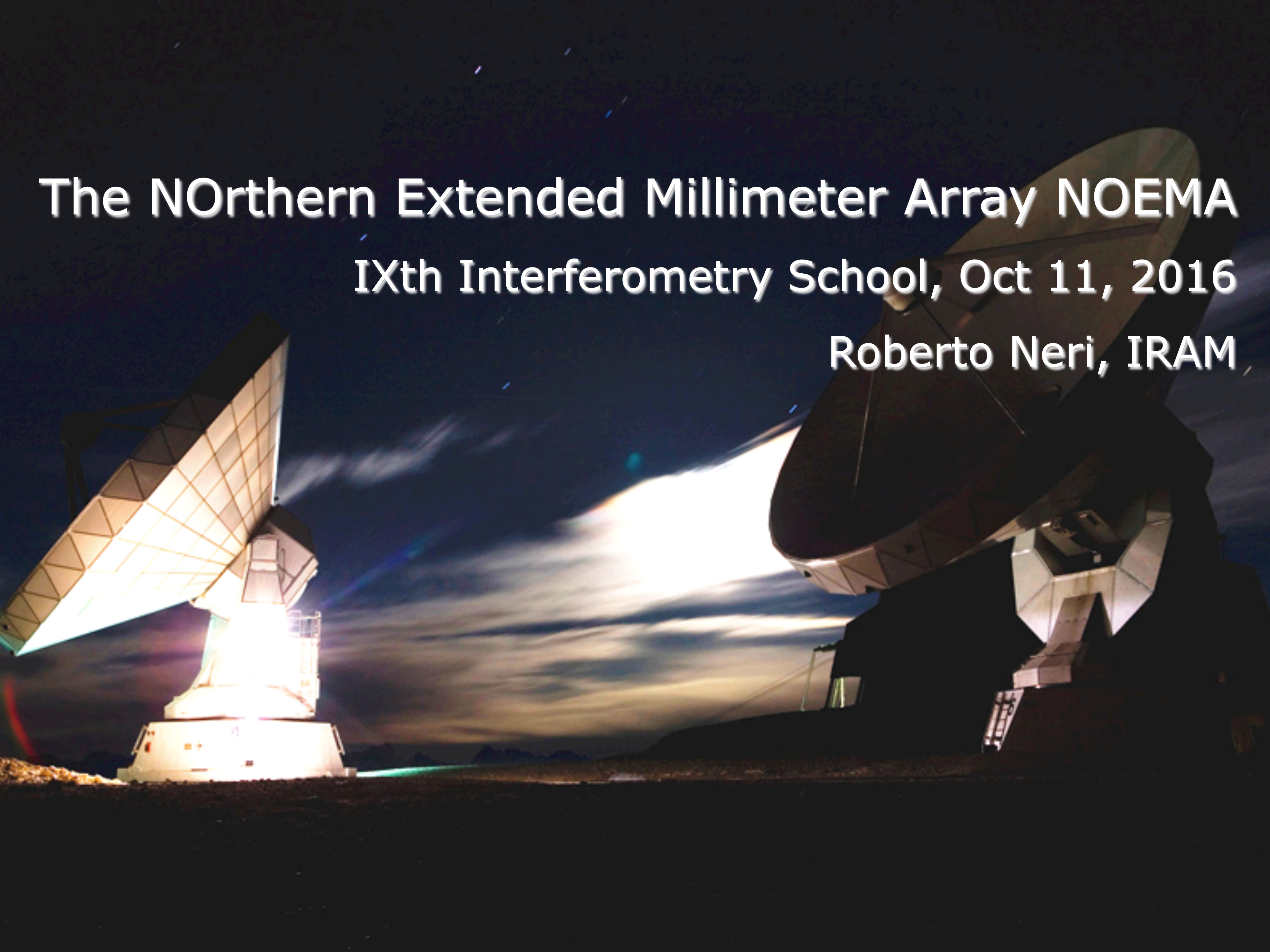
The NOrthern Extended Millimeter Array NOEMA

IXth Interferometry School, Oct 11, 2016

Roberto Neri, IRAM



The NOrthern Extended Millimeter Array NOEMA

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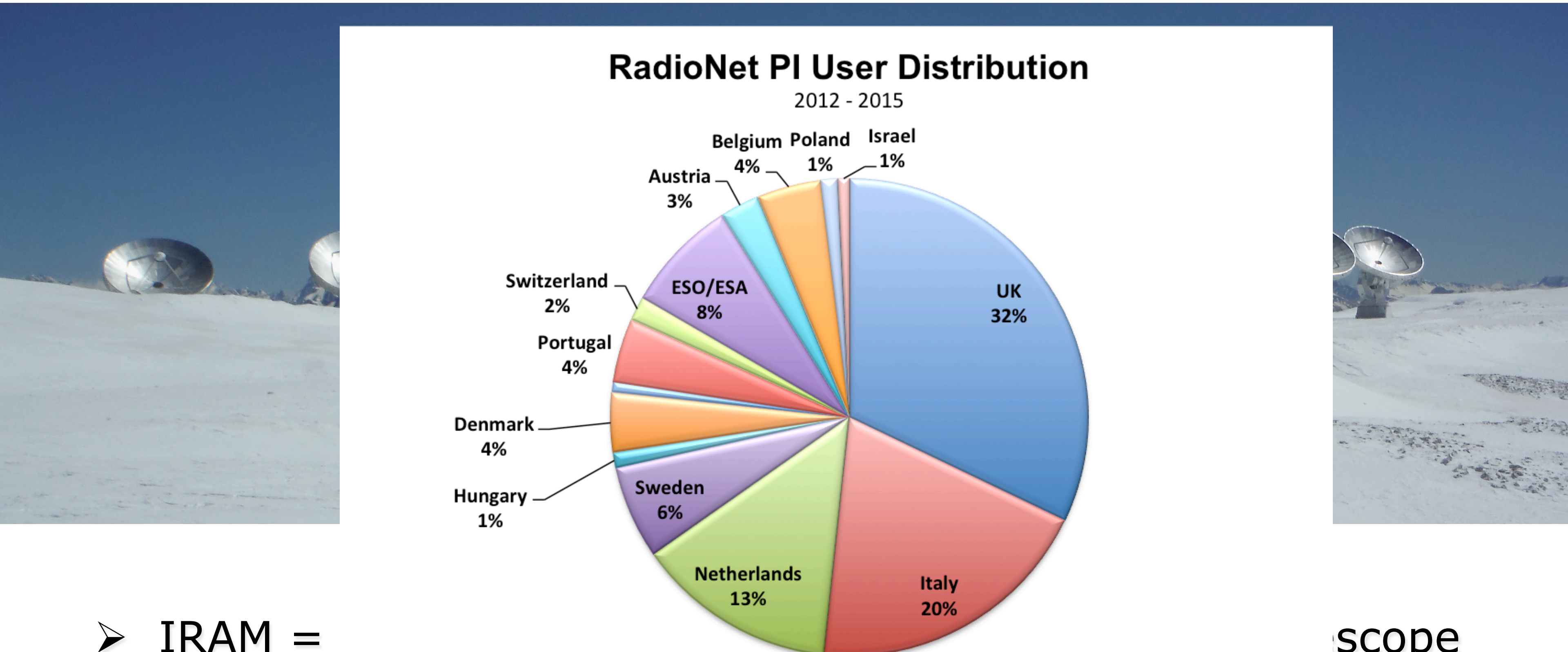
1. a general overview
2. instrumentation (receivers, correlators)
3. sensitivity considerations
4. position considerations

A view on the NOEMA Observatory

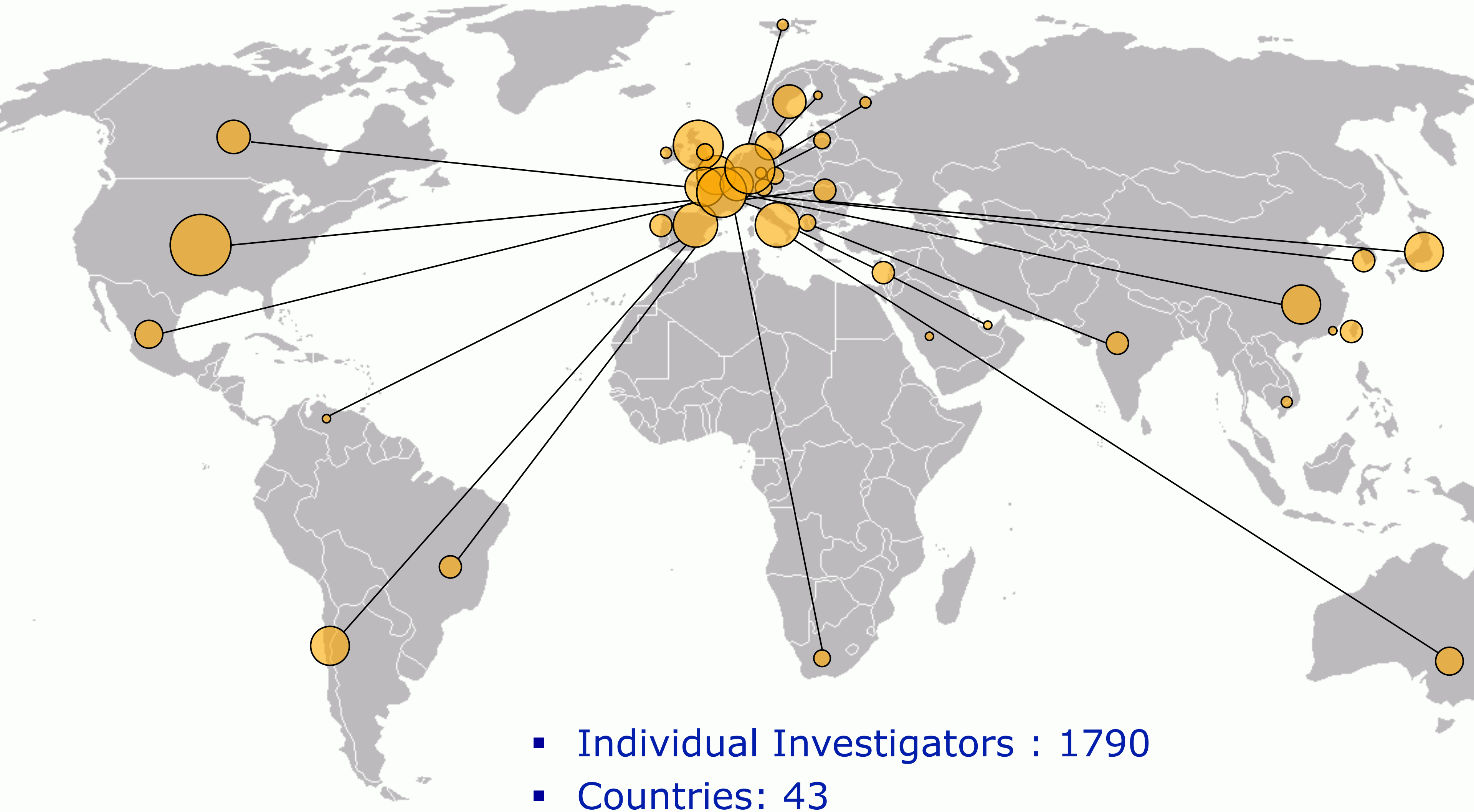
- IRAM = two observatories : NOEMA + IRAM 30m-telescope
- three partners: CNRS, MPG, IGN
- open time (up to 15%), RadioNet4

A view on the NOEMA Observatory



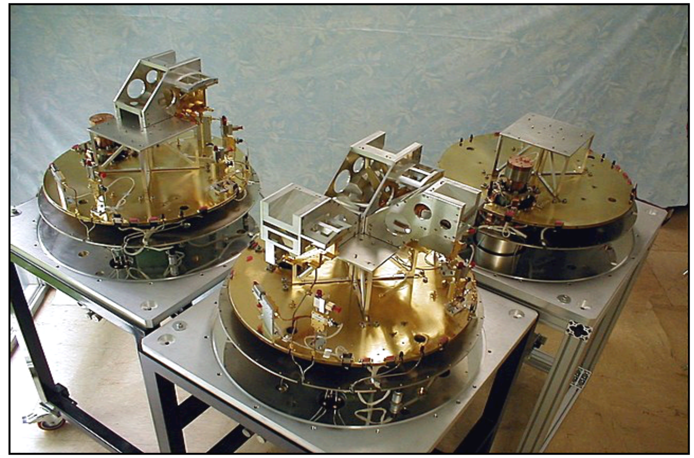
- IRAM = … scope
- three pa
- open time (up to 15%), RadioNet4

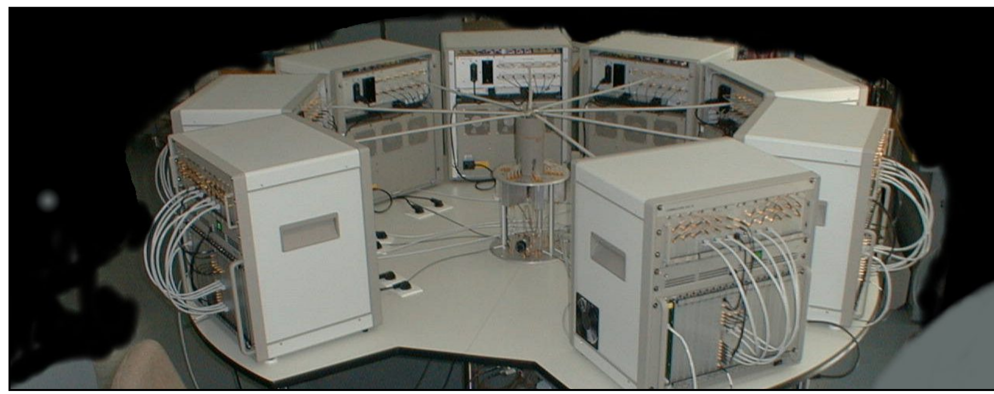
INVESTIGATORS DISTRIBUTION MAP
2010 – 2016



- Individual Investigators : 1790
- Countries: 43

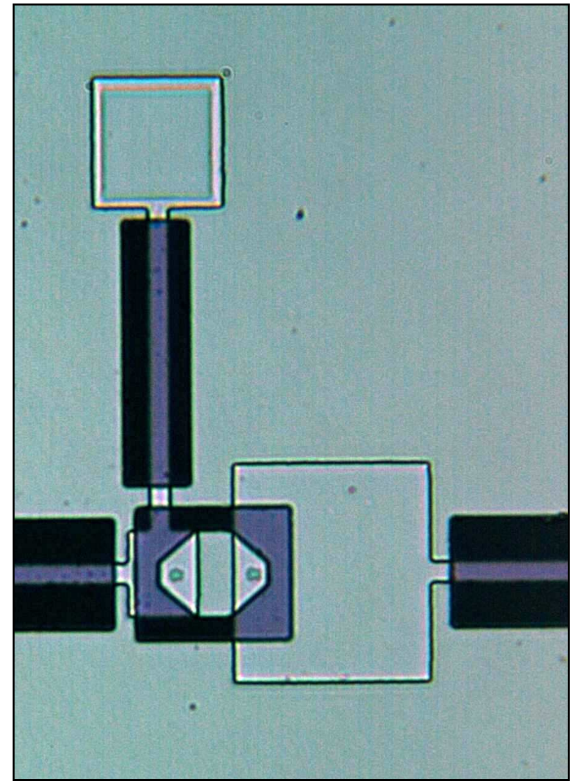
IRAM's expertise: pictures worth a thousand words





- Telescope design (~30 um), construction and operation
- Receiver design and development e.g. ALMA Band7, AETHRA
- HS-digital backends + LO systems e.g. PolyFix (32 GHz)

IRAM's expertise: pictures worth a thousand words

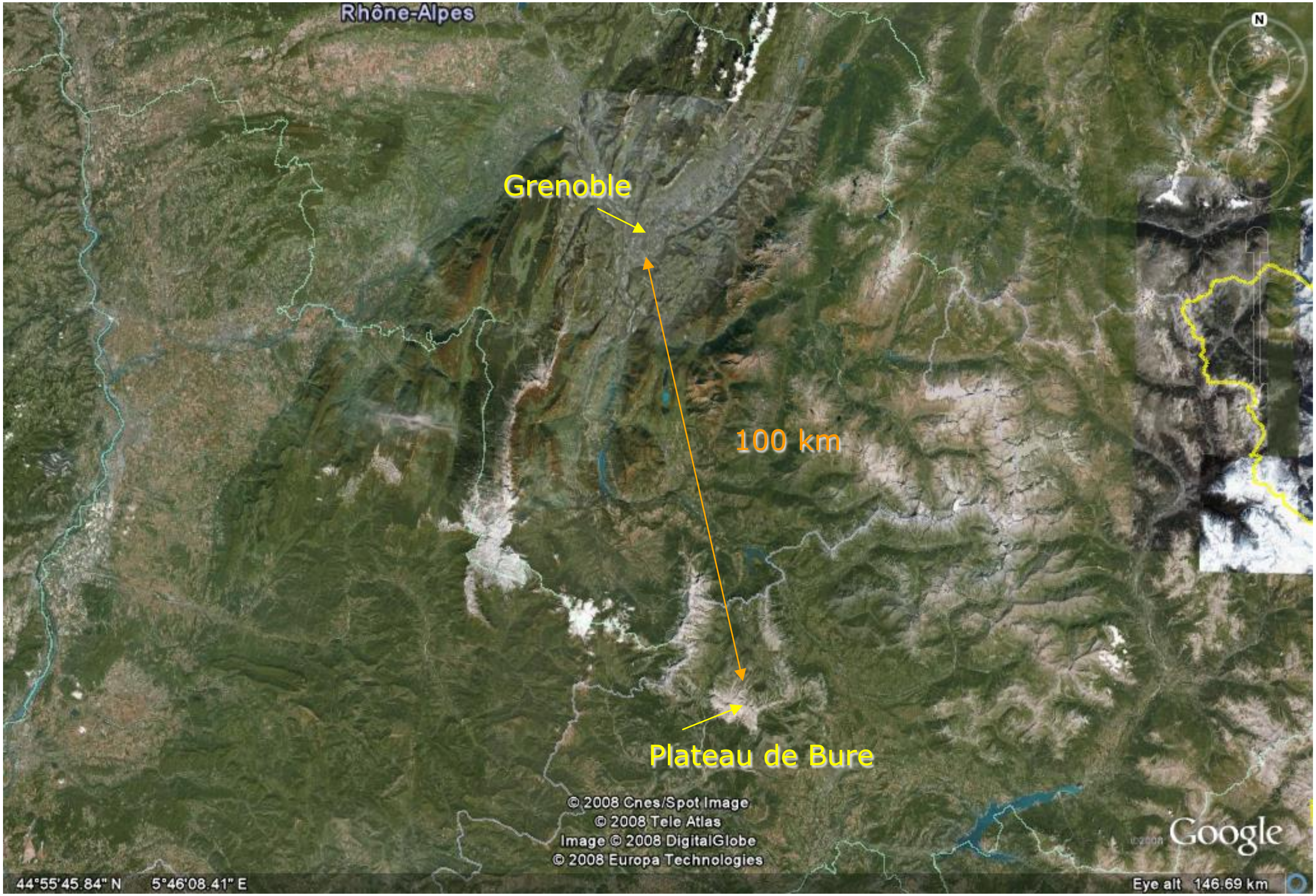


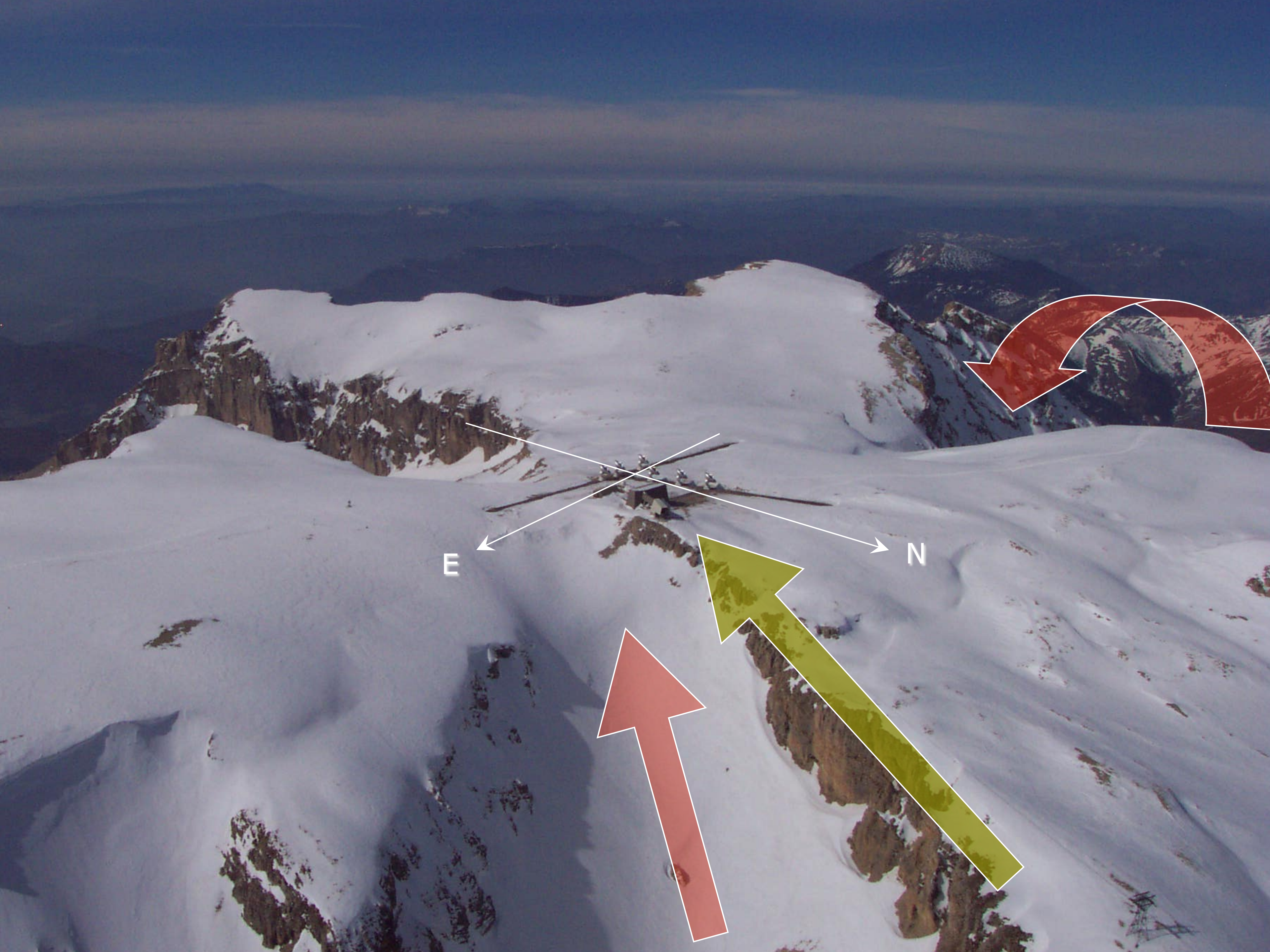
- Class 100 clean room for thin film technology
- complete mm/THz-wave technology laboratory
- developments for e.g. Herschel

progress timeline

Semester	Project	Done
W05/06	EW/NS track extensions	✔
W06/07	band 1 + band 3	✔
W07/08	band 2	✔
W09/10	WIDEX	✔
W10/11	band 4	✔
S12	double-array mode	✔
S13	LO reference system	✔
2015	N7 + 2SB receivers #1, #2	✔
2016	N8 + 2SB receivers #3, #4, #5, #6	(✔)
2017	POLYFIX + N9 + N10	

