Millimeter interferometers

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Outline

- The van Cittert–Zernike theorem
- The ideal interferometer

  $\hookrightarrow$ geometrical delay, source size, bandwidth
- The real interferometer

  $\hookrightarrow$ heterodyne receivers, delay correction, correlators
- Aperture synthesis

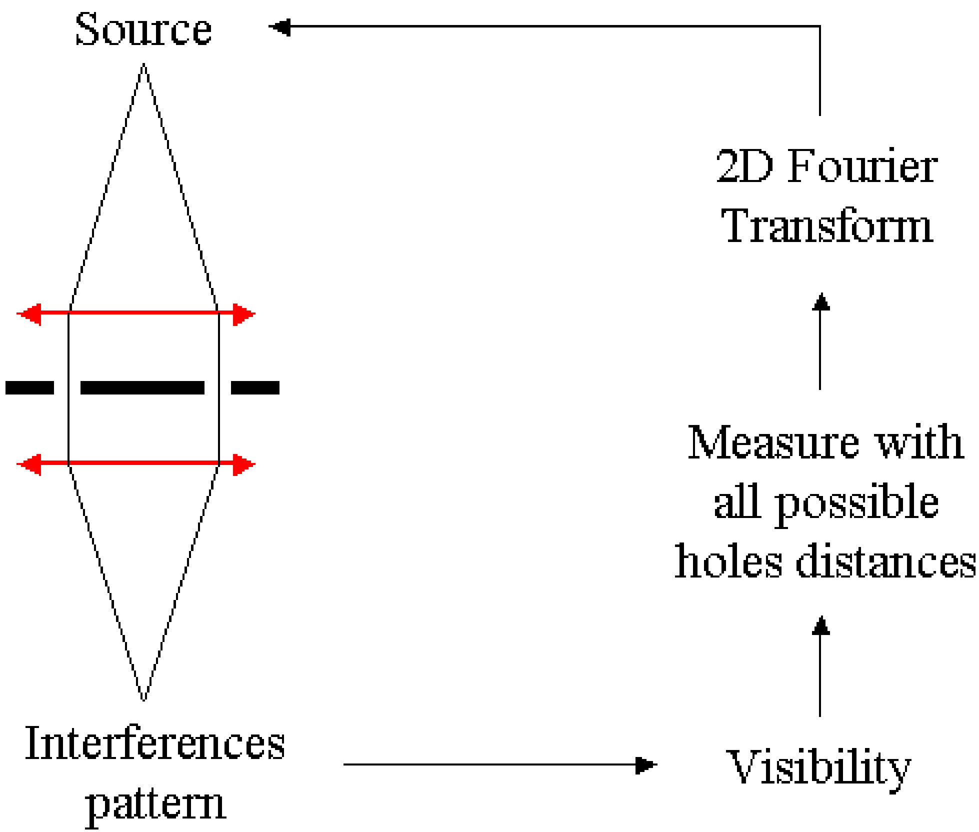
  $\hookrightarrow$ uv plane, field of view, transfer function
- Sensitivity

van Cittert–Zernike theorem

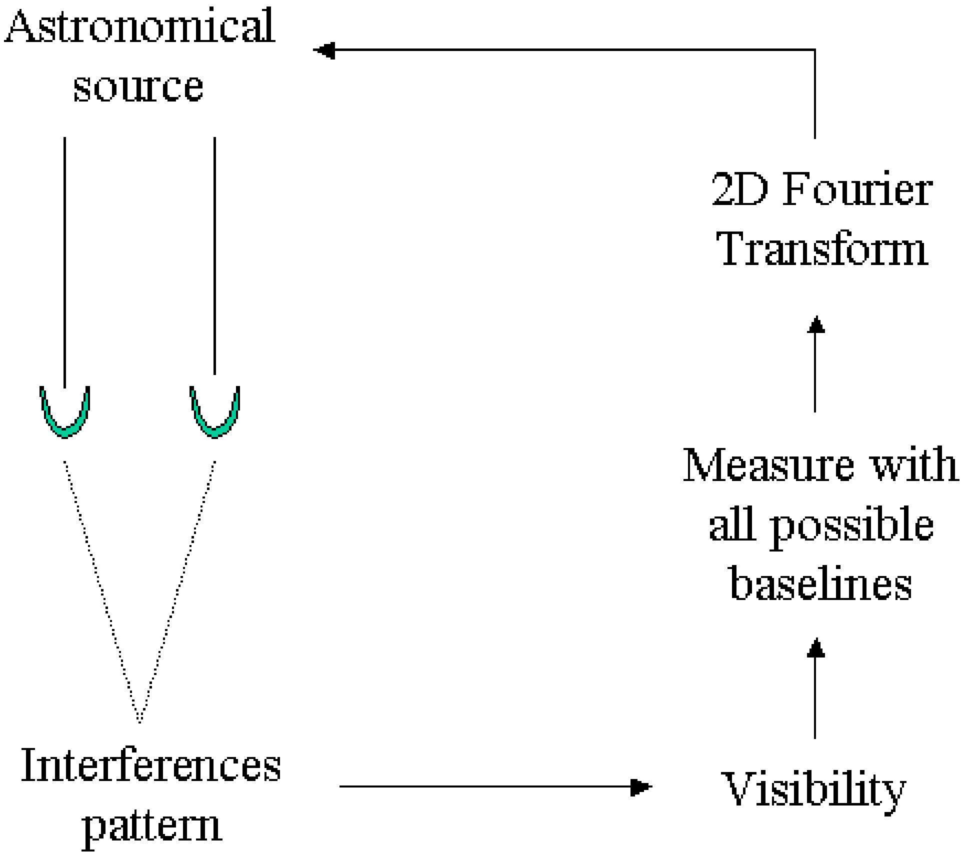
- Wiener-Kichnine theorem **(temporal)**
  - temporal autocorrelation of $S(t)$ = FT(spectra)
    $S(t_1)\,S(t_2) = \Sigma(\tau) \rightleftharpoons S(\nu)$
  - implementation: FT spectrometers
- **van Cittert–Zernike theorem (spatial)**
  - spatial autocorrelation of $S(x)$ = FT(brightness)
    $S(x_1)\,S(x_2) = \Sigma(u) \rightleftharpoons S(\alpha)$
  - implementation: aperture synthesis

van Cittert–Zernike theorem

Young's holes



Astronomical source



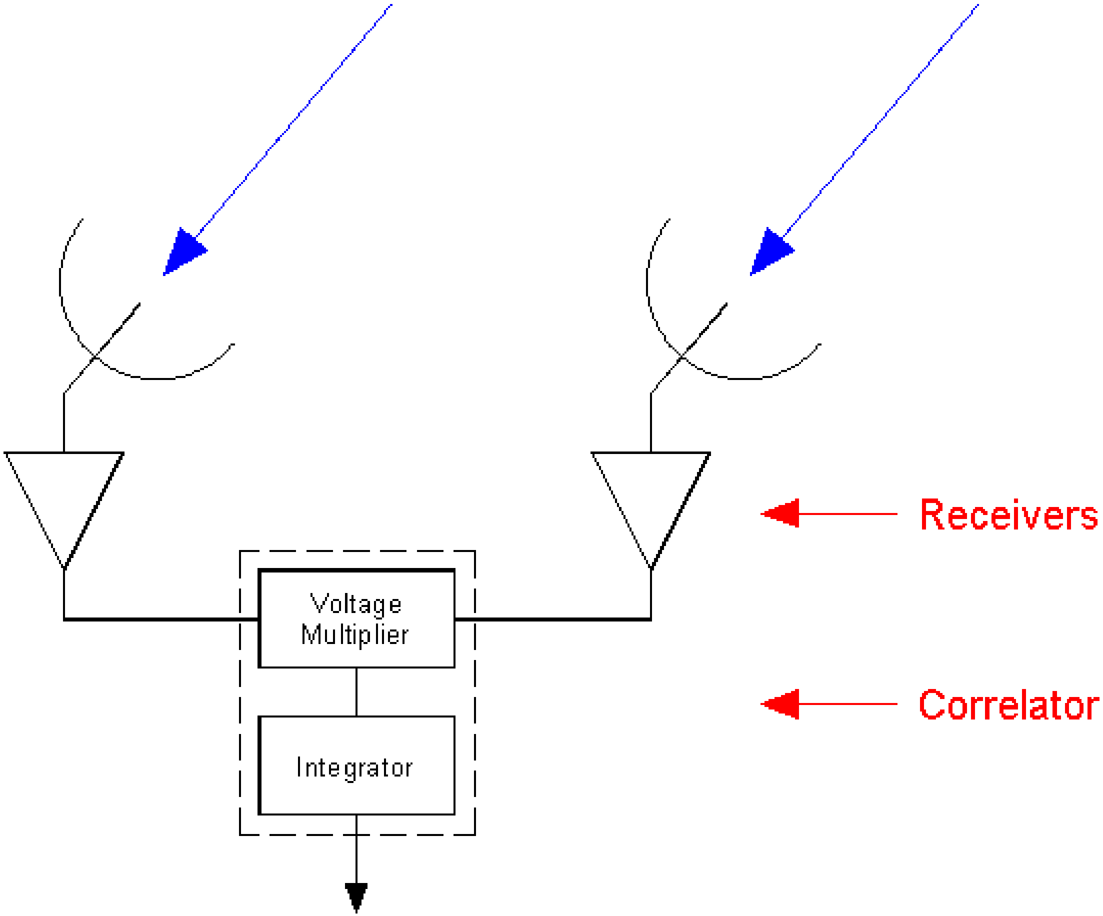
Implementing the van Cittert–Zernike theorem

