CONFIDENTIAL

Japanese Participation in ALMA:
A Proposal

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National Astronomical Observatory
of Japan

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1. Introduction

Looking back the history, we see three roots of the ALMA project, i.e., the Millimeter Array project (MMA) in the National Radio Astronomy Observatory of the United States, the Large Millimeter and Submillimeter Array project (LMSA) in Japan, and the Large Southern Array project (LSA) in Europe. After nearly two decades of intense effort in the three regions, they have evolved into a project to build and operate a single instrument ALMA that is unique in the world.

At its meeting in April 2001 in Tokyo, the Expanded ALMA Coordinating Committee (EACC) recognized the advantage of combining the three projects into a single global one, noted the strong ASAC support for a trilateral ALMA Project that leads to a significant enhancement in the science capability, and resolved to work towards the earliest possible final definition of the ALMA project with three partners. In accordance with this resolution, the Expanded ALMA Executive Committee (EAEC) and ASAC worked to define the three-way ALMA project (Atacama Large Millimeter/submillimeter Array) with its possible work breakdown in October 2001. In October 2001, an ASAC report was issued on the scientific justification and recommended priorities for the items that can possibly be brought in by the Japanese participation. With the approval of the project in the United States and in ESO in 2002, the project is entering the construction phase with the two official partners, who are building the "baseline" part of the project. In September 2002 in Garching, NAOJ explained an outline of the Japanese participation plan to the ALMA Coordination Committee (ACC), which welcomed the Japanese proposal.

The current proposal presents in detail the way of the Japanese participation to the construction of ALMA as the third major partner, and is meant to be a basis for the forthcoming negotiation between the ALMA Board and the National Astronomical Observatory of Japan (NAOJ). Section 2 reconfirms the principles that guide the proposal. Section 3 gives an overview of the proposed Japanese contribution plan with the contribution items, their scientific goals, and the organizational and management structure. A description of individual contribution items and the plans for their implementation are given in Section 4. ALMA/JP team at NAOJ and the collaborating researchers in universities in Japan have been making active developments of the key technologies related to the proposed contribution, and it is technically feasible for Japan. The status of the developments is described in Section 5. Schedule and values are proposed in Section 6, and steps toward the formal participation of Japan are discussed in Section 7.

2. Guiding Principles

The NAOJ proposes the Japanese participation plan under the following guiding principles.

Realization of the three-way ALMA

As a result of Japanese participation, we try to realize as much as possible the functions of the three-way ALMA that emerged from the joint effort made most intensively in 2001 by the three partners. NAOJ is preparing a financial plan to make it possible (see Section 3).

Optimization for science

We try to optimize the Japanese contribution for science within the available resources referring to the ASAC recommendations and discussions within Japanese scientific community that has a strong interest in submillimeter-wave astronomy. We note that the scientific power of ALMA should be valued not only at its start of operation in 2011 but also over the lifetime of the instrument.

Participation as the third major partner

We consider a framework in which Japan can contribute a significant fraction to the construction as the third major partner of ALMA. Japan will contribute also to the infrastructure and operation costs. Japan should obtain intellectual and economic benefit from ALMA in all phases in proportion to the value of their contribution, as the other partners do.

Clear interface with the “baseline” project

We try to keep the interface between the Japanese and bilateral parts of the trilateral ALMA project clean and simple, so that we can avoid unnecessary overhead cost and delay in the project.

3. Overview of the Japanese Participation Plan

3.1 The Contribution Items

Guided by the principles in Section 2 and based on discussions within the Japanese scientific community, NAOJ proposes to bring the four items to ALMA:

The Atacama Compact Array (ACA) system

A system of twelve 7-m antennas and four dedicated 12-m antennas all equipped with receiver frontend and backend systems. This system takes the short-baseline and single-dish data to be combined with the data from the 64-element array.

New receiver bands

- **Band 10**
- **Band 8**
- **Band 4**

Fabricate and install frontend cartridges of three new bands to the antennas of the 64-element array and the ACA system (80 antennas in total).

The Second Generation Correlator (2GC)

The correlator to be used for both the ACA system and the 64-element array. It has up to 8,000 – 64,000 spectral channels per baseline that can be used even at the maximum total bandwidth of 16 GHz. A flexible allocation of the frequency channels within the band is possible. A 3-bit sampling and processing is standard. The proposed 2GC contains the correlator for the 64-element array and the correlator for ACA under an unified design.

Contribution to infrastructure and operation

The infrastructure needed to accommodate the Japanese contribution items. NAOJ intend to share an appropriate fraction of the operation cost.

Table 3.1 shows a comparison of the project scope between the two-way baseline ALMA and the three-way ALMA after the Japanese participation.

NAOJ is preparing a request for the Japanese ALMA construction budget that starts in FY2004. The budget, if fully approved, can realize all of the above items (except for the operation cost that is to be requested separately).

Table 3.1: Comparison between the bilateral and trilateral ALMA

Items	Current bilateral project	With Japanese participation	Difference
Managemnet/administration			
	2 Executives	3 Executives	expanded
Site development/infrastructure			
	for baseline ALMA	includes infrastructure for Japanese contribution items	infrastructure for Japanese contribution items
Antennas			
12-m antennas	64	64 + 4 (for ACA)	4
7-m antennas		12 (for ACA)	12
transporters	2	2	
Receiver frontends			
baseline bands			
Band 3	64	64 + 4 + 12	4 + 12
Band 6	64	64 + 4 + 12	4 + 12
Band 7	64	64 + 4 + 12	4 + 12
Band 9	64	64 + 4 + 12	4 + 12
Water Vapor Radiometer	64	64 + 4 + 4 (for 7 m)	4 + 4 (for 7 m)
new bands			
Band 4		64 + 4 + 12	64 + 4 + 12
Band 8		64 + 4 + 12	64 + 4 + 12
Band 10		64 + 4 + 12	64 + 4 + 12
Backends			
LO	64	64 + 4 + 12	4 + 12
IF/digitizing	64	64 + 4 + 12	4 + 12
data transmission	64	64 + 4 + 12	4 + 12
Correlator			
baseline correlator for 64-element array	1	1	
second generation correlator for 64-element array and ACA		1	1
Computing			
	for baseline ALMA	includes computing for ACA and second generation correlator	computing for ACA and second generation correlator
System engineering/Integration			
	for baseline ALMA	includes activity to incorporate Japanese contribution items	expanded
Science			
	2 Executives	3 Executives	expanded

3.2 Scientific Goals

The above items altogether enhance the performance of ALMA greatly, and provide the science community in the world with new opportunities. In particular, these items will make ALMA a really powerful instrument in submillimeter-wave astronomy, whose great advancement is foreseen in the first quarter of this century. With this enhancement, ALMA will play an even more important role in answering key questions in astronomy such as origins of galaxies, planetary systems and life. ASAC has given the scientific justification of the items 1-3 in its recommendation on October 15, 2001. It is a result of active discussion among scientists from North America, Europe, Japan, and Chile. Japanese scientists joined as official members and contributed significantly to the report.

The ACA system recovers the spatially extended components of the objects and significantly enhance the imaging and photometric capability of ALMA in observing extended astronomical objects in any receiver band. It was given *"top priority"* in the ASAC recommendation. The ACA is expected to play a particularly important role for observations at high frequencies, where the objects will in general be larger than the primary beam. Numerical simulations show that in some cases the images without ACA will miss key information leading to an inaccurate interpretation of the data.

The new receiver bands will bring new observing windows to ALMA particularly at submillimeter wavelengths. These frequency bands were rated as *"top priority"* (Band 10) and *"high priority"* (Band 8 and Band 4) in the ASAC recommendation. Band 1 was ranked in between the two. Noting that the absolute ranking for the four bands was close, NAOJ propose here the three bands with its priority stated above based on the accumulated development efforts (see Section 5) and the community's interests in Japan.

- **Band 10 (787 – 950 GHz)** is the highest frequency observing band of ALMA, thus providing the highest angular resolution for a given configuration. It offers unique science opportunities such as observations of the excited [CI] fine structure line, red-shifted [CII] emission, and high excitation lines of fundamental molecules. It will provide continuum flux density information at the highest frequency of ALMA, which will be important for accurate determination of the spectral energy distribution of objects like protostellar cores, protoplanetary disks, protogalaxies and active galactic nuclei.

