ALMA Memo No. 315
A Japanese Plan of Receiver Developments for LMSA/ALMA

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ABSTRACT

We present a baseline plan of Japanese receiver developments for the Large Millimeter Submillimeter Array (LMSA) and the Atacama Large Millimeter Array (ALMA). Two receiver cartridge layouts for ALMA band 8 (385 – 500 GHz) have been proposed based on a quasi-optical sideband separation. These cartridges will be evaluated in a secondary focal receiver system with the Atacama Submillimeter Telescope Experiment (ASTE), which is one of Japanese R&D project of the LMSA and the ALMA. The ASTE 10 m submillimeter-wave telescope has been pre-installed at Nobeyama since February 2000 and will be installed at Pampa la Bola (el. 4800 m) in northern Chile in November 2001. Japanese candidates for the ALMA cryocooler are reported.

1. INTRODUCTION

Submillimeter-wave and millimeter-wave receivers from 80 to 900 GHz has been developed with a goal of low noise of 3 hν/k in DSB over broad band of 25 % for the Large Millimeter Submillimeter Array (LMSA). These receivers will be designed to meet the ALMA specification as possible. Millimeter-wave receivers have been developed based on the receivers operated at the Nobeyama Millimeter Array and the Nobeyama 45 m telescope. Some developments of submillimeter-wave bands of the ASTE receivers have been already carried out on the Mt. Fuji submillimeter-wave telescope, which has been operated by University of Tokyo and Nobeyama Radio Observatory since 1998 (Sekimoto et al. 2000). At the present stage, the receiver noise temperatures at 810 GHz and 500 GHz achieved at the Mt. Fuji telescope are 600 K in DSB and 300 K in SSB, respectively.

We have a plan to operate a new 10 m submillimeter telescope at Pampa la Bola (4800 m) in northern Chile as a single-dish submillimeter telescope as the Atacama submillimeter telescope experiment (ASTE), which is one of Research and Development activities for the LMSA. The telescope has been pre-installed at Nobeyama since February 2000 (Ukita et al. 2000). A photograph of the telescope is shown in Figure 1. After a test operation at Nobeyama for a year, it will be transported and installed at Pampa la Bola (el. 4800 m) in northern Chile in November 2001. Technical and scientific purposes in this experiment are 1) to develop and evaluate a high precision 10 m antenna under exposed conditions at the site, 2) to develop and test low-noise and broad band submillimeter receivers, 3) to test various techniques for submillimeter observations, and 4) to explore the southern hemisphere in the submillimeter band: Galactic Center, Magellanic Clouds, and so on.

We have 3 receiver layouts for the ASTE 10 m telescope: ASTE receivers, a second focal receiver, and an SIS photon camera. The ASTE receivers cover frequencies from 80 to 350 GHz and have a shaped Cassegrain optics to achieve higher aperture efficiency at millimeter-wave bands. A second focal plane receiver including a prototype cartridge for ALMA band 8 (385 – 500 GHz) will be installed for the ASTE in 2002. An SIS photon camera will be installed on the ASTE after evaluations of the antenna and heterodyne receivers (Matsuo et al. 2000). The optics will be changed to a normal Gaussian beam to optimize submillimeter-wave observations up to 850 GHz in the end of 2000. At the same time, the subreflector will be changed from 0.45 m diameter to 0.6 m diameter.

Figure 1: A new 10 m submillimeter telescope was installed at Nobeyama in February 2000. The other telescopes on the background are elements of the Nobeyama Millimeter Array. The size of the receiver cabin is 3.2 x 2.2 x 1.8 m^3 including an annex.

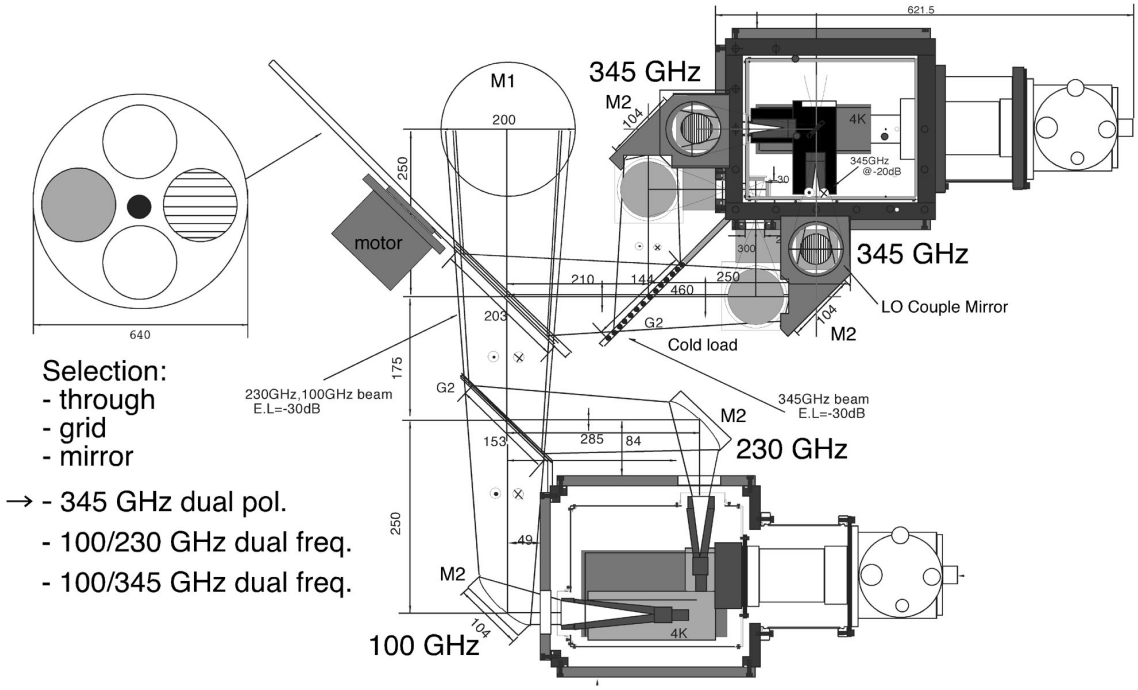

Figure 2: A layout of the ASTE receivers from 85 to 350 GHz in the receiver cabin of the 10 m telescope. The orientation of two cold heads of cryocoolers is parallel to the elevation axis. RF signal entering to M1 from the subreflector is reflected to a curved mirror of M2 with a right angle.

