SIS Receivers for Radio Astronomy – overview of existing instrumentation

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Outline

- Introduction – Heterodyne Detection

- SIS receivers – key technical details

- Mm/sub-mm (THz) observatories

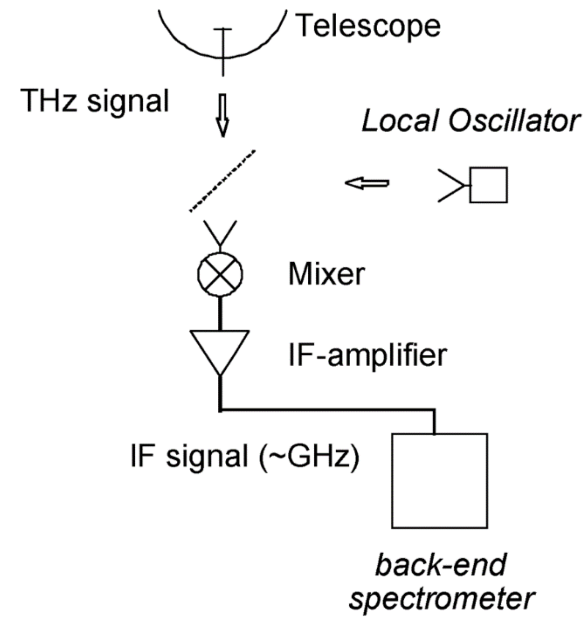
    - Ground-based Single Dish Telescopes
    - Interferometers
    - Space/balloon observatories (Herschel/TELIS)

- Future Projects
- Advanced Receivers
- SIS research groups in the world

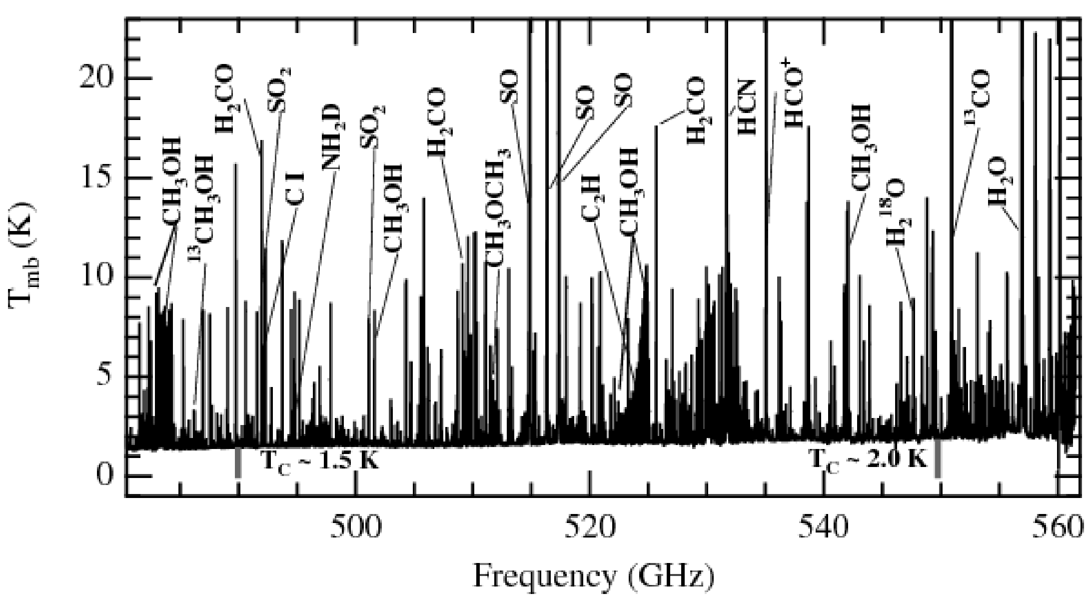
SIS receivers in mm/submm Radio Astronomy

Heterodyne Detection (SIS mixer)

