Progress Report
NASA Grant NAG5-12406
Search for Near-Earth Objects with Small Aphelion Distances
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Reporting Period

This report covers 2003 July 13 (the date of the previous progress report) to 2004 August 11 (the date of this writing), which corresponds to most of the second year of this project.

Personnel

There are only about 1.3 FTEs working on this project, with only about 1.05 FTEs receiving salary support. Postdoctoral research associate Fabrizio Bernardi is paid full-time out of this grant. He started 2003 July 1 and handles most of the observing runs, image processing and astrometric reductions, plus some software development. The P.I. Tholen is currently spending about 30 percent of his time, most of which is state-supported, working on this project. He writes the observing time proposals, participates in the observing runs on the larger telescopes, performs some image processing and astrometric reductions, inspects results for quality control prior to submission for publication, and writes a fair amount of software, in addition to handling the overall project management.

NEO Follow-up Astrometry

As noted in last year's progress report, delays in the completion of the Wide Field Imager for the 2.24-m telescope caused us to shift our efforts to the second priority of NASA's NEOO program, namely the determination of the accurate orbits for near-Earth objects. That effort requires astrometric follow-up observations, and we are pleased to report excellent results in this area. We had very successful observing runs in 2003 July, 2003 August, 2003 October, and 2004 July, with a few additional observations obtained during a 2004 January run and a shared run in 2004 May. The 2004 January run and a second run in 2004 May were largely lost to bad weather. During these runs, we observed well over 150 near-Earth objects, mostly in the R magnitude 20 to 23 range. During twilight, when the sky was too bright to observe the fainter asteroids, we often observed several brighter objects.

As noted in the previous progress report, we select most of our targets from the priority lists maintained by the Spaceguard Central Node (SCN). On rare occasions, the SCN does not update their lists fast enough, and we wind up observing an object that really does not need additional observations. For example, the SCN was unaware of the linkage found between 2000 GF2 and 2003 SO84, so in reality the object already had a 1295 day arc that we lengthened by a mere 95 days, which was unnecessary.

Table 1 shows most of the objects we've observed, the length of the observational arc both before and after our observations in days, whether this project acquired the last available observation of the object, the average R magnitude of our observations for that run, the RMS noise of the astrometric fit to the catalog reference sources in arcseconds, the average of the absolute values of the orbit solution residuals for our observations in arcseconds, the type of object, and occasional comments. Note that a handful of challenging cases still await reduction and are not included in the table.

Table 1. NEO Follow-up Astrometry

object	arc before (days)	arc after (days)	last obs.	R mag	RMS B1.0	mean resid.	object type (notes)
1937 UB			no	13.5	0.03	0.1	Apollo (through thick cirrus)
1998 DV9	1240	1982	yes	20.5	0.17	0.07	Apollo
1998 FG2	1124	1958	no	22.6	0.18	0.07	Apollo
1999 HX1	111	1564	yes	21.9	0.18	0.11	Amor
1999 OW3	1234	1473	no	21.3	0.17	0.20	Apollo (July)
1999 OW3	1473	1560	yes	19.7	0.15	0.11	Apollo (October)
1999 TZ4	1637	1679	yes	20.7	0.17	0.02	Amor
1999 TC10	124	1677	yes	22.3	0.15	0.11	Apollo (code 049 arc extension bad)
1999 VQ6	121	1390	no	22.5	0.08	0.04	Amor
2000 AC6	55	1395	yes	23.0	0.18	0.06	Aten
2000 AE205	53	1657	yes	20.8	0.15	0.04	Apollo
2000 AB246	913	1299	no	20.7	0.13	0.07	Amor (July)
2000 AB246	1299	1387	yes	21.0	0.14	0.18	Amor (October)
2000 EV70	46	1240	no	23.5	0.15	0.09	Apollo
2000 EB107	136	1329	yes	23.1	0.15	0.07	Amor
2000 GF2	1295	1305	no	19.7	0.17	0.04	Apollo (2003 SO84 - SCN not know)
2000 GF2	1307	1390	yes	23.1	0.12	0.16	Apollo (SCN error)
2000 GB147	536	1214	no	20.7	0.17	0.09	Amor
2000 JY8	63	1274	no	21.6	0.16	0.06	Amor (October single night)
2000 JY8	1274	1359	yes	22.4	0.14	0.08	Amor (January single night)
2000 RS11	290	1062	no	21.9	0.17	0.08	Apollo
2000 RD34	109	1063	no	20.6	0.10	0.04	Amor
2000 RW37	193	1418	yes	20.7	0.14	0.06	Apollo
2000 ST20	62	1327	yes	22.7	0.16	0.06	Amor
2000 SR43	179	1395	yes	21.6	0.16	0.07	Amor
2000 SU180	158	1036	no	22.1	0.18	0.05	Apollo
2000 WF6	77	1018	yes	23.0		0.18	Amor
2000 WJ10	150	1013	no	22.9	0.16	0.27	Amor (was 28 day arc before 568)
2001 CA32	66	993	yes	22.3	0.12	0.04	Amor
2001 DB3	208	986	yes	23.5	0.14	0.05	Amor
2001 DV8	90	923	no	22.2	0.12	0.09	Amor
2001 FB7	118	865	no	21.0	0.15	0.10	Amor
2001 JM1	49	810	no	21.1	0.13	0.01	Apollo
2001 LM5	87	1135	yes	21.6	0.14	0.03	Amor
2001 OG25	83	829	no	21.9	0.10	0.06	Amor
2001 QG96	85	707	yes	22.0	0.12	0.06	Amor
2001 RN	72	779	yes	22.5	0.13	0.04	Apollo
2001 SG10	63	771	yes	23.1	0.13	0.04	Apollo
2001 SD170	201	1092	yes	21.9	0.17	0.05	Amor
2001 SE286	216	1029	yes	20.3	0.13	0.06	Amor
2001 TP103	121	654	yes	22.5	0.16	0.09	Amor
2001 UW17	45	672	no	21.9	0.12	0.07	Amor
2001 VB76	218	984	yes	21.8	0.19	0.10	Apollo
2001 XQ30	177	596	yes	22.9	0.12	0.07	Amor
2001 YB1	62	621	yes	24.	0.1	0.05	Amor (was 22 day arc before 568)
2001 YX11	178	614	yes	22.8	0.17	0.03	Amor
2002 AC	209	665	yes	23.4	0.16	0.07	Apollo
2002 AC3	123	616	no	21.4	0.07	0.02	Amor
2002 AQ3	472	569	no	22.2	0.14	0.06	Amor
2002 AY3	85	599	no	22.5	0.15	0.05	Amor (August)
2002 AY3	599	659	yes	—	0.12	0.10	Amor (October)
2002 AT5	148	568	yes	23.7	0.15	0.11	Amor
2002 AO7	149	569	yes	23.6	0.16	0.09	Amor
2002 AR129	122	564	yes	23.1	0.14	0.13	Amor

