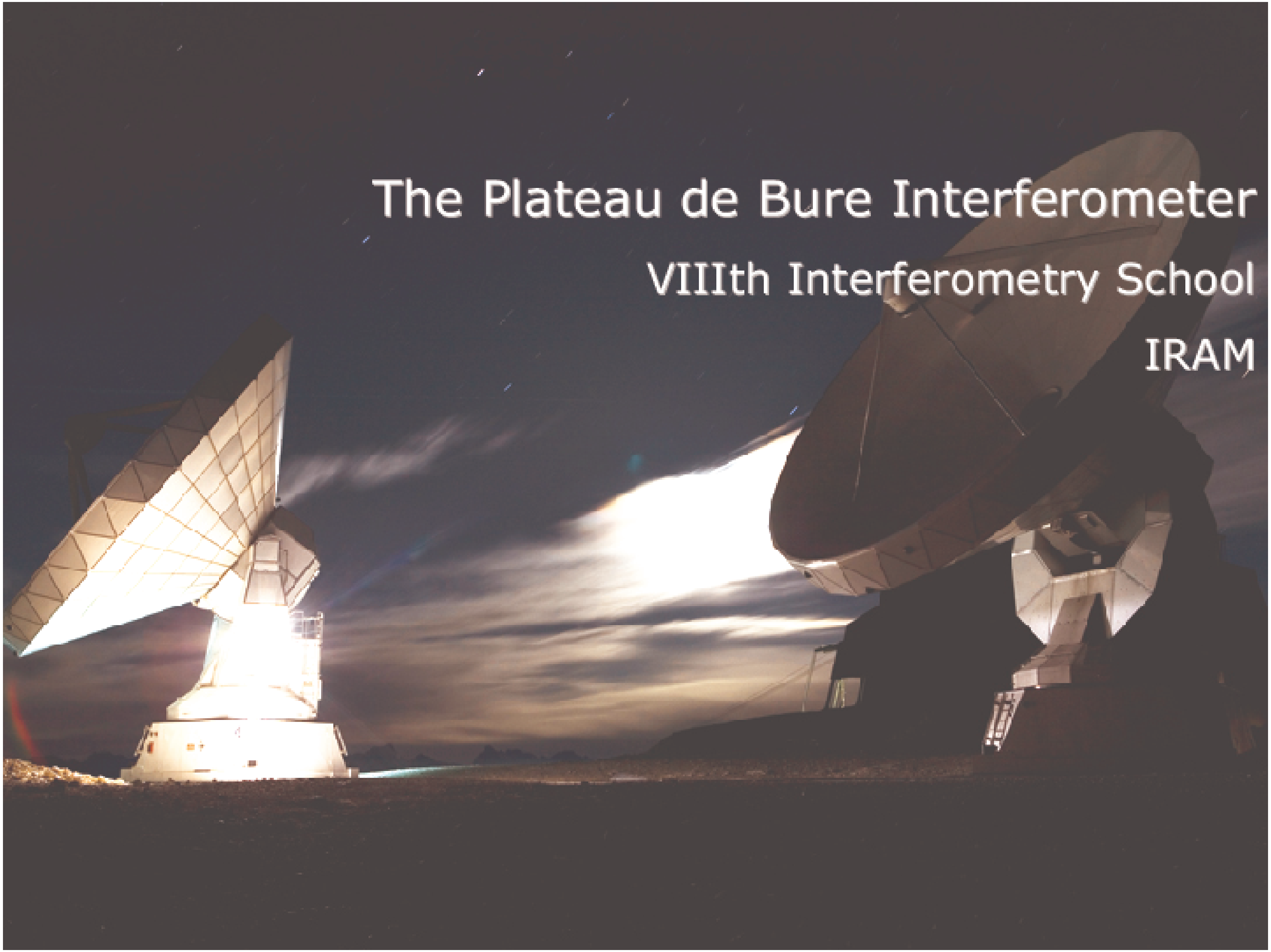
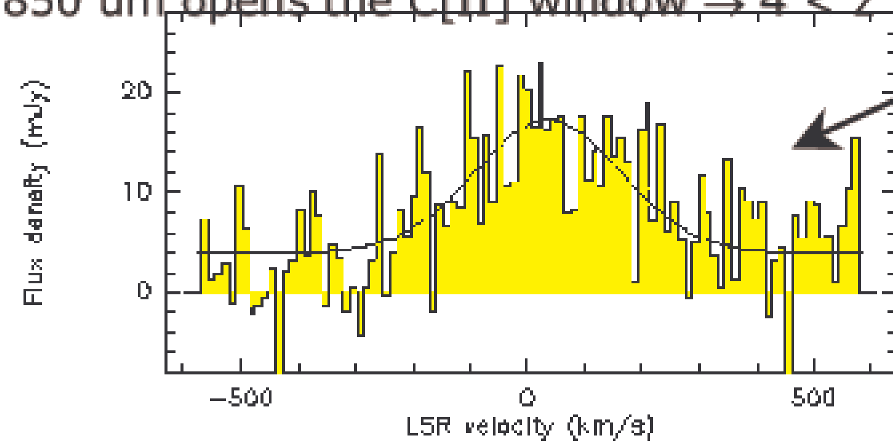

The Plateau de Bure Interferometer
VIIIth Interferometry School
IRAM

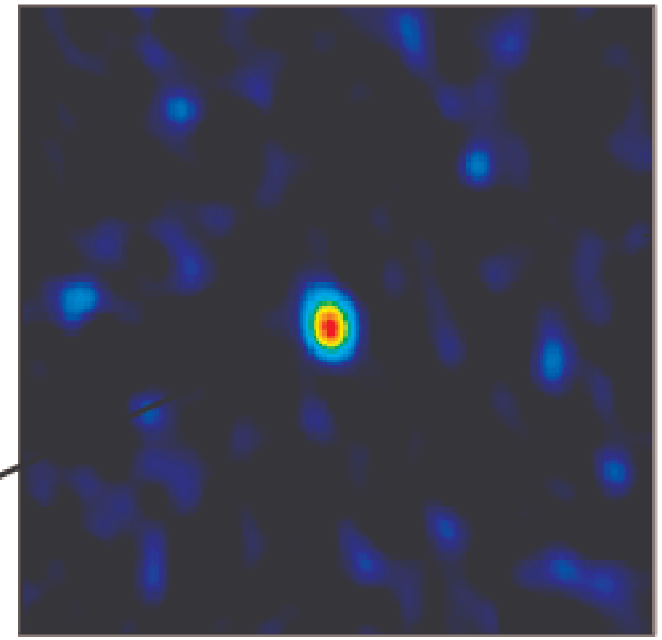
Star Formation @ high-z

- 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



PdBI on Jan 29, 2007

J1148+5251 @ 257 GHz



Walter et al. 2007

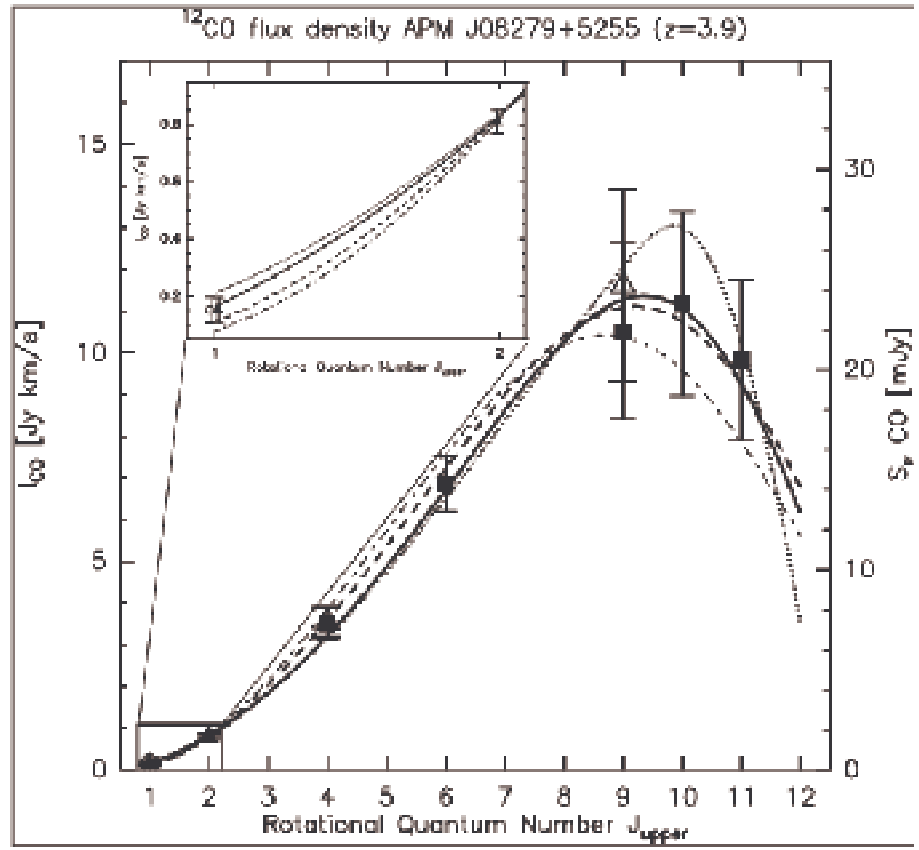
Maiolino et al. 2005

Gas Excitation Conditions @ z > 1

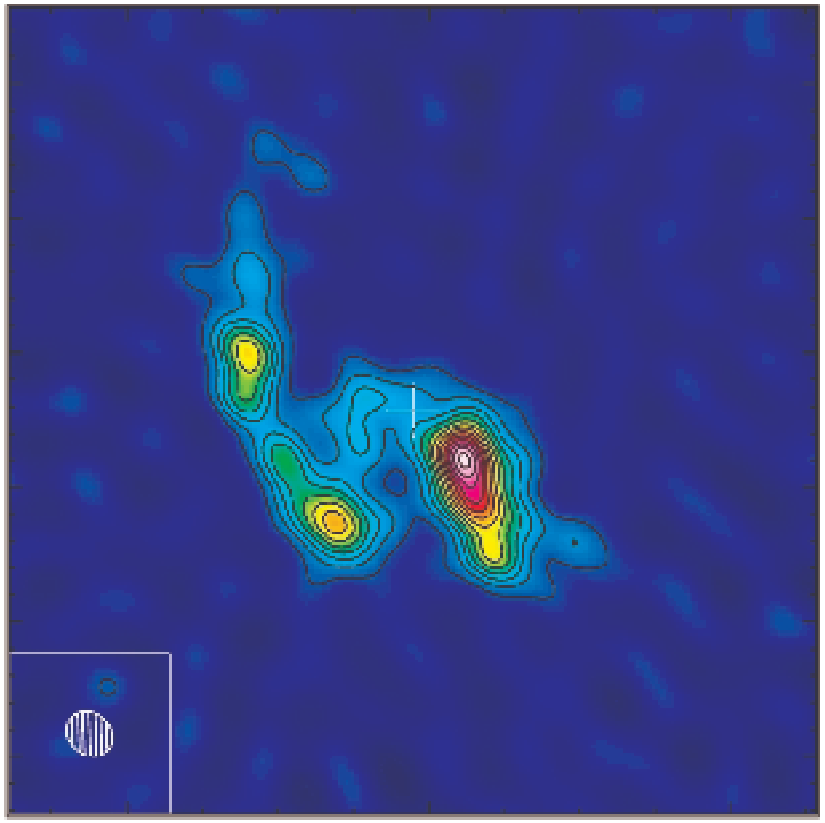
Molecular Lines:

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

- Detected: HCN, CN, HNC, HCO^+, C[I]
- Planned: H_2CO, H_2O, CH^+, HF, ...
- 850 um $\rightarrow$ complements the ML-SEDs



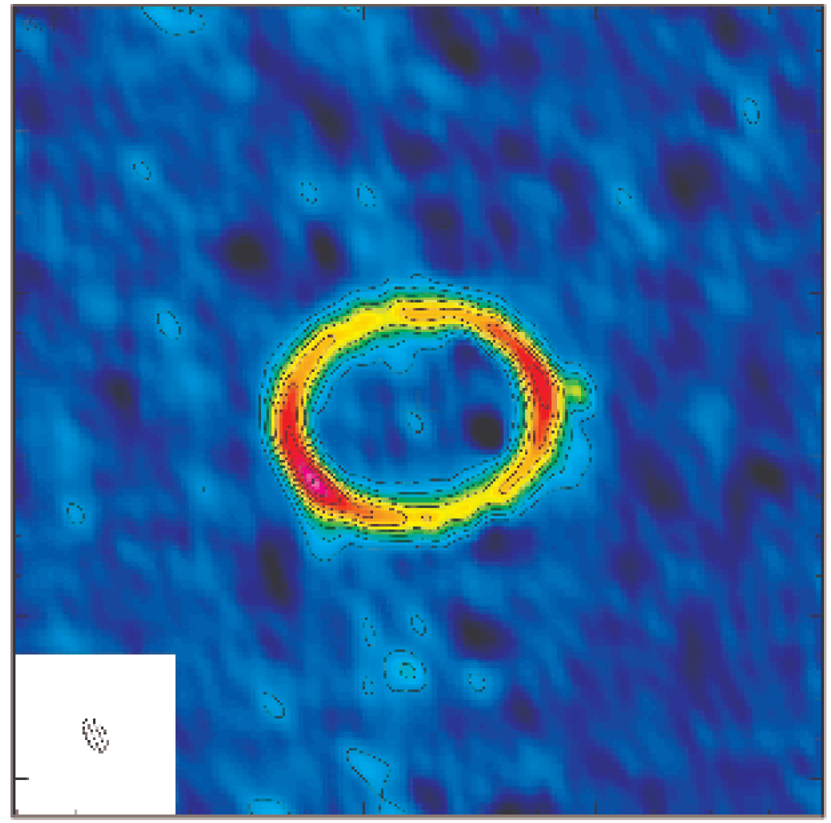
IC 342 @ 146 GHz



Rodriguez/Schinnerer et al. in prep.

C configuration

GG Tau @ 267 GHz



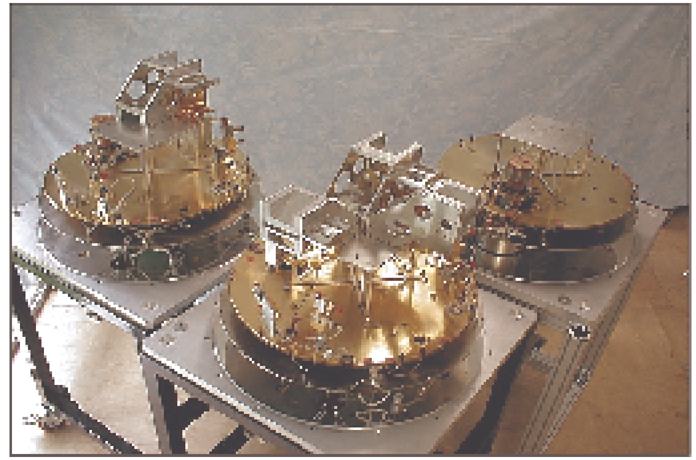
Piétu et al. submitted

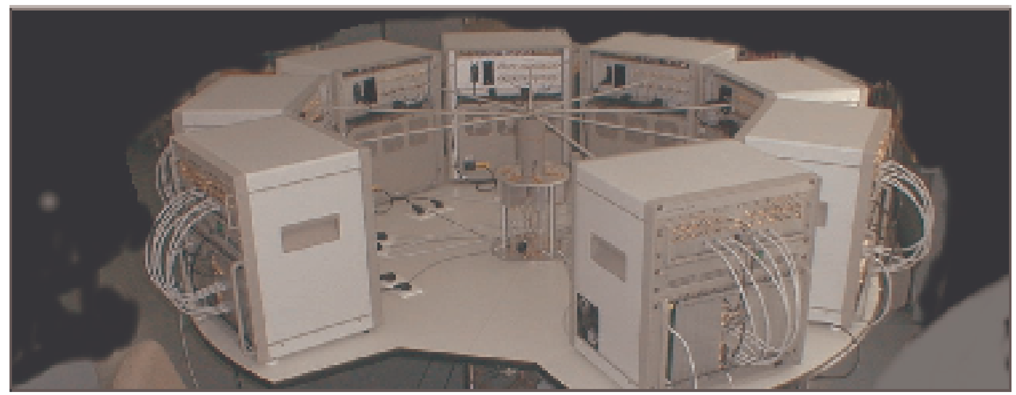
A+C configuration

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

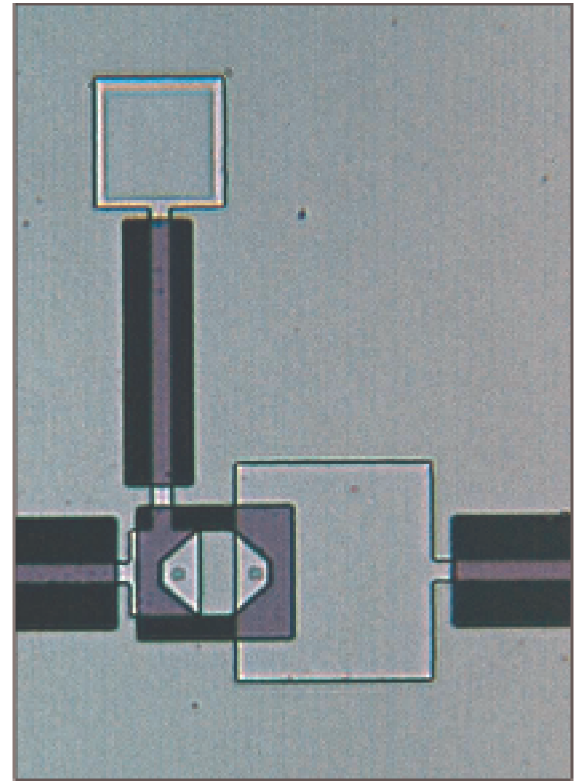
IRAM's expertise: pictures worth a thousand words





- Telescope design (~35 um), 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



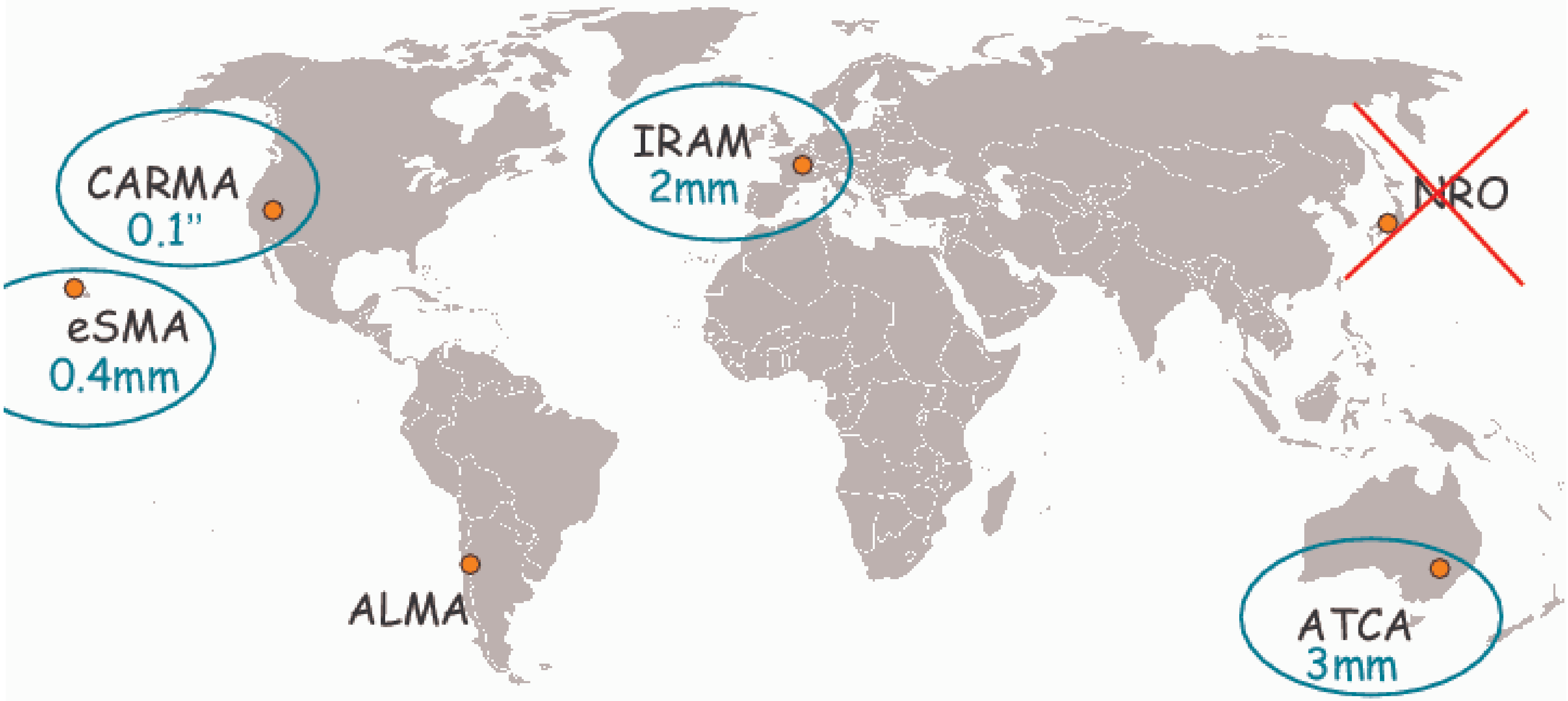
- Class 100 clean room for thin film technology
- Complete mm/THz-wave technology laboratory
- Developments for e.g. Herschel

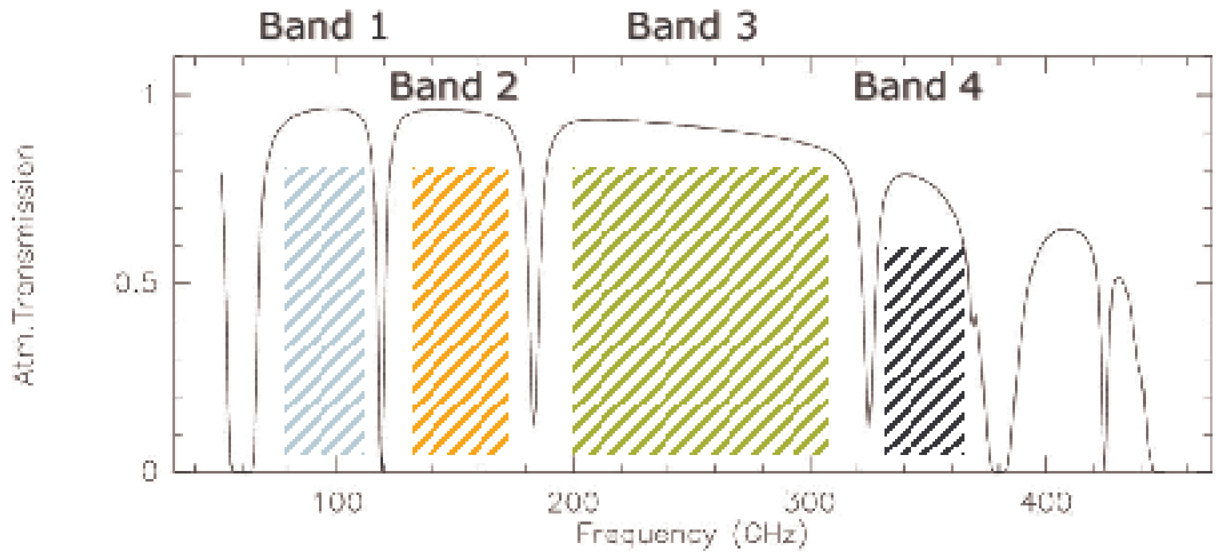
PdBI high impact upgrades

Semester	Upgrade	Done
W05/06	Track Extensions	**Y**
W06/07	FE: Band 1 and Band 3	**Y**
W07/08	FE: Band 2	**Y**
W09/10	BE: wideband correlator	**Y**
W10/11	FE: Band 4	Y
W12/13	NOEMA	

