# Very Long Baseline Interferometry (VLBI)

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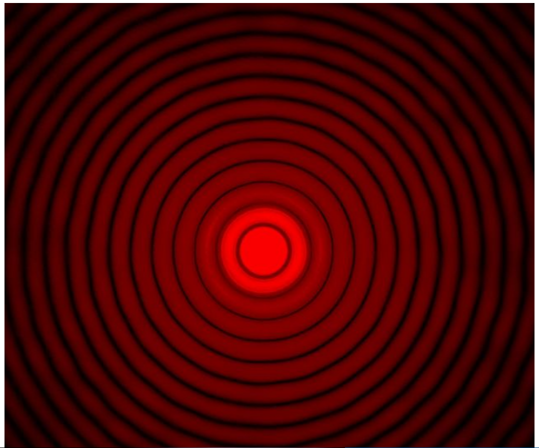
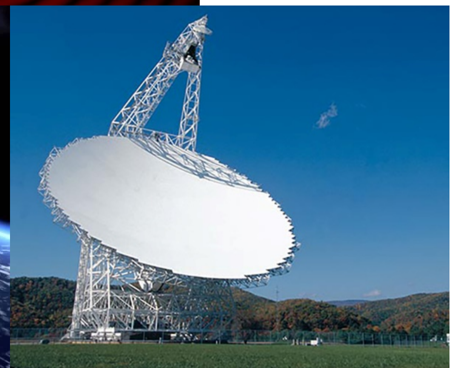
# Content

- Introduction to interferometry and VLBI
- VLBA (Very Long Baseline Array)

# Why VLBI

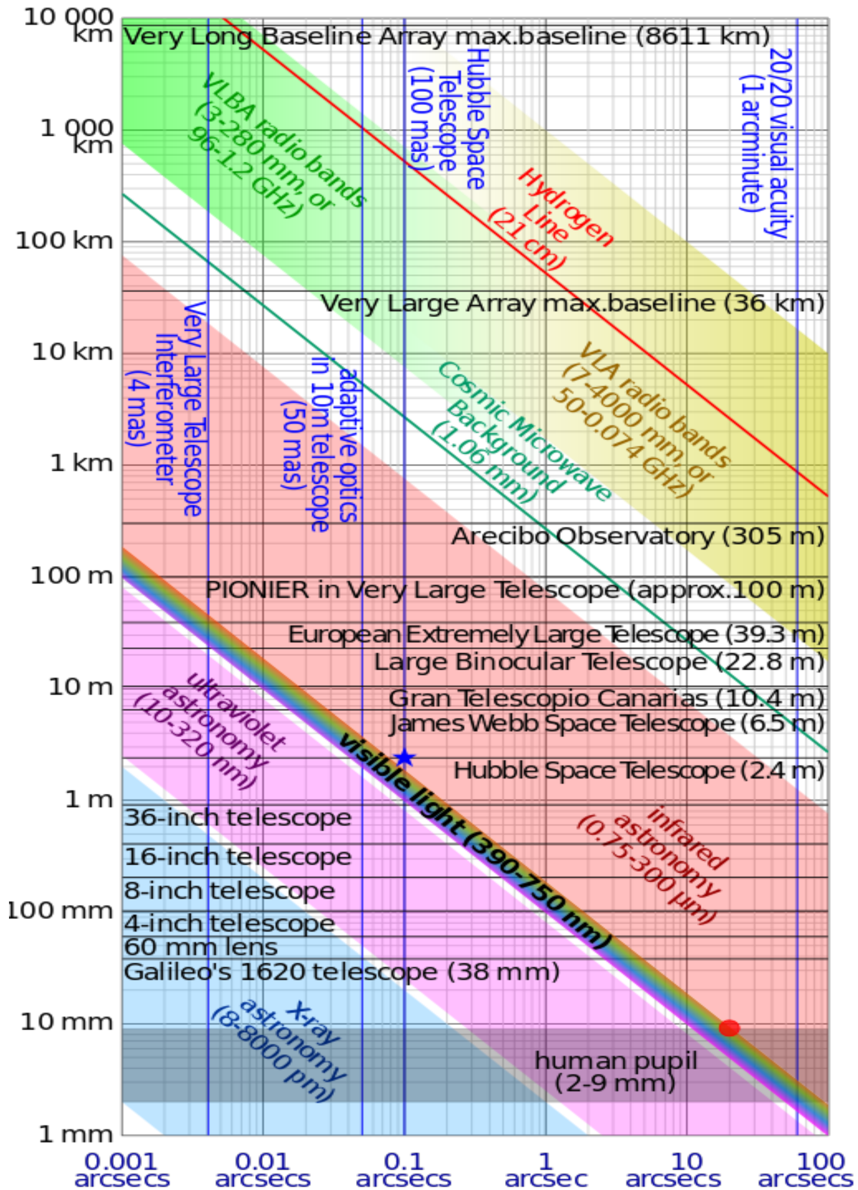
- In optics, airy disk is a point source best focused by an aperture.
- $\theta \approx 1.22\frac{\lambda}{D}$ . $D$ is the baseline range.
- Some typical D
  - Eye D = 10 mm @ $\lambda$=420 nm
    - $\theta$=1.5 arcmin
  - Single Telescope
    - Hubble 2.4 m. max 0.1 as(arcsec)
    - GBT(Green Bank Telescope) 110 m
    - FAST(500 m)





# Why VLBI

- How to increase D?
  - Telescope arrays
    - VLA(Very Large array)
    - VLBA
  - Baseline coverage
    - China. USA. Russia?
    - The Earth?
    - The Moon?




