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Optical Guiding of Radio Interferometers I: Tracking Optical and Radio Offsets

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ABSTRACT

We explore the benefits of moving toward optically-guided, radio-interferometric observations. Optical cameras mounted on the radio dishes give rapid measurement of the optical pointing error closer to the science targets than can be obtained with radio pointing measurements. In this memo we describe observations of the radio source 3c454.3 and the bright optical source HIP113963. We find that the use of optical reference pointing gives marked improvement over radio pointing especially during sunrise times when thermal effects are causing rapid change in radio pointing.

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1. Introduction

Pointing errors provide one of the fundamental limits to the image fidelity achievable with any radio telescope. Typical pointing errors $\sim \frac{1}{20} HPBW$ of the primary beam pattern ($\sim 6''$ at 100 GHz for a 6m diameter dish) significantly degrade the image fidelity which can be obtained with interferometer arrays like CARMA and ALMA. In this memo we describe experiments to develop optical pointing observations to peak up the radio pointing on the target sources in real time for the CARMA telescope.

Optical cameras mounted on the radio dishes give rapid measurement of the optical pointing error closer to the science target than can be obtained with radio pointing measurements. The sky density of stars and the sensitivity of the optical telescopes are sufficient to provide high signal to noise measurements close to the science targets. In this memo we analyze the relationship of the optical and radio pointing errors. We show that the measured optical pointing errors track the radio pointing errors and can be used to improve the radio pointing.

2. Data Collection

In this first study, we used the optical cameras already mounted on the 15 dishes at CARMA. The CARMA array has six 10m dishes (C1–C6), and nine 6m dishes (C7–C15). There are two different optical telescopes, lens caps and video cameras. Dishes C1–C6 have 4 inch optical apertures, and C7–15 have 3 inch apertures. C7–C12, C14, and C15 have fixed pupil video cameras with lens caps possessing an IR pass filter. C1–C6 have opaque lens caps but have adaptive pupil video cameras. C13 is a hybrid, having an adaptive pupil with an IR pass filter.

Ideally, we would measure the radio and optical offset of a source which is optically and radio bright and has a simple structure. There are amazingly few sources that satisfy these requirements given the present optical cameras at CARMA. These sources include Venus, Mars, RLeo, OCet, and perhaps, Uranus. The obvious candidate Jupiter is too large for our present array configuration, and radio pointing becomes difficult because the radio emission is resolved on nearly all baselines. As part of an attempt to improve the CARMA pointing model, an extended catalog of optical sources was identified and optimized for speed of optical data collection. More details will be available in an upcoming CARMA memo. We note here that a star brighter than 4.5 magnitudes was identified in nearly every 5×5 deg patch on the sky. This provides us with an excellent catalog of optically bright sources near the standard, radio bright pointing sources.

Due to the time of year and the desire to first test the radio-optical offsets at night when pointing is most stable, we selected the radio source 3c454.3 (flux 10 Jy) and the optical source HIP 113963 (Vmag 2.5, CARMA source HP113963). These are separated by less than a degree on the sky. We began the observations on July 10th, 2006 at 8:30 (UT). There were anomalies in the optical data related to clouds until about 9:00 and we start our analysis at that later time. Sunrise occurred at

12:50. Dishes 1, 4 and 13 continued optical observations well through sunrise to ∼14:30. For other dishes, optical pointing after sunrise was not possible.

For radio pointing we made interferometer measurements of the dish voltage patterns on a 7×7 azimuth and elevation cross of pointing offsets on the radio source 3c454.3 (details of data collection and reduction are described elsewhere). We used a $0.9 \times$ Nyquist sample interval to provide slight over sampling. Voltage patterns were measured first for the 6m dishes using the 10m dishes as a reference tracking 3c454.3, and then for the 10m dishes using the 6m dishes as reference dishes. Dishes 2, 3, 5, 11, and 15 were not available for these observations. 10s integrations were made at each pointing offset, and a single cross was done for each pointing measurement. Optical offsets were obtained via automated optical centroiding on HIP 113963 using the CARMA optical camera GUI and the stars pointing program (described elsewhere). The total time per radio pointing measurement was 8 minutes; the optical measurements took 1.5 minutes. These times will eventually be reduced by $\sim 30\%$.