(sub)mm-interferometers worldwide

(sub)mm-interferometers worldwide

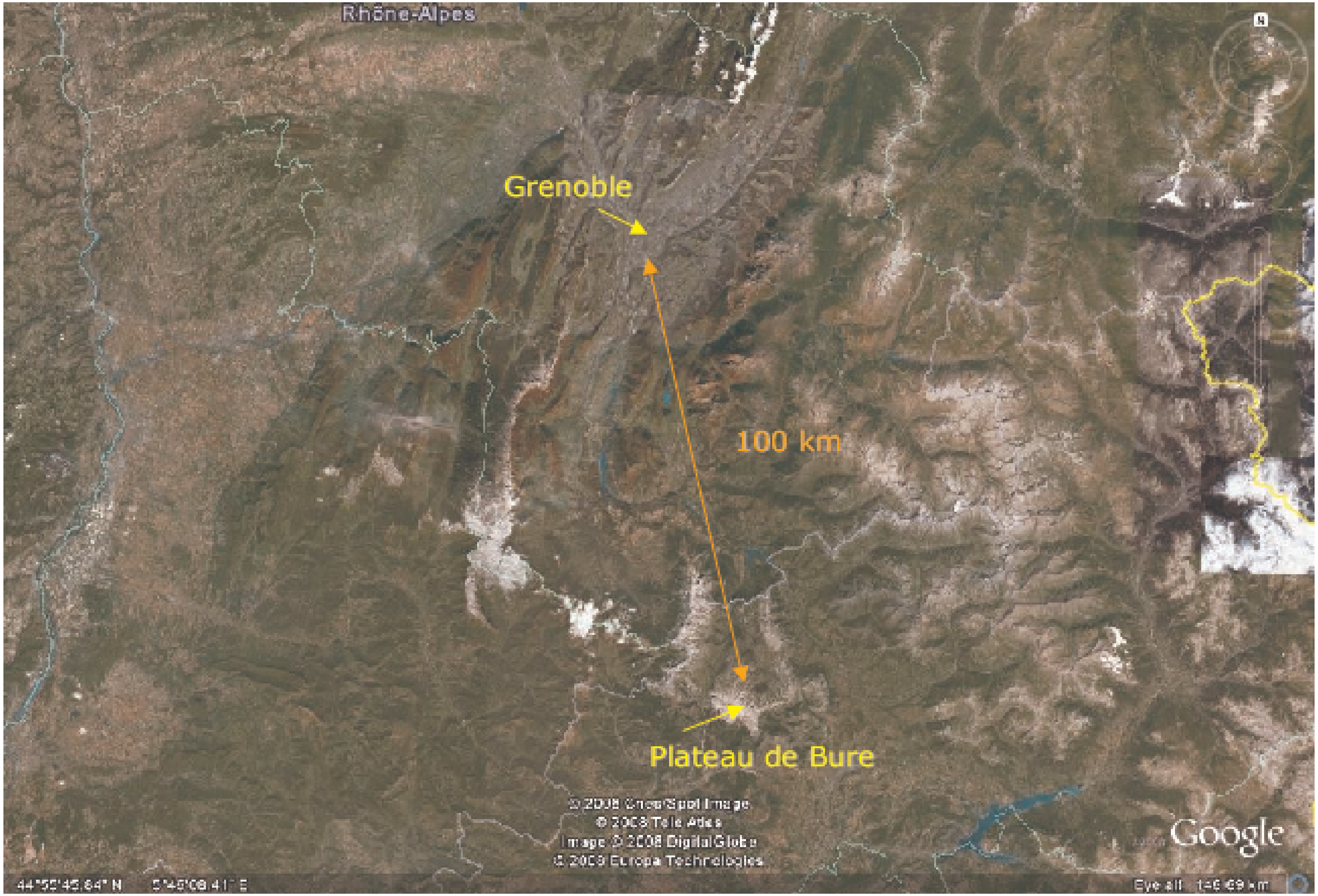




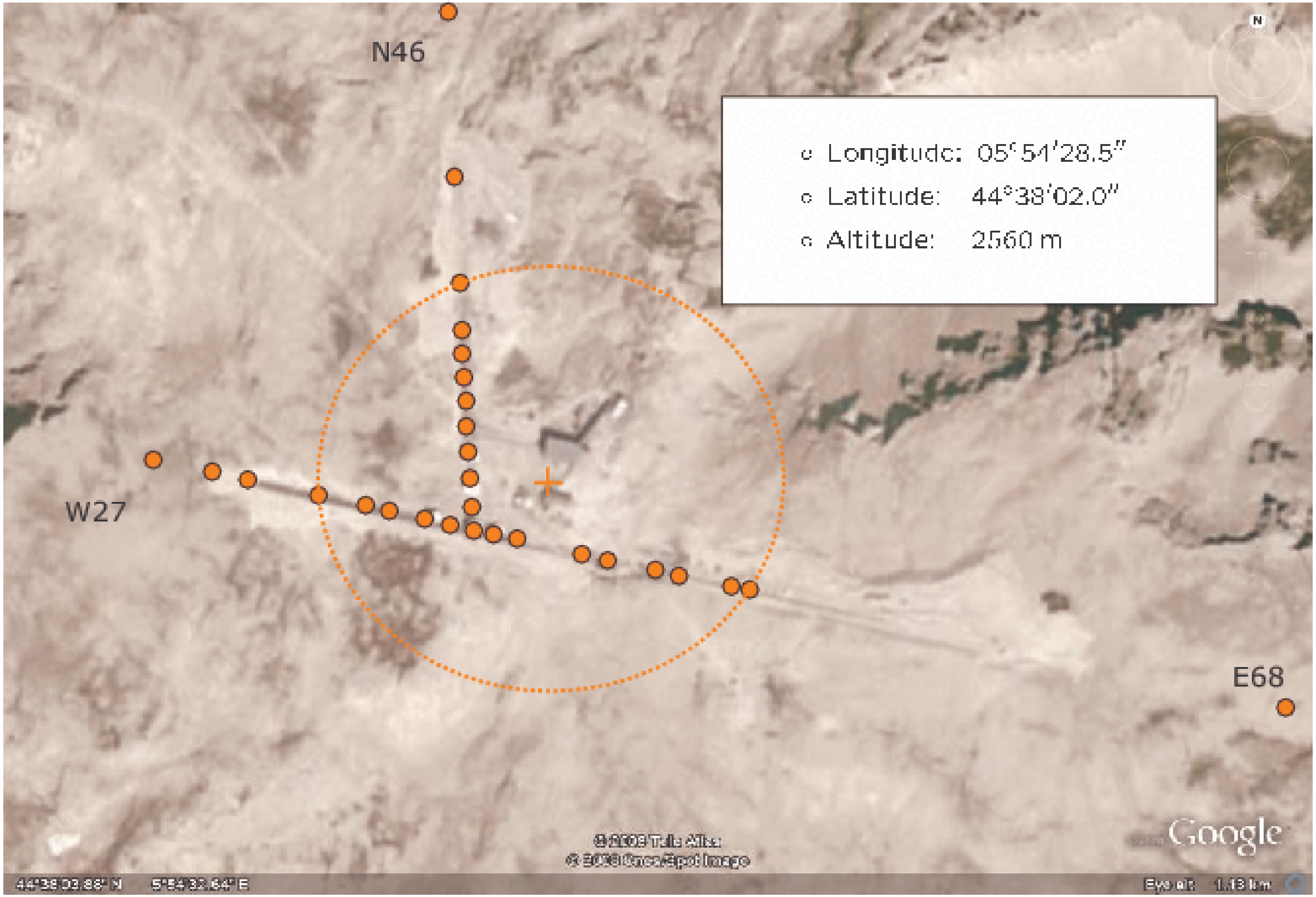
3mm = 100 GHz   2mm = 150 GHz   1mm = 300 GHz   0.8mm = 350 GHz

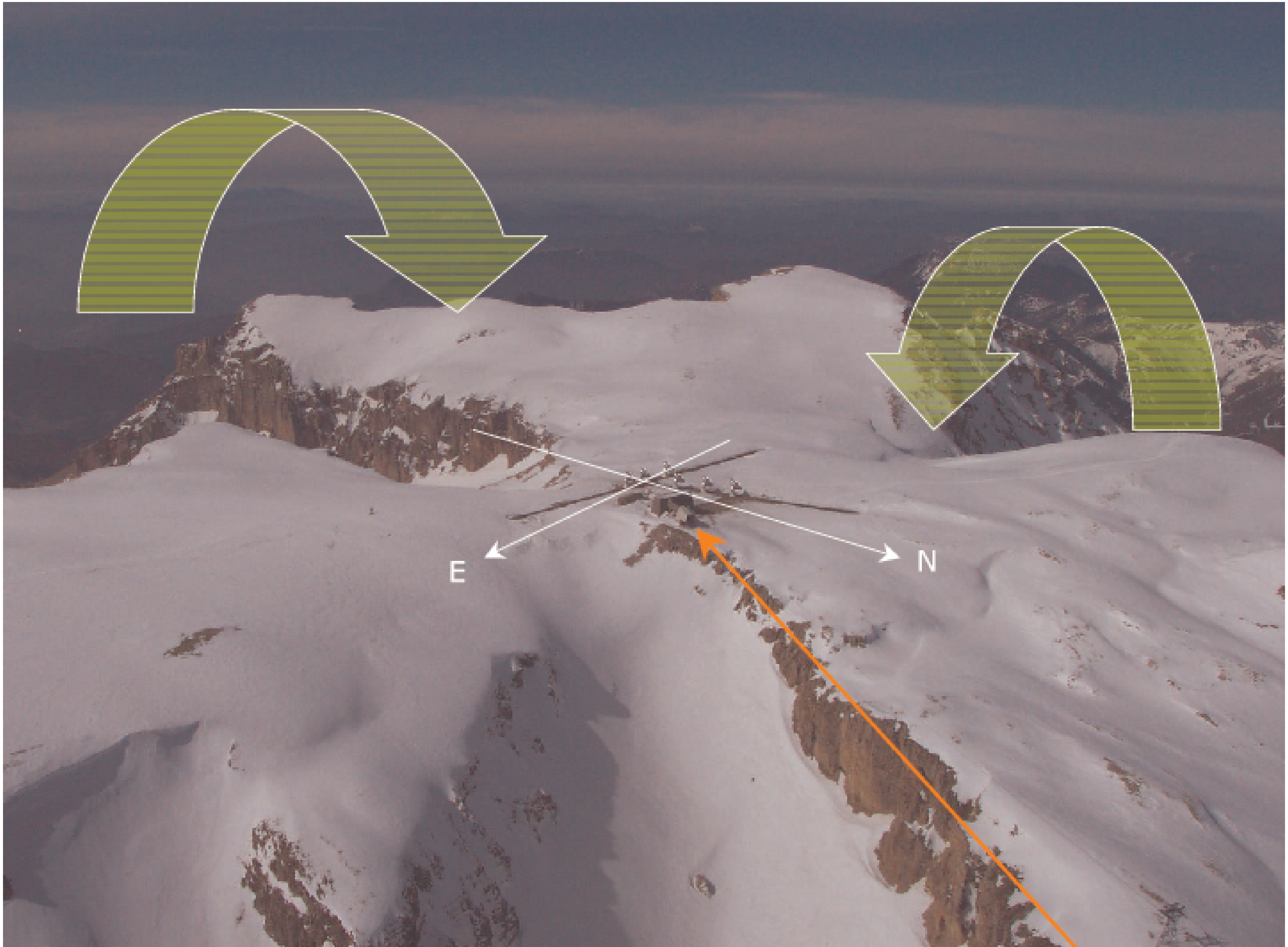
Interferometer	Atmospheric window	Ang.Resolution
ATCA	3mm	1.6"
PdBI	3mm, 2mm, 1mm, 0.8mm	0.3"
SMA	1mm-0.7mm, 0.4mm	(0.15")
CARMA	3mm 1mm	(0.1")

Large differences !



Rhône-Alpes
Grenoble
100 km
Plateau de Bure
© 2008 Cnes/Spot Image
© 2008 Tele Atlas
Image © 2008 DigitalGlobe
© 2008 Europa Technologies
Google

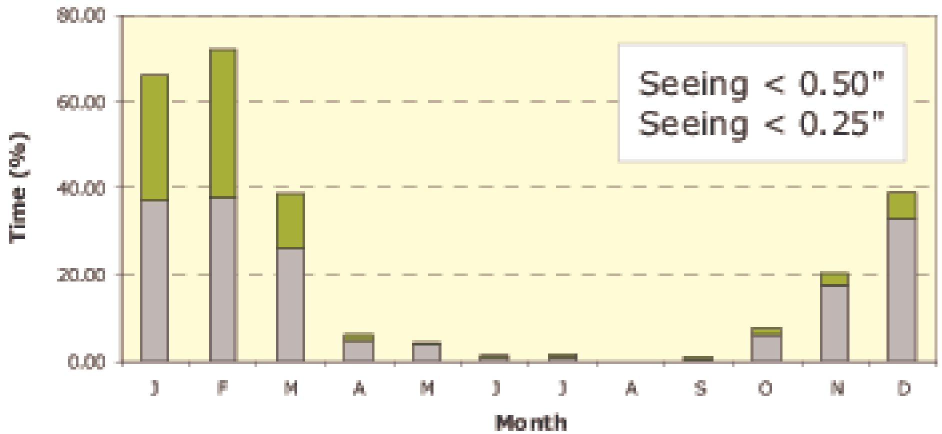

N46
W27
E68
Longitude: 05°54′28.5″
Latitude: 44°38′02.0″
Altitude: 2560 m
Google

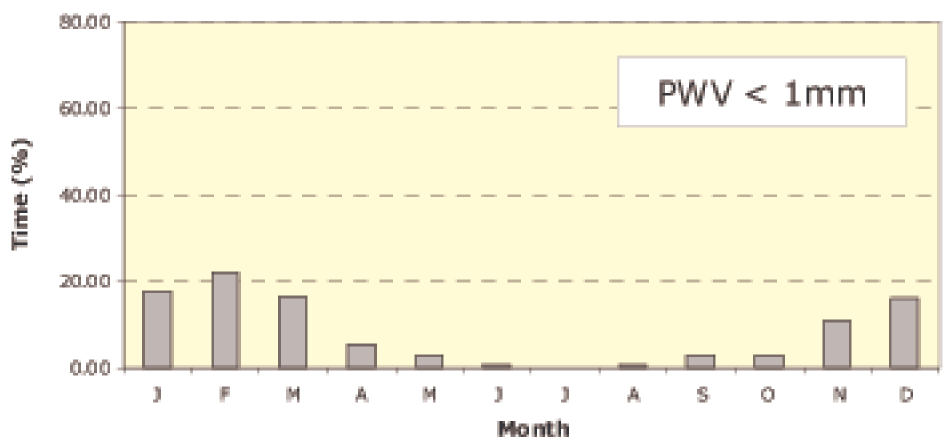

E
N

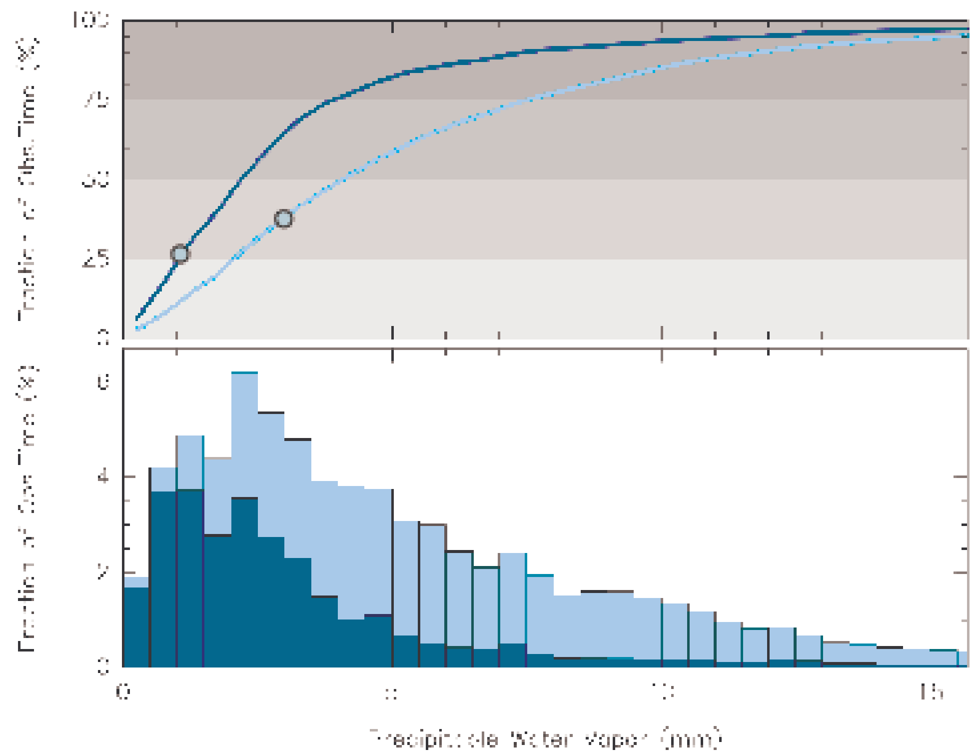
IRAM
Plateau de Bure

2004

some weather statistics (Jan 2001 >)







⇨ 2009: 80% of the observing time invested @ 3mm and 2mm

Plateau de Bure Interferometer Site

▷ Latitude :	05°54'28.5"
▷ Longitude :	44°38'02.0"
▷ Altitude :	2560 m
▷ RFI protection :	terrain shielding + NRQZ (30 km)
▷ Water vapor :	40% (<3mm); 25% (<1mm) in winter down to 0.3mm in best winter conditions submm conditions ~5 % of the time

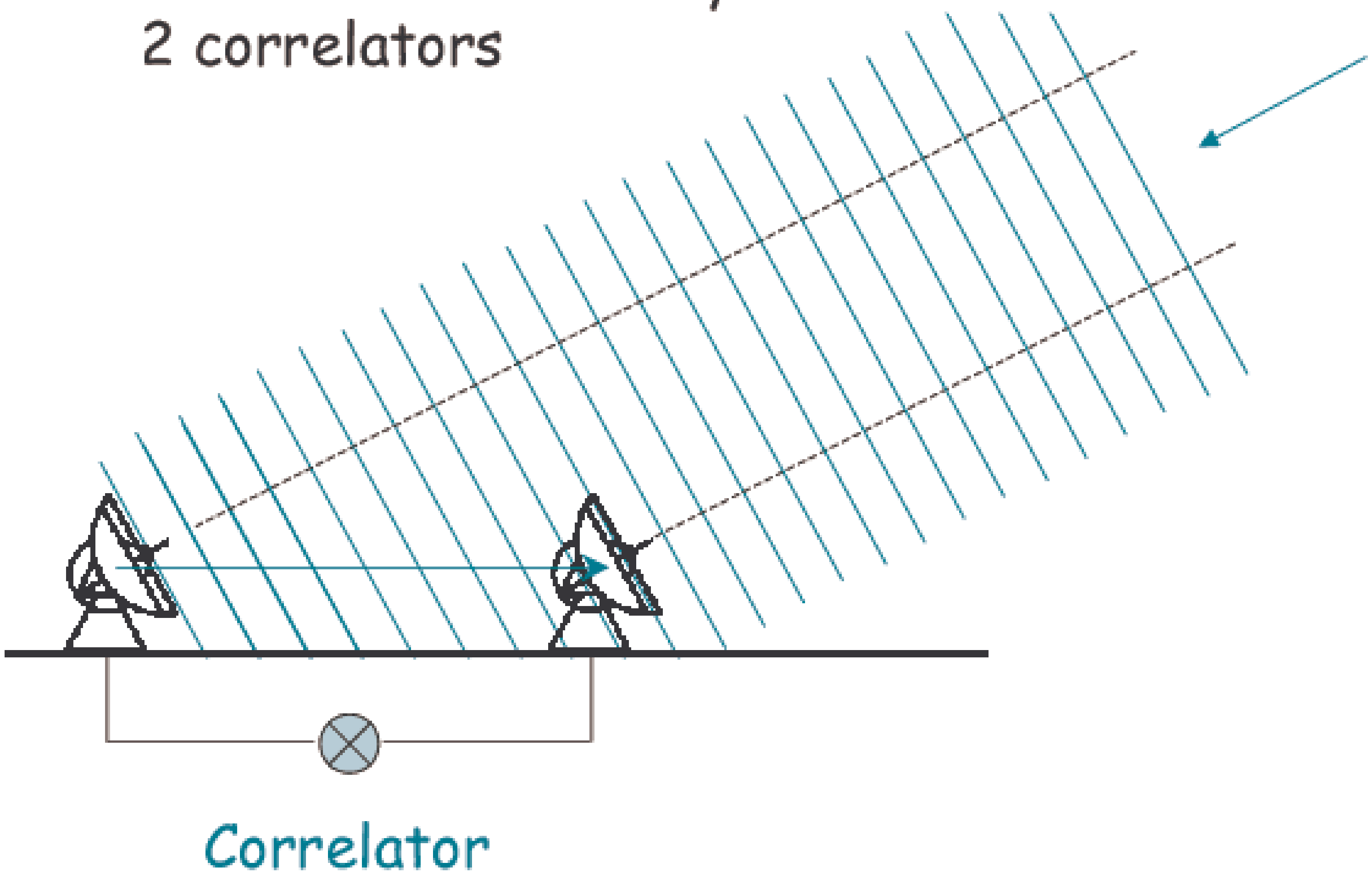
Plateau de Bure Interferometer Observatory

- ▷ Operation : 24 hrs, 365 days, service mode
  staff @ Bure + SOG @ Grenoble
- ▷ Team @ site : 6 staff members (+ 1 astronomer)
- ▷ Working schedule : 1 team per week, every 3 weeks

- ▷ VLBI @ 3mm : 5 days sessions, twice a year
  1mm intercontinental planned (+ ALMA)

