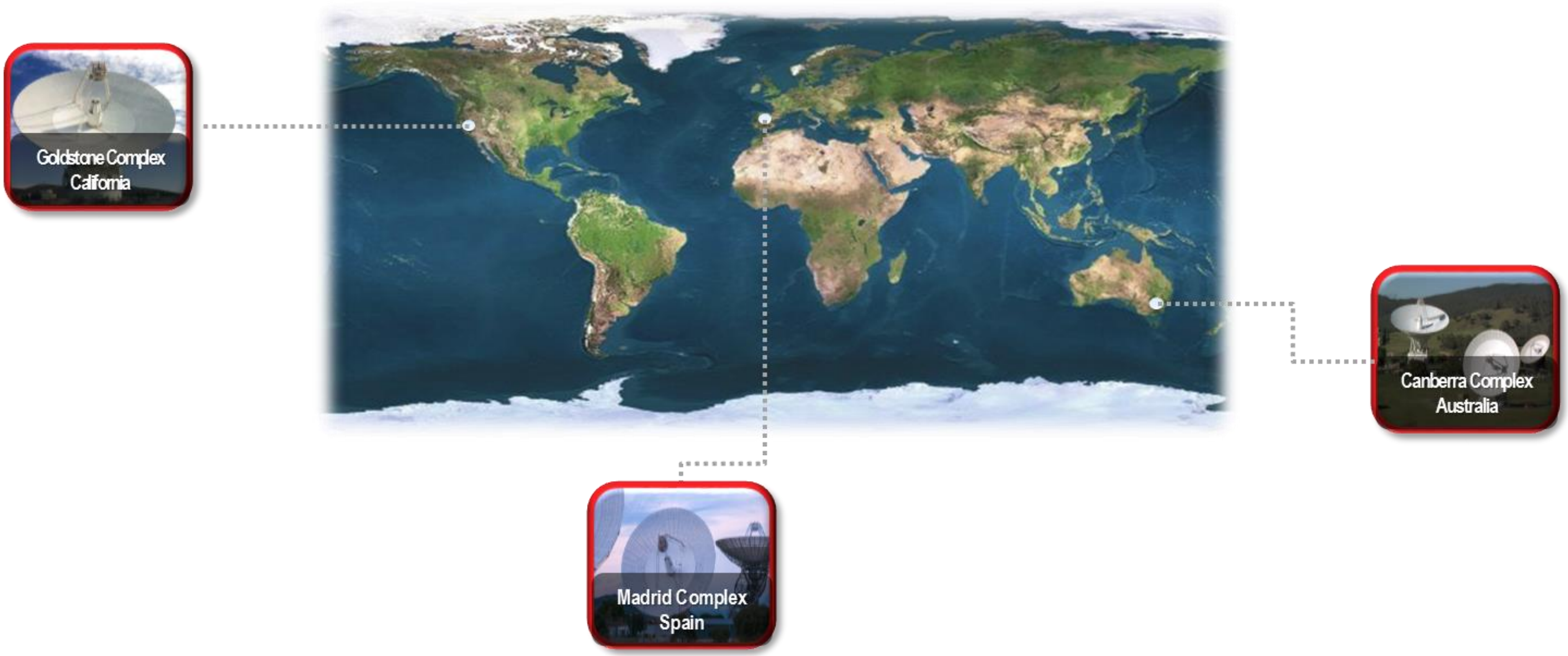


Very Long Baseline Array (VLBA)

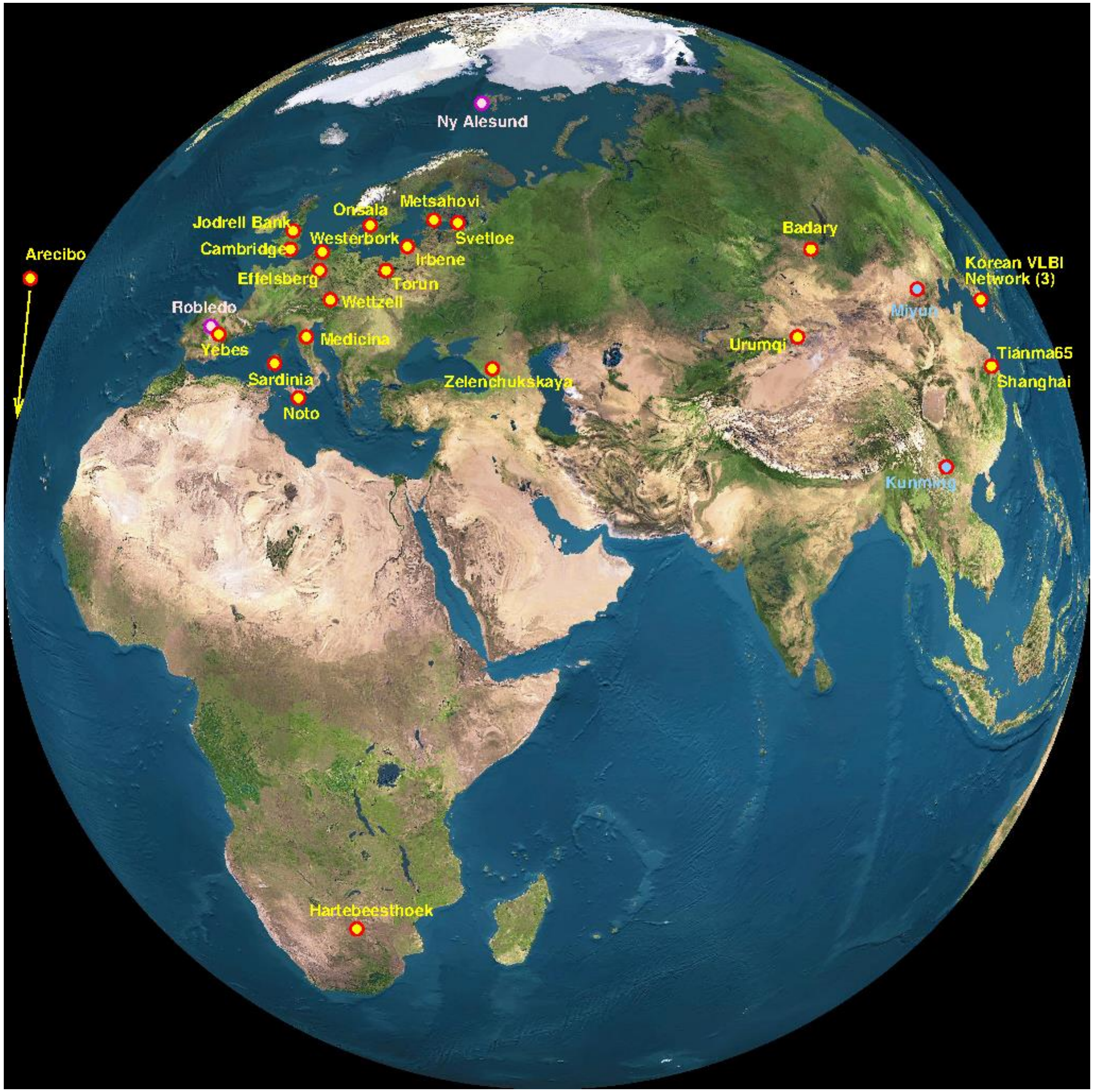
10 identical telescopes

VLBI….finally

Deep Space Network



VLBI….finally

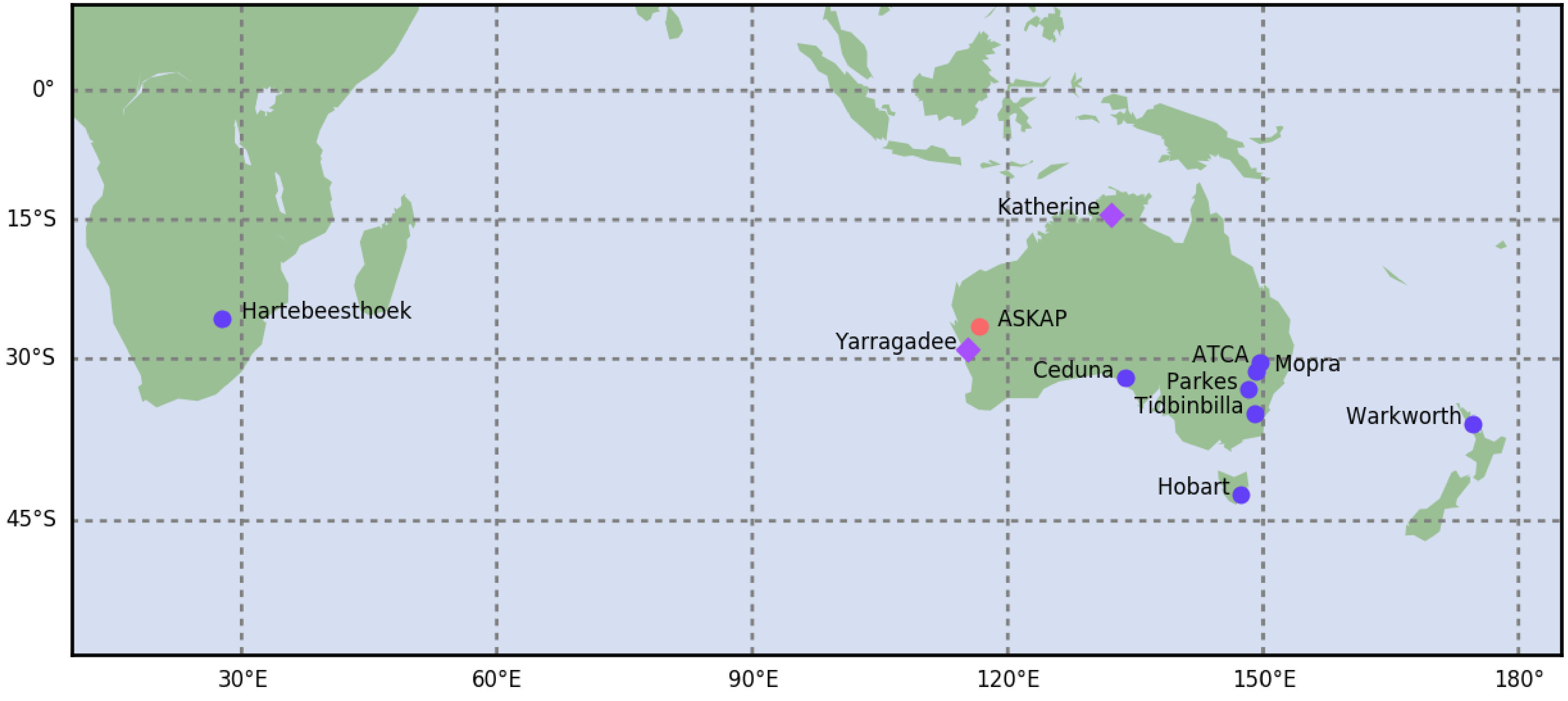


European VLBI Network (EVN)

21 Telescopes

VLBI….finally

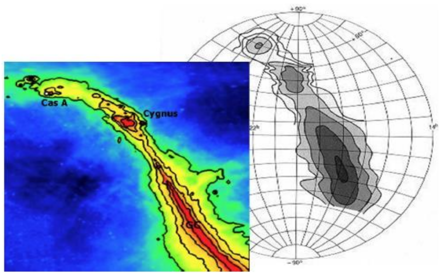
Australian Long Baseline Array (LBA)



