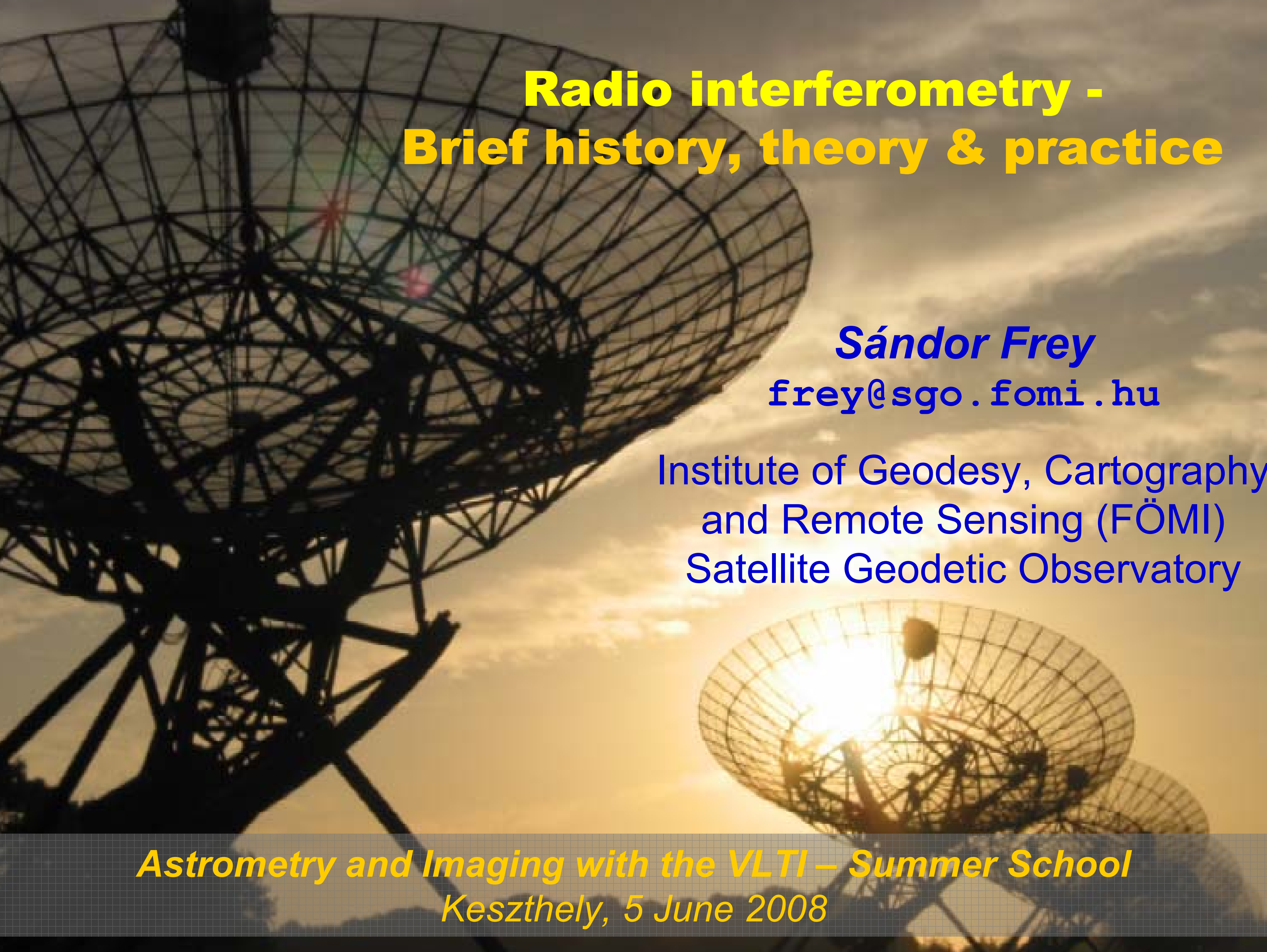

# Radio interferometry - Brief history, theory & practice


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Satellite Geodetic Observatory

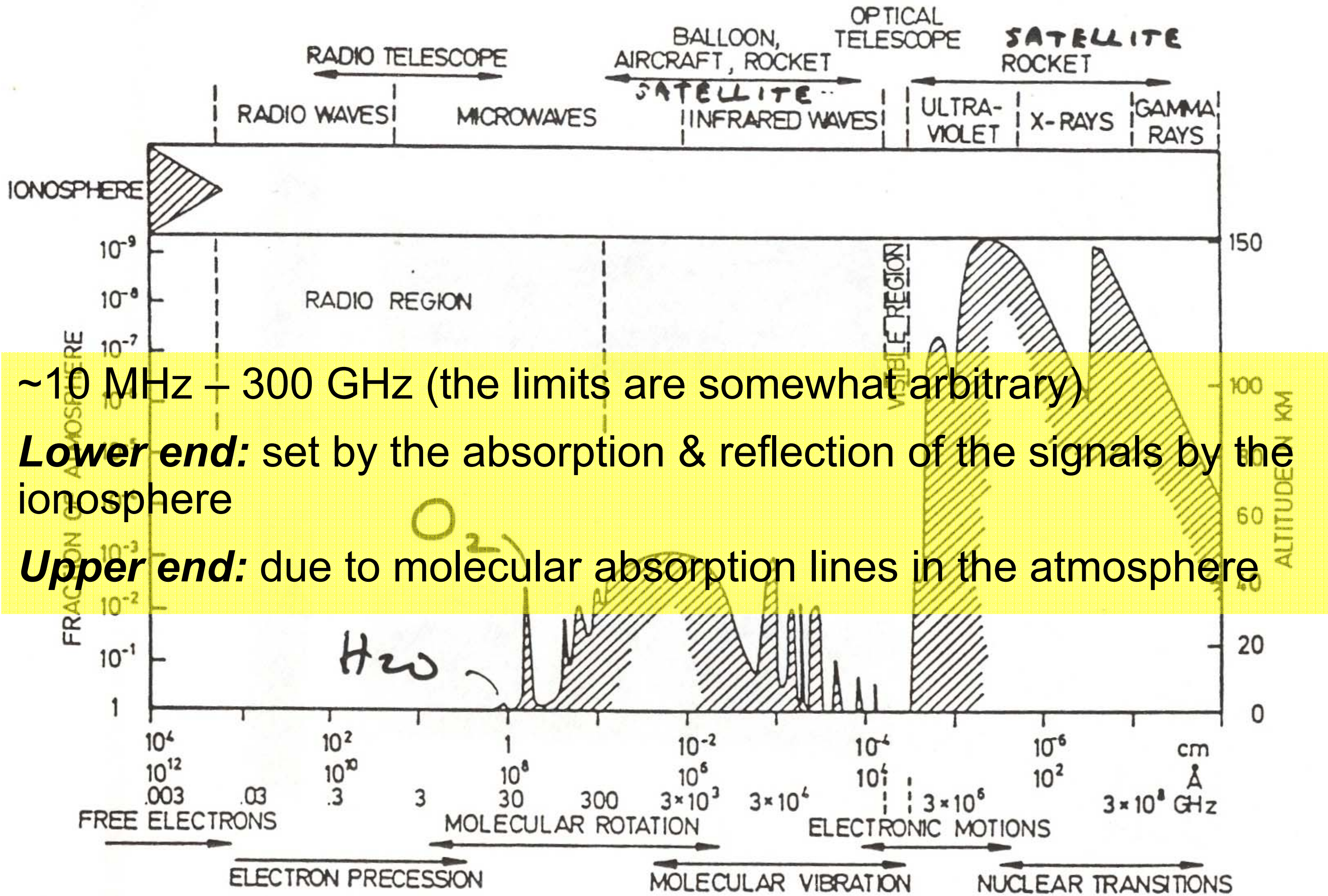

***Astrometry and Imaging with the VLTI – Summer School***

*Keszthely, 5 June 2008*

# The outline of the talk

- Radio astronomy & radio telescopes
- Why interferometry?
- Brief history of radio interferometers
- Optical vs. radio interferometry – differences
- Science with radio interferometry
- Interferometer arrays – available & planned
- Image reconstruction basics: methods, software
- Practical demo session *(later, if you survive…)*

# The atmospheric radio window

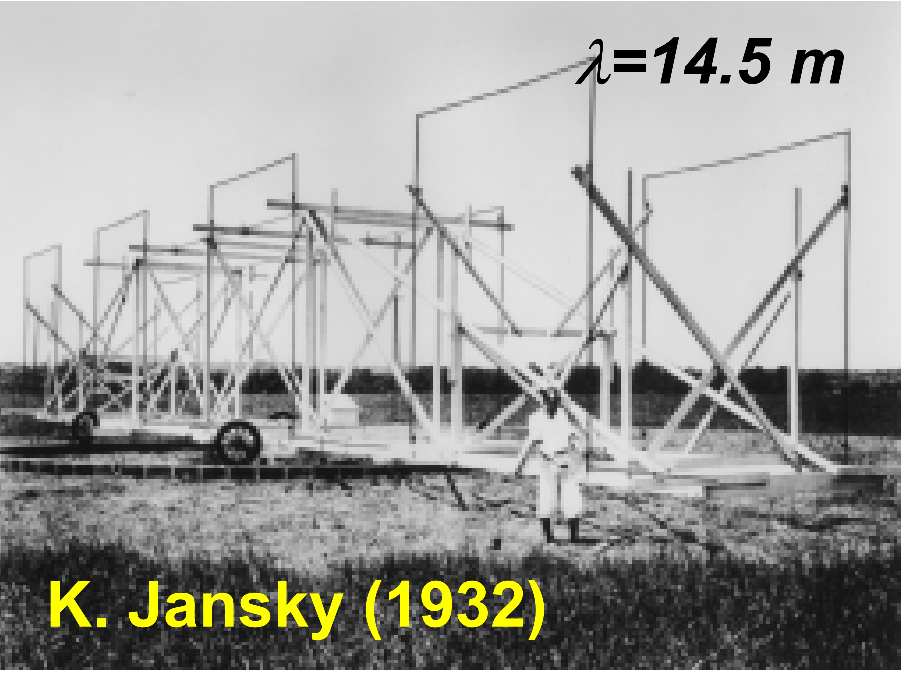


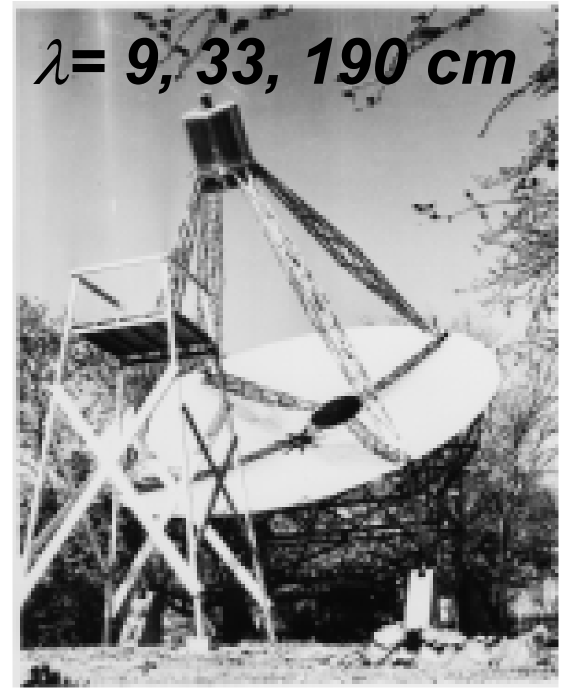

~10 MHz – 300 GHz (the limits are somewhat arbitrary)

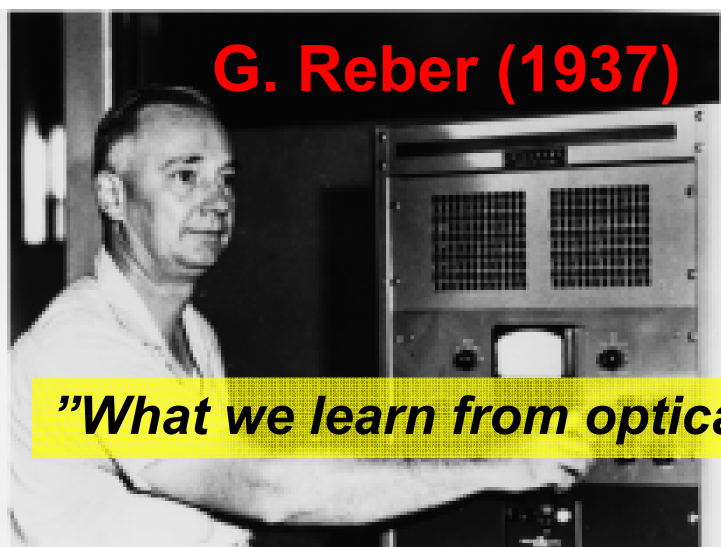
***Lower end:*** set by the absorption & reflection of the signals by the ionosphere

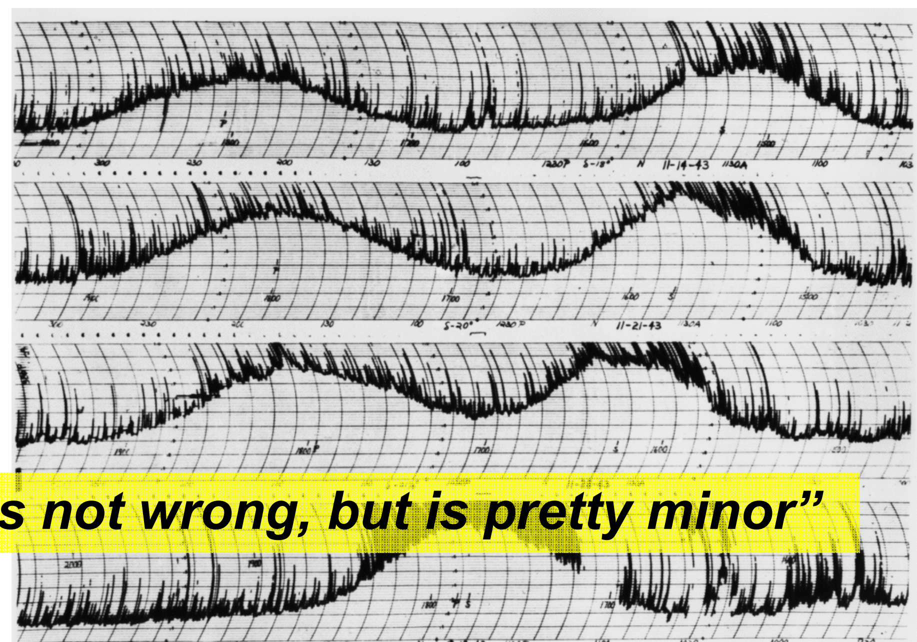
***Upper end:*** due to molecular absorption lines in the atmosphere

**Fig. 1.1.** The transmission of the earth atmosphere for electromagnetic radiation. The diagram gives the height in the atmosphere at which the radiation is attenuated by a factor 1/2

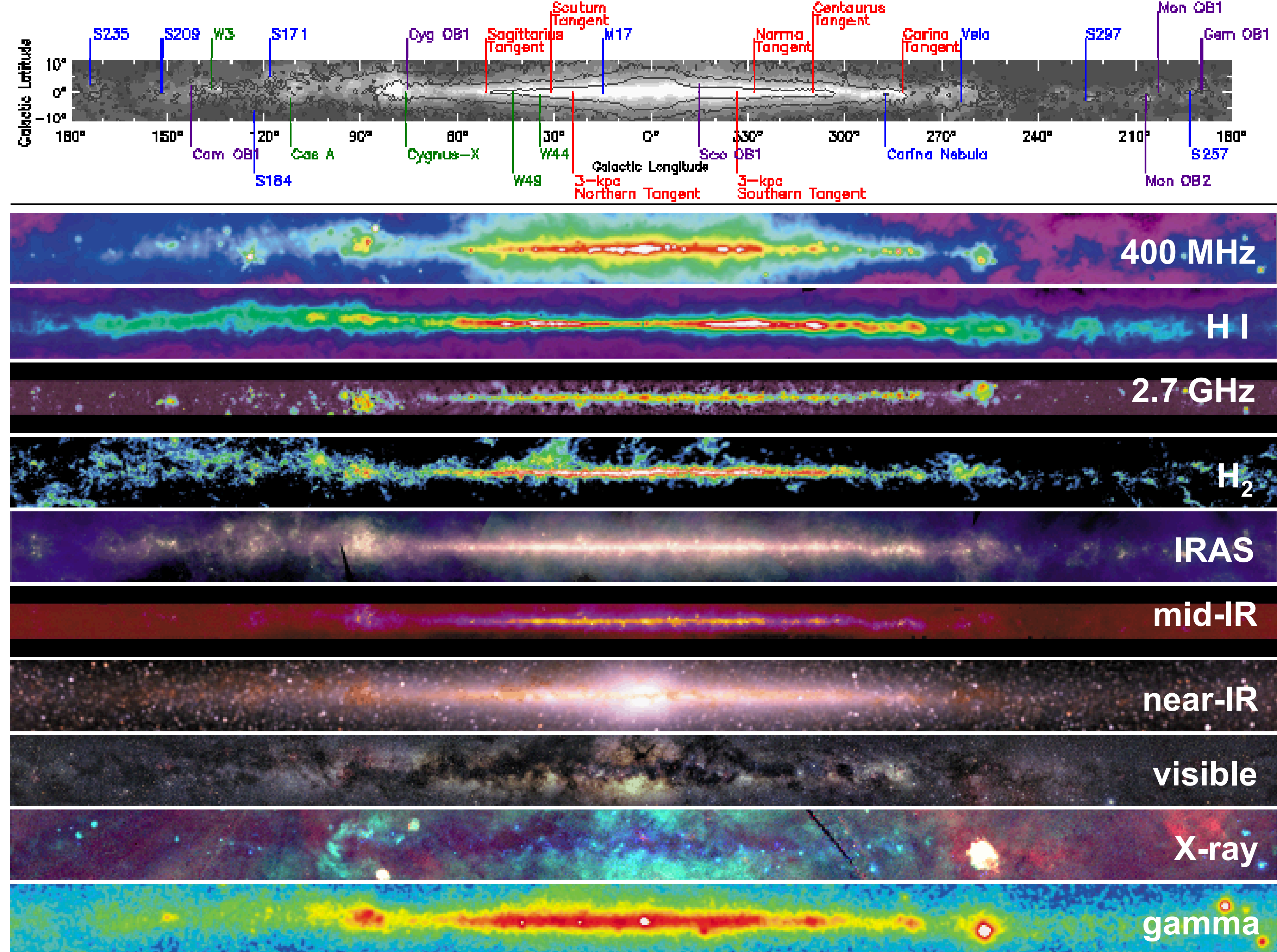


*"What we learn from optical is not wrong, but is pretty minor"*


S235
S209
W3
S171
Cyg OB1
Sagittarius Tangent
Scutum Tangent
M17
Norma Tangent
Centaurus Tangent
Carina Tangent
Vela
S297
Mon OB1
Gem OB1
Galactic Latitude
10°
0°
−10°
180°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
180°
Cam OB1
S184
Cas A
Cygnus-X
W49
W44
3-kpc Northern Tangent
Galactic Longitude
Sco OB1
3-kpc Southern Tangent
Carina Nebula
Mon OB2
S257
400 MHz
H I
2.7 GHz
$H_2$
IRAS
mid-IR
near-IR
visible
X-ray
gamma

# Radio telescopes

- Dipole arrays
- Reflectors (mostly paraboloid dishes)

