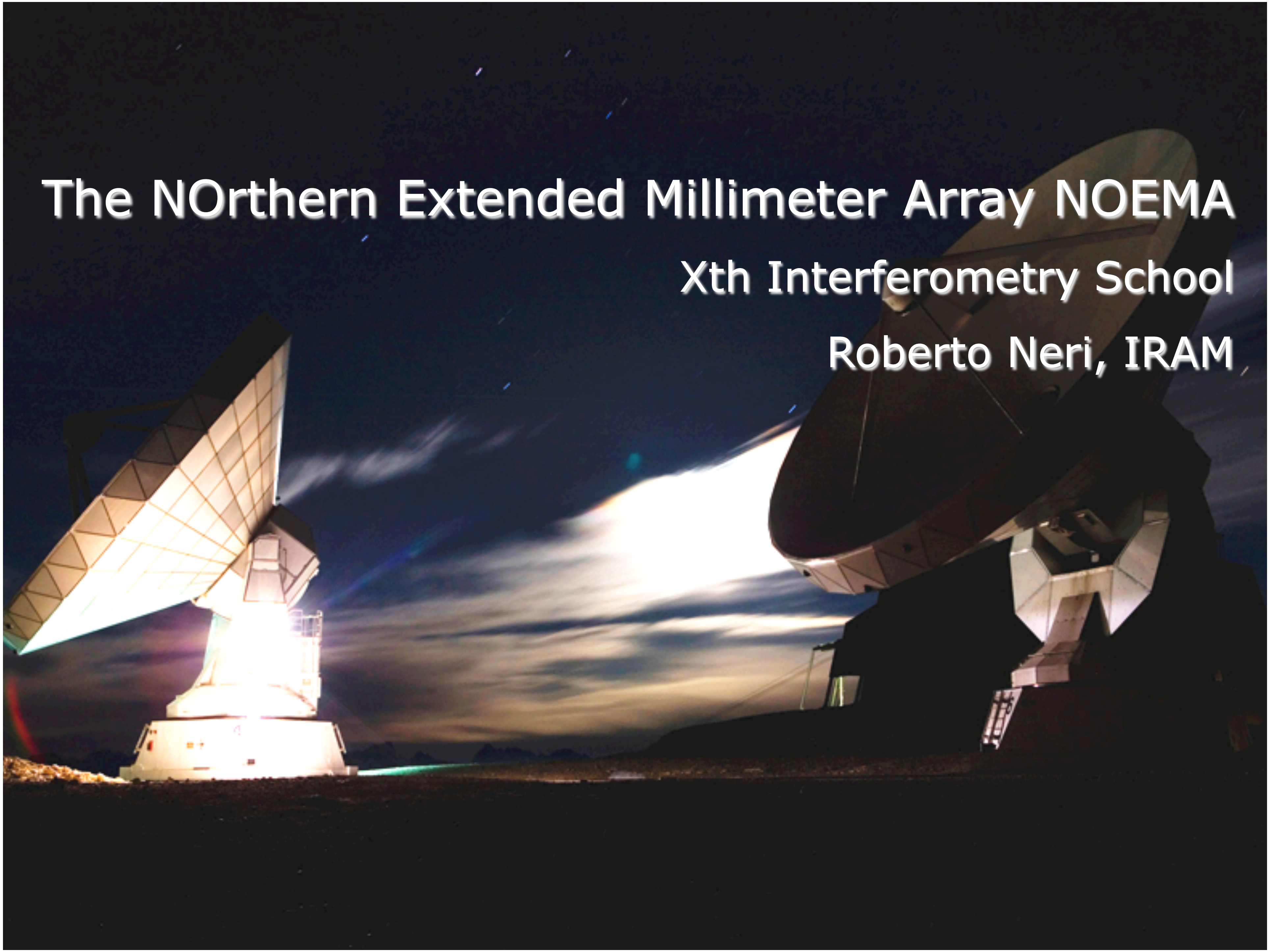

The NOrthern Extended Millimeter Array NOEMA
Xth Interferometry School
Roberto Neri, IRAM

The NOrthern Extended Millimeter Array NOEMA

Xth Interferometry School

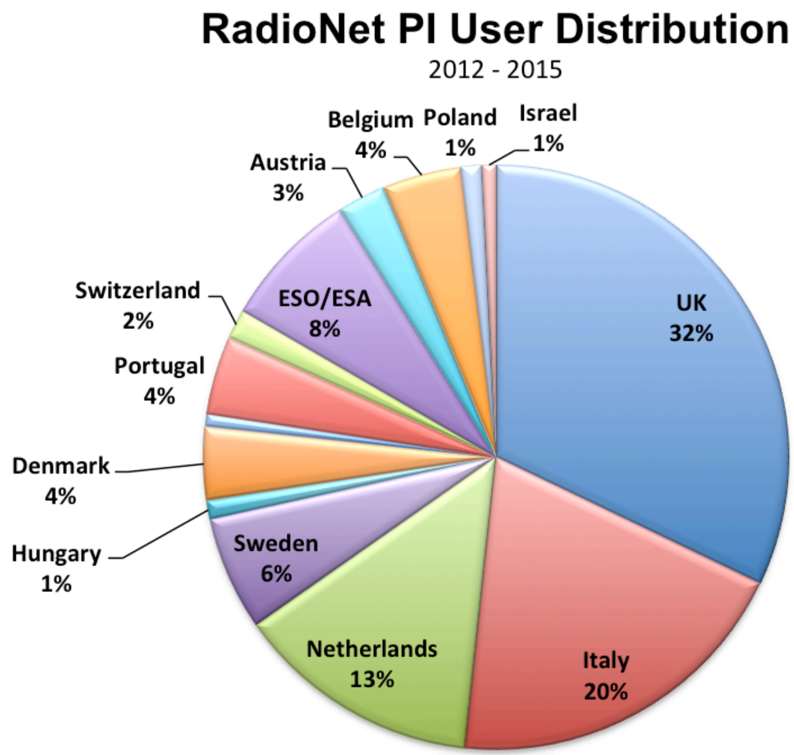
Roberto Neri, IRAM

1. a general overview
2. instrumentation
3. sensitivity considerations
4. phase considerations

A view on the NOEMA Observatory

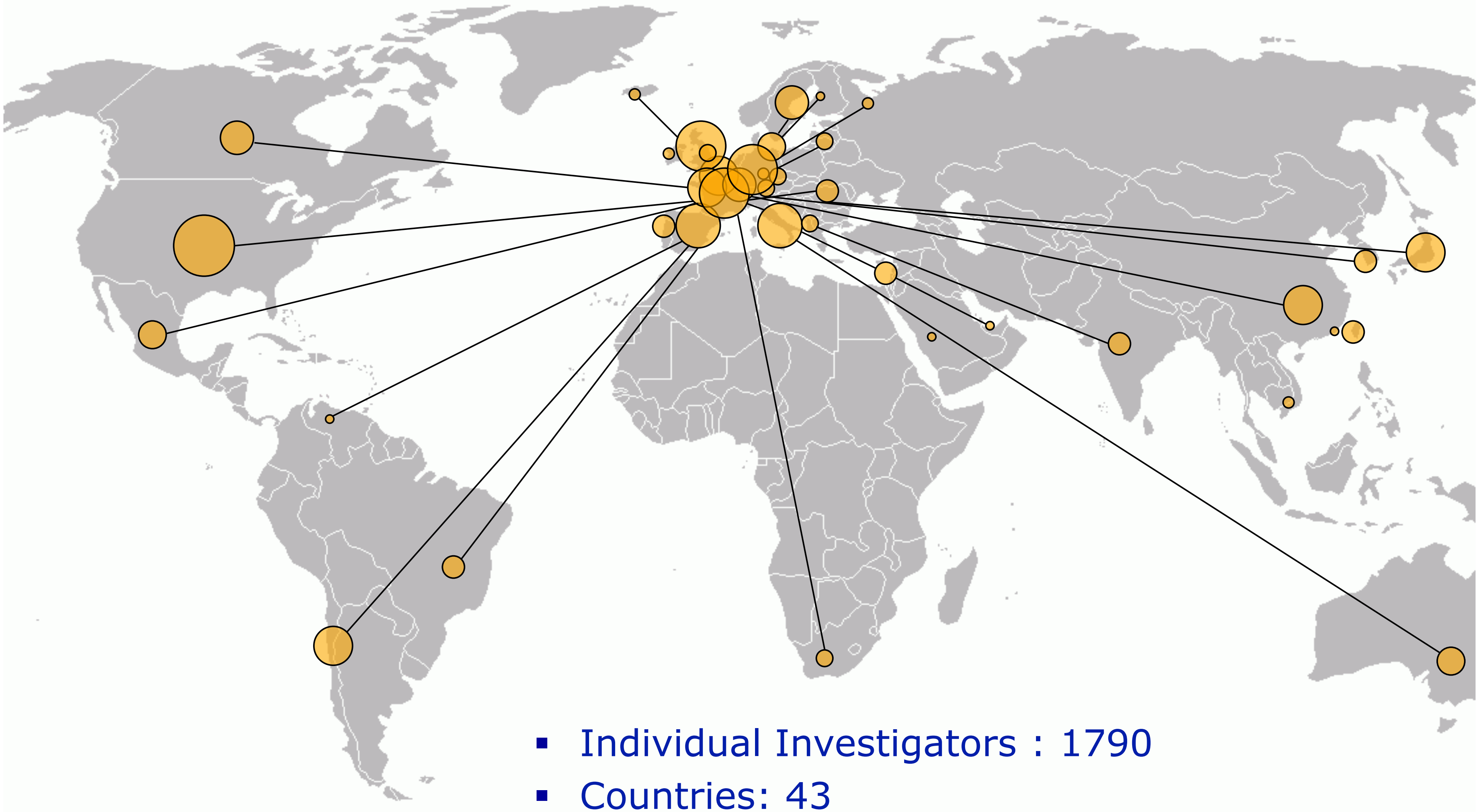
- IRAM = two observatories : NOEMA + IRAM 30m-telescope
- three partners: CNRS, MPG, IGN, >3000 astronomers
- open time (up to 15%), RadioNet

A view on the NOEMA Observatory



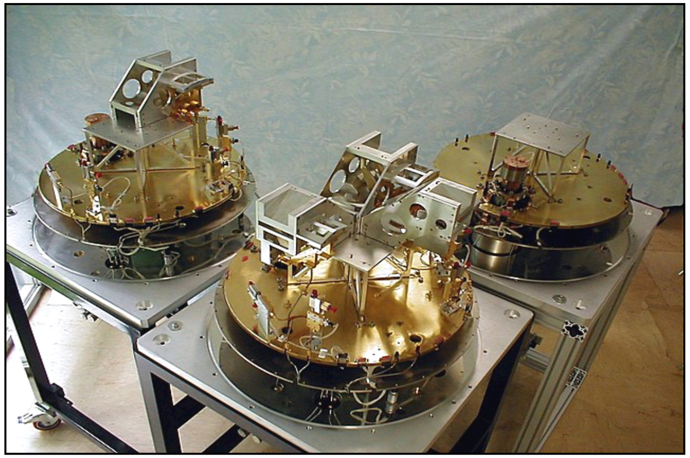
- IRAM = … scope
- three pa …
- open time (up to 15%), RadioNet

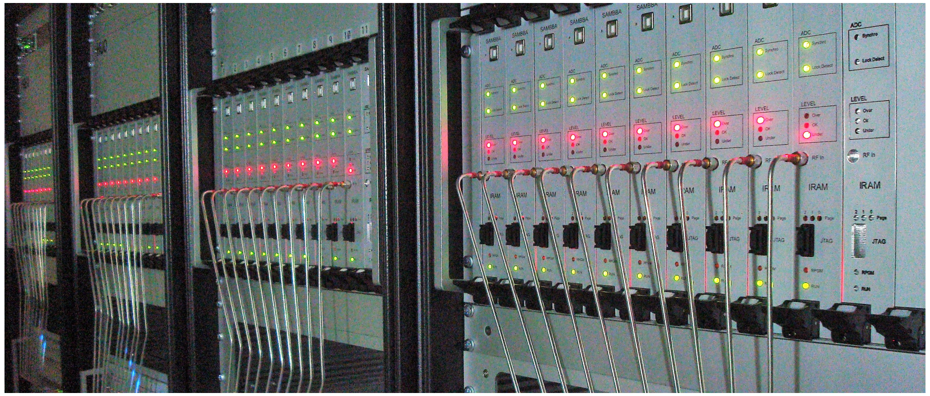
INVESTIGATOR DISTRIBUTION MAP
2010 – 2016



- Individual Investigators : 1790
- Countries: 43

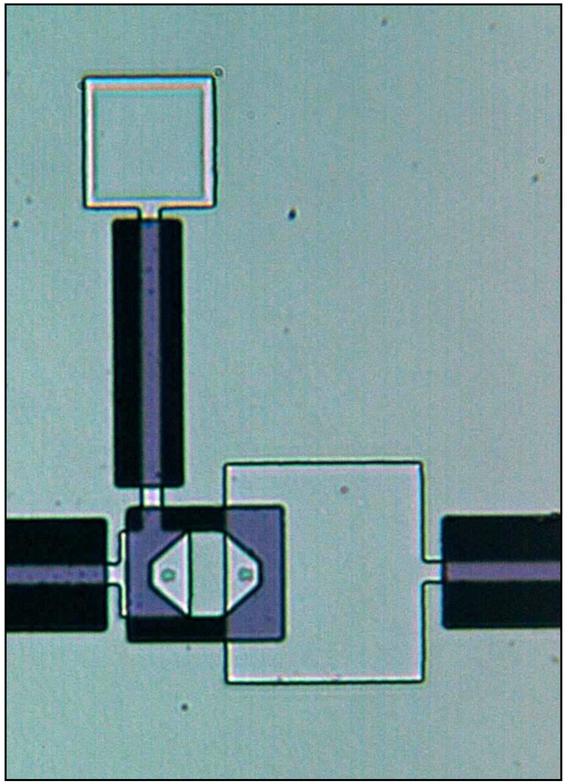
IRAM's expertise: pictures worth a thousand words





- Telescope design (~30 um), construction and operation
- Receiver design and development e.g. ALMA Band7, MPS, AETHRA
- HS-digital backends + LO systems e.g. PolyFiX (2x 2x 8 GHz)

IRAM's expertise: pictures worth a thousand words



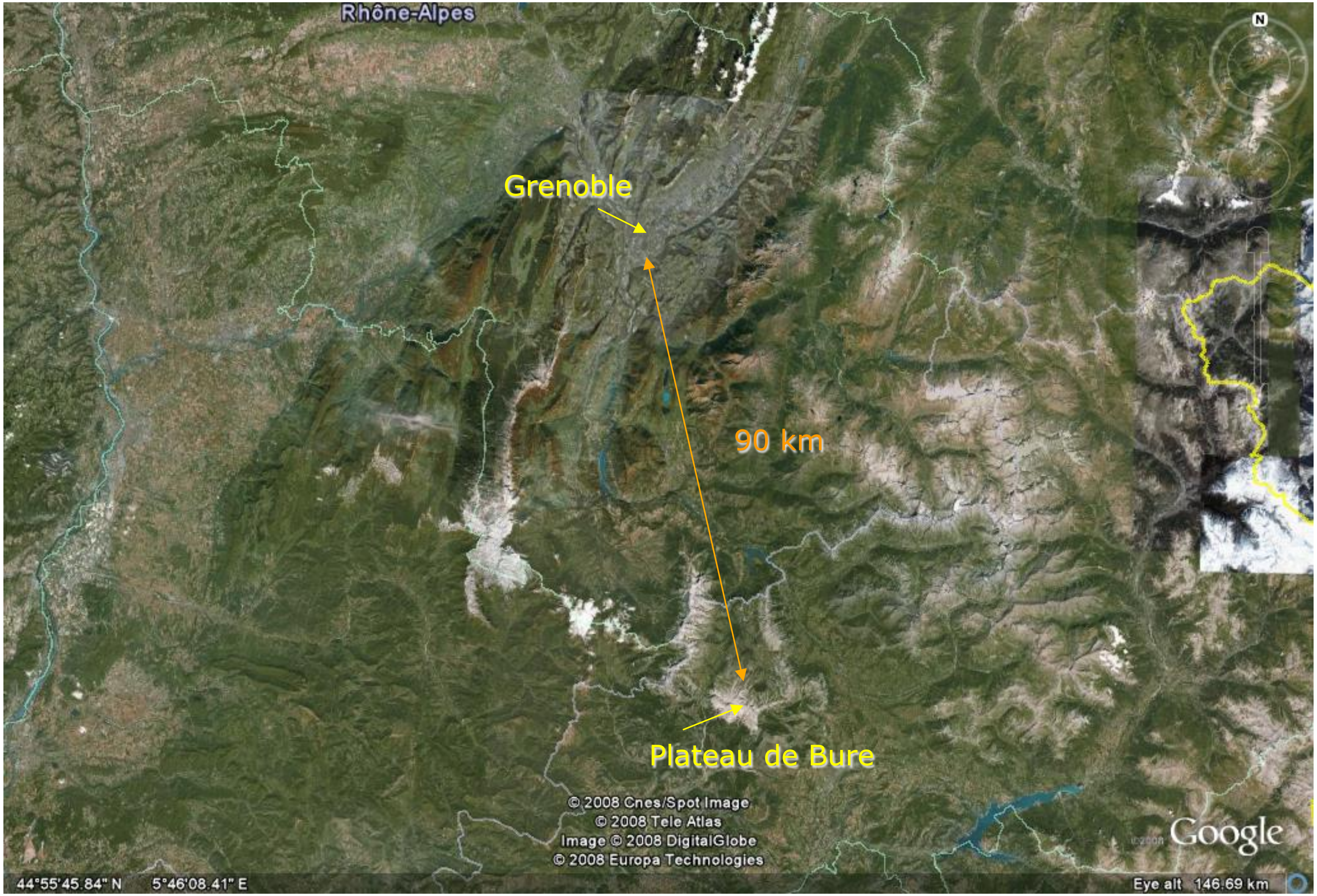
- high-precision micro-machining workshop
- Class 100 clean room for thin film technology
- complete mm/THz-wave technology laboratory

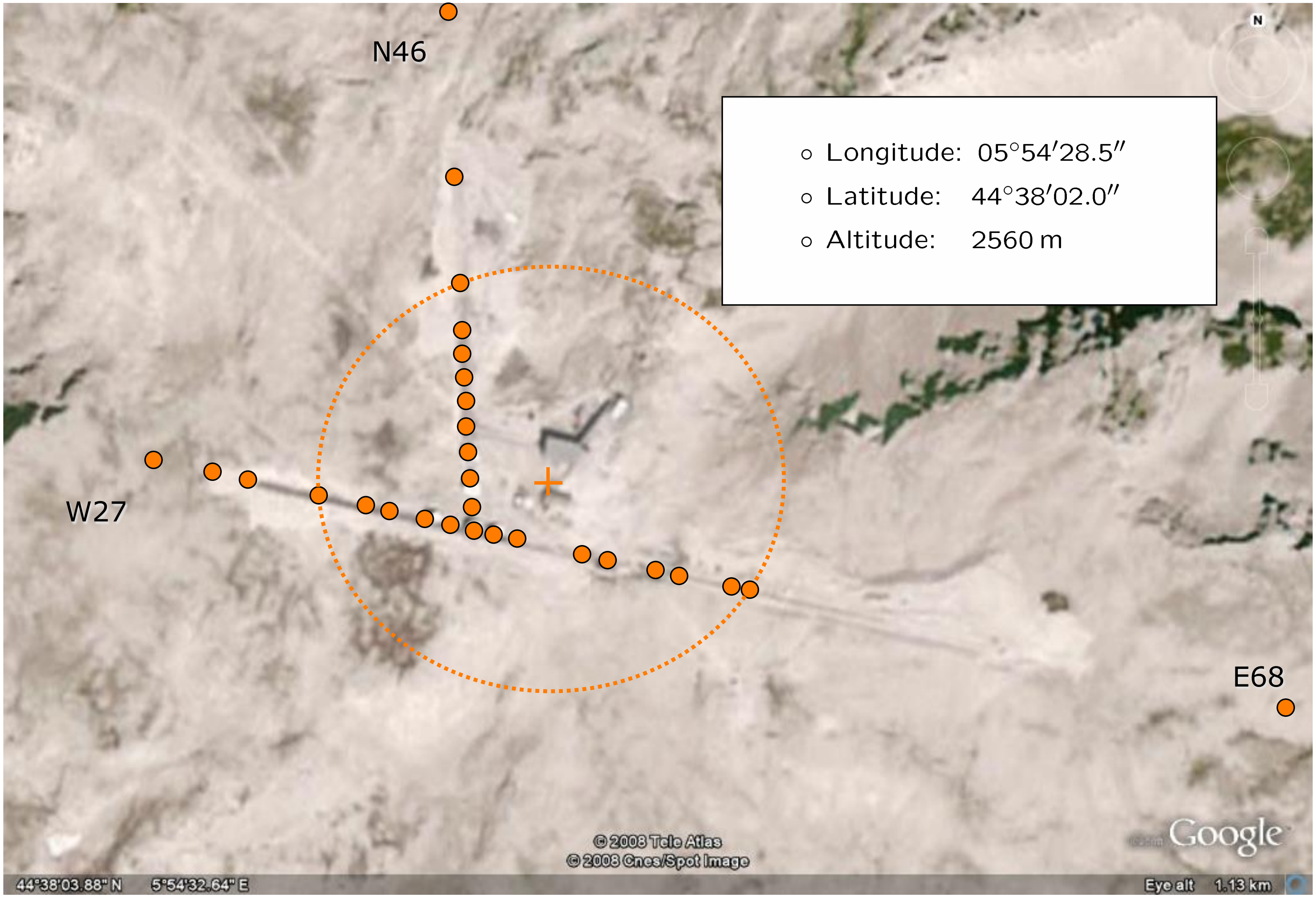
progress timeline

Semester	Project	Done
2010	WIDEX	✔
2011	band 4	✔
2012	double-array mode	✔
2013	LO reference system	✔
2015	N7 + 2SB receivers #1, #2	✔
2016	N8 + 2SB receivers #3, #4, #5, #6	✔
2017	N9 + POLYFIX	✔
2018	N10	✔
2019	VLBI + spectral survey @ 250 KHz	
2020/2021	N11 + new A configuration (1.7 km)	
2021/2022	N12 + dual band	

progress timeline

Semester		Done
2010		✔
2011		✔
2012		✔
2013		✔
2015	2	✔
2016	5, #6	✔
2017		✔
2018		✔
2019	KHz	
2020/2021	n	
2021/2022		