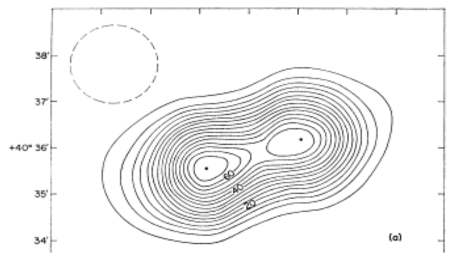
VLBI….finally

International VLBI Service (IVS) Network

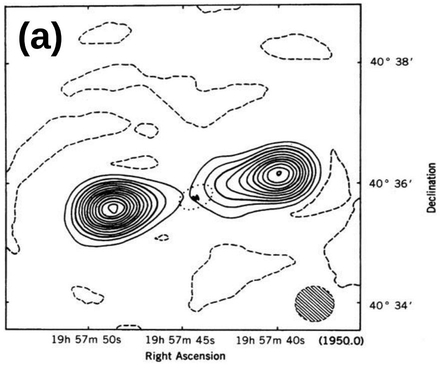
The quest for higher resolution



Grote 1938, 160 MHz, D=9m

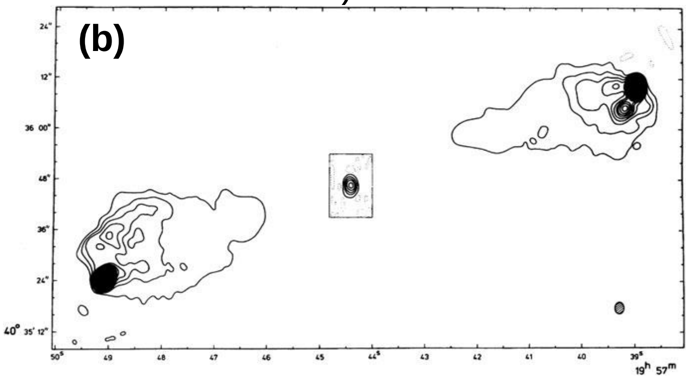


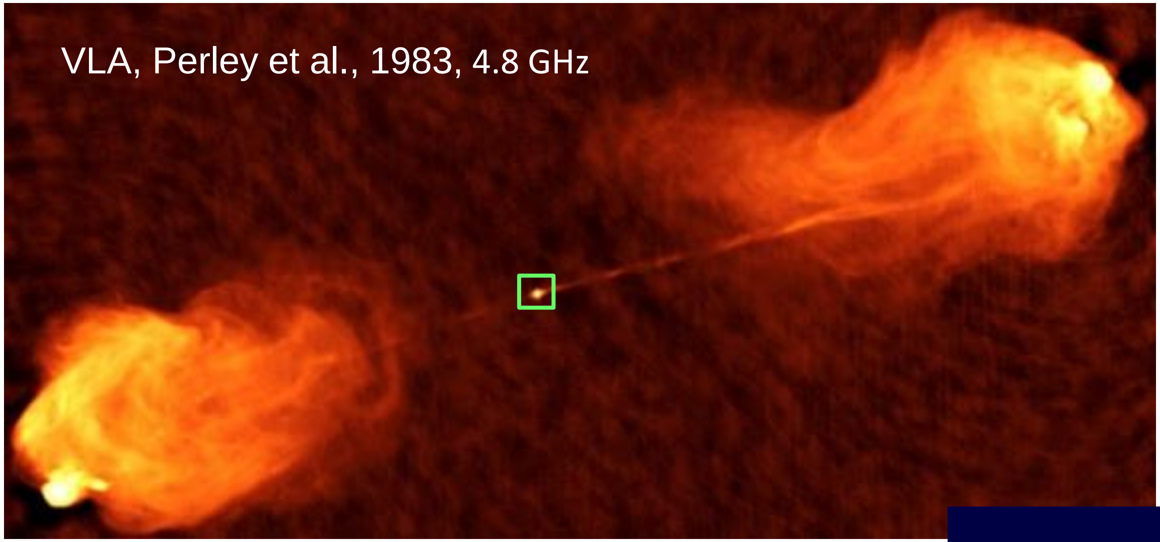
Meyer et al, 1968, 20 GHz, D=42.7m



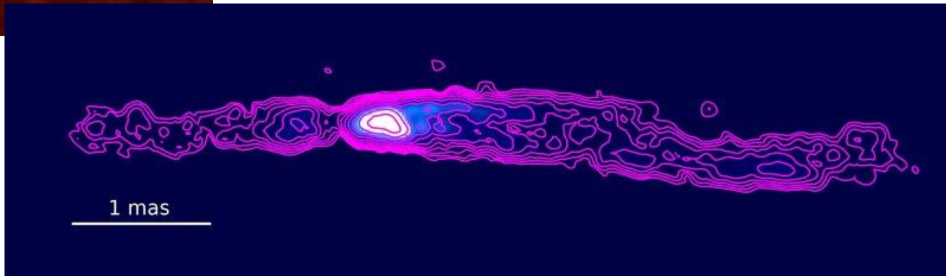
(a) Cambridge One-Mile Telescope @ 1.4 GHz (Ryle et al. 1965)

(b) Cambridge Five-Kilometre Radio Telescope @ 5 GHz (Hargrave and Ryle, 1974)





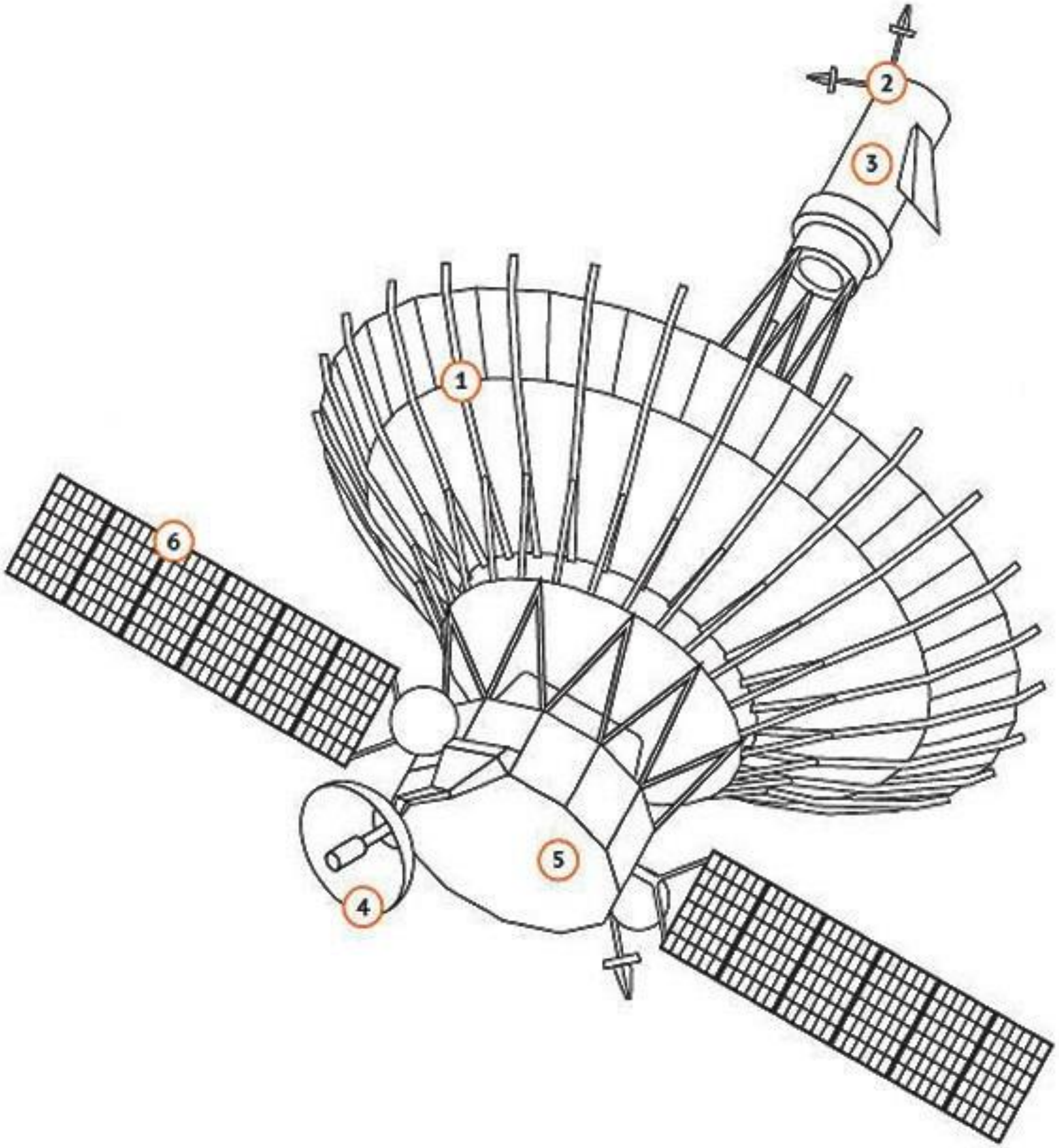
VLA, Perley et al., 1983, 4.8 GHz



VLBI @ 43GHz (Boccardi et al., 2016)

1mas=4.5 ly

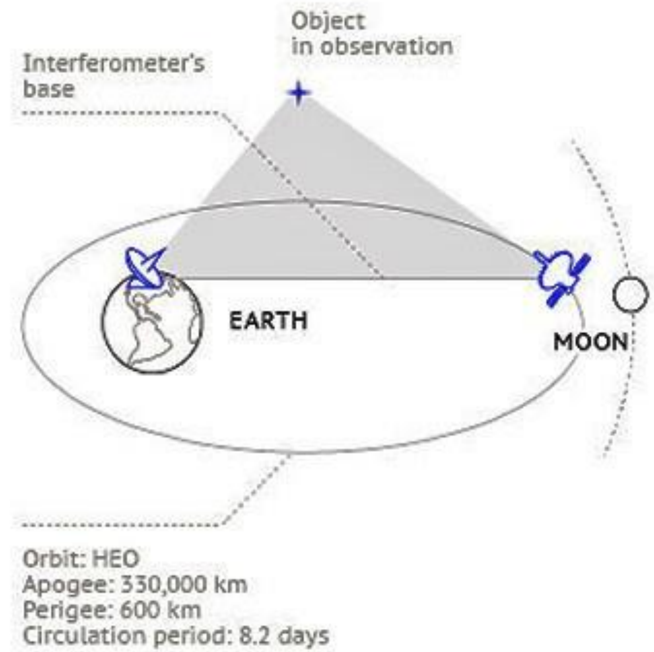
VLBI….even longer base lines



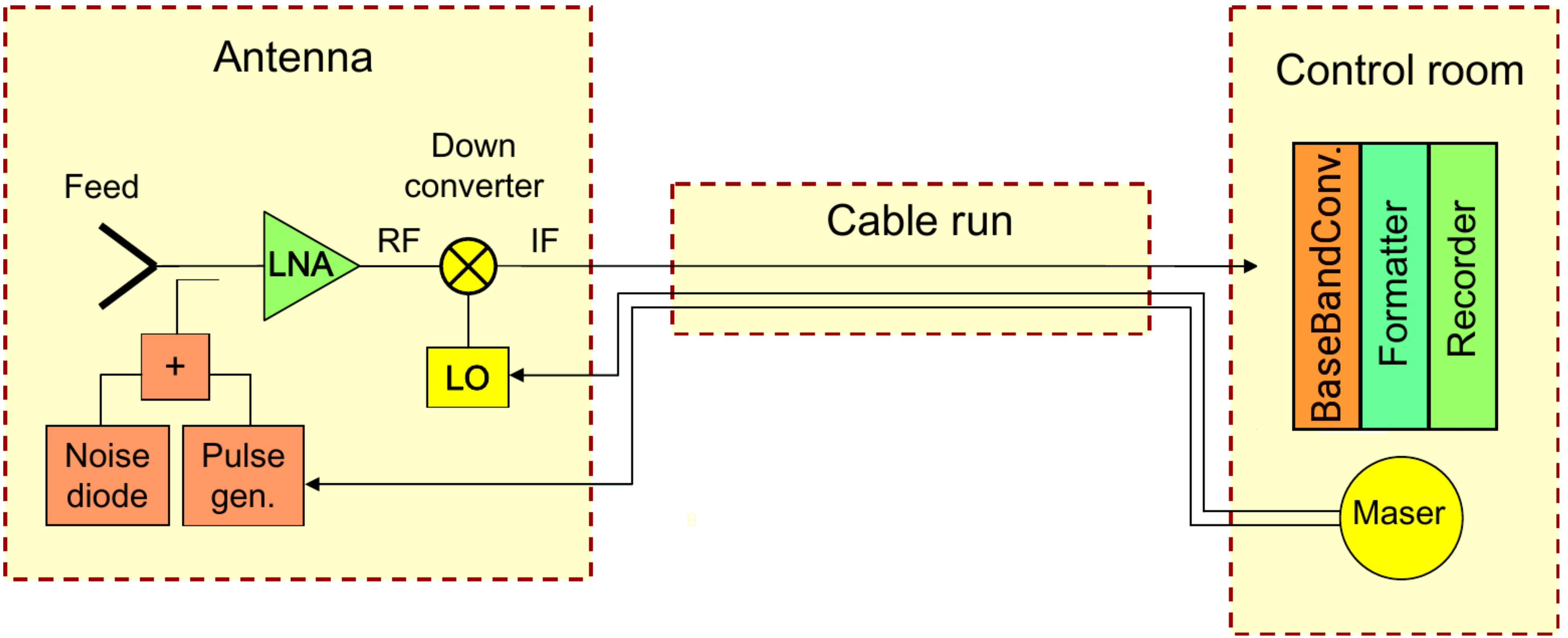
Radio Astron
launch: 18.07.2011)

D= 10m, max BL=330.000 km

7 µas @ 18-25 GHz



Instrumentation (traditional/analog)



[B. Petrachenko, 2013]

Antenna: Mount

Alt-az

- workhorse antenna mount for large radio telescopes
- fixed vertical axis (azimuth), and a moving horizontal axis (altitude or elevation)
- azimuth motion is typically ±270° the elevation motion is typically 5° to 85°.

Advantages:

- Easy to balance the structure and hence optimum for supporting a heavy structure.

Disadvantages:

- Difficult to track through the zenith due to the coordinate singularity (key hole).
- Complications with cable management due to 540° of azimuth motion (cable wrap problem).

Antenna: Mount

Equatorial

- fixed axis in the direction of the celestial pole (equatorial), and a moving axis at right angles to the equatorial axis (declination).

Advantages:

- Can be used without computer control – just get on source and track at the sidereal rate.
- No cable wrap ambiguity

Disadvantages:

- Difficult to balance the structure and hence sub-optimal for large structures.
- Key hole problem at the celestial pole.

Antenna: Mount

XY

- mainly used for high speed satellite tracking where key holes cannot be tolerated.
- Fixed axis points to the horizon and
- hence the only keyhole is at the horizon, which is too low for tracking.
- Full sky coverage can be achieved with ±90° motion in both axes.

