Proposal on the Procurement and Specifications of the ACA 12-m Antennas

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SUMMARY

NAOJ plans to deliver the ACA 12-m antennas based on the three new systems built in FY2004 - FY2006, and the Japanese prototype 12-m antenna refurbished and moved in FY 2005 - FY2006. The refurbishment will be sought to make the prototype 12-m antenna similar to the new ACA 12-m antennas.

In the procurement of the ACA 12-m antennas, NAOJ has a difficulty of discrepancy between the estimated cost and the appropriated budget. To avoid the risk of being unable to make a contract for the antennas, that can be a huge damage to the future ALMA funding in Japan, NAOJ requests an approval of its conservative approach by modifying the following terms in the technical specifications without serious damage to the science capabilities of the ACA antennas, in order to ensure a successful contract as scheduled:

1) Reduction of the maximum acceleration in azimuth and elevation --- **10** deg s^{-2} instead of 18 deg s^{-2} in azimuth and **5** deg s^{-2} instead of 9 deg s^{-2} in elevation. This change has a minimal impact on science and observations performed with the ACA system.

2) Inclusion of the well-established **VxWorks** as an option of the Antenna Control Unit (ACU) operation system in addition to the RTAI real-time Linux. The interface with the other part of the system should not be changed, so that there is no impact on the development of the software system. If this causes an extra cost in the future maintenance of the ACUs in the ACA antennas, NAOJ will take responsibility for it.

3) Extension of distance to a calibrator source from 2 deg to **4** degrees in the specification of offset pointing and repeatable residual delay. This change allows the ACA array with small collecting area to find a strong calibrator and to perform calibration with sufficient accuracy.

1. Background

With the funding available from April 2004 for the 8-year construction project, NAOJ started the procurement of deliverable items in accordance with the Japanese contribution plan discussed and agreed (with some details remaining to be defined) with the European and North American partners. In that context NAOJ plans to place a contract for the ACA 12-m antennas by the end of January 2005 for their delivery in Chile in 2006 - 2007.

For some major equipment such as the antennas and the correlator, the year of procurement and the budget for individual items are specified in our budget plan. This is a tight and inflexible constraint for NAOJ as well as the total yearly budget profile. Changing them requires a great deal of negotiation with MEXT. The Japanese government has a strong tendency to consider such an action as a signal of incomplete planning or a failure of the project, and we might lose their full support we currently receive. Because this would easily cost NAOJ a loss of as much as several percent of the

ALMA construction budget for the remaining years, we must execute the project carefully to avoid such an unfortunate situation.

NAOJ foresees a risk in placing the contract for the ACA 12-m antennas, primarily due to the bids exceeding the specified budget making us unable to contract as scheduled. To ensure a success in the process, we request the ALMA Board to allow NAOJ to take a conservative approach by relaxing some of the technical specifications that affects the scientific capability in a minimal way.

2. Procurement Plan of the ACA Antennas

NAOJ plans to deliver four 12-m antennas and twelve 7-m antennas for the ACA. Three of the four 12-m ACA antennas are newly built. NAOJ will deliver the prototype 12-m antenna as the fourth 12-m ACA antenna after refurbishment to make it compatible with the other three antennas as much as possible.

The budgets for the ACA antennas are in the category of major equipment budgets mentioned above. In addition, the procurements of newly-built antennas will be made with multi-year national debts; i.e., the contract will define the fixed total price and the payment schedule consistent with the scheduled progress of manufacturing in the coming two or three years. The budgets for the multi-year contracts are among the most inflexible constraints for NAOJ. Table 1 shows the procurement schedule for the ACA antennas.

Table 1. Procurement Schedule for the ACA Antennas

Antenna	Quantity	Fiscal Year
12-m (new)	3	2004 – 2006 (3-year national debt)
12-m (prototype)	1	2005 disassemble/refurbish
		2006 assemble in Chile
7-m (new)	2	2006 – 2007 (2-year national debt)
	5	2007 – 2008 (2-year national debt)
	5	2008 – 2009 (2-year national debt)

In FY2004, NAOJ must place a contract for the three new ACA 12-m antennas. We wished to make their specifications compatible as much as possible with the specifications of the 64-element 12-m antennas, which will be determined when the contracts are placed by the North American and European executives. For this reason, we have scheduled the procurement procedure on the latest possible course within this fiscal year as shown in Table 2. The contract by the end of January 2005 is required to leave enough time for a contractor to make a production for the part consistent with the payment in FY2004.

