KBO Astrometry Using Small Telescopes

**Rachel Bowens-Rubin, Katheryn Decker French,
Dora Gao, and Christina A Jaworsky
Department of Earth, Atmospheric, and Planetary Science
Massachusetts Institute of Technology
77 Massachusetts Ave
Cambridge, Massachusetts 02139 USA**

Received: April 6, 2010

Accepted: April 30, 2010

ABSTRACT

CCD images of Makemake (2005 FY9), the second largest Kuiper Belt Object (KBO), were taken with a 14-inch telescope during the summer of 2008. The position of Makemake was found by comparing its position on the frames to UCAC2 stars in the frame. Observations were limited by the tracking capabilities of the telescopes and atmospheric limitations. The average right ascension offset from the ephemeris was found to be 0.0134 ± 0.3394 arcseconds, and the average declination offset was found to be -0.3855 ± 0.4634 arcseconds. It is possible to do KBO astrometry with small telescopes, however several hundred frames are required to equal the quality of observations on larger telescopes.

I. INTRODUCTION

The study of the Kuiper Belt is an important and relatively new field of planetary astronomy. Although theorized in the 1950s by Edgeworth [1] and Kuiper [2], the first Kuiper Belt Object (KBO) was discovered in 1992 [3]. Since then, many more have been discovered. Understanding the Kuiper belt is essential to understanding solar system dynamics and evolution.

Precise astrometry and determinations of orbits, sizes, and shapes of KBOs are necessary to increase our knowledge of the Kuiper Belt. One important method for determining information about KBOs is to observe a stellar occultation. In order to predict an occultation, the astrometry must be precise to within the angle subtended by the KBO. A large KBO will subtend an angle of around 0.02 arcseconds [4].

Previous research in the field of KBO astrometry has required the use of large telescopes over long periods of time. Makemake was discovered using a 1.2-m telescope for 6 nights over the course of 2 months [5]. The Deep Ecliptic Survey [6-7] made use of a 4-m telescope with the

Mosiac 8192 x 8192 pixel CCD camera. Observing on smaller telescopes, however, is often much easier and less expensive than with larger telescopes, and commonplace observations of KBOs on small telescopes should be possible. This would help solar system population studies and the recovery of KBOs discovered in searches on larger telescopes.

Until recently, 14-inch telescopes were not sensitive enough to conduct KBO astrometry, but with the newest generation of CCD cameras, it is easier to observe faint objects with small telescopes. Over the course of this project, we were able to establish a procedure for observing a KBO with R magnitude 16.9 and obtaining astrometry with a 14-inch telescope comparable to that of programs using larger telescopes.

We present astrometric results for the KBO Makemake (2005FY9) using 14-inch telescopes at the George R. Wallace Astrophysical Observatory (WAO) and STL-1001E SBIG CCD cameras. The STL-1001E cameras made it possible to observe the KBO with a small telescope. Makemake was observed over 29 nights from June to

August of 2008 and astrometry was obtained for 728 frames.

II. OBSERVATIONS

a. Equipment

Makemake was observed for a total of 29 clear nights from June to mid-August. The observations of Makemake were carried out on a 14-inch Celestron C14 Schmidt-Cassegrain telescope at Wallace Astrophysical Observatory in Westford, Massachusetts. Images were taken with an SBIG STL-1001E camera and processed using CCDSoft. The telescopes were mounted on Paramount ME mounts. Observations were made starting in June and ending by mid-August, when Makemake was too low in the sky for useful observations to be made.

b. Star Field

Nightly observations of Makemake were made in frames with a field of view of 20.5 arcminutes. Five overlapping fields of view were used for the observations as Makemake moved in the sky, shown in Figure 1.

