THE GEO ENVIRONMENT AS DETERMINED BY THE CDT BETWEEN 1998 AND 2002

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ABSTRACT

The National Aeronautics and Space Administration (NASA) observed the geosynchronous environment (GEO ~36000 km) with the 0.6m CCD Debris Telescope (CDT) at Cloudcroft, NM, between January 1998 and December 2001. The datasets have been analyzed on a year-to-year basis; this paper will inter-compare the datasets to examine similarities and differences of the annual results. The CDT was operated in a GEO stare mode reaching a limiting magnitude of 17th which corresponds to a limiting diameter for a ~60 cm sphere (assuming a specular reflection and a 0.2 albedo). Observational and reduction techniques have improved over the CDT performance and analysis period. The entire CDT dataset has now been uniformly corrected for observed range, phase angle, and solar distance. The complete GEO dataset for the CDT will be presented in the context of distributions such as inclination, Right Ascension of the Ascending Node (RAAN), mean motion, and magnitude (size). Fluxes will be addressed in a subsequent paper.

1. INTRODUCTION

Understanding the evolving debris environment is essential if the human race continues to venture into space. Of particular interest is the geosynchronous environment where satellites have been placed since the 1960s. Debris in Geosynchronous Earth Orbit (GEO) has a potential for collision with operational satellites due to the extremely long lifetimes of the debris. The CCD Debris Telescope (CDT) conducted systematic searches of the GEO environment to help characterize and determine the extent of the debris found in this volume of near Earth space. The observations provided distributions in brightness, mean motions, inclination, ranges, and Right Ascension of Ascending Node (RAAN) of detected debris. Yearly reports (NASA/JSC publications) described details of the observing program and observed distributions. Following is a summary and inter-comparison of those observations whose observed magnitudes, in addition to observed range correction, have now also been corrected for a standard solar distance and a Lambertian phase function at a phase angle of 0°. Orbital elements were derived from two or more astrometric positions based on the assumption of a circular orbit (eccentricity = 0°). Using these assumed circular orbit (ACO) elements for both correlated targets (CTs) and uncorrelated targets (UCTs), we will define the dimensions of a GEO environment to be between 34000 km and 40000 km and 0° and 17° inclination. The scope of the paper is limited to the population distributions of the UCTs found in this limited GEO environment.

2. CDT DESCRIPTION

The CDT, a 32-cm Schmidt telescope, was equipped with a SITe 512 X 512 CCD camera. The pixels were 24 microns square (12.5) arcseconds) resulting in a 1.7° by 1.7° field-of-view. The actual observing sequence consisted of a series of four exposures taken of approximately the same field. Each exposure was 20 seconds in duration with a 15 second "dead time" between exposures used to read out the CCD and to reposition the telescope. On average, 250 fields were collected per night, or 1000 individual images. The CDT system was shut down at the end of 2001. Subsequently, NASA has transferred the CDT to the Aerospace Engineering and Physics Departments of the Embry-Riddle University in Arizona where it will be used as a teaching tool.

3. SEARCH STRATEGY

The CDT used a search strategy optimized to collect data at low solar phase angle where objects should be brightest. By observing near the GEO belt, most uncontrolled objects will sooner or later pass through the field-of-view. The CDT observed a strip of GEO space eight degrees tall, centered at minus five degrees declination (the GEO belt as viewed from Cloudcroft). This observational strip either led or followed the Earth's shadow by about ten degrees. The actual length of the strip depends upon the length of the night and the elevation of the Earth's shadow. The search pattern started in the east and gradually moved to the west, tracking the Earth's shadow.

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Studies have shown that the orbits of uncontrolled GEO objects oscillate around the stable Laplacian plane, which has an inclination of 7.5 degrees with respect to the equatorial plane. Numerous studies provide compelling arguments that most uncontrolled debris objects in GEO should be at inclinations less than or equal to 15 degrees (Vaughn, et al 1995). This oscillation is dominated by the combined effects of the Earth's oblateness (J2 term) and solar and lunar perturbations. The inclination oscillation period is ~50 years. Plots of the daily motion for cataloged GEO objects (right ascension (RA) vs. declination (DEC) as viewed from Cloudcroft) show that most objects are grouped on one side or the other of the GEO belt at any given time. Using this knowledge, the search strategy was altered to provide higher object count rates and sometimes to observe in areas where no significant objects were expected, to confirm or refute this belief.