- **Band 8 (385 – 500 GHz)** is a unique band among the ALMA frequency bands that receives the fundamental [CI] fine-structure line in our own and nearby galaxies. It also provides opportunities to observe the [CII] fine-structure line at an interesting redshifted range of z = 2.7 – 3.8, HDO fundamental transition in solar system objects, and CO J = 4 – 3 line in our own and local galaxies.

- **Band 4 (125 – 163 GHz)** covers a wavelength range where the atmosphere is very transparent even under mediocre conditions. It is a crucial band to measure redshifted CO and [CII] in critical redshift ranges. It also provides important opportunities for astrochemistry including deuterated molecules and measurements of the lowest frequency dust emission free from emission from ionized gas.

The Second Generation Correlator (2GC) will enhance the spectroscopic capability of ALMA (the 64-element array and ACA) by enabling observations with full bandwidth without sacrifice of number of spectral channels (i.e., spectral resolution) and sensitivity.

The 2GC was given *"very high priority"* in the ASAC recommendation. It can increase the observing speed of some highly ranked programs by a factor of two or more, especially in the areas of high-redshift galaxies and protoplanetary disks around young stars, which require long integration times. It also provides ALMA unique capabilities to probe deep into the centers of active galaxies and to make unbiased searches for absorption lines from the deep universe or for signals from pre-biotic molecules in planet forming regions.

A 3-bit sampling and processing is standard for the 2GC, which provides a 8 % gain in sensitivity of the entire ALMA system relative to the 2-bit processing that is standard in the baseline correlator. It is equivalent to adding five more 12-m antennas to the 64-element array.

The 2GC consists of two parts; one for correlating the signal from the 64-element array and another for correlating the signal from ACA. The correlation data from both parts are later combined by the data reduction pipeline software to construct final output images. To this end, detailed compatibility of the two correlation data is important. The 2GC proposed here is an ideal solution for this by providing correlation data for the 64-element array and ACA in identical observing modes and frequency response.

3.3 Organization and Management Structure

NAOJ proposes that Japan should participate as the third major partner in ALMA. This means that the following modifications are needed to the current organizational and management structure of ALMA:

- ALMA Board: participation of an appropriate number of Japanese delegates
- ASAC and AMAC: participation of an appropriate number of Japanese delegates
- Executives: NAOJ as the third executive
- Management IPT: inclusion of the Japanese project manager
- Other IPTs: inclusion of the Japanese members in the relevant IPTs

Figure 3A shows the organization chart of ALMA after the Japanese participation. This setup enables the Japanese participation as a major partner while keeping the project management centralized. The Joint ALMA Office and the three executives including their IPT members should communicate well to drive the unified project.

For an official Japanese participation in the form described above, an Agreement between NAOJ and the ALMA project is sought .

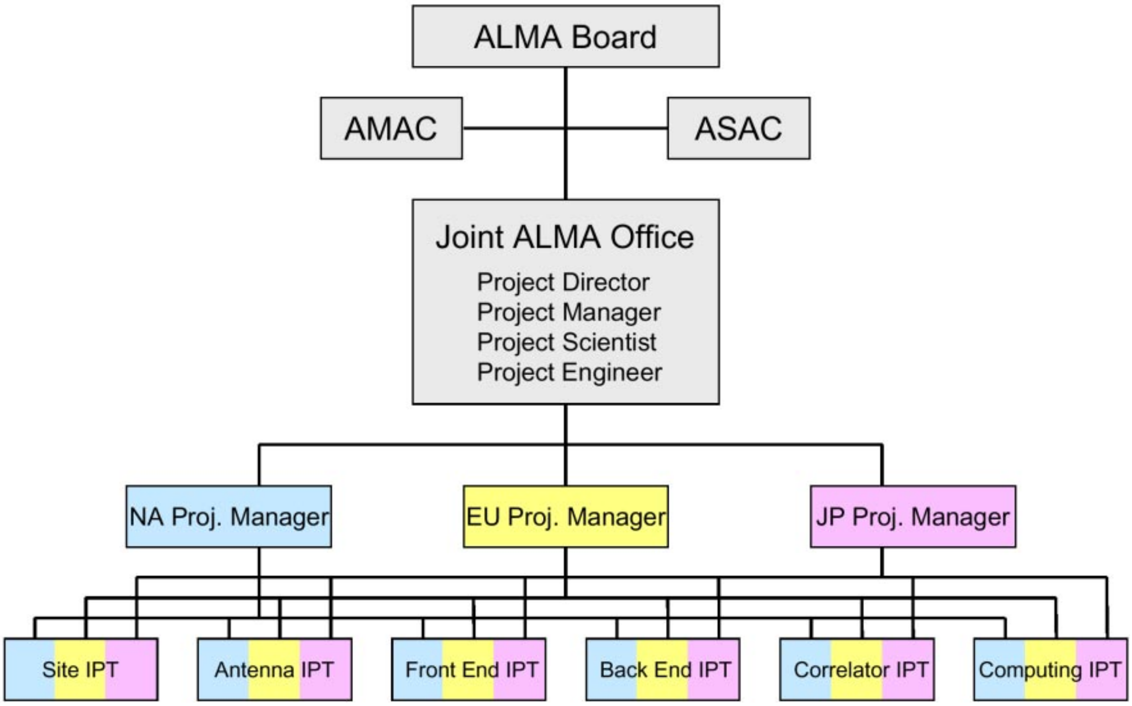

Figure 3A: The proposed organization of the ALMA project after the Japanese participation.

4. Contribution items

4.1 The Atacama Compact Array (ACA) System

Specification

The ACA system consists of twelve 7-meter antennas and four high-performance 12-meter antennas equipped with all the required frontends with the baseline receiver cartridges and the IF/backend systems. The number and diameter of the 7-m antennas are optimized based on the simulation work conducted by ASAC with an active participation of Japanese scientists. The four 12-meter antennas are equipped with the nutating subreflectors and the water vapor radiometers, and will be dedicated to accurate single-dish measurements and calibration of the 7-meter antenna array. The number of the 12-m antennas is based on the requirements for the speed of single-dish data collection and the sensitivity in calibration of the smaller antennas.

The ACA system will greatly improve the photometric accuracy and wide-field imaging capability of ALMA in all observing bands. This effect is particularly important in the highest frequency bands for which the field of view of the 64-element array defined by the primary beam of the 12-m antennas gets smaller than 10” in diameter. For these frequencies, the performance of the antennas becomes one of the limiting factors of the accuracy of the observational results. This is particularly true for the ACA antennas, because the spatially extended components generally have larger visibility amplitudes. If the data from the ACA suffers from inaccurate calibration, it would damage the final image constructed from the data from both the 64-element array and the ACA combined. As shown in Figure 4A, the surface accuracy specification of 25 microns rms adopted for the 64-element array antennas meets the requirement for ACA only marginally in Band 10, loosing 50 – 60 % of the effective collecting area relative to lower frequencies. It is desirable that the ACA antennas have a higher surface accuracy; i.e., 20 microns rms or better with a goal of 17 microns rms for the ACA 12-m antennas, and 17 micron rms or better for the 7-m antennas. The 17-micron accuracy reduces the above-mentioned loss down to 25 – 35 % (or increases the effective collecting area by a factor of 1.5 – 1.7) in Band 10, so that we can make more efficient and reliable measurements of the single-dish and short-baseline data at the highest frequencies. Observations in Band 9 will also benefit this gain in the effective collecting area (by a factor of 1.3).