2016	N8 + 2SB receivers #3, #4, #5, #6	(✔)
2017	POLYFIX + N9 + N10	

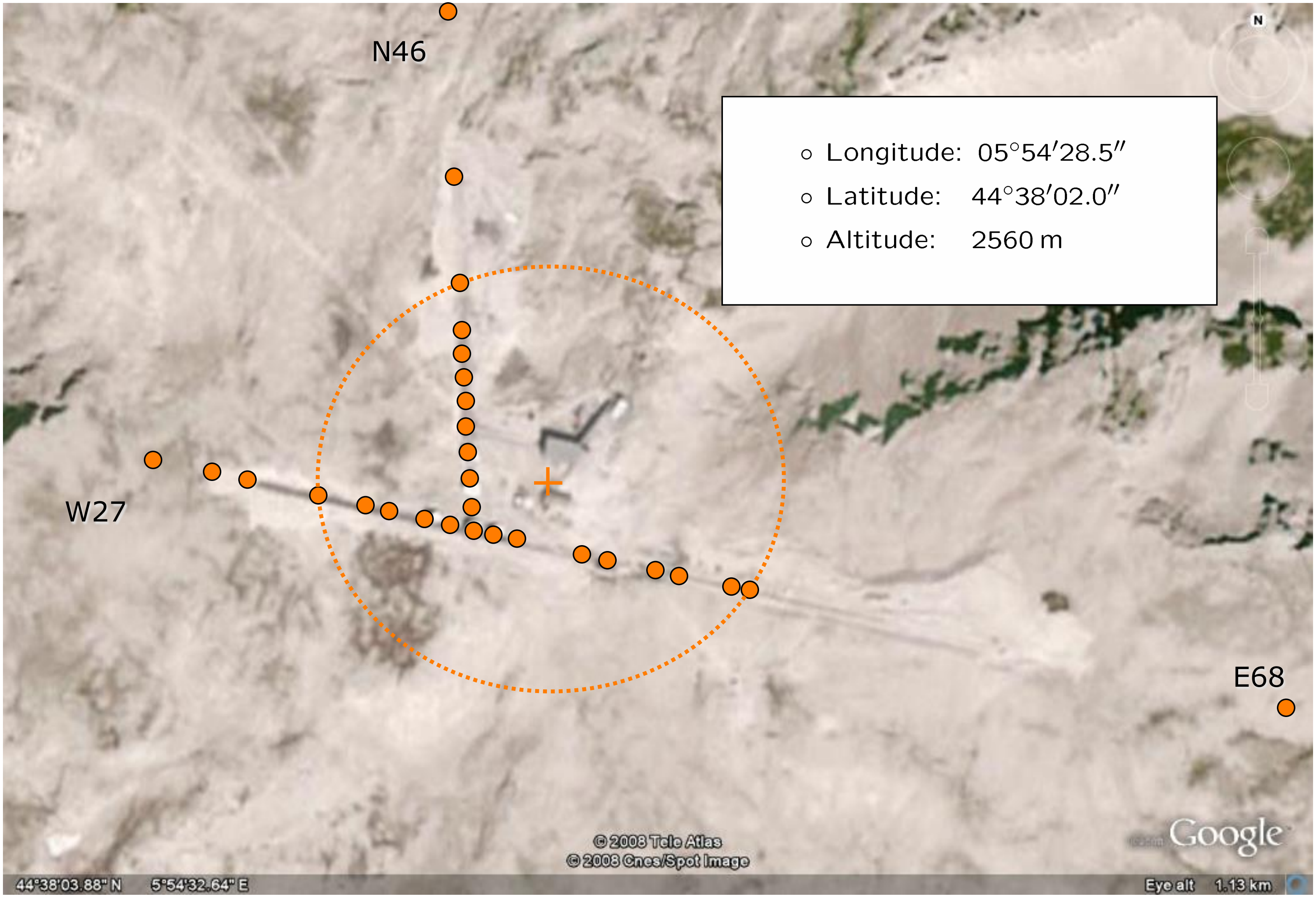

Rhône-Alpes
Grenoble
100 km
Plateau de Bure
© 2008 Cnes/Spot Image
© 2008 Tele Atlas
Image © 2008 DigitalGlobe
© 2008 Europa Technologies
Google
44°55'45.84" N
5°46'08.41" E
Eye alt 146.69 km


E
N

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



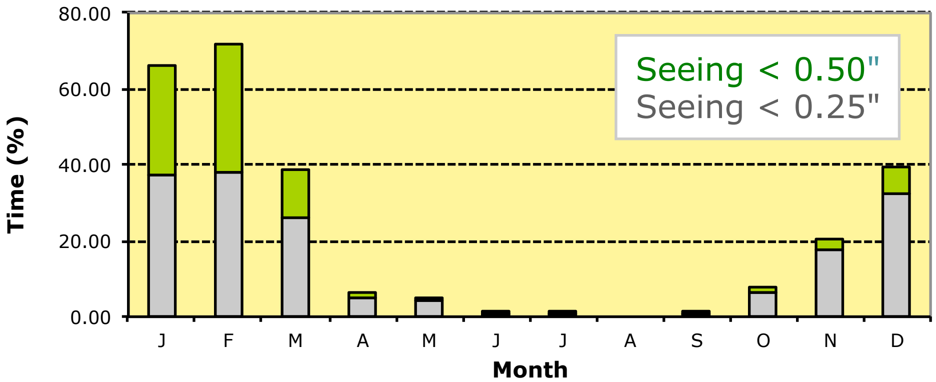
N46
W27
E68
○ Longitude: 05°54′28.5″
○ Latitude: 44°38′02.0″
○ Altitude: 2560 m
© 2008 Tele Atlas
© 2008 Cnes/Spot Image
Google
44°38'03.88" N 5°54'32.64" E
Eye alt 1.13 km

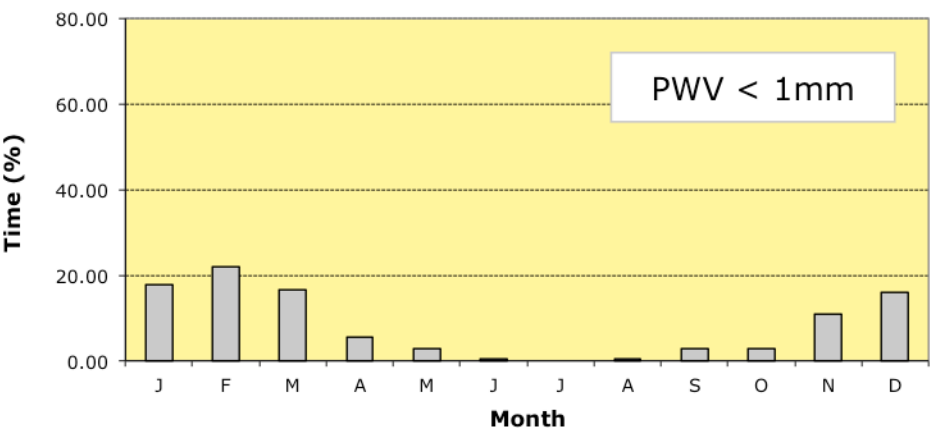
NOEMA site

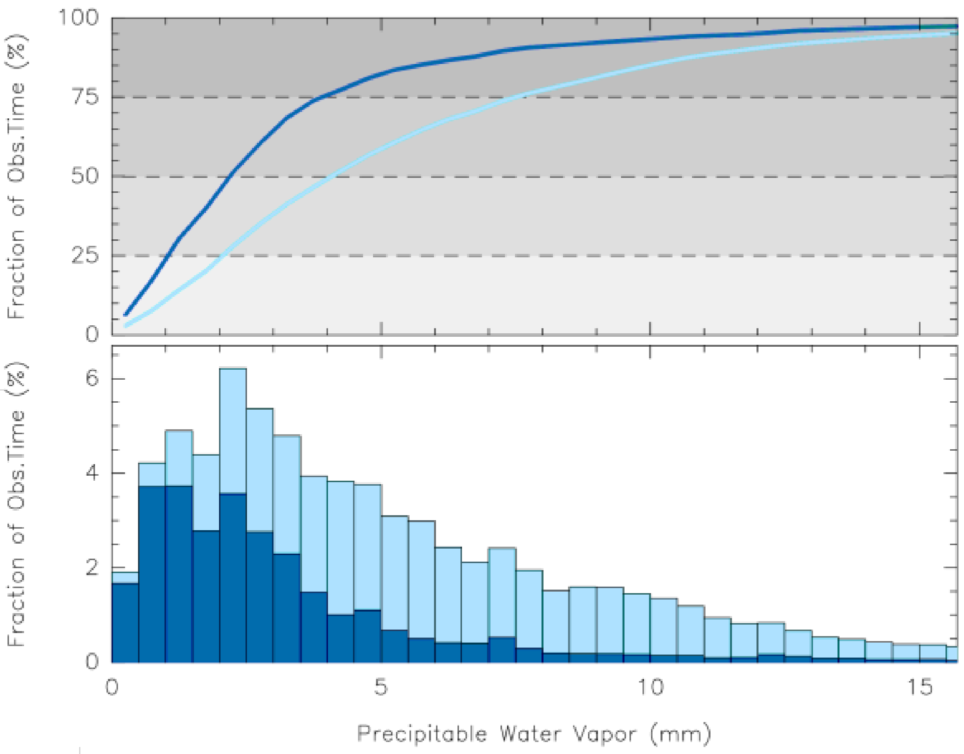
- Latitude : 05°54' 28.5"
- Longitude : 44°38' 02.0"
- Altitude : 2560 m
- RFI protection : terrain shielding + NRQZ (30 km)

- Water vapor : 40% (<3mm); 25% (<1mm) in winter
  down to 0.3mm in best winter conditions
  submm conditions ~5 % of the time
- Weather downtime : 25 - 35%

some weather statistics







⇨ 2015: 80% of the observing time invested @ B1-3mm and B2-2mm

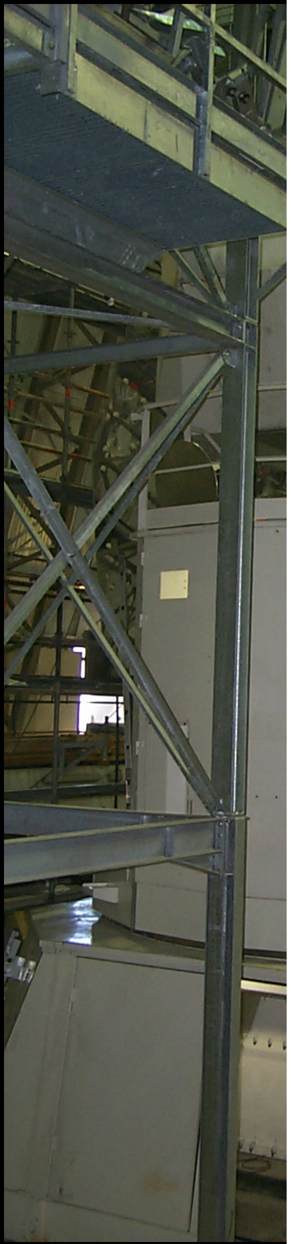
NOEMA observatory

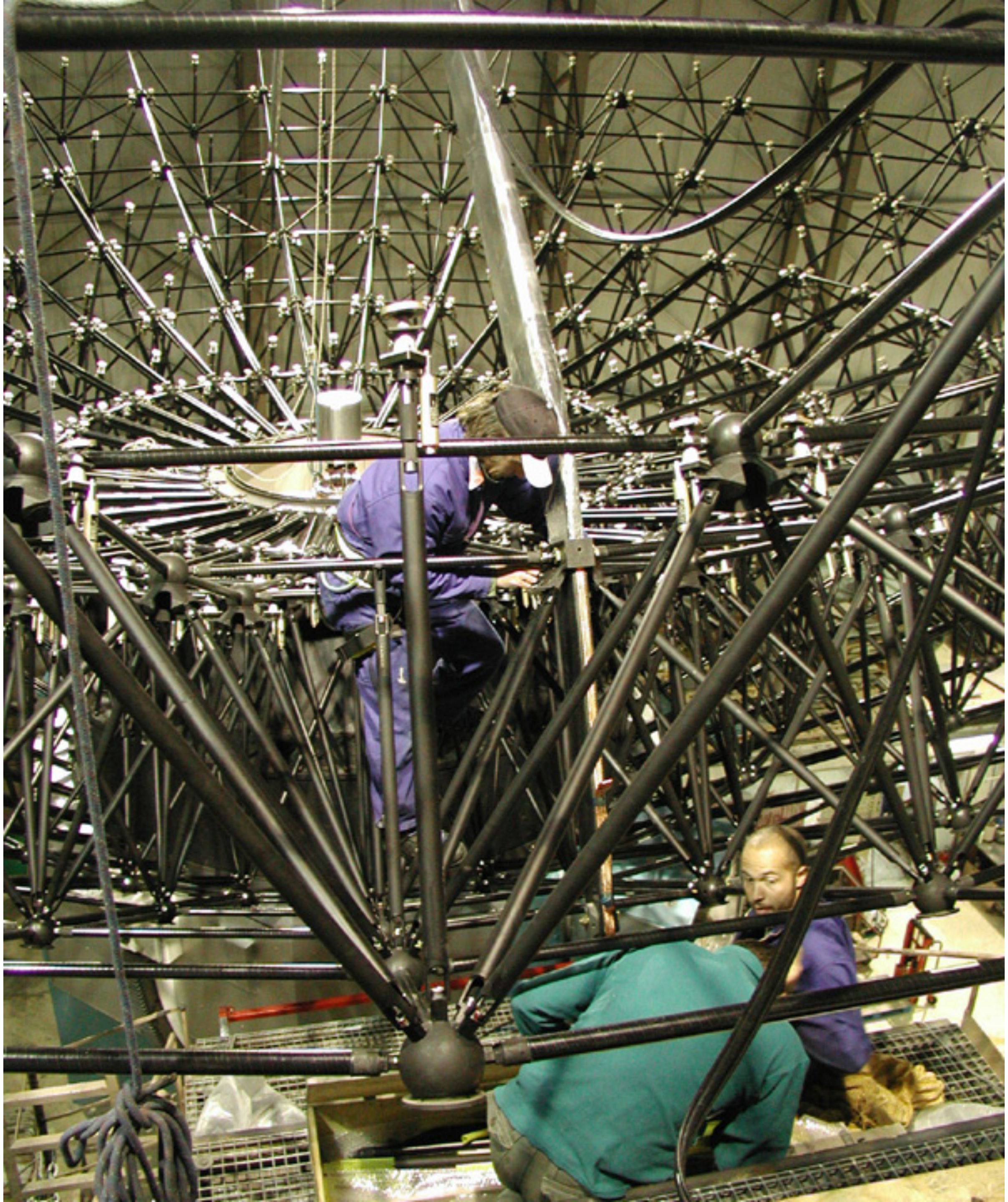
- Operation : 24 hrs, 365 days, service mode
  staff @ Bure + SOG @ Grenoble
- Team @ site : 6 staff members (incl. astronomer)
- Working schedule : 1 team per week, every 3 weeks

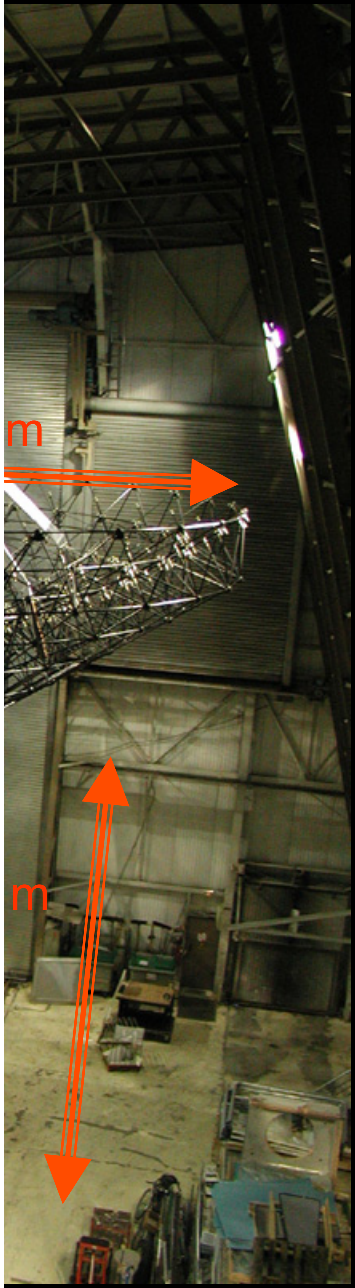
- VLBI @ 3mm : 5 days sessions, twice a year (GMVA)
  1mm intercontinental with ALMA in the future

NOEMA antennas

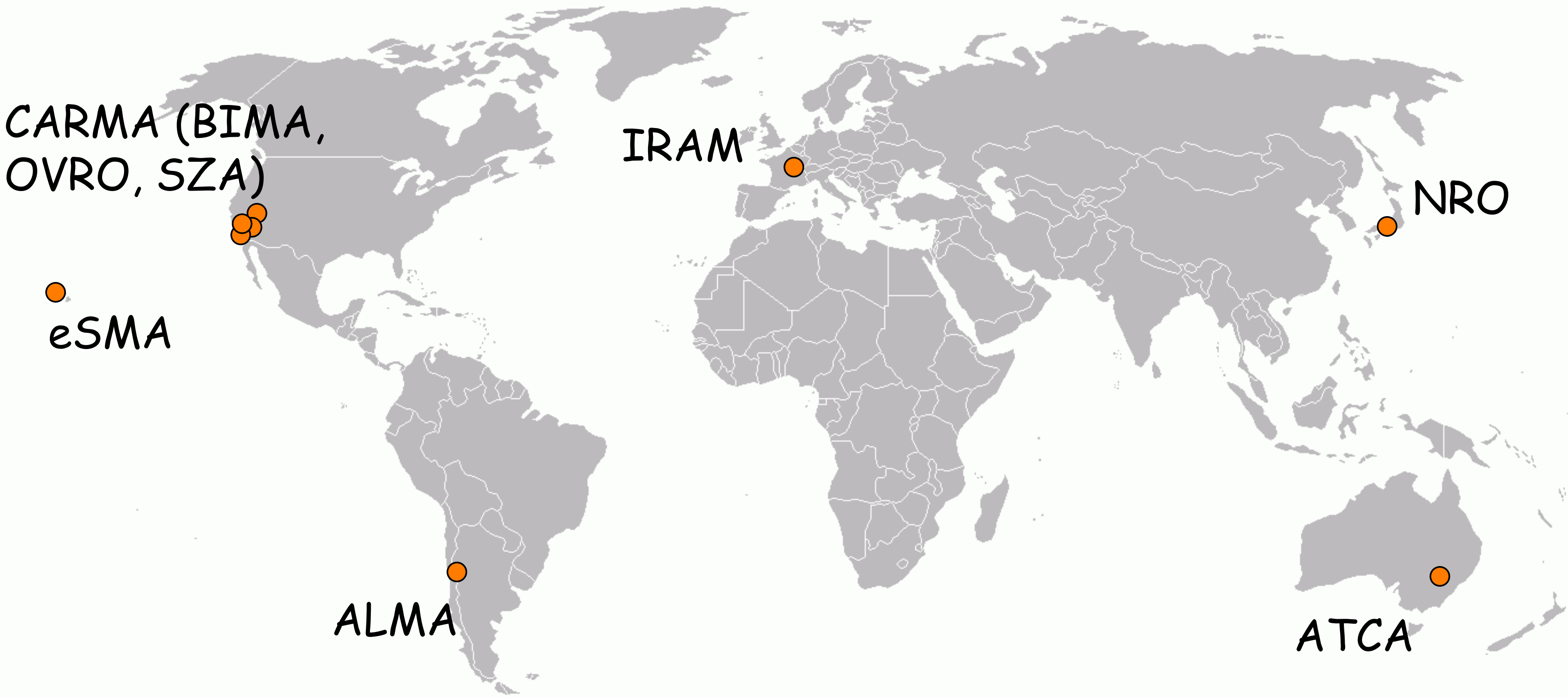
- antennas : 8, Cassegrain type
- collecting area : $177 m^2 \times 8 = 1416 m^2$ (2016)
- surface panels : 176, aluminum
- surface accuracy : 25 - 40 μm
- aperture efficiency : 0.65 @ 230 GHz
- primary beam : 21” @ 230 GHz
- pointing / tracking RMS : 1.5” / 0.2“
- wind speed (max) : 14 m/s



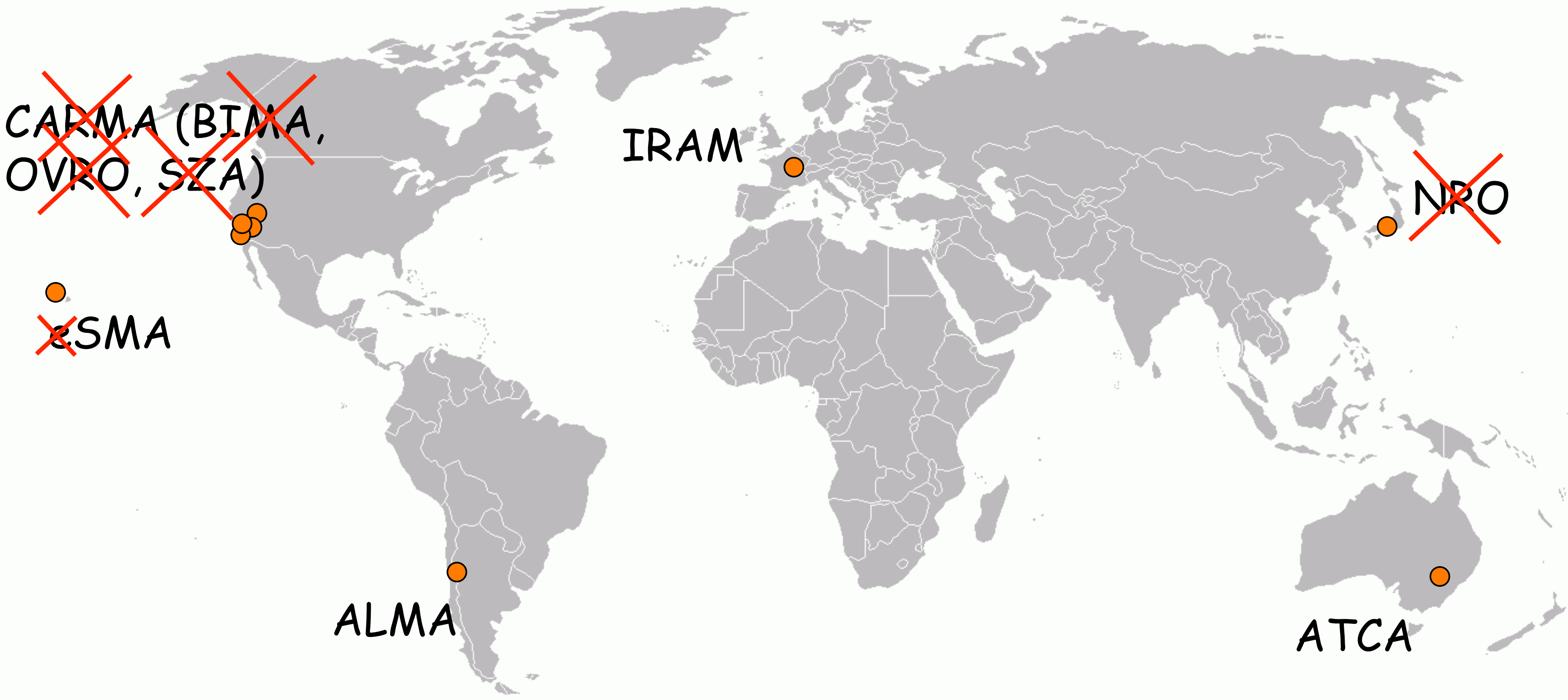



m
m

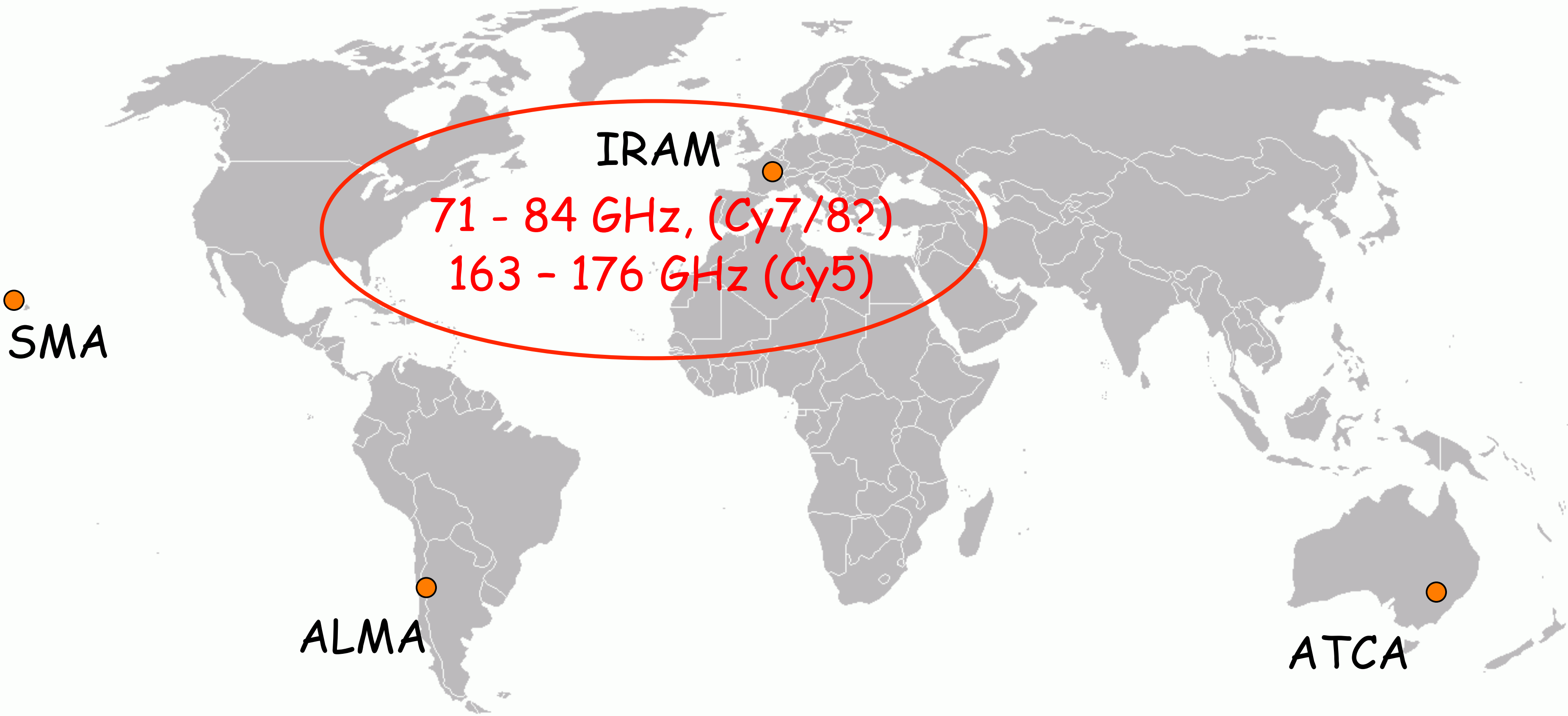
(sub)mm-interferometers worldwide (2010)