1. Build a device that measures the spatial autocorrelation of the incoming signal
2. Do it for all possible scales
3. Take the FT and get an image of the brightness distribution

Implementing the van Cittert–Zernike theorem

1. Build a device that measures the spatial autocorrelation of the incoming signal ⟶ **2-elements interferometer**
2. Do it for all possible scales ⟶ **N antennas**
3. Take the FT and get an image of the brightness distribution ⟶ **software**

The ideal interferometer
Sketch



Measurements

- The heterodyne receiver measures the incoming electric field $E\cos(2\pi\nu t)$
- The correlator is a multiplier followed by a time integrator:

$$r = < E_1 \cos(2\pi\nu t)\ E_2 \cos(2\pi\nu t) > = E_1\, E_2$$

- We have measured the spatial correlation of the signal!
- ...

The ideal interferometer
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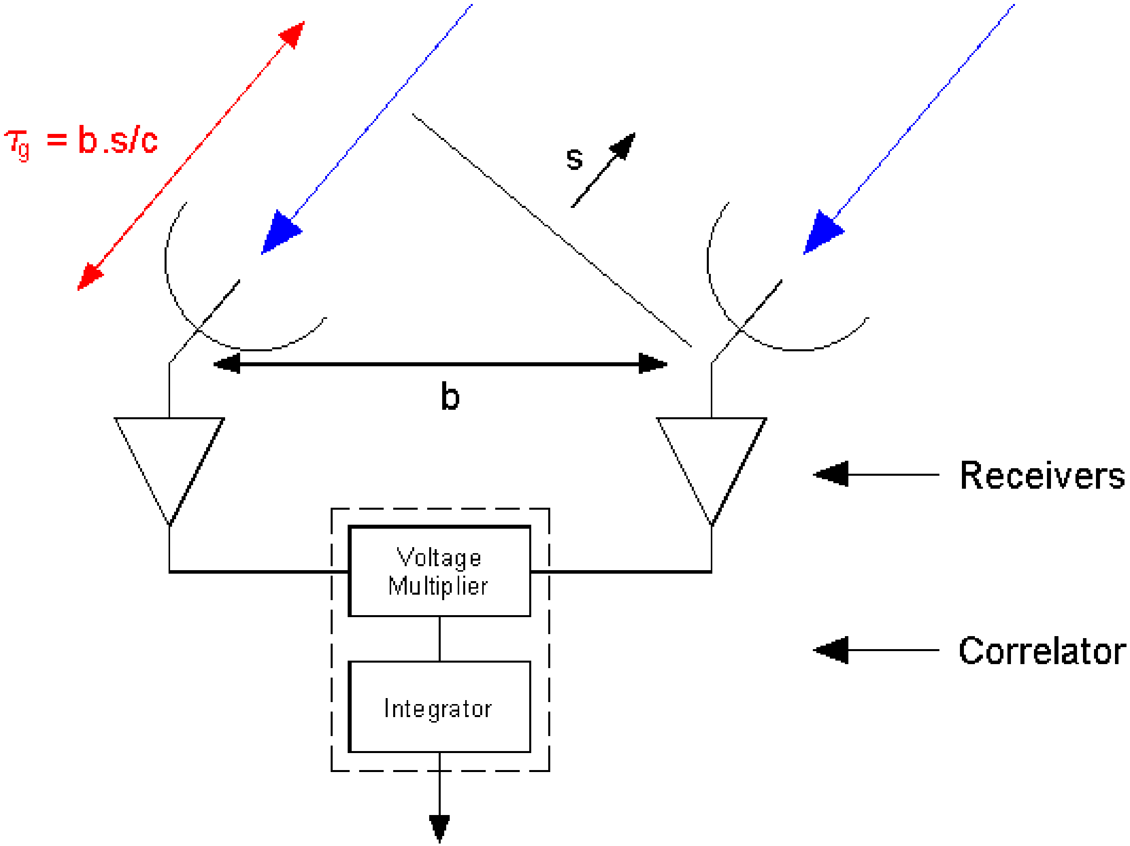
$$r = < E_1\cos(2\pi\nu t)\ E_2\cos(2\pi\nu t) > = E_1\,E_2$$

- We have measured the spatial correlation of the signal!
- **But we have forgotten the geometrical delay**

The ideal interferometer
Sketch



The ideal interferometer

Measurements

- There is a **geometrical delay** τ_g between the two antennas $\longrightarrow$ **more complex** experiment than the Young's holes
- Correlator output:

$$r = < E_1 \cos(2\pi\nu t)\ E_2 \cos(2\pi\nu t) > = E_1\, E_2$$

$$\begin{aligned} r &= < E_1 \cos(2\pi\nu(t-\tau_g))\ E_2 \cos(2\pi\nu t) > \\ &= E_1 E_2 \cos(2\pi\nu\tau_g) \end{aligned}$$

Measurements

- Correlator output: $r = E_1 E_2 \cos(2\pi\nu\tau_g)$
- τ_g varies slowly with time (Earth rotation) $\longrightarrow$ **fringes**
- Natural fringe rate:

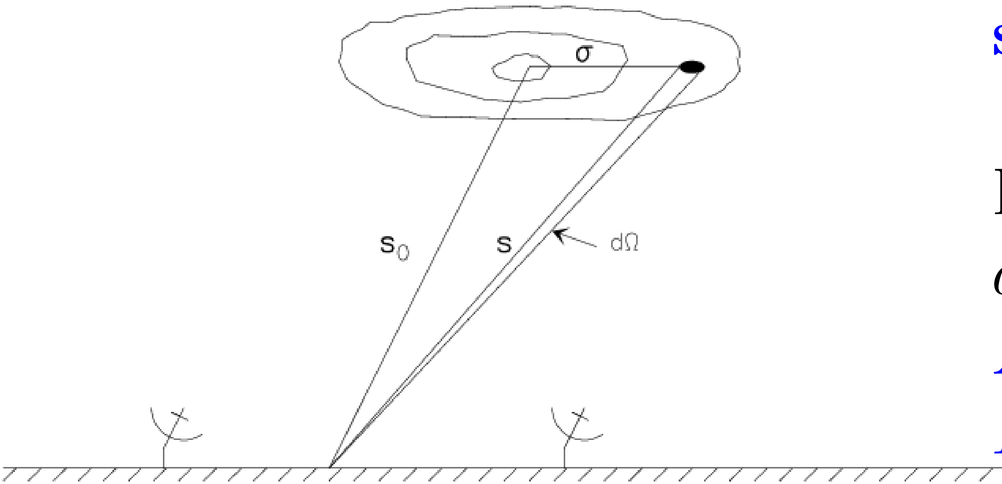
$$\tau_g = \frac{\mathbf{b.s}}{c} \qquad \nu \, \frac{d\tau_g}{dt} \simeq \Omega_{earth} \, \frac{\mathrm{b}\nu}{c}$$