object	arc before (days)	arc after (days)	last obs.	R mag	RMS B1.0	mean resid.	object type (notes)
2002 BP26	131	639	yes	22.2	0.12	0.05	Amor
2002 CW46	53	534	no	20.9	0.17	0.01	Amor (July single night)
2002 CW46	534	625	yes	22.2	0.15	0.06	Amor (October single night)
2002 EQ9	153	593	yes	23.2	0.14	0.10	Apollo
2002 EX11	85	534	yes	23.7	0.17	0.12	Amor
2002 EZ16	2607	2885	yes	19.3	0.15	0.01	Aten
2002 HQ11	45	465	yes	23.2	0.16	0.10	Apollo
2002 JN97	362	443	yes	22.0	0.17	0.06	Apollo
2002 KH3	167	616	yes	23.1	0.13	0.12	Amor
2002 NV	279	614	no	23.9	0.11	0.11	Amor (August)
2002 NV	614	676	yes	23.8	0.11	0.05	Amor (October)
2002 NN4	66	394	yes	21.2	0.10	0.03	Aten
2002 OD20	292	973	yes	22.3	0.15	0.04	Apollo
2002 QE7	132	704	yes	22.3	0.13	0.05	Amor
2002 TB70	54	294	yes	23.0	0.13	0.06	Apollo (July)
2002 UR3	279	366	no	20.4	0.16	0.08	Apollo
2002 VX91	19	352	yes	22.3	0.14	0.07	Aten
2002 XP37	54	327	yes	21.9	0.13	0.06	Aten
2002 XM90	184	595	yes	22.5	0.14	0.12	Amor
2003 AA	50	567	yes	21.2	0.14	0.07	Amor
2003 AD1	133	567	yes	22.1	0.16	0.02	Amor
2003 BL1	41	545	yes	20.8	0.16	0.02	Amor
2003 BC21	83	542	yes	22.3	0.16	0.06	Amor
2003 CG11	27	267	yes	24.8	0.15	0.05	Apollo
2003 CR20	49	170	no	21.7	0.15	0.07	Apollo (July)
2003 CR20	220	261	yes	21.2	0.12	0.02	Apollo (October)
2003 DA16	59	153	yes	23.0	0.17	0.04	Apollo
2003 EN16	50	145	yes	22.7	0.15	0.02	Amor
2003 ED50	15	232	yes	23.3	0.14	0.06	Apollo
2003 EF54	33	141	no	21.9	0.11	0.12	Apollo
2003 FH	182	221	yes	21.3	0.17	0.04	Apollo
2003 FF5	21	156	no	22.9	0.15	0.05	Apollo (August)
2003 FF5	156	213	yes	23.8	0.17	0.06	Apollo (October)
2003 FR6	30	123	yes	20.5	0.17	0.05	Amor
2003 GU41	26	200	yes	21.5	0.13	0.02	Apollo
2003 HP32	67	95	yes	21.1	0.14	0.07	Apollo
2003 HQ32	34	450	yes	22.3	0.13	0.03	Amor
2003 JD17	100	109	yes	22.3	0.14	0.02	Amor
2003 KO2	14	68	yes	21.8	0.13	0.03	Aten
2003 KW16	24	61	no	20.8	0.15	0.04	Amor (July)
2003 KW16	61	92	yes	21.4	0.14	0.04	Amor (August)
2003 LH	8	59	yes	24.6	0.13	0.03	Aten
2003 LO6	69	80	no	19.0	0.16	0.02	Amor
2003 MT	118	124	no	20.8	0.22	0.06	Amor
2003 ME1	9	36	yes	22.4	0.16	0.01	Apollo
2003 MD7	15	30	yes	20.5	0.14	0.02	Apollo
2003 ME7	49	118	yes	23.4	0.13	0.02	Amor (before 17 d arc - bad obs)
2003 NC	39	60	no	22.4	0.17	0.03	Apollo
2003 NW1	36	57	no	19.3	0.10	0.00	Apollo
2003 NL7	79	109	yes	21.5	0.15	0.09	Amor
2003 NP7	43	110	no	21.2	0.18	0.03	Amor
2003 OU	30	40	no	19.6	0.10	0.02	Apollo
2003 OC3	7	8	no	20.0	0.16	0.09	Apollo (July)
2003 OC3	29	41	no	21.0	0.14	0.06	Apollo (August)
2003 OC3	41	97	yes	21.8	0.17	0.07	Apollo (October)
2003 OR14	36	38	no	18.4	0.13	0.03	Amor

object	arc before (days)	arc after (days)	last obs.	R mag	RMS B1.0	mean resid.	object type (notes)
2003 PN5	15	83	yes	24.0	0.27	0.05	Amor
2003 PC11	53	81	no	18.9	0.12	0.01	Amor (twilight)
2003 QH5	65	65	yes	21.3	0.15	0.03	Apollo
2003 QK5	17	66	yes	22.9	0.17	0.06	Amor
2003 QU5	6	9	yes	20.4	0.10	0.08	Apollo
2003 QY29	3	5	no	18.3	0.15	0.10	Amor
2003 QB31	28	65	yes	22.0	0.13	0.03	Amor
2003 QQ47	5	5	no	18.1	0.10	0.04	Apollo
2003 QR79	2	2	no	18.6	0.15	0.06	Apollo
2003 QL96	59	60	yes	21.5	0.17	0.02	Amor
2003 RD5	17	59	yes	21.5	0.19		Amor
2003 RP8	36	49	no	19.5	0.15	0.03	Amor
2003 RM10	30	42	no	20.5	0.16	0.05	Apollo (precovered 1998)
2003 RW10	31	45	no	20.7	0.16	0.03	Amor
2003 RW11	16	40	yes	21.6	0.18	0.05	Apollo
2003 SL5	45	128	yes	23.2	0.15	0.01	Amor
2003 SQ15	36	38	yes	20.2	0.13	0.01	Apollo
2003 SY17	14	42	yes	21.8	0.17	0.05	Apollo
2003 SU84	6	40	yes	22.6	0.17	0.04	Apollo
2003 SD170	25	33	no	21.0	0.15	0.02	Amor
2003 SF170	24	33	no	20.3			Amor
2003 SN214	9	34	yes	23.4	0.21	0.02	Apollo
2003 SS214	29	29	no	17.8	0.13	0.02	Amor (twilight)
2003 SK215	18	32	yes	22.4	0.13	0.01	Amor
2003 SW222	22	29	no	19.1	0.10	0.03	Amor (twilight)
2003 SA224	12	25	no	18.8	0.13	0.00	Amor (twlight)
2003 UX5	7	7	no	18.1	0.15	0.03	Apollo (twilight)
2003 UL9	5	6	yes	20.2	0.15	0.07	Apollo
2003 UB10	8	10	no	19.8	0.15	0.03	Amor (precovered 2001)
2003 UL12	5	7	no	17.8	0.15	0.02	Apollo (twilight)
2003 UO12	8	8	no	19.7	0.13	0.08	Apollo
2003 UQ12	4	4	no	19.2	0.12	0.02	Apollo
2003 UY12	8	8	yes	19.2	0.13	0.02	Aten
2003 UY19	5	5	no	17.9	0.13	0.04	Apollo (twilight)
2003 UC22	2	7	no	19.9	0.12	0.01	Amor
2003 UP25	4	5	no	19.1	0.14	0.02	Amor
2003 UQ25	5	5	no	19.6	0.16	0.06	Apollo
2003 UW26	35	91	yes	21.9	0.16	0.00	Amor
2003 WM7	84	246	yes	20.7	0.15	0.04	Apollo
2003 YO1	131	244	yes				Apollo (precovered 1994)
2003 YO3	36	36	no	18.8	0.15	0.03	Apollo
2004 AE6	17	89	yes				Apollo
2004 BM11	7	8	no	18.3	0.09	0.01	Apollo (bad weather)
2004 FN17	88	117	no				Amor
2004 HZ	12	18	yes	21.9	0.11	0.11	Apollo (fast moving virtual impactor)
2004 HQ1	6	9	no	18.5	0.14	0.04	Apollo (fast rotator photometry)
2004 HQ1	18	19	yes	19.5	0.17	0.03	Apollo
2004 MC	15	37	yes				Apollo
2004 MX2	24	32	yes				Apollo
2004 MN4	0	1	yes	21.0	0.15	0.14	? (our two-nighter FMO)
2004 MO4	23	30	no				Amor
2004 MO7	0	35	yes	21.6	0.19	0.01	Apollo (our latest discovery)
2004 MP7	23	26	yes	20.2	0.25	0.03	Apollo
2004 NU7	5	8	yes				Amor
2004 NL8	10	10	no	17.9	0.19	0.06	Apollo (virtual impactor)
2004 NC9	2	7	no				Amor