(wiki)

# How VLBI work

- Receive signals V1 and V2 cause by geometry delay $\tau_g = \frac{\vec{b} \cdot \hat{s}}{c}$

$$V_1 = V \cos\left[\omega\left(t - \tau_g\right)\right]$$

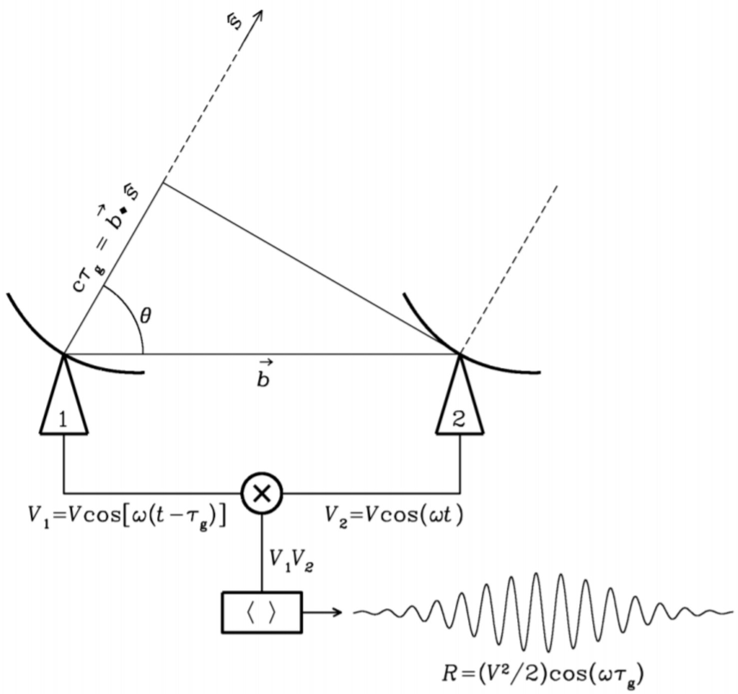
$$V_2 = V \cos\left[\omega t\right]$$

- Cross Correlator

$$V_1 V_2 = \frac{V^2}{2}\left[\cos\left(2\omega t - \omega\tau_g\right) + \cos(\omega\tau_g)\right]$$

- Take time average long enough

$$R = \langle V_1 V_2 \rangle = \frac{V^2}{2}\cos(\omega\tau_g)$$



# How VLBI work

- even

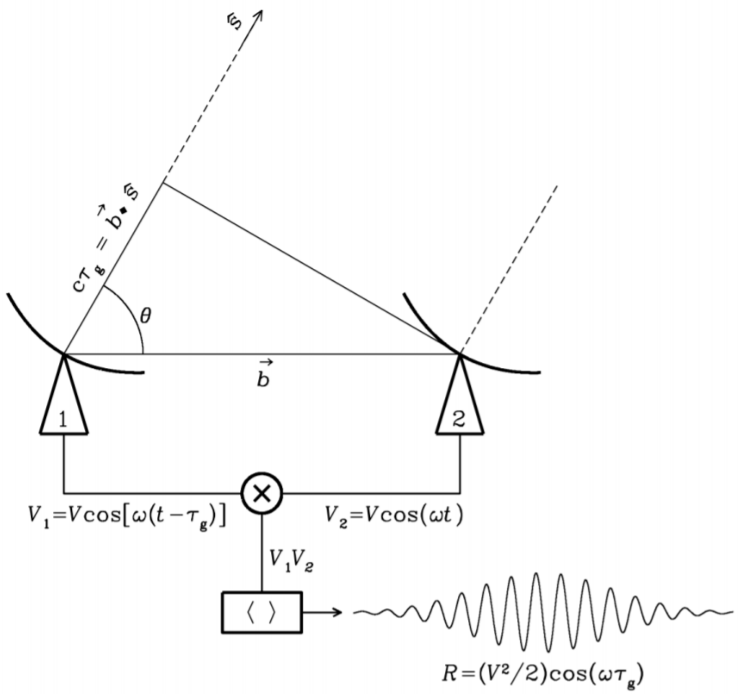
$$\int R_c = \int I_\nu(\hat{s})\cos\left(2\pi\nu\frac{\vec{b}\cdot\hat{s}}{\mathrm{c}}\right)d\Omega$$

- odd

$$\int R_s = \int I_\nu(\hat{s})\sin\left(2\pi\nu\frac{\vec{b}\cdot\hat{s}}{\mathrm{c}}\right)d\Omega$$

$$\Rightarrow R = \int I_\nu(\hat{s})\exp\left(-i\ 2\pi\nu\frac{\vec{b}\cdot\hat{s}}{\mathrm{c}}\right)d\Omega$$

- Amplitude : $(R_s^2+R_C^2)$^1/2
- Phase: $\tan^{-1}(\frac{R_S}{R_C})$



# How VLBI work

We have done with $R(t)$ to $R(\nu)$

$$R = \int I_\nu(\hat{s}) \exp\left(-i\, 2\pi\nu \frac{\vec{b}\cdot\hat{s}}{c}\right) d\Omega$$

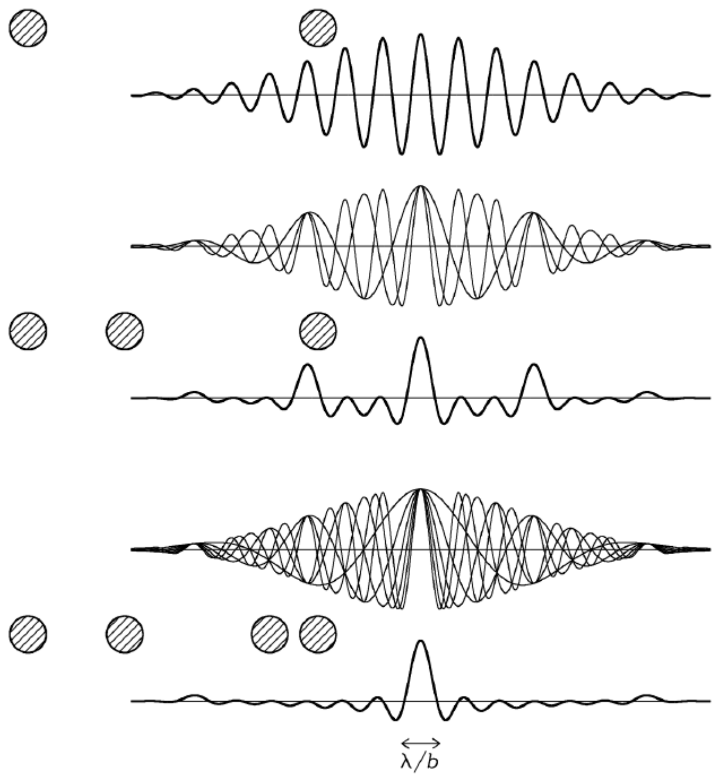
For different frequency $\nu_1$ and $\nu_2$, Fourier components are not same.

