Advanced Technology for Modern Radio Telescopes

and some history

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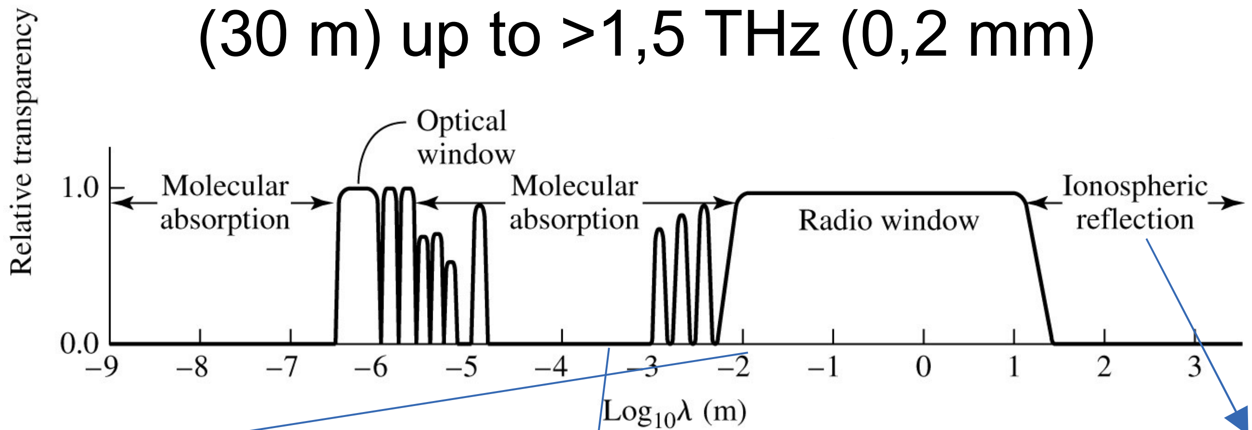
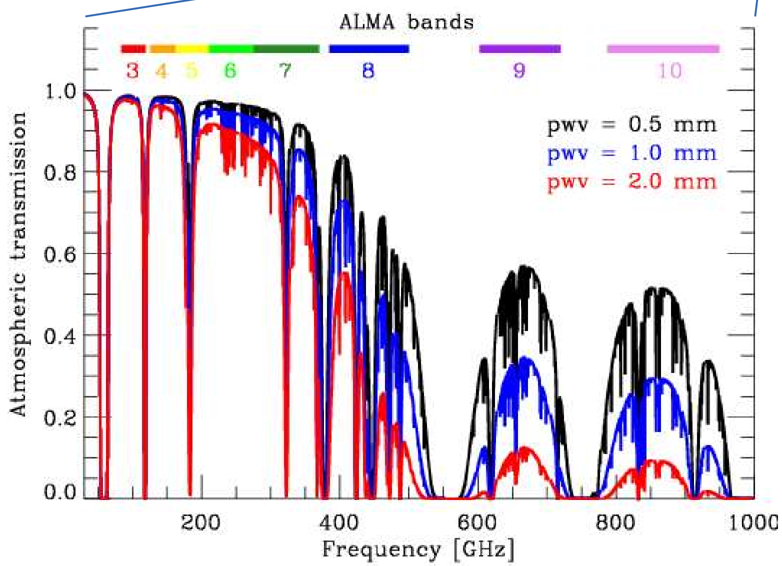
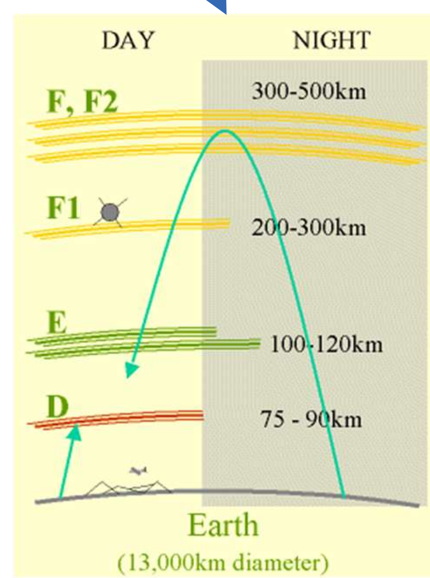
7th EIROforum School on Instrumentation

The radio spectrum

- Radio astronomy operates between ~10 MHz (30 m) up to >1,5 THz (0,2 mm)

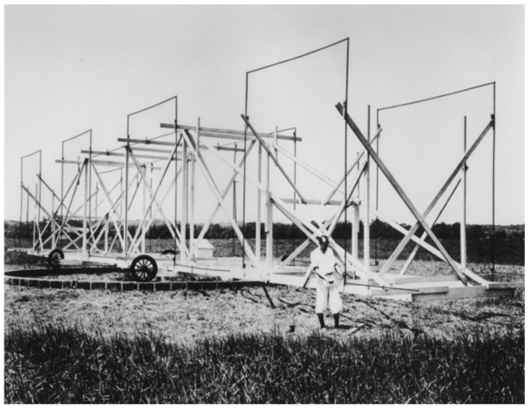






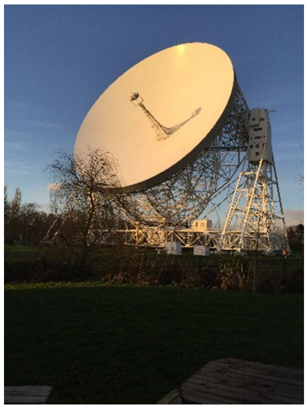
A condensed history of radio telescopes

- Radio astronomy is a relatively young discipline in experimental astronomy but has seen a very rapid development ….

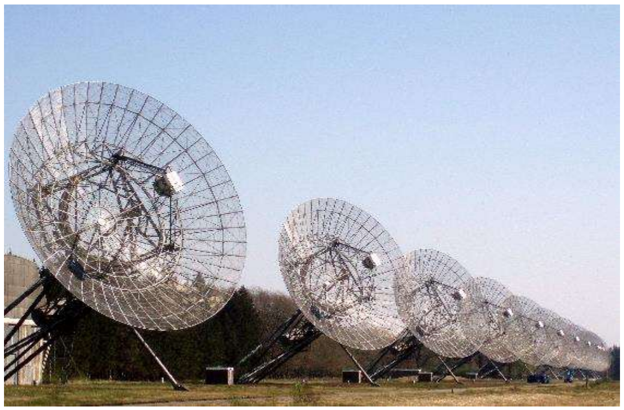


Karl Jansky (US) – 1932
detected radiation at
20.5 MHz from the Milky Way

Grote Reber (US) – 1937
9 m parabolic antenna
Operating at 3.3 GHz / 900 MHz / 160 MHz



Lovell Telescope (UK) – 1957
76 m parabolic antenna
Operating up to ~5 GHz



Westerbork Synthesis Radio Telescope (WSRT) (NL) – 1970
14 X 25 m parabolic antenna
Operating up to ~8.4 GHz

A condensed history of radio telescopes

- … and continues to make technological progress.

Green Bank Telescope – 2000
100 m off-set parabolic antenna
Operating up to ~116 GHz

Low Frequency Array (LOFAR)
2012 Phased array
Operating range 10-250 MHz

Atacama Large Millimeter/submillimeter Array (ALMA) - 2013
54 x 12 m / 12 x 7 m
Operating range 30-950 GHz

FAST Telescope – 2016
500 m spherical antenna
Operating up to ~3 GHz

Outline

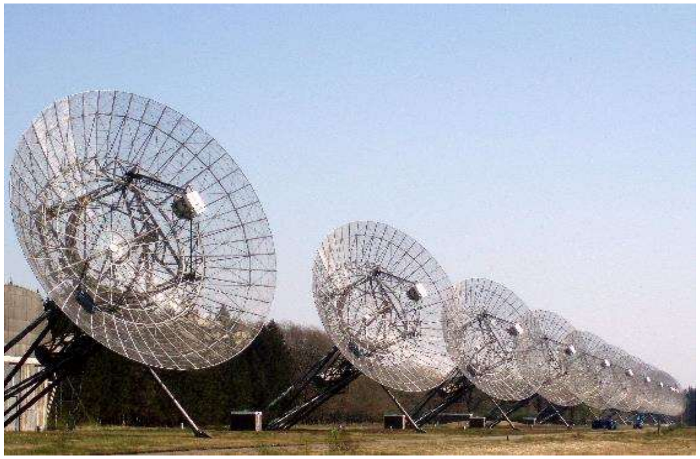
- Key performance drivers for radio telescopes
  - Sensitivity
  - Angular resolution
  - Frequency coverage
- Design examples of modern radio telescopes
  - Atacama Large Millimeter/submillimeter Array (ALMA)
- Some new receiver technologies
  - Phased array feeds
  - Aperture arrays
- Care about the EM environment
  - Radio Frequency Interference