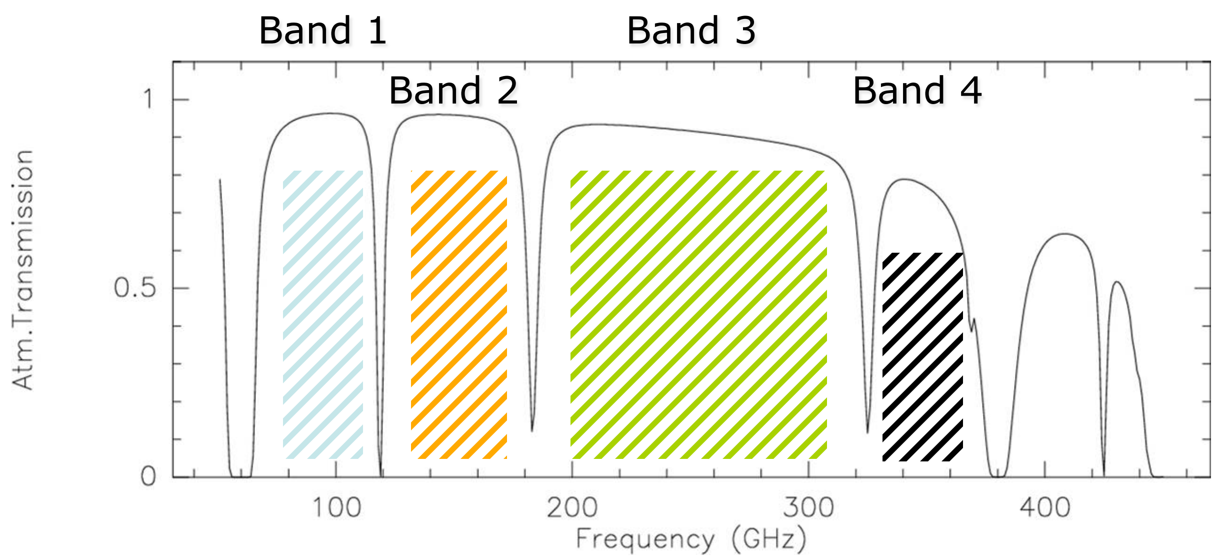


(sub)mm-interferometers worldwide (2016)



(sub)mm-interferometers worldwide (2016)

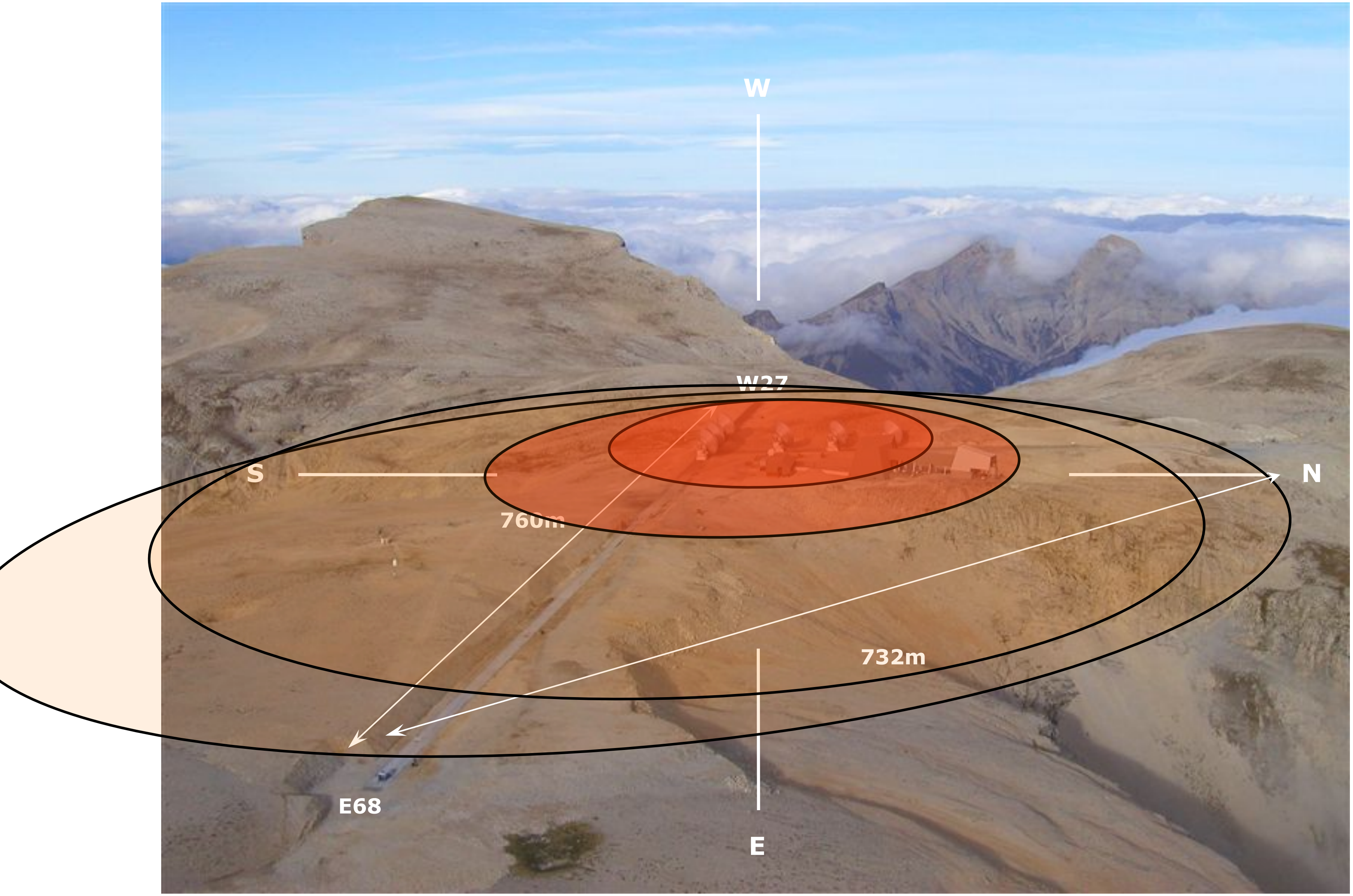




3mm = 100 GHz   2mm = 150 GHz   1mm = 300 GHz   0.8mm = 350 GHz

Interferometer	Atmospheric window	Ang.Resolution
ATCA	3mm	1.6" @ 105 GHz
NOEMA	3mm, 2mm, 1mm, 0.8mm	0.2" @ 300 GHz
SMA	1mm, 0.8mm, 0.4mm	0.15" @ 690 GHz
ALMA	3mm 1mm ⇨ Band 10	0.03" @ 350 GHz

Large differences !

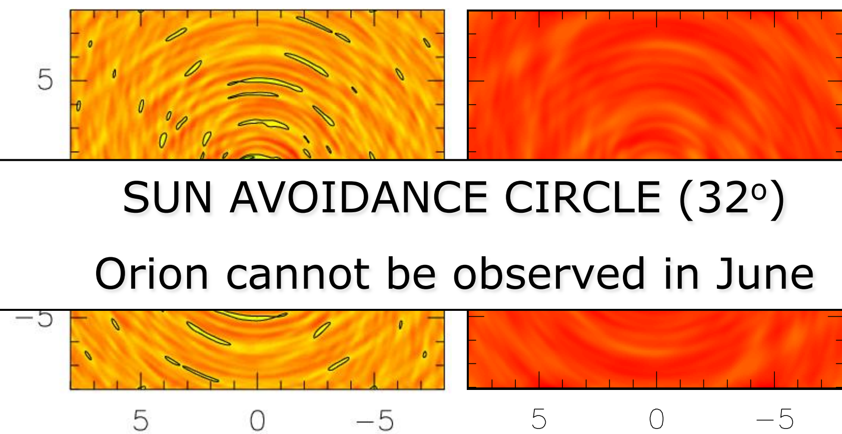

W
W27
S
N
760m
732m
E68
E

NOEMA array configurations

Design: 3 configurations, optimization 40^o decl.

Boissier 2016

PdBI-
A @ 230

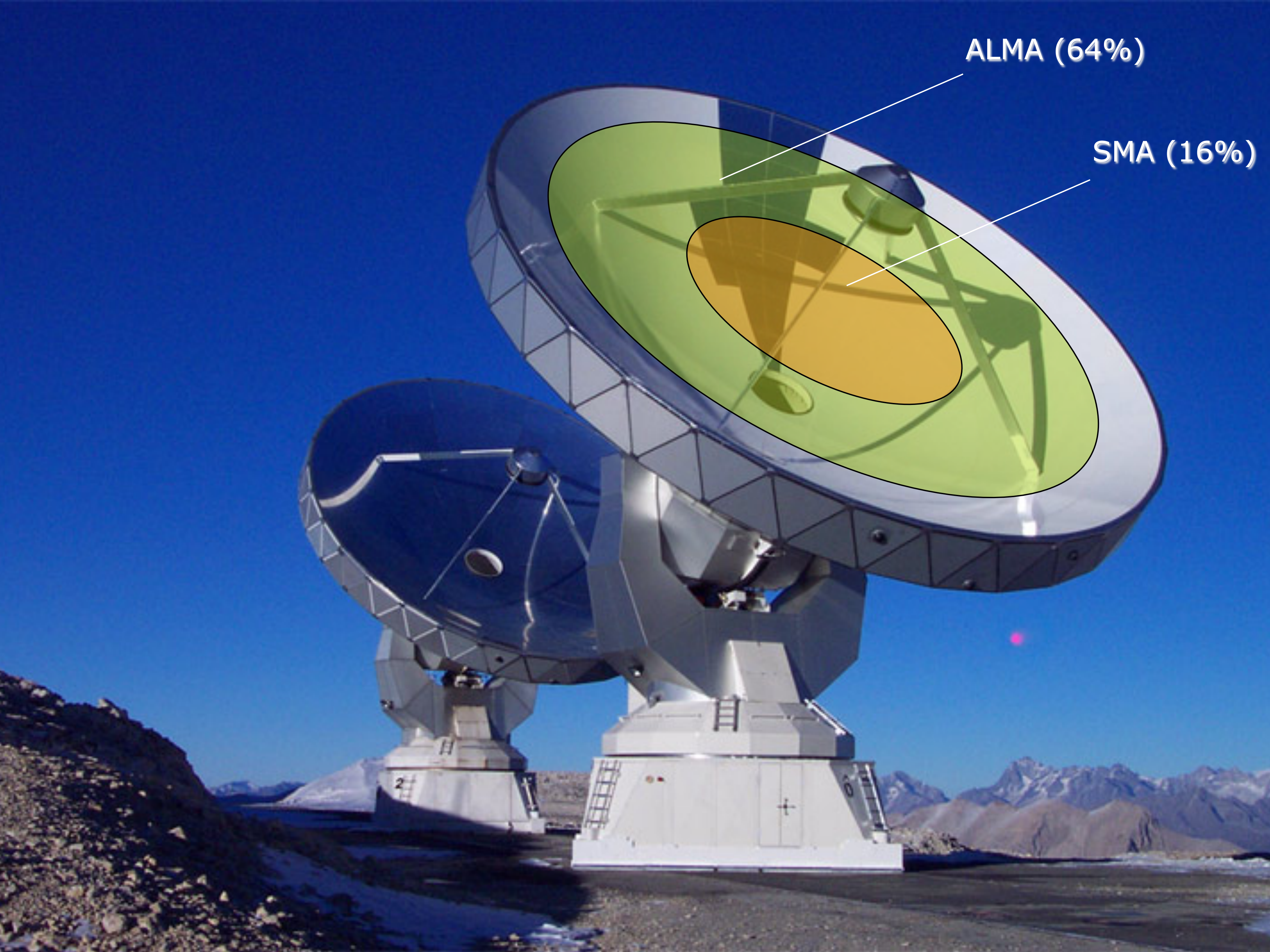


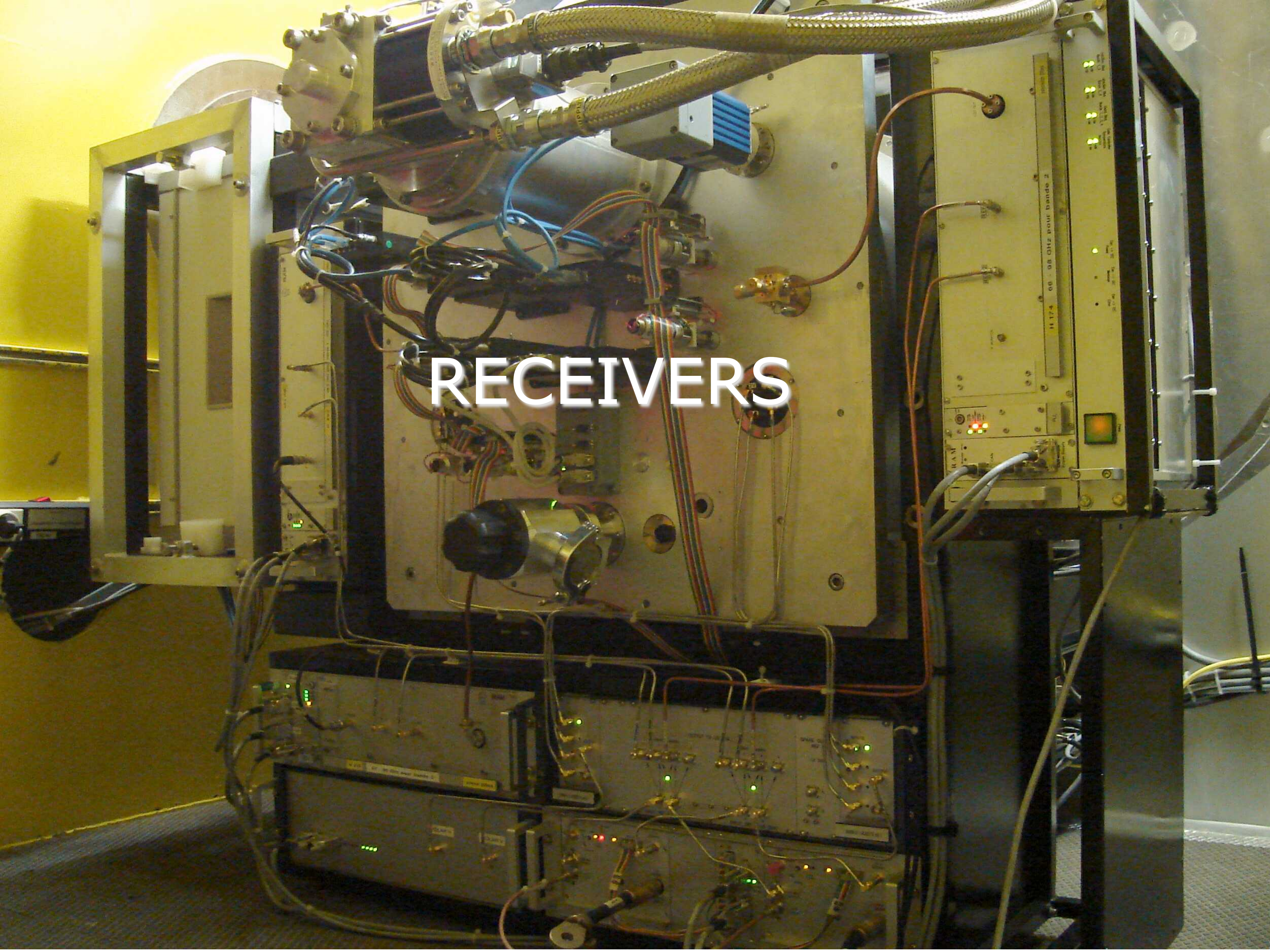
EMA-10
230 GHz

SUN AVOIDANCE CIRCLE (32^o)

Orion cannot be observed in June

Configurations	D	C	A
Months	Apr – Nov	Mar - Apr Nov - Dec	Jan - Mar
Resolution @ 230 GHz	2″		0.3″-0.4″ 0.2″ (2018/2019)


ALMA (64%)
SMA (16%)


RECEIVERS
H 174 68 - 98 GHz pour bande 2

NOEMA state of the art receiver technology

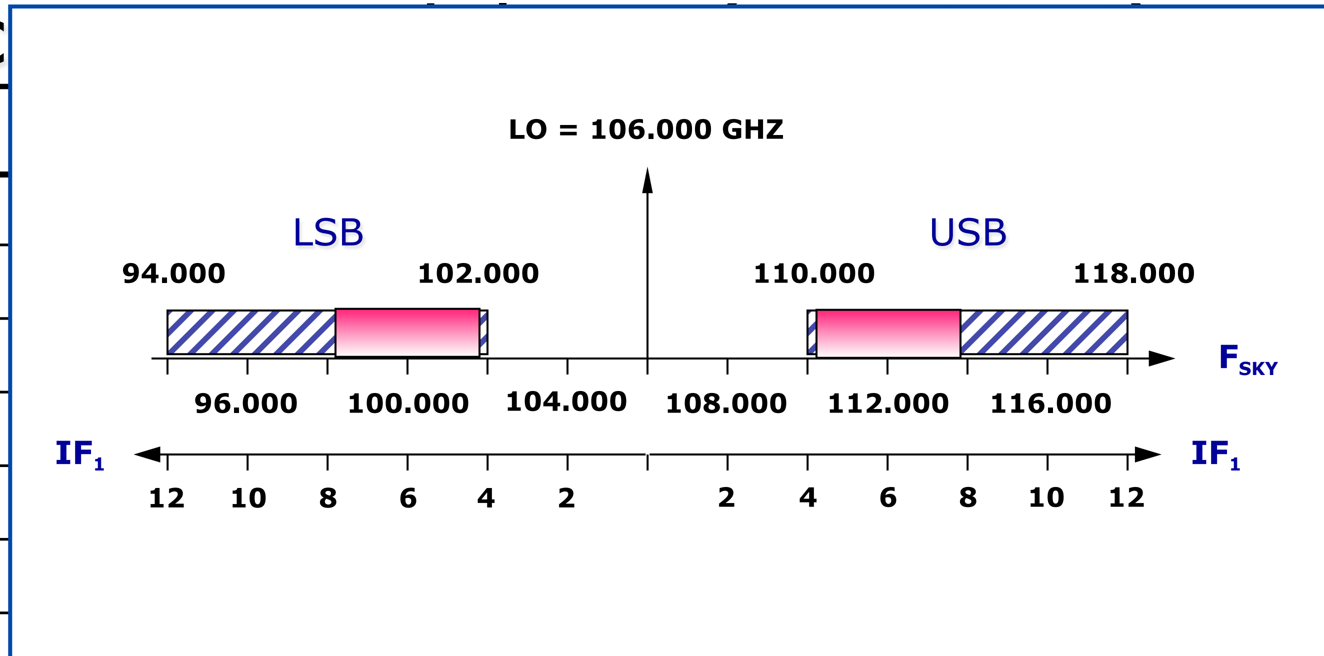
- closed cycle cryocoolers ⇨ no liquid He refills
- SIS mixers ⇨ 8 GHz Band in each polarization
  ⇨ USB and LSB operation (2SB)
- fully reflective optics ⇨ lower loss
- design optm ⇨ high density, best EMI control, simplified wiring
- tuneless mixers and LOs for band 4 ⇨ simplified frequency tuning and switching

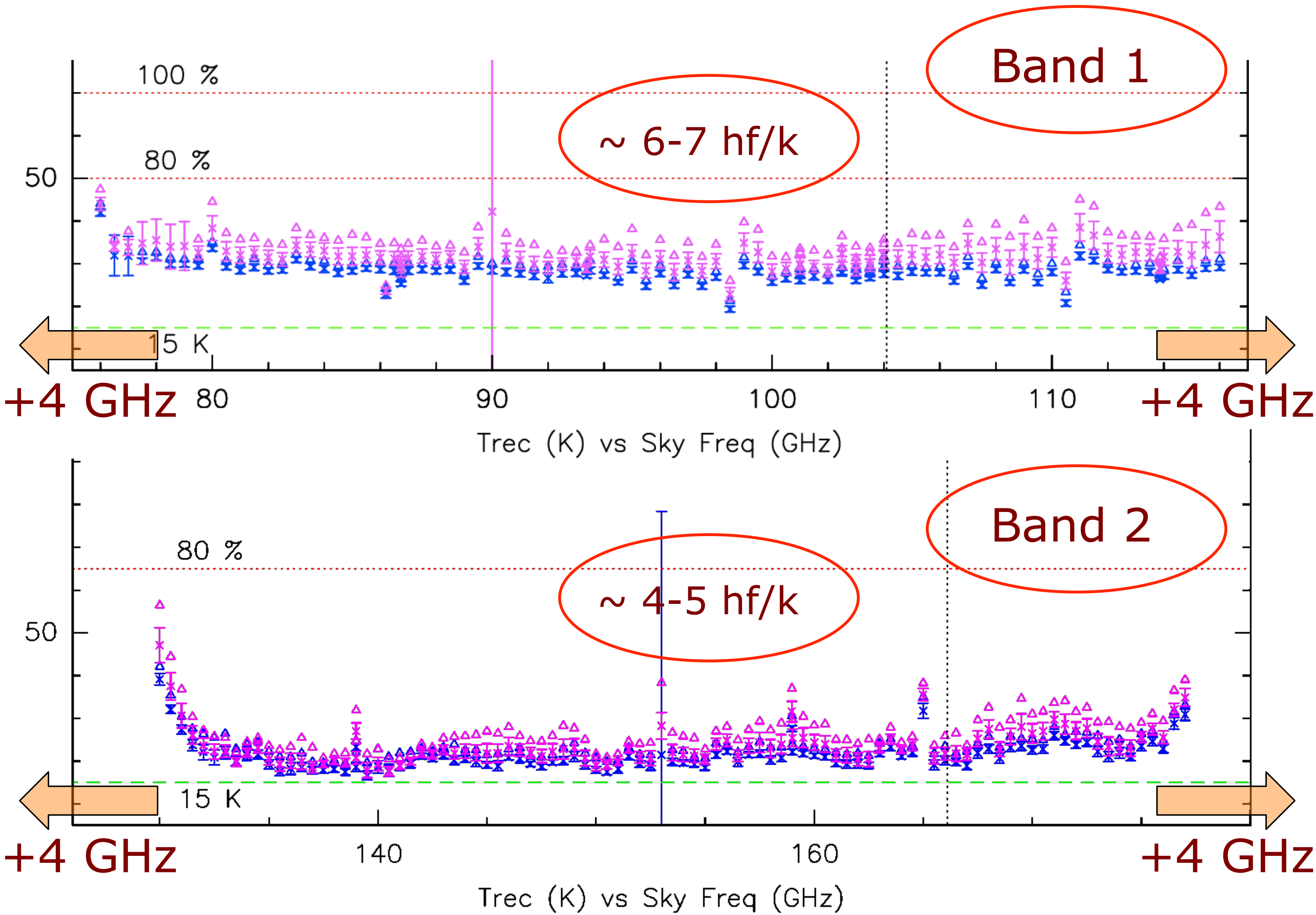
SEP 2016 = 6 ANTENNAS EQUIPPED

DEC 2016 = ALL ANTENNAS EQUIPPED WITH 2SB RECEIVERS

NOEMA rec

Item		
RF bands		
WVR radiometer		
B1 = ALMA Band 3		
B2 = ALMA Band 4		
B3 = ALMA Band 6		
B4 = ALMA Band 7		
RF response	2SB mixers	LSB and USB image gain <-10dB
IF band	4 – 12 GHz	total of 32 GHz
Polarization	dual linear	circular also possible
Observing mode	single frequency dual polarization	second band in standby potential for Dual freq, Dual pol



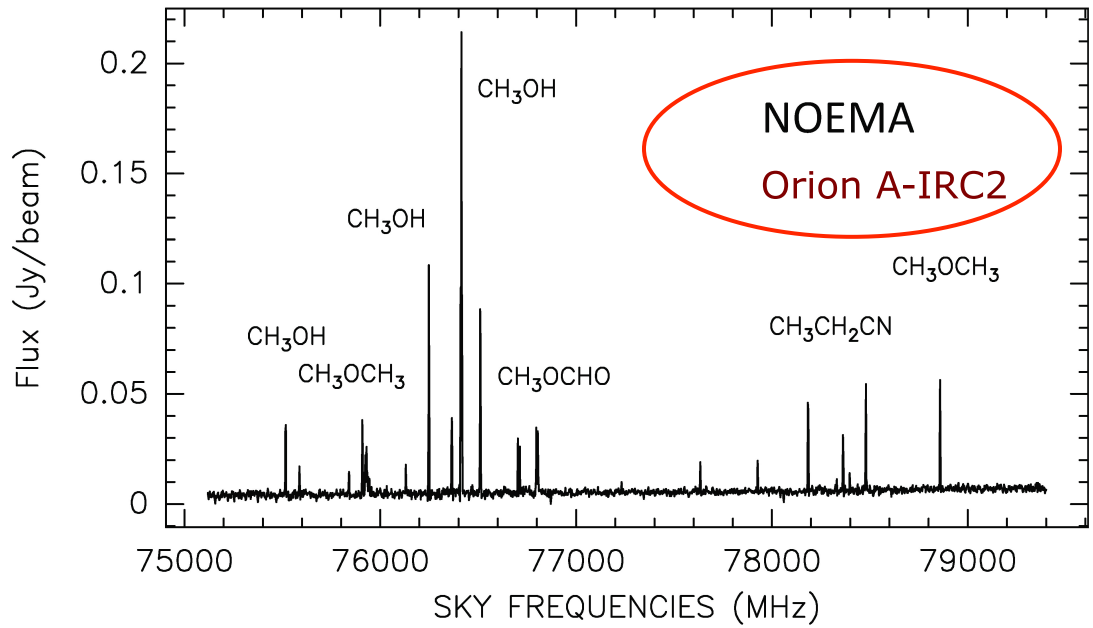

Band 1
~ 6-7 hf/k
100 %
80 %
50
15 K
+4 GHz
80
90
100
110
+4 GHz
Trec (K) vs Sky Freq (GHz)
Band 2
80 %
~ 4-5 hf/k
50
15 K
+4 GHz
140
160
+4 GHz
Trec (K) vs Sky Freq (GHz)