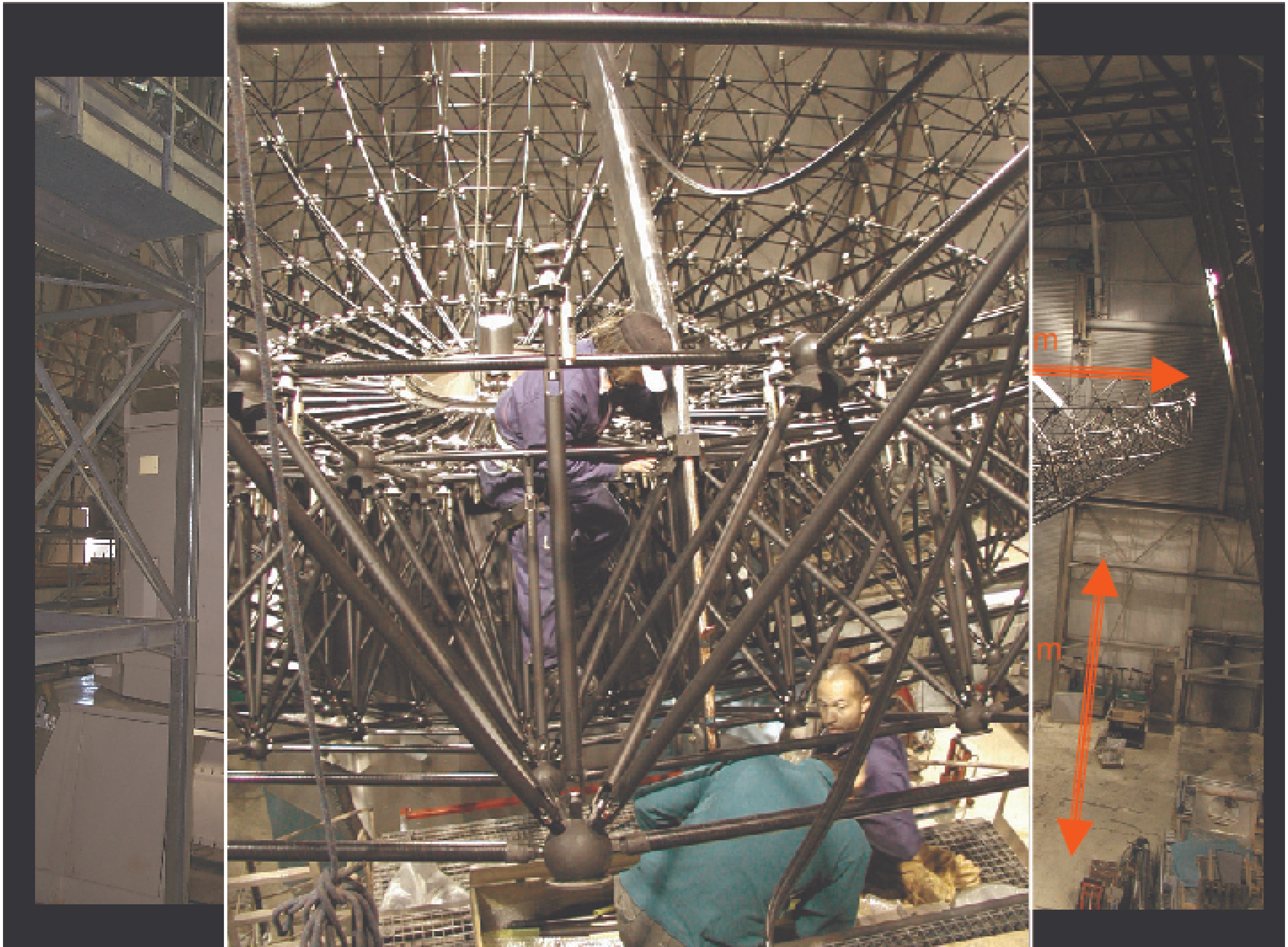
The Plateau de Bure Interferometer

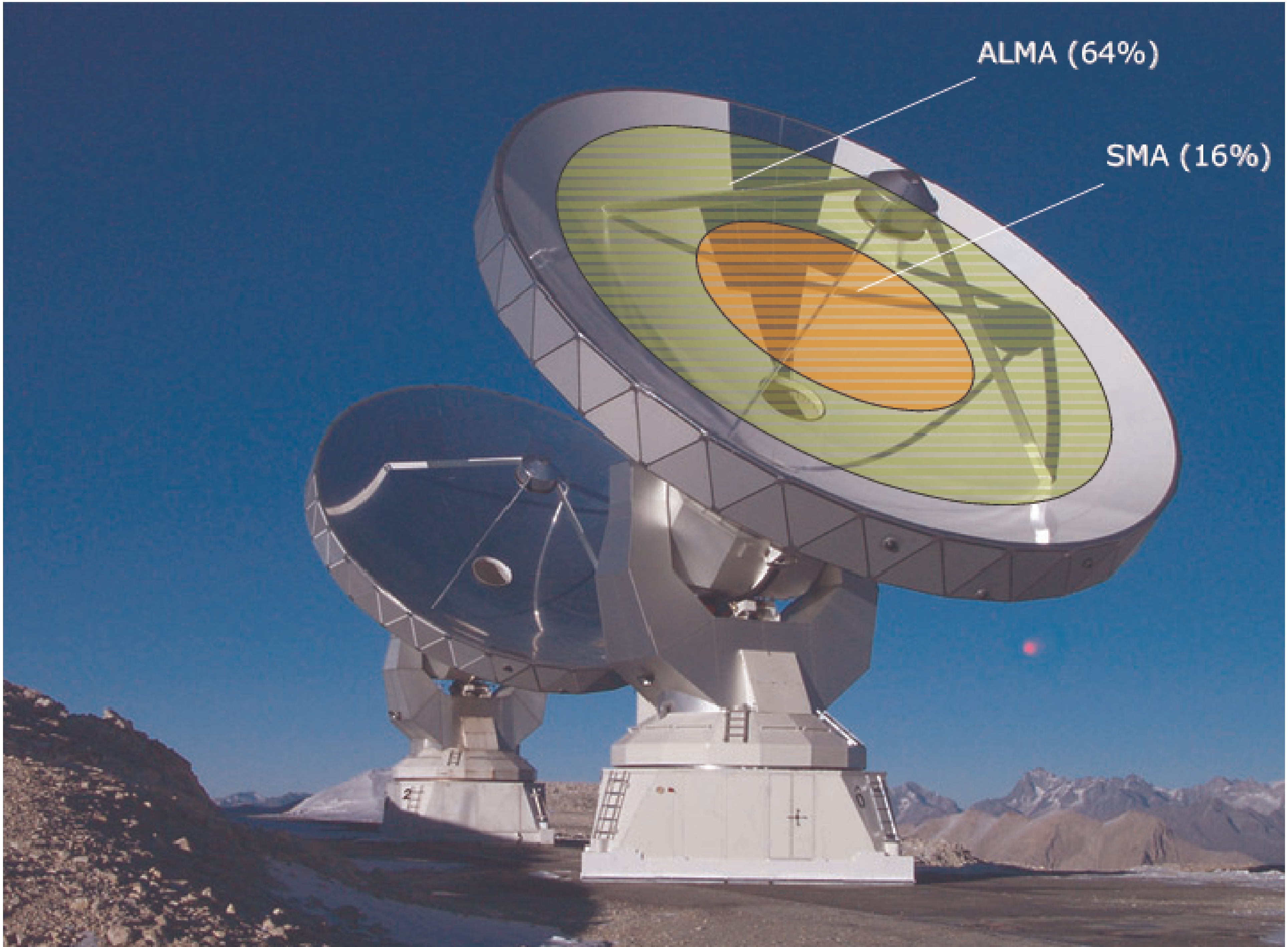
= ensemble of 6 antennas +
6 receivers + 12 delay lines +
2 correlators



Plateau de Bure Interferometer Observatory

▷Antennas :	6, Cassegrain Type
▷ Collecting area :	$177m^2$ x 6 = $1060m^2$
▷ Surface panels :	176, aluminum
▷ Surface accuracy :	35 - 50 μm
▷ Aperture efficiency :	0.65 @ 230 GHz
▷ Primary beam :	21" @ 230 GHz
▷ Pointing / tracking RMS :	1.5" / 0.2"
▷ Wind speed (max) :	14 m/s


m
m


ALMA (64%)
SMA (16%)


RECEIVERS

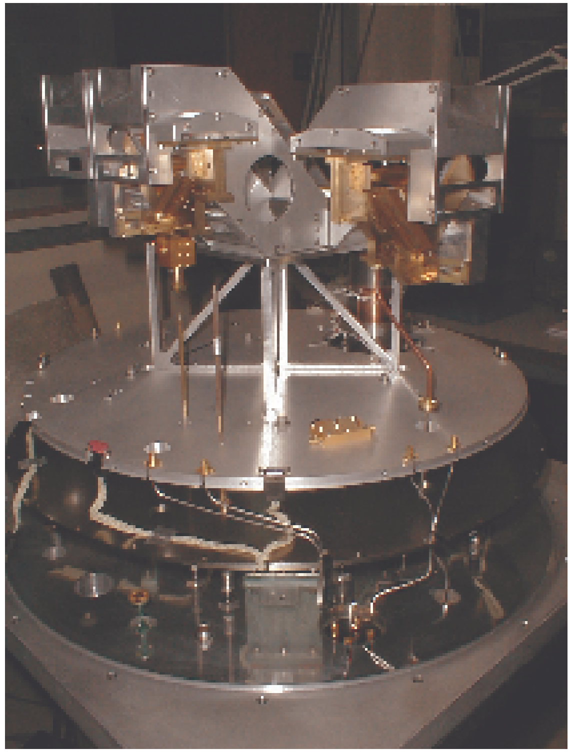
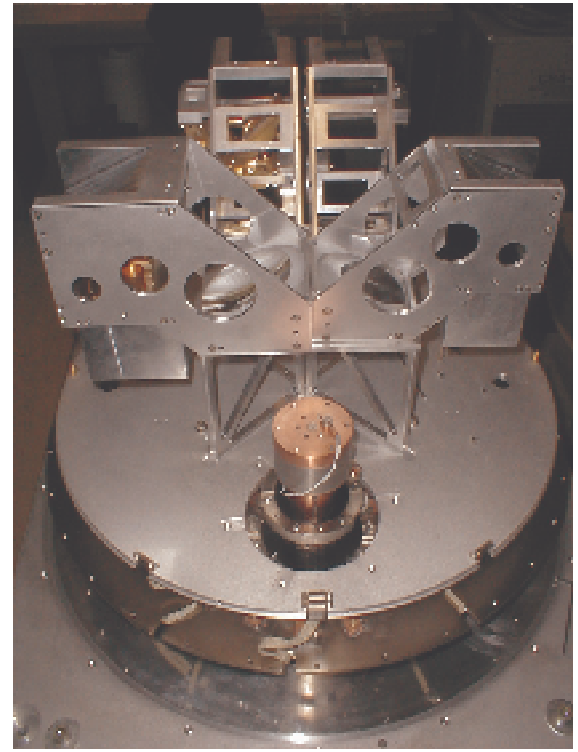
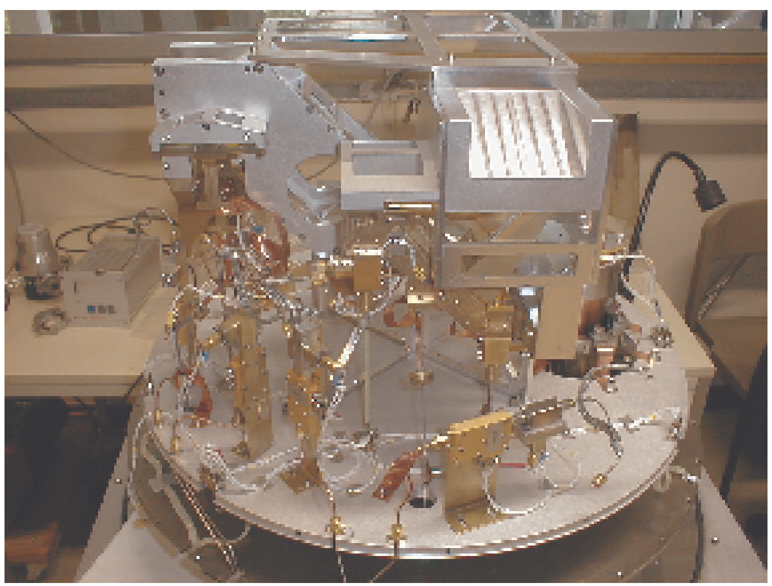
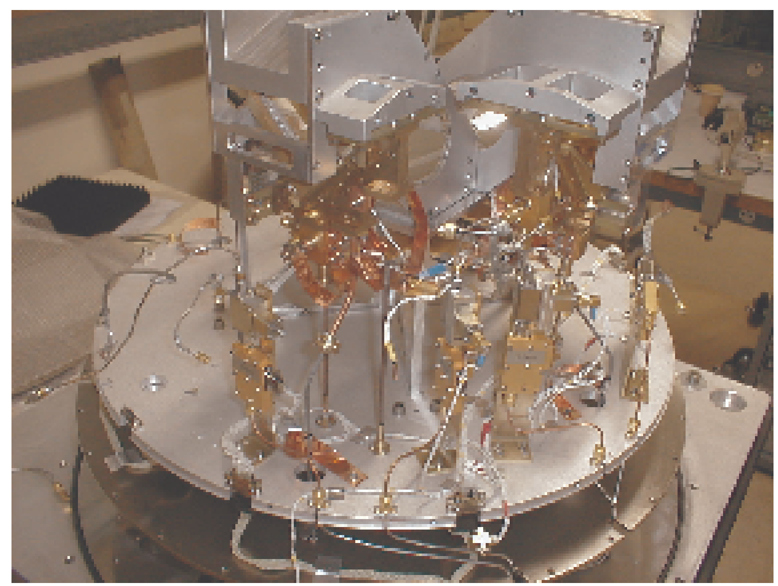
PdBI State of the art receiver technology

> Jan 2007

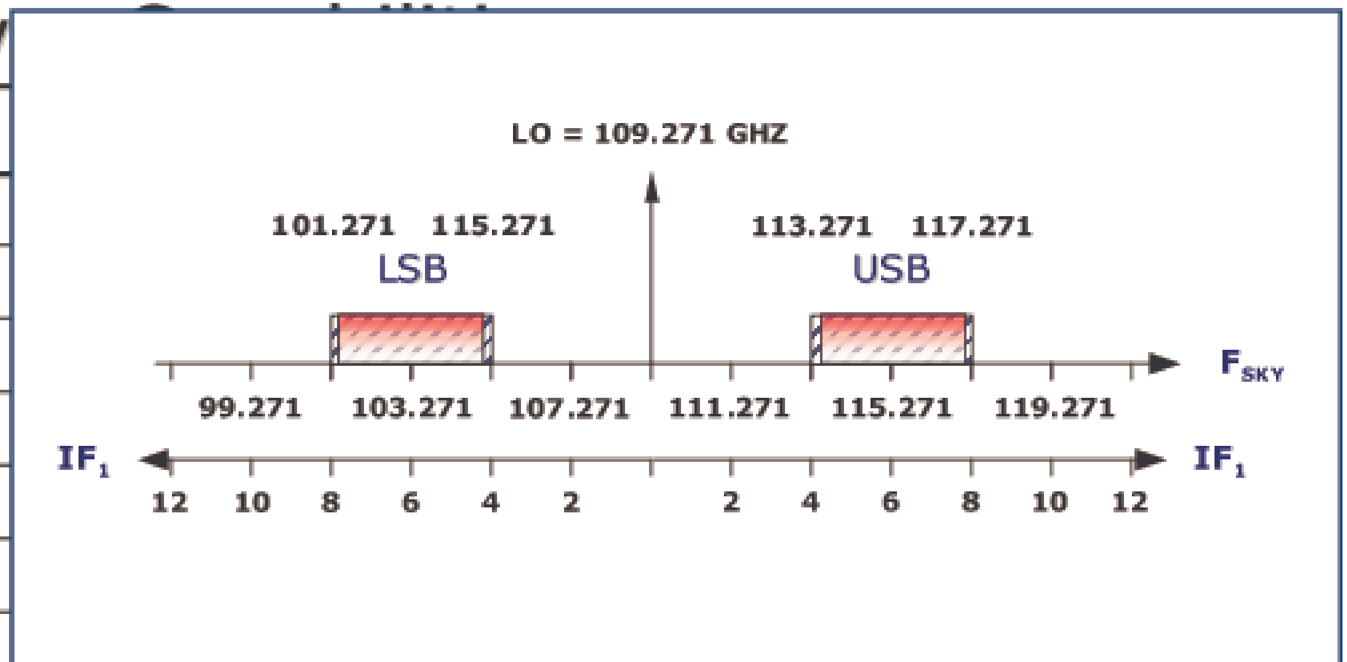
- Closed cycle cryocoolers ⇨ no liquid He refills
- SIS mixers in full-height waveguide ⇨ wideband, allow USB or LSB operation
- Fully reflective optics ⇨ lower loss
- New Design ⇨ higher density, better EMI control, simplified wiring

> Dec 2010

- Tuneless mixers and LOs for band 4 ⇨ simplified frequency tuning and switching

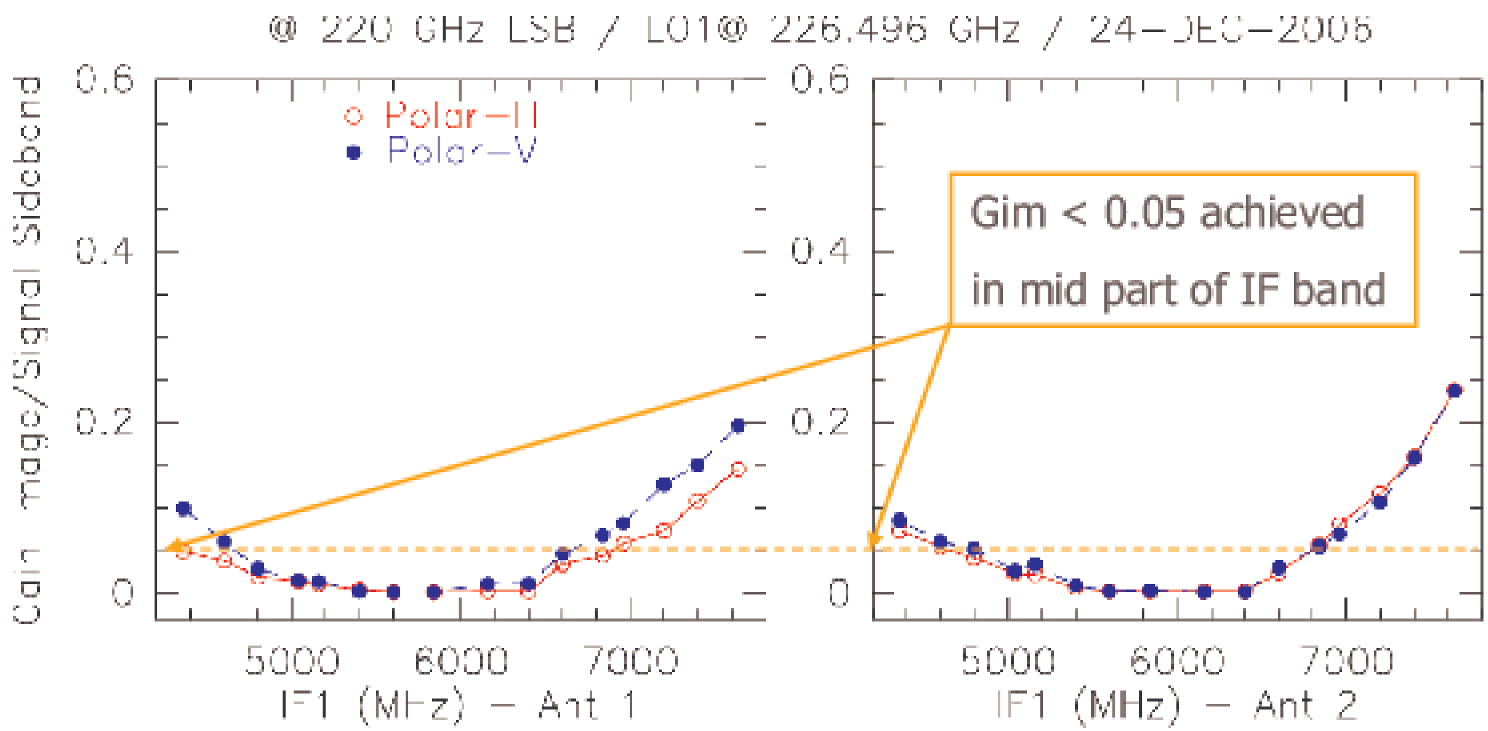
PdBI Receiv



Item		
RF bands		
1 = ALMA Band 3		
2 = ALMA Band 4		
3 = ALMA Band 6		
4 = ALMA Band 7		
RF response	SSB	LSB or USB Image Gain <-10dB
IF band	4 – 8 GHz	
Polarization	Dual linear	Circular also possible
Observing mode	Single frequency Dual polarization	Second band in standby Potential for Dual freq, Dual pol

PdBI Receiver Image Rejection

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

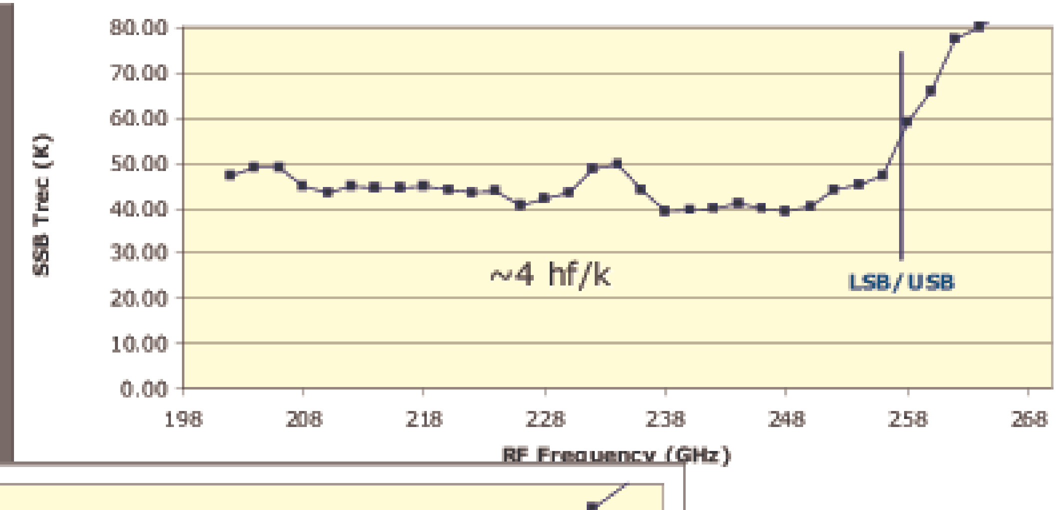


$X_{dB} = 10*\log10(Gim)$

Band3

12 mixers

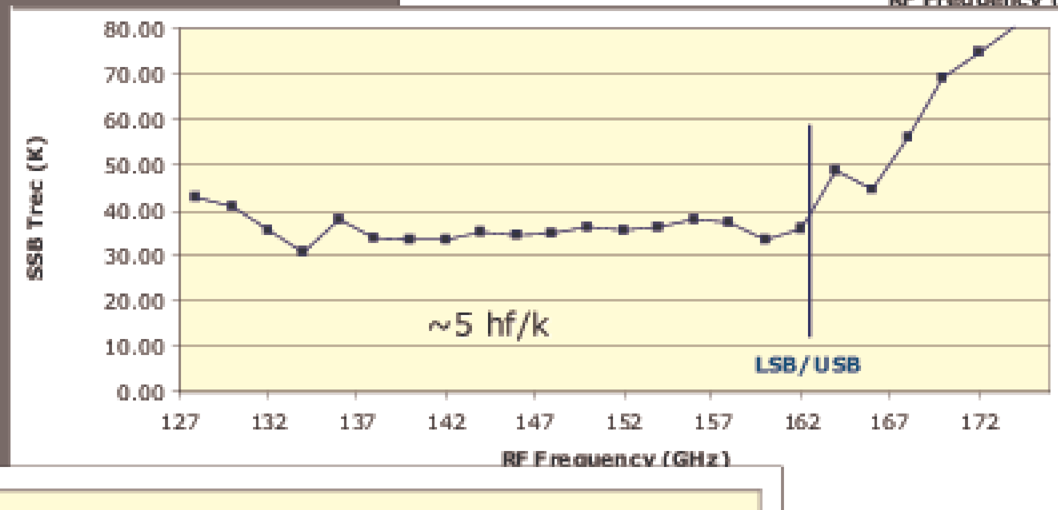
(June 2010)

