A SEARCH FOR DEBRIS IN GEO

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ABSTRACT

During the interval from December, 1992 through August, 1994, five observing runs were conducted on Mt. Haleakala, Maui, HI by personnel from the NASA Johnson Space Center. The instrument used for the investigation was a 0.32-m diameter , f/1.3 Schmidt telescope with a Thompson 7882 (384X576) CCD. The objective of the study was the detection of small uncataloged objects at or near geosynchronous altitudes. A total of 13516 CCD images (6758 fields) were recorded; an object of some type was detected in 26.7% of these fields. Of all of the objects detected, 208 did not correlate with any known satellite. For these, orbital elements were derived assuming circular orbits. Without knowing the time history of the orbits of these objects, it is not possible to determine their origin. However, it is clear that a measurable debris population exists in and near the geosynchronous orbit.

1. INTRODUCTION

The observation of objects in, or near, geosynchronous orbit is almost completely the realm of the optical community. Such observations have been made for several decades in the United States, by elements of the Deep Space Network such as GEODSS, AMOS, and MOTIF, and others. Other space-faring nations have similar programs. The particular sites mentioned above have in common the circumstance that they are encumbered with the responsibility of regular and directed observations of specific targets in the GEO environment with, historically, little time available for uncorrelated target (UCT) searches. It should be remembered that the number of satellites being placed in GEO continues to grow with time. Thus the requirement for observation grows even without the possible addition of fragmentation debris.

To illustrate this point, consider that on February 21, 1992 a Titan 3C Transtage (1968-081E, Sat No. 03432) was observed to break up, producing at least 20 observable pieces -- indeed, the images were videotaped by an observer at the Maui GEODSS sensor (Refs. 1,2). No orbital data were generated on these fragments by USSPACECOM Space Surveillance Center. All of these clearly observable pieces were lost.

Earlier, on June 23, 1978, another historical breakup, that of EKRAN 2 (1977-092A, Sat. No.10365), went completely undetected (Ref.1). It only became known in 1992 when the Commonwealth of Independent States (CIS) revealed the event. Obviously any fragments from this breakup have gone, if not undetected, certainly uncatalogued. The existence of one missed breakup in GEO immediately raises the question: "Have there been others ?"

Indeed, Kasimenko *et al.* (Ref. 3) have identified candidates for breakups in or near geosynchronous orbits from unexplained changes in values of the semi-major axis of upper stages used to put satellites into geosynchronous orbits. They found 12 objects that showed significant changes in orbital semi-major axes, and suggested that these may have collided with some other object. Most of these were 4th stages with inclinations near 1 degree.

Very small debris has been found near the geosynchronous orbit. Bagrov, *et al.* (Ref. 4) accidentally observed a debris fragment near the geosynchronous orbit. This object had an estimated area of about 0.15 square meters, and was at an inclination of about 0.7 degrees, and had the optical characteristics of glassy material.

Because of the potential of collision with valuable assets in GEO and the essentially infinite residence of any debris in the GEO environment, the authors of this report felt that a survey that set its focus on GEO debris was in order. Eventually an accurate GEO debris census must be obtained.

The objective of this study was to carry out a dedicated search for debris in the GEO and near-GEO environment.

In late 1992 an agreement was established between NASA Johnson Space Center and the U.S. Air Force Maui Space Surveillance Site that allowed NASA to conduct telescopic investigations of the GEO orbital debris environment at their Haleakala site.

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2. TELESCOPE SYSTEM DESCRIPTION

The NASA CCD Debris Telescope (CDT) is a 0.32-m diameter, f/1.3, transportable Schmidt telescope whose primary image sensor is a Thompson 7882 (384X576) CCD. Since each pixel is 23 X 23 microns and the image scale at the focal plane is approximately 11.5 seconds of arc per pixel, the net useful field of view is 1.8° X 1.2°.

The CDT is supported on a massive, three-axis mount that allows for positioning in azimuth , elevation , and position angle of the telescope tube so that cardinal orientation (e.g., E/W alignment) may be selected. The telescope pointing is controlled by a menu-driven BASIC program running in a computer dedicated to the mount control function. Among the menu options for mount control is the pointing of the telescope to predetermined fields as a function of time; the pointing instructions are usually stored in a data file that is read by the BASIC program.