We made three estimates of the pointing RMS for comparison. First, the standard deviation of the pointing errors for all the voltage patterns and reference dishes was calculated. Next, we average the pointing errors over all the reference dishes at a given time. These values were then interpolated to the optical pointings for direct comparison. We calculate a standard deviation of this sample and use it as the radio RMS when comparing to the optical data. Finally, we calculated the standard deviation of the optical minus the interpolated, averaged, radio offsets.

3. Results

Our results are shown in Table 1. The three RMS values discussed above are labelled as Rad, RadAvg and Opt-Rad, respectively. The first column is the dish number. The azimuth and elevation axes are described independently, each receiving a value for RMS of the radio sample, the averaged radio sample and the optical-radio sample. The final pair of columns describes the initial time and final time over which the RMS values were calculated. We divide our sample into two comparison sets, indicated by Table 1a and 1b. Table 1a includes all the data obtained including some measurements through sunrise for some dishes. Table 1b includes only data until sunrise to provide a uniform sample of data without dish illumination effects.

Prior to sunrise the radio pointing accuracy of the 10m dishes is only slightly poorer than the optical-radio pointing. For the 6m dishes the optical-radio pointing is better than the radio pointing for all dishes except C7 and C12. In several cases the pointing RMS is improved by nearly a factor of two.

For the data including sunrise, Table 1a, it is useful to focus on Carma 1, 4 and 13 as these have the longest time post sunrise to track data trends. For these three dishes, the azimuth pointing RMS is poorer when this post sunrise data is included for both radio and optical-radio pointing. The azimuth pointing is not significantly degraded by using optical-radio pointing measurement.

However, for elevation, the pointing RMS is reduced from 3.6, 4.8 and 11.9" to 2.7, 1.5 and 3.0", respectively, a dramatic improvement in all cases. The degree to which the radio and optical-radio offsets track after sunrise is shown in Figures 1-6. Figures 1-2 show azimuth and elevation pointing errors for Carma 1. Figures 3-4 show Carma 4 and Figures 5-6 show Carma 13. Radio points are shown as Xs and optical points are shown as squares. The vertical line indicates sunrise.

4. Discussion

For the night-time data, the 10m dishes have better than $2''$ RMS pointing. Use of optical reference pointing provides little to no benefit over this range. However, during sunrise, the radio pointing alone results in a significant increase in elevation RMS pointing while the optical reference pointing keeps the RMS to nearly the night-time levels.

The situation for the 6m dishes is somewhat different. During sunrise, the elevation change in radio pointing can be as large as $40''$ while optical reference pointing, mostly available on Carma 13, keeps the elevation RMS below $3''$. The azimuth radio pointing over sunrise does not appear to be degraded and the benefit of using an optical reference pointing in the azimuth axis is negligible. Differential heating across the dish may change the radio pointing axis during this time. Where the 6m and 10m dishes differ is over the night-time hours. With the exception of Carma 7 and 12, the azimuth pointing is improved to some degree from the use of optical reference pointing. And, with the exception of Carma 14, the elevation pointing is improved and this improvement is a factor of two in some cases. Carma 14 does not degrade with the use of optical reference pointing.

5. Conclusions

Optical reference pointing over sunrise, when thermal effects are causing rapid change in pointing offsets, gives marked improvement over radio pointing. Radio peak up observations over this time are not practical. The large slews, often necessary for radio pointing, imply large changes in dish orientation with respect to the sun, resulting in changing illumination patterns. It is therefore unlikely that an offset derived in another part of the sky would even apply locally to the science target. Plus, the rapidly changing offsets seen in Figures 1-6, especially in the elevation axis, indicate that pointing would have to be very frequent indeed. In some cases the pointing is changing by $10''$ per hour. To maintain $5''$ RMS pointing, radio pointing would be required at $\sim$30 minute intervals. A 6-8 minute radio pointing and a $\sim$3 minute slew in each direction would result in significant loss of time for the science source. On the other hand, optical pointing requires only 1.5 minutes, including the slew time, and closely tracks the radio pointing errors. We also note that the use of optical reference pointing generally produces smaller RMS at night-time as well. This improvement is larger for the 6m dishes. Carma 12 is a notable exception to these results.

We have since obtained additional data sets. While typically one or two dishes do not seem to have consistent radio and optical pointing, for the remaining 10 to 12 dishes the use of optical offset pointing improves radio pointing. Examination of the data indicates that it is likely that the discrepant pointing behavior is not caused by a failure of offset optical pointing. Dishes that show deviation in one data set typically do not in others, implicating hardware or software failures.