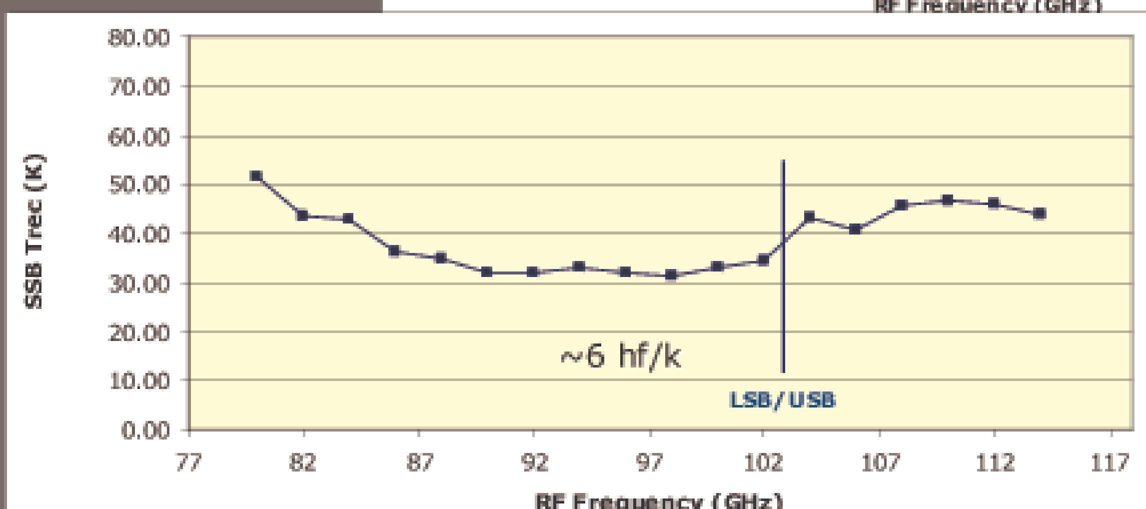


Band2

12 mixers

(June 2010)



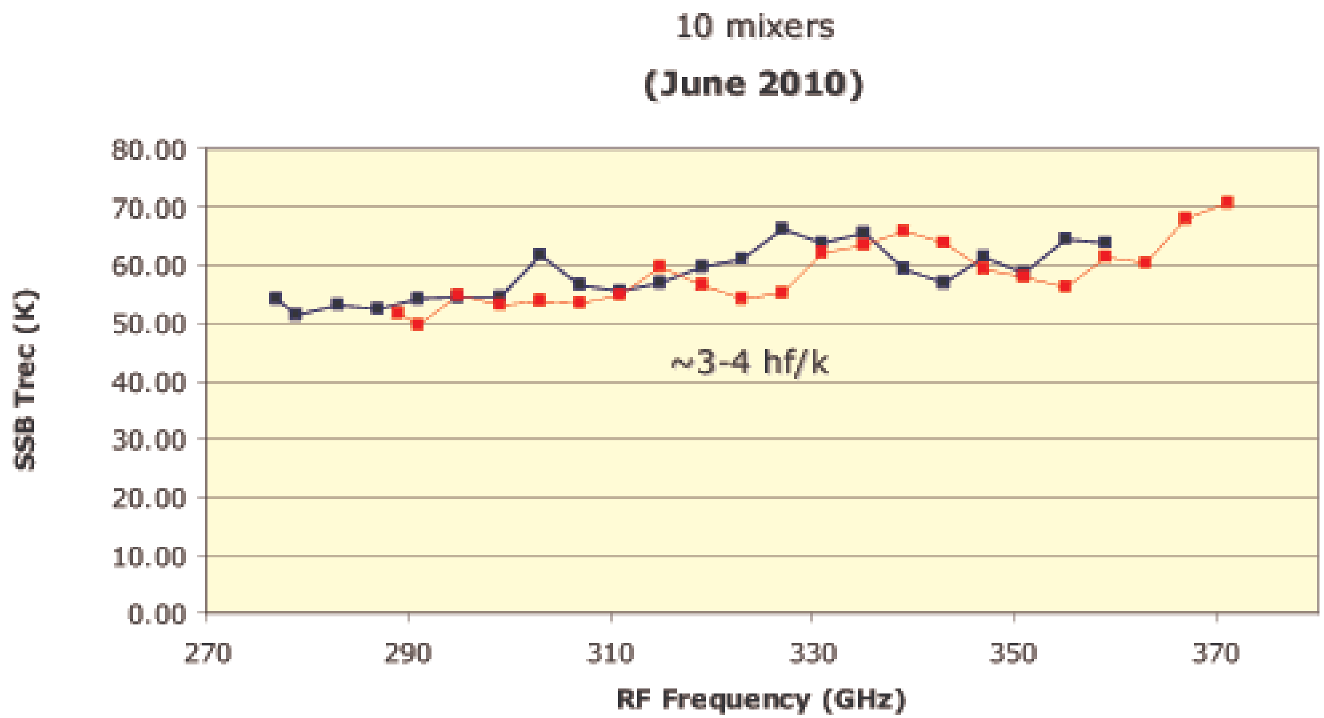


Band1

12 mixers

(June 2010)

PdBI Receiver Band 4

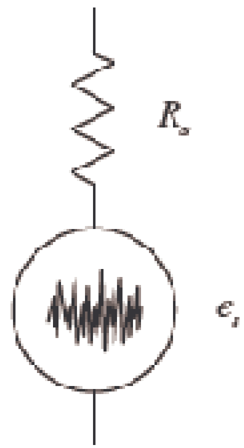


⇨ Winter 2010/2011

Noise Power

The output power of a ...

... Resistor :



$$P_N = kT\Delta\nu$$

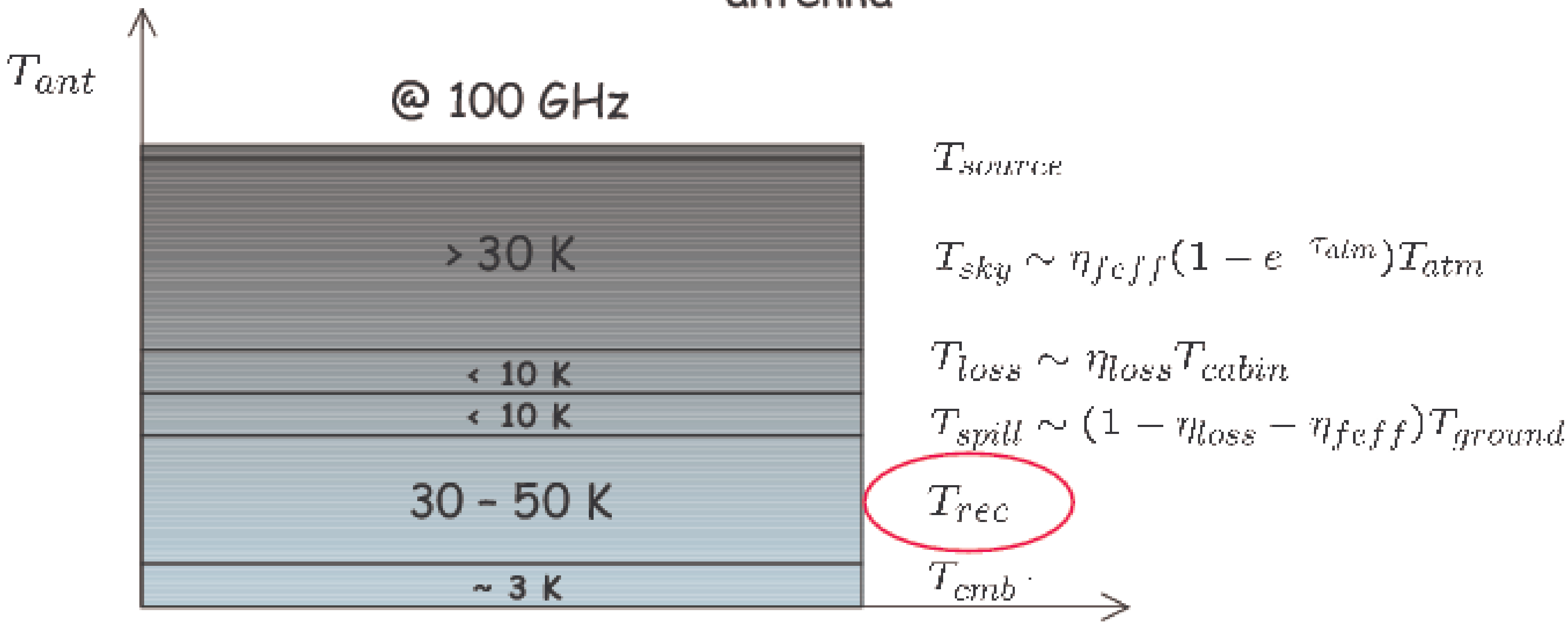
... Receiving System :

$$P_N = kT_{ant}\Delta\nu$$

Antenna System Temperature

Antenna System Temperature

is the temperature of the equivalent blackbody observed by the antenna



$$T_{ant} = T_{cmb} + T_{sky} + T_{spill} + T_{loss} + T_{rec}$$

We refer the **System Temperature**

Noise Power →

$$T_{sys} = \frac{e^{\tau_{atm}}}{\eta_{feff}} T_{ant}$$

and the **Antenna Temperature**

Astronomical Signal →

$$T_A^{\star} = \frac{e^{\tau_{atm}}}{\eta_{feff}} T_{source}$$

$$= \frac{\eta_A A}{2k} S$$

to an ideal antenna located outside the atmosphere.

PdBI System Temperatures

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

ATM (Cernicharo, Pardo)

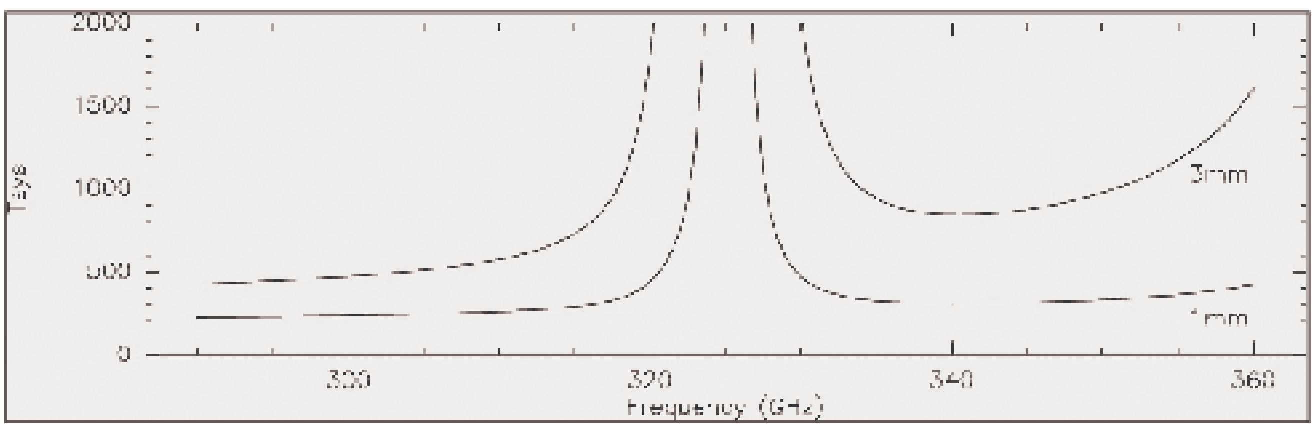
	PWV	G	η_{eff}	Trec	τ	Tsys
100 GHz	3	0.05	0.95	32	0.07	77
150 GHz	3	0.05	0.92	35	0.10	113
230 GHz	1	0.05	0.87	50	0.07	141
350 GHz	1	0.05	0.84	60	0.27	336

System temperatures @ 350 GHz

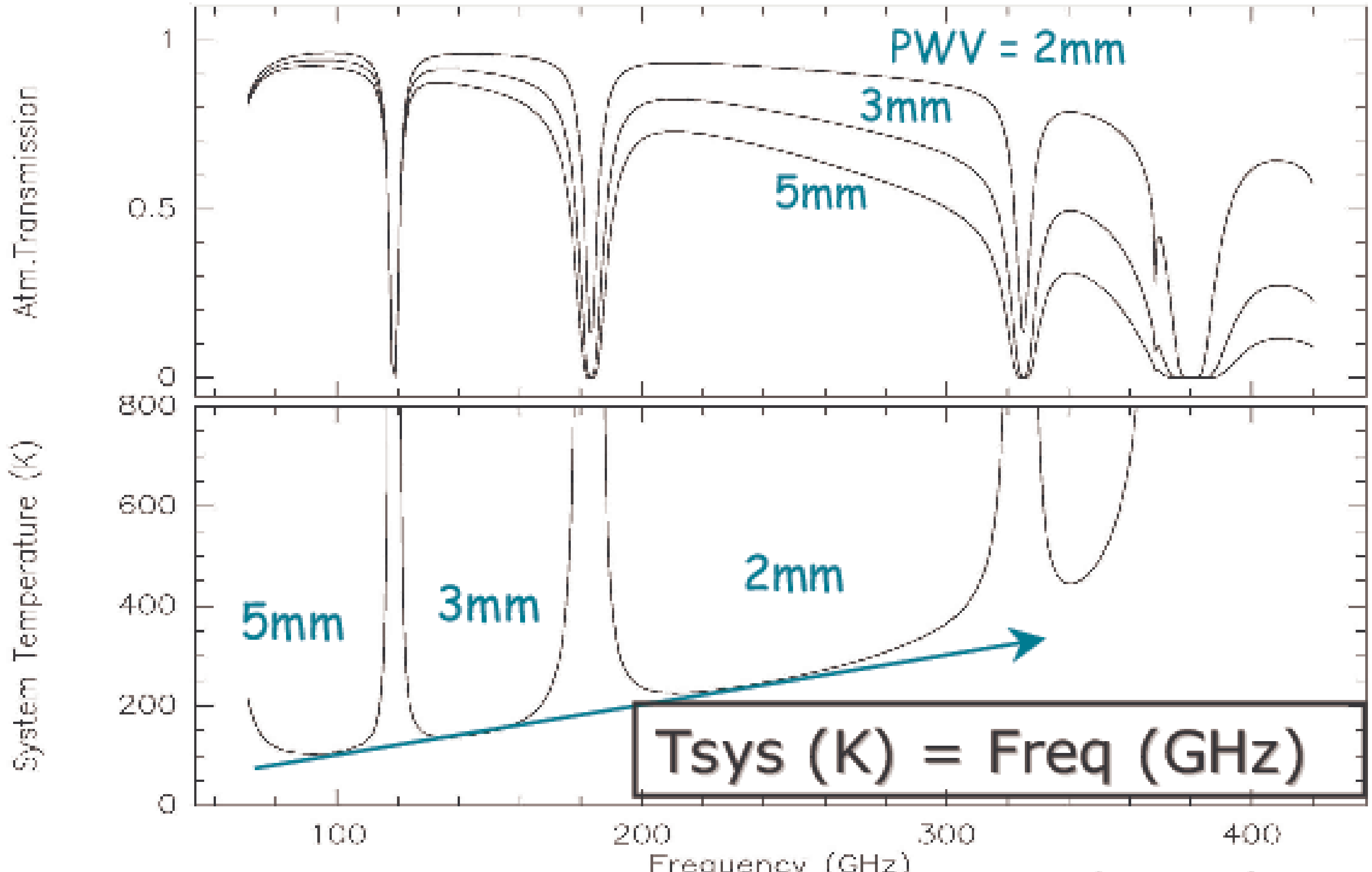
ATM (Cernicharo 1985)

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



PdBI System Temperatures

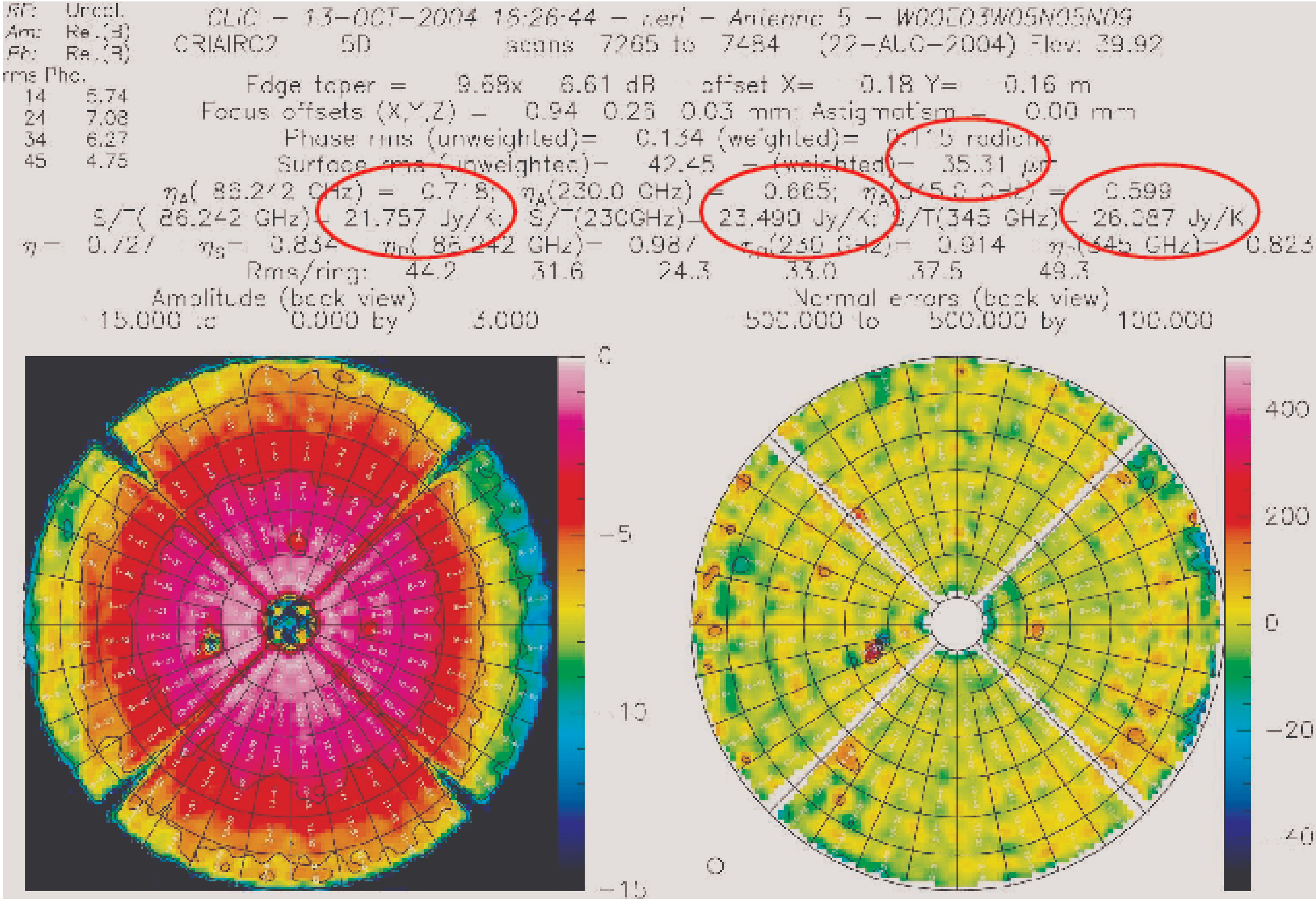


Pardo et al. 2007

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 $\exp(-\sigma_P^2/2) \leq 0.95$
N_P	Linear Polarizations (1 - 2)
T_{SYS}	System Temperature (K)
$\Delta\nu$	Spectral Bandwidth (39 kHz - 3600 MHz)
Δt	Integration Time On-Source (sec)



CLIC - 13-OCT-2004 18:26:44 - Antenna 5
scans 7265 to 7484 (22-AUG-2004)
rms Pha.
14 5.74
24 7.08
34 6.27
45 4.75
Edge taper = 9.68x 6.61 dB offset X= 0.18 Y= 0.16 m
Focus offsets (X,Y,Z) = 0.94 0.25 0.03 mm; Astigmatism = 0.00 mm
Phase rms (unweighted)= 0.134
Surface rms (unweighted)= 42.45 35.31
S/T(86.242 GHz)= 21.757 Jy/K; S/T(230GHz)= 23.490 Jy/K; S/T(345 GHz)= 26.287 Jy/K
0.727 0.834 0.987 0.914 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
0
-5
-10
-15
400
200
0
-200

Point source sensitivities:

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

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

$\rightarrow 22 \times \sigma_T$ [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%

PdBI System Temperatures

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

ATM (Cernicharo, Pardo)

	PWV	G	η_{eff}	Trec	τ	Tsys
100 GHz	3	0.05	0.95	32	0.07	77
150 GHz	3	0.05	0.92	35	0.10	113
230 GHz	1	0.05	0.87	50	0.07	141
350 GHz	1	0.05	0.84	60	0.27	336