Table 2. Procurement Steps for the ACA 12-m Antennas in FY2004

2004 Sept. 27	Request for comments to the draft specifications issued (official gazette)
2004 Oct. 18	Deadline for the comments
2004 Nov. 05	Call for tender issued (official gazette)
2004 Dec. 27	Deadline for bids and technical proposals
2005 Jan. 31	Opening of bids and placement of contract

According to the Japanese rules, we are not generally allowed to negotiate with the potential contractor on the specifications and price in the period between the opening of the bids and contract. If all the bids are higher than the appropriated budget at that time, and if we need to relax some of the specifications to accommodate the procurement within budget, we need to do it by recycling the process from call for tender. This means that we fail to contract within FY2004, a bad signal to our government that can easily result in a loss of about 2 billion yen from the total construction budget.

To avoid this risk in “one-shot” bidding, we carefully analyzed the cost estimate and the specification of the ACA 12-m antennas in October 2004. Based on that, we propose a relaxation of some of the technical specifications that 1) will affect the science capability in a minimal fashion and 2) will ensure that we can succeed in placing a contract as scheduled.

3. Science Requirements

The ACA system consists of a cluster of twelve 7-m antennas and four 12-m antennas surrounding the 7-m antenna cluster. The system supplements the 64-element array with short baseline interferometer data (with the 7-m antennas) and total-power data (with the ACA 12-m antennas), that significantly enhance the fidelity of ALMA images for extended sources (more detail is described in ACA Project Description available on the ALMAEDM).

The 12-m antennas in the ACA system have two major roles: 1) taking total-power images by mapping in the single-dish mode, and 2) performing calibration of the 7-m antennas in the interferometer mode. In the bilateral ALMA, four of the 64 antennas were planned to play the role 1 as well as providing the short baseline data and establishing the calibration over a wide range of UV distance with short baseline data. The first two functions themselves are the main purposes of the ACA system in the Enhanced ALMA. The third one needs to be developed in details for high precision images and may occasionally require even cross-correlation between the 64-element array and the ACA system. Only a small amount of time will be spent on this purpose because the ACA 12-m antennas will be mostly engaged in taking total-power images.

3.1. Total-power mapping

For sources larger than the primary beam of a 12-m antenna, the total-power mapping is best done in the on-the-fly (OTF) mode, i.e., continuous scans over the source while data being taken. The ACA 12-m antennas will spend much of their lifetime operating in this OTF total-power mapping mode. In the past observations, raster scans are frequently adopted, which are probably not the most efficient method for total-power imaging. Currently several scanning methods including curved trajectories such as Lissajous scans are under study. For continuum observations of extended objects, the scanning performance of the ACA 12-m antennas limits the accuracy of the total-power maps, and therefore limits the quality of the final ALMA images (e.g. Tsutsumi et al., 2004, ALMA Memo 488; Holdaway 2004, ALMA Memo 490).

3.2. Calibration of the 7-m antennas

The ACA 7-m antenna array takes interferometric data while the ACA 12-m antennas are doing total-power mapping. When the 7-m antenna array observes a calibration source, the ACA 12-m antennas suspend the total-power mapping and join the 7-m antenna array to enhance the calibration efficiency and accuracy. After the calibration sequence, the ACA 12-m antennas resume the total-power mapping. This will happen with a cycle time of 5 - 15 minutes. The required accuracies of amplitude and phase calibration are the same as those in ALMA Calibration Requirements and Specification.

From the above considerations on the science requirements, we can derive the following:

- **The ACA 12-m antennas should be optimized for the total-power mapping in the OTF mode.**
- **The typical cycle time for switching the ACA antennas between the object and the calibration source is 5 – 15 minutes. Even in a possible non-standard calibration sequence such as decorrelation correction the shortest cycle time will be about 30 seconds.**

- **The ACA antennas may be rarely required to do fast switching in the same manner (cycle time as short as 10 second cycle) as the 64-element antennas.**
- **The ACA array is expected to spend only a small fraction of time on cross correlation/calibration with the 64-element array.**

4. Technical Requirements

4.1. Total-power mapping

As described in the science requirements, the ACA antennas spend most of its lifetime on performing total-power observations in the single dish mode. The trouble in continuum observations is variable atmospheric emission stronger than most astronomical sources. The OTF technique promises to be quite effective at removing the atmospheric emission and gain instabilities (1/f noise). Recently, the dump rate of total-power data has been changed to be 0.5 milli-seconds. If 1 % loss of S/N ratio is allowed with this dump rate, the maximum slew speed of the OTF will be 0.5 deg s^{-1}. Further, the beam broadening is negligible even at the highest observing frequency[*].