Sensitivity

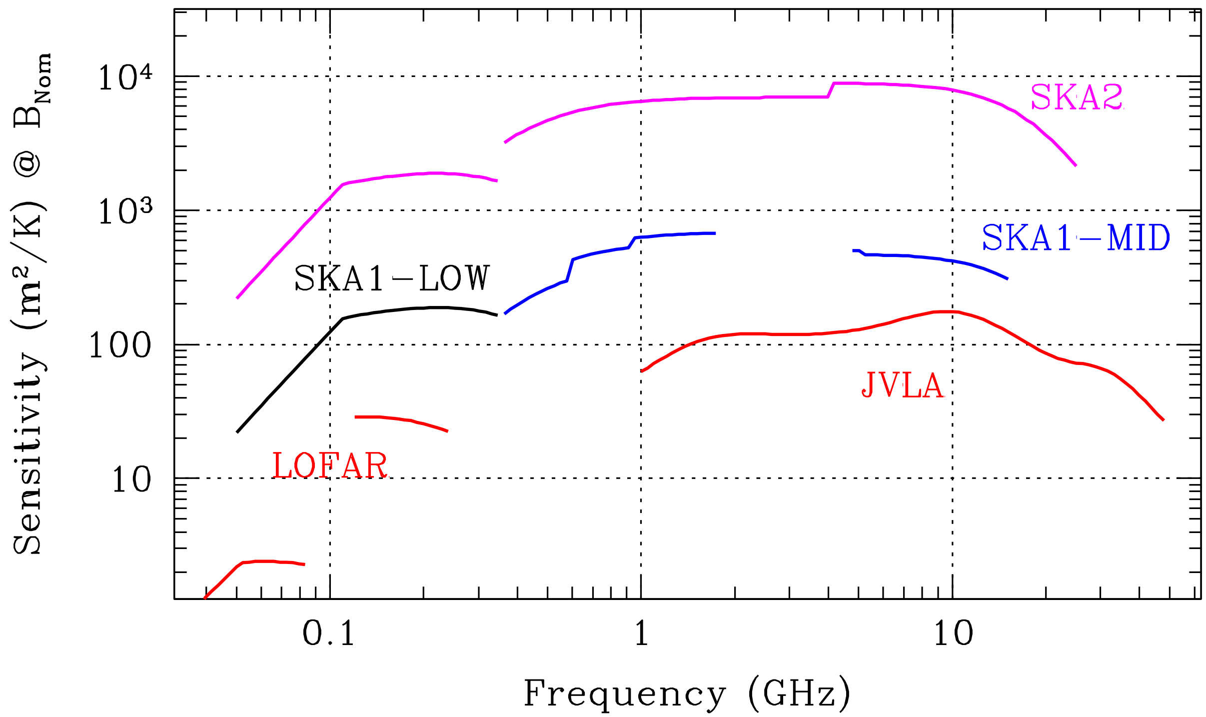
- Sensitivity equation expressed in flux density S

$$\Delta S = \frac{S_{sys}}{\sqrt{B \cdot t}} \qquad S_{sys} = \frac{2 \cdot \eta \cdot k \cdot T_{sys}}{A_{eff}}$$

- ✓ Increased integration time *t*
- ✓ Increase collecting area A_{eff} (larger dishes / combining multiple dishes)
- ✓ Reduction of system noise sources T_{sys} (e.g. amplifiers, antenna spill over)
- ✓ Increase observing bandwidth *B* (only works for continuum sources, e.g. thermal radiation)



A sensitivity comparison



- LOFAR (EU): > 1 km^2 (@ 30 MHz)
- SKA1-Low (AUS): 465.500 m^2 (@ 100 MHz)
- SKA1-Mid (SA): 26.555 m^2 (η_{ap} = 80%)
- JVLA (USA): 13.250 m^2

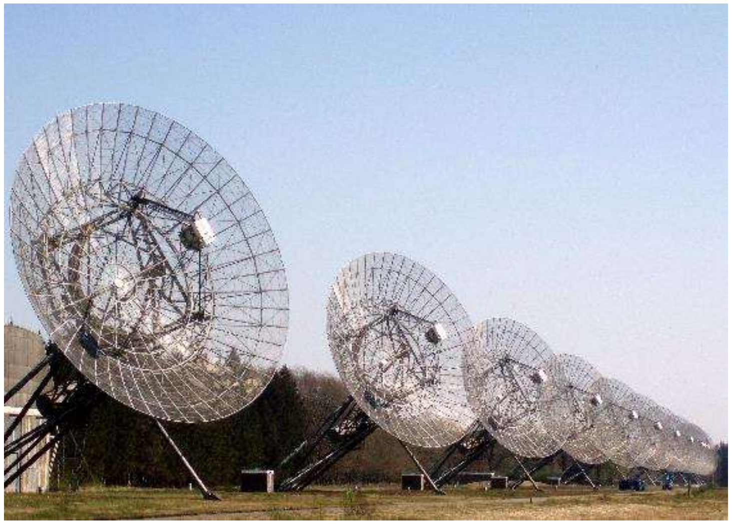
Angular resolution

- Antenna Half-Power Beam Width (HPBW) as a measure for angular resolution

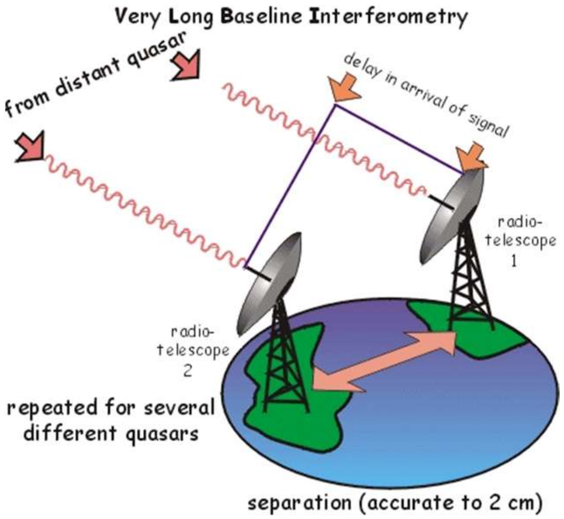
$$\theta_{HPBW} = k.\frac{\lambda}{D}$$

  ✓ Increase aperture size D

  ✓ Increase frequency → smaller λ

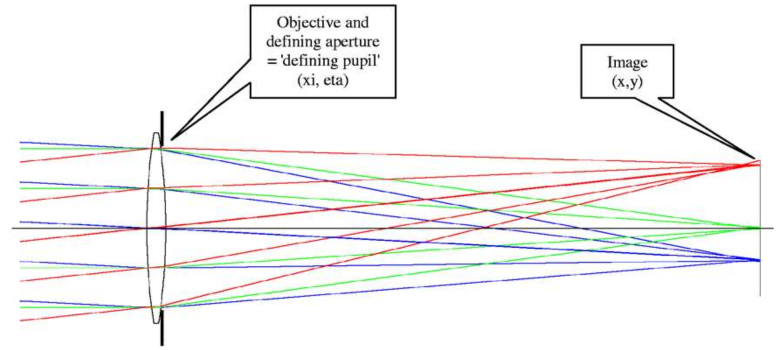


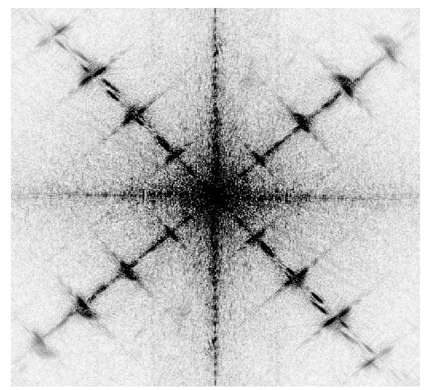
- Practical limits to increasing D
  - Aperture synthesis
    - WSRT (3 km), VLA (27 km), SKA Phase 1 (150 km)
  - Very Long Baseline Interferometry
    - < 100 – > 300.000 km



Aperture Synthesis

- Spatial autocorrelation of field distribution in a pupil plane and its intensity distribution in an image plane are related by a Fourier transform
- The pupil plane is sampled by the individual antennas
  (Nyquist–Shannon sampling theorem)
- 1-D (e.g. WSRT) and 2-D (e.g. ALMA) arrays are being used
- Sampling points are enhanced by using earth rotation

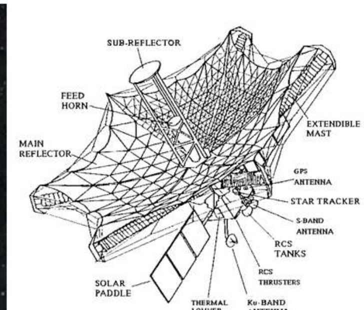




This is the amplitude of the Fourier transform of an image of an typical Dutch object.