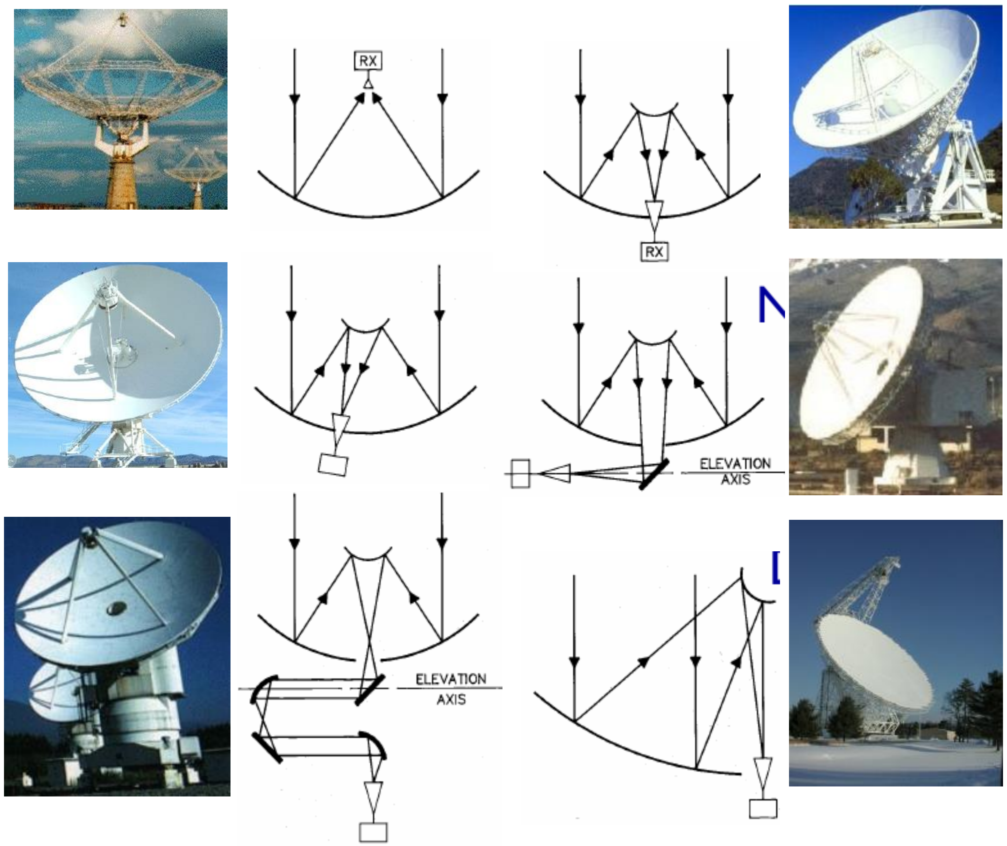
Advantages:

- No place where an object cannot be tracked (i.e. no key holes).
- No cable wrap ambiguity

Disadvantages:

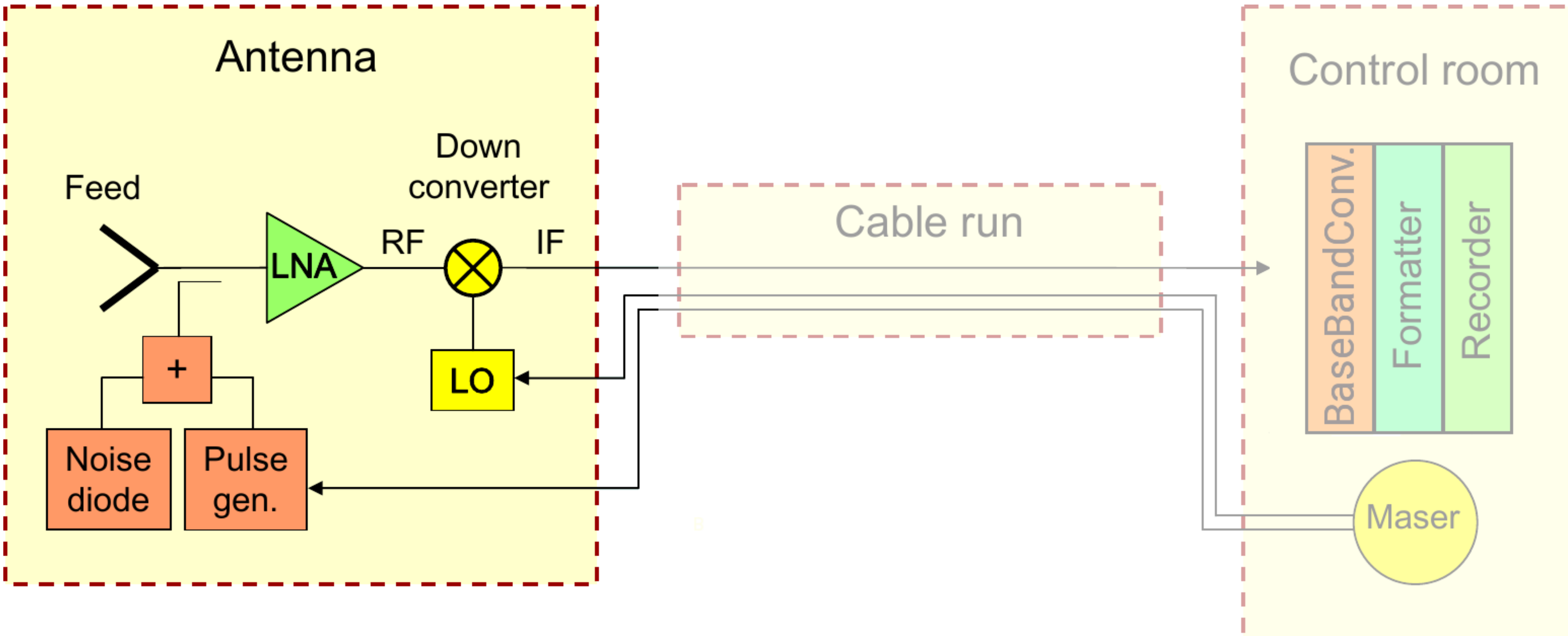
- Structurally difficult to construct.

Antenna: Optics, i.e. reflector configutation



- **Prime focus**: simple, good for low frequencies, but receiver and electronics must be light
- **On-axsis Cassegrain**: more suitable for higher frequencies
- **Offset Cassegrain**: more complicated, but allows fast switching between multiple receivers (frequencies)
- **Nasmyth**: switching between frequencies, receivers can remain stable (important for some cryogenic cooling methods), but more complicated
- **Offset Gregorian**: provides clean beamshape and minimizes RFI effects, but polarization is asymmetric

Instrumentation (traditional/analog)



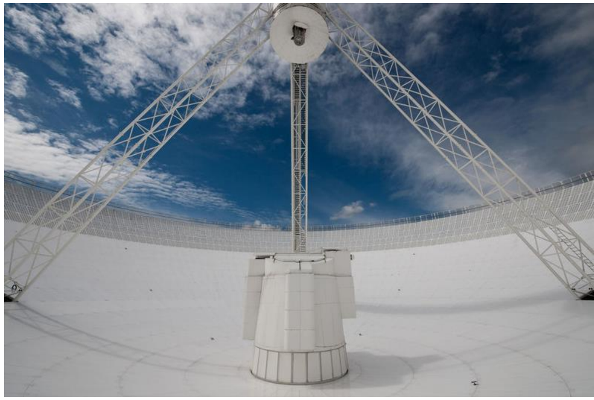
Front End

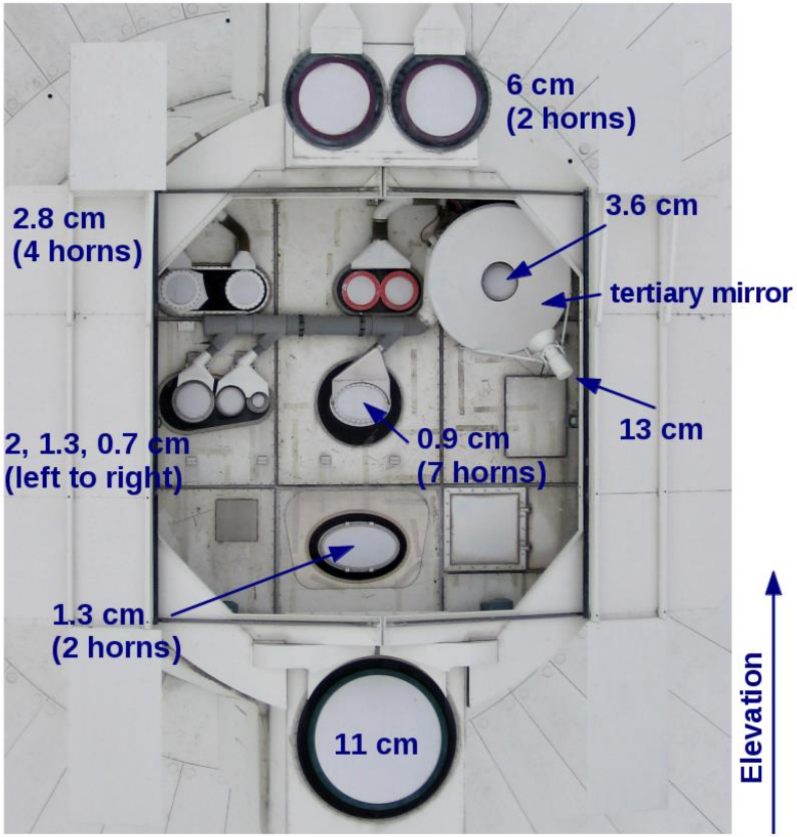
[B. Petrachenko, 2013]

Front End

- Feed horn + receiver + amplifier
- The part that takes in the time-variable electric field that has been concentrated by the antenna and provides the initial amplification of the signal at the incoming radio frequencies.
- Outputs some time-variable signal (usually a voltage) that can be processed by other electronic devices
- At gigahertz frequencies the front end usually consists of a “feed horn” that shapes the response (directivity) of the receiver to control the illumination of the primary or secondary (or higher order) reflector and guide (waveguide) the electric field to the electronics that actually receive the incoming signal, plus those “receiver” electronics
- Receiver electronics usually cooled as much as possible (liquid helium) to reduce system noise

Feed

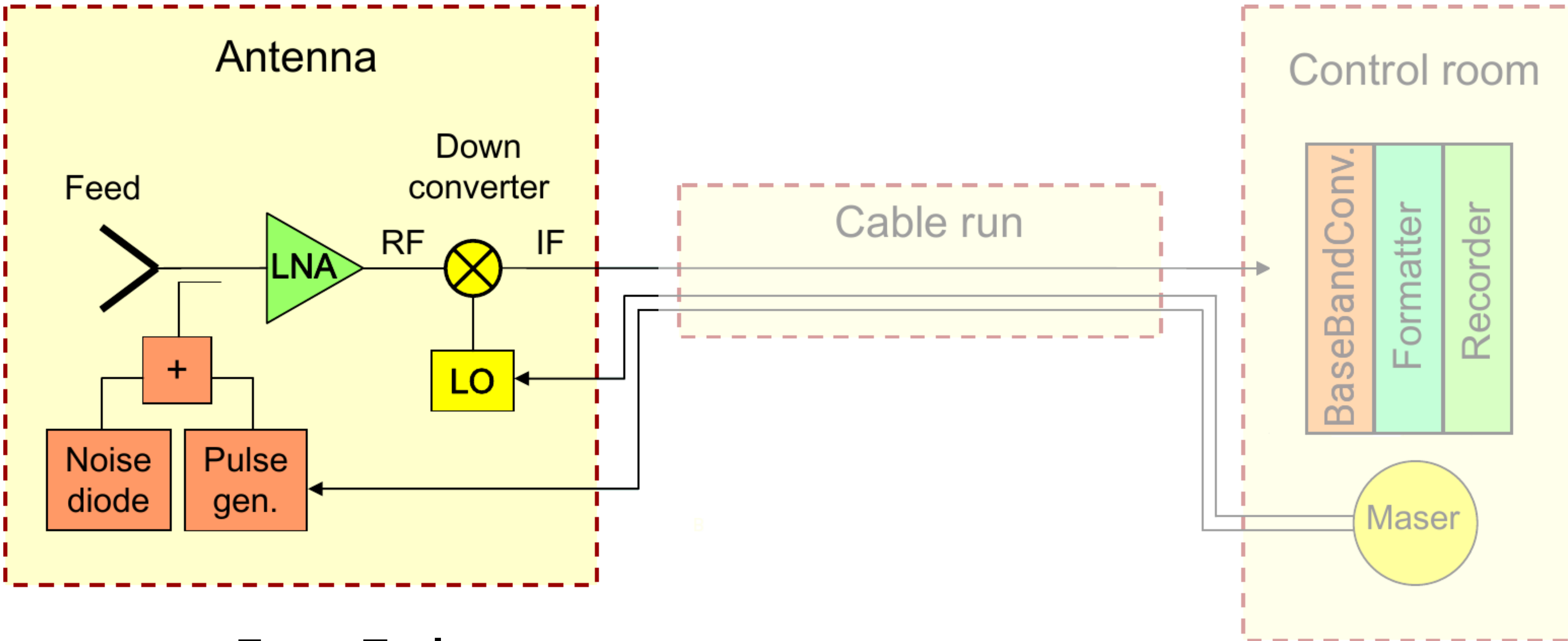




	Frequency GHz	Wave lenght cm
L	1 - 2.6	30 - 15
S	2.6 - 3.95	15 - 7.5
C	3.95 - 5.8	7.5 – 3.75
X	8.2 - 12.4	3.75 – 2.5
K_u	12.4 - 18	2.5 – 1.67
K	18 - 26.5	1.67 – 1.11
K_a	26.5 - 40	1.11. -0.75
Q	33 - 50	0.75 – 0.59

[Effelsberg, Max Plank Institute for Radioastronomy]