From these results, we can make a strong case for an optical telescope system that allows us to see fainter stars during the day rather than fainter stars in general. It is unclear that getting a more sensitive system, allowing us to observe stars closer to our science target, would provide benefit. Perhaps, if we could go sufficiently faint, we could actively guide on the optical source, but we are still limited by how well we can determine, and possibly parametrize, the optical-radio pointing. On the other hand, an optical telescope system which can see fainter stars during the day would allow us to make more frequent, nearby measurements during the times when the radio dish pointing is poorest, i.e. when the sun is up.

6. Next Test

With the help of Colby Kraybill, we plan on attempting to integrate images to see how much fainter we can go with the current equipment. An additional test, now underway, is to institute optical-radio pointing during observations of a science target. We can directly compare the image fidelity obtained with and without optical-radio pointing.

Table 1a: RMS pointing accuracy of all data, including post sunrise.

Ant	Az RMS (arcseconds)			Elev RMS (arcseconds)			Begin	End
	Rad	RadAvg	Opt-Rad	Rad	RadAvg	Opt-Rad	UT	UT
1	2.56	2.03	2.49	5.70	3.59	2.68	9.00	14.50
4	2.82	1.97	1.75	8.06	4.80	1.54	9.00	14.82
6	2.05	1.04	1.09	8.08	1.49	1.52	9.00	13.16
7	6.29	2.29	2.71	18.72	3.75	3.08	9.00	12.84
8	4.80	3.83	1.79	23.68	2.53	2.19	9.00	12.68
9	3.74	1.73	1.65	21.13	2.62	2.65	9.00	12.83
10	4.83	2.22	2.00	18.07	3.12	2.02	9.00	12.68
12	6.75	1.98	5.25	19.43	4.20	2.38	9.00	12.84
13	5.74	3.69	4.17	21.28	11.88	2.95	9.00	14.64
14	4.43	4.02	3.21	24.27	3.43	2.79	9.00	12.84

Table 1b: RMS pointing accuracy of night-time data only.

Ant	Az RMS (arcseconds)			Elev RMS (arcseconds)			Begin	End
	Rad	RadAvg	Opt-Rad	Rad	RadAvg	Opt-Rad	UT	UT
1	1.87	1.51	1.58	2.00	1.53	1.56	9.00	12.80
4	1.35	1.32	1.55	1.67	1.46	1.27	9.00	12.80
6	1.19	0.88	1.03	1.78	1.57	1.61	9.00	12.80
7	2.55	2.23	2.65	4.07	3.42	3.11	9.00	12.80
8	3.92	3.83	1.79	2.84	2.53	2.19	9.00	12.80
9	2.02	1.75	1.68	2.40	2.27	2.45	9.00	12.80
10	2.64	2.22	2.00	3.30	3.12	2.02	9.00	12.80
12	2.43	2.00	5.36	4.36	3.87	2.41	9.00	12.80
13	4.33	4.20	3.12	5.19	4.66	2.50	9.00	12.80
14	4.35	4.07	3.22	3.53	2.76	2.76	9.00	12.80