2. ASTE RECEIVERS AT NOBEYAMA

The ASTE receiver layout in the receiver cabin is shown in Figure 2. The size of the receiver cabin on the 10 m telescope is 3.2 x 2.2 x 1.8 m^3 including an annex, which size is almost comparable to the US and EU ALMA 12 m receiver cabin. The shaped beam is produced by a combination of a subreflector and a curved mirror of M1. RF signal entering to M1 from the subreflector is reflected to a curved mirror of M2 with a right angle. The optics between subreflector and horn involves these two ellipsoidal mirrors essentially.

A submillimeter-wave receiver (345 GHz) and a millimeter one (100 & 230 GHz) have been separately developed for the Nobeyama operation of the 10 m telescope. The rotating switch consisted of a through hole, grid and plane mirror provides RF signals for two receivers. The primary purpose of these receivers is an evaluation of the antenna such as holography measurements, so that the holography receiver of the 100 GHz band holds direct position to the M1. The cryocooler axis is parallel to the elevation axis to minimize the motions of the cold head. A suspension frame of two receivers is hung from a ceiling of a receiver cabin at the Cassegrain. The deformation of the frame has been calculated to be less than 0.04 mm by a FEM calculation. All mixers in the receivers are parallel-connected twin junction (PCTJ) or distributed junction (DJ) made at Nobeyama Radio Observatory (Shi et al. 1997). At present stage, the receiver noise temperature of the millimeter receiver is 30 K in DSB from 94 GHz to 114 GHz and 60 K in DSB from 210 to 230 GHz.

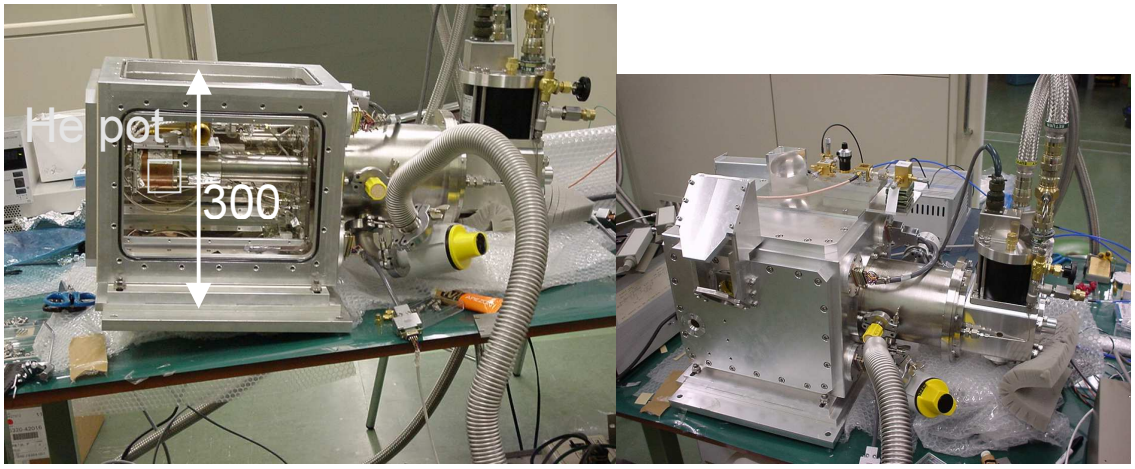

Figure 3: Photographs of the ASTE 350 GHz receiver. The cryocooler is Sumitomo RDK408DA. The cryocooler employs a He pot made of copper on the head of the 4K stage.

Figures 3 shows photographs of the 350 GHz submillimeter receiver on the ASTE 10 m telescope. The left picture of Figure 3 shows inside cryostat and the right one shows an outside view of the receiver. We employed a Nb-based PCTJ SIS mixer developed by Shi et al. (1997). The mixer horn is a corrugated type with 20.3 mm in diameter and 68.8 mm in length. The horn is connected with the mixer block by a waveguide of 0.736 mm x 0.368 mm. The waveguide is reduced to 0.736 mm x 0.184 mm at the position of the SIS junction. The LO signal is coupled quasi-optically to the RF signal by a polarizing grid at the front of the cryostat window. The LO system is composed of a tripler and a Gunn oscillator around 110 GHz made by Radiometer Physics. The LO power is around 2 mW from 320 to 360 GHz. The coupling factor of LO at the polarizing grid is –15 dB. The grid is made of tungsten wire with 20 μm diameter and 80 μm pitch. The vacuum cryostat is made of aluminum. The vacuum degree is 2 x 10^{-7} torr at the 4K operations.

The LNA (Nitsuki 9838C) with a gain of 30 dB in a bandwidth of 4.5 – 7.0 GHz is attached loosely on the 4K stage. We use two isolators between the mixer and the LNA. The bias of 2.0 mV for the SIS mixer is applied from the first isolator. An I-V curve of the receiver is shown in Figure 4. The magnetic filed around

800 gauss is applied to suppress the Josephson current of the SIS mixer by two permanent magnets. The normal state resistance is 15 Ω. The gap voltage is 2.73 V. The leakage resistance of 40 Ω is due to a parallel resistance of 50 Ω at the second isolator. The original dc I-V curve of the mixer measured without the second isolator is also shown in Figure 4. We confirmed that the receiver noise temperature was almost same without the second isolator, but the receiver was unstable.

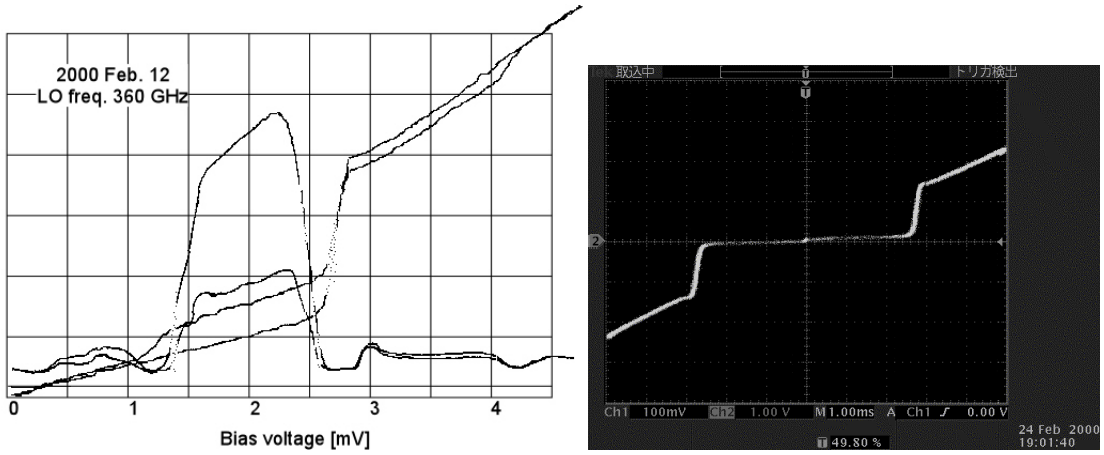

Figure 4: Left: I-V curve of the 350 GHz receiver and IF power output versus the SIS bias voltage. Right: The original I-V curve of the mixer measured without the second isolator.