4. OBSERVATIONAL DATASETS

4.1. Data Processing and Summary Reports

The final data reduction software packages produced astrometric positions for each detection that were fitted under the assumption of a circular orbit to produce inferred values for the inclination, range, mean motion, and RAAN. The visual magnitudes reported refer to the magnitude of the first detection of an object and are transformed instrumental magnitudes to the Johnson V magnitude system by comparison to field stars. These V magnitudes were corrected to a standard range of 36,000 km, standard solar distance of 1 astronomical unit (AU) and corrected for the observed phase angle using the assumption of a Lambertian phase function at 0°. The corrections for solar distance were less than ±0.03 mag. On average the change in the correction for phase angle was less than ±0.10 mag. The CT magnitudes are now more accurate compared to previously published values because the actual predicted orbital range is used instead of the range inferred from the assumption of circular orbits. The difference in the range correction for the "limited" GEO environment is less than ±0.15 mag. UCT magnitudes were range corrected using their ACO range. These photometric corrections follow the procedures given by Barker, et al. (2004) and Africano, et al. (2005, this conference). These corrections provide a uniform photometric system to compare observations and derive optical cross sections for the objects. We defer to discussions within these papers to describe all the caveats and assumptions regarding photometric systems. CDT absolute magnitudes are uncertain by at least ±0.4 due to intrinsic photometric errors.

The four calendar years (CY) are summarized in Tab. 1 where the objects with known US Space Surveillance Network (SSN) numbers are denoted as CTs. Those objects without known orbital elements or assigned SSN numbers are designated as UCTs. Details of the observational periods and nightly data logs can be found in the yearly published reports (Africano, 2000; Jarvis, 2001, 2005a, 2005b). Portions of the CDT datasets have been presented earlier (Africano, et al 2001, Jarvis, et al 2003). The detections are reported as unique per night (UPN) as all detections of the same object within one night were used in calculating the assumed circular orbit elements. UPN indicates that regardless of how many frames within a night an object appeared, it was counted only once. No attempts were made to link targets between nights. The 1998 dataset is not complete as some of the older datasets will require additional processing.

Table 1. Observational Summary

Calendar Year (CY)	# of Nights	On-sky hours	# of Detections (UPN)	# of CTs (UPN)	# of UCTs (UPN)
1998	58	~255	5765	4606	1159
1999	81	~530	5746	4829	917
2000	48	~255	3416	2983	433
2001	53	~380	3894	3307	587

4.2. Detection Rates

On average, as seen in Tab. 2, ~61% of the fields contained no detections while ~39% had at least one object detected per field. In both 2000 and 2001, non-GEO and less populated GEO regions were examined to hunt for objects in unanticipated orbits.

Table 2. CDT fields with detected objects

# of Obj in Field	1998		1999		2000		2001	
	Fields	%	Fields	%	Fields	%	Fields	%
0	5864	56	5855	58	4993	59	8490	69
1	2764	26	2486	25	2158	26	2377	19
2+	1844	18	1693	17	1295	15	1354	12

In general these fields had large solar phase angles, thus the objects were fainter on average leading to a lower detection rate.

4.3. NOSEE discussion

Data reduction included predicting which known satellites from the United States Satellite catalog will be seen in which frame. If a satellite was predicted to be present but evidence for its presence was not found, it was listed as a "nosee". There are multiple potential reasons for an object's non-detection. It is important to understand why an object (either a CT or UCT) was not seen as it will aid in the understanding of the debris environment and the limits of this method of analysis. Lack of detection of an object does not necessarily mean it isn't present; it can indicate a change in the orbital elements or even below a limiting magnitude.

Fifty-eight nights in the 1998 dataset were examined in detail to help better understand the significance of nosees in the debris environment. Conclusions of that nosee study (Jarvis, et al. 2001) were: 1% of the nosees remained unexplained; 99% of the nosees were explained by (1) motion too fast across field due to high mean motion or inclination; (2) field of view insufficient to capture full length of streak; (3) epoch of prediction two-line element (TLE) more than 20-30 days from observation time; (4) obscuration by stellar image streak; (5) variation in magnitude, flashing or non-photometric conditions; (6) less than 2 detections in frame set due to (1, 2, 4 or 5); (7) below limiting magnitude due to viewing geometry, albedo, and shape.

When compared to the total number of CTs (UPN) in GEO orbit seen in the 58 day sample the nosee rate was ~1%. As observational and data reduction techniques significantly improved for the following 3 datasets, an upper limit to the nosee rate for this program is less than 1%. Additionally, we will assume that the nosee rate is the same for UCTs as for CTs because we missed seeing a portion of the UCT population for many of the factors listed above. This assumption may have problems because UCTs are systematically fainter than CTs. This assumption could also be complicated by the photometric variations due to complex shapes and tumbling rates see(Africano, et al 2005 this conference).