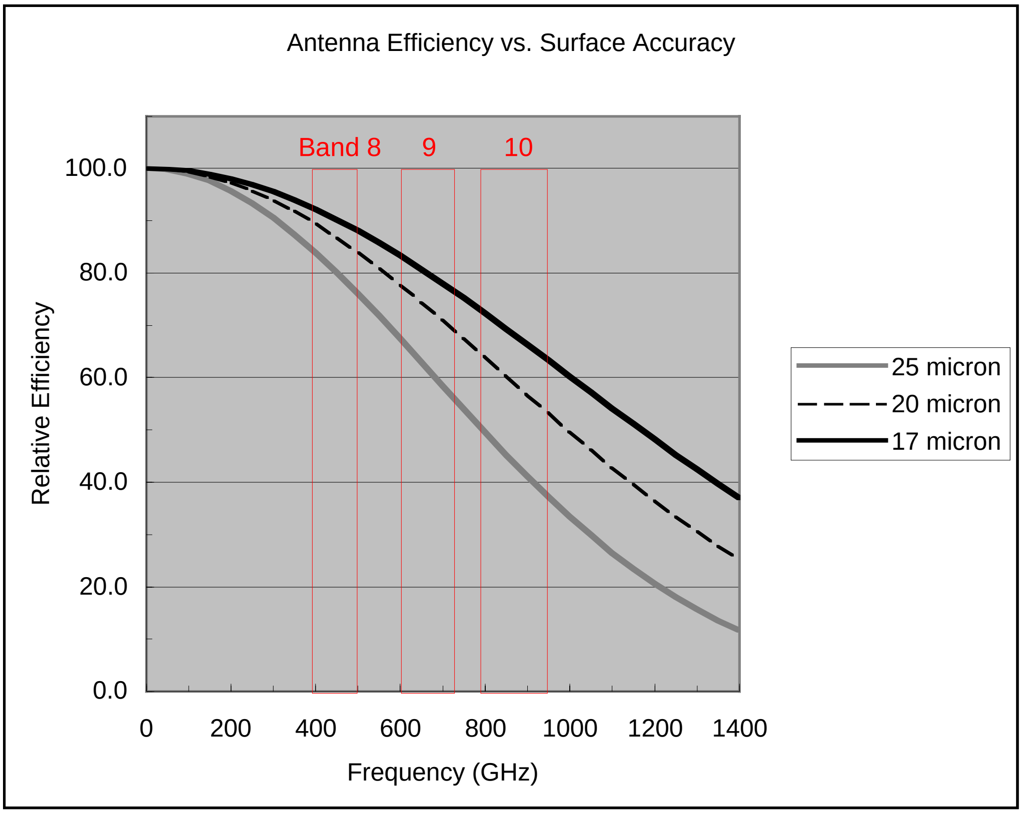

Figure 4A: The relative efficiency of an antenna as a function of observing frequency.

The antenna transporters for the 64-element array can be used to move both the 12-m and 7-m ACA antennas; an adapter may be required to interface between the antenna and the transporter.

Table 4.1: Specification of the ACA antennas

Diameter	7 m	12 m
Number of antennas	12	4*
Surface error [rms]	≤ 17 µm	≤ 20 µm (goal ≤ 17 µm)
Relative pointing error [rms]	0.6 arcsec with calibration made every 15 min on sources within 4˚	0.6 arcsec with calibration made every 15 min on sources within 2˚
Close packing ratio	1.25	1.25
Compatibility with the ALMA antenna transporter	yes (with an adapter)	yes (with an adapter)
Nutating subreflector	no	4 antennas**
Water Vapor Radiometer	4 antennas	4 antennas

*One of the 12-m antennas can be the prototype antenna after refurbishment.

**The nutating subreflectors are built as an Euro/N. A. task

Design and implementation plan

The implementation plan of the ACA system is currently being prepared by NAOJ, and an outline of the technical proposal will be made in March 2003. The key elements of the plan are described in the following.

The ACA 12-m antennas are based on one of the prototype 12-m antennas evaluated jointly at the ALMA Test Facility, with an improved surface accuracy. NAOJ intends to refurbish the Japanese prototype antenna to deliver as one of the ACA antennas, if the prototype is qualified for such an use. For the ACA 7-m antenna design, some of the design elements of the 12-m antenna will be carried over while optimizing the design referring to the scientific and operational requirements of the ACA system. The 12-m antennas will be delivered first, and some of them can join in the early science operations of ALMA. The delivery of the 7-m antennas will follow, and the entire system will be ready in FY2011. The ACA antennas will be assembled at OSF.

NAOJ requests that the European and North American partners deliver, on the Japanese budget, the items including the followings (see also Section 4.6):

- Frontend

    - Cryostats for the ACA 12-m antennas
    - Warm optics assemblies for the ACA 12-m and 7-m antennas
    - Windows and IR filters, solar filters
    - Band 3, 6, 7, and 9 cartridges for the ACA 12-m and 7-m antennas
    - Water vapor radiometers for the ACA 12-m and 7-m antennas
    - Calibration systems
    - Associated electronics (IF selection switches, monitor/control)
    - Frontend service and exchange vehicle
- Backend
    - IF/digitizer/transmitter/LO systems

In addition to the above items, NAOJ requests a loan of two sets of pre-production receiver frontends to be installed to the first and second ACA 12-m antennas in 2007 1Q. NAOJ proposes that the four ACA 12-m antennas be equipped with the nutating subreflectors that are being built as a task of the bilateral project.

The design optimization of the 7-m antenna is underway, and it remains an open question whether we can use the same frontend cryostat (developed for the 12-m antennas) also for the 7-m antennas. If the 7-m antenna design requires a major modification of the cryostat, NAOJ will design and produce them for the 7-m antennas.

The optical parameters at the focus of the 7-m antenna are different from those of the 12-m antennas, and the input optics in front of the receiver feed need to be modified accordingly. NAOJ requests the partner who designed the input optics for the 12-m antenna to make the required modification to match the 7-m antenna optics.

Among the receiver frontend cartridges made in Europe or in North America for the 7-m antennas, Band 3 is of special importance in the testing, commissioning, and the early science operations phase. NAOJ therefore asks their delivery in 2Q 2007 with the highest priority. NAOJ would like to have cartridges of the other bands (Band 6, 7, 9) delivered as soon as they becomes available, but no later than the completion of the production of Band 10 cartridges for the 7-m antennas.

NAOJ intend to set up an integration center in Japan to assemble and test the receiver frontends for the ACA antennas before shipping them to Chile.

4.2 New Receiver Bands

Specification

Table 4.2 shows the noise performance in the "Specifications of the ALMA frontend assembly" (Ver. 2.0, Apr. 25, 2001) for the new receiver bands that NAOJ proposes to deliver. NAOJ will make its best effort to achieve them. Developments are being made to realize the 2SB operation for Band 4. The uniformity and reliability of a total of 80 cartridges per band are equally important, and they are subjects of intense consideration and development.

Fabrication and implementation plan

NAOJ intend to produce and deliver Band 4 and Band 8 cartridges in a same schedule as that for Band 3, Band 6, and Band 7, so that the Japanese cartridges can be integrated in the frontend system along with the baseline band cartridges. Band 10 requires some more development. Based on the experience in the production of Band 8 cartridges, NAOJ will finalize the Band 10 production model. NAOJ will have a pre-series production run and a careful evaluation before producing the large number of cartridges.

Table 4.2: Receiver noise specifications of the new receiver band cartridges

	Band 4		**Band 8**		**Band 10**	
RF range	125 - 163 GHz		385 - 500 GHz		787-950 GHz	
	over 80 %	any freq.	over 80 %	any freq.	over 80 %	any freq.
SSB receiver noise temperature*	47 K (goal 26 K)	76 K (goal 40 K)	181 K (goal 93 K)	270 K (goal 181 K)	438 K (goal 351 K)	655 K (goal 525 K)

* For DSB response, these values should be multiplied by 0.5.

4.3 The Second Generation Correlator (2GC)

Specification

One of the scientific requirements for the ALMA 2GC is that it has a highest frequency resolution better than 5 kHz, so that we can achieve a sufficient velocity resolution even for the narrowest line observed in Band 1. Cross correlators that can simultaneously realize this high frequency-resolution (5 kHz) and the full IF band coverage (16 GHz in total) for all antenna pairs (2,016) are ideal instruments for ALMA. If we uniformly sample every 5 kHz over the 16 GHz bandwidth (i.e., 3×10^6 frequency channels per baseline), the data output rate would overwhelm the computing power downstream. However, the 2GC being considered is capable of allocating frequency channels with various frequency resolution over the band to fit the data flow in the computing capacity without losing important astronomical information. The 2GC supports 3-bit correlation to minimize the sensitivity loss caused by quantization of the signal, recovering 8 % in sensitivity relative to the baseline correlator, for which 2-bit correlation is standard. This is equivalent to adding 5 more 12-m antennas to the 64-element array. The 2GC also supports an observational mode in which the 64-element array is divided into at least four subarrays. These specifications are summarized in Table 4.3.