4.2. Calibration of the 7-m antennas

Since the maximum baseline length of the ACA system will be less than 50 m, the atmospheric phase error is expected to be very small. In addition, phase screen moves faster than 10 m s^{-1} and takes only a few seconds to cross the ACA. At the ALMA site, the fast switching becomes effective when the projected baseline of the array exceeds about 100 m. Given the compactness of the ACA and the small collecting area of the 7-m antennas, the fast switching is not effective to remove the atmospheric phase error (e.g. Holdaway 2004, ALMA Memo 491). Instead, we will calibrate the phase of the ACA system by switching between the object and a calibration source with a longer cycle time of 5 - 15 minutes, as we commonly do in millimeter-wave interferometers. In addition, the Water Vapor Radiometers (WVRs) on the four 12-m antennas will help us to correct for the short-timescale phase fluctuation.

Also the de-correlation correction will be calibrated by the WVR onboard ACA 12m antennas. Alternatively, de-correlation could be estimated from each baseline's rms phase error by frequent observations of a nearby calibration source (Holdaway 2004, ALMA Memo 491). The rms phase fluctuation on the calibration source is used to estimate the degree of de-correlation. Since we are not actually tracking the phase, but measuring the statistics of the phase, medium switching cycle (30 - 300 seconds per cycle) will be required. This sequence can not be a standard practice because it significantly degrades the efficiency of the total-power mapping, the most important role of the ACA 12-m antennas.

High precision in visibility amplitude is needed for imaging with high dynamic range. This also holds for cross calibration between the 64-element array and the ACA array. A concrete calibration strategy is to be studied for cross correlation/calibration. Fast switching may not be required in most cases and rather moderate switching of 30 second is adequate for the purpose as briefly explained in the Appendix 1. Furthermore, only a small fraction of time will be spent on cross correlation/calibration by the ACA 12m antennas.

5. Specification of the ACA 12-m antennas

The basic concept and specifications of the ACA 12-m antennas are similar to those of the 12-m antennas defined for the 64-element array. However, under the budgetary pressure, we need to tailor

[*] Sramek CRE summary A for ALMA-52.06.00.00-001-A-CRE

the specifications of the ACA 12-m antennas by analyzing the cost impact of each item and by optimizing for the ACA use. Such specifications we have identified are 1) the maximum acceleration in the drive performance and 2) the operating software for the Antenna Control Unit (ACU). We also note that there are some areas in which tighter specifications are required, namely 3) distance to a calibration source.

5.1. Drive performance

Velocity and Acceleration

- Maximum azimuth angular velocity: > 6 deg s^{-1} (unchanged)
- Maximum elevation angular velocity: > 3 deg s^{-1} (unchanged)
- Maximum azimuth angular acceleration: > **10 deg s^{-2}** (<-- 18 deg s^{-2})
- Maximum elevation angular acceleration: > **5 deg s^{-2}** (<-- 9 deg s^{-2})

On the fly total-power mapping

We here consider raster scans for the OTF mapping as an example case following the Antenna Technical Specification† because we have not had the most optimized scan methods. Detailed studies and comparisons of different scan strategies are currently being carried out. As mentioned in the previous section, we adopt a scan rate of 0.5 deg s^{-1} on the sky across a target source of one degree in size and a turn-around time of 0.8 seconds. As for the pointing accuracy, it is not necessary for the antenna during the scan to be precisely pointed to pre-commanded positions (< 2" rms). It is necessary for the actual beam position of the antenna under primary operating conditions to be precisely known (< 0.6" rss) for each total-power data (0.5 msec) from position measurement events. These specifications must be fulfilled even with the reduced acceleration.

The measurements of the actual position must be made within 10 microseconds at the 24 msec timing events. The main reflector, subreflector, and elevation axis must be rigid enough to behave as a single structure (e.g. Ukita, et al., 2004, Proc. SPIE 5489, pp 1085-1093). It is possible for the actual beam position of the antenna to be estimated with an accuracy of 0.1 arcsec rms for every 0.5 msec data from position measurement events under the primary operating condition.

