The Plateau de Bure Interferometer

Roberto Neri

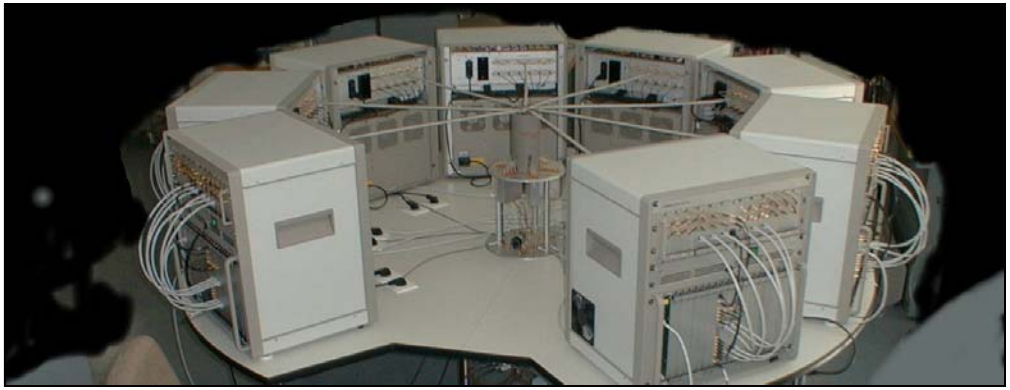
IRAM

VIth Interferometry School

The Plateau de Bure Observatory

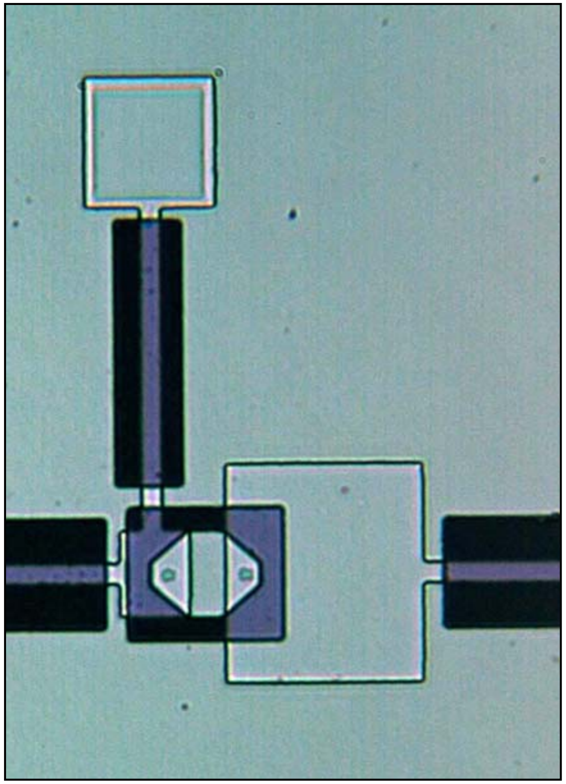
- IRAM = two observatories : Plateau de Bure Array + Pico Veleta 30m
- Three partners: CNRS, MPG, IGN
- Open to the international astronomical community → RadioNet

IRAM's expertise: pictures worth a thousand words



- Telescope design, construction and operation
- Receiver design and development e.g. ALMA Band7, AMSTAR
- HS-digital backends + LO systems e.g. dual 4 GHz correlator

IRAM's expertise: pictures worth a thousand words



- Class 100 clean room for thin film technology
- Complete mm/THz-wave technology laboratory
- Developments for e.g. SMA, Herschel

Milestones and Memories:

- Jun 1979: *design work started*
- Jun 1987: *first light on antenna number one*
- Dec 1988: *first fringes with 2 antennas*
- Jan 1990: *3-antennas array open to guest observers*
- Oct 1994: *VLBI test observations with Pico Veleta*
- Apr 1995: *first fringes at 230 GHz*
- Jan 1996: *fringes in the A configuration (408 m)*

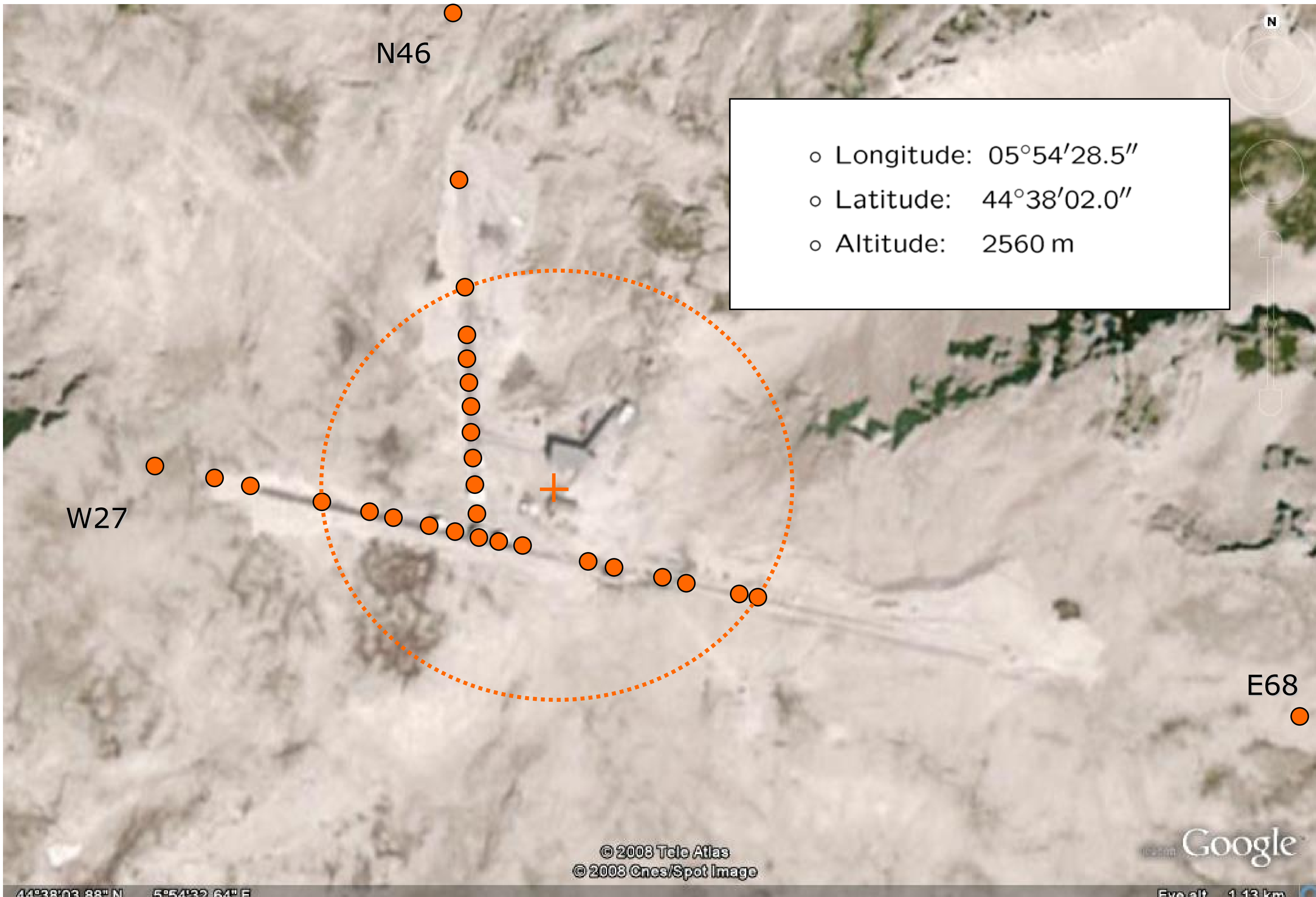
- Jul 1st, 1999: *cable-car accident*
- Dec 15th, 1999: *helicopter accident*

- Sep 2001: *new NB correlator (8$\times$320 MHz)*
- Dec 2001: *first light on antenna 6*
- Sep 2004: *antennas equipped with 22 GHz radiometers*
- Nov 2005: *extension of the NS and EW tracks*
- Oct 2006: *new generation receivers: 3mm and 1mm*
- Jul 2007: *first light at 2mm*

Next Milestones:

- 2009: *first light at 0.8mm*
- 2009: *new WB correlator (2000$\times$2 MHz)*


Rhône-Alpes
Grenoble
100 km
Plateau de Bure
© 2008 Cnes/Spot Image
© 2008 Tele Atlas
Image © 2008 DigitalGlobe
© 2008 Europa Technologies
Google
44°55'45.84" N
5°46'08.41" E
Eye alt 146.69 km

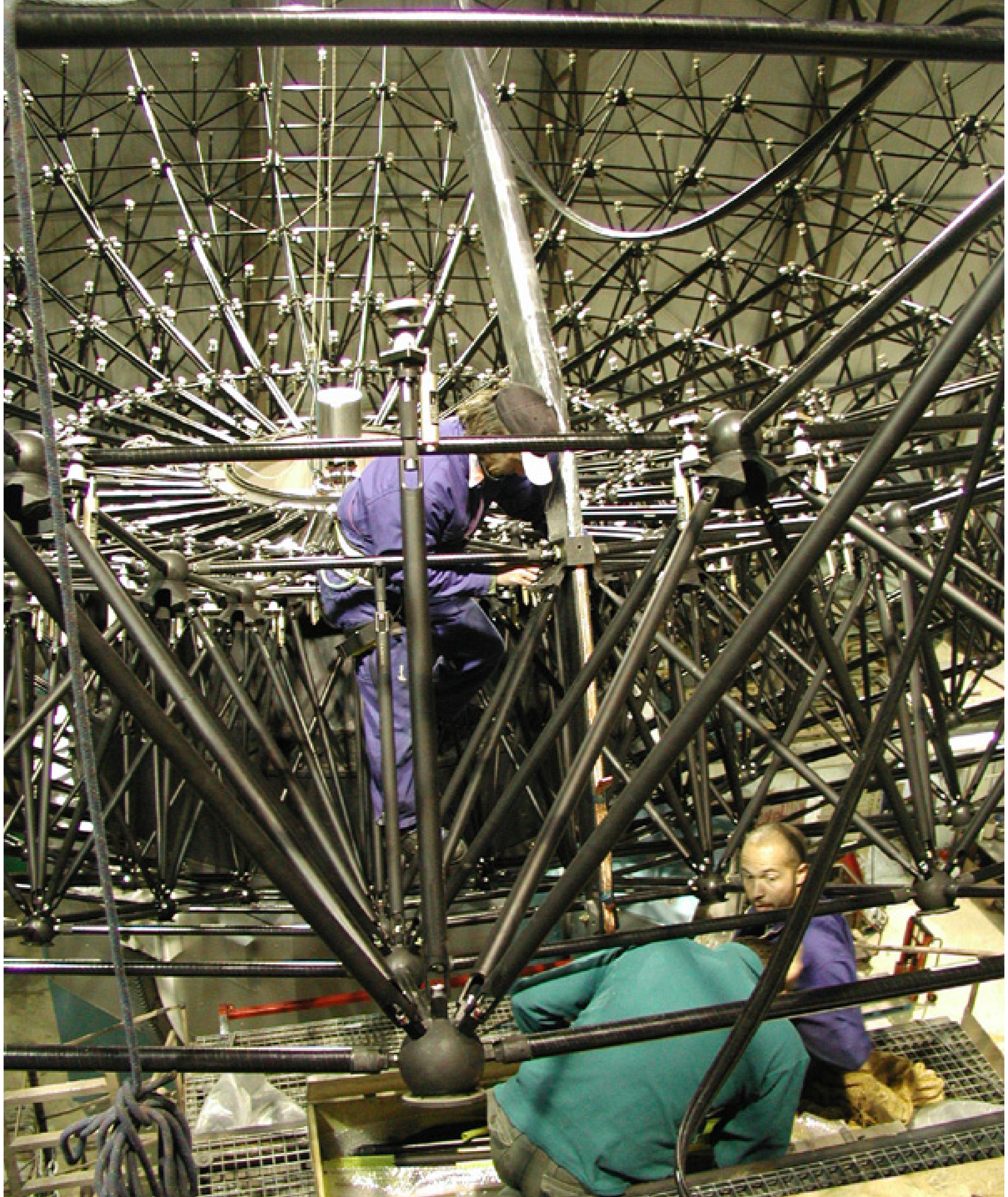

N46
W27
E68
○ Longitude: 05°54′28.5″
○ Latitude: 44°38′02.0″
○ Altitude: 2560 m
© 2008 Tele Atlas
© 2008 Cnes/Spot Image
Google
44°38'03.88" N 5°54'32.64" E
Eye alt 1.13 km

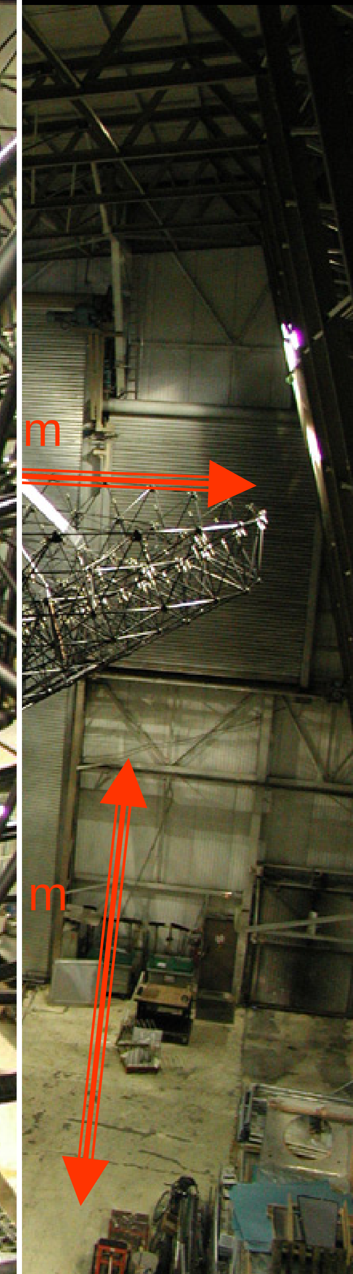
The Plateau de Bure Interferometer

- Plateau in the French Alps at an altitude of ~2550m
- Staff access by helicopter and ground transport ~ 1 week
- Non-stop operation

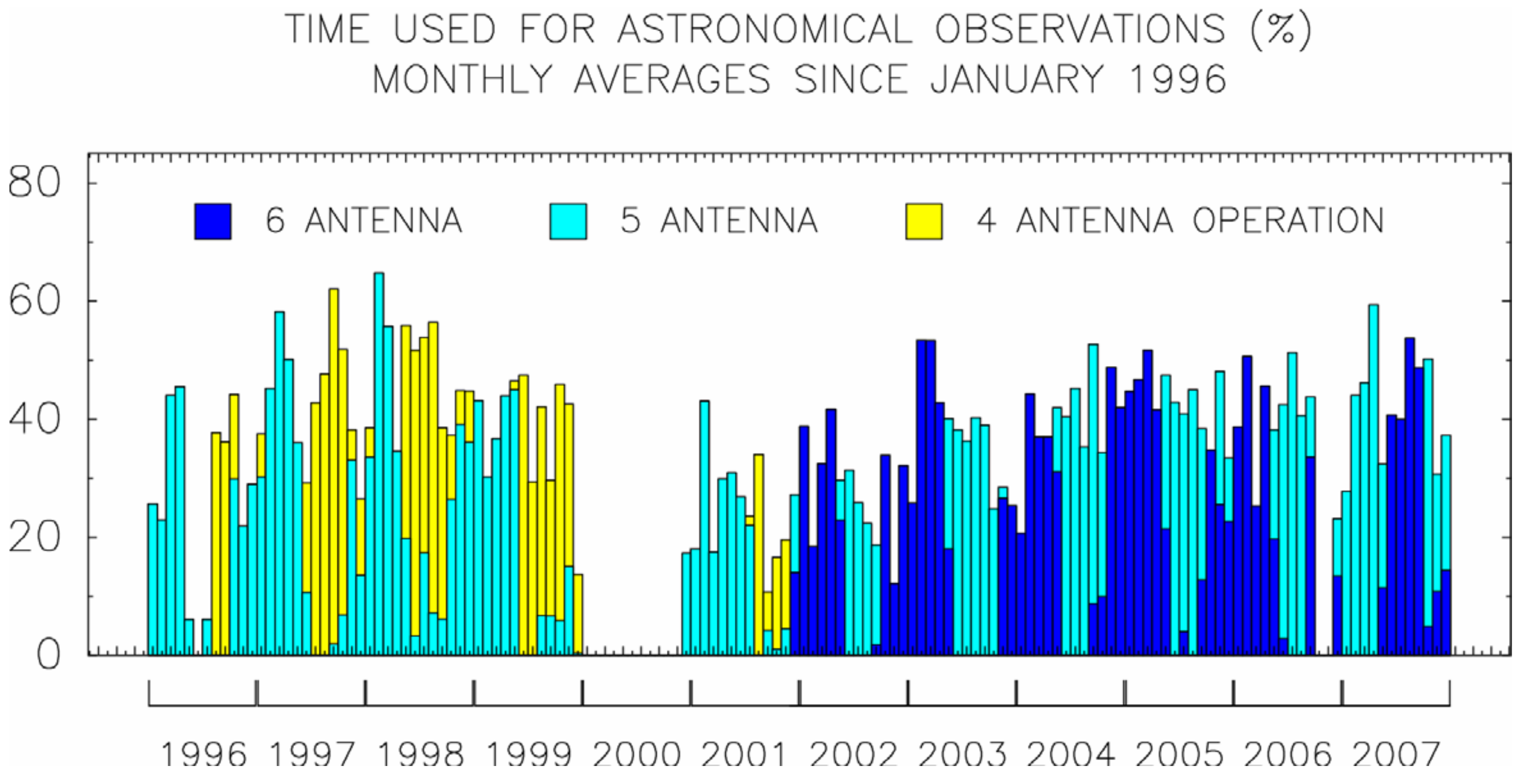

IRAM
Plateau de Bure
2004


ANTENNAS

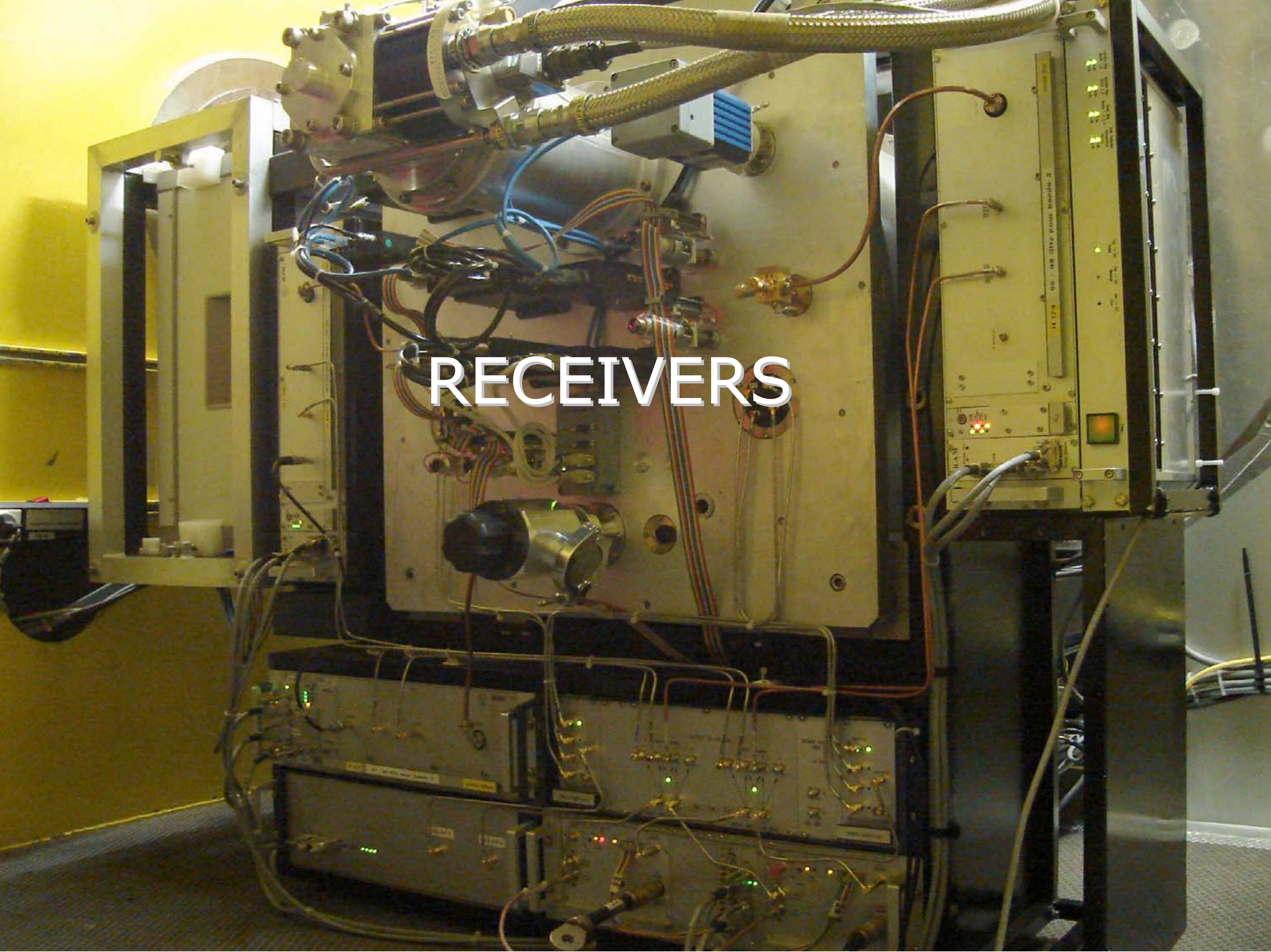



m
m

Number of antennas?