Rhône-Alpes
Grenoble
90 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

NOEMA site

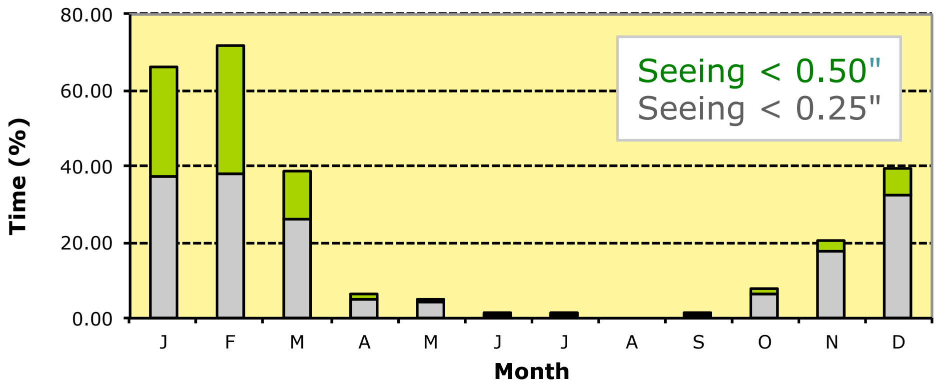
- Latitude : 05°54' 28.5"
- Longitude : 44°38' 02.0"
- Altitude : 2560 m
- RFI protection : terrain shielding + NRQZ (30 km)

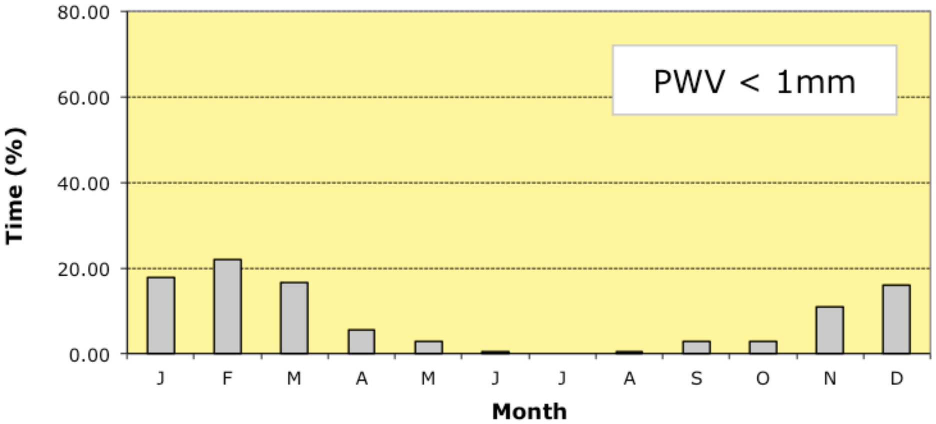
- Water vapor : 40% (<3mm); 25% (<1mm) in winter
  down to 0.3mm in best winter conditions
  submm conditions ~5 % of the time

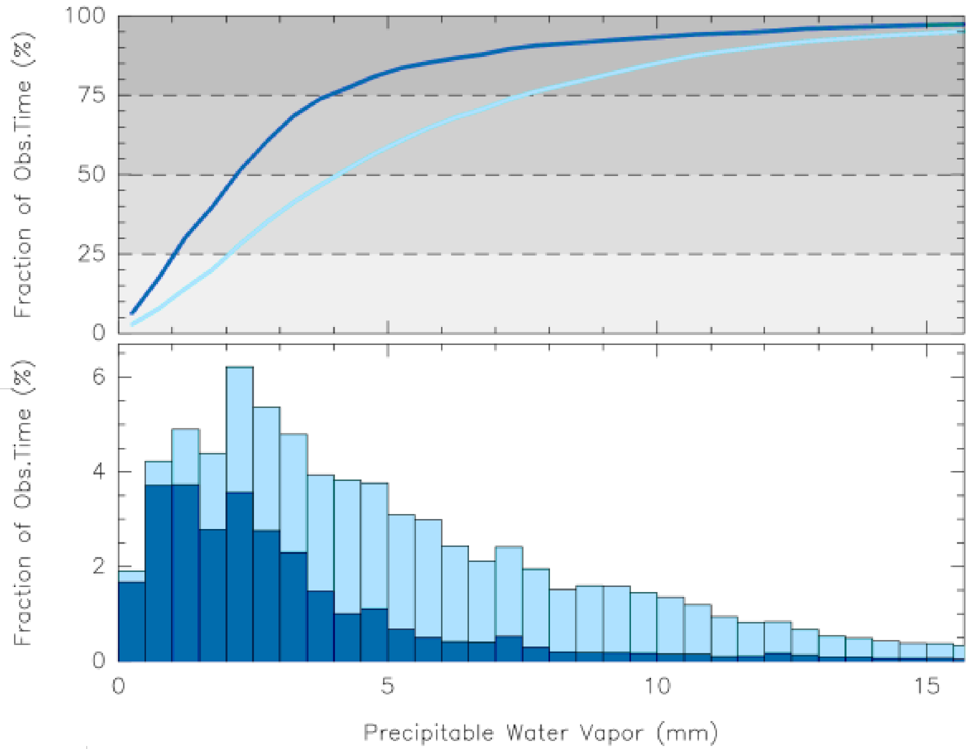
NOEMA site

➢ 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
➢ Weather downtime :	25 - 35%

some weather statistics







⟹ 2017: 80% of the observing time invested @ 3mm and 2mm

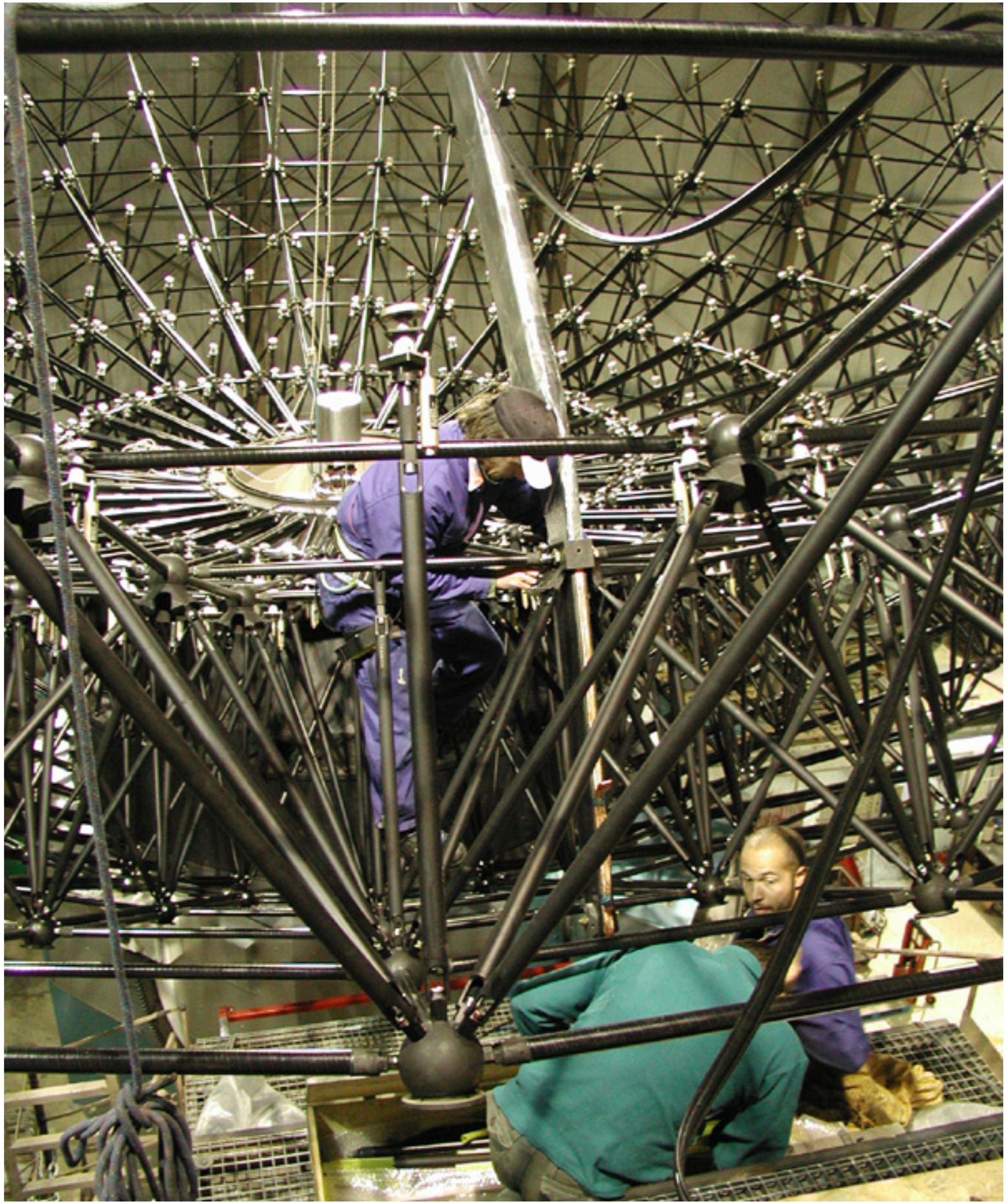
NOEMA observatory

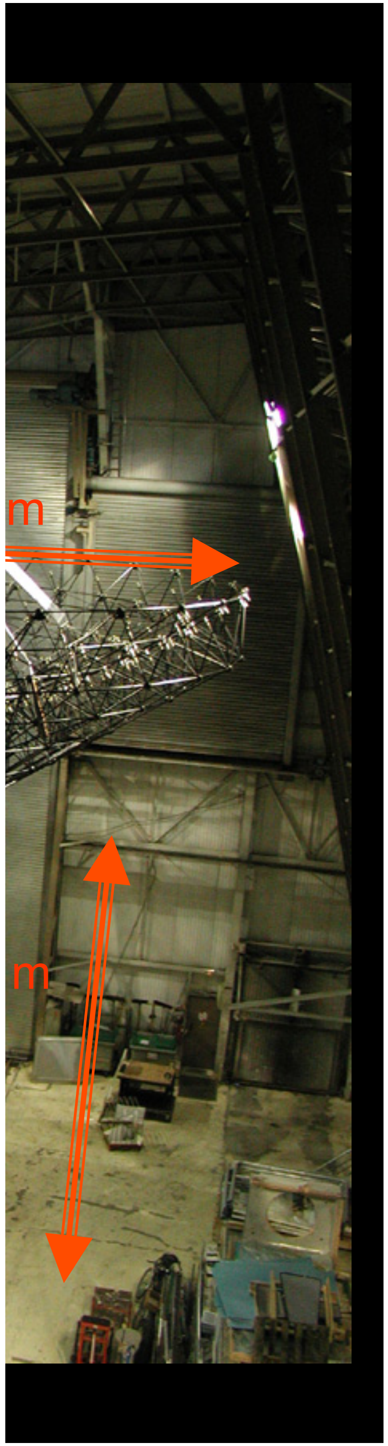
- Operation : 24 hrs, 365 days, service mode
  staff @ Bure + SOG @ Grenoble
- Team @ site : 6 staff members (incl. astronomer)
- Working schedule : 1 team per week, every 3 weeks

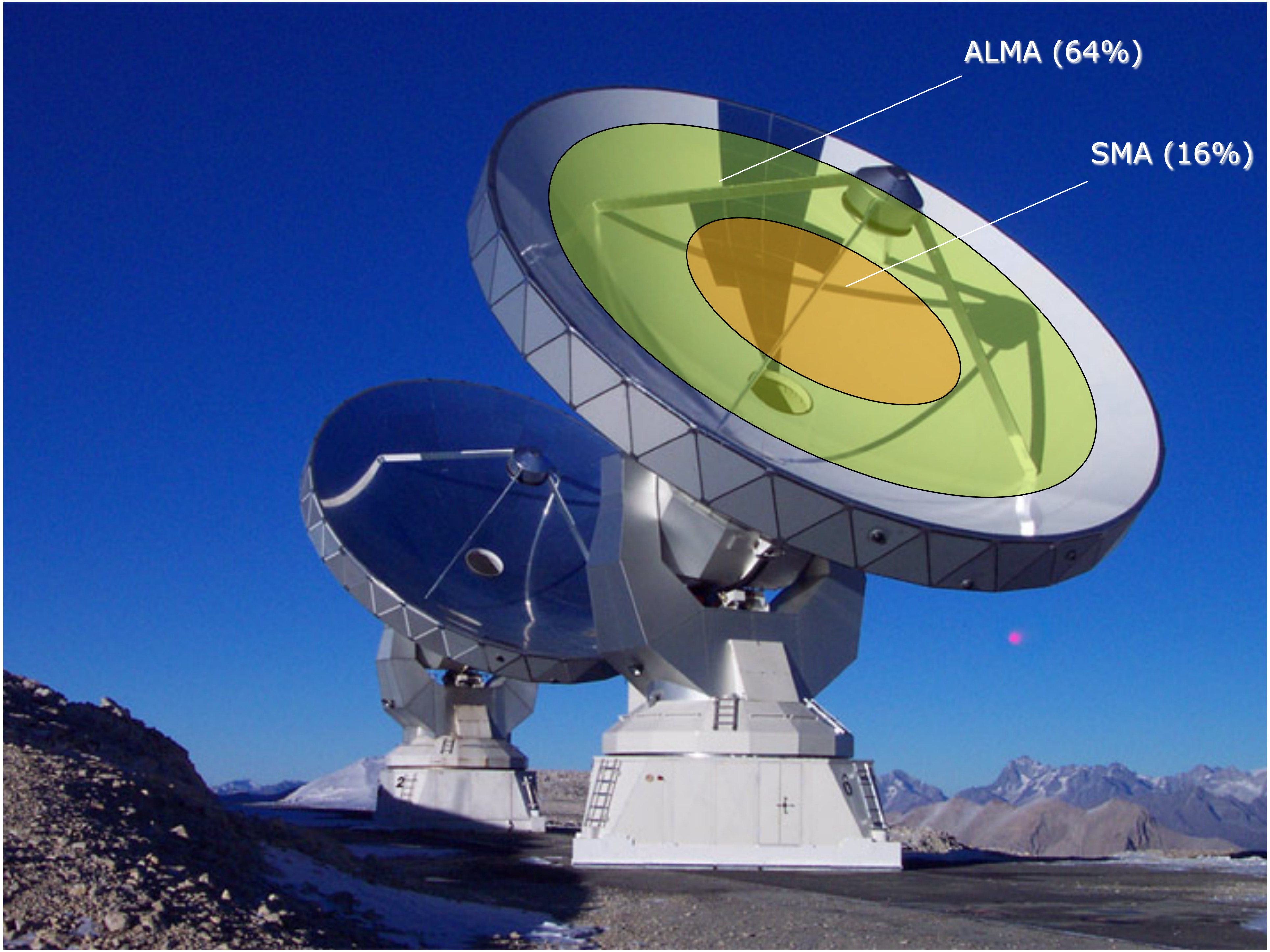
- VLBI @ 3mm> : suspended (2019)

NOEMA antennas

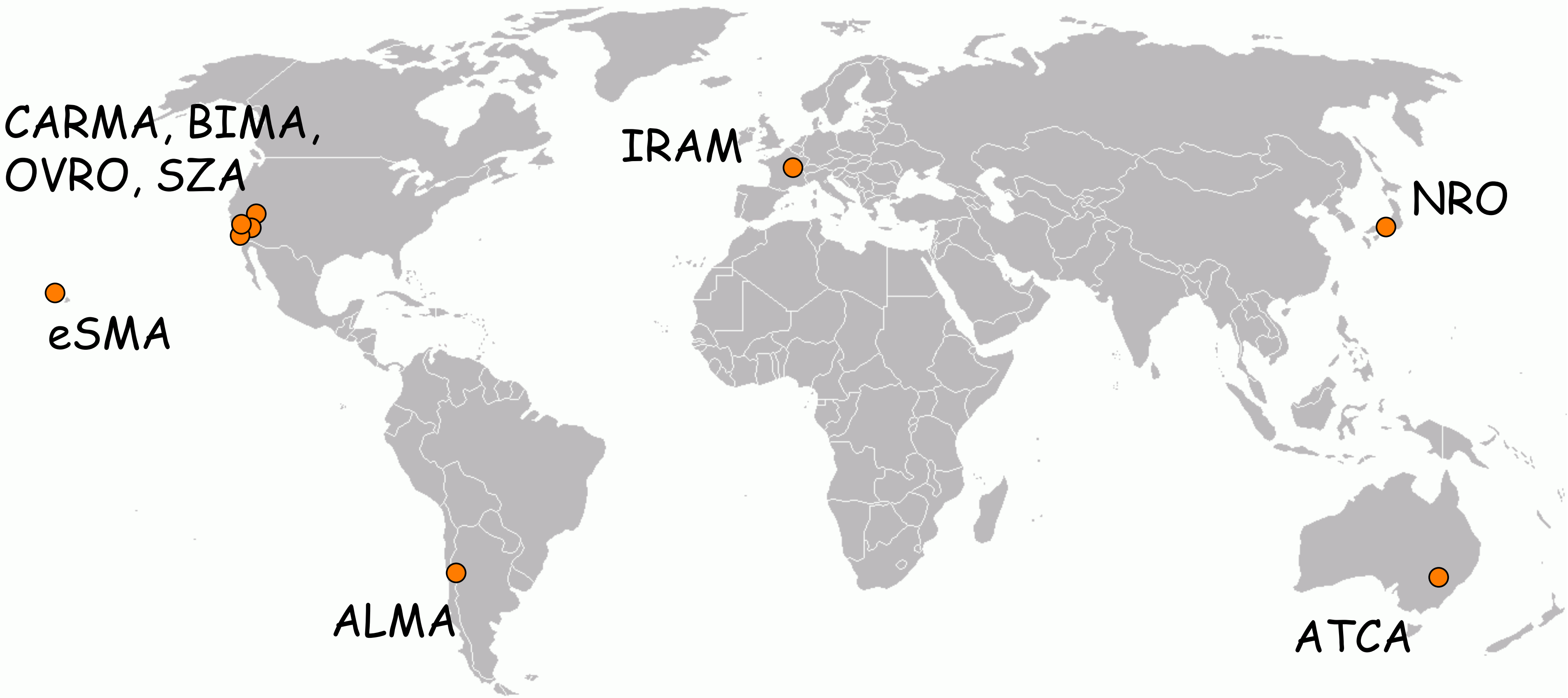
- antennas : 10, Cassegrain type
- collecting area : $177m^2$ x 10 = $1770m^2$
- surface panels : 176, aluminum
- surface accuracy : 25 - 40 µm
- aperture efficiency : 0.65 @ 230
- primary beam : 21" @ 230 GHz
- pointing / tracking RMS : 1.5" / 0.2"
- wind speed (max) : 14 m/s



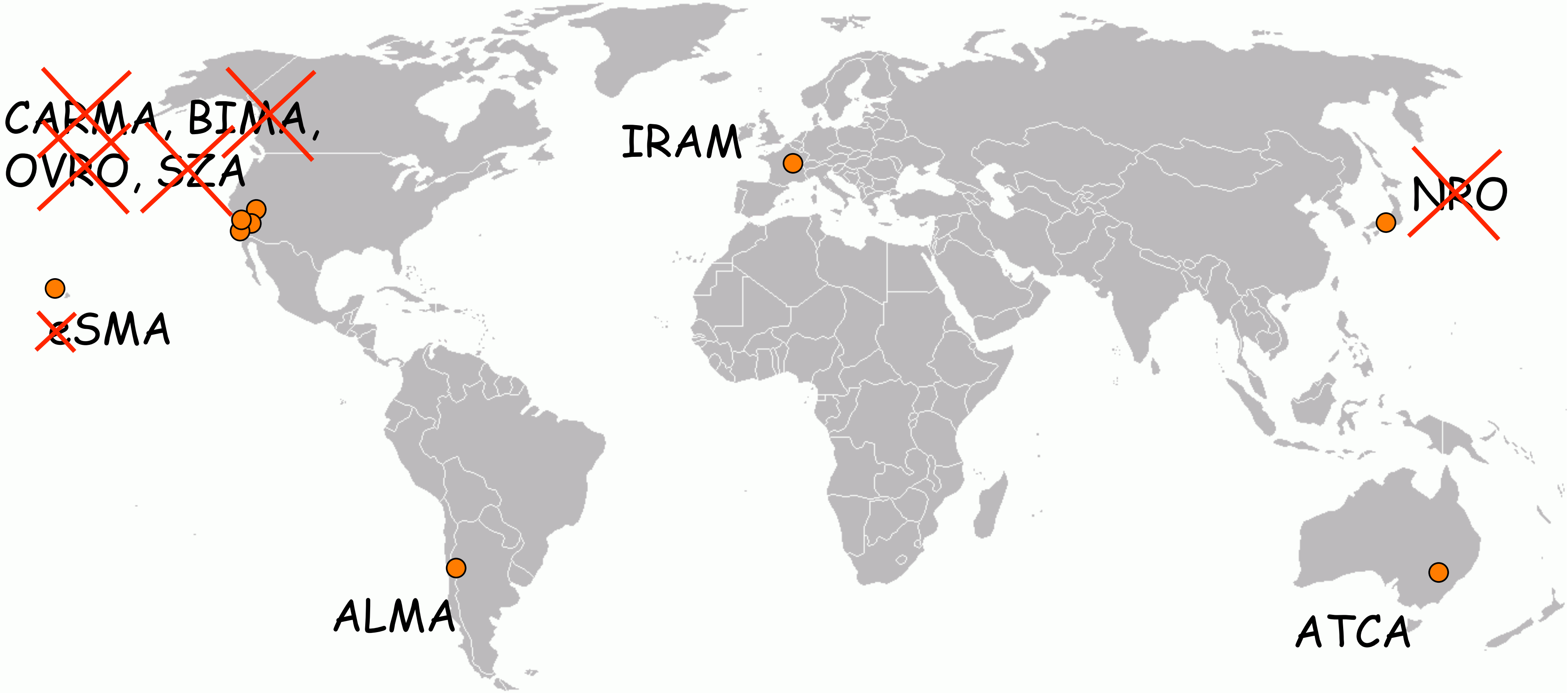

m
m


ALMA (64%)
SMA (16%)

