# Feasibility of Small Optical Telescopes for ALMA Pointing

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## ABSTRACT

The ability of small, light weight telescopes equipped with low-cost CMOS cameras to measure optical pointing for ALMA is demonstrated. This work was motivated by the significant amount of telescope time used for radio pointing during ALMA science operations. For example, during the first 5.5 months of ALMA Cycle 7, 69.5 hours of PI Science time on the 12m array was used for radio pointing at night, corresponding to 6.8% of nighttime operations time for ALMA. Assuming ~75% of nighttime operations have clear weather suggests that ~100 hours of additional ALMA science time could be recovered annually if optical pointing were available.

A 5cm aperture fixed-focus telescope using an inexpensive uncooled CMOS camera was combined with a low-power single board computer to control the camera and generate astrometric pointing solutions on the fly from acquired images. The open-source Astrometry.net software package (Lang et al., 2010) was used to perform blind pointing solutions from acquired images. An operational version of this system would allow continuous pointing observations in parallel with science observations for ALMA on clear nights. The use of a small fixed-focus telescope minimizes system cost, complexity, and thermal effects, and maximizes mechanical simplicity and reliability.

# Feasibility of Small Optical Telescopes for ALMA Pointing

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## 1. Summary

This report investigates the feasibility of using small, light weight telescopes equipped with low-cost CMOS[1] cameras to measure optical pointing for ALMA. The motivation for this work is the significant amount of time used for radio pointing during ALMA science operations. For example, during the first part of Cycle 7, from 1 October 2019 through the Covid-19 imposed shutdown on 19 March 2020, 69.5 hours of PI Science Observation time on the 12m array was used for radio pointing at night, corresponding to 6.8% of nighttime observations with the 12m array. The assumption that ~75% of the nights are clear for ALMA implies that ~50 hours additional science observing time could have been achieved if radio pointing were to be replaced by fast optical pointing.

The concept for the optical pointing system consists of a 5cm aperture fixed-focus telescope with an uncooled CMOS camera, plus a low-power single board computer to control the camera and generate astrometric pointing solutions from the images acquired. Key to the success of the system is the open-source Astrometry.net software package (Lang et al., 2010) which performs blind plate solutions for astronomical images. Such a system would allow pointing observations in parallel with radio observations, both at the start of each scan and during a scan as well, effectively allowing nearly continuous pointing measurements. Equally important is the use of a small fixed-focus telescope that minimizes thermal effects due to its small size, and maximizes mechanical simplicity through the use of fixed focus with an athermalized design concept.

For proof of the concept a suitable camera and a single board computer to control it and run the astrometry software were acquired. Observations successfully demonstrated sub-arcsecond astrometric repeatability in blind pointing on the sky using a simple field setup. A 1-second exposure and a few seconds of CPU time yielded astrometric results suitable for ALMA optical pointing, with measured precision (repeatability) under 1 arcsecond rms. Despite its modest cost, the sensitivity of the camera ensures that accurate pointing measurements can easily be achieved pointing anywhere on the sky. In particular, pointing at specific bright stars is not required to achieve precise optical pointing.

There are several advantages offered by the use of optical pointing. First is the increase in observing efficiency during night time observations, when the best conditions are available for ALMA science observations. Optical pointing would gain the equivalent of 8 to 10 nights of observations per year, based on the equivalent of 4 to 5 nights of observation time dedicated to

[1] Complementary Metal Oxide Semiconductor

pointing during the first half of Cycle 7. This time savings would a direct benefit from eliminating the ~2.8 minutes used per schedule block for pointing observations.

A second advantage is the potential for nearly continuous pointing measurements while observing science and calibration targets. This would enable continuously updated accurate pointing at all frequencies, without depending on offsets from radio pointing measurements taken on pointing targets many degrees from the target of interest. This would be especially valuable for high frequency observations: In Band 10 the full-width half-maximum of the ALMA primary beam is as small as 6.4 arcseconds, and suitable targets for pointing calibration are more difficult to find. Rapid feedback of the antenna pointing with 1-2 arcsecond accuracy every few seconds would directly benefit such high frequency observations.

## 2. Introduction

Modern CMOS cameras, in concert with innovative astrometric software, provide an opportunity to equip ALMA telescopes with individual optical pointing cameras. Such cameras would allow a new paradigm for ALMA pointing, significantly reducing the amount of observing time dedicated to pointing observations during nighttime operations. The expected reduction in pointing time would reduce the average of 2.8 minutes per Schedule Block execution, using radio pointing, to only a few seconds using optical pointing. Conceptually, such an optical pointing system can be viewed as a black box that reports where it is pointed on the sky every few seconds, with arcsecond precision and accuracy, using no external inputs other than power and basic communication. The system would consist of low-cost, high-sensitivity CMOS cameras on small, lightweight, fixed-focus telescopes plus a small single-board computer to process the images and report the pointing results. The system is small enough and economical enough that all ALMA telescopes could be so equipped.

The remainder of this report is organized into the following sections:

3. ALMA Science time used for pointing during Cycle 7, 30 Sept. 2019 - 19 March 2020
4. Optical Pointing System Concept
5. Prototype Optical Pointing System
6. Test setup
7. Test Results with Prototype: Astrometric Repeatability
8. Test Results with Prototype: Twilight Observations
9. Further work
10. Conclusions

## 3. ALMA Science time used for pointing during Cycle 7, 30 Sept. 2019 - 19 March 2020

### 3.1 Summary of Pointing Time

Measuring the actual time used for pointing by ALMA determines the potential amount of observing time that could be saved if optical pointing is practical and efficient. The goal of this analysis is to determine both the total amount of nighttime observing time used for pointing, and the corresponding fraction of observing time. Spoiler Alert: ALMA achieved 1,014.9 hours of successful *nighttime* Schedule Block executions during the period 2019 September 30 through 2020 March 19 on the 12m array for time designated as PI Observations. Of that 1,014.9 hours, 69.4 hours (6.8%) were used for pointing measurements. Allowing for 25% cloudy weather during science observations at night, ~62 additional science Schedule Blocks could have been executed during the first half of Cycle 7 if the time dedicated to radio pointing were instead used for science observations. Extrapolated to a full one-year ALMA Observing Cycle, about 100 hours of observing time could be recovered through the use of optical pointing.