Some of the information in Table 1 is also shown graphically in several histograms. Figure 1 shows the distribution of the measured R magnitudes for the near-Earth asteroids we have observed. Approximating the distribution with a Gaussian, we find that the average brightness of our observations is R = 21.4 (or B = 22.6 for comparison with LINEAR), with 68 percent of the observations falling between R = 19.8 and R = 23.0; note that most of the observations at the bright end of the distribution were made during twilight or through some clouds, when observations of the fainter objects were not possible. In particular, the single observation of 1937 UB (Hermes) was the best of several exposures, taken when the transparency was only one tenth that of a cloud-free sky.

We are now routinely using the USNO-B1.0 reference catalog for our astrometric solutions, and the preliminary results we reported last year have been confirmed. Figure 2 shows the distribution of the RMS residuals in arcseconds of the astrometric fits to the reference sources in the field after outlier rejection has taken place. Depending on galactic latitude, we can typically have anywhere from 30 to 150 reference sources in our 7.5 by 7.5 arcmin field. The mean RMS residual is a bit less than 0.15 arcsec, and the solutions are almost always better than 0.20 arcsec. With at least 30 sources included in our solutions, the random error in the astrometric fits are therefore usually less than 0.04 arcsec. Systematic zone error in the catalog is therefore almost always going to dominate over the random error in the catalog. Although the Hipparcos, Tycho, and UCAC2 astrometric catalogs are better than the USNO-B1.0, none of them have the depth or spatial density of stars to be of any use to us. Only the predecessors of the B1.0 catalog, namely the USNO-A2.0 and A1.0 catalogs, have the necessary depth and spatial density to satisfy our needs. Our experience shows the B1.0 to be at least a factor of two better than the A2.0 in overall astrometric quality, though the B1.0 appears to contain more false sources than the A2.0 does.

In addition to the random and systematic errors in the reference catalog, the other source of astrometric noise is the random error in the position of the asteroid being measured. We attempt to expose for a signal-to-noise ratio (SNR) of at least 5, though we often do better than that; however, the actual brightness of the asteroid does not always match the ephemeris prediction, usually because of a combination of rotational lightcurve effects, aspect angle, and uncertainty in the true absolute magnitude of the target asteroid. Also, at extreme zenith distances, the seeing can be somewhat less predictable. It is not uncommon for us to observe as far south as −45 deg and have, in fact, been as far south as −54 deg. For the very faintest objects, we have to settle for a lower SNR. Nevertheless, for typical seeing of 0.8 arcsec, the random centroiding error on the target asteroid is therefore usually less than 0.1 arcsec. Figures 3, 4, and 5 show the orbit solution residuals for our asteroid astrometry in right ascension, declination, and total angular distance, respectively. Gaussian approximations to the first two of these distributions show standard deviations of about 0.09 arcsec in both axes, though both distributions appear to be leptokurtic. The leptokurtosis is probably due to the relationship between our observations and the ones obtained at other observatories. In many cases our observations are temporally isolated from the others; as can be seen in Table 1, we have sometimes extended the length of the observational arc by over a factor of ten. It is therefore easy for the orbit solution to pass right through the mean of our observations, ignoring whatever systematic zone error may be present in the catalog, thereby yielding smaller residuals than would otherwise be the case. In such cases, we are really measuring the internal consistency of our observations, or the random error in our centroids. These observations probably create the narrow peak, whose width appears to be less than 0.05 arcsec, a distribution one would expect for 1.0 arcsec seeing and a SNR of 10. In other