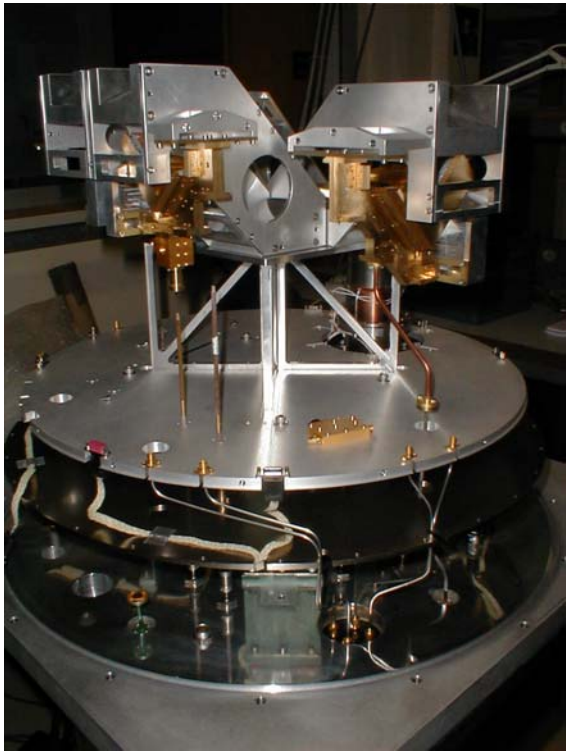
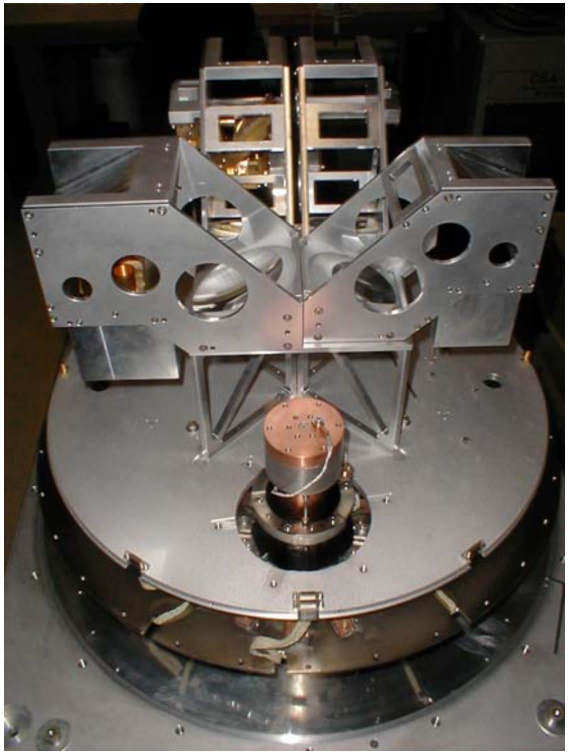
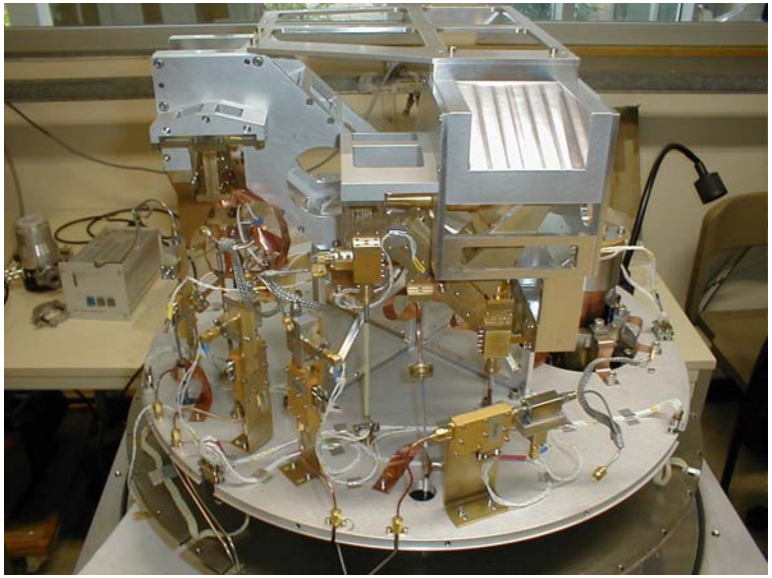
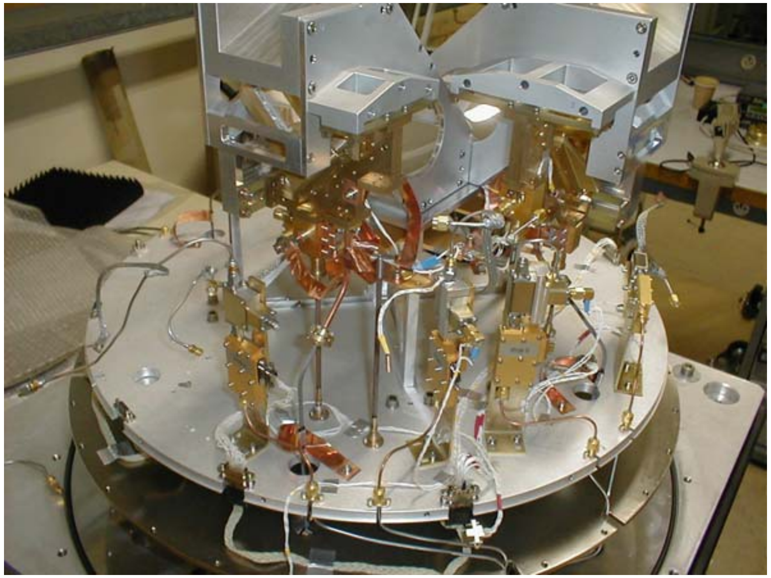


RECEIVERS



State of the art receiver technology

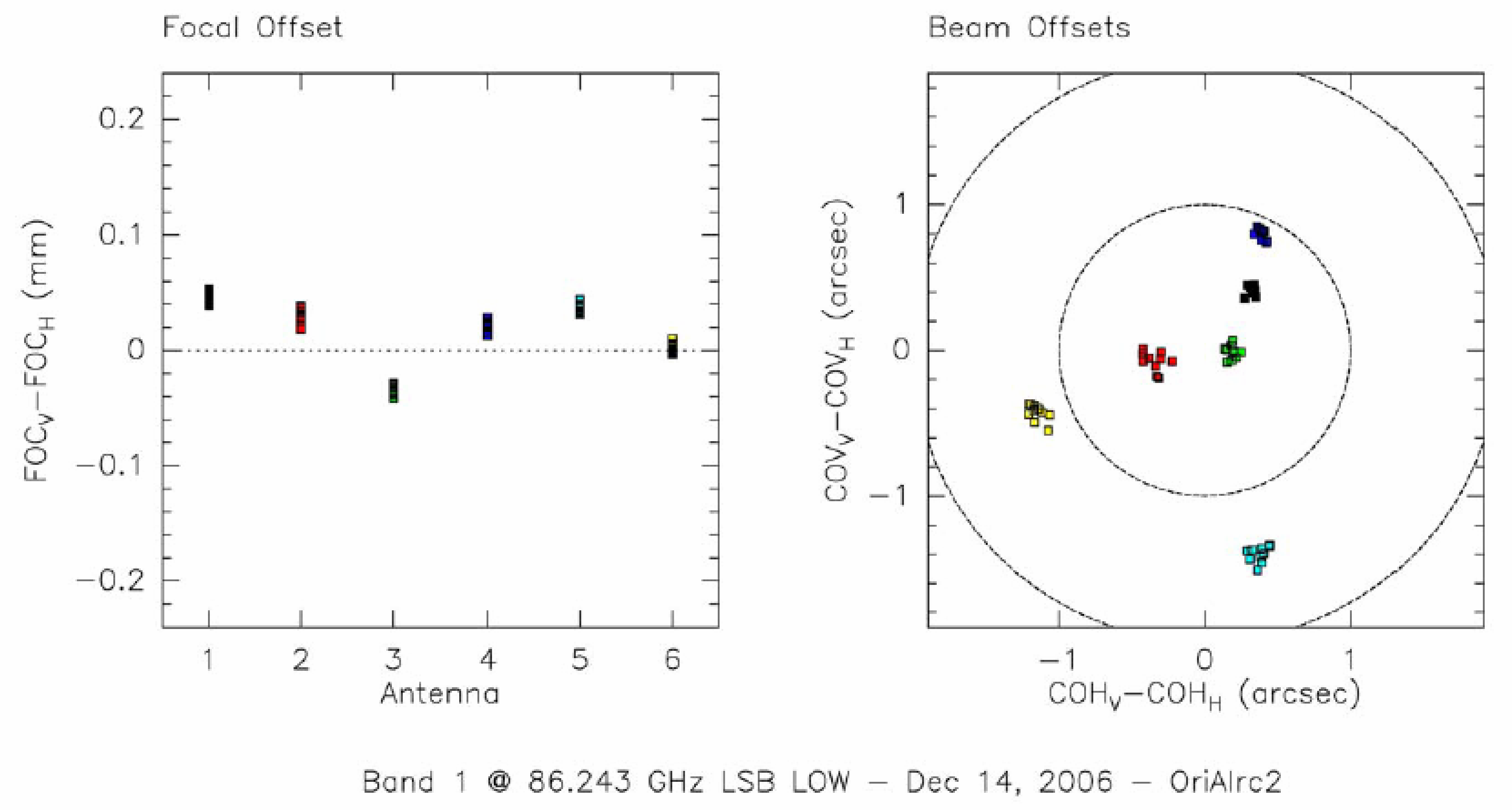
- Closed cycle cryocoolers ⇒ no liquid He refills
- SIS mixers in full-height waveguide ⇒ wideband, allow USB or LSB operation
- Fully reflective optics ⇒ lower loss
- New Design ⇒ higher density, better EMI control, simplified wiring

Receiver capabilities

Item	Value	Notes
RF bands		
	19 - 26	Atmospheric phase correction
1	80 – 117	
2	129 – 174	
3	200 – 267	
4	277 – 371	Fall 2009
RF response	SSB	LSB or USB Image Gain <-10dB
IF band	4 – 8 GHz	Available at FE/BE interface
Polarization	Dual linear	Circular also possible
Observing mode	Single frequency Dual polarization	Second band in standby Potential for Dual freq, Dual pol

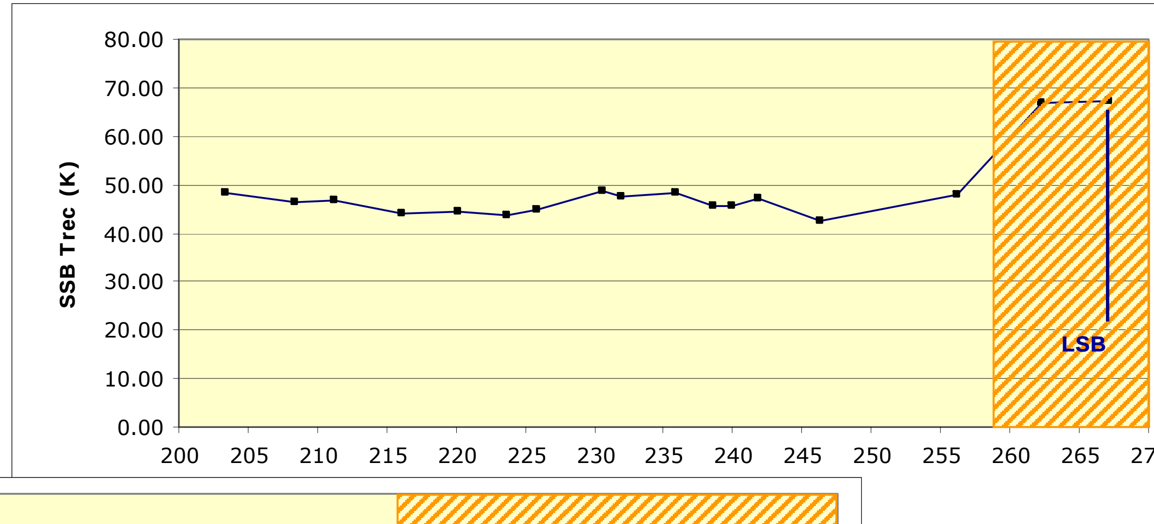
Band1 Beams : vertical vs horizontal



Band3

12 mixers

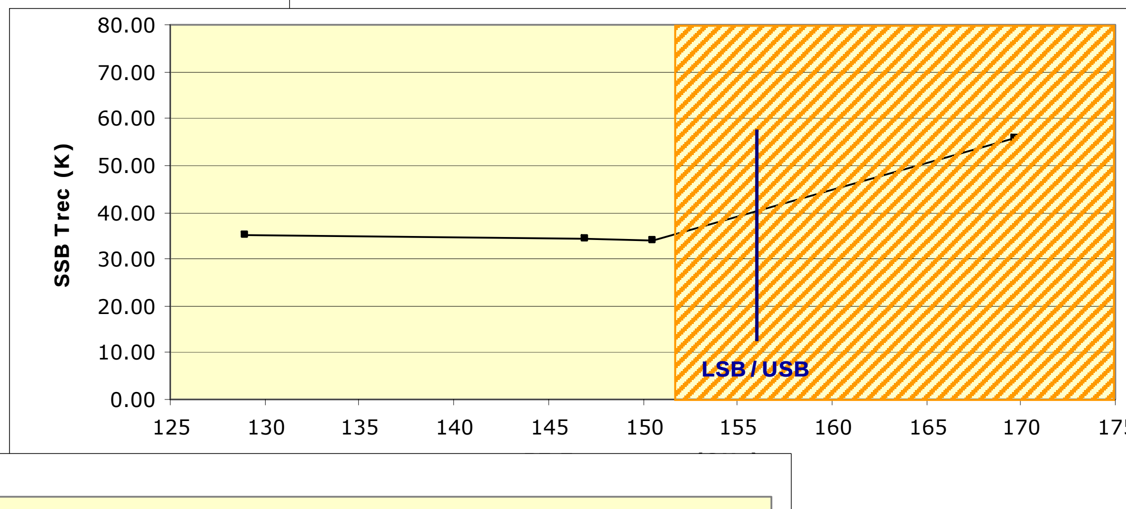
(Oct-Feb 2008)

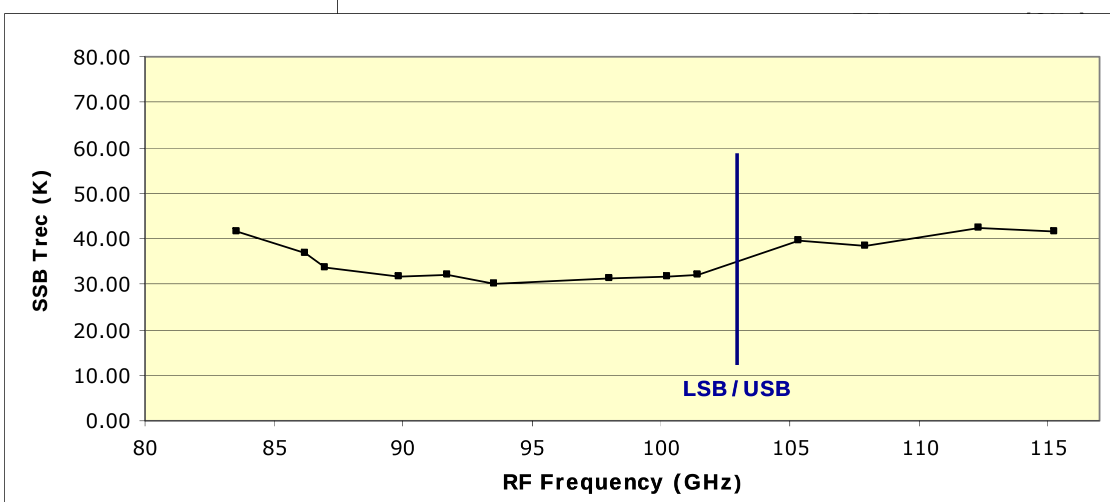


Band2

12 mixers

(Jan–Feb 2008)





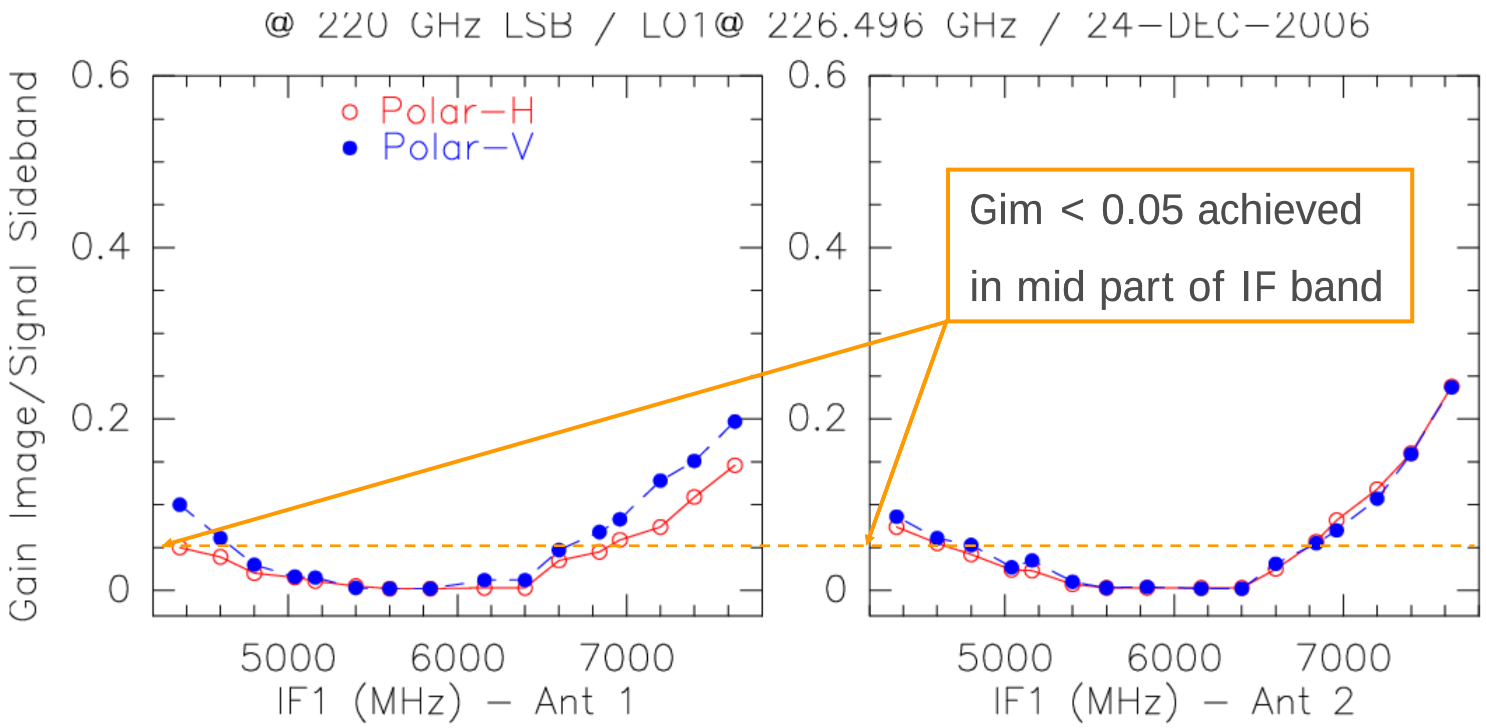
Band1

12 mixers

(Oct-Feb 2008)

Image rejection

- Optimized for center of IF band
- Usually better than 10dB over 50% of IF band



System temperatures

Winter values: Tamb=273K, A=1.4 airmass

ATM (Cernicharo 1985)

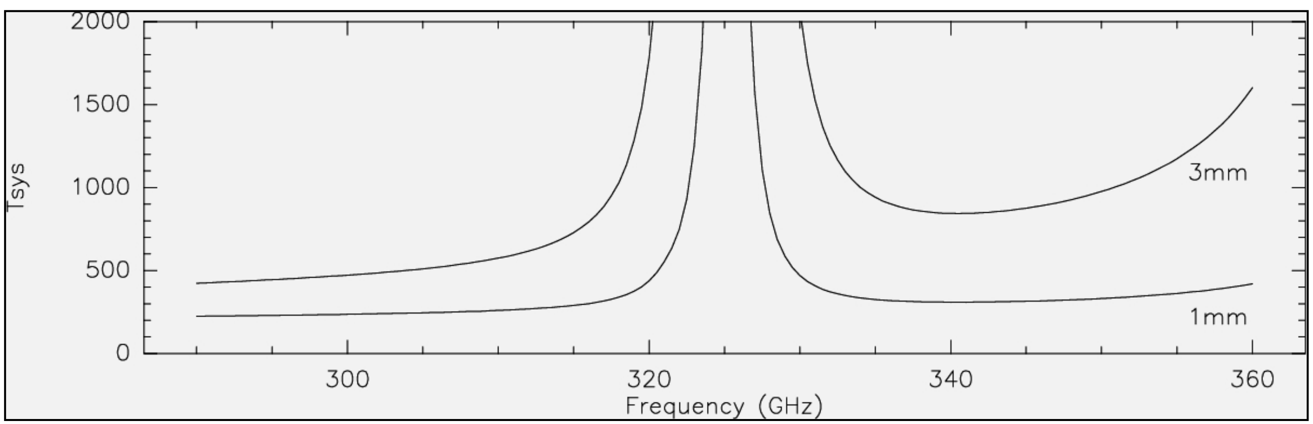
	PWV	G	η	Trec	τ	Tsys
100 GHz	3	0.02	0.95	32	0.07	77
150 GHz	3	0.02	0.92	35	0.10	113
230 GHz	1	0.02	0.87	50	0.07	141
350 GHz	1	0.02	0.84	60	0.27	336

System temperatures @ 350 GHz

ATM (Cernicharo 1985)

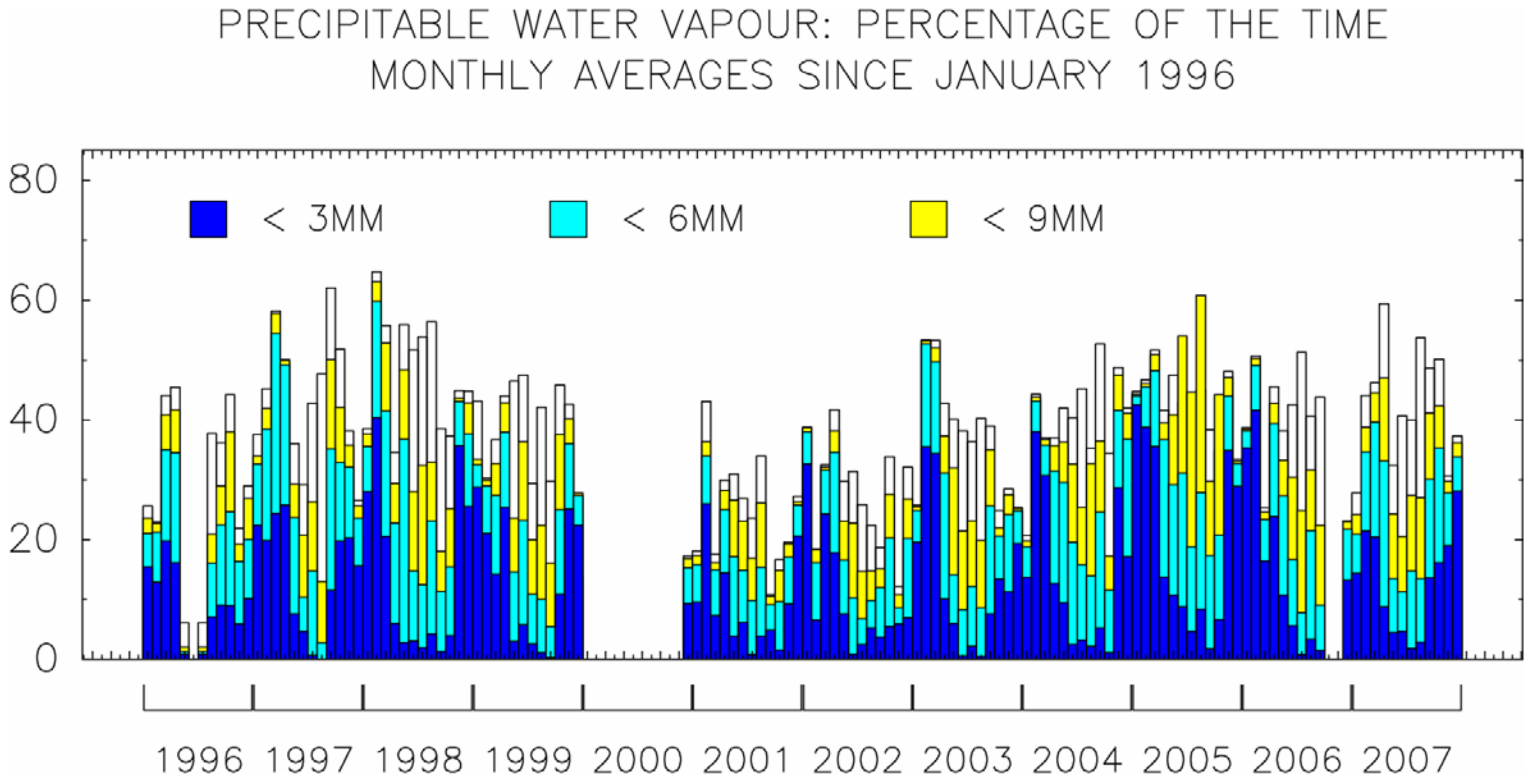
Winter values: Tamb=273K, A=1.4 airmass

	PWV	G	η	Trec	τ	Tsys
350 GHz	1	0.01	0.84	60	0.27	336
350 GHz	3	0.01	0.84	60	0.80	1000