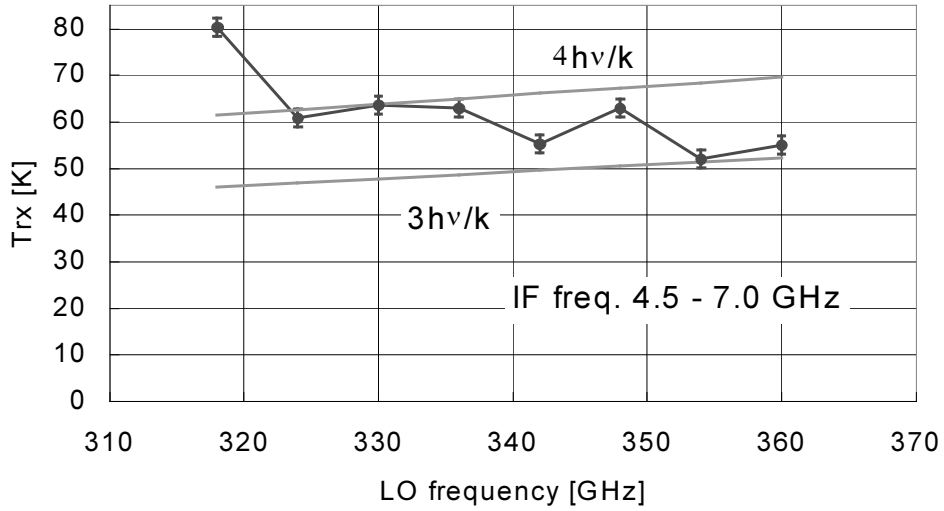

Figure 5 Receiver noise temperatures in DSB of the 350 GHz receiver. Frequency band is limited by the LO. The noise temperature was measured at the front of the receiver in the IF center frequency of 6.0 GHz with 30 MHz bandwidth.

A noise temperature has been measured at the position of the M2 mirror in an experimental room before an installation on the telescope (Figure 5). The best Y factor in this experiment was 4.2 dB at a LO frequency of 354 GHz, which value corresponds to the receiver noise temperature of 52 K in DSB. The measurements were done in the center IF frequency of 6.0 GHz with 30 MHz bandwidth. The noise temperature falls between 3 hν/k and 4 hν/k between 325 and 360 GHz. The LO frequency is locked to a reference signal by a PLL.

We measured the noise contribution before mixing to be 22 K at 354 GHz by changing the LO power. It contributes a half of the receiver noise temperature of 52 K. Some losses in front of the horn are a vacuum

window made of Kapton with 12.5 μm thickness, a infrared shield made of a fibrous-porous form of PTFE (Zitex G106) with 150 μm thickness and a pore of 50 %, and the LO coupling grid. The noise temperature of the IF amplifier is 10 ± 1 K in the all IF band. The temperatures on the mixer block, cold head, the bias isolator, and the 40 K stage is 4.0 K, 3.7 K, 4.7 K, and 36 K, respectively.

The submillimeter receiver has a cold calibrator at the 40 K stage for intensity calibrations. The standard chopping wheel method needs to know a weighted sky temperature with an atmospheric opacity at a submillimeter-band for intensity calibration. However, it is difficult to measure the temperature in the case of large opacity such as ~1 at 492 GHz even at the ALMA site in Chile.

All optical components in the receiver cabin must be aligned at an accuracy of less than 0.4 mm. The beam efficiency is degraded by -0.1 dB in maximum with a 0.4 mm displacement of an optical component. We align them as follows: The M1 mirror is aligned to the optical axis defined by the main reflector. An interface plate and the receiver suspension frame are adjusted on the ceiling of the receiver room as a reference of the M1. Most optical components including the M2 are mounted to the receiver suspension with an accuracy of 0.2 mm. Cooled optical components inside the cryostat are aligned to the M1 by a laser beam collimated by two pin-holes mounted in replace of the mixer horn.

3. A SECOND FOCAL RECEIVER ON ASTE

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Table 1: Optical parameters of the ASTE 10 m telescope in Chile

Primary Diameter	Dm		10000
Primary focal length	fm		3500
Secondary diameter	ds		620
Magnification	M		22.857
effective focal length	fe	M fm	80000.0
secodary eccentricity	es	(M+1)/(M-1)	1.092
frimary focal ratio	fm/Dm		0.35
secondary focal ratio	fe/Dm	M fm/Dm	8.00
interfocal distance	fs	d(M+1)(16f^2M-D^2)/16/M/D/f	5061.44
curvature	Rs	d(16f^2M-D^2)/16/D/f	4849.29
Half-angle of secondary	θ	2atan(D/4fe)	3.58