Fig. 1 - R Magnitude Distribution

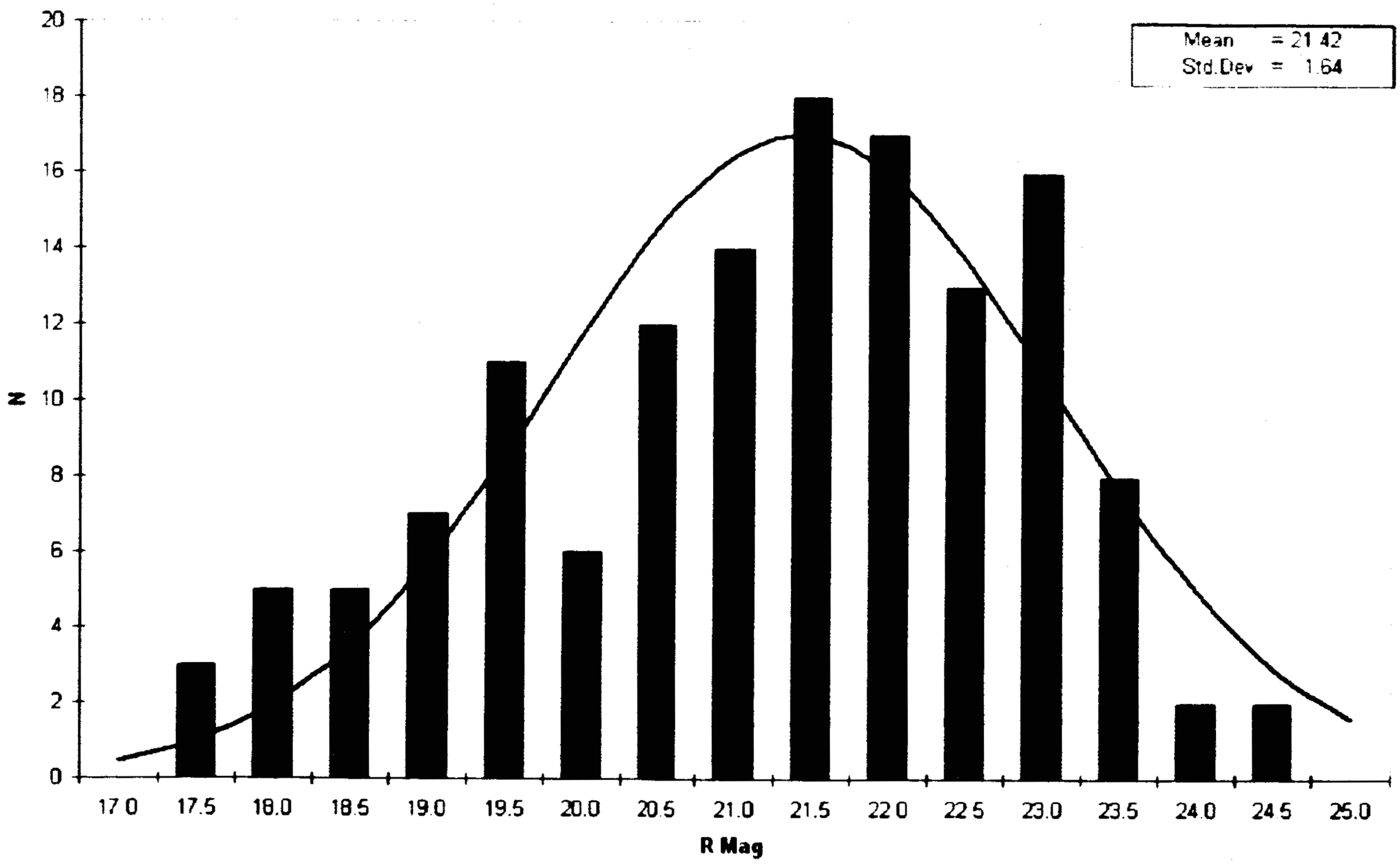


Fig. 2 - Astrometric Fit Residuals Distribution

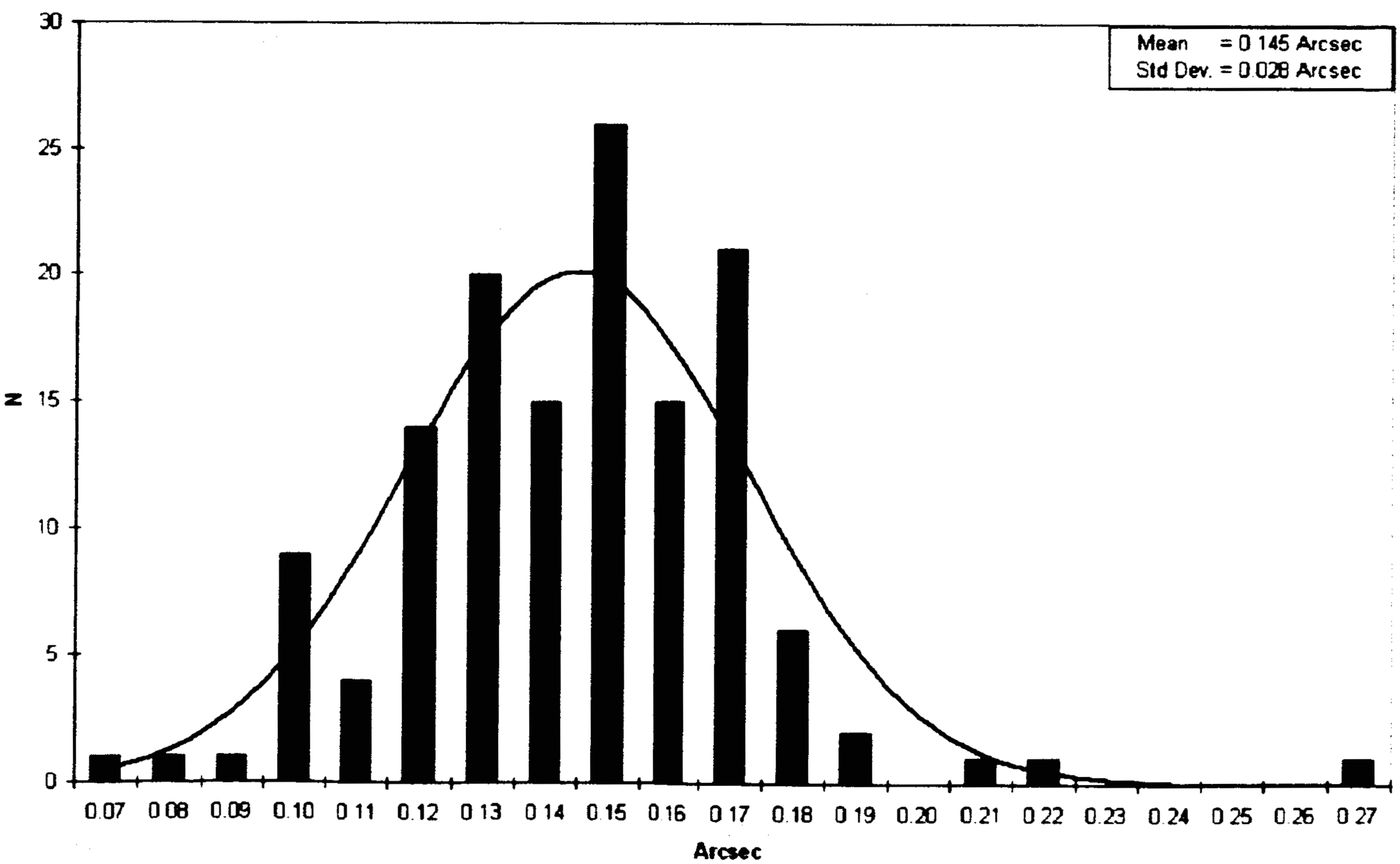


Fig. 3 - Orbit Solution Right Ascension Residuals

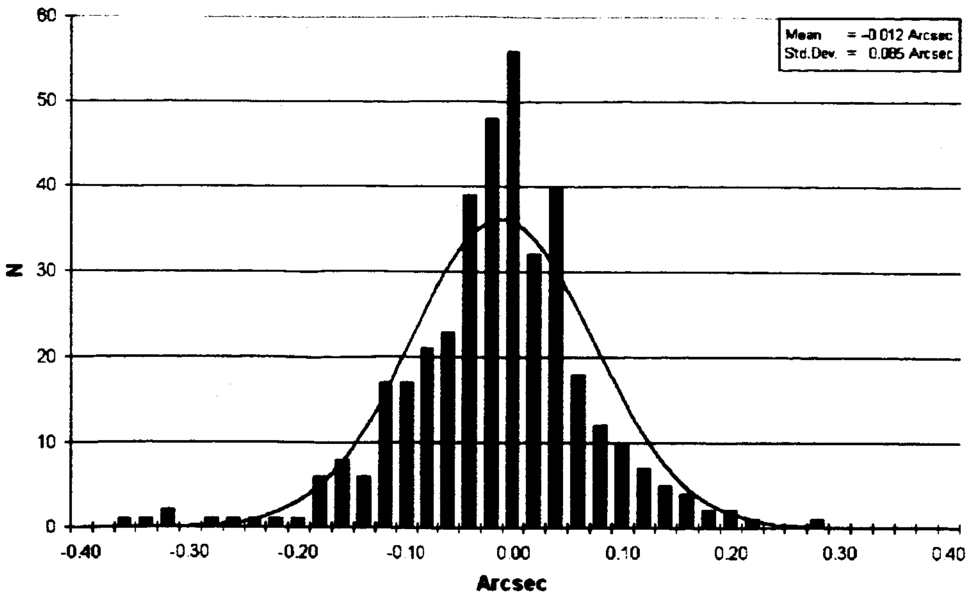


Fig. 4 - Orbit Solution Declination Residuals

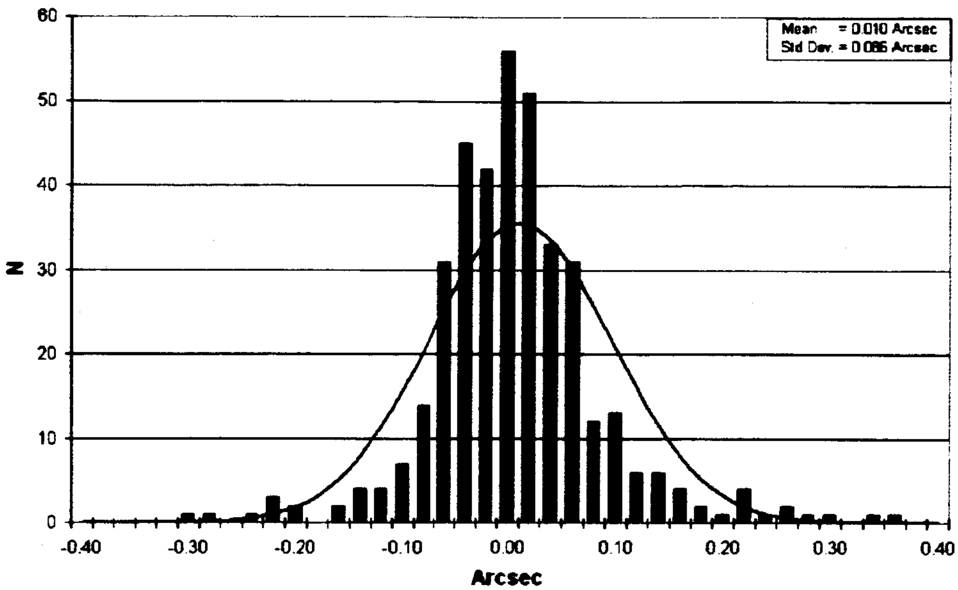
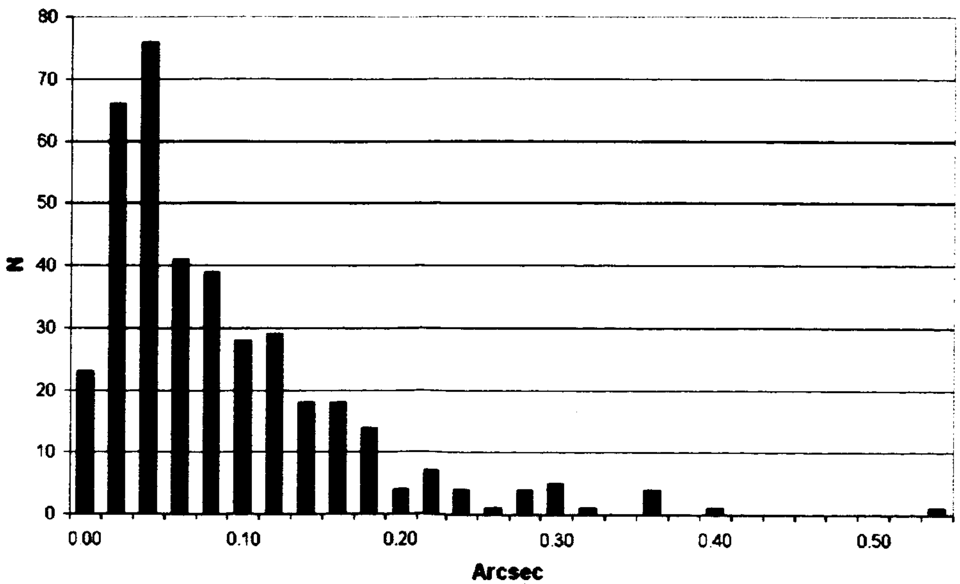


Fig. 5 - Orbit Solution Total Residuals Distribution



cases, however, our observations are surrounded by those obtained at other observatories where they use references catalogs less accurate than the B1.0, or have coarser pixel scales, and by sheer strength of numbers, the orbit solution is forced to pass through their observations, leaving our observations with larger residuals than would otherwise be the case. These observations probably create the extended tails of the distribution. The means of both distributions are very close to zero, indicating no global systematic bias in our astrometric reductions.

These results give us an estimate of the size of the systematic zone errors in the B1.0 catalog, which appear to be about 0.1 arcsec or less, in order to account for the overall distribution of residuals, knowing the random errors in the astrometric fits and the random errors in the centroids of the asteroids. To obtain a better estimate of the systematic zone errors in the catalog, we could compute orbit solutions for asteroids observed exclusively by us; however, it would take a few years to accumulate the necessary positions over sufficiently long arcs.