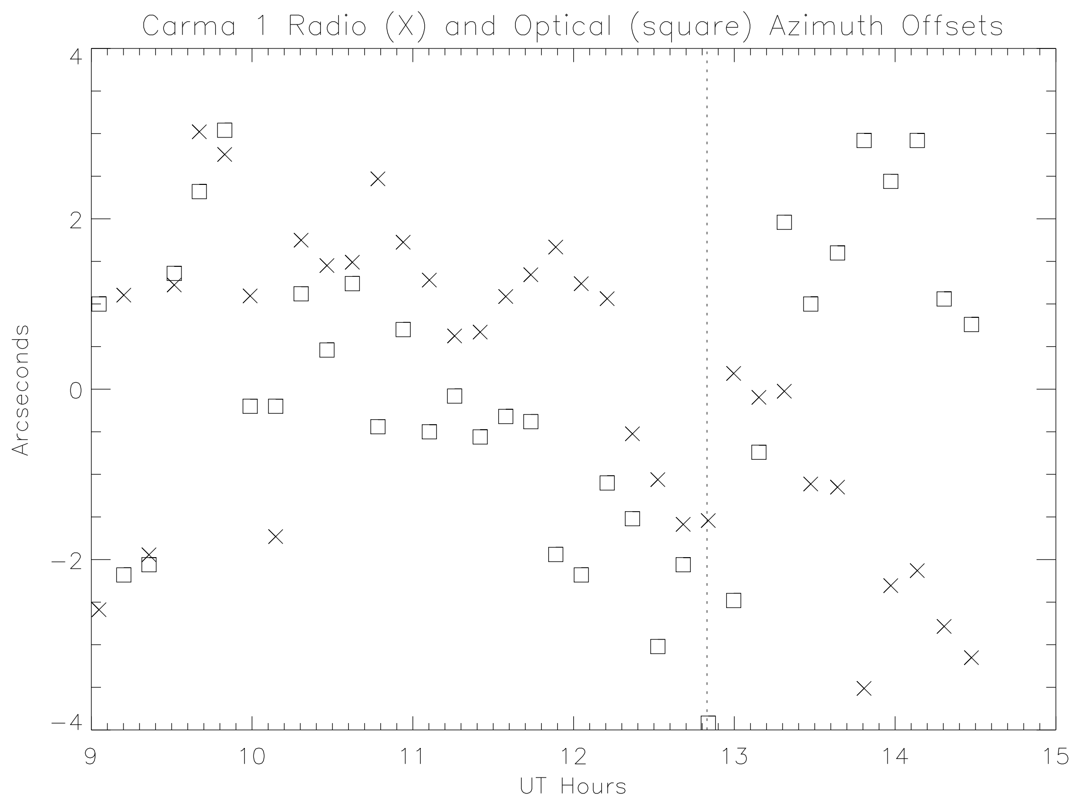

Fig. 1.— Carma 1 Azimuth pointing in arcseconds. Squares represent the optical data points while Xs are the averaged radio pointing measurements interpolated to the times of the optical pointing. The dashed line at 12.8 hours indicates sunrise.

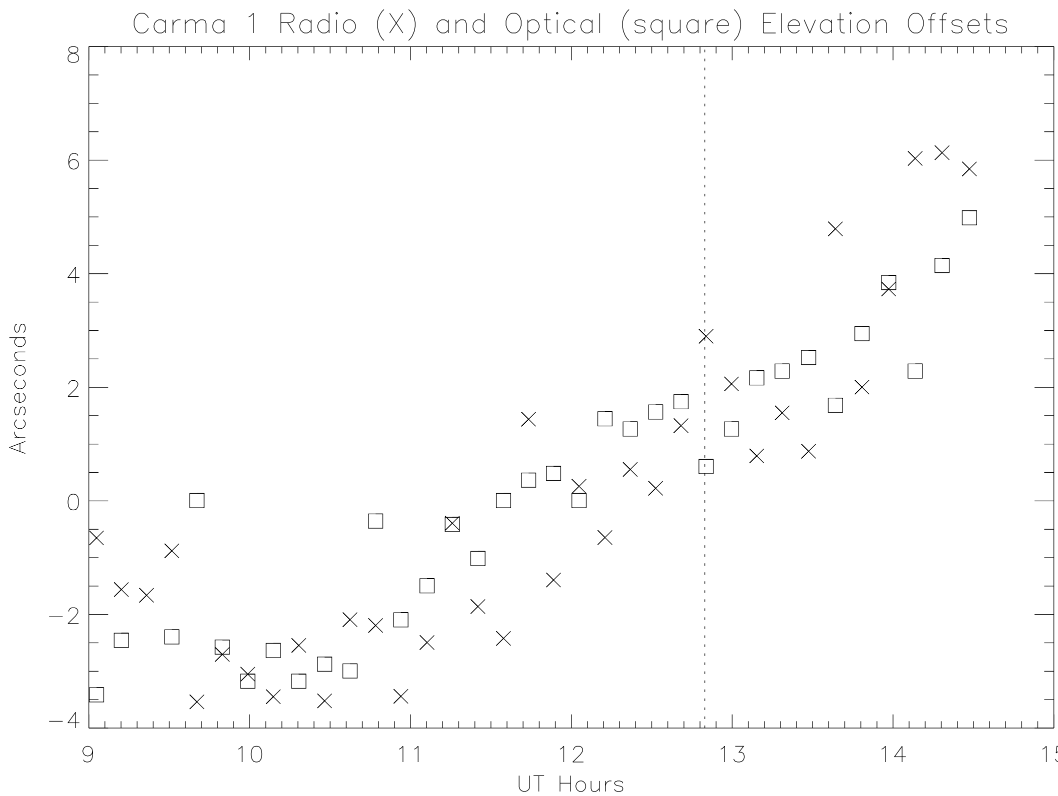

Fig. 2.— Carma 1 Elevation pointing in arcseconds. Squares represent the optical data points while Xs are the averaged radio pointing measurements interpolated to the times of the optical pointing. The dashed line at 12.8 hours indicates sunrise.