- Very High Spectral Resolution R (>10^6)
- Coherent Detection – Interferometry

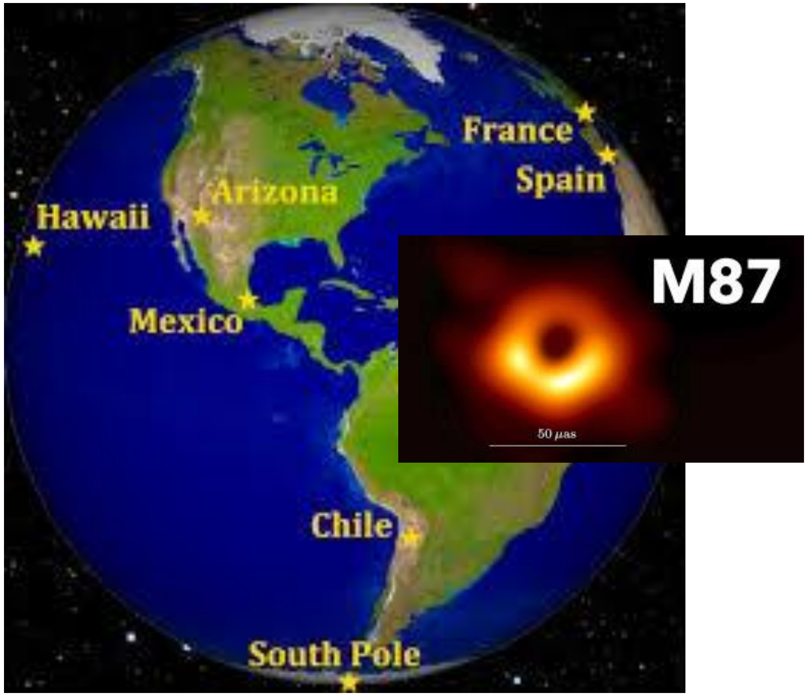


Herschel – HIFI spectra Orion KL. *A&A 521, L20 (2010)*

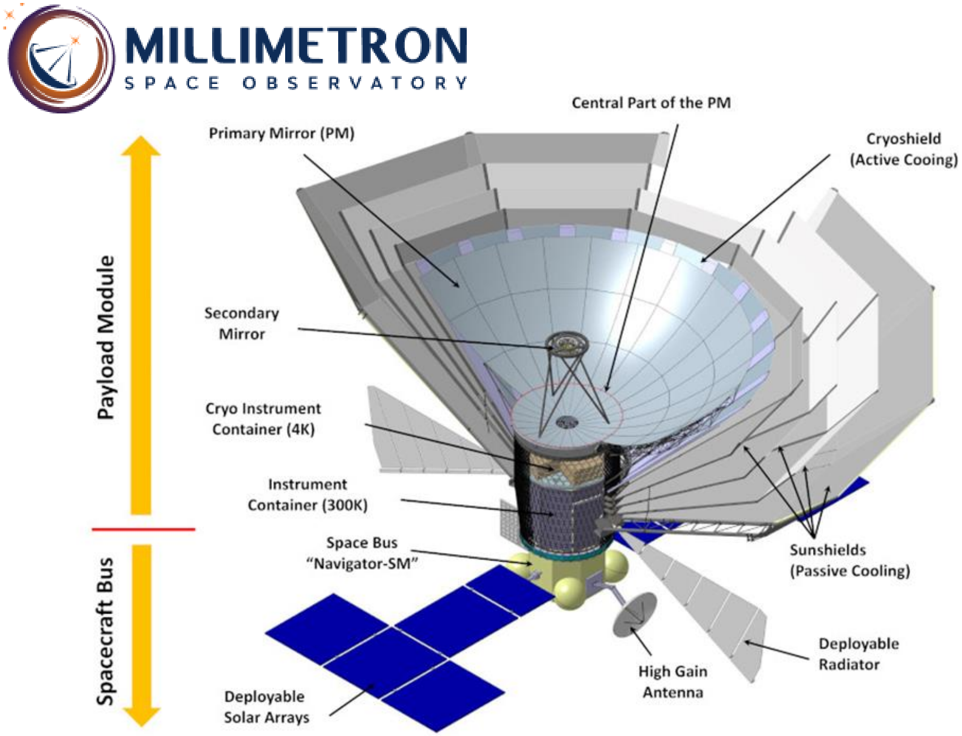


SIS receivers in Interferometry

Event Horizon Telescope (EHT)
230 GHz VLBI

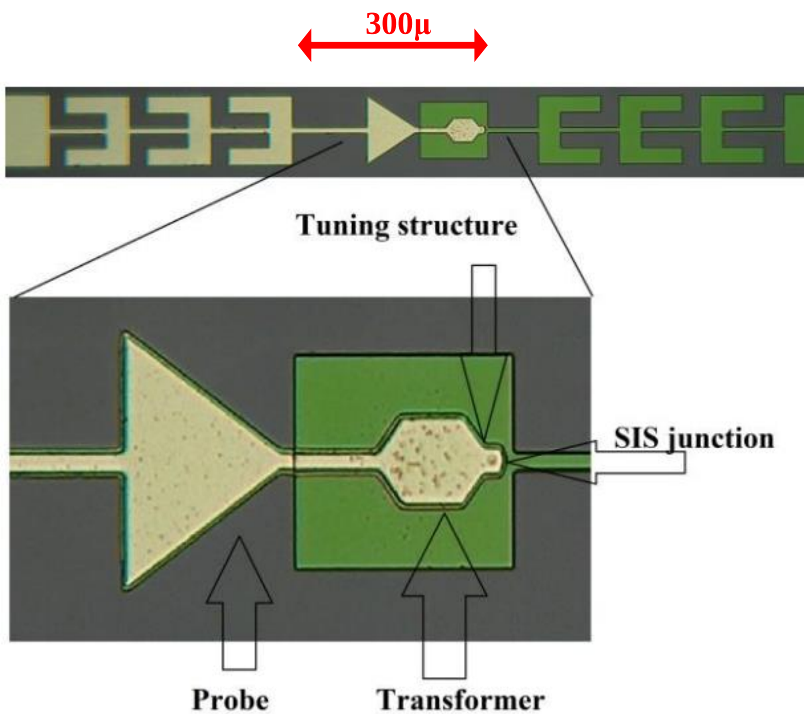


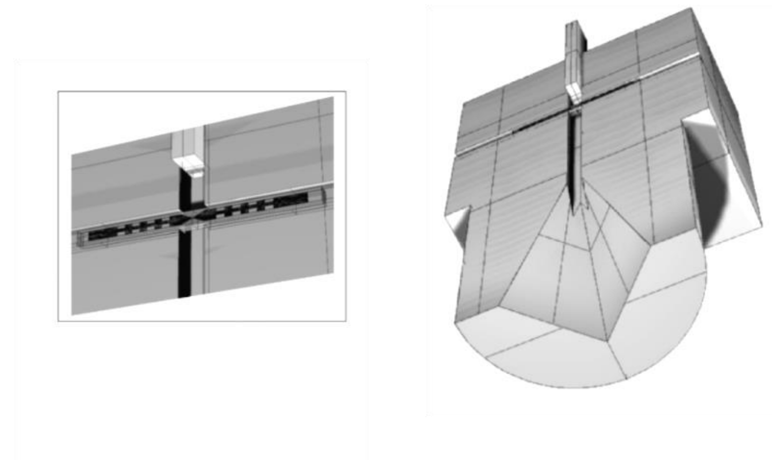
Earth-Space VLBI

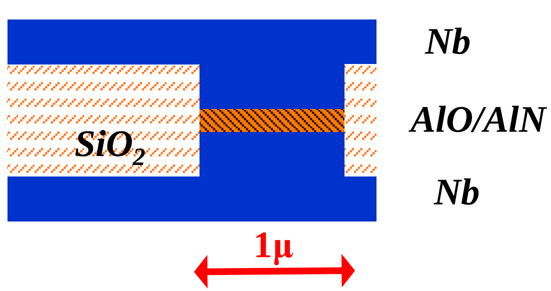


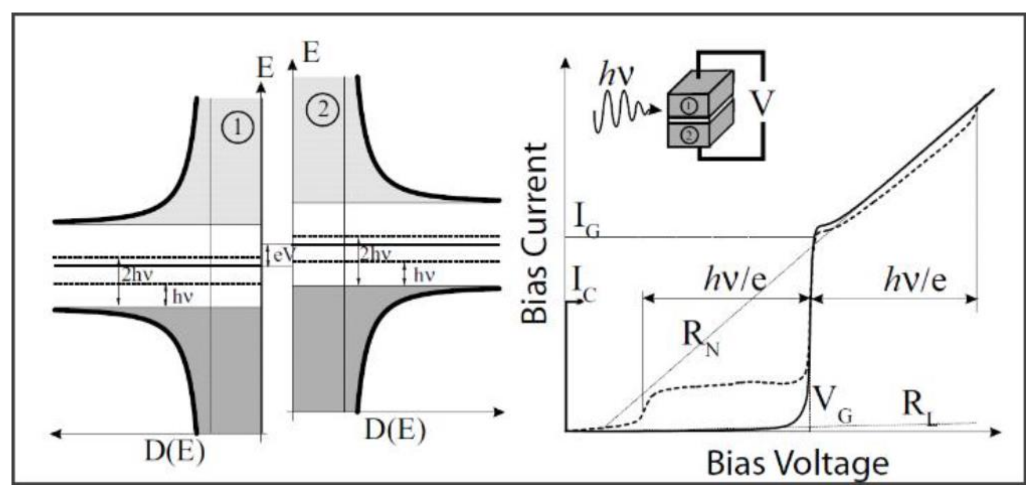
SIS mixer technical details

SIS – Superconductor-Insulator-Superconductor tunnel junction
The most sensitive mixer in the range 100-1000 GHz