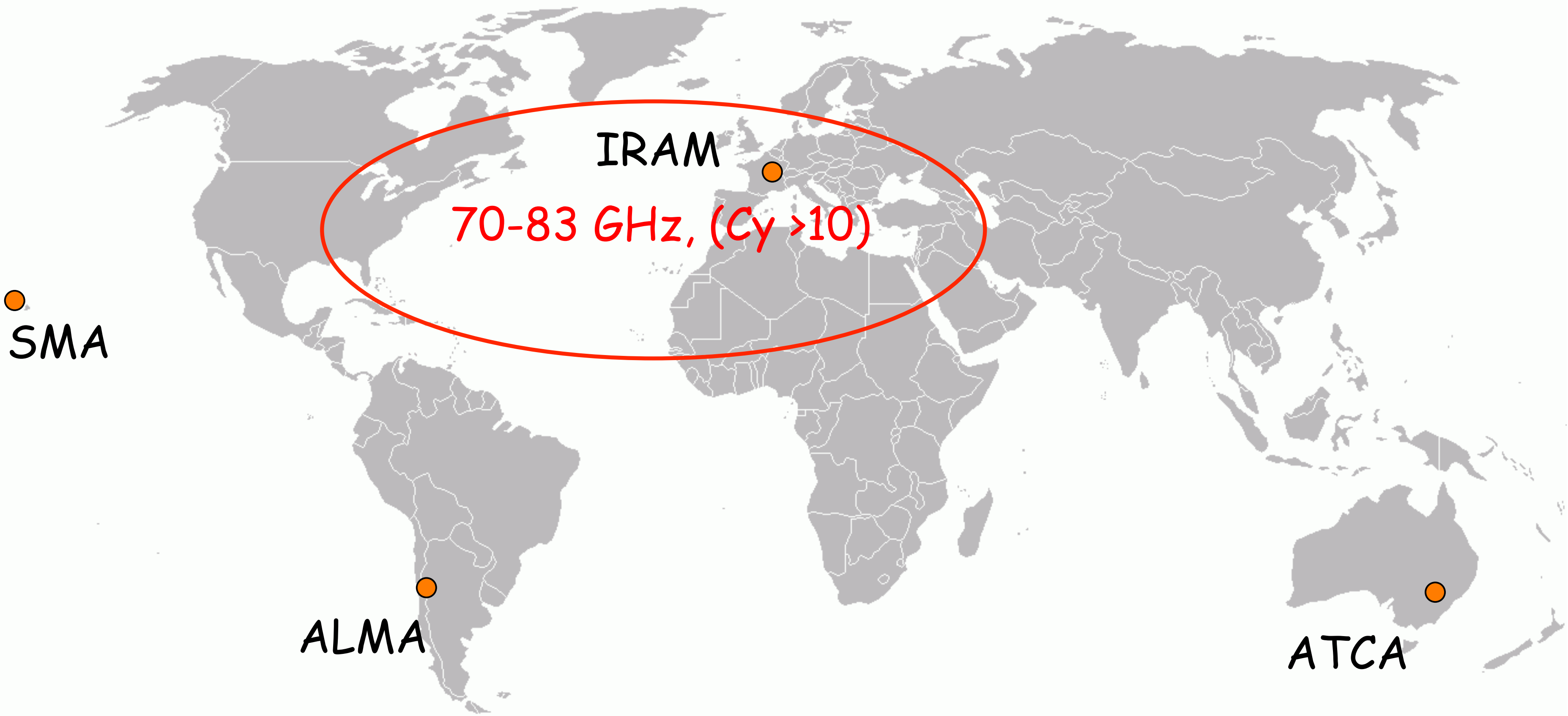
(sub)mm-interferometers worldwide

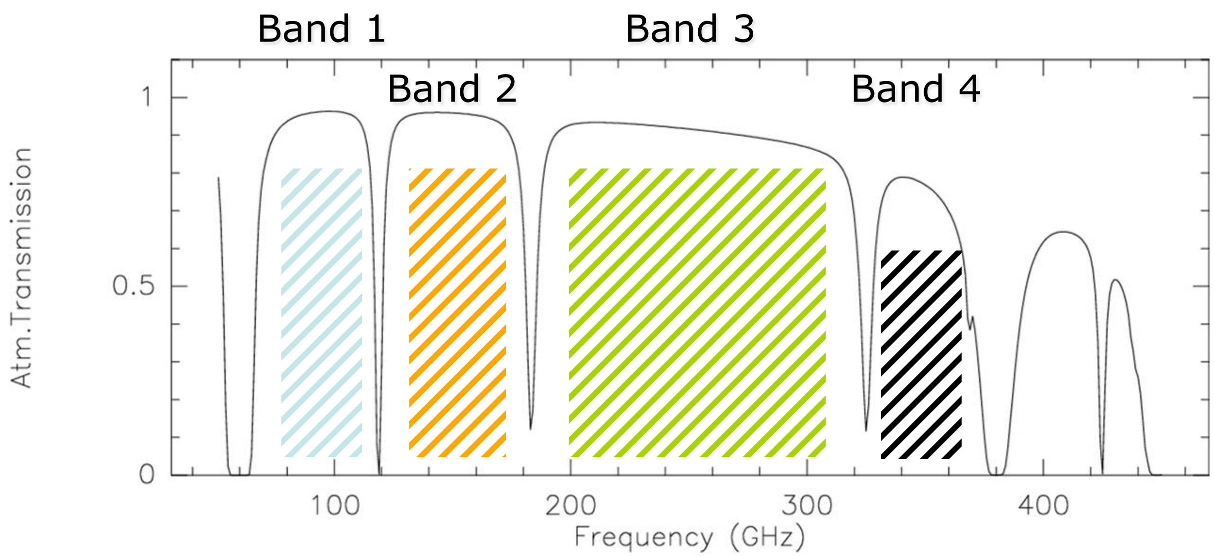


(sub)mm-interferometers worldwide



(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" @ 105 GHz
NOEMA	3mm, 2mm, 1mm, 0.8mm	0.4" @ 230 GHz
SMA	1mm, 0.8mm	0.5" @ 230 GHz
ALMA	3mm, 2mm, 1mm ⇨ Band 10	0.02" @ 230 GHz

Large differences !

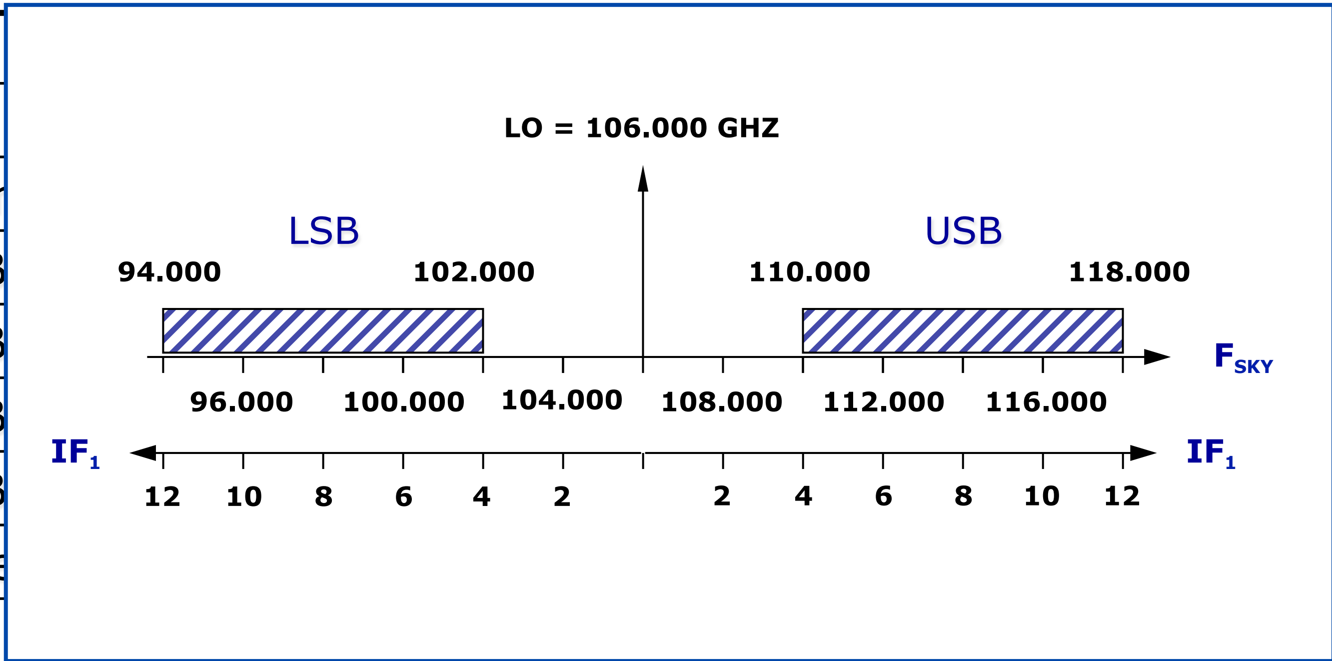

RECEIVERS

NOEMA state of the art receiver technology

- closed cycle cryocoolers ⇨ no liquid He refills
- SIS mixers ⇨ 8 GHz Band per polarization and sideband
  ⇨ USB and LSB operation (2SB)
- fully reflective optics ⇨ lower loss
- new design ⇨ higher density, better EMI control, simplified wiring
- in the near future tuneless mixers and LOs ⇨ simplified frequency tuning and switching

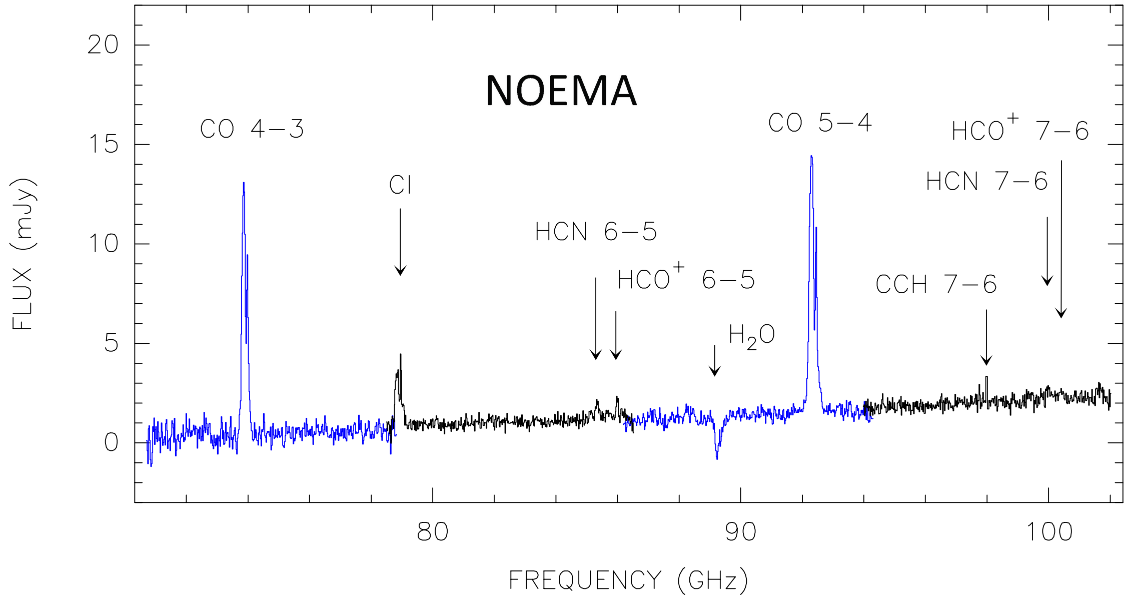
NOEMA receiver capabilities

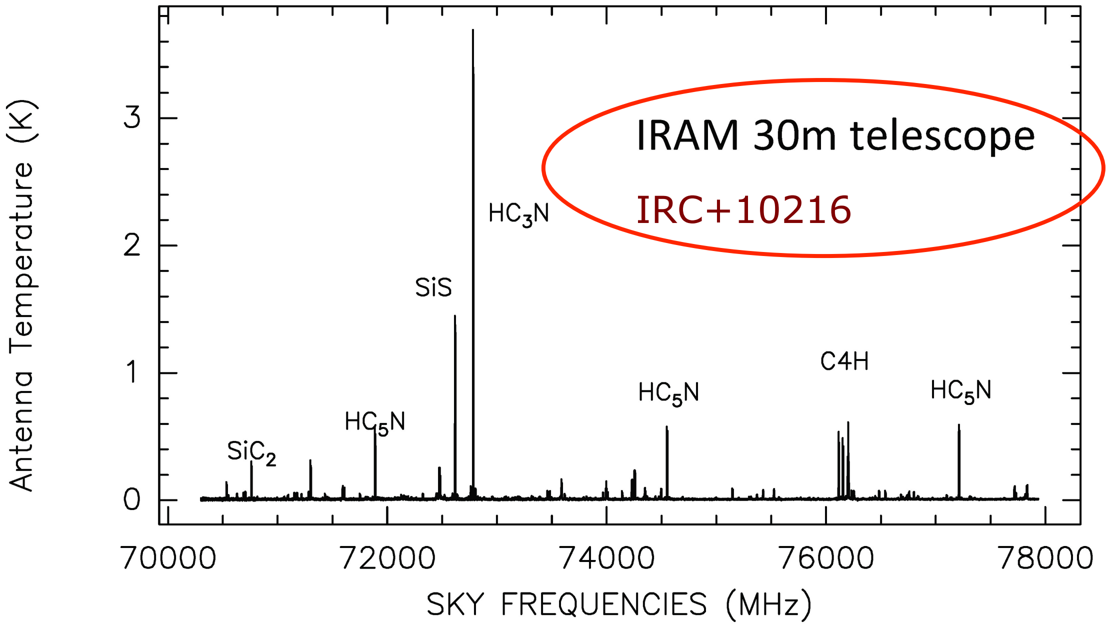
Item		
RF bands		
WVR radiom		n
1 = ALMA B		
2 = ALMA B		
3 = ALMA B		
4 = ALMA B		
RF response		10dB
IF band		
Polarization	dual linear	circular also possible
Observing mode	single frequency dual polarization	second band in standby potential for Dual freq, Dual pol

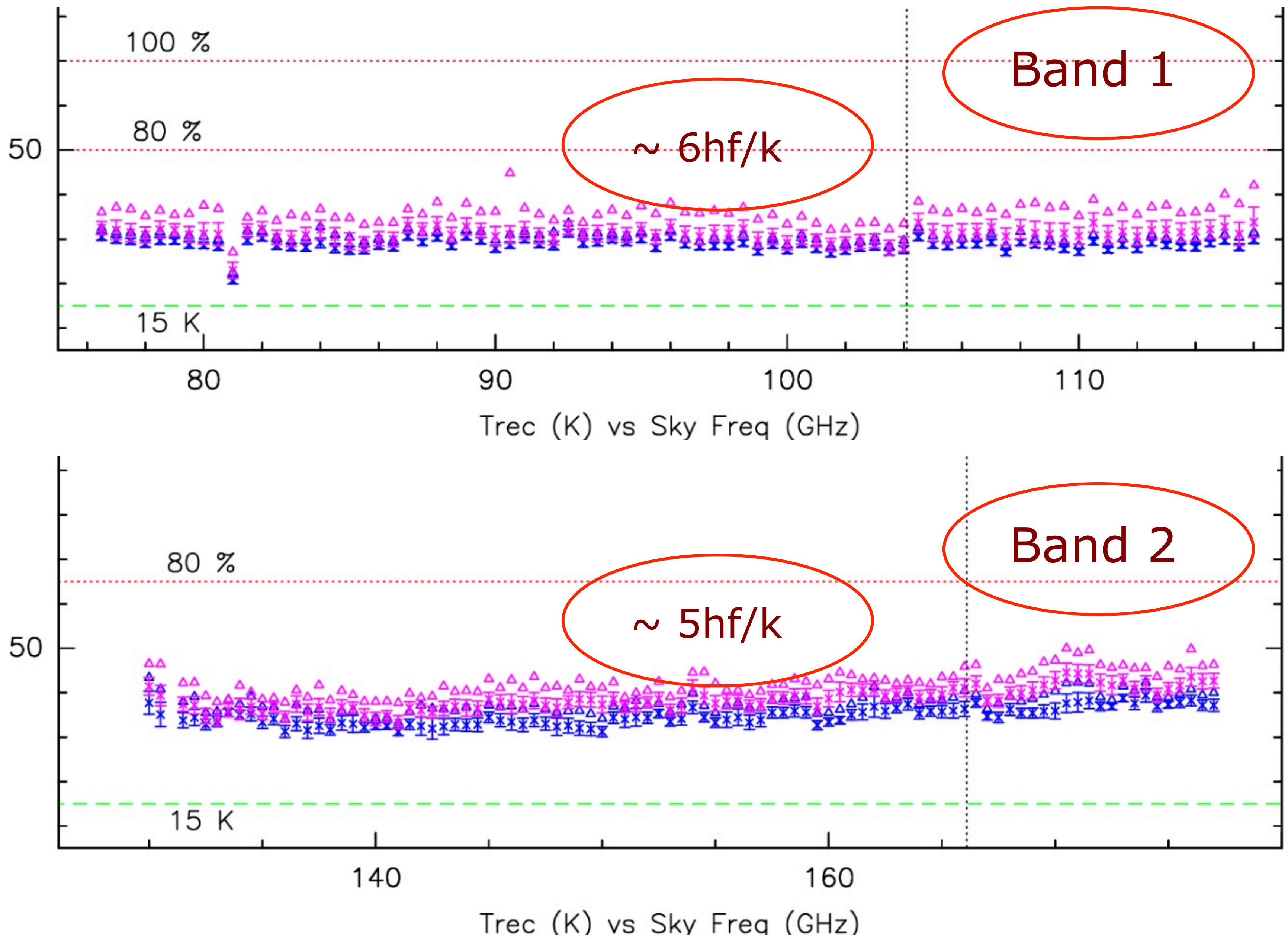


70-80 GHz band offers

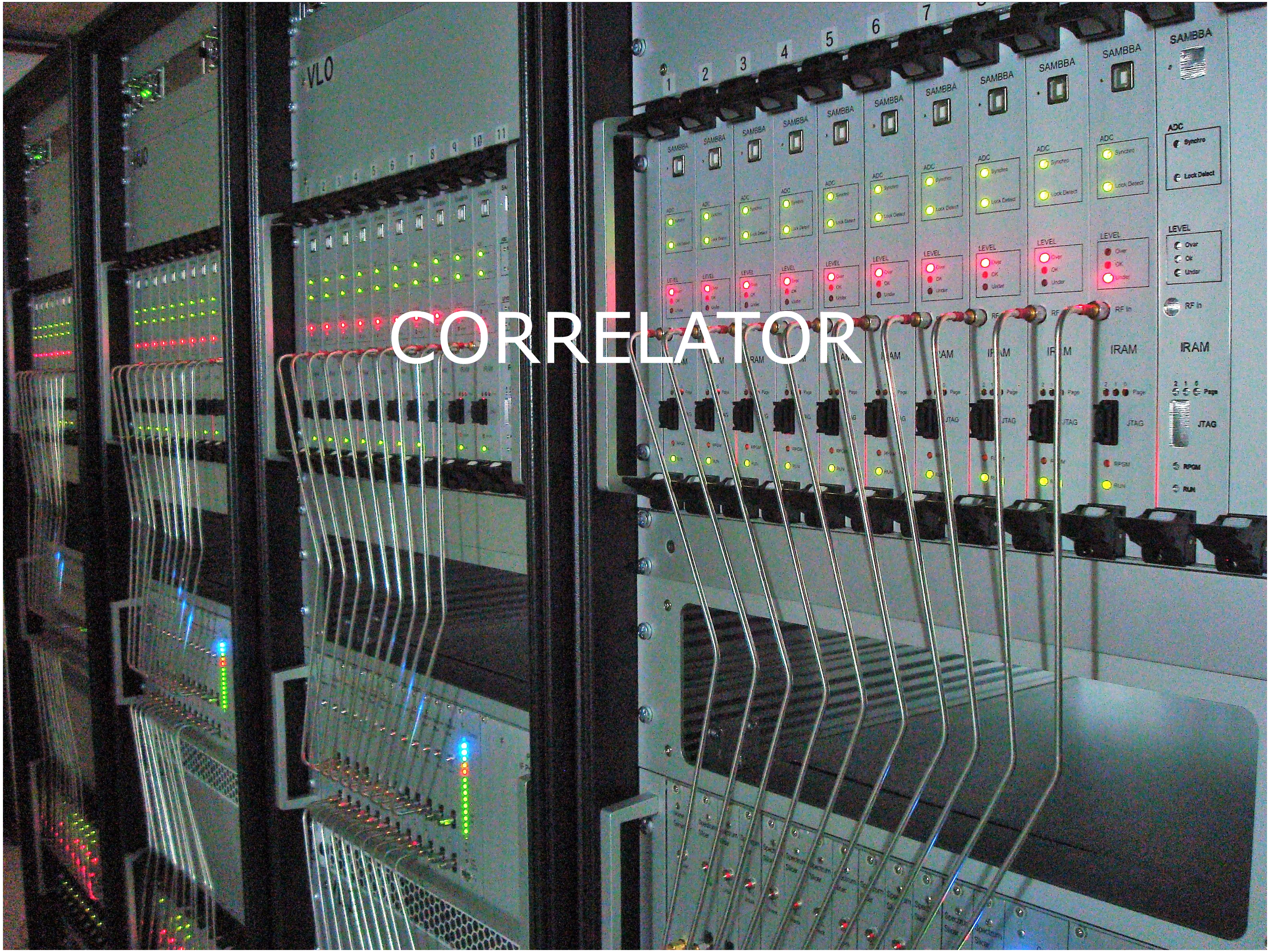
- new discovery space
- deep molecular line surveys
- first-ever opportunity to perform synthesis mapping (no ALMA)
- NOEMA + 30m telescope to sample spatial scales down to 1.3”



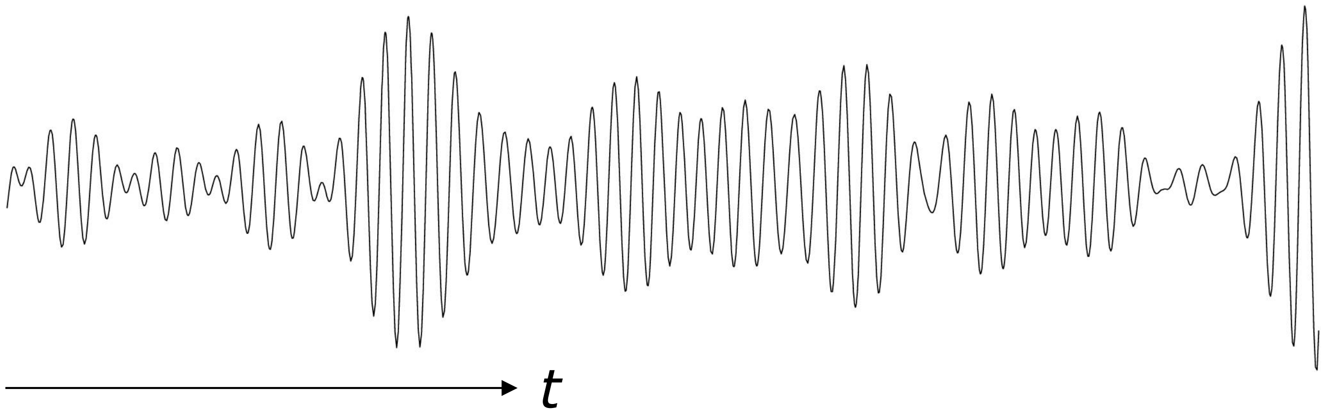




100 %
80 %
50
15 K
~ 6hf/k
Band 1
80
90
100
110
Trec (K) vs Sky Freq (GHz)
80 %
50
15 K
~ 5hf/k
Band 2
140
160
Trec (K) vs Sky Freq (GHz)