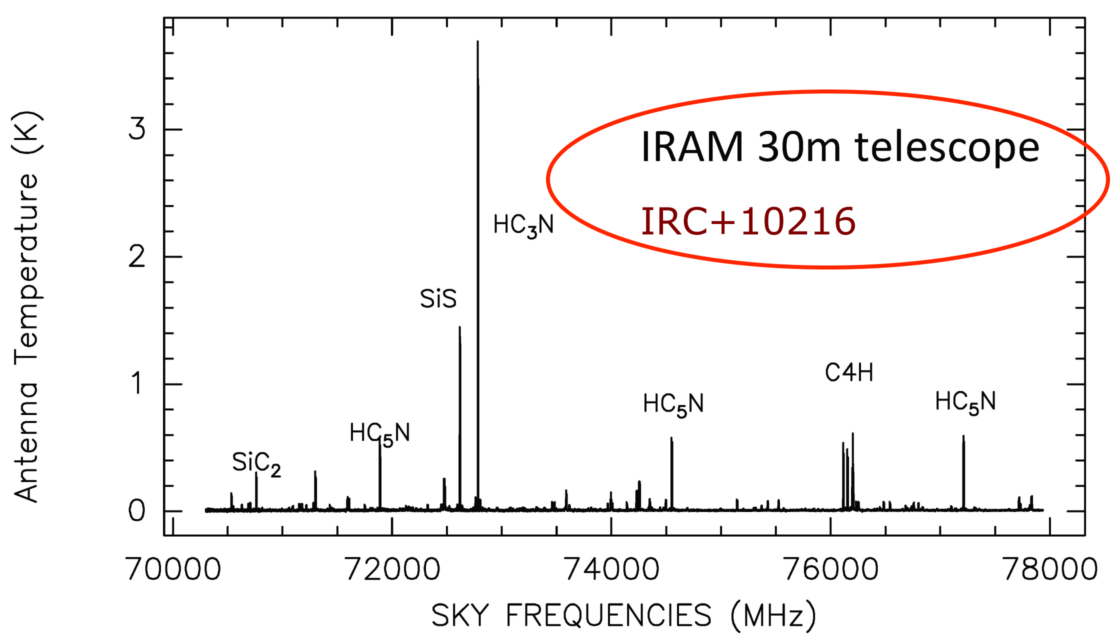
70-80 GHz band offers

- 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”

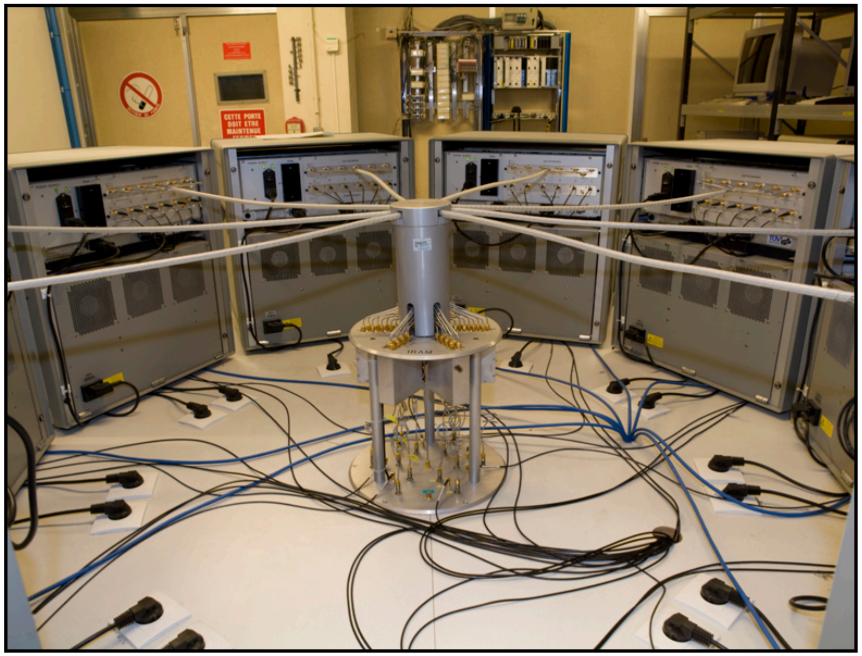
NOEMA:

- 74.7-80 GHz, Dec 01, 2016
- 70.8-80 GHz in 2017





NB - Correlator



WB – Correlator (WIDEX)

today: NOEMA runs two correlators in parallel

spring 2017: PolyFix (lecture by J.Boissier)

NOEMA correlators

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 not supported yet

⇨ galactic work, planetary work

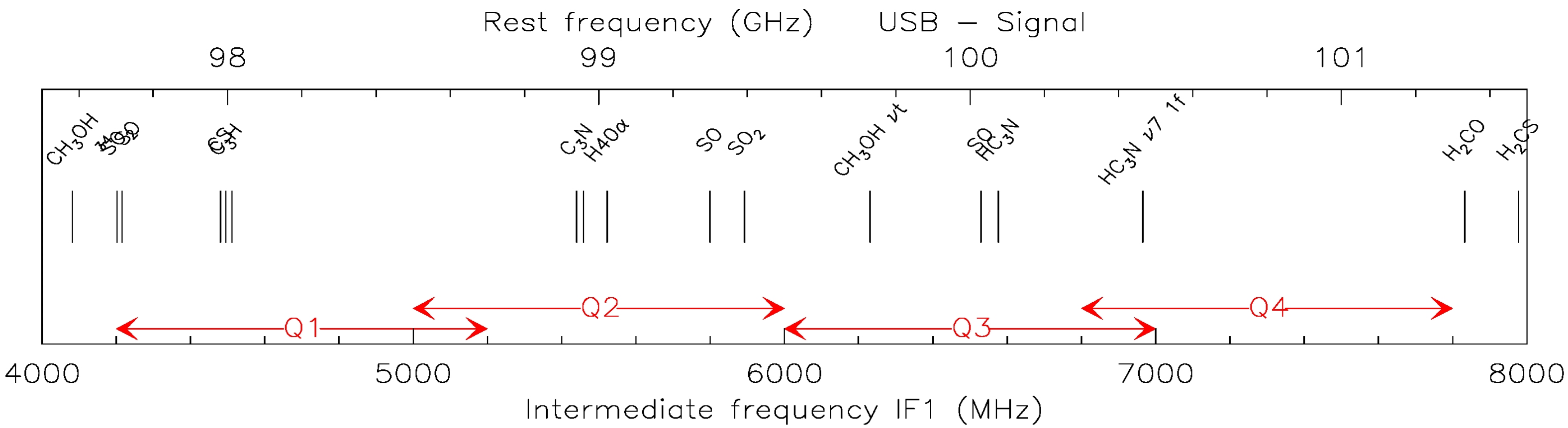
⇨ multi-resolution, line de-blending

⇨ extragalactic work, line searches (@ high redshift)

⇨ improved relative line intensity calibration

⇨ sensitive continuum ⇨ calibration, polarization, spectral index

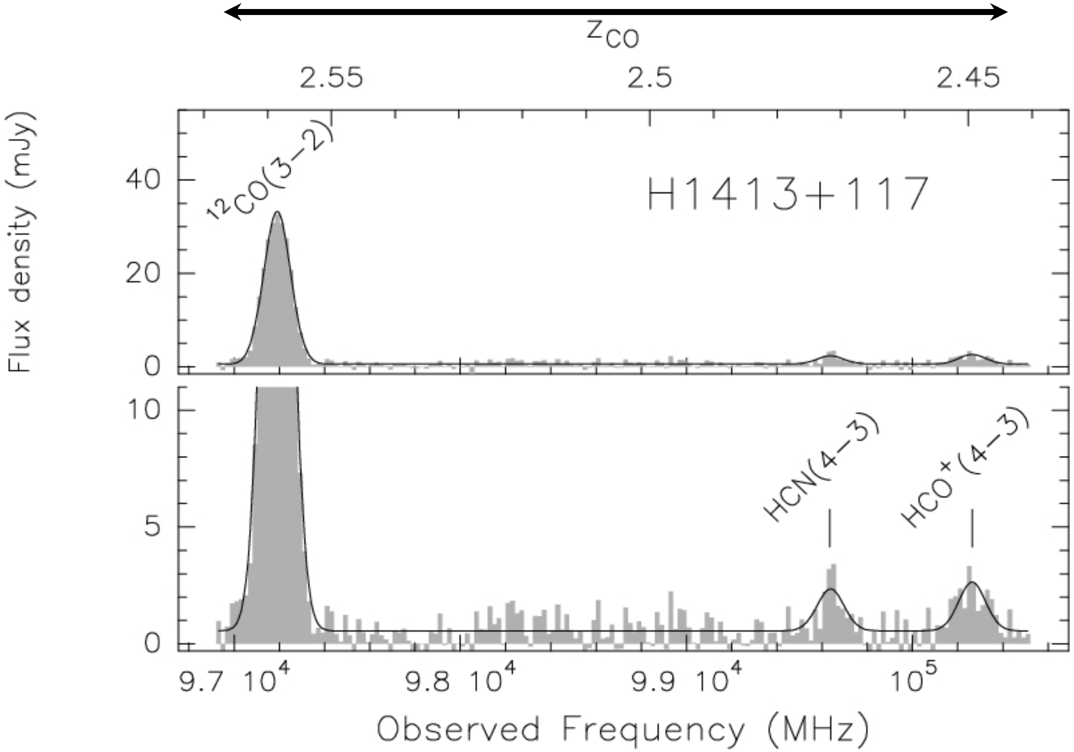
a 3.6 GHz IF but …



- 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)	Channel (MHz)	Δv (100 / 230) (km/s)	Sensivity (100 / 230) (mJy after 1 hr)
320	2.5	7.5 / 3.3	2.3 / 5.9
160	0.6	1.9 / 0.8	4.7 / 12.0
80	0.3	0.9 / 0.4	6.6 / 17.0

WIDEX = 3.6 GHz in each polarization



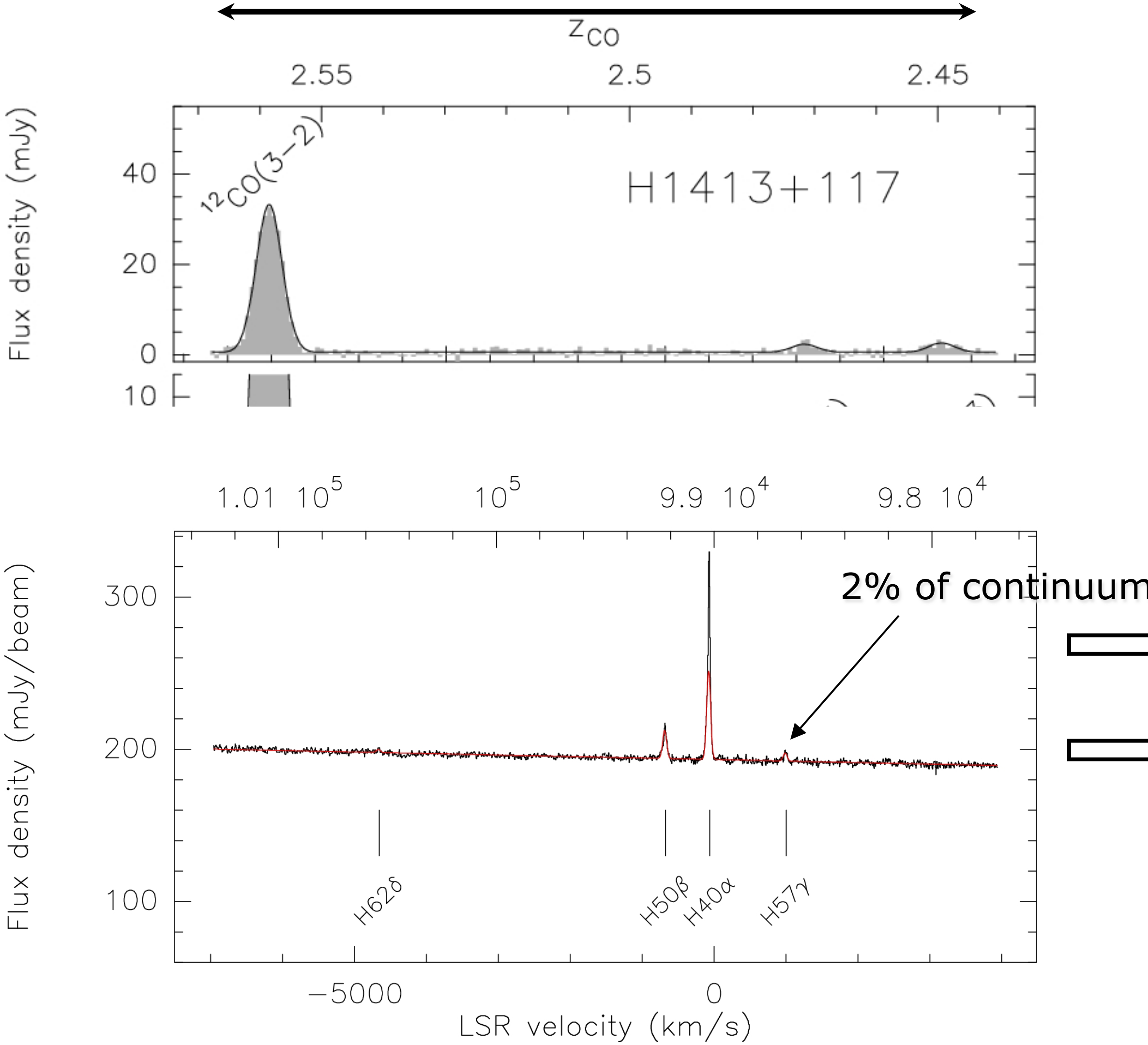
spect.cover. = 3.6 GHz
chan.sampl. = 20 MHz
integra.time = 2.2 hrs

r.m.s. = 0.66 mJy

⇨ coarse spec. resolution
⇨ high spec. resolution

Narrow Band Correlator Units (up to 8)

3.6 GHz in each polarization



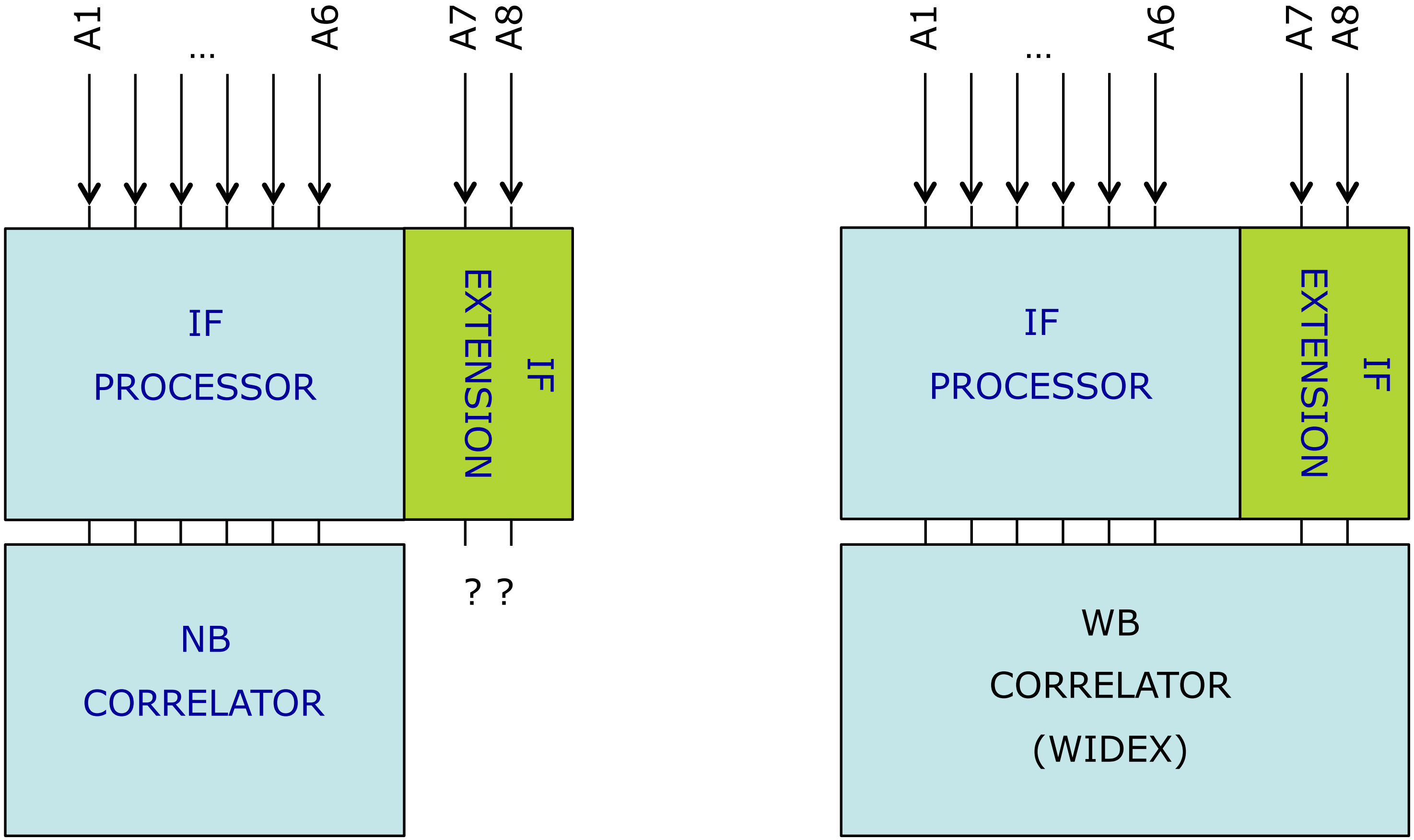
spect.cover. = 3.6 GHz
chan.sampl. = 20 MHz
integra.time = 2.2 hrs

r.m.s. = 0.66 mJy

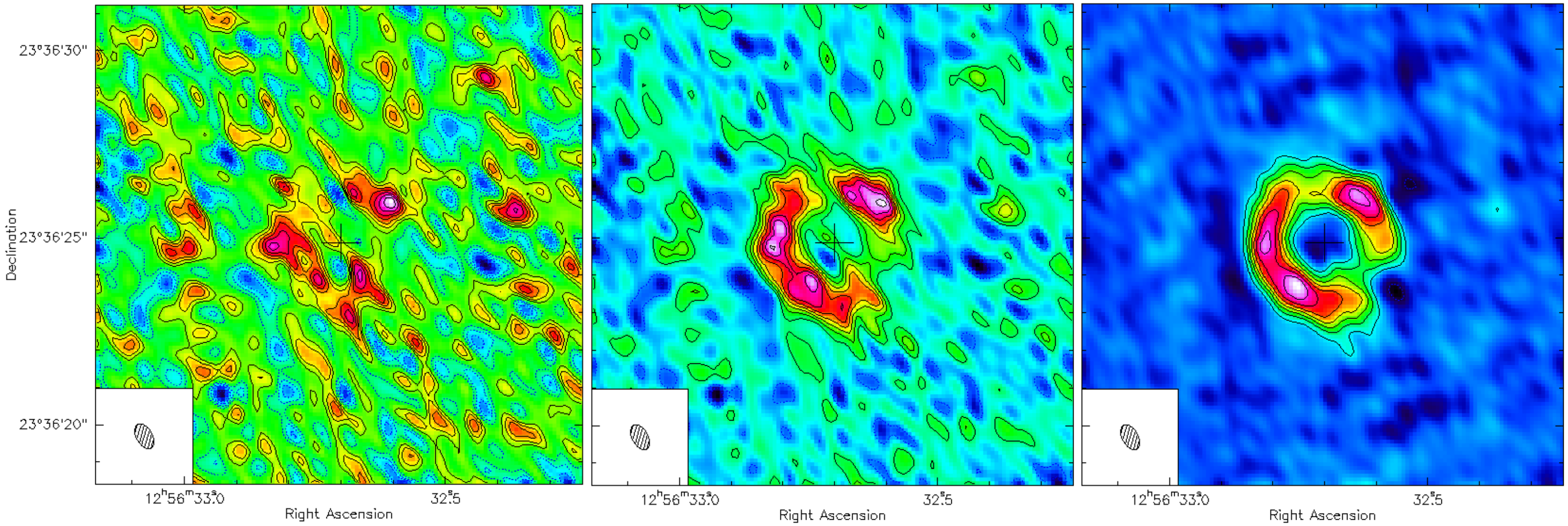
⇨ line searches

⇨ improved relative line intensity calibration

IF processor extension + WIDEX



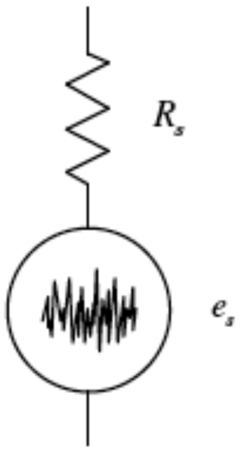
sensitivity considerations



Noise Power

The output power of a ...

... Resistor :



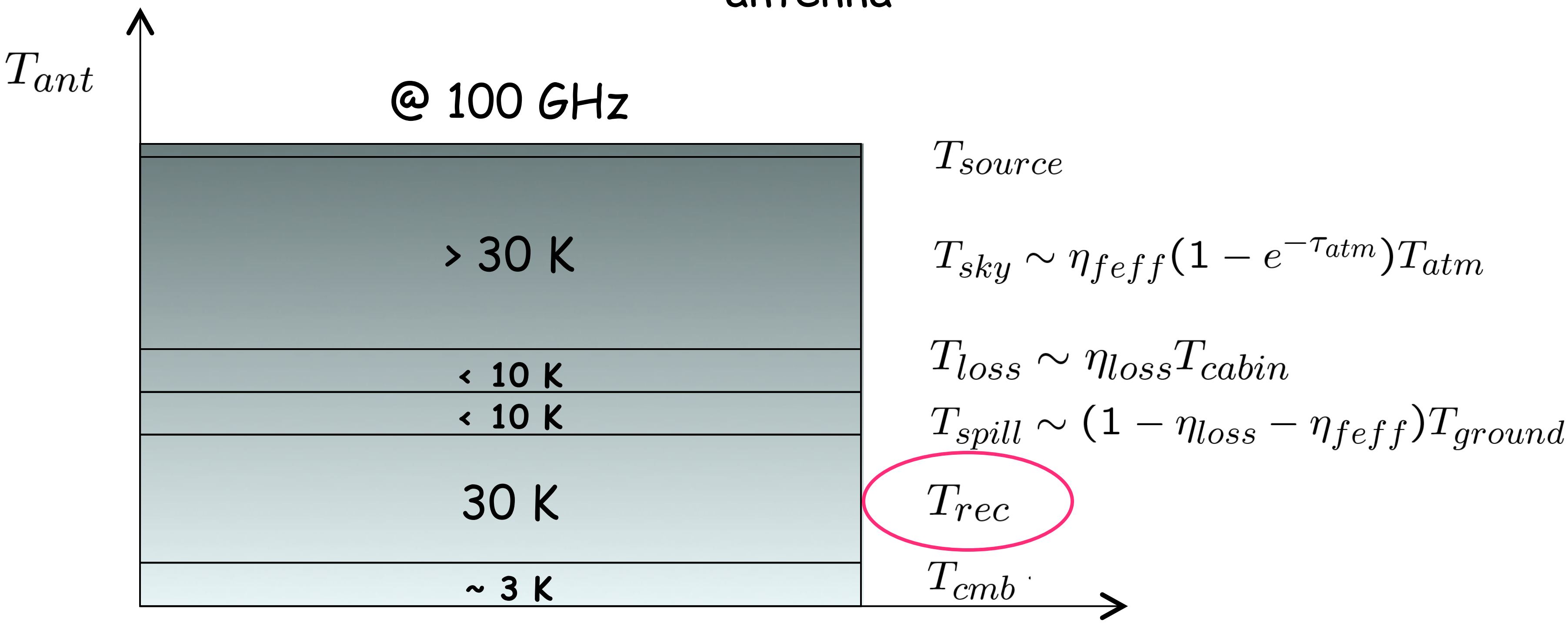
... Receiving System :

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

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.