*Typical properties of reflectors:*

can be directed towards any point on the sky

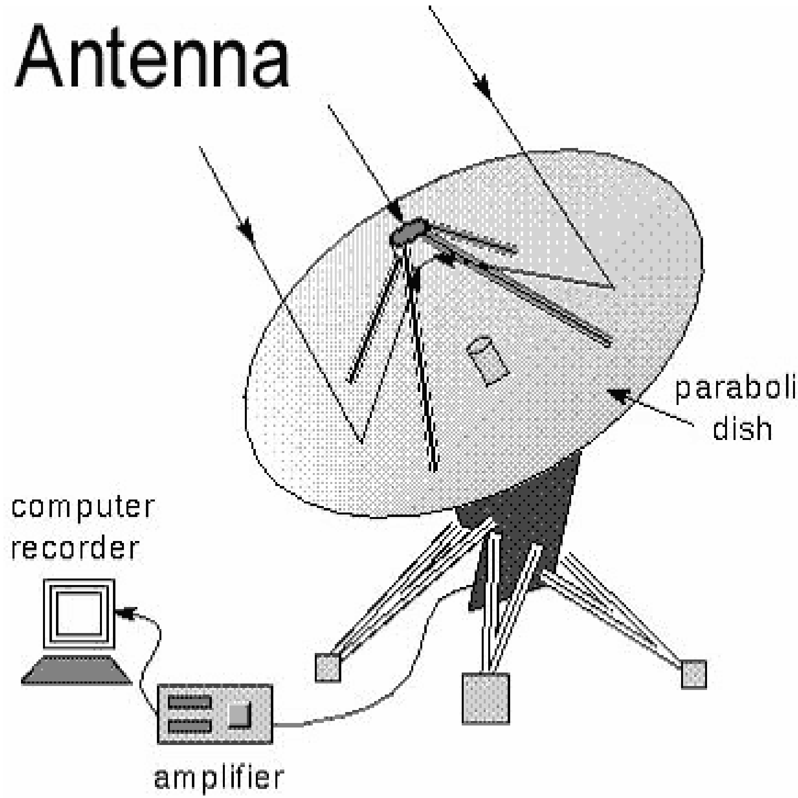
steerable dishes to track sources' apparent motion

radiation is reflected (metal surface) and focused

surface accuracy needed depends on the wavelength

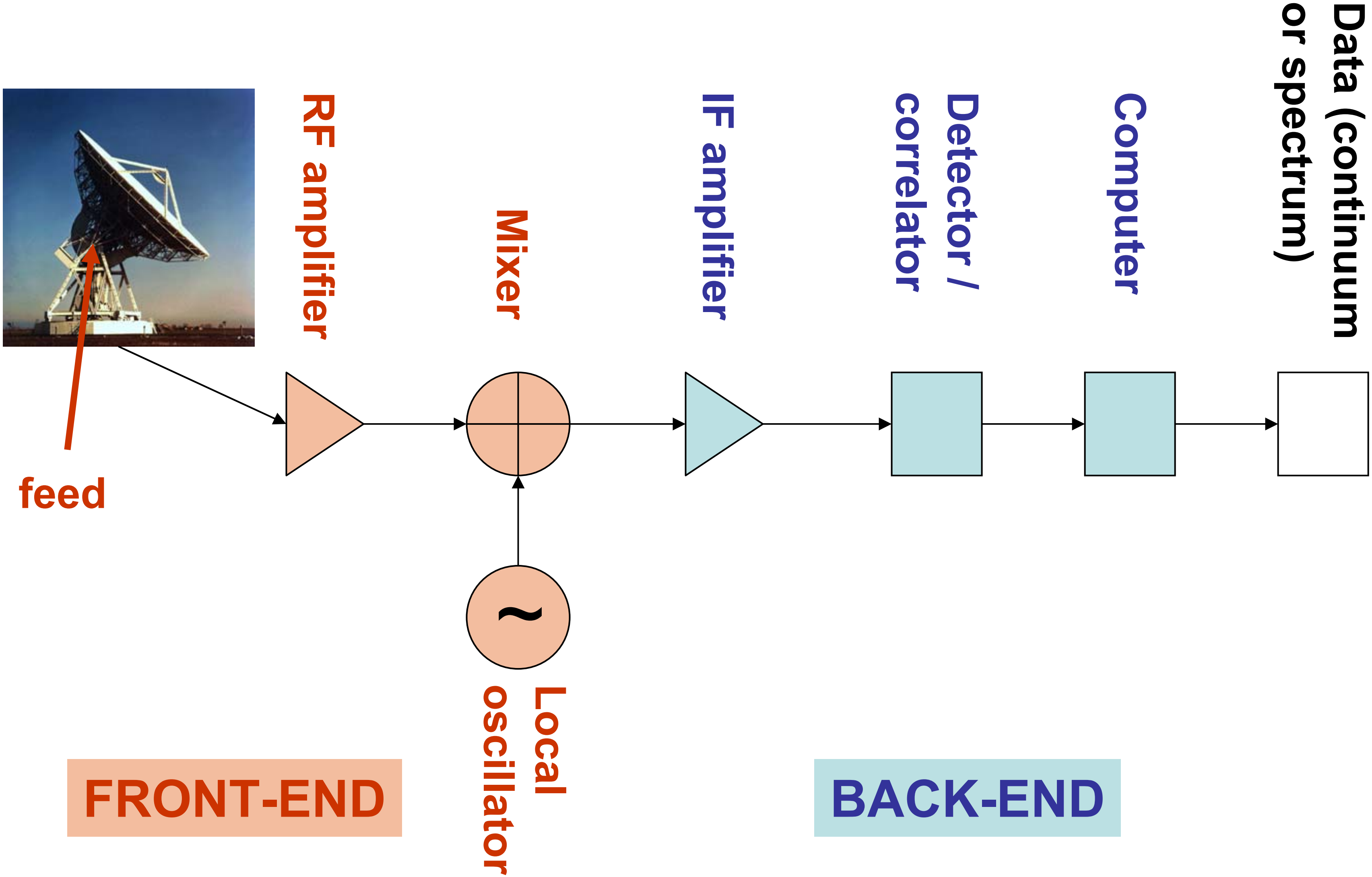
dipole at the focus (primary or Cassegrain)

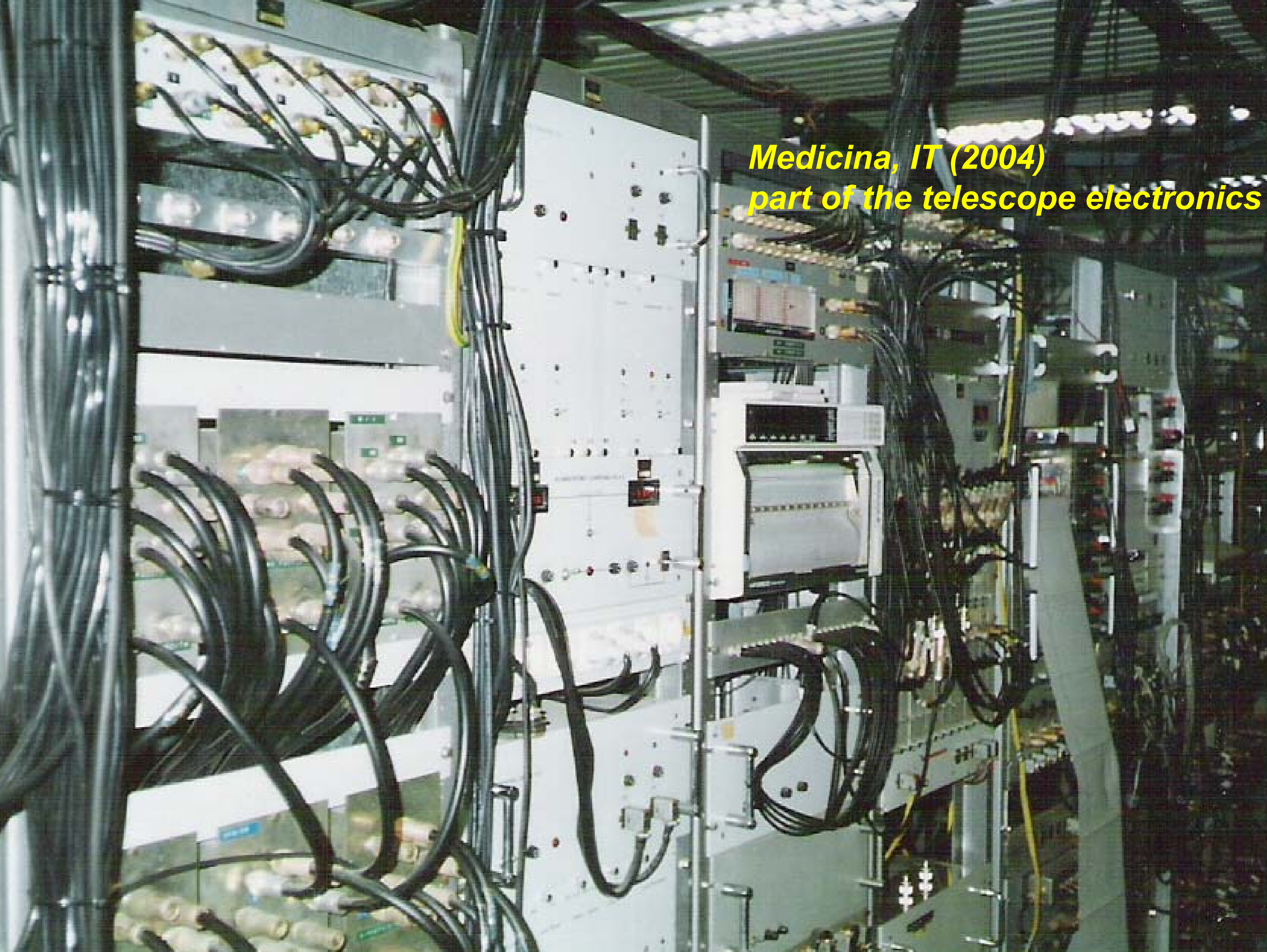
the weak signal is amplified



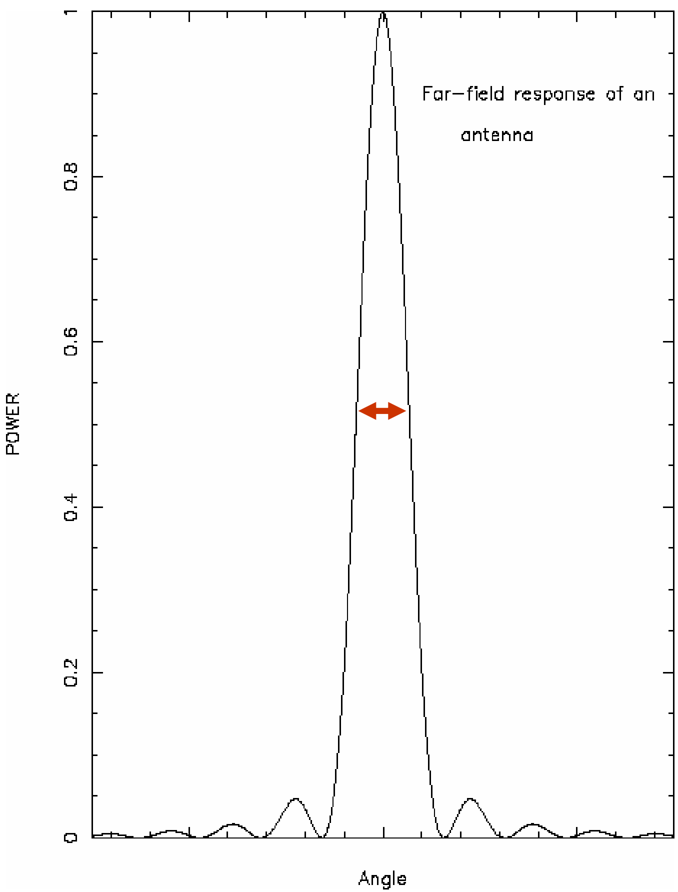

A radio telescope reflects radio waves to a focus at the antenna.

# Scheme of the radio telescope instrumentation




Medicina, IT (2004)
part of the telescope electronics

# Diffraction, beam, antenna gain



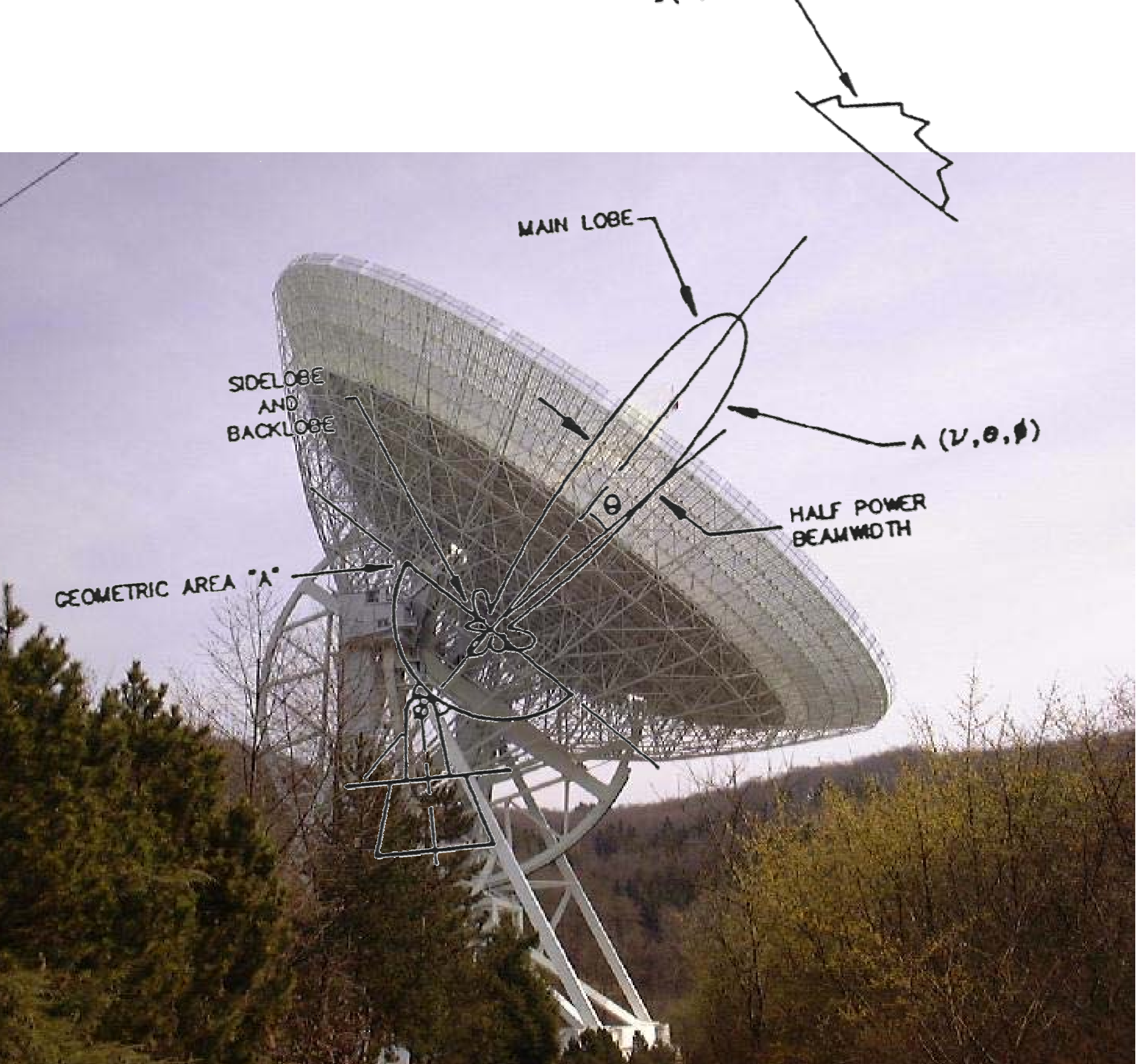

diffraction pattern produced by the aperture

Main lobe characterised by the half-power beamwidth
$\theta = 1.22\ \lambda / D$

(Sidelobes are also present!)

Solid angle $\Omega = \lambda^2 / A$

Antenna gain $G = 4\pi / \Omega$

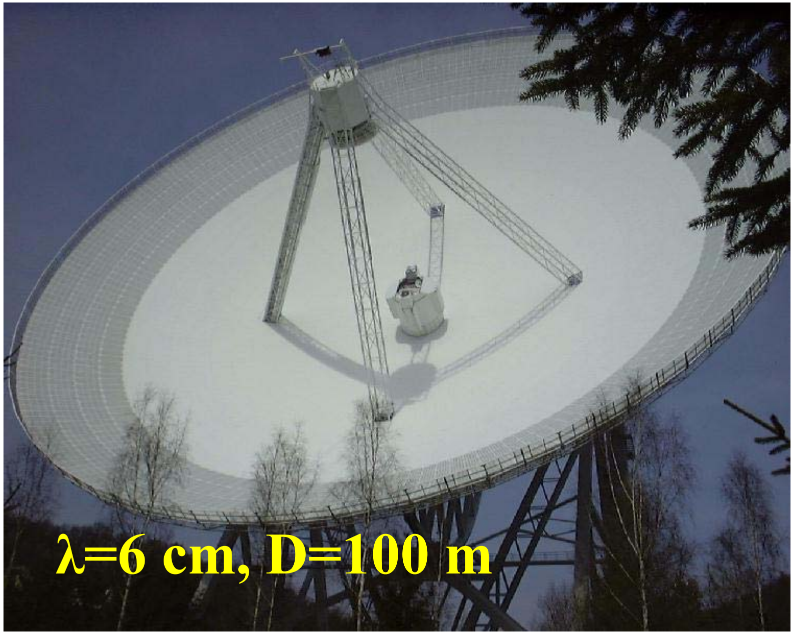

MAIN LOBE
SIDELOBE AND BACKLOBE
A (ν,θ,φ)
θ
HALF POWER BEAMWIDTH
GEOMETRIC AREA "A"

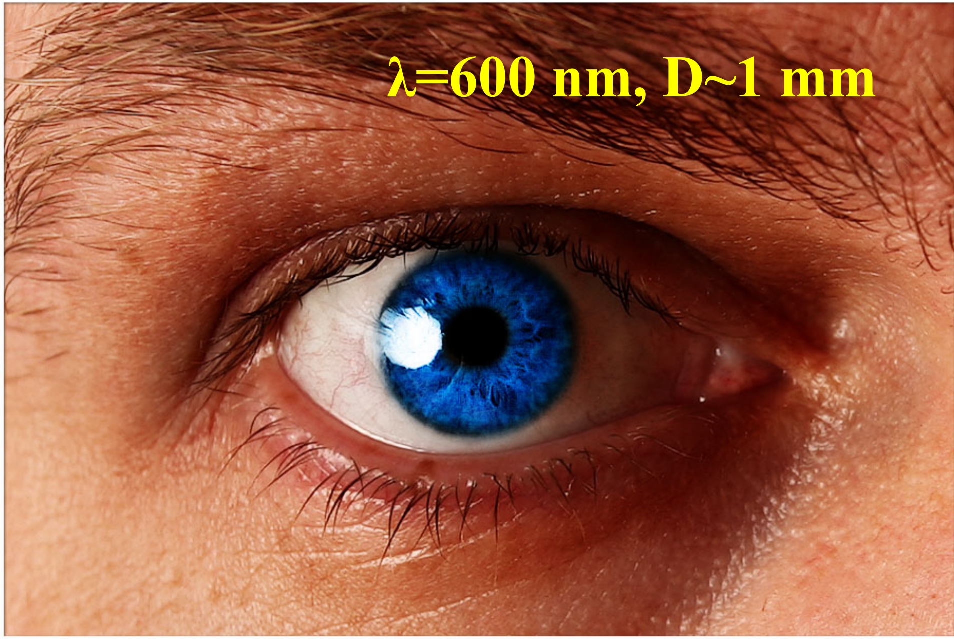
## *Examples for angular resolution:*

| λ | θ = 1’ | θ = 1” | θ = 1 mas |
|---|---|---|---|
| 5 m | 20 km | 1 200 km | ~$10^6$ km |
| 50 cm | 2 km | 120 km | ~$10^5$ km |
| 5 cm | 200 m | 12 km | ~$10^4$ km |
| 500 nm | 2 mm | 12 cm | 120 m |

For the Hubble Space Telescope (λ=500 nm, D=2.4 m) it is θ ≈ 50 mas

For the Effelsberg radio telescope (λ=6 cm, D=100 m) it is θ ≈ 2’



# The role of radio telescope size

The power collected by a radio telescope is $P \sim S_\nu \, A \, \Delta\nu$
⇨ useful to have large collecting area (and large bandwidth if possible)

The angular resolution (primary beam width) is $\theta \sim \lambda / D$
⇨ larger telescopes are better in terms of resolution

However, there is a technical / financial limit at $D \approx 100$ m for constructing fully steerable dishes (Green Bank Telescope, Effelsberg)

Larger radio telescopes are either non-steerable (Arecibo: D=305 m spherical surface), or interferometers.

Arecibo, Puerto Rico

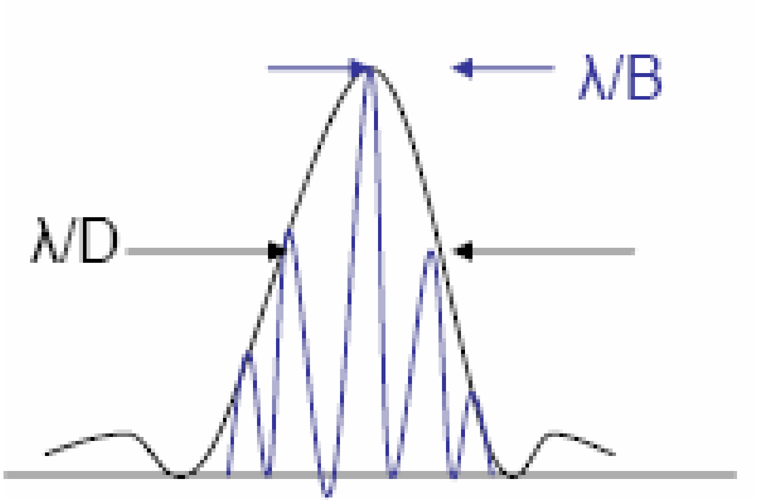
# Interferometry

Two-slit interferometer (Young)
Interferometry in optical astronomy: Michelson (1891) – Jupiter’s moons

Two light rays are combined in a telescope

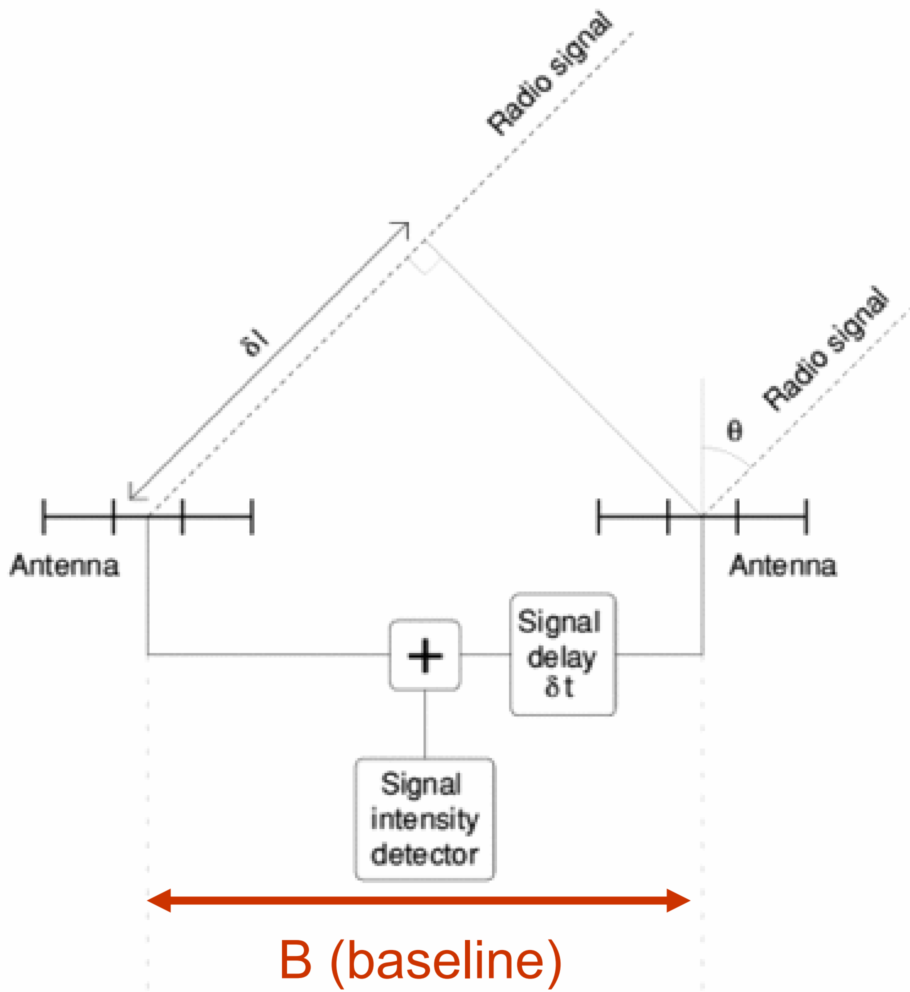
If the star’s angular extent is „small”, the interference pattern consist of light and dark stripes (called *fringes*)

D – slit aperture diameter
B – distance between the slits




$$\text{fringe visibility} = \frac{\text{brightness of maxima} - \text{brightness of minima}}{\text{brightness of maxima} + \text{brightness of minima}}$$

# Scheme of a two-element radio interferometer




As the source passes (e.g. due to the Earth rotation), the delay between the times when the wavefront reaches the two antennas changes.