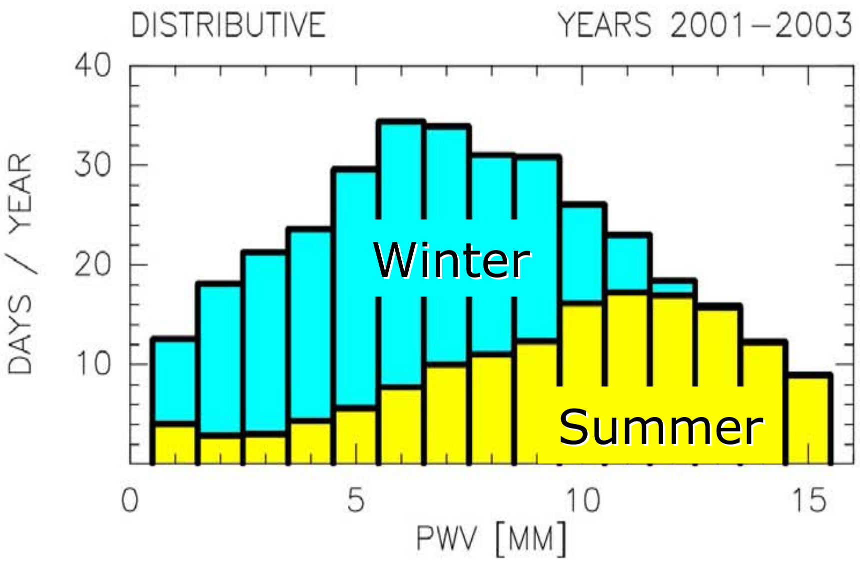
ATMOSPHERE

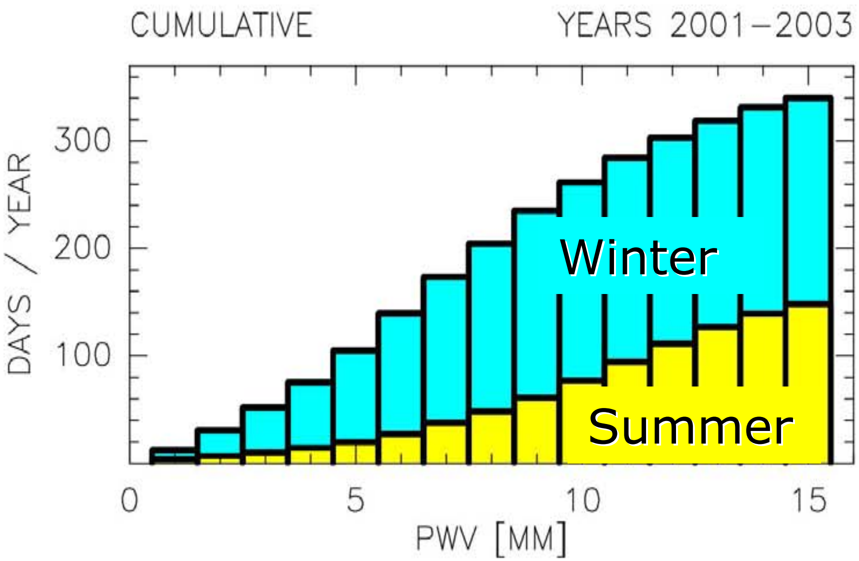
Weather @ PdB



- PWV : down to 0.3 mm in winter time
- Submillimeter observing conditions ~ 30 days / year
- Wind : up to 60 m/s
- Time scale : 4-5 days

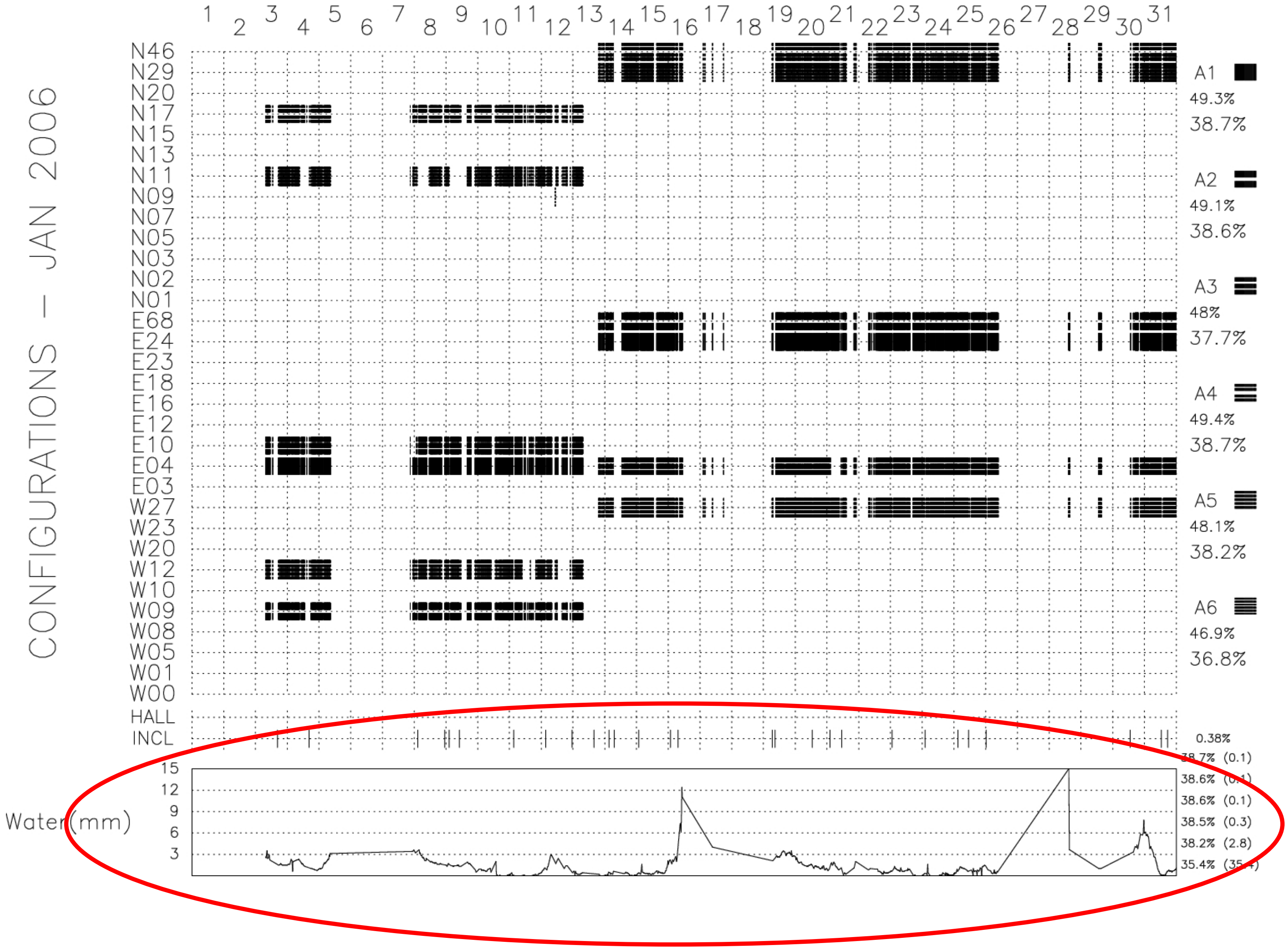
PWV @ Plateau de Bure





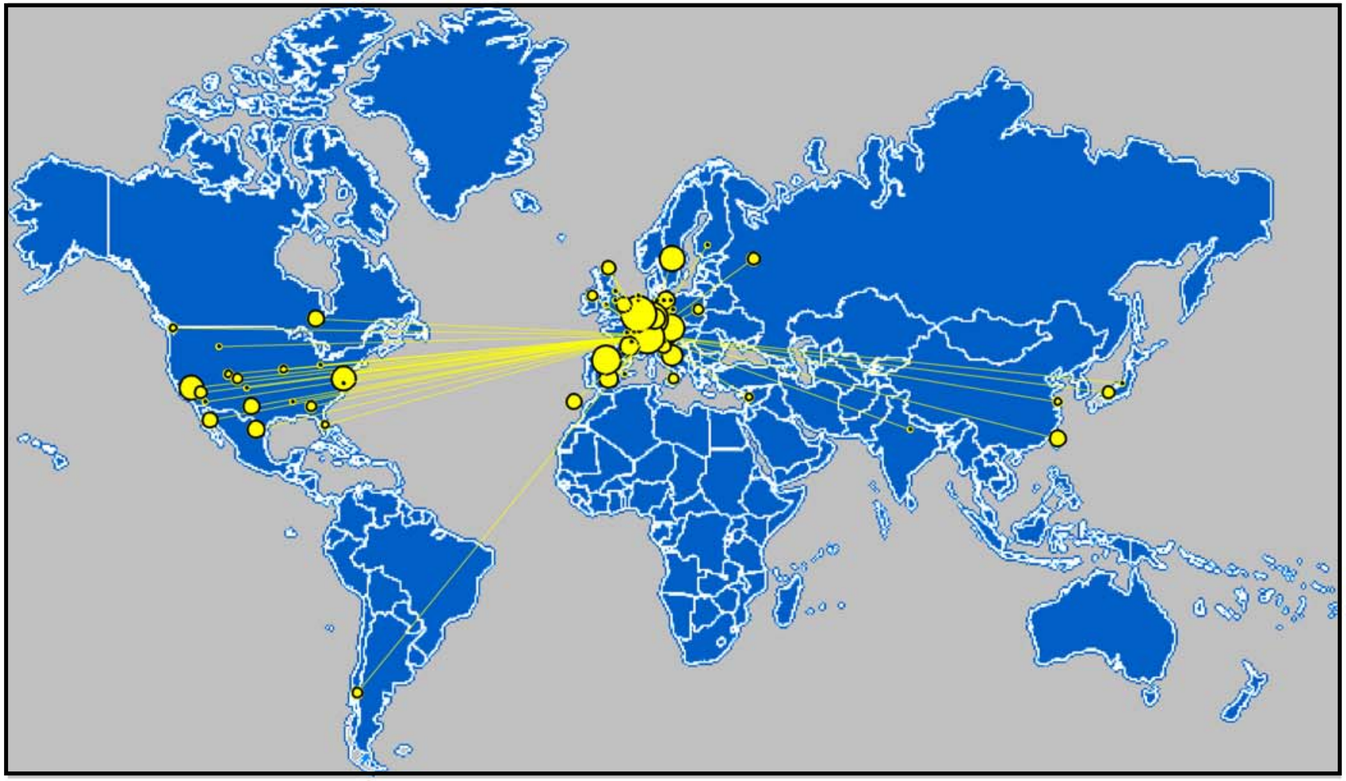
Winter = November to April

Summer = May to October

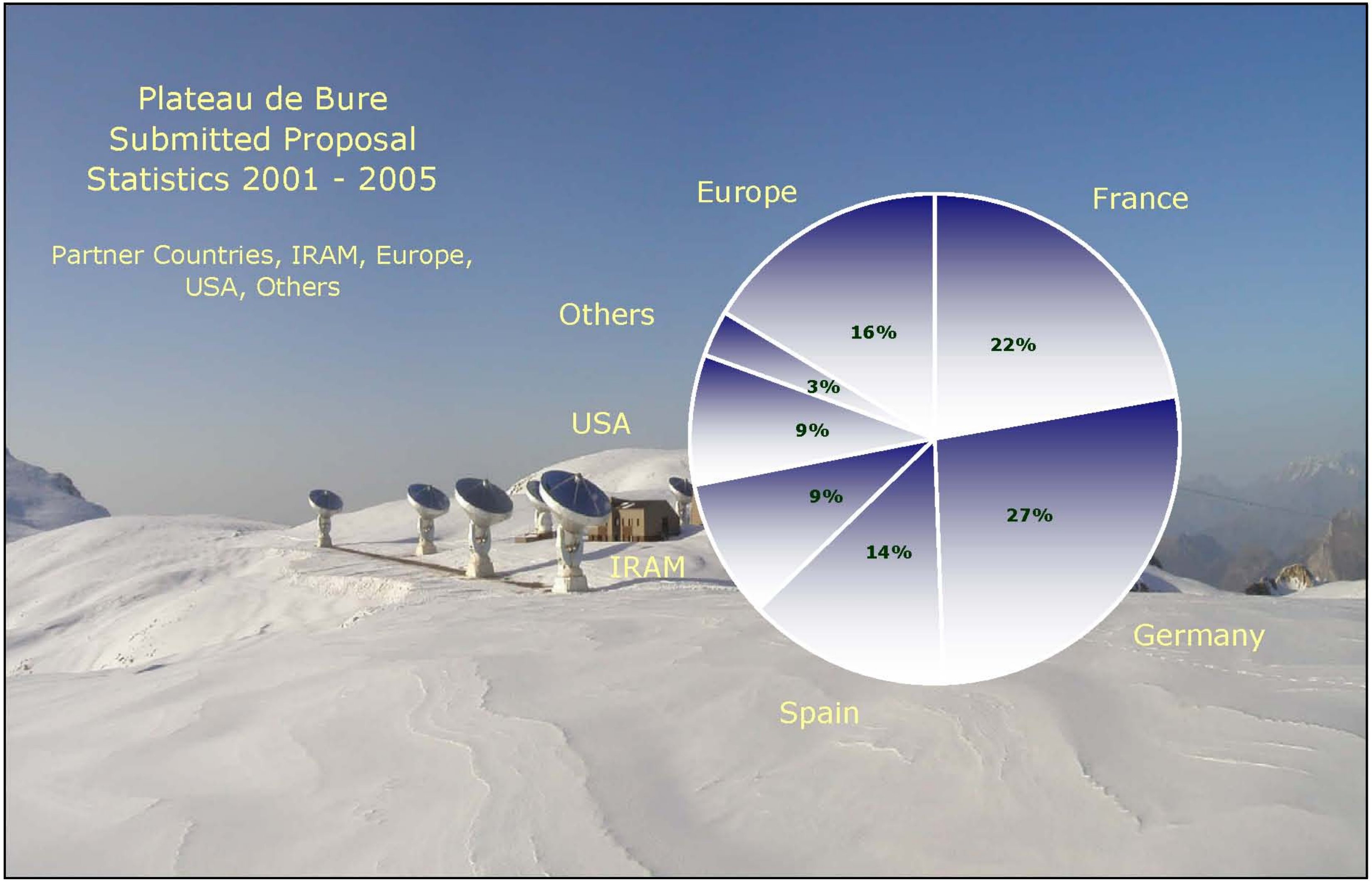

CONFIGURATIONS – JAN 2006
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
N46
N29
N20
N17
N15
N13
N11
N09
N07
N05
N03
N02
N01
E68
E24
E23
E18
E16
E12
E10
E04
E03
W27
W23
W20
W12
W10
W09
W08
W05
W01
W00
HALL
INCL
A1
49.3%
38.7%
A2
49.1%
38.6%
A3
48%
37.7%
A4
49.4%
38.7%
A5
48.1%
38.2%
A6
46.9%
36.8%
0.38%
38.7% (0.1)
38.6%
38.6% (0.1)
38.5% (0.3)
38.2% (2.8)
35.4%
Water (mm)
15
12
9
6
3

SOME STATISTICS

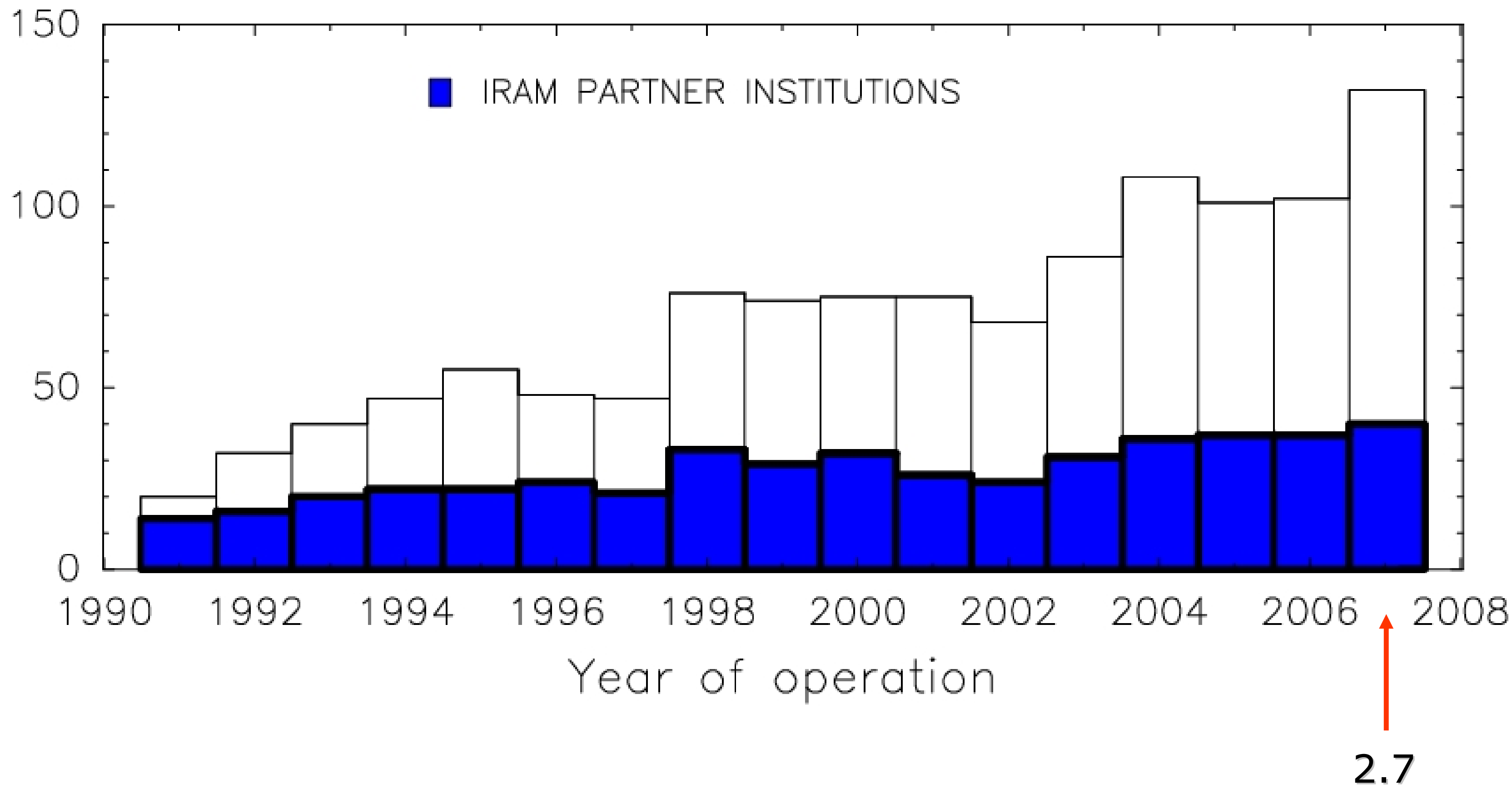
Where is the IRAM community from?



- More than 500 users from all over the world


Plateau de Bure
Submitted Proposal
Statistics 2001 - 2005
Partner Countries, IRAM, Europe,
USA, Others
Europe
France
Others
USA
IRAM
Spain
Germany
16%
22%
3%
9%
9%
14%
27%

Institutions statistics

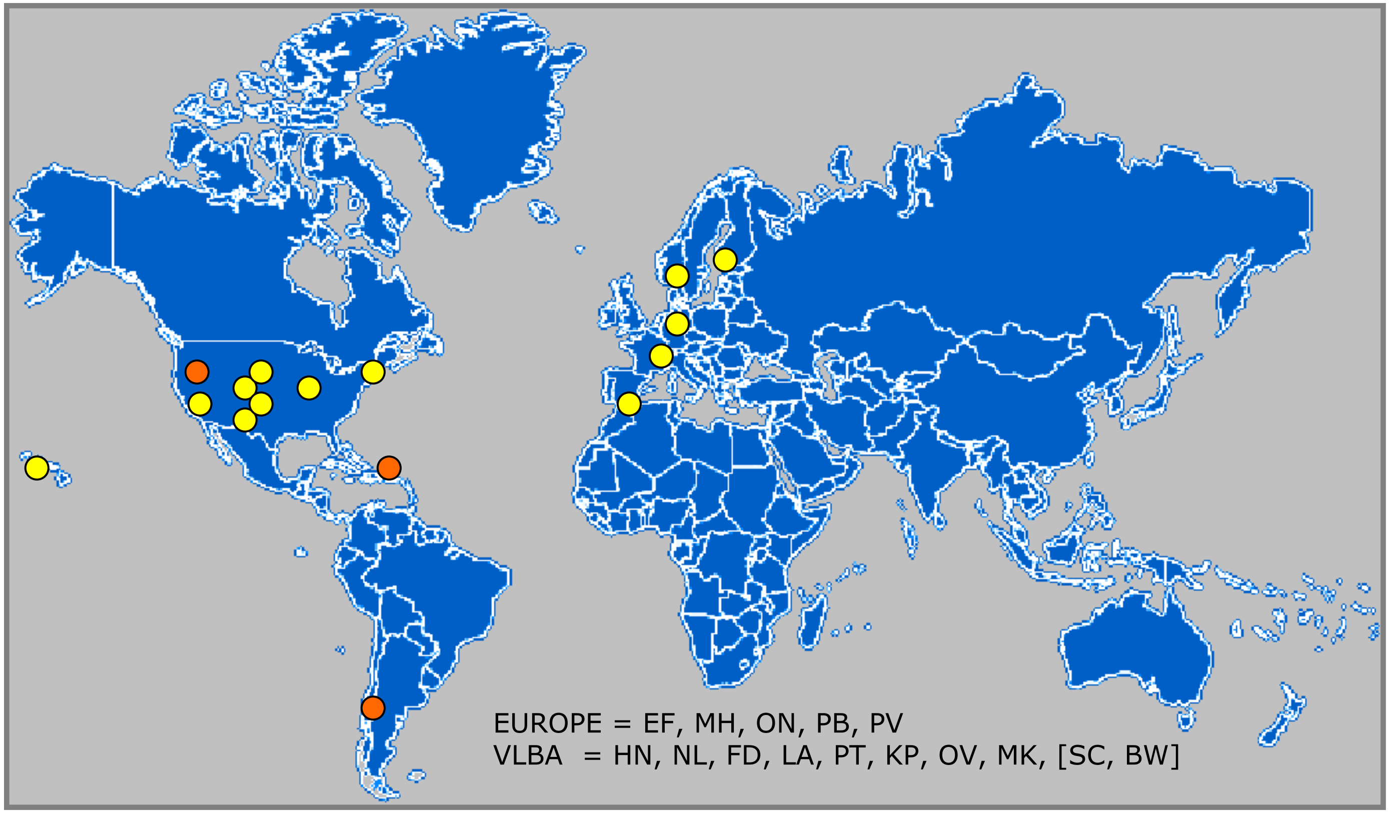


PdBI Science Drivers

Science Drivers 2005 >	Allocated Time	Keyword
Galaxies @ high-z : LBG, SMM, ERO, RG	30%	"CSF history"
Nearby Galaxies : Spirals, (U)LIRGs	30%	"dynamics + structure"
YSO : Prestellar Clouds → T-Tauri Stars	30%	"SF + evolution"
Evolved Stars	5%	"mass loss"
Chemistry, Solar System, …	5%	