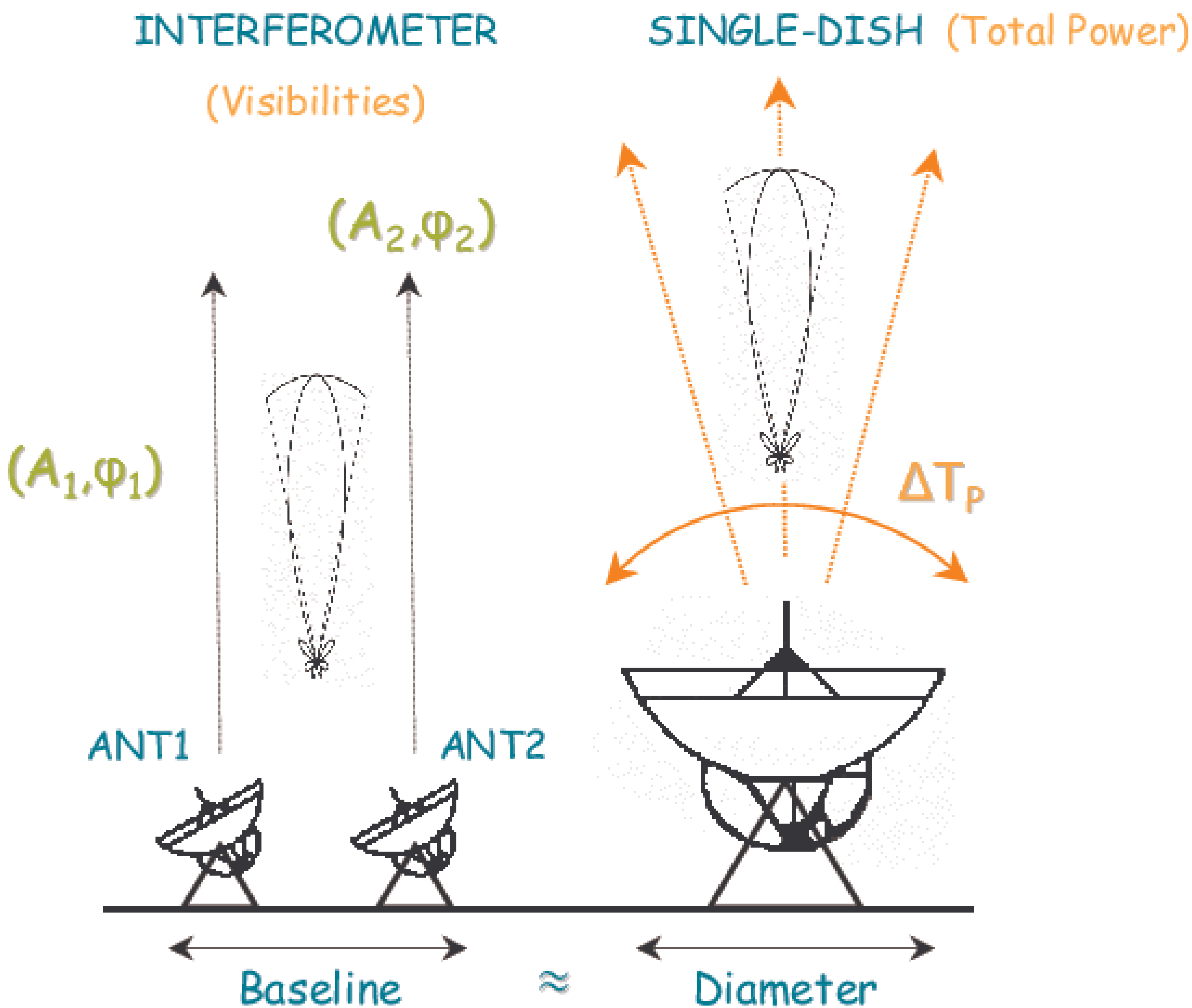
One baseline, two antennas:

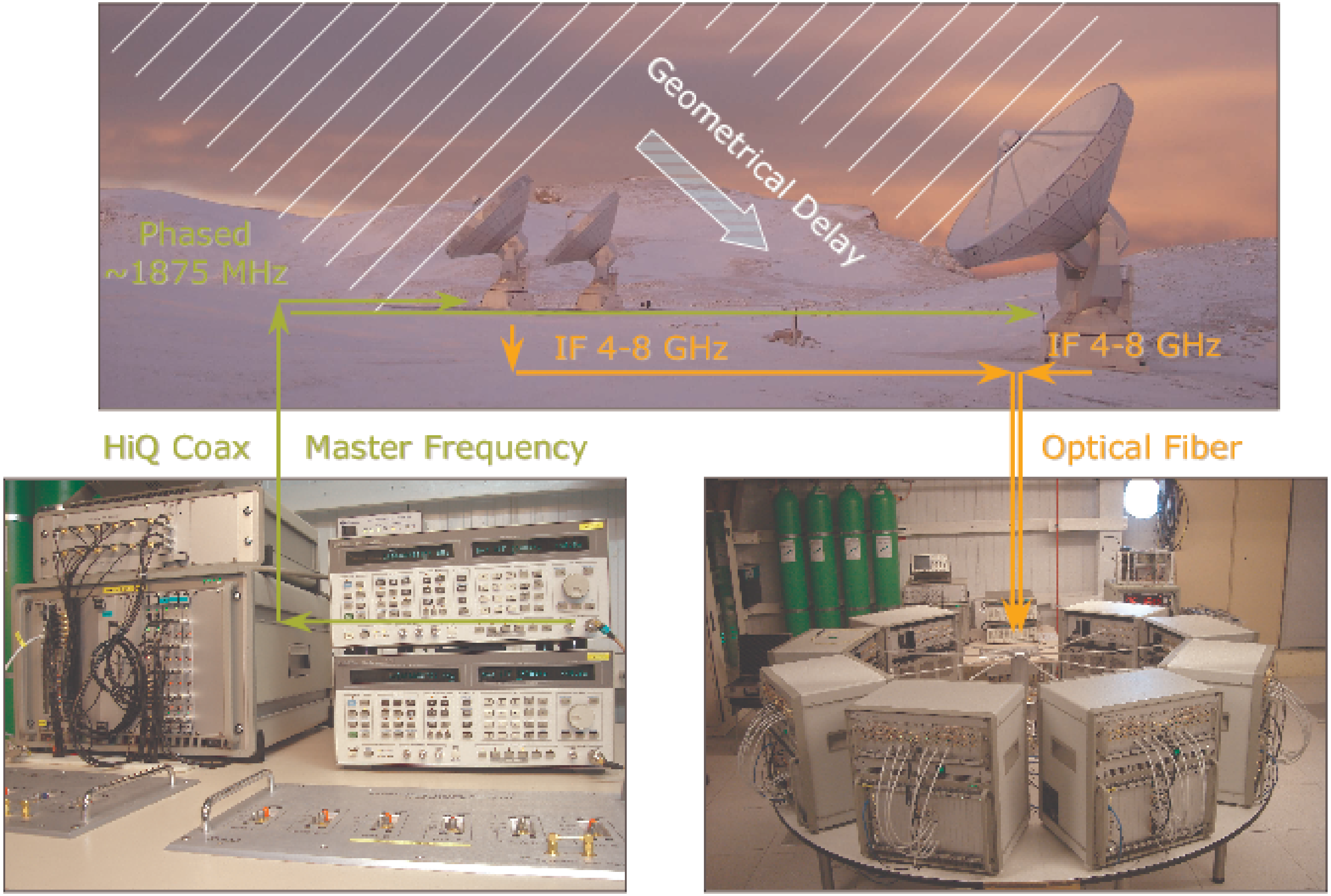
$$\sigma_S \simeq \frac{2k}{\eta_a A} \times \frac{< T_{\mathsf{SYS}} >}{\sqrt{2\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}} = \frac{\sqrt{T^1_{\mathsf{SYS}} \times T^2_{\mathsf{SYS}}}}{\sqrt{2\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}} \quad [\mathrm{Jy}]$$

$$\mathrm{Ex@100GHz}: \ \sigma_S \simeq 22 \times \frac{100}{\sqrt{2 \times 3600\, 10^6 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 19\,\mathrm{mJy}$$

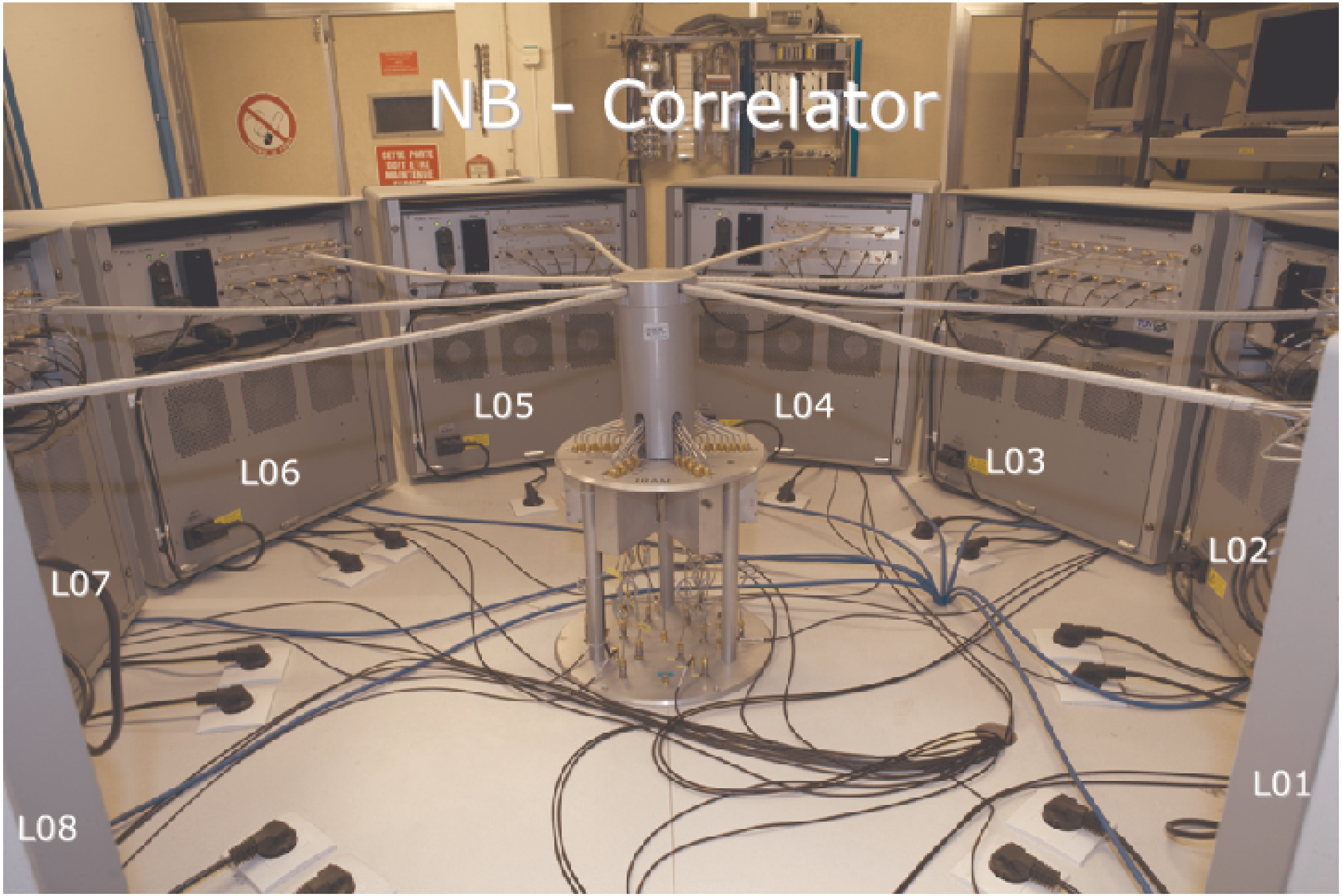
The PdBI array:

$$\mathrm{Ex@100GHz}: \ \sigma_S \simeq 22 \times \frac{100}{\sqrt{30 \times 3600\, 10^6 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 4.7\,\mathrm{mJy}$$


INTERFEROMETER
(Visibilities)
SINGLE-DISH (Total Power)
(A2,φ2)
(A1,φ1)
ΔTP
ANT1
ANT2
Baseline
≈
Diameter



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

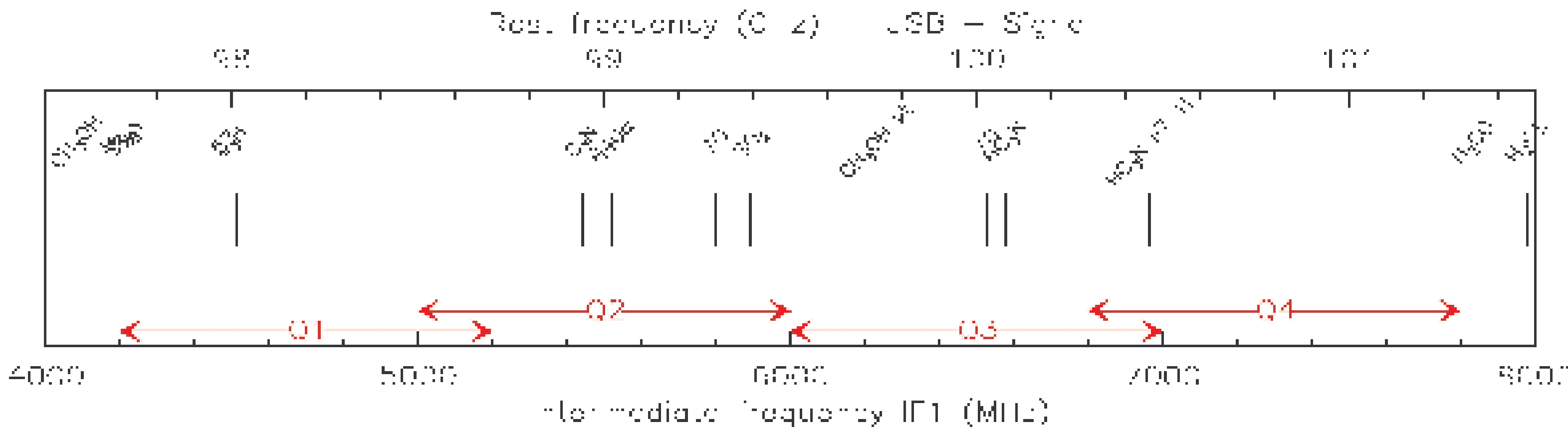

NB - Correlator
L05
L04
L06
L03
L02
L07
L01
L08

NB-Correlator Modes

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

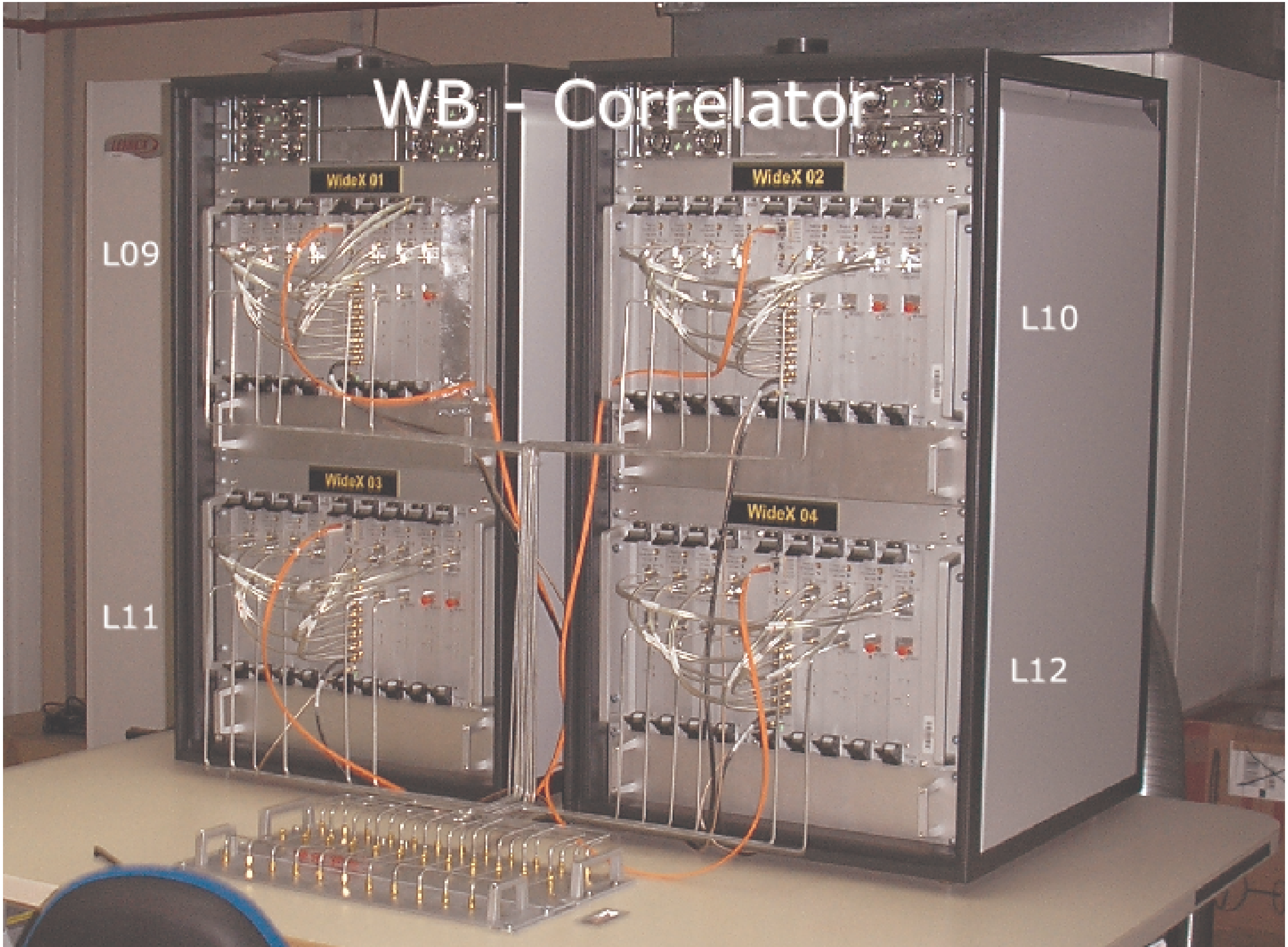
Bandwidth	Mode	Channels	Spacing
320 MHz	DSB	2 x 64	2.5 MHz
160 MHz	SSB	1 x 128	1.25 MHz
160 MHz	DSB	2 x 128	0.625 MHz
80 MHz	SSB	1 x 256	0.312 MHz
80 MHz	DSB	2 x 256	0.156 MHz
40 MHz	SSB	1 x 512	0.078 MHz
20 MHz	SSB	1 x 512	0.039 MHz

A 4 GHz RF but …



- correlator accepts only 2 quarters ; max bandwidth = 2 x 1 GHz
- 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


WB - Correlator
WideX 01
WideX 02
WideX 03
WideX 04
L09
L10
L11
L12

PdBI backends

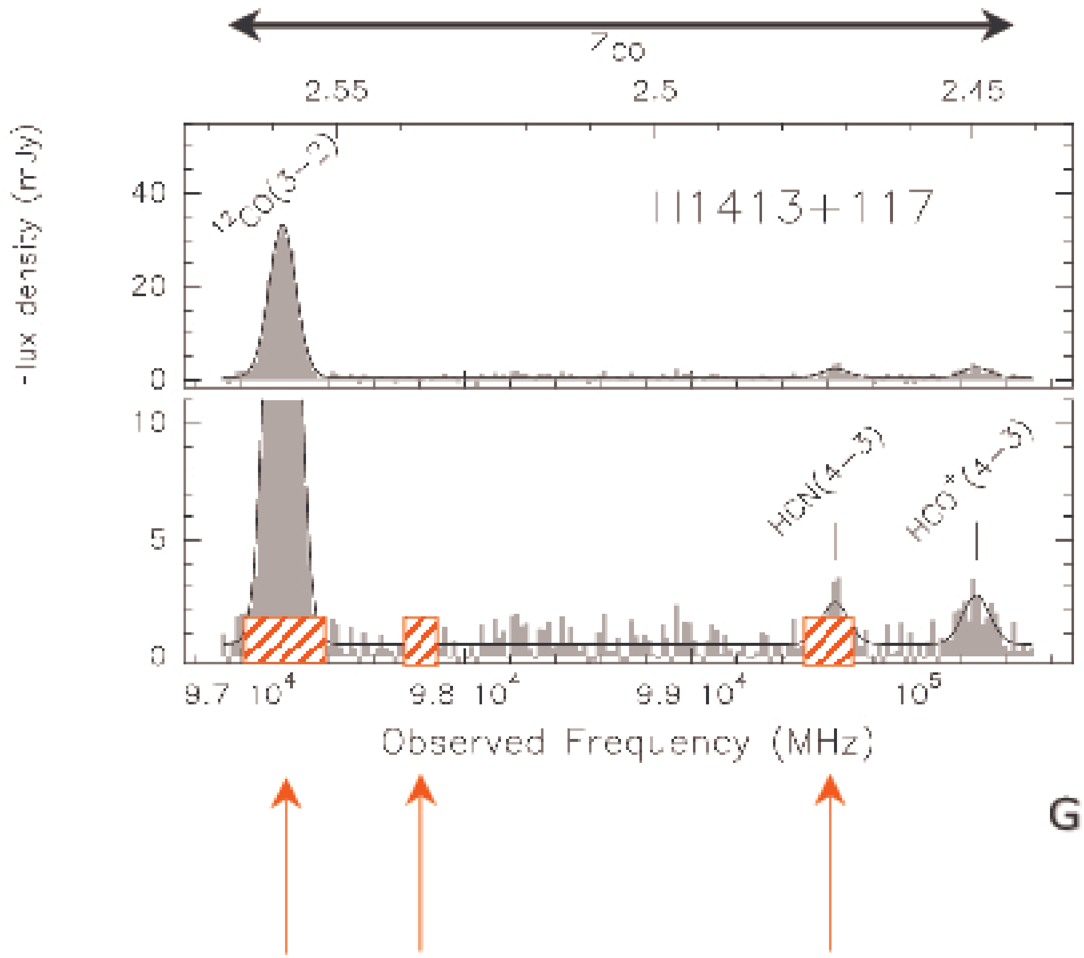
Item	Value	Notes
Correlator		
1 = Narrow Band	8 Units : 20 – 320 MHz	Freq.res : 0.039 – 2.5 MHz
2 = Wide Band	4 Units : 2 GHz	Freq.res : 2 MHz Fixed
IF band	4.2 – 7.8 GHz	IF processor limited
Polarization	Dual linear	Full Stokes in 2011

⇒ line searches (@ high redshift)