### 3.2 Selection of Night Time Schedule Blocks

For this analysis all 12m array Schedule Block (SB) Executions marked with a "SUCCESS" Status were included, regardless of their QA0 status. ALMA WebShiftLog was used to search for all such schedule blocks, using the search criteria as shown in Figure A-1 (SB Executions only, 12(m) PI Observations on the BL correlator ending in Success, 2019-09-30 through 2020-04-01, searched month by month).

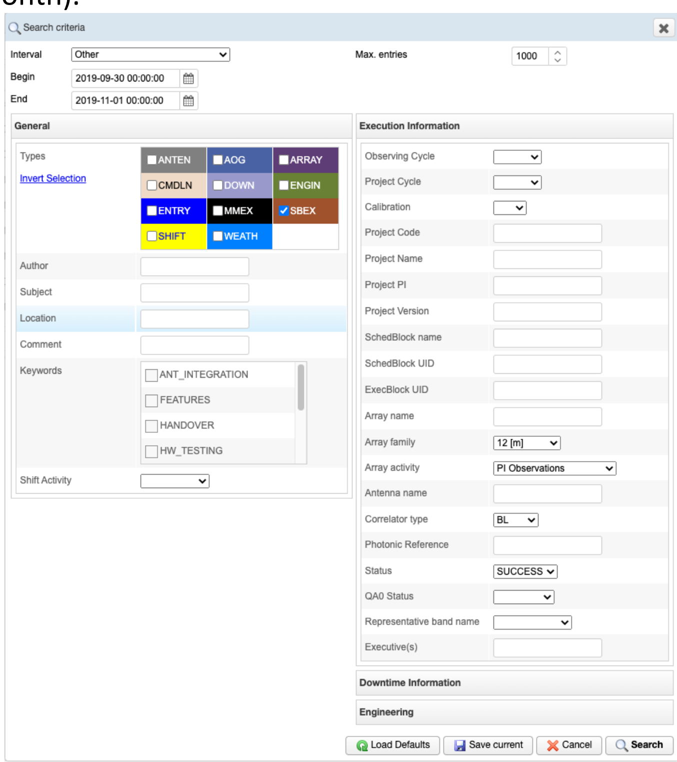


Figure 3.1: WebShiftLog search criteria used for SB selection (1st month of 6 shown, yielding 749 SB executions in October 2019)

The SB selection criteria described above yielded a total of 3,473 SB successful executions during PI Science Observations on the 12m array, which break down by type of SB as follows:

- Standard Interferometry: 2,020 executions
- Focus: 781 executions
- IFDelays: 264 executions
- BandCheckout: 219 executions
- PhaseCheck: 101 executions
- FEDelays: 44 executions
- VLBI: 19
- Other: 25 executions

Standard Interferometry, Focus, PhaseCheck, and VLBI all used radio pointing observations (Note: Only executions with the full 12m array were included in this analysis; 12 SB executions with only 10 antennas were excluded).

The straightforward approach for optical pointing is to assume nighttime observation under clear conditions. Based on preliminary measurements with the small optical telescope presented in this report in section 8, the sky is dark enough for optical pointing observation when the Sun is 5 degrees or more below the geometric horizon, corresponding to Civil twilight. Given that pointing normally occurs during the first part of an SB, a conservative working definition of nighttime for ALMA is when, at the start of an observation, the Sun is 6 degrees below the horizon when setting, or when it is 10 degrees below the horizon when rising. This definition ensures that optical pointing measurements can be made during the first part of any SB execution.

The National Oceanic and Atmospheric Administration provides convenient tables for calculating sunrise and sunset at https://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html. Using their calculation routines (with small modifications for the desired elevations as described above) it is possible to calculate the daily start and end of twilight for the ALMA site, corresponding to the times when optical pointing is feasible. Applying these time ranges to the 3,473 selected Cycle 7 SB executions yielded 1,597 SB executions observed under night time conditions, after the Sun was at least 6 degrees below the horizon at the start of the night, and with the Sun at least 10 degrees below the horizon at the end of the night.

The ALMA on line tool AQUA (ALMA Quality Assurance) was used to extract the amount of time used for pointing, if any, from each SB execution. A small script (written with the Keyboard Maestro application running under MacOS) opened each SB in AQUA in turn and extracted the pointing time and the number of antennas in use for each of the 1,597 night time SB executions during Cycle 7.

### 3.3 Analysis for ALMA Nighttime Observing

The total amount of successful observing time used for PI Observations on the 12m array, with 38 or more antennas, during nighttime as defined above, was 1,014.9 hours in 1,597 SB executions from 2019Sep30 through 2020Mar19. The total amount of time dedicated to pointing observations during those 1,014.9 hours was 69.4 hours, corresponding to 6.8% of all successful time.

There were 1,056 successful science SBs executed at night, with an average length of 53.3 minutes and an average of 2.8 minutes used for pointing measurements (thus, 5.1% of each science SB was used for pointing, on average). The total amount of time used for night time pointing during the execution of science SBs was 48.2 hours.

There were also 541 successful calibration and system SBs executed at night, with an average length of 8.6 minutes and an average of 2.4 minutes used for pointing measurements (28% of each calibration and system SB was used for pointing, on average). The total amount of time used for nighttime pointing during the execution of system and calibration SBs was 21.2 hours. This means that 30% of the time used for pointing observations by ALMA arose from calibration and system SBs.

If ~25% of nighttime at the ALMA site is too cloudy to allow optical pointing, roughly 52 additional hours of science observing could have been executed during the period 2019 September 30 through 2020 March 19 had efficient optical pointing been in use instead of radio pointing. This corresponds to the execution of ~62 additional science SBs, the equivalent of about 5 nights of observing time over the six months of observing that were analyzed. Over an entire observing Cycle, lasting a full year, it can be estimated that the equivalent of ~10 nights of observing time is currently lost to pointing observations during clear nighttime conditions. The potential increase in effective observing time accrues from both the increased efficiency of science SBs as well as the significant reduction in time required for calibration and system SBs that perform pointing calibration.

## 4. Optical Pointing System Concept

### 4.1 System Concept

The concept for the proposed ALMA optical pointing system is built around three key components, all of them available as inexpensive catalog items:

- A small fixed-focus telescope with a 5 cm f/5 primary lens.
- An uncooled CMOS Camera with ~$6 \times 10^6$ pixels and yielding a ~2 square degree field of view.
- A small single board computer to control the camera and acquire images, and automatically process the acquired images using the Astrometry.net blind pointing astrometry package.