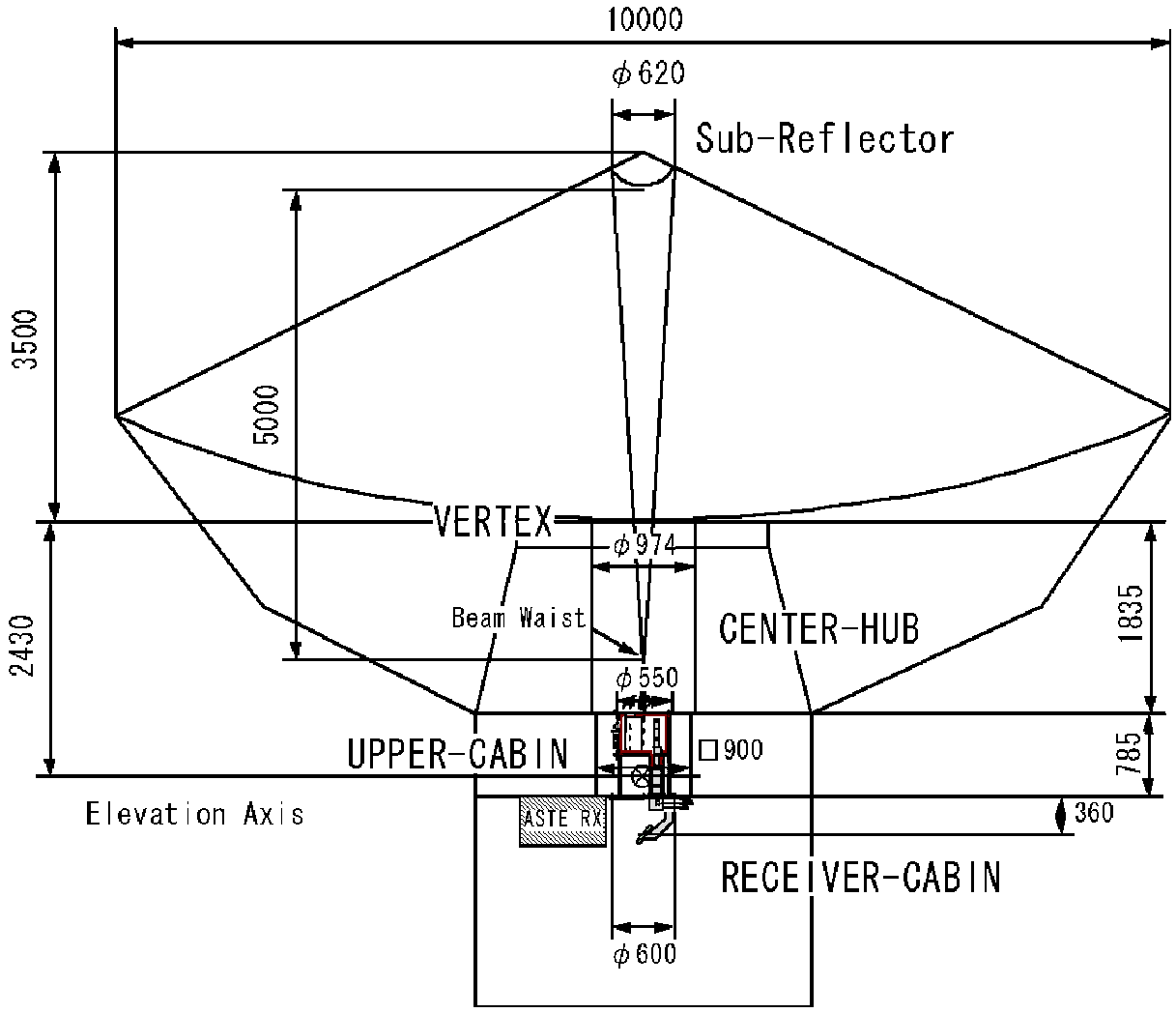

Figure 6. A layout of a secondary focal receiver fixed at the ceiling of the receiver cabin and an ASTE receiver in the receiver cabin.

We are developing a second focal receiver located in the upper cabin of the ASTE 10 m telescope as shown in Figure 6. The purpose is evaluations of (1) a proposed ALMA band 8 (385 – 500 GHz) cartridge, (2) an ALMA band 10 (787 – 950 GHz) cartridge, (3) ALMA cartridge and cryostat, and (4) Japanese candidates of cryocoolers on the ASTE 10 m telescope at the site. The size of the cryostat is limited to 500 mm diameter due to the 600 mm diameter of the ceiling of the receiver cabin. The cryostat and cartridge interface are designed as similar to those of the ALMA receiver as possible to evaluate prototype ALMA cartridges at the site. The cryostat will be fixed at the ceiling of the receiver cabin.

Figure 7 shows a schematic drawing of the second focal receiver. A plane mirror at the center of the cryostat selects RF signals to 3 bays for the band cartridges with a diameter of 150/170 mm. For the initial operation, the prototype ALMA band 8 and 10 cartridges are planned. The 3rd cartridge will be planned to a 230/650 GHz receiver for winter season and a 100/350 GHz receiver for summer season. A holography receiver at 100 GHz with room temperature operation will be mounted. The LO signal for submillimeter cartridges will be coupled from the side panel of the cryostat, because it is not available to a cooled multiplier built in the cartridge at the present stage.

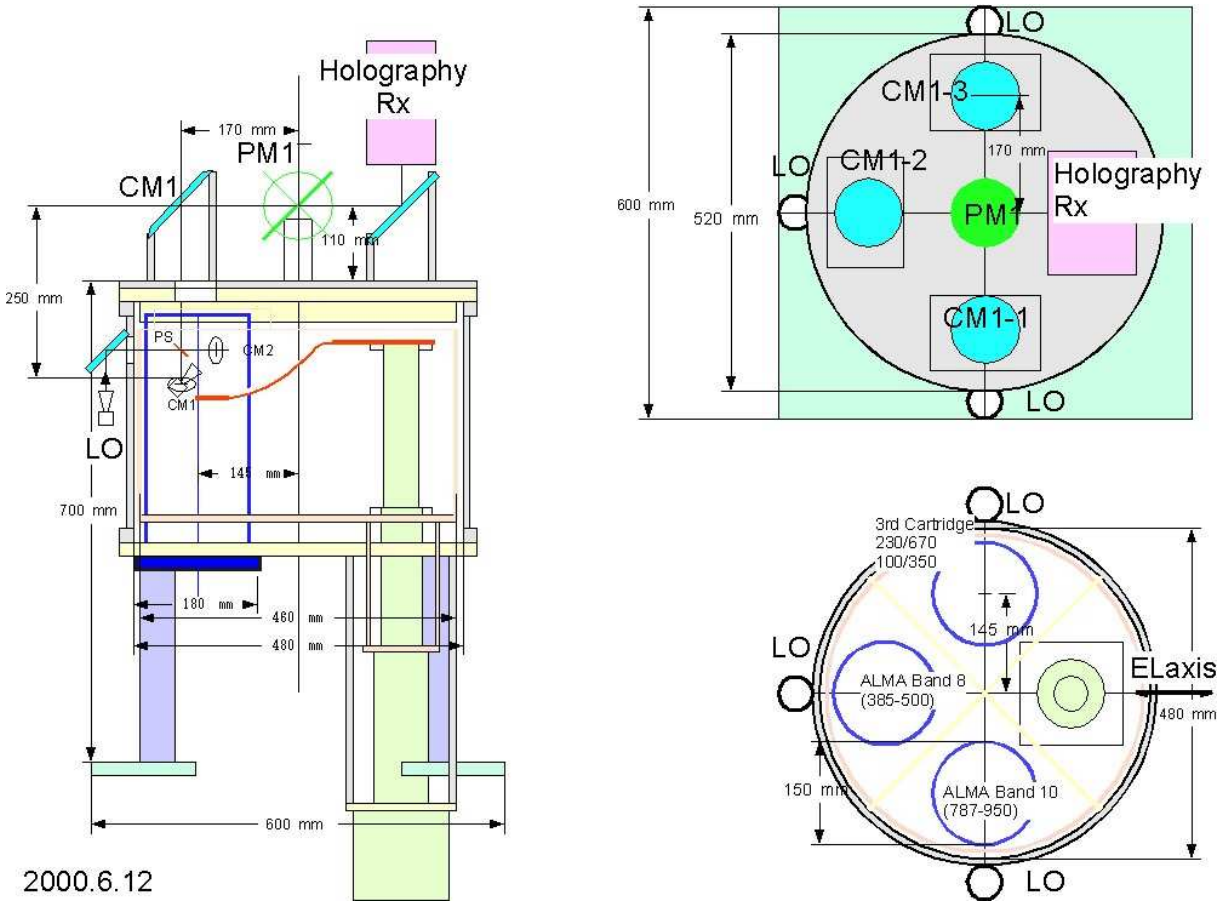

Figure 7 A design of the second focal receiver for the ASTE 10 m telescope.