We have improved our level of automation over the past year. Previously, astrometry was performed by manually measuring the centroids of a dozen or so reference stars selected manually from the catalog. The resulting coordinates were then manually entered into a data file that was then processed by our software. Now we automatically extract all sources from the reference catalog (dozens to hundreds) and predict, to within a small offset that depends on the pointing accuracy of the telescope, the pixel coordinates of each source. Once shifted to align the actual and predicted pixel coordinates, software automatically determines the centroids of each reference source along with any asteroids. In most cases we still need to tell the centroiding software the length and orientation of the reference star trails that usually result from a long exposure on a moving target, and we still need to add manually the pixel coordinates of any moving object we wish to measure. Software then performs the astrometric fit with an outlier rejection step. The most time-consuming part usually comes at the end when we inspect the results. If the residuals are larger than we expect, we investigate why. Invariably we'll find something that needs to be fixed manually, such as a cosmic ray hit near the asteroid, or a field star that is interfering with the image of the asteroid, or non-uniform reference star trails caused by variable transparency (clouds), and so on. When working on extremely faint targets, glitches like these are frustratingly common, as might be expected, considering the higher spatial density of faint field stars and galaxies, and the fact that the number of cosmic ray hits is proportional to the length of the exposure. This quality control step slows us down, but we believe the results are worth the extra effort. We are one of the very few astrometric programs whose results are being published by the Minor Planet Center to one extra digit of precision, and that extra digit is warranted.