5. DEFINITION OF GEO ENVIRONMENT

The goal of the CDT program was to define the debris environment in the geosynchronous region of near Earth space. All of the detections on a given night have been fitted to circular orbits as part of the reduction process. In this section we will use the orbital elements for CTs determined via the circular orbit assumption method (ACO) with those elements determined by the SSN observations (TLEs) to define the GEO environment. Since the UCTs have only ACO determined elements, there is a need to test the validity of the use of these elements to define the distributions of UCTs. Comparison will be made between the range, inclination, mean motion, RAAN and eccentricity (ACO ecc=0°) of these objects. Fig. 1 compares the inferred or ACO range with the known or TLE range for the entire dataset of CTs observed in 2001. Since the ACO ranges are not valid for non-GEO orbits (i.e. objects having eccentricities > 0.1), all the points do not fall on the straight line. The CT distribution presented in Fig. 1 contains "true" GEO objects as well as those with high inclinations (Molniya, sunsynchronous) and objects with large eccentricities that are in transition from low Earth orbits to GEO and above (supersynchronous and GTO orbits).

Several investigations of the CT distributions were undertaken to test a definition of GEO space; {eccentricity < 0.04, inclination < 17°, and ACO ranges between 34,000 and 40,000 km}. When these definitions {} were applied to the 2001 dataset, only the objects shown in Fig. 2 remained. Similarly, the 1998, 1999 and 2000 CDT datasets were limited to this definition {} of GEO. Remainder of this paper is devoted to discussion of these subsets (~ ½ of detections) of the entire CDT dataset which hereafter is denoted by {}.

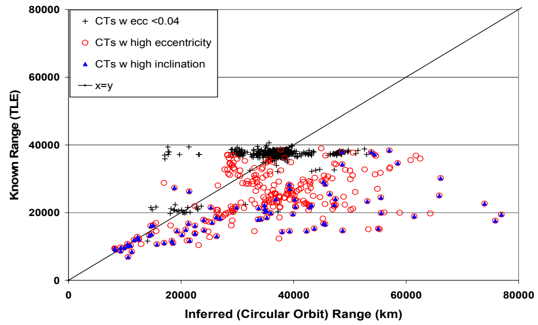

Figure 1. Known vs. ACO ranges for CTs in 2001.

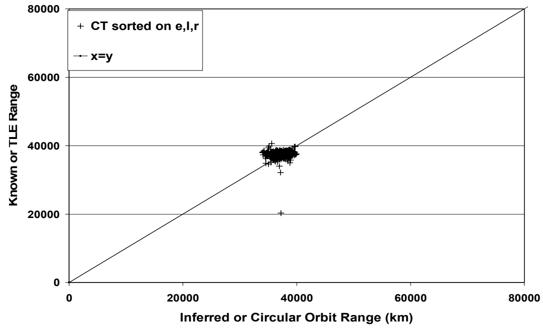

Figure 2. CTs within GEO limits {} in 2001.

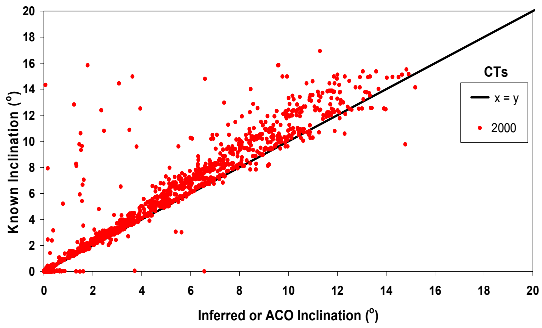

Figure 3. Known vs. ACO Inclinations within GEO {}.

Fig. 3 demonstrates the inclination errors introduced by using ACO elements. A bias is noted in all four years in that the ACO inclination is systematically smaller than the true inclination. Preliminary investigations into the cause of this bias and scatter above the x=y line show the magnitude of the inclination error is inversely related to the time between observations which were used to determine the circular orbital elements. Our goal is to investigate these biases as they are identified. The mean motion and RAAN distributions were similar over the 4 year period, but due to the uncertainty in determining the RAAN values for low inclinations, neither the RAAN nor mean motion distributions were used in defining additional limits.