In order to account for the motion of Makemake, while still obtaining the most accurate astrometry possible, a new field of view was used each month, centered on the midmonth position from June until August predicted by Starry Night Pro 6 and JPL's Horizons. Two transitional frames were used between the months of June and July. The frames contained an average of 20 UCAC2 reference stars, which were used in the data analysis process. The reference stars, shown in Figure 2, were spread across the entire frame to maximize the accuracy of the astrometric fit.

c. Exposure Time Calculation

The exposure time of the frames needed to be long enough to distinguish Makemake from the background, but short enough to prevent the stars from trailing. The trailing was caused by imperfect tracking of the telescope, which resulted in the stars appearing elongated. In the beginning of the summer, when Makemake was still relatively high in the sky, a series of

twenty consecutive three-minute exposures was taken. But as Makemake got lower in the sky, it was apparent that three-minute exposures were too long and were causing stars to appear elongated. As a solution, a series of 60 consecutive one-minute exposures were used for the rest of the observations. The difference in elongation is seen in Figure 3.

Although shortening the exposure time to one minute solved the elongation problem, Makemake's pixel counts were only 10 to 20 percent higher than the counts in the backgrounds. Images could not be stacked to boost the signal because the alignment process distorted the image to line stars up between frames.

d. Data Calibration

After 29 nights of observation (summary shown in Table 1), the data had to be calibrated for the reduction and analysis process. The goal of the calibrations was to remove background from the frames. For each night, dark frames were subtracted from each light image to remove extraneous signal due to dark current. In June, the autodark reduction feature in CCDSoft was used to subtract the dark frame. Autodark reduction subtracted a single dark frame taken at the beginning of the series from all the exposures in the series. However, since autodark only used one dark frame, it added unnecessary noise. Instead, ten one-minute dark frames were averaged and subtracted from the frames to dark correct the data taken in July and later. An average of ten dark frames reduced the noise added by subtracting the dark current.

III. ANALYSIS

a. Creating a Subnetwork of Stars

The first step in analyzing the images was to create a network of comparison stars for each field, which would then be used for every frame corresponding to that field. The correct field was determined from the coordinates in the fits header of one specific frame containing the field in question. Coordinates for the comparison stars were found using the UCAC catalog [8]. Due to pointing calibrations of the telescope, there was an offset between the catalog and the

Figure 1. Starfields: Field A was used for the month of June, Field B was used on July 1st and 2nd, Field C was used on July 6th and 7th, Field D was used from July 8th to July 31st, and Field E was used for the month of August. The circles indicate the position of Makemake on June 8th, July 11th, and August 12th. Consistent fields were needed from night to night in order to observe the same standard stars. This image was obtained through the Aladin sky atlas [9].

Figure 2. Sample Image: This is a sample image of the August field of view. Makemake is boxed and the reference stars are in cross hairs. The comparison stars are distributed throughout the field to produce a better astrometric fit.

Figure 3. Effect of Exposure Time: The image on the left was taken with an exposure time of 1-minute. The image on the right was taken with an exposure time of 3-minutes. Due to the telescope tracking, the stars in the 3-minute frame look elongated. Because the KBO was small, the elongation is affected by the exposure time more than in a large bright star.

Figure 4. *Left:* Before Initial Astrometric fit: The boxes show where the stars are placed in the UCAC catalog. Before fitting, the UCAC catalog does not match the actual star location. The offset is corrected by astrometric fitting. *Right:* Post Second Astrometric fit: After the second astrometric fit, the UCAC catalog and actual star positions are matched. The boxes represent the position of the stars in the UCAC catalog. The star positions are now aligned with the UCAC catalog.