Toward the unified design

Two architectures are being considered for the ALMA 2GCs: Hybrid-XF type and FX-type. In an XF-type correlator the cross-correlation is calculated before Fourier transform on the post-detection stage, and ‘Hybrid’ means that a FIR digital filter bank is installed before the correlation unit. In contrast, an FX-type correlator performs Fourier transform before cross (X) multiplication.

The correlator design teams from Japan, Europe, and North America met at Nobeyama in August 2001 to find a way to realize the expected scientific merits through the 2GCs. It was agreed to take steps to establish the “unified design” through collaborations along the specification in Table 4.3, which were set as minimum requirements according to the advices by ASAC. NAOJ and the bilateral project will define the unified design in

2003, considering the cost, schedule, performance, and feasibility.

Reason for a single correlator design for the 64-element array and ACA

For the operation of ALMA with ACA, two correlator units are required; one for correlating the signal from the 64-element array and another for correlating the signal from ACA. The correlation data from both units are later combined by the data reduction pipeline software to construct final output images. To this end, detailed compatibility of the two correlation data is important, especially in the spectral response of individual frequency channels. The center frequencies and the bandwidths of the spectral channels need to be identical for the two correlation data to be combined. Furthermore, a difference in correlator architecture may caouse different spectral response of individual channels. These differences would complicate the imaging process in the data reduction and may cause unwanted error in the final images.

The 2GC proposed here is an ideal solution for this by providing correlation data for the 64-element array and ACA in completely identical observing modes and frequency response. This will greatly simplify the observational and data reduction processes and make the final image outputs from ALMA most reliable.

Table 4.3: Specifications of the Second Generation Correlator for ACA

Specifications		Remarks
Number of antennas	64 + 16	the 64-element array and ACA
Number of correlations	2016 + 120	No cross correlation between the 64-element array and ACA
Bandwidth per baseband	2 GHz	2GHzx8Basebands/baseline; Input = 4 Gsps 3 bits
Input clock frequency	125 MHz	
Correlation mode	cross, auto	
180-degree phase switching	yes	
Image band rejection (90-degree switching)	yes	
delay compensation	yes	
Highest frequency resolution	< 5 kHz	Without a reduction of the total bandwidth
Correlation: Number of bits	≥ 3	
Maximum number of frequency-channels per baseline	≥ 8 k	
Typical integration time	0.1 – 10 sec	
Minimum integration time	1 or 16 msec	1msec applies to auto-corr.
Maximum number of channels @ 16 msec-integration	≥ 96	Data rate ≥ 12 Mega visibilities per second
Sub-array	≥ 4 + ACA	

Fabrication and implementation plan

The current plan is to construct the 2GC systems in two steps. NAOJ will first build the unit for ACA. The unit for the 64-element array will be built later incorporating the experiences with the construction and test operation of the ACA part. The circuit boards of the 2GC for the 64-element array need to be re-designed because the time delay from the production of the 2GC for ACA may make some of the key electronic parts unavailable.

It is not decided whether we should locate 2GC at the Array Operation Site (AOS) or at the Operation Support Facility. A fiber patch panel is required at AOS to direct the optical signal from the 64-element array to the baseline correlator or to 2GC. 2GC has optical signal input ports. NAOJ requests that the European and North American partners deliver, on the Japanese budget, the items including the followings (see also Section 4.6):

- Computing (with the Japanese effort participating)
    - Pipeline softwares
    - Data archiving

4.4 Infrastructures

NAOJ will contribute to the infrastructures required for the installation and operation of the Japanese contribution items. It includes the followings:

- Infrastructure needed to construct, operate, and maintain the instruments realized by the Japanese participation (i.e., ACA system, receiver frontends, and 2GC)
- Additional rooms for human activities (e.g., offices, meeting rooms, labs, and dorms)

4.5 Operation

NAOJ intends to contribute an appropriate share of the operational cost of ALMA.

4.6 Items requested to be delivered by partners

The items to be contributed by Japan include parts, units, and assemblies that have been developed for the baseline ALMA and being delivered by the European or North American partners. In order to avoid duplication of development effort and to increase the efficiency of the project, NAOJ requests that the European and North American partners deliver, on the Japanese budget, the items listed in Table 4.4.

Table 4.4: Items requested to be delivered by the European and North American Partners

Item	Quantity	Delivery time	Remarks
Receiver frontends			
Cryostats for 12-m antenna	4 sets	#1-2: 2007 1Q #3-4: 2007 4Q	
Warm optics assemblies for 12-m antenna	4 sets	#1-2: 2006 4Q #3-4: 2007 4Q	
Warm optics assemblies for 7-m antenna	12 sets	#1-2: 2007 2Q #3-6: 2007 3Q – 4Q #7-12: 2008 2Q – 2009 3Q (one per quarter)	optics design modified for 7-m
Windows, IR filters, solar filters	16 sets	2006 4Q	
Band 3 cartridge assemblies for 12-m antenna	4	#1-2: 2007 1Q #3-4: 2008 1Q	
Band 6 cartridge assemblies for 12-m antenna	4	2010 4Q – 2011 3Q	
Band 7 cartridge assemblies for 12-m antenna	4	2010 4Q – 2011 3Q	
Band 9 cartridge assemblies for 12-m antenna	4	2010 4Q – 2011 3Q	
Band 3 cartridge assemblies for 7-m antenna	12	#1-2: 2007 2Q #3-6: 2007 3Q – 4Q #7-12: 2008 2Q – 2009 4Q (one per quarter)	optics design modified for 7-m
Band 6 cartridge assemblies for 7-m antenna	12	#1-4: 2007 3Q - 2008 1Q #5 – 12: 2008 3Q – 2010 2Q (one per quarter)	optics design modified for 7-m
Band 7 cartridge assemblies for 7-m antenna	12	#1-4: 2007 3Q - 2008 1Q #5 – 12: 2008 3Q – 2010 2Q (one per quarter)	optics design modified for 7-m

Table 4.4 (continued)

	Band 9 cartridge assemblies for 7-m antenna	12	#1-4: 2007 3Q - 2008 1Q #5 – 12: 2008 3Q – 2010 2Q (one per quarter)	optics design modified for 7-m
	Water vapor radiometer assemblies for 12-m antenna	4	2006 4Q – 2007 1Q	
	Water vapor radiometer assemblies for 7-m antenna	4	2007 2Q – 2007 4Q	optics design modified for 7-m
	Calibration systems for 12-m antenna	4 sets	#1 – 2: 2005 3Q #3 – 4: 2007 1Q	
	Calibration systems for 7-m antenna	12 sets	#1 – 2: 2007 2Q – 3Q #3 – 12: 2007 4Q – 2009 4Q	optics design modified for 7-m
	Associated electronics for frontend	16 sets	2007 1Q – 2009 4Q	
	Frontend service and exchange vehicle	1	2006 1Q	
Backends				
	LO system in antenna	16 sets	#1 – 4: 2005 4Q – 2006 2Q #4 – 16: 2006 4Q – 2009 4Q	
	IF	16 sets	#1 – 6: 2005 4Q – 2007 1Q #7 – 16: 2007 Q4 – (one per quarter)	
	Digitizer	16 sets	#1 – 4: 2006 1Q – 2006 2Q #5 – 8: 2007 3Q – 2007 4Q #9 –16: 2008 1Q – 2010 2Q	
	Optical transmitter	16 sets	#1 – 4: 2006 1Q – 2006 2Q #5 – 8: 2007 3Q – 2007 4Q #9 –16: 2008 1Q – 2010 2Q	
	Optical fiber patch panel	1	2006 2Q at the latest	to switch correlators

Table 4.4 (continued)

Computing				
	Pipeline software upgrade		2008 2Q	
	Data archiving software upgrade		2008 2Q	
	Data archiving hardware upgrade		2008 2Q	
Site development/infrastructure				
	Infrastructure for Japanese contribution items		TBD	detailed items TBD

In addition to the items listed in Table 4.4, NAOJ requests a loan of two sets of pre-production receiver frontends to be installed to the first and second ACA 12-m antennas in 2007 1Q. NAOJ proposes that the ACA 12-m antennas be equipped with the nutating subreflectors that are being built as a task of the bilateral project.