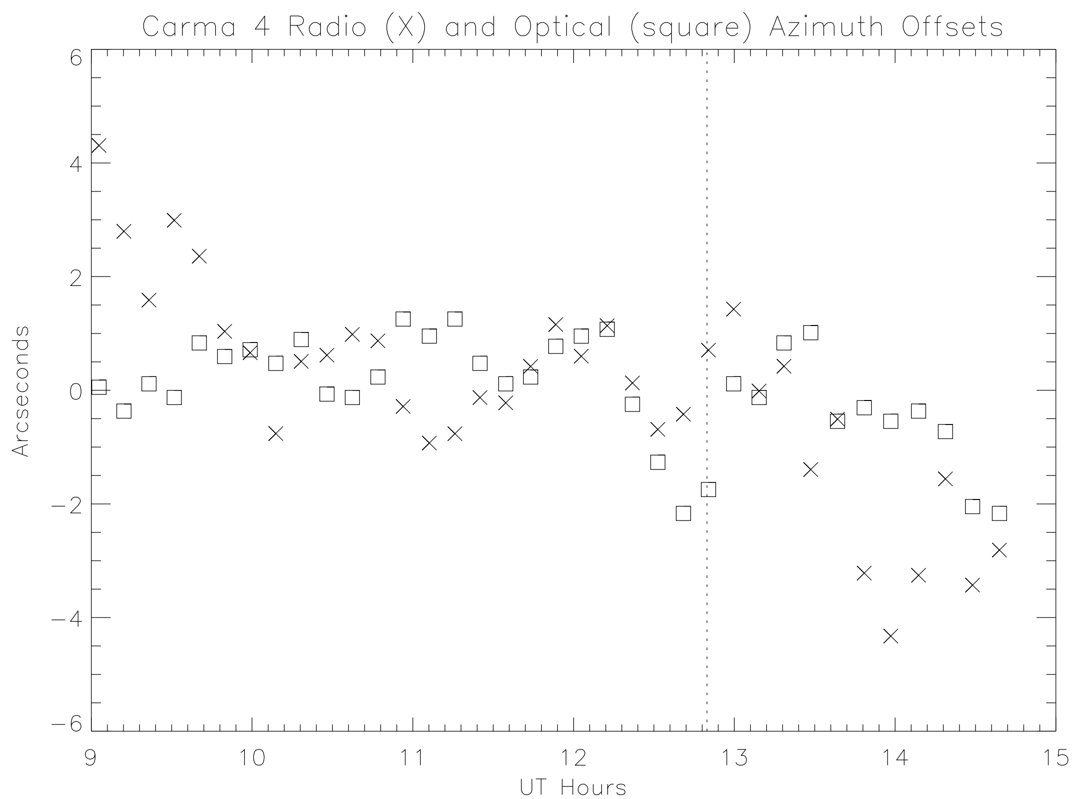

Fig. 3.— Carma 4 Azimuth pointing in arcseconds. Squares represent the optical data points while Xs are the averaged radio pointing measurements interpolated to the times of the optical pointing. The dashed line at 12.8 hours indicates sunrise.