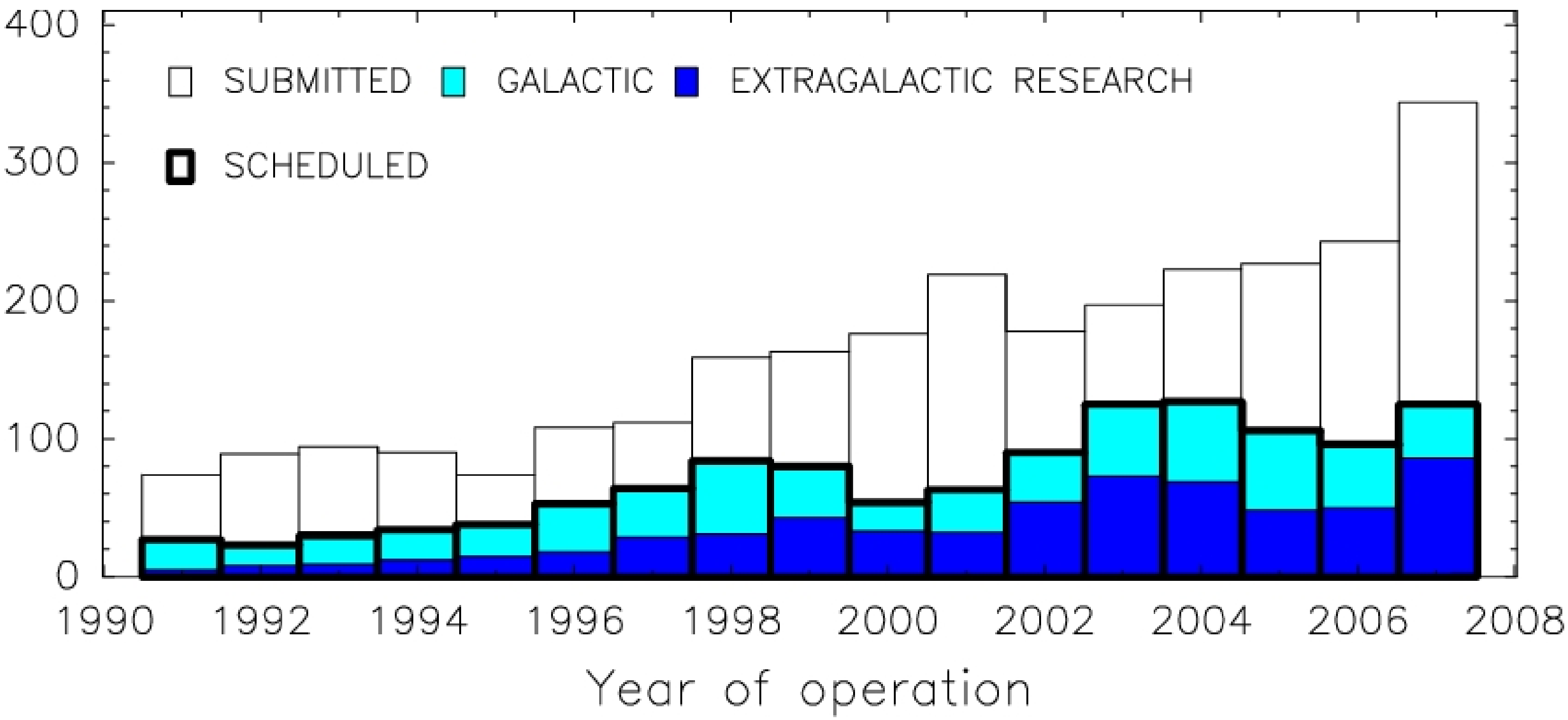
VLBI	10 days	

Global 3mm-VLBI Observations



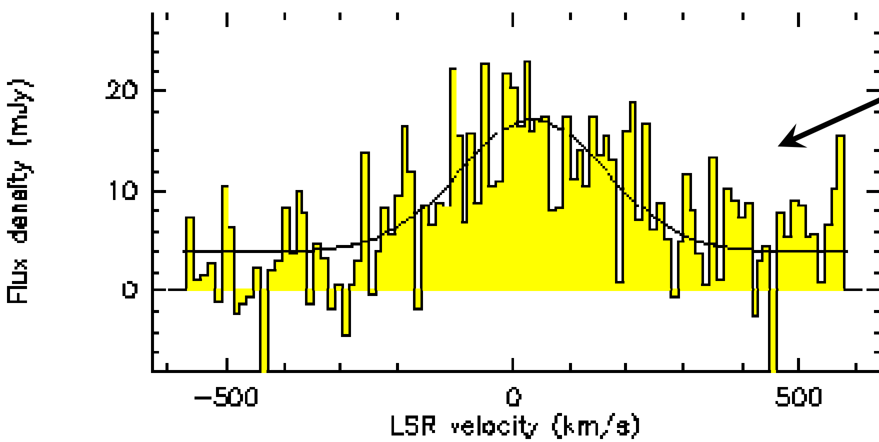
2 sessions every year = 2 weeks

Science Statistics

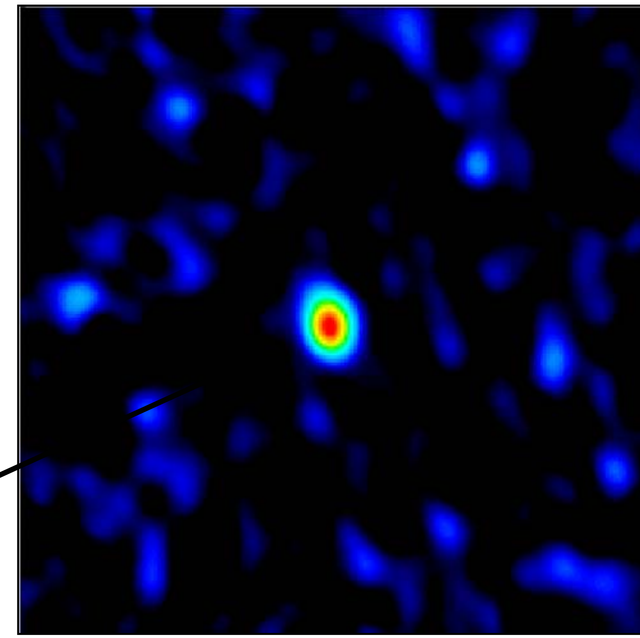


Star Formation @ high-z

- C[II] @ 158 um
- Is produced in PDRs → UV-radiation
- Tight C[II]/^{12}CO correlation
- Tracer of SF in SB galaxies → PDRs ~ 40% M_{Gas}
- J1148 detected @ z =6.42 (!)
- 850 um opens the C[II] window → 4 < z < 6



J1148+5251 @ 257 GHz



Walter et al. 2007

Maiolino et al. 2005

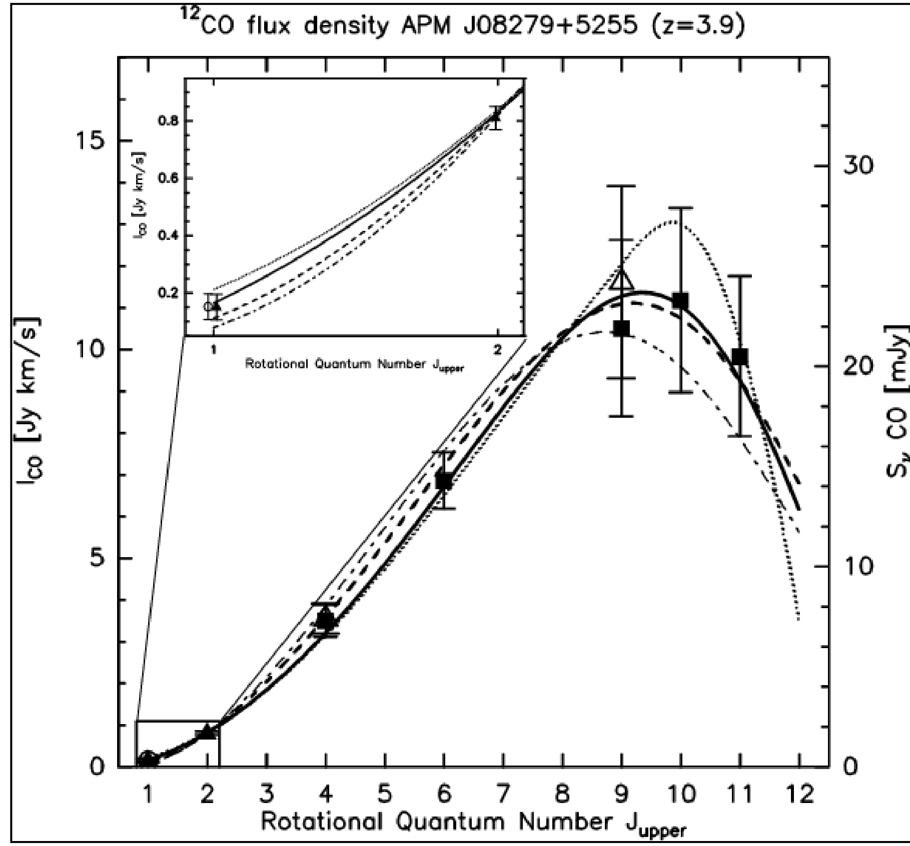
PdBI on Jan 29, 2007

Gas Excitation Conditions @ z > 1

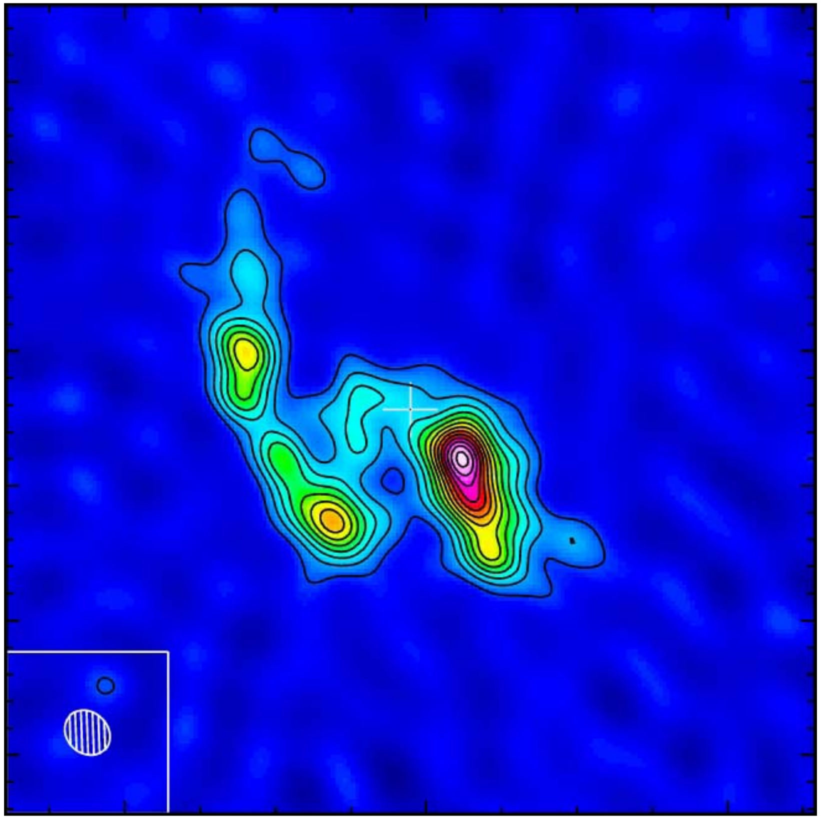
Molecular Lines:

- ^{12}CO(11-10) (!) detected @ z = 4
- ^{12}CO @ high-z traces warm gas and dust
- Limits on virial mass + $\alpha(M/L') \rightarrow M_{Gas}$
- 850 um → ^{12}CO-SED @ z = 2.5

- Detected: HCN, CN, HNC, HCO^+, C[I]
- Planned: H_2CO, H_2O, …
- 850 um → complements the ML-SEDs



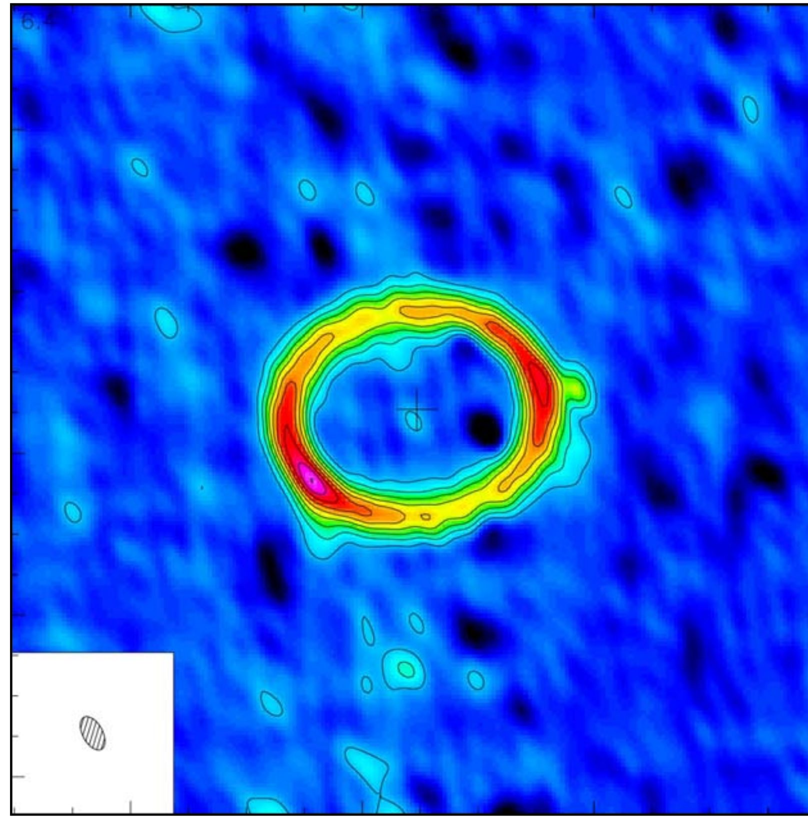
IC 342 @ 146 GHz



Rodriguez/Schinnerer et al. in prep.

C configuration

GG Tau @ 267 GHz



Piétu et al. in prep.

A+C configuration

PdBI’s SENSITIVITY

The point source sensitivity

$$\sigma_S = \frac{2k}{\eta_A A} \times \frac{< T_{\mathsf{SYS}} >}{\eta_C \eta_J \eta_P \sqrt{N(N-1)\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}}$$

A	Collecting Area of a Single Antenna (177 m^2)
η_A	Aperture Efficiency (0.70 @ 3mm; 0.45 @ 1mm)
η_C	Correlator Efficiency (0.88)
η_J	Instrumental Jitter $\exp(-\sigma_J^2/2) \simeq 0.95$
η_P	Atmospheric Decorrelation $\exp(-\sigma_P^2/2) \leq 0.95$
T_{SYS}	System Temperature
$\Delta\nu$	Spectral Bandwidth (39 kHz - 2000 MHz)
Δt	Integration Time On-Source
N_P	Linear Polarizations (1 - 2)

ATMOSPHERE (SITE)

Seeing

Transparency

$$\sigma_S = \frac{2k}{\eta_A A} \times \frac{< T_{\mathrm{SYS}} >}{\eta_C \eta_J \eta_P \sqrt{N(N-1)\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}}$$

Receivers

Antenna

Local Oscillators

Correlator

INSTRUMENTAL PERFORMANCE

Single Dish Efficiency (Jy/K)

ATMOSPHERE (SITE)

Seeing   Transparency

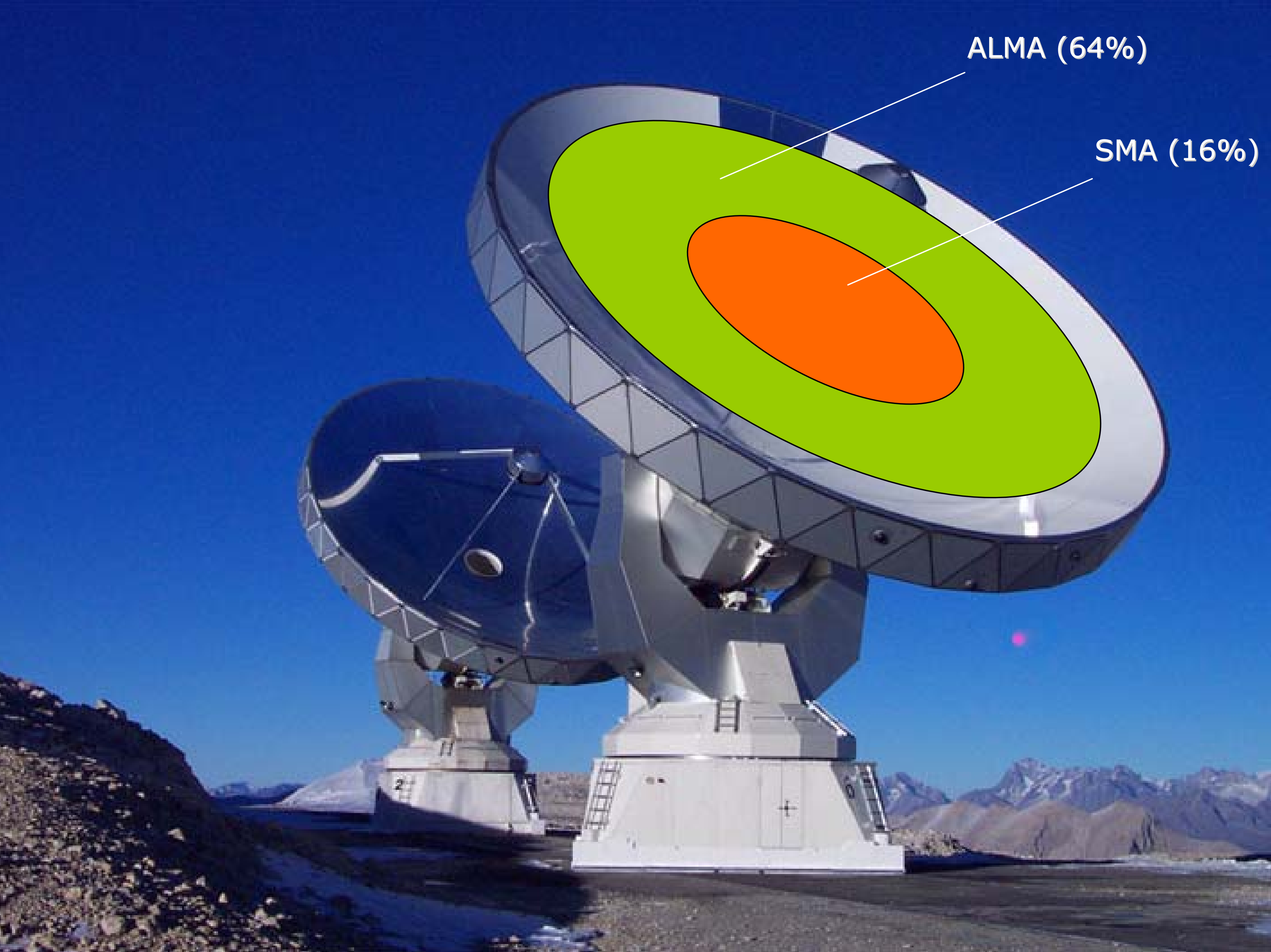
$$\sigma_S = \frac{2k}{\eta_A A} \times \frac{< T_{\mathrm{SYS}} >}{\eta_C \eta_J \eta_P \sqrt{N(N-1)\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}}$$

$$\eta_A = \eta_{\mathrm{Blocage}} \cdot \eta_{\mathrm{Spillover}} \cdot \eta_{\mathrm{Receiver}} \cdot \eta_{\mathrm{Ruze}}$$

Antenna   Local Oscillators

Correlator

INSTRUMENTAL PERFORMANCE


ALMA (64%)
SMA (16%)

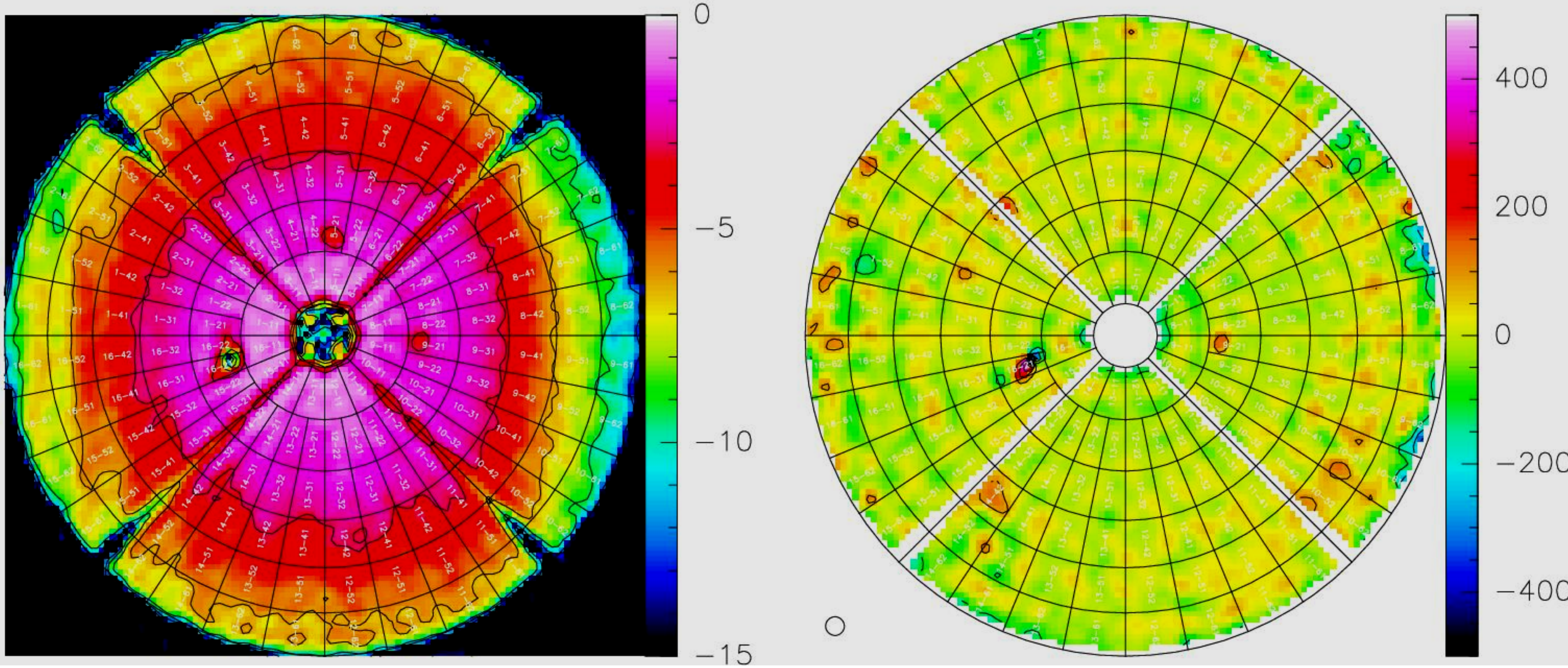
RF: Uncal.
Am: Rel.(B)
Ph: Rel.(B)
rms Pha.