In small finite frequency range $\Delta\nu$ center at $\nu_C$

$$R = \int \left[(\Delta\nu)^{-1} \int_{\nu_c-\frac{\Delta\nu}{2}}^{\nu_c+\frac{\Delta\nu}{2}} I_\nu(\hat{s}) \exp\left(-i\, 2\pi\nu \frac{\vec{b}\cdot\hat{s}}{c}\right) d\nu\right] d\Omega$$

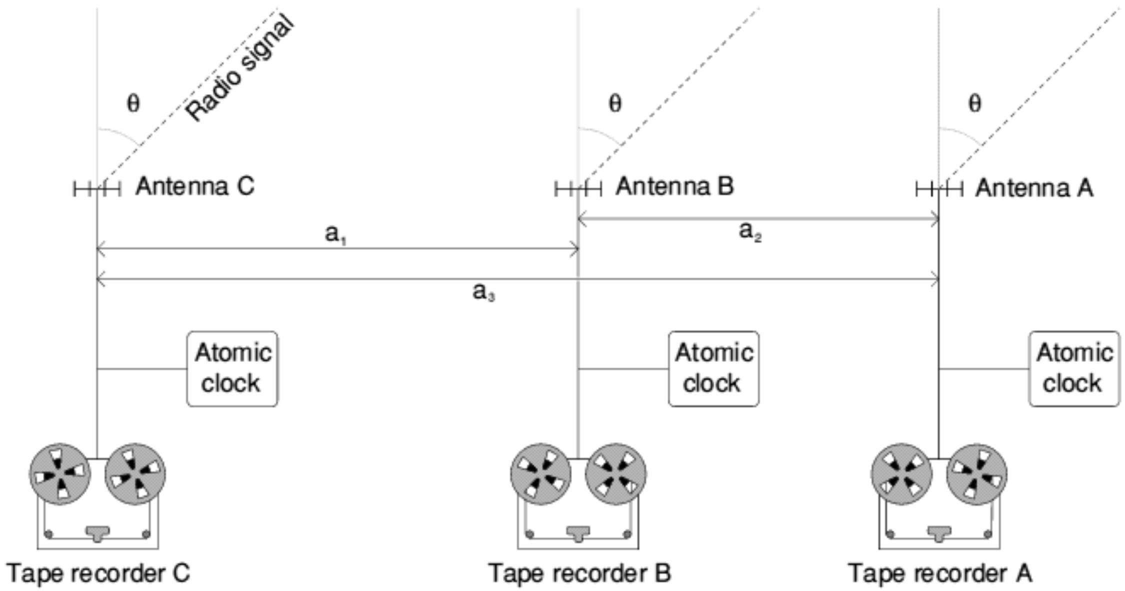
$$\Rightarrow R = \int I_\nu(\hat{s}) \mathrm{sinc}(\Delta\nu\tau_g) \exp\left(-i\, 2\pi\nu \frac{\vec{b}\cdot\hat{s}}{c}\right) d\Omega$$

For a finite bandwidth and delay, the fringe amplitude is attenuated by the factor $\mathrm{sinc}(\Delta\nu\tau_g)$



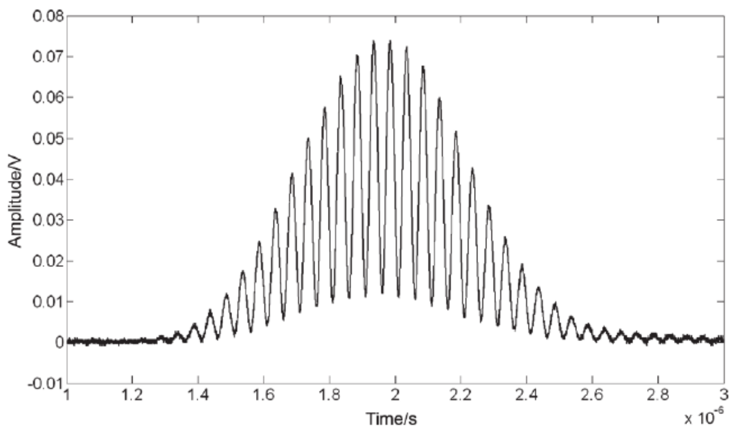
# A simplified VLBI

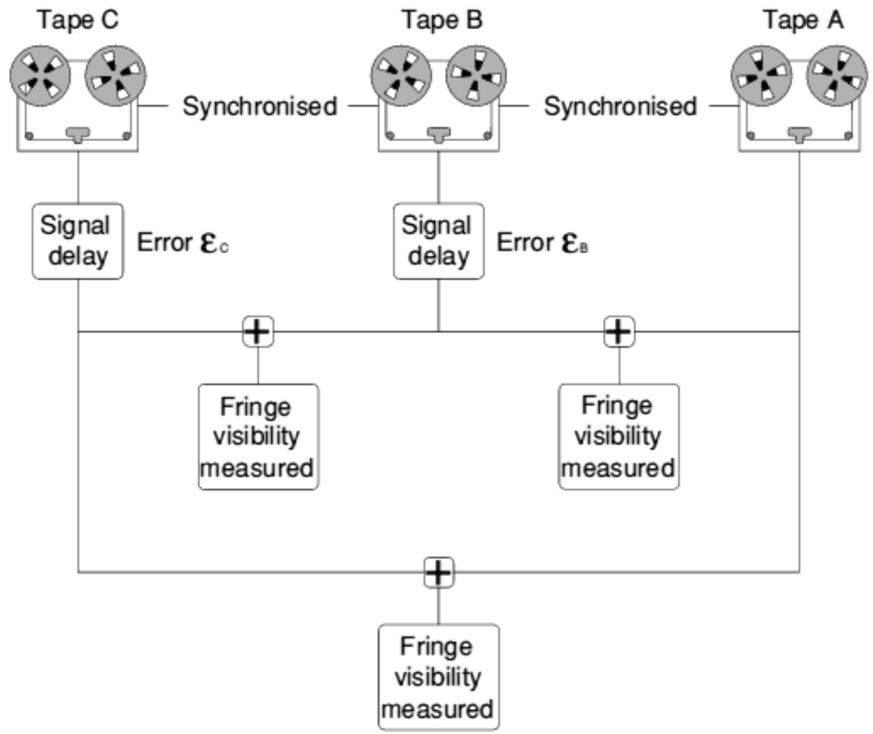
- Receiver
  - antennas
- Sampling
  - atomic clock on GPS
- Transport
  - Fiber-optic paths
- Correlator