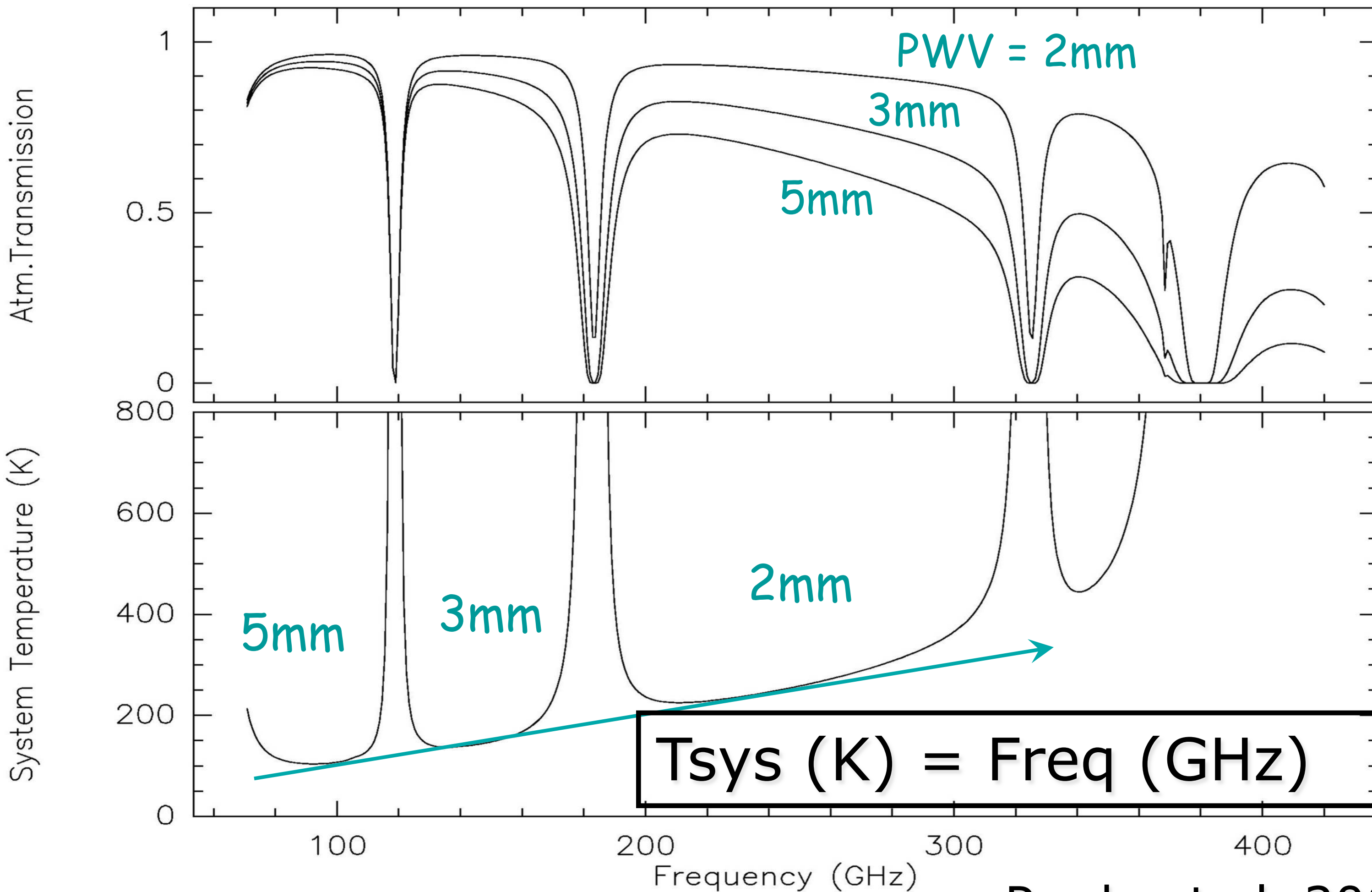
NOEMA system temperatures

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

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)

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

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

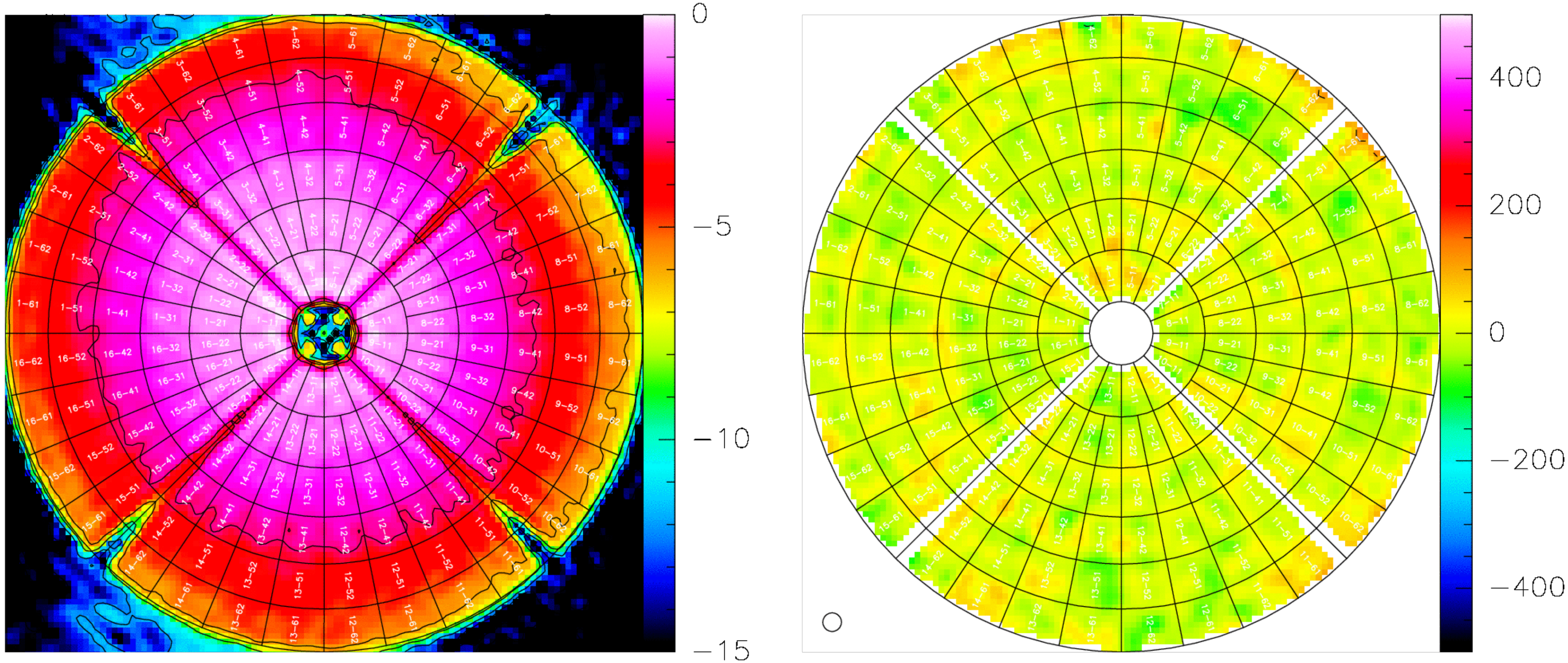
S/T(86.243 GHz)= 19.518 Jy/K; S/T(230GHz)= 20.362 Jy/K; S/T(345 GHz)= 21.651 Jy/K

η_I= 0.806 −η_S= 0.731 −η_P(86.243 GHz)= 0.993 −η_P(230 GHz)= 0.952 −η_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



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

Point source sensitivities:

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

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

$\rightarrow 22 \times \sigma_T$ [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 $\leq 20\%$

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

One baseline, two antennas:

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

Ex @ 100 GHz:

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

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

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

The NOEMA array (N8, 2016):

$$\mathrm{Ex} @ 100\mathrm{GHz}: \quad \sigma_S \simeq 22 \times \frac{100}{\sqrt{56 \times 3600\,10^6 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 3.9\,\mathrm{mJy}$$

The NOEMA array (N10, 2017):

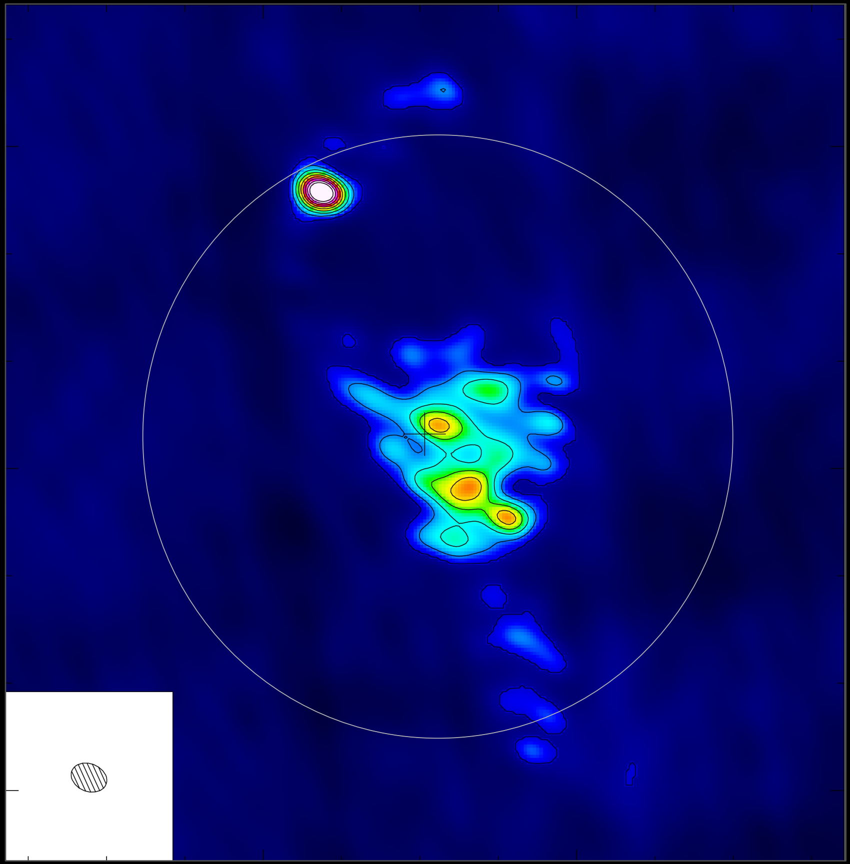
$$\mathrm{Ex} @ 100\mathrm{GHz}: \quad \sigma_S \simeq 22 \times \frac{100}{\sqrt{132 \times 15600\,10^6 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 1.3\,\mathrm{mJy}$$

The NOEMA array (N12, 2019):

$$\mathrm{Ex} @ 100\mathrm{GHz}: \quad \sigma_S \simeq 22 \times \frac{100}{\sqrt{132 \times 15600\,10^6 \times 1}} \times \frac{1}{\sqrt{2}} \simeq 1.1\,\mathrm{mJy}$$

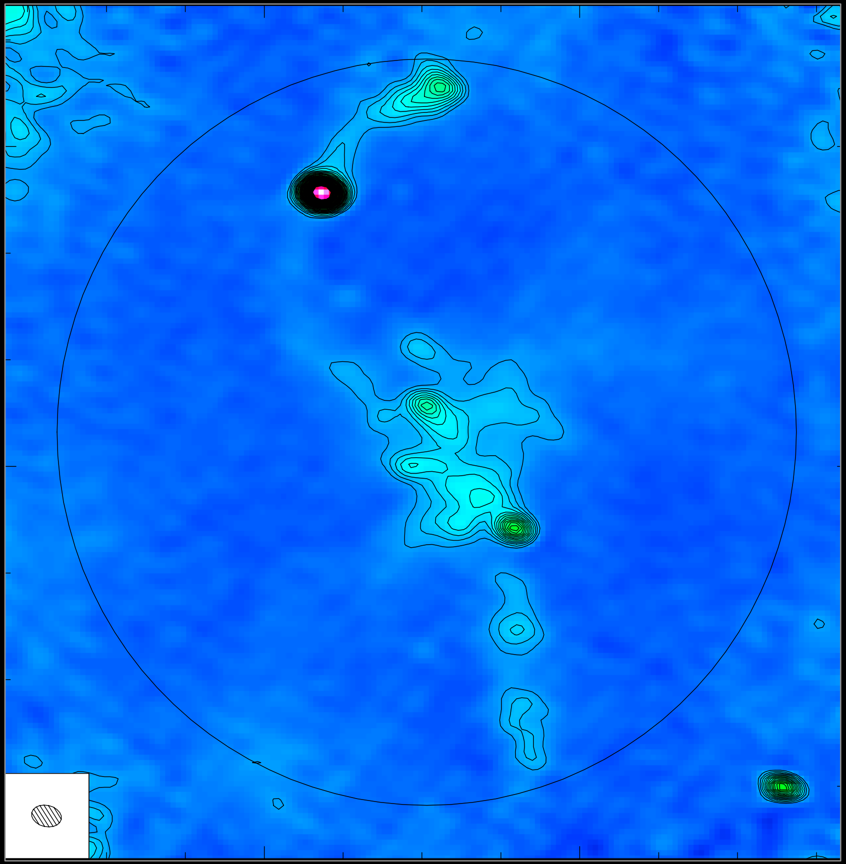
ALMA45 is twice as sensitive as N12 (continuum)

NOEMA8



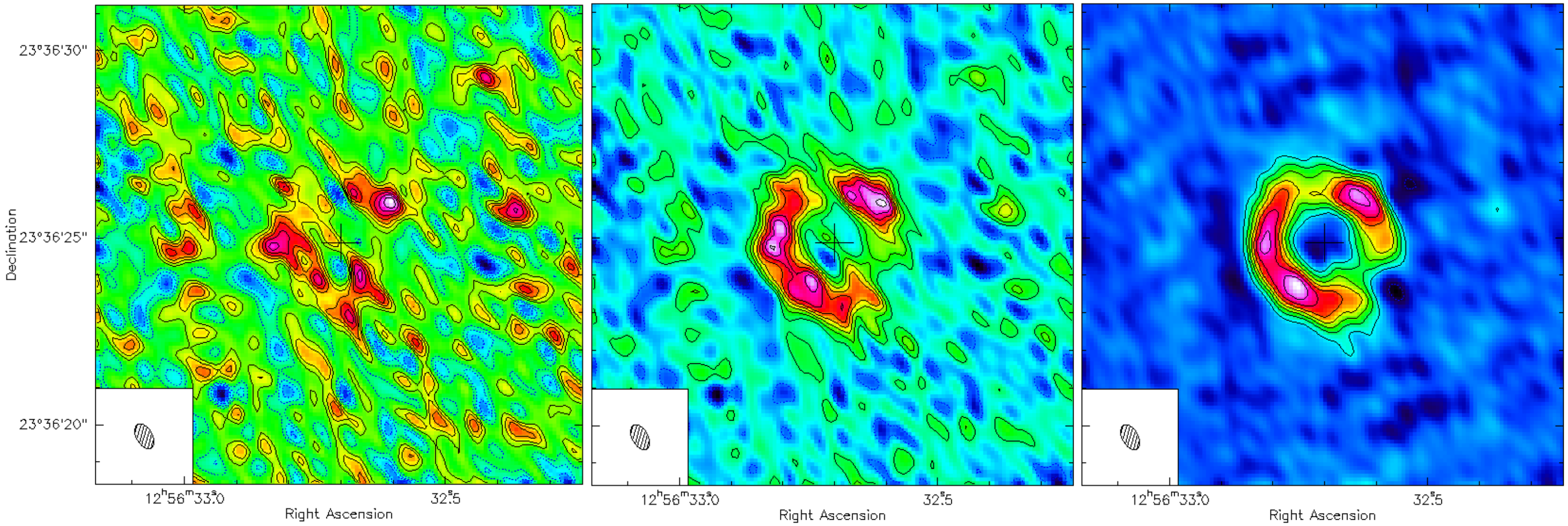
OMC2-FIR4, SOLIS LP
Caselli & Ceccarelli, B1
RMS = 0.10 mJy/(3.5x2.7”)

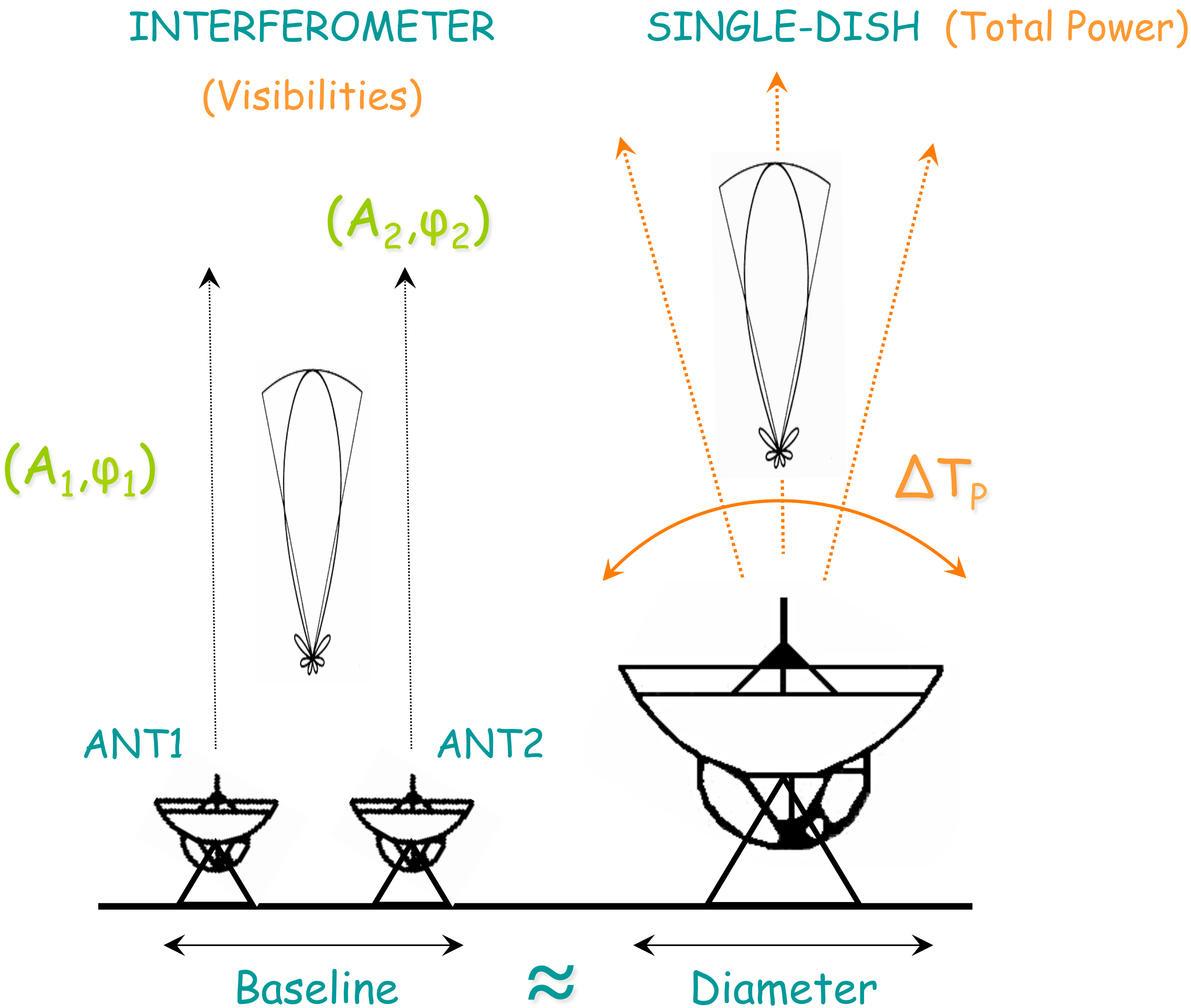
ALMA35 Cy 3



OMC2-FIR4,
Ceccarelli2015.1.00261.S, B3
RMS = 0.15 mJy/(2.9x2.0”)

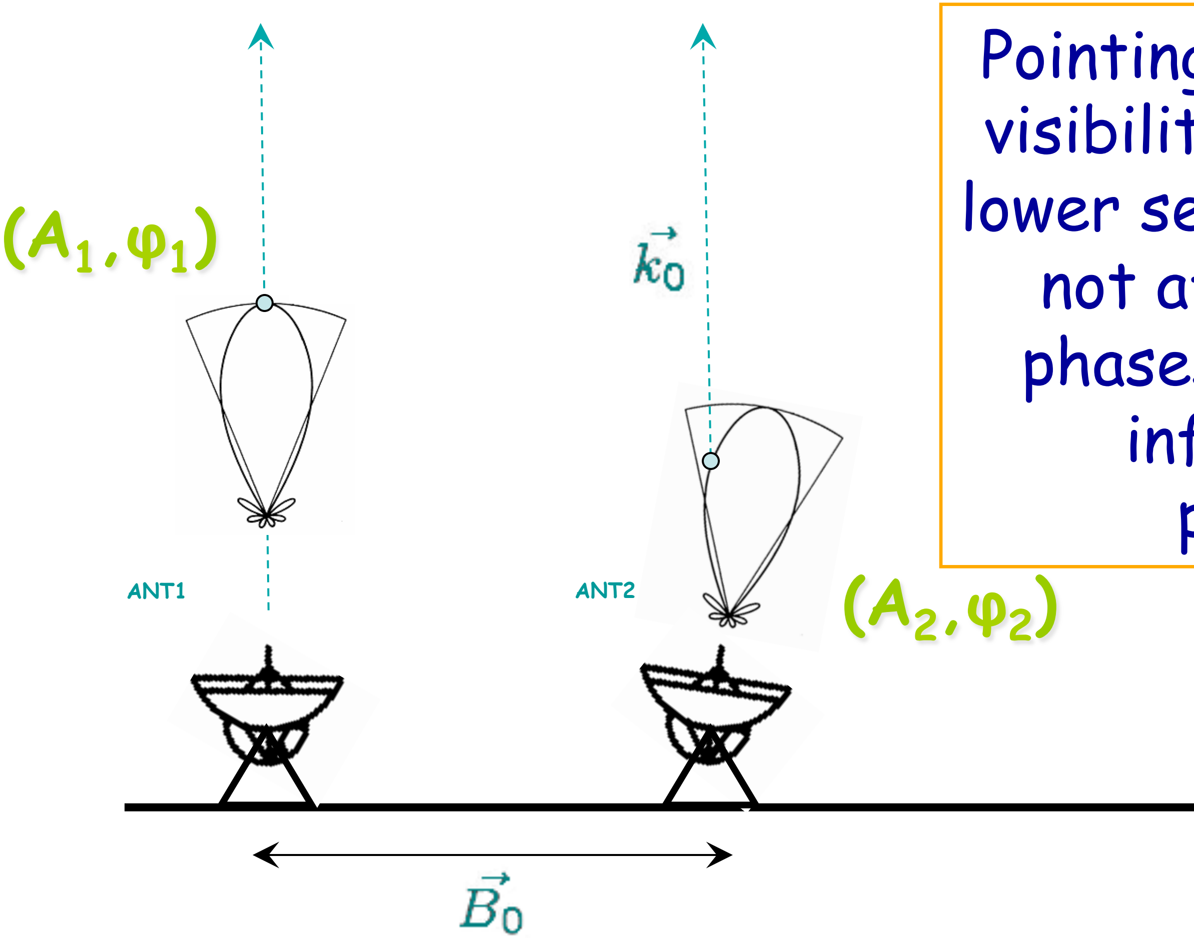
position considerations




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

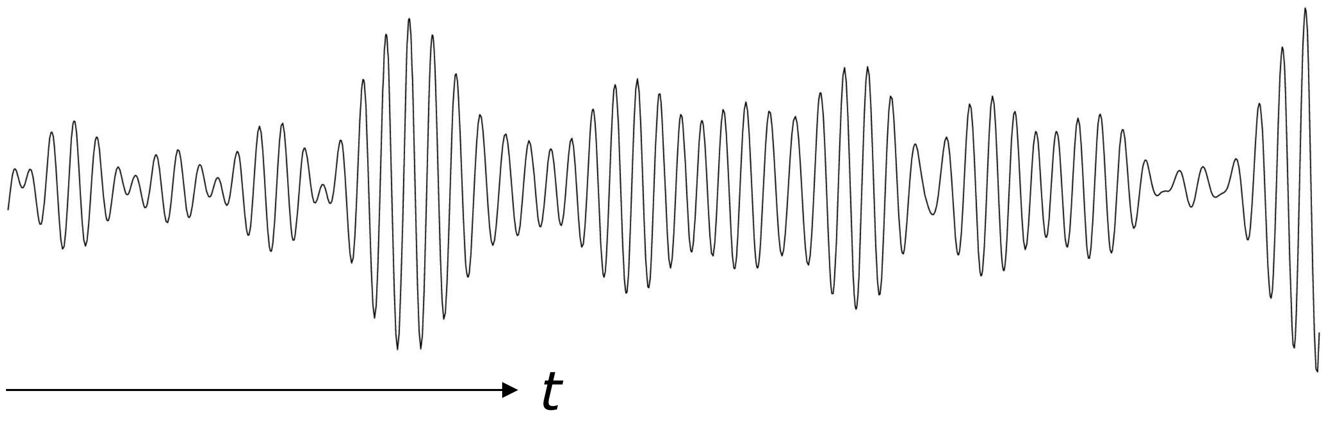
INTERFEROMETER

(Visibilities)



Pointing offsets modify visibility amplitudes (⇒ lower sensitivity) BUT do not affect visibility phases (⇒ positional information is preserved)