Switching to mosaic CCD cameras will complicate matters, because the coordinates of the center of each CCD are not the same as the coordinates of the telescope, which is what are usually included in the headers of the images. We have written some software that can adjust the coordinates to reflect the actual location of the CCD in the focal plane relative to the optical axis of the telescope, but the software will need to be customized for each different mosaic camera that we use, and we will need to measure one image for every chip manually the first time. That is a step currently in progress.

It is worth noting that the average RMS residual for the orbit solutions of numbered asteroids observed since the availability of modern astrometric catalogs (and after outlier rejection) is about 0.65 arcsec. So in terms of area on the celestial sphere, our astrometry is about a factor of 40 better than the typical astrometry being reported for asteroids. In closing this section, we know that there are other observatories that contribute more astrometric observations of NEOs than we do. We know that there are a few observers with smaller telescopes and wider fields who are able to utilize the Tycho or UCAC2 catalogs and produce somewhat better astrometry of NEOs. And we know that a few programs (notably Tim Spahr at Mt. Hopkins, Rob McNaught at Siding Spring, and Spacewatch II) can reach magnitudes that overlap with the bright side of our magnitude distribution. However, when it comes to a combination of all three aspects, no other NEO astrometric program can match ours in terms of depth (reaching to R magnitude 25), accuracy (typically 0.1 arcsec), and number (well over 150 NEOs observed in the past year, many on two different nights, and usually with two observations on each night). We are extremely proud of these results, even though they do not represent the primary goal of this project.

Searching for Near-Earth Asteroids with Small Aphelion Distances

As we noted in our previous progress report, a crack that developed in one of the seven lenses of our focal reducer during the manufacturing process introduced a ten month delay in the delivery of that lens. Once that lens was received, fabrication of the focal reducer had to compete for shop time with other projects. The focal reducer was finally completed earlier in 2004. At that time it became possible to mate the focal reducer and its integrated shutter and filter wheel assembly with the upgraded 8192×8192 CCD mosaic camera; however, it was discovered that two of the eight devices in the mosaic were not functioning. Trouble-shooting of the camera was delayed because of competing interests of the P.I. for that project (G. Luppino). As a result, several more observing runs originally scheduled for survey work with the Wide Field Imager were rescheduled with our narrow field 2048×2048 CCD camera, which we used to perform very successful astrometric follow-up observations of NEOs, as described in the previous section.

The Wide Field Imager finally saw first light in 2004 May. One night of telescope time was scheduled for engineering of the instrument prior to be being scheduled for actual use. However, the weather did not permit any testing of the instrument on the sky that night. The first two nights of our scheduled run were also lost to bad weather. On the final night, the instrument was finally on the sky, and that night effectively turned into an engineering night as we discovered all the annoying little "teething troubles" that new instruments usually go through. Most importantly, it gave us a set of test images that we could use to develop new astrometric models for the camera. We expected some field distortion, such that linear fits would not be sufficient to achieve the inherent accuracy of the B1.0 catalog. Indeed, that was the case. We have now modified our astrometric reduction software to handle higher order distortion. Code was written and tested up to the fourth order, though in practice we have not yet encountered distortion high enough to justify using anything higher than third order. At the moment, we are fitting all coefficients to every image, which runs the risk of introducing errors wherever there are not sufficient reference sources to constrain the astrometric model. We have witnessed one instance of a half arcsecond offset being introduced to the position of a bright, numbered asteroid that fell near the outer edge of a CCD. While that error may seem insignificant to most other astrometric programs, it is a factor of five worse than we are capable of delivering and is therefore of considerable concern. We may find it necessary to take images of a dense astrometric field, find the coefficients that model the distortion, and then fix the values of the coefficients for the higher order terms, while solving only for the linear terms in each image to accommodate differential refraction and other variable effects, such as changes in image scale caused by a temperature-induced change in focal length, but until we actually try it, we won't know if keeping the higher order terms fixed will be sufficient. Such a procedure would force us to use a different set of coefficients for every detector we use, which could become as high as sixty, as will become evident in the next paragraph.

Because of the frustrating delays in the completion of the Wide Field Imager for the 2.24-m telescope, with which we expected to do the bulk of our survey work, we decided to start applying for time on other wide field imaging instruments, including SuPrime-Cam on the 8-m Subaru telescope (ten CCDs covering 34 by 27 arcmin), MegaPrime on the 3.6-m Canada-France-Hawaii telescope (forty CCDs covering a square degree of sky), and 90prime on the 2.29-m Bok telescope of the University of Arizona's Steward Observatory (four CCDs covering a square degree of sky). The first of these runs occurred in 2004 June when we had two fractional nights on Subaru and six fractional nights on the Bok telescope. Additional runs on Subaru are scheduled in August, September, and December. The CFHT time will be executed in queue mode, and we have been allocated 12 hours of high-priority time (meaning that it will be executed when the weather cooperates) to be distributed throughout the fall semester. (Note that an additional hour of CFHT time has been allocated in September specifically to recover the virtual impactor 1994 WR12, which is considered lost, but which experiences an ephemeris uncertainty minimum in September, such that it can be recovered in three MegaPrime fields.) We also have some 2.24-m time scheduled with the Wide Field Imager, but experience tells us that it would be premature to predict the condition of the instrument.

Despite variable transparency caused by clouds during the June Subaru run, we found five new objects moving faster than main-belt objects, plus three other fast-moving objects that were identified with known NEOs, in less than six hours of total telescope time. The incredible potential of this telescope and instrument combination under good weather conditions should be obvious. Follow-up observations of the Subaru discoveries were planned for the Bok telescope, where we found one more fast moving object while attempting to recover one of the Subaru discoveries. Unfortunately, two fractional nights were lost to early monsoon weather in Arizona, and the performance of the telescope was compromised on another night by high winds, which caused the telescope to shake and images to be smeared. The 90prime instrument is also having its own "teething troubles", including non-coplanar CCDs and slight tilts of the devices, causing non-uniform focus over the field, plus a clock error. We succeeded in recovering one of the Subaru discoveries, and we still have some hope that as time permits, stacking of images will permit us to go deep enough to recover a couple more. Proper stacking, however, requires a good astrometric model for the field distortion, which we did not have prior to the first run with that instrument. We are in the process of measuring the positions of known numbered asteroids that appeared in the 90prime field to determine the correction to the clock. Although we had verified the accuracy of the clock in the Linux-based user interface computer, it turns out that the 90prime instrument gets its time from a WindowsXP-based PC that controls the camera, and its clock suffered from an error of about 3 minutes.