# A simplified VLBI (cont)

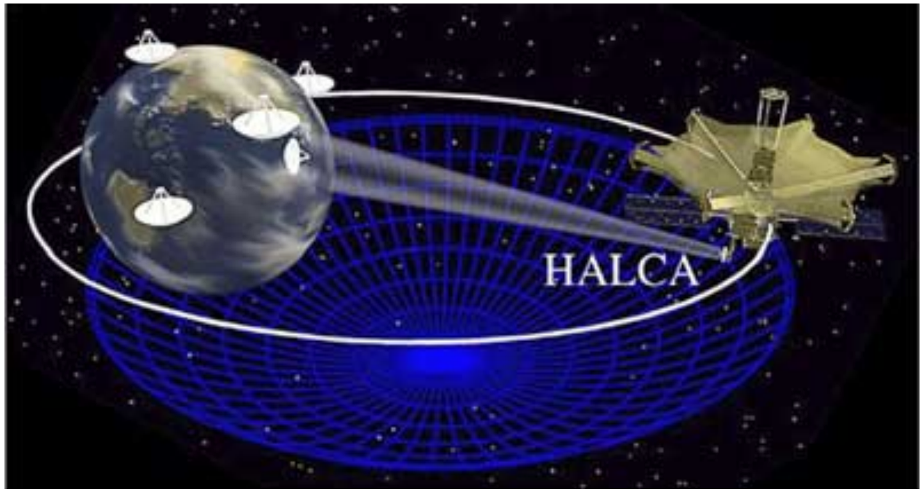
- Interferometry
- Different distance to sources
  - Approximate: geometry
  - Precise: interference fringes



# VLBI arrays

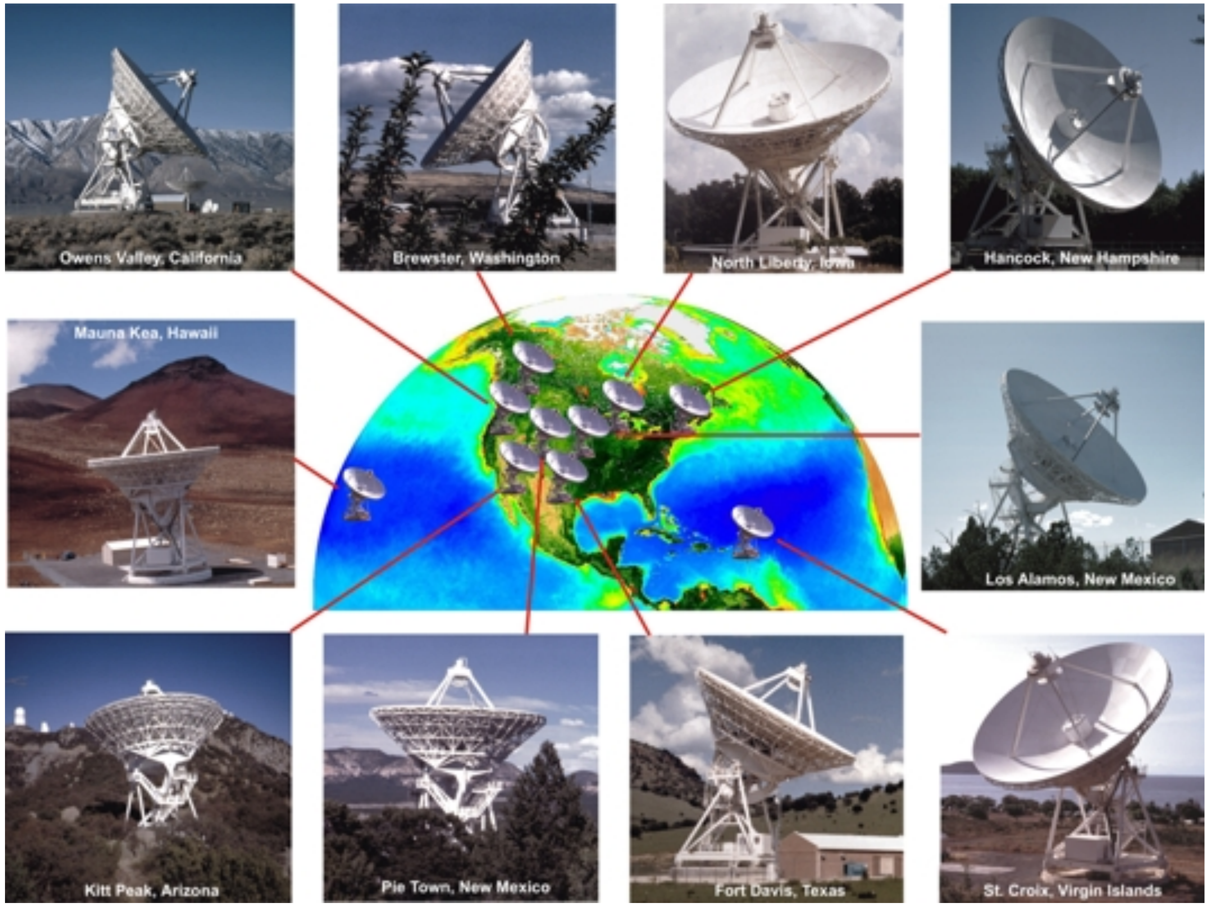
- EVN (European VLBI Network)
- VLBA
- …
- e-VLBI
- Space-VLBI



# VLBA

- 10×25m telescopes
- Longest baseline: 8611 km
- Wavelength: 3 mm- 90 cm
- Resolution:
  0.17mas@7mm-22mas@90cm