⇒ improved relative line intensity calibration

⇒ sensitive continuum ⇒ calibration, polarization, spectral index

3.6 GHz in each polarization



spect.cover. = 3.6 GHz
chan.sampl. = 20 MHz
integra.time = 3.6 hrs

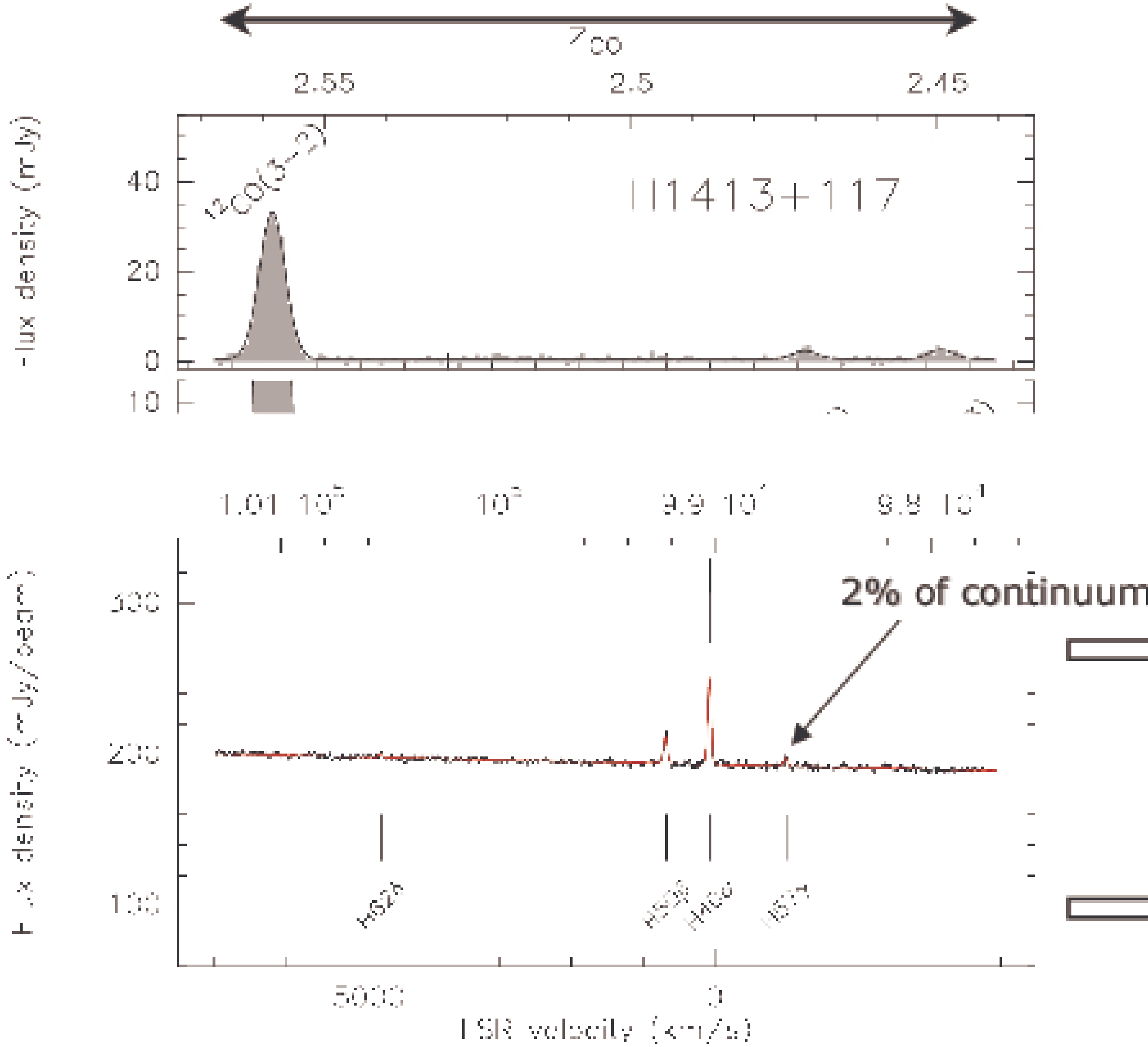
r.m.s. = 0.66 mJy

⇨ line searches

Guélin et al. in prep

Narrow Band Correlator Units (up to 8)

3.6 GHz in each polarization



Thum et al. in prep

spect.cover. = 3.6 GHz
chan.sampl. = 20 MHz
integra.time = 3.6 hrs

r.m.s. = 0.66 mJy

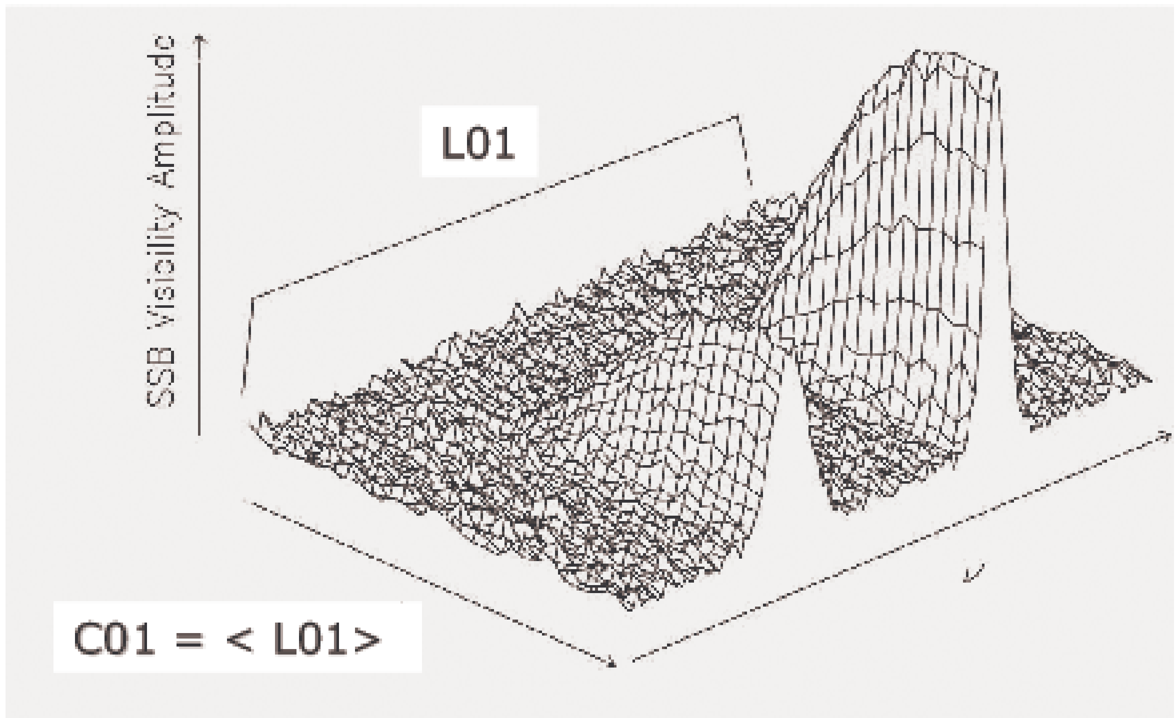
⇨ line searches

⇨ improved relative line intensity calibration

Each correlator unit produces Line and Continuum data:

⇨ L01, ..., L12 : one visibility spectrum per SCAN (mostly 45 sec)

⇨ C01, ..., C12 : one spectral averaged visibility per RECORD (1 sec)



Bandwidth	Mode	Channels	Spacing
20 MHz	SSB	1 x 512	0.039 MHz
320 MHz	DSB	2 x 64	2.5 MHz

One baseline, two antennas:

$$\sigma_S \simeq \frac{2k}{\eta_a A} \times \frac{< T_{\rm SYS} >}{\sqrt{2 \Delta\nu \Delta t}} \times \frac{1}{\sqrt{N_P}} = \frac{\sqrt{T^1_{\rm SYS} \times T^2_{\rm SYS}}}{\sqrt{2 \Delta\nu \Delta t}} \times \frac{1}{\sqrt{N_P}} \quad [\rm Jy]$$

Ex @ 100 GHz:

$$\sigma_S \simeq 22 \times \frac{100}{\sqrt{2 \times 0.039\, 10^6 \times 45}} \times \frac{1}{\sqrt{1}} \simeq 1.2\ \rm Jy$$

$$\sigma_S \simeq 22 \times \frac{100}{\sqrt{2 \times 2.5\, 10^6 \times 45}} \times \frac{1}{\sqrt{1}} \simeq 150\ \rm mJy$$

$$\sigma_S \simeq 22 \times \frac{100}{\sqrt{2 \times 3600\, 10^6 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 18\ \rm mJy$$

Scan types:

- **IFPB:** auto- and cross-correlations on white noise → backend calibration.
- **AUTO:** auto-correlations on the sky → backend calibration.
- **CALI:** auto-correlations (total power measurements) on a cold load (15K), table (290K) and on the sky → interferometer temperature scale.
- **CORR:** on-target cross-correlations → complex visibilities (K) in the uv–plane.
- **POIN = CORR** → antenna pointing (Az±, El±)
- **FOCU = CORR** → antenna focus (ΔF)
- **GAIN = CORR** → receiver image to signal sideband calibration → interferometer temperature scale.
- **FLUX = CORR** → visibility flux density calibration scale ($W/m^2/Hz/K$)

CALIBRATOR 1

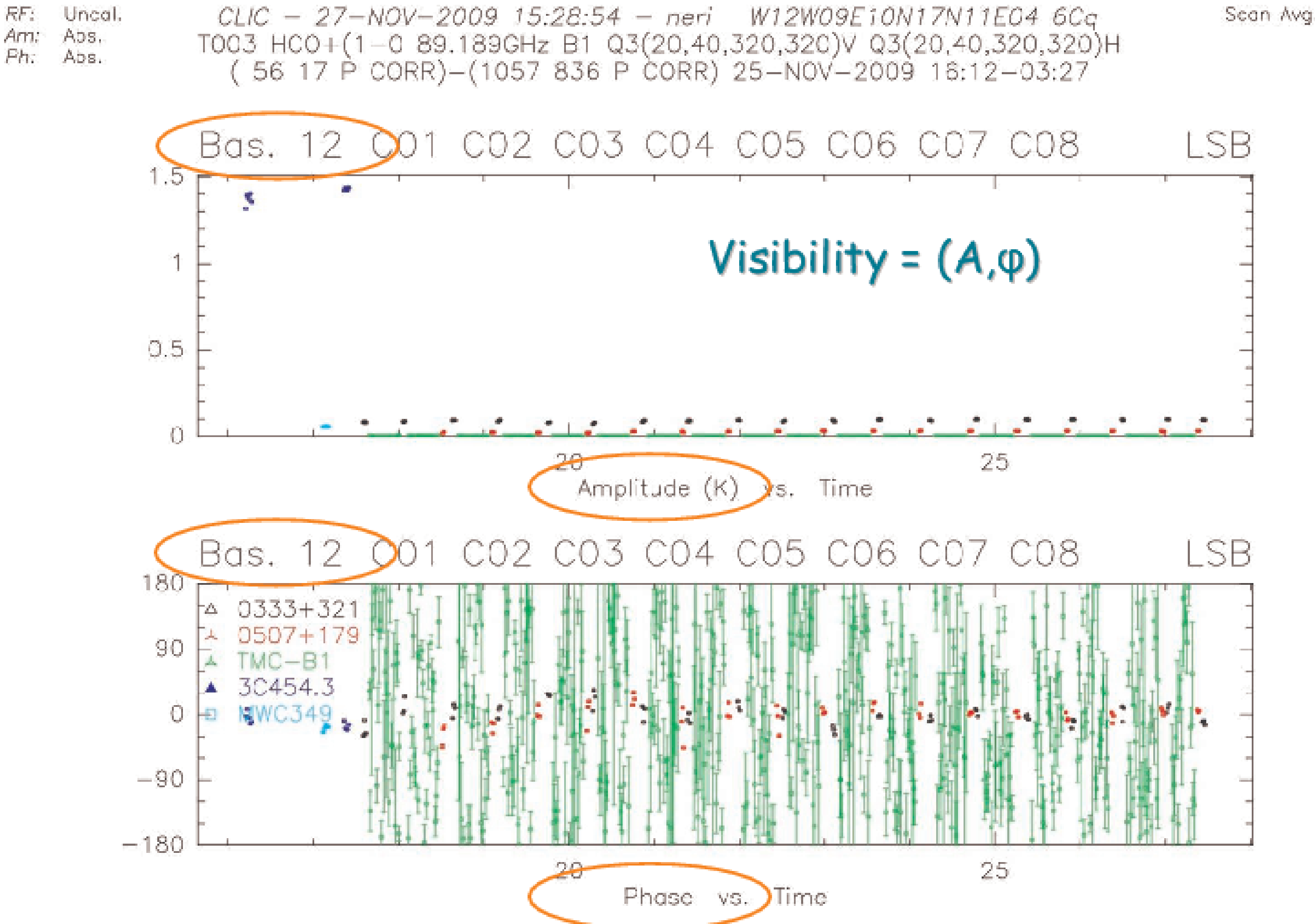
BANDPASS CALIBRATION	→ FPB	(2x 5 sec)
TABLE / SKY CALIBRATION	→ CAL	(1x2x 5 sec)
ANTENNA POINTING	→ POIN	(2x 60 sec)
ANTENNA FOCUS	→ FOCU	(5x 15 sec)
CORRELATIONS	→ CORR	(3x 45 sec)

(CALIBRATOR 2)

(BANDPASS CALIBRATION	→ FPB)	
(TABLE / SKY CALIBRATION	→ CAL)	
(CORRELATIONS	→ CORR)	

SOURCE

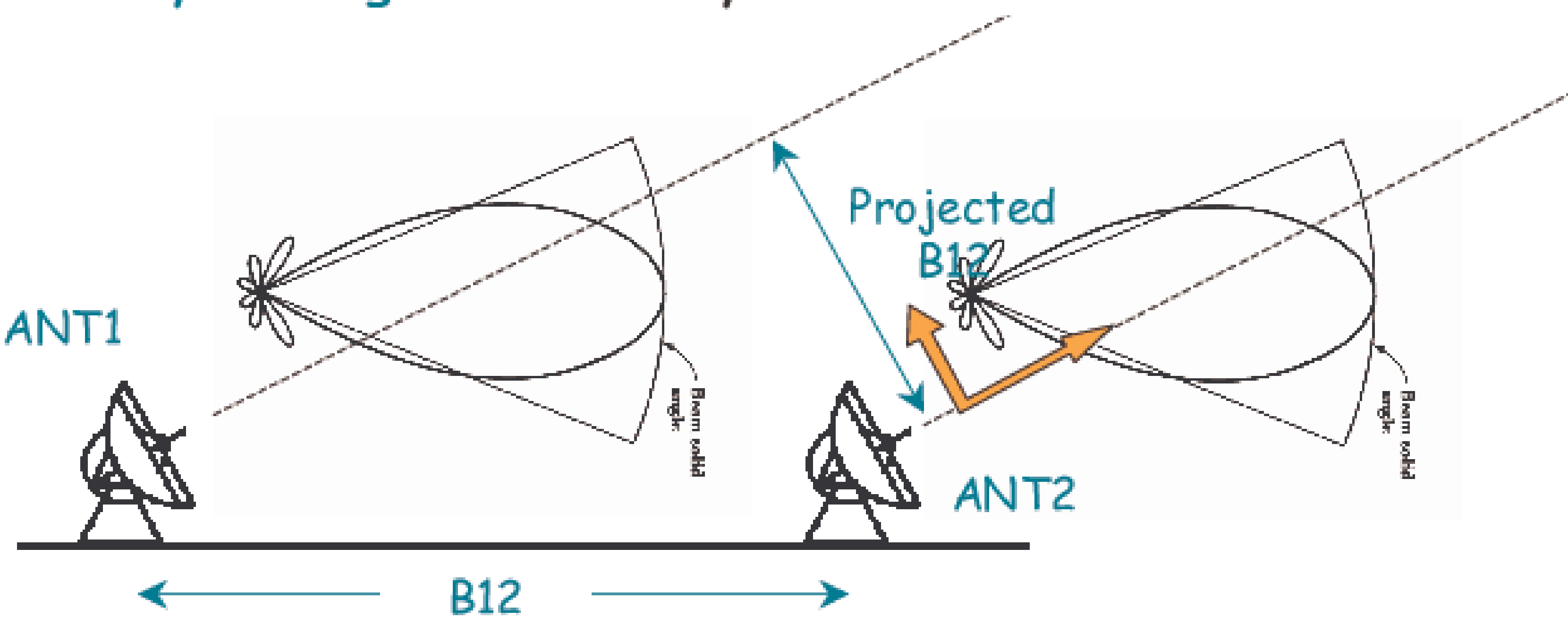
BANDPASS CALIBRATION	→ FPB	
TABLE / SKY CALIBRATION	→ CAL	
CORRELATIONS	→ CORR	(30x 45 sec)

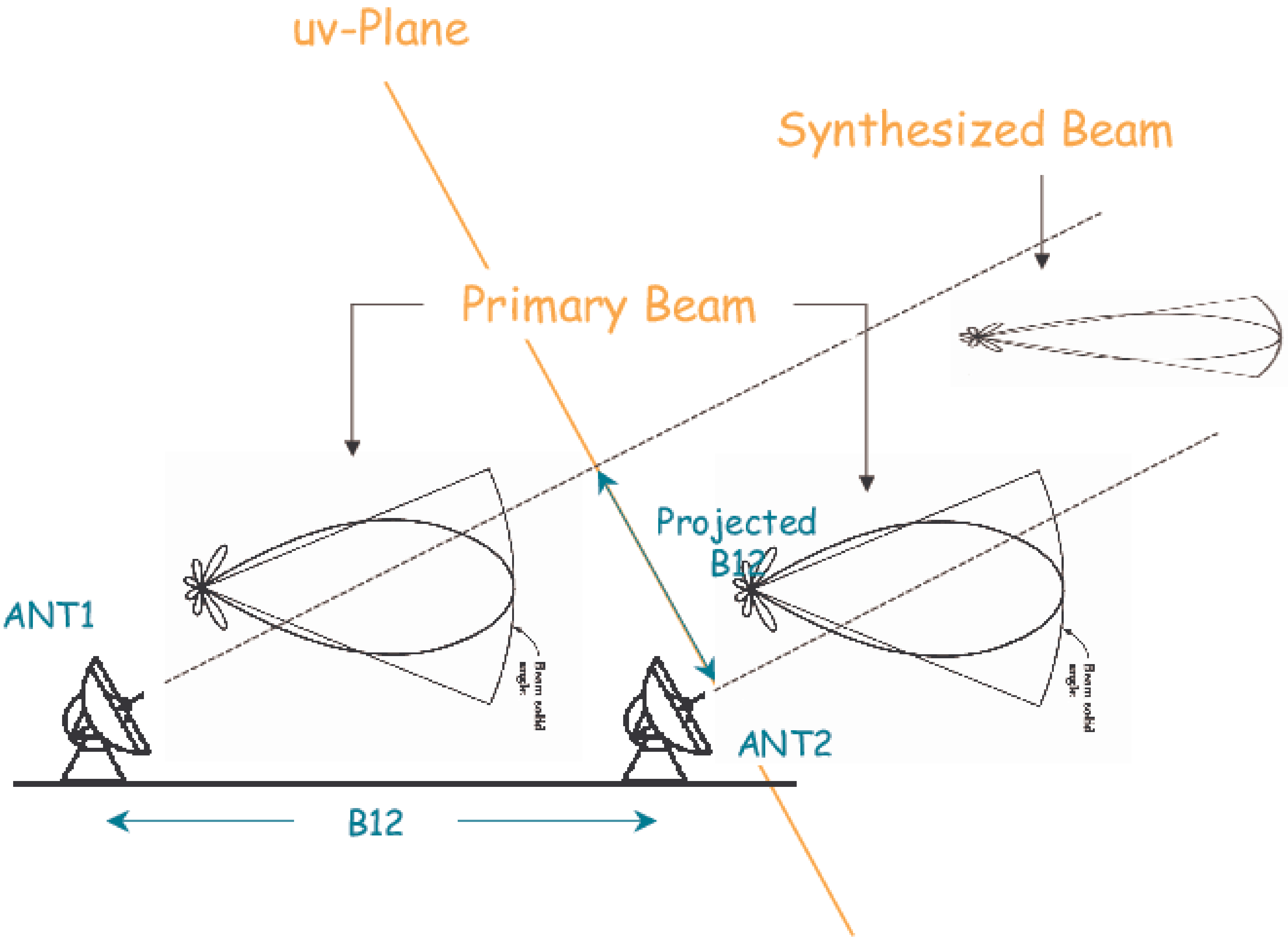

RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC – 27-NOV-2009 15:28:54 – neri W12W09E10N17N11E04 6Cq
T003 HCO+(1–0 89.189GHz B1 Q3(20,40,320,320)V Q3(20,40,320,320)H
(56 17 P CORR)–(1057 836 P CORR) 25-NOV-2009 18:12–03:27
Scan Avg.
Bas. 12 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Visibility = (A,φ)
Amplitude (K) vs. Time
Bas. 12 C01 C02 C03 C04 C05 C06 C07 C08 LSB
0333+321
0507+179
TMC-B1
3C454.3
MWC349
Phase vs. Time

Baseline Bij : distance between two antennas

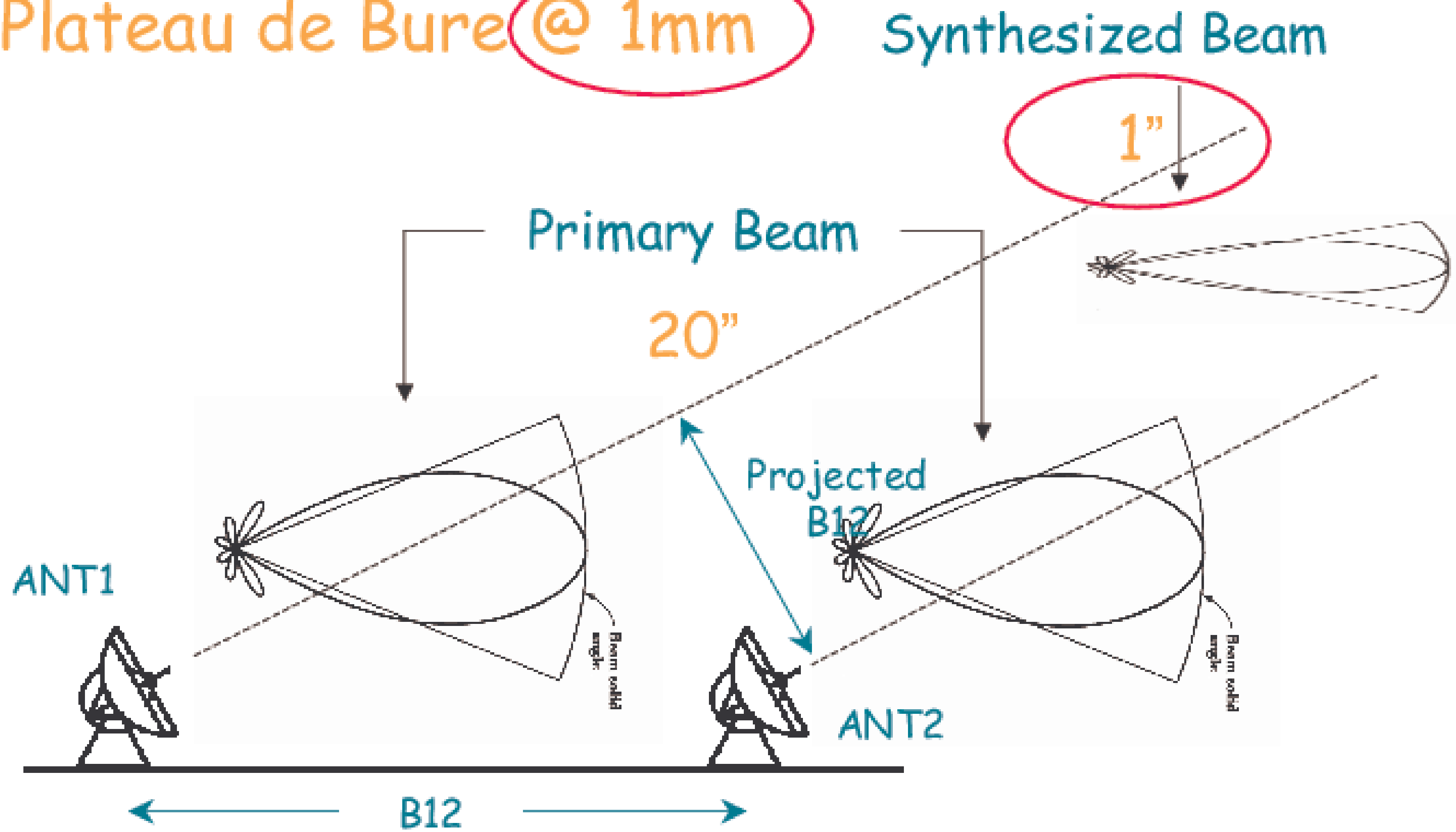
Projected Baseline Bij : distance between two antennas as seen from the sky