CORRELATOR
VLO
SAMBBA
ADC
LEVEL
IRAM
JTAG

Temporal coherence function

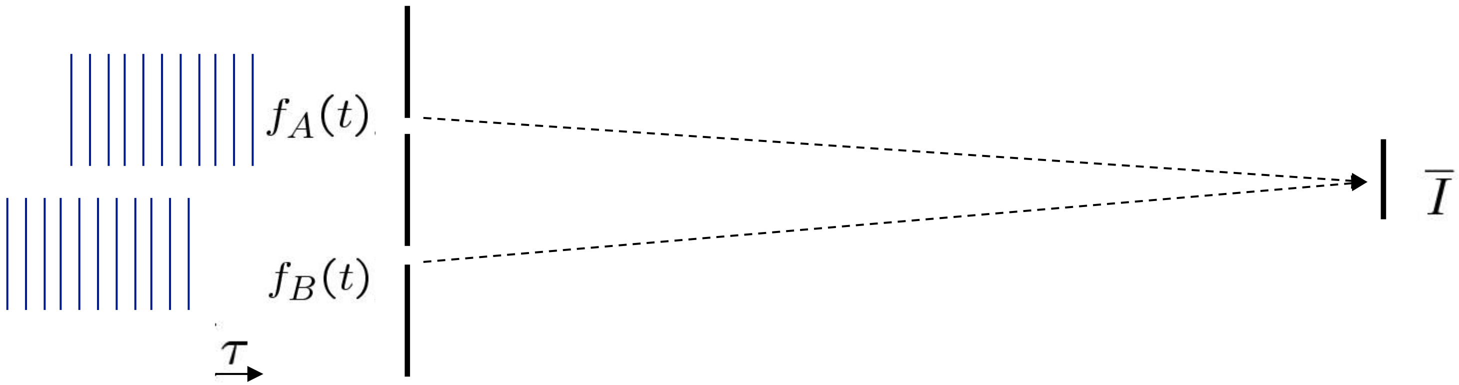


Correlation coefficient:

$$\gamma(\tau) = \overline{f(t)f^*(t+\tau)}/\overline{|f(t)|^2}$$

$$f(t) = A\,e^{i\omega t} \quad \Rightarrow \quad \gamma(\tau) = e^{-i\omega\tau} \quad \Rightarrow \quad |\gamma(\tau)| = 1$$

Temporal coherence



Correlation coefficient:

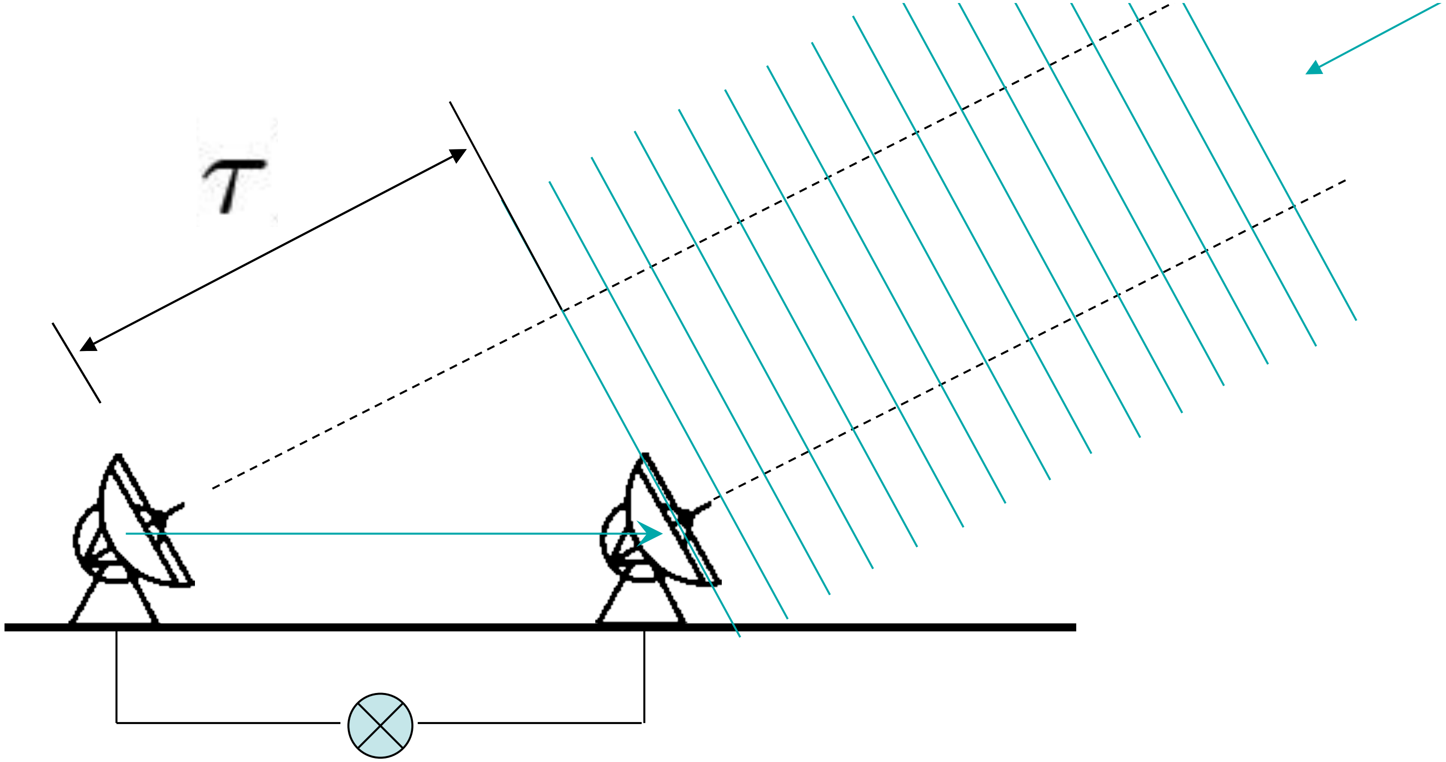
$$\gamma_{AB} = f_A(t) f_B^*(t+\tau) / (\overline{|f_A(t)|^2}\, \overline{|f_B(t)|^2})^{\frac{1}{2}}$$

$$V = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} = 2|\gamma_{AB}|(\overline{I}_A \overline{I}_B)^{\frac{1}{2}} / (\overline{I}_A + \overline{I}_B)$$

$\overline{I}_A = \overline{I}_B$ ⇨ $\boxed{V = |\gamma_{AB}|}$

An interferometer

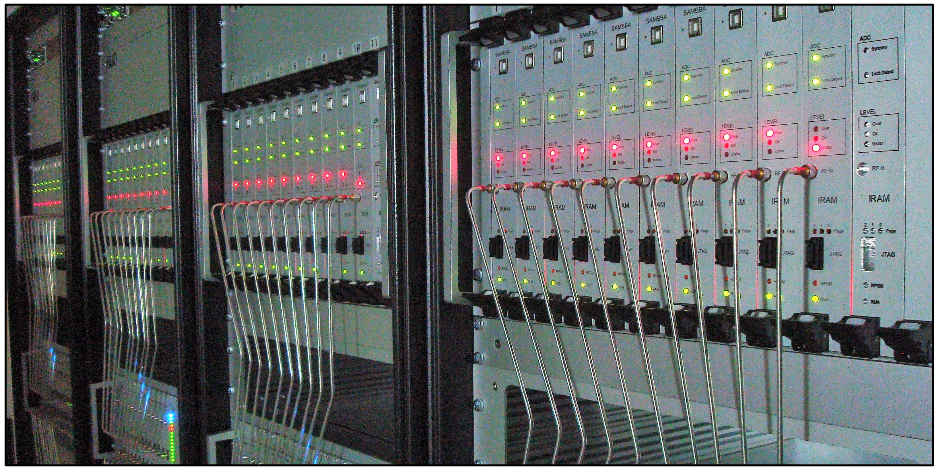
measures the temporal coherence of the incoming wavefront



Correlator

$$V = \gamma(\tau) = FFT(I(w))$$

PolyFiX



- (32 GHz = 8 GHz x 2 sidebands x 2 polarizations) x 12 antennas
- data output = >140.000 spectral channels

Full 32 GHz band, 16000 x 2 MHz

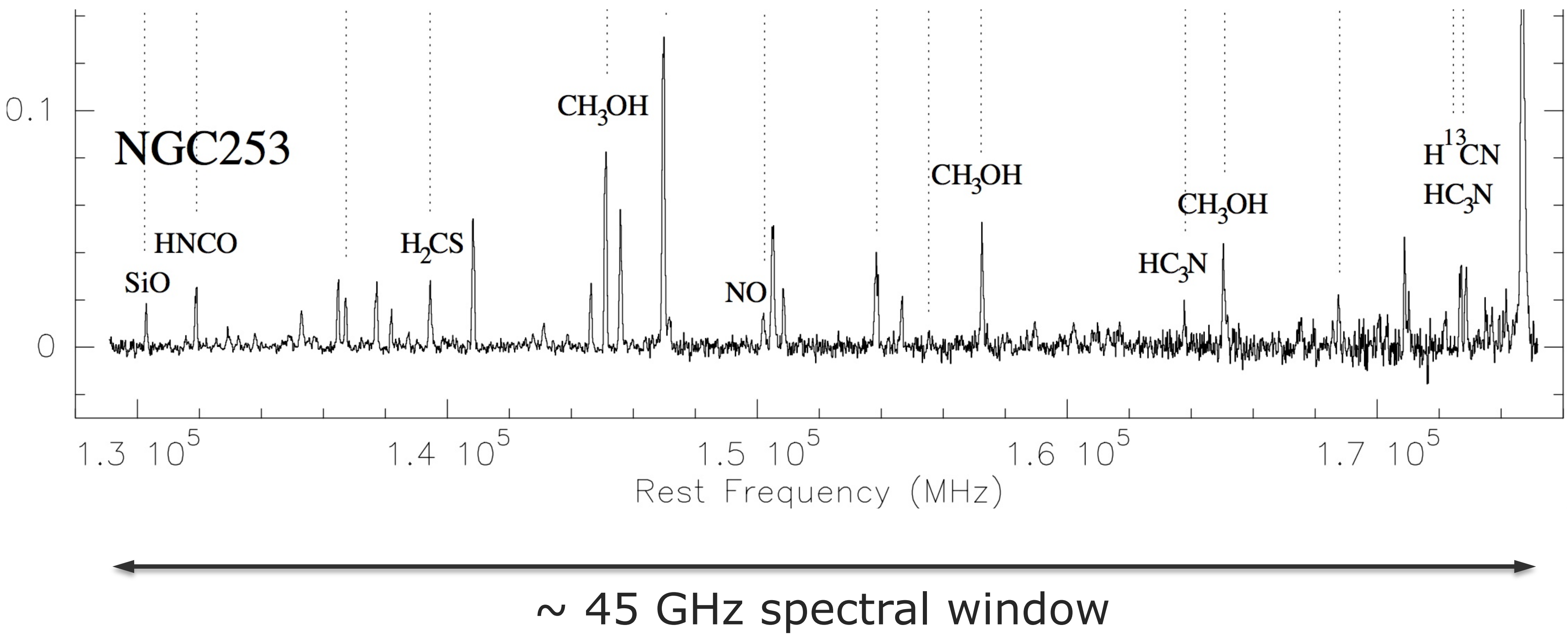
AND

up to 128 spectral windows of 64 MHz, 1024 x 62.5 KHz

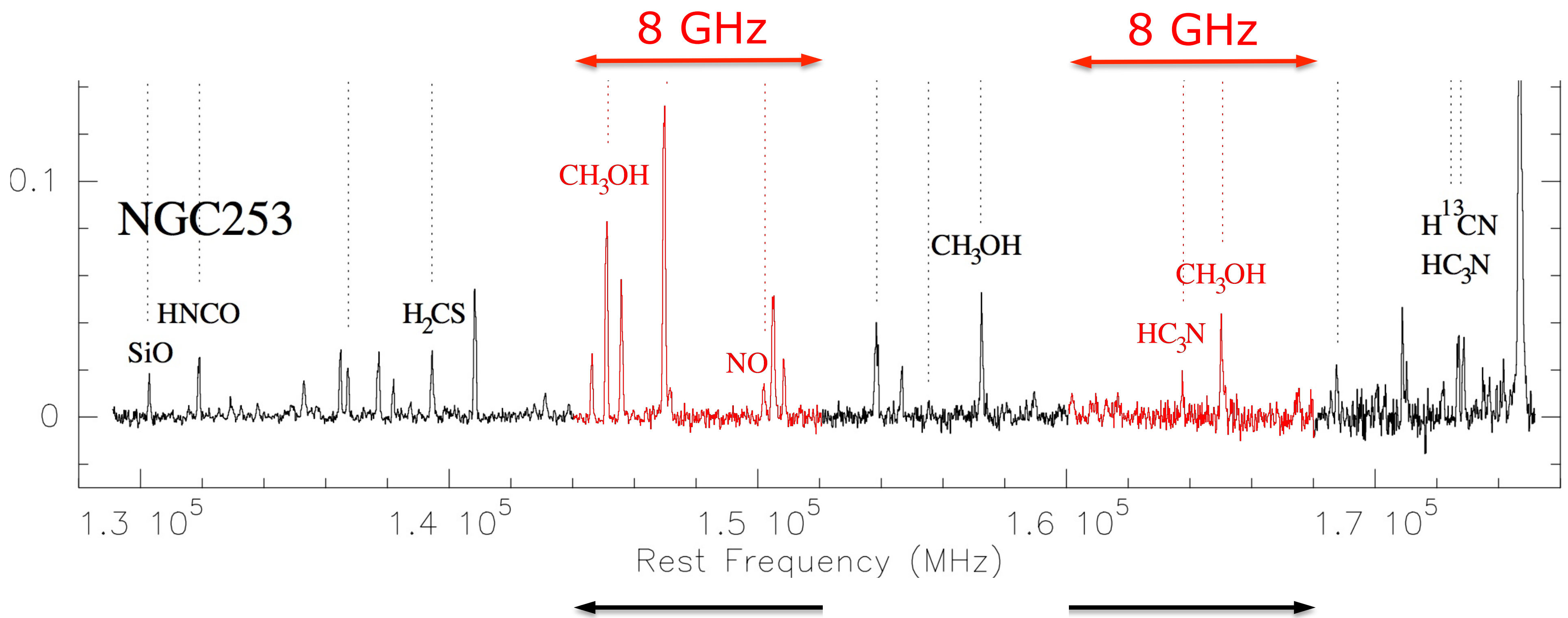
- 5-bit sampling = correlation efficiency close to 100%

NGC 253 spectral survey @ 2mm

Martín et al. 2006

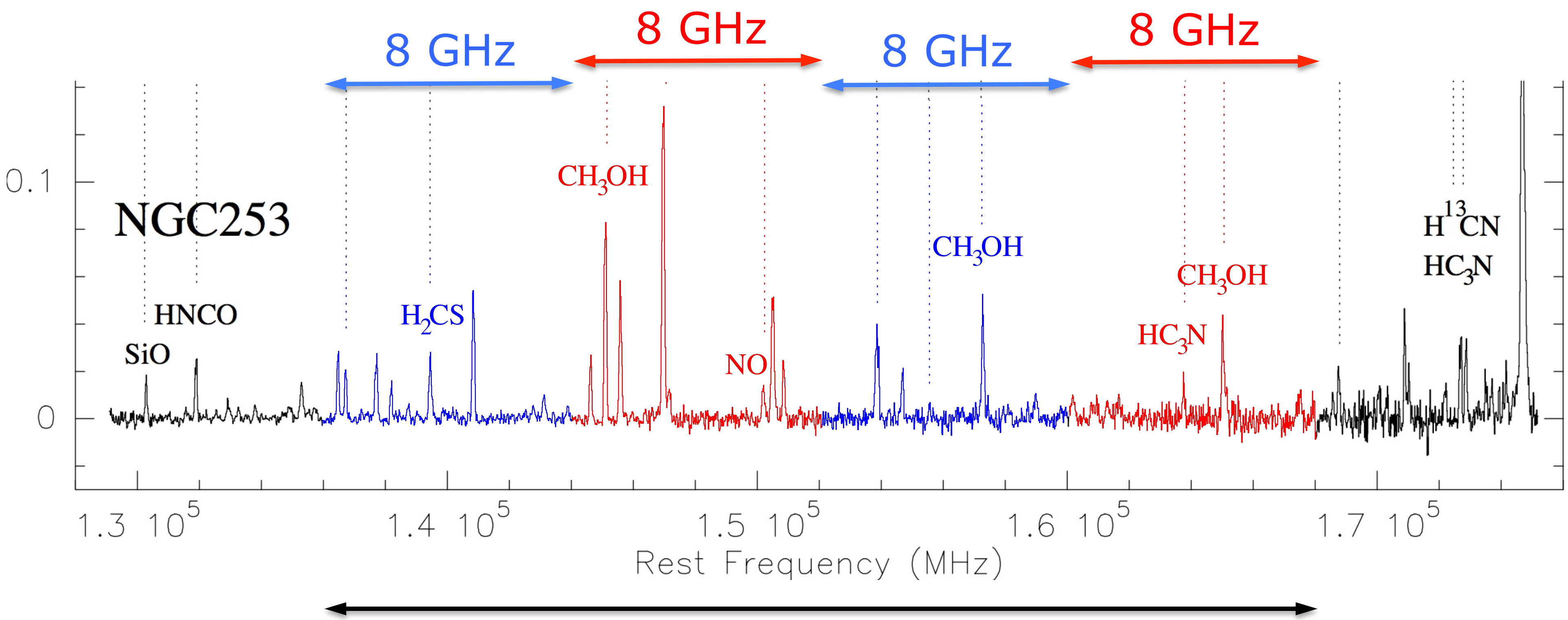


PolyFiX



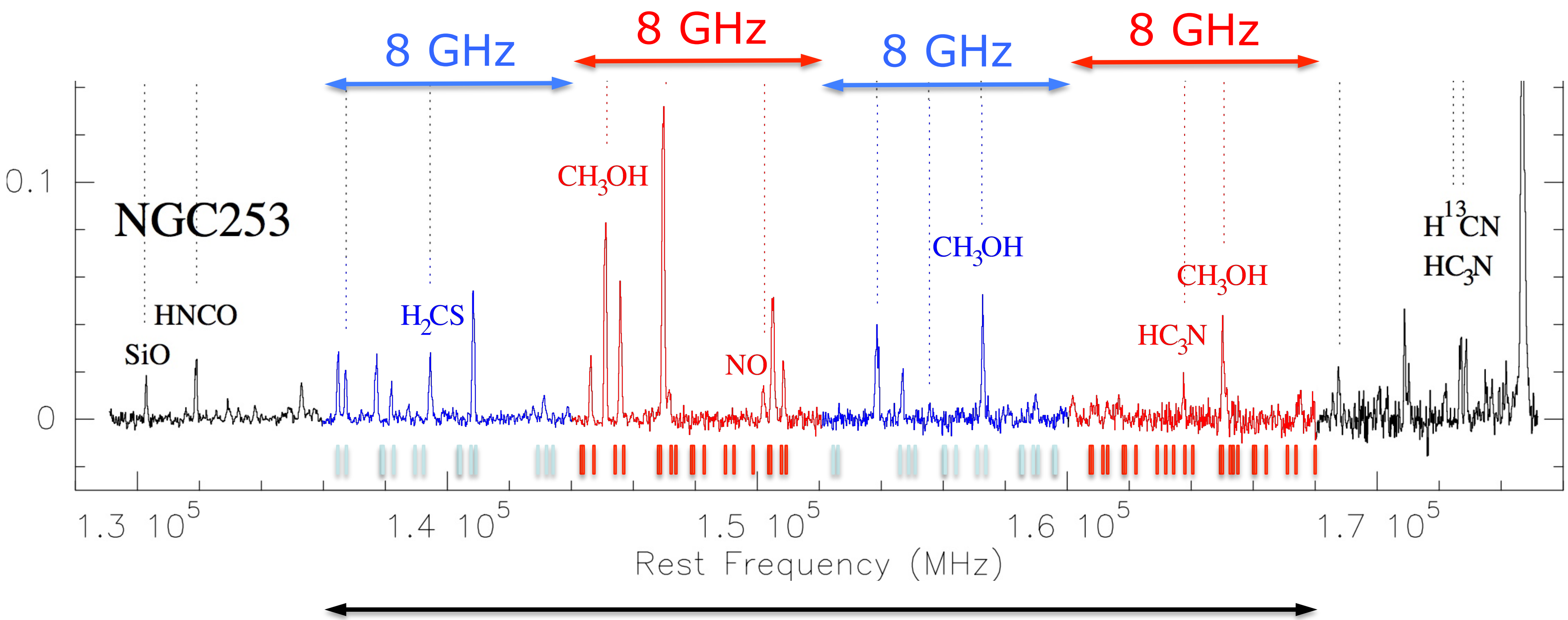
16 GHz / polarization @ 2 MHz resolution = 1 tuning

PolyFiX



32 GHz / polarization @ 2 MHz resolution = 2 tunings

PolyFiX



32 GHz @ 2 MHz resolution = 2 tunings

AND

128x 64 MHz channels @ 62.5 KHz /per tuning

> 140.000 spectral channels /per tuning

PolyFiX

8 GHz ⟷ 8 GHz ⟷ 8 GHz ⟷ 8 GHz

- extragalactic + galactic work, line searches (@ high redshift)
- improved relative line intensity calibration
- sensitive continuum : improves calibration, spectral index, multi-frequency synthesis, self-calibration