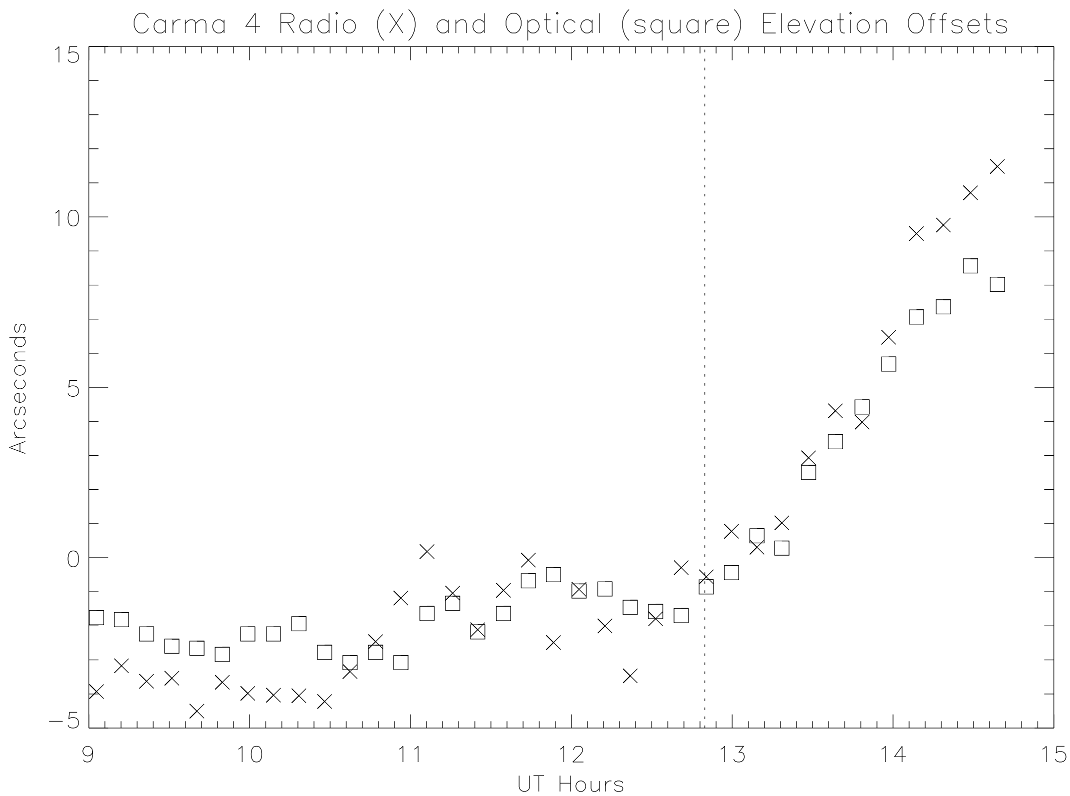

Fig. 4.— Carma 4 Elevation pointing in arcseconds. Squares represent the optical data points while Xs are the averaged radio pointing measurements interpolated to the times of the optical pointing. The dashed line at 12.8 hours indicates sunrise.