~ 50 Hz for $b = 800$ m and $\nu = 250$ GHz

The ideal interferometer
Measurements

- Correlator output: $r = E_1 E_2 \cos(2\pi\nu\tau_g)$
- τ_g varies slowly with time (Earth rotation) $\longrightarrow$ **fringes**
- τ_g is **known** from the antenna position, source direction, time $\longrightarrow$ could be corrected
- Problems: the source is **not a point source**
  the signal is **not monochromatic**

The ideal interferometer
Source size



$\mathbf{s} = \mathbf{s_o} + \sigma$

Power received from $d\Omega$: $A(\mathbf{s})I(\mathbf{s})d\Omega$

$A(s)$ = beam

$I(s)$ = source

Correlator output: $r = E_1 E_2 \cos(2\pi\nu\tau_g)$

$$r = A(\mathbf{s})I(\mathbf{s})d\Omega \cos(2\pi\nu\tau_g(\mathbf{s}))$$

Source size

- Correlator output integrated over source:

$$R = \int_{Sky} A(\mathbf{s}) I(\mathbf{s}) \cos(2\pi\nu\mathbf{b}.\mathbf{s}/c)\, d\Omega$$
$$= |V| \cos(2\pi\nu\tau_g - \varphi_{\mathrm{V}})$$

- **Complex visibility:**

$$V = |V| e^{i\varphi_{\mathrm{V}}} = \int_{Sky} A(\sigma) I(\sigma) e^{-2i\pi\nu\mathbf{b}.\sigma/c} d\Omega$$

Source size

$$R = \int_{Sky} A(\mathbf{s}) I(\mathbf{s}) \cos(2\pi\nu \mathbf{b}.\mathbf{s}/c)\, d\Omega$$

$$= \cos\left(2\pi\nu\frac{\mathbf{b}.\mathbf{s}_o}{c}\right) \int_{Sky} A(\sigma) I(\sigma) \cos(2\pi\nu \mathbf{b}.\sigma/c) d\Omega$$

$$- \sin\left(2\pi\nu\frac{\mathbf{b}.\mathbf{s}_o}{c}\right) \int_{Sky} A(\sigma) I(\sigma) \sin(2\pi\nu \mathbf{b}.\sigma/c) d\Omega$$

$$= \cos\left(2\pi\nu\frac{\mathbf{b}.\mathbf{s}_o}{c}\right) |V| \cos\varphi_{\mathrm{V}} - \sin\left(2\pi\nu\frac{\mathbf{b}.\mathbf{s}_o}{c}\right) |V| \sin\varphi_{\mathrm{V}}$$

$$= |V| \cos(2\pi\nu\tau_g - \varphi_{\mathrm{V}})$$

The ideal interferometer
Summary

- Correlator output:

$$r = \; < E_1 \cos(2\pi\nu t) \; E_2 \cos(2\pi\nu t) > = E_1 \, E_2$$

$$r = E_1 E_2 \cos(2\pi\nu\tau_g) \qquad \longleftarrow \text{delay}$$

$$R = |V| \cos(2\pi\nu\tau_g - \varphi_{\rm V}) \qquad \longleftarrow \text{source size}$$

- Complex visibility V resembles a Fourier Transform:

$$V = |V| e^{i\varphi_{\rm V}} = \int_{Sky} A(\sigma) I(\sigma) e^{-2i\pi\nu \mathbf{b}.\sigma/c} d\Omega$$

The ideal interferometer
Summary

- Correlator output:

$$r \;=\; < E_1 \cos(2\pi\nu t)\;\; E_2 \cos(2\pi\nu t) > \;=\; E_1\, E_2$$
$$r \;=\; E_1 E_2 \cos(2\pi\nu\tau_g) \qquad \longleftarrow \text{delay}$$
$$R \;=\; |V| \cos(2\pi\nu\tau_g - \varphi_{\mathrm{V}}) \qquad \longleftarrow \text{source size}$$

- **3D version of van Cittert–Zernike**
  - We do **not** measure $r = FT(I)$
  - We measure $R =$ something related to V, which resembles the FT(I)

Bandwidth

- Integrating over a finite bandwidth $\Delta\nu$

$$R = \frac{1}{\Delta\nu} \int_{\nu_0-\Delta\nu/2}^{\nu_0+\Delta\nu/2} |V| \cos(2\pi\nu\tau_g - \varphi_{\rm V}) \; d\nu$$
$$= |V| \cos(2\pi\nu_0\tau_g - \varphi_{\rm V}) \; \frac{\sin(\pi\Delta\nu\tau_g)}{\pi\Delta\nu\tau_g}$$

- The fringe visibility is attenuated by a $\sin(x)/x$ envelope (= bandwidth pattern) which falls off rapidly

Summary

- Correlator output:

$$r = < E_1 \cos(2\pi\nu t)\; E_2 \cos(2\pi\nu t) > = E_1\, E_2$$

$$r = E_1 E_2 \cos(2\pi\nu\tau_g) \qquad \longleftarrow \text{delay}$$

$$R = |V| \cos(2\pi\nu\tau_g - \varphi_{\rm V}) \qquad \longleftarrow \text{source size}$$

$$R = |V| \cos(2\pi\nu_0\tau_g - \varphi_{\rm V})\, \frac{\sin(\pi\Delta\nu\tau_g)}{\pi\Delta\nu\tau_g} \qquad \longleftarrow \text{bandwidth}$$

- We measure R, which is related to V, which resembles the FT(I). R also depends on τ_g.

The ideal interferometer

Delay correction

$$R = |V| \cos(2\pi\nu_0\tau_g - \varphi_{\rm V}) \, \frac{\sin(\pi\Delta\nu\tau_g)}{\pi\Delta\nu\tau_g}$$

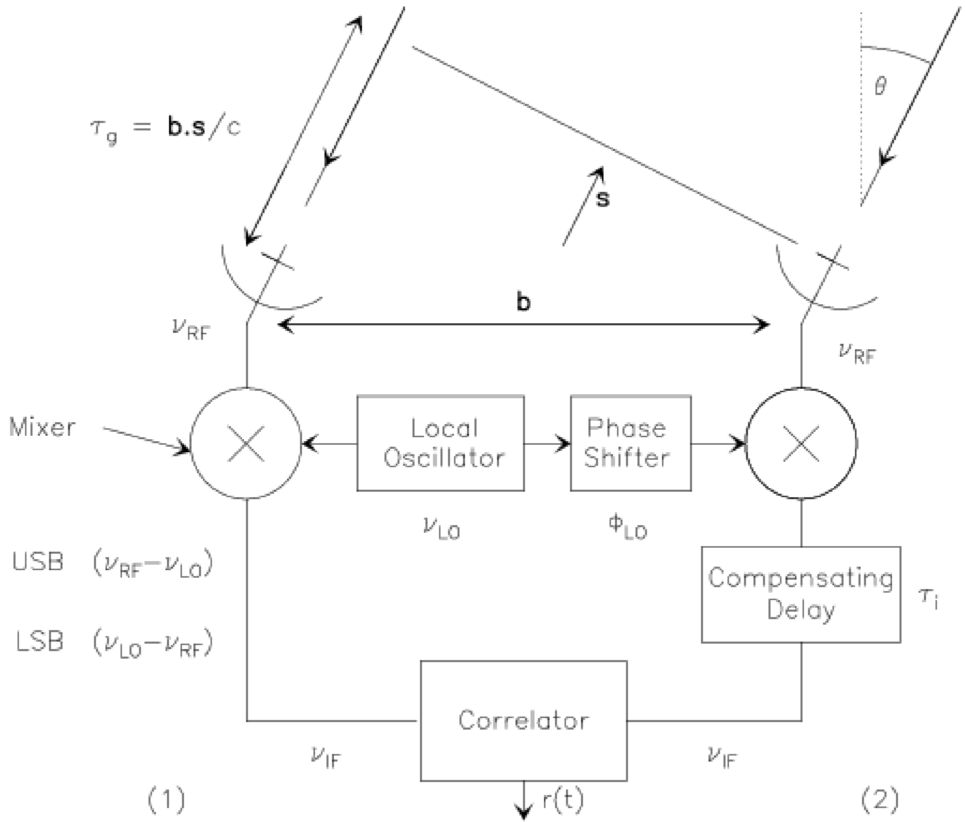
- τ_g varies with time because of the Earth rotation $\longrightarrow$ rapid decrease of R (1% for a path length difference of $\sim$2 cm and $\Delta\nu = 1$GHz)
- Tracking a source requires the **compensation of the geometrical delay**
- Inteferometry requires temporal coherence!