4. ALMA BAND 8 (385 – 500 GHZ) CARTRIDGE LAYOUTS

Some layouts for an ALMA band 8 cartridge are proposed for the ALMA Joint Receiver Working Group. The layouts are based on a quasi-optical sideband separation scheme proposed by Inatani et al. 1998. The principle (Figure 8) is the same as Kerr and Pan (1996). Comparison of some methods for submillimeter side-band separation is shown in Table 2.

4.1 Quasi-Optical Sideband Separation

A layout is shown in Figure 9. It employs a quasi-optical side-band separation scheme proposed by Inatani et al. (1998). Its performance has been proven at 492 GHz with the Mt. Fuji submillimeter-wave telescope (Figure 10, Sekimoto et al. 2000). RF and LO signals are divided and coupled by means of a single wire grid. The RF signal is fed to two mixer horns with a phase difference of 180 degree, but the LO signal is with that of 270 degree. The latter phase difference is generated by a reflective circular polarizer composed of a plane mirror and a wire grid. After the IF signals are diplexed with 90 degree phase difference, the USB and LSB signals are obtained.

This scheme employs 4 mixers to receive 2 polarizations and both upper and lower sidebands. It needs no mechanical tuner, which is a merit compared with a Martin Papulett Interferometer side band separation (cf . Baryshev and Wild 2000). Two local oscillators are cooled to 80 K and coupled to RF signals with –10 dB if the output power is 100 micro W. It would be possible to cover the IF bandwidth of 4 – 12 GHz if there is an adequate LNA for this band. This layout will fit into a cylindrical cartridge of 170 mm diameter. The

beam diameter is shown in Figure 11. The side band rejection ratio depends on an amplitude and phase imbalance of two circuits. We estimate the side band rejection is greater than 15 dB.

This scheme employs an IF 90 degree hybrid, which is commercially available such as Electrodyne Co. For example, a product of type MV-48 covers IF frequency of 4.0 – 8.0 GHz with amplitude balance 0.5 dB, phase balance 3 deg, insertion loss 0.25 dB, VSWR 1.30 at room temperature. We have developed an IF 90 degree hybrid with IF frequency of 2.0 – 2.5 GHz at 4K operation for the Mt. Fuji submillimeter-wave telescope. We will improve an IF 90 degree hybrid with IF frequency of 4.0 – 8.0 GHz for 4K operation.

Table 2 Comparison of some methods of submillimeter-wave sideband separation

	QO SBS	FPI+QO SBS	MPI
sideband rejection	< -15dB	< -15 dB	< -15dB
LO coupling	10 dB (80K)	2 dB	10 dB (80K)
mechanical tuner	0	2	2
IF bandwidth	4 - 12 GHz	4 - 8 GHz	4 - 12 GHz