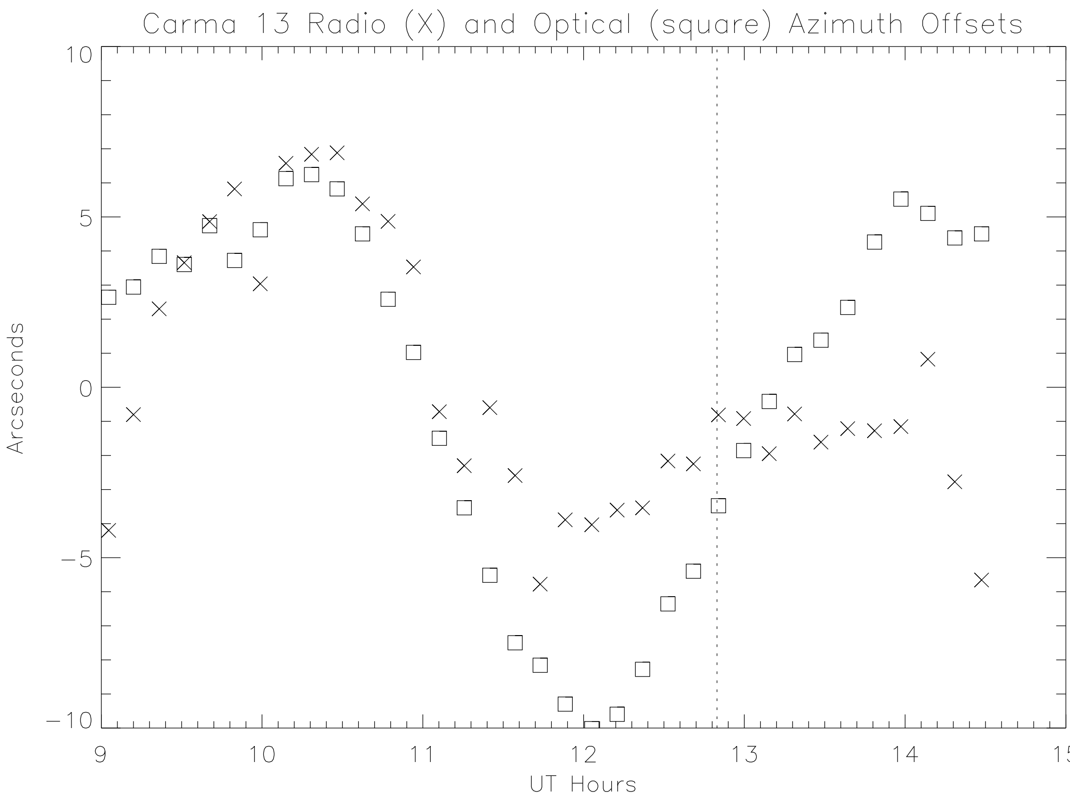

Fig. 5.— Carma 13 Azimuth pointing in arcseconds. Squares represent the optical data points while Xs are the averaged radio pointing measurements interpolated to the times of the optical pointing. The dashed line at 12.8 hours indicates sunrise.

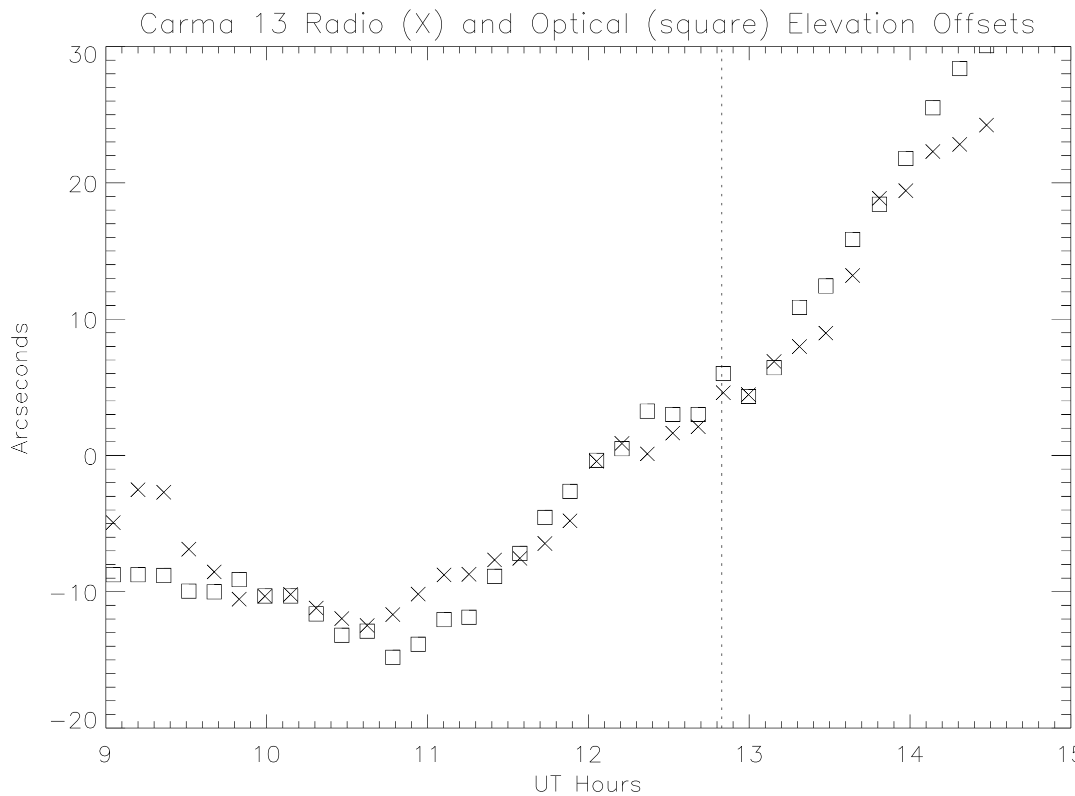

Fig. 6.— Carma 13 Elevation pointing in arcseconds. Squares represent the optical data points while Xs are the averaged radio pointing measurements interpolated to the times of the optical pointing. The dashed line at 12.8 hours indicates sunrise.