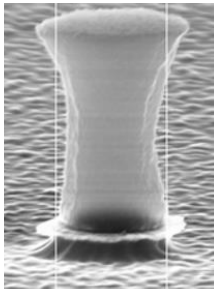




Operating T ≤ 4.2K – cryogenic

SIS: junction-mixer-receiver

1μ



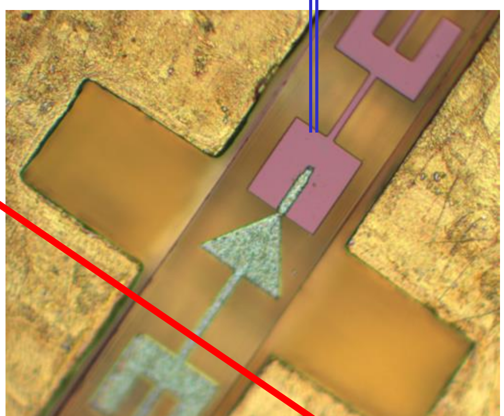
SIS junction

~100 kpc

12m

ALMA Telescope

Receiver cartridge

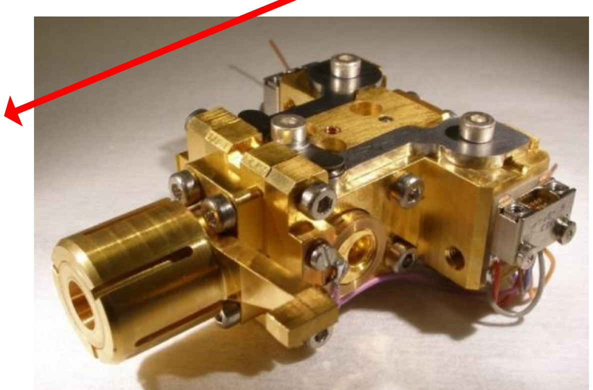


Mixer Chip

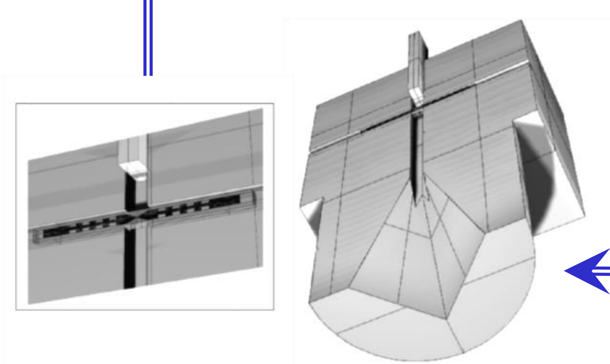
300μ

≈ 600 mm

≈ 50mm



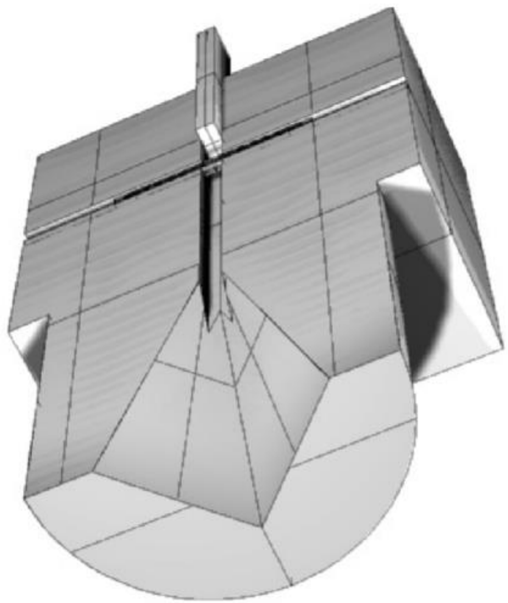
Mixer Chip in waveguide

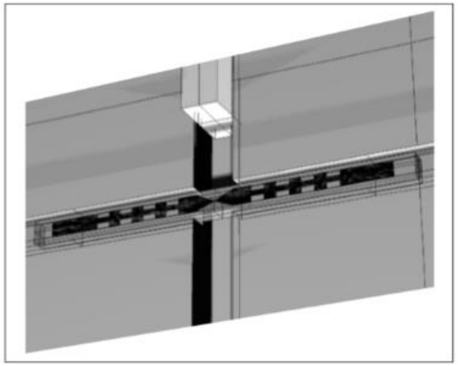


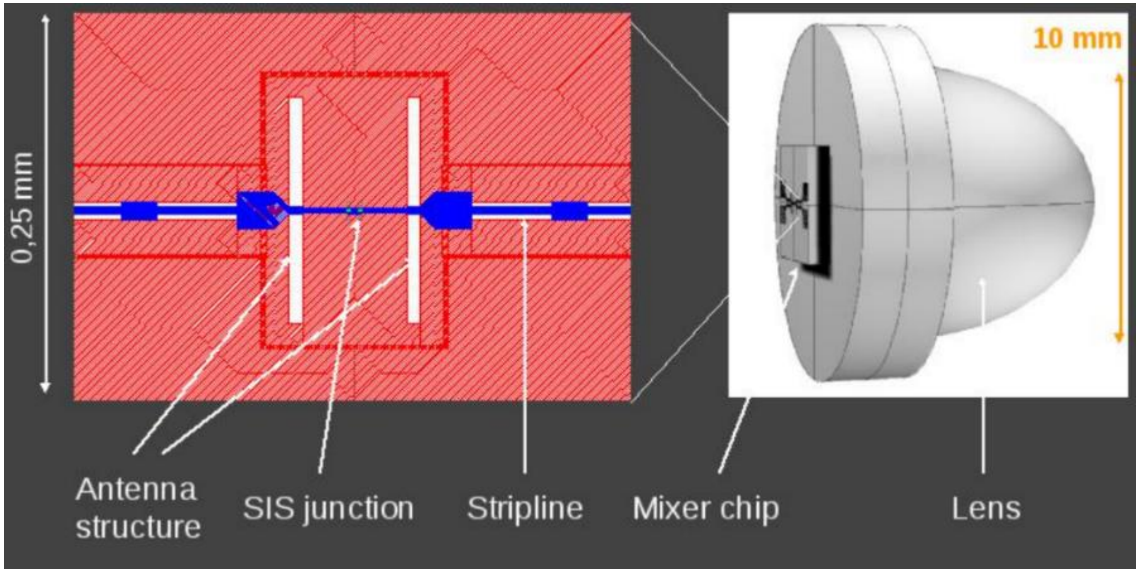
Mixer assembly

SIS mixer – optical coupling

Waveguide





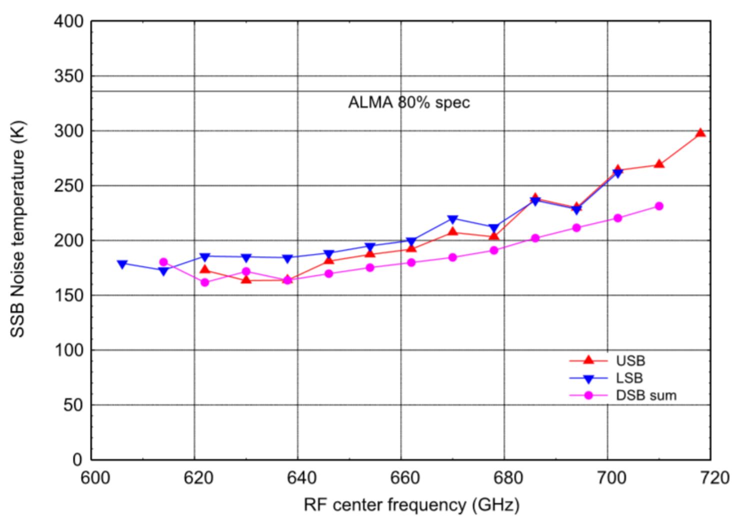


Quasioptical

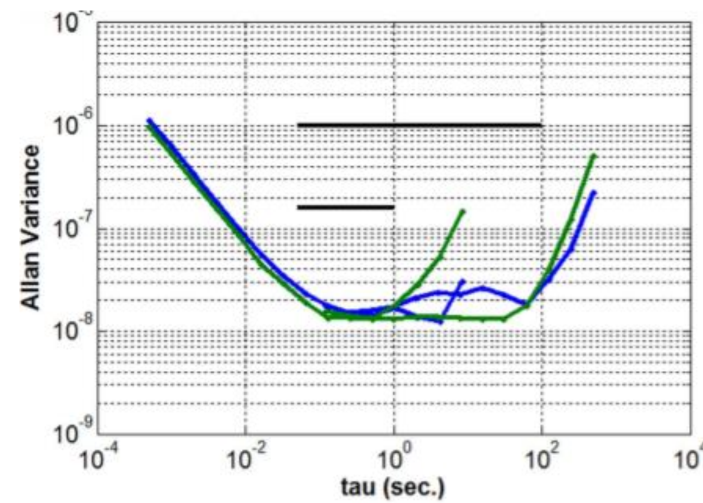
SIS receiver – key parameters

1) Noise temperature (Sensitivity)
2) Stability
3) Intermediate Frequency (IF) bandwidth
4) Sideband Rejection Ratio (for 2SB/SSB)

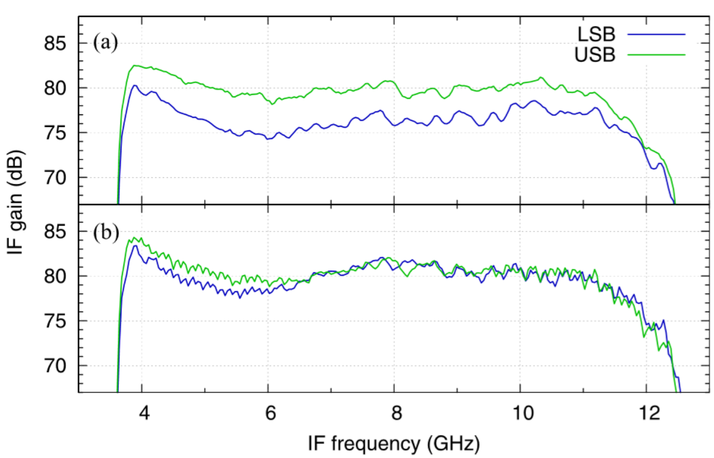
Noise temperature (Sensitivity)



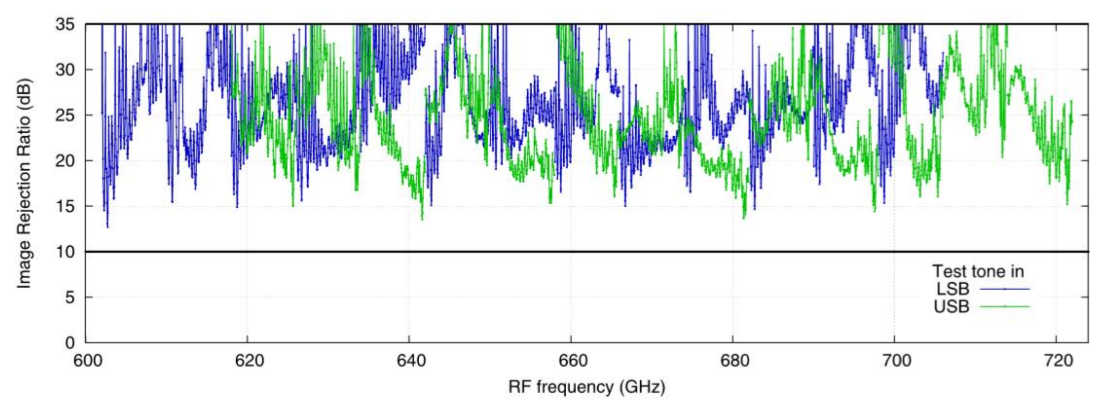
Stability



Intermediate Frequency (IF) bandwidth



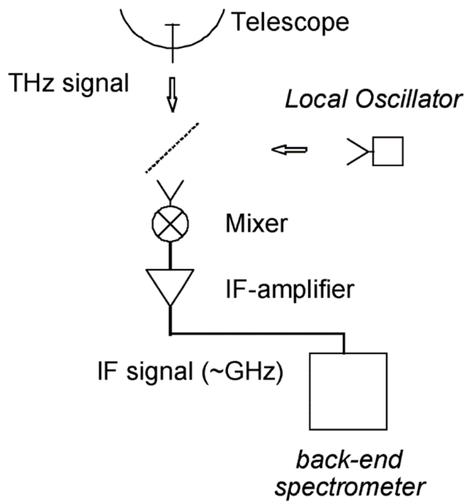
Sideband Rejection Ratio (for 2SB/SSB)



Data from: Hesper et al. IEEE TST 2017, Belitsky et al. A&A 2018

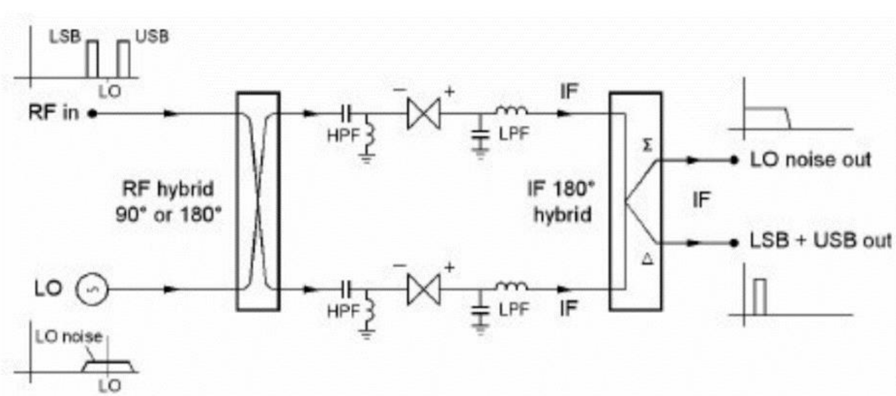
Types of SIS-mixers

DSB (Dual sideband) mixer

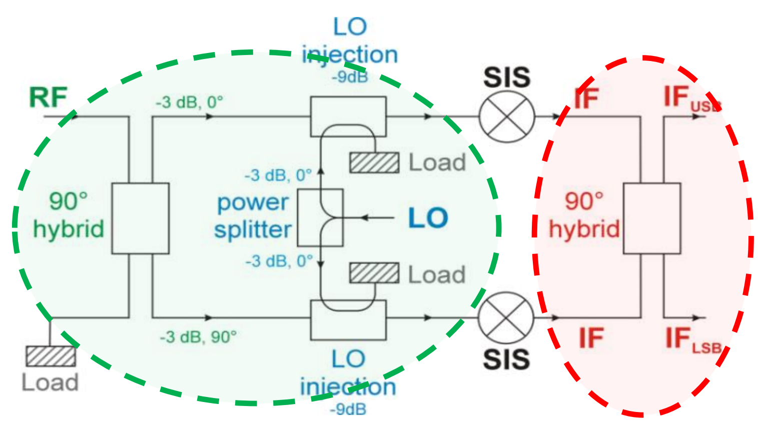


- DSB (Dual sideband)
- Balanced Mixer
- Sideband Separating (2SB / SSB)
- Balanced 2SB