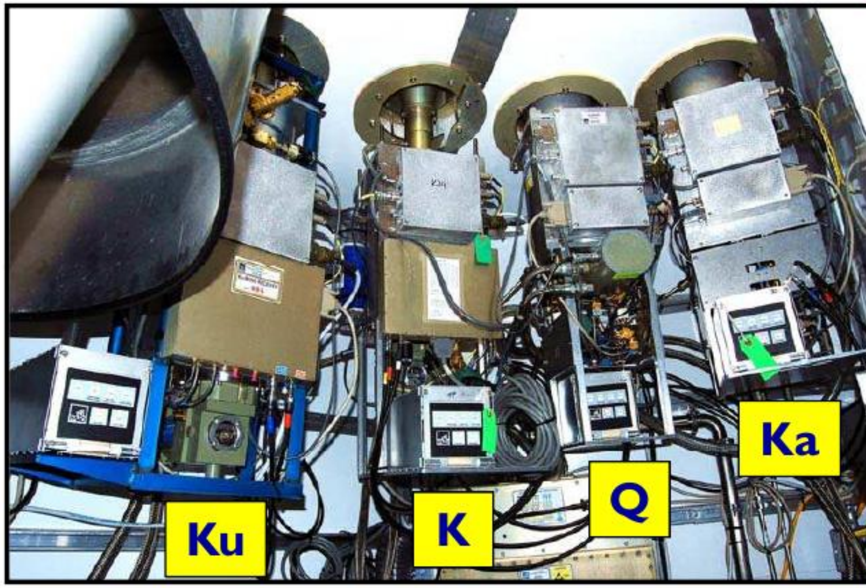
Instrumentation (traditional/analog)



Front End

[B. Petrachenko, 2013]

Connecting Feed Horns to receivers



Upper Level

C = 4 - 8 GHz
X = 8-12 GHz
Ku = 12-18 GHz
K = 18-26 GHz
Ka = 26-40 GHz
Q = 40-50 GHz

Vertex Cabin

Lower Level

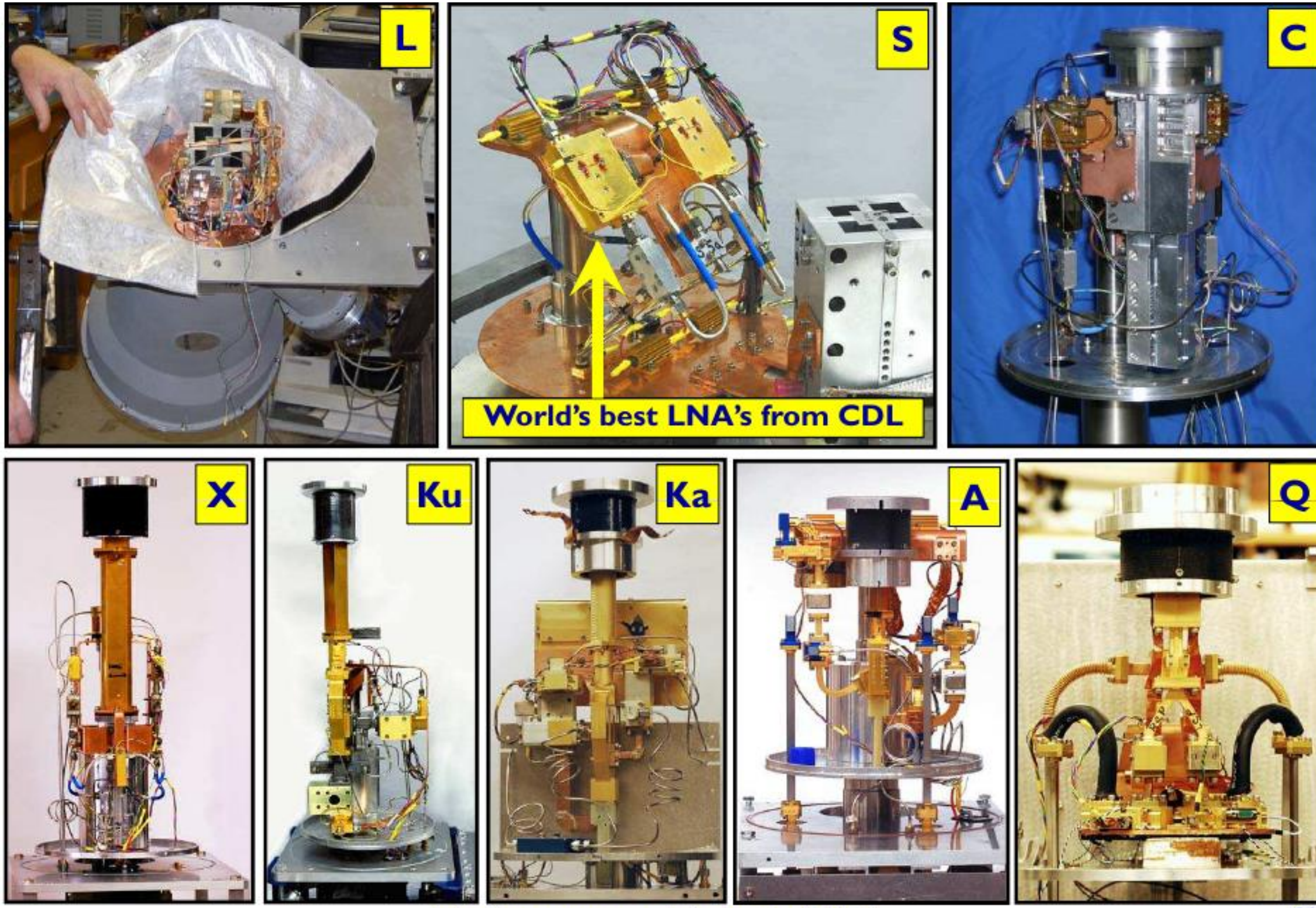
L = 1-2 GHz
S = 2-4 GHz

Total number of JVLA cryogenic receivers = 8 x 30 = 240

Paul Harden's JVLA Front-End Web Pages - http://www.aoc.nrao.edu/~pharden/fe/fe.htm

27

Receiver



http://www.aoc.nrao.edu/~pharden/fe/fe.htm

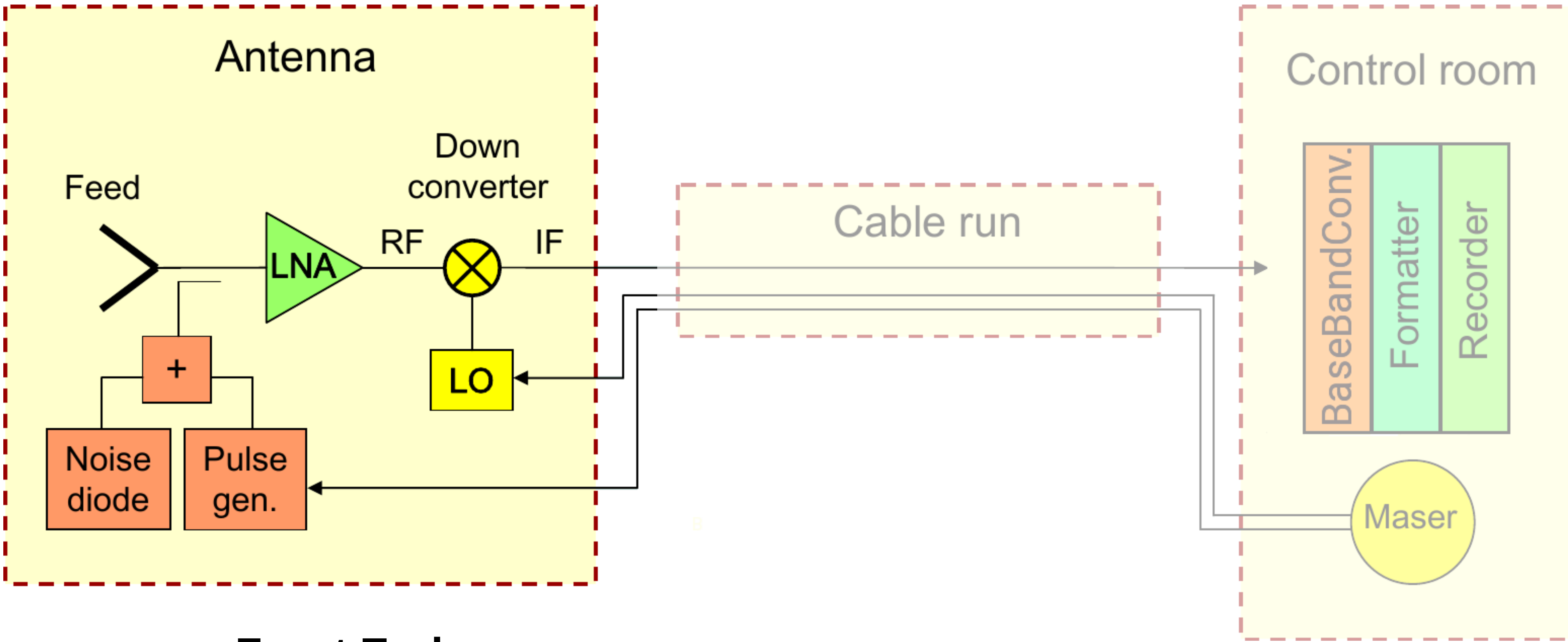
28

Amplifiers

- Need to amplify the received signal so that it is strong enough to work with.
- Remember that astronomical sources are very weak. We use the unit of Jansky to measure flux density, where 1 Jansky = 1 Jy $\equiv 10^{-26}$ W m^{-2} Hz $^{-2}$, and a 1 Jy source is quite bright, astronomically speaking.

NRAO Cryogenic Low Noise Amplifiers (LNAs) on the VLA,VLBA.

Instrumentation (traditional/analog)

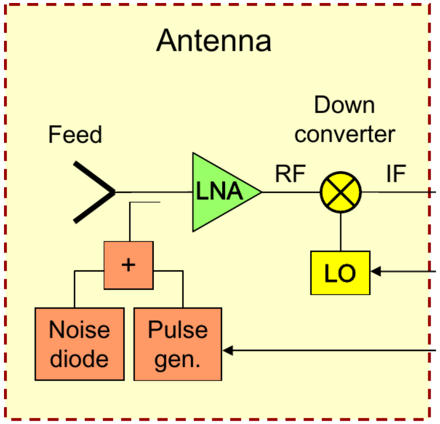


Front End

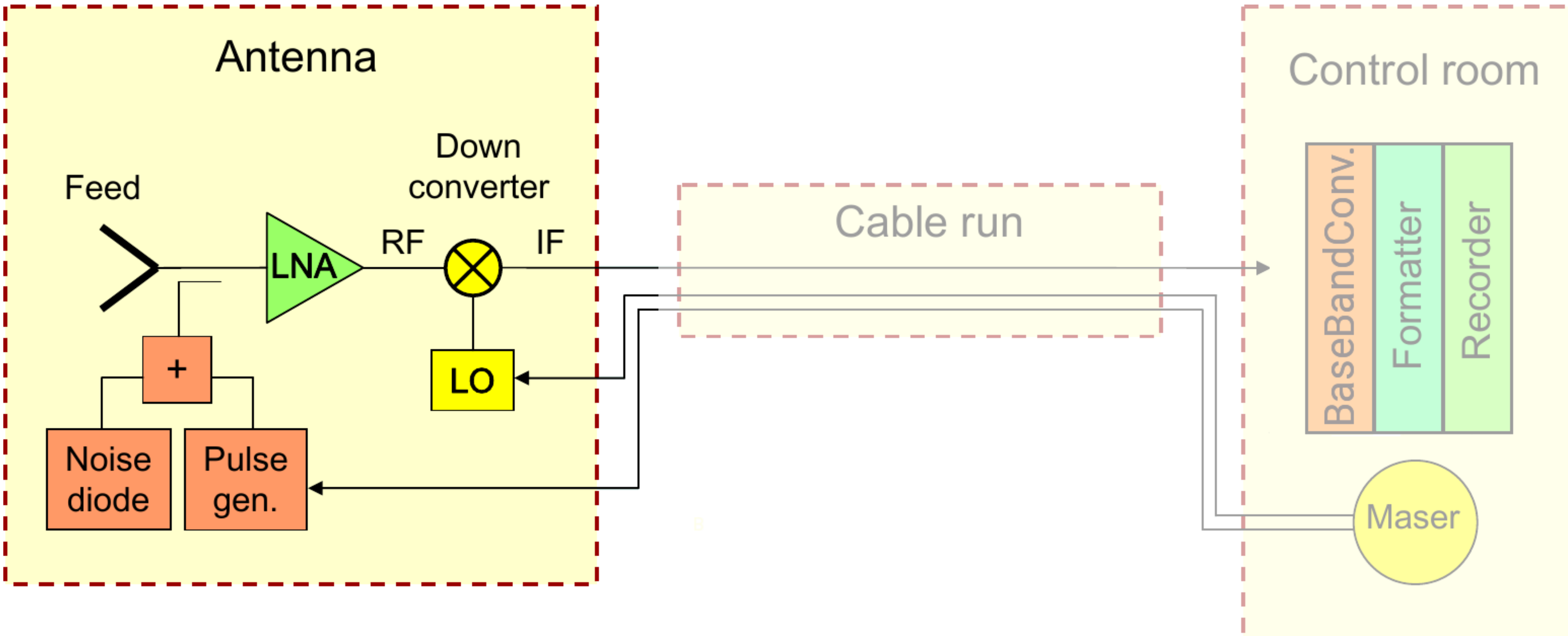
[B. Petrachenko, 2013]

Noise Cal / Phase Cal / Cable Cal

- Noise Cal measures time variations & frequency dependence of system temperature.
- The phase calibration system measures **time variations of instrumental phase vs. frequency.**
- This is particularly important for cable delays that can vary with antenna pointing direction and hence correlate with station position.
- A train of narrow pulses (~50 ps) is injected ahead of, in, or just after the feed - typically at the same location as the noise cal signal. Typical pulse rate is 1 MHz.
- Since the PCAL signal follows exactly the same path (from the point of injection onward) as the astronomical signal, any changes experienced by the calibration signal are also experienced by the astronomical signal. → calble cal = measured variation at comtrol room.
- Phase Cal also used by the correlator!