The Apollo-type asteroid 2004 MO7 was discovered by this project on 2004 Jun 16 UT with the SuPrime-Cam instrument on the Subaru 8-m telescope. The solar elongation at the time was 71 deg, and the apparent V magnitude was 21. The motion in right ascension was 150 arcsec per hour, which made it a candidate for being an Earth Trojan asteroid, but the orbit refinement shows that not to be the case. The Minor Planet Center has computed an absolute magnitude of 18.6 for the object, and it was on the various risk pages until our July follow-up observations, when the orbit was refined sufficiently to compute a minimum orbit intersection distance (MOID) of 0.056 AU.

Whenever we find a relatively large NEO at small solar elongation, we like to investigate why the object was missed by the major surveys. That is, we are interested in finding the various ways that an asteroid can hide from the surveys, which has rather obvious implications for their ability to discover 90 percent of the population within a ten year time frame. Figure 6 shows the apparent V magnitude, solar elongation, and declination of 2004 MO7 as a function of time. The vertical dotted line corresponds to the time of discovery, and the horizontal axis extends from ten years before to ten years after discovery. Note that in 2003, the asteroid reached an apparent V magnitude of 17.7 at a solar elongation of about 145 deg. However, the declination at the time was –40 deg, putting it too far south for the northern hemisphere surveys. Prior to its southward excursion, it was north of the –30 declination limit of those surveys, as bright as magnitude 18, and at a solar elongation in excess of 90 deg for two weeks, but then the object was close to the galactic center, and those two weeks were centered on full Moon. As the figure demonstrates, the Earth-asteroid orbital geometry repeats with a period of about seven years. There are three brief excursions to solar elongations greater than 90 deg in three consecutive years, all at southerly declinations, and then the asteroid hides for four years. A very good question is how well the current NEO population models account for such pathological cases.

Figure 7 shows the orbits of both 2004 MO7 and the Earth, where the dotted lines indicate the distance perpendicular to the plane of the ecliptic. Note that almost all the orbit that lies beyond the orbit of the Earth, and can therefore theoretically put the object in the opposition region, is south of the ecliptic. Only a very short segment of the orbit is both north of the ecliptic and outside the Earth s orbit, so good northerly apparitions are indeed extremely rare.

Fig. 6 – Observability of 2004 MO7

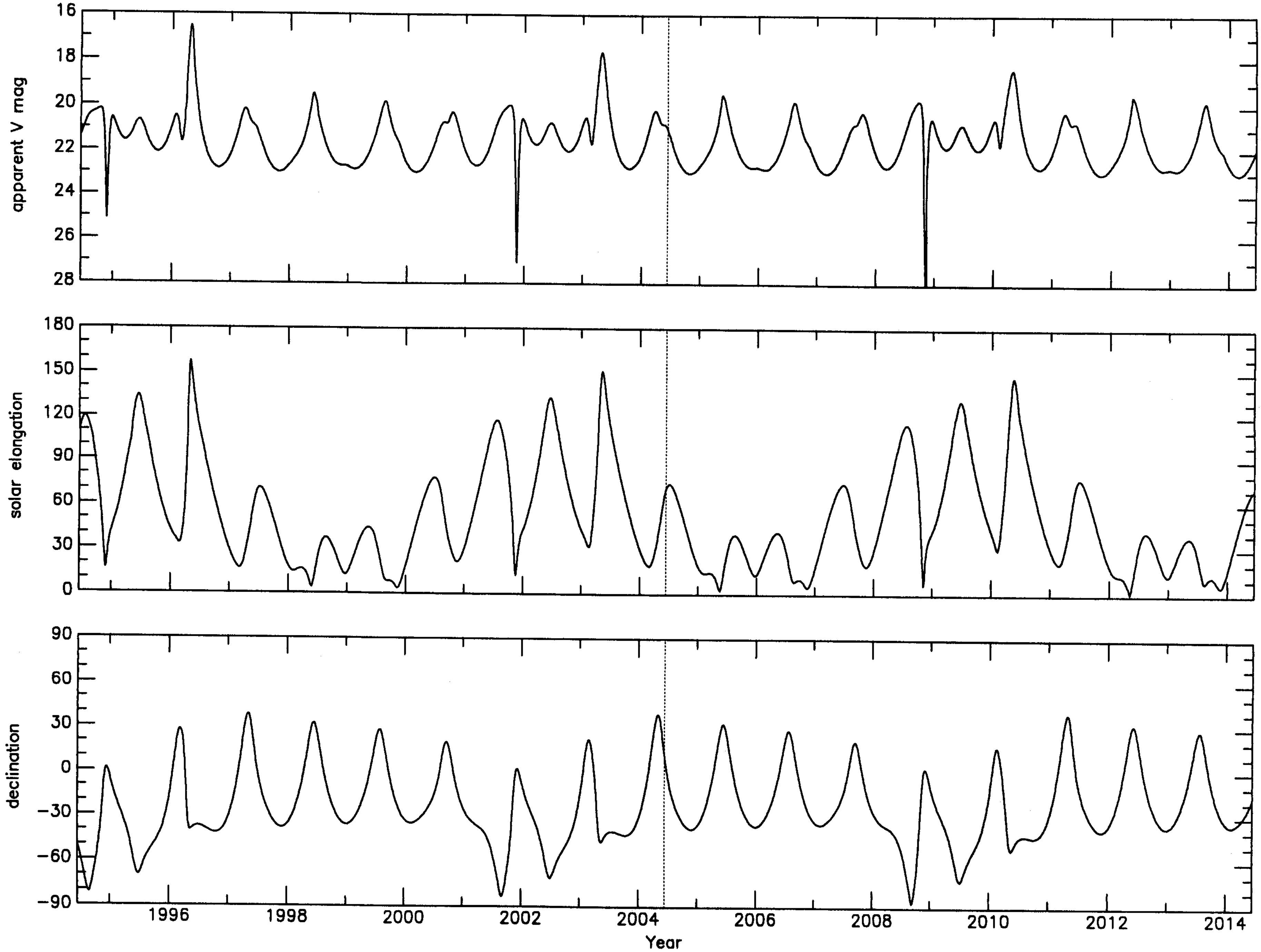
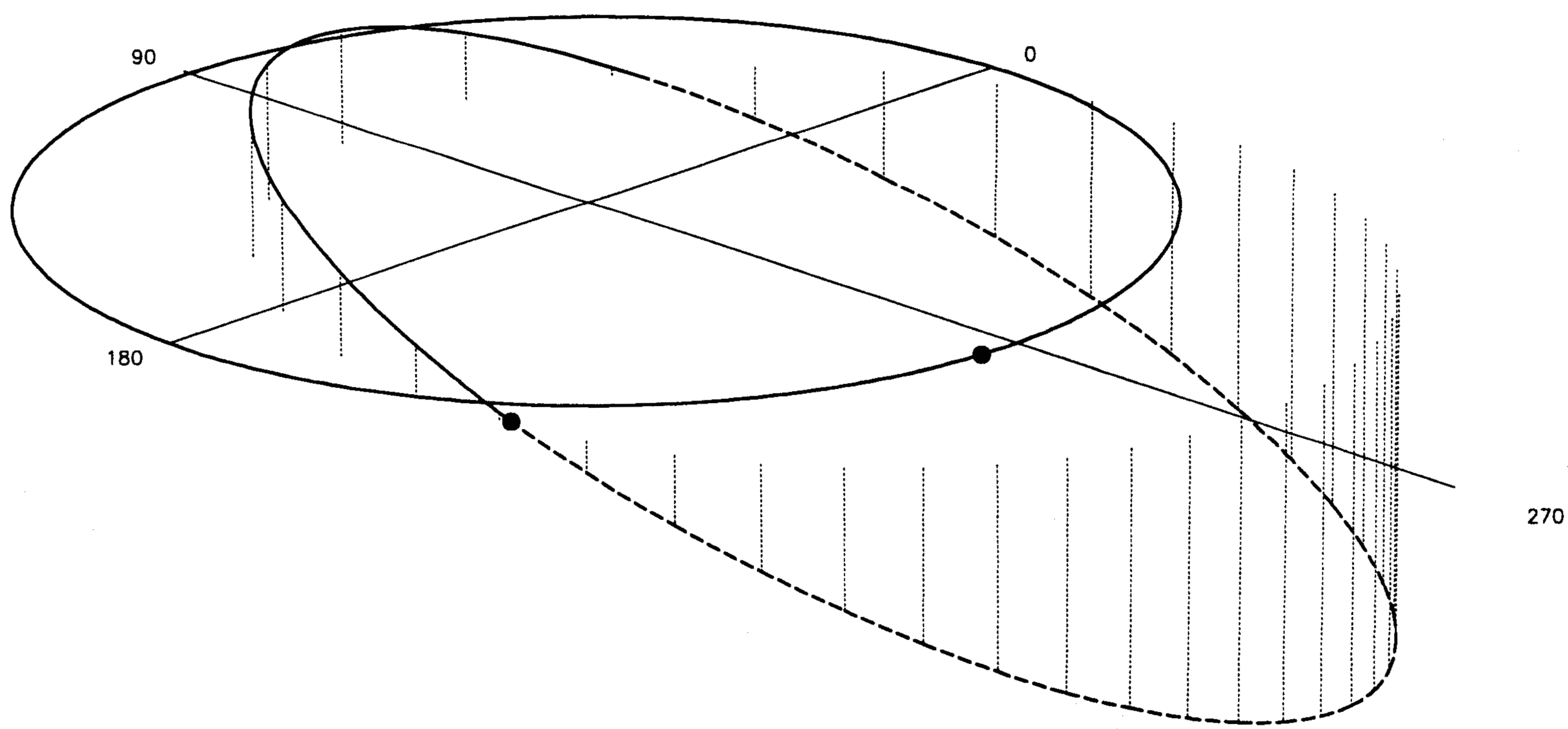