14	5.74
24	7.08
34	6.27
45	4.75

CLIC – 13–OCT–2004 16:26:44 – neri – Antenna 5 – W00E03W05N05N09
ORIAIRC2 5D scans 7265 to 7484 (22–AUG–2004) Elev: 39.92

Edge taper = 9.68x 6.61 dB – offset X= –0.18 Y= –0.16 m
Focus offsets (X,Y,Z) = 0.94 0.26 0.03 mm; Astigmatism = 0.00 mm
Phase rms (unweighted)= 0.134 (weighted)= 0.115 radians
Surface rms (unweighted)= 42.45 – (weighted)= 35.31 μm
η_A(86.242 GHz) = 0.718; η_A(230.0 GHz) = 0.665; η_A(345.0 GHz) = 0.599
S/T(86.242 GHz)= 21.757 Jy/K; S/T(230GHz)= 23.490 Jy/K; S/T(345 GHz)= 26.087 Jy/K
η_l= 0.727 –η_S= 0.834 –η_P(86.242 GHz)= 0.987 –η_P(230 GHz)= 0.914 –η_P(345 GHz)= 0.823
Rms/ring: 44.2 31.6 24.3 33.0 37.5 49.3

Amplitude (back view) –15.000 to 0.000 by 3.000
Normal errors (back view) –500.000 to 500.000 by 100.000



Interferometric Efficiency (Jy/K)

ATMOSPHERE (SITE)

Seeing Transparency

$$\sigma_S = \frac{2k}{\eta_A A} \times \frac{< T_{\mathrm{SYS}} >}{\eta_C \eta_J \eta_P \sqrt{N(N-1)\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}}$$

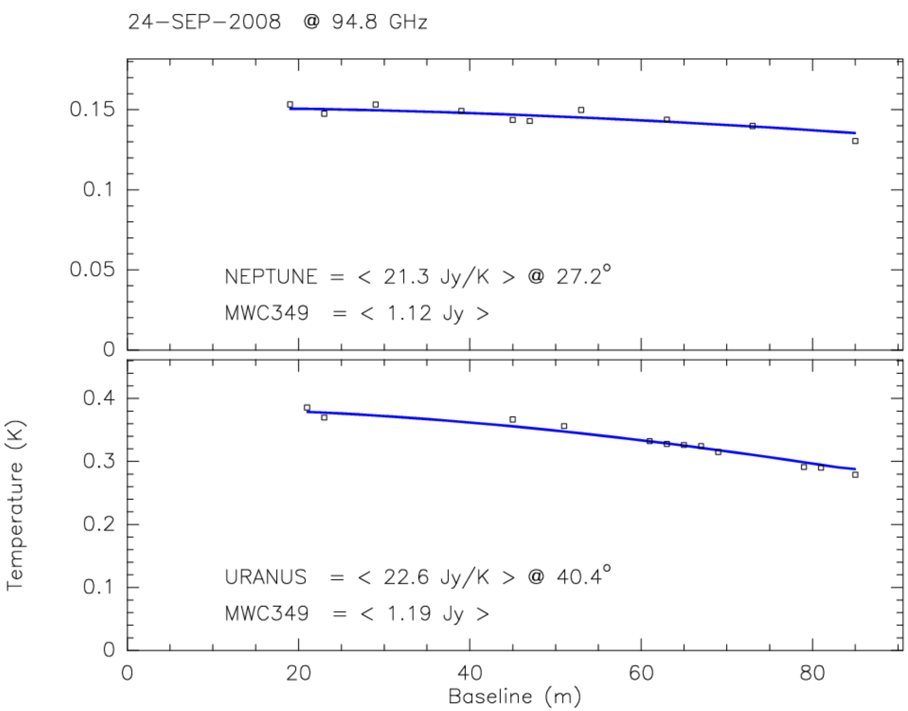
Receivers

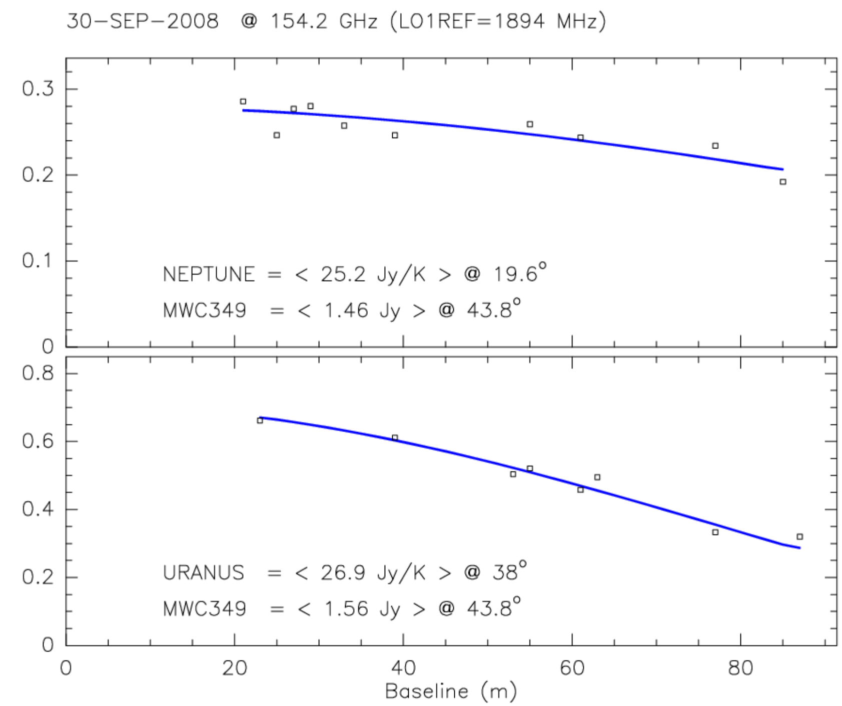
Antenna Local Oscillators

Correlator

INSTRUMENTAL PERFORMANCE

PdBI's antenna efficiency





22 Jy/K @ 95 GHz

26 Jy/K @ 154 GHz

Point source sensitivities:

$$\sigma_S = \frac{2k}{\eta_A A \times \eta_J} \times \frac{< T_{\mathsf{SYS}} >}{\eta_C \eta_P \sqrt{N(N-1)\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}}$$

$$= \frac{2k}{\eta_A A \times \eta_J} \times \sigma_T$$

$\rightarrow 22 \times \sigma_T$ [Jy] @ 3mm Calibration precision $\leq$ 10%
$\rightarrow 26 \times \sigma_T$ [Jy] @ 2mm Calibration precision $\leq$ 15%
$\rightarrow 35 \times \sigma_T$ [Jy] @ 1mm Calibration precision $\leq$ 20%

ATMOSPHERE (SITE)

Seeing Transparency

$$\sigma_S = \frac{2k}{\eta_A A} \times \frac{< T_{\mathrm{SYS}} >}{\eta_C \eta_J \eta_P \sqrt{N(N-1)\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}}$$

Receivers

Antenna Local Oscillators

Correlator

INSTRUMENTAL PERFORMANCE

System Noise

Winter values: Tamb=273K, A=1.4 airmass

ATM (Cernicharo 1985) ↓

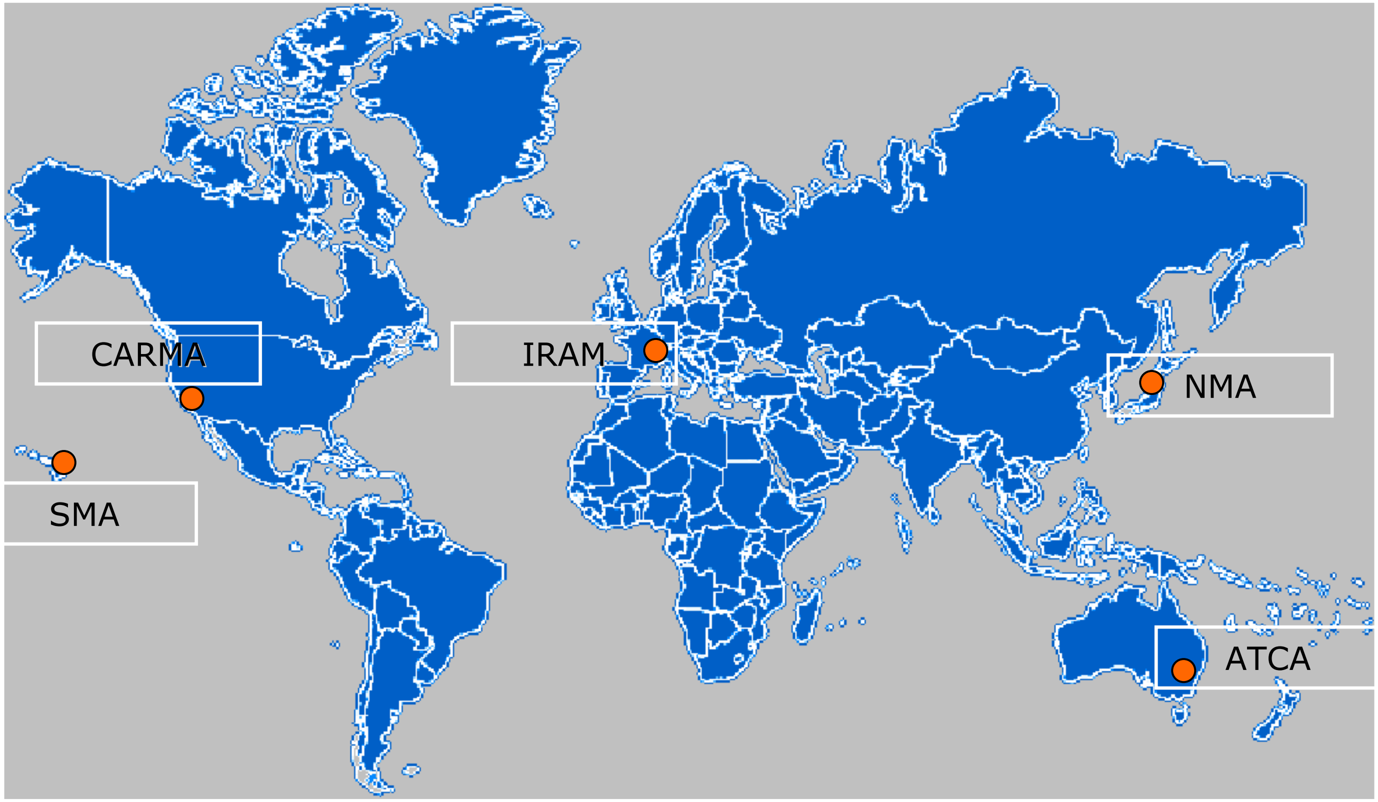
	PWV	G	η	Trec	τ	Tsys
100 GHz	3	0.02	0.95	32	0.07	77
150 GHz	3	0.02	0.92	35	0.10	113
230 GHz	1	0.02	0.87	50	0.07	141
350 GHz	1	0.02	0.84	60	0.27	336

One baseline, two antennas:

$$\sigma_T \simeq \frac{< T_{\mathsf{SYS}} >}{\eta_C\sqrt{2\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}} = \frac{\sqrt{T^1_{\mathsf{SYS}} \times T^2_{\mathsf{SYS}}}}{\eta_C\sqrt{2\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}} \quad [\mathsf{K}]$$

$$\mathsf{Ex @ 3mm:} \quad \sigma_T \simeq \frac{77}{0.88\sqrt{2 \times 1000\,10^6 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 1.4\,\mathsf{mK}$$

$$\rightarrow \sigma_S \simeq 22 \times 1.2 \simeq 30\,\mathsf{mJy}$$

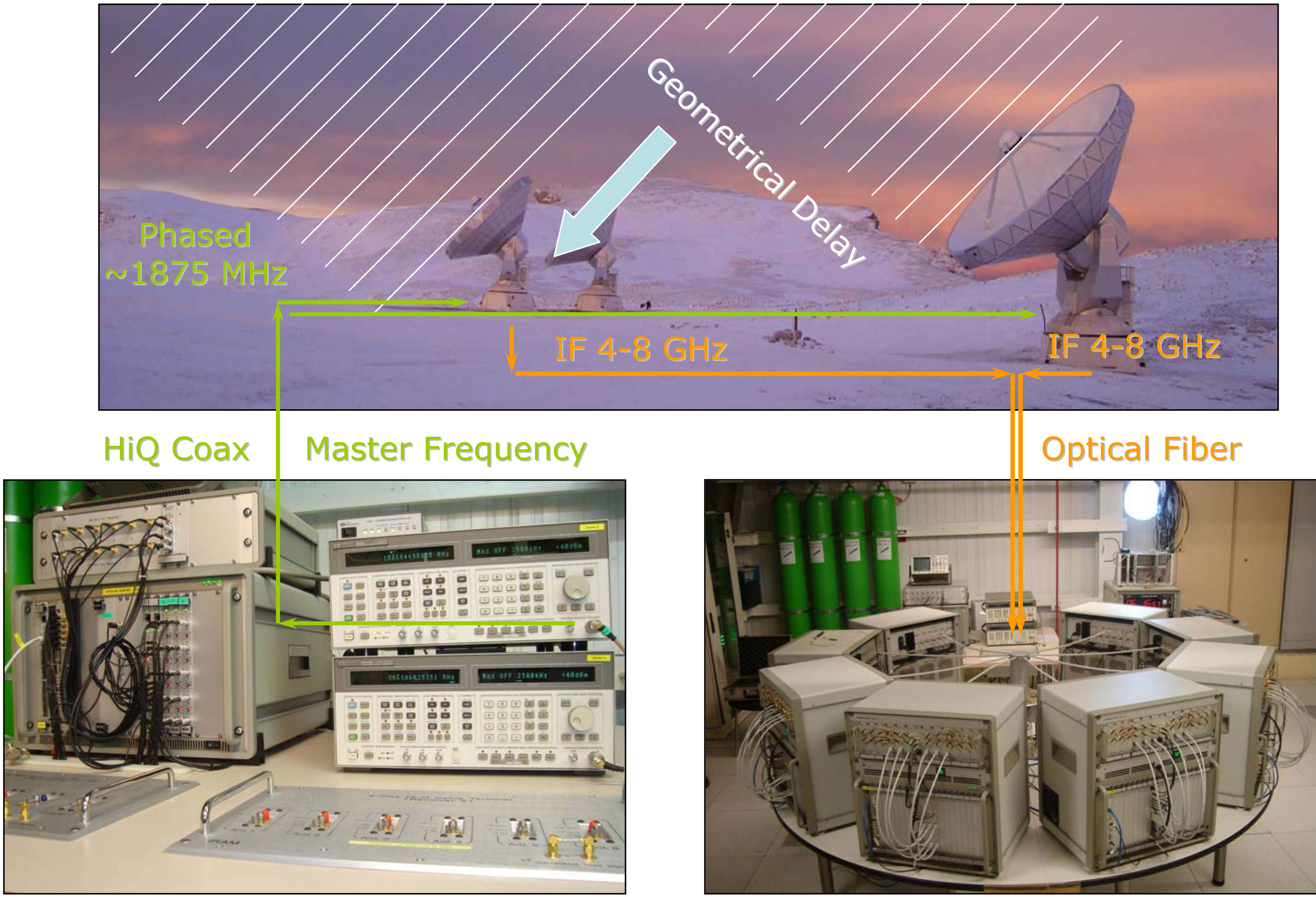

CARMA
IRAM
NMA
SMA
ATCA

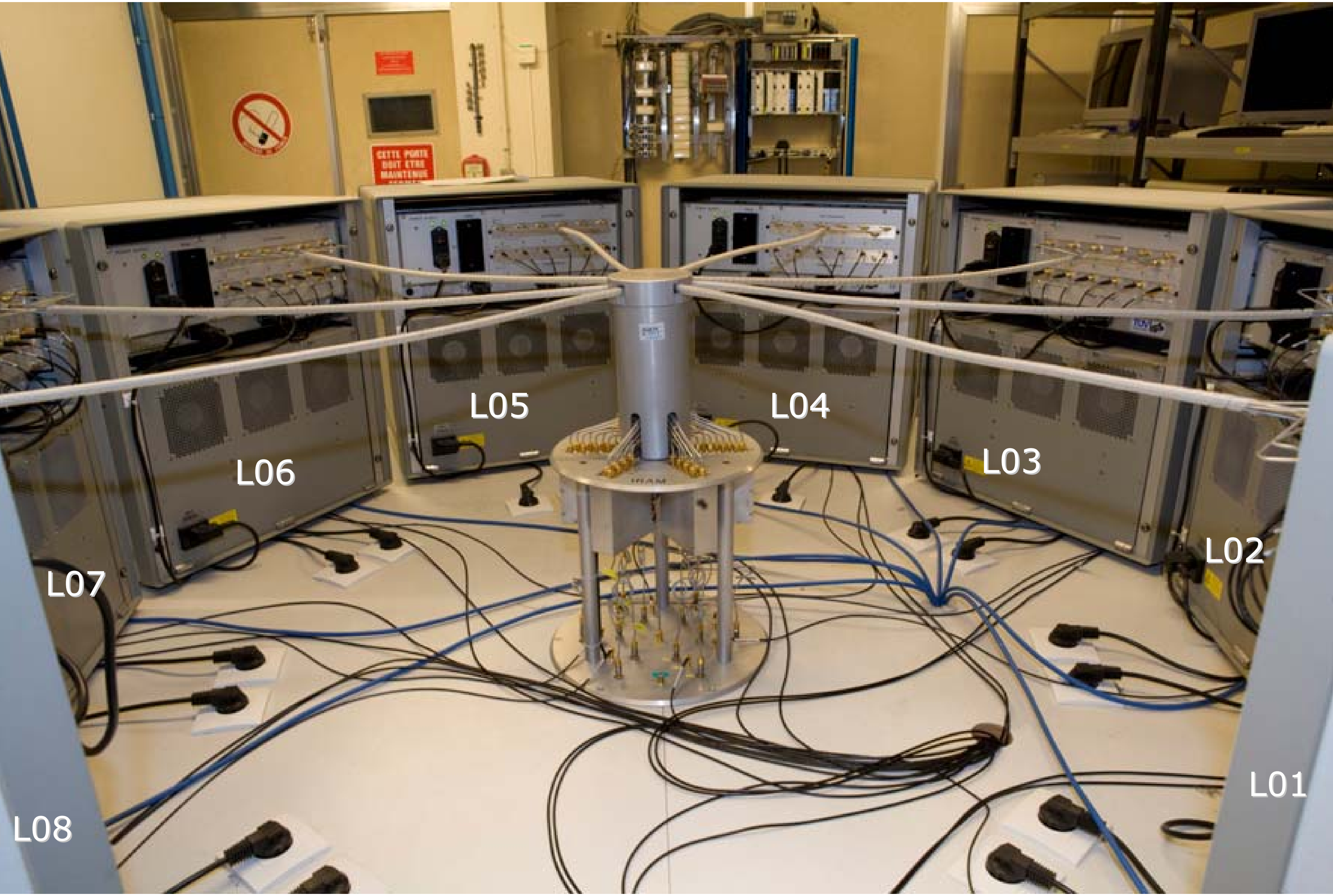
Interferometers: A comparison

	NMA		CARMA		IRAM		SMA	
Altitude	1300		2200		2600		4200	
Antennas	6		15		6		8	
Baseline (m)	350		2000		770		500	
	3mm	1mm	3mm	1mm	3mm	1mm	3mm	1mm
IRAM Sensitivity	0.42	0.06	(0.72)	(0.78)	1.00	1.00	—	0.36
IRAM Speed	0.18	—	(0.52)	(0.62)	1.00	1.00	—	0.13

Sensitivity= $\frac{\eta_A D^2 \sqrt{N(N-1)}}{T_{\mathrm{sys}}}$, Speed= $[\frac{\eta_A D^2 \sqrt{N(N-1)}}{T_{\mathrm{sys}}}]^2$

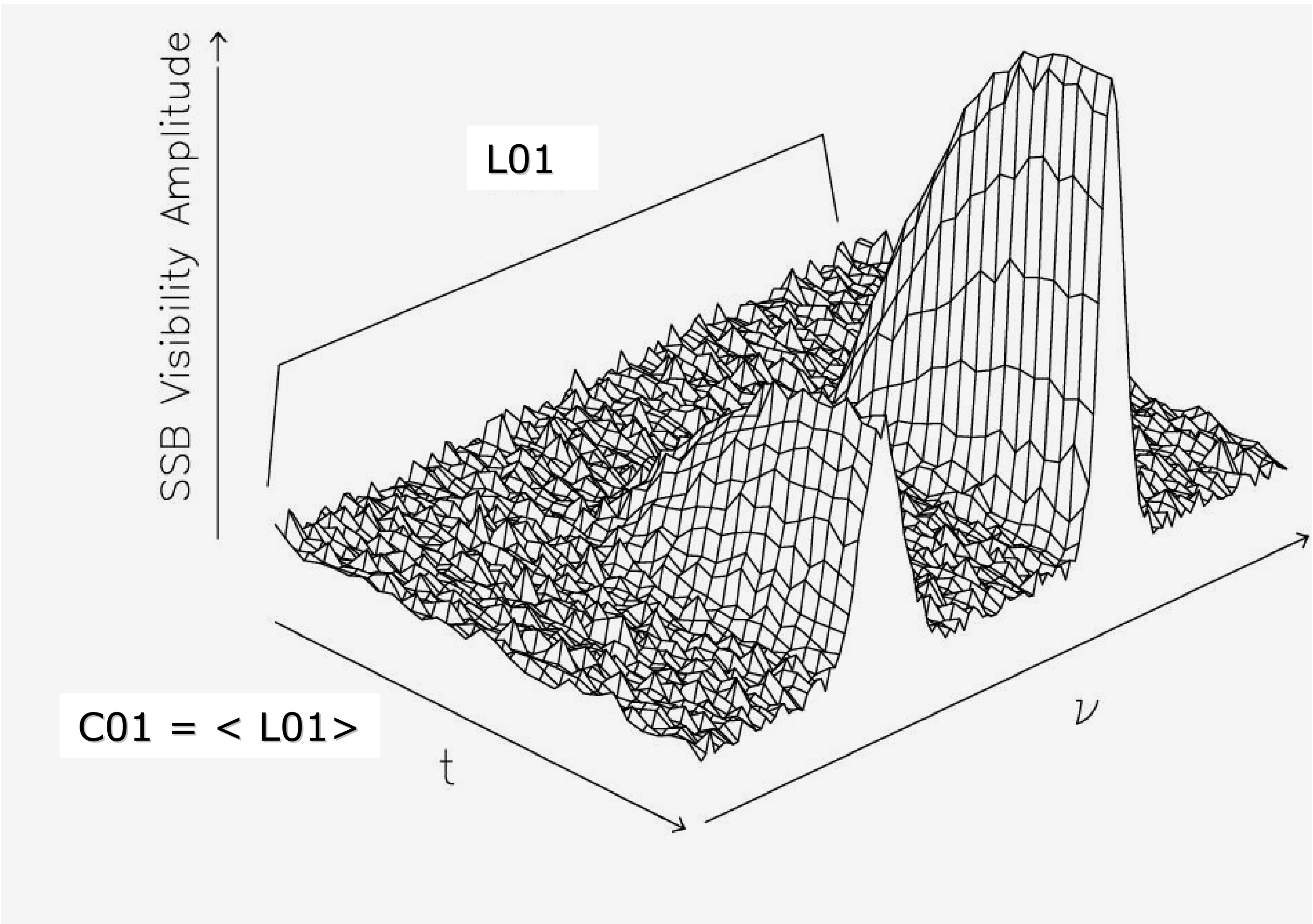
PdBI’s SPECTRAL CAPABILITIES


Geometrical Delay
Phased
~1875 MHz
IF 4-8 GHz
IF 4-8 GHz
HiQ Coax
Master Frequency
Optical Fiber


CETTE PORTE
DOIT ETRE
MAINTENUE
L05
L04
L06
L03
L02
L07
L01
L08

Each correlator unit produces Line and Continuum data:

- L01, …, L08 : one visibility spectrum per scan (45 sec or 60 sec)
- C01, …, C08 : one spectral averaged visibility per time unit (1 sec)

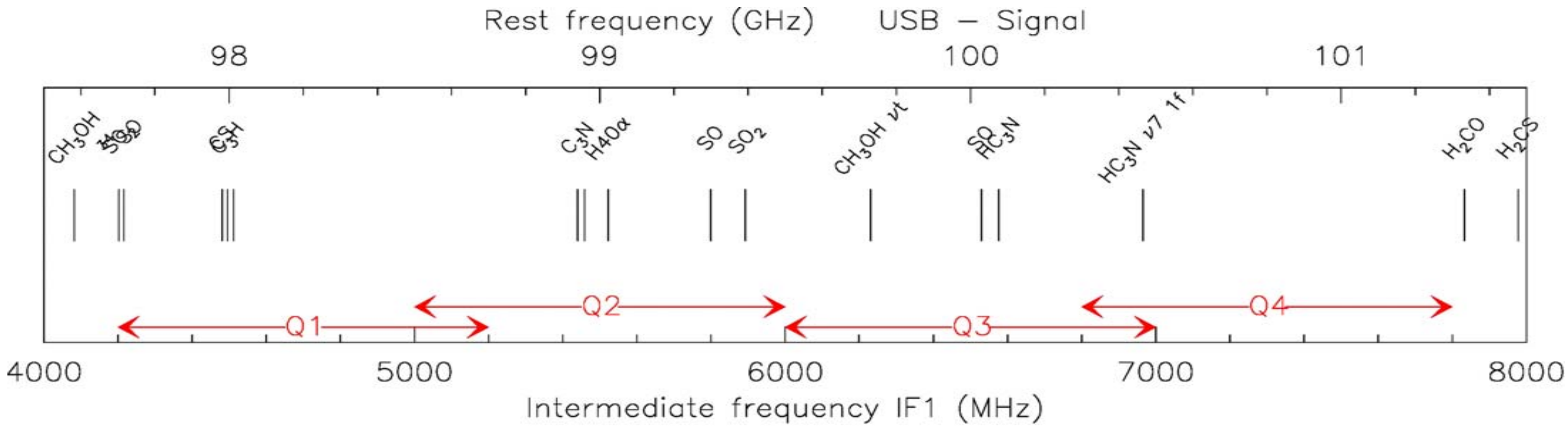


Correlator Modes

http://www.iram.fr/IRAMFR/TA/backend/cor6A/index.html

Bandwidth	Mode	Channels	Spacing
320 MHz	DSB	2 x 64	2.5 MHz
160 MHz	SSB	1 x 128	1.25 MHz
160 MHz	DSB	2 x 128	0.625 MHz
80 MHz	SSB	1 x 256	0.312 MHz
80 MHz	DSB	2 x 256	0.156 MHz
40 MHz	SSB	1 x 512	0.078 MHz
20 MHz	SSB	1 x 512	0.039 MHz