5. Development Status

5.1 Antennas

Development of precision antennas is the key to the ACA system. NAOJ has developed and accumulated various technologies related to precision antennas.

NAOJ has constructed a precision 10-m antenna for submillimeter observations. After testing at Nobeyama, it was transported to Chile and installed at Pampa la Bola. This submillimeter telescope experiment (ASTE) provides an excellent opportunity to develop observing technologies including the precision antennas. Some of the development highlights are shown in Figure 5A. The surface has been adjusted to 29 mm rms (as of Nov. 2002) with the holography technique with a good room for further improvement. The gear-driven mounting has been measured to have an excellent tracking accuracy as well as an absolute pointing accuracy.

NAOJ is currently building a 12-m prototype antenna according to the ALMA specification (Figure 5B). It will be delivered in the second quarter of 2003 at the antenna evaluation facility at Socorro, and its performance will be evaluated as a joint task of the ALMA Antenna Evaluation Group (AEG). This prototype will be the base of our four 12-m antennas, and the AEG activity will ensure the feasibility of the Japanese contribution in the antenna area.

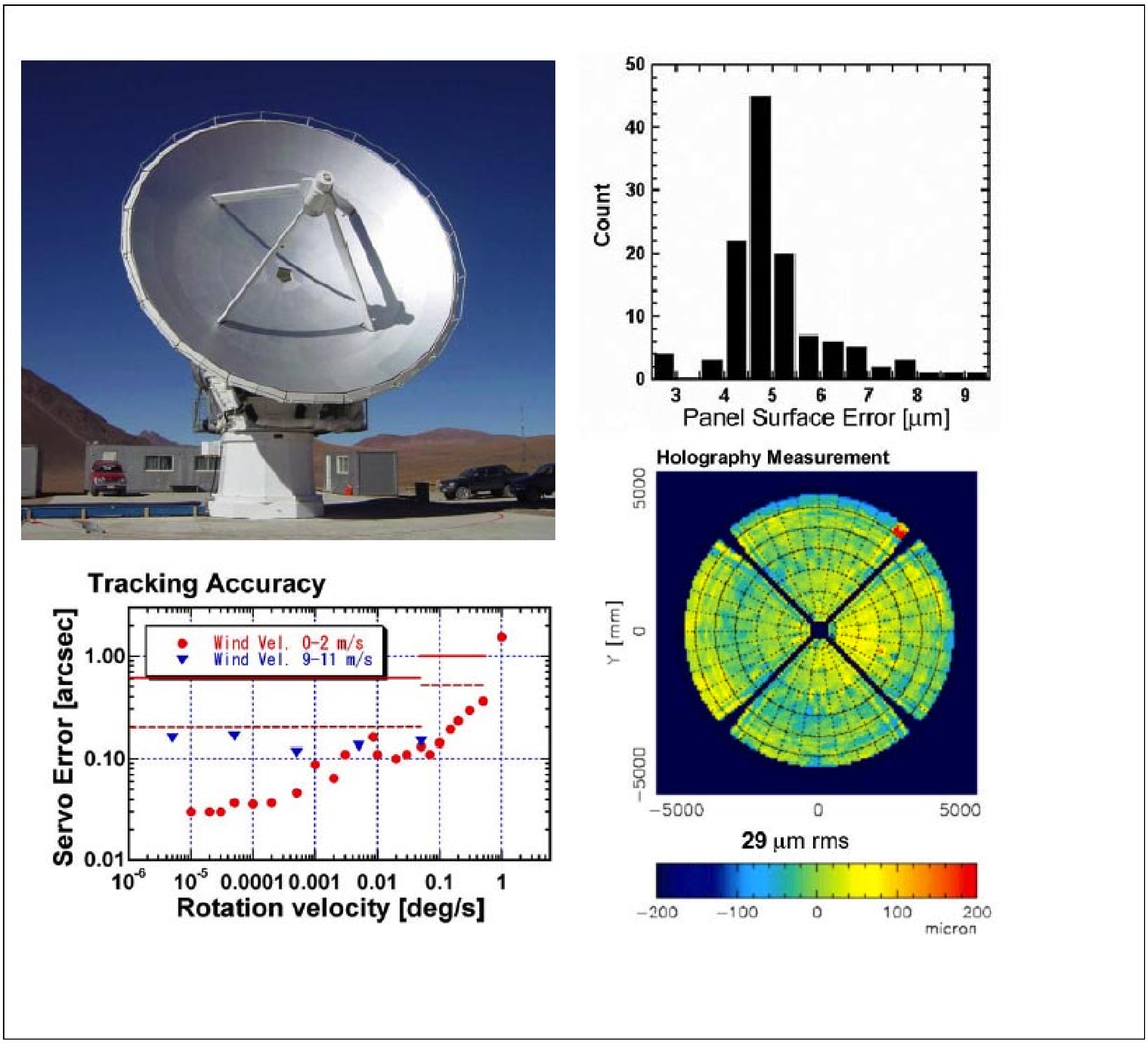

Figure 5A: The precision 10-m antenna installed at Pampa la Bola for ASTE, and its measured performances; tracking accuracy measured at Nobeyama (lower left), factory-measured panel surface errors (upper right), and the holographic measurement as of October, 2002.

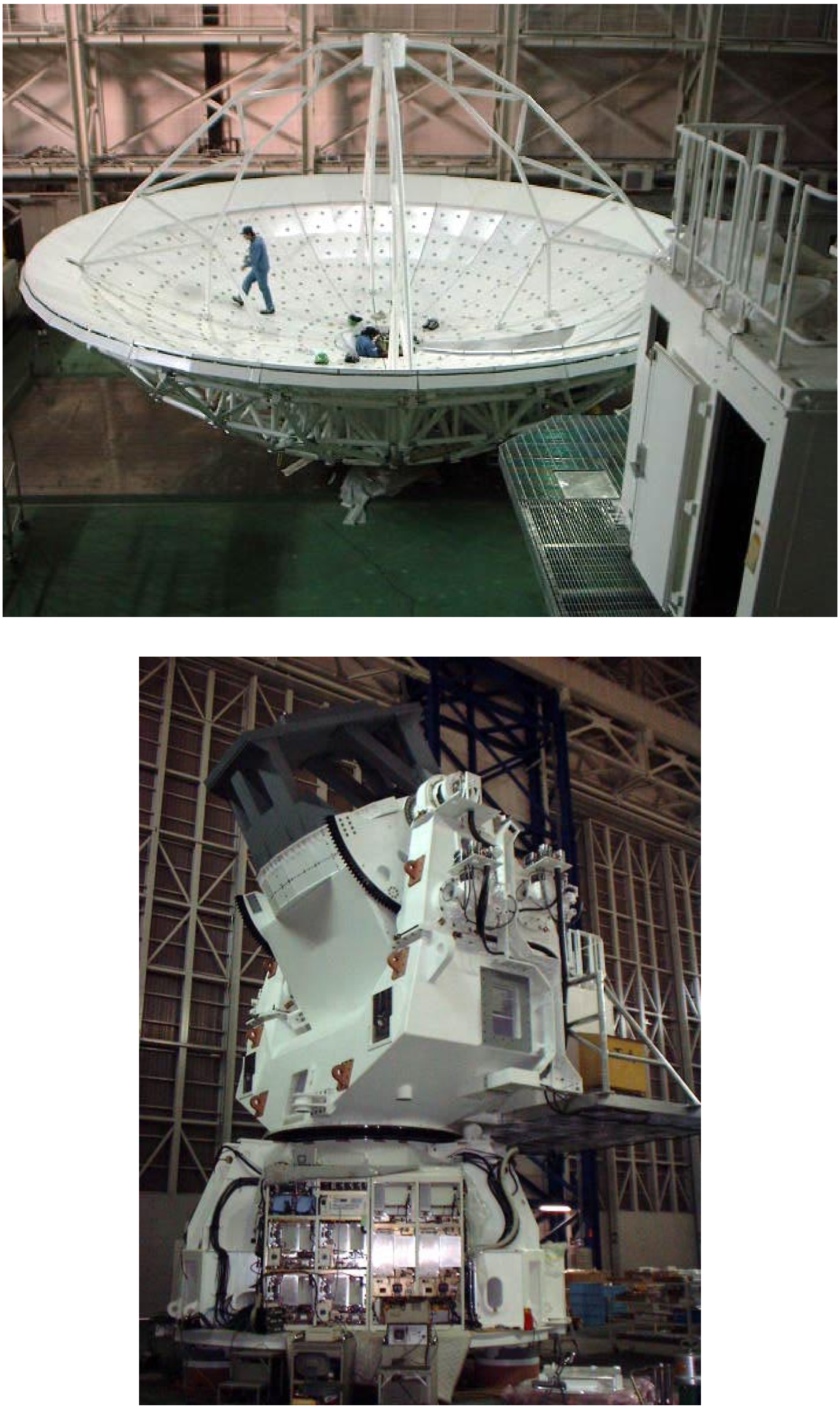

Figure 5B: The 12-m prototype antenna pre-assembled at Mitsubishi Electric Co.