The angular resolution will become
$\theta \sim \lambda / B$

# Radio interferometry: milestones

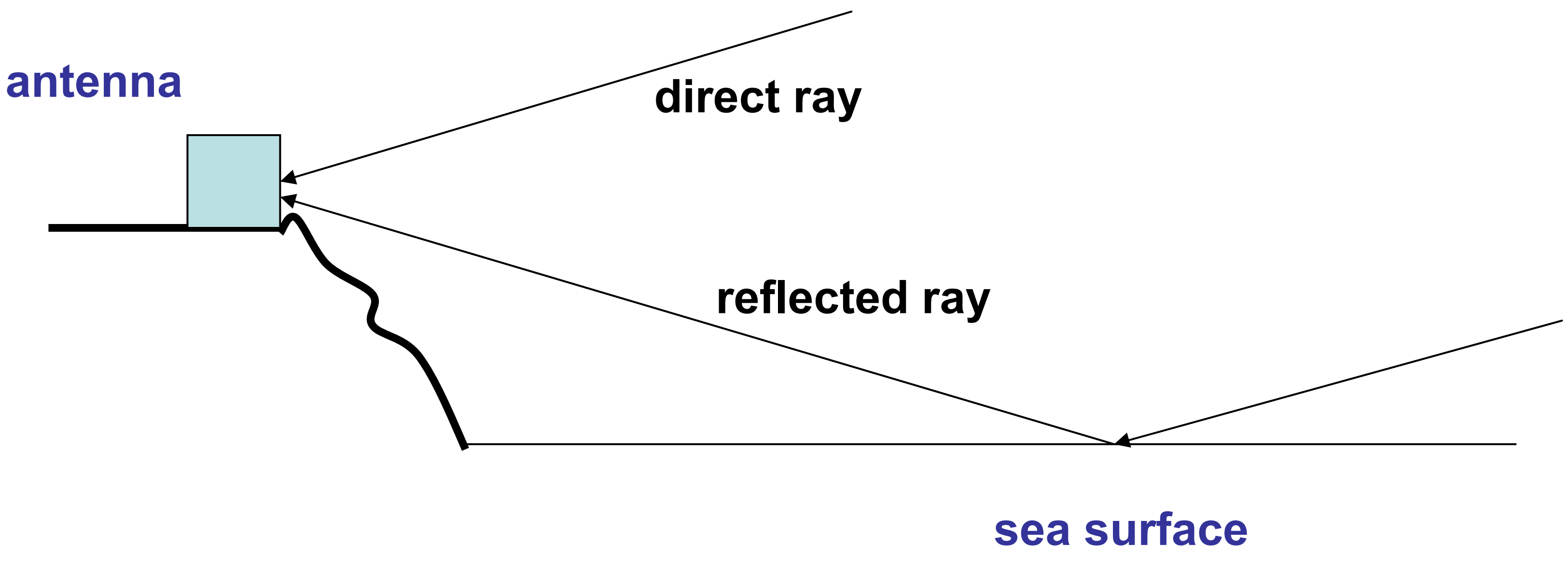
Sea interferometer (Australia, 1946)
Jodrell Bank Interferometer (UK, 1958)
One-Mile Telescope (UK, 1963)
Green Bank Interferometer (USA, 1964)
Very Long Baseline Interferometry (VLBI) (USA, Canada, 1967)
Westerbork Synthesis Radio Telescope (The Netherlands, 1974)
Very Large Array (VLA) (USA, 1978)
Australia Telescope Compact Array (1989)
Very Long Baseline Array (VLBA) (USA, 1990)
Giant Meterwave Radio Telescope (GMRT) (India, 1997)
HALCA space VLBI satellite (Japan, 1997)

# Radio interferometry: early history

Technique developed in Australia and the United Kingdom from the1940's

*Sea cliff interferometer* (1946)

Reflection on the sea surface: phase change $\pi$ + extra path length



# Phase switching (Ryle, 1952)

$V_1(t)$ and $V_2(t)$ are the signal voltages from the two telescopes

Early (adding) interferometers detected $(V_1+V_2)^2$

If the phase of one signal is periodically reversed, the output is alternating between $(V_1+V_2)^2$ and $(V_1- V_2)^2$
The difference between these is $4V_1V_2$ – proportional to the time average of the cross-correlation of the two signals

Since the noise contributions of the two amplifiers are not correlated, the correlator interferometer is less sensitive to the variation in sytem noise

# Aperture synthesis

Variation of antenna baselines allow us to learn more about the radio source structure

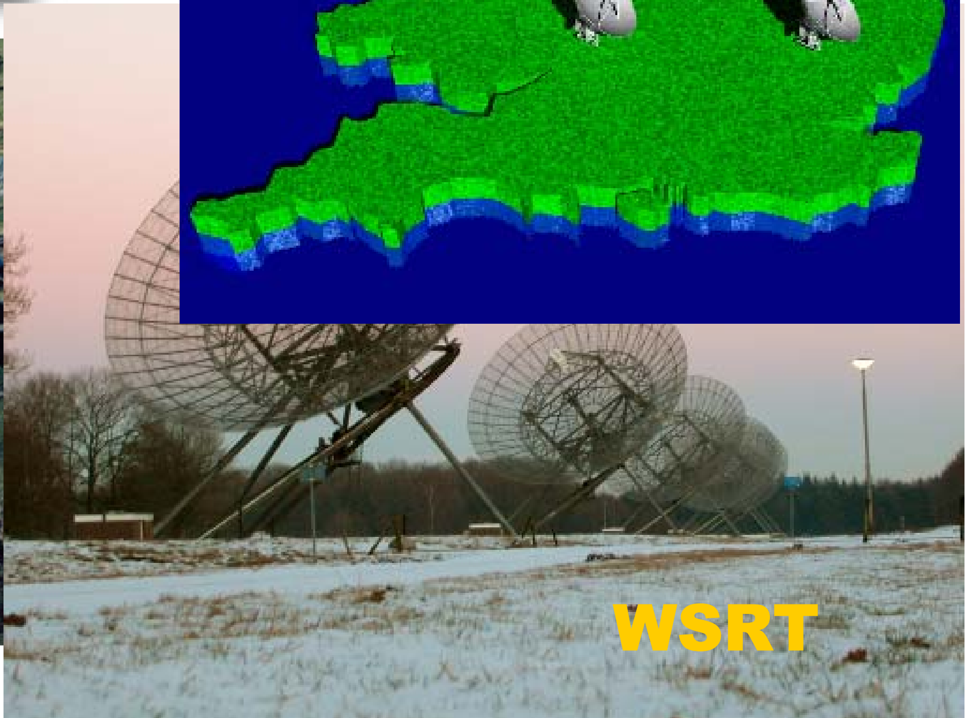
Even with a linear array, projected baselines change as the Earth rotates, and two-dimensional visibility data can be collected for high-declination objects

The first Earth rotation synthesis instrument: *Cambridge One-Mile Telescope* (Ryle)

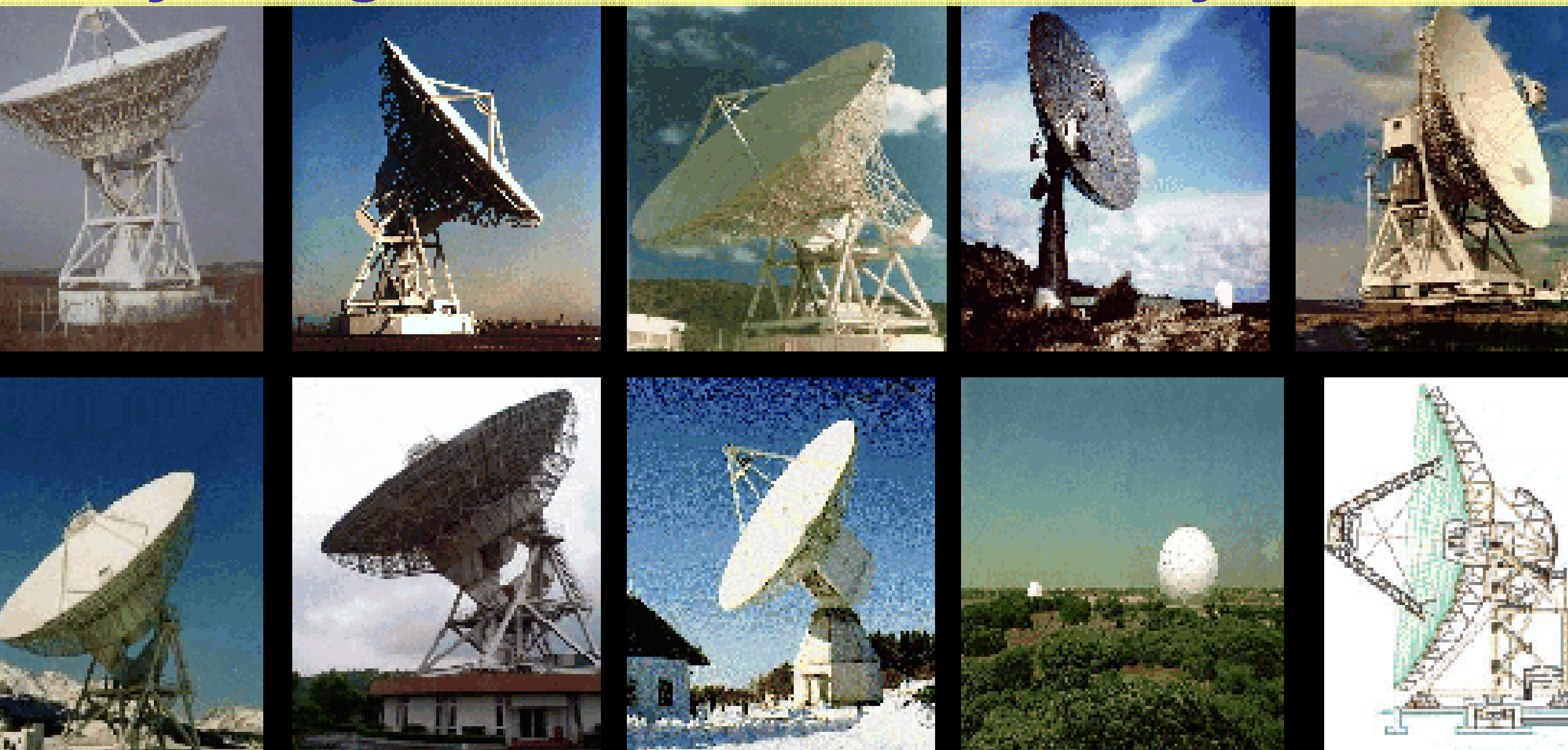
With $n$ antennas, $n(n-1)/2$ baselines can be obtained simultaneously

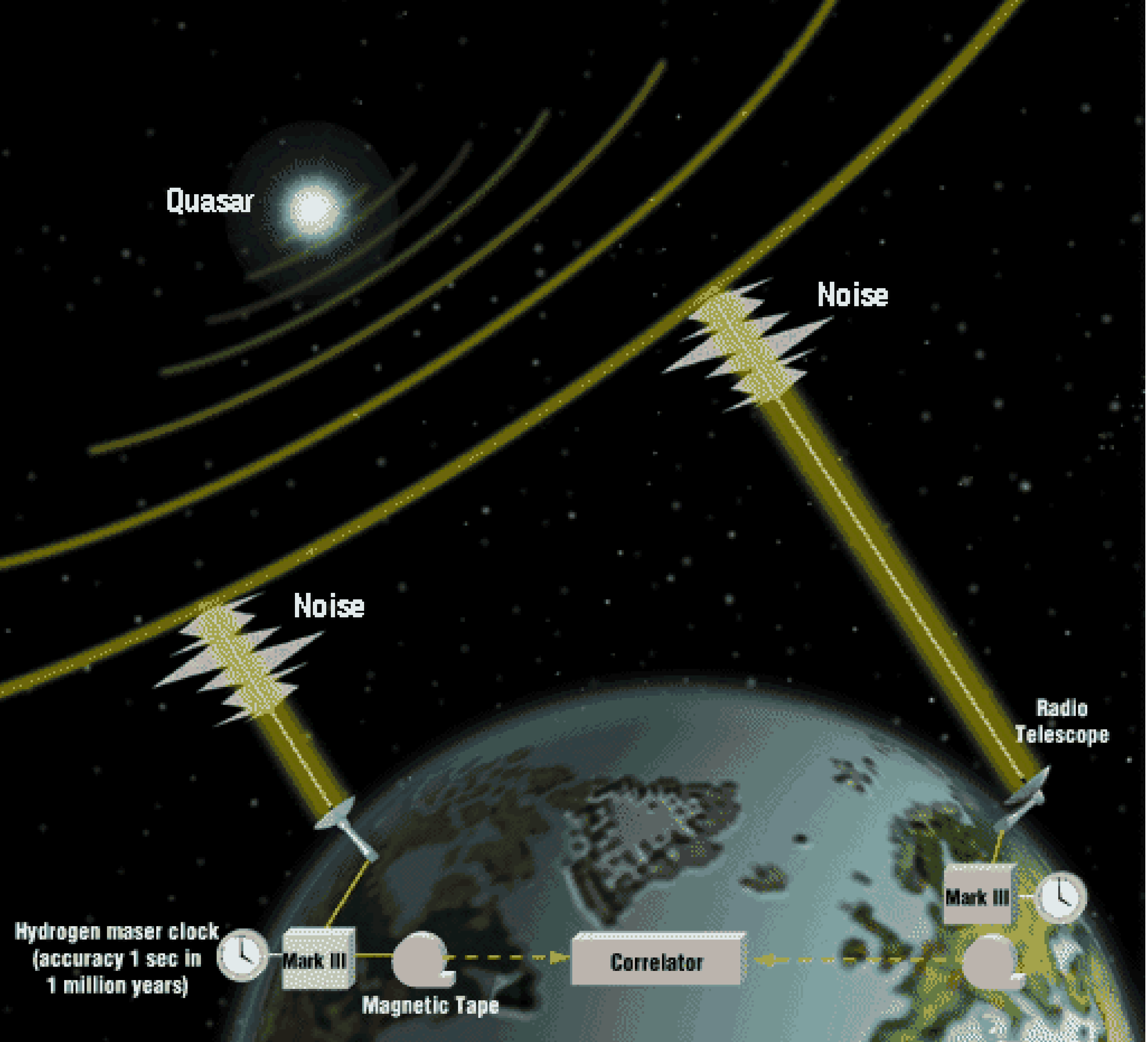
# Examples of connected-element radio interferometers



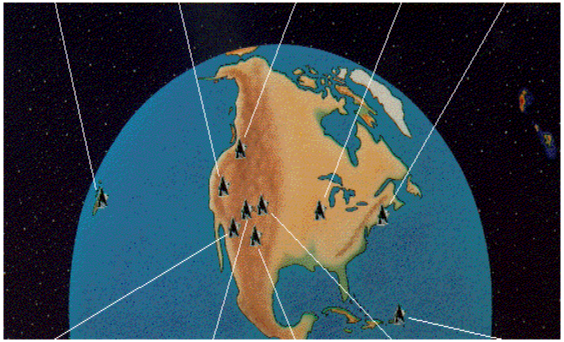
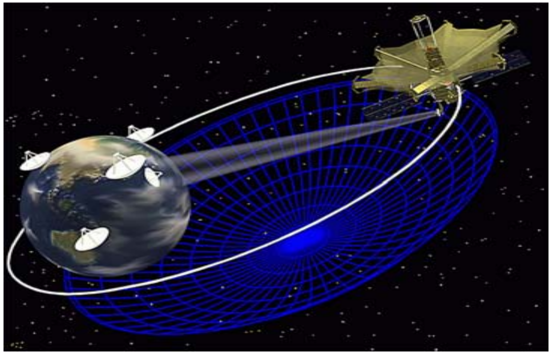
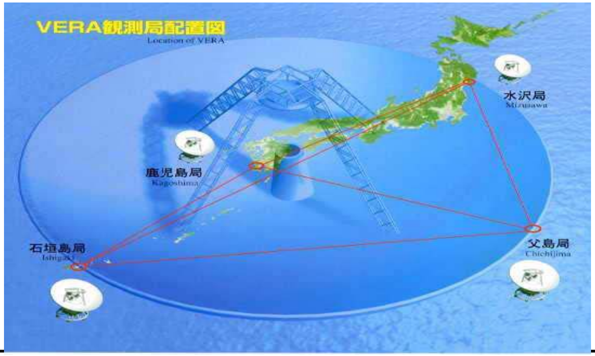
# Very Long Baseline Interferometry networks



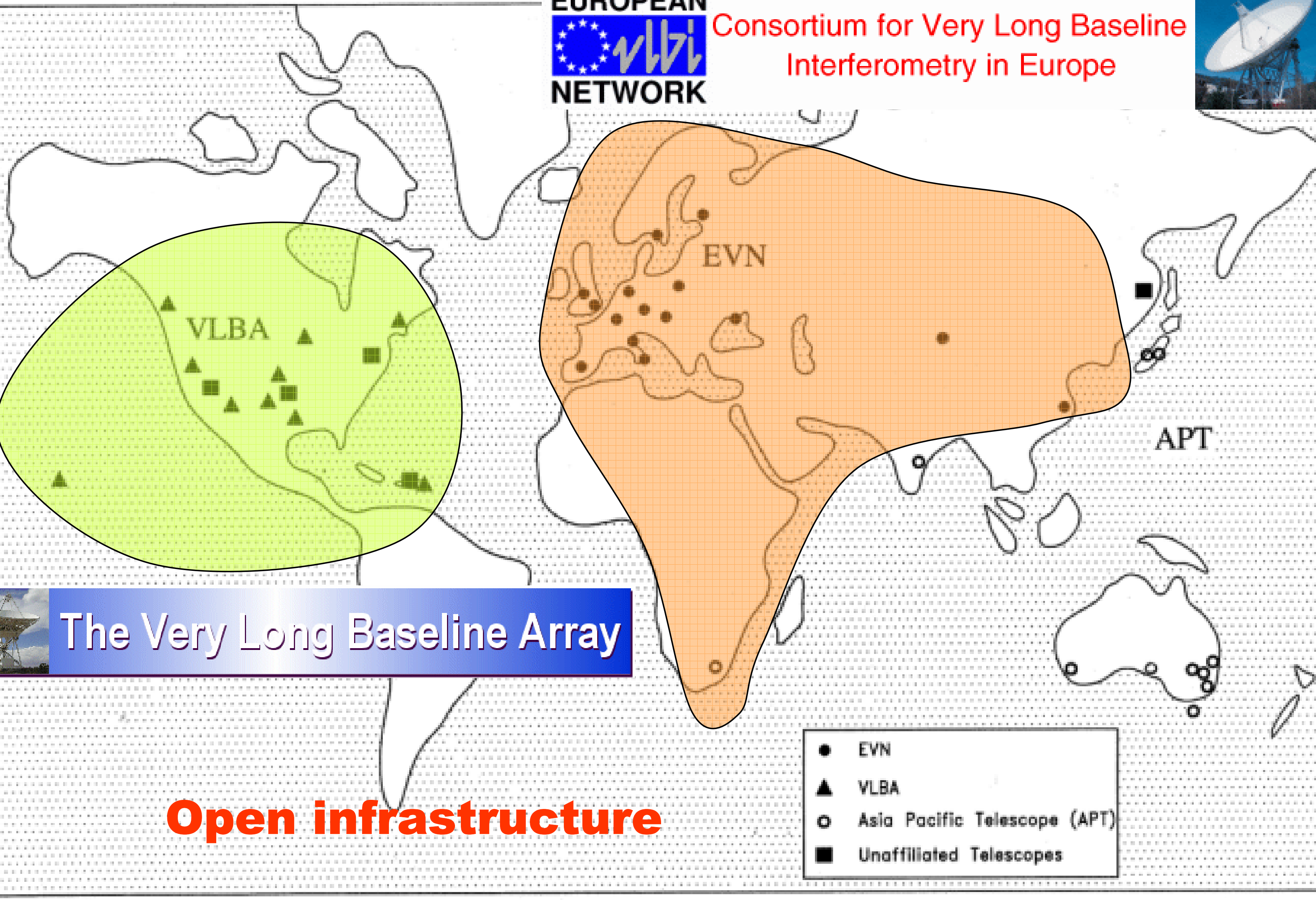



**V**ery
**L**ong
**B**aseline
**I**nterfero
metry

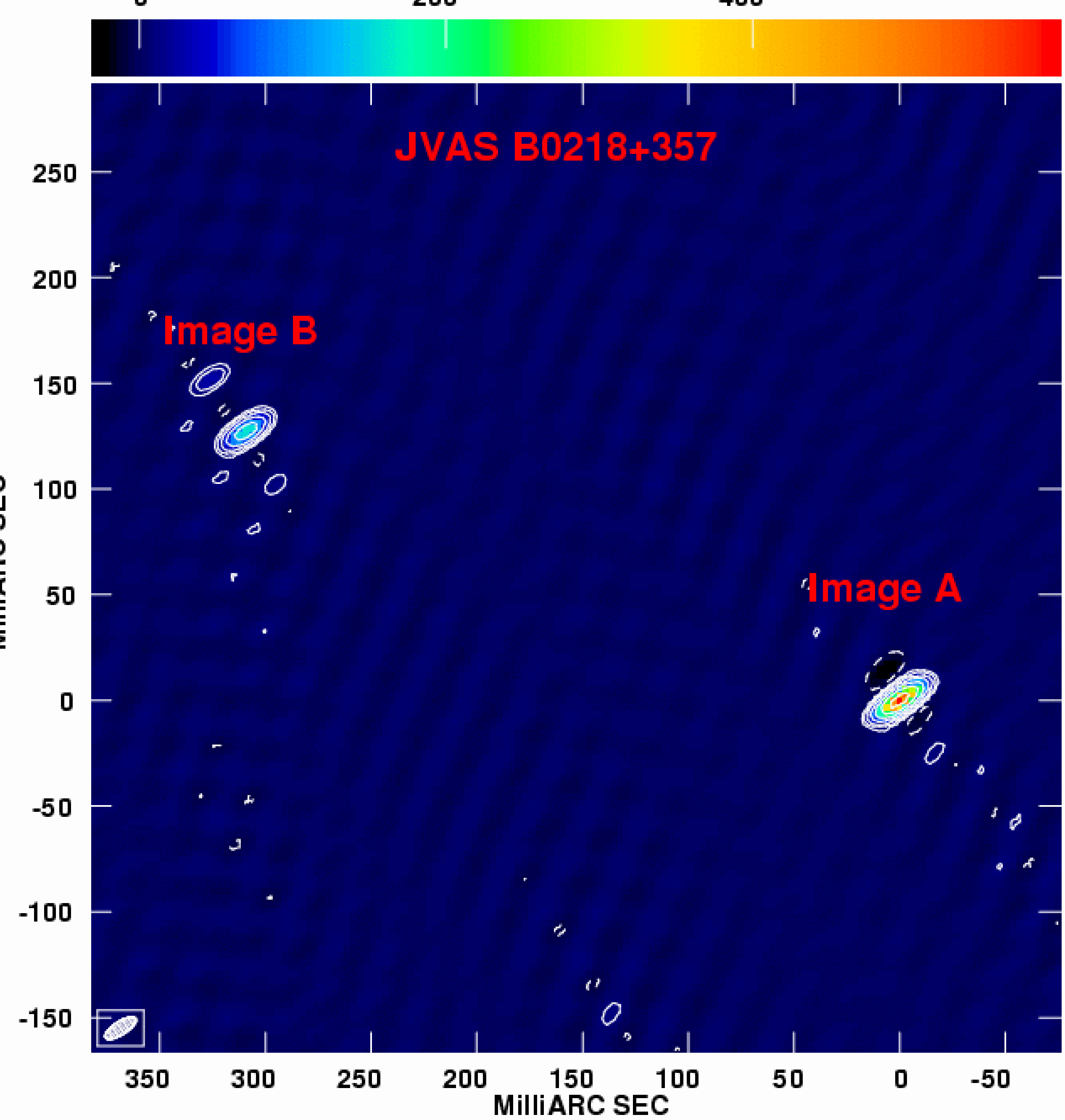
# VLBI facilities worldwide

| | |
|---|---|
| EUROPEAN vlbi NETWORK | VLBA  |
| CMVA<br>THE COORDINATED MILLIMETER VLBI ARRAY | VSOP  |
| Australian LBA & APT<br>LBA | VERA  |