A 4 GHz RF but …



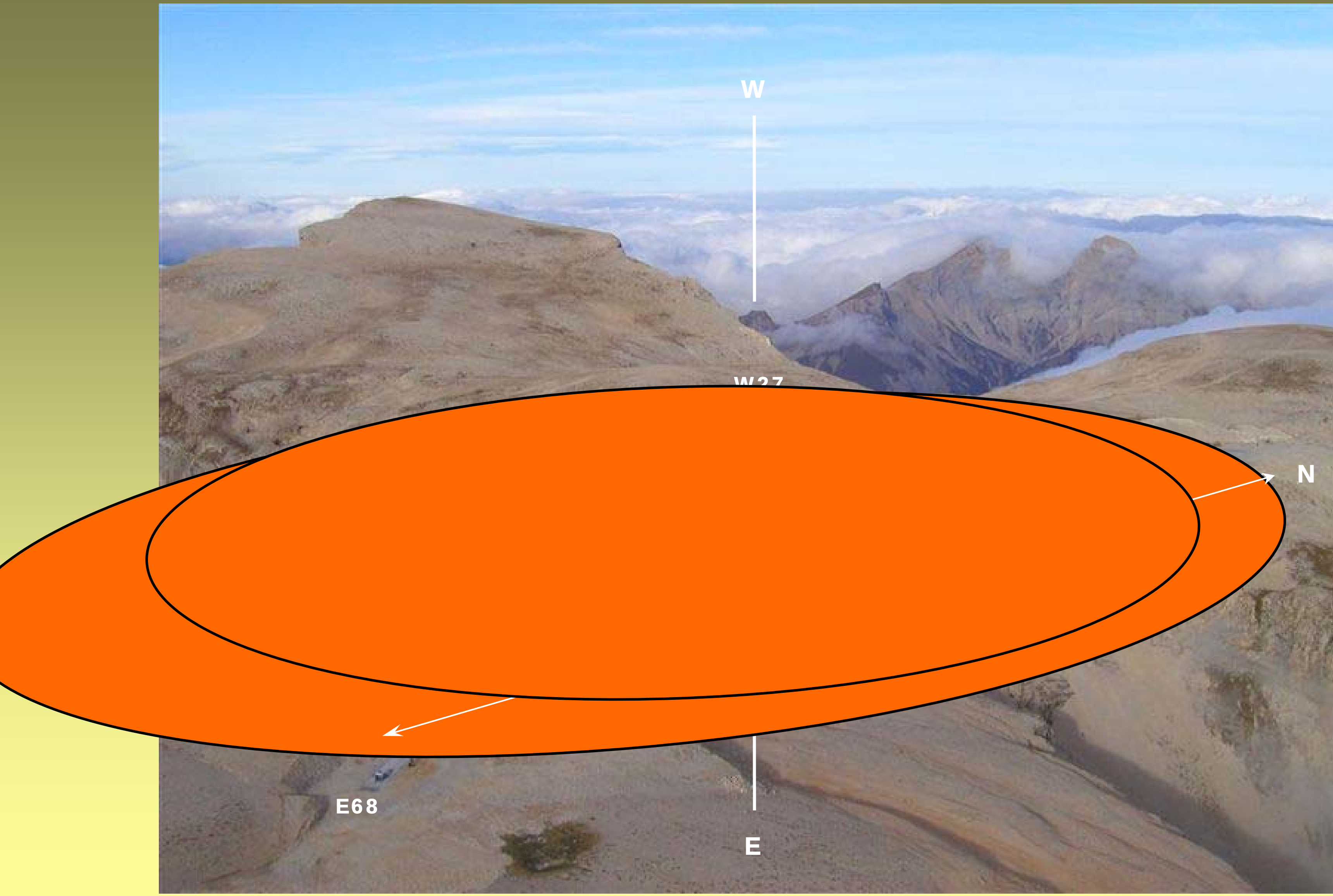
- correlator accepts only 2 quarters ; max ΔB = 2 x 1 GHz
- linear polarization : H and/or V, but no cross-products
- eight (8) correlator units : 20 … 320 MHz (40 KHz … 2.5 MHz)

Band (MHz)	Effective (MHz)	Channel (MHz)	Δv (100 / 230) (km/s)	Sensivity (100 / 230) (mJy after 1 hr)
320	2000	2.5	7.5 / 3.3	5 / 12
160	1000	0.6	1.9 / 0.8	9 / 25
80	500	0.3	0.9 / 0.4	12 / 35

PdBI's SPATIAL RESOLUTION

AND

FIELD OF VIEW



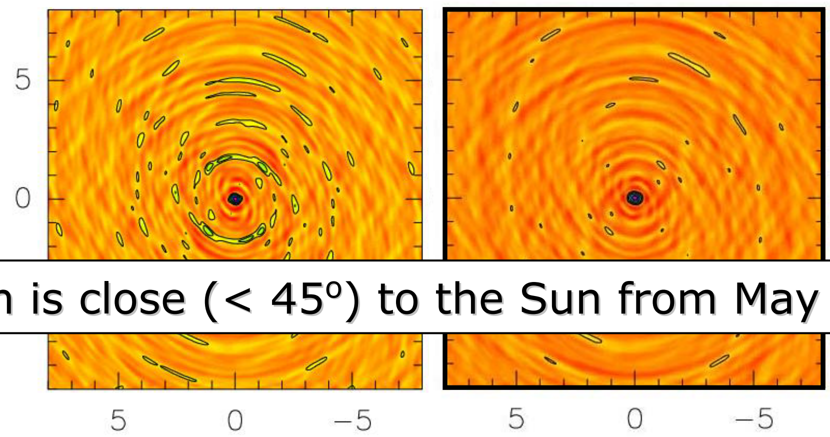
W
W27
N
E68
E

Array configurations

Design: 4 configurations, optimization 20° decl.

Karastergiou et al. 2006

A @ 230 GHz



AB @ 230 GHz

Orion is close (< 45°) to the Sun from May to July

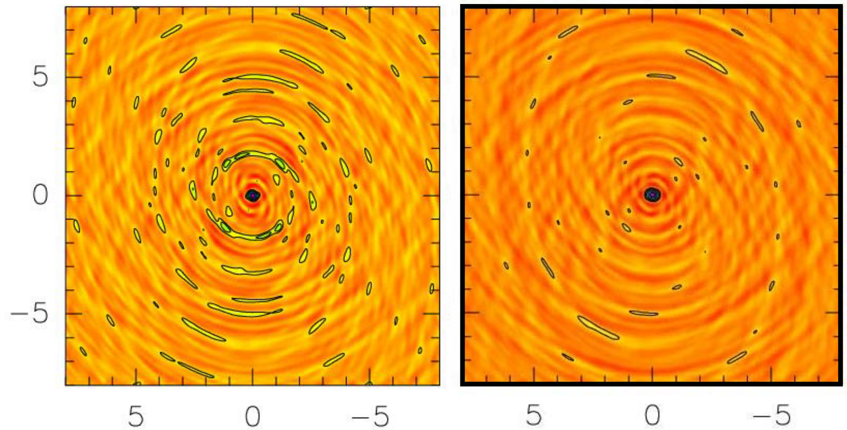
Configurations	D	C	B	A
Months	Apr – Nov	Mar - Apr Nov - Dec	Jan - Mar	Jan - Mar
Resolution @ 230 GHz	3″			0.3″

Array configurations

Design: 4 configurations, optimization 20° decl.

Karastergiou et al. 2006

A @ 230 GHz



AB @ 230 GHz

AB config	3mm	2mm	1.2mm	0.8mm
400 pc	350 AU	250 AU	150 AU	100 AU
z = 5	5000 pc	3000 pc	2000 pc	1500 pc

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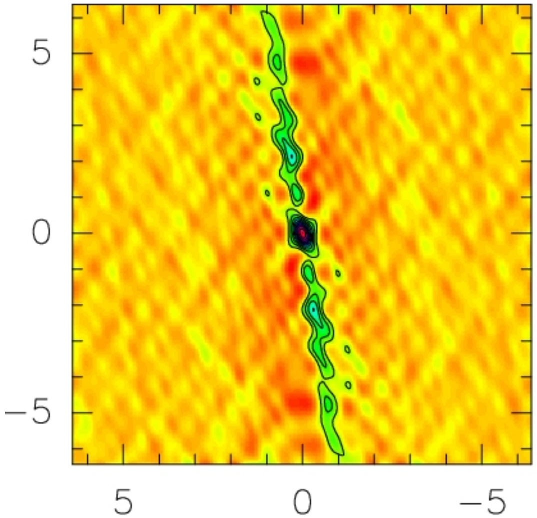
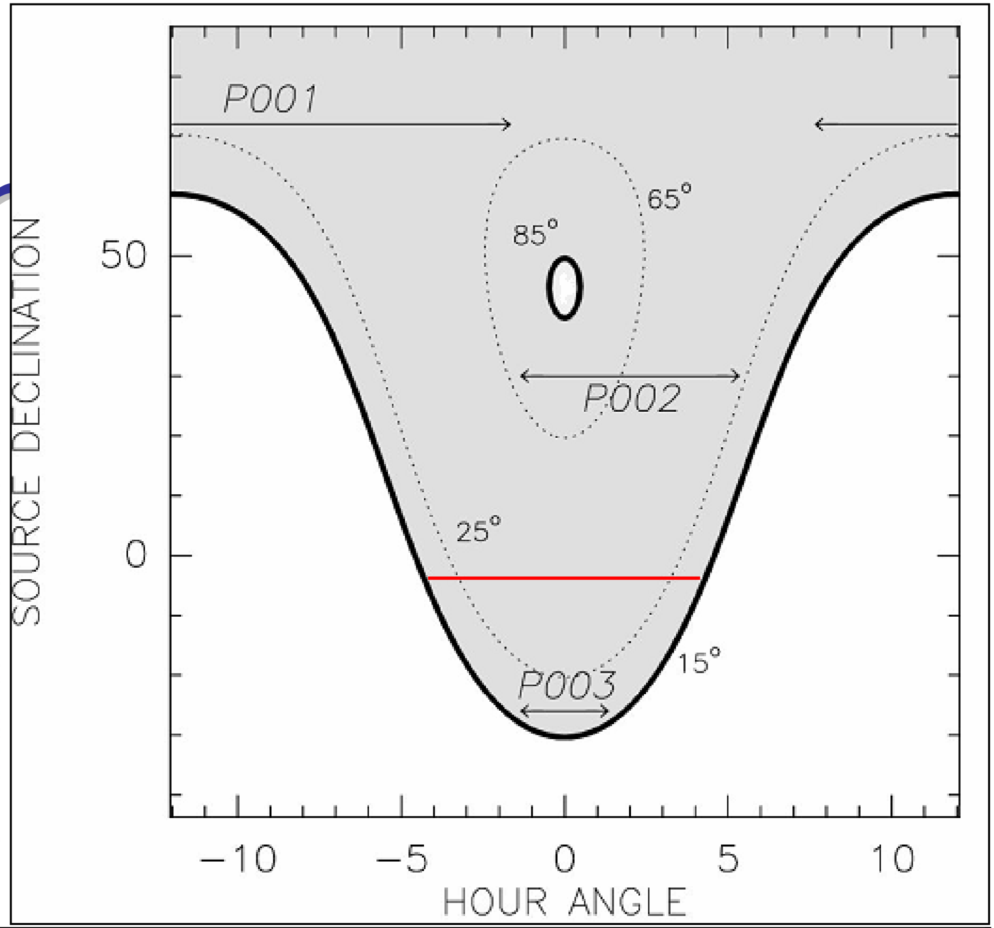
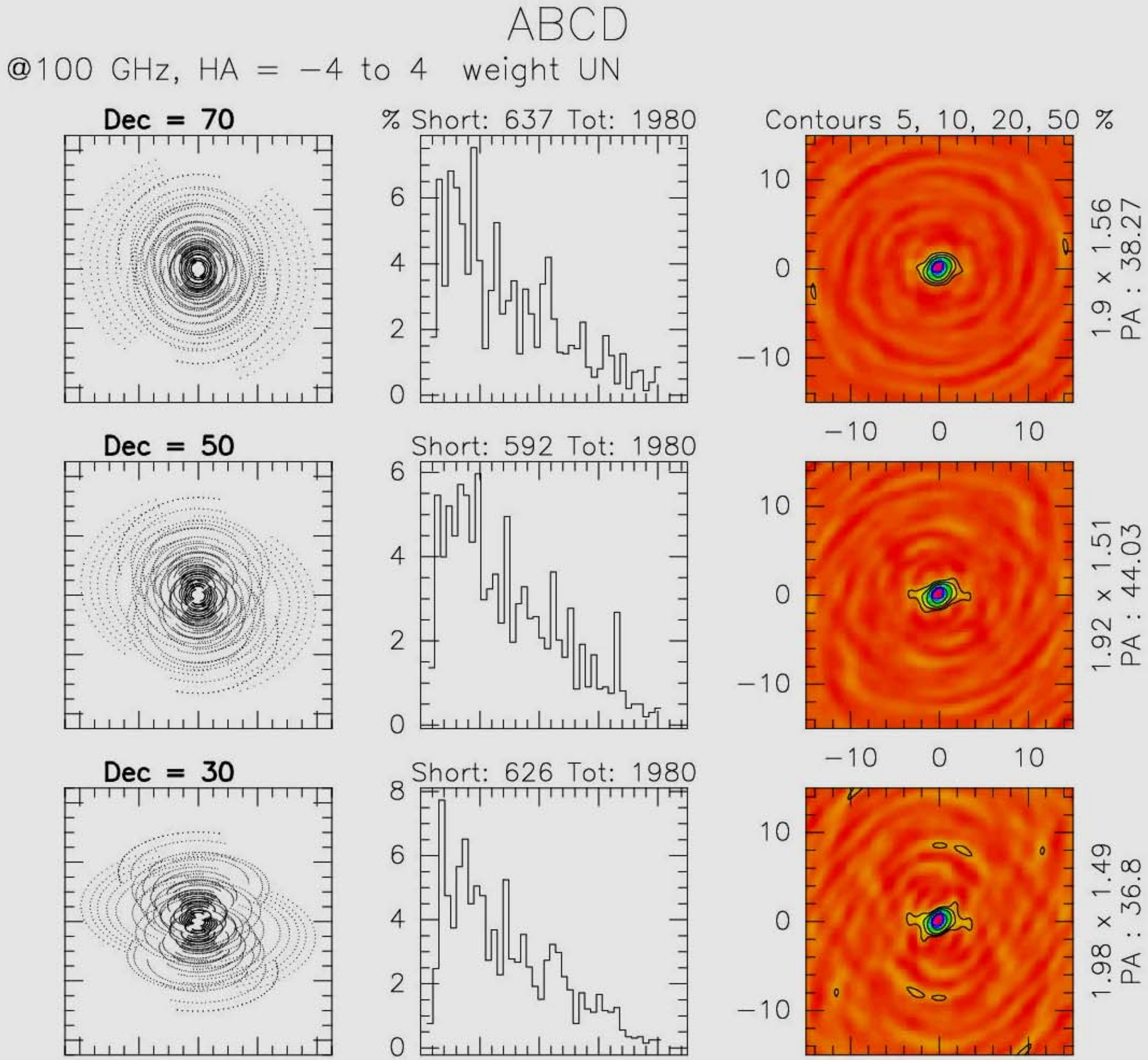
Th



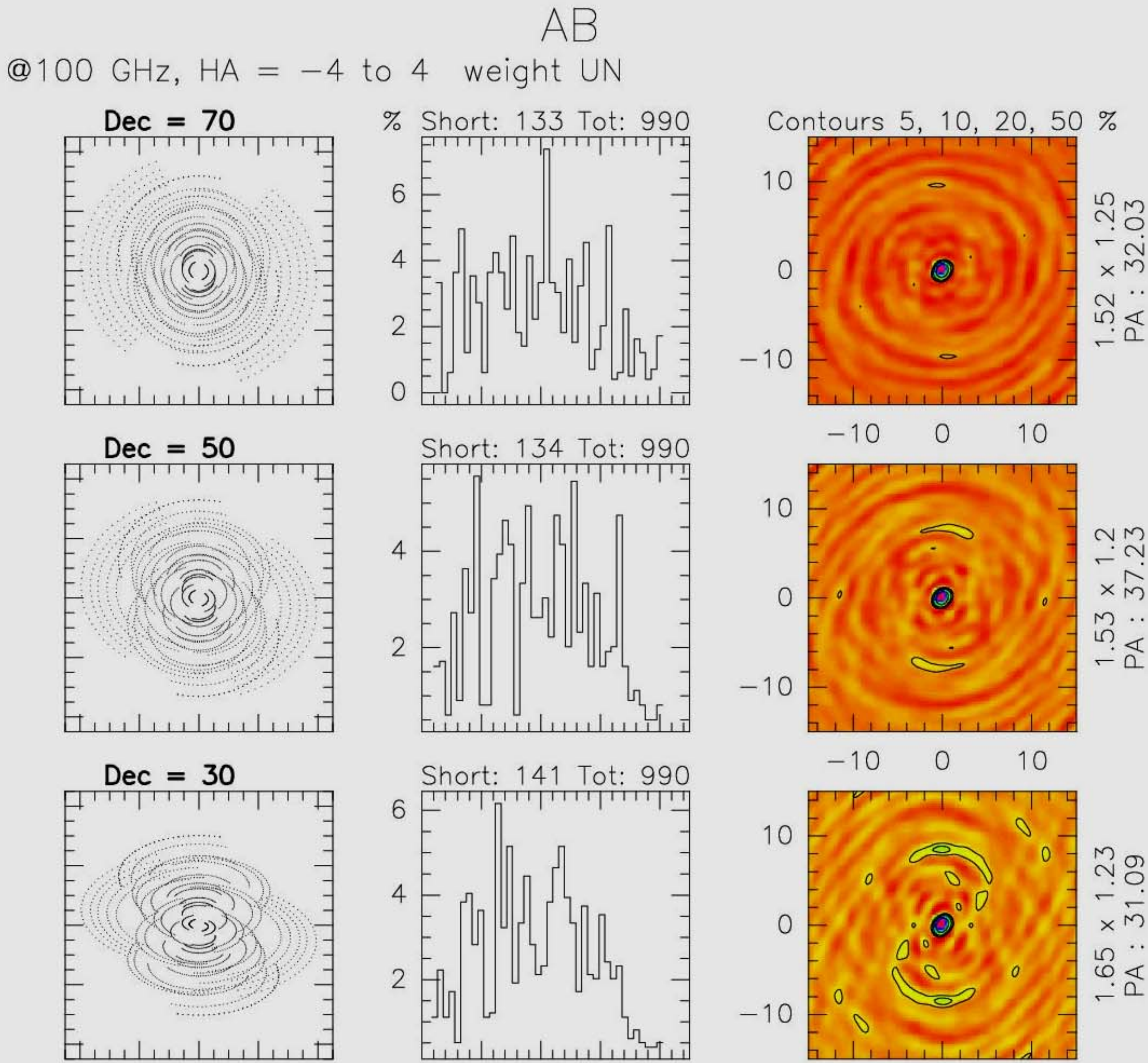


	Orion @ -5°	W51N @ 14°	S140 @ 63°
T	8 hrs	12 hrs	24 hrs
D	400 pc	8300 pc	910 pc
″	0.70″ x 0.41″	0.51″ x 0.45″	0.47″ x 0.40″

⇨ observing efficiency ~60%



ABCD
@100 GHz, HA = −4 to 4 weight UN
Dec = 70
% Short: 637 Tot: 1980
Contours 5, 10, 20, 50 %
1.9 x 1.56
PA : 38.27
Dec = 50
Short: 592 Tot: 1980
1.92 x 1.51
PA : 44.03
Dec = 30
Short: 626 Tot: 1980
1.98 x 1.49
PA : 36.8


AB
@100 GHz, HA = −4 to 4 weight UN
Dec = 70
% Short: 133 Tot: 990
Contours 5, 10, 20, 50 %
1.52 x 1.25
PA : 32.03
Dec = 50
Short: 134 Tot: 990
1.53 x 1.2
PA : 37.23
Dec = 30
Short: 141 Tot: 990
1.65 x 1.23
PA : 31.09

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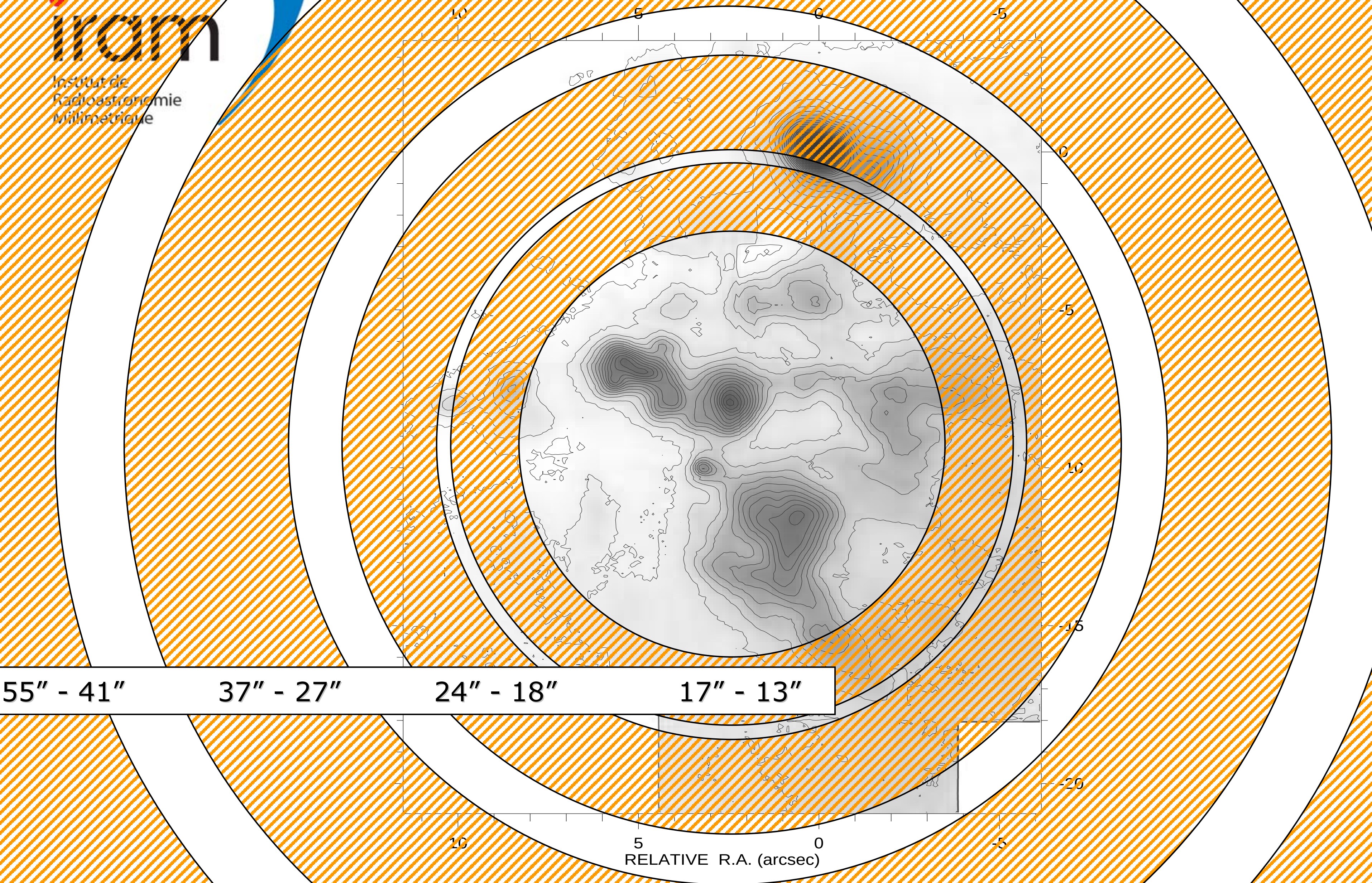
Orion BN/KL 0.3" @ 12.5 um (Keck)

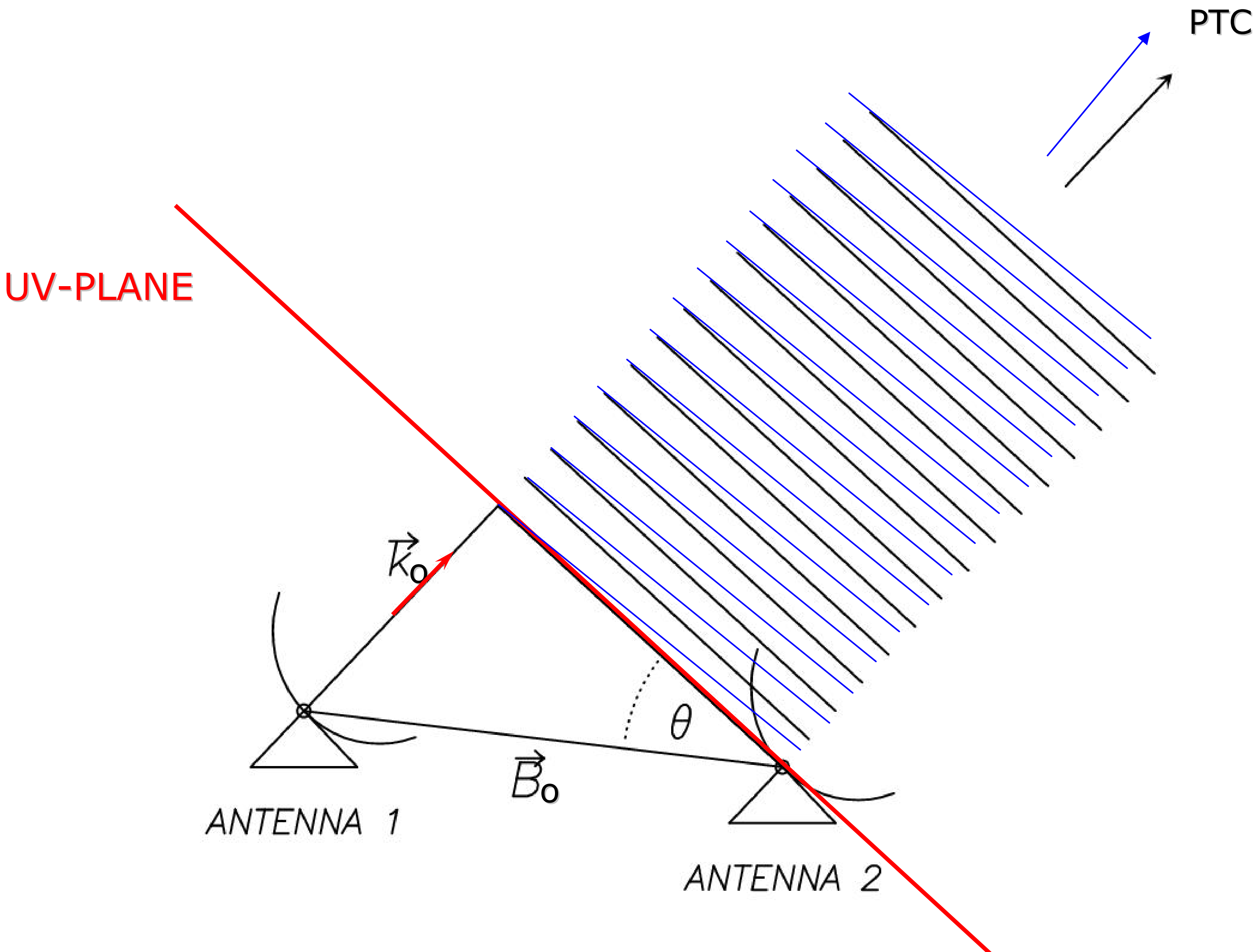


Array operation

- Astronomical observations are executed following a well-defined and fully automated cyclic sequence of operations.