6. APPLICATION OF GEO CRITERIA or { }

6.1. Application of GEO Limits on Distributions

How good is the assumption of circular orbits for the CT and UCT populations? When we applied the GEO limits {e<0.04, I<17° and range [34-40,000km]} to the yearly datasets we calculated differences or errors introduced by assuming circular orbits. We can use these differences between the values of the known and ACO orbital parameters to assess the accuracy of the circular orbit assumption for the UCTs for which we have only ACO derived orbital parameters.

Table 3. Differences or Errors between the Known and the ACO Orbital Parameters

Year	1998		1999		2000		2001	
Parameter	Ave err	± stdev	Ave err	± stdev	Ave err	± stdev	Ave err	± stdev
Ecc.	-0.0001	0.003	-0.001	0.003	-0.003	0.004	-0.0013	0
Range(km)	-23	1038	-15	757	-7	495	-28	702
Inc (°)	-0.3	1.1	-0.3	1.7	-0.4	1.1	-0.3	1.8
MM (rev/day)	0.002	0.03	0.001	0.03	0.001	0.02	0.001	0.03
RAAN (°)	10	82	11	88	11	86	9	82

Tab. 3 details the average errors and their standard deviations for each year. In all cases the average errors are smaller than their standard deviation (stdev) which suggests utilizing the ACO values to interpret the distribution of UCTs will not introduce large errors.

Analysis of each yearly dataset showed that the sample of the GEO population defined by the ACO range included at least 95% of the sample defined by the known range values for the CTs and vice versa**.** For each year we examined the set of CTs as defined by the eccentricity, inclination and either the known or ACO ranges. Less than 2% of the core population was not common to both the known and ACO populations. Most of the non-members were either on the boundaries of the limits or had very large eccentricities or inclinations implying these CTs were GTO objects going through the GEO belt region. In summary, the assumption of circular orbits for those objects within the GEO limits {} is valid and can be used to define the low eccentricity GEO population of UCTs. The high eccentricity UCT population reported by several observers is approximately 1-2 magnitudes fainter than the CDT could detect.

6.2. Repeatability Analysis

Objects that were seen by the CDT more than once in an observing year are termed "repeaters". By understanding the causes behind repeaters we can better judge our percent chance of seeing objects based upon whatever biases may apply (i.e. magnitude, orbital elements, etc), thus enhancing our population modeling. No attempt was made to correlate UCTs between nights in the CDT program; so we need to understand statistically how many of the UCTs are potentially repeat detections. Since the orbital behavior of non-functioning spacecraft should have the same form as debris, (within limits of the effects as related to area-to - mass ratios), we divided the CT population into two subsets, functioning and non-functioning. CTs that were non-functional at the end of a calendar year were listed as non-functional for the entire year. It is a reasonable assumption that it will take a few months for a CT to become completely free from the station-keeping momentum changes and begin drifting only under the gravitational forces, however a later study may consider these "transitional objects" in greater detail. As noted in Section 3, uncontrolled or non-functional CTs should drift to higher inclinations as they are perturbed by gravitational forces. They should reach a maximum of 15° before decreasing as part of their 50 year inclination oscillation. The non-functional and functional distributions of CTs are shown in Fig. 4 for 2000 (other years had similar distributions).

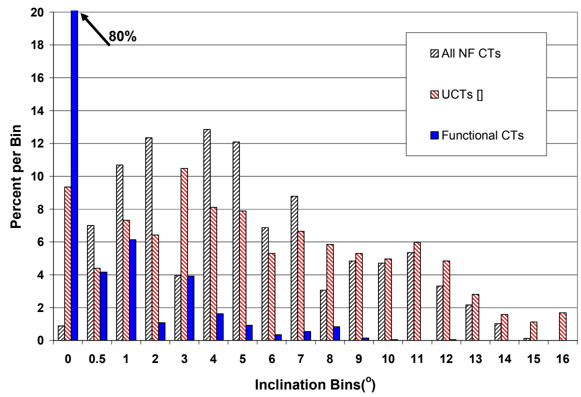

Figure 4. Inclinations for functional and non-functional CTs within GEO {} for 1998.

Approximately 85% of the functional CTs had inclinations less than 1° and none above 10°, whereas the non-functional CTs had broad peaks in the 2-3° and 10° inclination regions. The non-functional dataset was binned into four bins according to the number of times a CT was detected during the year. The distribution of non-functional CTs (Fig. 5) that repeated more than 10 times peaked at lower inclinations when compared to the distribution of the CTs that repeated 1-4 times. In general, the distribution of non-repeaters was zero below 6° inclination and effectively flat above 7°, but as shown in Fig. 5 the distribution was subject to small number statistics where there were only a total of 9 non-repeaters.