## Consortium for Very Long Baseline Interferometry in Europe




**Open infrastructure**




# e-VLBI

***The first real-time EVN image***

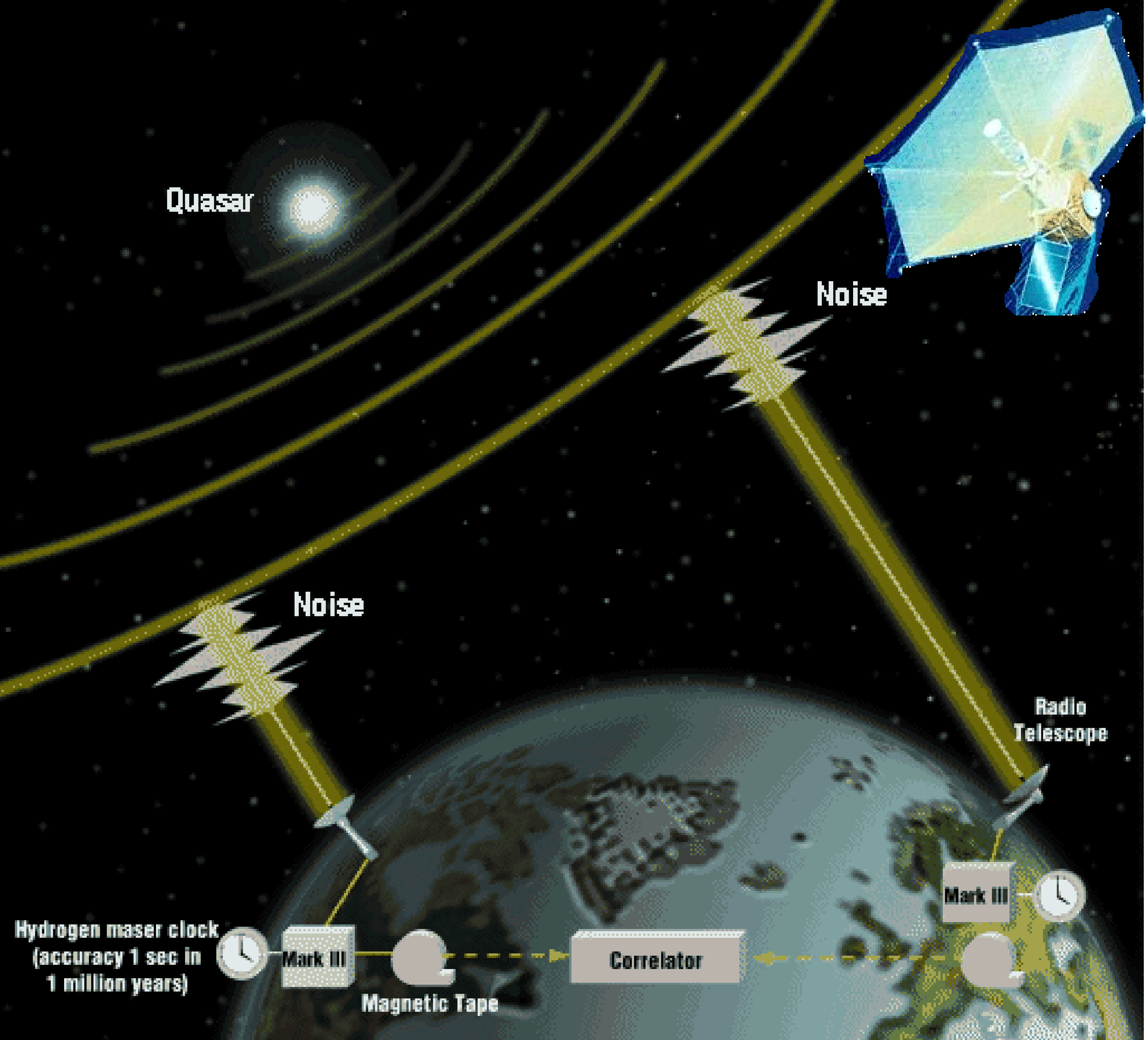
28 Apr 2004
~ 2 hours
Onsala (SE),
Jodrell Bank (UK),
Westerbork (NL)

Data transfer via optical cables to the JIVE correlator

Data rate32 Mbit/s

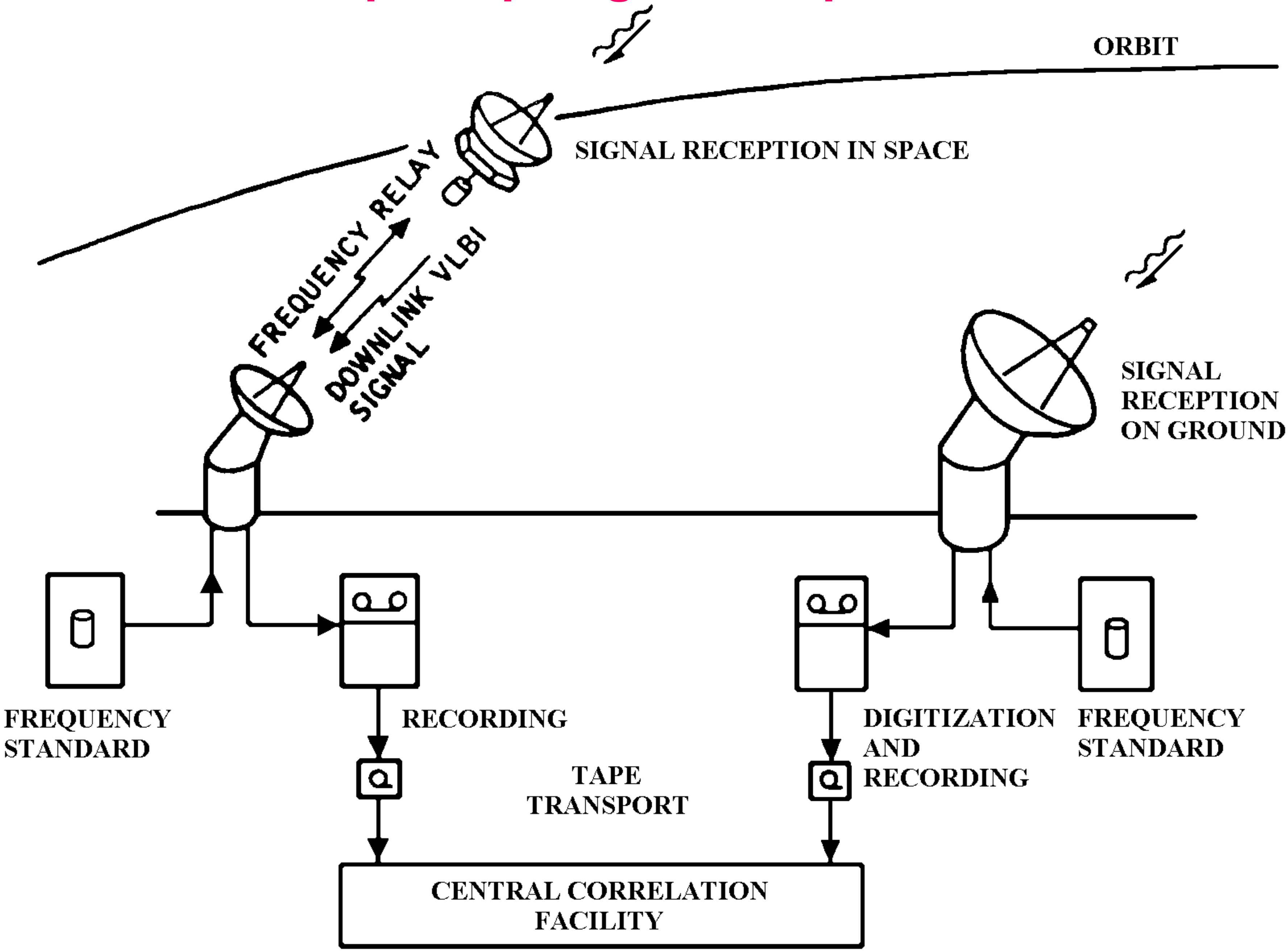
# EXPReS


http://www.expres-eu.org/

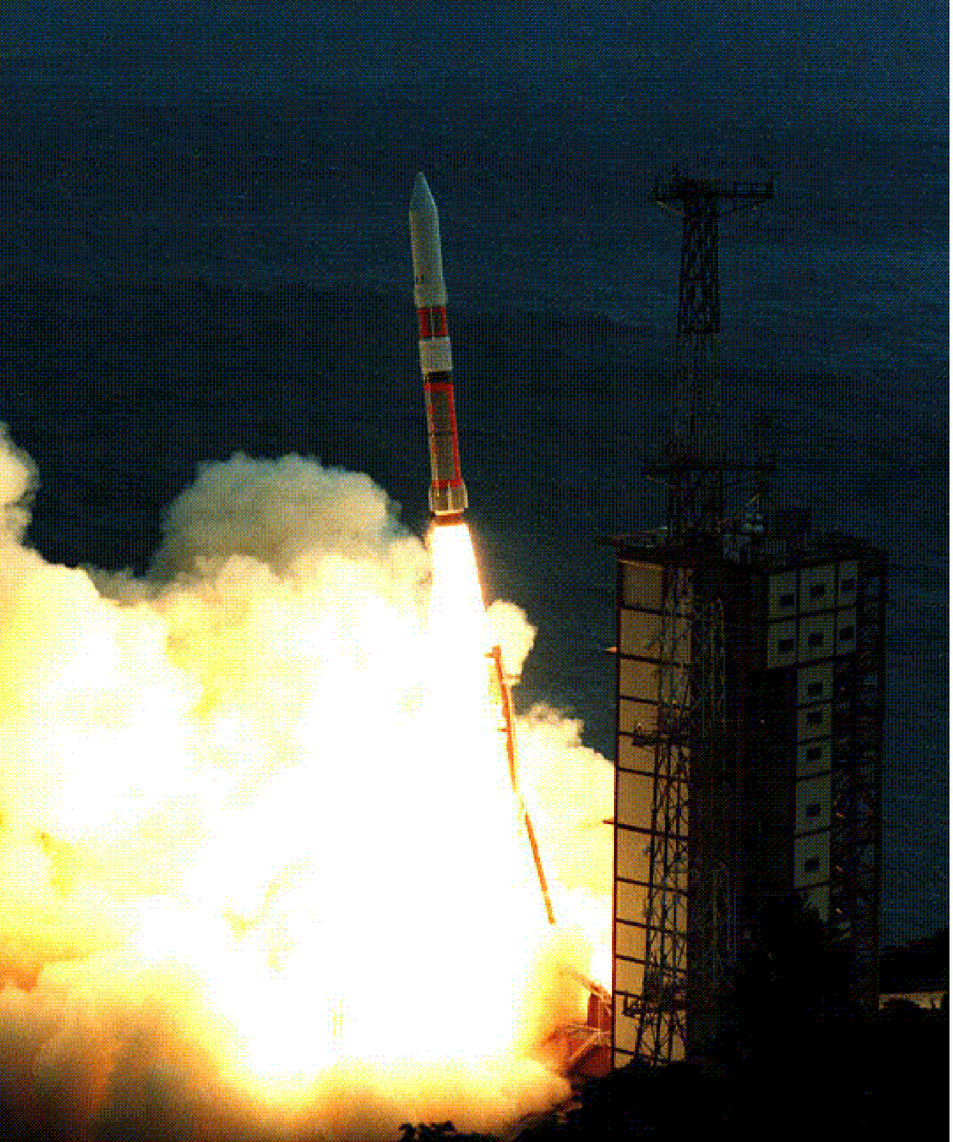



**S**pace
**V**ery
**L**ong
**B**aseline
**I**nterfero
metry

# SVLBI in principle: ground-space baseline



# VSOP
## (VLBI Space Observatory Programme)



http://www.vsop.isas.jaxa.jp/

# ISAS (Japan)

***HALCA start:*** February 12, 1997 (new M-V rocket)

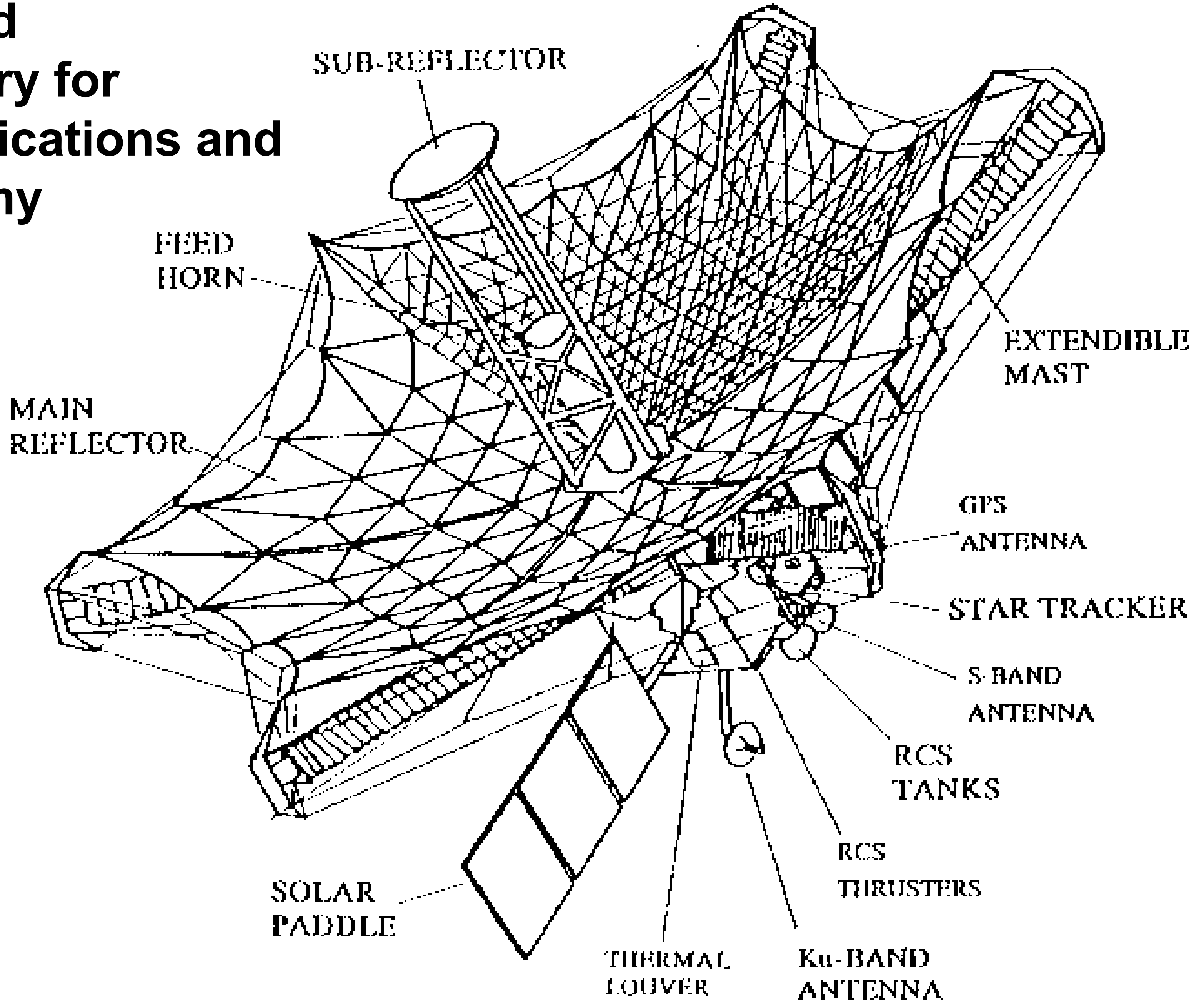
8-m parabolic antenna on board HALCA

***observing frequencies:***
1.6 and 5 GHz
***recording data rate:*** 128 Mbps
***bandwidth:*** 32 MHz

***orbital period:*** 6.3 h
21 400km (apogee)
560 km (perigee)

***baselines:*** up to ~30 000 km
(~3× increase in resolution)

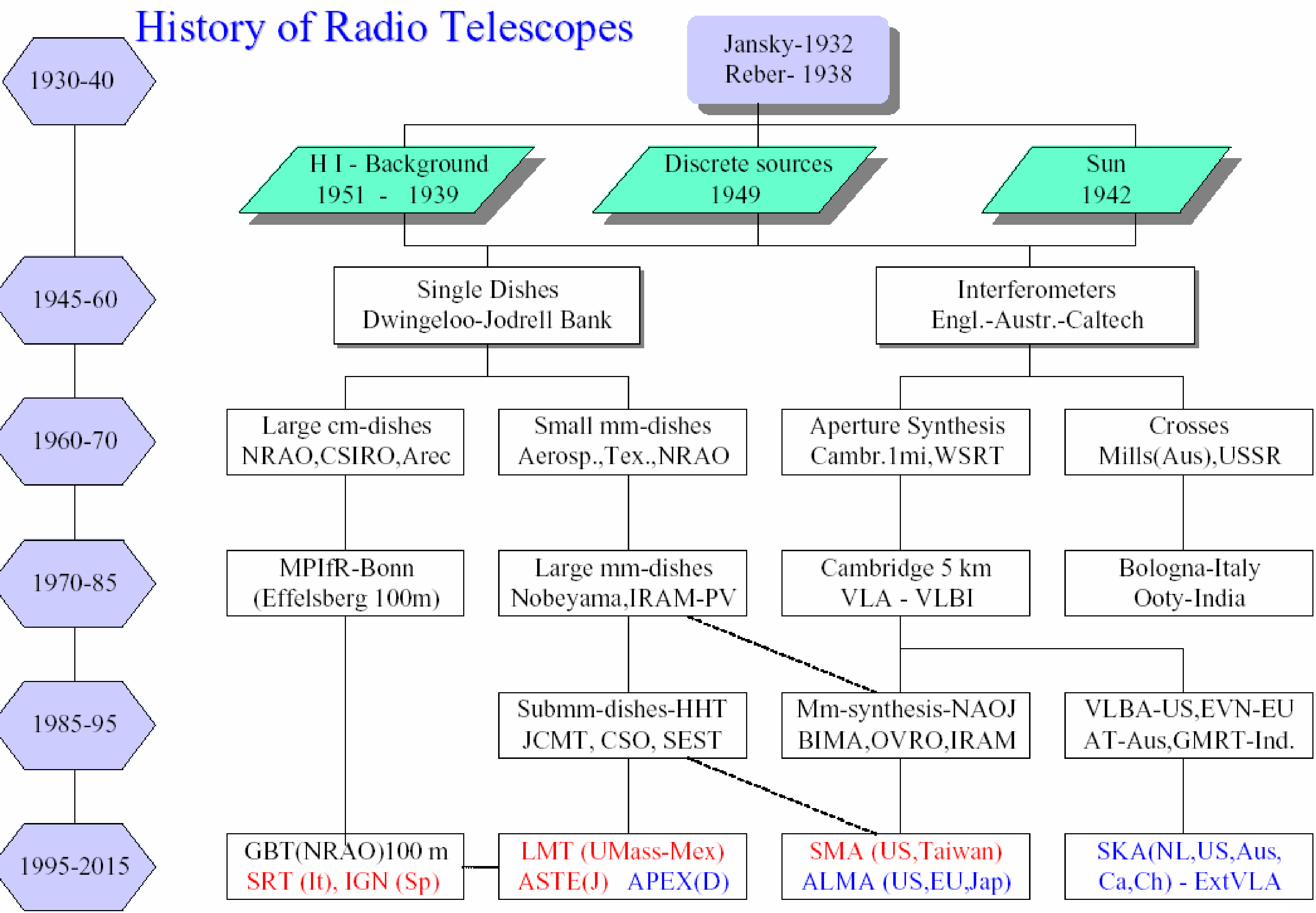
**H**ighly
**A**dvanced
**L**aboratory for
**C**ommunications and
**A**stronomy




a truly global VLBI:
>40 ground radio telescopes from all over the world

5 ground tracking stations
*(USA, Japan, Australia, Spain)*

3 correlators
*(USA, Canada, Japan)*


History of Radio Telescopes
1930-40
1945-60
1960-70
1970-85
1985-95
1995-2015
Jansky-1932
Reber- 1938
H I - Background
1951 - 1939
Discrete sources
1949
Sun
1942
Single Dishes
Dwingeloo-Jodrell Bank
Interferometers
Engl.-Austr.-Caltech
Large cm-dishes
NRAO,CSIRO,Arec
Small mm-dishes
Aerosp.,Tex.,NRAO
Aperture Synthesis
Cambr.1mi,WSRT
Crosses
Mills(Aus),USSR
MPIfR-Bonn
(Effelsberg 100m)
Large mm-dishes
Nobeyama,IRAM-PV
Cambridge 5 km
VLA - VLBI
Bologna-Italy
Ooty-India
Submm-dishes-HHT
JCMT, CSO, SEST
Mm-synthesis-NAOJ
BIMA,OVRO,IRAM
VLBA-US,EVN-EU
AT-Aus,GMRT-Ind.
GBT(NRAO)100 m
SRT (It), IGN (Sp)
LMT (UMass-Mex)
ASTE(J) APEX(D)
SMA (US,Taiwan)
ALMA (US,EU,Jap)
SKA(NL,US,Aus,
Ca,Ch) - ExtVLA

# Optical vs. radio interferometry

In **optical** interferometers the light rays coming from the celestial source are directly interfered and produce the fringe pattern.