Angular resolution

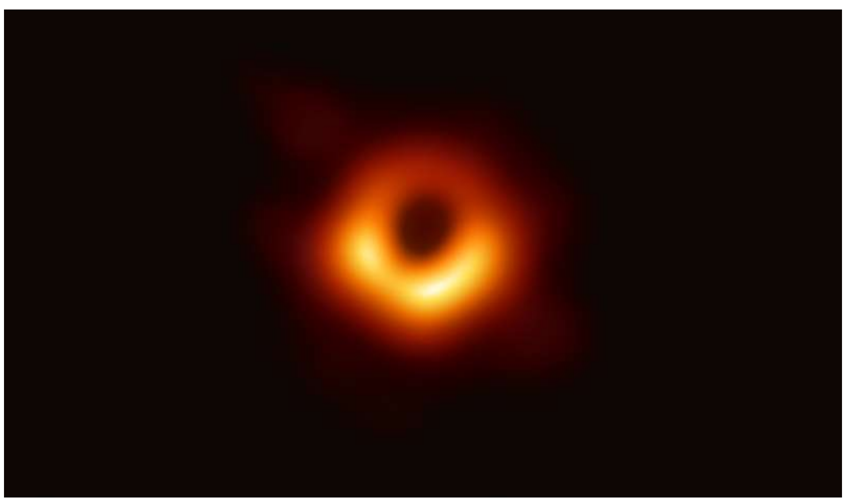
- Very Long Baseline Interferometry
  - Groundbased VLBI
    - European VLNI Network
      - 327 MHz – 43 GHz
      - Resolution: 30 marcs – 150 μarcs
    - Event Horizon Telescope
      - 230 / 450 GHz
      - Resolution: 10 μarcs (goal)
  - Space VLBI
    - HALCA - VSOP
      - 1997 - 2005
      - 8 m diameter reflector
      - Baseline 56 – 21.400 km
      - 1.6 GHz / 5 GHz / 22 GHz
      - Resolution: ~120 μarcs
    - Radioastron – Spektr-R
      - 2011 - current
      - 10 m diameter reflector
      - Baseline 10.000 – 339.000 km
      - 327 MHz / 1.6 GHz / 5 GHz / 22 GHz
      - Resolution: ~8 μarcs

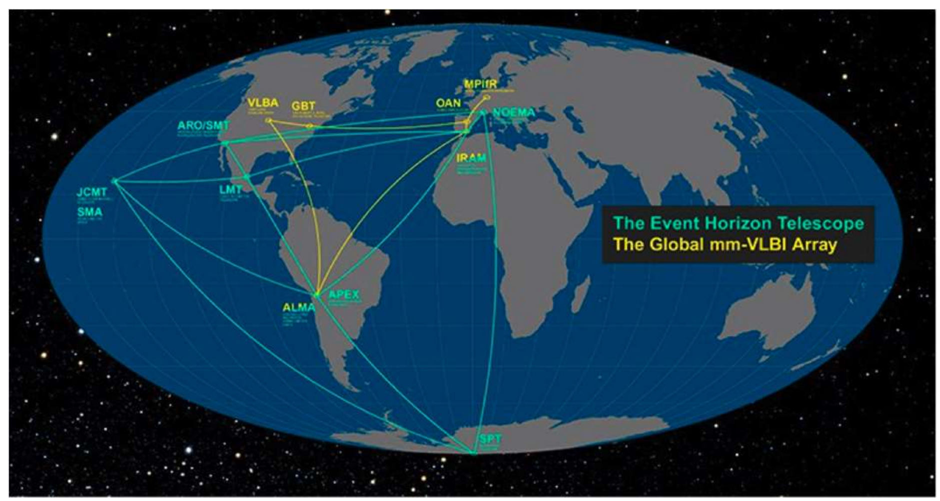


SRT antenna on the beginning of deployment in Lavochkin Association (2002)

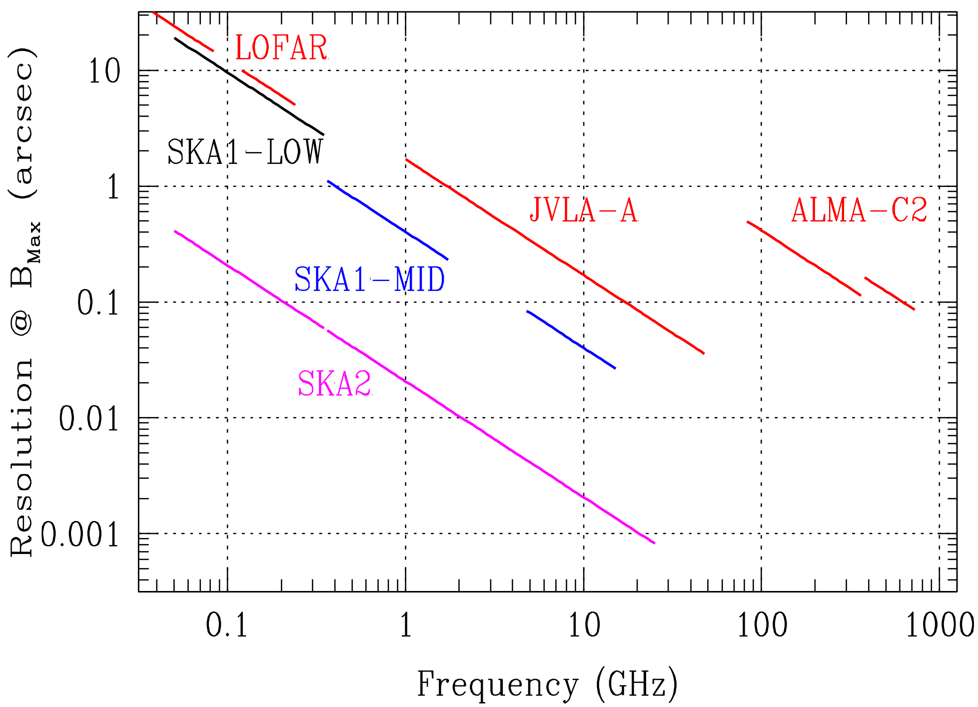
The Event Horizon Telescope

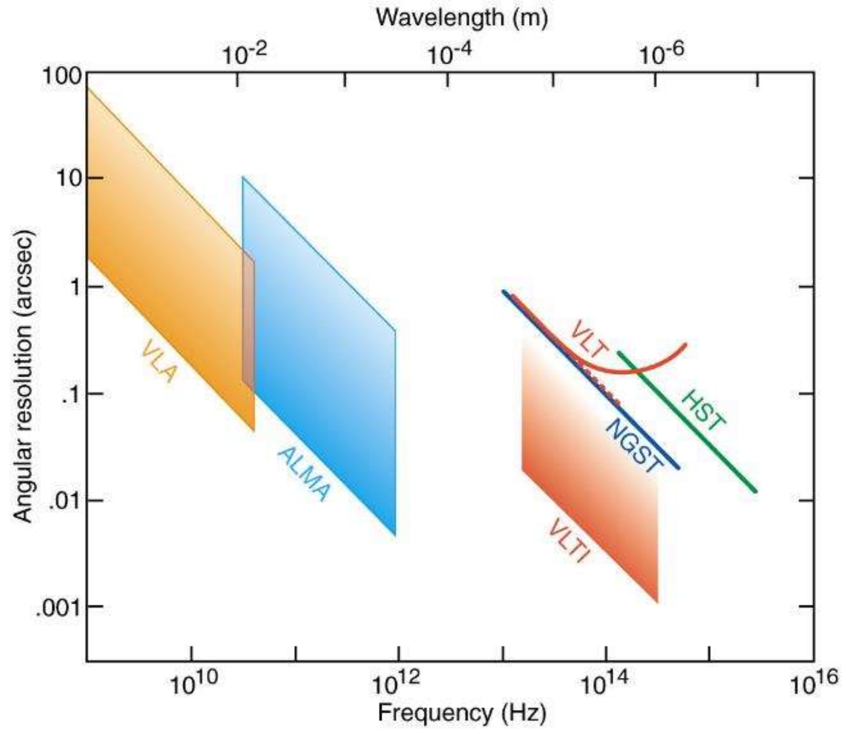
- First image of a black hole (see ESO announcement)
- Two VLBI arrays that link radio dishes across the globe
  - Global mm-VLBI Array observes at a wavelength of 3 mm
  - EHT observes at a wavelength of 1.3 mm
    - angular resolution (λ/d_p) of about 25 μarcs (equivalent to standing in New York and being able to read the date on a quarter in Los Angeles)





Angular resolution comparison





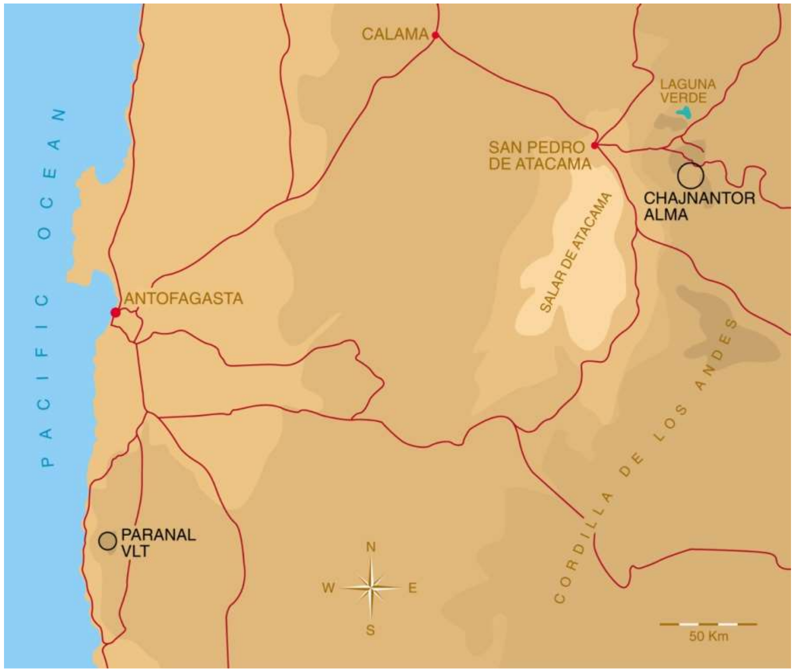
What is ALMA?