- Built in 1986.2 – 1993.5
- Cost: $ 85 million

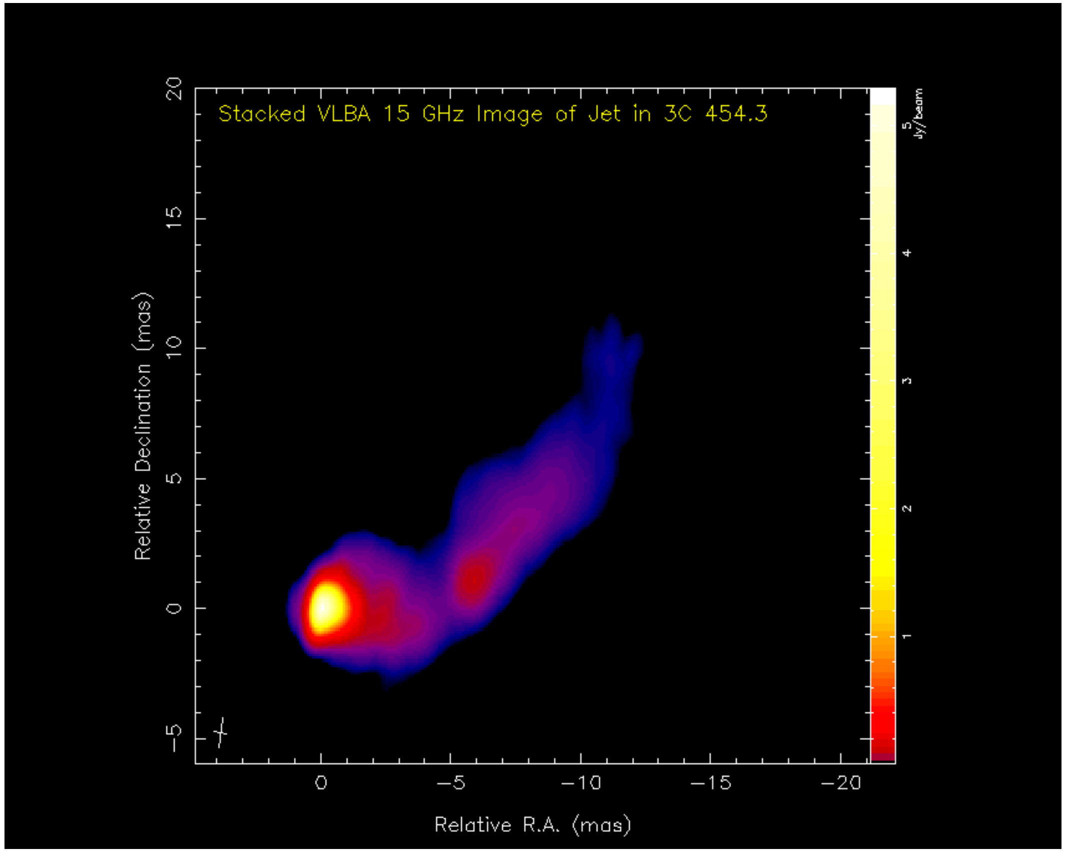


# Some Purposes and Highlights

- Celestial reference frame (CRF)
  - MOJAVE PROGRAM (**M**onitoring **O**f **J**ets in **A**ctive galactic nuclei with **V**LBA **E**xperiments)
  - **Reveal first-ever black-hole visual binary**
  - **Found Nearly Naked supermassive BH**
  - **…**
- Terrestrial reference frame (TRF),
- Earth orientation parameters (EOP)

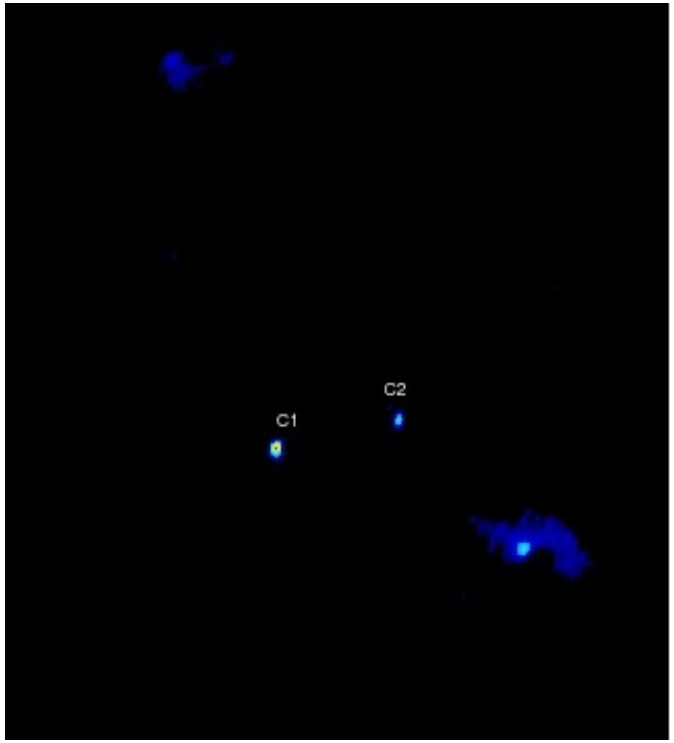
# MOJAVE PROGRAM

- VLBA 2 cm Survey 15 GHz for quasars.
- mainly 1994-2002
- long-term program to monitor radio brightness and polarization variations in jets associated with active galaxies visible in the northern sky
- Resolution: < 1 mas
- Correct Gaia’ s direction shift
    - 6 % did not agree well between VLBI and Gaia



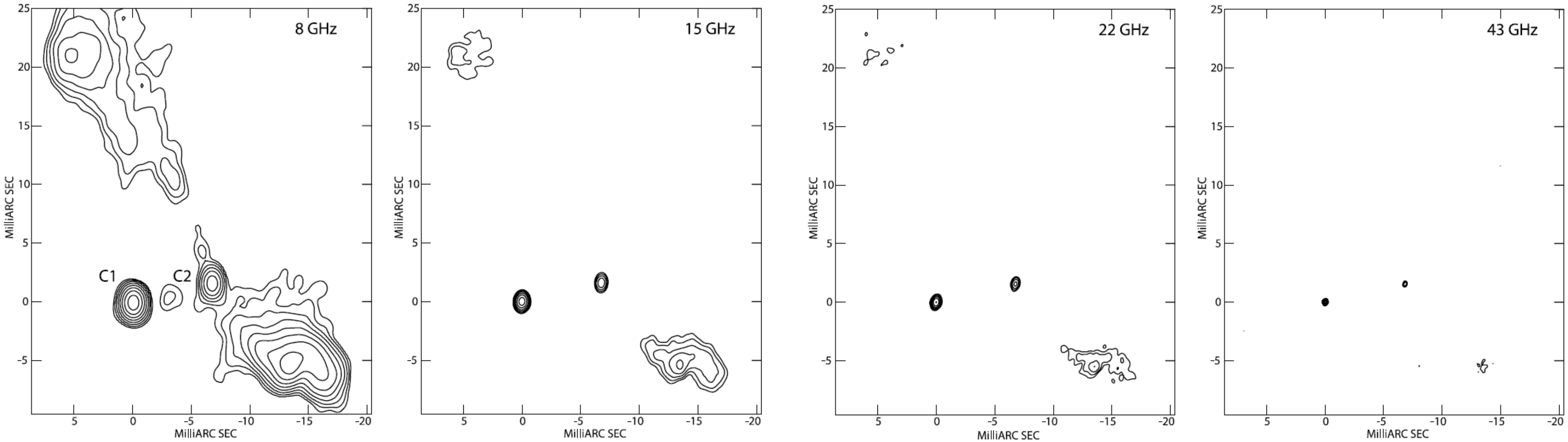
# Reveal first-ever black-hole visual binary