5.2 Receivers

Developments for ALMA frontend are very active in Japan. In 2002 July, the first engineering model (EM) for Band 8 cartridge with the single-mirror optics was cooled and measurements were made of the receiver noise temperature and gain stability. Pre-prototypes of Band 10 and Band 4 receivers are also being developed as ALMA cartridges. These receivers are tested in the cartridge test cryostat, copies of which are being provided to the North American and European groups developing ALMA cartridges (Figure 5C).

The Band 4, Band 8, Band 10 EM/pre-prototype cartridges have been installed on the ASTE 10-m telescope in Pampa la Bola and tested in the actual observing conditions. Figure 5D shows one of the initial results of the [CI] 492 GHz line observation with the Band 8 cartridge.

The submillimeter receiver developments are based on the experience of the 810 and 490 GHz receivers on the Mt. Fuji submillimeter telescope. It has been operated for four years under remote control and is producing an unprecedented amount of survey data in the [CI] 492 and 809 GHz lines. NAOJ has established mixer designs called Parallelly-Connected Twin Junction (PCTJ) for submillimeter bands and Non-homogeneous Distributed Junction (NDJ) for millimeter bands. For band 10 SIS junctions, tests are being made for two types of junctions with new materials, i.e. NbTiN and NbN. These technologies are applied to the EM cartridges.

Figure 5C: ***(upper)*** **Receiver frontend cartridges under development for Band 4 (left), Band 8 (middle) and Band 10 (right).** ***(lower)*** **The cartridge test cryostat. Its copies are being shipped to the ALMA frontend development sites in Europe and North America.**

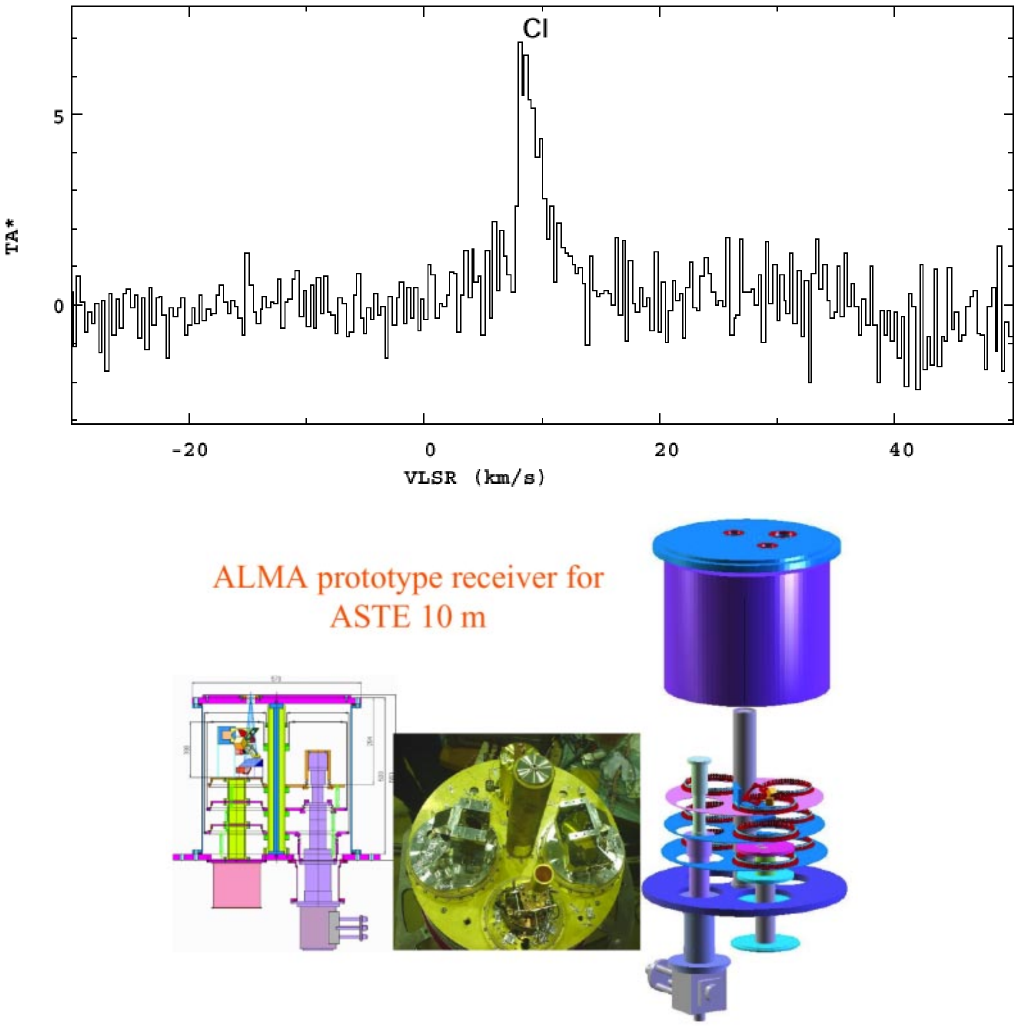

Figure 5D: ***(upper)*** **The [CI] 492 GHz line observed from Orion-KL by ASTE with the engineering model of the ALMA Band 8 cartridge. The receiver operates in DSB mode and the antenna temperature scale should be doubled for spectral lines.** ***(lower)*** **The ALMA-type cryostat used in the observation with ASTE. This was the first opportunity to test the concept of cartridges and thermal links adopted for ALMA in the real observing environment in Atacama.**

5.3 Photonic LO

A photonic local oscillator for use at 100 GHz has been developed, and was verified to have the output power and low noise suitable for use in the ALMA system. The photomixer using NTT uni-travelling carrier photodiode has been demonstrated to have high power of 2 mW at 100 GHz and low amplitude noise of < (7 – 17) K/μW in the frequency range of 98 – 105 GHz. It was successfully tested in an actual astronomical observation at the 45-m telescope in Nobeyama. As far as we know, this is the first astronomical spectroscopic observation with a photonic LO. Photomixers for higher frequencies are under development (Figure 5E).

Based on the developments described above, NAOJ collaborates with the bilateral ALMA project and proposes a hybrid option for the first local oscillators (LOs) of ALMA in which a direct photonic LO driver is used to drive cold multipliers (Figure 5F; Ishiguro et al. 2001, ALMA memo 435). This option simplifies the LO part of the cartridge in the baseline ALMA, and retains the future possibility for a fully photonic LO system including submillimeter bands with a minimal modification.