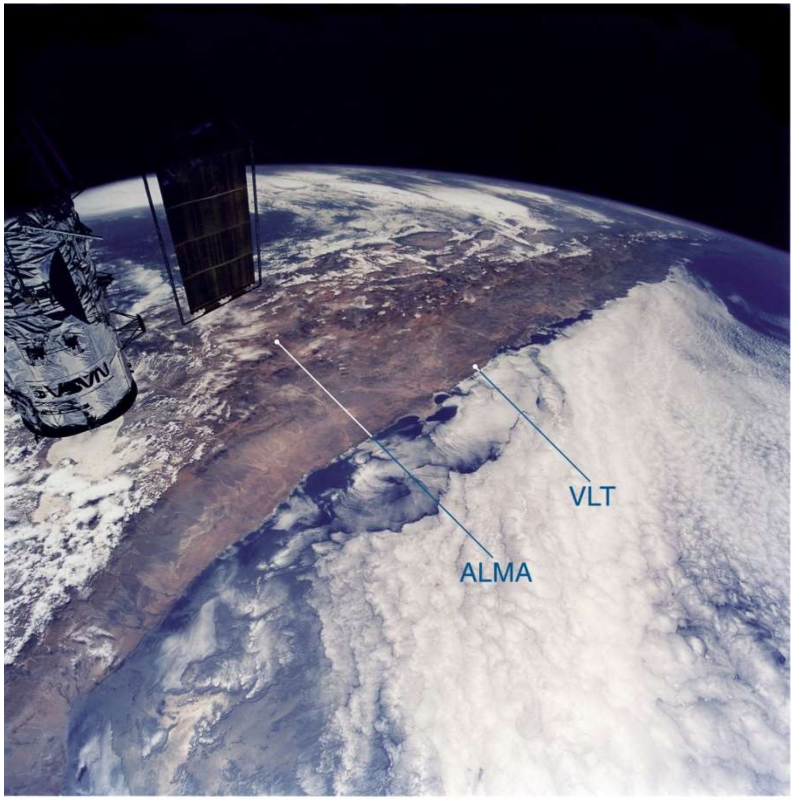
- **The Atacama Large Millimeter/submillimeter Array** - a global endeavor to build an interferometric array of radio telescopes operating at wavelengths between 10 and 0.3 mm (30 to 950 GHz)
  - 7000 m^2 collecting area (54 12-m ∅ antennas & 12 7-m ∅ antennas)
  - 5000-m altitude site in Chile
  - Reconfigurable antennas allowing baselines up to 14 km

- **The ALMA Partners**
  - Europe (ESO on behalf of its 16 member states)
  - North America (NRAO representing US and Canada)
  - East Asia (NAOJ representing Korea and Taiwan)

Geographical location of ALMA

- Northern Chili / 2nd Region
- Atacama desert





View of Northern Chile (NASA Space Shuttle)

ESO PR Photo 24b/99 (8 June 1999)


San Pedro de Atacama (2400m),
AOS (5000m)
OSF (2900m)

Llano de Chajnantor

- Chajnantor plateau, elevation 5000+ m

ALMA baseline instrument

- Key technical parameters:
  - 54 & 12 antennas:
    - 12 m / 7 m diameter, Cassegrain configuration
    - Surface accuracy: < 25 μm rms / 12 m - < 15 μm rms / 7 m
    - Pointing accuracy: 0.6 arcsec (offset, 2 deg in position and 15 min time), 2.0 arcsec (absolute)
    - Nutating sub-reflector (4 antennas)
  - Zoom configuration:
    - Baseline length up to ≈ 14 km
    - 192 antenna stations
    - All antennas fully reconfigurable over all antenna pads
  - Front ends:
    - Dual polarisation
    - IF bandwidth: 8 GHz / polarisation
  - Correlator:
    - Number of baseband inputs: 8 / antenna
    - Maximum sampling rate per baseband input: 4 GHz
    - Digitising format: 3 bit - 8 level
    - Correlation format: 2 bit - 4 level

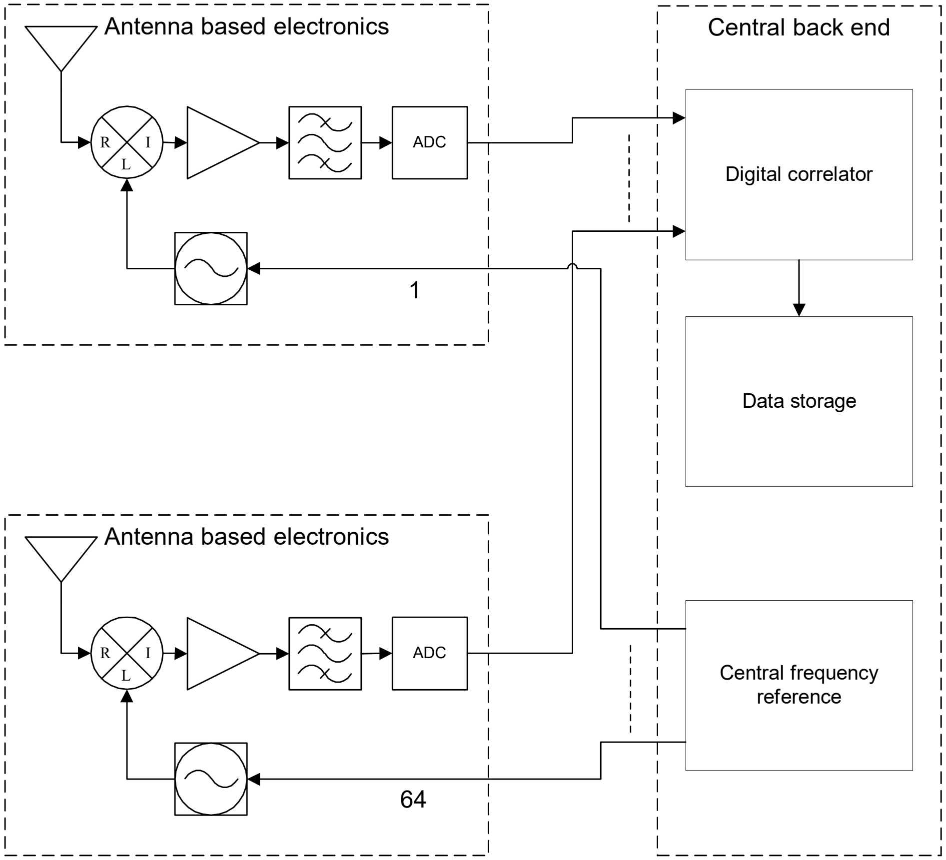
ALMA Front End key specifications

ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Receiver technology
		T_{Rx} over 80% of the RF band *	T_{Rx} at any RF frequency *		
1	31.3 – 45 GHz	17 K	28 K	USB	HEMT
2	67 – 90 GHz	30 K	50 K	LSB	HEMT
3	84 – 116 GHz	37 K (40K)	62 K (50K)	2SB	SIS
4	125 – 169 GHz	51 K (45K)	85 K (55K)	2SB	SIS
5	163 - 211 GHz	65 K	108 K	2SB	SIS
6	211 – 275 GHz	83 K (45K)	138 K (60K)	2SB	SIS
7	275 – 373 GHz	147 K (80K)	221 K (90K)	2SB	SIS
8	385 – 500 GHz	196 K (160K)	294 K (270K)	2SB	SIS
9	602 – 720 GHz	175 K (100K)	263 K (150K)	DSB	SIS
10	787 – 950 GHz	230 K	345 K	DSB	SIS

* In brackets achieved noise temperature

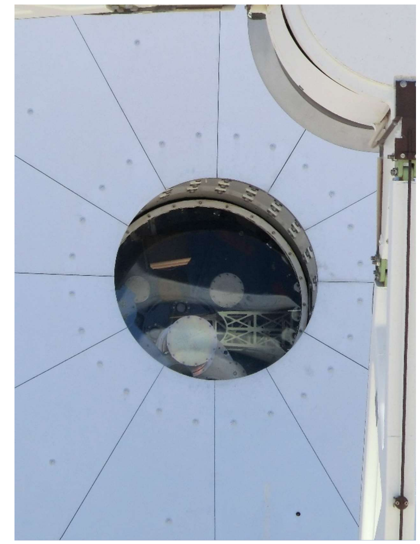
Simplified ALMA block diagram

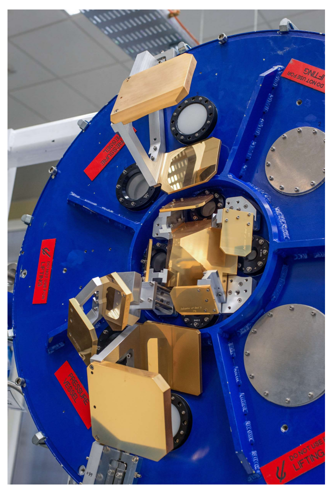
- Receiver systems:
  - Super heterodyne architecture
  - Dual frequency conversion (only single conversion shown)
- Optical transmission systems for digitised IF (~100 Gb/sec each antenna) and LO reference distribution
- The depicted system is located at the Array Operations Site at 5000+ m.
- Remotely controlled from the Operations Support Facility at ≈2800 m.