Temporal coherence function

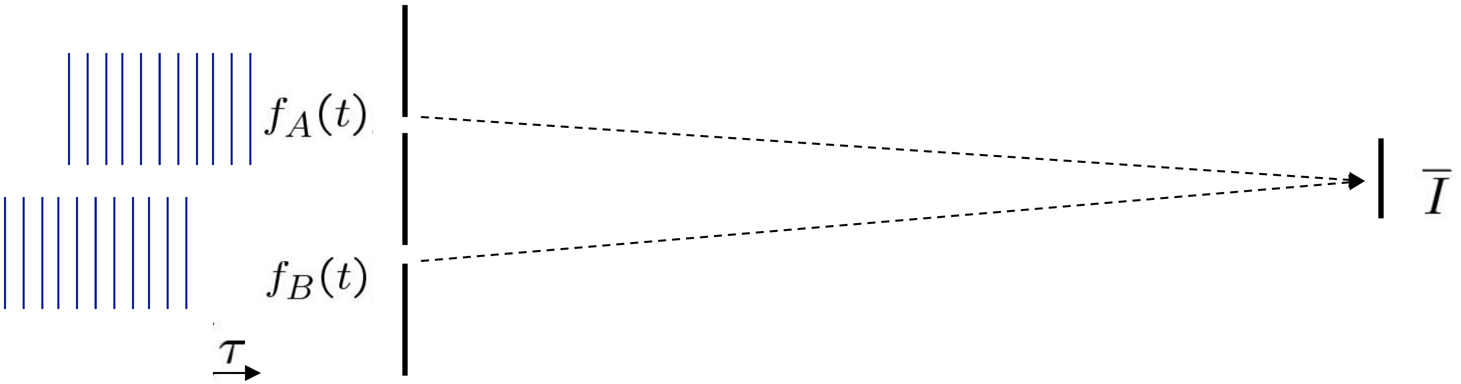


Correlation coefficient:

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

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

Temporal coherence



Correlation coefficient:

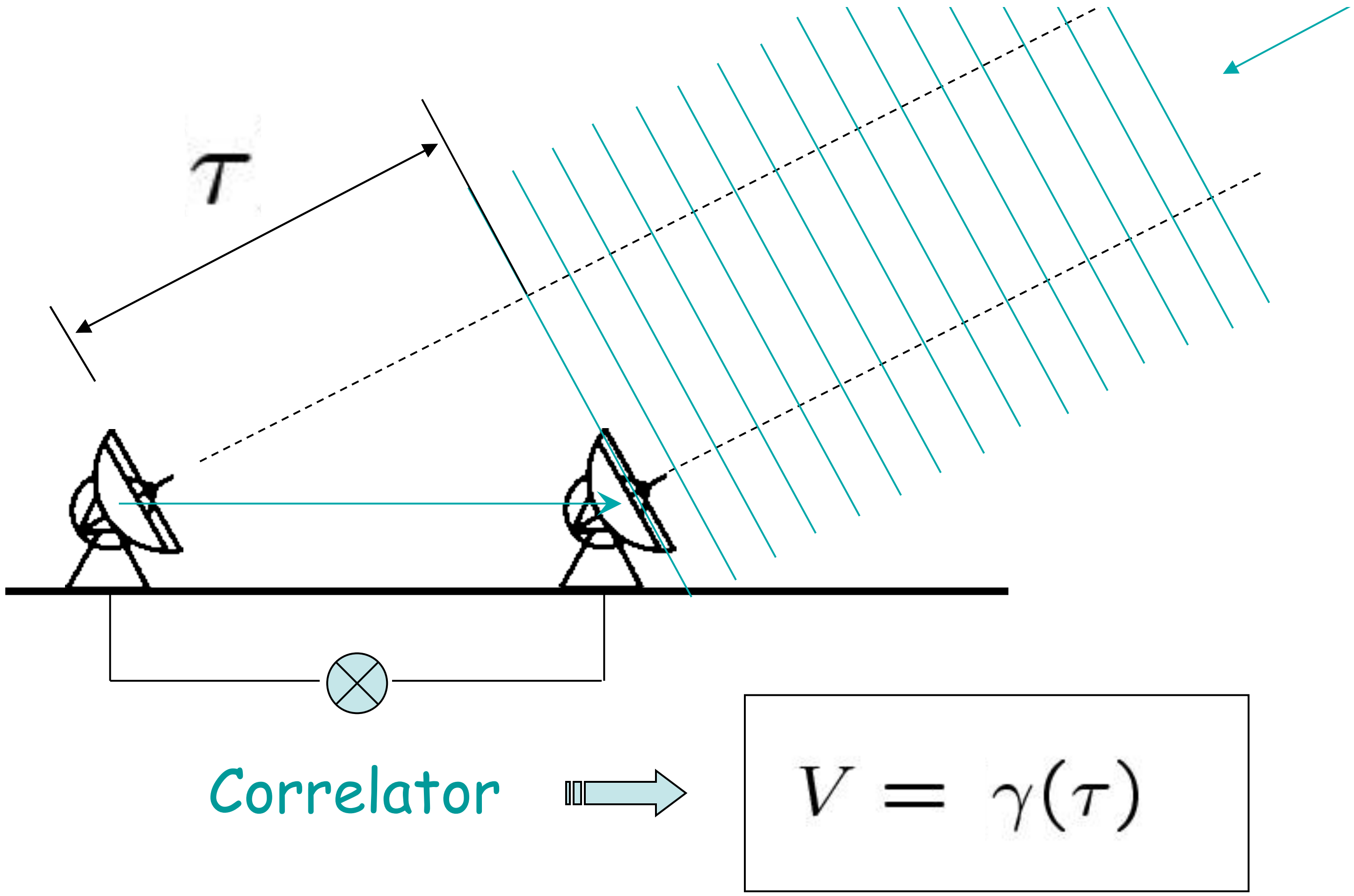
$$\gamma_{AB} = f_A(t) f_B^*(t+\tau) / (\overline{|f_A(t)|^2}\ \overline{|f_B(t)|^2})^{\frac{1}{2}}$$

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

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

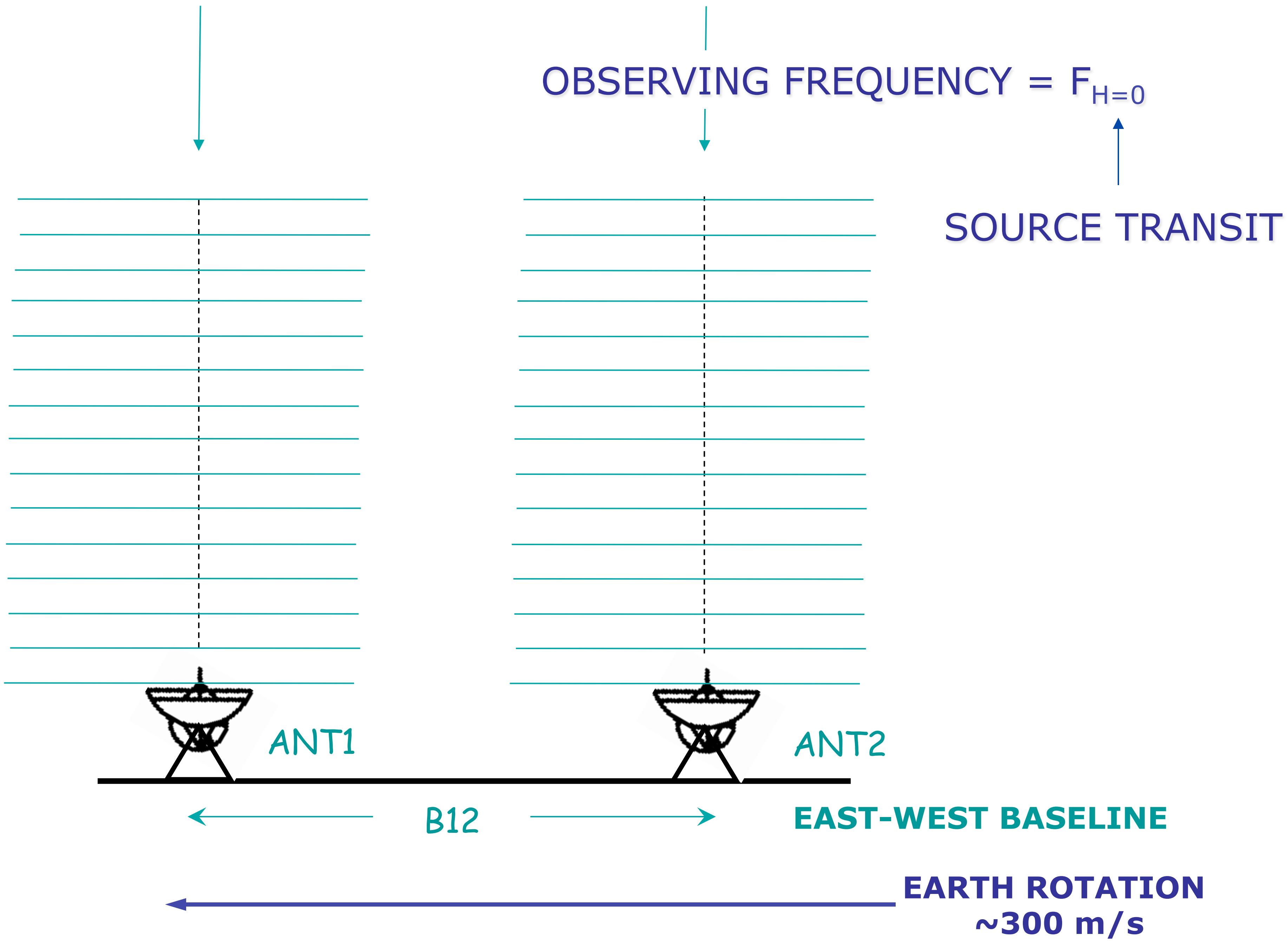
An interferometer

measures the temporal coherence of the incoming wavefront



Scan types:

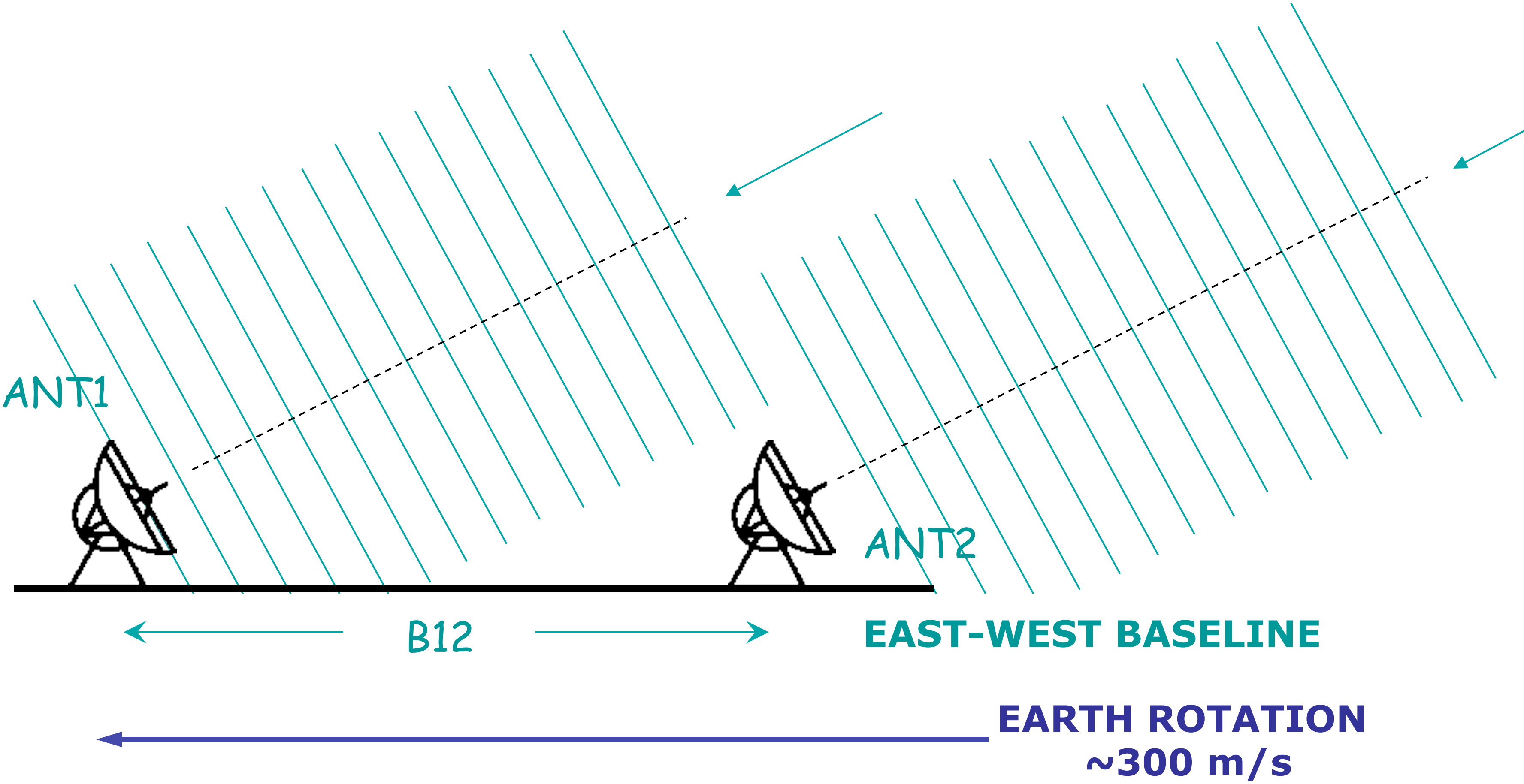
- **IFPB:** auto- and cross-correlations on white noise $\rightarrow$ backend calibration.
- **AUTO:** auto-correlations on the sky $\rightarrow$ backend calibration.
- **CALI:** auto-correlations (total power measurements) on a cold load (15K), table (290K) and on the sky $\rightarrow$ interferometer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

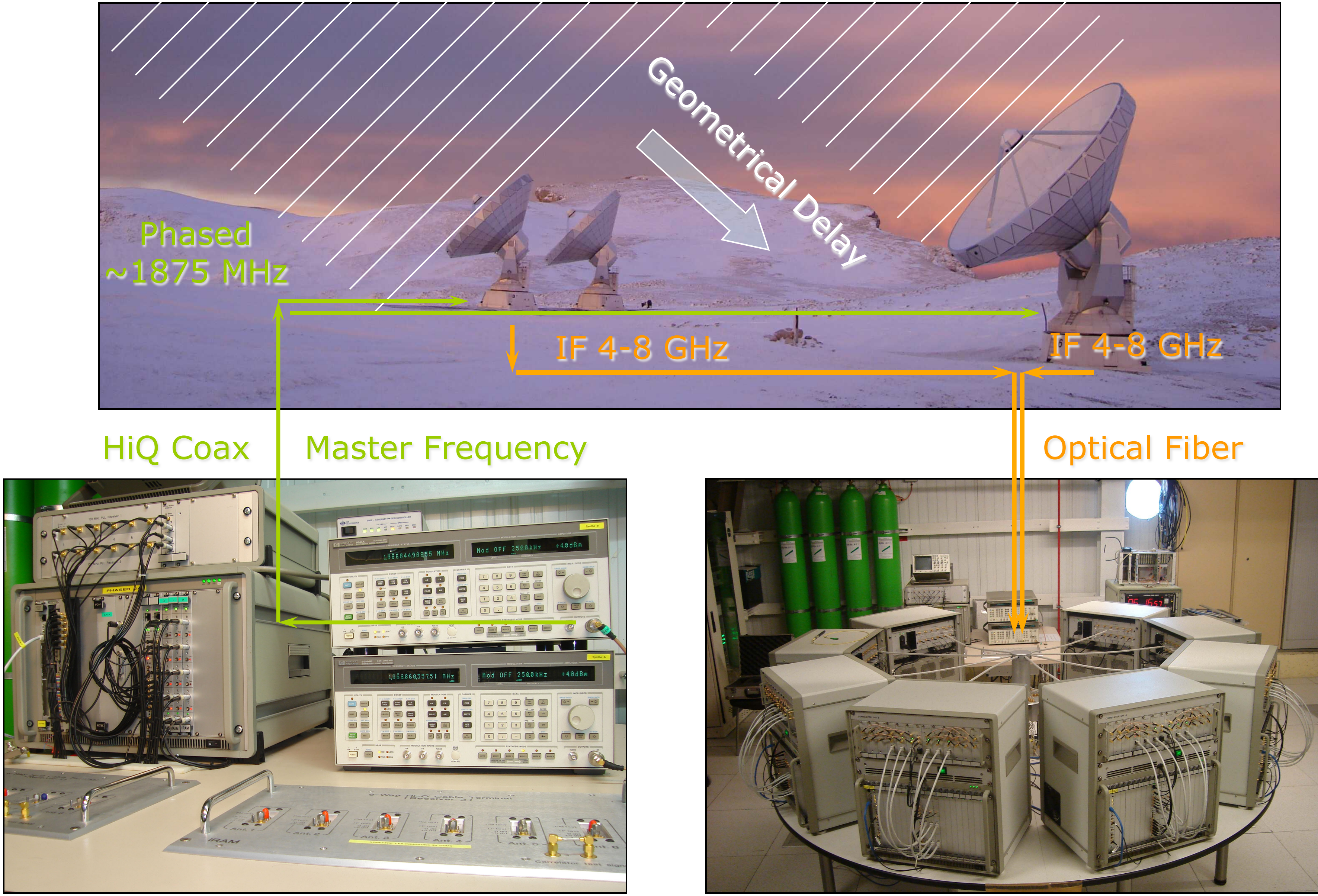

OBSERVING FREQUENCY = $F_{H=0}$
SOURCE TRANSIT
ANT1
ANT2
B12
EAST-WEST BASELINE
EARTH ROTATION
~300 m/s

SOURCE TRANSIT

SOURCE RISES $F_{H<0} > F_{H=0} > F_{H>0}$ SOURCE SETS

⇨ DEPENDS ON THE SKY POSITION

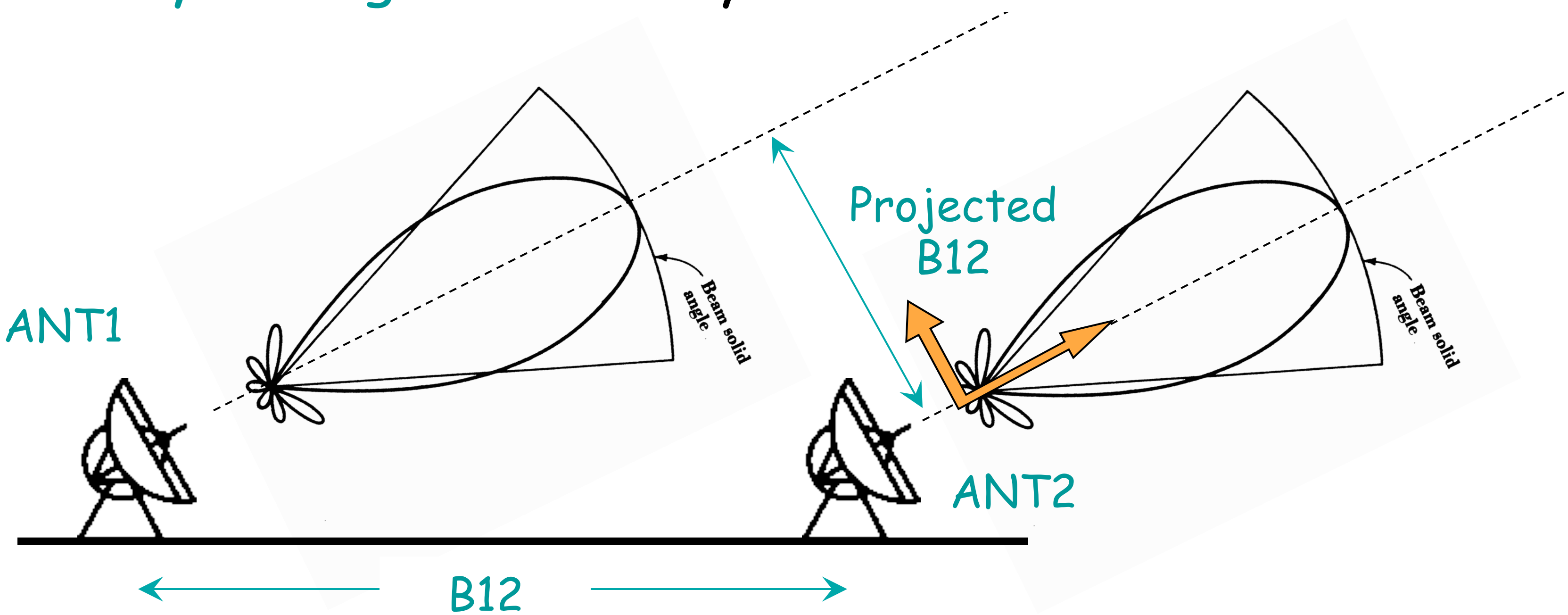


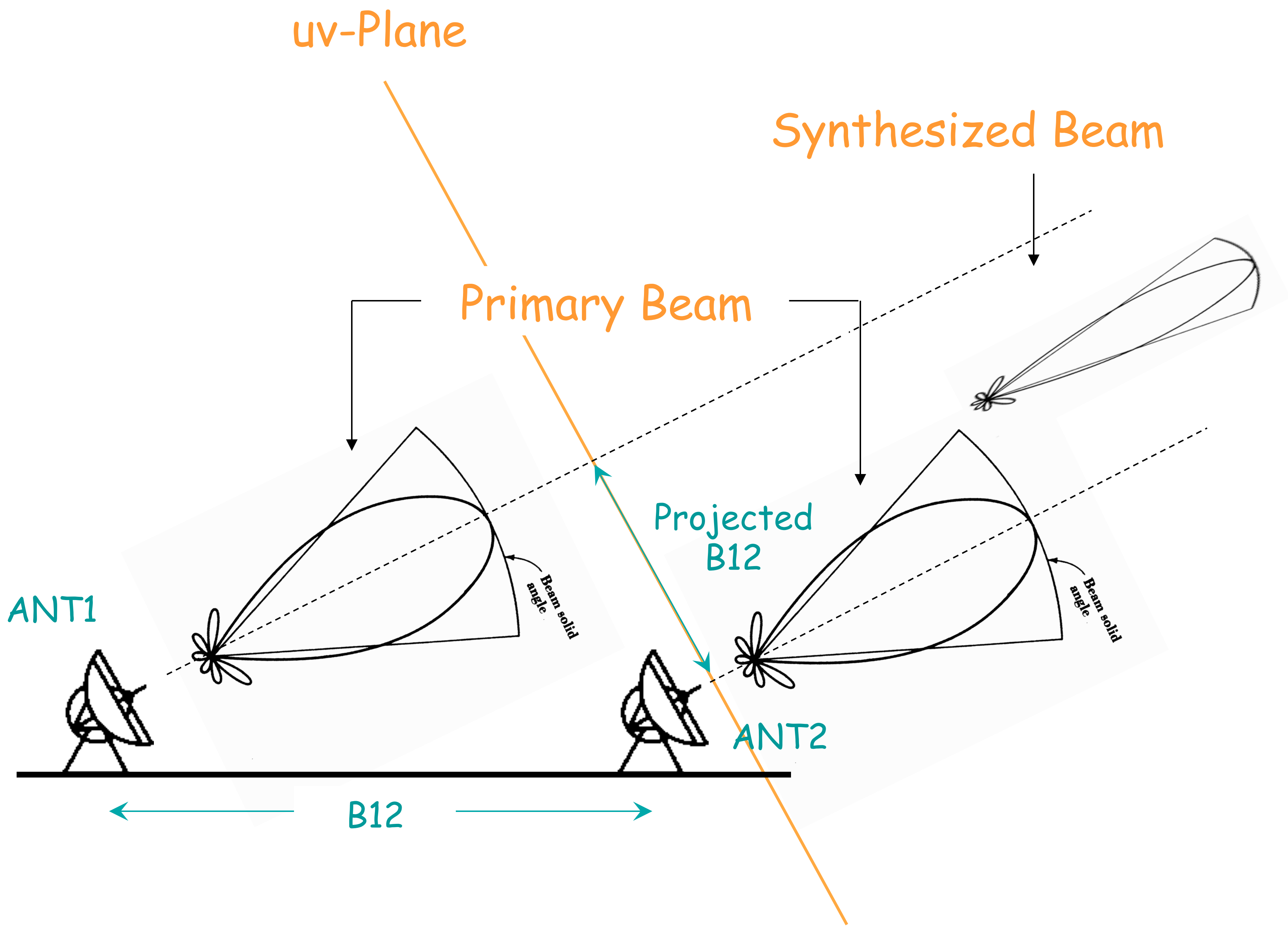

Geometrical Delay
Phased
~1875 MHz
IF 4-8 GHz
IF 4-8 GHz
HiQ Coax
Master Frequency
Optical Fiber

