ALMA Memo 288
An Optical Pointing System for the ALMA Prototype Antennas

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Abstract

In this memorandum we present an outline of the design requirements for an optical pointing telescope for the ALMA prototype antennas. The proposed system will draw heavily upon the experience with the successful optical pointing system in use at the 12 Meter Telescope on Kitt Peak. The system will be composed of an optical refracting telescope, a commercial CCD camera, a PC-based frame grabber, a control PC, and a software control system. This system will be able to work in tandem with the telescope control system to acquire star positions, measure their intensities, and produce fits to stellar positions to sub-arcsecond accuracy. The information gathered by this optical pointing system will be used to assess the stability and accuracy of the ALMA antenna tracking system and the form and stability of the ALMA telescope pointing behavior. It will serve as a fundamental tool for the diagnostic tests to be conducted on the ALMA prototype antenna.

The system I describe in the following parallels a collaborative effort to build an optical pointing and tracking system for the GBT (see GBT memo by Phil Jewell for further information).

1 Introduction

Optical pointing systems have become standard equipment on millimeter and submillimeter telescopes. There are benefits and limitations associated with the reliance on optical pointing systems on radio telescopes:

1. Benefits:
   (a) There are many more bright stars which can be used as optical pointing sources than radio pointing sources.
   (b) With a CCD camera, optical data acquisition can be done in a few seconds, as opposed to the minute time scales necessary for radio pointing measurements.
   (c) Positions of optical stars can be derived to sub-arcsecond accuracy, which is a much higher precision than that obtainable through single antenna radio measurements.
2. Limitations:
   (a) Differences between the position and behavior of the optical and radio signal paths can make the derivation of the radio pointing coefficients from optical pointing measurements difficult.
   (b) Optical pointing is not possible during overcast weather conditions.
   (c) Optical pointing cannot be used in the daytime, unless the system has been designed with near-infrared sensitivity.

Optical pointing systems find application in such areas as:

- Pointing and tracking diagnosis
- Pointing coefficient derivation and monitoring
- Auto-guiding

2 Design Considerations

An optical pointing system for the applications described above can be constructed from off-the-shelf commercial components. The main components of the optical pointing system are:

- Optical telescope
- Commercial CCD camera (with near-infrared sensitivity if daytime observations are desired)

- PC-based frame grabber
- Control PC
- Data acquisition and analysis system

In the following, we discuss the design considerations for each of these components.

2.1 Optical Telescope

2.1.1 Sensitivity

The optical telescope system should be sensitive enough to detect large numbers of astrometric stars (which represent a small subset of the existing stars at any given magnitude) with exposures of no more than a few seconds. The magnitude sensitivity of an optical telescope can be derived from the magnitude relation:

$$m_a - m_b = 2.512 \log_{10}\left[\left(\frac{D_a}{D_b}\right)^2\right] \tag{1}$$

where m_a and m_b are the limiting magnitudes and D_a and D_b are the diameters of two optical telescope systems. The optical pointing system on the 12 Meter Telescope has a $3.''25$ (8.255 cm) refracting telescope and CCD camera with an overall limiting magnitude of about 7. For example, assuming that $m_b = 9.5$ in Equation 1, we need an optical telescope with a diameter 3.1 times as big as the one in 12 Meter Telescope optical pointing system, or $D_b = 10.''2$ (25.908 cm).

The sensitivity requirements for an optical pointing telescope differ from those for an optical guiding system. If one can construct a system which is sensitive to a limiting visual magnitude of about 10, then in any given field it is likely that there will be an astrometric star which can be used for pointing or tracking. For pointing alone, a limiting visual magnitude of 7 is sufficient to provide several hundred astrometric stars which can be used to derive pointing characteristics.

2.1.2 Resolution and Field-of-View

The detector will be a CCD placed in the focal plane. Atmospheric seeing will limit the actual resolution to about $1''$–$3''$. Since the ability to find the centroid of a star is proportional to the actual resolution divided by the signal-to-noise of the measurement, the pointing precision is much less than the actual resolution. A resolution of about 1″ per CCD pixel should be sufficient.

The plate scale of the optical telescope system is given by:

$$PS = 206.2648 \times \left(\frac{1}{Mf}\right) arcsec/\mu m \tag{2}$$

where f is the focal length of the telescope in millimeters and M is the magnification factor by any additional optics in the system. By combining the plate scale with the length (l_{CCD}, in μm), width (w_{CCD}, in μm), and number of samples in the horizontal (N_l) and vertical (N_w) dimensions, we can derive the field-of-view (FOV) and effective plate scale (EPS) of the optical pointing system:

$$FOV = PS \times l_{CCD} \times w_{CCD}\ arcsec^2 \tag{3}$$

$$EPS = \frac{1}{PS}\left(\frac{l_{CCD} \times w_{CCD}}{N_l \times N_w}\right) arcsec^2 \tag{4}$$

Note that N_l and N_w are the *smaller* of the number of CCD pixels in each dimension and the sampling produced by the frame grabber.