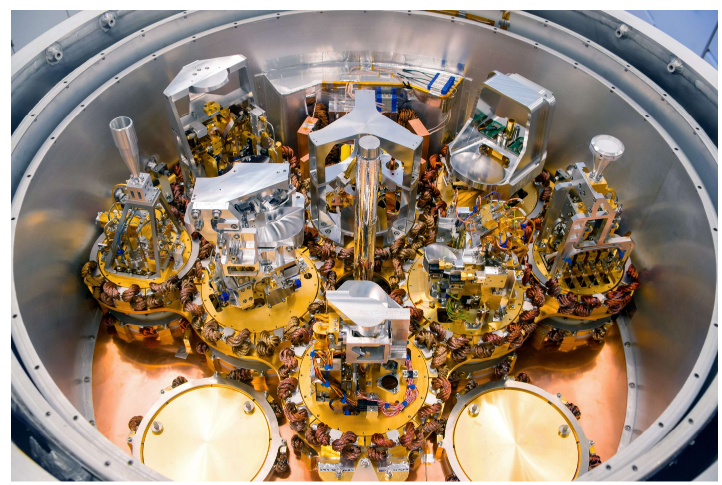


ALMA / Front End Assembly

- Cryogenic (~ -270 deg. Celsius) receivers at each antenna





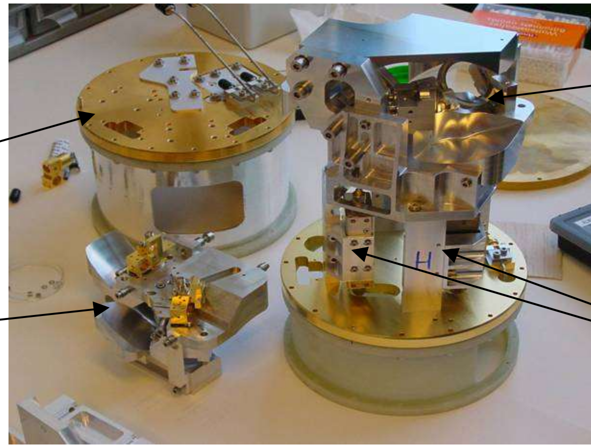


ALMA Band 9 Cartridge

4 + 110 K Stage Assembly (NOVA/SRON)

Partially Assembled 110K Stage

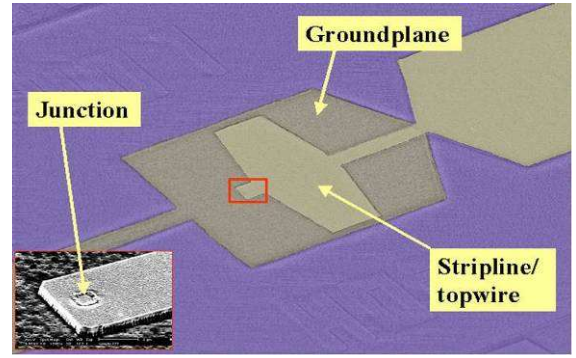
1st Optics Block



2nd Optics Assembly Integrated on 4K Plate

4-12 GHz Isolators

SIS Junction Lay Out (TUD)

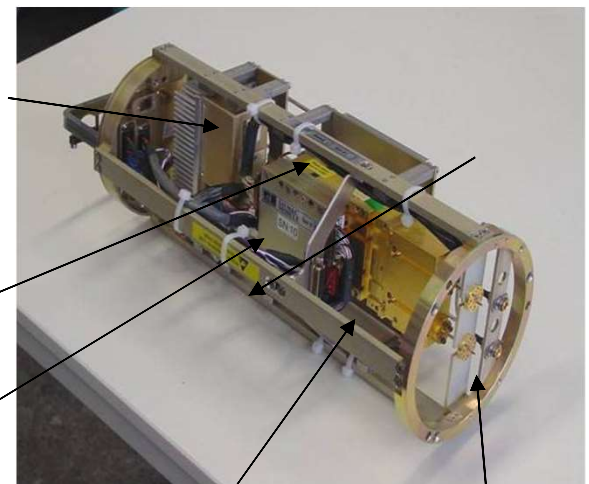


Warm Cartridge Assembly (NRAO)

YIG Oscillator (15-20 GHz)

LO Phase Lock

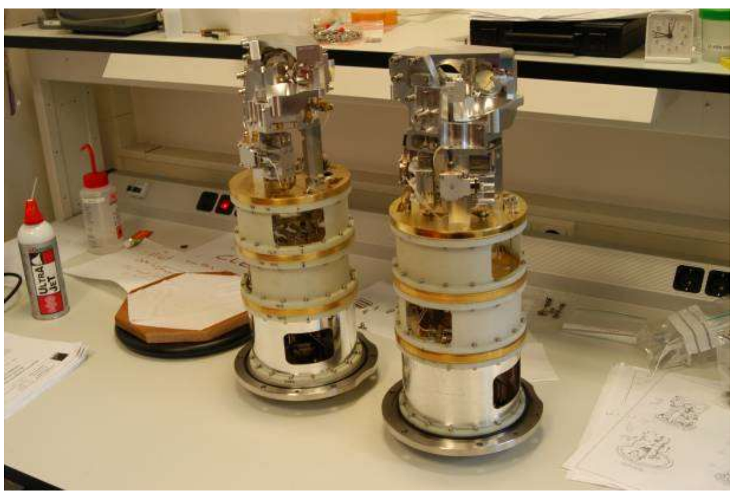
LO Bias Electronics



Space for Cartridge Bias Electronics

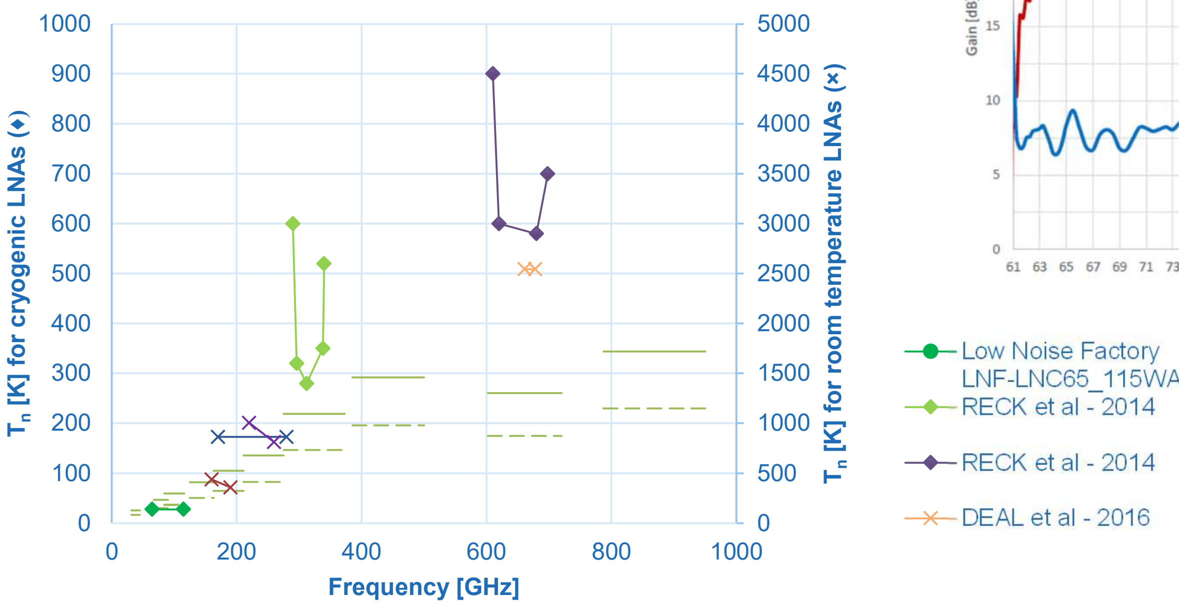
WR8 Waveguide Outputs (2)