Date*	Time Started*	Frames Taken	Frames Used	ExpTime (min)	Autodark	Observers
6/8	02:15	20	0	4	Yes	RBR, KDF
6/9	03:27	20	18	3	Yes	DG, CAJ
6/10	01:45	20	20	3	Yes	KDF, CAJ
6/11	01:38	20	0	3	Yes	KDF, DG
6/12	02:22	20	0	3	Yes	KDF, CAJ
6/13	02:17	20	0	3	Yes	RBR, DG
6/18	02:49	20	20	2	Yes	RBR, DG
6/21	02:46	20	0	3	Yes	DG, CAJ
6/22	01:58	36	22	1	Yes	RBR, CAJ
6/26	03:27	60	55	1	Yes	RBR, CAJ
6/27	03:25	60	0	1	Yes	DG, CAJ
6/28	01:42	42	0	1	Yes	DG, CAJ
7/2	03:00	32	21	1	No	RBR, KDF
7/3	02:05	60	57	1	No	RBR, KDF
7/7	01:54	60	60	1	No	RBR, KDF
7/8	02:14	60	58	1	No	DG, CAJ
7/9	01:54	60	33	1	No	KDF, CAJ
7/11	01:30	60	58	1	No	KDF, CAJ
7/12	01:41	60	49	1	No	KDF, CAJ
7/13	01:35	60	9	1	No	DG, CAJ
7/16	01:50	60	42	1	No	RBR, DG
7/17	01:56	60	51	1	No	DG, CAJ
7/27	01:32	60	0	1	No	RBR, KDF
7/29	01:32	57	30	1	No	KDF, CAJ
7/30	02:20	60	0	1	No	DG, CAJ
8/2	01:11	60	0	1	No	KDF, CAJ
8/5	01:12	60	9	1	No	RBR, DG
8/10	01:04	40	29	1	No	RBR, DG
8/13	00:41	40	29	1	No	KDF, CAJ

*Date and Time are in UT.

Table I. Summary of Observations. Note: Not all frames could be used due to clouds and tracking problems.

actual frame, as shown in Figure 4 (left).

To account for the offset, an initial astrometric fit was run on several stars to find a function relating right ascension and declination to the pixel coordinates. A six-parameter model using a point-spread function was used to calculate the fit. The parameters varied to create this model were plate scale, rotation angle, central RA and DEC of the chip, and two linear cross-terms for the plate scale and rotation angle.

Upon obtaining an initial astrometric fit, the next step was to achieve a more precise second fit that included more stars in the frame. As many stars as possible were included, unless they would have reduced the quality of the fit. Specifically, stars with a pixel count of over 65,535 were considered

saturated and were not included. Stars too close to the edge of the frame were likely to drop off the frame, so they also were not used. Additionally when two stars were very close together, they were not included because the point-spread functions were not separable. The second fit generated a final network of stars with the right ascension, declination, for the center pixel of the network (Figure 4 right).

b. Star Centroiding

In order to obtain a more accurate position for each star, the center of the star was determined and substituted for the value found in the second fit. Using the subnetwork generated previously from the

second fit, the entire centroiding and fitting process was repeated using the new network instead of the UCAC catalog. Using the specific subnetwork of stars narrowed the initial offset error between the center of the star in the frame, and the center of the star in the network, and thus made for an easier calibration on the individual frames. The right ascension and declination of the subnetwork was updated for the time of each frame. The updated time allowed for a direct correlation between the map of the sky at a specific time in the night (when the frame was taken) and the right ascension and declination of the center of the frame to be established.

Because each frame shifted with respect to the other frames (and the reference subnetwork), minor calibrations were still required. By manually inputting the pixel coordinates of a specific reference star, the offset was determined. The shift in pixel coordinates was applied to the rest of the frame using a point spread function for each star, which then located the center of each star.

c. Astrometric Fitting

After the centroiding process, a third

astrometric fit was run on each frame to establish a function between the pixel corresponding to the center of the star and its known right ascension and declination. As before, the same six-parameter model was used. This model had a typical error in RA and DEC of 0.07 arcseconds. Any frames with an error larger than 0.12 arcseconds were discarded to keep the data set as consistent as possible.

A final point-spread function was applied to locate the exact center of the KBO. Frames where the KBO was elongated or near hot pixels, such as the examples in Figures 3 and 5, were discarded. The center of the KBO in pixel coordinates was then mapped to a right ascension and declination using the third astrometric fit.

IV. DISCUSSION

When the results from the analysis (Figures 6 and 7) were compared to those found by the MIT ECM (Ephemeris Correction Model) (Figures 8 and 9), the residuals between the observed and predicted ephemerides were found to be consistent. The RA offsets were close to

Figure 5. The Effect of a Hot Pixel: Makemake when it is near a hot pixel. Before centering (left), Makemake was centered and the hot pixel was at the bottom of the frame. Since the hot pixel had higher counts than Makemake, the point spread function recorded it as the center of the KBO. So, in the centered frame (right), the hot pixel appeared in the center, while the KBO was shifted up. Frames like these had to be discarded because the astrometric fit would not be performed on Makemake.