Balanced Mixer



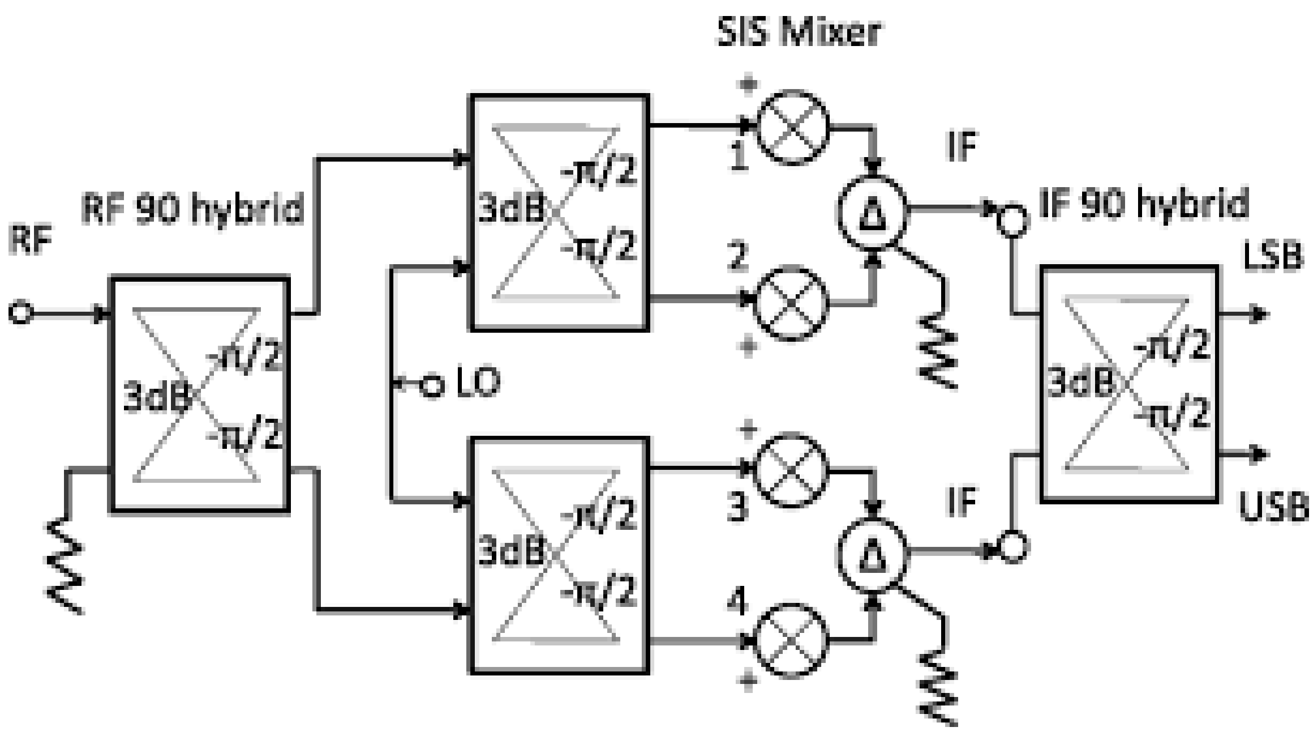
Sideband Separating Mixer
2SB (Two sideband) / SSB (Single Sideband)



Types of SIS-mixers

- DSB (Dual sideband)
- Balanced Mixer
- Sideband Separating (2SB / SSB)
- Balanced 2SB

Balances Sideband Separating Mixer
Balanced 2SB mixer



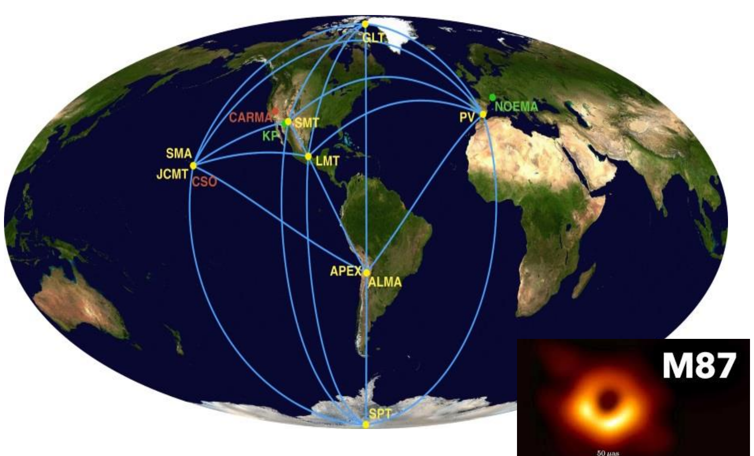
Observatories utilizing SIS-receivers

- Observatories with SIS receivers
  - Ground-based
    - Single-dish

      - APEX -Chile
      - IRAM (PV) – Spain
      - SMT Arizona
      - JCMT – Hawaii
      - GLT Greenland
      - LMA – Mexio
      - SPT - South Pole
      - Onsola – Sweden
      - …
    - Interferometers

      - ALMA
      - NOEMA
      - SMA
      - CARMA
      - Nobeyama
  - Space

    - Hershel (HiFi)
  - Balloon-borne
    - TELIS



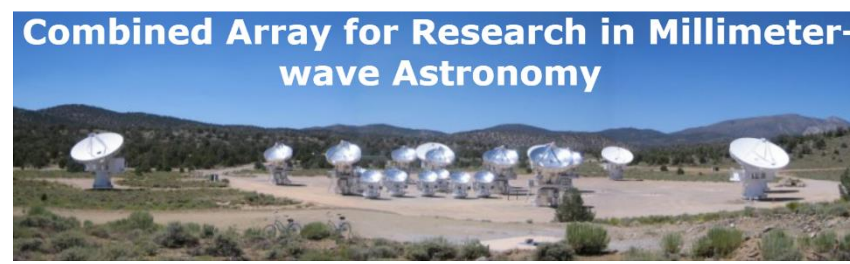
Interferometers

Name	Antennas
ALMA	12m*54 +7m*12
NOEMA	15m*12
SMA (MMA)	6m*8
CARMA	10.4m*6 +6.1m*9 +3.5m*8
Nobeyama	10m*6 +45m