**Radio** interferometers are fundamentally different.
Here the incoming radiation is mixed with the local oscillator signals.
This method allows amplification, digitization, storage, transportation and correlation with signals coming from other telescopes.

Wavelengths are much longer in radio (factors of $10^3$-$10^6$)
$\rightarrow$ **handicap** *(from the point of view of single-telescope resolution…)*
But: baselines in radio can be much larger (> Earth diameter, SVLBI)
$\rightarrow$ **best resolution in astronomy** (sub-mas)

Atmosphere: less severe in radio
atmospheric coherence scale > antenna size
variation time scale ~min (radio) vs. ms (optical)
$\rightarrow$ phases can be calibrated in radio (with nearby compact source)

# Science highlights (VLBI)

***Astrophysics***

- active galactic nuclei, imaging the close vicinity of supermassive BHs
- masers (galactic and extragalactic)
- radio stars, supernovae
- microquasar jets

***Astrometry***

- definition and densification of the celestial reference frame (ICRF)

***Geodesy/geophysics***

- terrestrial reference frame
- Earth orientation and rotation (the length of day)
- tectonic plate motion

***Space science***

- Spacecraft tracking (Huygens, SMART-1)

# Interferometric imaging: some theory

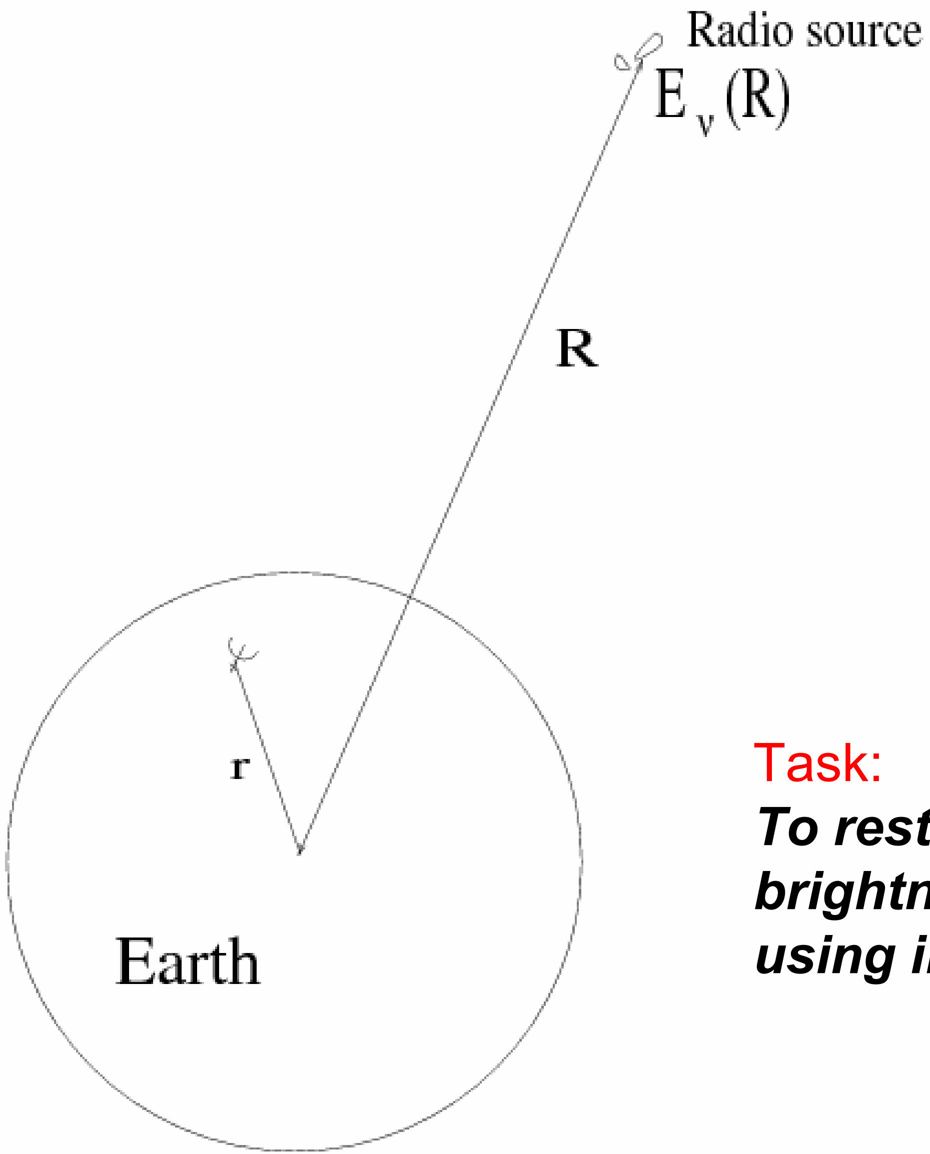
***Recommended reading:***

Clark B.G. (1995): Interferometers and Coherence Theory, *ASP Conf. Ser. 83*, p. 3
(on-line: http://www.cv.nrao.edu/vlbabook/clark.ps.gz)

Cornwell T. (1995): Imaging Concepts, *ASP Conf. Ser. 83*, p. 39
(on-line: http://www.cv.nrao.edu/vlbabook/cornwell.ps.gz)

Jackson N.J. (2006): Principles of interferometry
(on-line: http://www.jb.man.ac.uk/~njj/int.ps.gz)

Thompson A.R., Moran J.R., Swenson G.W., Jr. (1986): *Interferometry and Synthesis in Radio Astronomy* (New York: Wiley; reprints: Malabar: Krieger)
*(for the more serious)*




Task:

***To restore the radio source brightness distribution on the sky, using interferometric visibility data***

The fundamental equations of aperture synthesis *(from Clark 1995)*

$$\mathbf{E}_\nu(\mathbf{r}) = \int_{\text{source}} P_\nu(\mathbf{R},\mathbf{r})\mathbf{E}_\nu(\mathbf{R})\, dS$$

*P* describes how the electromagnetic radiation propagates through the space between the source at ***R*** and the antenna at ***r***

Simplified for an empty space:

$$\mathbf{E}_\nu(\mathbf{r}) = \int \frac{\mathbf{E}(\mathbf{R}) e^{2\pi i\nu|\mathbf{R}-\mathbf{r}|/c}}{|\mathbf{R}-\mathbf{r}|}\, dS$$

*the quasi-monochromatic component of the time-varying electric field*

The correlation of the field at two different observer locations $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ (i.e. two ends of an interferometer):

$$\mathbf{V}_\nu(\mathbf{r}_1, \mathbf{r}_2) = \langle \mathbf{E}_\nu(\mathbf{r}_1)\mathbf{E}^*_\nu(\mathbf{r}_2)\rangle$$

After a reasonable assumption that the radiation from two different points of the source is uncorrelated, we get

$$\mathbf{V}_\nu(\mathbf{r}_1, \mathbf{r}_2) = \int \left\langle |\mathbf{E}(\mathbf{R})|^2 \right\rangle |\mathbf{R}|^2 \frac{e^{2\pi i\nu|\mathbf{R}-\mathbf{r}_1|/c}}{|\mathbf{R}-\mathbf{r}_1|} \frac{e^{-2\pi i\nu|\mathbf{R}-\mathbf{r}_2|/c}}{|\mathbf{R}-\mathbf{r}_2|} dS$$

If $\boldsymbol{R} >> \boldsymbol{r}$ (the far-field condition), then

$$|\mathbf{R}-\mathbf{r}| = \sqrt{|\mathbf{R}|^2 + |\mathbf{r}|^2 - 2\mathbf{r}\cdot\mathbf{R}} \approx |\mathbf{R}| - \frac{\mathbf{r}\cdot\mathbf{R}}{|\mathbf{R}|}$$

Further simplifications to make the life easier:
- ignore the vector nature of ***V***
- introduce the intensity of the radiation field $I = |\mathbf{R}|^2 \langle |\mathbf{E}_\nu| \rangle^2$
- use the unit vector ***s*** pointing to the direction of ***R***
- integrate over the solid angle subtended by the radio source

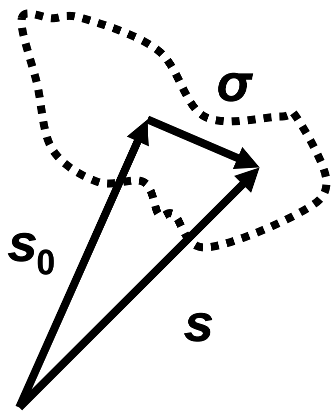
$$V_\nu(\mathbf{r}_1, \mathbf{r}_2) = \int I_\nu(\mathbf{s}) e^{-2\pi i \nu \mathbf{s}\cdot(\mathbf{r}_1 - \mathbf{r}_2)/c} \, d\Omega$$

*V is the spatial coherence function*

Important note: it depends on $\mathbf{r}_1 - \mathbf{r}_2$ only, i.e. one end of the baseline can be moved into an arbitrary location

Under certain conditions, $V$ is invertible, and the intensity distribution of the source can be resonstructed.

Let's introduce a special coordinate system:




$\boldsymbol{s} = \boldsymbol{s}_0 + \boldsymbol{\sigma}$

the source is "small" $\rightarrow \boldsymbol{s}_0 \perp \boldsymbol{\sigma}$

$\boldsymbol{s}_0 = (0, 0, 1)$ *phase center*

$\boldsymbol{s} = (x, y, 1)$

The coordinates of the baseline vector $\boldsymbol{r}_1 – \boldsymbol{r}_2$ in this system are

$$\boldsymbol{r}_1 – \boldsymbol{r}_2 = c/\nu\ (u, v, w) = \lambda\ (u, v, w)$$

We can now rewrite the spatial coherence function with the *(x, y)* sky coordinates and the *(u, v)* coordinates:

$$V_\nu(\mathbf{r}_1, \mathbf{r}_2) = \int I_\nu(\mathbf{s}) e^{-2\pi i \nu \mathbf{s}\cdot(\mathbf{r}_1 - \mathbf{r}_2)/c} \, d\Omega$$

$$V_\nu(u, v, w) = e^{-2\pi i w} \iint I_\nu(x, y) e^{-2\pi i (ux + vy)} \, dx \, dy$$

Fourier-transform, may be formally inverted:

$$I_\nu(x, y) = \iint V_\nu(u, v) e^{2\pi i (ux + vy)} \, du \, dv$$

In practice, the spatial coherence fuction is (by far) not sampled everywhere in the *(u, v)* plane – i.e. our hypothetical aperture is not filled *(see coverage plots later)*

Instead, we have a sampling function *S(u, v)*, of which the possible values are 1 or 0, if measrements are taken or not

$$I_\nu^D(x, y) = \iint V_\nu(u, v) S(u, v) e^{2\pi i(ux+vy)}\, du\, dv$$

This is called **dirty image** in the radio interferometry jargon

$I_\nu^D = I_\nu * B$ , where $B(x, y) = \iint S(u, v) e^{2\pi i(ux+vy)}\, du\, dv$

is the **dirty beam** or, in other words, the interferometer's response to a point source (PSF)

In practical imaging, the sampling function *S(u, v)* is coupled with some form of data weighting

$$S(u,v) = \sum_k w_k \delta(u - u_k)\delta(v - v_k)$$

For example, *natural weighting* uses some power (-2 or sometimes -1) of the noise associated with the *k*-th data point (optimal for image noise level):

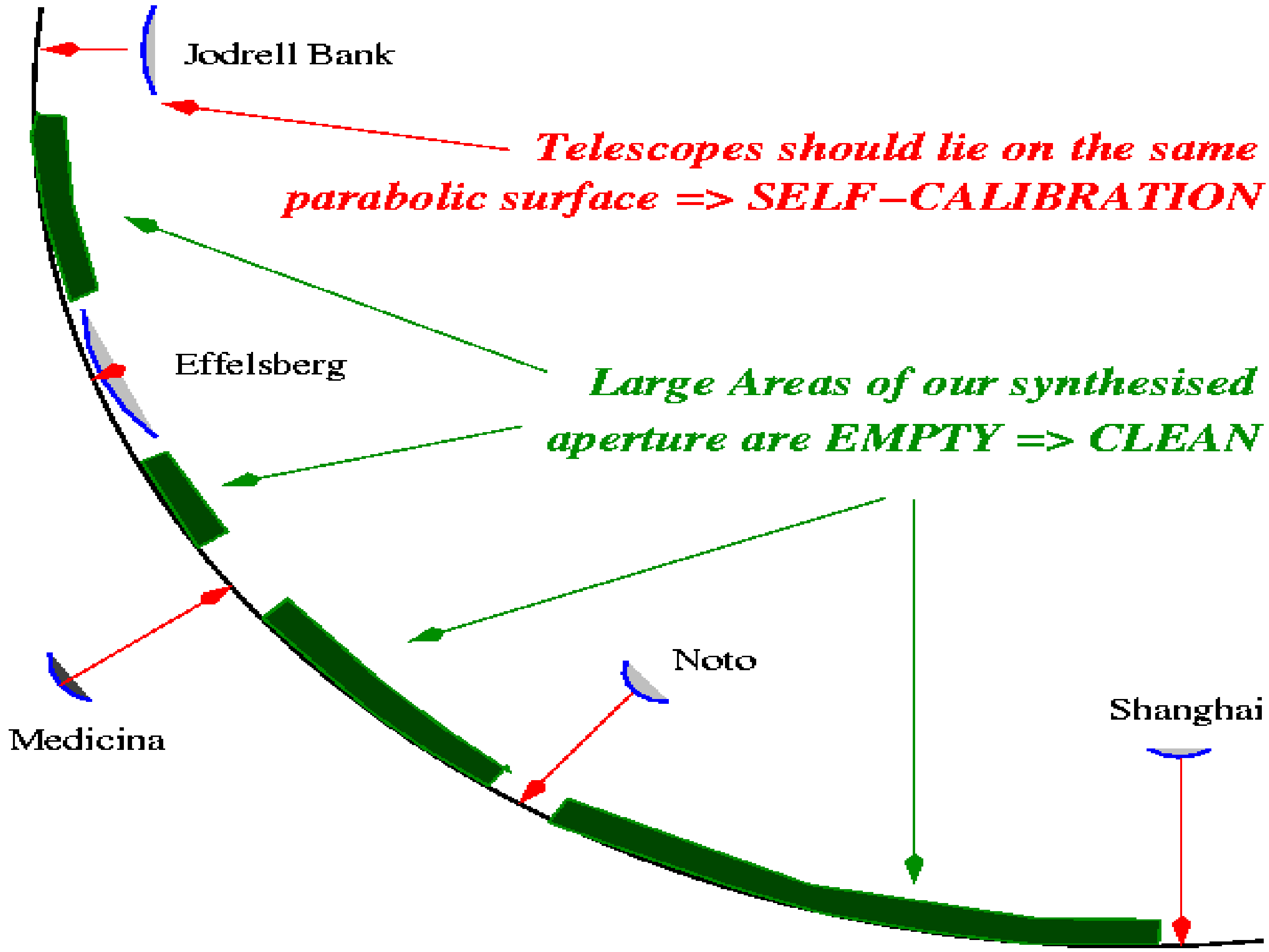
$$w_k = \frac{1}{\sigma_k^2}$$

In *uniform weighting*, the weight attached to a visibility point is inversely proportional to the local density of the data points in the *(u,v)* plane (optimal for high angular resolution):

$$w_k = \frac{1}{\rho(u_k, v_k)}$$

***Task:*** *to synthesise a giant radio telescope from small antennas*

- Earth rotation helps to fill in the (*u*,*v*) plane
- Computational “tricks” are needed to restore the source brightness distribution on the sky (i.e. to make an image of the source)



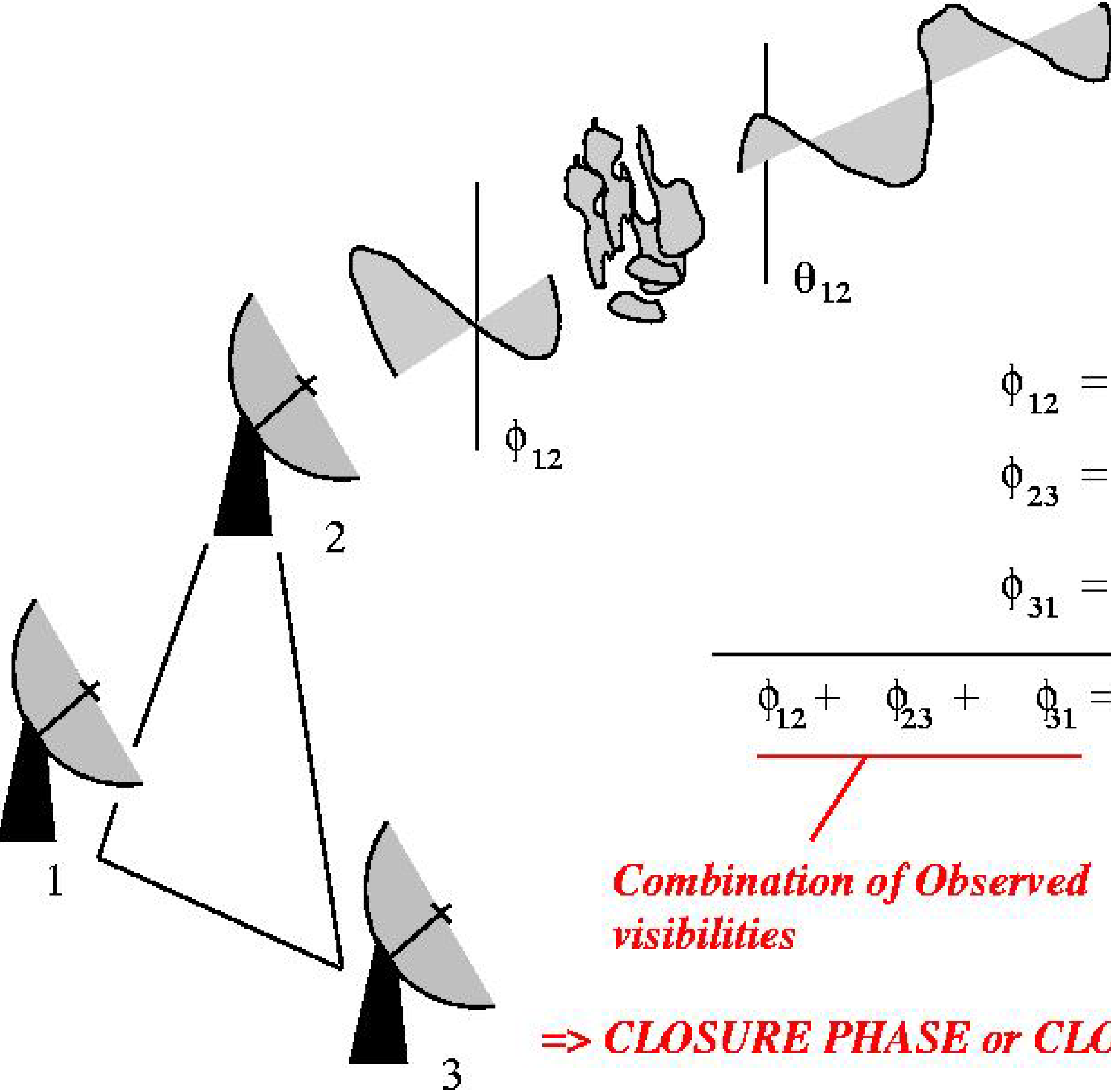
# Trick #1: Self-calibration

• Path length of radiation from the radio source to the telescope is not constant, e.g. phase errors are introduced via atmosphere above telescopes, clock errors, etc.