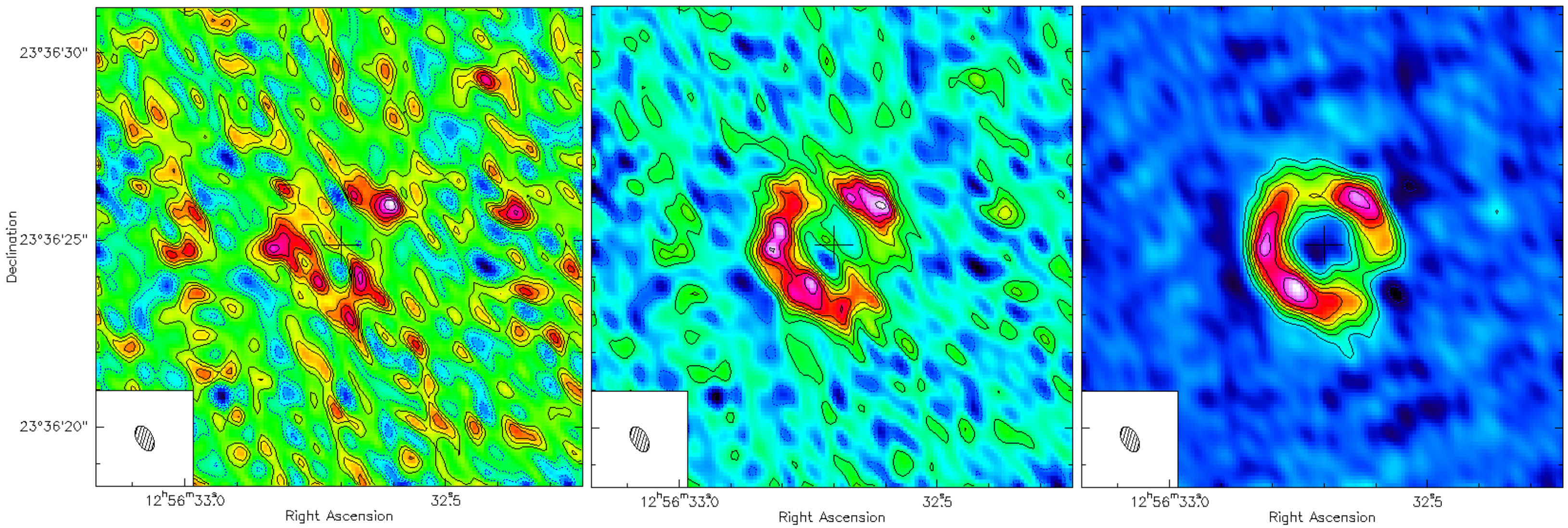
32 GHz @ 2 MHz resolution = 2 tunings

AND

128x 64 MHz channels @ 62.5 KHz /per tuning

> 140.000 spectral channels /per tuning

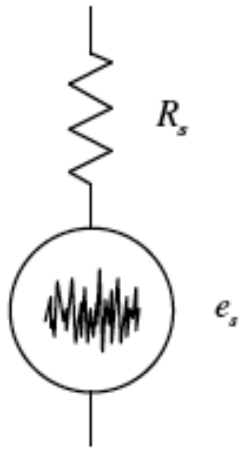
sensitivity considerations



Noise Power

The output power of a …

… Resistor :



$$P_N = kT\Delta\nu$$

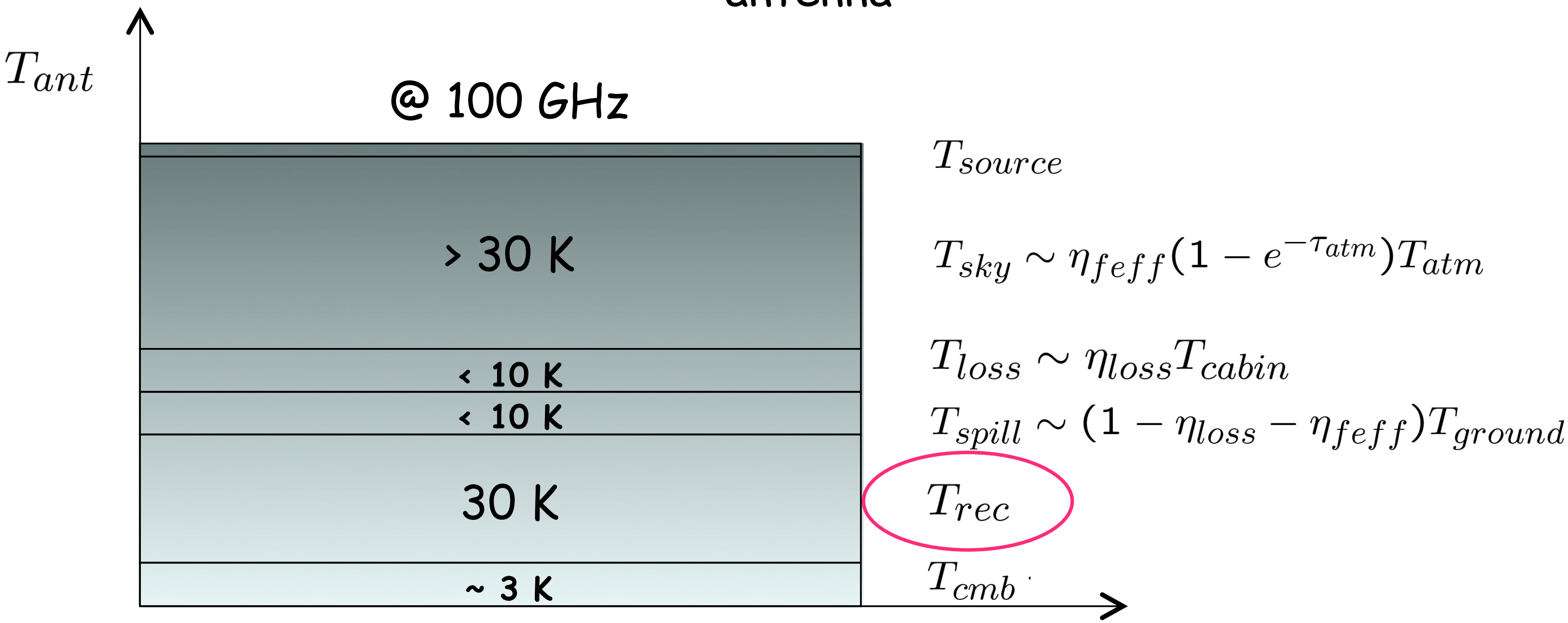
… Receiving System :

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

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.

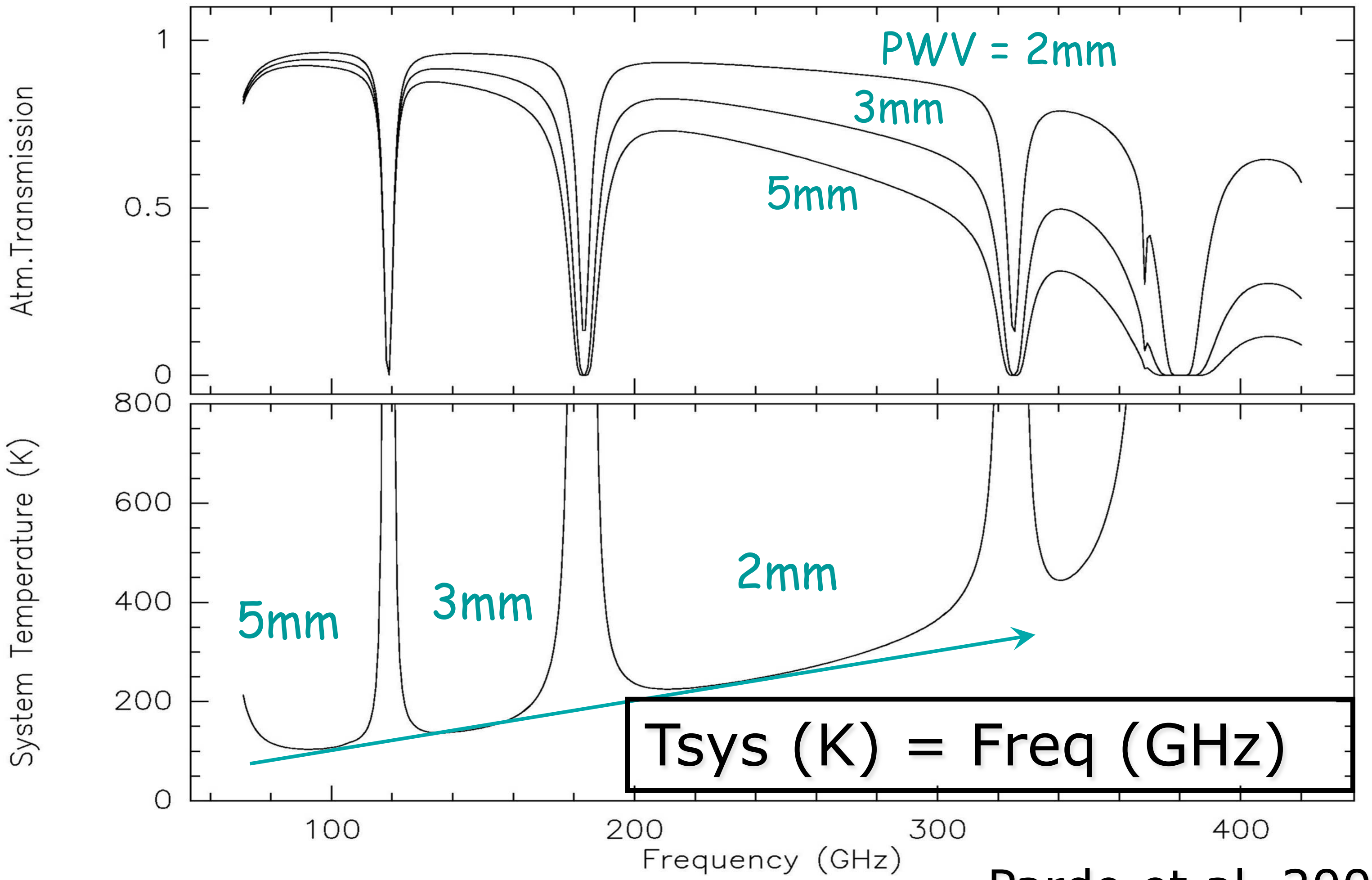
NOEMA system temperatures

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

ATM (Cernicharo, Pardo)

	PWV	G	η_{eff}	Trec	τ	Tsys	Obs. Tim
100 GHz	3	0.05	0.95	32	0.07	77	90%
150 GHz	3	0.05	0.92	35	0.10	113	70%
230 GHz	1	0.05	0.87	50	0.07	141	30%

NOEMA system temperatures



Pardo et al. 2007

INSTRUMENTAL PERFORMANCE

SD efficiency (Jy/K)

ATMOSPHERE

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

interferometric efficiency (Jy/K)

ATMOSPHERE

Seeing   Transparency

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

Antenna   Correlator   Local Oscillators

$\eta_J \eta_P$	degrades the signal
η_C	degrades the noise

η_C = 1.00 (= 5-bit sampling)

06-may-2016-holo-r1

CLIC - 06-MAY-2016 09:11:47 - beaklini@pipeline-pd - Ant 8 - W09N17N09E04W12E12N13

RF: Fr.(B)
Am: Rel.(B)
Ph: Rel.(B)

3C454.3 7ant-Special scans 8335 to 8438 06-MAY-2016 06:08UT El: 56.44

rms	Pha.
17	13.4
27	4.87
37	5.39
47	11.6
57	14.3
67	13.3

Edge taper = 12.13x 11.19 dB - offset X= -0.45 Y= 0.24 m

Focus offsets (X,Y,Z) = -0.41 0.11 0.00 mm; Astigmatism = 37.6 μm (178.2deg.)

Phase rms (unweighted)= 0.085 (weighted)= 0.083 radians

Surface rms (unweighted)= 26.90 - (weighted)= 25.66 μm

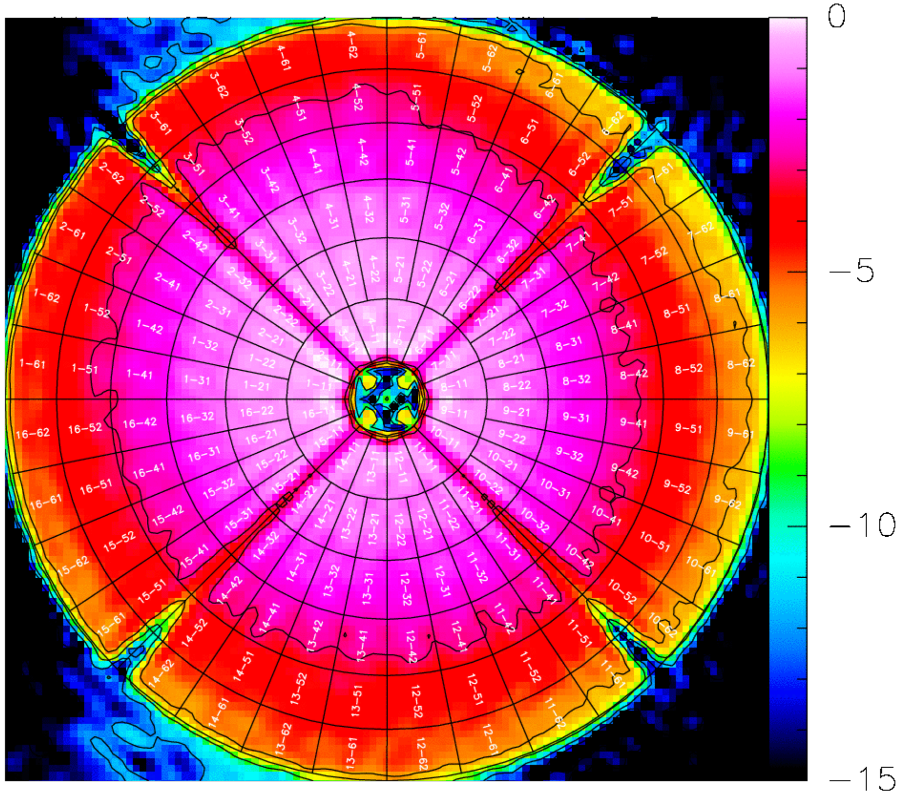
η_A(86.243 GHz) = 0.800; η_A(230.0 GHz) = 0.767; η_A(345.0 GHz) = 0.721

S/T(86.243 GHz)= 19.518 Jy/K; S/T(230GHz)= 20.362 Jy/K; S/T(345 GHz)= 21.651 Jy/K

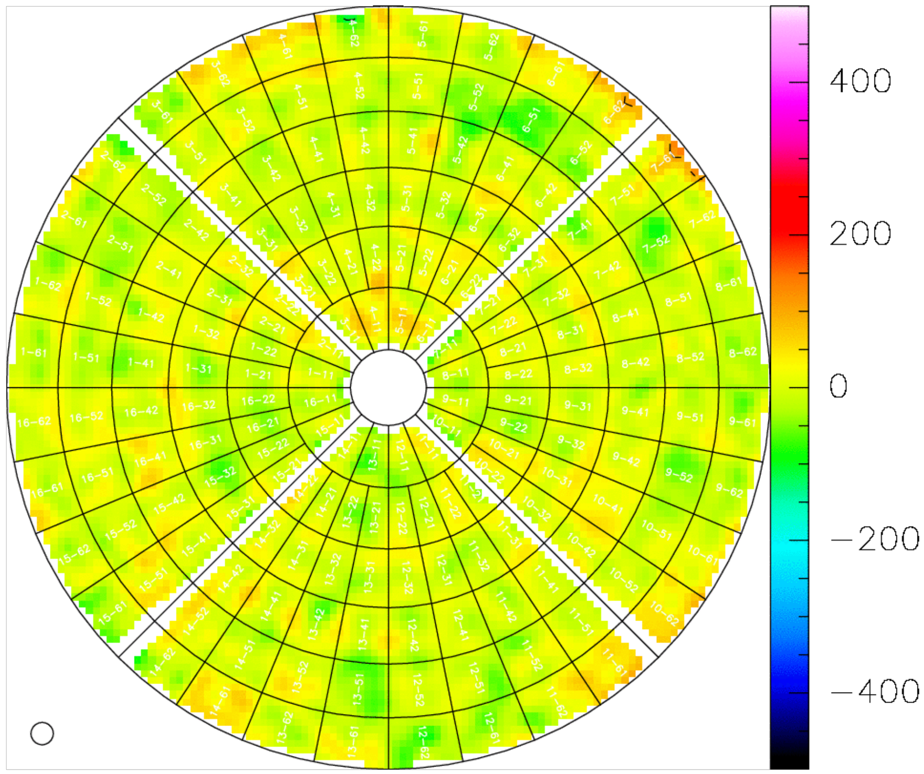
η_I= 0.806 $-\eta_S$= 0.731 $-\eta_P$(86.243 GHz)= 0.993 $-\eta_P$(230 GHz)= 0.952 $-\eta_P$(345 GHz)= 0.895

Rms/ring: 29.5 23.1 22.8 22.5 25.5 31.8

Amplitude (back view)
-15.000 to 0.000 by 3.000



Normal errors (back view)
-500.000 to 500.000 by 100.000



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 $\leq 20\%$

One baseline, two antennas:

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

Ex @ 100 GHz:

$$\sigma_S \simeq 22 \times \frac{100}{\sqrt{2 \times 0.0625\, 10^6 \times 45}} \times \frac{1}{\sqrt{1}} \simeq 0.9\,\mathrm{Jy}$$

$$\sigma_S \simeq 22 \times \frac{100}{\sqrt{2 \times 2.0\, 10^6 \times 45}} \times \frac{1}{\sqrt{2}} \simeq 116\,\mathrm{mJy}$$

$$\sigma_S \simeq 22 \times \frac{100}{\sqrt{2 \times 16\, 10^9 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 8.7\,\mathrm{mJy}$$

The point source sensitivity

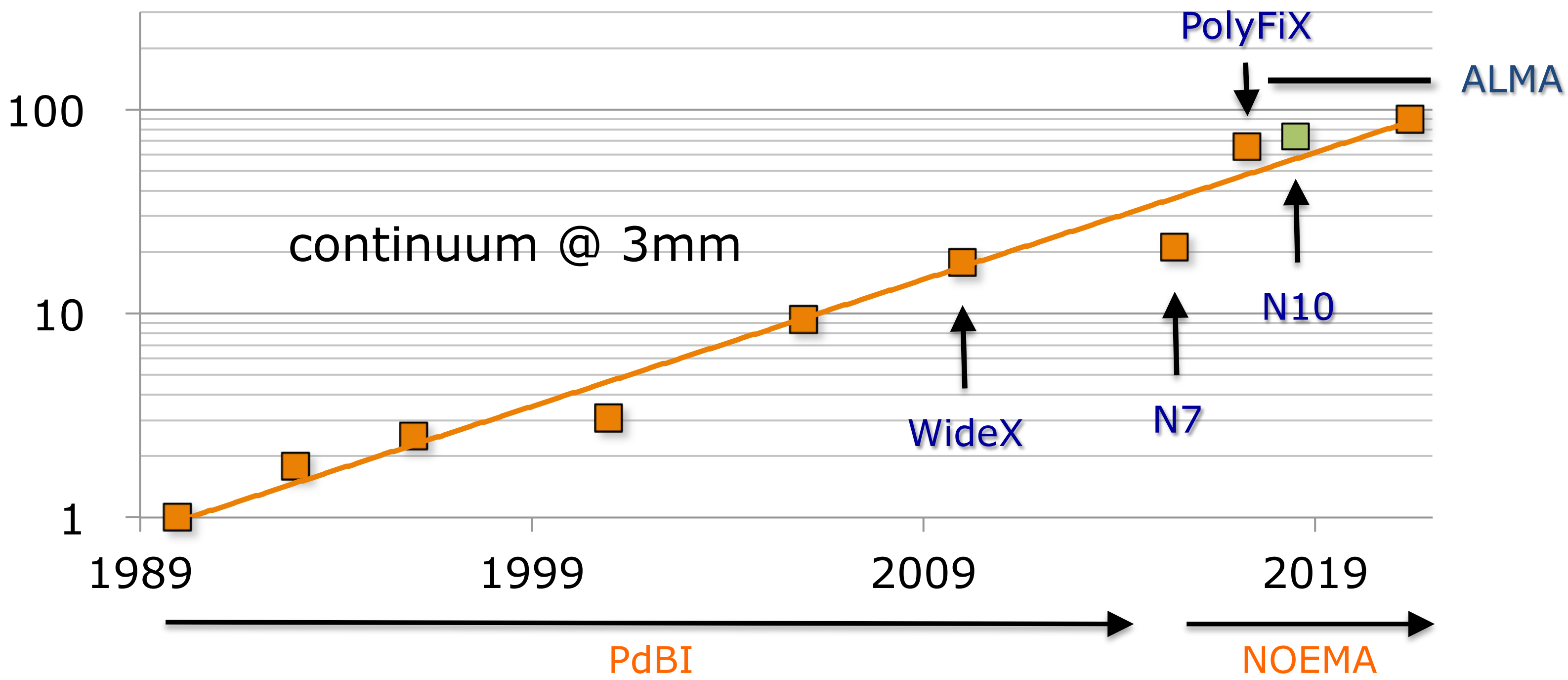
$$\sigma_S = \frac{2k}{\eta_A A} \times \frac{< T_{\mathsf{SYS}} >}{\eta_C \eta_J \eta_P \sqrt{N(N-1)\Delta\nu\Delta t}} \times \frac{1}{\sqrt{N_P}}$$

A	Collecting Area of a Single Antenna (177 m^2)
η_A	Aperture Efficiency (0.70 @ 3mm; 0.45 @ 1mm)
η_C	Correlator Efficiency (0.99)
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 (62.5 kHz - 16000 MHz)
Δt	Integration Time On-Source (sec)