The system operates by using short exposures to image a patch of sky and then solving for the pointing position automatically using the Astrometry.net software package. The proposed system (telescope plus camera) is sensitive enough that there will be many background stars in the image, anywhere on the sky. This ensures that an astrometric pointing solution can be determined regardless of direction. For example, the 6.4-megapixel CMOS camera and a 5 cm aperture as described in this report detects stars to ~13$^{th}$ magnitude or fainter, in a ~2 sq. degree field of view, with a 1 second exposure. On average there are ~135 stars 13$^{th}$ magnitude or brighter per square degree. For example, see https://spacemath.gsfc.nasa.gov/stars/6Page103.pdf, which presents the following formula for approximate N(m), the average number of stars per square degree brighter than magnitude m:

$$\mathrm{Log}_{10}N(m) \sim -0.0003\ m^3 + 0.0019\ m^2 + 0.484\ m - 3.82$$

The large number of stars detected by the camera system ensures that the pointing system *does not* require the use of known pointing targets or reference stars. Instead, the system performs a "blind" pointing solution based only on the field stars in the acquired images, anywhere on the sky. In practice, the pointing camera could take images and return a pointing solution every 2-3 seconds, continuously. After an antenna has finished slewing and an antenna is tracking the sky an accurate pointing solution would be available within seconds and updated rapidly thereafter.

The heart of this system is the use of the Astrometry.net software package to perform blind astrometric solution of arbitrary sky images. The software is freely available as open-source code (available from https://astrometry.net under the terms of the GNU GPL version 2. license). Lang *et al.* (2010) summarize the solution process as follows: "After robust source detection is performed in the input image, asterisms (sets of four or five stars) are geometrically hashed and compared to pre-indexed hashes". Lang *et al.* demonstrate that the astrometric solution success rate is 99.9 to 100% using indices built from USNO and 2-MASS catalogs, with no false positives (i.e., a correct solution is found in 99.9% or more of cases, and no incorrect solutions are found). Supplying specific information such as the approximate plate scale or approximate pointing position is not required, although supplying the approximate plate scale or position will reduce the amount of CPU time required to find the astrometric solution. The approximate plate scale can be easily determined for a system through either calculation or direct measurement; the approximate pointing position might be useful to reduce the processing time if it doesn’t create a communication bottleneck.

The system can function as a black box that autonomously delivers pointing results for the telescope on which it is mounted, with sub arcsecond precision. The images collected by the single board computer (attached to the camera) are processed locally by Astrometry.net, so the required communications interface to the ALMA control system is low bandwidth and the image data could normally be discarded. The ALMA control system would not have any need to collect or process the raw camera images. In practice it will be necessary to account for a pointing offset between the optical axis of the optical pointing system and the radio pointing axis, and variable terms such as differential gravitational sag or differential refraction between the optical and radio pointing axes. The TPoint software package, currently in use by ALMA for modeling and correcting telescope pointing, is fully capable of modeling such effects, ensuring that the full precision of the optical pointing measurements can be transferred to the radio observations with ALMA telescopes once the system is calibrated.

Physically the system should be small (the telescope is ~6 cm diameter for a 5 cm optical aperture, ~30 cm in length, and ~700 gm in mass) and can use inexpensive catalog items and off-the-shelf technology. For simplicity and reliability, the system would be fixed focus, and the camera is uncooled. Minimal camera calibration (bad pixel mapping only) or even no camera calibration is required, based on the tests reported here. While the camera could possibly use the same mount point as used for the far larger and heavier optical pointing telescopes used during ALMA construction, the camera could alternatively be mounted inside the hexapod can at the telescope prime focus. The latter option provides the close coupling between the optical axis of the camera and the radio axis of the telescope, as well as potentially better protection of the camera from weather.

### 4.2 Approximate System Cost (Hardware)

An optical pointing system for ALMA can be realized for very modest hardware costs; there will also be associated costs for final design and control system modifications that are difficult to estimate at the present time. Table 4.1 summarizes the approximate hardware costs for an optical pointing telescope system per antenna in 2020:

Table 4.1: Optical pointing system approximate hardware costs, per antenna

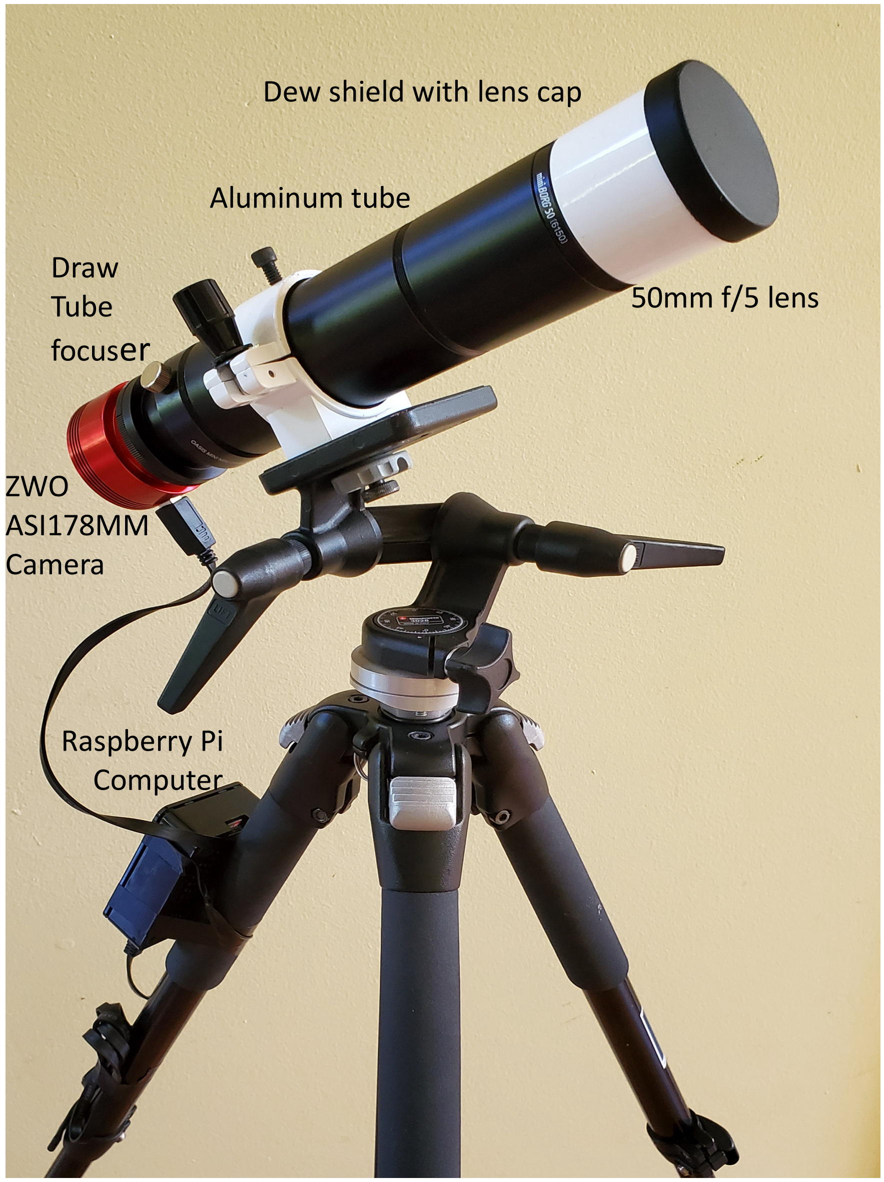
| Item | Unit Cost | Comments |
|---|---|---|
| ASTRO HUTECH - MINI BORG GUIDE SCOPE 50ACH F/5 BASIC SYSTEM | \$300 | 2021 Catalog price for 50cm f/5 telescope with aluminum tube |
| ZWO ASI178MM 6.4 Megapixel USB3.0 Monochrome Astronomy Camera for Astrophotography | \$400 | Typical in-stock price of suitable cameras |
| Single board computer for image acquisition & analysis | \$200 | Packaged single board computer with CAN bus interface |
| Optical window | \$100 | Typical cost, catalog item, with UV/IR cutoffs |
| Automated Lens Cap | \$150 | Allowance |
| Mounting Hardware | \$150 | Allowance |
| USB Cabling, converters | \$100 | Allowance |
| Miscellaneous | \$200 | Allowance |
| 25% Contingency | \$400 | Allowance |
| | | |
| Total hardware cost per antenna: | \$2,000 | (Costs estimated as of 2020) |

## 5. Prototype Optical Pointing System

To test the basic feasibility of an optical pointing system as outlined in the preceding sections, a prototype optical pointing system was assembled using commercially or freely available components, as follows (See Figure 5.1):

- Telescope: Astro Hutech - Mini Borg Guide Scope with a 50mm f/5 achromatic lens, aluminum tube, and a simple sliding tube focus (the "Oasis Mini Mini Draw Tube"). The 250mm focal length of the lens yields a plate scale of 0.83 arcseconds per micron. This guide scope option is essentially an aluminum tube with a modest length of tube in front of the lens for protection from dew and standard screw threads for attaching a CMOS or CCD camera.
- UV/IR Cut filter: A simple filter (the ICE 37mm UV IR Cut Filter Optical Glass Multi-Coated MC 37) was used to block UV and IR wavelengths due to the unwanted sensitivity of the camera to those wavelengths, where the performance of a simple achromat isn't expected to be optimal.
- Camera: ZWO ASI178MM CMOS camera featuring a 6.44-megapixel detector with 2.4µ pixels in a 3096 pixels x 2080 array, with a peak quantum efficiency of 81% in the visible spectrum. When used with the 50mm f/5 lens, the plate scale is 1.98 arcseconds per pixel, well matched to the nominal resolution of the primary lens. The ASI178MM uses a USB-3 interface for camera power, control, and communication. See technical details at https://astronomy-imaging-camera.com/product/asi178mm-mono/.
- Single Board Computer: Raspberry Pi model 4B with a 1.5 GHz processor, 4 GB RAM, and a 32 GB micro-SD card serving as the local hard disk for the Raspberry PI. The Raspberry Pi runs a version of the Linux OS ported to the Raspberry Pi, namely Raspbian GNU/Linux 10 (buster). For the prototype tests the specialized "Astroberry Server" port of the OS (https://www.astroberry.io) was used for convenience. While the USB-3 ports on the Raspberry Pi can power the ASI178MM if the Raspberry Pi itself is powered with a suitable 5V 3.1-amp USB-C power supply, in practice a powered USB-3 hub was used to ensure stable operation of the camera. Note that, as of 2024, a newer generation of Raspberry PI computer is now available, with 2-3x the processing speed.
- Camera Control Software: For the prototype system, camera control and image collection were accomplished using the publicly available KStars/Ekos package included with Astroberry Server. This software provided control of the camera functions and basic image sequencing for the tests conducted with the prototype system.
- Astrometric Software: The Astrometry.net package was installed on the Raspberry Pi to reduce images as they were collected by the Ekos package. A simple BASH script was used to control the data reduction: Whenever the camera control software deposited a new image in a specific folder on the micro SD card the Astrometry.net package would be started up to solve the latest image and save the results in a log file.

Figure 5.1: Prototype Optical Pointing system mounted on a tripod.



## 6. Test Design

The goal of the tests described here was to measure the astrometric repeatability of images taken with the prototype system. Initial tests using a small German Equatorial Mount to point the prototype system were not conclusive because of the mechanical pointing errors from the tracking mount used in such a portable field setup. The tests reported here therefore used a much simpler setup, with the prototype system mounted on a tripod and pointed in a fixed direction. Exposure times were short enough, 1.0s, that smearing of the images due to Earth rotation was insignificant.

Figure 6.1 shows a typical uncalibrated image, taken with a 1.0 second exposure. In the image stars as faint as 13$^{th}$ magnitude are easily detected.