Array Configuration : layout of the antenna stations



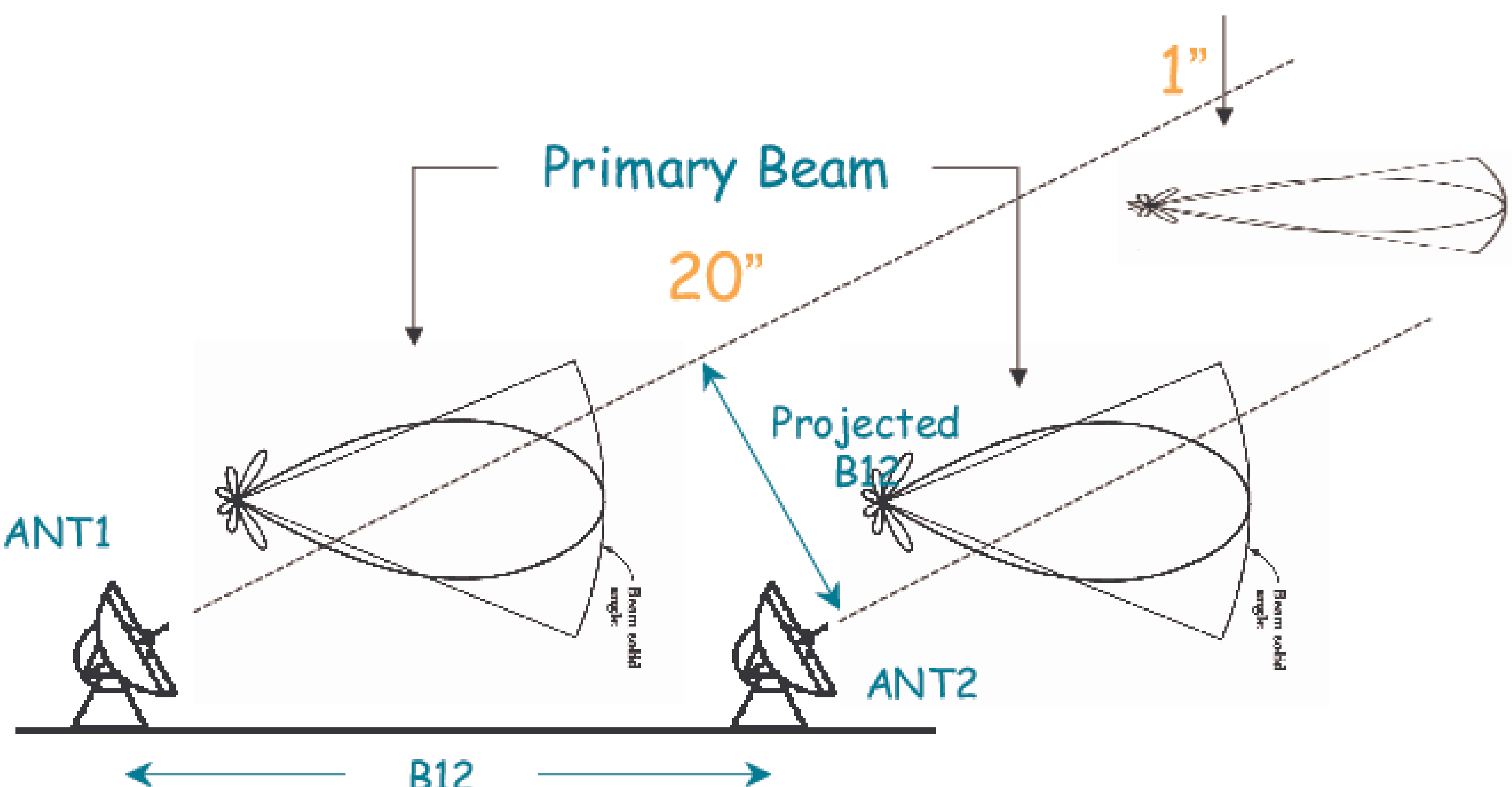

uv-Plane
Synthesized Beam
Primary Beam
Projected
B12
ANT1
ANT2
B12

Plateau de Bure @ 1mm



C configuration = 200m

Plateau de Bure @ 1mm



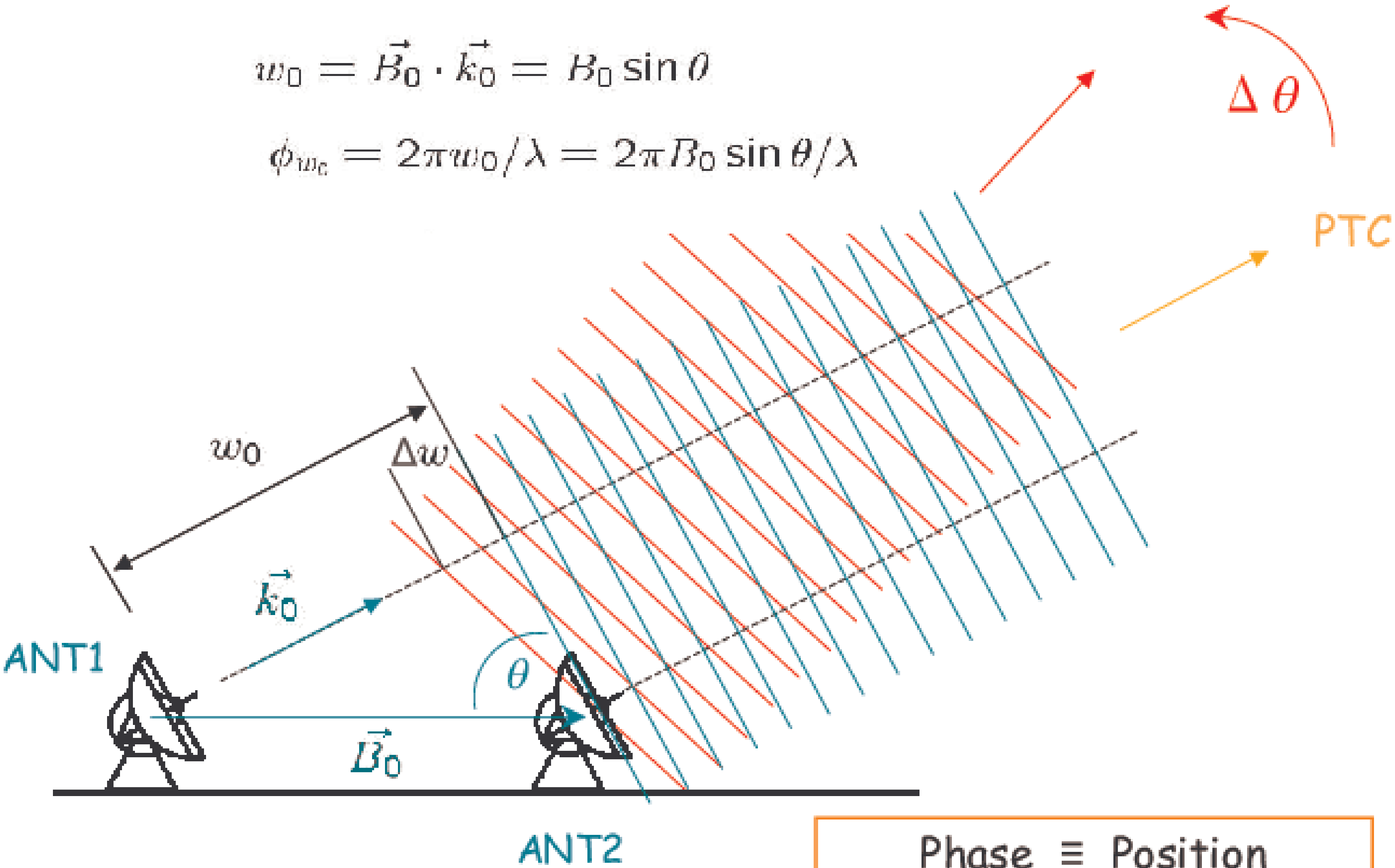
Minimum projected baseline = 15m

SHORT SPACINGS ⇨ 30m Telescope

The phase equation

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

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

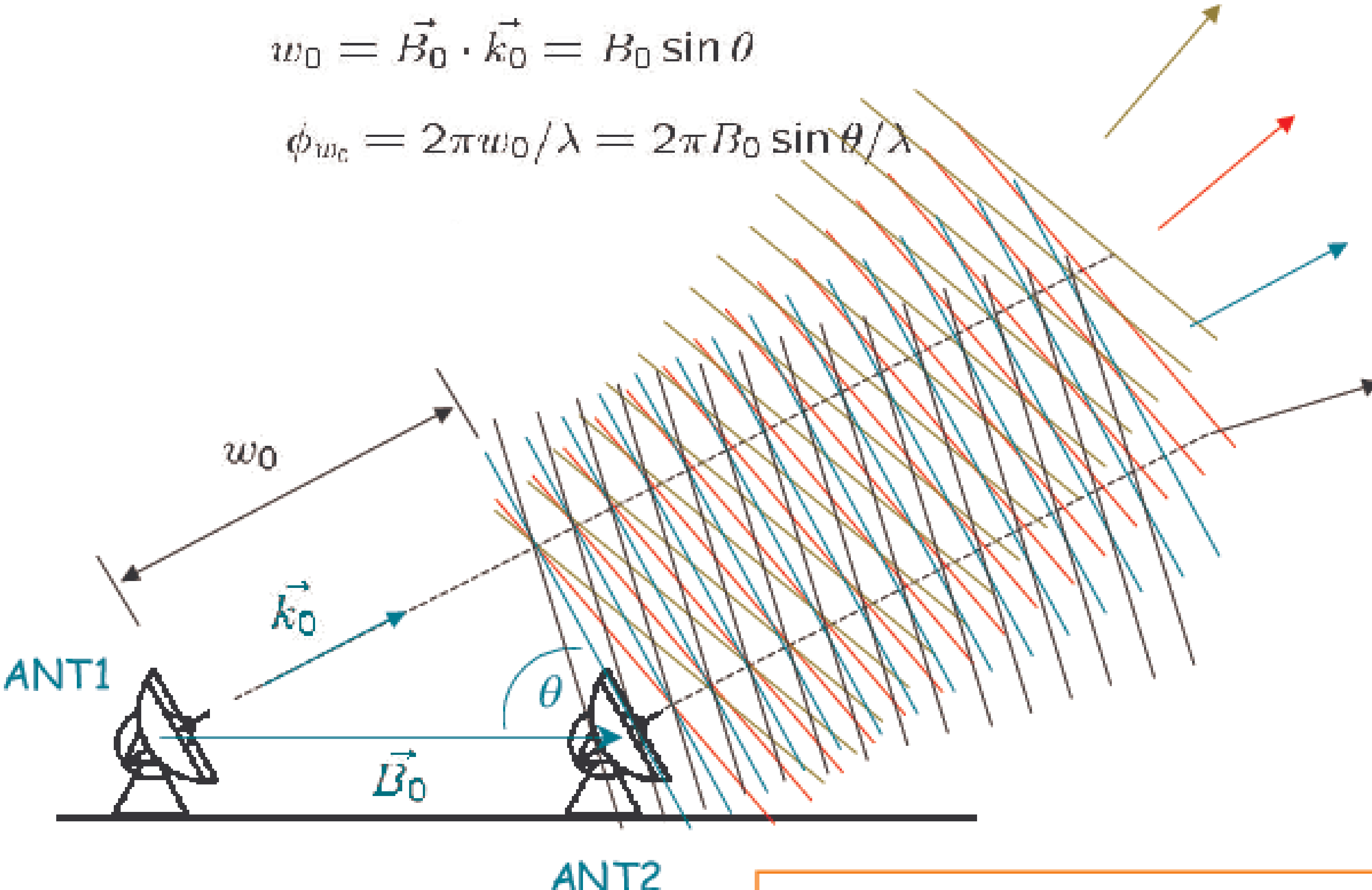


Phase ≡ Position

The phase equation

$$w_0 = \vec{B}_0 \cdot \vec{k}_0 = B_0 \sin\theta$$

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



Dealing with ambiguities ...

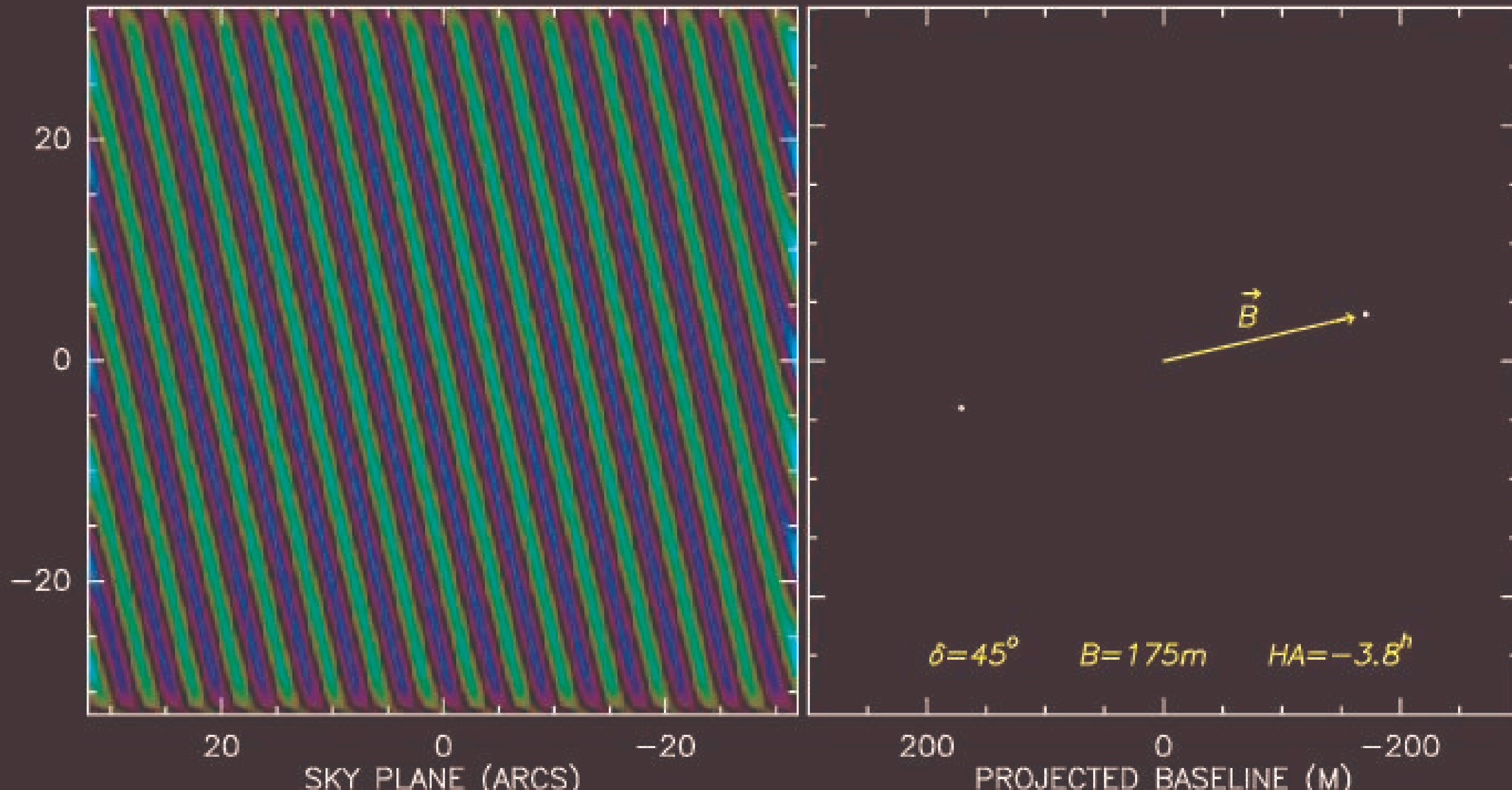
Dealing with $\omega_0 = \vec{k_0} \cdot \vec{B_0}$

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

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

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

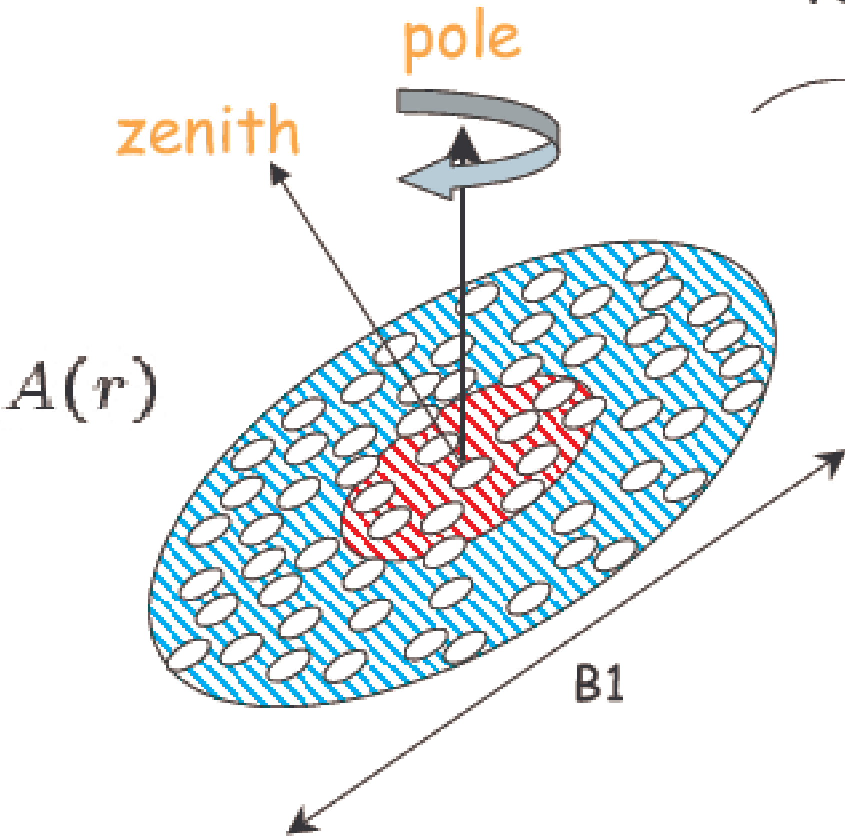
Ex: a source displaced by a single beam $\theta = \lambda/B_0$ shows an offset of 360° in the signal phase.



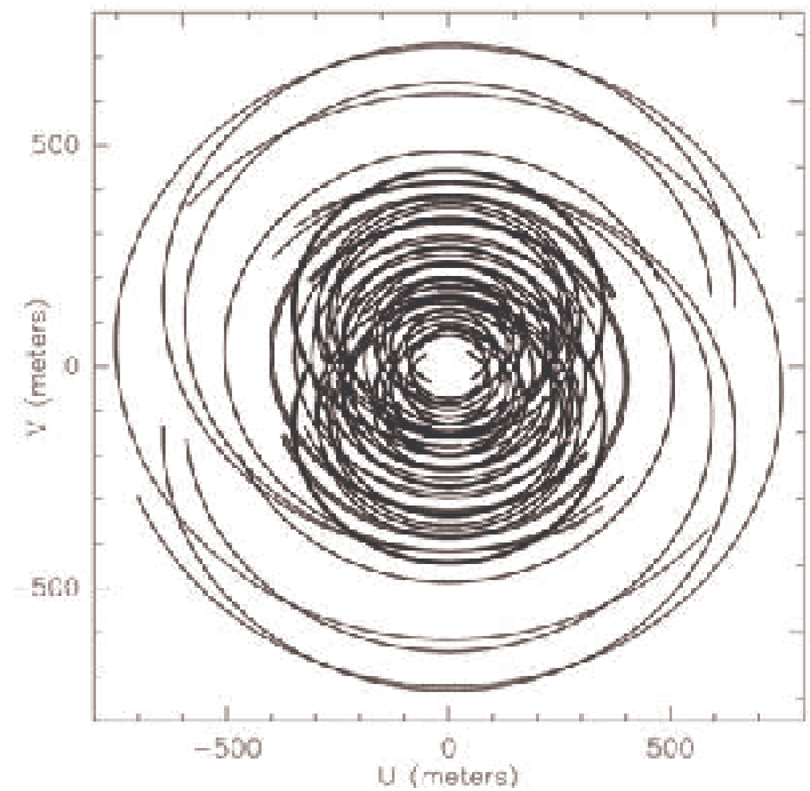
20
0
−20
20
0
−20
SKY PLANE (ARCS)
$\vec{B}$
δ=45°
B=175m
HA=−3.8ʰ
200
0
−200
PROJECTED BASELINE (M)