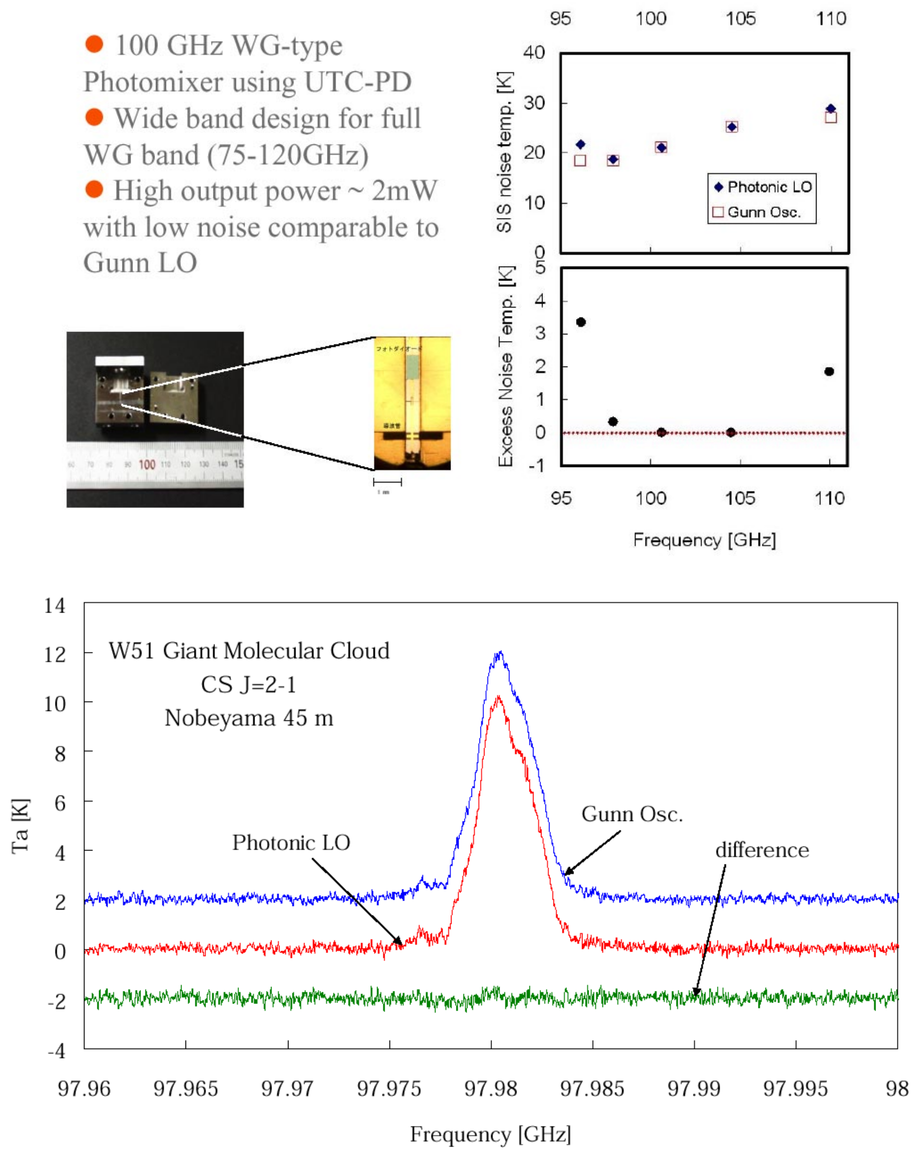

Figure 5E: *(upper)* The low noise high-power photomixer developed by NAOJ and NTT in Japan. *(lower)* Comparison of the spectral lines observed at the 45-m telescope at Nobeyama with a conventional Gunn oscillator as an LO (upper blue trace) and the photonic LO (middle red trace). The integration time is the same for both observations, and the results are virtually identical (lower green trace).

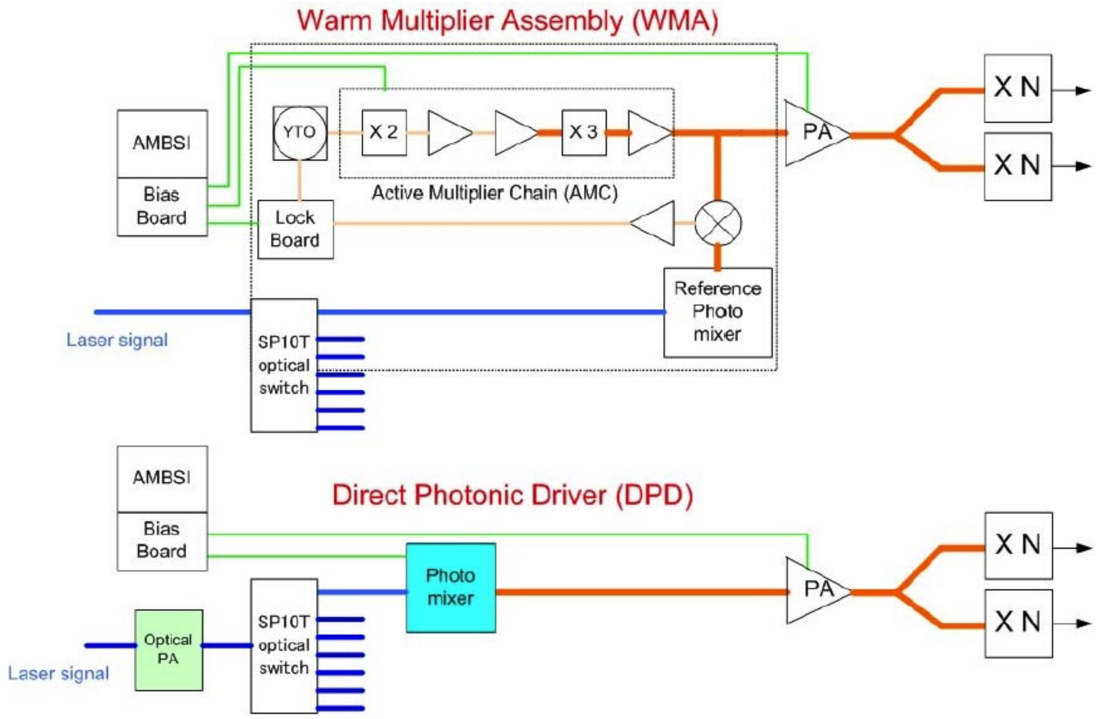

Figure 5F: The block diagrams of the baseline (Warm Multiplier Assembly, upper) and the proposed hybrid-photonic (Direct Photonic Driver, lower) options for the ALMA local oscillator system. The hybrid option is much simpler than the current baseline system and is capable of evolving into a fully photonic LO system without multipliers with minimum cost.

5.4 Correlator

NAOJ is one of the centers of expertise in design and development of multi-channel spectro-correlators for radio astronomy. In 2001, NAOJ has built a test FX correlator for ALMA and tested it in the real observation with the Nobeyama Millimeter Array (NMA), which showed its spectacular power by detecting twenty different spectral lines from Orion-KL in one frequency setting. Japanese correlator team has coordinated the development effort with the European correlator team to reach a unified design for the ALMA Second Generation Correlator.

To examine the feasibility of the ALMA 2GC that fulfills the two ALMA requirements simultaneously, i.e., high spectral resolution and wide bandwidth, we developed a test correlator system (Figure 5G). It consists of (i) 2-bit analog-to-digital converters (ADCs) working at a 4-GHz sampling rate and (ii) an FX-type digital correlator that can divide a 2-GHz correlation signal from one baseline into 131,072 frequency channels.

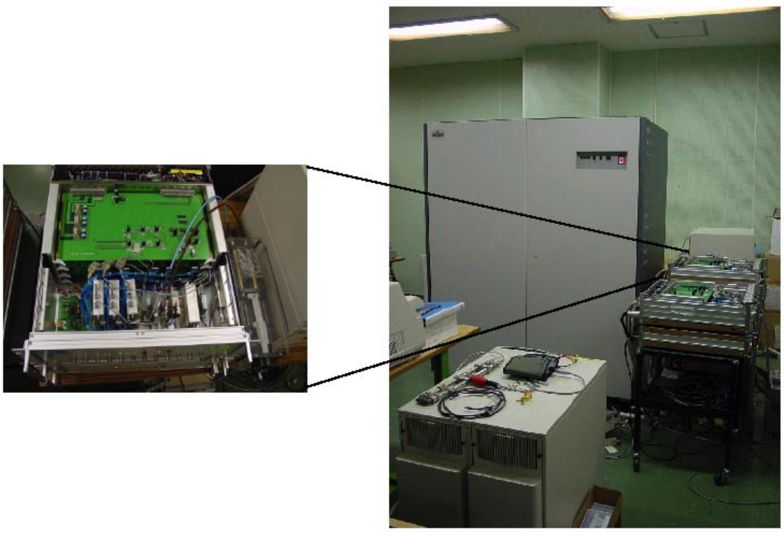

Figure 5G: The test correlator system installed at the Nobeyama Radio Observatory

A 2048-MHz and 131,072-channel fringe spectrum of the Orion-KL regions was obtained with an integration time of 70 minutes (Figure 5H). Twenty lines are found in the spectrum (Table 5.1); it was the first time that such a wide-band astronomical fringe was obtained from a single correlation product of digitized signals. All of the features can be identified to the transitions of known gas species, implying that the test correlator system correctly divides the signal into different frequency components.