Step Response

Fast switching phase calibration requires the antenna to move from a target source to a calibrator up to 1.5 degrees away on the sky. With the reduced acceleration, the antenna shall have a step response that fulfills the following:

> For a step amplitude of 1.5 degrees on the sky, the antenna shall settle to within 3 arcsec peak pointing error in **1.8 seconds** (<-- 1.5 seconds for the 64-element array) of time and within 0.6 arcsec peak pointing error in **2.3 seconds** (<-- 2.0 seconds for the 64-element array).

The antenna uses its maximum acceleration to travel a distance of 3.0 (1.5) degrees in Az (El) and approaches near a target source in 0.83 and 1.10 seconds (ideal cases) for an acceleration of 18 (9) deg s^{-2} and **10 (5) deg s^{-2}**, respectively. The time spans required for the settling process are practically constant regardless of maximum acceleration, because the antenna does not use its maximum acceleration capability during the settling phases.

5.2. Operating software within the Antenna Control Unit (ACU)

The technical specifications for the 64-element array require that the ACU microprocessors should run the RTAI real-time Linux operating system. However, we realize that some potential bidders have been using well-established VxWorks operating system and that an adoption of RTAI real-time Linux would add a significant cost. We need to add an option to adopt VxWorks as the operating

† ALMA-34.00.00.00-006-A-SPE

system of the ACU on condition that the interface with the Antenna Bus Master (ABM) remains unchanged.

5.3. Distance to calibration sources

Finally, we note that the ACA system requires severer specification for distance to a calibration source than the 64-element array, because of the smaller collecting area of the ACA array. The typical distance to a calibrator source is 2 degrees for the 64-element array. Since the ACA sensitivity is approximately 3.5 times less than the 64-element array, it is expected to find a calibrator of **4 degrees** away on the sky with integration time doubled. This shall be applicable to the specifications in the areas of Offset Pointing Errors and Repeatable Path Length Errors.

6. Cost analysis

6.1. Drive performance

An analysis shows that a large capacitor (capacitor bank) is required to meet the original acceleration specifications within the electric power limit of 55 kVA. The relaxed specification proposed here saves the cost of the capacitor and the associated cabling. It would also save the refurbishment cost of the prototype 12-m antenna. The total saving would be about 120 million yen.

6.2. Operating software

To introduce a new operating system for the ACU, the contractor need to set up a team that supports it by establishing and updating the developing environment. Increased testing will also be needed in the debugging process to mitigate a risk associated with the new operating system. The increase in the non-recurrent cost due to all these activities is estimated as at least about 50 million yen.

6.3. Distance to the calibration sources

We estimate that there will be no significant cost increase caused by the tightened specifications on the distance to the calibration source.

7. Impact analysis on science

The specification changes of ACA 12-m antennas proposed here have a minimal impact on science and observations which is expected to be performed with the ACA system, because the specifications secure all capabilities requested/needed for the ACA 12-m antennas, i.e., OTF capability, phase calibration of the array, and calibration of amplitude de-correlation.

Currently, there are no formal plans to cross-correlate ACA and ALMA antennas[‡]. In fact, the baseline correlator is capable of handling data only for 64 antennas. The present proposal in the specifications change does not close the door to cross correlation. Indeed, the impact of the change is minimal even in such cases, as estimated below.

According to the specifications for the step response given above, the time required for an ACA 12-m antenna to move to a calibration source 1.5 degrees away and settle within 0.6 arcsec peak pointing error is **2.3 seconds**, compared with 2.0 seconds in the case of the original specifications. In case of fast switching with 10 second cycle time, the observing efficiency is degraded by 3.4 % as shown in the Appendix 2. A longer switching cycle such as 20 seconds reduces the loss to 1.1 %.

8. Impact analysis on operations

From a viewpoint of long-term operations, we prefer to keep the number of types (designs) of antennas as small as possible. NAOJ's approach to this is to make all the ACA antennas (12-m and 7-m antennas) as similar as possible. The compatibility between the three new ACA 12-m antennas

[‡] ACA project book; Holdaway 2004, ALMA Memo 491

and the refurbished prototype 12-m antenna will be sought within our budgetary constraints. Also, sharing a significant part of the design between the ACA 12-m antenna and the ACA 7-m antenna (e.g., structural design except for the dishes, drive and control system, etc.) can be sought. This will also save the design cost of the 7-m antennas in the procurement that starts in FY2006. All these considerations, albeit within our constraints of the Japanese budget and rules, should minimize the extra operations cost.