- 2 cores in elliptical galaxy 0402+379 (Rodriguez et al,2006)
  - 750 million ly from earth
  - Combined mass 15 billion solar mass
  - 24 ly between two BH




VLBA image of the central region of the galaxy 0402+379, showing the two cores, labeled C1 and C2, identified as a pair of supermassive black holes in orbit around each other.

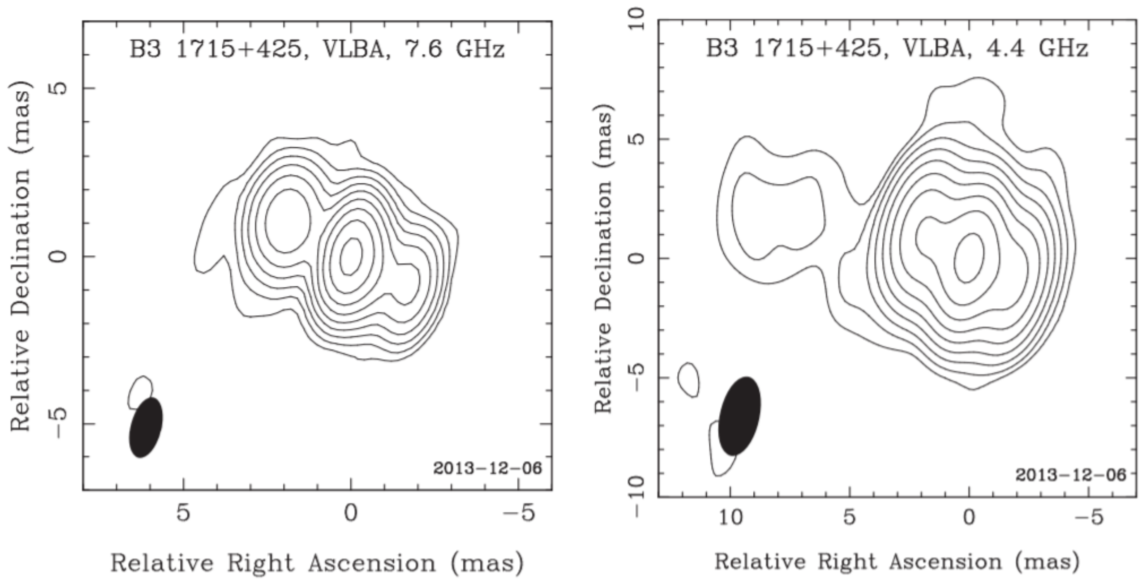
# Reveal first-ever black-hole visual binary




Naturally weighted 2005 VLBA images of 0402+379 at 8, 15, 22 and 43 GHz. Contours are drawn beginning at 3  and increase by factors of 2 thereafter.

# Found Nearly Naked supermassive BH

- Cluster ZwCl 8193. with z = 0.1754
  - 2 billion ly from earth
  - symmetric radio source B3 1715+425
  - Too bright
    - 3×10^10 K @ 7.6 GHz
  - Too luminous
    - 10^25 W/Hz @1.4 GHz
  - V > 2000 km/s
  - M<10^9 solar mass
  - R<3000 ly



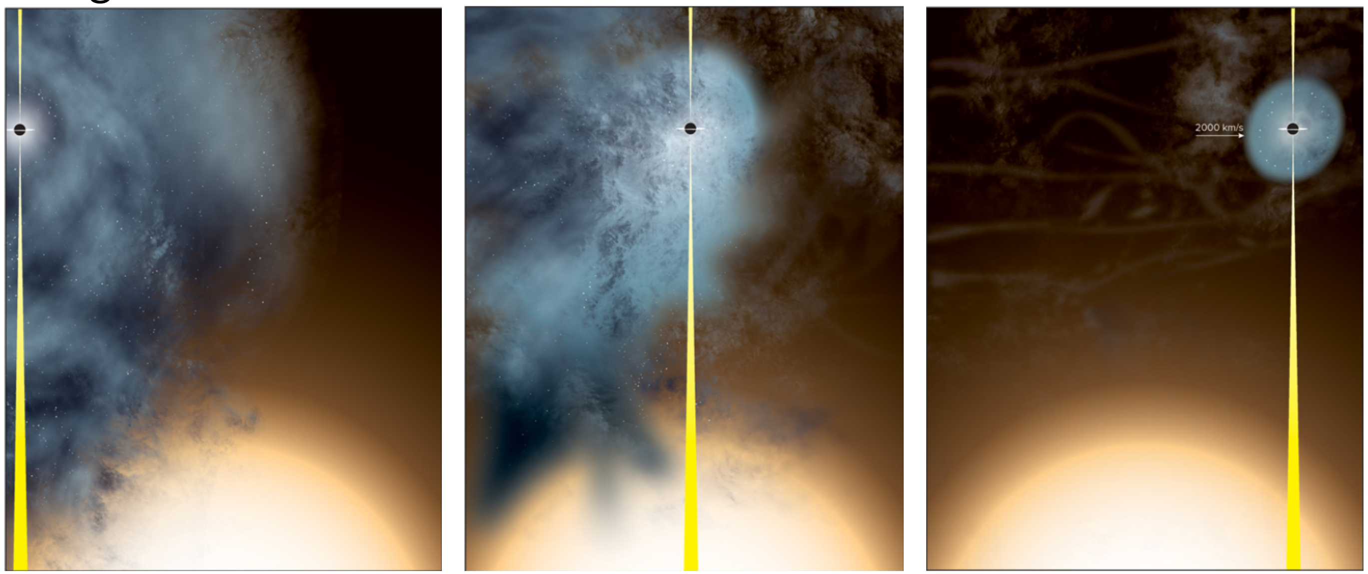

VLBA X-band (7.6 GHz) and C-band ( 4.4GHz) natural-weighting image

Condon et al. 2017

# Found Nearly Naked supermassive BH

- Formation by artist’ s conception
  - 2 galaxies encounter
  - Small one was stripped
  - A black hole and a small galactic remnant remain
- Future