• For an array of *N* telescopes we measure (instantaneously) *N(N-1)/2* corrupted interferometer measurements

• ***self-calibration*** is based on understanding that the corrupted visibilities mostly arise from telescope-based errors – and there are only *N* of these

• it is possible to solve for these *N* errors by using combinations of the corrupted visibilities (closure quantities) AND an assumed model of the source (***hybrid mapping,*** see later...)




$$\phi_{12} = \theta_{12} + \phi_1 - \phi_2$$

$$\phi_{23} = \theta_{23} + \phi_2 - \phi_3$$

$$\phi_{31} = \theta_{31} + \phi_3 - \phi_1$$

$$\phi_{12} + \phi_{23} + \phi_{31} = \theta_{12} + \theta_{23} + \theta_{31}$$

***Combination of Observed visibilities***

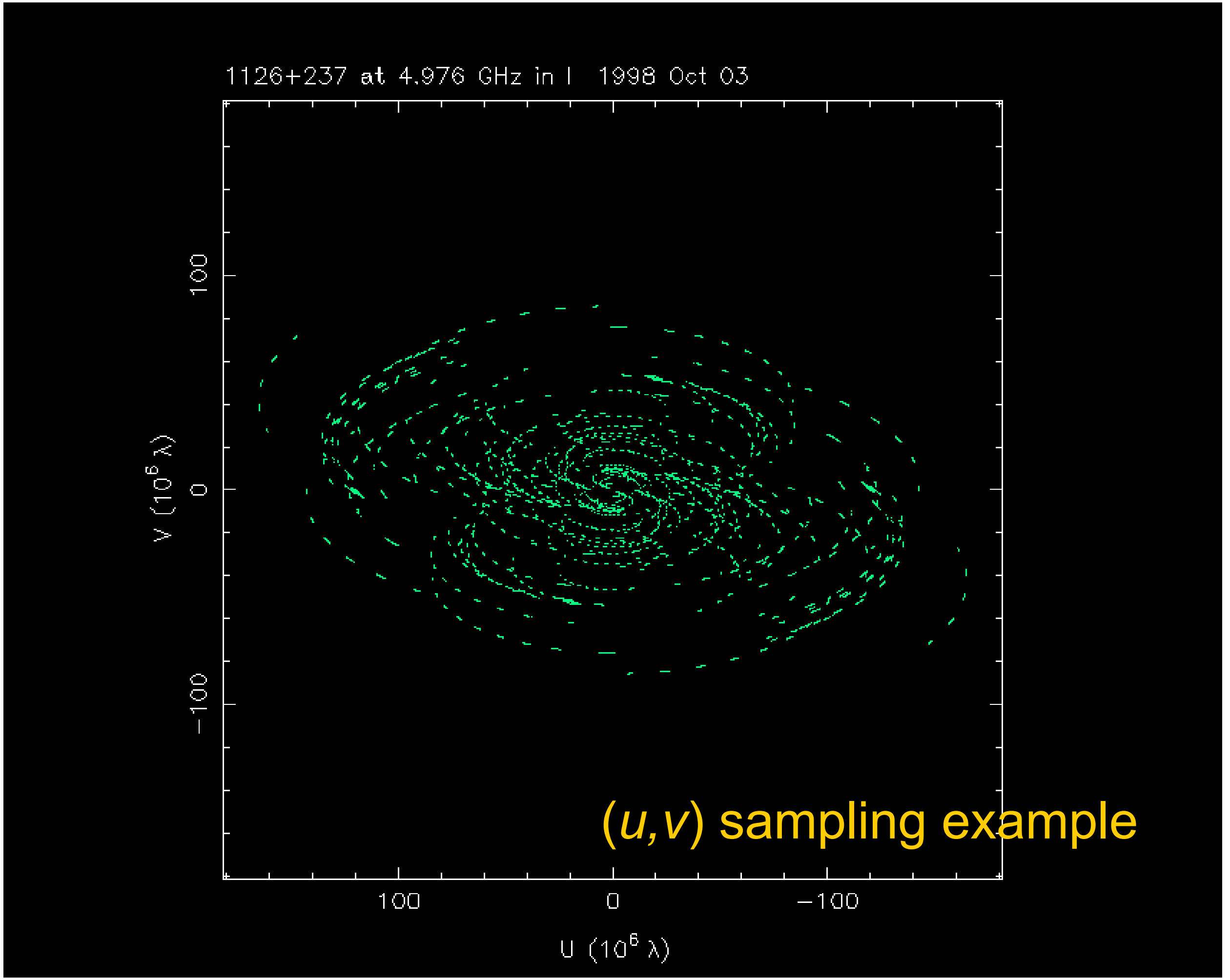
***Combination of TRUE visibilities***

***=> CLOSURE PHASE or CLOSURE QUANTITIES***

*(amplitudes are multiplicative; we need min. 4 antennas for closure)*

# Image deconvolution

- A VLBI synthesised aperture is not filled with data (in fact mostly ***empty***!)

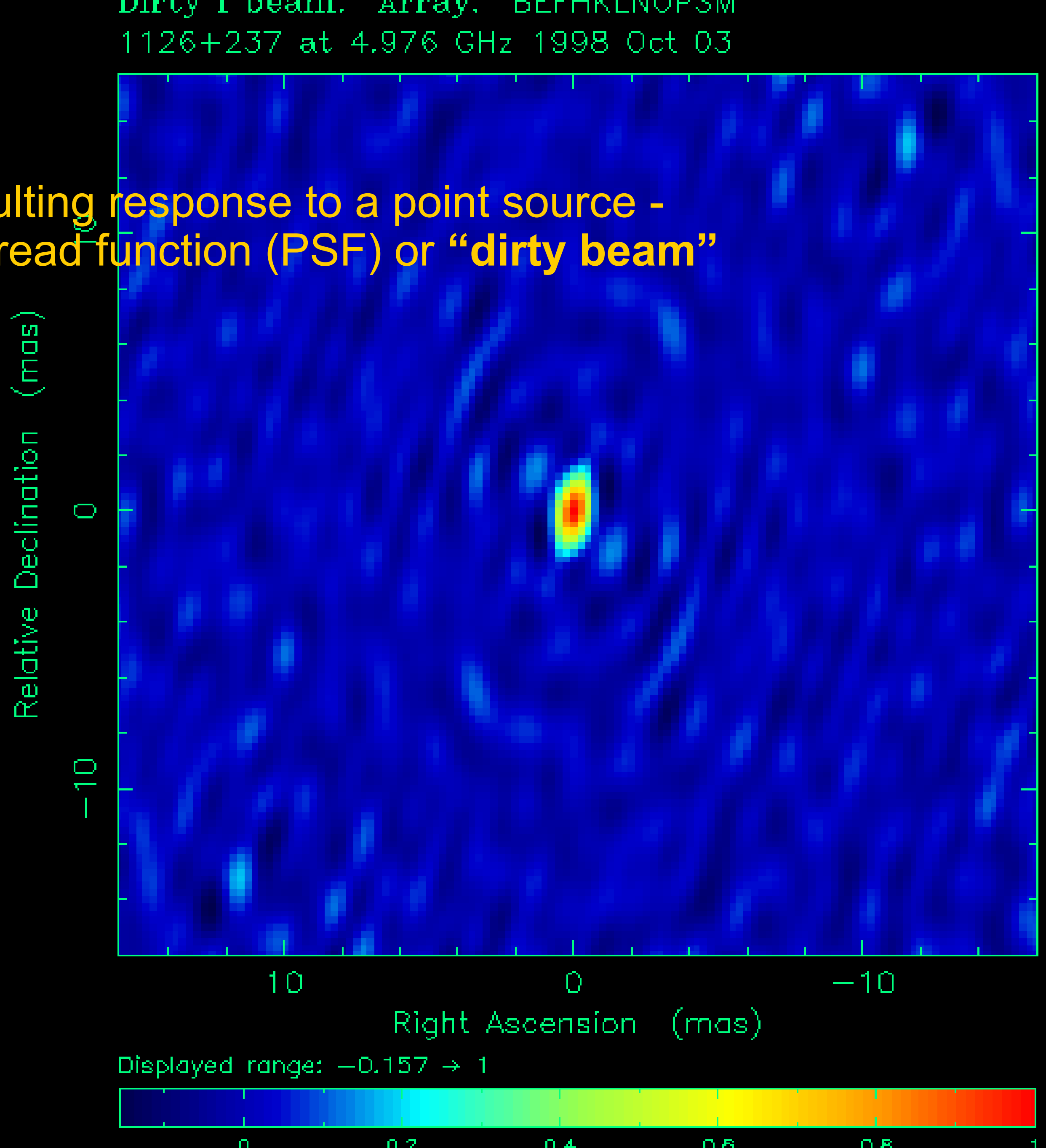


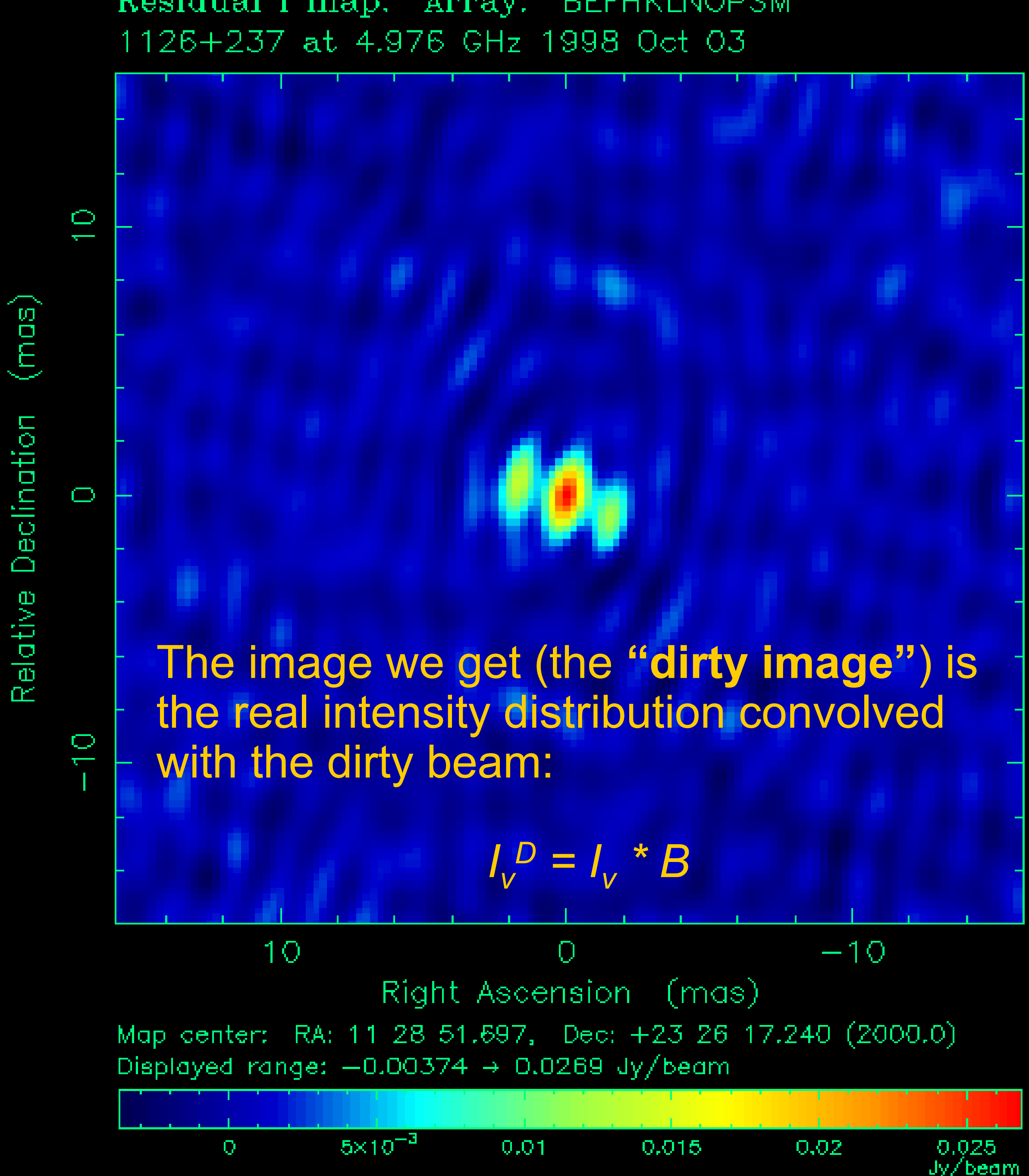
# Software

*Examples shown here (and the demonstration session) are prepared with the Caltech* ***Difmap*** *difference mapping software, one of the standard VLBI imaging packages*
*(see:* `www.astro.caltech.edu/~tjp/citvlb`*)*

*"The" radio interferometry data reduction package is the NRAO Astronomical Image Processing System (****AIPS****), suitable for initial calibration, fringe-fitting, editing, averaging, imaging, and a lot more…*
*(*`www.aips.nrao.edu`*)*

The resulting response to a point source -
point spread function (PSF) or **“dirty beam”**






The image we get (the **"dirty image"**) is the real intensity distribution convolved with the dirty beam:

$$I_\nu^D = I_\nu * B$$

# Trick #2: CLEAN algorithm

• Basic assumption: the sky brightness distribution can be decomposed into a finite number of ***point sources***

• Sequence of steps:
- pick the brightest point in the dirty map
- multiply the peak by the loop gain (<1)
- subtract a point source response (dirty beam) with a flux density maximum * the loop gain from the dirty image
- store the component's position and intensity
- next iteration (until there is a peak above the noise level on the residual map)

• after many iterations, a CLEAN component model is built up at the end

• final image: the ***CLEAN model*** convolved with an ***"ideal" beam*** (a fitted Gaussian in practice) + the residual image is added

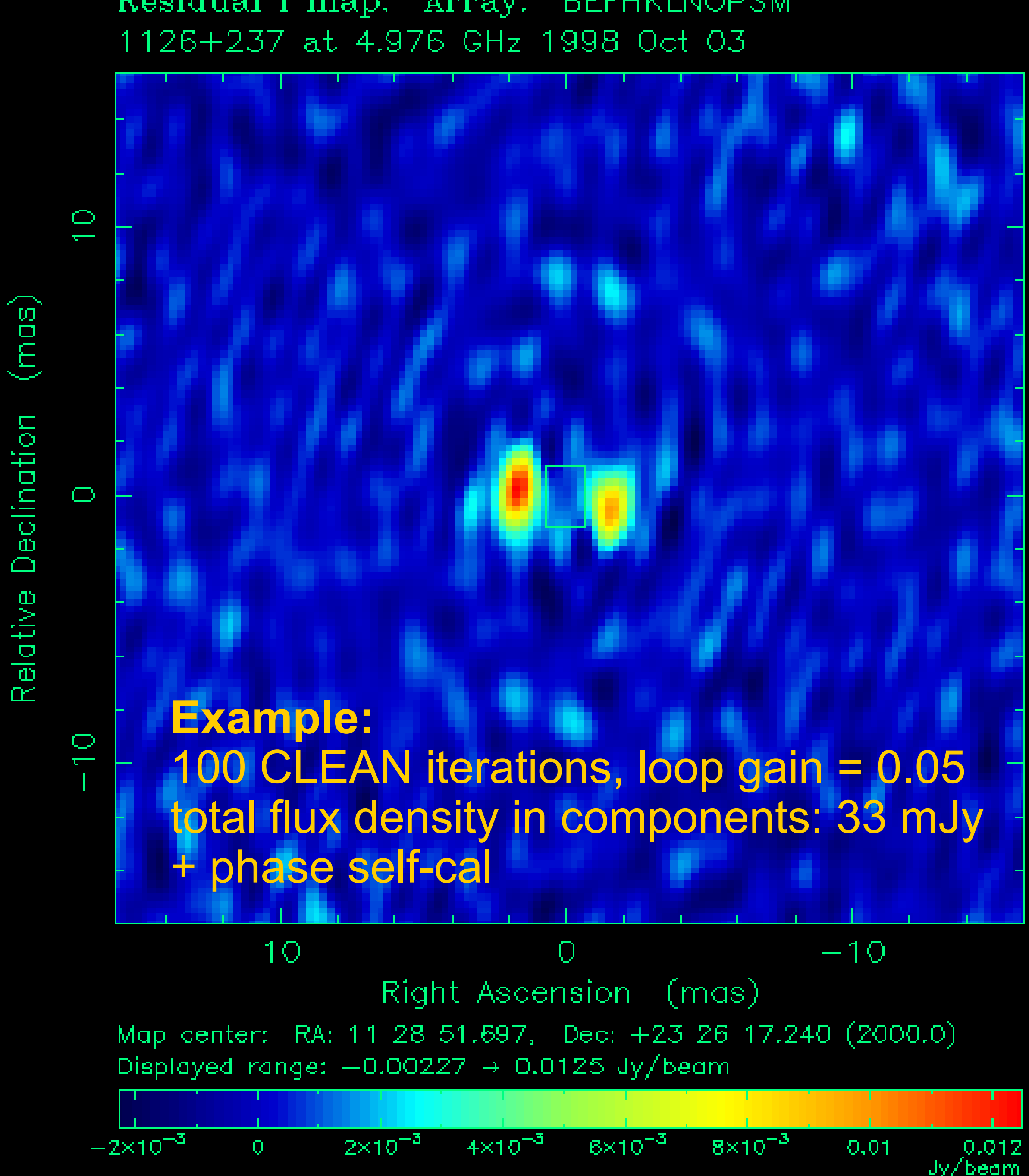
# Hybrid mapping

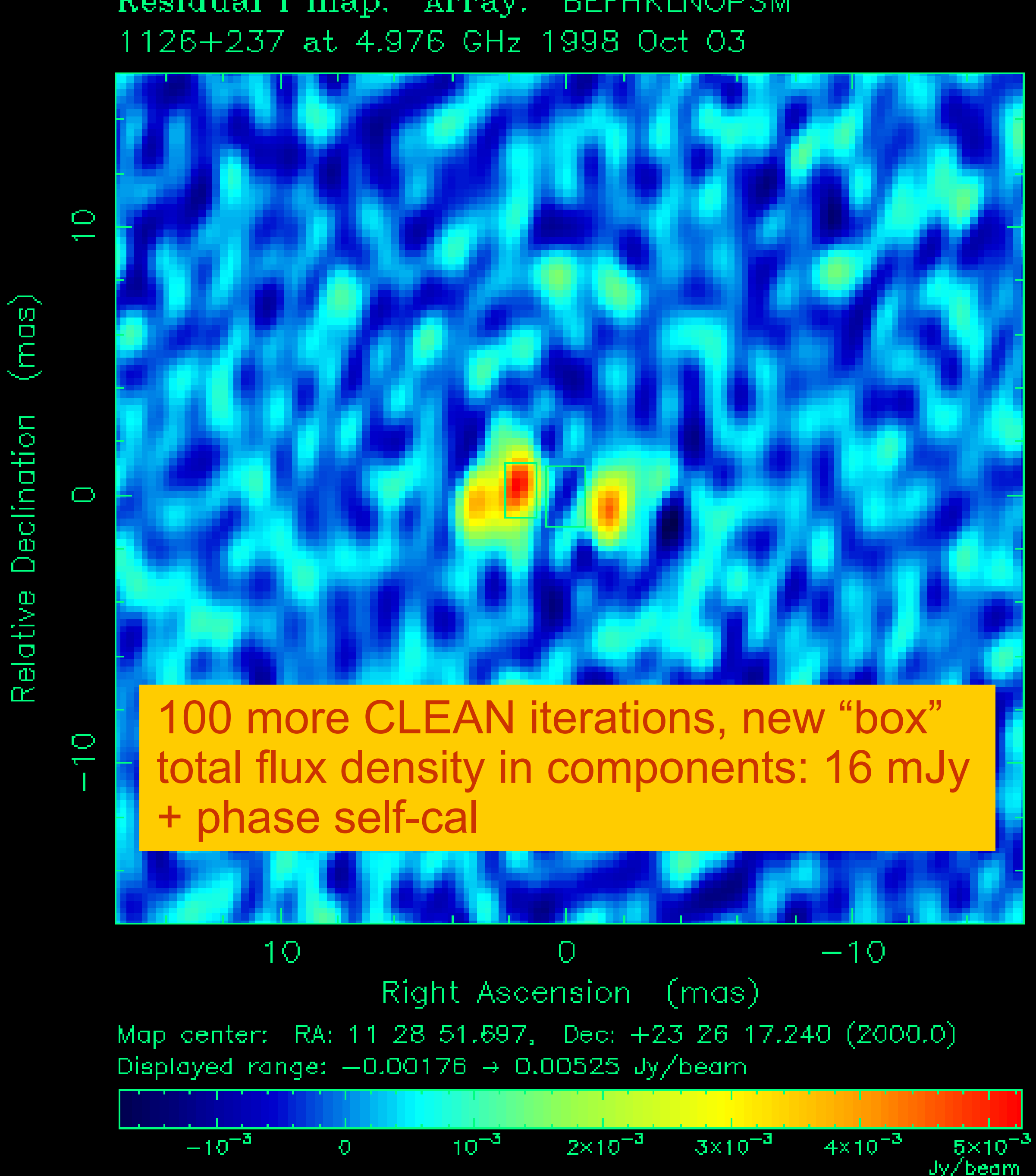
• A combination of ***deconvolution*** (e.g. CLEAN) and ***self-calibration***
• The CLEAN model from the previous stage is used as a source model for self-cal

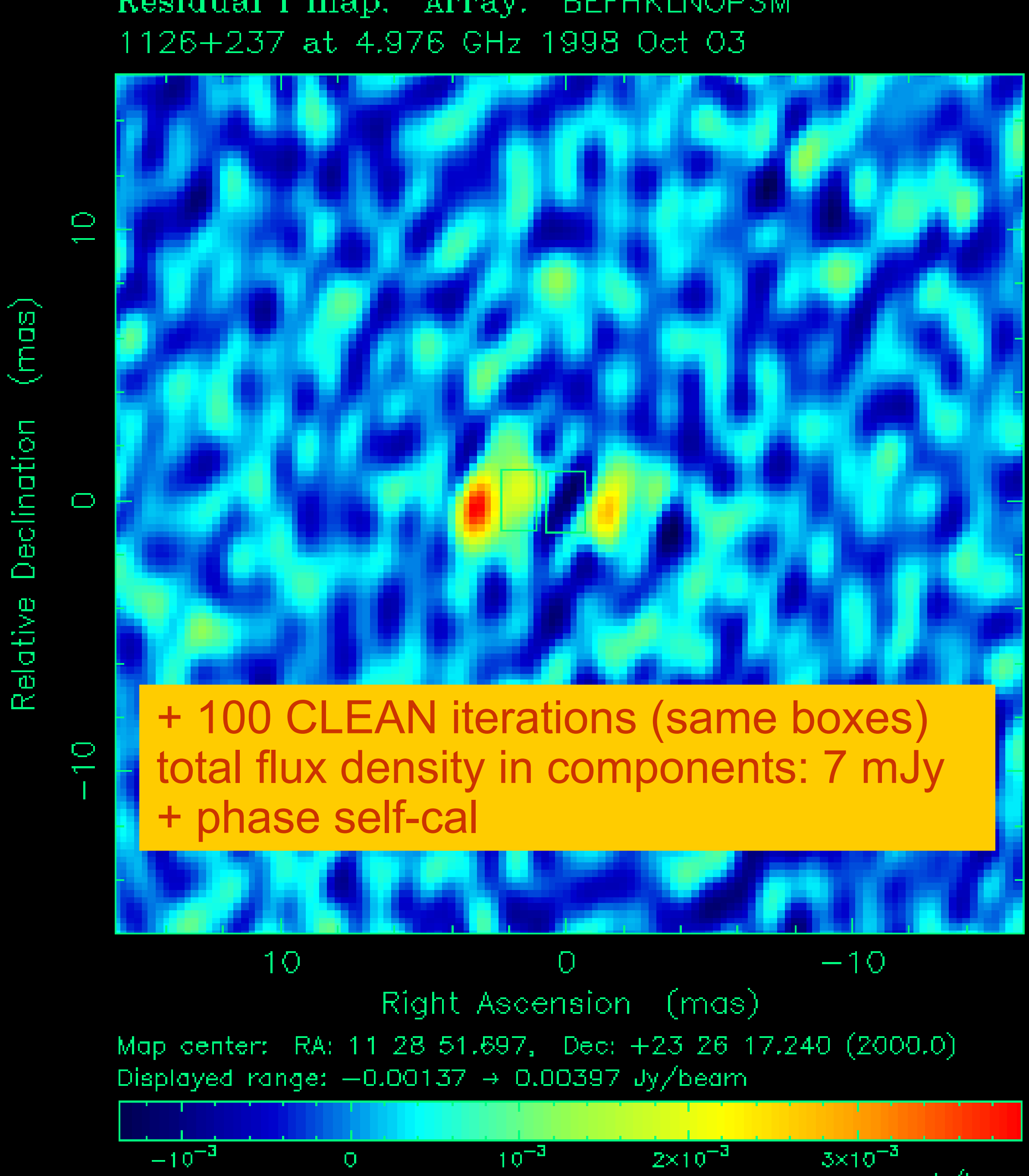
• Sequence of steps:
- start with a simple initial source model (i.e. point)
- predict visibilities according to the model
- keep the observed amplitudes
- solve for antenna-specific phase errors using the closure phases
- correct the observed visibilities with antenna phase errors
- form a new dirty image
- use deconvolution (CLEAN) to obtain an improved model
- next iteration