The performance of the CDT was gauged from the observation of well-calibrated photometric standard star fields. Based on such tests, the CDT exhibits performance characterized by the detection of 17.1 magnitude stars in a 30 second exposure. A solar illuminated object of this magnitude at geosynchronous distance, and having an albedo between 0.2 and 0.1, would have a diameter of about 0.35-m to 0.50-m.

3. DEBRIS SEARCH STRATEGY

To detect the smallest debris pieces possible it is desirable to observe them under nearly face-on (small phase angle) solar illumination. This condition may be most closely obtained for objects near the anti-solar point. Since the Earth's shadow projected into space has a finite angular diameter, on the order of 10° at geosynchronous distances, it is not possible to meet the condition of exact face-on illumination (phase = 0°); rather, an angular displacement from the antisolar point of about 12° is required to clear the shadow. Either shadow-leading or shadow-trailing locations would suit the objective.

From any observing station, objects observed more than about three hours from the meridian begin to suffer noticeable atmospheric extinction. Since the objective of this project was to observe small and intrinsically faint debris objects, there was little point in observing outside a window that extended more than plus or minus 3 hours in hour angle from the meridian.

Further, since numerous studies (e.g., Ref. 5) provide compelling arguments that uncontrolled debris objects in GEO should be at inclinations less than or equal to 15°, a reasonable N/S limit to the survey is obvious.

Therefore, for all observations obtained with the CDT from Maui, a fixed grid of fields from 3 hours East to 3 hours West and ranging +/- 20° in declination was established. Each field was characterized by hour angle, declination, elevation, azimuth, and sub-center point (latitude and longitude).

On any given observing run, a subset of these reference fields was selected for observation. Typically, four fields were selected that either led or followed the antisolar point at a fixed angular distance. Once the telescope was pointed at a particular field, two 30-second exposures were made and written to disk storage. The telescope was then moved to the next field and the process repeated. Four fields, staggered in declination, could be observed in 7.2 minutes; following this, the telescope was shifted 1.8 degrees West and the declination sequence repeated. The observing protocol for this type of "step-and-stare" observing is ideally suited to automated control.

4. GEO OBSERVATIONS ON HALEAKALA

The observing runs on Maui required a three-part team -- night observers, a day analyst, and computational support from the Johnson Space Center in Houston. The night observers were responsible for the execution of the observing program; the day analyst performed "quick-look" measurements of each night's data, and Houston computational support provided daily uploading of the telescope control files.

4.1 Search Control File Preparation

The activities for each night of observing began with the uploading of the search file for the mount control program as well as a log sheet file that, when printed out, gave the night observers a means of logging their observations in real time. The most useful aspect of the printed log was that it was annotated with the prediction of "known" objects and thus aided the observers in discriminating against false identification of UCTs. In addition, the notes made by the observers on the log served as the primary guide for the day analyst's measurement efforts.

4.2 Description of a Typical Night of Observing

Once the CDT systems were powered up, the first order of business was to load the search file just received from Houston, called GSRCH.DAT, that would be used by the mount control program to control all data acquisition for the evening.

Once the telescope dome was opened and all CDT systems started and verified to be running normally, the usual sequence of CCD frames were obtained (bias, dark fields, and flat fields). Following these CCD health checks, the mount control system was exercised by pointing to several bright stars to verify the accuracy and repeatability of the pointing. Several non-tracked images were taken to verify the tube rotation and, hence, the E/W alignment. Telescope focus was also checked and adjusted as required. Once all of the CDT systems were checked out, standard star field images were obtained.

At this point in the observing, if there were no special observations to be performed, the mount control program was started and placed in a standby mode pending the initialization of the GEO program. Once underway, if all was running smoothly, the GEO data taking activity would proceed automatically. As each image was acquired and displayed, the observers noted the presence and approximate locations in each image of all objects observed on the log sheet.

At the end of the night, all data products were checked into the storage vault on the mountain pending the arrival of the day analyst. Several hours after the departure of the observing team, the day analyst would arrive, start up the image processing portion of the CDT system, and proceed to make measurements on the images using the observer-annotated log sheets as a guide. The "quick-look" results were not accurate enough for detailed orbit calculations but were invaluable in discriminating between objects that were definitely part of the catalogued population and those that were good UCT candidates.