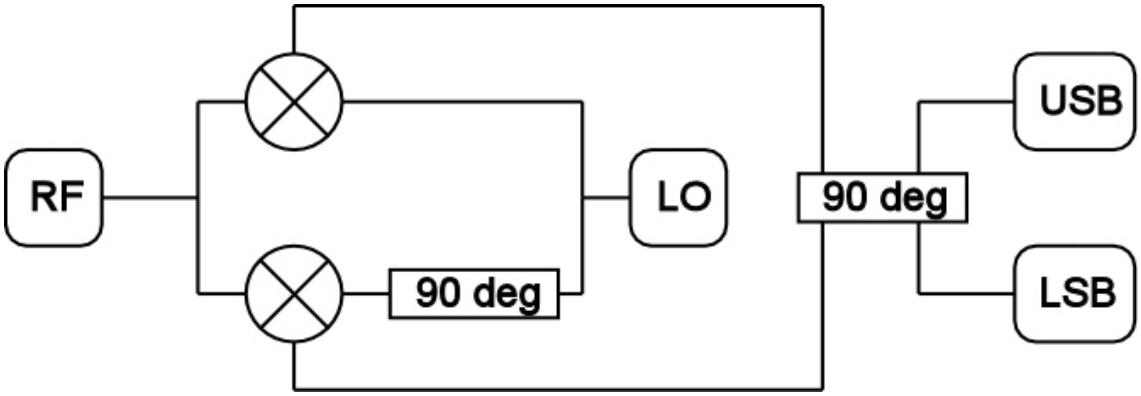

Figure 8: Principle of a sideband separating mixer

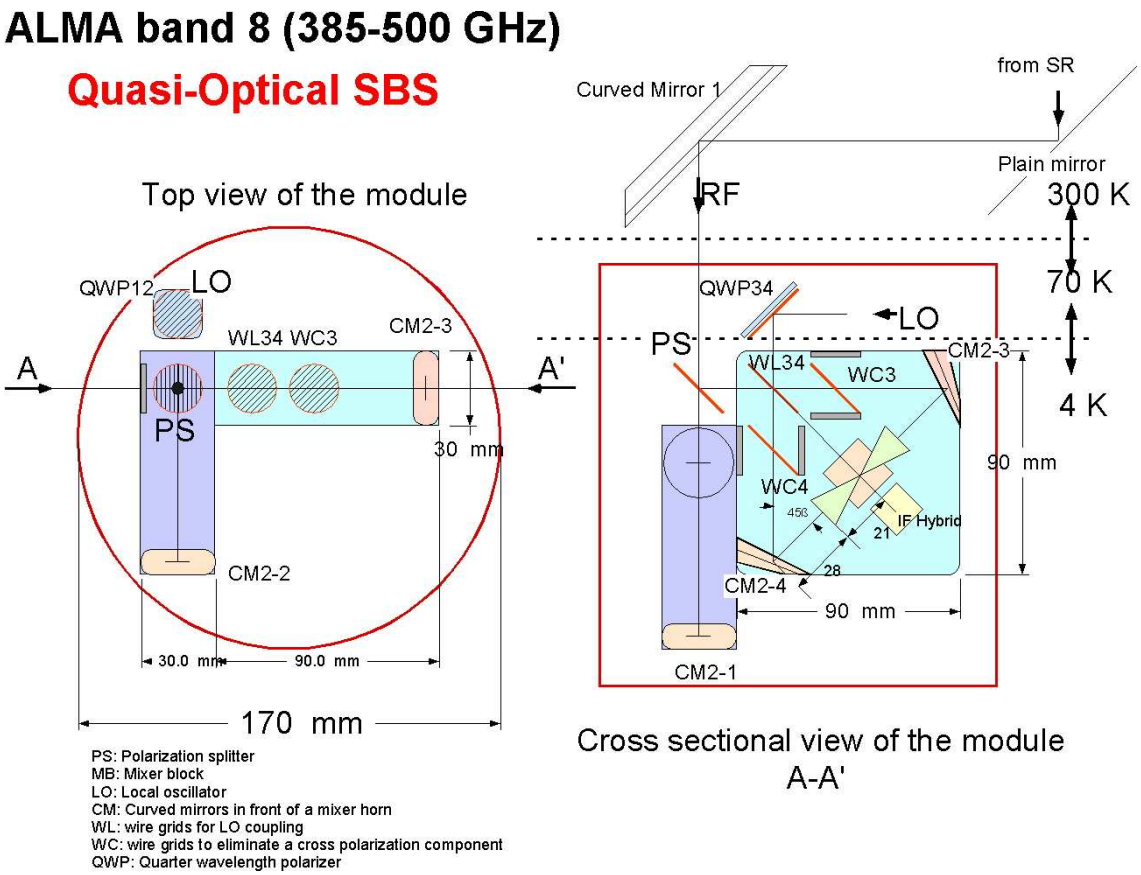

Figure 9 Schematic drawing of a proposed layout for an ALMA band 8 cartridge

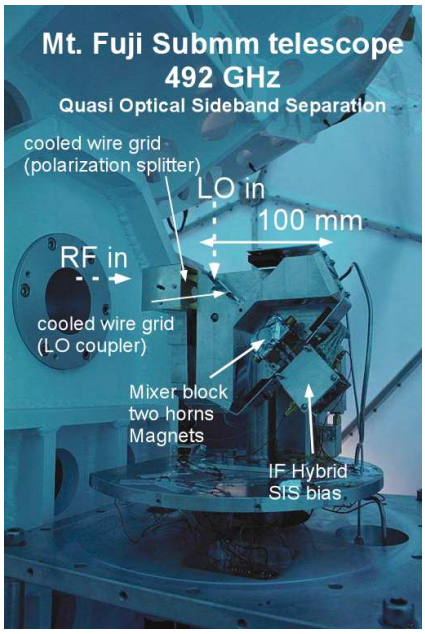

Figure 10 A quasi-optical sideband separation receiver at 492 GHz on the Mt. Fuji submillimeter-wave telescope (Sekimoto et al. 2000)

Table 3: Optical components in a proposed ALMA band 8 cartridge (Figure 9)

PS	1	Polarization splitter
WL	2	Wire grid for LO coupling
WC	4	Wire grid to eliminate X-pol
CM2	4	Curved Mirror #2
MB	2	Mixer block
QWP	2	Quarter wavelength polarizer
LO	2	Local oscillator
CML	2	Curved mirror for LO

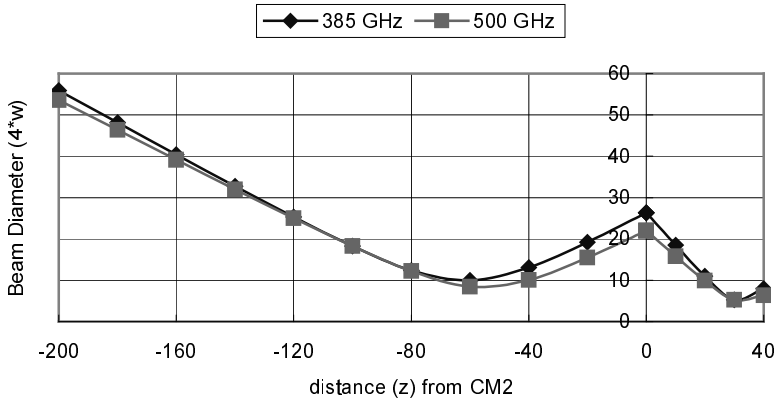

Figure 11 Beam diameter of the proposed cartridge

4.2 Quasi-Optical sideband separation with Folded Fabry Perot Interferometer

We proposed a new configuration for quasi-optical side band separation mixers with a capability of a LO diplexer, which employs a folded Fabry Perot interferometer (FPI) as shown in Figure 12. This configuration satisfies the ALMA specification of dual polarization, side band separation, IF frequency: 4 – 8 GHz, LO power of 100 μW.

This scheme employs 4 mixers to receive 2 polarizations and both upper and lower sidebands. The coupling efficiency of the LO signals to the RF signals is around – 2 dB thus, we need only 20 micro W of LO. It needs cooled mechanical tuners to adjust the separation of two meshes. Another drawback of this method is insufficient for coverage of the ALMA IF specification of 4 – 12 GHz.

The folded Fabry Perot interferometer is composed of two meshes and a curved mirror in principle (Goldsmith 1998). It is transparent for circular polarized LO and reflects RF signals. The folded FPI for room temperature operation is commercially available by Farran Inc. Typical assembly is composed of two meshes, a curved mirror, and a plane mirror.

Figure 13 shows response of FPI with a free spectral range of 9 GHz, which has a round trip of 2d = 33 mm. A folded FPI with a mesh reflectivity of r = 0.9 can cover the IF frequency of 2 – 8 GHz. But it is very difficult to extend the IF frequency up to 12 GHz due to the physical size of the FFPI. It is necessary to

adjust a tuning range of the round trip, Δd = d*Δf/f = 0.35 mm with a resolution of $\delta d = \frac{0.025\lambda}{F} = 0.6$ micro m, where $F = \frac{\pi|r|}{1-|r|^2}$ is finesse (Goldsmith 1998).