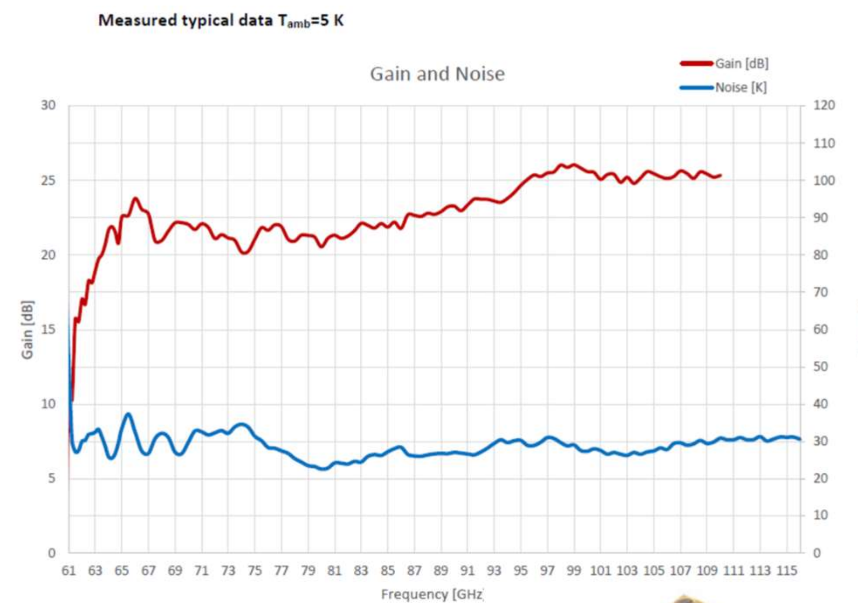
Cartridge Assembly (NOVA/SRON)



Cryo sub-mm Low Noise Amplifiers

- Replacing SIS-mixers by III-V transistor technology
  - Increased RF bandwidth
  - Reduced cooling requirements: ~20 K instead of < 4 K

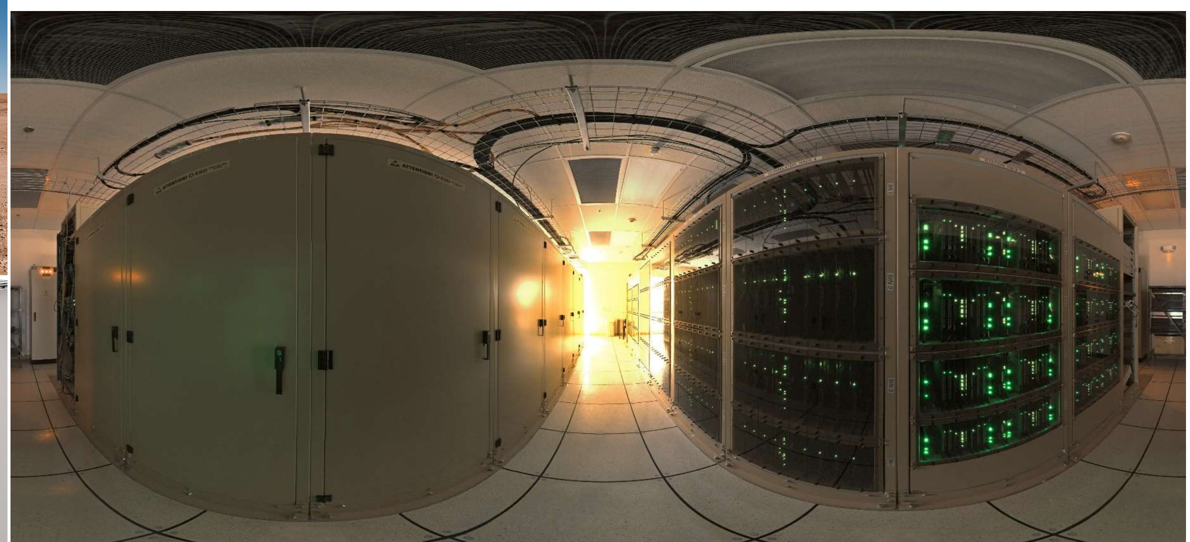




- Ratio left / right y-axis is 1 / 5
  - Demonstrated reduction in T_n when cooling LNA from room temperature to ~ 25 K (see e.g. Reck et al)

ALMA Correlator

- Calculates visibilities (real time) from signals from all 66 antennas
  - Dedicated supercomputer with 134 million processors performing up to 17 quadrillion (17 000 000 000 000 000) operations per second

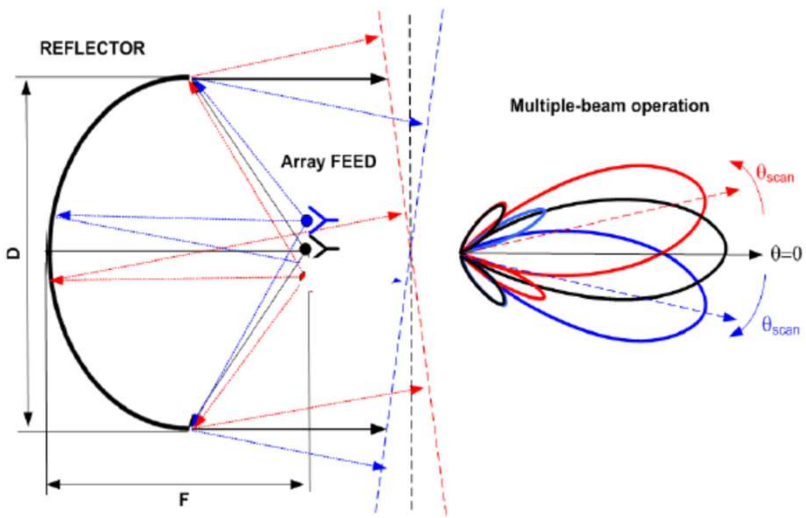


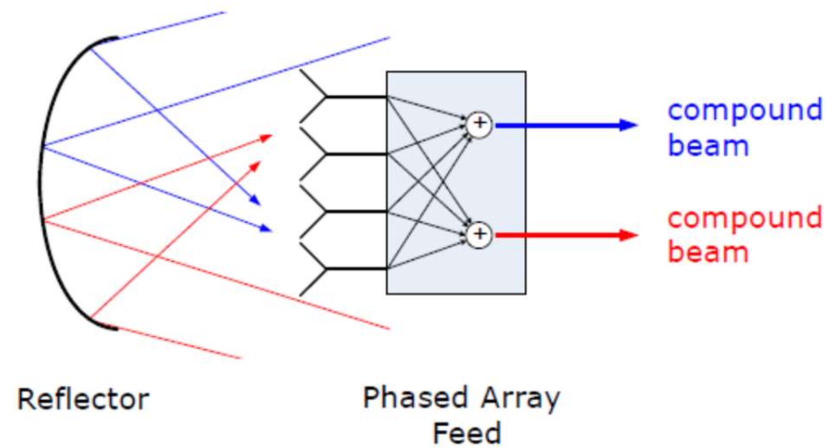
Multiple feeds in focal plane

- Enlarging of FOV with multiple feed in focal plane

Under sampled focal plane (d > ½ λ)
Focal plane arrays
Mainly at (sub-)mm telescopes

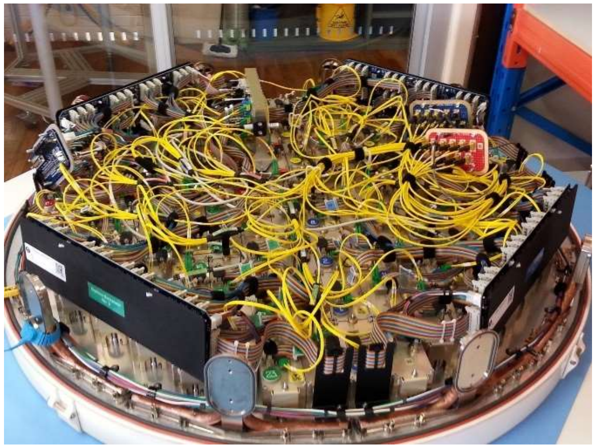
Densely sampled focal plane (d < ½ λ)
Phased array feeds
Focus at cm telescopes