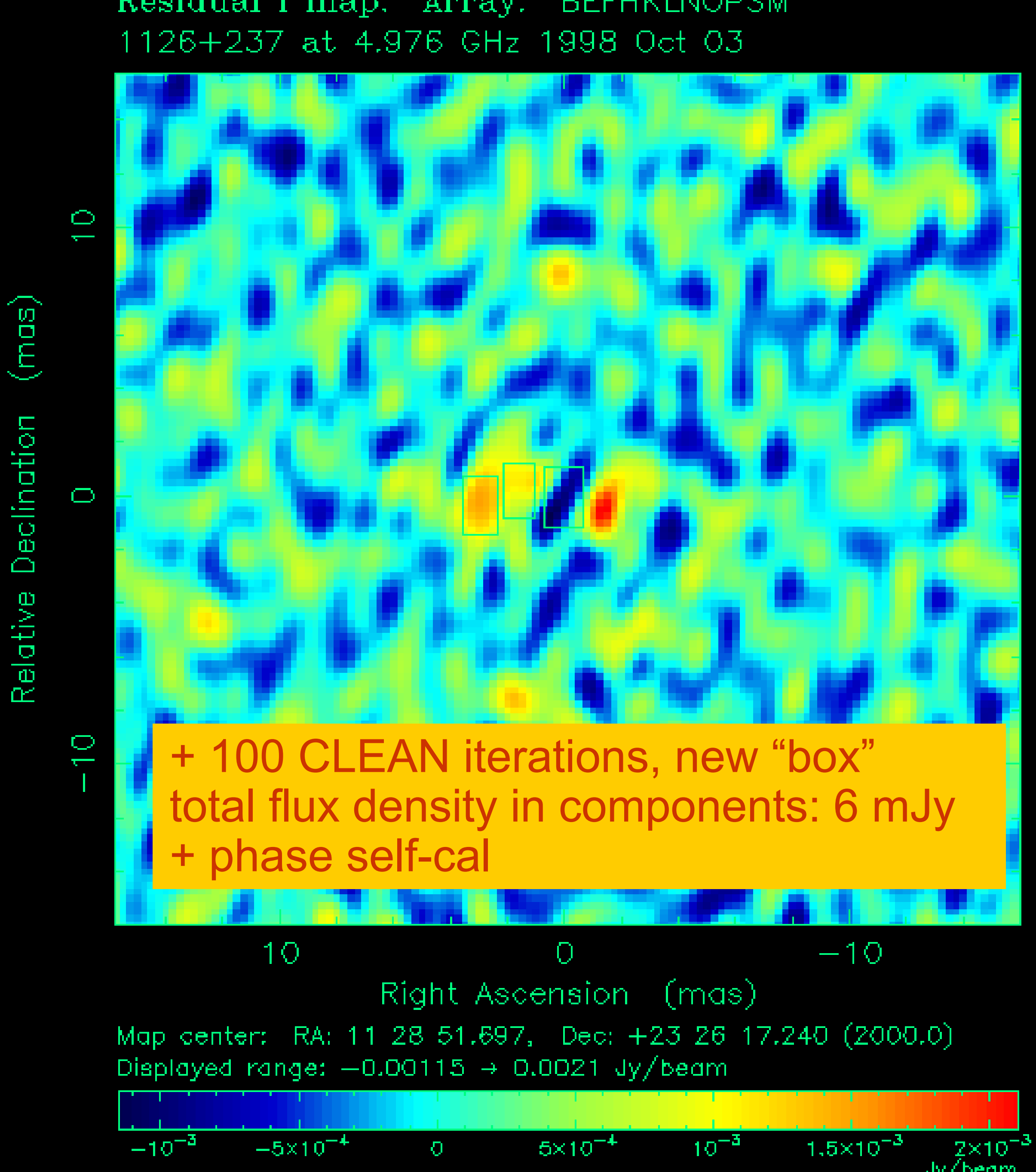
• after sufficient number of phase-only self-cal, antenna gain (amplitude) corrections can be determined gradually

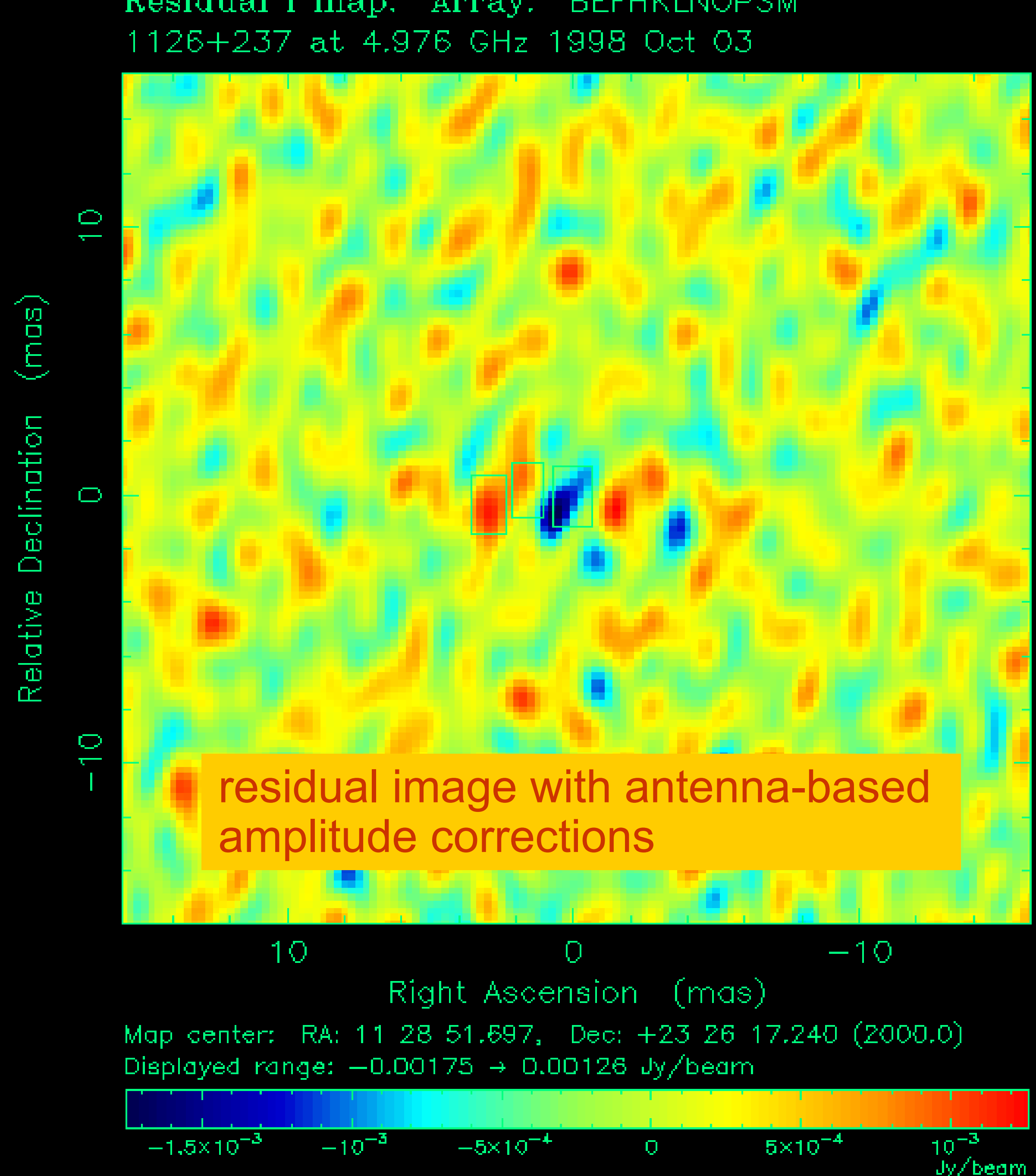
• the process converges to the final image
• *a SNR of at least ~3 is needed within the atmospheric coherence time*

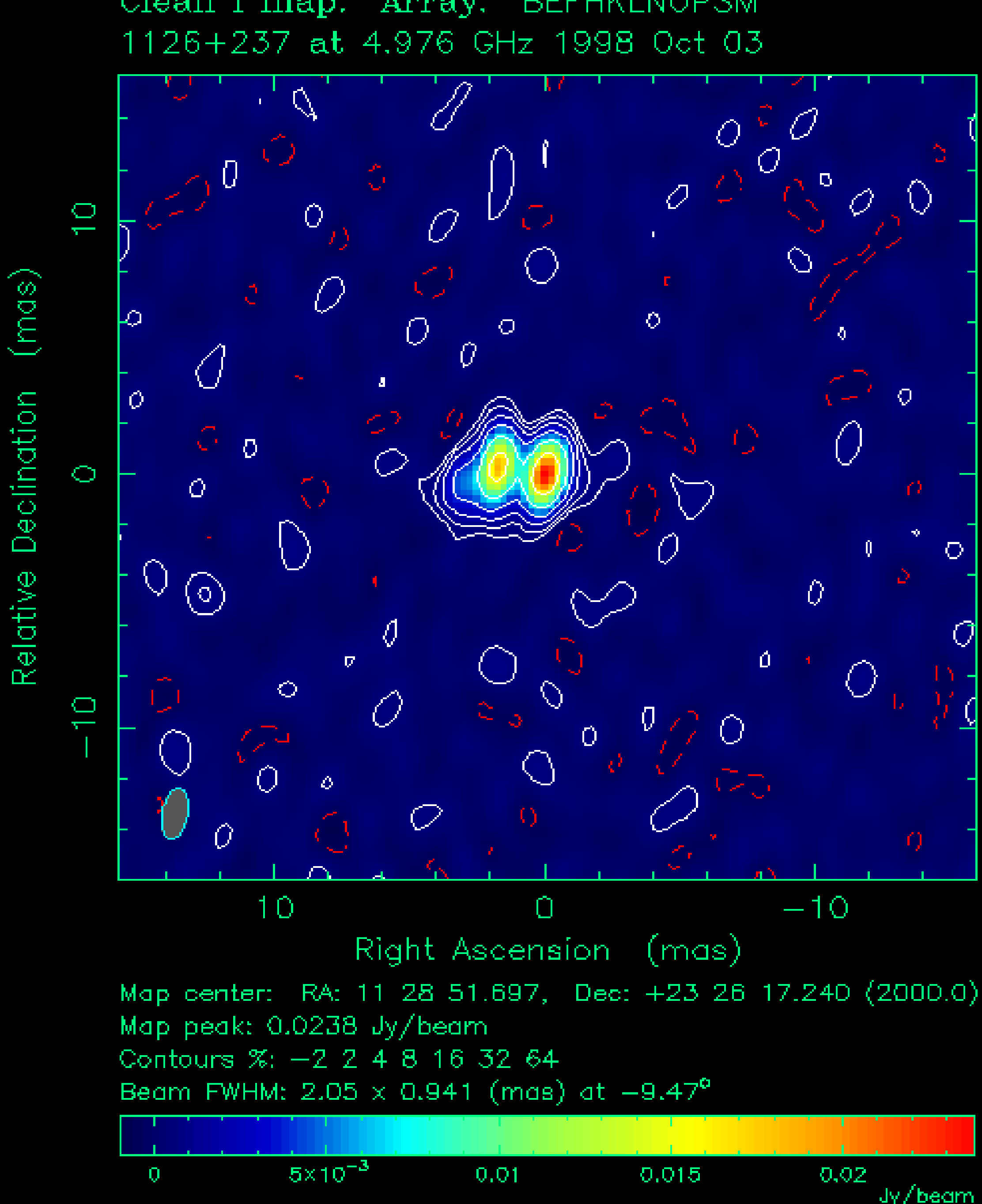

1126+237 at 4.976 GHz 1998 Oct 03
Example:
100 CLEAN iterations, loop gain = 0.05
total flux density in components: 33 mJy
+ phase self-cal
Relative Declination (mas)
10
0
−10
Right Ascension (mas)
Map center: RA: 11 28 51.697, Dec: +23 26 17.240 (2000.0)
Displayed range: −0.00227 → 0.0125 Jy/beam
−2x10^−3
0
2x10^−3
4x10^−3
6x10^−3
8x10^−3
0.01
0.012
Jy/beam

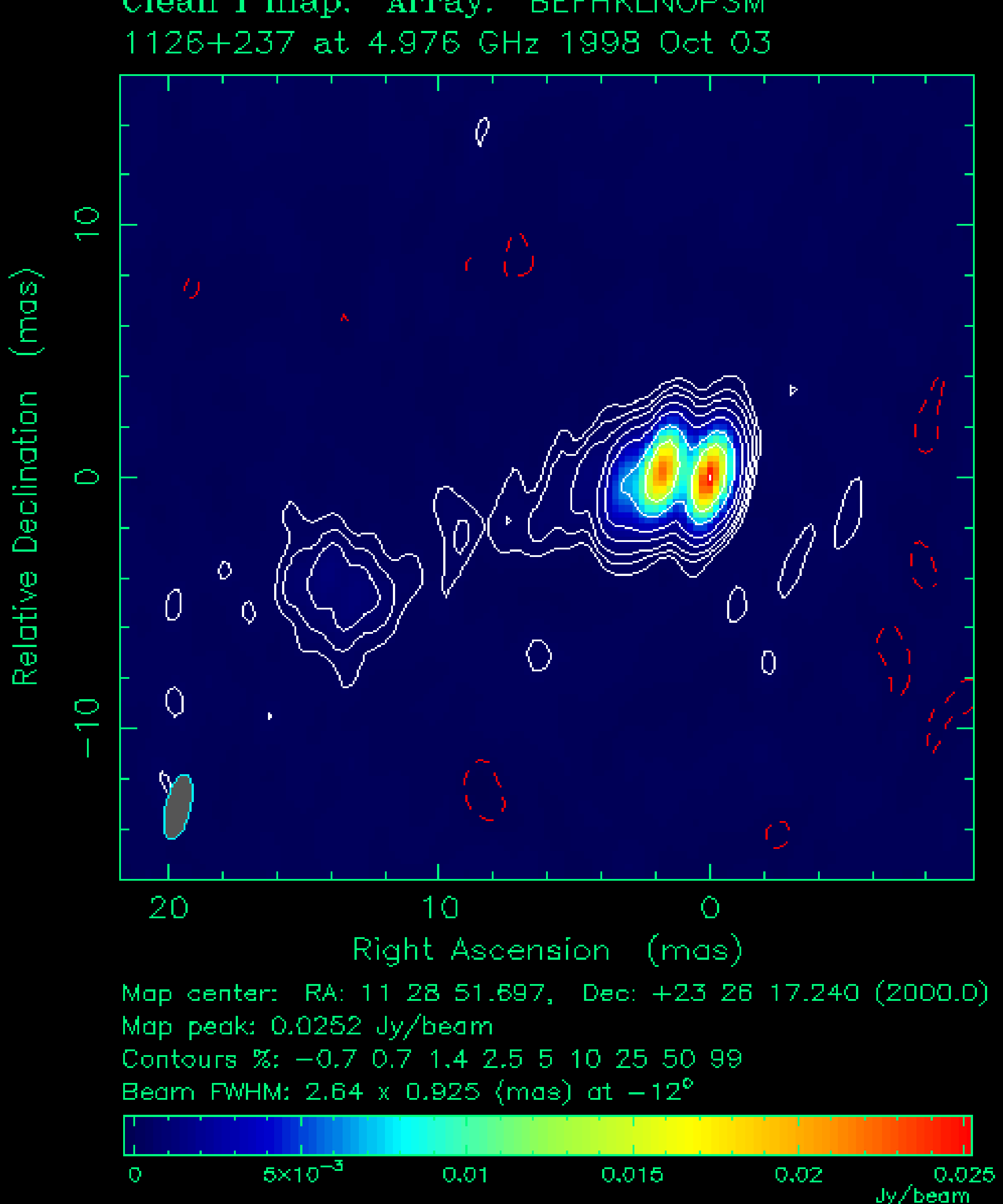

Residual I map. Array: BEFHKLNOPS3M
1126+237 at 4.976 GHz 1998 Oct 03
Relative Declination (mas)
10
0
−10
Right Ascension (mas)
Map center: RA: 11 28 51.697, Dec: +23 26 17.240 (2000.0)
Displayed range: −0.00176 → 0.00525 Jy/beam
−10^−3
0
10^−3
2x10^−3
3x10^−3
4x10^−3
5x10^−3
Jy/beam
100 more CLEAN iterations, new "box"
total flux density in components: 16 mJy
+ phase self-cal


1126+237 at 4.976 GHz 1998 Oct 03
10
0
−10
Relative Declination (mas)
10
0
−10
Right Ascension (mas)
Map center: RA: 11 28 51.697, Dec: +23 26 17.240 (2000.0)
Displayed range: −0.00137 → 0.00397 Jy/beam
$-10^{-3}$
0
$10^{-3}$
$2\times10^{-3}$
$3\times10^{-3}$
+ 100 CLEAN iterations (same boxes)
total flux density in components: 7 mJy
+ phase self-cal


1126+237 at 4.976 GHz 1998 Oct 03
Relative Declination (mas)
10
0
−10
Right Ascension (mas)
+ 100 CLEAN iterations, new “box”
total flux density in components: 6 mJy
+ phase self-cal
Map center: RA: 11 28 51.697, Dec: +23 26 17.240 (2000.0)
Displayed range: −0.00115 → 0.0021 Jy/beam
$-10^{-3}$
$-5\times10^{-4}$
0
$5\times10^{-4}$
$10^{-3}$
$1.5\times10^{-3}$
$2\times10^{-3}$


Residual I map. Array: BEFHKLNOPSM
1126+237 at 4.976 GHz 1998 Oct 03
Relative Declination (mas)
10
0
−10
Right Ascension (mas)
residual image with antenna-based
amplitude corrections
Map center: RA: 11 28 51.697, Dec: +23 26 17.240 (2000.0)
Displayed range: −0.00175 → 0.00126 Jy/beam
−1.5×10⁻³ −10⁻³ −5×10⁻⁴ 0 5×10⁻⁴ 10⁻³
Jy/beam


Clean I map. Array: BEFHKLNOPSM
1126+237 at 4.976 GHz 1998 Oct 03
Relative Declination (mas)
10
0
−10
Right Ascension (mas)
10
0
−10
Map center: RA: 11 28 51.697, Dec: +23 26 17.240 (2000.0)
Map peak: 0.0238 Jy/beam
Contours %: −2 2 4 8 16 32 64
Beam FWHM: 2.05 x 0.941 (mas) at −9.47°
0
5x10−3
0.01
0.015
0.02
Jy/beam

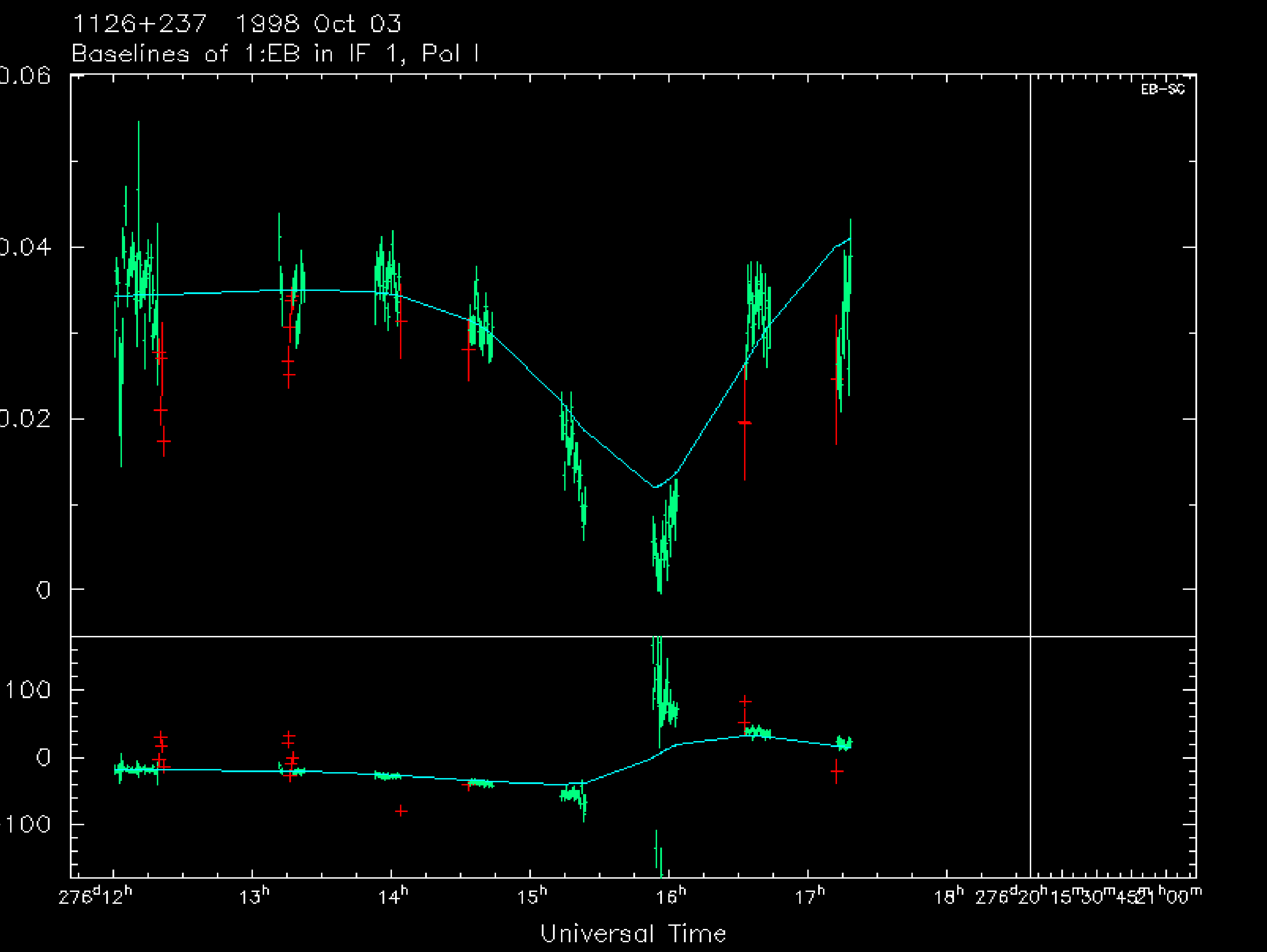

1126+237 at 4.976 GHz 1998 Oct 03
Relative Declination (mas)
Right Ascension (mas)
Map center: RA: 11 28 51.697, Dec: +23 26 17.240 (2000.0)
Map peak: 0.0252 Jy/beam
Contours %: -0.7 0.7 1.4 2.5 5 10 25 50 99
Beam FWHM: 2.64 x 0.925 (mas) at -12°
Jy/beam