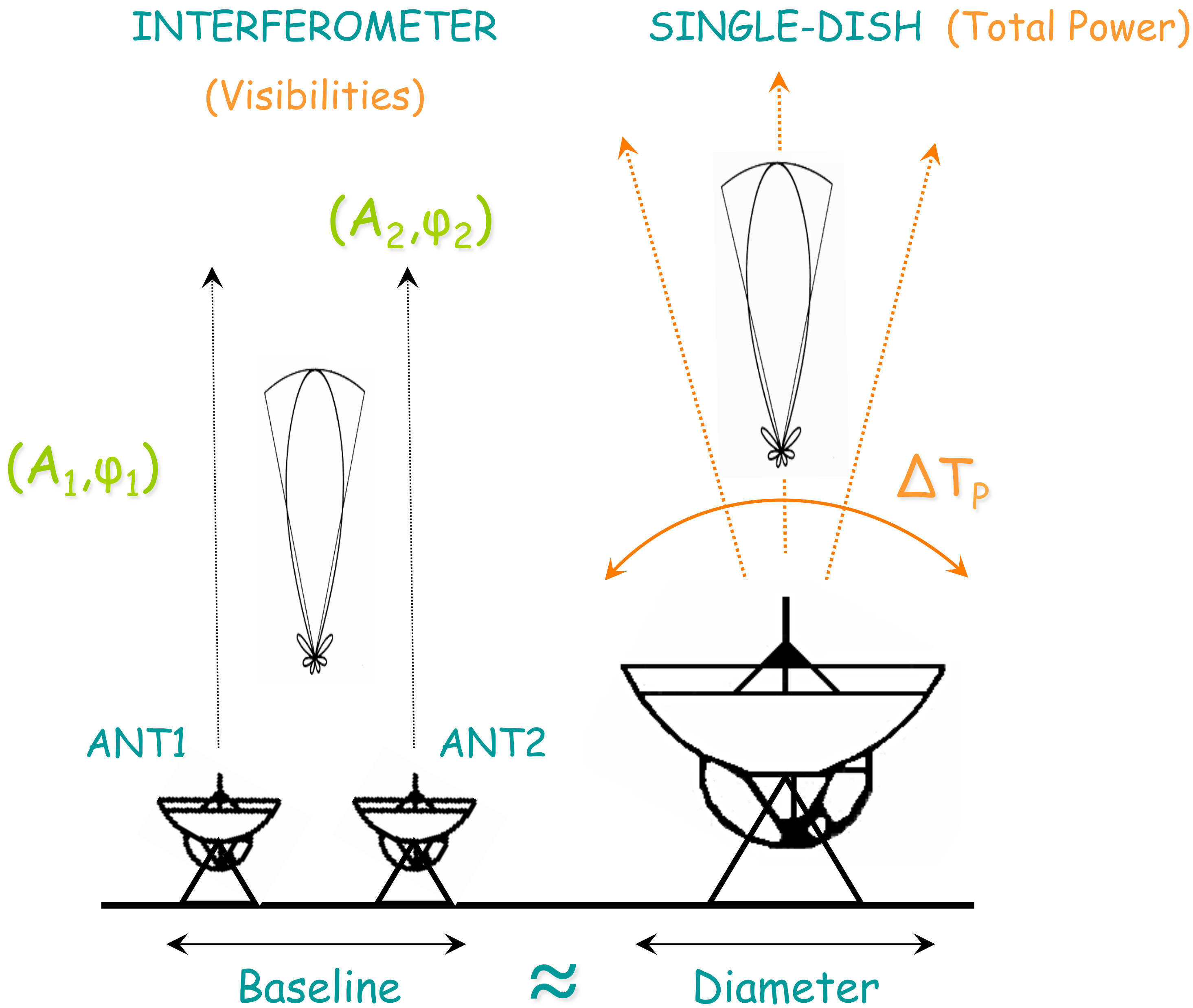
NOEMA sensitivity over the years

- initial PdBI capabilities multiplied by orders of magnitude

  100x cont. sensitivity, 7x line sensitivity ⇨ ALMA like sensitivities



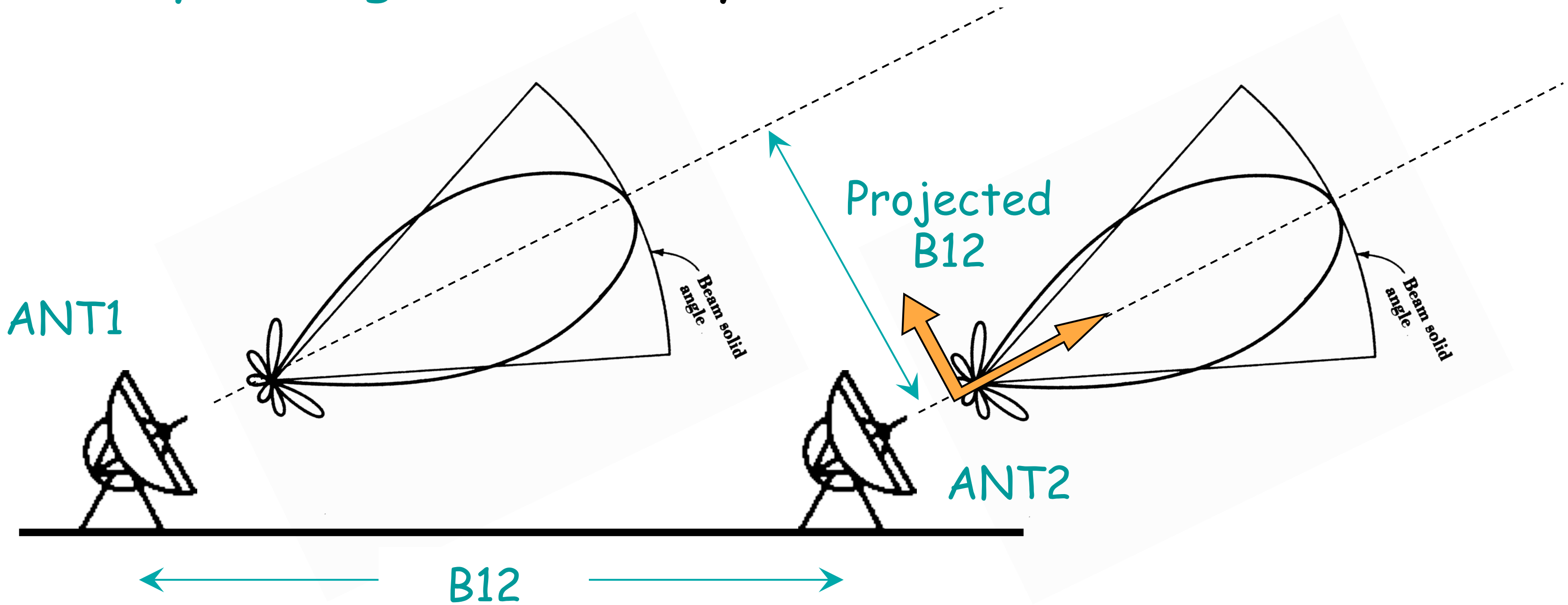
NOEMA will reach >65% ALMA continuum sensitivity @ 3mm
>45 % ALMA line sensitivity @ 3mm

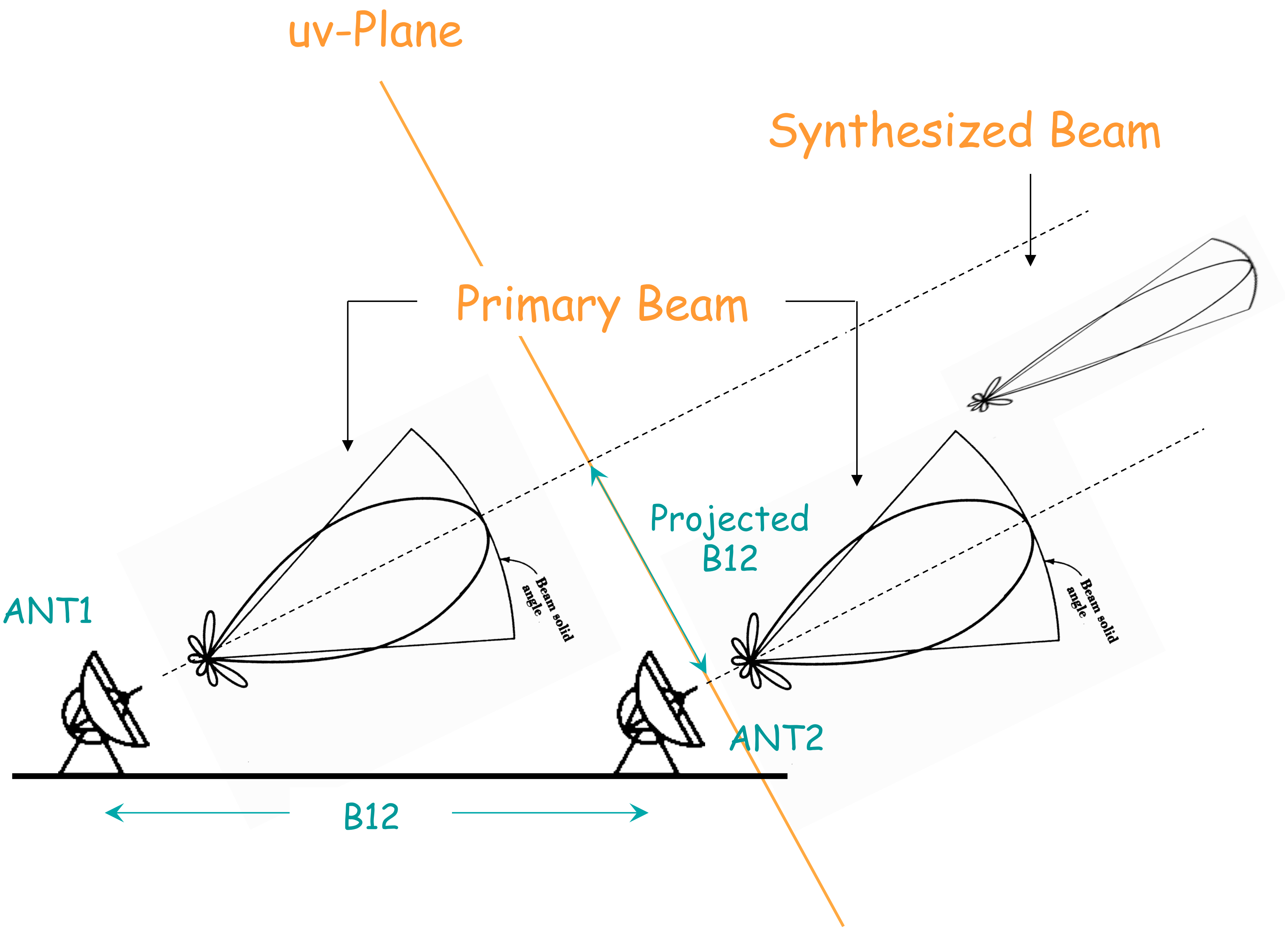

INTERFEROMETER
(Visibilities)
SINGLE-DISH (Total Power)
(A_2,φ_2)
(A_1,φ_1)
ΔT_p
ANT1
ANT2
Baseline
≈
Diameter

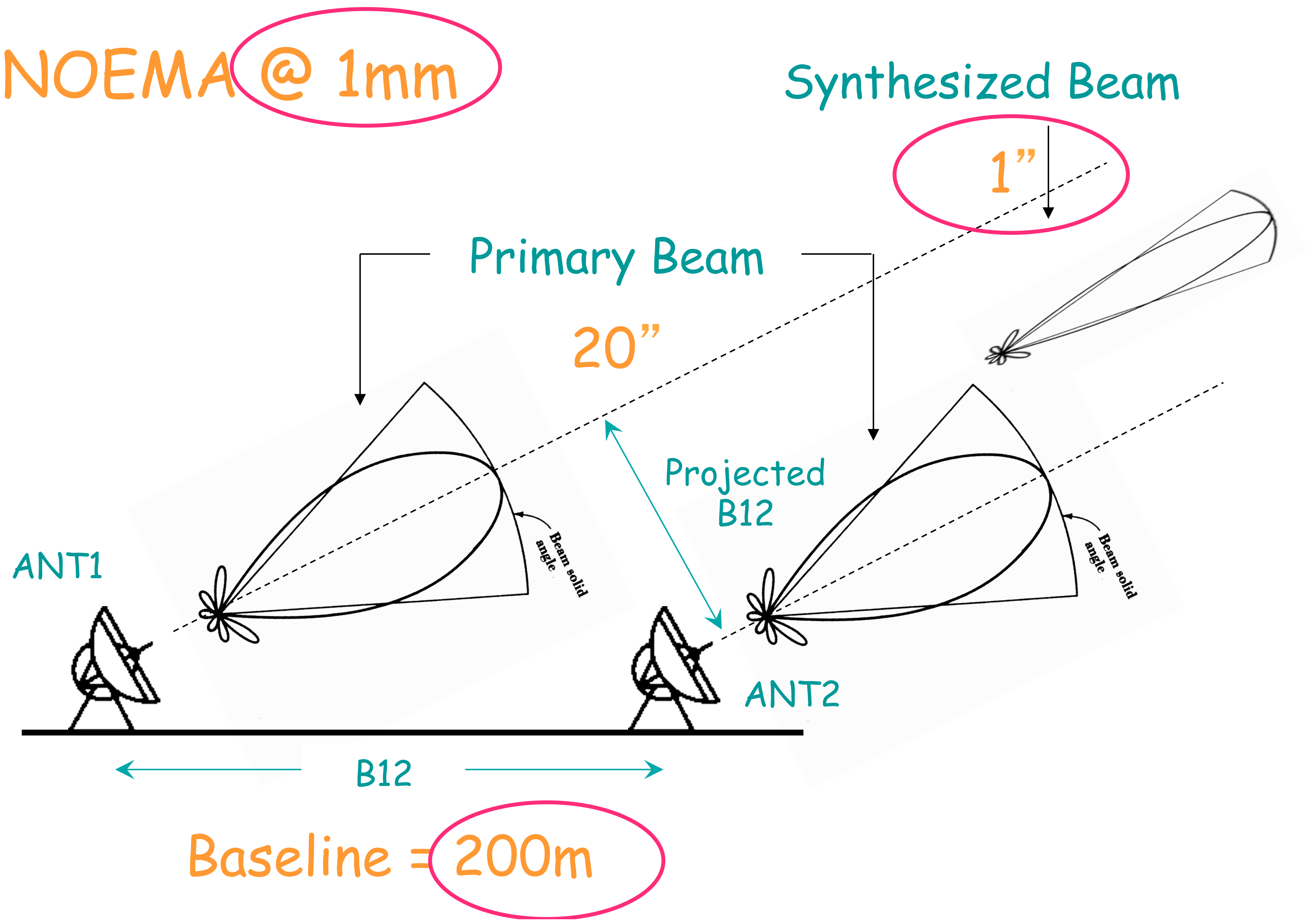
Baseline Bij : distance between two antennas

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

Array Configuration : layout of the antenna stations

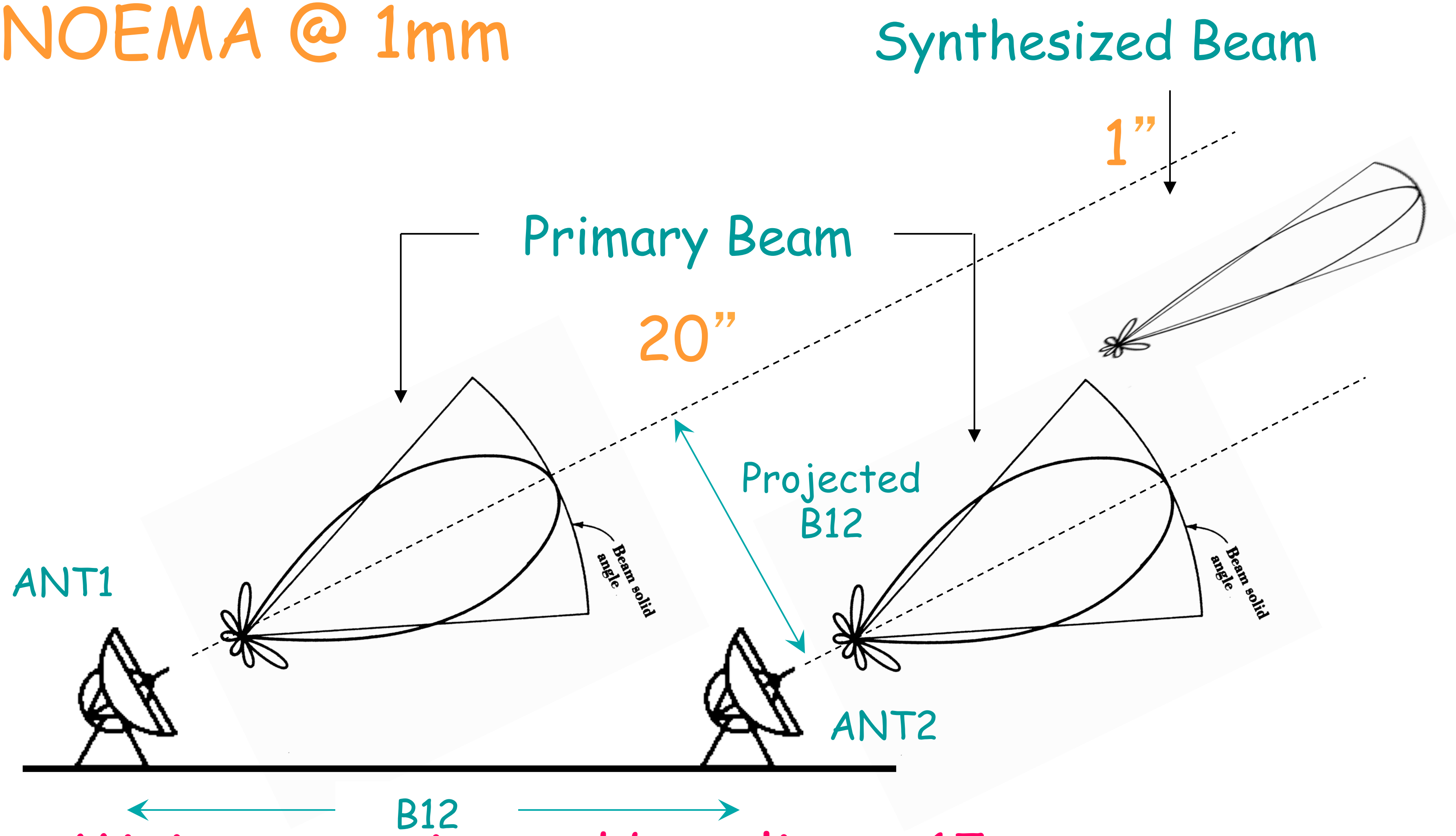



uv-Plane
Synthesized Beam
Primary Beam
Projected B12
Beam solid angle
Beam solid angle
ANT1
ANT2
B12



NOEMA @ 1mm
Synthesized Beam
1”
Primary Beam
20”
Projected
B12
Beam solid
angle
Beam solid
angle
ANT1
ANT2
B12
Baseline = 200m

NOEMA @ 1mm



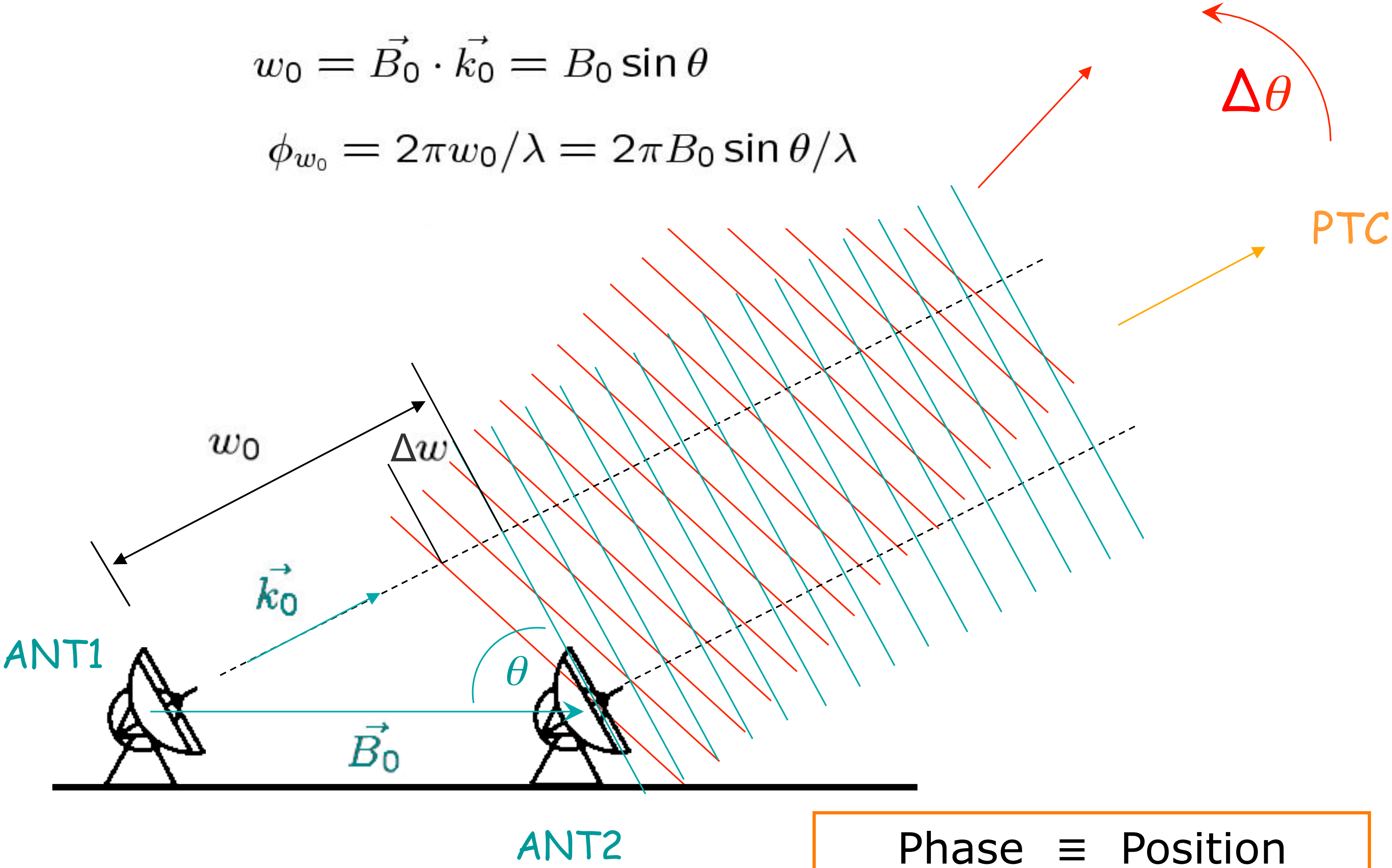
Minimum projected baseline = 15m

SHORT SPACINGS ⇨ 30m Telescope

The phase equation

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

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

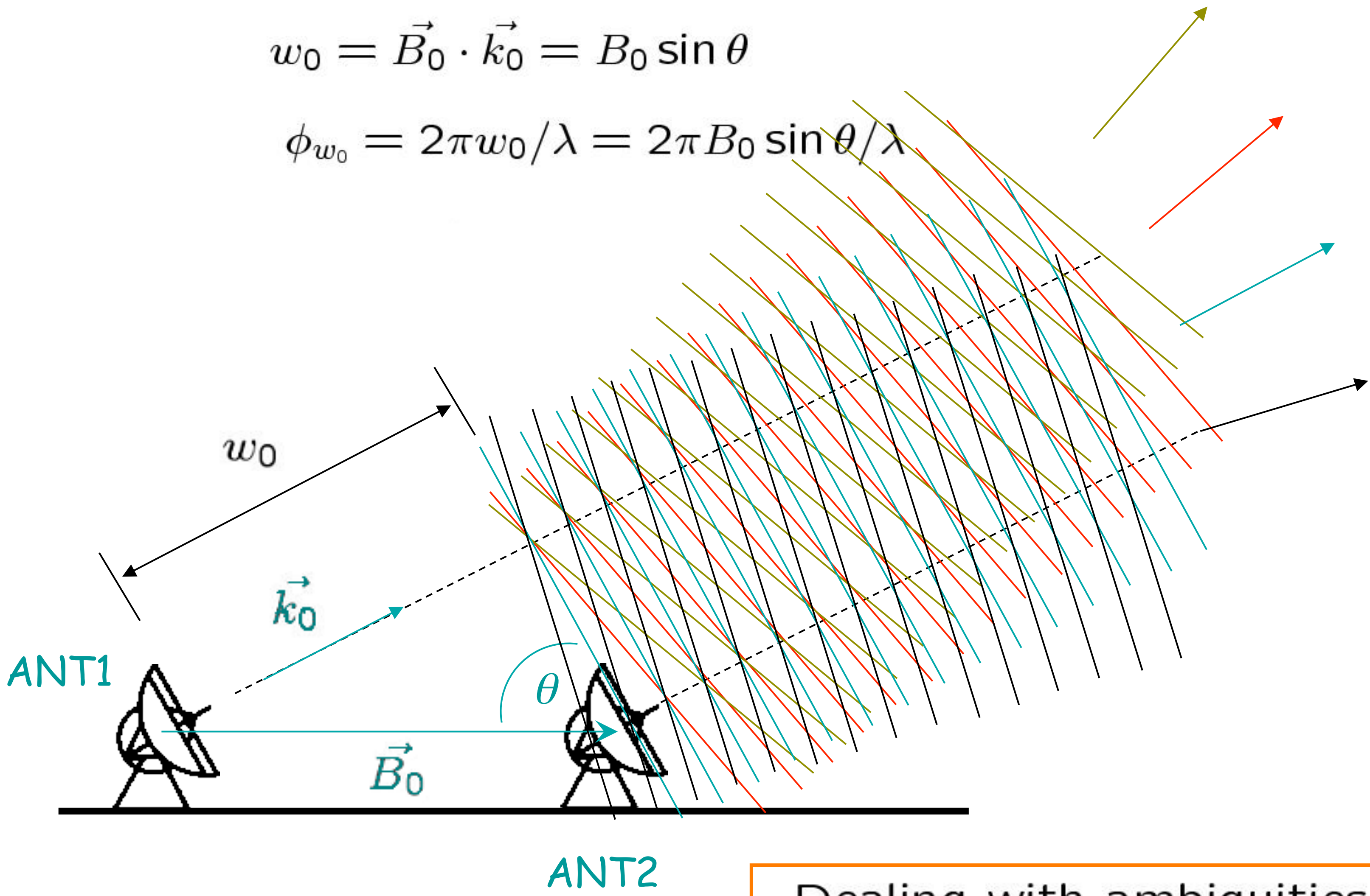


Phase ≡ Position

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 ...