The maintenance of the ACU software needs to be considered. In principle, the ACU software does not need to be modified unless the ABM software modifications require a change in the ICD between them. Besides, the core part of the ACU software such as a servo program will be unlikely modified. Possible change shall occur when a significant change in the telescope pointing algorithm or metrology scheme is required. If the change in the present request causes an extra cost in the future maintenance of the ACUs in the ACA antennas, NAOJ will take responsibility for the cost.

Appendix 1. Cross Calibration Strategy

For high fidelity imaging with the ACA and the ALMA 64-element array, it is critical to realize the accurate cross calibration which corrects the amplitude scale difference between the ACA data and the 64-element array data. The cross calibration procedure is as follows:

1. Observing several flux calibrators with the ACA and the 64-element array simultaneously.
2. Solving amplitude gain for each antenna in the antenna based mode.
3. Correcting amplitude gain of each antenna to fit observed visibility to predicted visibility profiles of flux calibrators.

To achieve high precision, the calibration observations with the ACA and the 64-element array should be done simultaneously under the same atmospheric condition. However, it is not required to take cross-correlation between the ACA and the 64-element array, because sufficient accuracy of the amplitude gain is achievable only with the ACA in a reasonable integration time. For example, it is possible to obtain better than 1 % accuracy in 30 second integration using a 300 mJy calibrator at 90 GHz.

Therefore, for the cross calibration, the ACA antennas is required to track several flux calibrators sequentially with each integration time of about 30 seconds.

Appendix 2. Loss of Observing Efficiency

This section explains how the loss of observing efficiency is calculated. All the antennas are assumed to perform equally except for the step response (acceleration). The figure illustrates an observing sequence with a 10 second switching cycle time using a calibrator 1.5 deg distant. Case 1 is the sequence of the 64-element array antenna element, Case 2 represents the baselines involving the ACA 12-m antennas, and Case 3 denotes baselines of the 64-element array antennas in the observations including the ACA 12-m antennas. In the last case, the antennas from the 64-element array have to wait for the ACA antennas to settle to a calibrator, they need not wait for the ACA antennas in observing a target source. Since the signal to noise ratio is proportional to square root of the number of baseline, it is given by

$$Observing\ Efficiency = \sqrt{\frac{\eta_{case2} \cdot N_{case2} + \eta_{case3} \cdot N_{case3}}{N_{case1}}}$$

where N is the number of baselines for each case, and η is the integration time ratio of case 2/3 to case1.

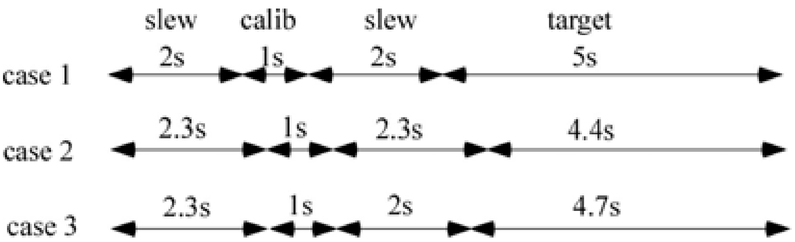

Figure: Observing sequence

We take an example of a 64 antenna array that consists of 60 antennas from the 64-element array and four ACA antennas. In case of 10 second cycle time and 1 second integration for calibration as shown in the figure, η_{case2} is 0.88 (=4.4/5), η_{case3} is 0.94 (=4.7/5), N_{case2} is 246 (=4*3/2+4*60), N_{case3} is 1770 (=60*59/2), and N_{case1} is 2016 (=64*63/2). Thus, the observing efficiency is calculated to be 0.966; 3.4 % loss in efficiency. If 20 second cycle time is taken, the observing efficiency is 0.989; 1.1 % loss in efficiency.

$$Observing\ Efficiency = \sqrt{\frac{4.4/5 \cdot (4 \cdot 3/2 + 4 \cdot 60) + 4.7/5 \cdot (60 \cdot 59/2)}{64 \cdot 63/2}} \cong 0.966.$$

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