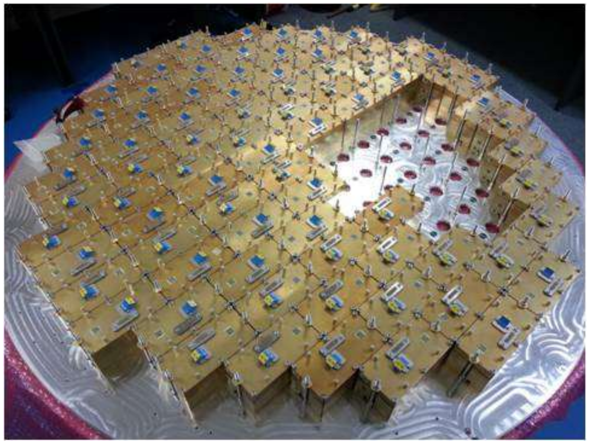


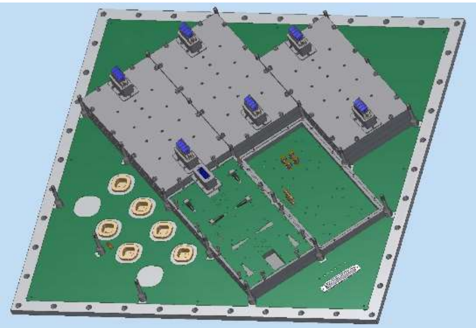


PAF Development – CSIRO (AUS)

- Focussed on 650 – 1700 MHz
- Concepts demonstrated 5 x 4 array (40 Elements)

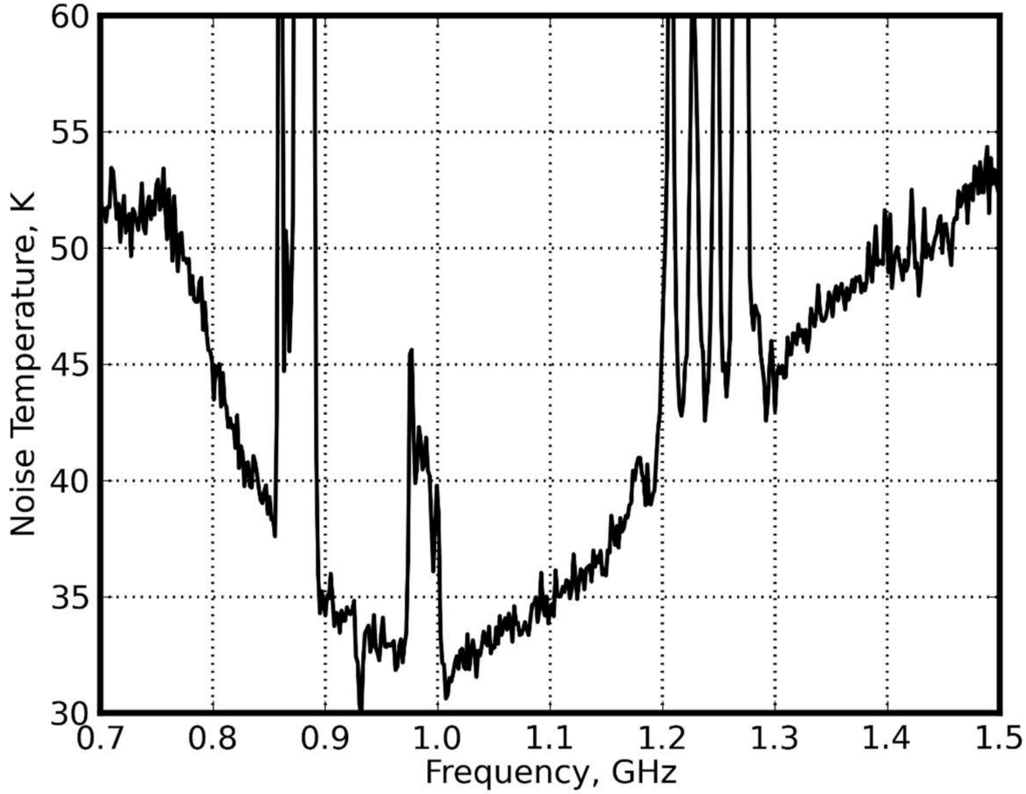


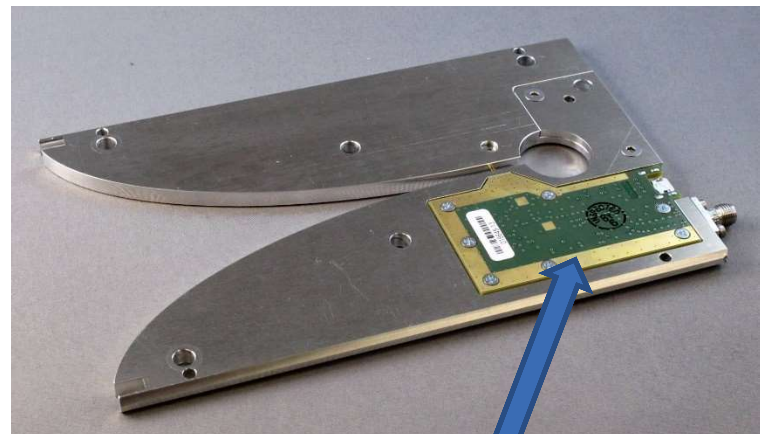


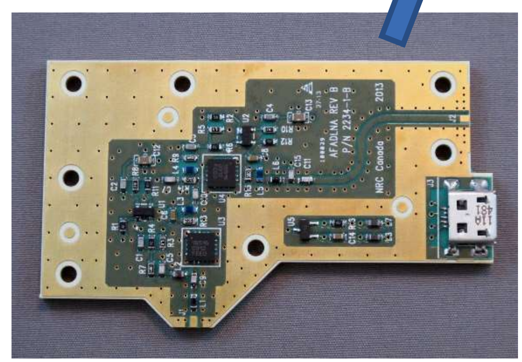


PAF Development - NRC (CA)

Array Noise Temperature



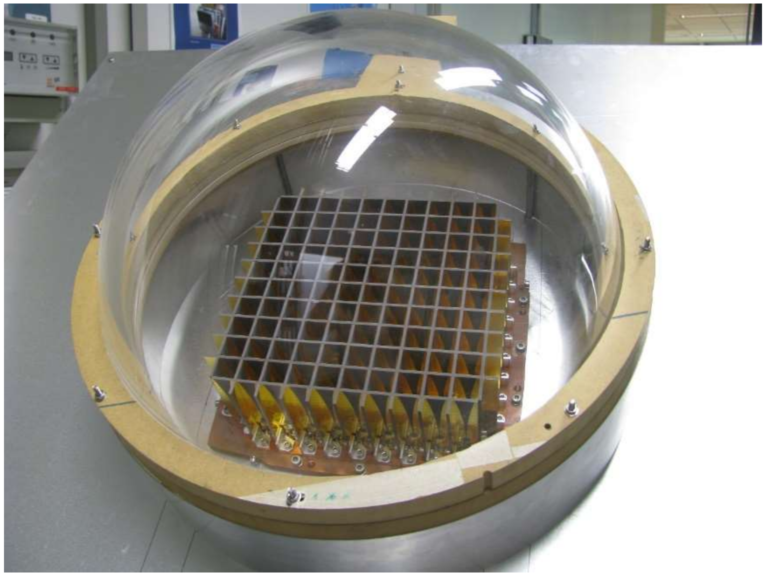


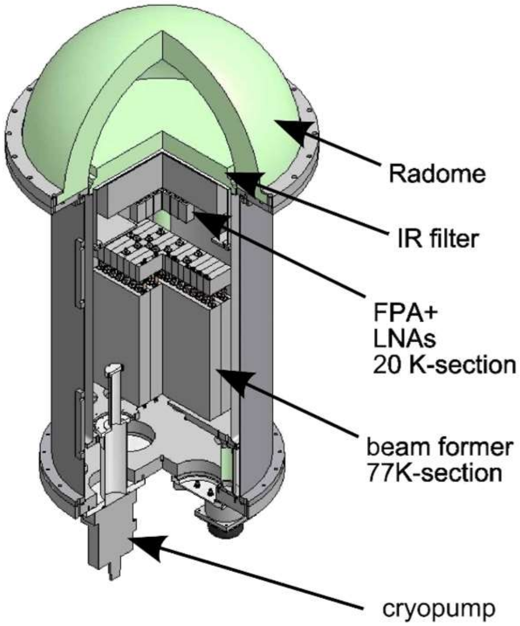


Thick Vivaldi element and LNA

PAF Development – ASTRON / JBCO

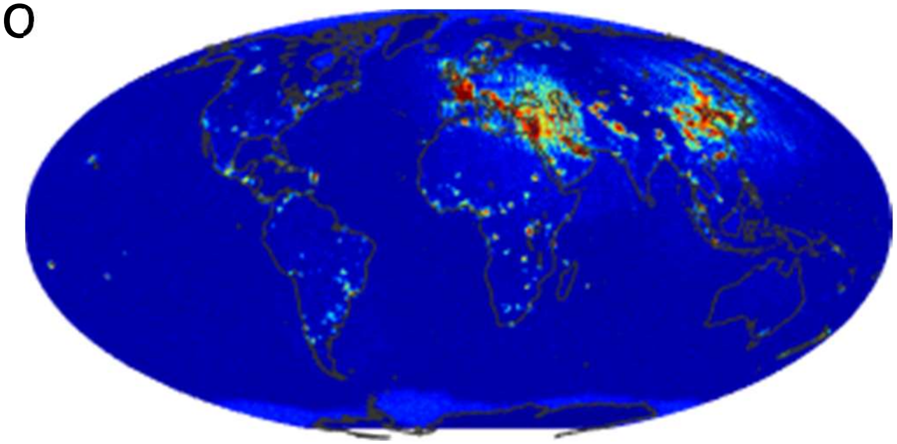
- PHAROS
  - Cryogenic receiver
  - MMIC 0.2-2GHz LNA (ASTRON)
  - Analog beamformer