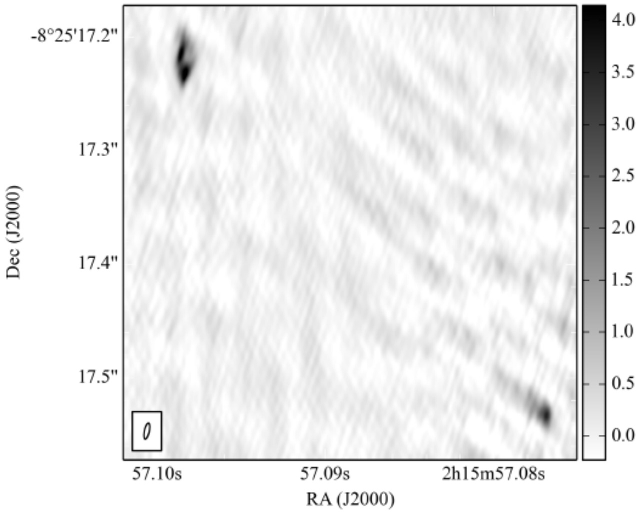
  BH probably will lose more mass and cease forming new stars.




*Credit: Bill Saxton, NRAO/AUI/NSF*

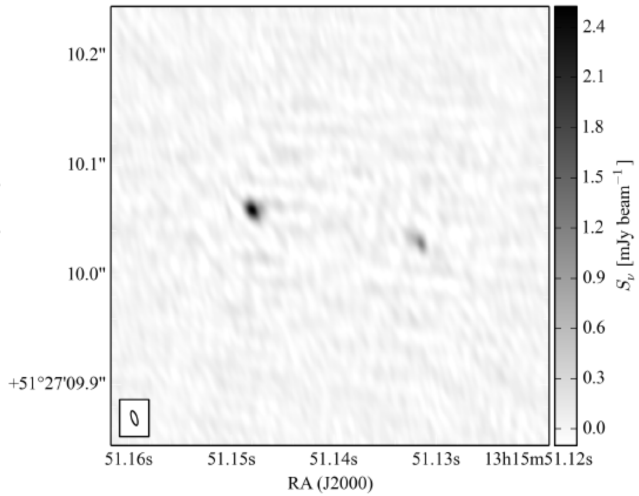
# Test the hypothesis that IFRS contain AGNs in a large sample of sources

- IFRS(infrared-faint radio sources)
- Most IFRSs contain AGN
- 35 core detected in 57 IFRSs
- Confirming compact cores in IFRS based on
  - SED modelling,
  - radio-to-IR flux density ratios
  - emission lines in optical spectra.




VLBA map of IFRS F0030

2 components was found
Top-left: 21.8 mJy
Bottom-right: 6.0 mJy
Separation: 442.1 ± 0.3 mas
1.7-3.8 kpc @ 0.5<z< 12



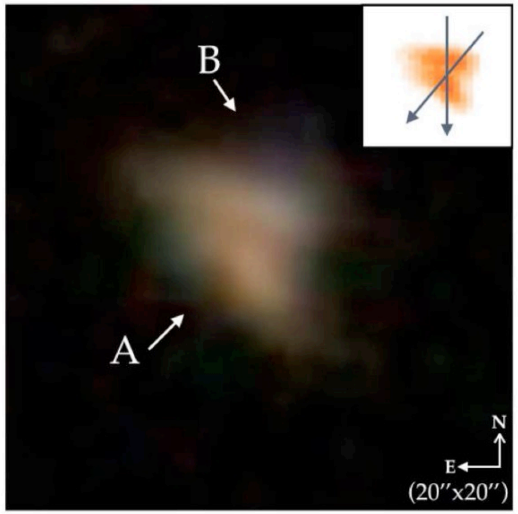

VLBA map of IFRS F0257

2 components was found
left: 5.7 mJy
right: 2.1 mJy
Separation: 155.5 ± 0.2 mas
0.6-1.3 kpc

Herzog et al. 2015

# Infalling H I gas in a merging galaxy pair

- Radio source J0942+0623 (z = 0.123) companion with a normal star-forming galaxy
- Strong H I 21cm line detected
- Observed with VLBA on 2012 June 15, 17 and 22.
  - resolve the radio source into a compact symmetric object with the hotspot separation of 89 pc (40mas).
  - 4.8 kpc (2.2 as) for SDSS.
  - Cold HI gas (T<10^4 K) falling in source
  - young radio source may have been triggered by the gas infalling.




SDSS(Sloan Digital Sky Survey) colour composite image of the merging galaxy pair.