The ideal interferometer
Delay correction

$$R = |V| \cos(2\pi\nu_0\tau_g - \varphi_\mathrm{V}) \, \frac{\sin(\pi\Delta\nu\tau_g)}{\pi\Delta\nu\tau_g}$$

- Tracking a source requires the **compensation of the geometrical delay**
- This can be achieved by introducing an **instrumental delay** in the correlator
- If delay is compensated, one can measure $R = |V| \cos(\varphi_\mathrm{V})$

The real interferometer
Sketch



Heterodyne detection

- In the receiver **mixer**, the incident electic field is combined with a **local oscillator** signal

$$\begin{aligned} U(t) &= E\cos\left(2\pi\nu t + \varphi\right) \\ U_{\rm LO}(t) &= E_{\rm LO}\cos\left(2\pi\nu_{\rm LO} t + \varphi_{\rm LO}\right) \\ \nu_{\rm LO} &\simeq \nu \end{aligned}$$

- The mixer is a **non-linear** element:

$$I(t) = a_0 + a_1(U + U_{\rm LO}) + a_2(U + U_{\rm LO})^2 + a_3(...)^3 + ...$$

Heterodyne detection

- There are terms at various frequencies and harmonics
- A **filter** selects the frequencies such that;

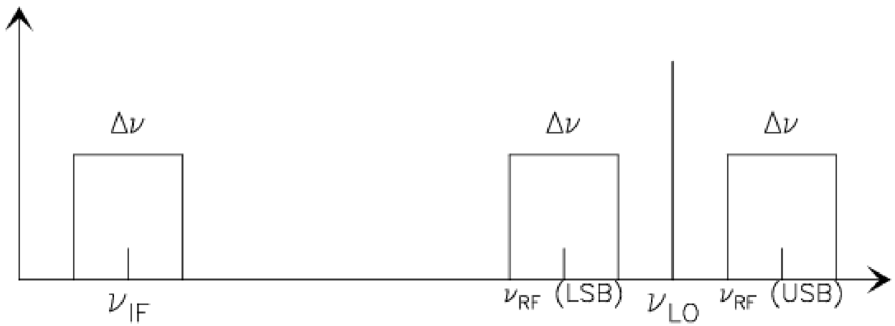
$$\nu_{\rm IF} - \Delta\nu/2 \leq |\nu - \nu_{\rm LO}| \leq \nu_{\rm IF} + \Delta\nu/2$$

- $\nu_{\rm IF}$ is the **intermediate frequency**
- $\nu_{\rm IF}$ such that amplifiers and transport elements available
- PdBI: $\nu_{\rm IF} = 4$–8 GHz, ALMA: $\nu_{\rm IF}$ =4–12 GHz

The real interferometer
Heterodyne detection

- The receiver output is

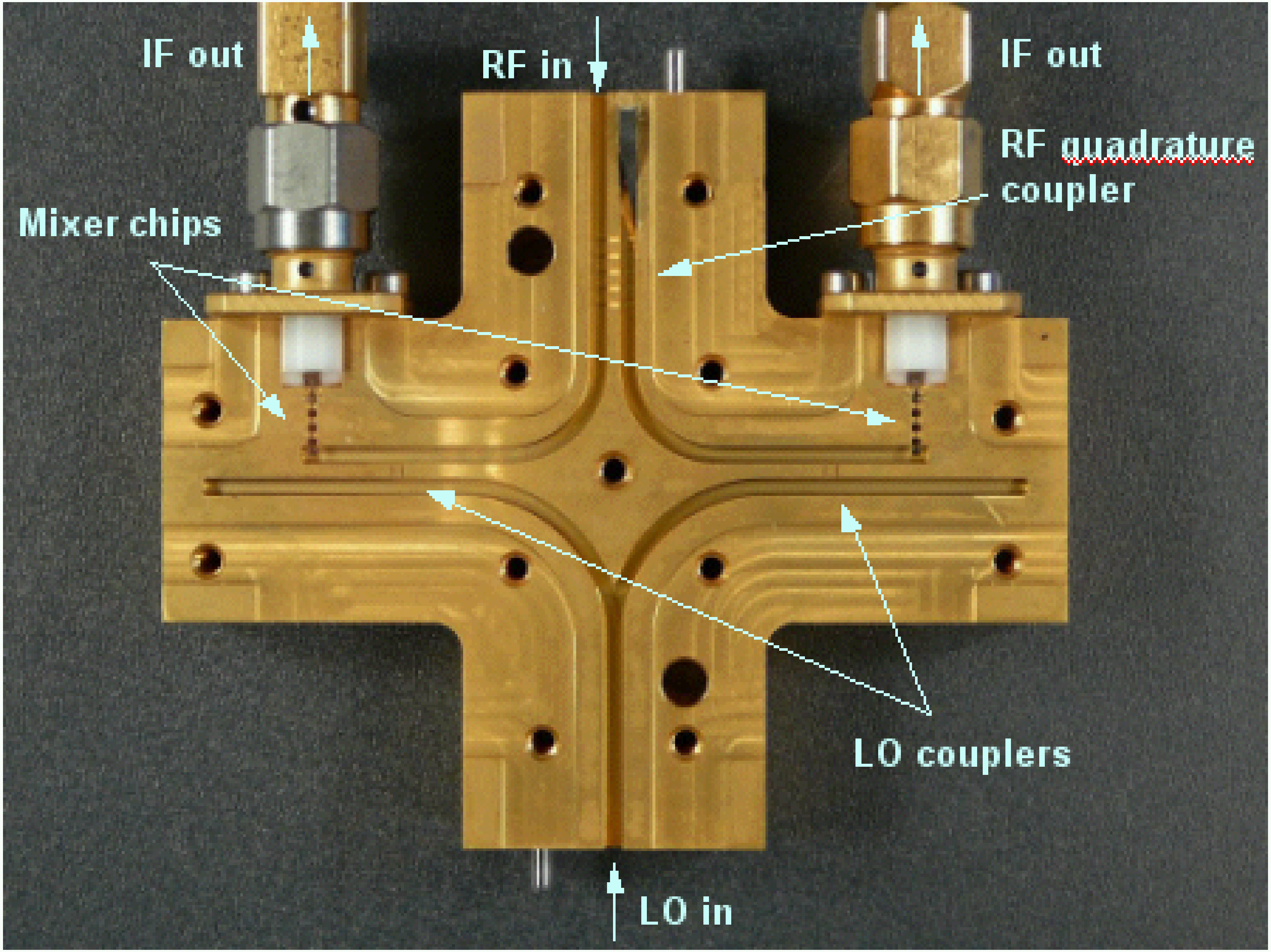
$$I(t) \propto E\,E_{\rm LO} \cos\left(\pm\left(2\pi(\nu-\nu_{\rm LO})t+\varphi-\varphi_{\rm LO}\right)\right)$$