Instrumentation (traditional/analog)



Front End

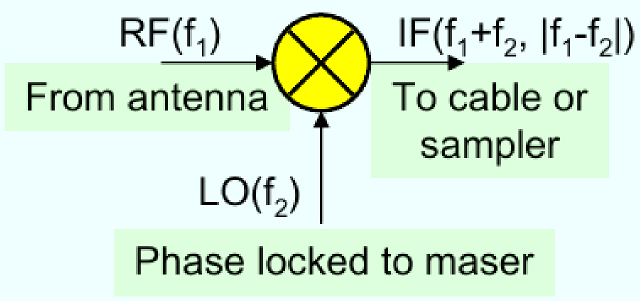
[B. Petrachenko, 2013]

Down Converter: Mixer

- High frequency electronics are noisy and expensive. High frequency signals are rapidly absorbed, and they are difficult to propagate over long distances. Cheaper and better electronics can be built for low frequencies.

- A down converter translates a signal downward in frequency to allow for signal transmission on cables or for digitization.

- An important element of a down converter is a mixer. Conceptually, a mixer can be considered a multiplier producing outputs at the sum and difference frequencies of the two inputs:

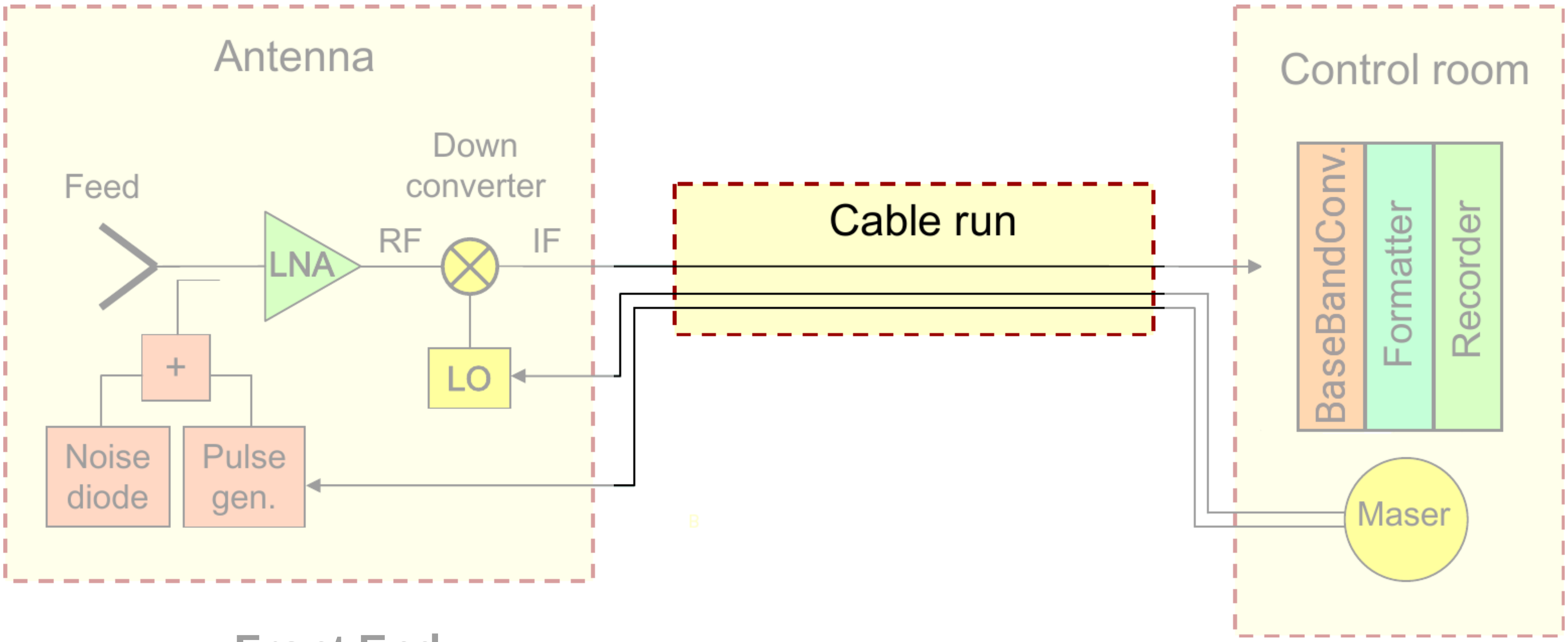


$$\cos(f_1 t) \times \cos(f_2 t) = \frac{\cos(f_1 + f_2)t + \cos(f_1 - f_2)t}{2}$$

- If the frequency **sum** is isolated using a filter this is referred to as an **up converter**.

- If the **difference** is isolated using a filter this is referred to as a **down converter**.

Instrumentation (traditional/analog)

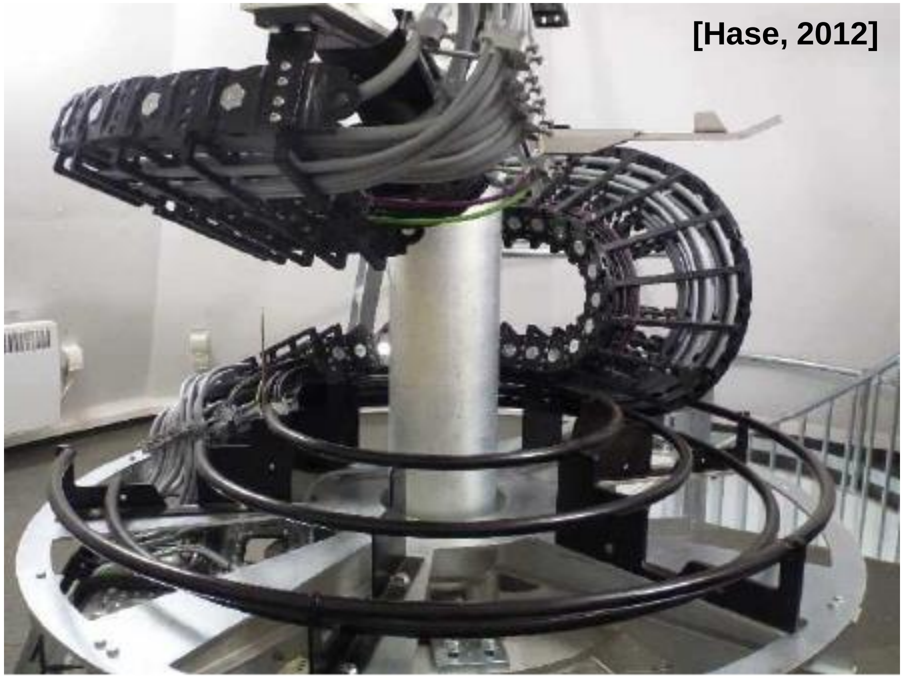


Front End

[B. Petrachenko, 2013]

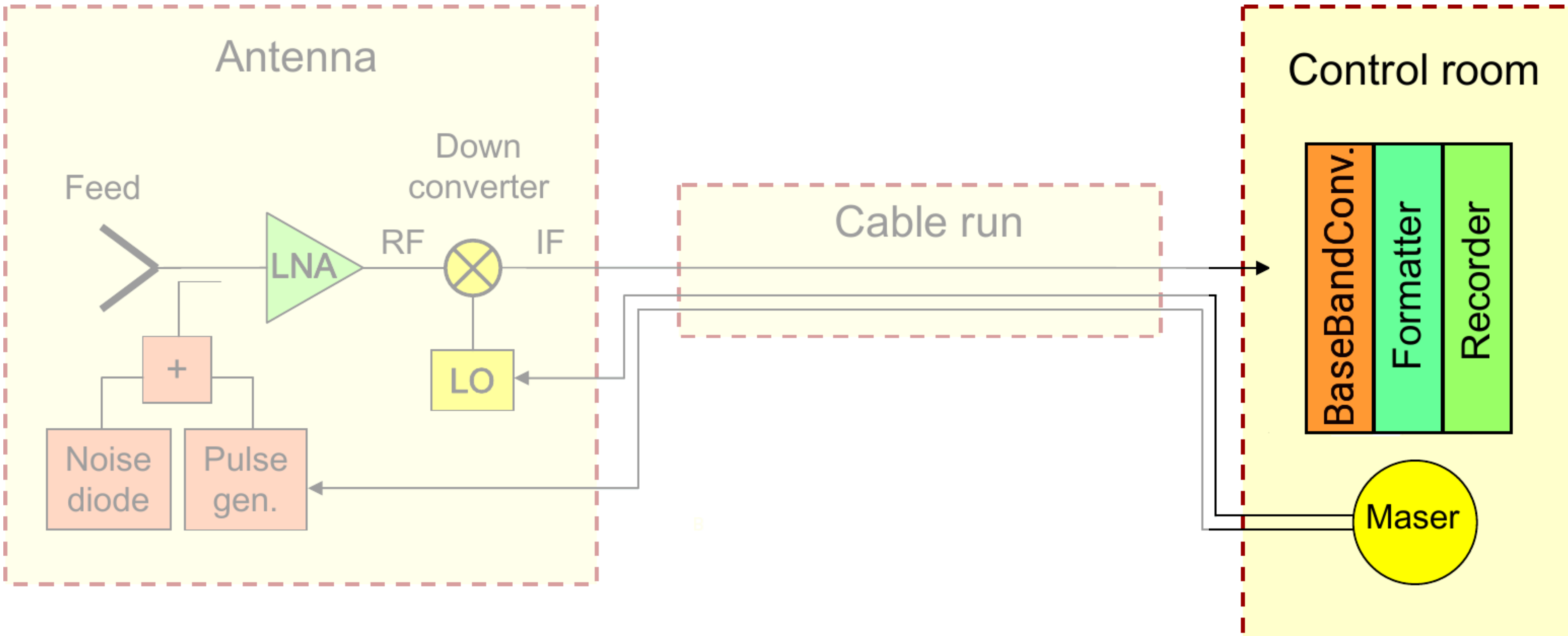
Cable Wrap

- The antenna has to be able to move to point at objects in the sky → bending cables
- Bending cables changes the properties of how they transmit electrical signals — phase/delay changes are the most significant
- This goes for fiber optics too.



guided cable wrap
2011 TTW

Instrumentation (traditional/analog)



Back End

[B. Petrachenko, 2013]

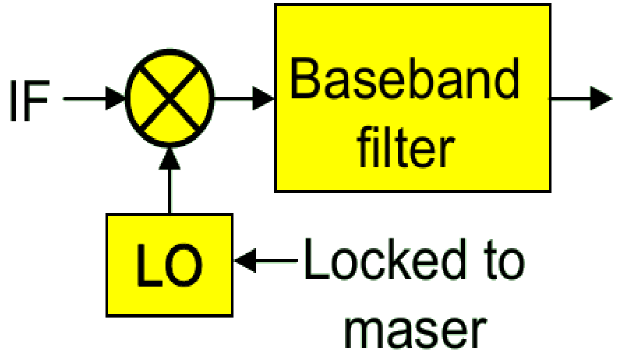
Purpose of Backend

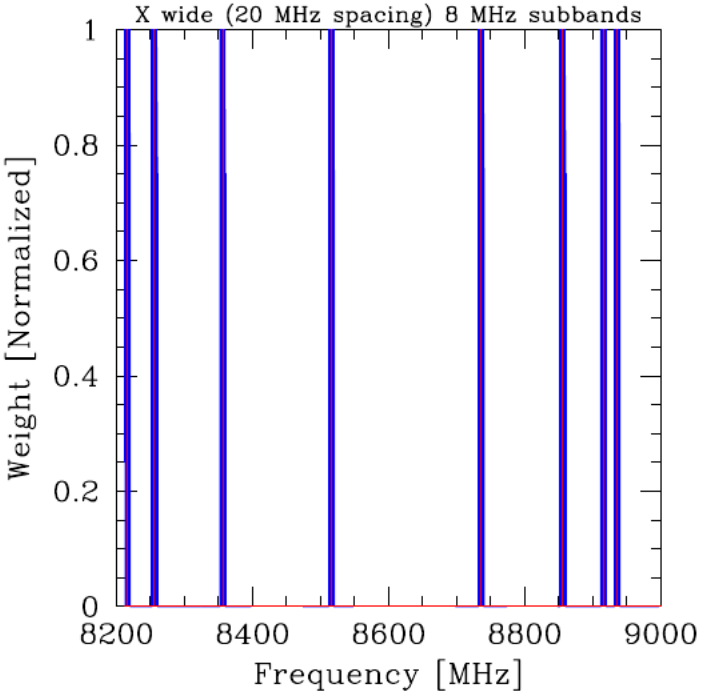
- The backend …
  - breaks up the signal received by the telescope into manageable bandwidth chunks,
  - digitizes (samples) the data,
  - collects data and puts the data into a recognized data format,
  - writes the data to some storage medium,
  - or sends the data along some network connection to a correlator.