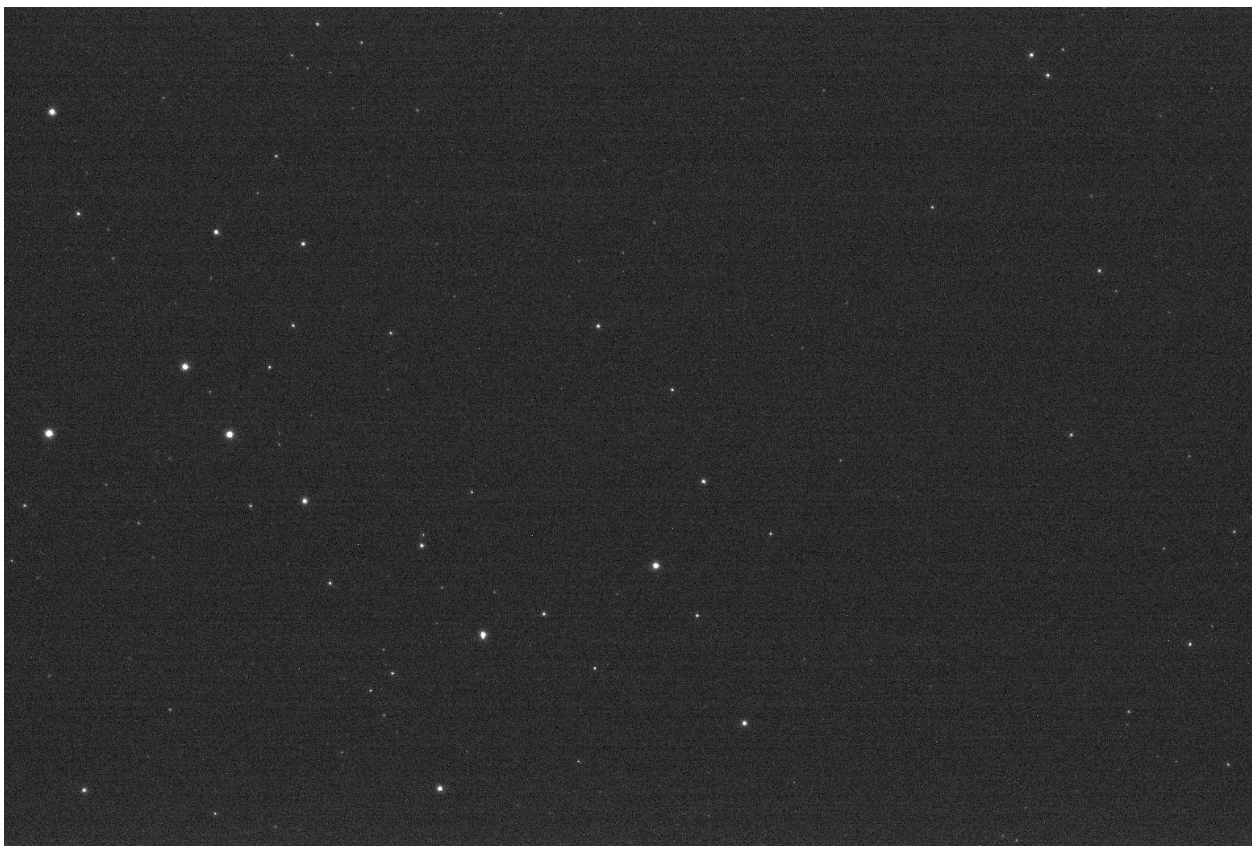


**Figure 6.1:** A typical raw image from the prototype optical system with a one second exposure

For the test a sequence of 300 images was collected and saved to the SD card in the Raspberry Pi. In principle the images should show a Right Ascension that increases linearly with time, and a constant Declination. In practice there were small drifts in the pointing in both coordinates. These drifts were presumably due to slow thermal drifts in the pointing of the telescope, which was mounted on a basic steel tripod (see Figure 5.1). These drifts were subsequently removed using polynomial smoothing to reveal the underlying pointing rms. For tests taken rapidly (with all images collected in 10 minutes or so) a linear drift term was sufficient to model the drifts in the residual position. For tests taken over longer periods of time, up to two hours, higher order polynomials such as quadratic or cubic, were sufficient to remove the drift terms.

Given the simple experimental setup there is a small possibility that there are slow systematic terms in the pointing solutions. While unlikely, it will be important in future measurements to rule out such systematic effects.

## 7. Test Results with Prototype: Astrometric Repeatability

The test reported here in detail was conducted on the night of 2020 June 12/13 after some experience with the system had been gained. The observations were made from a site at 205m elevation in Crozet, Virginia on a typical summer evening under reasonably clear skies. The site has moderate amounts of light pollution but experience has shown that the system is not particularly sensitive to background light (see Section 8). Much better conditions would be typical at the ALMA site, with better atmospheric clarity and minimal light pollution, along with colder temperatures which would improve the noise performance of the CMOS cameras.

The prototype optical pointing telescope was mounted on a tripod as shown in Figure 5.1. Image acquisition and reduction was controlled by a Raspberry Pi single board computer running the Astroberry port of the Raspbian version of Linux. Prior to the observations the focus of the system was adjusted with the draw tube focuser and then locked into place. The telescope was aimed at a northerly Declination to reduce the effects of image smearing from Earth rotation; subsequent reduction of the images revealed the Declination to be +73.85 degrees.

Three series of 100 images, each image with 1 second exposure time, were collected for the test reported here. Each series used approximately 340 seconds, including time to download the images from the camera to the Raspberry Pi and a brief pause between the images. There was also an approximately five minute pause before the second series and another similar pause before the third series of images. The total time of the test spanned 1625 seconds.

Each of the 300 images was autonomously processed through the Astrometry.net package to plate solve the image for the image scale and image center RA and Dec, using a simple script to manage the image processing procedure. The following commands were used to execute Astrometry.net from the BASH command line on the Raspberry Pi:

```
# Solve the field using Astrometry.net solve-field
# -p               => no plot output
# -l 2             => Limit CPU time to 2 seconds
# -L 1.975 -H 1.985=> Pixel scale is between 1.975 and 1.985 arcsec/pixel (to save time)
# -u "app"         => Units for pixel scale limits are arcsec/pixel
# --fits-image     => Assume image is a FITS image (to save time)
# --nsigma 8       => Sources will have at lease 8 SNR
# -8 neg           => specify parity of image (to save time)
# -N none          => don't write out a new file with the WS coordinates (saves time)
# -o scratch       => working files will all begin with "scratch"
# -z 1             => Integer resample by factor of 1
```

```
    # -d 30            => Include 30 stars (depth) in solution
    # $image           => the image file to be solved
    # append 2>/dev/null => suppress bash error messages
  solve-field -d 30 -p -l 2 -L 1.975 -H 1.985 -u "app" --fits-image --nsigma 8 -8 neg -N none \
            -o scratch -z 1 $image 2>/dev/null  > scratchoutput.txt
```