LSB **USB**

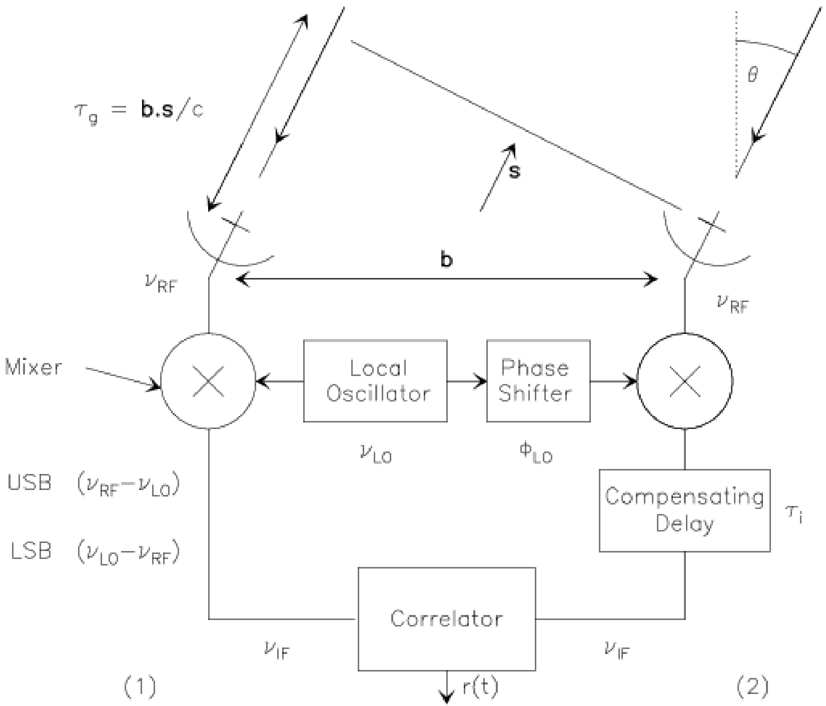
Heterodyne detection

- **DSB** receivers accept both LSB and USB frequencies, i.e. their output is the sum of LSB and USB
- **SSB** receivers accept only LSB or USB (response very strongly frequency dependant)
- **2SB** receivers are 2 DSB receivers combined such that the two bands are independently output (and processed)


IF out
RF in
IF out
RF quadrature
coupler
Mixer chips
LO couplers
LO in

The real interferometer

Delay tracking



- A compensating delay is introduced in one of the branch of the interferometer, **on the IF signal**
- Equivalent to the delay lines in IR interferometers

The real interferometer

Delay tracking

- Phases of the two signals (USB):

$$\varphi_1 = 2\pi\nu\tau_g \qquad \varphi_1 = 2\pi\nu\tau_g = 2\pi(\nu_{\mathrm{LO}} + \nu_{\mathrm{IF}})\tau_g$$
$$\varphi_2 = 0 \qquad \varphi_2 = 2\pi\nu_{\mathrm{IF}}\tau_i$$

- Correlator output:

$$R = |V|\cos(2\pi\nu\tau_g - \varphi_{\mathrm{V}})$$
$$R = |V|\cos(\varphi_1 - \varphi_2 - \varphi_{\mathrm{V}})$$
$$R = |V|\cos(2\pi\nu_{\mathrm{LO}}\tau_g - \varphi_{\mathrm{V}})$$

Fringe Stopping

- Delay tracking not enough because applied on the IF
- Solution: in addition to delay tracking, **rotate the phase of the local oscillator** such that at any time:

$$\varphi_{\mathrm{LO}}(t) = 2\pi\nu_{\mathrm{LO}}\tau_g(t)$$

- τ_g is computed for a reference position = **phase center**
- Phase center = pointing center in practice, though not mandatory

Fringe stopping

- Phases of the two signals (USB):

$$\begin{aligned}\varphi_1 &= 2\pi\nu\tau_g = 2\pi(\nu_{\mathrm{LO}} + \nu_{\mathrm{IF}})\tau_g \\ \varphi_2 &= 2\pi\nu_{\mathrm{IF}}\tau_i + \varphi_{\mathrm{LO}} \\ \varphi_{\mathrm{LO}} &= 2\pi\nu_{\mathrm{LO}}\tau_g\end{aligned}$$

- Correlator output:

$$\begin{aligned}R &= |V|\cos(\varphi_1 - \varphi_2 - \varphi_{\mathrm{V}}) \\ R &= |V|\cos(\varphi_{\mathrm{V}})\end{aligned}$$

Complex correlator

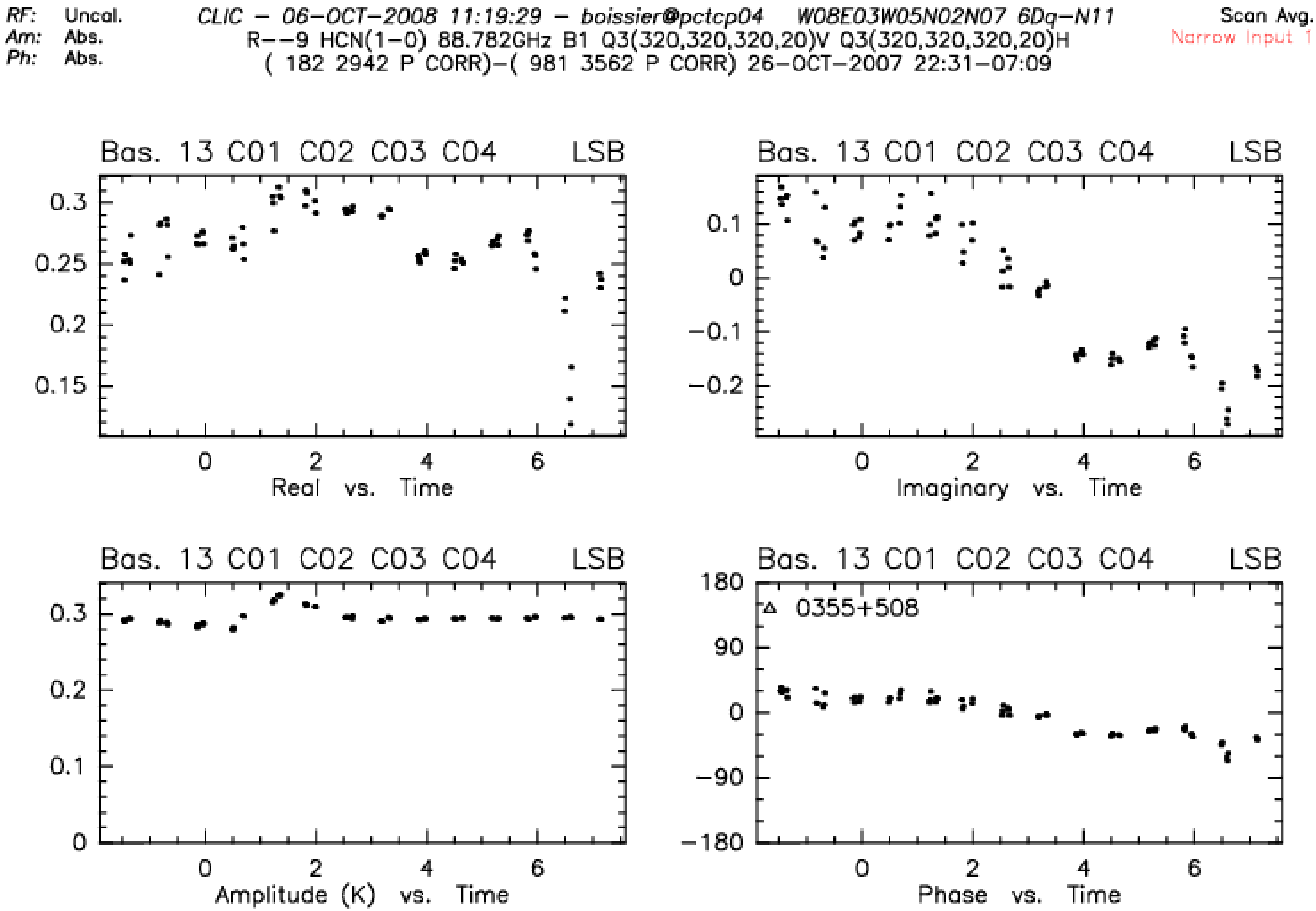
- After fringe stopping:

$$R = |V| \cos(-\varphi_{\mathrm{V}})$$

- The corrections were so good that there is **no time or delay dependance** any more $\longrightarrow$ cannot measure $|V|$ and φ_{V} separately.
- A second correlator is necessary, with one signal phase shifted by $\pi/2$: $R_i = |V| \sin(-\varphi_{\mathrm{V}})$
- **The complex correlator measures directly the visibility**

The real interferometer
Complex correlator

- The correlator measures the real and imaginary parts of the visibility. **Amplitude and phases are computed off-line.**
- Amplitude and phases have more physical sense
  - Visibility amplitude = **correlated flux**
  - The atmosphere adds a **phase** to the incoming signals
    $\longrightarrow$ measured phase = visibility + $\varphi_1 - \varphi_2$