→ The backend converts the analog signal from the receiver into a digital signal the can be processed by digital electronics, and stores the data for later processing by the correlator

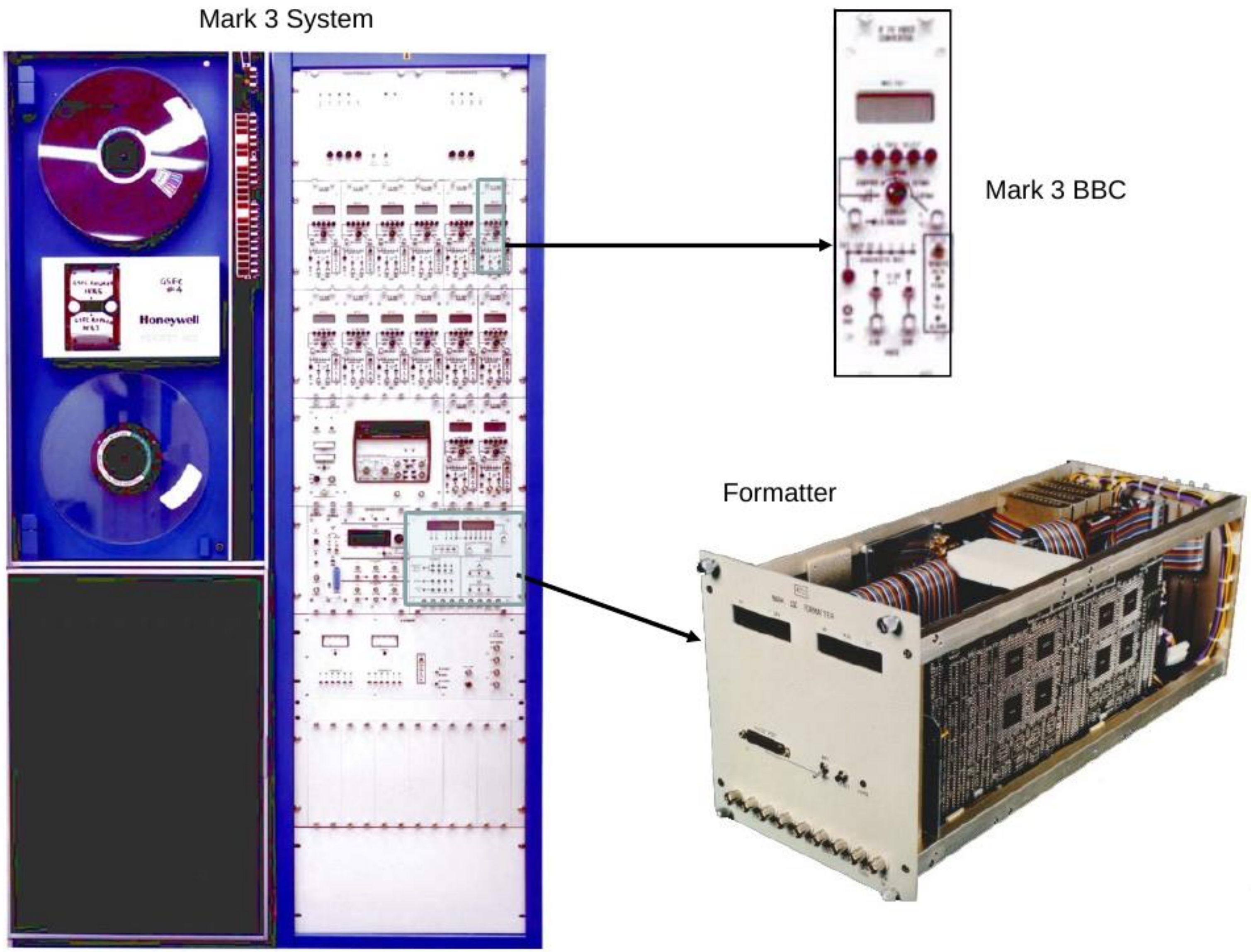
Baseband Converter

- The IF signal from the receiver comes in, typically with signal at several hundreds of megahertz.
- The signal is mixed with another LO signal, so that the IF signal at the LO frequency is now at 0 MHz.
- This new signal gets filtered so that only a small bandwidth remains.
- Choose upper- or the lower-sideband.
- → digitise, format & record





Analog Back End



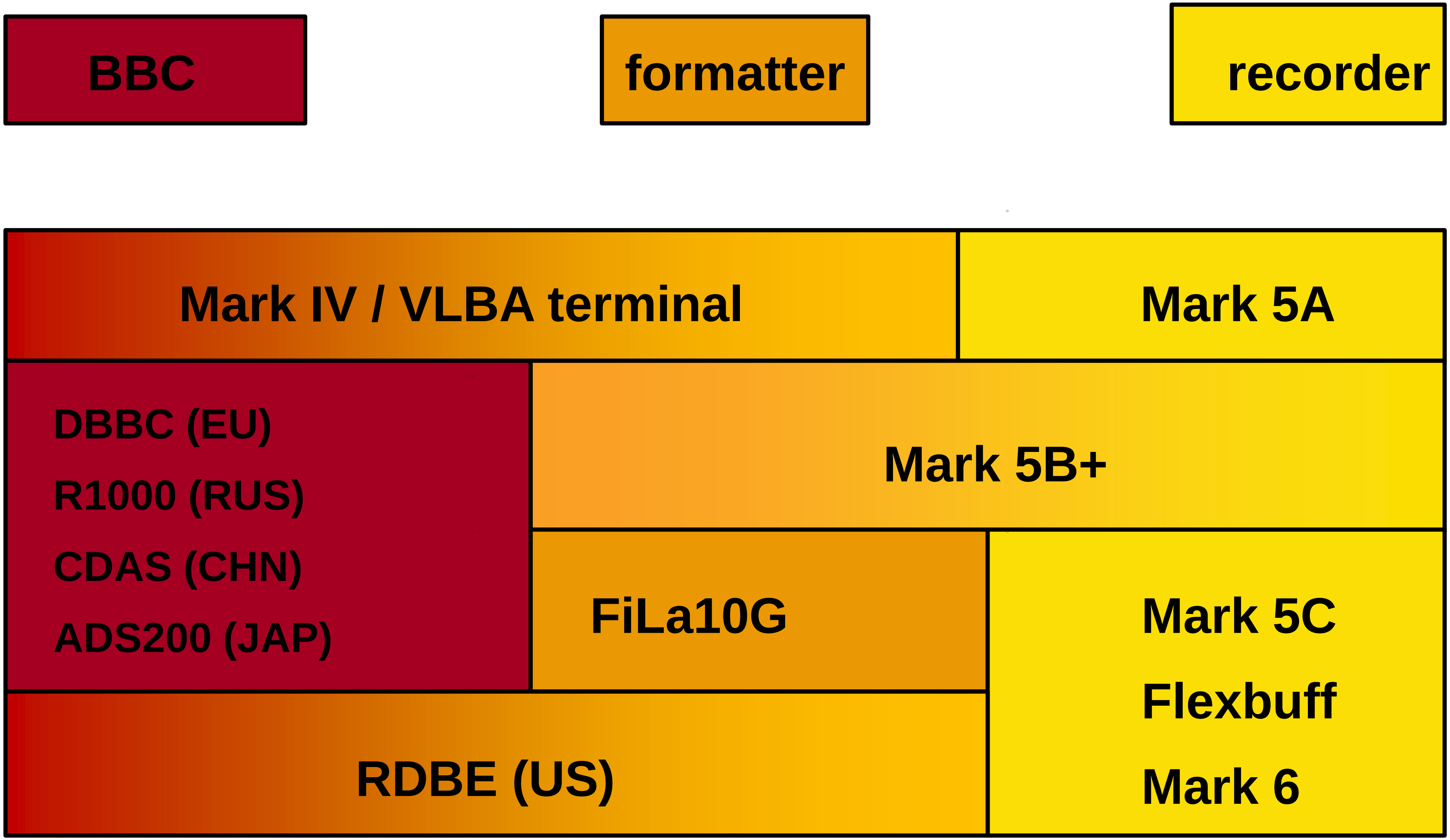
Digital Backend, ex. Effelsberg

FiLa10G Formatter

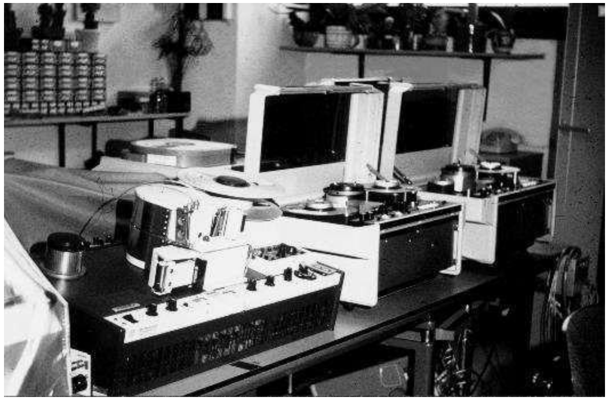
Mark 6 Recording Unit

DBBC

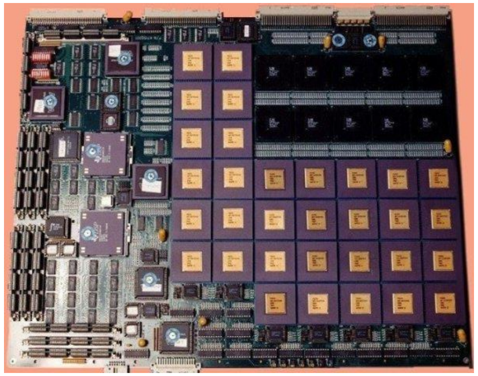
Modern Back Ends



Correlation



1978 - 1992
MK II correlation with various playback drives over the years
2" Ampex, 1" IVC, RCA VCR



Since 1999
MK IV correlator & board

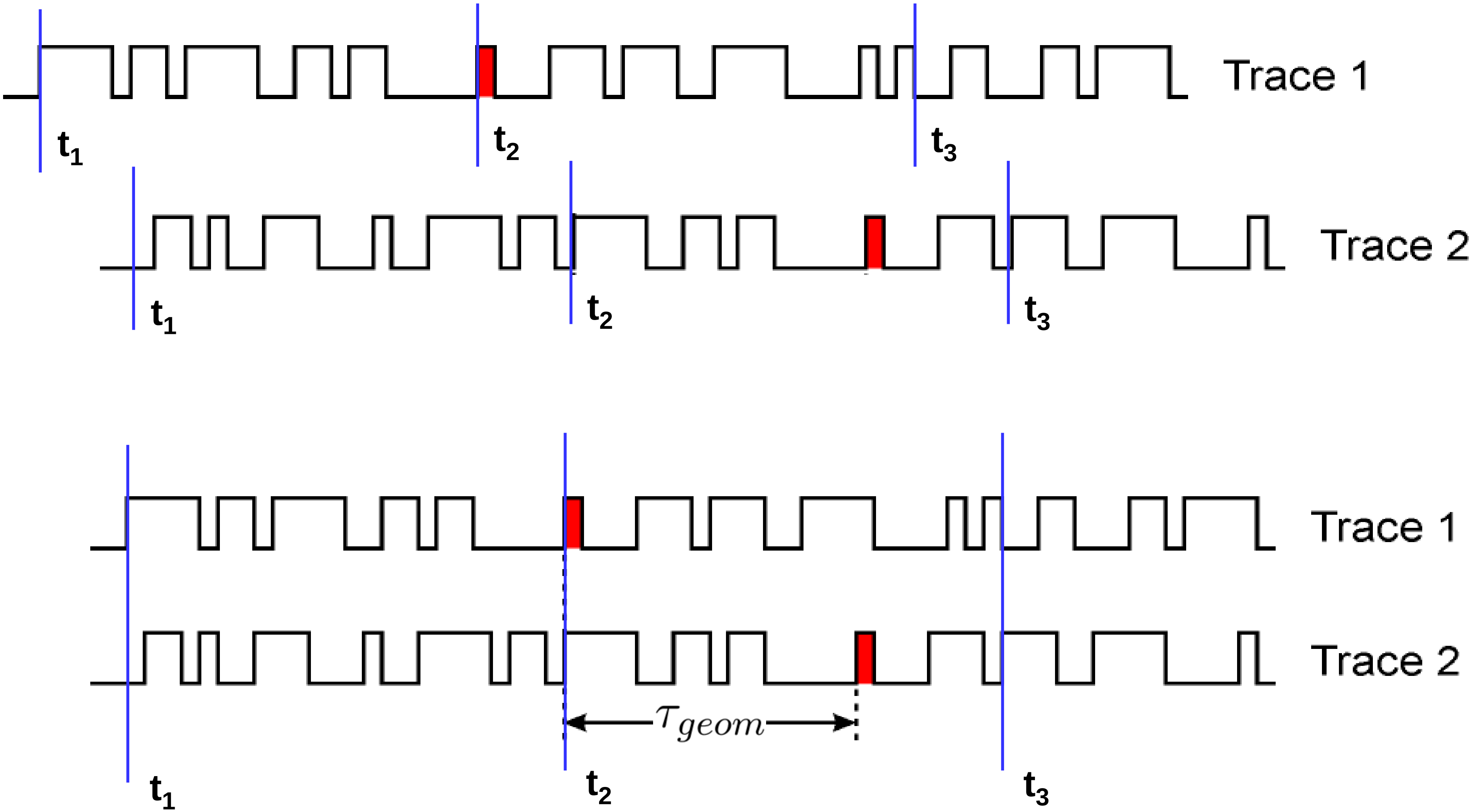
Software Correlator
First Fringes: April 2010
VLBI HPC cluster

[MPI Bonn]

Correlation

- **Synchronize data.**
- Apply geometrical delay model.
- Correct for known Doppler shifts
- Correlation
- Calibration
- RFI mitigation.
- Fringe finder in selectable search time window.
- Accumulate (integration time from msec to sec) and write data to archive in FITS format.
- Post-processing