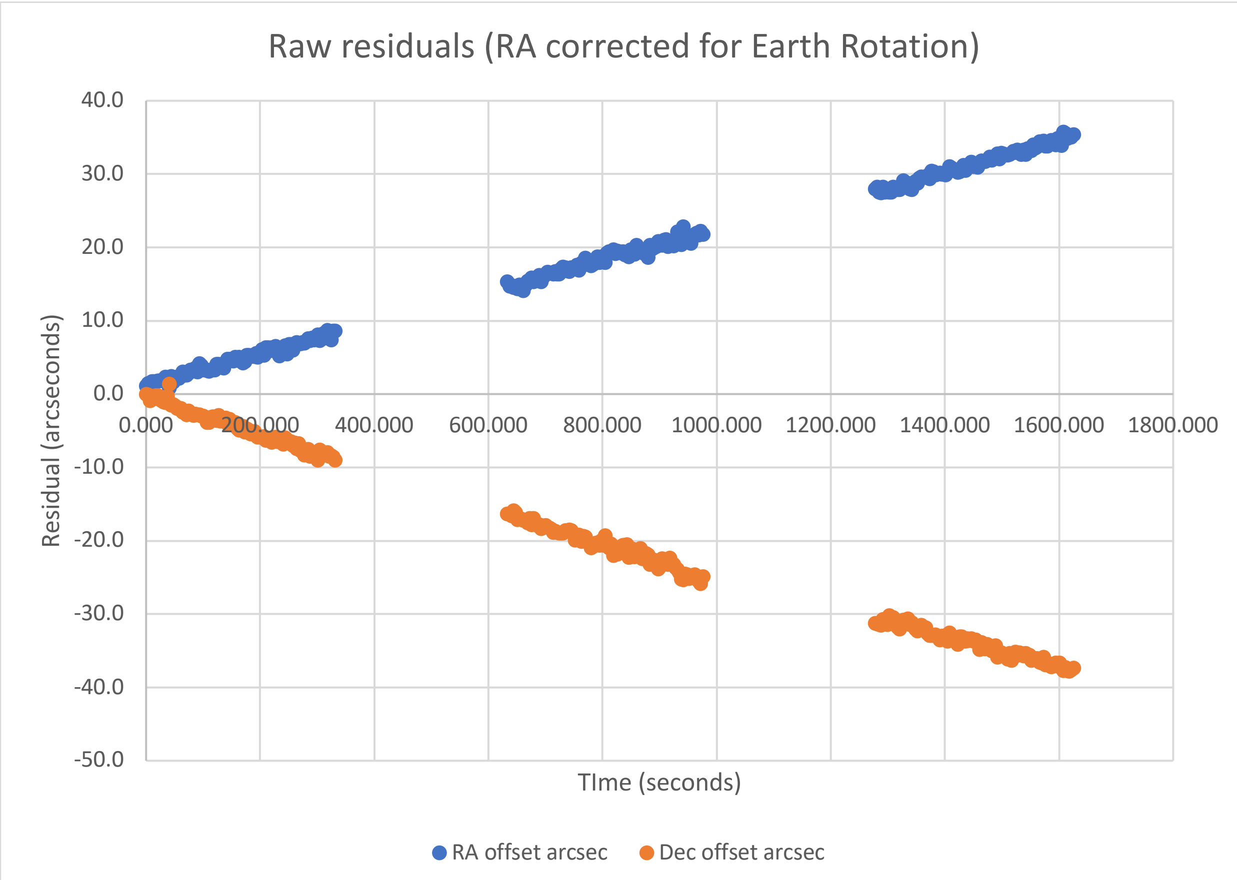
The scratch file resulting from each execution of Astrometry.net, scratchoutput.txt, was processed to yield a 1-line text log for each of the 300 images. The first few and last few lines from one of the log files are shown in Table 7.1, with one line per image. During the 27 minutes of the data collection the R.A. increased by 6.8 degrees as expected; the Dec drifted ~38 arcseconds during the observations. It should be noted that in this test the Raspberry Pi CPU didn't keep up with the 3.4 second cadence of the images – about 12 seconds was needed to process each image. Several options, such as 2x2 binning, using an approximate position, or a faster CPU should be able to significantly reduce this time.

**Table 7.1:** Astrometry.net results for first and last 5 images in the 300-image test from 2020-Jun-12/13. File is the FITS image file from the camera, n sources is the number of raw sources detected in the image, scale is the plate scale in arcsec/pixel resulting from the astrometric solution, RA and Dec are the resulting solution for the coordinates of the center of the respective images in degrees.

| File | n_sources | scale | index_file | RA degrees | Dec degrees | Time UTC |
|---|---|---|---|---|---|---|
| 1x1_Light_1_secs_2020-06-12T23-10-27_001.fits | 262 | 1.98028 | index-4208.fits | 211.000256 | 73.864088 | 2020-06-13T03:10:25.483 |
| 1x1_Light_1_secs_2020-06-12T23-10-30_002.fits | 342 | 1.98004 | index-4208.fits | 211.013967 | 73.864075 | 2020-06-13T03:10:28.760 |
| 1x1_Light_1_secs_2020-06-12T23-10-33_003.fits | 350 | 1.97941 | index-4208.fits | 211.026653 | 73.863835 | 2020-06-13T03:10:31.909 |
| 1x1_Light_1_secs_2020-06-12T23-10-37_004.fits | 245 | 1.97936 | index-4208.fits | 211.041677 | 73.863485 | 2020-06-13T03:10:35.359 |
| 1x1_Light_1_secs_2020-06-12T23-10-40_005.fits | 231 | 1.97983 | index-4208.fits | 211.055911 | 73.863370 | 2020-06-13T03:10:38.680 |
| **… 290 entries not shown…** | … | … | … | … | … | … |
| 1x1_Light_1_secs_2020-06-12T23-37-07_296.fits | 371 | 1.97878 | index-4209.fits | 217.718887 | 73.848793 | 2020-06-13T03:37:05.919 |
| 1x1_Light_1_secs_2020-06-12T23-37-11_297.fits | 359 | 1.97888 | index-4209.fits | 217.733415 | 73.848702 | 2020-06-13T03:37:09.359 |
| 1x1_Light_1_secs_2020-06-12T23-37-14_298.fits | 344 | 1.97958 | index-4209.fits | 217.747789 | 73.848558 | 2020-06-13T03:37:12.858 |
| 1x1_Light_1_secs_2020-06-12T23-37-18_299.fits | 344 | 1.97933 | index-4208.fits | 217.762887 | 73.848463 | 2020-06-13T03:37:16.358 |
| 1x1_Light_1_secs_2020-06-12T23-37-21_300.fits | 338 | 1.97885 | index-4209.fits | 217.777071 | 73.848728 | 2020-06-13T03:37:19.849 |