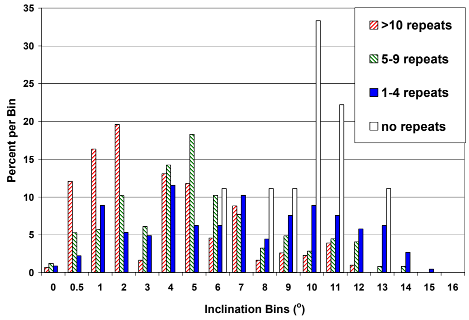

Figure 5. Repeat non-functional CT detections in 1998.

The statistics of the repeater analysis are presented in Tab. 4. In the next to last column are the numbers of UCTs detected and in the last column the number of UPY (unique per year) UCTs that exist if we apply the repeatability factor derived for each year.

Table 4. Repeatability statistics for Non Functional CTs within the ACO/GEO limits

Year	# of NF CTs	Ave no. of repeats	% Detected	UPY CTs	# of UCTs	# of UPY UCTs
1998	786	6.61	15	119	711	108
1999	782	5.47	18	143	707	129
2000	622	4.23	24	147	368	87
2001	784	5.56	18	141	325	58

The average number of 96 UPY UCTs (within the limits of the CDT's sensitivity) over the four year period is in excellent agreement with the statistically estimated number of 100 (Matney et al. 2002).

This section presents sample distributions which are representative of the four year set of distributions. Fig. 6 illustrates that UCT ranges peak between 38,000 and 39,000 km and the distribution closely follows that of the CTs within the limited GEO range {}.

Fig. 7 demonstrates the changes in the UCT population as defined by the angular momentum vector. While the UCT distribution has more scatter than the corresponding yearly CT distribution, the drift of the angular momentum vector can be seen between each of the years. The same amount of drift is seen in the CTs.

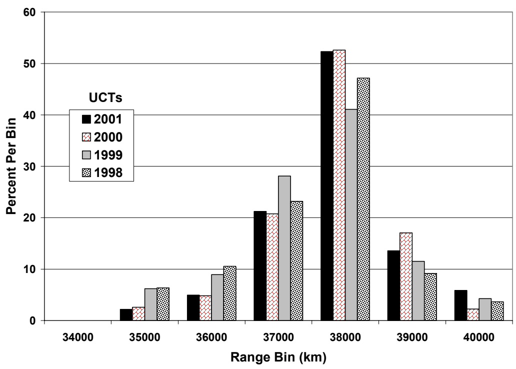

Figure 6. Range histogram for all 4 years of UCTs.

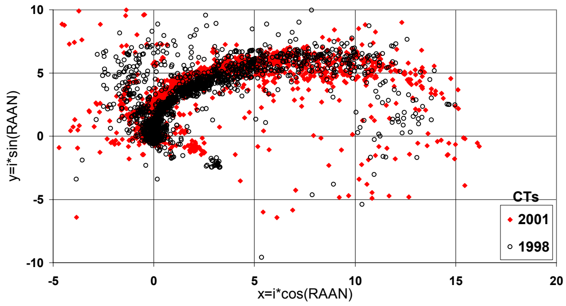

Figure 7. Polar RAAN for CTs in 1998 and 2001.

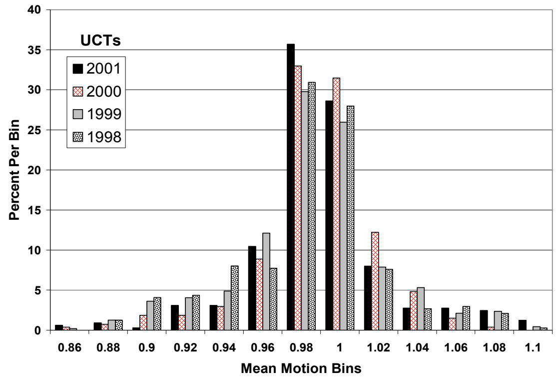

Figure 8. MM histogram for all 4 years of UCTs.