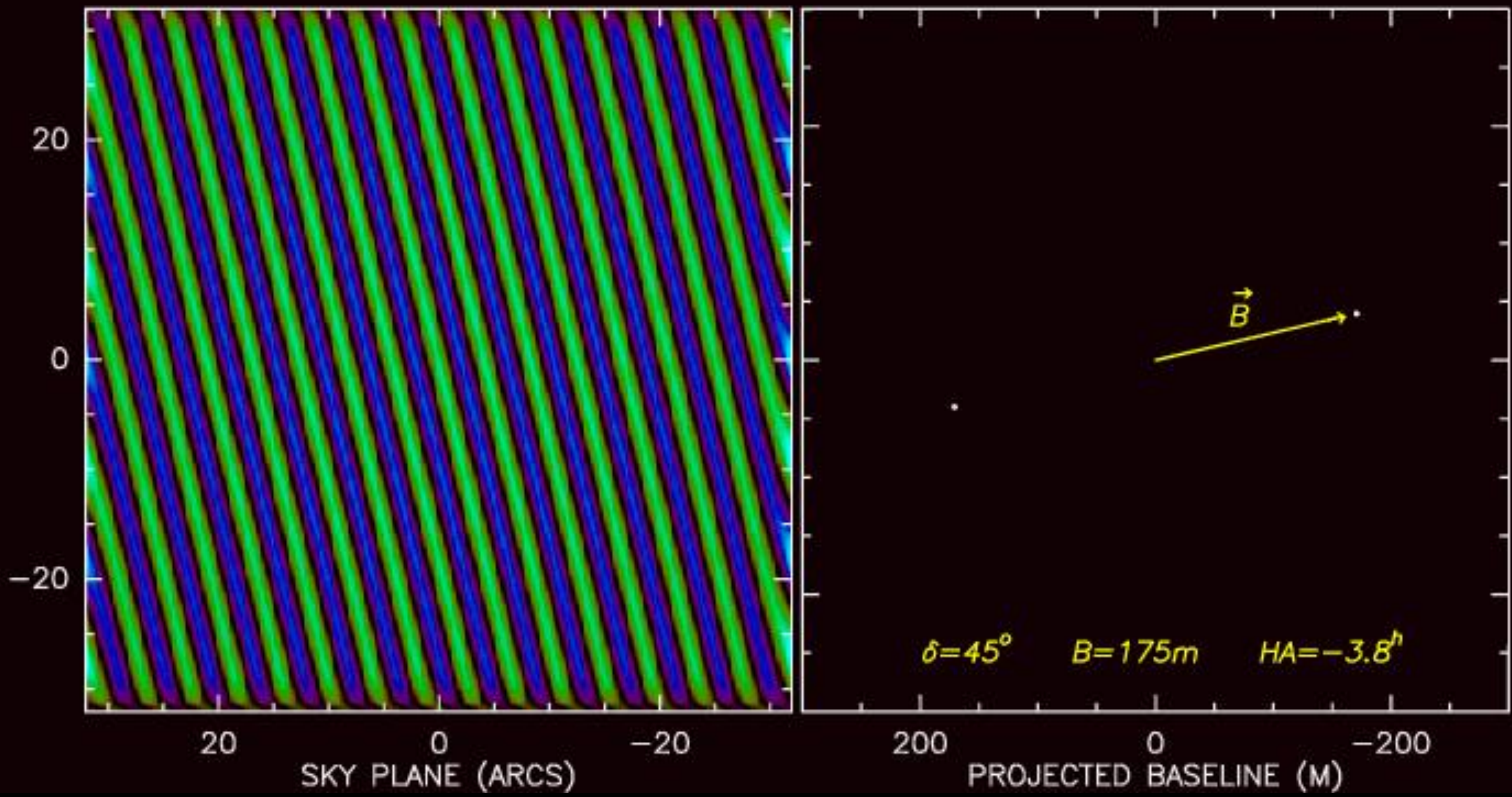
Dealing with $\omega_0 = \vec{k_0} \cdot \vec{B_0}$

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

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

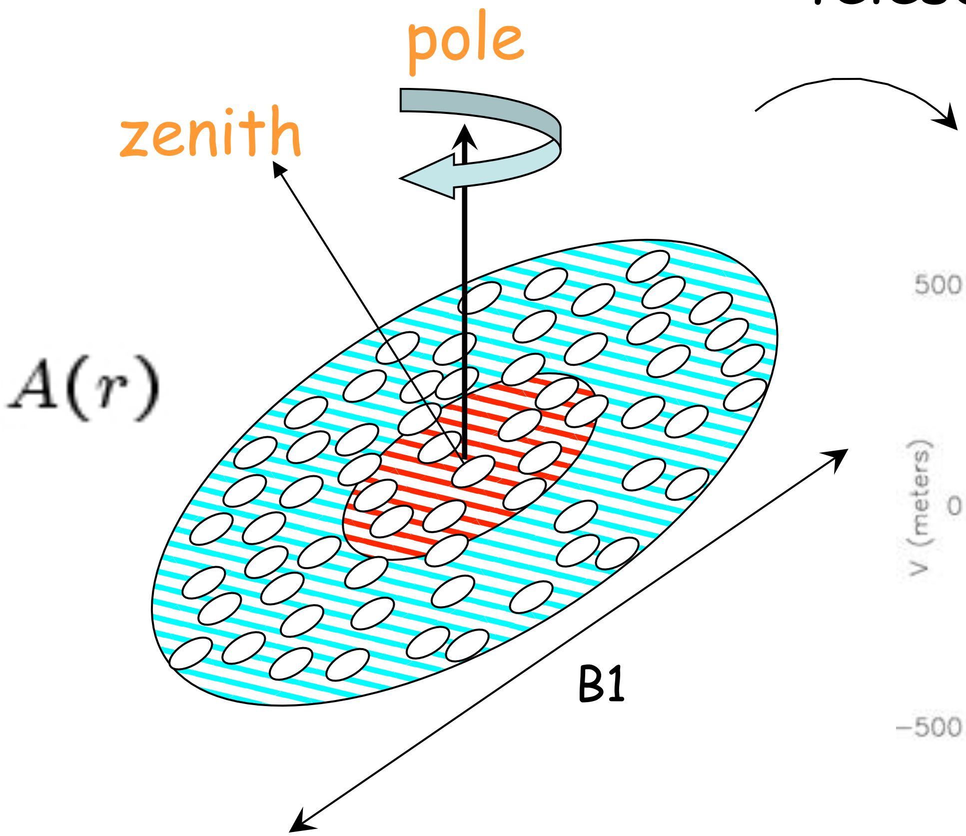
$$\theta_N = \lambda/B_0 \times N = \pm 2'' \times N$$

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

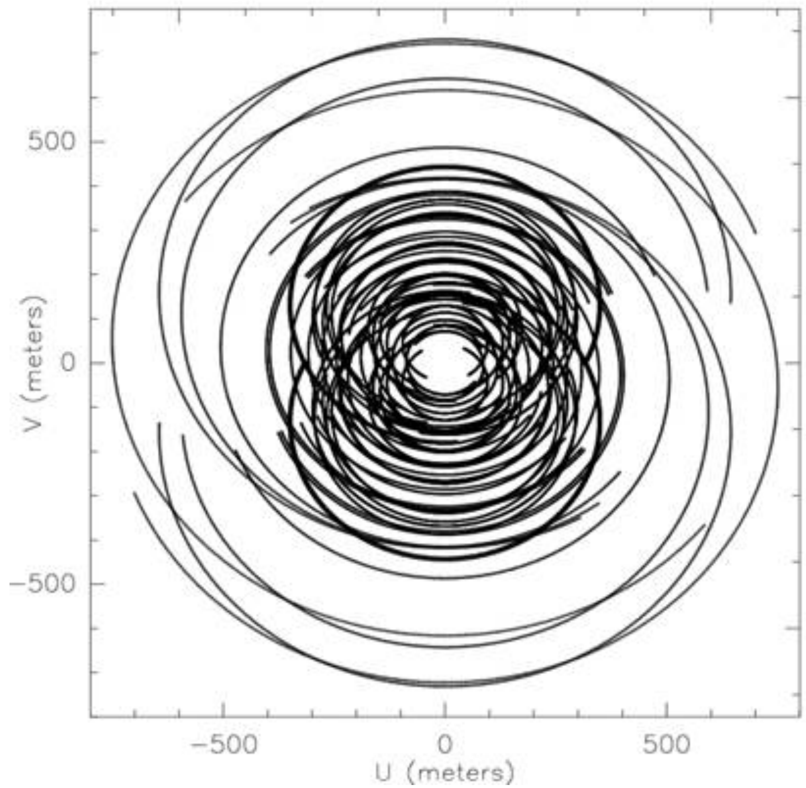

20
0
−20
20
0
−20
SKY PLANE (ARCS)
B
δ=45°
B=175m
HA=−3.8h
200
0
−200
PROJECTED BASELINE (M)

Super-Synthesis or Earth Rotation Synthesis

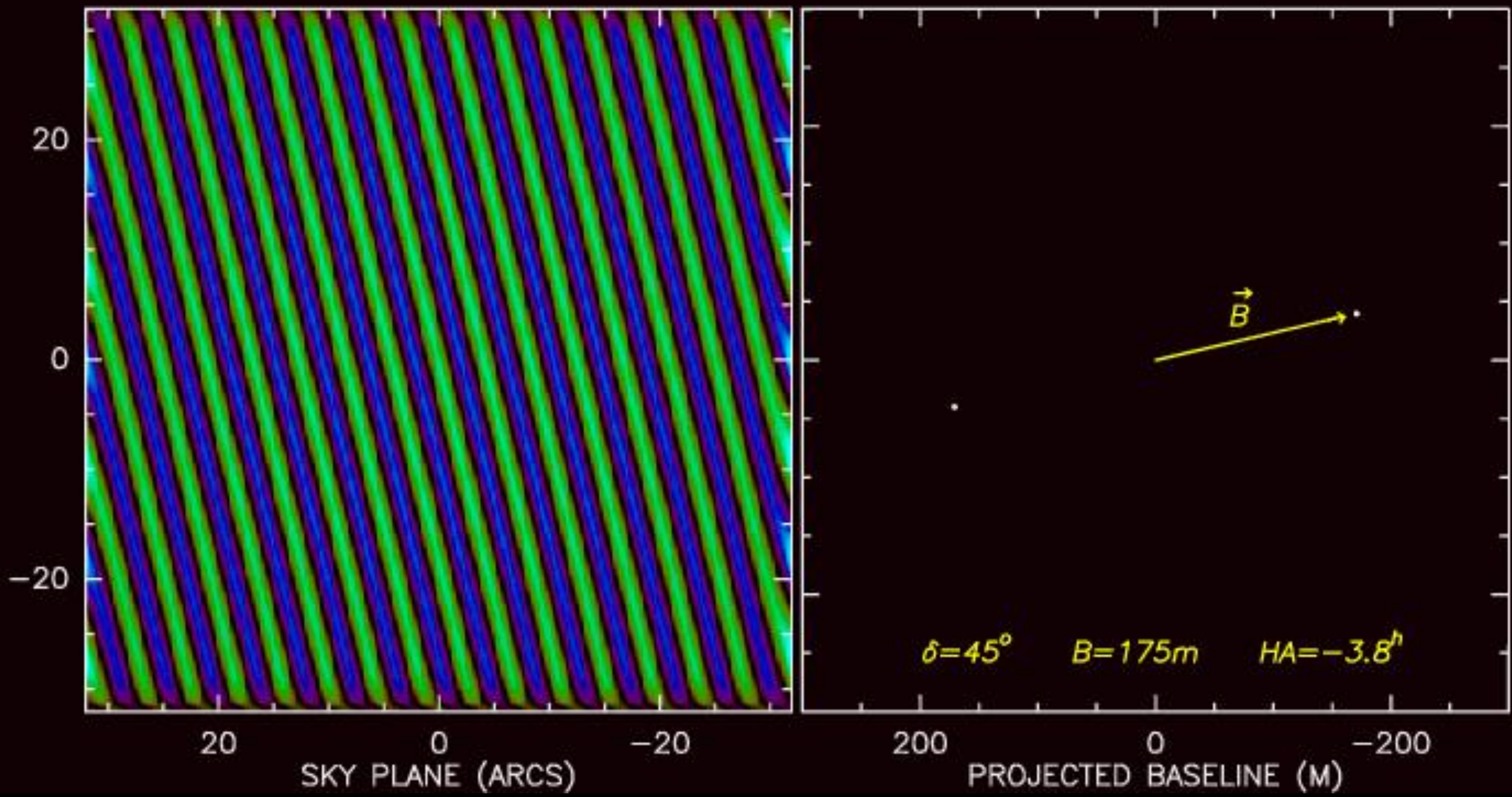
is the technique by which the elements of an interferometer sweep out the aperture of a large telescope