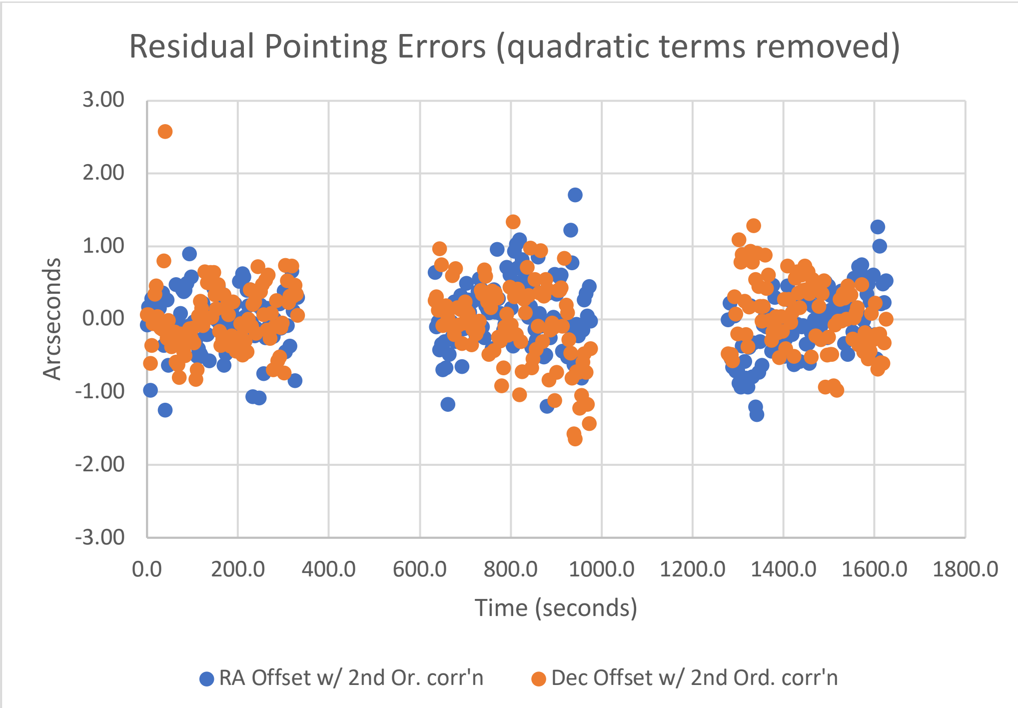
The next step in the data reduction was to subtract the linear increase with time of the Right Ascension from the measured positions, using the average Declination to calculate the proper rate. This was done a priori using the average observed declination to calculate a residual RA offset in arcseconds from the first image. Subtracting the coordinates of the first image from all images then yielded the offset of each image relative to the zero-point set by the first image. In an ideal experiment the relative offsets would only show a scatter due to noise in the astrometric solutions: The Declination would be constant and the Right Ascension would increase linearly with time. In practice, however, after subtraction of the linear R.A. term the relative offsets showed drifts in both residual R.A. and Dec, most likely due to thermal drifts in the pointing of the telescope and the steel tripod supporting it. Figure 7.1 shows the residual offsets for the 300 images vs. time, showing similar drifts in RA and Dec, relative to the first image in the series.

**Figure 7.1:** Residual pointing offsets prior to removal of drift terms



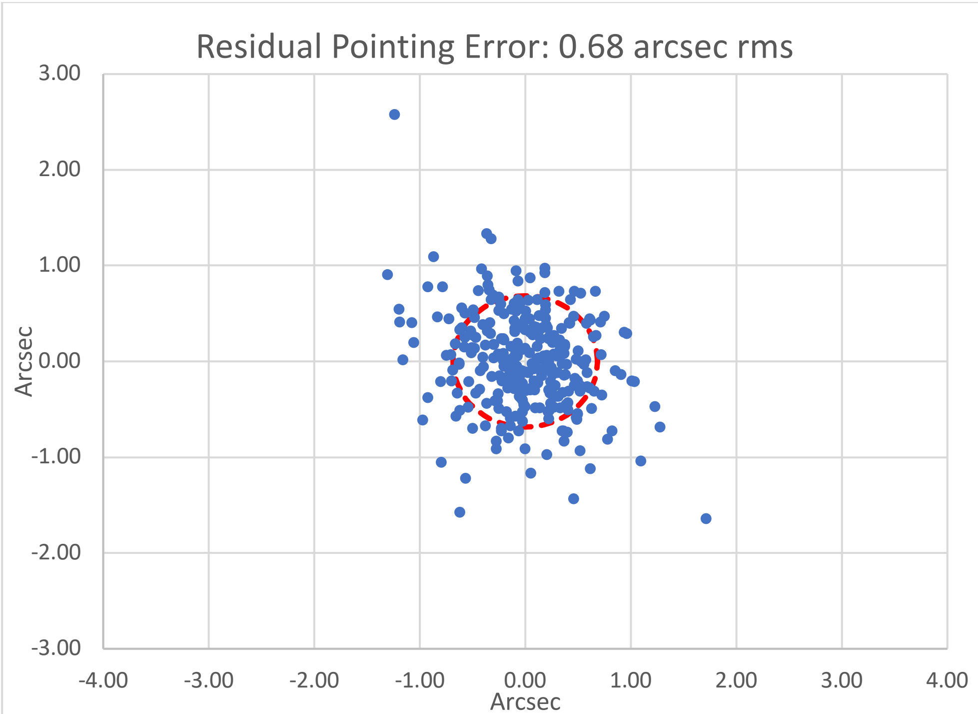

The final step in data reduction was to remove quadratic drift terms from the observed residuals. This was done under the explicit assumption that the drift terms were due to residual thermal effects in the tripod supporting the telescope. As seen in Figure 5.1, the tripod used for these measurements had a system of cantilevered axes to support the telescope, which may be especially susceptible to temperature effects. Future experiments could test this hypothesis, using some combination of thermal insulation and/or a more stable mount, to verify the assumption that the drifts seen here were due to residual thermal effects. Figure 7.2 shows the pointing residuals in R.A. and Dec. as a function of time, after removal of quadratic drift terms.