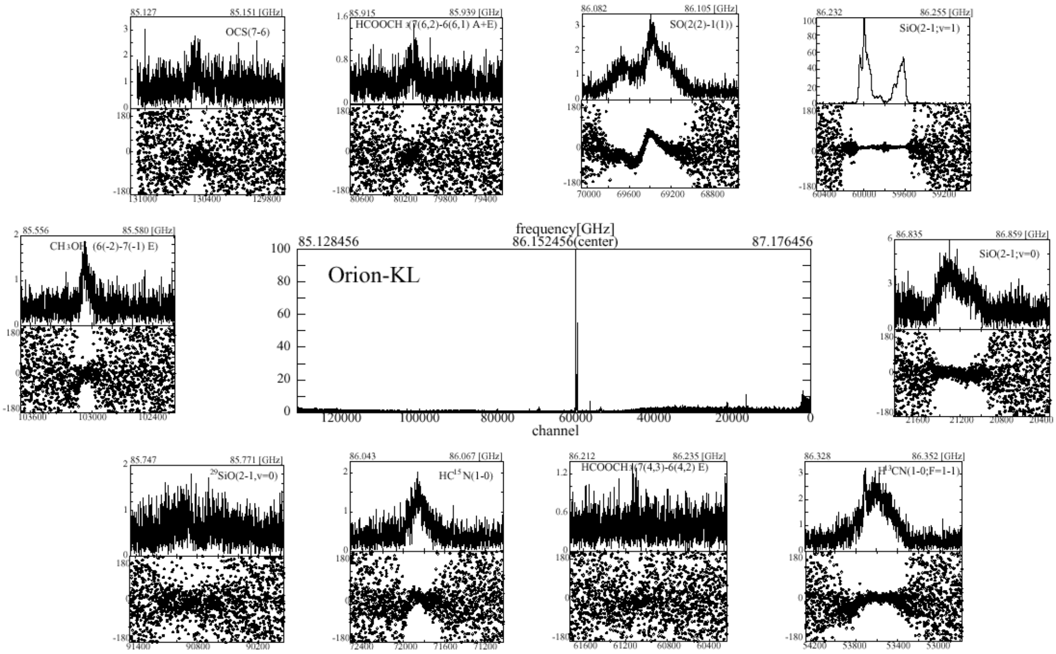

Figure 5H: Observational result of the test correlator

Table 5.1: List of spectral lines detected in the spectrum in Figure 5F

Detected line	Freq (GHz)	Normalized amp.	Detected line	Freq (GHz)	Normalized amp.
OCS(7-6)	85.139	2.20	HCOOCH3(7(4,4)-6(4,3) A)	86.210	1.00
CH3CCH (5(1)-4(1))	85.456	1.10	HCOOCH3(7(4,3)-6(4,2) E)	86.224	1.10
CH3CCH (5(0)-4(0))	85.457	1.20	SiO(2-1;v=1)	86.243	100.00
CH3OH(6(-2)-7(-1)E)	85.568	1.80	HCOOCH3(7(3,5)-6(3,4) A)	86.266	0.89
29SiO(2-1;v=0)	85.759	1.30	H13CN(1-0;F=1-1)	86.340	2.70
HCOOCH3(7(6,2)-6(6,1) A+E)	85.927	1.10	CH3OH(7(2)-6(3) A-)	86.616	2.70
HCOOCH3(7(5,2)-6(5,1) E)	86.021	0.67	SO2(8(3,5)-9(2,8))	86.639	2.00
HCOOCH3(7(5,3)-6(5,2) A)	86.029	0.78	CH3CH2CN(10(1,10)-9(1,9))	86.820	2.40
HC15N(1-0)	86.055	1.80	SiO(2-1;v=0)	86.847	4.40
SO(2(2)-1(1))	86.094	3.10	CH3OH(7(2)-6(3) A+)	86.903	2.20

6. Schedule and Values

The planned schedule of the Japanese contribution is shown in Appendix A. The major milestones are shown in Table 6.1.

The values of the deliverables of the Japanese contribution in year 2000 US Dollars are listed in Appendix B. The values in the table do not include the indirect cost for NAOJ functioning as the executive. If the values in the European and North American contribution include such indirect costs, NAOJ will evaluate the indirect cost to be added.

Table 6.1: Draft milestones of the Japanese construction

ALMA-J	Milestones	Bilateral ALMA	
4Q 2004	First Band-4 & Band-8 Cartridges		
	@ NA/EU Integration Center		
	(for Pre-Series Production FE)		
1Q 2005	Engineering Model of Band-10		
	Cartridge @ NA/EU IC	2Q 2005	First FE @ OSF
1Q 2006	**First ACA (new) 12m Antenna @ OSF**	4Q 2005	First 12m Antenna @ OSF
		4Q 2005	First FE @ OSF
		4Q 2005	First 1/4 BL Correlator @ OSF
4Q 2006	**First ACA 7m Antenna @ OSF**		
1Q 2007	**ACA part of the Second Generation**		
	Correlator (2GC) complete @ OSF/AOS		
1Q 2007	First Band 4 & 8 Cartridges @NA/EU Integ.		
	Center (Production Model)		
2Q 2007	First ACA 12m FE (band 3, 4, & 8)		
	@ OSF (Production Model)		
3Q 2007	First band 10 Cartridge for ACA	3Q 2007	Start Early Science
	(Pre-Series Production Model)		
1Q 2008	First ACA 7m FE (Band 3, 4, 6-10)		
	@ OSF (Production Model)		
2Q 2008	**Start ACA System Commissioning**		
3Q 2008	First Band-10 Cartridge @IC		
	(Production Model)	4Q 2008	BL Correlator complete @AOS
4Q 2009	Last ACA 7m Antenna @ OSF		
3Q 2011	**2GC for 64-element array @OSF/AOS**		
4Q 2011	**Start ACA Full Operation**	4Q 2011	Completion of Construction
			(Full Operation)

7. Toward the agreement on partnership

Budget request in Japan

NAOJ will submit the ALMA construction budget request to MEXT in June 2003. MEXT will submit the ALMA budget request to the Ministry of Finance (MoF) by the end of August 2003. The government budget draft will be released in the end of December 2003. An inclusion of the ALMA construction in it almost certifies its funding. It becomes fully approved when the Diet passes the FY2004 budget in March 2004.

Agreement

In parallel with the negotiation on the Japanese participation proposal, drafting of the agreement on construction and operation (we tentatively call it “agreement” here) should be made. It is helpful for the Japanese funding that NAOJ have the draft of the agreement in hand when it negotiates with the government in early 2003. We hope that ALMA Board can agree on the basic part of the agreement by October 2003 to ensure the Japanese funding and to leave enough time for final adjustments and ratification.

Milestones

Table 7.1 shows the milestones for the official participation of Japan from FY2004.

Table 7.1: Milestones for official Japanese participation

2003 Jan.	NAOJ and MEXT start negotiations with the Ministry of Finance (MoF) and the Ministry of Foreign Affairs (MoFA)
2003 before Jun.	ALMA Board agrees on the NAOJ budget request plan ALMA Board and NAOJ discusses a draft trilateral agreement
2003 Jun.	NAOJ submits its budget request to MEXT
2003 Aug.	MEXT submits its budget request to MoF
2003 Sept./Oct.	ALMA Board and NAOJ agrees on the basics of the trilateral agreement
2003 Dec.	Japanese government issues its FY2004 budget draft
2004 Mar.	Japanese Diet approves the FY2004 budget
2004 Apr.	Trilateral agreement signed (Japanese official participation)

When the prospect of the Japanese funding gets high enough, we need to establish the trilateral ALMA organization structure as early as possible to enable a smooth start of the trilateral project including the Japanese construction in FY2004.

Appendix

A) Draft schedule of the Japanese contribution

B) Draft list of deliverables and their estimated values

C) ALMA/JP Organization