Figure 6. Makemake RA Residuals Over Time: The residuals for the RA are consistently near zero, though they vary greatly. Makemake's observed RA is close to the prediction by the ephemeris.

Figure 7. Makemake DEC Residuals Over Time. The Residuals for the DEC are consistently negative. Makemake was observed to be slightly south of the predicted ephemeris.

Figure 8. Makemake MIT RA Ephemeris Correction Model: The RA residuals predicted by the MIT ephemeris correction model are close to zero, which is consistent with the observed positions.

Figure 9. Makemake MIT DEC Ephemeris Correction Model: The DEC residuals predicted by the MIT ephemeris correction model are slightly negative, which predicts that Makemake should be slightly south of the Minor Planet Center ephemeris. The DEC residuals are again consistent with the observed positions.

Figure 10. Makemake RA Position Errors Over Time: The error in right ascension plotted for each night of images was smaller for nights at the beginning of the observing period. This is believed to be caused by a combination of longer exposure times and lower air masses.

Figure 11. Makemake DEC Position Errors Over Time: The error in declination appears to follow the same trend as the right ascension error. The error at the start of the observing period is lower overall than the end.

zero in both models, and the DEC offsets were consistently negative. The RMS of the RA offset was 0.33 when compared to the JPL Ephemeris, and 0.30 when compared to the MIT ECM. The RMS of the DEC offset was 0.46 when compared to the JPL Ephemeris and 0.26 when compared to the MIT ECM. This confirms that the observed DEC values were closer to the MIT ECM than to the JPL Ephemeris.

IV. ERROR ANALYSIS

There were five main sources of error analyzed in the data. The total error can be seen in Figures 10 and 11. One of the most significant sources of error was the Earth's atmosphere. The error was predicted to be higher at higher airmasses, when the object was low in the sky. A strong trend was not generally observed for a single night (Figures 12 and 13), but the trend of increasing error with increasing airmass was clearly visible over the course of all of the observations (Figures 14 and 15). This is believed to be because observations were only taken over short ranges of airmasses for any given night. The plot of the error over the course of all observations covers a wider range of airmasses, and so a stronger correlation can be seen.

High solar altitudes were a source of error for some nights. Towards the end of the observing period, Makemake was setting early in the night, and there was only a short time window between sunset and when Makemake set. In an attempt to get more images, observations were made before astronomical twilight on some nights. A clear trend of increasing error with increasing solar altitude was observed when the solar altitude was above -14 degrees (Figures 16 and 17). When data was taken after the sun was below -14 degrees, solar altitude was not a source of error, but its effects can be seen for nights such as July 11th, 2008 (Figures 18 and 19) when data was taken starting at a solar altitude of -11 degrees.

The random error in our data was analyzed by studying its change with exposure time (Figures 20 and 21). As expected, the error was less in 3-minute exposures than in 1-minute exposures. The mean RA error was 0.212 for the 60-second exposures, and 0.124 for the 180-second

exposures. The mean DEC error was 0.183 for the 60-second exposures and 0.106 for the 180-second exposures.

The quality of the astrometry of the images was found to depend on the number of stars used in the fit (Figures 22 and 23). To reduce the error, images were not used if less than 9 stars were available for the fit.

The overall error was greater for the right ascension measurements than for the declination measurements. For the 60-second exposures, the mean RA error was 0.212, and the mean DEC error was 0.183. This was most likely caused by slight imperfections in the Paramount telescope mount tracking accumulated over time. Imperfect tracking could have caused the images to be slightly blurred during an attempt to point at a steady right ascension coordinate. This effect would have affected the right ascension astrometry measurements more than the declination measurements, which is consistent with our calculated errors.

I. RECOMMENDATIONS FOR FUTURE WORK

The following recommendations are made to those wishing to carry out similar astrometry measurements on KBOs with small telescopes.