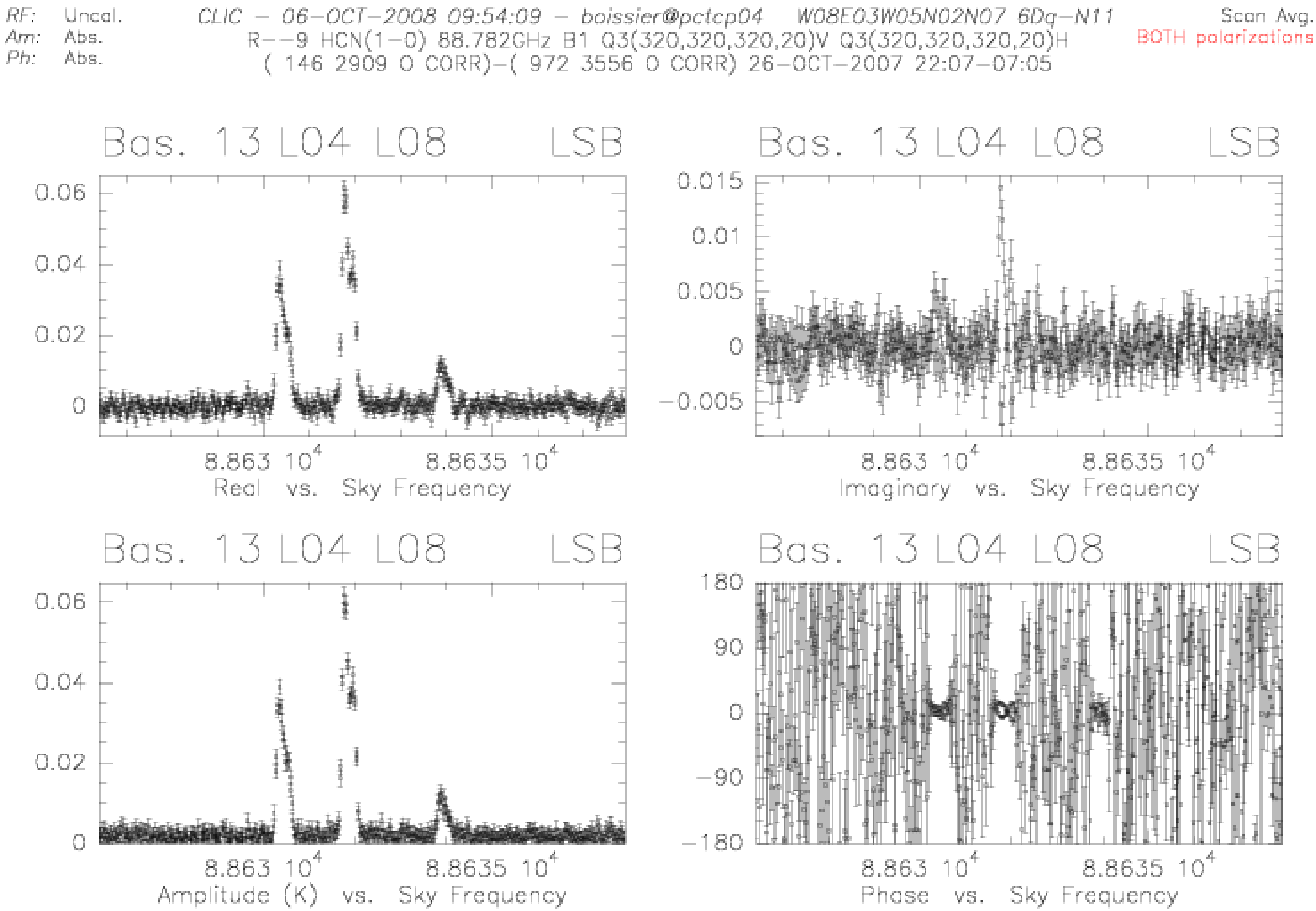

RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC - 06-OCT-2008 11:19:29 - boissier@pctcp04 W08E03W05N02N07 6Dq-N11
R--9 HCN(1-0) 88.782GHz B1 Q3(320,320,320,20)V Q3(320,320,320,20)H
(182 2942 P CORR)-(981 3562 P CORR) 26-OCT-2007 22:31-07:09
Scan Avg.
Narrow Input 1
Bas. 13 C01 C02 C03 C04 LSB
Real vs. Time
Bas. 13 C01 C02 C03 C04 LSB
Imaginary vs. Time
Bas. 13 C01 C02 C03 C04 LSB
Amplitude (K) vs. Time
Bas. 13 C01 C02 C03 C04 LSB
0355+508
Phase vs. Time

Spectroscopy

- Remember the Wiener-Kichnine theorem?
- Calculate the correlation function for several delay $\delta\tau \longrightarrow$ measurement of the **temporal correlation** $\longrightarrow$ FT to get the spectra:

$$V_\nu(u,v,\nu) = \int V(u,v,\tau) e^{-2i\pi\tau\nu} d\nu$$

- Nothing to do with geometrical delay compensation – $\delta\tau \sim 1/\delta\nu$ here
- Mixed up implementation in correlator software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(146 2909 0 CORR)-(972 3556 0 CORR) 26-OCT-2007 22:07-07:05
Scan Avg.
BOTH polarizations
Bas. 13 L04 L08 LSB
Real vs. Sky Frequency
Imaginary vs. Sky Frequency
Amplitude (K) vs. Sky Frequency
Phase vs. Sky Frequency
8.863 10^4
8.8635 10^4

Implementing the van Cittert–Zernike theorem

1. Build a device that measures the spatial autocorrelation of the incoming signal ⟶ **2-elements interferometer**
2. Do it for all possible scales ⟶ **N antennas**
3. Take the FT and get an image of the brightness distribution ⟶ **software**

Aperture synthesis

Complex visibility

- Complex visibility:

$$V = |V| e^{i\varphi_{\mathrm{V}}} = \int_{Sky} A(\sigma) I(\sigma) e^{-2i\pi\nu \mathbf{b}.\sigma/c} d\Omega$$

- Going from 3-D to 2-D? ...some algrebra...
- OK providing that:

$$(\text{max. field of view})^2 \times \text{max. baseline} \ll 1$$

$$\Longrightarrow \frac{(\text{max. field of view})^2}{\text{resolution}} \ll 1$$

Complex visibility

$$V(u,v) = \int_{Sky} A(\ell,m) I(\ell,m) e^{-2i\pi\nu(u\ell+vm)} d\Omega$$

- uv plane is perpendicular to the source direction, **fixed wrt source** $\longrightarrow$ **back to Young's hole**
- Price: limit on the field of view
- Approximation **ok in (sub)mm domain**, problem at wavelengths > cm

Aperture synthesis
(Field of view)

- Field of view is limited by
  - the **antenna primary beam**: the interferometer measures $A \times I$
  - the **2D visibility approximation**
  - the frequency averaging (bandwidth)
  - the time averaging (integration)

  $\hookrightarrow$ averaging in the uv plane; possible only if limited field of view

Aperture synthesis
(Field of view)

- Values for Plateau de Bure

θ_s	ν (GHz)	2-D Field	0.5 GHz Bandwidth	1 Min Averaging	Primary Beam
$5''$	80	$5'$	$80''$	$2'$	$60''$
$2''$	80	$3.5'$	$30''$	$45''$	$60''$
$2''$	230	$3.5'$	$1.5'$	$45''$	$24''$
$0.5''$	230	$1.7'$	$22''$	$12''$	$24''$

- Problem with 2D field: software; with bandwith: split the data for imaging; with time averaging: dump faster.
- **Primary beam is the main limit on the FOV**