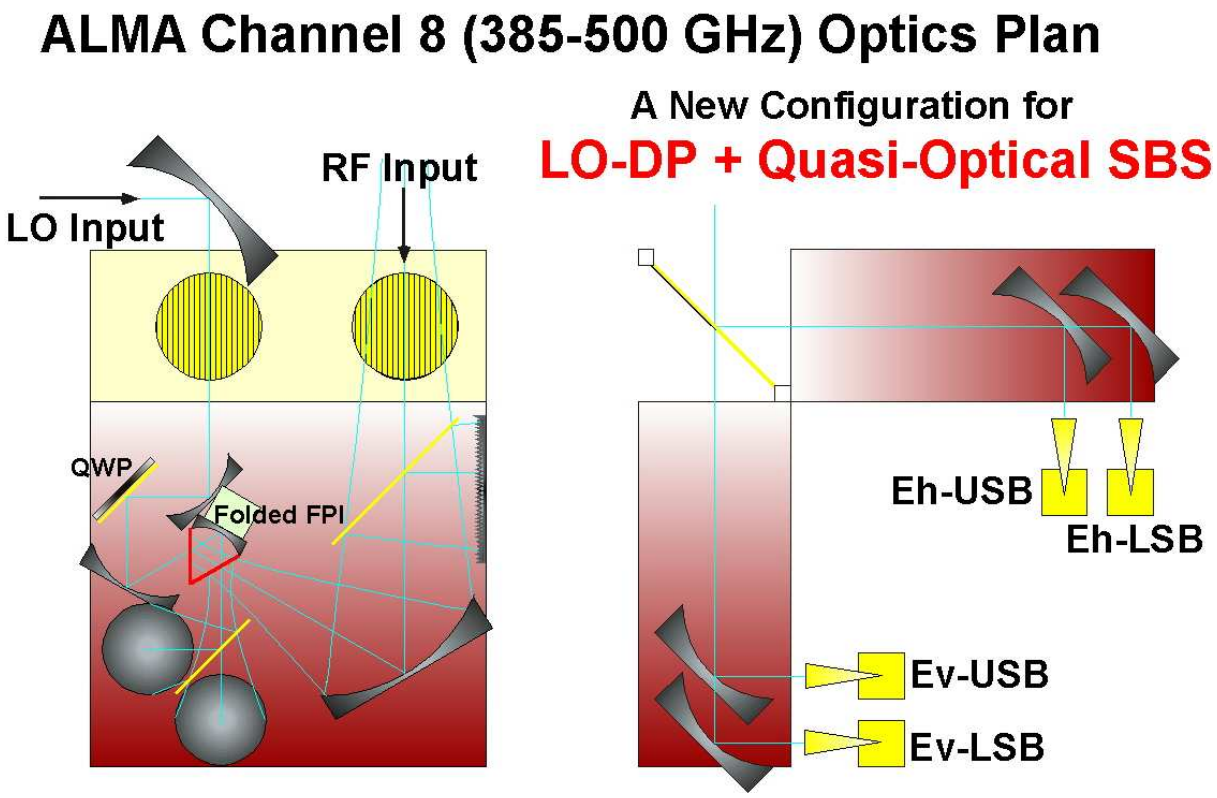

Figure 12 A schematic drawing of quasi-optical sideband separation with a folded Fabry-Perot interferometer as a LO diplexer. The folded FPI, which is composed of two meshes, a curved mirror and mechanical tuner, is transparent for circular polarized LO and reflects RF signals.

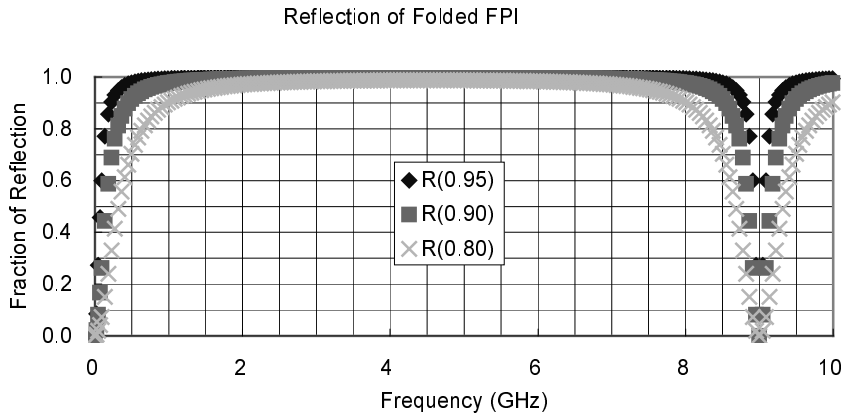

Figure 13 A folded Fabry Perot interferometer reflectivity depending on the IF frequency. The free spectral range of this folded FPI is 9 GHz. Three lines correspond to reflectivity of the

mesh.

5. CRYOCOOLERS

Two stages Gifford-Macmahon cryocooler with a capacity of 1 W at the 4 K stage for power consumption of 7.5 kW (Sumitomo RDK408DA) is employed for the ASTE receivers (see Figure 3). This product is utilized for MRI (magnetic resonance imaging) as medical appliances, and the accumulative production is greater than 1500 pieces. The orientation dependence of the cooling capacity is less than 10 % in the specification. The cooling capacity of the first stage is 20 W at 30 K. The air-cooled compressor (Sumitomo CSA-71) is installed at the side of the U-fork of the antenna.

The cryocooler employs a He pot to stabilize temperature of the 4 K stage (Li et al. 1997). A copper pot (50ϕ x 50 mm) connected to the helium line with a capillary tube is mounted on the 4 K stage (see Figure 3). The pressure in the He pot is constant independent of the temperature of the cold head. The pot works as a thermal buffer even in 4 K because of the high volumetric specific heat of pressurized helium at 4 K. With a He pot, the periodic temperature variation of the 4 K stage is reduced from 0.5 K to 0.02 K at the cold head. The temperature ripple at a surface of the mixer block was less than 10 mK because some materials at the 4 K stage serve as additional heat buffer. It takes 3 hours to cool the mixer block from 300 K to 4 K.

We have three candidates for the ALMA cryocooler; 1) Daikin JT + GM, 2) Mitsubishi 3 stages GM, 3) Sumitomo dual 2 stage GM as tabulated in Table 4. For cryocooler, reliability is very important. An indicator of the reliability is accumulative production number. GM 2 stage by Sumitomo has been produced over 1500 pieces so far. Daikin has also produced 200 JT cryocoolers. They have been adopted in many astronomical telescopes such as NANTEN 4m, IRAM, SMA. These cryocoolers will be tested at the site. There are many merits in pulse tube cryocooler such as low mechanical vibration, however, at the present stage, we do not have a good candidate for the ALMA cryocooler.

Table 4 Japanese candidates for the ALMA cryocooler.

Manufacturer	Daikin	Mitsubishi	Sumitomo	ALMA spec
Method	JT+GM 2 stage	GM 3 stage	Dual GM 2 stage	
Accumulative production	200	(100)	(1500)	
4K capacity	2.1 W	1 W	1 W	0.5 - 1 W
15 K capacity	10 W	7 W	5 W	10
80 K capacity	10 W	40 W	12 W	40
Power consumption	6.4 kW	7.5 kW	7.5 kW	

6. TIMELINE

The timeline of receiver development is shown in Figure 14. At Nobeyama, we test the receiver in the frequency range up to 350 GHz. In FY2000, we will make interferometric observations up to 350 GHz with an existing telescope. The antenna will be disassembled in May 2001 and will be transported to Chile. We will operate the ASTE receiver up to 350 GHz from December 2001 to evaluate the antenna and to observe astronomical objects at submillimeter and millimeter bands. We will evaluate a prototype of an ALMA band 8 cartridge (385 – 500 GHz) with a second focal receiver from January 2002.