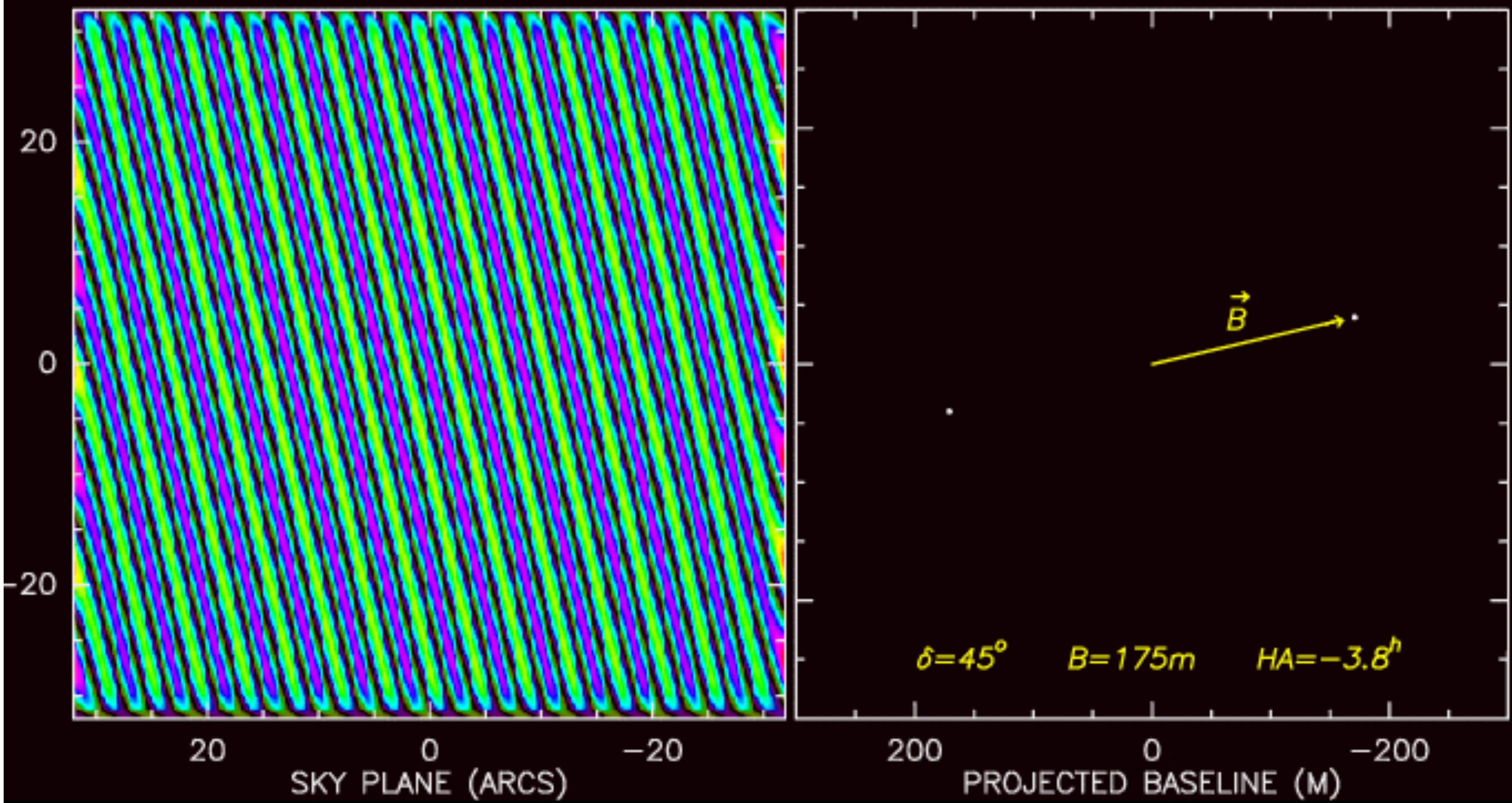
$$\mathrm{OTF} = A(r) \star A(r)$$



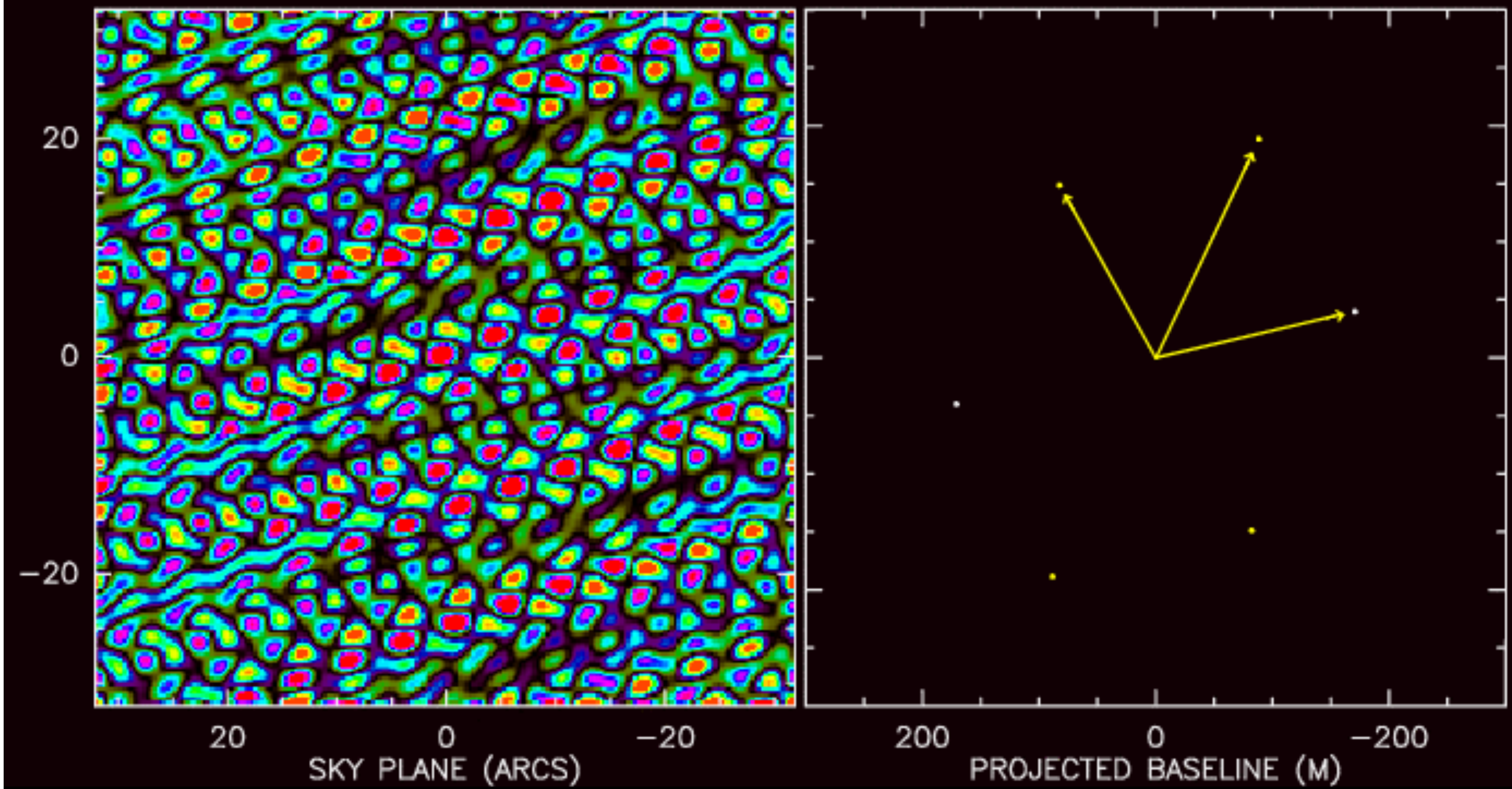
http://www.iram.fr/~neri/ASTRO-A.GIF

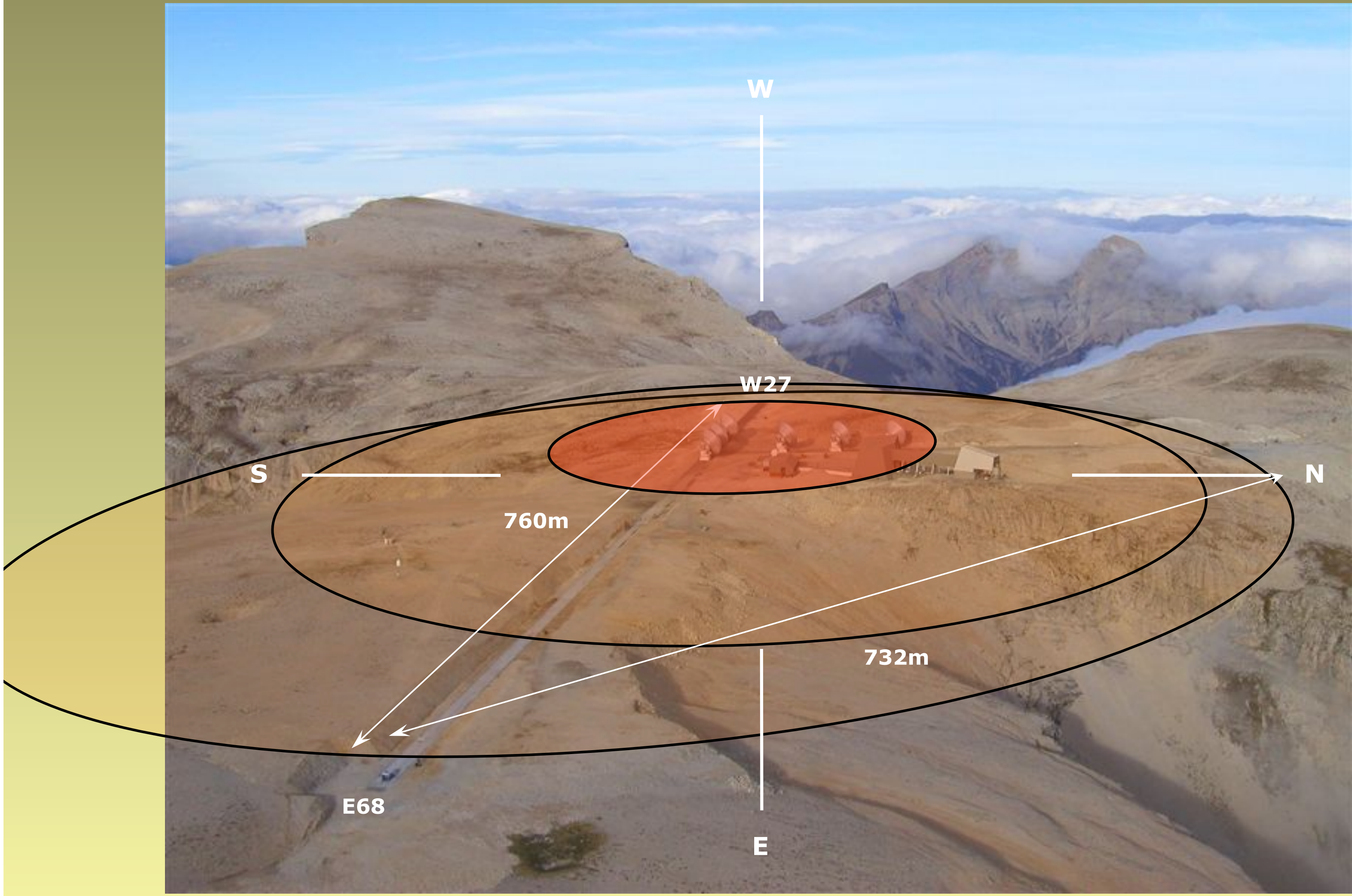


http://www.iram.fr/~neri/ASTRO-B.GIF



http://www.iram.fr/~neri/ASTRO-C.GIF

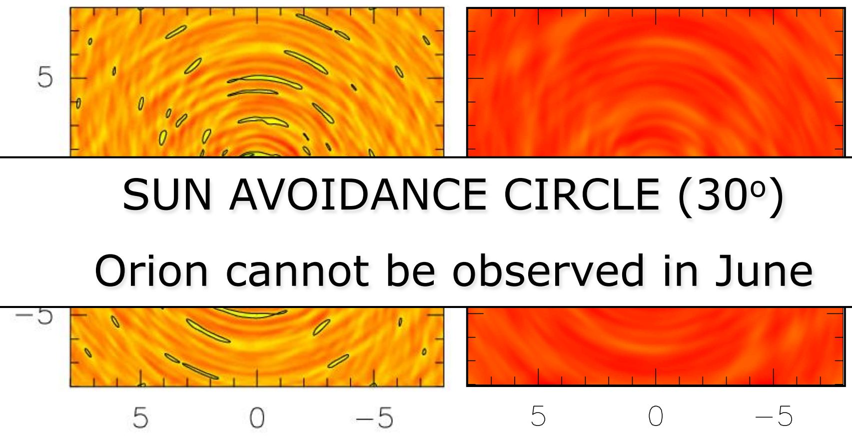



W
W27
S
N
760m
732m
E68
E

NOEMA array configurations

Design: 3 configurations, optimization 40^{o} decl.

Karastergiou et al. 2006



PdBI-
A @ 230

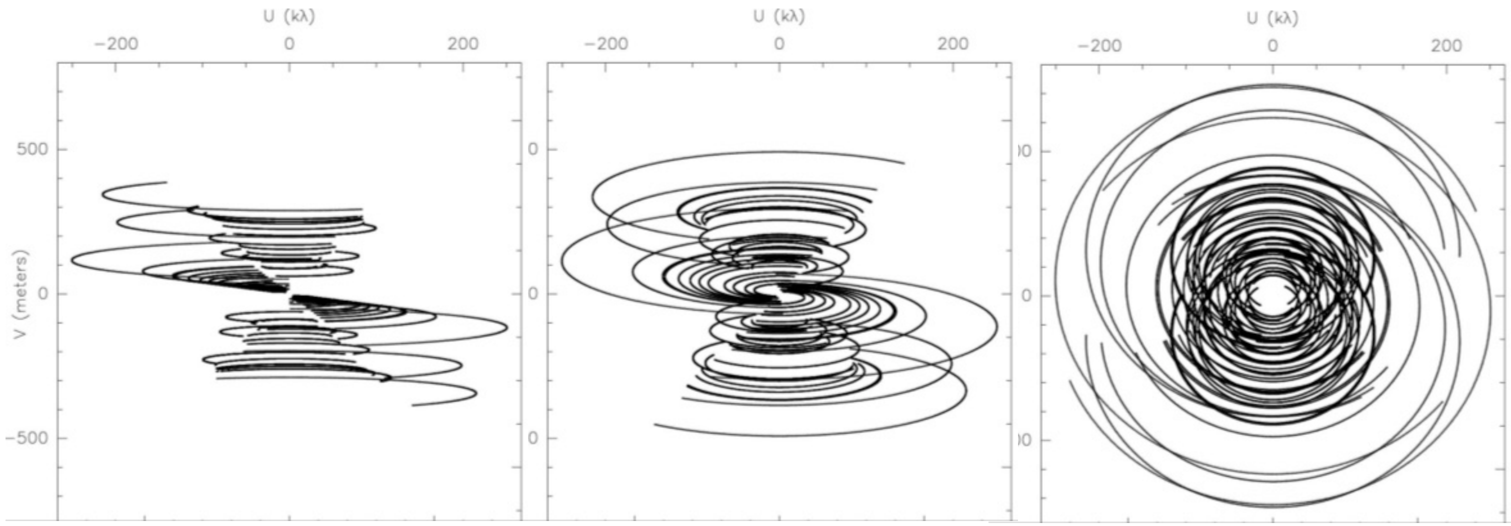
EMA-12
230 GHz

SUN AVOIDANCE CIRCLE (30^{o})

Orion cannot be observed in June

Configurations	D	C	A
Months	Apr – Nov	Mar - Apr Nov - Dec	Jan - Mar
Resolution @ 230 GHz	1.6” NOEMA-10 1.1” NOEMA-12		0.4” NOEMA-10 0.2” NOEMA-12

NEOMA configurations @ 230 GHz
Three Examples



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

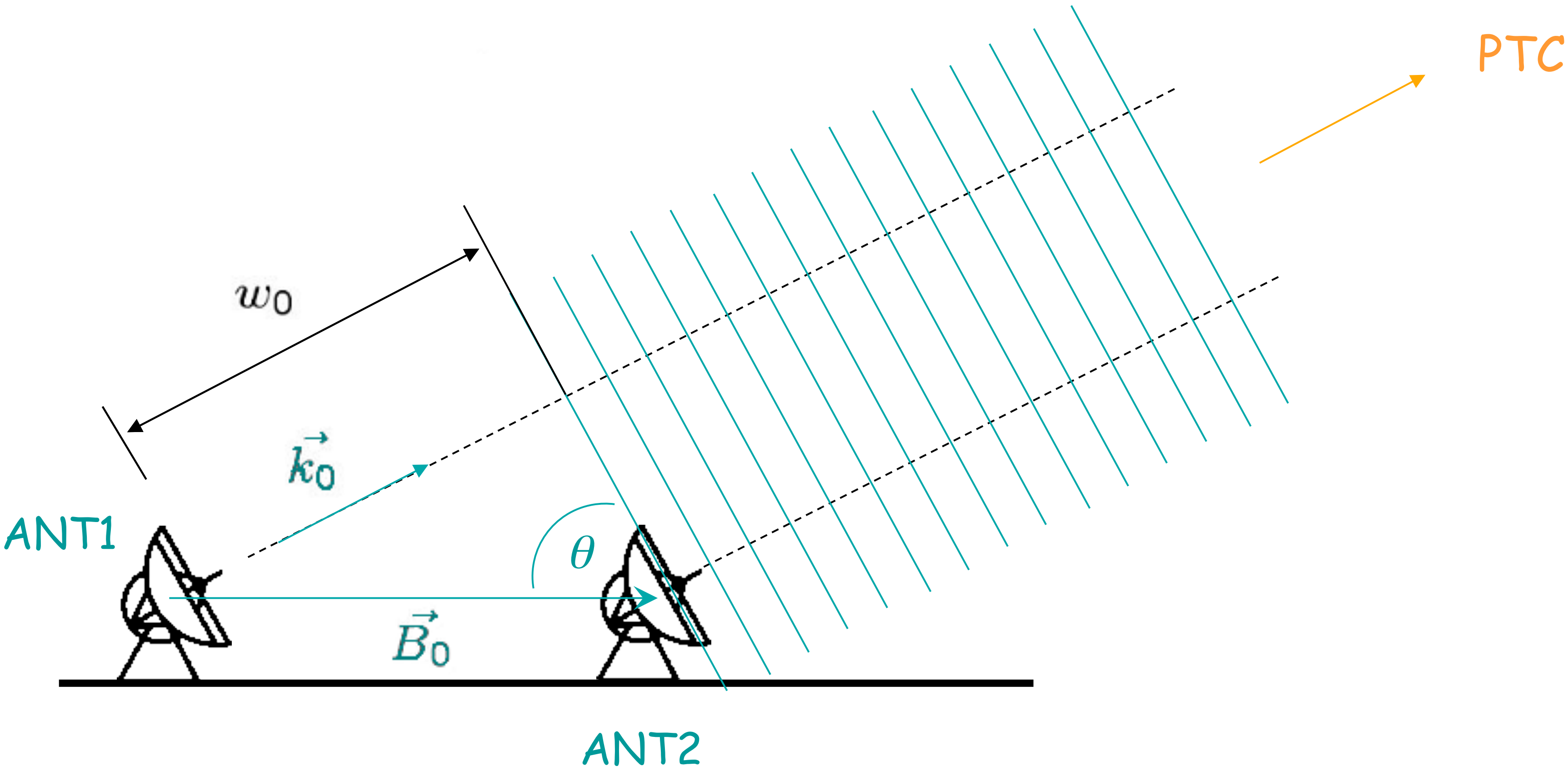
NOEMA - sources of position uncertainty

- mechanical imperfections of an antenna (+subreflector)
- wind effects on the antenna structure
- thermal load on the antenna structure
- atmospheric phase stability
- time and delay errors
- precision in the calibrators absolute position
- SNR of the source
- accuracy of baseline measurements
- ....

The phase equation

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

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



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

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

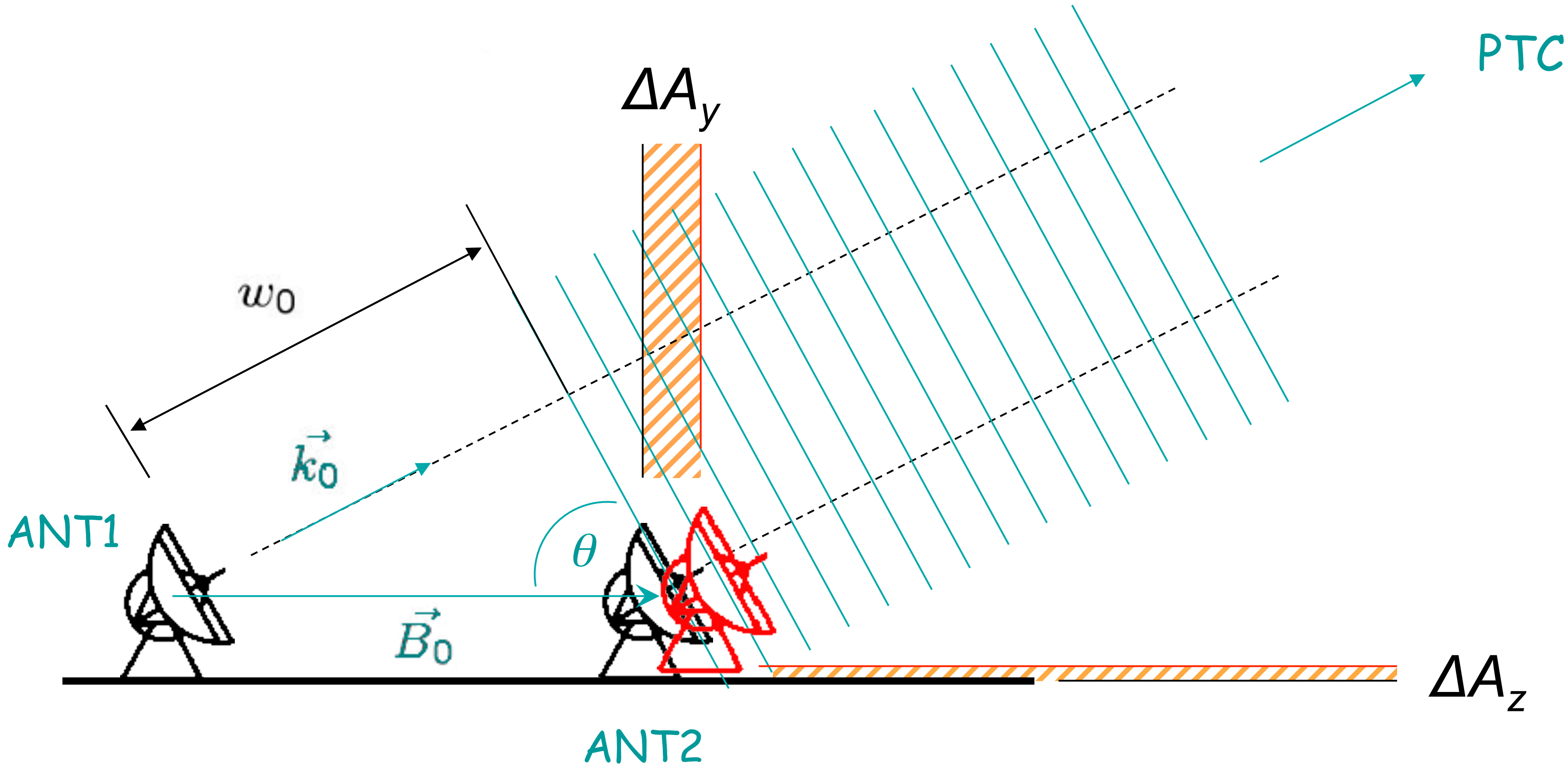
where A is the offset between the azimuth and elevation axis of an antenna.

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.

The phase equation

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

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



$$
\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}]
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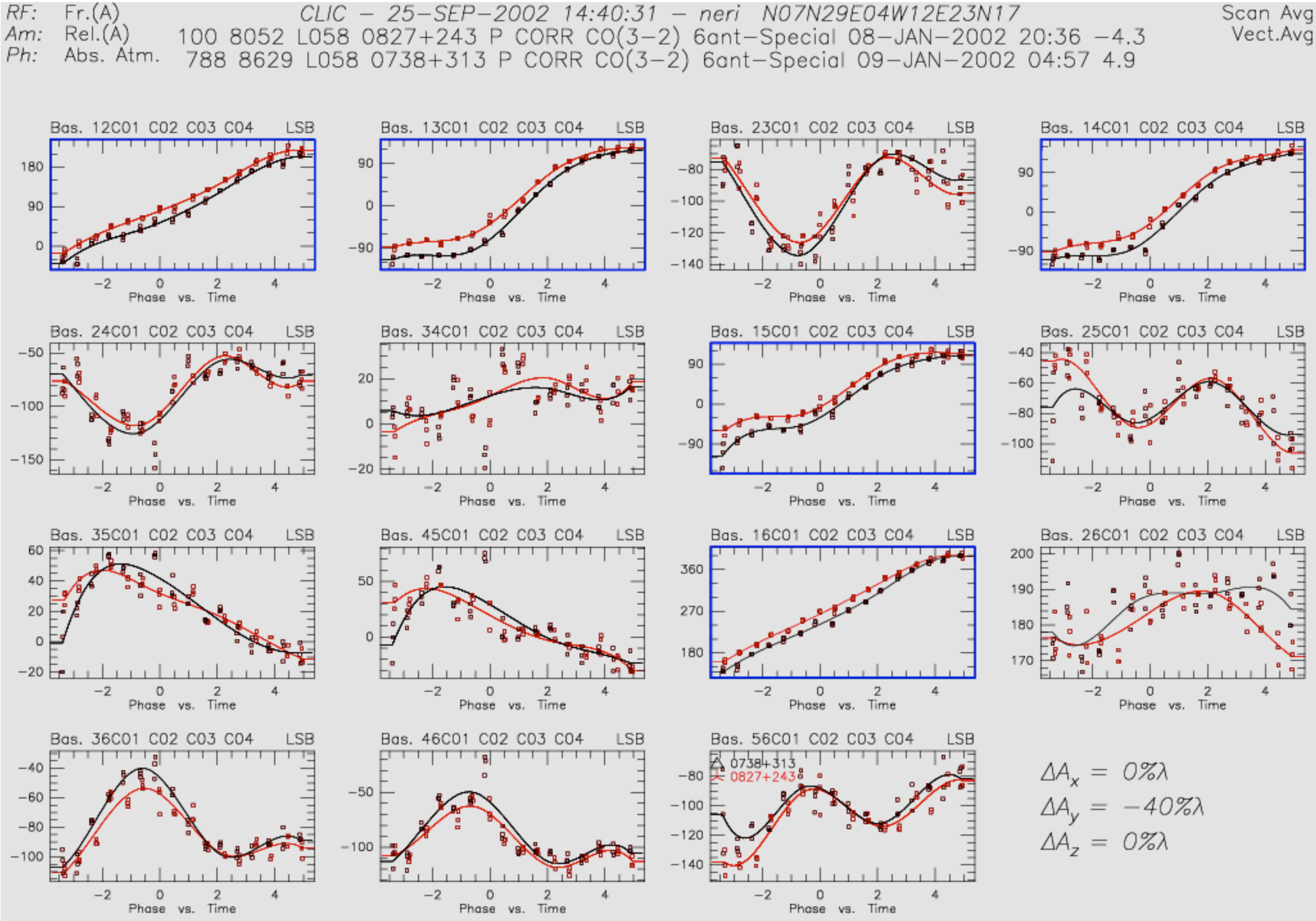
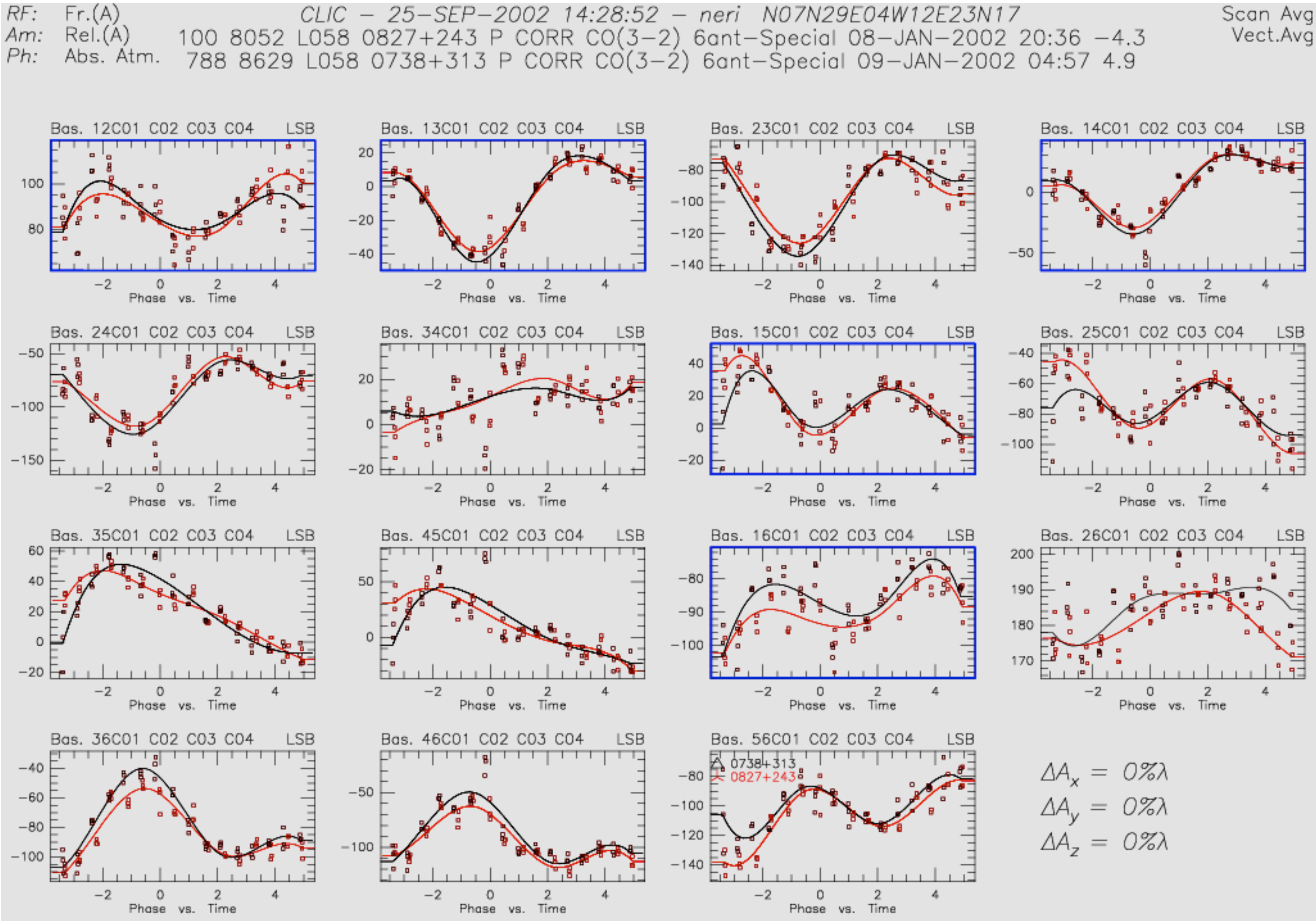

RF: Fr.(A)
Am: Rel.(A)
Ph: Abs. Atm.
CLIC – 25-SEP-2002 14:40:31 – neri N07N29E04W12E23N17
100 8052 L058 0827+243 P CORR CO(3-2) 6ant-Special 08-JAN-2002 20:36 -4.3
788 8629 L058 0738+313 P CORR CO(3-2) 6ant-Special 09-JAN-2002 04:57 4.9
Scan Avg
Vect.Avg
Bas. 12C01 C02 C03 C04 LSB
Bas. 13C01 C02 C03 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

NOEMA - sources of position 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

NOEMA - sources of position 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