Complex visibility

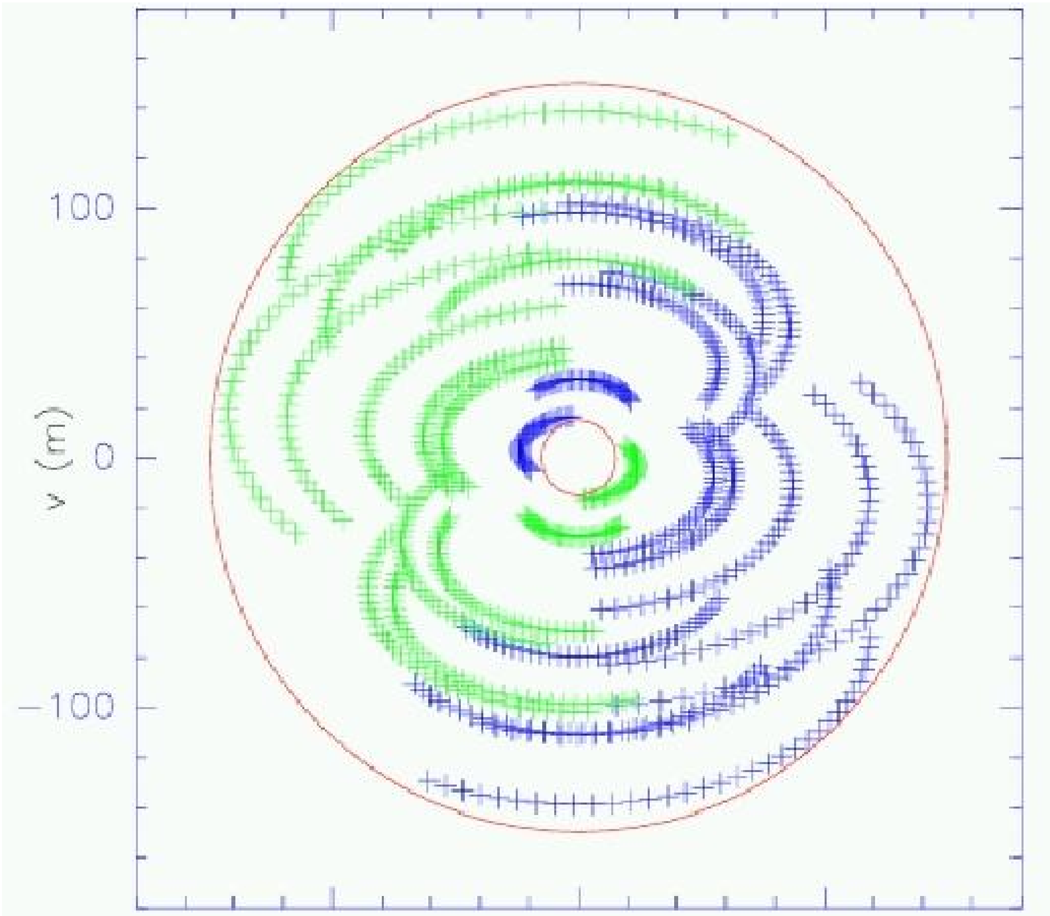
$$V(u,v) = \int_{Sky} A(\ell,m) I(\ell,m) e^{-2i\pi\nu(u\ell+vm)} d\Omega$$

- uv plane is perpendicular to the source direction, **fixed wrt source** $\longrightarrow$ **back to Young's hole**
- Price: limit on the field of view
- Approximation **ok in (sub)mm domain**, problem at wavelengths $>$ cm

Aperture synthesis
uv plane

- uv plane is perpendicular to the source direction, **fixed wrt source** $\longrightarrow$ **back to Young's hole**
- (u, v) is the 2–antennas **vector** baseline projected on the plane perpendicular to the source
- (u, v) are **spatial frequencies**
- ... Earth rotation ... (spherical trigonometry) ...
- (u, v) describe an **ellipse** in the uv plane (for $\delta = 0\,\text{deg}$, a line)

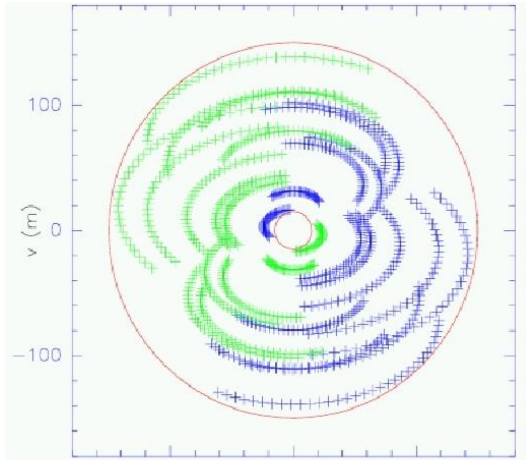
Aperture synthesis
uv plane coverage



Summary

- We started with Young's hole experiment and the van Cittert–Zernike theorem
- An interferometer is **more complex**, because the two antennas (holes) are not in a plane perpendicular to the source direction $\longrightarrow$ geometrical delay, etc.
- What we are measuring is not FT(I), but the **visibility** V, which resembles a FT
- For small field of view = practical case, V is the 2D FT of the sky brighthness distribution ($\times$ the primary beam)
- **Back to the van Cittert–Zernike theorem**

Aperture synthesis
Image formation

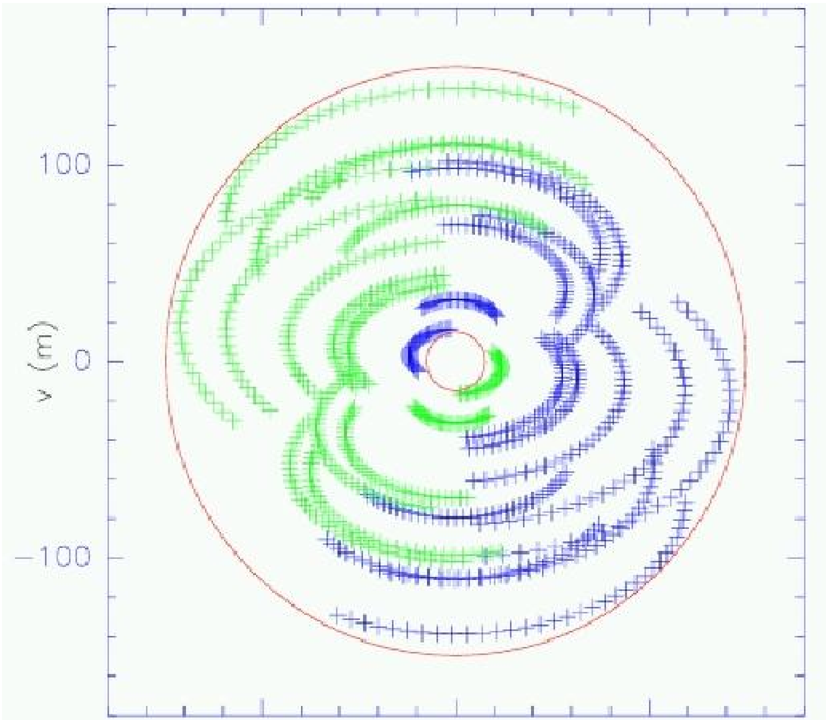


Measurements = uv plane sampling × visibilities

After FT: dirty map = dirty beam ∗ image

The FT of the uv plane coverage gives the dirty beam = the PSF of the observations

Aperture synthesis
Image formation



Max. baseline gives the angular resolution

Aperture synthesis

Image formation

Single-dish observations of a point source

$$\text{Aperture function} \quad \rightleftharpoons \quad \text{Voltage pattern}$$

$$\downarrow |\cdot|^2$$

Power pattern

= PSF = Primary beam

Aperture synthesis

Image formation

Single-dish observations of a point source

Aperture function $\rightleftharpoons$ Voltage pattern

$\star \downarrow$ $\qquad\qquad$ $\downarrow |\cdot|^2$

Transfer function $T(u, v)$ $\rightleftharpoons$ Power pattern

= PSF = Primary beam

Transfer function describes how spatial frequencies are transmitted by the telescope

Aperture synthesis

Image formation

Interferometer observation of a point-source

Aperture function $\rightleftharpoons$ Voltage pattern

$\star \downarrow$ $\qquad$ $\downarrow |\cdot|^2$

Transfer function $\mathbf{T}(\mathbf{u},\mathbf{v})$ $\rightleftharpoons$ Power pattern $B(\ell, m)$

= PSF

= synthesized beam

Aperture synthesis = **sample directly the transfer function** of a huge instrument (diameter ∼ max. baseline).

Aperture function? Does not exist...