4.4 Summary of Observing Runs

During the course of the GEO debris search project, five observing runs were executed. The dates of these runs, with the total number of clear nights given in parentheses were: December, 1992 (2), February, 1993 (9), May, 1993 (12), August, 1993 (10), and April, 1994 (9). This is a total of 42 nights or 252 hours of observing.

5. DATA REDUCTION

Once the image data were obtained, the immediate objective was to reduce the inventory of all objects seen to only those that were most strongly suspected of being UCTs. Once the identification was complete, the next step was to re-measure, with greater accuracy, the temporal and spatial coordinates of the suspected UCTs and to derive orbital elements for them, subject to the assumption that their orbits were circular.

5.1 Processing Requirements and Facilities Description

Data reduction activities could not begin in earnest until all of the observing runs were completed and the CDT system had been returned to NASA Johnson Space Center in Houston, since the only system suitable for reading the image storage media was the unique computer and FORTH system on which the data were written. Consequently, data reduction and analysis activities did not get under way until late in 1994.

5.2 Data Inventory

During the five observing runs at Maui, a grand total of 14375 CCD images were recorded including calibration, flat fields, bias fields, dark fields, and standard star observations. Considering images of debris search fields only, 13516 CCD images were obtained -- two each on a total of 6758 fields.

Top level screening (based on all observing runs), without regard as to whether or not any given detection was of a catalogued object or potential UCT, produced the following statistics ...

\> Fields w/ one or more objects:
1872 Fields; 27.7% of 6758
\> Fields w/ exactly one objects:
2324 Fields; 17.2% of 6758
\> Fields w/ exactly two objects:
1364 Fields; 9.96% of 6758
\> Fields w/ three or more objects:
74 Fields; 0.005% of 6758

The December, 1992 and February, 1993 data were analyzed by Henize only to the level of identification of probable UCTs. About 30% of the observations were found to be probable UCTs. Unfortunately, only the raw data were preserved. Insufficient time and resources were available to reconstruct the observing sequences for detailed analysis. The remainder of the data were analyzed in depth by the procedures described below.

5.3 Development of Data Reduction Tools

In order to improve the positional and temporal measurements over those generated via the use of the "quick-look" efforts of the daytime analyst, several new FORTH words were written. The primary difference in the measurement values returned by these FORTH words and the ones used by the day analyst is in the actual determination of an image centroid (rather than a simple midpoint between user-selected endpoints as was the case with the "quick-look" program).

Further, an interactive routine was written that allowed the user to carefully select the region of an image to refer to as the background; then bright stars could be avoided (a problem with the automated "quick-look" procedure).

Finally, a FORTH routine was written that provided the actual time of mid-exposure for each frame. The great advantage of the "quick-look" program was its automated character. The new routines, although providing excellent temporal and positional measurements, proved to be very labor intensive. Thus, instead of re-measuring all of the images, it was determined, from an examination of several dozen cases of observations of catalogued objects, that the "quick-look" data would be suitable for culling out the most probable UCTs. Once the catalogued objects had been separated out of the data set, only the remainder would be re-measured.

5.4 Separation of Known Objects from Probable UCTs

From the "quick-look" data set and the disk directory for each night, a master file was created that included a local object number, UT date and time, RA, Dec., AZ, EL, astronomical magnitude, and calculated spherical equivalent diameter for each observation. The immediate objective at this step in the process was to discern whether or not a particular observation corresponded to a known object. To do this, the first action necessary was to extract, from the NASA-JSC data base, all epochs of two-line element sets for deep space objects closest to the epochs of observation. With the element sets (elsets) of known objects in hand, look angles could be calculated using the LAMOD routine of the SATRAK program and compared for correlation. Any match of an observation to a prediction of a known member of the GEO or near-GEO environment, within reasonable uncertainty, would eliminate that object as a possible UCT. The question then became: "What may be considered reasonable uncertainty for the correlation effort ?"