Synchronisation



Correlation

- Synchronize data.
- **Apply geometrical delay model.**
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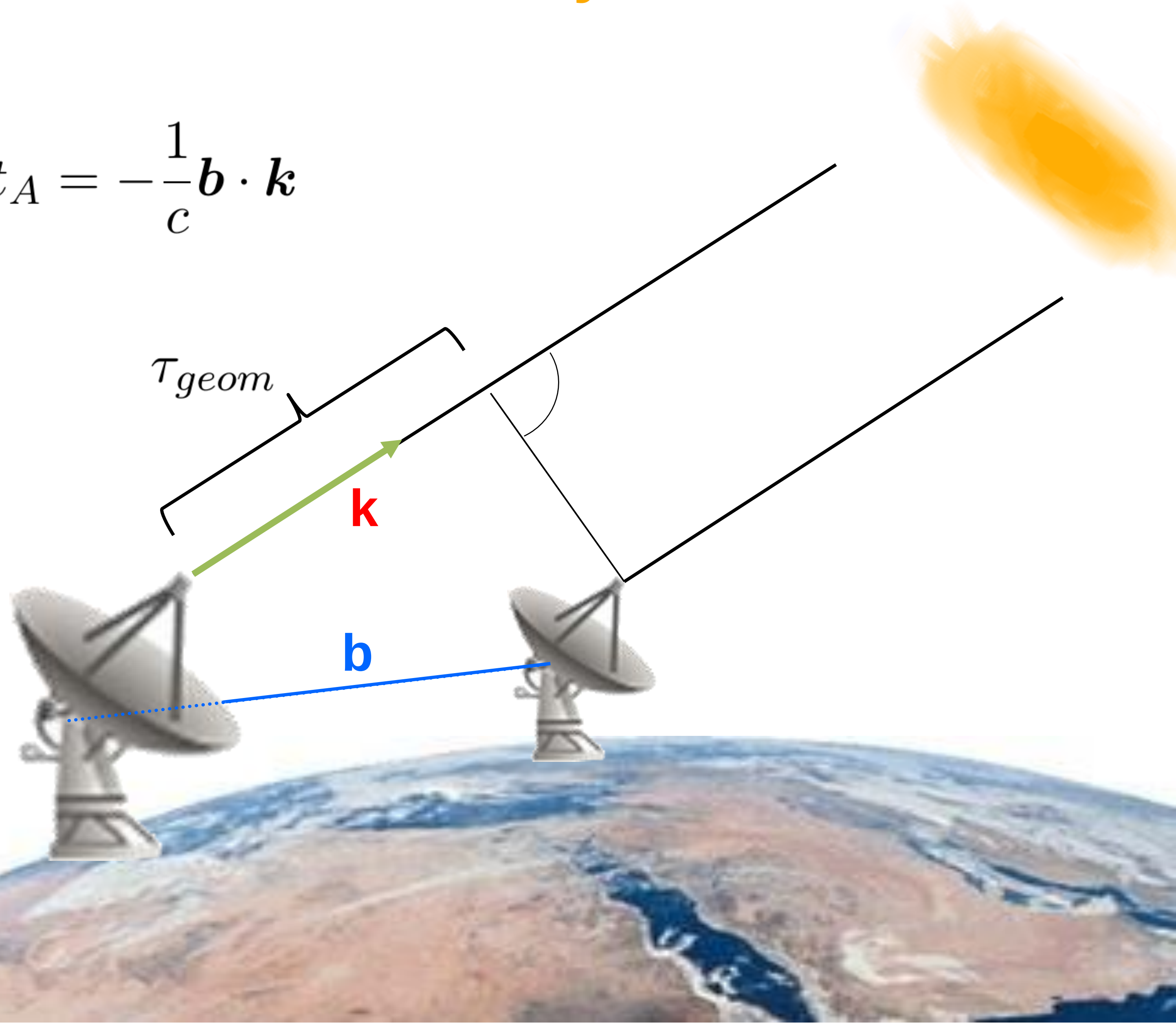
- Correlation
- Calibration
- RFI mitigation.
- Fringe finder in selectable search time window.
- Accumulate (integration time from msec to sec) and write data to archive in FITS format.
- Post-processing

Geometrical delay

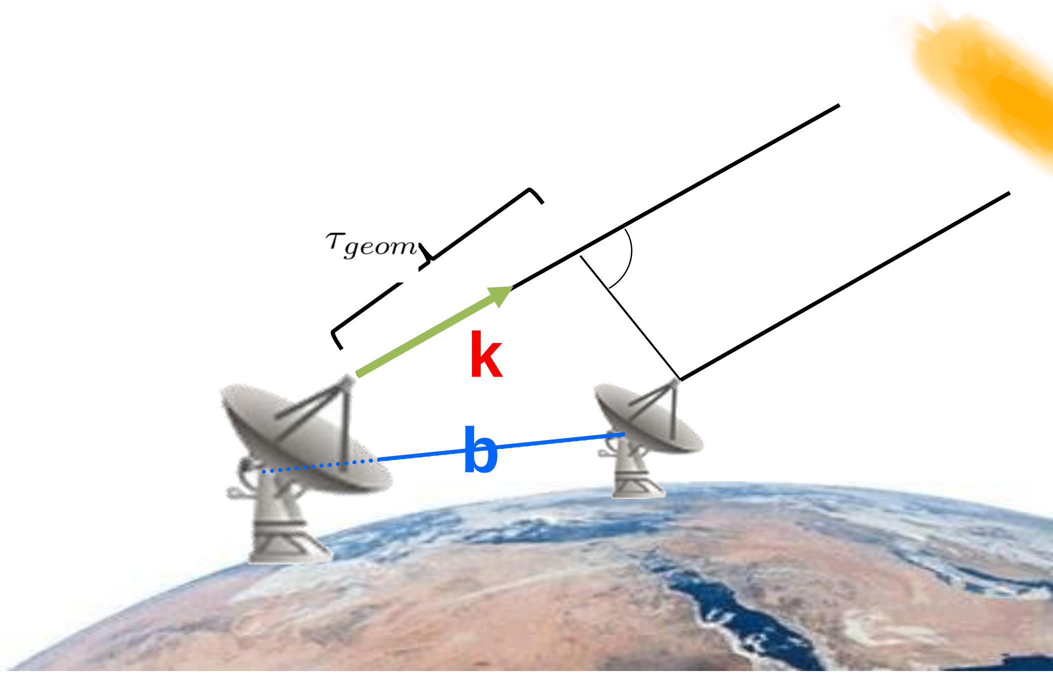
$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\boldsymbol{b} \cdot \boldsymbol{k}$$



Geometrical delay

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\boldsymbol{b} \cdot \boldsymbol{k}$$

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\,\boldsymbol{b} \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$

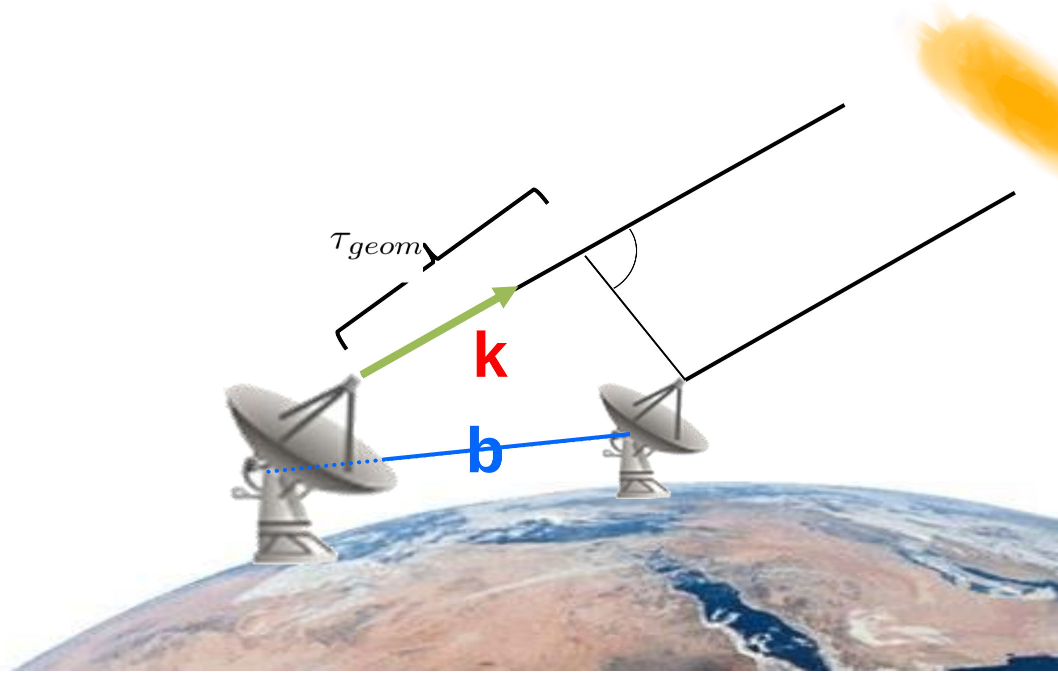


Geometrical delay

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\boldsymbol{b} \cdot \boldsymbol{k}$$

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\,\boldsymbol{b} \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\,(\boldsymbol{b} + \Delta\boldsymbol{b}) \cdot \boldsymbol{W} \cdot \boldsymbol{R} \cdot \boldsymbol{Q} \cdot \boldsymbol{k}$$



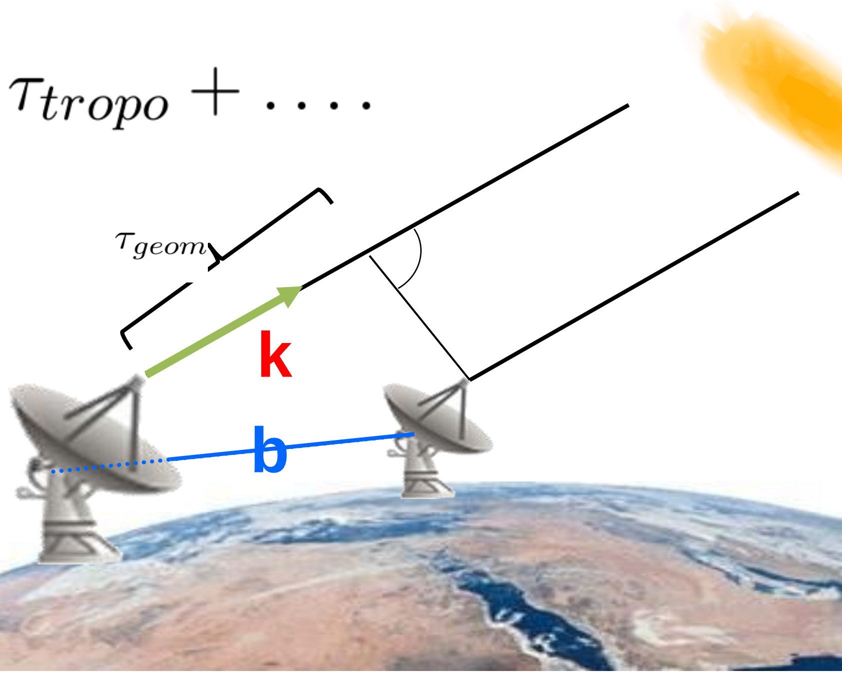
Geometrical delay

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\boldsymbol{b}\cdot\boldsymbol{k}$$

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\,\boldsymbol{b}\cdot\boldsymbol{W}\cdot\boldsymbol{R}\cdot\boldsymbol{Q}\cdot\boldsymbol{k}$$

$$\tau_{geom} = t_B - t_A = -\frac{1}{c}\,(\boldsymbol{b}+\Delta\boldsymbol{b})\cdot\boldsymbol{W}\cdot\boldsymbol{R}\cdot\boldsymbol{Q}\cdot\boldsymbol{k}$$

$$+\,\tau_{instr} + \tau_{clock} + \tau_{iono} + \tau_{tropo} + \ldots.$$

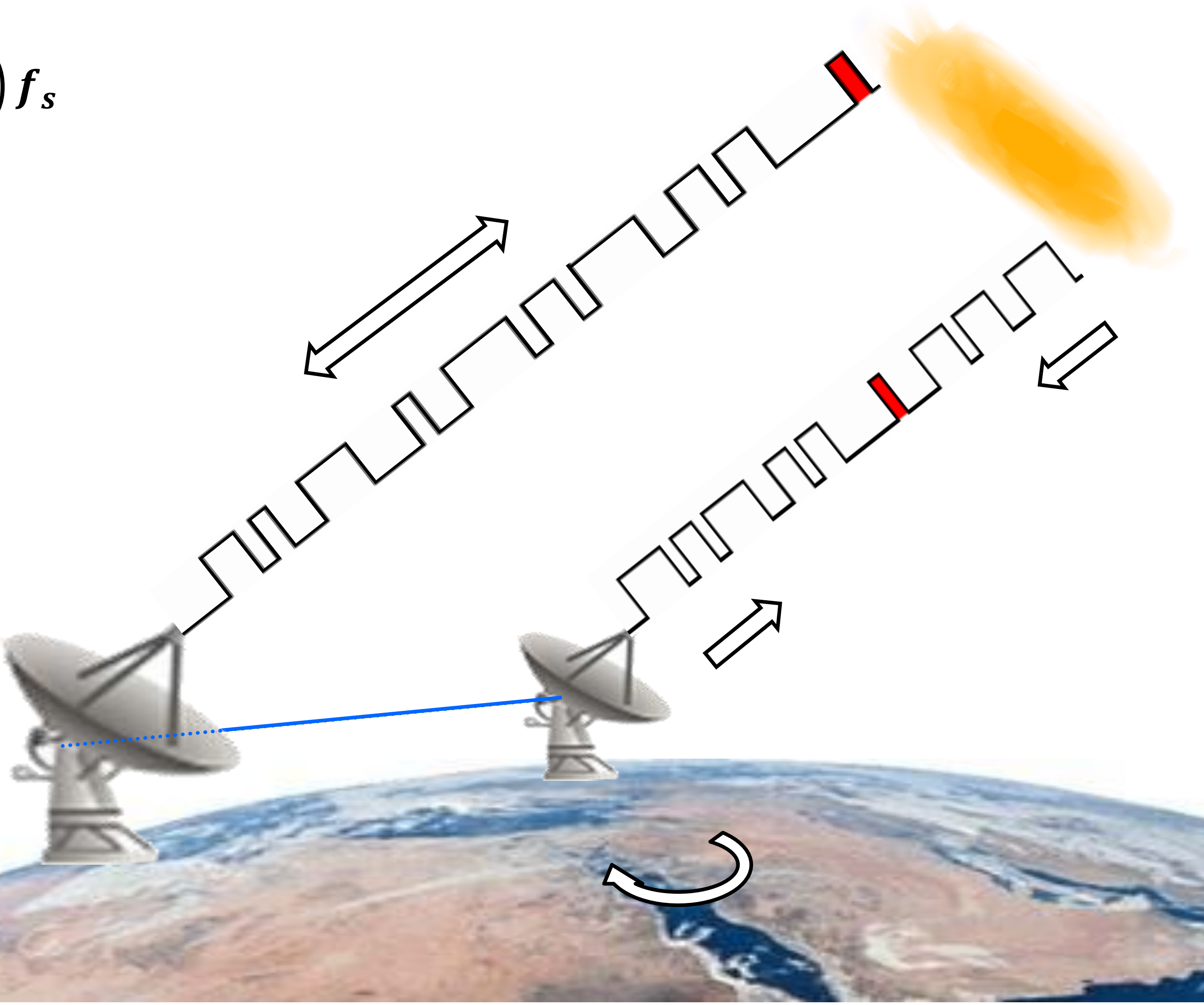


Correlation

- Synchronize data.
- Apply geometrical delay model.
- **Correct for known Doppler shifts**
- Correlation
- Calibration
- RFI mitigation.
- Fringe finder in selectable search time window.
- Accumulate (integration time from msec to sec) and write data to archive in FITS format.
- Post-processing