Sensitivity

Radiometric formula

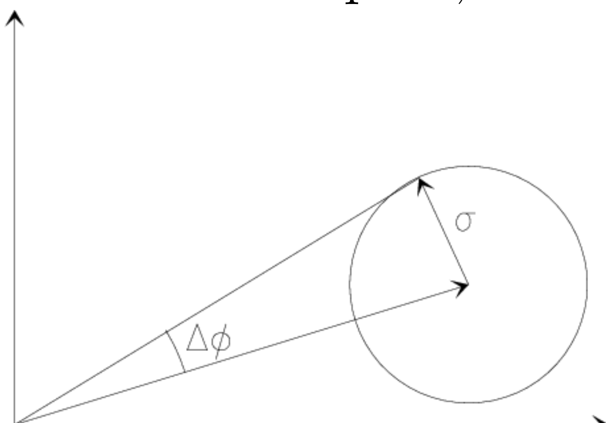
- Measurement of visibilities is limited by noise emitted by atmosphere, antenna, ground, receivers.
- The rms noise for the baseline ij is given by:

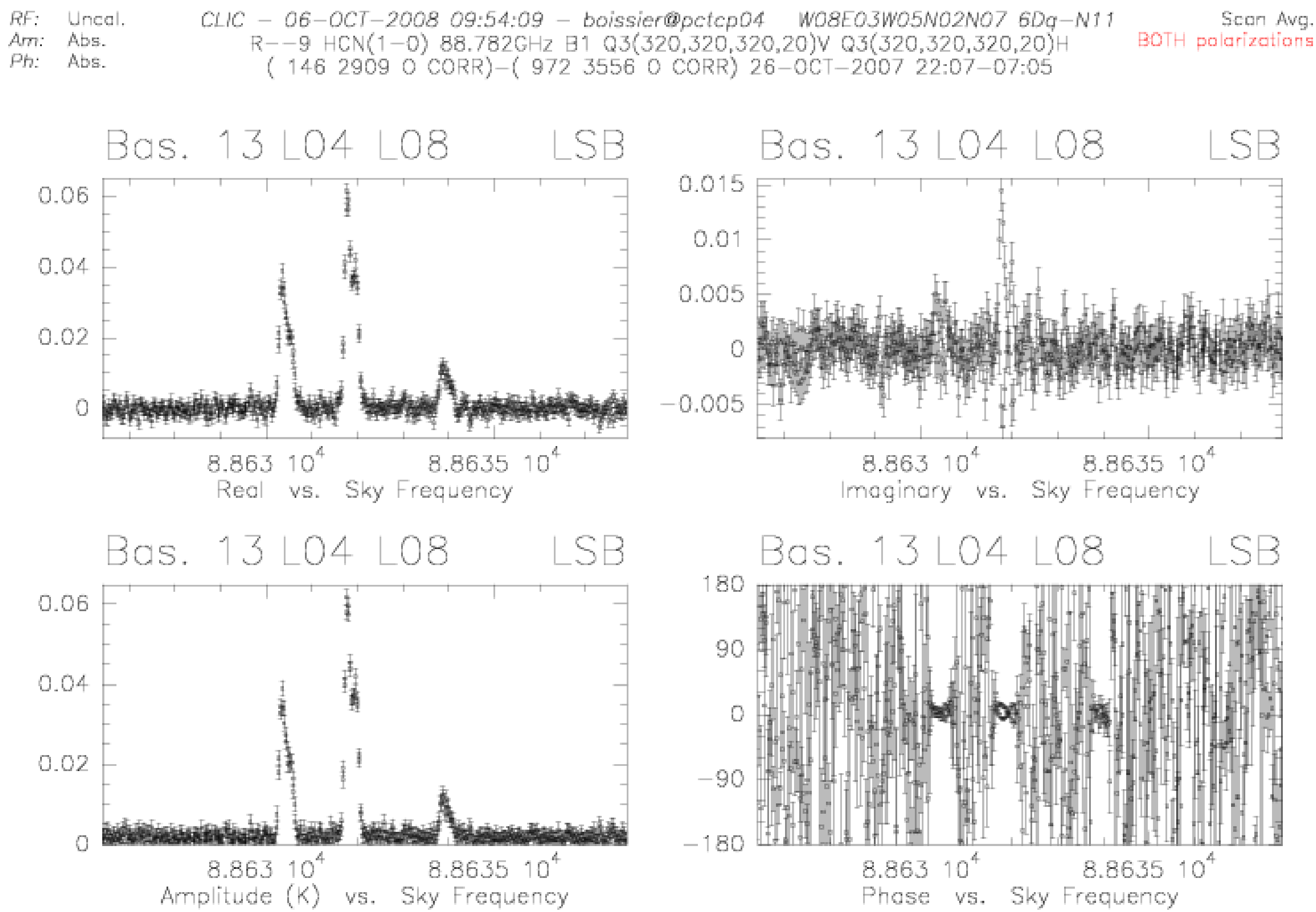
$$\delta S_{ij} = \frac{2k}{A\eta_{\mathrm{A}}\eta_{\mathrm{Q}}\eta_{\mathrm{P}}} \cdot \frac{\sqrt{T_{\mathrm{SYS}i}T_{\mathrm{SYS}j}}}{\sqrt{2B\,T}}$$

  - A antenna physical aperture
  - η_{A} antenna aperture efficiency
  - η_{Q} efficiency for the correlator
  - $T_{\mathrm{SYS}i}$ system noise temperature (single dish)
  - B bandwidth
  - T integration time
  - η_{P} phase decorrelation factor (LO jitter)

Radiometric formula

- This is the noise on the **real** and on the **imaginary** parts of the visibilities (measured independently)
- This is also the noise on the **amplitude** S
- Noise on the phase more complex, of the order of σ/S





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Bas. 13 L04 L08 LSB
Amplitude (K) vs. Sky Frequency
Bas. 13 L04 L08 LSB
Phase vs. Sky Frequency

Radiometric formula

- For N identical antenna/receivers, i.e. $N(N-1)/2$ baselines, the **point-source** sensitivity is:

$$\delta S = \frac{2k}{A\eta_{\mathrm{A}}\eta_{\mathrm{Q}}\eta_{\mathrm{P}}} \cdot \frac{T_{\mathrm{SYS}}}{\sqrt{N(N-1)\,B\,T}}$$

- Scales as $\sim 1/N$
- Sensitivity to extended sources depends on angular resolution

Sensitivity
Phase decorrelation

- **Short term phase errors** in the local oscillators (jitter) will cause a **decorrelation** of the signal and reduce the visibility amplitude by a factor

$$\eta_{\mathrm{P}}(\mathrm{baseline12}) = e^{-({\sigma_1}^2+{\sigma_2}^2)/2} = \eta_1\eta_2$$

- Requirements:

η_1	0.99	0.98	0.95	0.90
σ_1 (degrees)	8.1	11.5	18.3	26.4

Phase decorrelation

- $\eta_{\mathrm{P}} = 0.9 \longrightarrow \eta_1 = 0.95 \longrightarrow \sigma_1 = 18\,\mathrm{deg}$
- PdBI: LO derived from a reference at 1.8 GHz
- Phase stability required $= \sigma_1$ (1.8 GHz/230 GHz) $\sim 0.15°$
- **Very stable** oscillators are required
- Phase decorrelation due to the atmosphere is a more severe problem

Phase decorrelation

- $\eta_{\rm P} = 0.9 \longrightarrow \eta_1 = 0.95 \longrightarrow \sigma_1 = 18\,\deg$
- PdBI: LO derived from a **reference at 14 GHz**
- Phase stability required $= \sigma_1$ (14 GHz/230 GHz) $\sim 1^\circ$
- **Very stable** oscillators are required
- Phase decorrelation due to the atmosphere is a more severe problem

Other instrumental issues

- Phase lock systems to control φ_{LO}
- Real-time monitoring and correction of the phase offset in the cables or fibers
- Complex phase switching is used to cancel offsets, separate/reject side bands, ...
- Antenna position measurements, to get the delay, u, v
- Antenna deformations, e.g. thermal expansion (delay)
- Accurate focus measurements (delay)
- Atmospheric phase monitoring
- ...

Summary
It works!