Baseline Bij : distance between two antennas

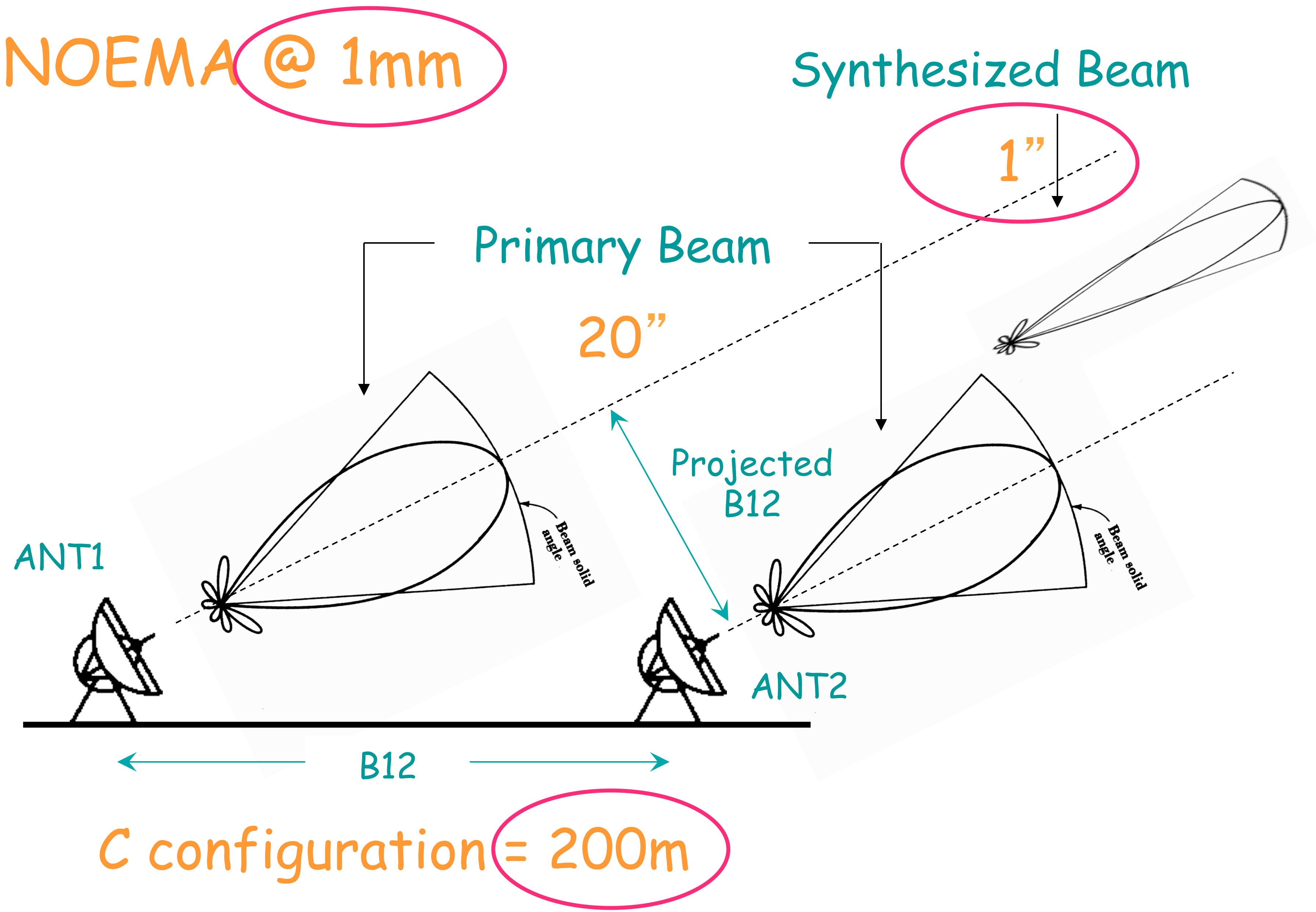
Projected Baseline Bij : distance between two antennas as seen from the sky

Array Configuration : layout of the antenna stations

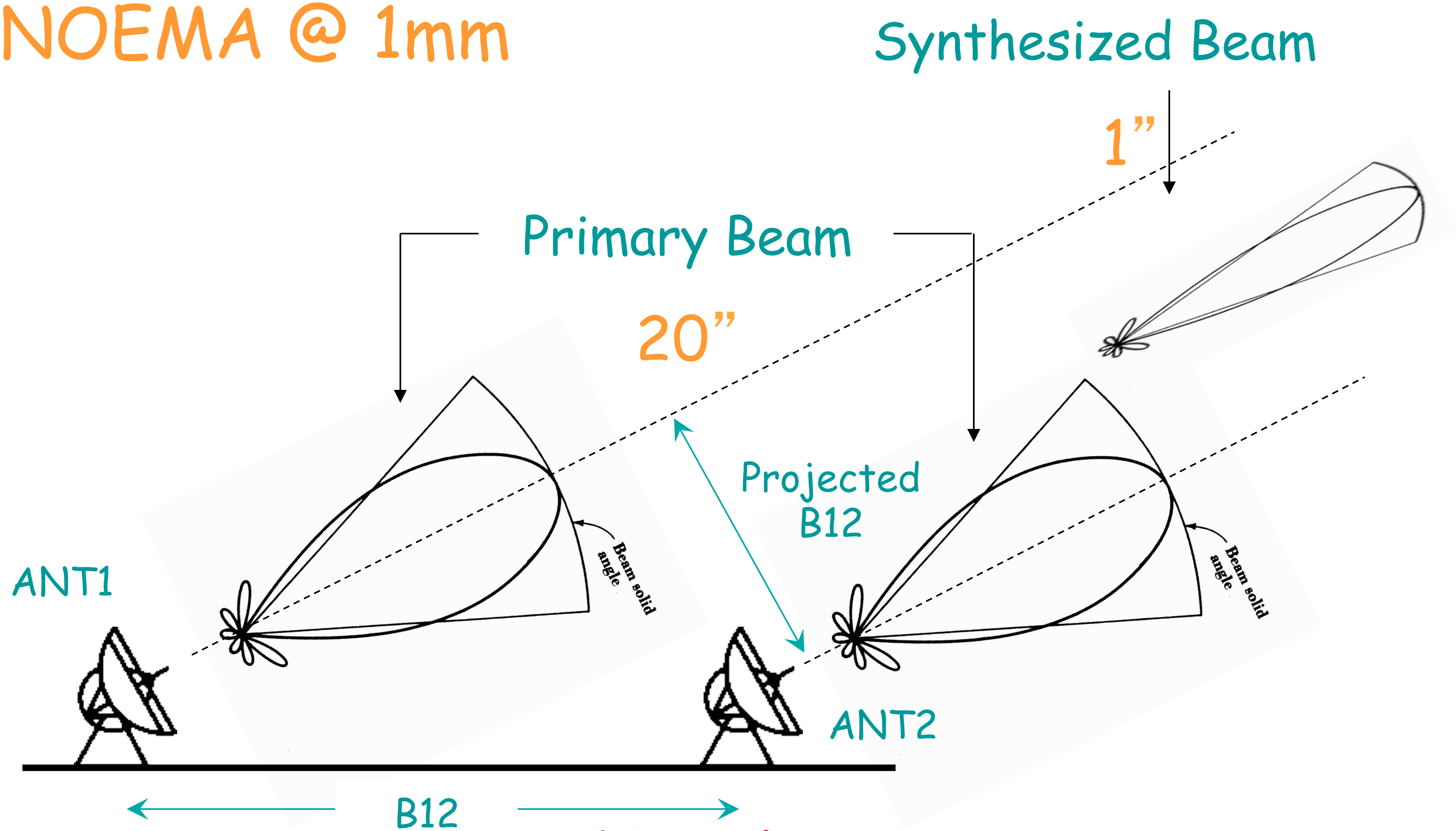




uv-Plane
Synthesized Beam
Primary Beam
Projected
B12
Beam solid angle
Beam solid angle
ANT1
ANT2
B12


NOEMA @ 1mm
Synthesized Beam
1"
Primary Beam
20"
Projected
B12
Beam solid angle
ANT1
ANT2
B12
C configuration = 200m

NOEMA @ 1mm



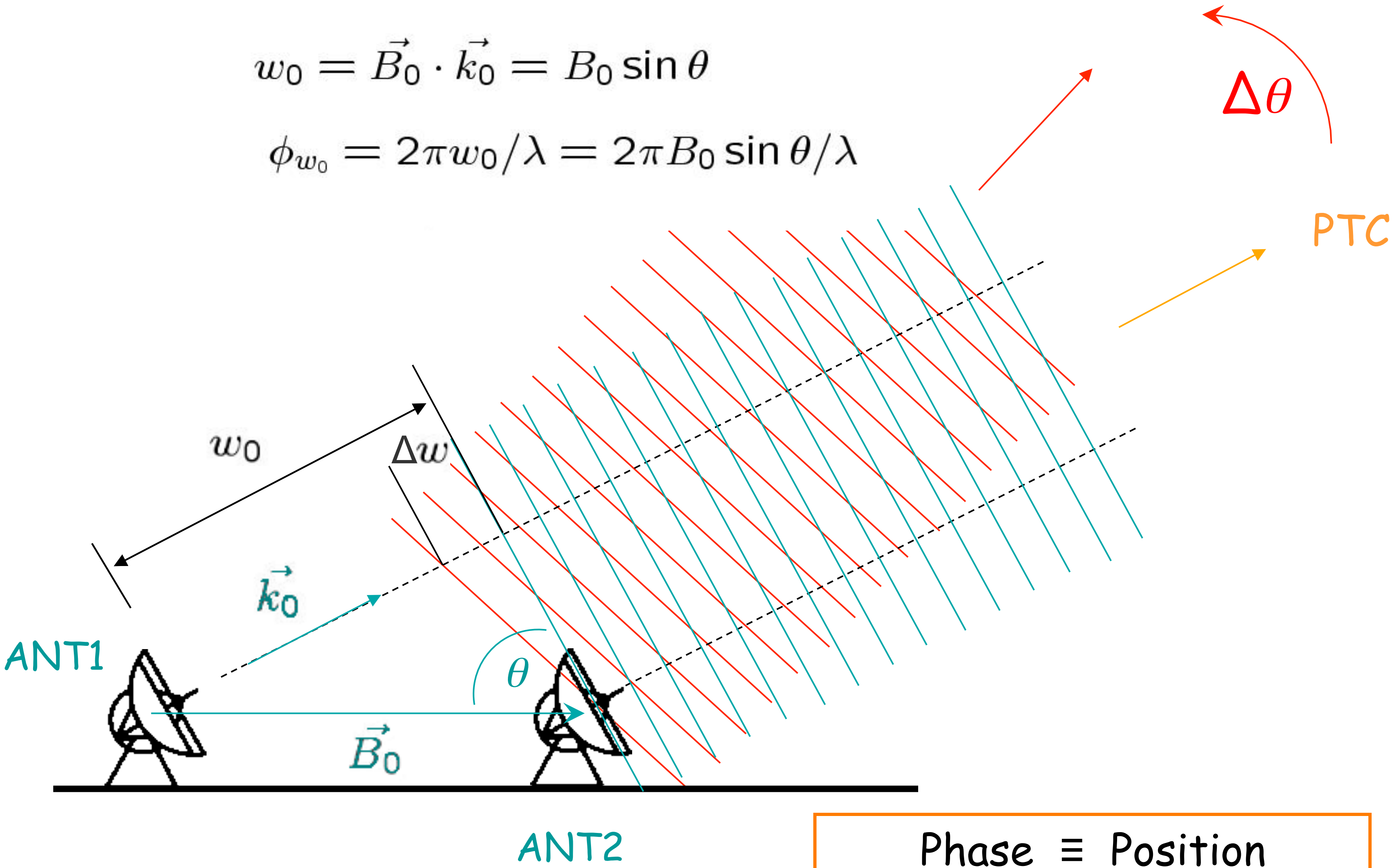
Minimum projected baseline = 15m

SHORT SPACINGS ⇨ 30m Telescope

The phase equation

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

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

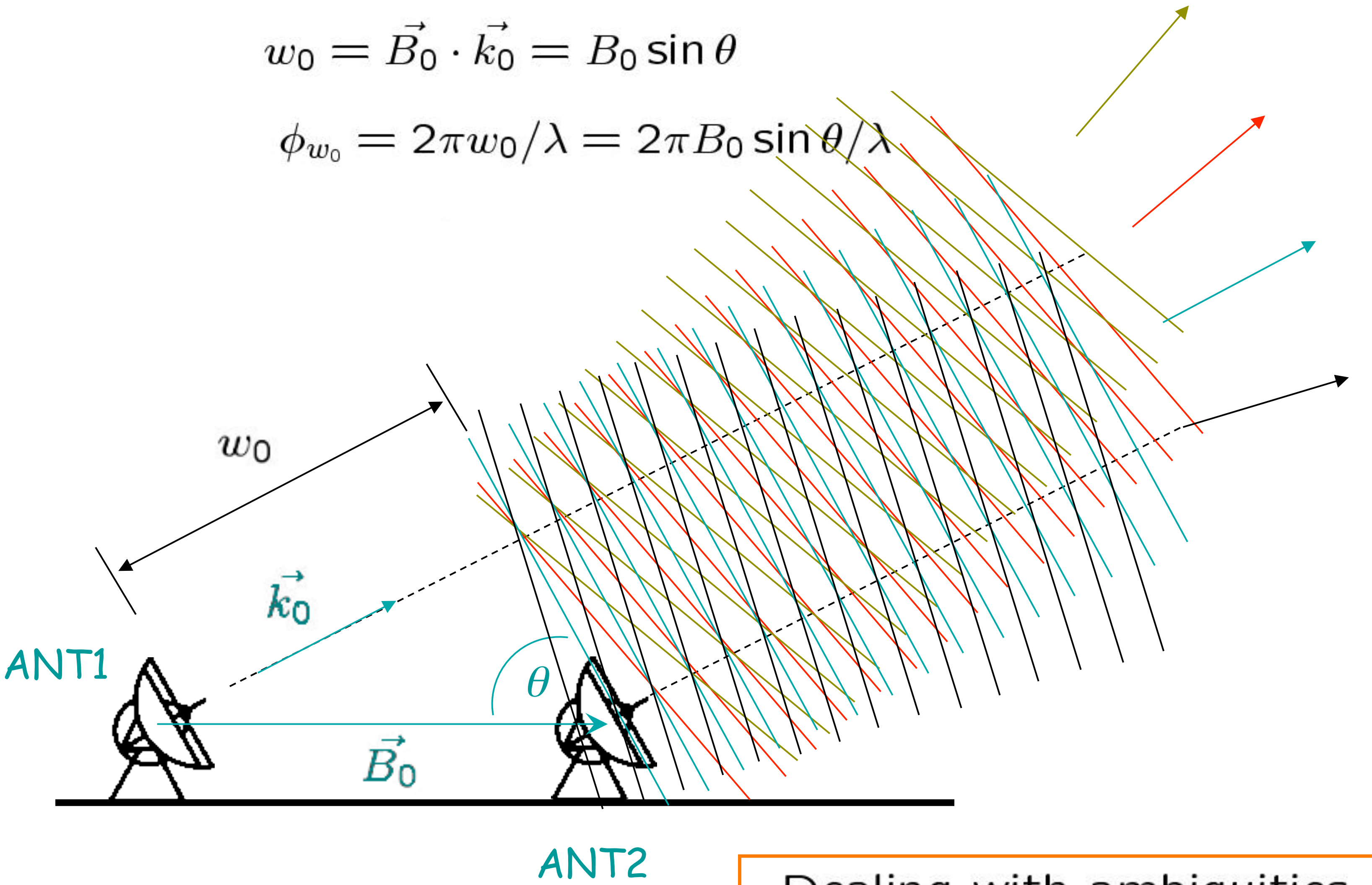


Phase ≡ Position

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 . . .

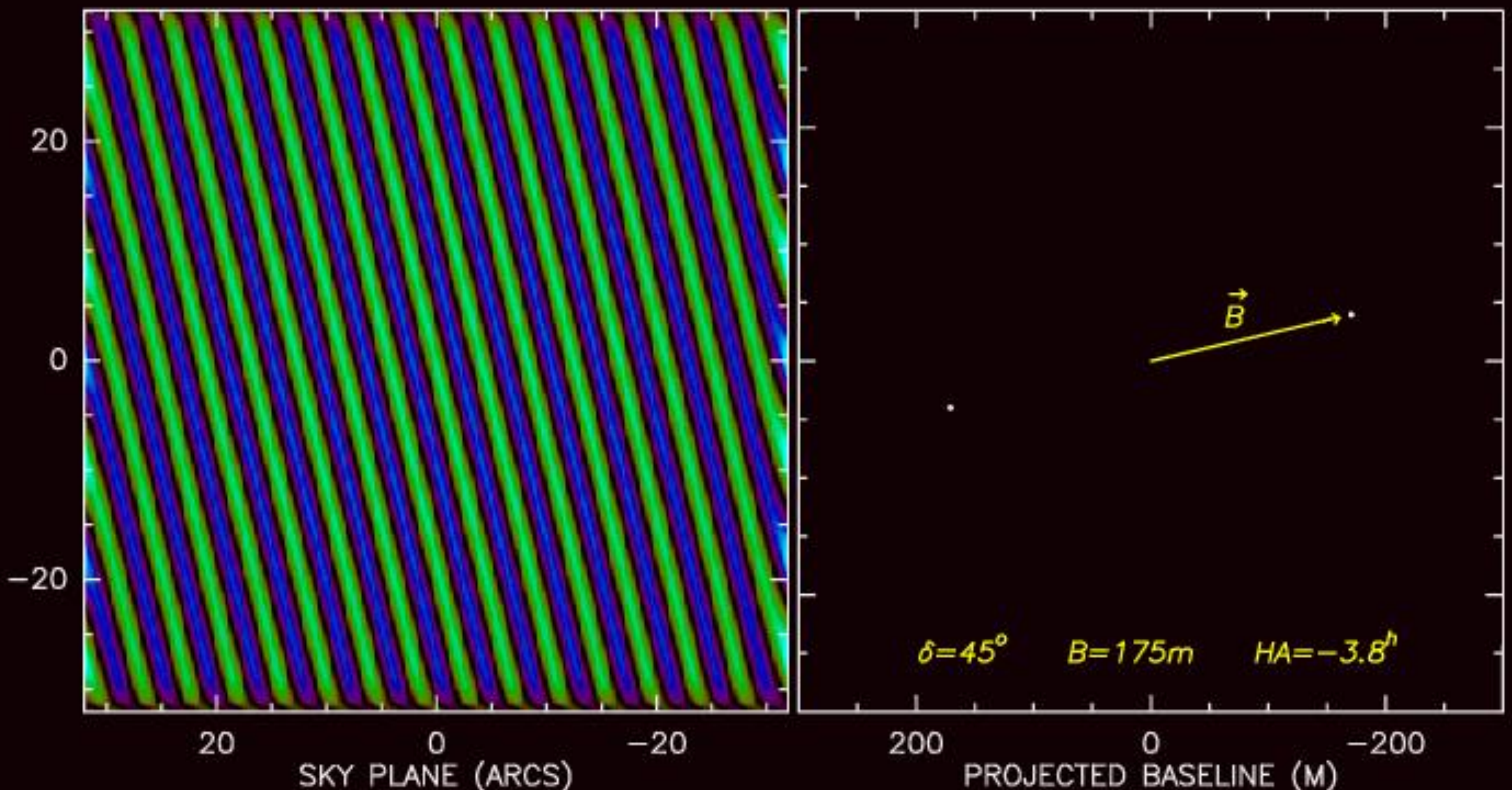
Dealing with $\omega_0 = \vec{k_0} \cdot \vec{B_0}$

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

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

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

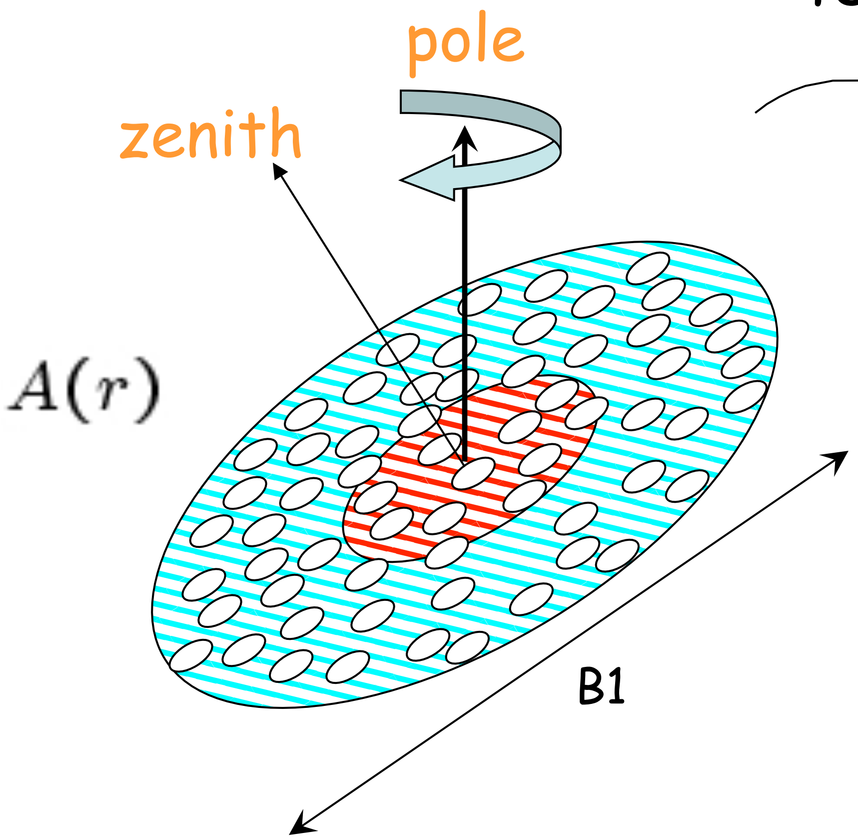
Ex: a source displaced by a single beam $\theta = \lambda/B_0$ shows an offset of 360° in the signal phase.



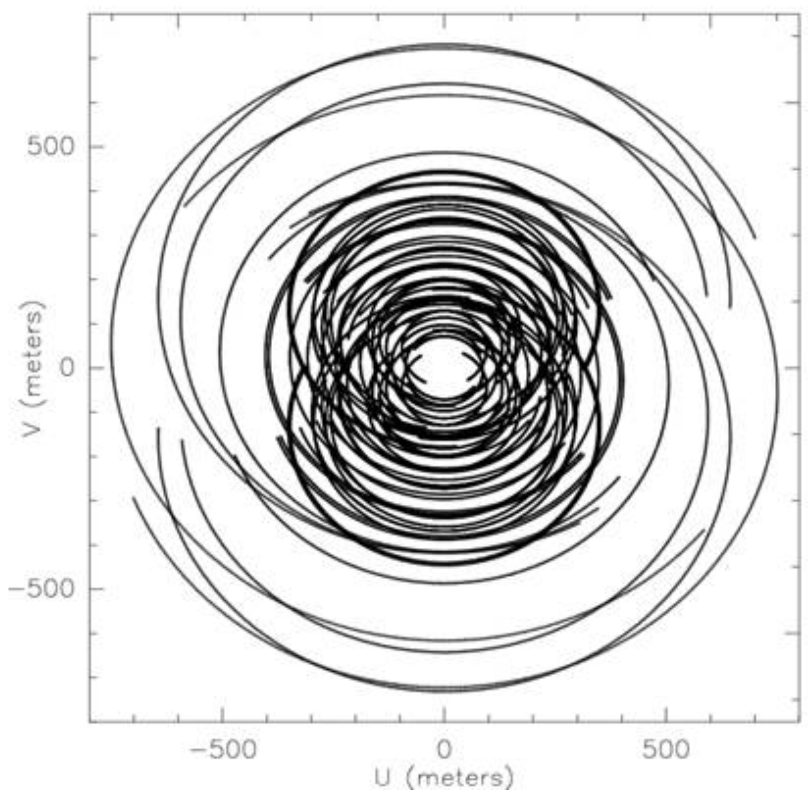
20
0
−20
20
0
−20
SKY PLANE (ARCS)
$\vec{B}$
δ=45°
B=175m
HA=−3.8h
200
0
−200
PROJECTED BASELINE (M)