Doppler shift

$$f_o = \left(1 + \frac{v_o - v_s}{c}\right) f_s$$



Correlation

- **What was is all about…?**

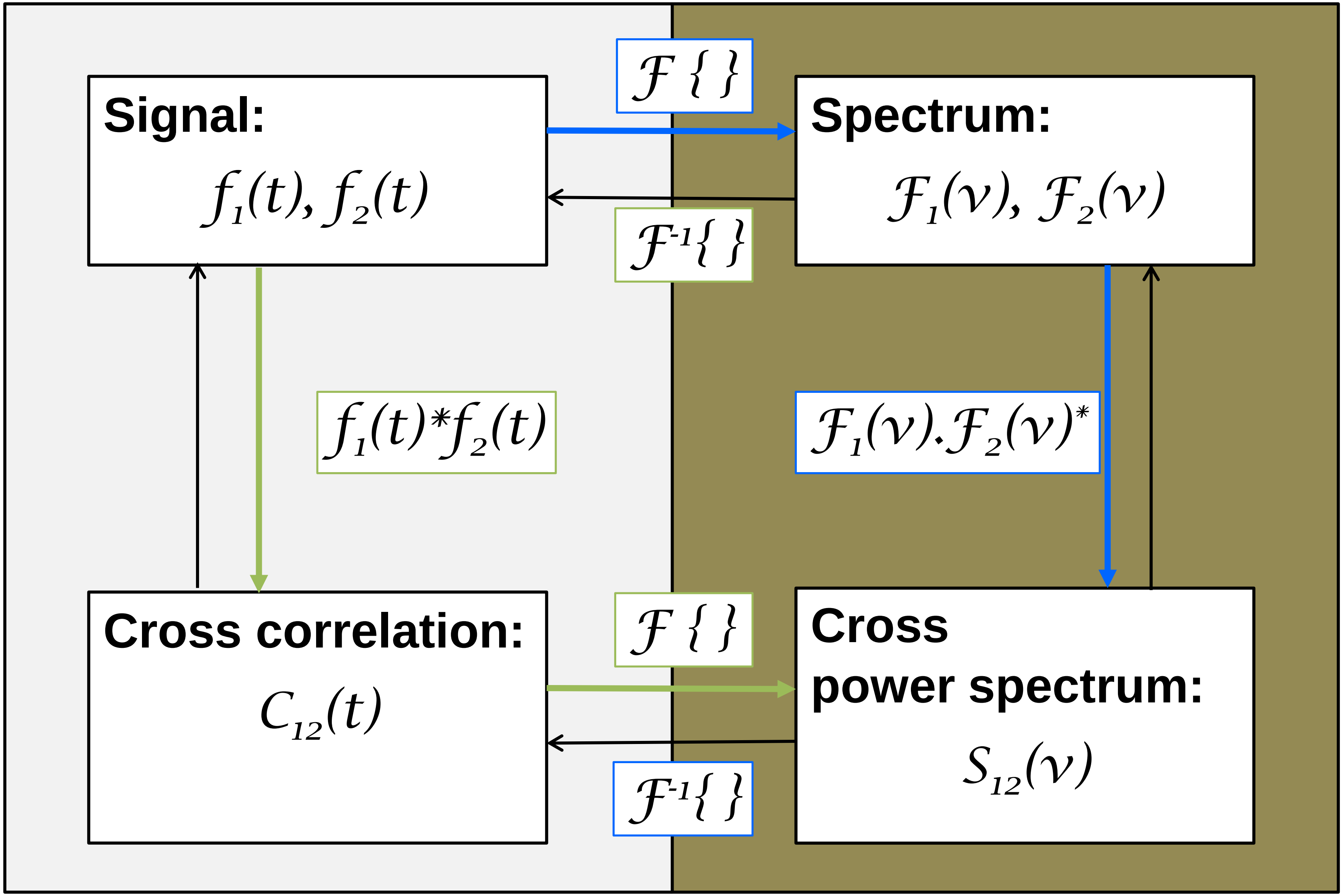
$$V(u,v) = \int\int I(l,m)e^{-2\pi i(ul+vm)}dl\,dm$$

$\Downarrow$ **FT^{-1}** $\qquad$ $\Uparrow$ **FT**

$$I(l,m) = \int\int V(u,v)e^{2\pi i(ul+vm)}du\,dv$$

$$V_{ij} = <E_i E_j^*>$$

Correlation



Correlation

- Synchronize data
- Apply geometrical delay model
- Correct for known Doppler
- **Correlation**
  - FX type: VLBA, DiFX, EVN SFXC s/w
  - XF : JIVE, Haystack, VLA, SoftC, JPL s/w
- Calibration
- RFI mitigation
- Fringe finder in selectable search time window
- Accumulate (integration time from msec to sec) and write data to archive in FITS format
- PPost-processing

Correlation

- Synchronize data
- Apply geometrical delay model
- Correct for known Doppler
- Correlation
- **Calibration**
- RFI mitigation
- Fringe finder in selectable search time window
- Accumulate (integration time from msec to sec) and write data to archive in FITS format
- Post-processing

Correlation

- Compensates physical error sources, e.g.
  - Atmosphere at high frequencies
  - Ionosphere at low frequencies
  - Different antenna sizes and efficiencies
  - Electroncis (bandpass, delays and phase differences)

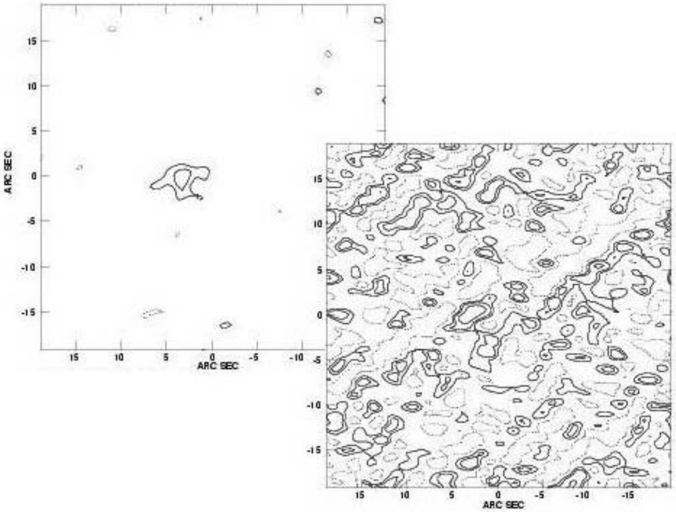
- **Flux Density Scale Calibration**
  - Scaling wrt. known source + flux density
- **Bandpass and Delay Calibration**
  - Correct for impurities in the models, i.e. incorrect station coordinates

Correlation

- Synchronize data
- Apply geometrical delay model
- Correct for known Doppler
- Correlation
- Calibration
- **RFI mitigation**
- Fringe finder in selectable search time window
- Accumulate (integration time from msec to sec) and write data to archive in FITS format
- Post-processing

Correlation

- Radio Frequency Interference mitigation
  - Avoidance
  - **Observation stag**e: install a bandpass or high/low pass filter in a receiver
  - **Correlation:** anti-coincidence protocols to identify the RFI components, together with digital mitigation processing (filtering)
  - **Post-Correlation:** flagging and excising

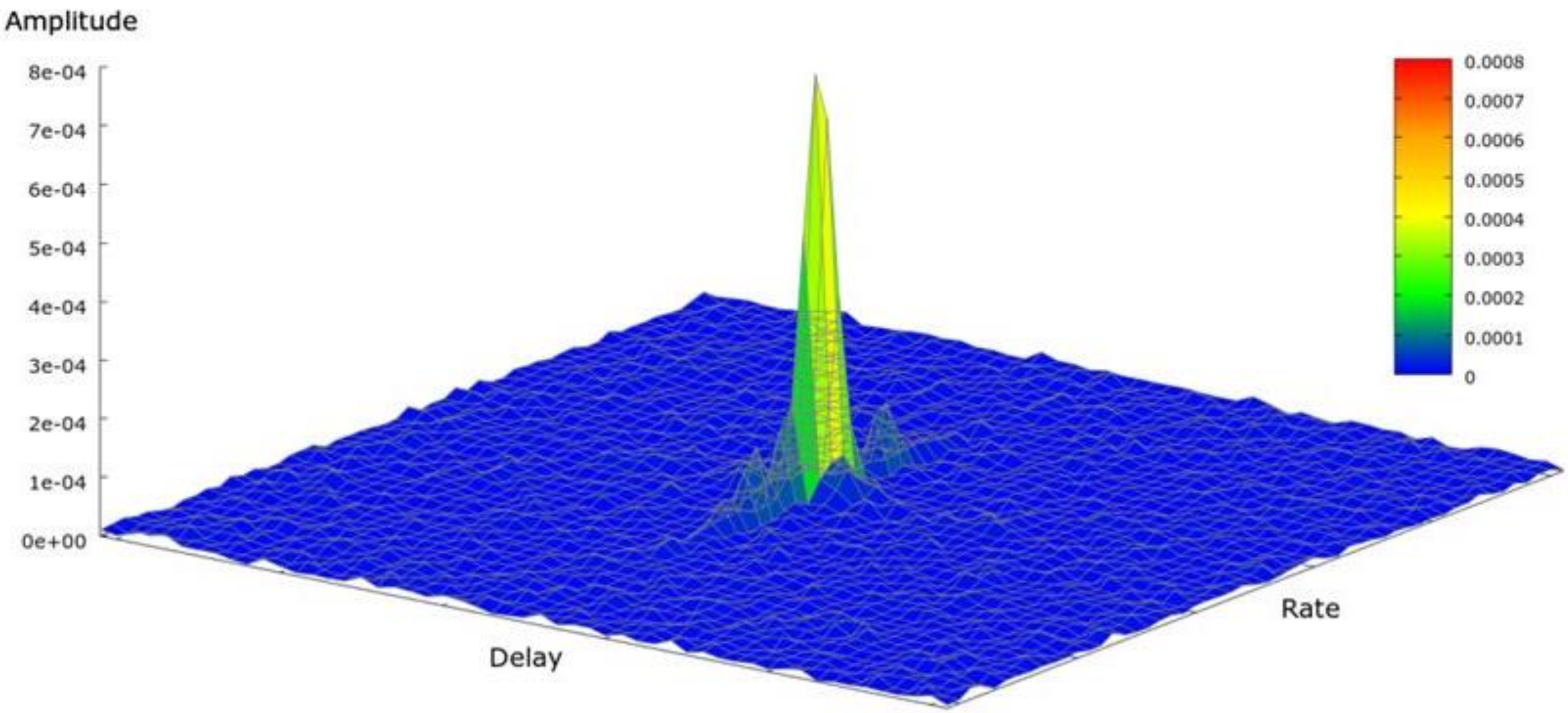


VLA, satellite passing within 25° (NRAO)

Correlation

- Synchronize data
- Apply geometrical delay model
- Correct for known Doppler
- Correlation
- Calibration
- RFI mitigation
- **Fringe-fitting / searching**
- Accumulate (integration time from msec to sec) and write data to archive in FITS format
- Post-processing

Correlation



Correlation

- Synchronize data
- Apply geometrical delay model
- Correct for known Doppler
- Correlation
- Calibration
- RFI mitigation
- Fringe-fitting / searching
- **Accumulate (integration time from msec to sec) and write data to archive in FITS format**
- Post-processing

Correlation

- Synchronize data
- Apply geometrical delay model
- Correct for known Doppler
- Correlation
- Calibration
- RFI mitigation
- Fringe-fitting / searching
- Accumulate (integration time from msec to sec) and write data to archive in FITS format
- **Post-processing: make some nice pics ^^**

Thanks for your attention!