Chile

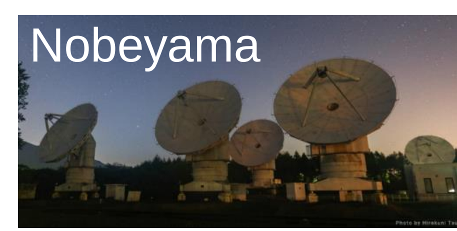
France

USA
Hawaii



USA
California

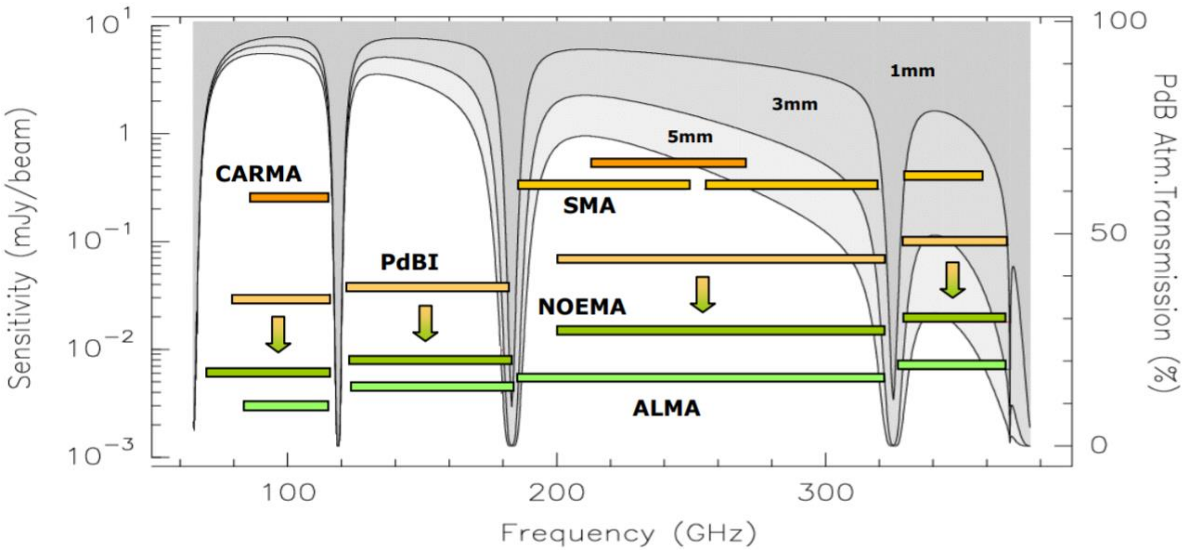
Japan

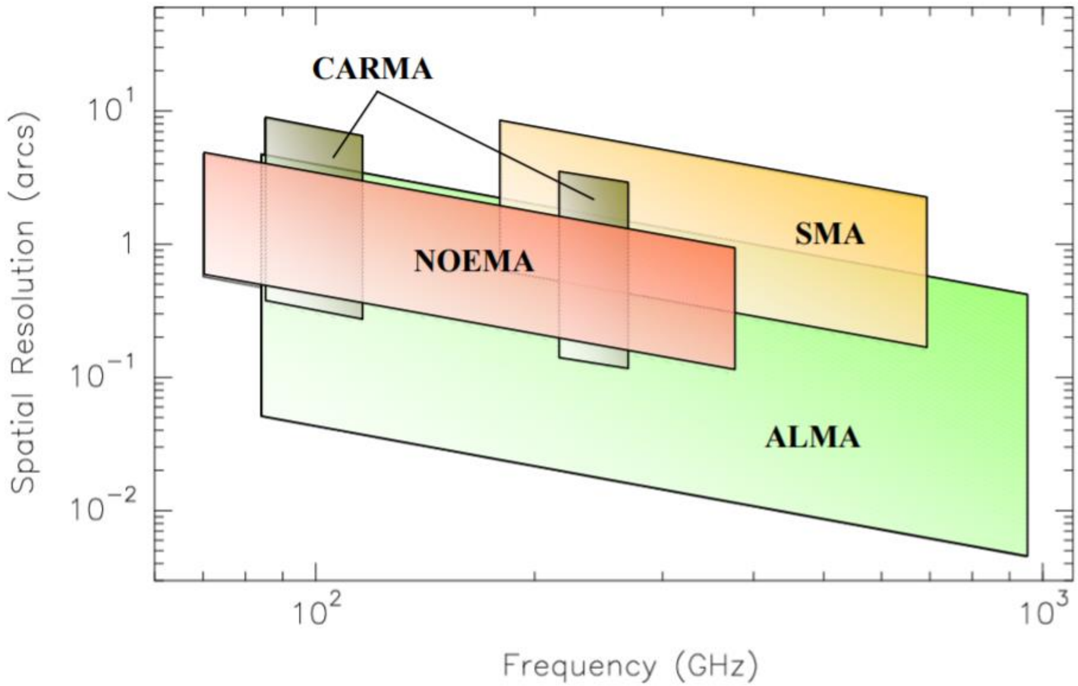


Interferometers

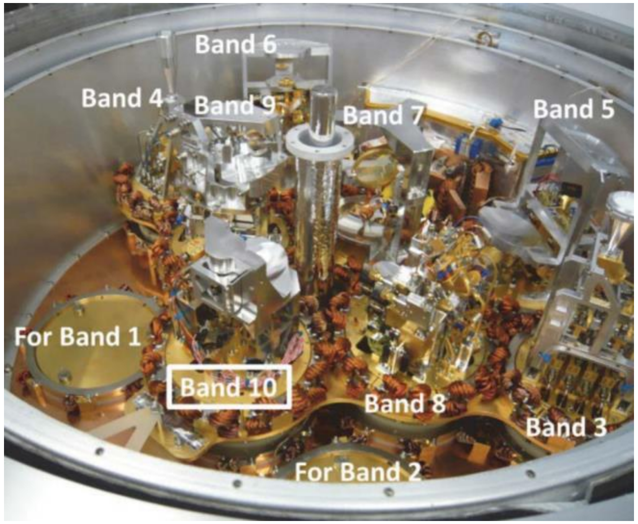
ALMA	**S** **m^2**	**L** **Km**	**Location** **hight, km**	**Antenna surf,** **RMS, mkm**	**Max frequency** **for SIS receiver, GHz**	
ALMA	6500	16	5.0	25	<950	
NOEMA	2120	2.0	2.5	35	<375	
SMA (MMA)	170	0.5	4.1	12	<408	
CARMA	772 (+78)	2.0	2.2		<256	
Nobeyama	78 (+1590)	0.6	1.35	50 (100)	<230 (<150)	

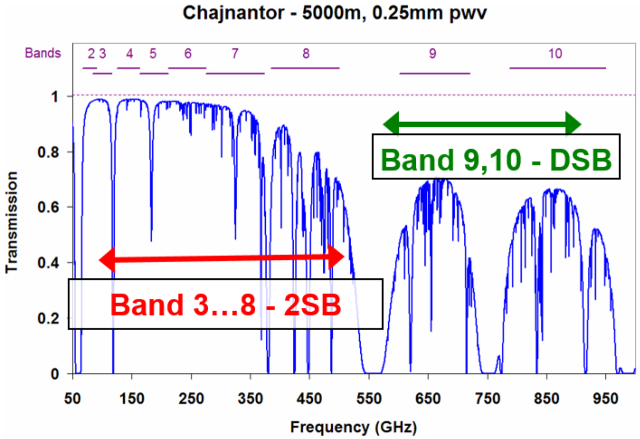
Interferometers





ALMA Sensitivity





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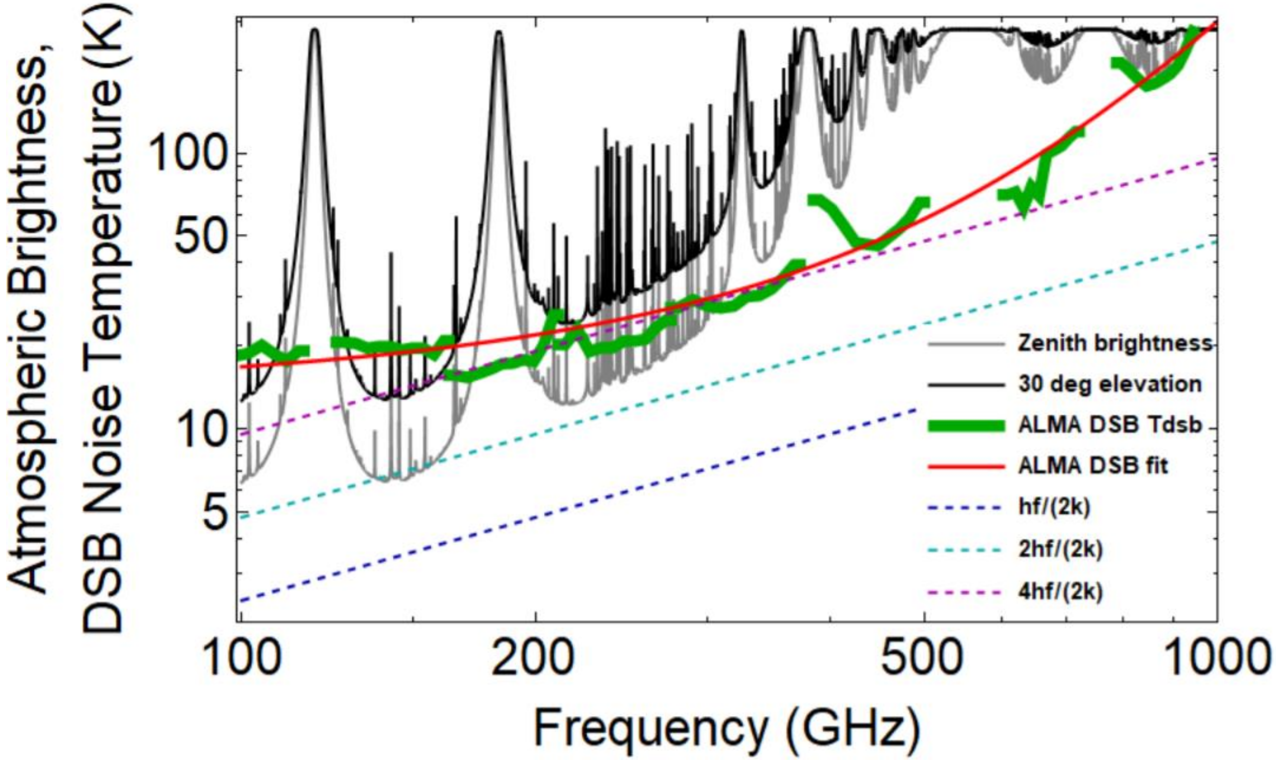
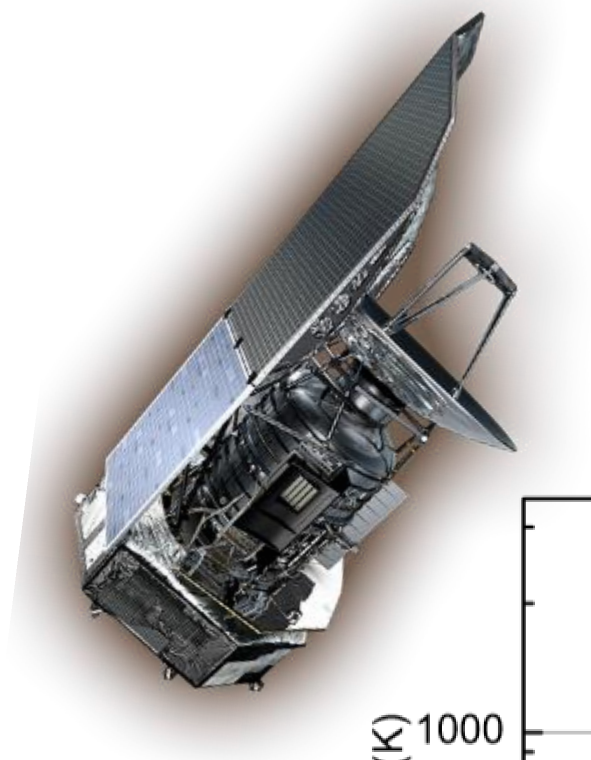
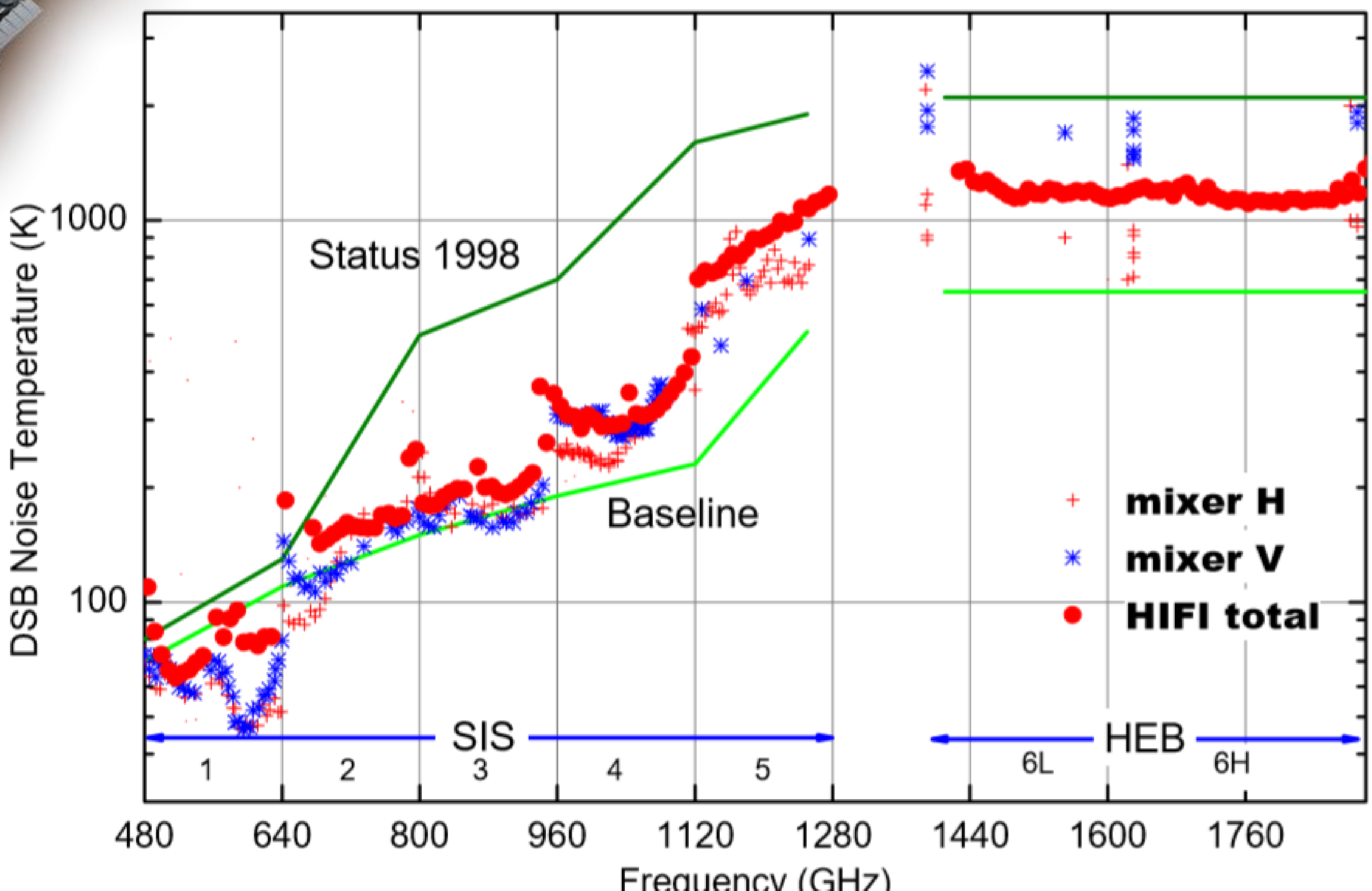