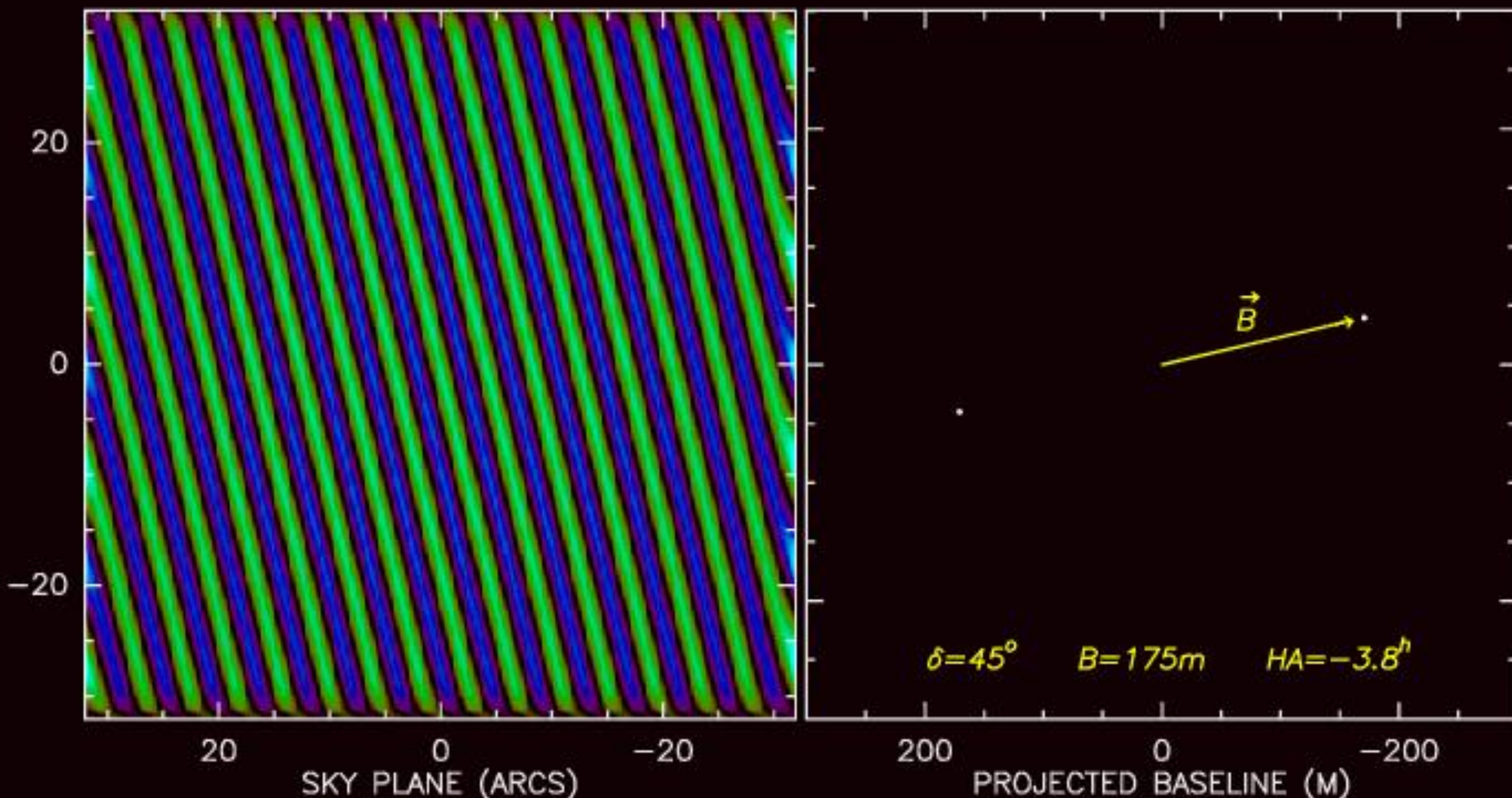
Super-Synthesis or Earth Rotation Synthesis

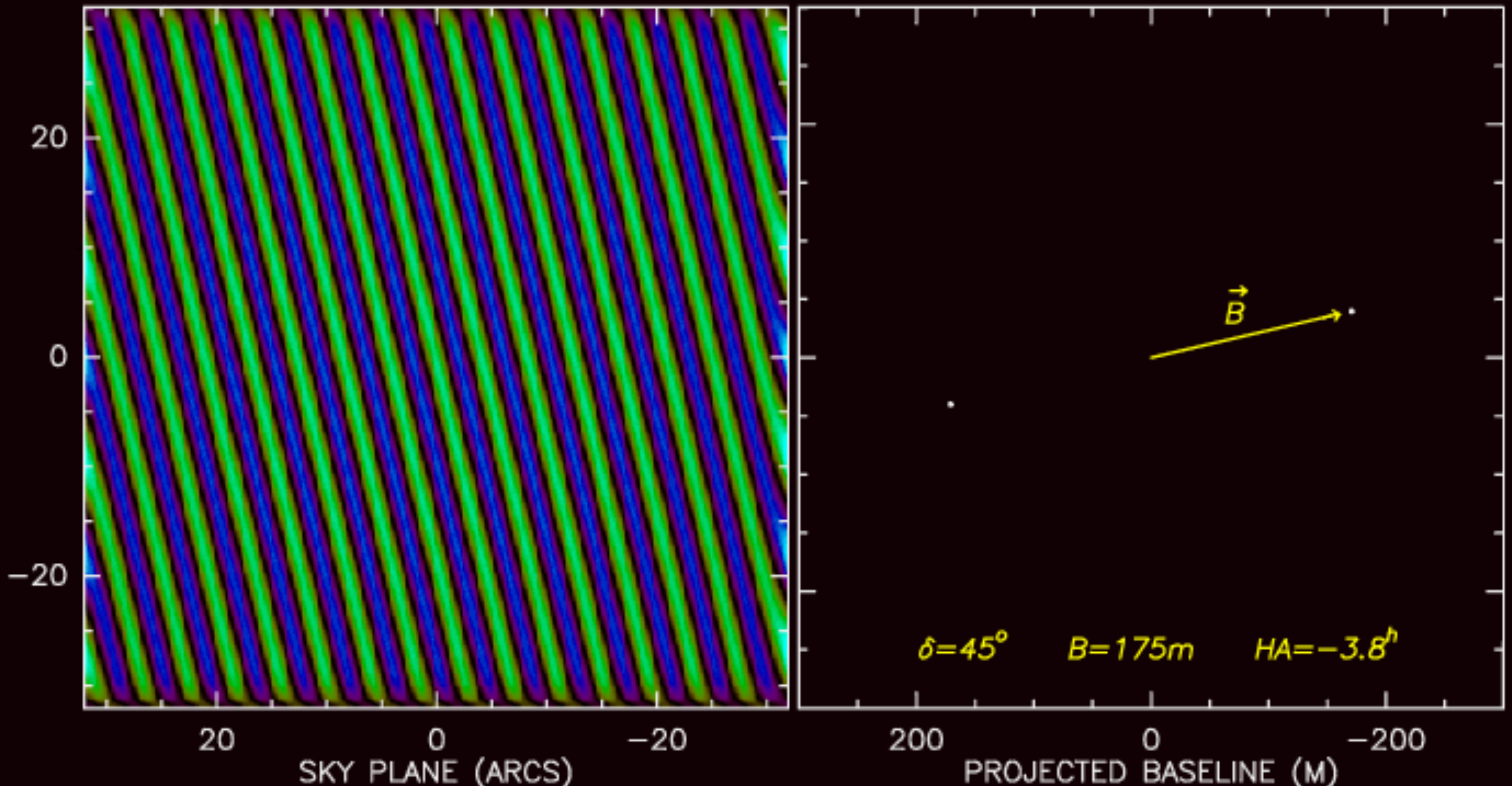
is the technique by which the elements of an interferometer sweep out the aperture of a large telescope

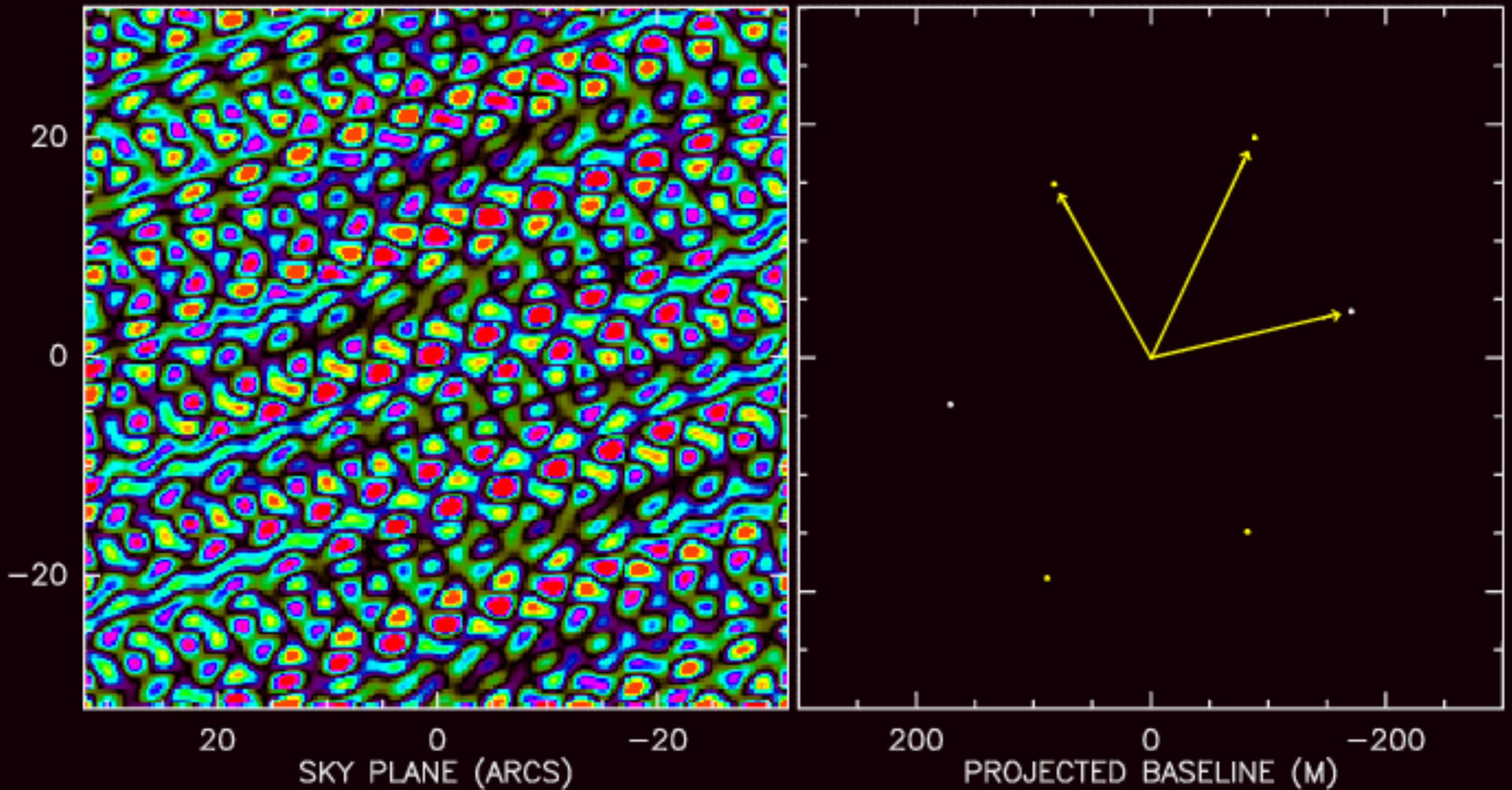


$$\mathrm{OTF} = A(r) \star A(r)$$




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)
$\vec{B}$
$\delta=45°$
$B=175m$
$HA=-3.8^h$
200
0
−200
PROJECTED BASELINE (M)


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

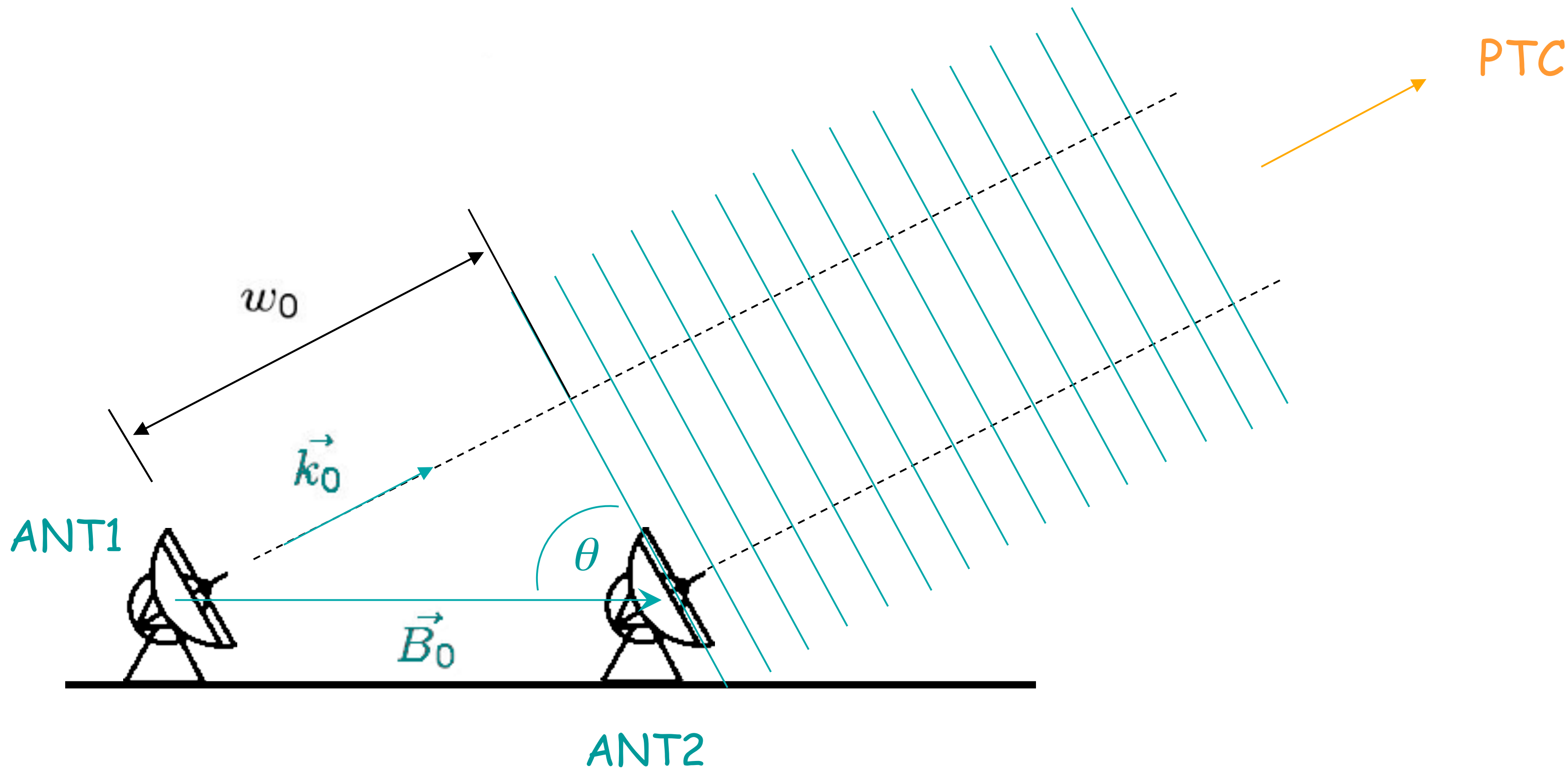
NOEMA - sources of position uncertainty

- 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

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

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



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

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

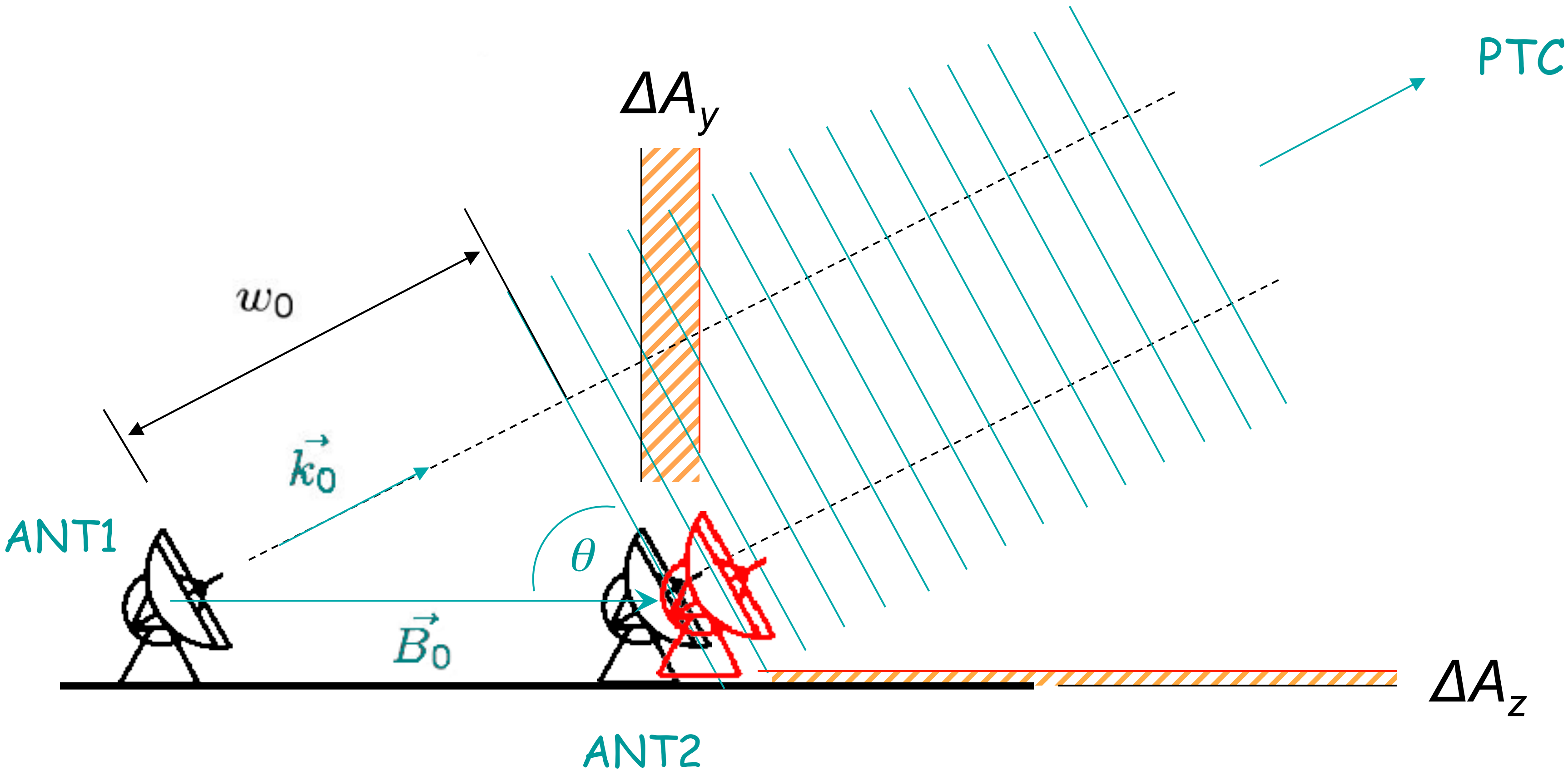
where A is the offset between the azimuth and elevation axis of an antenna.

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.

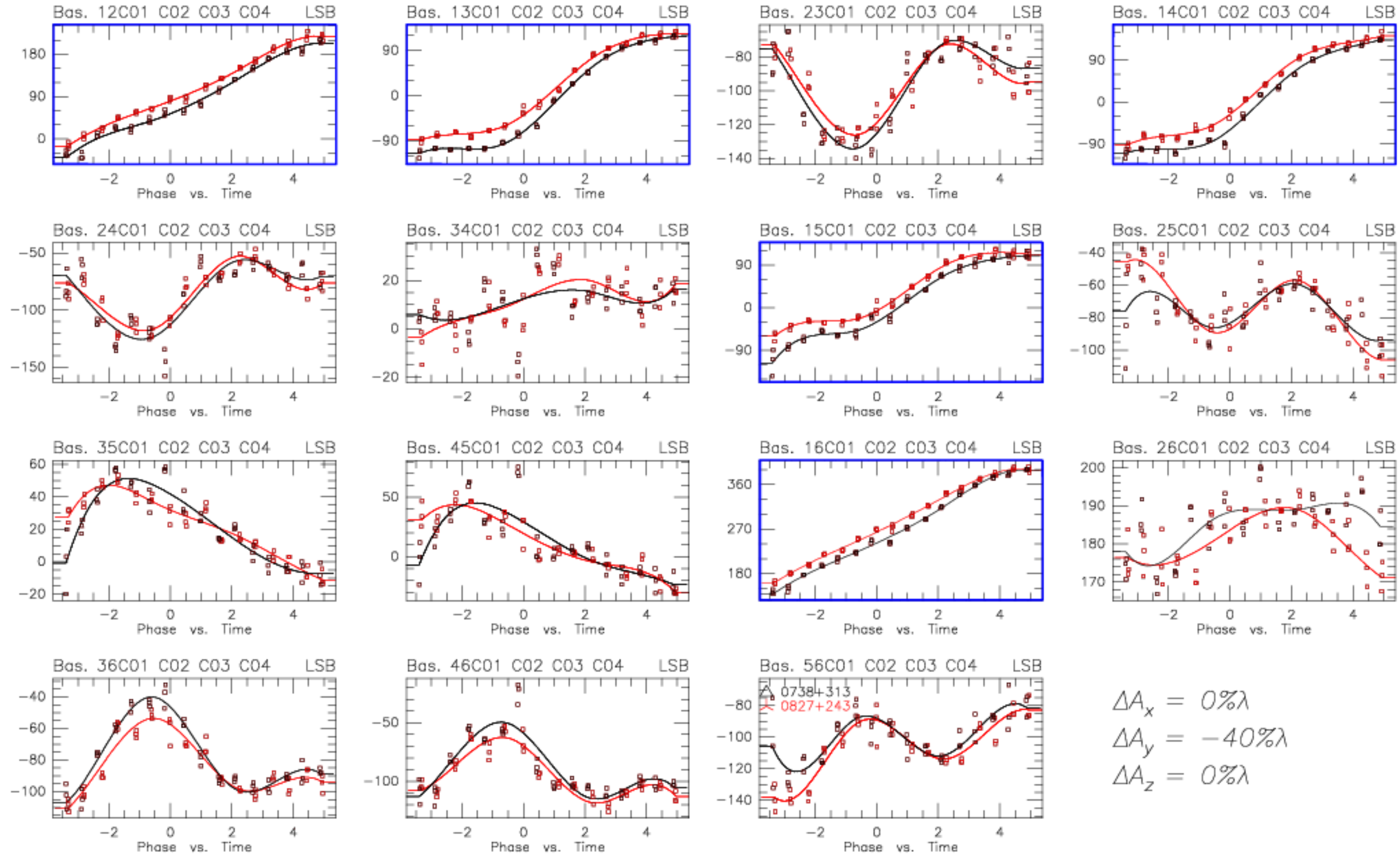
The phase equation

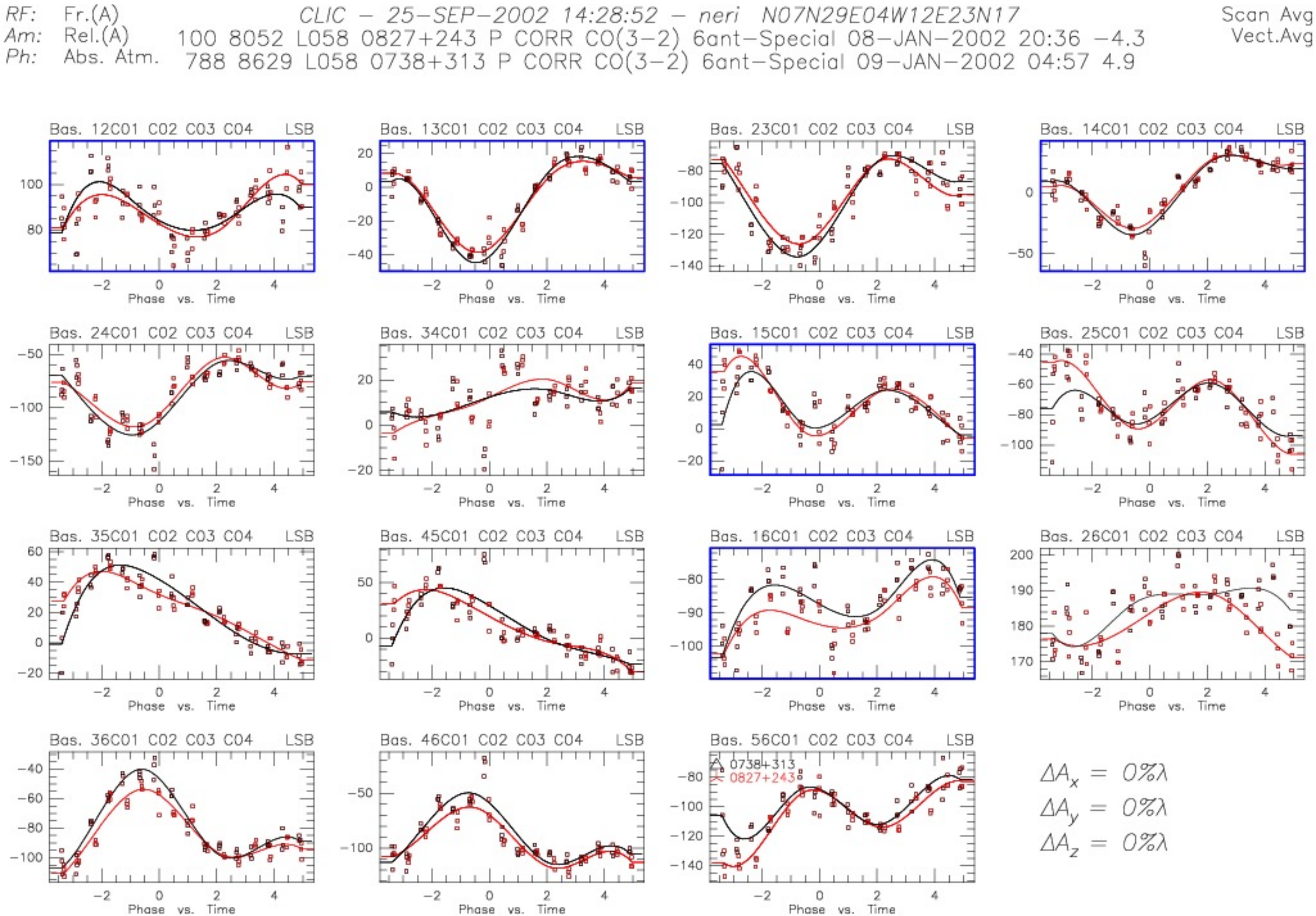
$$w_0 = \vec{B_0} \cdot \vec{k_0} = B_0 \sin\theta \simeq B_0 \cdot \theta$$

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



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





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