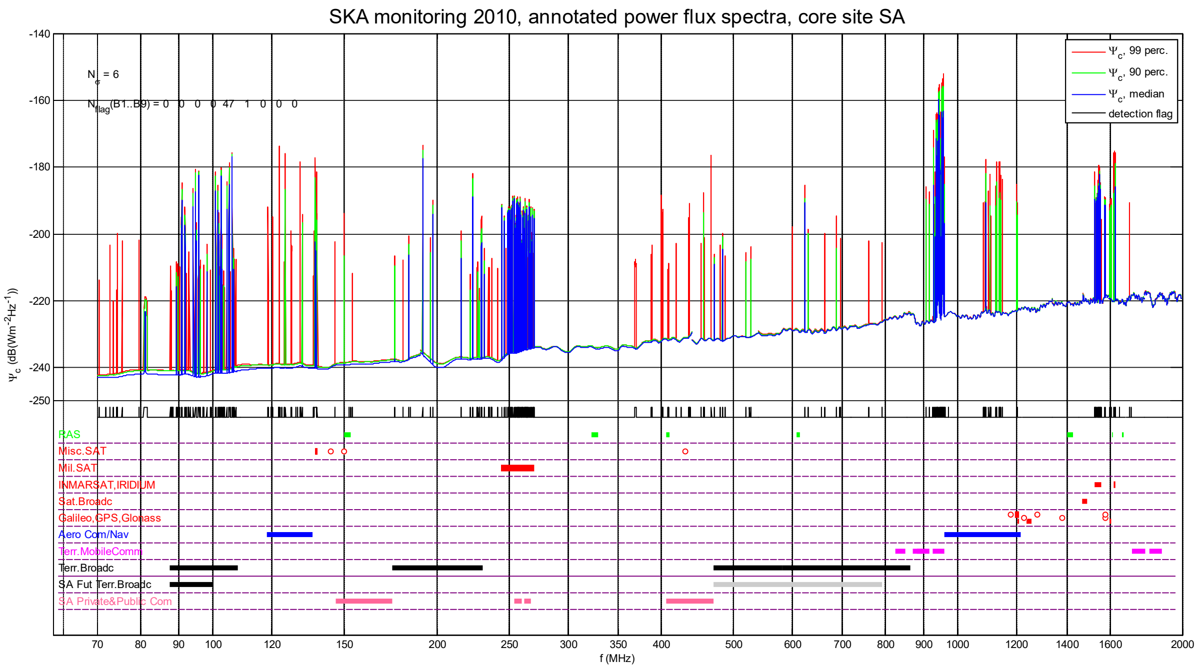


Radio Frequency Interference

- RFI is increasing threat to radio astronomy
  - Passive service



Global RFI map @ 1,4 GHz
from NASA Acquarius



RFI from Satellite Constellations

Constellation (Registering Nation)	Altitude (km)	Number of satellites
Starlink Generation 1 (US)		
Today: 1378	5,50	1,584
	1,110	1,600
	1,130	400
	1,275	375
	1,325	450
Starlink Generation 2 (US)		
Pending approval	328	7,178
	334	7,178
	345	7,178
	373	1,998
	499	4,000
	604	144
	614	324
	360	2,000
OneWeb Phase 2 (US, UK) Today: 128	1,200	1,764
	1,200	2304 ~~23,040~~
	1,200	2304 ~~23,040~~
Amazon Kuiper (US)		
	590	784
	610	1,296
	630	1,156
Sat Revolution (Poland)	350	1,024
CASC Hongyan (China)	1,100	320
CASIC Xingyun Lucky Star (China)	1,000	156
CommSat (China)	600	800
Xinwei (China)	600	32
AstromeTech (India)	1,400	600
Boeing (US)	1,030	0 ~~2,956~~
LeoSat (Luxembourg)	1,423	0 ~~108~~
Samsung (Korea)	2,000	4,700
Yaliny (Russia)	600	135
Telesat LEO (Canada)	1,000	[illegible]
Total		~~96,437~~
		~60 000

COU-1928 report
bit.ly/ESOcou1928

...planned telecom mega-constellations
as of early 2021:

- ~30 (sub-) constellations
- ~100 000 satellites

As of today:

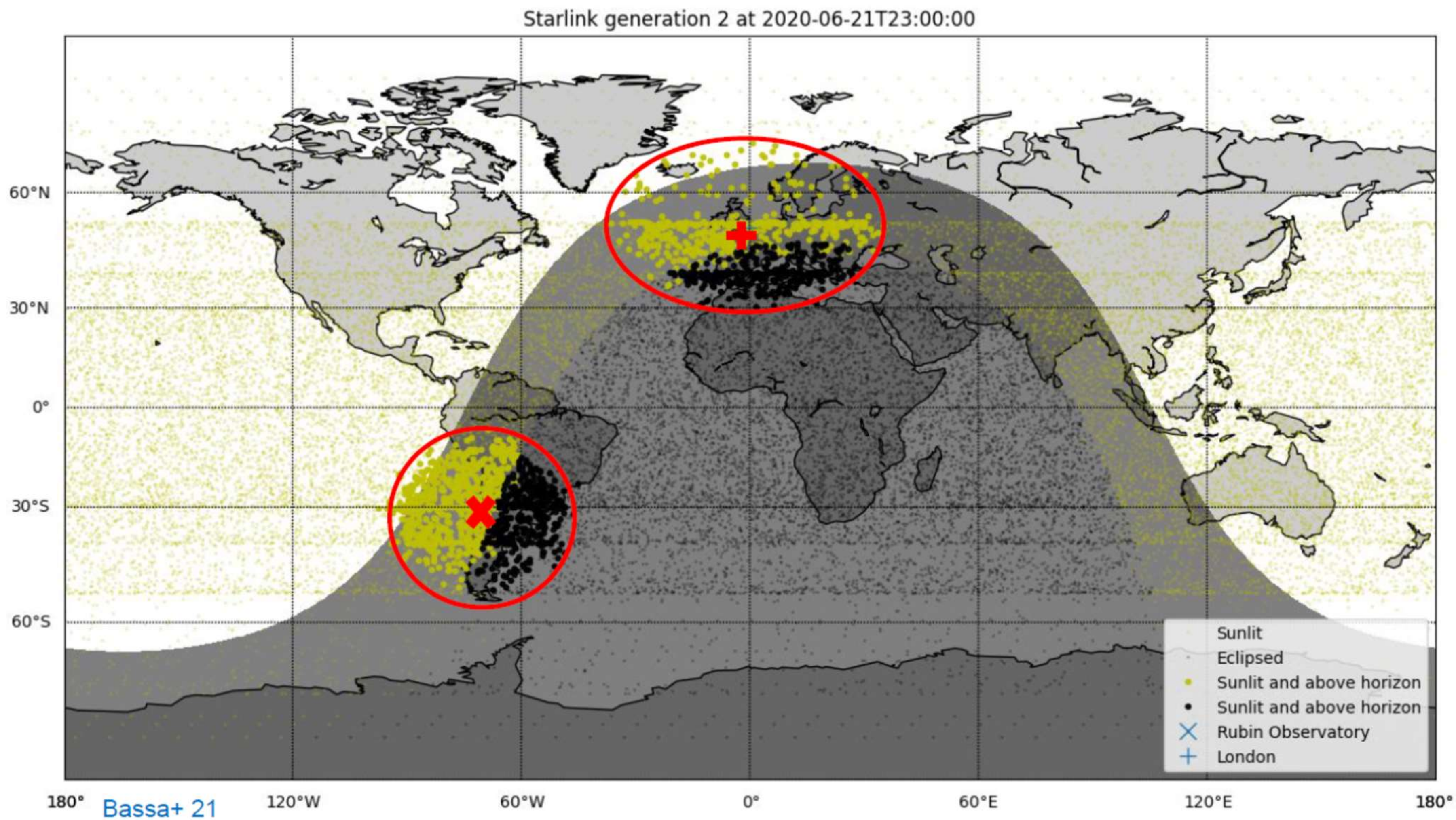
- ~1500 satellites in LEO constellations
  +2800 pre-existing satellites
- Not all constellations have filed application
- Boing + Leosat withdrew their application
- OneWeb bankrupted and revived
- OneWeb downscaled to 6300 sat

Total @2030: ~ 60 000 satellites

Caveat:

- Few filings end up in launches (~10%)
- MANY more non-telecom constellations have filed
  (but they are much smaller spacecrafts)
  (but but they still contribute to crowding)

RFI from Satellite Constellations (cont.)



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Thank you!