HIFI Sensitivities





Observatories utilizing SIS-receivers

- Observatories with SIS receivers
  - Ground-based
    - Single-dish

      - APEX -Chile
      - IRAM (PV) – Spain
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    - Interferometers

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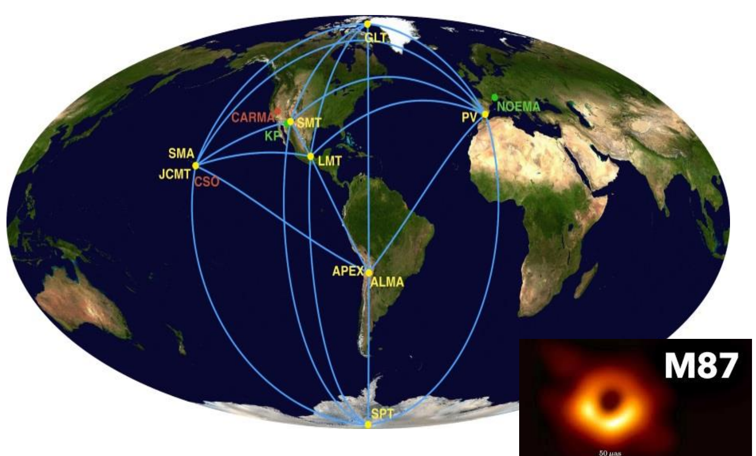


SIS instruments at APEX

SIS instruments at APEX

Facility instrumentation

Instrument (FE/BE)	Type	Freq [GHz]	HPBW (arcsec)	IF range [GHz]	Beams	Pol	Cabin	Status
nFLASH230 FFTS1	Het SIS (2SB)	196-281	32-22	4-12	1	Dual	A	OK
SEPIA345 FFTS1	Het SIS (2SB)	272-376	23-17	4-12	1	Dual	A	OK
nFLASH460 FFTS4G	Het SIS (2SB)	378-507	17-12	4-8	1	Dual	A	OK
SEPIA660 FFTS1	Het SIS (2SB)	578-738	10-9	4-12	1	Dual	A	OK

PI instrumentation

Instrument (FE/BE)	Type	Freq [GHz]	HPBW (arcsec)	IF range [GHz]	Beams	Pol	Cabin	Status
SEPIA180 FFTS1	Het SIS (2SB)	157-211	39-31	4-8	1	Dual	A	OK
PI230 FFTS4G	Het SIS (2SB)	200-270	31-23	4-12	1	Single	B	OK
LASMA FTTS4G	Het SIS (2SB) array	268-375	23-17	4-8	7	Single	B	OK
CHAMP690 FFTS4G	Het SIS (DSB) array	620-720	9-7	4-8	7	Single	B	NO
CHAMP810 FFTS4G	Het SIS (DSB) array	780-850	7-6	4-8	7	Single	B	NO

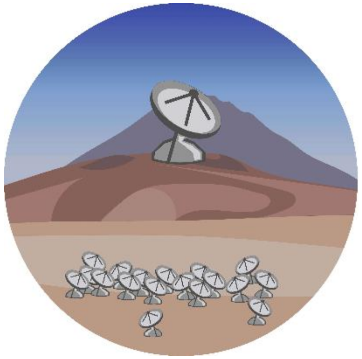
New observatories for SIS receivers

- LLAMA (Argentina)
- (?) Sufa Russia/Uzbekistan
- (?) South Africa/Namibia

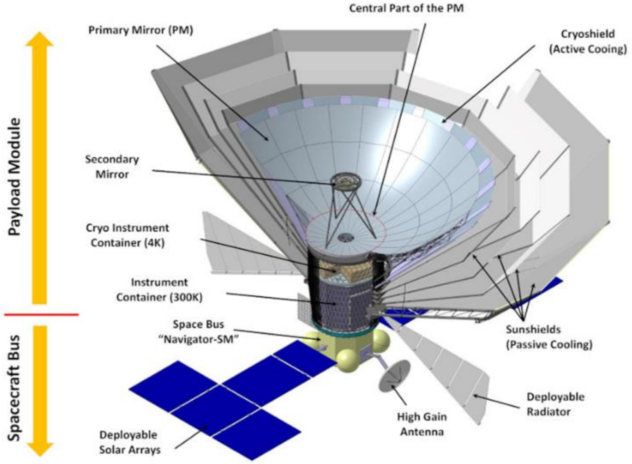
Large Latin American Millimeter Array

+ EHI (?)
Event Horizon Interferometer

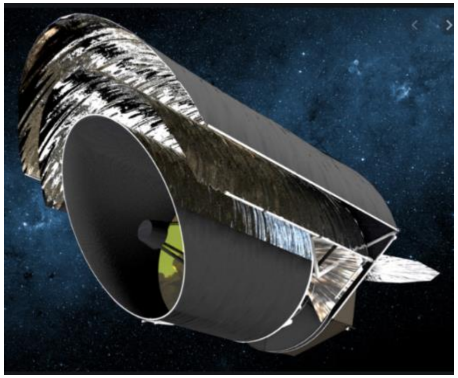
AtLast – Chile (ESO)
Atacama Large Aperture Submillimeter Telescope
~50m
1k array!!!