2.1.3 Mounting

The mounting of the optical pointing system should meet the following requirements:

- It should be rigidly attached to the structure of the telescope so that it mimics the motion and flexure of the radio telescope structure.
- It should be accessible.

Two traditional locations for optical pointing systems are the prime focus and the backup structure (where an access hole in a panel must be made).

2.2 CCD

The requirements for the CCD detector are driven by the need for sub-arcsecond spatial resolution. Most commercial CCD detectors have a sufficient number of pixels and sensitivity to meet these requirements. For daytime operation, extended near-infrared sensitivity is an option that can be found on many commercial CCD detectors.

2.3 Frame Grabber

The frame grabber should conform to the type of control computer (in this case, a PCI-bus based PC). It must be able to process at least the same number of pixels as exist in the CCD and have sufficient memory and frame transfer capacity to process images which are a few seconds in duration.

2.4 Control PC

The requirements for the control PC are not very stringent. Any PC with a > 200 MHz processor will be sufficient. The operating system used is determined by the requirements for the frame grabber driver, data acquisition, and analysis systems.

2.5 Data Acquisition and Analysis System

We will pattern the data acquisition and analysis system for the ALMA optical pointing system after that developed for the existing 12 Meter Telescope optical pointing system. For optical pointing observations at the 12 Meter Telescope (see Figure 1), the system works as follows:

1. A list of available astrometric stars are selected from a master catalog. These stars are selected based on a specified limiting magnitude and are sorted by declination band, with alternating increasing and decreasing azimuth for adjacent bands.

2. A manual calibration is performed in which a bright star is selected and observed to determine the approximate centroid of the optical telescope focal point on the CCD. A subset of pixels is then chosen around the star to define a search region for subsequent star retrievals.

3. The telescope control computer sends the J2000 source coordinates to the radio telescope positioning system, and the radio telescope slews to the star. Once the star is acquired, frame integration begins.

4. The frame grabber acquires images of the star at a rate of 8–10 frames per second. The PC reads the CCD array from the frame grabber buffer and integrates the signal for approximately 5 seconds.

5. Once the integrated image is acquired, it is written to a raw data file in the same format as that used for regular radio astronomical data. The data is written as a raster image to this file. An on-line data

display is used to assess the quality of the data being obtained and to alert the observer to possible problems.

6. Once all of the available stars are measured, analysis of these measurements are done off-line. In this analysis, a search algorithm finds the brightest pixel in the array. Using this starting value, gaussians are fit in azimuth and elevation to derive a fitted position for the star. Note that since the accuracy at which one can determine the centroid of a gaussian is inversely proportional to the signal-to-noise ratio of the measurement, the centroid can be derived to a much higher precision than the actual resolution of the optical pointing system.

3 Summary and Current Design Characteristics

The design requirements for the ALMA optical pointing system are listed in Table 1.

Table 1: ALMA Optical Telescope Specifications

Sensitivity	$\geq 7^{th}$ magnitude in 5 second exposure
CCD array	754×484
Frame Grabber sampling	640×480 (RS-170)
Effective plate scale	$1.''55 \times 1.''55$ per detector pixel
Field of view	$16' \times 12'$
Mount location	Backup structure (requires access hole in panel)
Mount	Gimbaled movement; accessible

The current design specifications for the ALMA prototype optical pointing system are listed in Table 2.

Table 2: ALMA Prototype Optical Telescope Components

Component	Model	Specifications	Cost
Telescope	Meade 4″ (10.16 cm)	Apochromatic Refractor	\$1200
	model 102ED	f/9 (914mm focal length)	
		2.7″ (6.858 cm) rack and pinion focuser	
Camera	Cohu 4810-2000	754×484 pixels	
		$\times 2$ Barlow lens	
		8.8×6.6mm image area	
		0.02-0.2 lux	
		IR to 1050μm	\$1347
Frame Grabber	Imaging Technologies	Half-slot PCI	
	PC-Vision	1024×1024	
		640×480 sampling (RS-170)	
		2MB VRAM	
		4ms frame transfer	\$1187.50
PC	Pentium PCI Bus	450 MHz	\$2000
Filter Wheel	commercial	2-position (IR/clear)	\$100
Video Monitor	commercial		\$500
Mount (gimbaled)	NRAO design	Remote control (?)	\$1000 (parts)
			\$5000 (labor)
Misc Electronics	NRAO design		\$1000 (parts)
			\$4000 (labor)
Software	NRAO design	Existing system	\$8000 (labor)
Total Cost			\$25,334.50

Figure 1: The 12 Meter Telescope optical pointing telescope. This system has been used to diagnose and characterize the pointing behavior of the 12 Meter Telescope for over 10 years.