**Figure 7.2:** Residual pointing offsets after to removal of quadratic drift terms




Once the residual drifts are removed, the residual pointing error can be calculated as an rms error in arcseconds. This yields a pointing residual error of 0.68 arcseconds rms, as shown in Figure 7.3.

**Figure 7.3:** Residual RMS pointing errors after correction for sidereal motion and residual thermal drifts. The dashed circle corresponds to the measured rms pointing error of 0.68 arcseconds.




## 8. Test Results with Prototype: Twilight Observations

Preliminary tests were performed to characterize the behavior of the prototype system shortly after sunset as the sky was growing dark. Reliable (small residual) astrometric solutions required the detection of ~10 stars, which occurred when the Sun was at an elevation of ~-4.6 degrees (~4.6 degrees below the horizon). These measurements were made on a clear, cold November evening at just 207m elevation above sea level. The sky darkness and observing conditions are certain to be much better at the AOS, so the assumption that the Sun must be 6 degrees below the horizon appears to be somewhat conservative. The prototype system could detect stars and find plate solutions well before any stars were visible to the naked eye.

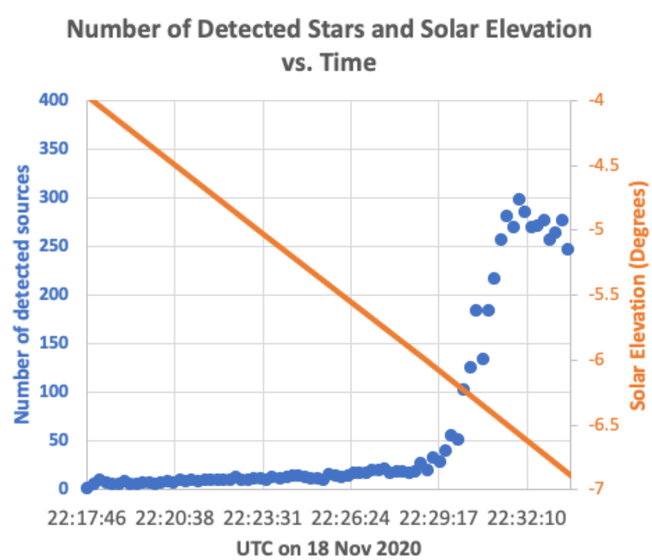



**Figure 8.1:** Number of Detected Stars and Solar Elevation vs. Time. Reliable astrometric solutions were achieved starting about 22:21 UTC, when ~10 stars were detected and the Sun had reached ~4.6 degrees below the horizon (Nominal sunset was twenty minutes earlier, at 17:01 Local Time, or 22:01 UTC).

## 9. Further Work

Several issues and opportunities for improvement arise based on the experience thus far with this simple prototype system. A key area for improvement is processing speed: Fully processing the astrometric solution for an image required about 12 seconds of elapsed time on a Raspberry Pi 4B single board computer. Several approaches that might reduce this processing time, possibly by a factor of 2 or 3, are included in the list below. A second broad issue is whether the residual drifts that are observed are indeed due to thermal effects in the steel tripod and aluminum telescope tube used for the prototype. The use of an improved tripod mount, along with thermal insulation of the system might be able to address this issue. The final broad area for investigation would be sorting out the practical aspects of implementing the system, such as the feasibility of using fixed focus (possibly combined with an athermalized optical design) and the practical limits for use near sunset and sunrise.

- Measure performance gains when providing plate scale, and effect of setting a fixed plate scale if possible
- Measure performance gains when providing approximate position
- Investigate performance gains using USB/SD or SSD to boot and run rather than memory card
- Test the effect of 2x2 binning of the input image on star detection, solution speed, and rms residual errors
- Test if hot pixel removal improves solution speed or reliability or estimated number of targets
- Optimize settings for running Astrometry.net such as number of targets and snr limits
- Demonstrate that observed drifts are thermal effects
- Demonstrate suitability of fixed focus over a measured temperature range
- Quantify the relationship between solar distance below the horizon, image binning (1x1 or 2x2) and solution reliability.
- Adopt the latest version of the Raspberry PI single board computer with its 2-3x faster processor and increased memory.

## 10. Conclusion

Small inexpensive optical telescopes hold the promise that ALMA can significantly reduce the amount of night time observing dedicated to routine pointing measurements. The prototype optical telescope described here can detect stars to 13$^{th}$ magnitude or fainter with a 1 second exposure, which is more than sufficient to allow blind astrometric pointing solutions anywhere on the sky. Coupled with a small single board computer, small optical telescopes can become, in effect, simple black boxes that accurately report their pointing position on the sky with a precision below 1 arcsecond rms. It must be emphasized that this precision can be achieved anywhere on the sky, with no requirement to be pointed solely at bright stars. The time required to achieve these astrometric pointing measurements is limited mainly by the computing power of the supporting single board computer. While the prototype system used about 12 seconds to solve each image, improvements in the solution parameters and/or a faster processor should be able to reduce the cycle time for an astrometric pointing solution to 4 seconds or less.

The potential benefit of using optical pointing for night time observations can be seen by considering the actual amount of time currently dedicated to pointing observations. During the first half of Cycle 7 observing, from 30 September 2019 through 19 March 2020, 6.8% of nighttime PI Science observing was dedicated to pointing. After allowing for ~25% cloudy nights, the approach described here could potentially increase the effective amount of scientific observing available to ALMA by the equivalent of ~10 nights (about 100 hours) per year.

Finally, optical pointing would be of direct benefit to observations at the highest frequencies observed by ALMA, where the ability to offset point is limited by the small primary beams and scarcity of calibrators at those frequencies. Optical pointing as envisioned here could update antenna pointing before and during high frequency observations with high precision.

## References

Lang, D., Hogg, D. W.; Mierle, K., Blanton, M., & Roweis, S., 2010, Astrometry.net: Blind astrometric calibration of arbitrary astronomical images, Astronomical Journal 137, 1782–1800. http://arxiv.org/abs/0910.2233