Millimetron
10m

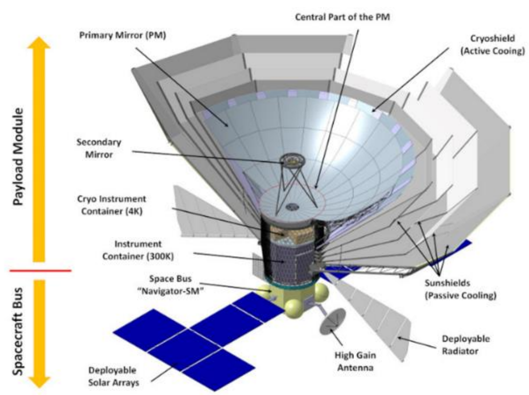


Origins Space Telescope
OST (NASA)
~6m
64x array



Millimetron

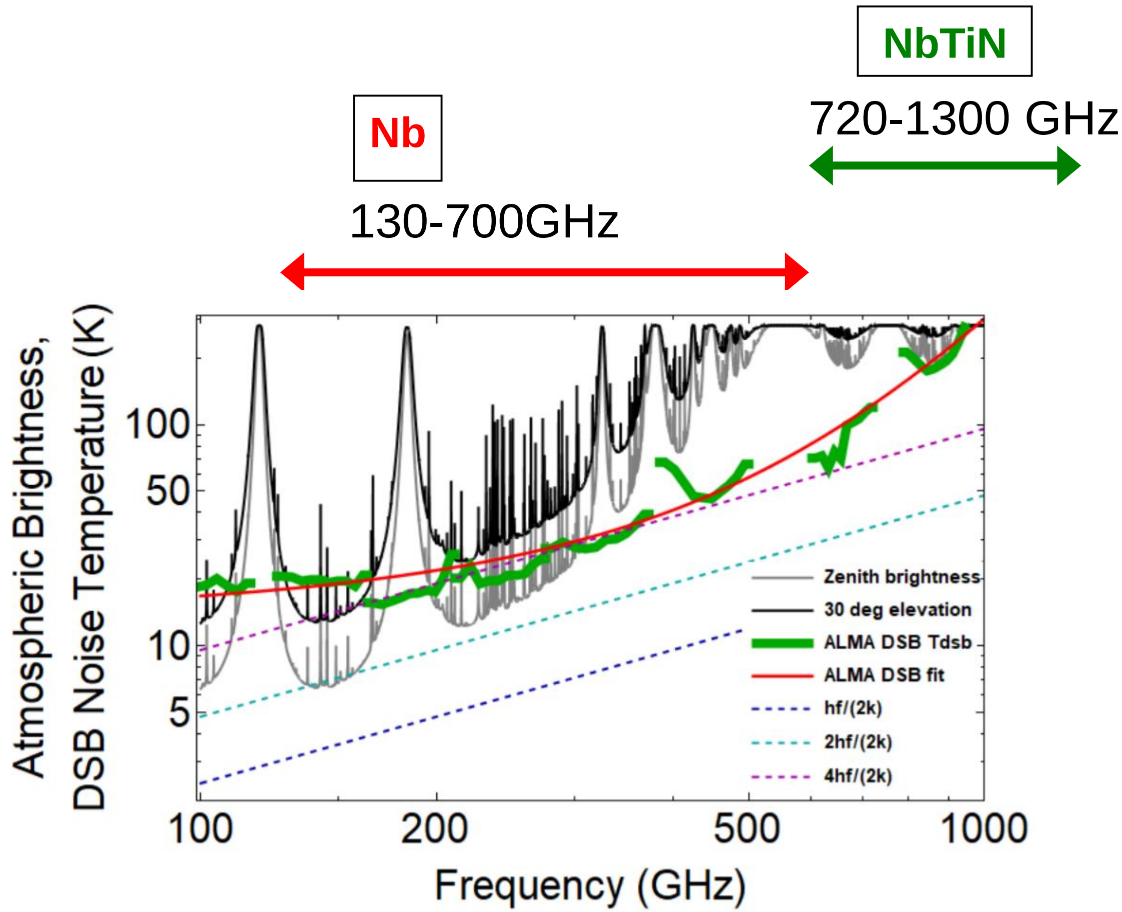
Observatory	Instrument	Frequency_start, GHz	Frequency_stop, GHz	Wavelength (central point), μ	dφ, asec	field of view, amin	Tn_min, K	Tn_max, K	Tn_min, K (goal)	Tn_max, K (goal)	Sideband SSB-1 DSB-2	N_pixels	IF_min, GHz	IF_max, GHz
Millimetron	VLBI_1	33	50	7229			20	25	8	12	1	1	4	12
	VLBI_2	84	116	3000			40	45	32	32	1	1	4	12
	VLBI_3	211	275	1235			50	60	40	50	1	1	4	12
	VLBI_4	275	373	926			60	90	50	80	1	1	4	12
	M1	460	600	566			120	160	111	144	1	3	4	12
	M2	752	950	353			300	460	240	360	1	3	4	12
	M3	950	1150	286			300	400	250	350	2	7	4	12
	M4	1600	2100	162			385	505	250	300	2	7	1	6
	M5	2450	3000	110			850	850	300	350	2	7	1	6
	M6	4770	5800	57			1100	1400	500	600	2	7	1	6
	Past_cryo1	500	600	545			1100	1100	600	600	2?		4	12
	Past_cryo2	1050	1150	273			2000	2000	1100	1100	2?		4	12



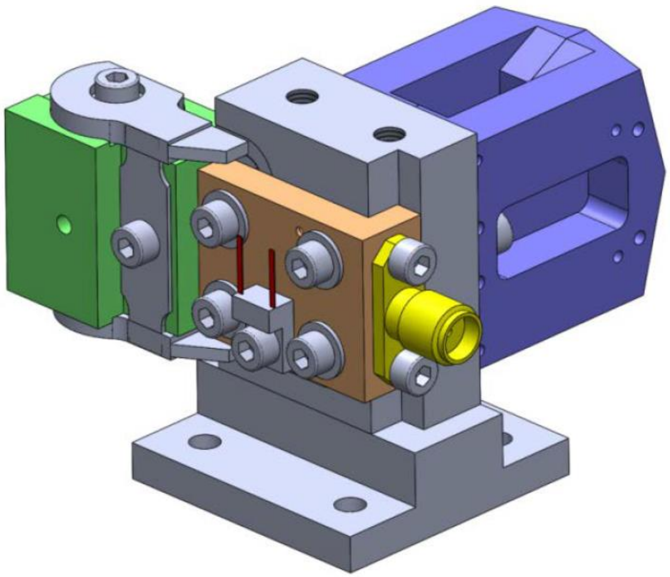
SIS receiver technology

- IRE RAS (Moscow, Russia)
- NAOJ (Tokyo, Japan)
- Chalmers (Goteborg , Sweden)
- IRAM (Grenoble, France)
- LERMA (Paris, France)
- Cologne University (Germany)
- USA
    - E.Tong (Boston)
    - A. Kerr (NRAO)
    - J. Kooi (Caltech/JPL)
    - C.Groppy (Arizona Uni)
- Korea (?)
- China (?) Shengcai Shi

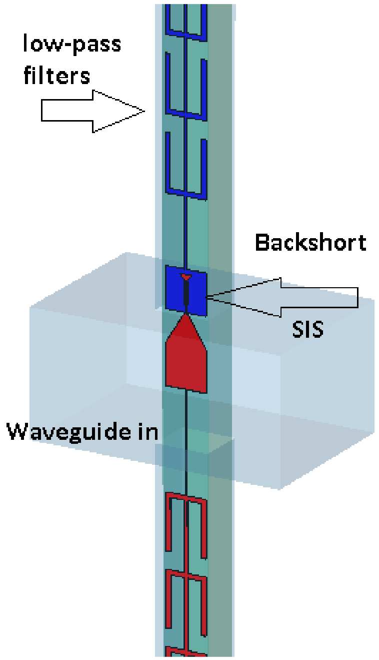
- NOVA (Groningen, Netherlands)
- MPIfR (Bonn, Germany)
- + ASC (Moscow, Russia)