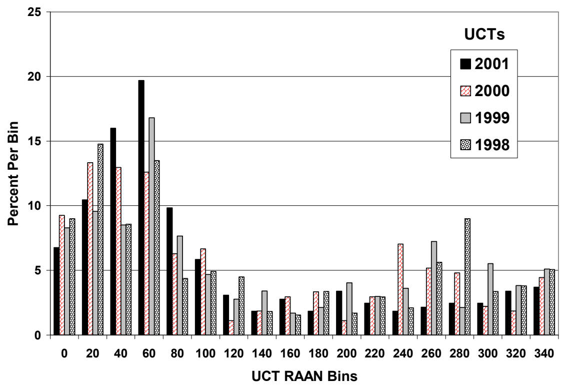

Figure 9. RAAN histogram for all 4 years of UCTs.

Nothing unusual is seen in the 4 years of UCT mean motions presented in Fig. 8 except that the distribution is broader than the CTs. We see more year-to-year variation in the UCT RAAN distribution in Fig. 9.

The increase in scatter within the UCT RAAN versus inclination distribution is easily seen in Fig. 10. There are clumpings of objects seen for a particular year that do not appear in other years at the same coordinates. The major feature seen in Fig. 10 is caused by the precession of the orbital planes due to the Earth's oblateness plus solar and lunar perturbations on the orbital planes. The only clumping that does seem to repeat is at ~260° RAAN and 4-6° inclination. These and other similar features of the entire set of distributions are subjects of on-going investigations.

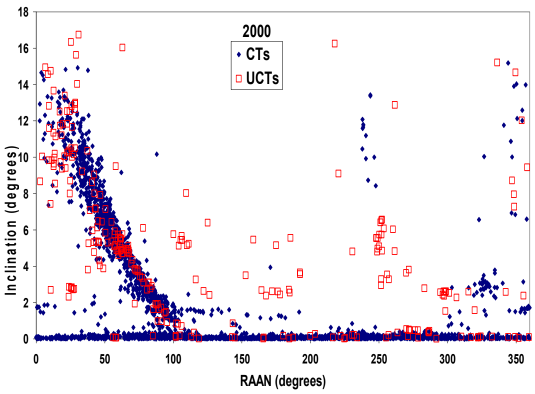

Figure 10. RAAN vs. Inc for CTs and UCTs in 2000.

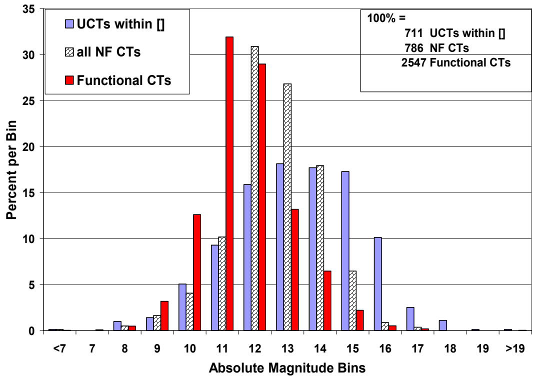

Figure 11. Histogram for 1998, UCTs, functional and non-functional CTs.

A basic conclusion to be drawn from the CT and UCT absolute magnitude distributions (Fig. 11) is the UCTs are significantly fainter (>1 mag) than the functional CTs. The non-functional CTs are distributed in a similar manner as the UCTs which are another indicator that they are good tracers of the behavior of UCTs. Previous publications of CDT data have used a 0.2 albedo and a specular reflection to derive a characteristic diameter for a given magnitude. If one assumes a diffuse Lambertian reflection the corresponding diameter would be decreased by a factor of 1.63. For example, an object with an absolute magnitude of 17^{th} with a specular assumption would have a size of 58 cm, whereas the diffuse assumption would yield a size of 35 cm for the same albedo of 0.2.

7. CONCLUSIONS

In general, all 4 years of CDT UCT data show similar distributions in inclination, eccentricity, RAAN, mean motion and magnitude, thereby indicating a general stability in the UCT environment between 1998 and 2002. The inclination distribution of non-functional CTs is similar to those seen for UCTs. Analysis of the repeatability of non-functional CTs within each observing year provided evidence that each unique UCT is seen ~5.5 times a year which reduces the total number of unique UCTs to about 100 per year. UCTs and CTs showed the same amount of drift is seen in the angular momentum plot between calendar years, confirming the same behavior related to gravitational perturbations of their orbital planes. The ratio of UPY UCTs to UPY CTs is similar over the four years. The absolute magnitudes of the UCTs are 1-2 magnitudes fainter than the non-functional CTs for all four years. If a Lambertian phase function is used to convert the observed magnitudes into characteristic sizes instead of a specular phase function, the resulting size is a factor of 1.63 smaller. Thus, the detection limit of 60 cm for the CDT is 35 cm for a diffuse Lambertian scatterer.

8. REFERENCES

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