Srianand et al. 2015

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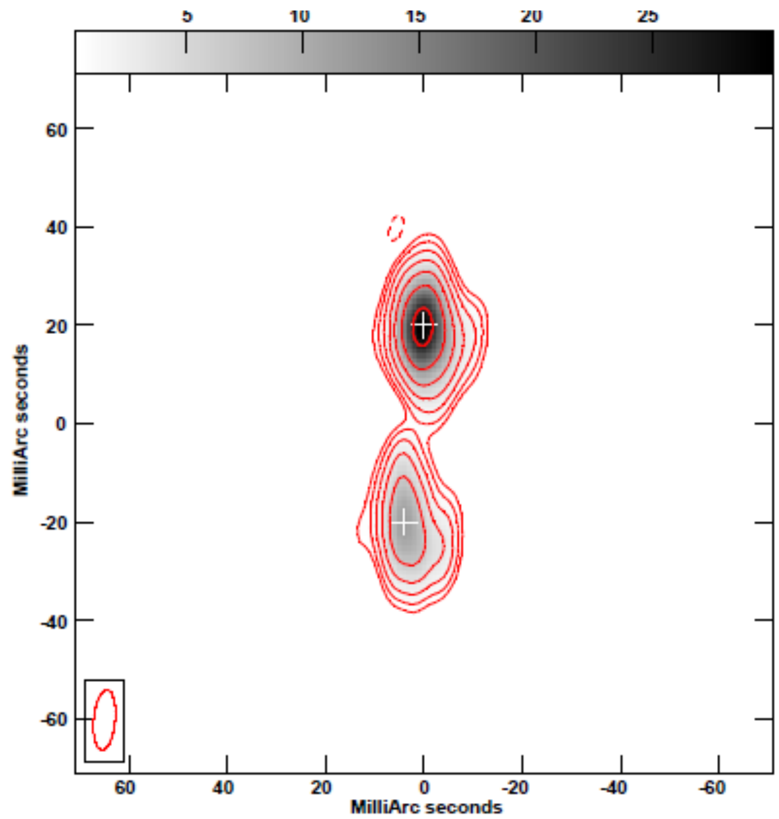
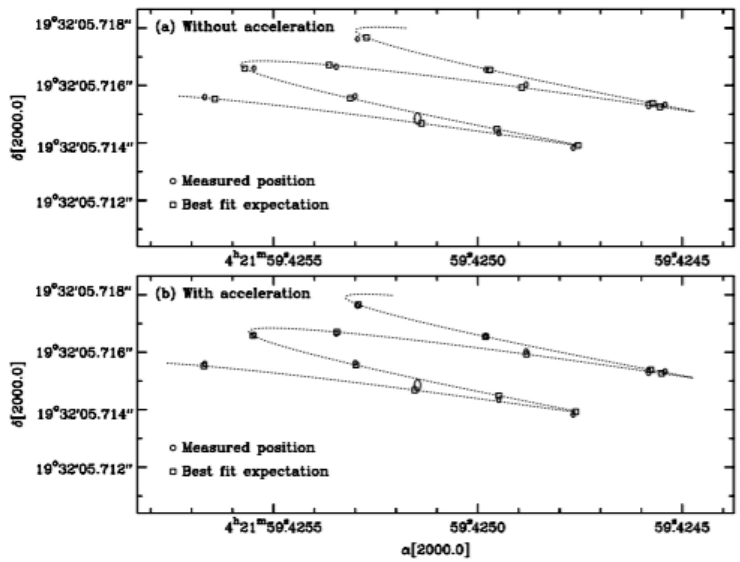



VLBA image of J0942+0623. The rms in the image is 90 μJy /beam

# Observation of T Tau Sb

- T Tau Sb, one of the companions of the famous young stellar object T Tauri
- Observation
  - Parallax: 6.82±0.03 mas
  - Distance: 146.7±0.6 pc (1.5σ)
- Improvement for Hipparcos
  - Distance: $177^{+68}_{-39}$pc (1σ)

- The relative error of VLBA is about 0.4%, against nearly 30% for the Hipparcos result, a gain of almost 2 orders of magnitude



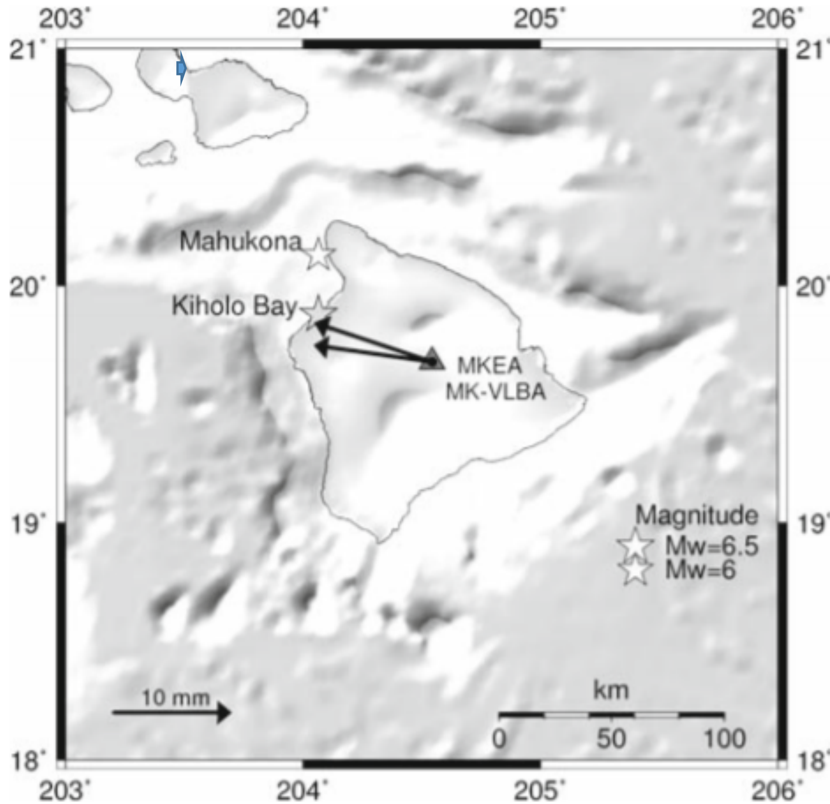

Measured positions of T Tau Sb and best fits, both (a) without and (b) with acceleration terms.

Loinard et al, 2007

# Geodesy

- Earth Rotation
- Earth Orientation
- tectonic plate motions
  - 2006.10.15: 2 earthquake struck Hawaii (6.7 & 6.0)
  - Displacement caused by earthquake
    - ➢ Up = –7.7 ± 1.3 mm
    - ➢ East = –10.0 ± 0.4 mm
    - ➢ North = 1.5 ± 0.4 mm

VLBA improved the position and velocity determinations for geodetic stations by 10–40% (Gordon, 2017)




The arrows show the mk-vlba site displacement caused by these events from analysis of VLBI observations (bottom) and GPS observations (above) (**Petrov et al, 2009)**

# Summary

- VLBI can get higher resolution by increase baseline.

- VLBA help to get a better result of astronomy and geodesy
  - Quasars
  - BH
  - HI spectral
  - T Tauri star
  - IFR
  - …

- Map the sky

# Reference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