- Take images with the maximum exposure time possible without saturating stars to be used in the astrometry fit. With the equipment used here (described in Section 1), this was around 180 seconds.
- Do not start taking data until the sun is more than 14 degrees below the horizon. Although more frames can potentially be obtained this way, it is a large source of error.
- Similarly, observe the KBO through as little airmass as possible.
- Choose a field of view around the KBO with the most stars that can be used to make an astrometric fit.

VI. CONCLUSIONS

The possibility of using small telescopes for KBO astrometry measurements opens the door for more work to be done in the field. Despite the fact that using a larger telescope naturally

Figure 12. Makemake RA Position Errors vs. Airmass for July 12th, 2008 (UT): The error vs. airmass for the night of July 11th, 2008 shows no strong correlation.

Figure 13. Makemake DEC Position Errors vs. Airmass for July 12th, 2008 (UT): The error vs. airmass in one night of observing had a weak trend.

Figure 14. Makemake RA Position Errors vs. Airmass: RA error increased with higher airmasses as expected. Images taken though airmasses above 2.3 resulted in significantly more error than those below.

Figure 15. Makemake DEC Position Errors vs. Airmass: Like RA error, DEC error also increased with higher airmasses as expected. Images taken through airmasses above 2.3 resulted in significantly more error than those below.

Figure 16. All Nights Makemake RA Position Errors vs. Solar Altitude: The RA error for each solar altitude was found to be higher for altitudes above -14 degrees and fairly consistent below -14 degrees. Several nights of images were affected by higher errors resulting from observations taken too early in the night.

Figure 17. All Nights Makemake DEC Position Errors vs. Solar Altitude: The DEC error for each solar altitude was found to be higher for altitudes above -14 degrees and fairly consistent below -14 degrees, similar to the RA error. Several nights of images were affected by higher errors resulting from observations taken too early in the night.

Figure 18. Makemake RA Position Errors vs. Solar Altitude for July 11th, 2008 (UT): For the night of July 11th, 2008 observations were taken starting at a solar altitude starting at -11 degrees (right side of graph). The RA error at solar altitudes between -11 and -14 degrees was observed to be greater than the error at lower solar altitudes. This night was atypical and the effect of solar altitude was insignificant in the error in the majority of nights of the observations.

Figure 19. Makemake DEC Position Errors vs. Solar Altitude for July 11th, 2008 (UT): For the night of July 11th, 2008 observations were taken starting at a solar altitude starting at -11 degrees (right side of graph). The DEC error at solar altitudes between -11 and -14 degrees was observed to be greater than the error at lower solar altitudes. This night was atypical and the effect of solar altitude was insignificant in the error in the majority of nights of the observations.

produces less error, it is more practical to use a small telescope and reduce the error by taking many frames. More extensive surveys are possible with smaller telescopes, because observing time is more accessible and less expensive. Although Makemake is one of the brightest KBOs, this process could potentially be done for dimmer KBOs as well. We would like to see small telescopes used to calculate and correct the ephemerides of many KBOs.

ACKNOWLEDEMENTS

We would like to thank James Elliot for his support of our project and advice, Alan Midkiff for his help at Wallace Observatory, Jane Connor for her writing suggestions, and Elizabeth Adams and Matthew Lockhart for their help in observations planning and data reduction.

Figure 20. Makemake RA Position Errors vs. Exposure Time: The RA error was less for greater exposure times. This is expected because the error is proportional to the square root of the number of photons received.

Figure 21. Makemake DEC Position Errors vs. Exposure Time: The DEC error was less for greater exposure times, similar to RA. This is expected because the error is proportional to the square root of the number of photons received.

Figure 22. Makemake RA Position Errors vs. Number of Stars Used: The RA position error showed a slight dependence of the number of stars used in the astrometric fit. The error was lowered as more stars were used.

Figure 23. Makemake DEC Position Errors vs. Number of Stars Used: The DEC position error showed a slight dependence of the number of stars used in the astrometric fit. The error was lowered as more stars were used.