Fig. 7 — Orbits of 2004 MO7 and Earth, positions as of 2004 Jun 16



Publications

New NEO discoveries, and most, but not all, second opposition recoveries of NEOs are published on *Minor Planet Electronic Circulars*. The Minor Planet Center requires two nights of observation before issuing an MPEC for a second opposition recovery. In a few cases, the recovery was secure on the basis of just a single night of observation, so the Minor Planet Center did not issue a separate MPEC.

MPEC 2004-P40	(2004)	2003 AA
MPEC 2004-P34	(2004)	2000 AE205
MPEC 2004-P27	(2004)	2002 XM90
MPEC 2004-P18	(2004)	2003 BL1
MPEC 2004-P11	(2004)	2003 HQ32
MPEC 2004-P05	(2004)	2003 BC21
MPEC 2004-P03	(2004)	2002 OD20
MPEC 2004-O49	(2004)	2002 QE7
MPEC 2004-O46	(2004)	2003 WM7
MPEC 2004-O44	(2004)	2001 LM5
MPEC 2004-O41	(2004)	2000 RW37
MPEC 2004-O38	(2004)	2003 AD1
MPEC 2004-O36	(2004)	2000 SR43
MPEC 2004-O32	(2004)	2001 SE286
MPEC 2004-M68	(2004)	2004 MO7
MPEC 2004-J45	(2004)	1999 TC10
MPEC 2004-J44	(2004)	2000 ST20
MPEC 2004-J34	(2004)	Comet C/2004 HV60 (Spacewatch)
MPEC 2004-F59	(2004)	2002 EX11
MPEC 2004-E13	(2004)	2000 JY8
MPEC 2004-C13	(2004)	2002 AY3
MPEC 2004-B61	(2004)	2000 AC6
MPEC 2003-W25	(2003)	2001 SG10
MPEC 2003-W18	(2003)	2000 EB107
MPEC 2003-W07	(2003)	2002 XP37
MPEC 2003-V54	(2003)	2002 VX91
MPEC 2003-V37	(2003)	2002 AC
MPEC 2003-V31	(2003)	2002 CW46
MPEC 2003-V30	(2003)	2001 HW15
MPEC 2003-V29	(2003)	2002 NV
MPEC 2003-V04	(2003)	2001 DB3
MPEC 2003-U100	(2003)	2002 EQ9
MPEC 2003-U94	(2003)	2003 GU41
MPEC 2003-U75	(2003)	2002 BP26
MPEC 2003-U74	(2003)	2001 RN
MPEC 2003-U73	(2003)	2001 CA32
MPEC 2003-U29	(2003)	2000 GD147
MPEC 2003-U10	(2003)	2002 AT5

MPEC 2003-U01	(2003)	2002 AO7
MPEC 2003-T66	(2003)	2002 TB70
MPEC 2003-T60	(2003)	2001 XQ30
MPEC 2003-T17	(2003)	1999 HX1
MPEC 2003-T10	(2003)	2001 QG96
MPEC 2003-S92	(2003)	2001 TP103
MPEC 2003-S74	(2003)	2002 AR129
MPEC 2003-S68	(2003)	2002 HQ11

Astrometric observations are published in the *Minor Planet Circulars*. Note that the full batches containing observation summaries are being prepared by the Minor Planet Center with decreasing frequency (only seven batches since the beginning of 2003).

MPC 51527 (2004 May 4 batch)
MPC 50618 (2004 Feb 6 batch)
MPC 49906 (2003 Nov 9 batch)
MPC 49443 (2003 Sep 10 batch)
MPC 48642 (2003 Jun 14 batch)
MPC 47526 (2003 Feb 16 batch)
MPC 46873 (2002 Nov 20 batch)