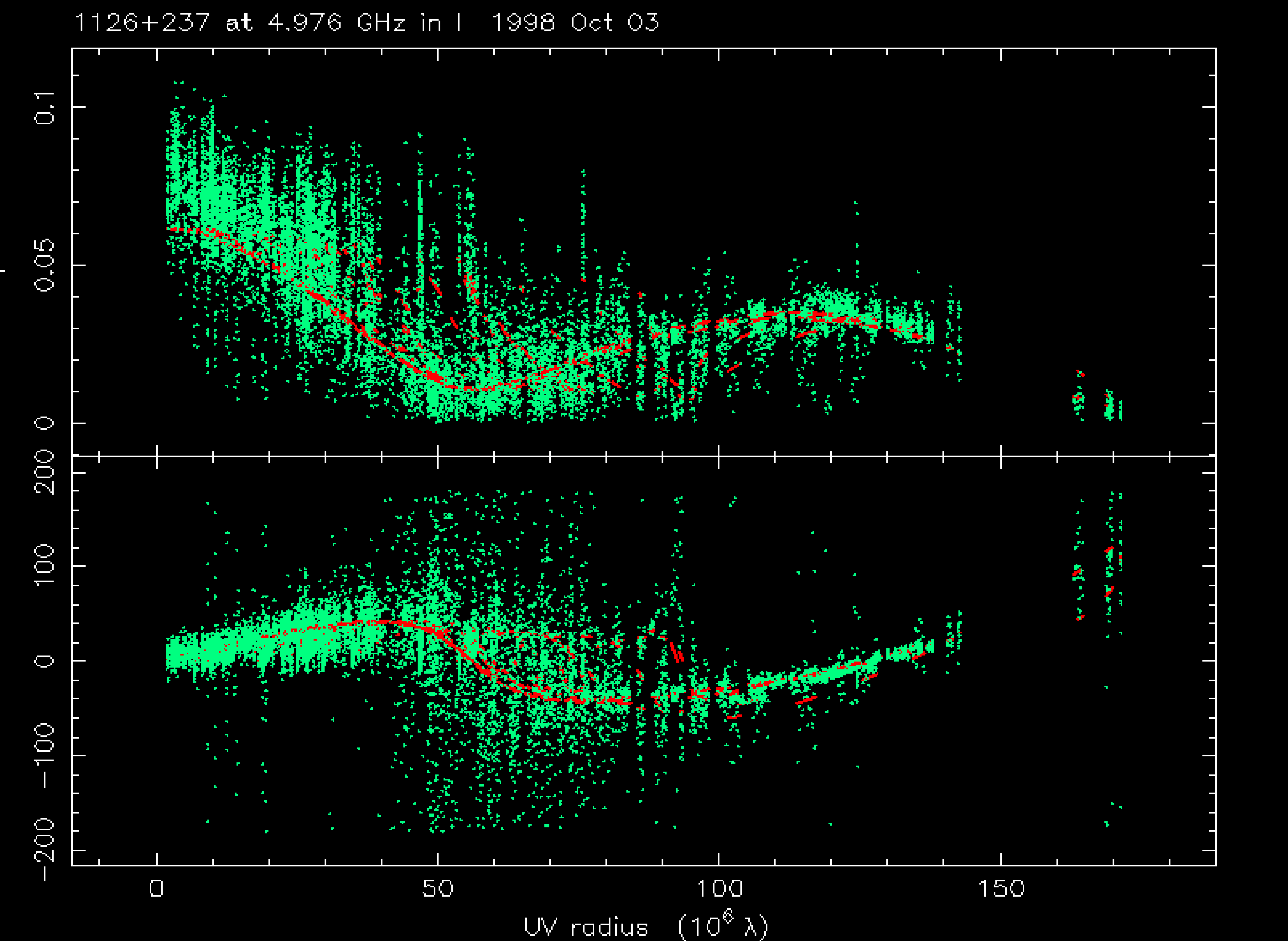
# Observed vs. model visibilities

It can be (and must be) checked how the ***observed*** and the ***model*** visibility amplitudes and phases are related during the hybrid mapping process, to keep an eye on convergence

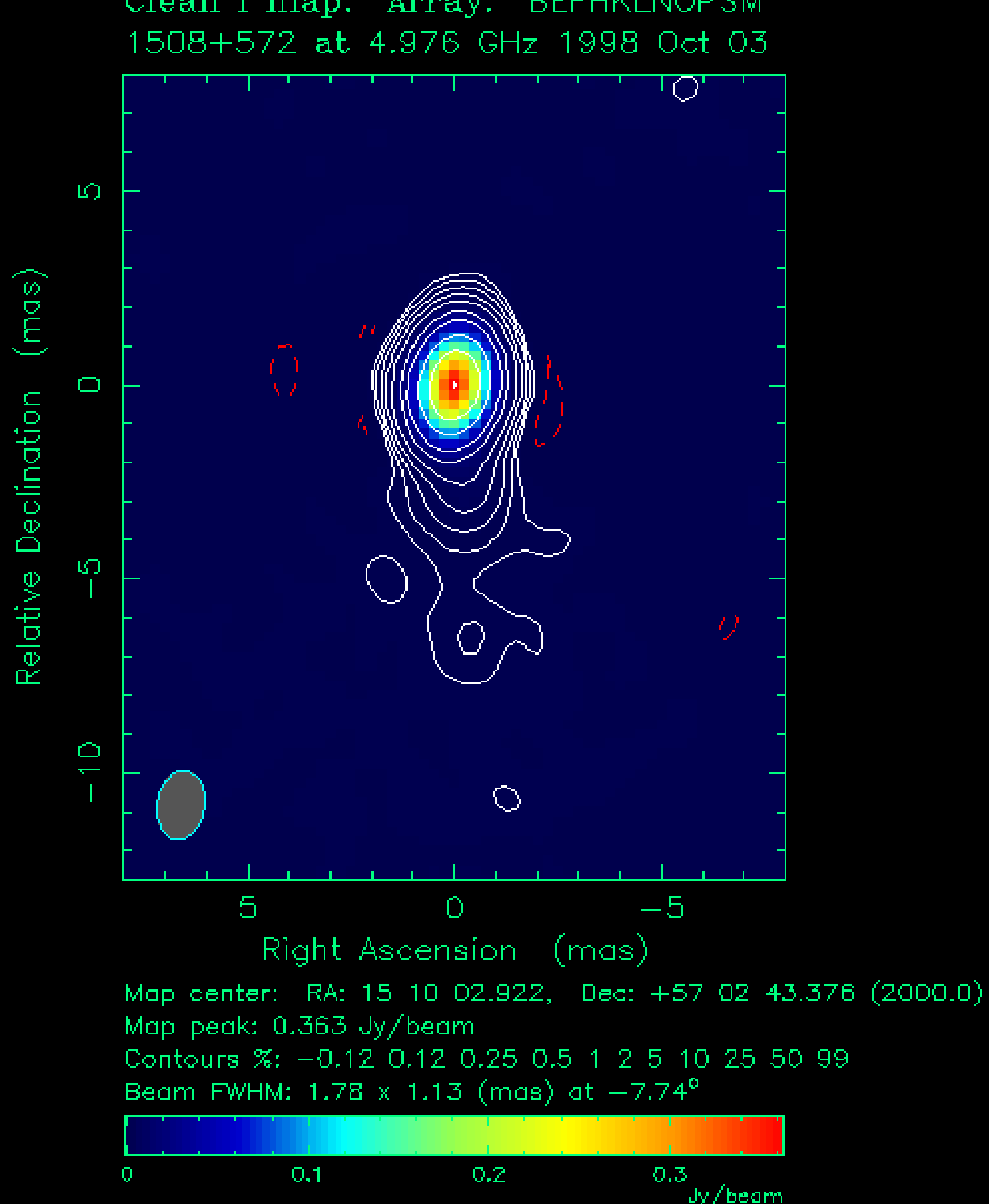
• amplitude & phase plots for each VLBI baseline as a function of time (**`vplot`**)

• correlated flux density & phase vs. projected baseline length plots (**`radplot`**)


1126+237 1998 Oct 03
Baselines of 1:EB in IF 1, Pol I
EB-SC
0.06
0.04
0.02
0
100
0
-100
276d12h
13h
14h
15h
16h
17h
18h
276d20h15m30m45m21h00m
Universal Time

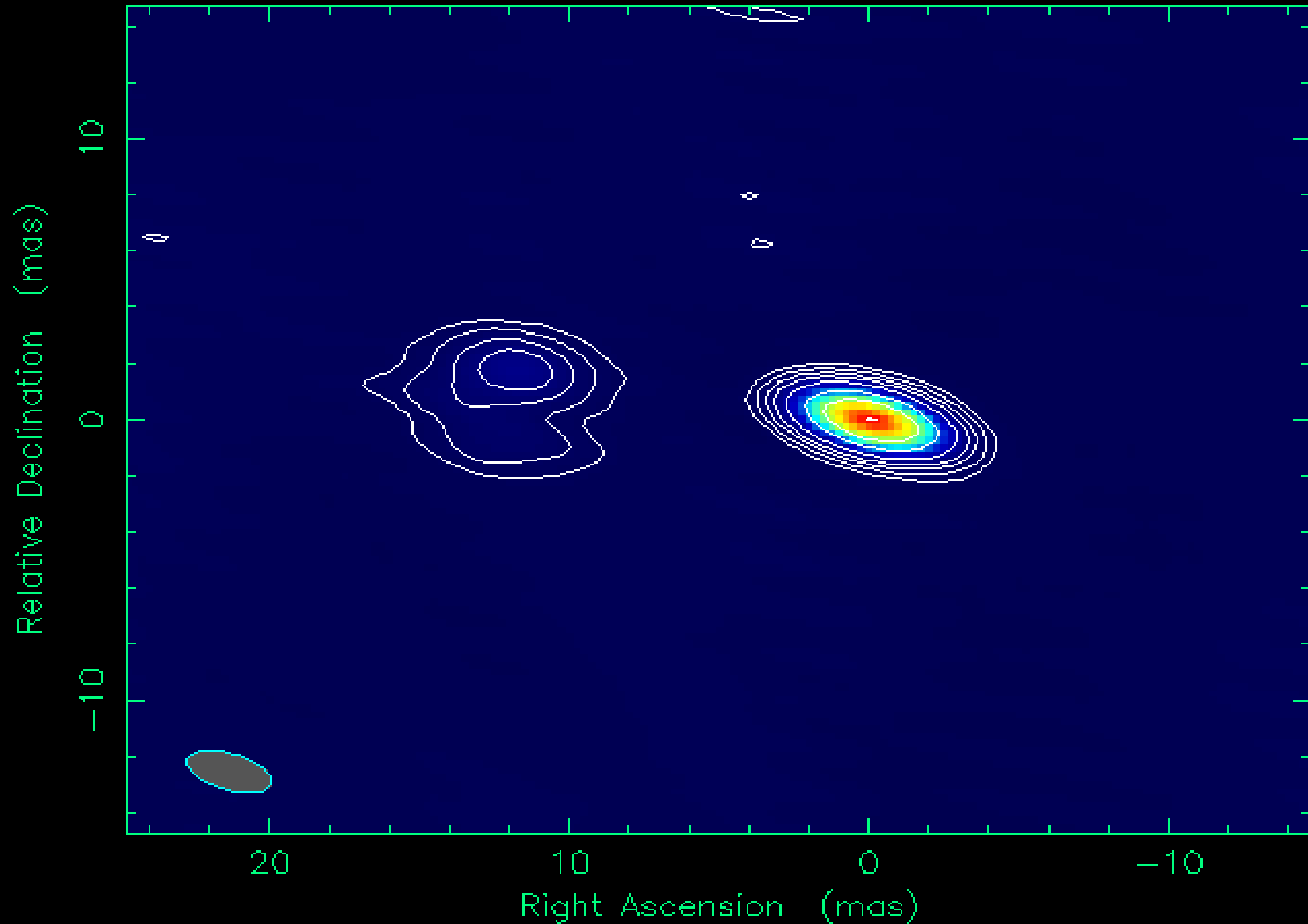


1126+237 at 4.976 GHz in I 1998 Oct 03
0.1
0.05
0
200
100
0
−100
−200
0
50
100
150
UV radius (10$^6$ λ)

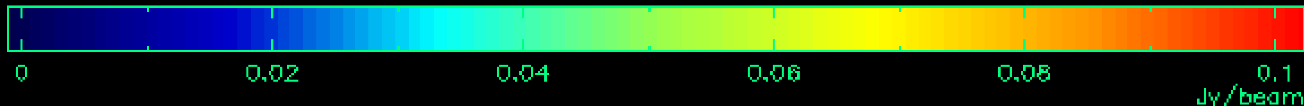


Clean I map. Array: BEFHKLNOPS3M
1508+572 at 4.976 GHz 1998 Oct 03
Relative Declination (mas)
5
0
−5
−10
Right Ascension (mas)
5
0
−5
Map center: RA: 15 10 02.922, Dec: +57 02 43.376 (2000.0)
Map peak: 0.363 Jy/beam
Contours %: −0.12 0.12 0.25 0.5 1 2 5 10 25 50 99
Beam FWHM: 1.78 x 1.13 (mas) at −7.74°
0
0.1
0.2
0.3
Jy/beam

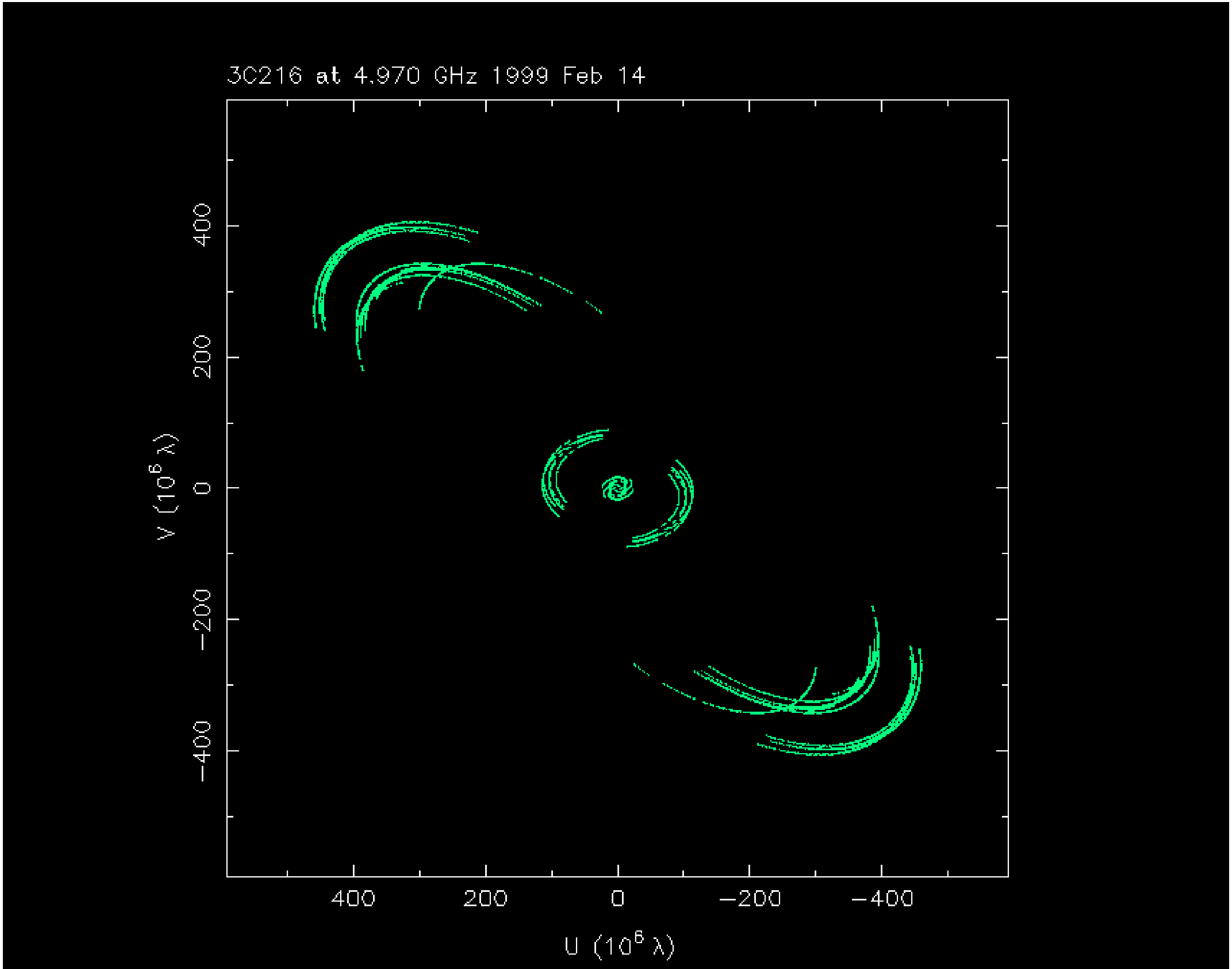
Clean I map. Array: EVN
J2134−04 at 4.971 GHz 1999 Nov 26



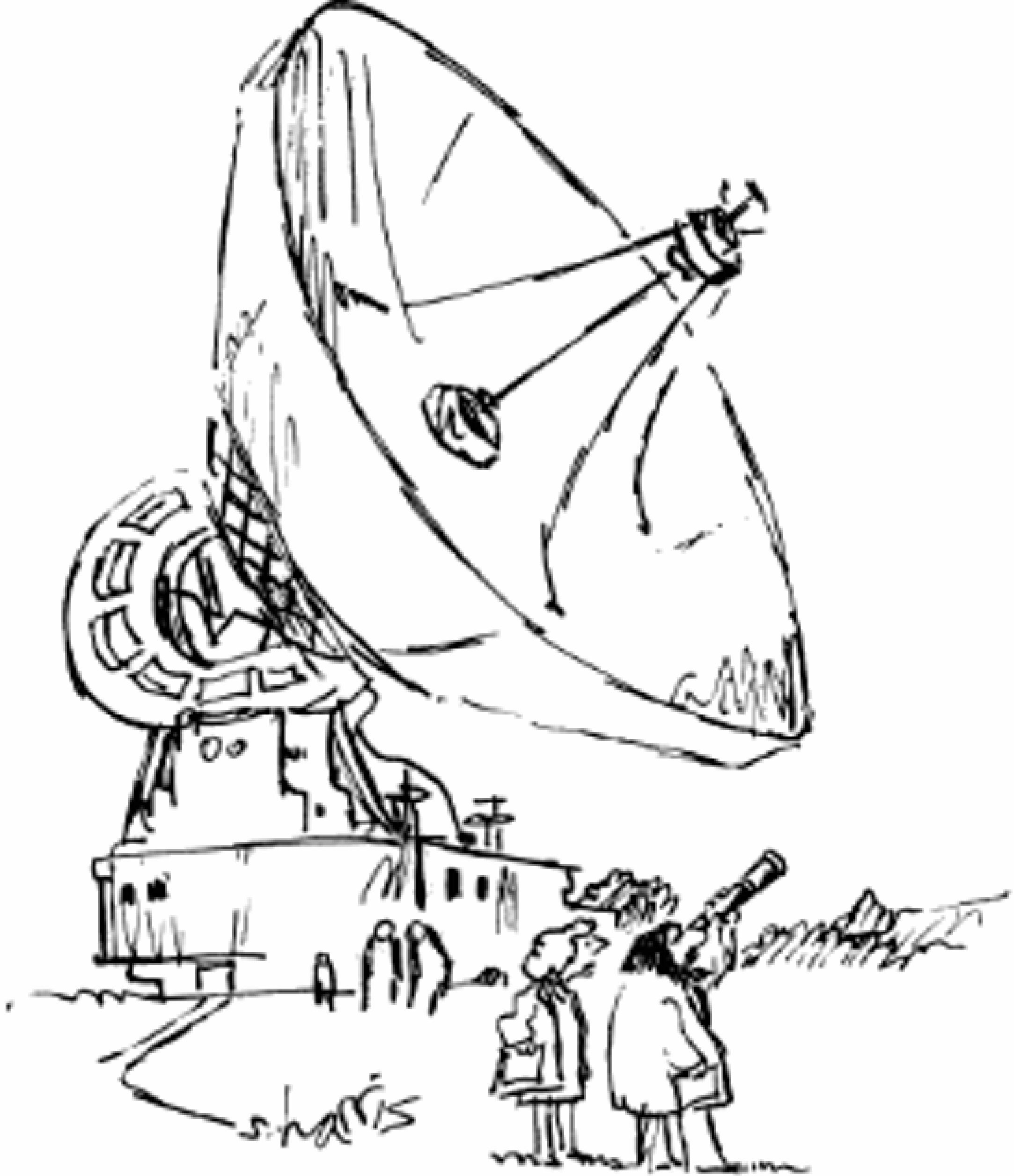

Map center: RA: 21 34 12.020, Dec: −04 19 09.900 (2000.0)
Map peak: 0.102 Jy/beam
Contours %: 0.7 1.5 3 5 10 25 50 99
Beam FWHM: 2.95 x 1.26 (mas) at 73.2°



# Space VLBI: (*u*,*v*) coverages



*Thanks for your attention!*




"Just checking."