REFERENCES

1. Edgeworth, K. E. 1949. The origin and evolution of the Solar System. *MNRAS* 109, 600–609.
2. Kuiper, G. P. 1951. On the Origin of the Solar System. *Proceedings of the National Academy of Science* 37, 1–14.
3. Jewitt, D., J. Luu, and B. G. Marsden 1992. 1992 QB1. *IAU Circ.* 5611, 1–+.
4. Elliot, J. L., and S. D. Kern 2003. Pluto's Atmosphere And A Targeted-Occultation Search For Other Bound KBO Atmospheres. *Earth Moon and Planets* 92, 375–393.
5. Brown, M. E., C. A. Trujillo, D.

- Rabinowitz, and B. G. Marsden 2005. 2005 FY9. Minor Planet Electronic Circulars, 42–+.
6. Elliot, J. L., S. D. Kern, K. B. Clancy, A. A. S. Gulbis, R. L. Millis, M. W. Buie, L. H. Wasserman, E. I. Chiang, A. B. Jordan, D. E. Trilling, and K. J. Meech 2005. The Deep Ecliptic Survey: A Search for Kuiper Belt Objects and Centaurs. II. Dynamical Classification, the Kuiper Belt Plane, and the Core Population. *AJ* 129, 1117–1162.
 7. Millis, R. L., M. W. Buie, L. H. Wasserman, J. L. Elliot, S. D. Kern, and R. M. Wagner 2002. The Deep Ecliptic Survey: A Search for Kuiper Belt Objects and Centaurs. I. Description of Methods and Initial Results. *AJ* 123, 2083–2109.
 8. Zacharias, N., S. E. Urban, M. I. Zacharias, G. L. Wycoff, D. M. Hall, D. G. Monet, and T. J. Rafferty 2004. The Second US Naval Observatory CCD Astrograph Catalog (UCAC2). *AJ* 127, 3043–3059.
 9. Bonnarel, F., P. Fernique, O. Bienaymé, D. Egret, F. Genova, M. Louys, F. Ochsenbein, M. Wenger, and J. G. Bartlett 2000. The ALADIN interactive sky atlas. A reference tool for identification of astronomical sources. *A&AS* 143, 33–40.

UNI Physics provides students with the personal mentoring typical of smaller colleges but adds the resources of a larger research university. Students and faculty work together on research projects, and students have the opportunity to continue research during summers as paid Undergraduate Research Fellows in Physics.

www.uni.edu/physics

Why Sigma Xi?

THE HONOR SOCIETY FOR SCIENTISTS AND ENGINEERS

<p>Gain professional credentials</p> <p>Being active in Sigma Xi demonstrates to employers and graduate schools that you have achieved a high standard of excellence. As a member of this prestigious society, you join the company of over 180 Nobel Prize winners and other distinguished scientists and engineers.</p>	<p>Receive research funding</p> <p>Twice annually, the Sigma Xi Grants-in-Aid of Research program awards research grants to nearly 1,000 graduate and undergraduate students. As a Sigma Xi member you will be eligible to apply for grants from all available funds.</p>	<p>Build your professional network</p> <p>Gain valuable leadership experience and make career contacts. Through local chapters, Sigma Xi provides a unique platform for interacting within a multi-disciplinary community of researchers, educators, administrators and others, both within and outside your institution.</p>	<p>Become a lifelong learner</p> <p>Stay current in all fields with <i>American Scientist</i>, Sigma Xi's award winning magazine. As a member benefit, your <i>American Scientist</i> subscription is a valuable resource that offers articles in a variety of disciplines, resources and a comprehensive book review section.</p>	<p>Contribute to the scientific community</p> <p>Sigma Xi members form a powerful international network at over 500 institutions. Through individual members and chapters, Sigma Xi addresses ethics, education, advocacy for research funding, public understanding of science, diversity and international networking.</p>	<p>Have fun</p> <p>Build community and a sense of belonging with other scientists at your institution. Get involved in a special event with the help of others at your local chapter.</p>
--	--	--	---	---	--

Recent chapter events have included:

- Student research symposia
- Outreach and mentoring
- Workshop series
- Social events
- Resource activities for K-12 students and teachers
- Awards for outstanding teaching and research
- Lecture series

www.sigmaxi.org

Sigma Xi, The Scientific Research Society • 99 Alexander Drive • P.O. Box 13875 • Research Triangle Park, NC 27709 • 919-548-4691 • 800-243-6534