We are investing a mass production method of ALMA receiver cartridges. Developments of the 25 multi-beam SIS receiver on the Nobeyama 45 m telescope (Sunada et al 2000) are a good experience. We are trying to reduce a fabrication cost of microwave components such as mixer blocks. Cooled LNAs with 4 – 8 GHz band for mass production have been developed with Nitsuki Co.

Remote control system of receiver system has been developed on the Mt. Fuji submillimeter-wave telescope (Sekimoto et al. 2000). It is necessary to improve this system for the ALMA receiver. We will carry out some tests of remote control system for a receiver system on the ASTE.

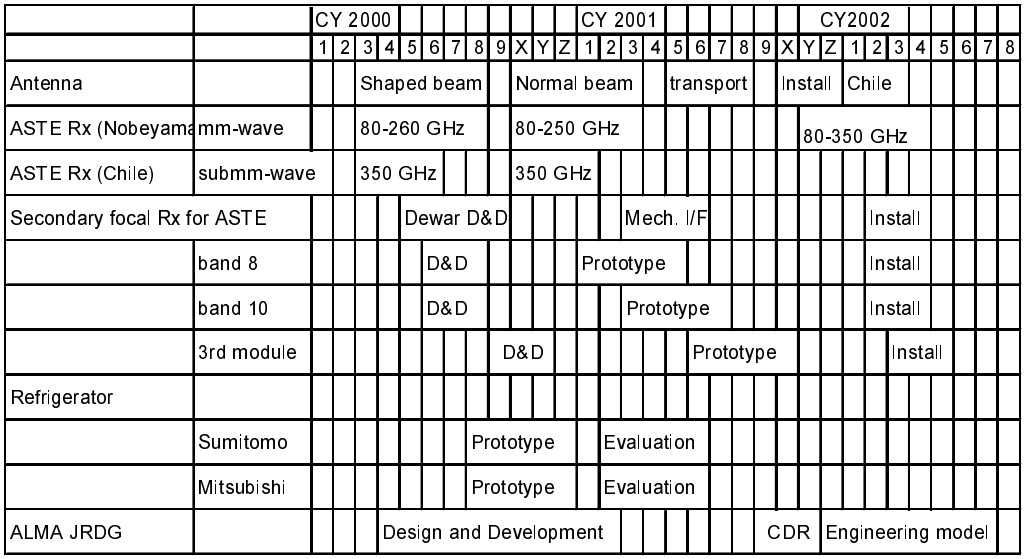

Figure 14: Timeline of a receiver development for the ASTE/LMSA

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APPENDIX A. JAPANESE SIS RECEIVERS

Telescope	Frequency (GHz)	Trx (K)	SSB/DSB	SSB method	IF (GHz)	mixer	horn	Beam efficiency	LO coupling method	LO coupling factor
Nobeyama 45 m telescope										
S115Q (4 beam)	107 - 118	100(DSB)	SSB*2	MixerBlock Design	5.0-7.0	fixed tuned	corrugated	0.55 (main)	C.G.C.	-20 dB
S100	79 - 115	130(SSB)	SSB	MPI	1.2-1.8	fixed tuned	corrugated	0.58(main)	PTFE	-20 dB
S80	69 - 115	130(SSB)	SSB	MPI	1.2-1.8	fixed tuned	corrugated	0.5(main)	PTFE	-20 dB
S40	32 - 50	80(SSB)	SSB	MPI	1.2-1.8	backshorts	corrugated	0.72 (main)	C.G.C.	-20 dB
S40M (6 beam) *1	40-50	40(DSB)	DSB		1.2-1.8	fixed tuned	corrugated		C.G.C.	-20 dB
BEARS (25 beam)	82-116	70(DSB)	DSB		2.0-2.6	fixed tuned	corrugated	0.55(main)	C.G.C.	-20 dB
Rainbow(band1)	80 - 120	30 - 60	DSB		4.5 - 7.0	fixed tuned	corrugated		C.G.C.	-20 dB
Rainbow(band2)	129-152	40 - 80	DSB		4.5 - 7.0	fixed tuned	corrugated		C.G.C.	-20 dB
Rainbow(band3)	213-237	40 - 120	DSB		4.5 - 7.0	fixed tuned	corrugated		C.G.C.	-20 dB
	*1 Ibaraki U. & Hosei U.									
	*2 Fixed tuned SSB									
Nobeyama Millimeter Array										
	80 - 120	30 - 60	DSB		4.5 - 7.0	fixed tuned	corrugated	0.65 (aperture)	C.G.C.	-20 dB
	129-152	40 - 80	DSB		4.5 - 7.0	fixed tuned	corrugated	0.53 (aperture)	C.G.C.	-20 dB
	213-237	40 - 120	DSB		4.5 - 7.0	fixed tuned	corrugated	0.29 (aperture)	C.G.C.	-20 dB
NANTEN	4 m telescope									
	90 - 115	100 (SSB)	SBR > 10 dB	backshort tuned	1.2 - 1.8	2 backshorts	corrugated	~0.7	C.G.C.	-20 dB
VST1 60-cm telescope										
	220-230	250	SSB	MPI	1.2-1.7	fixed tuned	corrugated	0.95 (sun)	C.G.C.	-20 dB
Mt. Fuji 1.2m telescope										
	330 - 350	100	DSB		1.8 - 2.5	fixed tuned	diagonal	0.8 (moon)	wire grid	-13 dB
	490 - 495	300	SSB	Quasi-optical	1.8 - 2.5	fixed tuned	diagonal	0.75 (moon)	wire grid	-13 dB
	800 - 810	600	DSB		1.8 - 2.5	fixed tuned	diagonal		wire grid	-10 dB
Nobeyama 10m submm telescope										
	85 - 120	25	DSB		4.5 - 7.0	fixed tuned	corrugated		C.G.C.	-20 dB
	210 - 230	50	DSB		4.5 - 7.0	fixed tuned	corrugated		C.G.C.	-20 dB
	320 - 360	52	DSB		4.5 - 7.0	fixed tuned	corrugated		Wire grid	-15 dB
BSMILES(Balloon-borne Superconducting Submillimeter-WaveLimb-emission sounder)										
	649 - 651	126 – 167(DSB)	SSB	MPI	5.0 - 7.0	fixed tuned	corrugated		wire grid	-15 dB