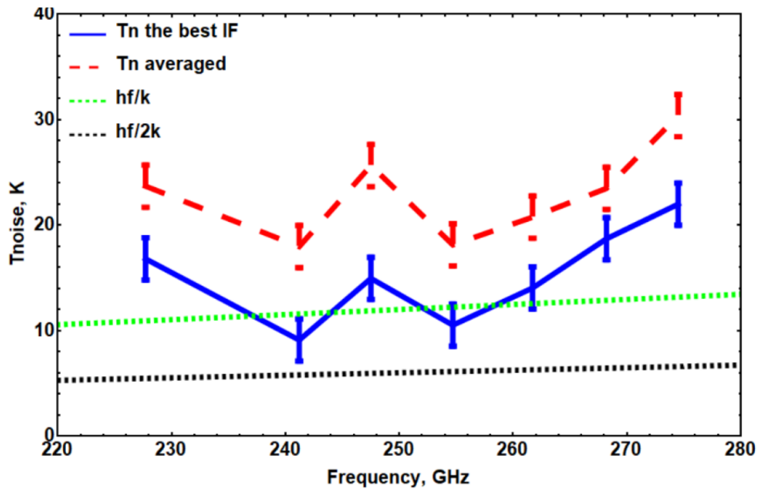


2SB SIS receiver 211-275 GHz (NOVA-IRE-ASC)



kapteyn astronomical institute





Advances in SIS receiver technology - Arrays

COHERENT ARRAY RECEIVER SUMMARY

System	Type	Telescope	Year Completed	Npix	Tuning Range	Polarizations	Sideband Mode	Processed Bandwidth	Still Active
NRAO 8-beam	Schottky SIS	NRAO 12 m	1988	8	~230 GHz[3]	1	DSB	300 MHz	N
QUARRY	Schottky	FCRAO	1992	15	86-115 GHz	2	SSB	320 MHz	N
CHAMP	SIS	CSO	1998	16	410-520 GHz	2	SSB	2 GHz	N
DesertStar	SIS	HHT	2003	7	320-370 GHz	1	DSB	250 MHz	N
PoleStar	SIS	AST/RO	2000	4	807.5 GHz[2]	1	DSB	1 GHz	N
BEARS	SIS	Nobeyama 45 m	1998	25	82-116 GHz	1	DSB	512 MHz	Y
HERA	SIS	IRAM 30 m	2001	9[4]	220-260 GHz	1[4]	SSB	1 GHz	Y
CHAMP+	SIS	APEX	2007	7[1]	620-720 780-950 GHz	1	SSB	2.8 GHz	Y
HARP	SIS	JCMT	2005	16	320-370 GHz	1	SSB	1.9 GHz	Y
SMART	SIS	NANTEN2	2001	8[1]	460-490 800-880 GHz	1	DSB	1 GHz	Y
SEQUOIA	HEMT	FCRAO	1999	32	85-115 GHz	2	n/a	40 MHz[5]	Y
Supercam	SIS	HHT	n/a	64	330-360 GHz	1	DSB	250 MHz	n/a
STO	HEB	STO	n/a	4[1]	1.45 & 1.90 THz[2]	1	DSB	1 GHz	n/a

Groppi el al. IEEE TST 2011

CHAMP+ 7 pixels (600-720 GHz)
7 pixels (800-950 GHz)

SuperCam (64 pix)

Figure 8: The SuperCam cryostat

HARP at JCMT – 16 pixels
(325 – 375 GHz)

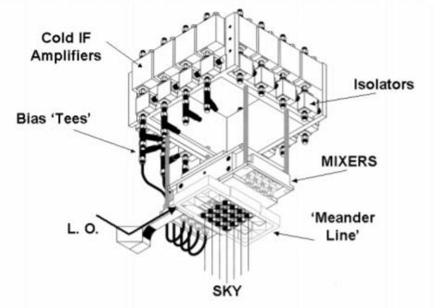


Figure 9. The HARP imaging array.

SIS mixer arrays - issues

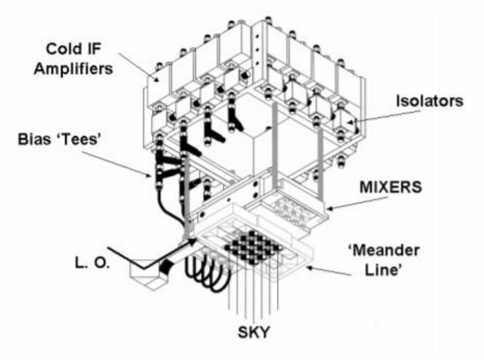


Figure 9. The HARP imaging array.

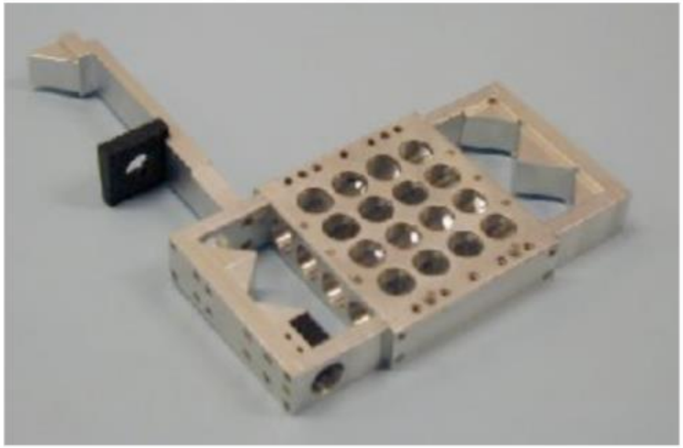


Figure 11. Photograph of the assembled LO coupler, also showing one mirror of the LO relay and the stop.

SuperCam.
64 pix - ??? …42

Figure 8: The SuperCam cryostat

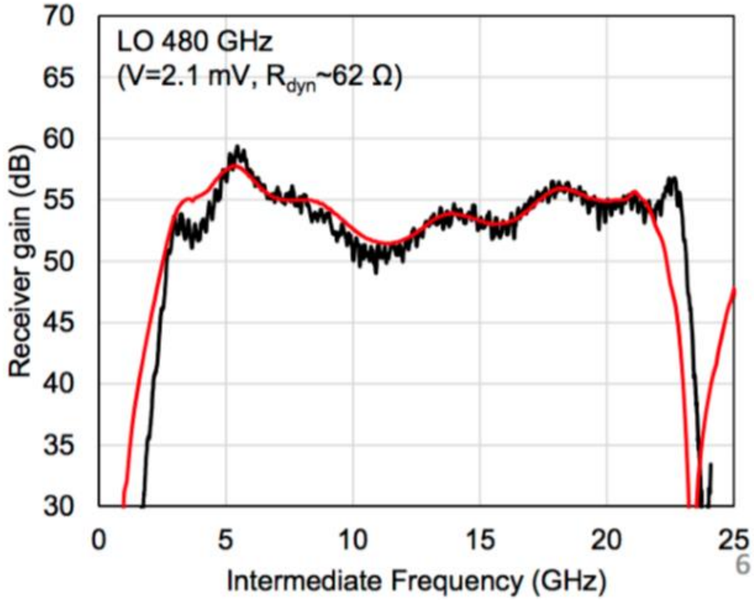
HARP at JCMT – Heterodyne Array Receiver Program

HARP

- 325 – 375 GHz 16 detector SSB SIS array receiver
- Currently HARP cannot be tuned to frequencies 325-329 GHz LSB and 335 – 339 GHz USB.
- 14 of the 16 receptors (detectors) are operational; H00 and H14 are not operational.
- H04 and H13 have bad baselines for frequencies lower than 340GHz
- Receptor H04/R05 is unusable at frequencies below 332.5 GHz
- PIs with projects involving jiggle maps on extended sources may wish to review the central pointings and/or K-mirror orientations in their MSBs.
- The lack of these receptors hampers jiggle mapping. Work is ongoing to replace the broken receptors. The largest square fully sampled field of view with a HARP jiggle map is currently 1.5'x1.5'. If the full 2'x2' jiggle field of view is required we recommend using a small raster instead (114"x114" 1/4 array spaced basket weaved). This will be less efficient with a factor of about 1.5 in time.
- Sensitivity variations creating striping – worst at 13CO/C18O

Advances in SIS receiver technology

Wide IF: 4-20 GHz
(*Kojima et at. IEEE TST 2018*)



Multi channel concepts:
(*Groppi, Baryshev et al. IEEE TST 2019)*

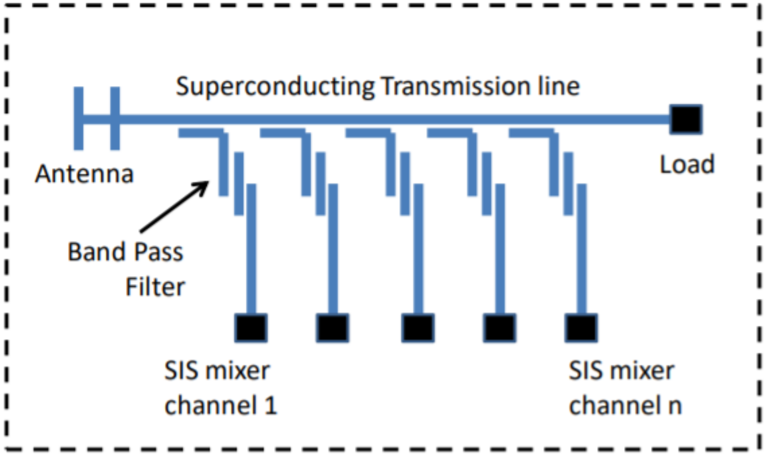
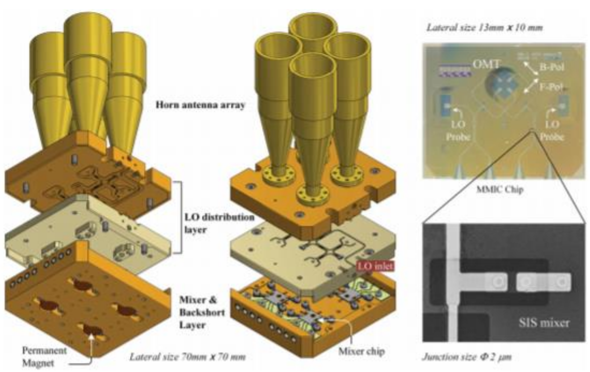


Fig. 5. Principle diagram of an on-chop combined frequency array receiver.

Planar technology
(*Shan et at. IEEE TST 2020*)



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Conclusion

- SIS mixers are the key instrument for THz Interferometry and one of the key technology for ground-based Radio-astronomy
- Development in Russia is actively going in collaboration with the Netherlands