- Compared to a single-dish antenna the astronomical setup of an interferometer involves a number of additional operations to maximize instrumental performance in view of positional precision and sensitivity $\rightarrow$ BASELINE, DELAY...

The Interferometer Case



The phase equation

$$w_0 = \vec{B_0} \cdot \vec{k_0} = B_0 \sin\theta$$

$$\phi_{w_0} = 2\pi w_0/\lambda = 2\pi B_0 \sin\theta/\lambda$$

If the point-source of interest is offset by an angle $\Delta\theta$ from the reference direction, the total phase offset is:

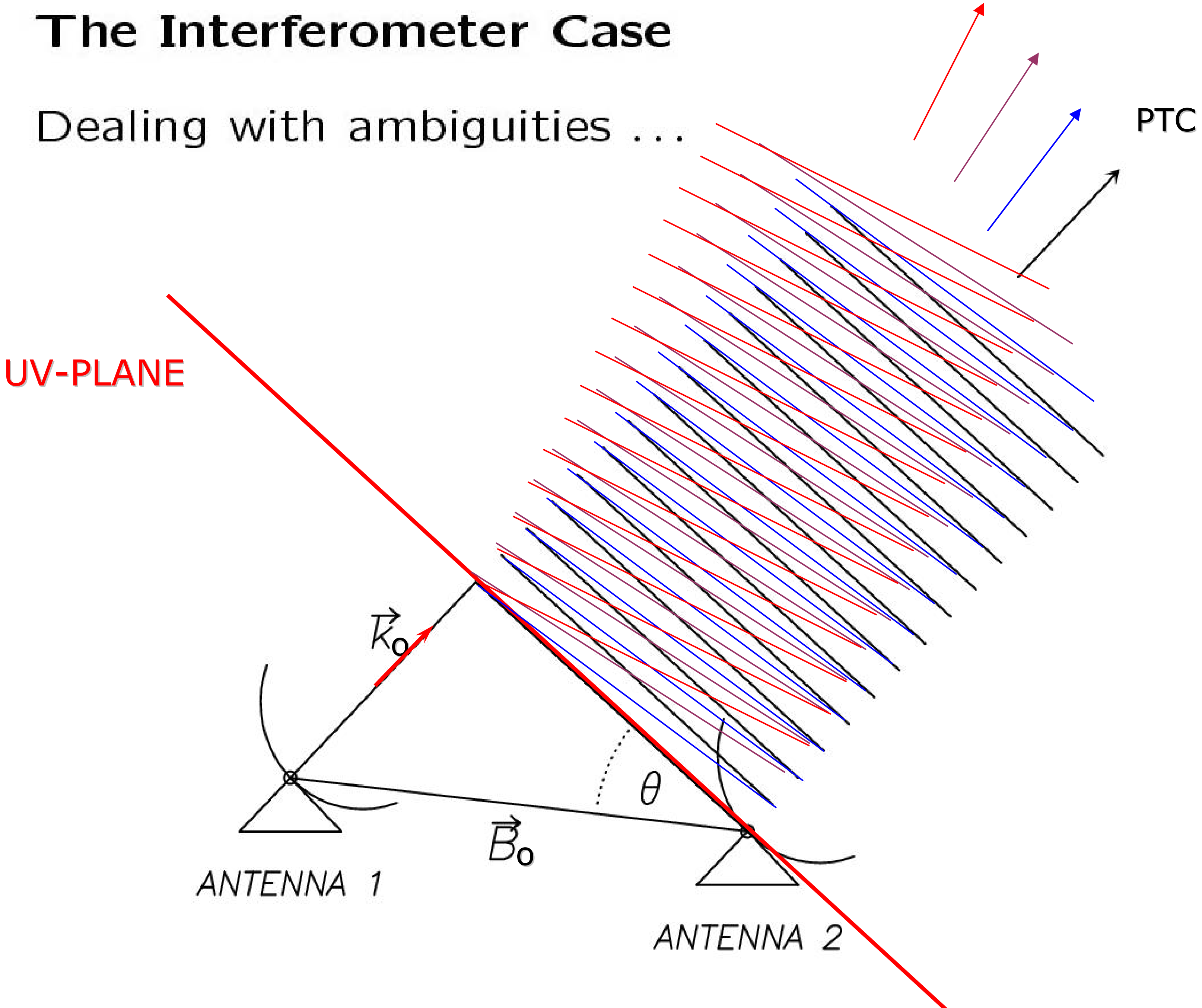
$$\phi_{w_0} = 2\pi w_0/\lambda = 2\pi B_0 \sin(\theta + \Delta\theta)/\lambda$$

With $\vec{B_0} = (B_x, B_y, B_z)$ and an astronomical frame defining $\vec{k_0} = (\cos H \cos\delta, -\sin H \cos\delta, \sin\delta)$

$$\rightarrow \phi_{w_0} = 2\pi\,(B_x \cos H \cos\delta - B_y \sin H \cos\delta + B_z \sin\delta)/\lambda$$

The Interferometer Case

Dealing with ambiguities ...



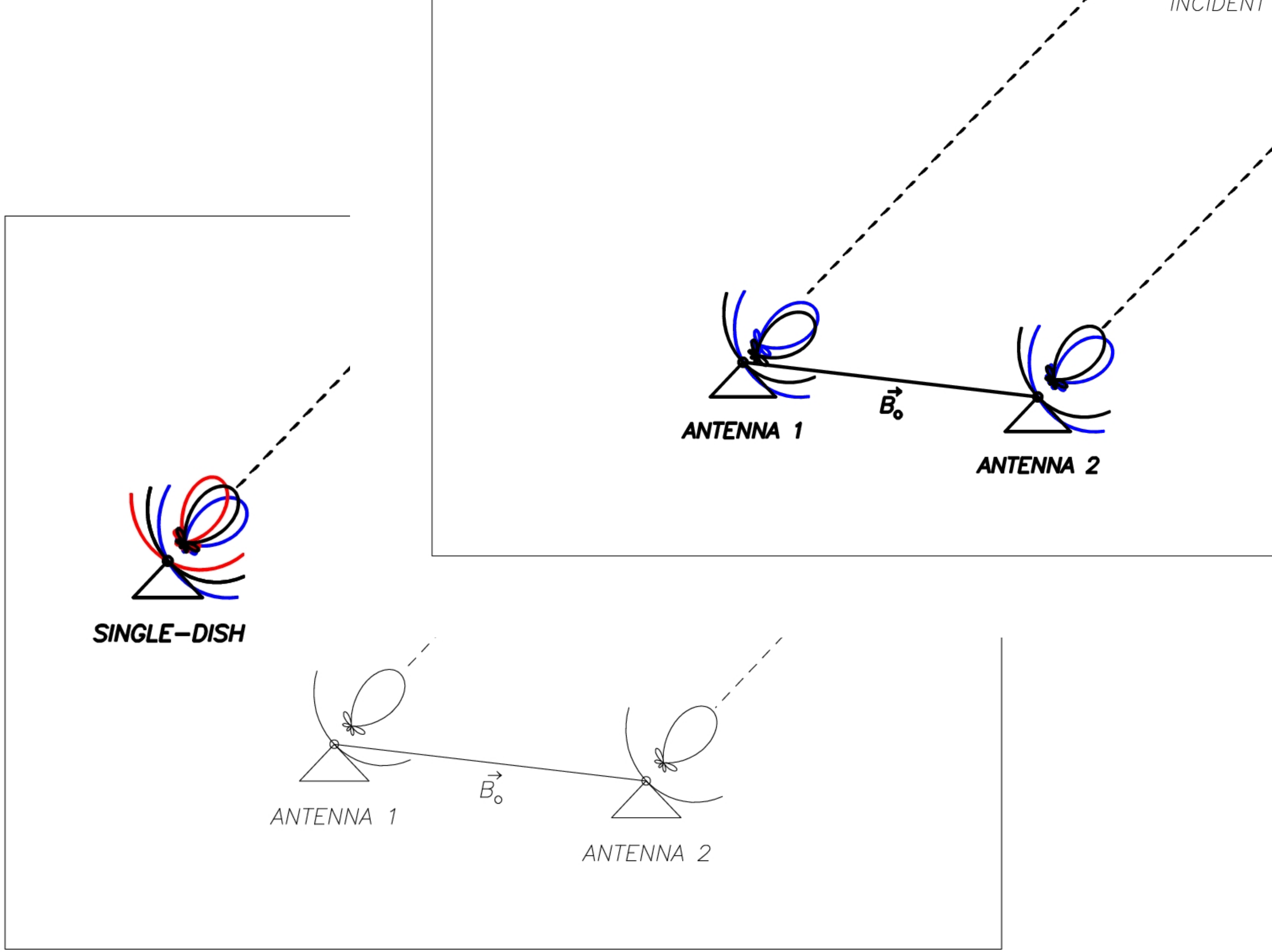
Dealing with $\quad \omega_0 = \vec{k_0} \cdot \vec{B_0}$

$$\rightarrow 2\pi\omega_0/\lambda = 2\pi B_0 \sin\theta/\lambda = \pm 2\pi N$$

Ex: with $B_0 = 300\,\mathrm{m}$ and $\lambda = 3\,\mathrm{mm}$, the positional ambiguity on the skyplane becomes:

$$\theta_N = \lambda/B_0 \times N = \pm 2'' \times N$$

Ex: a source displaced by a single beam $\theta = \lambda/B_0$ shows an offset of 360° in the signal phase.



INCIDENT
ANTENNA 1
$\vec{B}_o$
ANTENNA 2
SINGLE-DISH
ANTENNA 1
$\vec{B}_o$
ANTENNA 2

Dealing with ambiguities ...

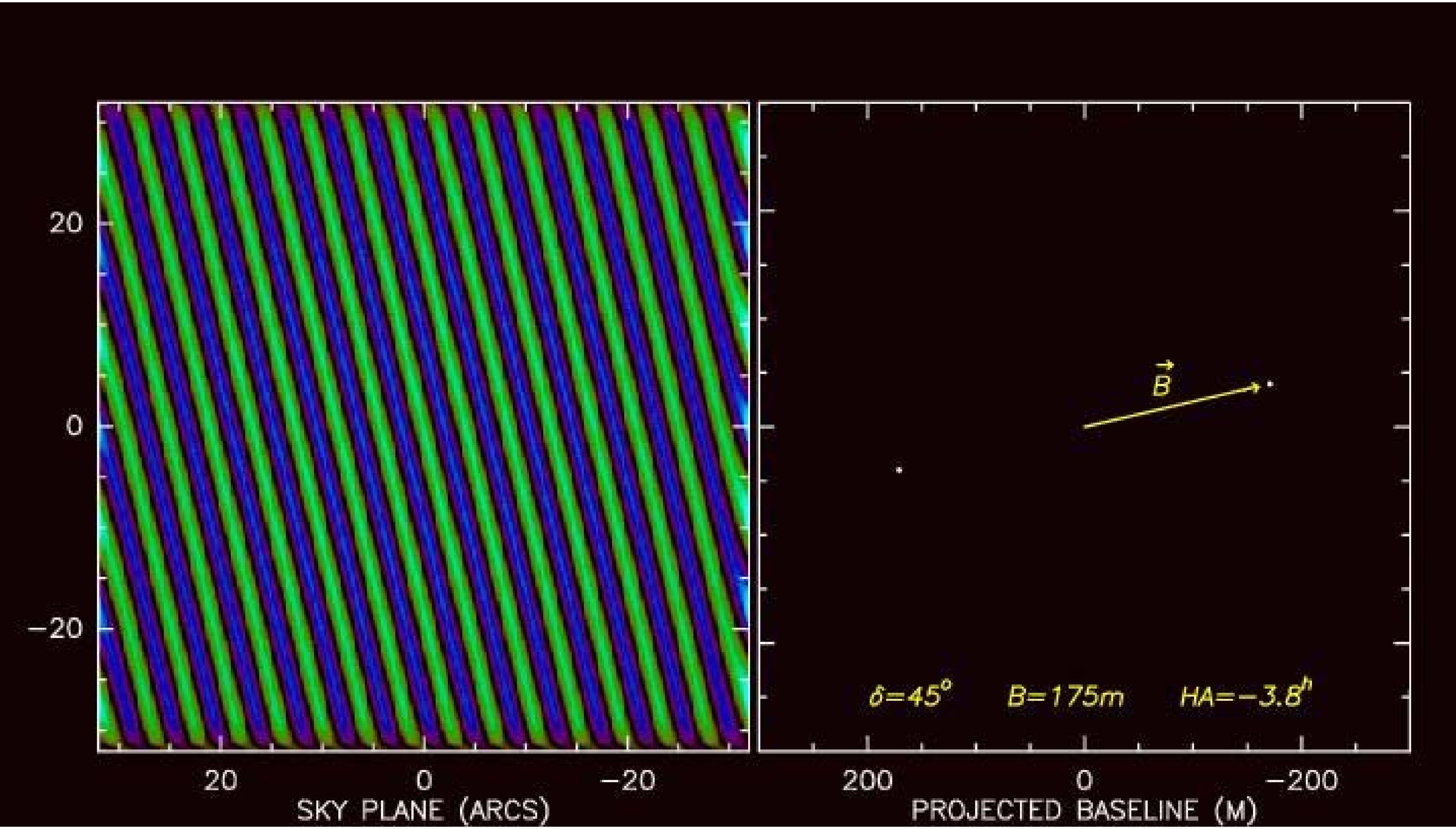
$$\rightarrow 2\pi B_0 \sin\theta/\lambda = \pm 2\pi N$$

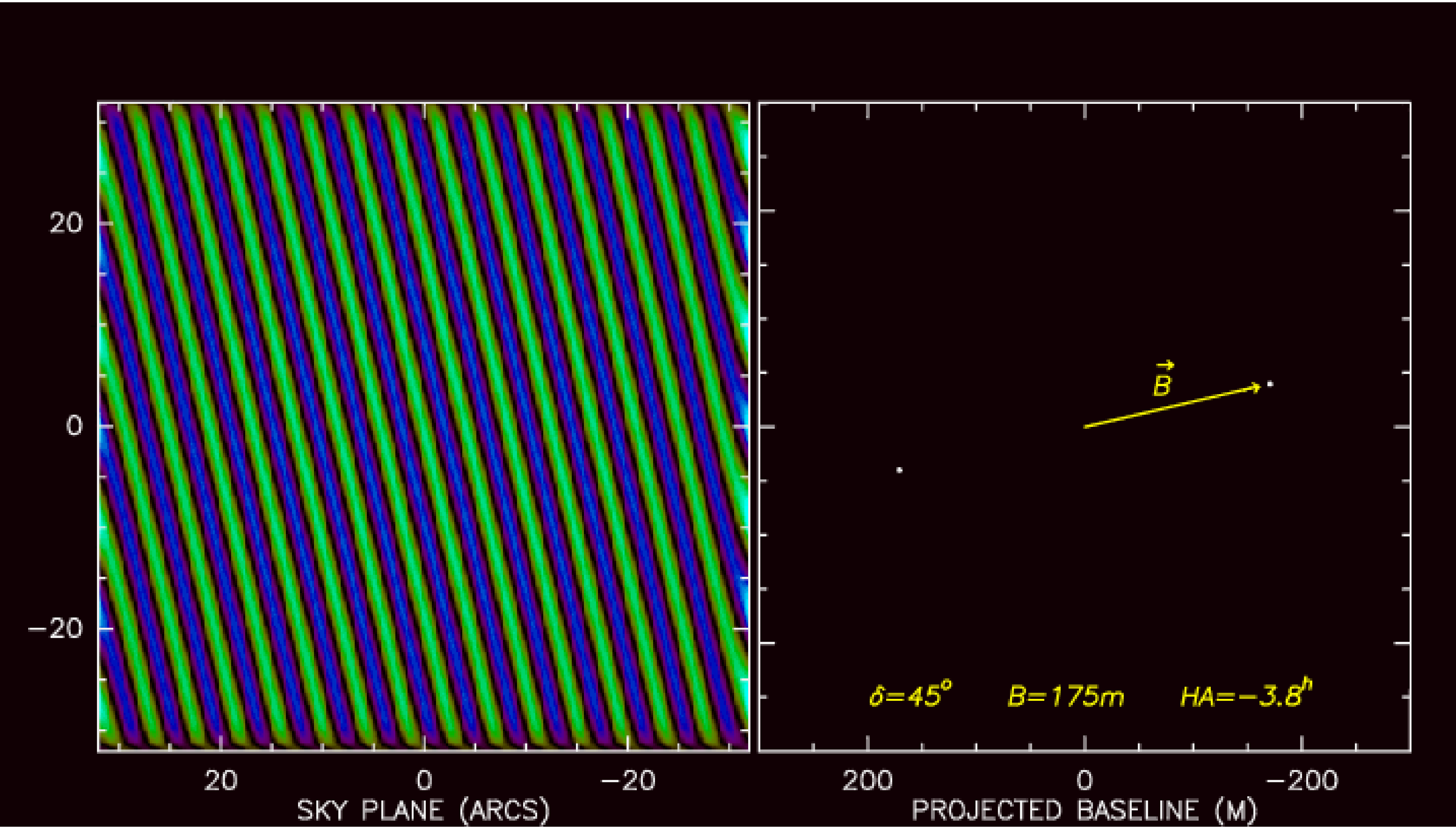
$$F(\theta) \sim \cos(2\pi\, \theta\, \vec{B}_P/\lambda)$$

$$f(\vec{B}) \rightleftharpoons F(\theta)$$

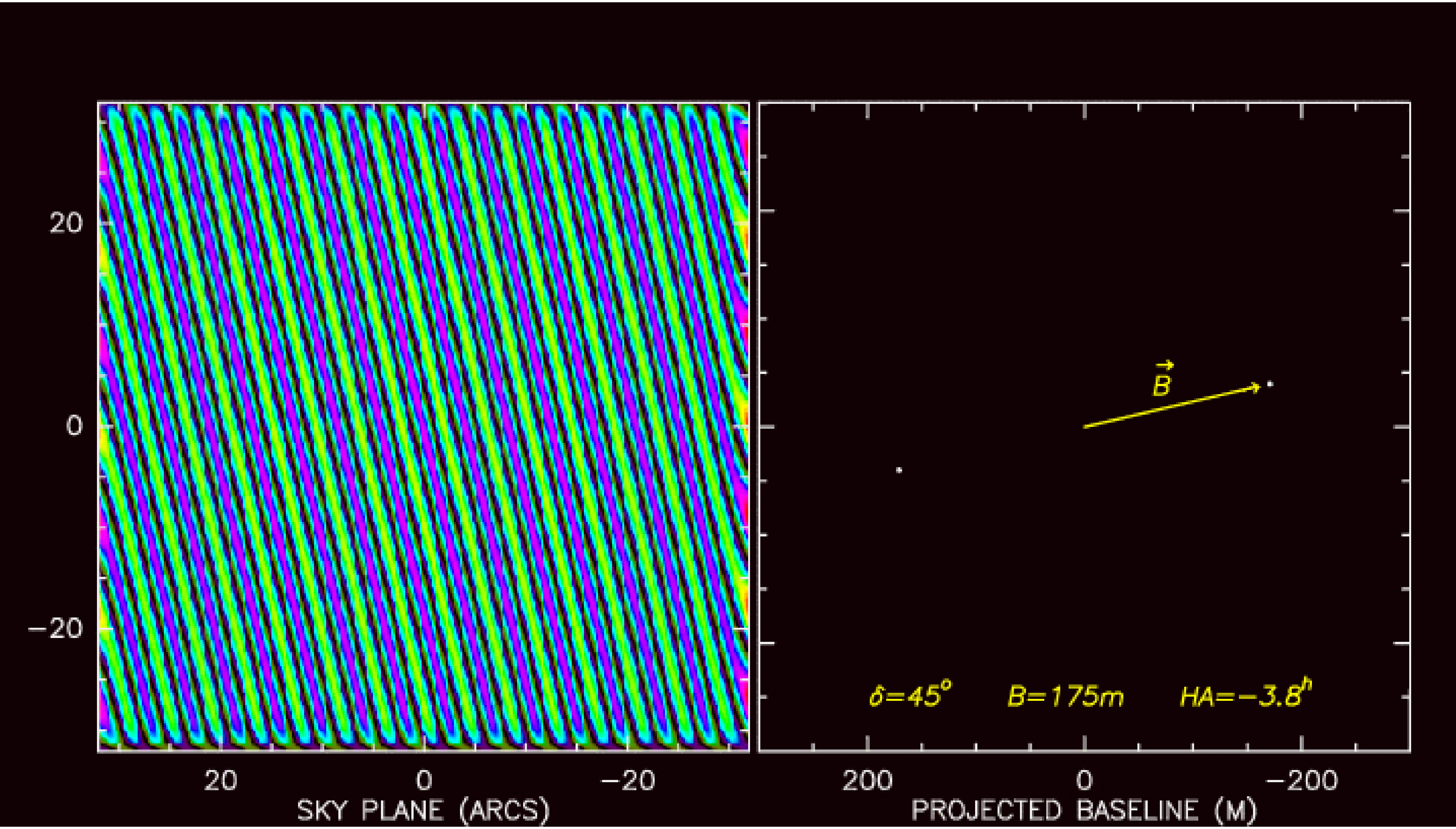
$$f(\vec{B}) = \delta(\vec{B} - \vec{B}_0) + \delta(\vec{B} + \vec{B}_0)$$

$\longrightarrow$ the radioastronomical source is somewhere on a sinusoidal line grid whose spatial frequency is proportional to baseline length.