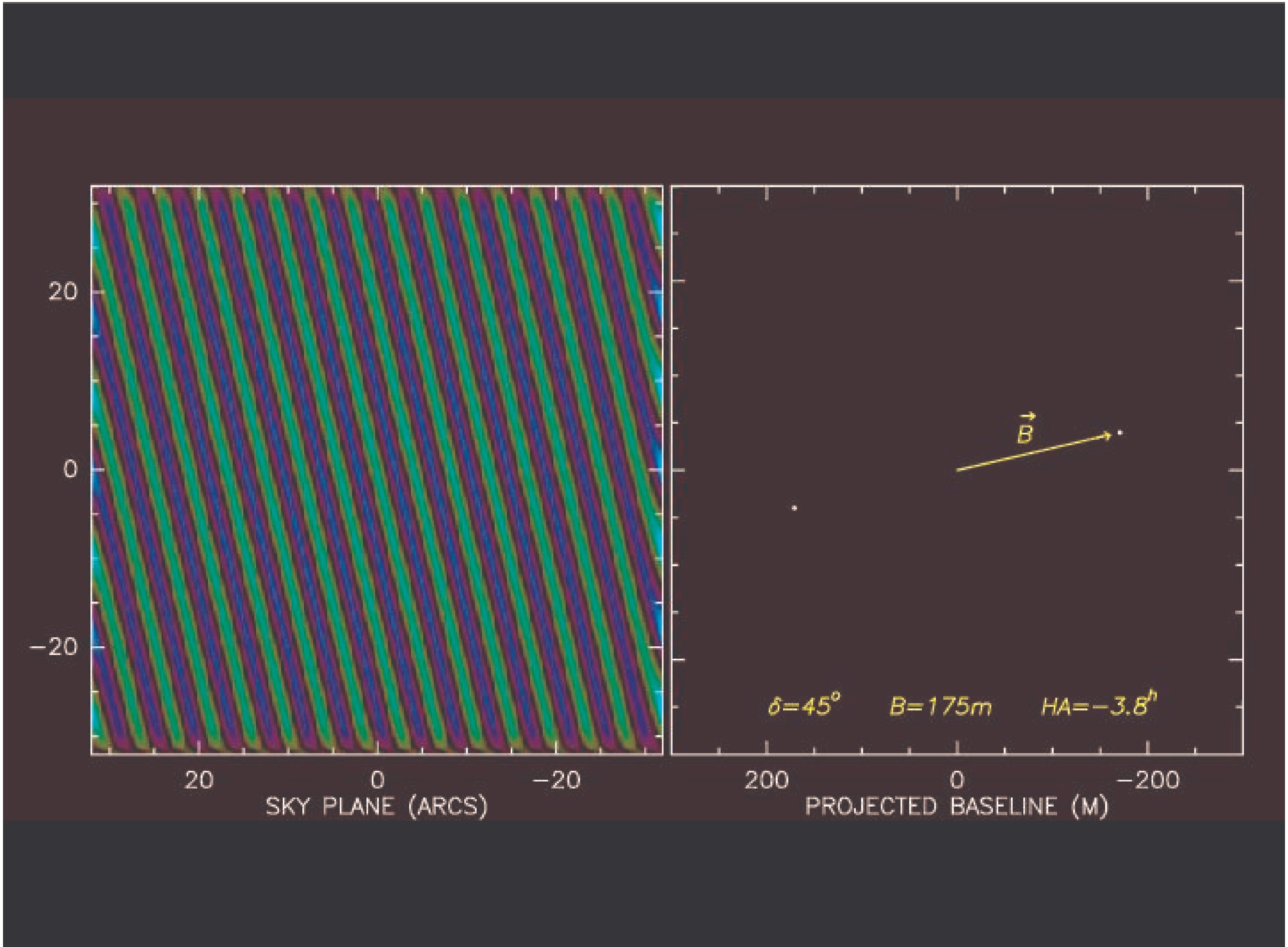
Super-Synthesis or Earth Rotation Synthesis

is the technique by which the elements of an interferometer sweep out the aperture of a large telescope

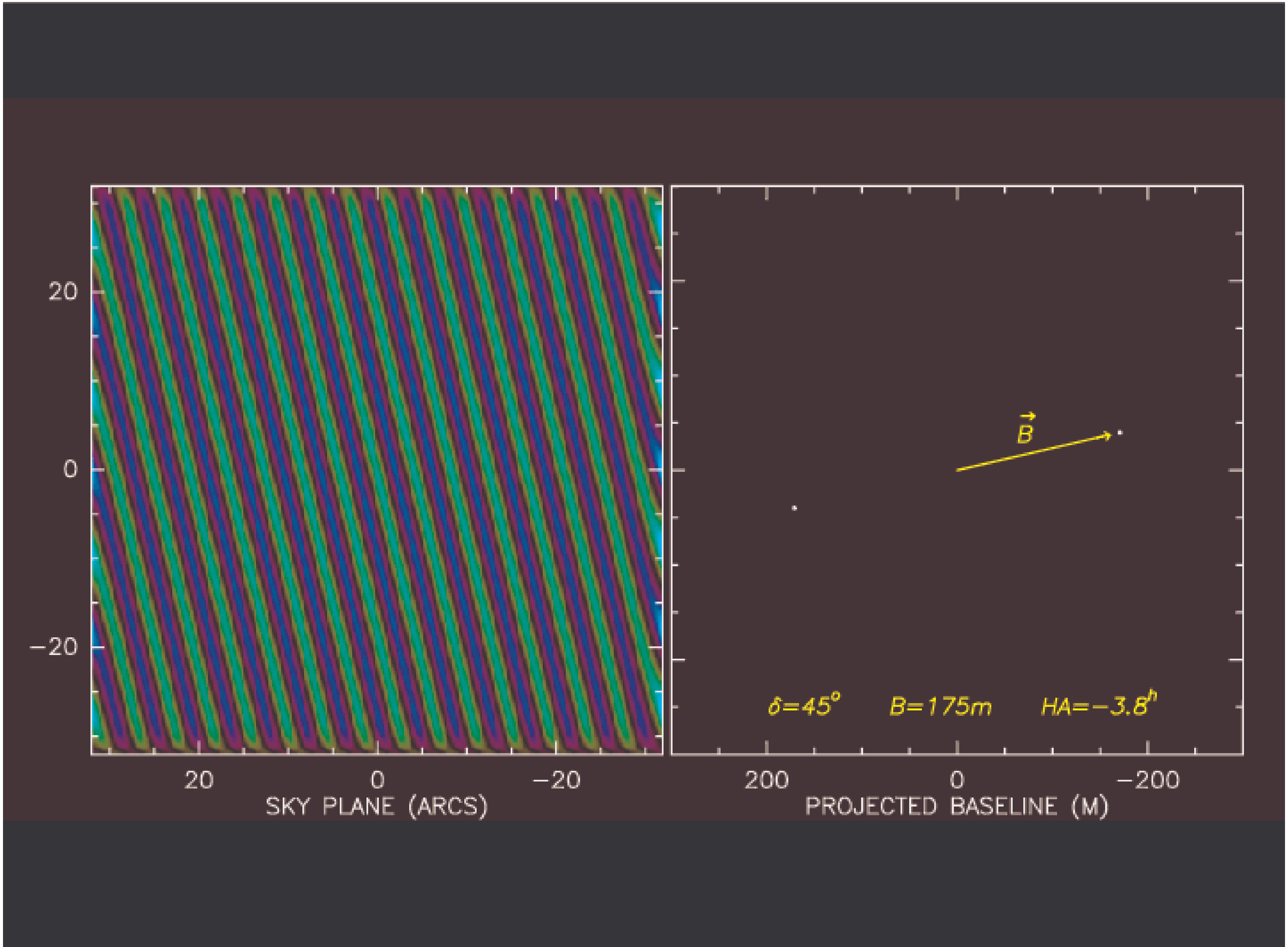


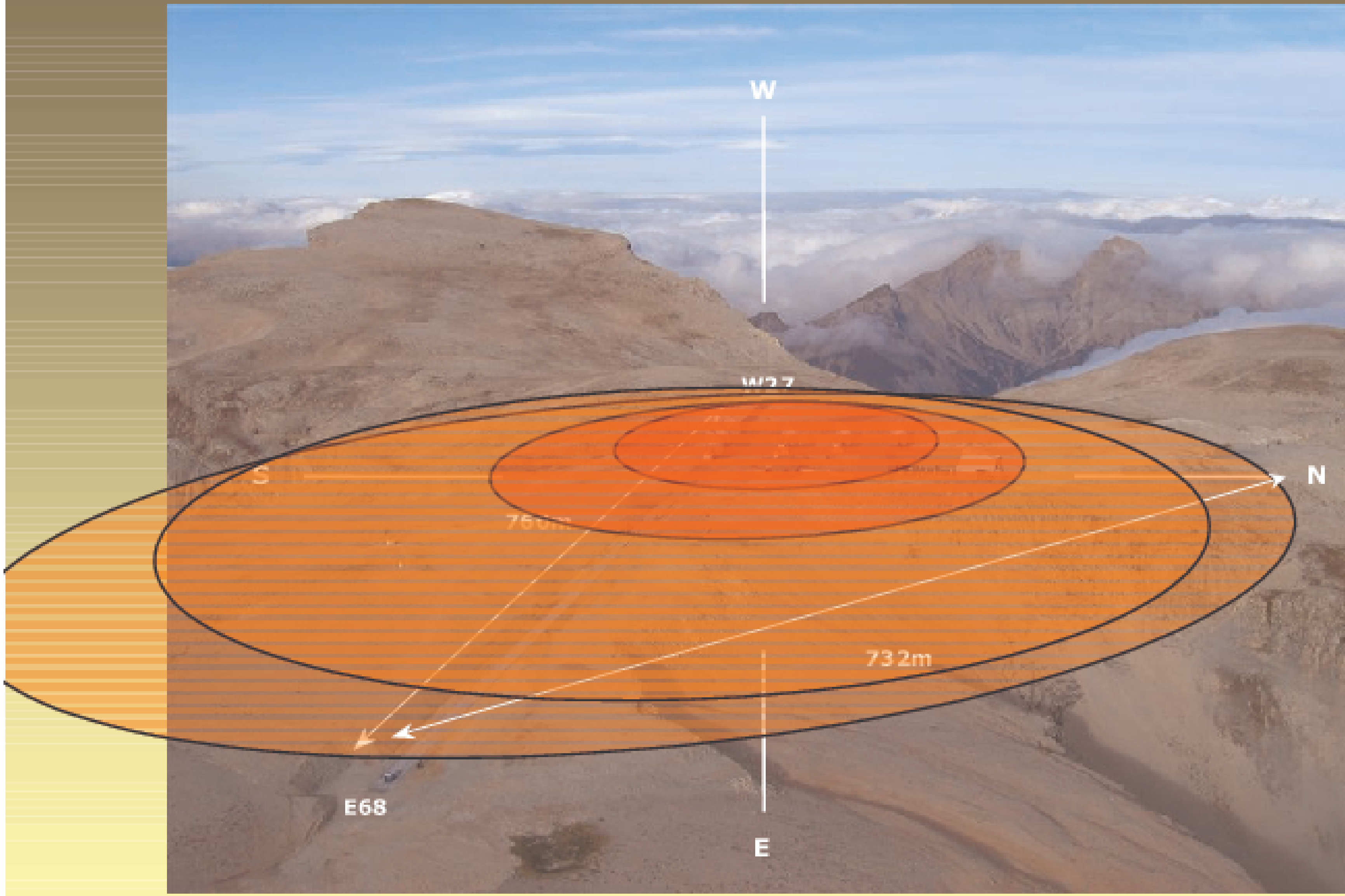
$$\mathrm{OTF} = A(r) \star A(r)$$





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



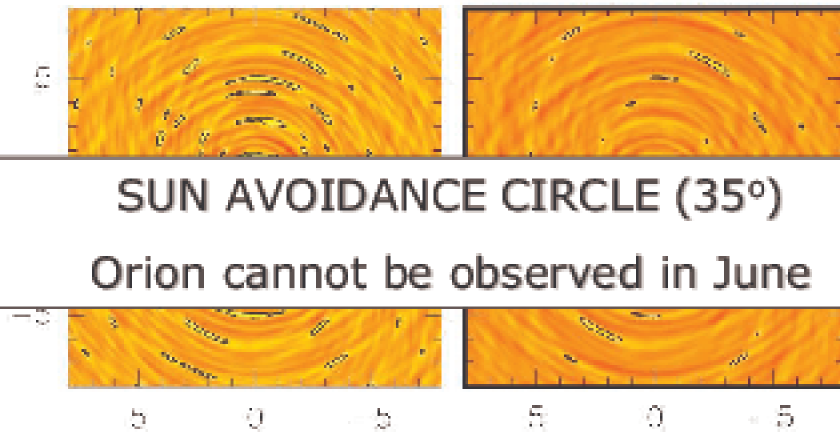
W
S
N
732m
E68
E

Array configurations

Design: 4 configurations, optimization 20° decl.

Karastergiou et al. 2006

A @ 230 ... 230 GHz



SUN AVOIDANCE CIRCLE (35°)

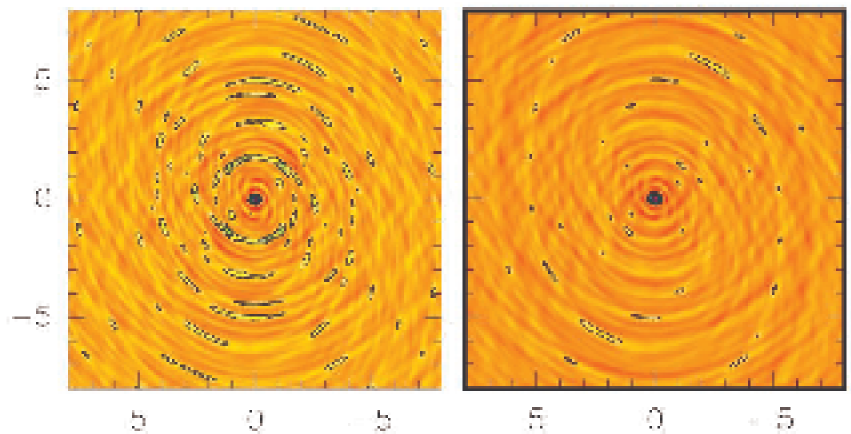
Orion cannot be observed in June

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.

A @ 230 GHz

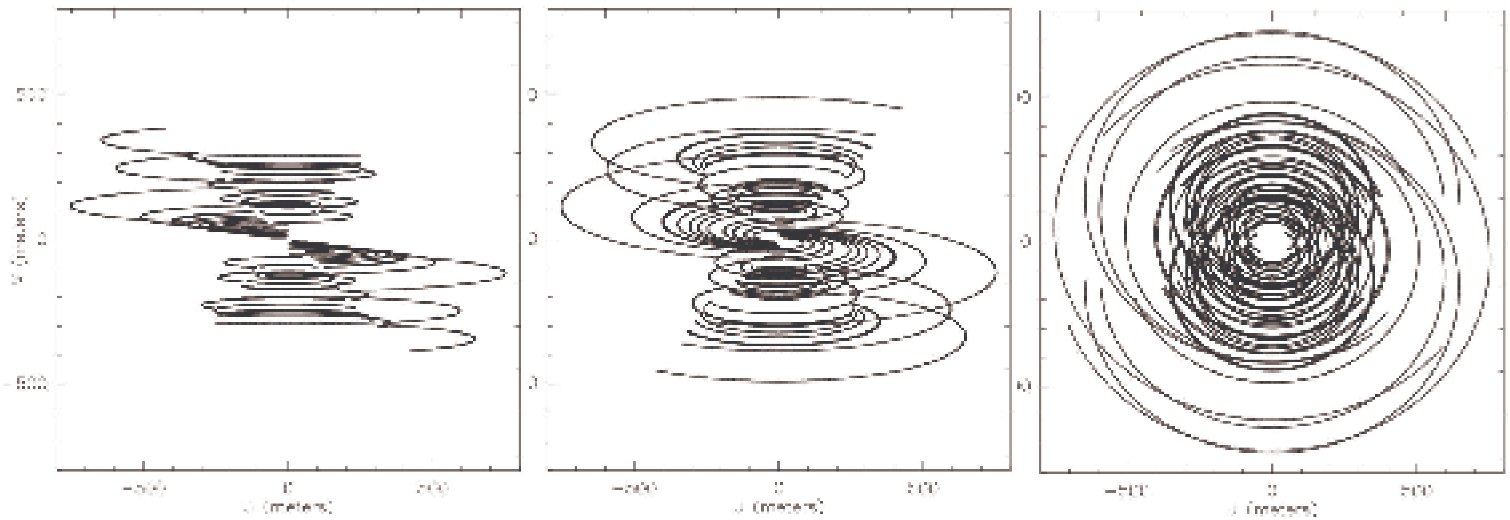


Karastergiou et al. 2006

AB @ 230 GHz

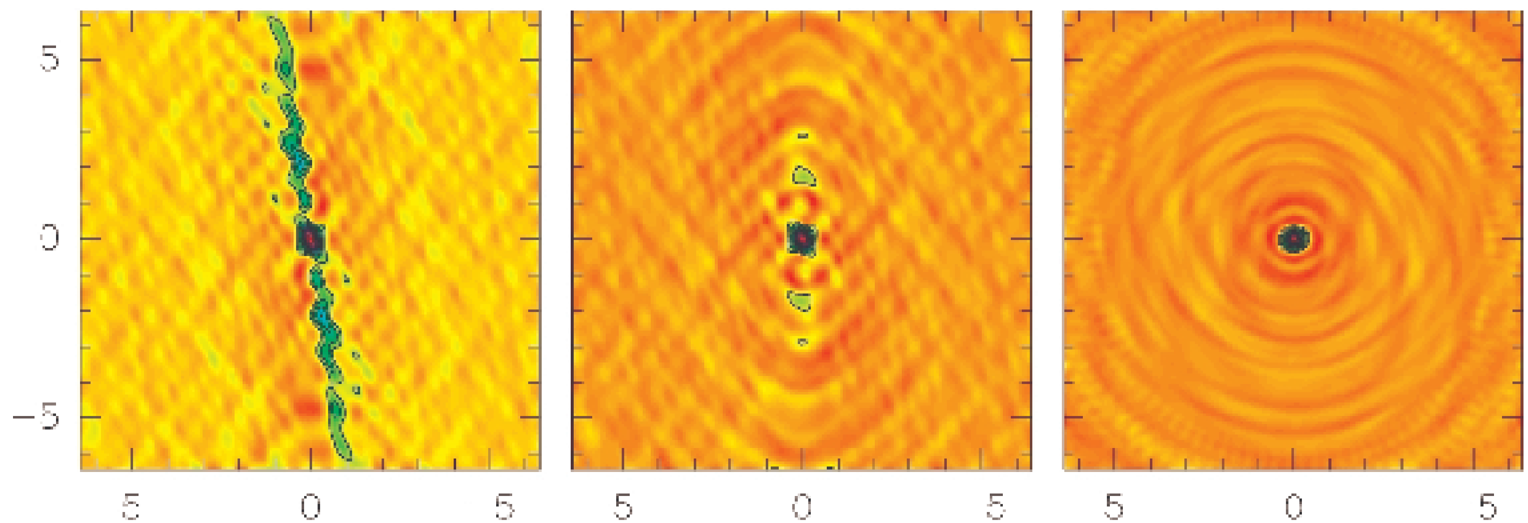
Configurations	D	C	B	A
Months	Apr – Nov	Mar - Apr Nov - Dec	Jan - Mar	Jan - Mar
Resolution @ 230 GHz	3"			0.3"

PdBI's AB configurations @ 230 GHz
Three Examples



	Orion @ -5°	W51N @ 14°	S140 @ 63°
Δt	8 hrs	9 hrs	10 hrs

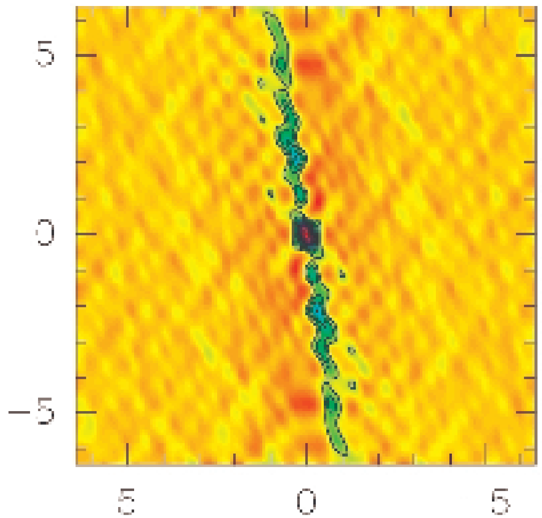
PdBI's AB configurations @ 230 GHz
Three Examples

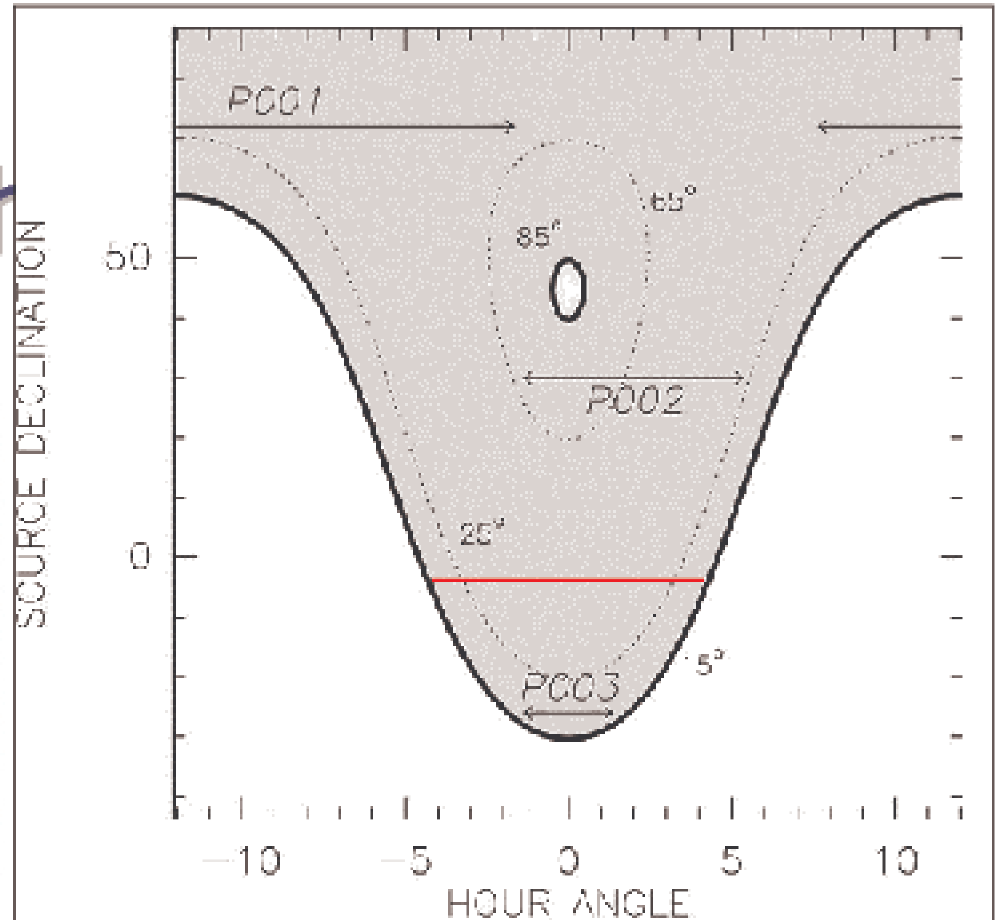


	Orion @ -5°	W51N @ 14°	S140 @ 63°
Δt	8 hrs	9 hrs	10 hrs
D	400 pc	8300 pc	910 pc
"	0.70" x 0.41"	0.51" x 0.45"	0.47" x 0.40"

iram
Institut de Radioastronomie Millimétrique

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%

PdBI in a Nutshell

Frequency	80 to 371 GHz
Bandwidth	3.6 GHz both polarizations, backshort tuning
Spectral resolution	39 KHz (50 m/s @ 230 GHz) – 3600 MHz
Angular resolution	0.3" – 3" @ 230 GHz
Continuum flux sensitivity	0.6 mJy/beam in 1 min @ 100 GHz
Dynamic range	1:100 (spectral), 1:50 (imaging) @ 100 GHz
Short spacings	30m telescope