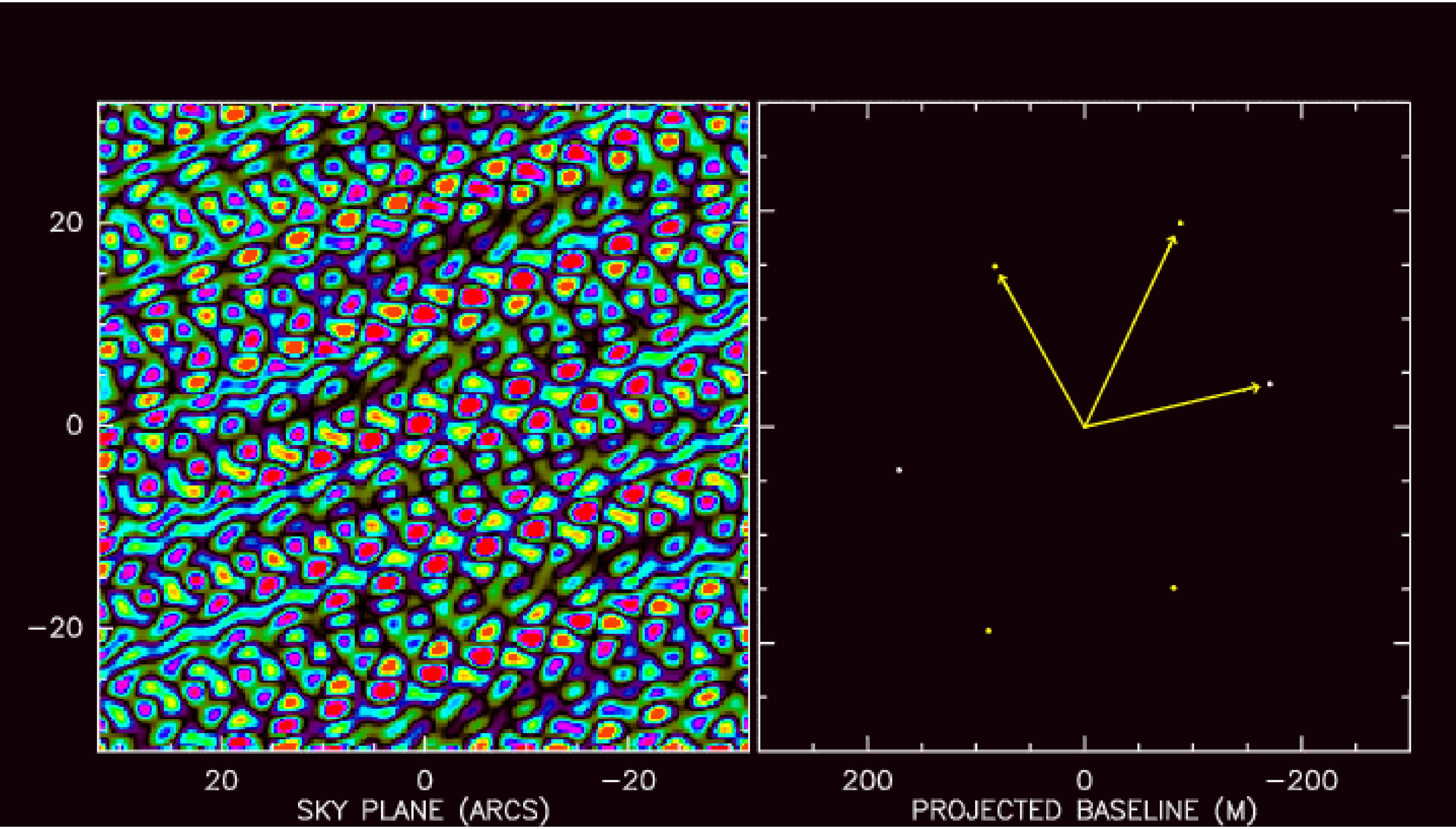

20
0
−20
20
0
−20
SKY PLANE (ARCS)
B
δ=45°
B=175m
HA=−3.8h
200
0
−200
PROJECTED BASELINE (M)



20
0
−20
20
0
−20
SKY PLANE (ARCS)
B⃗
δ=45°
B=175m
HA=−3.8ʰ
200
0
−200
PROJECTED BASELINE (M)



20
0
−20
20
0
−20
SKY PLANE (ARCS)
B
δ=45°
B=175m
HA=−3.8h
200
0
−200
PROJECTED BASELINE (M)



20
0
−20
20
0
−20
SKY PLANE (ARCS)
200
0
−200
PROJECTED BASELINE (M)

Assume an error in each component of B and k, one gets:

$$w = \vec{B} \cdot \vec{k} = (\vec{B}_0 + \delta\vec{B}) \cdot (\vec{k}_0 + \delta\vec{k})$$

$$= w_0 + \vec{B}_0 \cdot \delta\vec{k} + \delta\vec{B} \cdot \vec{k}_0 + \delta\vec{B} \cdot \delta\vec{k}$$

We distinguish two limiting cases:

- $\delta\vec{k} = 0 \longrightarrow$ we measure baselines using objects whose positions are known to be very accurate.

$$w = w_0 + \delta\vec{B} \cdot \vec{k}_0$$

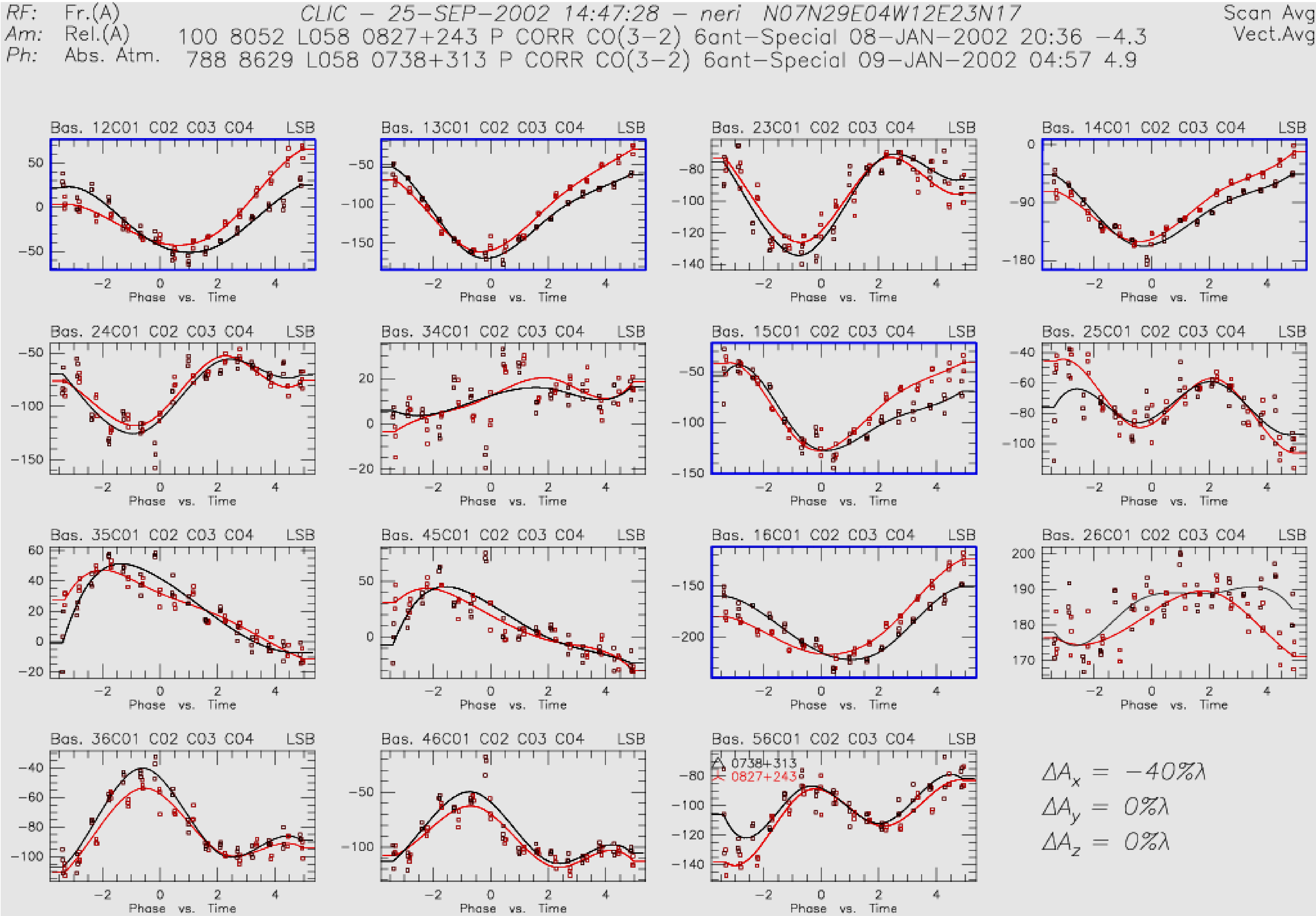
- $\delta\vec{B} = 0 \longrightarrow$ we measure source positions using baselines known with high positional accuracy.

$$w = w_0 + \vec{B}_0 \cdot \delta\vec{k}$$

$$
\begin{aligned}
\Delta\phi^{ij} = \; & 2\pi/\lambda \cdot \\
& [\Delta\alpha \cdot (B_x^{ij} \sin H \cos\delta + B_y^{ij} \cos H \cos\delta) + \\
& \Delta\delta \cdot (B_y^{ij} \sin H \sin\delta - B_x^{ij} \cos H \sin\delta + B_z^{ij} \cos\delta) + \\
& (B_x^{ij} \cos H \cos\delta - B_y^{ij} \sin H \cos\delta + B_z^{ij} \sin\delta) + \\
& (A^i - A^j) \cos \mathrm{El}]
\end{aligned}
$$

where A is the offset between the azimuth and elevation axis of an antenna.

In practice, an LSQ-analysis is used to derive the unknowns (B_x,B_y,B_z) from the meaurements of the many observed $\Delta\phi^{ij}$ at $10 - 15$ different hour angles H and declinations δ.

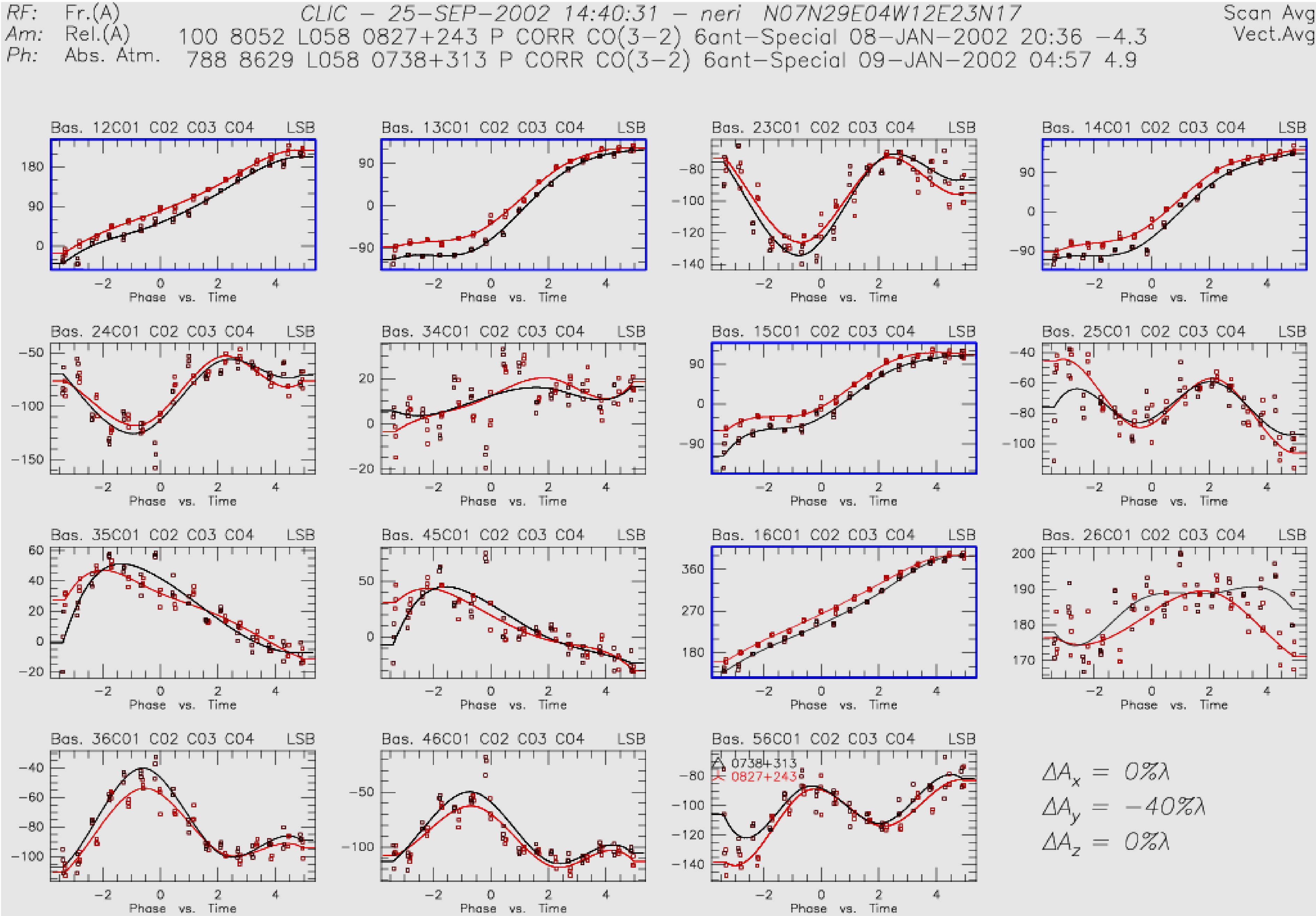


RF: Fr.(A)
Am: Rel.(A)
Ph: Abs. Atm.
CLIC – 25-SEP-2002 14:47:28 – neri N07N29E04W12E23N17
100 8052 L058 0827+243 P CORR CO(3–2) 6ant–Special 08–JAN–2002 20:36 –4.3
788 8629 L058 0738+313 P CORR CO(3–2) 6ant–Special 09–JAN–2002 04:57 4.9
Scan Avg
Vect.Avg
Bas. 12C01 C02 C03 C04 LSB
Bas. 13C01 C02 C03 C04 LSB
Bas. 23C01 C02 C03 C04 LSB
Bas. 14C01 C02 C03 C04 LSB
Bas. 24C01 C02 C03 C04 LSB
Bas. 34C01 C02 C03 C04 LSB
Bas. 15C01 C02 C03 C04 LSB
Bas. 25C01 C02 C03 C04 LSB
Bas. 35C01 C02 C03 C04 LSB
Bas. 45C01 C02 C03 C04 LSB
Bas. 16C01 C02 C03 C04 LSB
Bas. 26C01 C02 C03 C04 LSB
Bas. 36C01 C02 C03 C04 LSB
Bas. 46C01 C02 C03 C04 LSB
Bas. 56C01 C02 C03 C04 LSB
Phase vs. Time
0738+313
0827+243
$\Delta A_x = -40\%\lambda$
$\Delta A_y = 0\%\lambda$
$\Delta A_z = 0\%\lambda$

$$\Delta\phi^{ij} = \; 2\pi/\lambda\cdot$$
$$[\Delta\alpha\cdot(B_x^{ij}\sin H\cos\delta + B_y^{ij}\cos H\cos\delta)+$$
$$\Delta\delta\cdot(B_y^{ij}\sin H\sin\delta - B_x^{ij}\cos H\sin\delta + B_z^{ij}\cos\delta)+$$
$$(B_x^{ij}\cos H\cos\delta - B_y^{ij}\sin H\cos\delta + B_z^{ij}\sin\delta)+$$
$$(A^i - A^j)\cos \mathrm{El}]$$

where A is the offset between the azimuth and elevation axis of an antenna.

In practice, an LSQ-analysis is used to derive the unknowns (B_x,B_y,B_z) from the meaurements of the many observed $\Delta\phi^{ij}$ at $10-15$ different hour angles H and declinations δ.

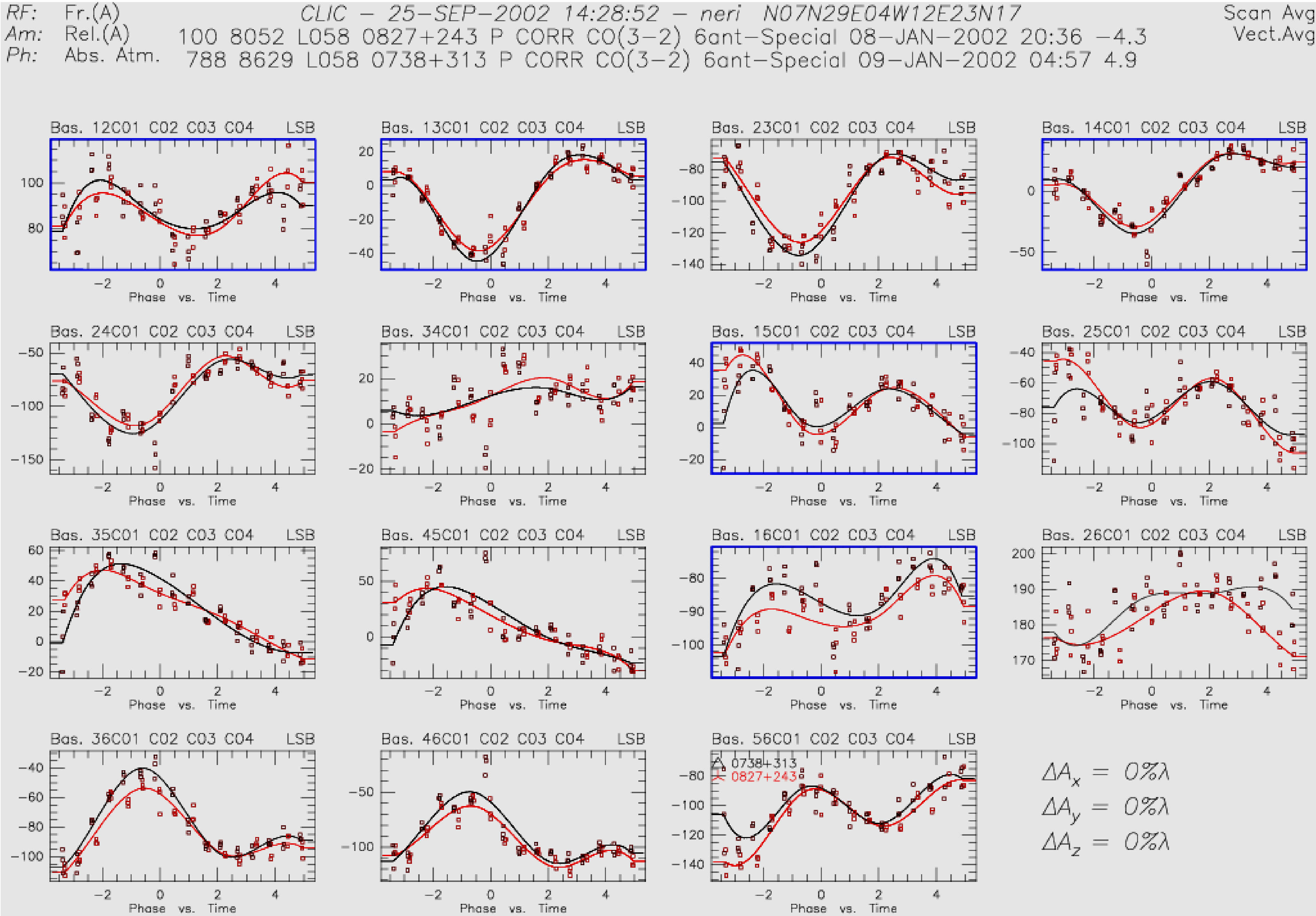


RF: Fr.(A)
Am: Rel.(A)
Ph: Abs. Atm.
CLIC – 25-SEP-2002 14:40:31 – neri N07N29E04W12E23N17
100 8052 L058 0827+243 P CORR CO(3–2) 6ant–Special 08–JAN–2002 20:36 –4.3
788 8629 L058 0738+313 P CORR CO(3–2) 6ant–Special 09–JAN–2002 04:57 4.9
Scan Avg
Vect.Avg
Bas. 12C01 C02 C03 C04 LSB
Bas. 13C01 C02 C03 C04 LSB
Bas. 23C01 C02 C03 C04 LSB
Bas. 14C01 C02 C03 C04 LSB
Bas. 24C01 C02 C03 C04 LSB
Bas. 34C01 C02 C03 C04 LSB
Bas. 15C01 C02 C03 C04 LSB
Bas. 25C01 C02 C03 C04 LSB
Bas. 35C01 C02 C03 C04 LSB
Bas. 45C01 C02 C03 C04 LSB
Bas. 16C01 C02 C03 C04 LSB
Bas. 26C01 C02 C03 C04 LSB
Bas. 36C01 C02 C03 C04 LSB
Bas. 46C01 C02 C03 C04 LSB
Bas. 56C01 C02 C03 C04 LSB
Phase vs. Time
0738+313
0827+243
ΔAx = 0%λ
ΔAy = –40%λ
ΔAz = 0%λ

$$
\begin{aligned}
\Delta\phi^{ij} = \; & 2\pi/\lambda \cdot \\
& [\Delta\alpha \cdot (B_x^{ij} \sin H \cos\delta + B_y^{ij} \cos H \cos\delta) + \\
& \Delta\delta \cdot (B_y^{ij} \sin H \sin\delta - B_x^{ij} \cos H \sin\delta + B_z^{ij} \cos\delta) + \\
& (B_x^{ij} \cos H \cos\delta - B_y^{ij} \sin H \cos\delta + B_z^{ij} \sin\delta) + \\
& (A^i - A^j) \cos \mathrm{El}]
\end{aligned}
$$

where A is the offset between the azimuth and elevation axis of an antenna.

In practice, an LSQ-analysis is used to derive the unknowns (B_x,B_y,B_z) from the meaurements of the many observed $\Delta\phi^{ij}$ at $10-15$ different hour angles H and declinations δ.


RF: Fr.(A)
Am: Rel.(A)
Ph: Abs. Atm.
CLIC − 25−SEP−2002 14:28:52 − neri N07N29E04W12E23N17
100 8052 L058 0827+243 P CORR CO(3−2) 6ant−Special 08−JAN−2002 20:36 −4.3
788 8629 L058 0738+313 P CORR CO(3−2) 6ant−Special 09−JAN−2002 04:57 4.9
Scan Avg
Vect.Avg
Bas. 12C01 C02 C03 C04 LSB
Bas. 13C01 C02 C03 C04 LSB
Bas. 23C01 C02 C03 C04 LSB
Bas. 14C01 C02 C03 C04 LSB
Bas. 24C01 C02 C03 C04 LSB
Bas. 34C01 C02 C03 C04 LSB
Bas. 15C01 C02 C03 C04 LSB
Bas. 25C01 C02 C03 C04 LSB
Bas. 35C01 C02 C03 C04 LSB
Bas. 45C01 C02 C03 C04 LSB
Bas. 16C01 C02 C03 C04 LSB
Bas. 26C01 C02 C03 C04 LSB
Bas. 36C01 C02 C03 C04 LSB
Bas. 46C01 C02 C03 C04 LSB
Bas. 56C01 C02 C03 C04 LSB
Phase vs. Time
0738+313
0827+243
ΔAx = 0%λ
ΔAy = 0%λ
ΔAz = 0%λ

- How accurate: Though no high accuracy is needed for antenna positioning (positioning from the required spot is routinely within a wavelength), high precision is needed for the actual position: must be known to within a small fraction of a wavelength (0.1–0.3 mm).

Ex: $\Delta\vec{B} = 0.3\,\text{mm}$ and $\Delta\vec{k} = 3^\circ \rightarrow 20^\circ$

with $B = 60\,\text{m} \rightarrow \Delta\theta \leq 0.36''$
with $B = 400\,\text{m} \rightarrow \Delta\theta \leq 0.06''$

PdBI – Sources of uncertainty

TELESCOPE	$\Delta\theta$	Calibration
Axes Non-Intersection	$\leq 0.20''$	Yes
AzEl Bearings	$\leq 0.15''$	Yes
OBSERVATION		
Focus Offset	$\leq 0.15''$	Partially
Calibrator Distance	$\leq 8\,10^{-2}\,\theta_B$	No
Atmospheric Seeing	$\leq 6\,10^{-2}\,\theta_B$	No
Pointing Offset	$\leq 2\,10^{-2}\,\theta_B$	Partially

PdBI – Other sources of uncertainty

OBJECT	$\Delta\theta$	Calibration
Source Intensity	$\leq\ 10^{-1}\,\theta_B$	No
Calibrator Position	$\leq\ 0.02''$	No
MISCELLANEOUS		
Bandwidth smearing	$\leq\ 0.08''$	No
Visibility averaging	$\leq\ 0.06''$	No
Gravitational lensing	$\leq\ 0.02''$	No
Primary beam correction	$\leq\ 0.02''$	No