To address the correlation requirement issue, measurements of two dozen well-known objects were made and processed as though they were unknowns. Then, for the nights of observation, look angles were generated using element sets (elsets) appropriate to the epochs of observation. At the times of actual observation, the predicted azimuths and elevation angles matched to within +/- 0.35^{o} (4 sigma).

With these tests on well-known tracked objects as a guide, a program called GEOIDBAT was written to cross compare all observations with predicted positions of known GEO or near-GEO objects. Any object that correlated to within +/- 3 minutes in UT and, simultaneously, to within +/- 0.5^{o} was considered identified. If an observation was not correlated on the first pass through the data set, the angular separation was relaxed to +/- 1.5^{o} and possible correlations were noted. These cases were examined one at a time pulling in other considerations such as anticipated angular rate and position angle of motion. Finally, any observation not correlating with a known object under these criteria was identified as a potential UCT.

For the last three observing runs, under discussion here, a total of 1202 observations were processed as described above. Employing the procedures outlined above, 901 of these observations were correlated with known members of the deep space population. The total number of unique objects represented by this number is 189 ; this implies an average redundancy of observation of 4.8 times per object. Some objects, typically those drifting out of control, were observed only once or twice, whereas well-controlled or low inclination objects were observed often during this survey -- a few as many as 15 to 20 times. Since the UCT population may be expected to be composed of uncontrolled objects, it may be reasonable to expect that the redundancy of observation will be lower than for the known objects.

The remaining 301 observations were identified as potential UCTs. A final screening of the original data produced an additional 23 UCT observations for a total of 324.

5.5 Measurement of the Final Set of Images

Once the prime UCT candidates were identified, all were re-measured using the interactive routines described in section 5.3. In addition to measurement of astrometric and photometric parameters for each object, suitable fiducial marks were measured such as the location of SAO stars. The UT mid-times of each exposure were also noted.

5.6 Orbit Determinations with Circular Orbit Assumption

The measurement data, providing angular positions at two separate times, were sufficient to derive orbits for the observed objects assuming a circular orbit. The positional data were batch processed to the point of providing a summary of circular orbit data in a format suitable for input to SATRAK SIMORB's module which was used to generate two-line elsets.

Once all 324 element sets were determined, it was possible to cross-correlate and compare them for redundancy. Again, observations of cataloged objects were used as a guide in this process. Specifically, from 41 observations of 8 different objects, the 1 sigma values for critical orbital elements, separately determined from different observation pairs, were ...

> Inclination : +/- 0.2°
> Mean Motion : +/- 0.003 rev/day
> RAAN : +/- 2.0°

In some cases, notations from the original observational logs alone were sufficient to verify that two or more observations were due to the same object. In the end the 324 element sets were determined to be from 208 unique objects; the redundancy factor is thus 1.6 and much smaller than for the ensemble of known objects observed.

The final tally of observed objects: 189 known; 208 UCTs.

6. DATA ANALYSIS

The discussions of this section are based on the examination of various combinations of orbital elements of the observed UCTs.

6.1 The UCT Population -- How Significant ?

The sum of known objects and UCTs in the GEO regime, as identified in this study, is 397 objects; the UCTs represent 52.4% of this total. However, since these two groups are not, empirically, equally observable, a correction should be made to account for their relative observability. Multiplying the 208 count of UCTs by the factor (1.6/4.8)· yields 69.3 which corrects the drifting UCT population numbers to a number comparable to the locally observable , and more stationary, population.; this calculation yields a "true" value of [(69.3)/(189+69.3)]* 100% = 26.8% for the UCT portion of the GEO population.

6.2 Characteristics of UCT Orbital Parameters

Three figures are presented below (Figs. 1, 2, 3) to exhibit groupings in each correlative plot of UCT orbital elements.

6.3 Observed Magnitudes and Inferred Sizes

During the data reduction, instrumental brightness units were measured and recorded for each object. From observations made by Mulrooney (Ref. 6) of standard stars, and verified at several times during the survey program, the instrumental brightness units were converted to astronomical magnitudes. After an allowance was made for an average atmospheric extinction of about 0.25 magnitudes, equivalent object sizes were calculated under the assumptions of a sphere having albedo = 0.2. This value of albedo was derived from the observed magnitudes of cataloged objects for which accurate size information was available. All

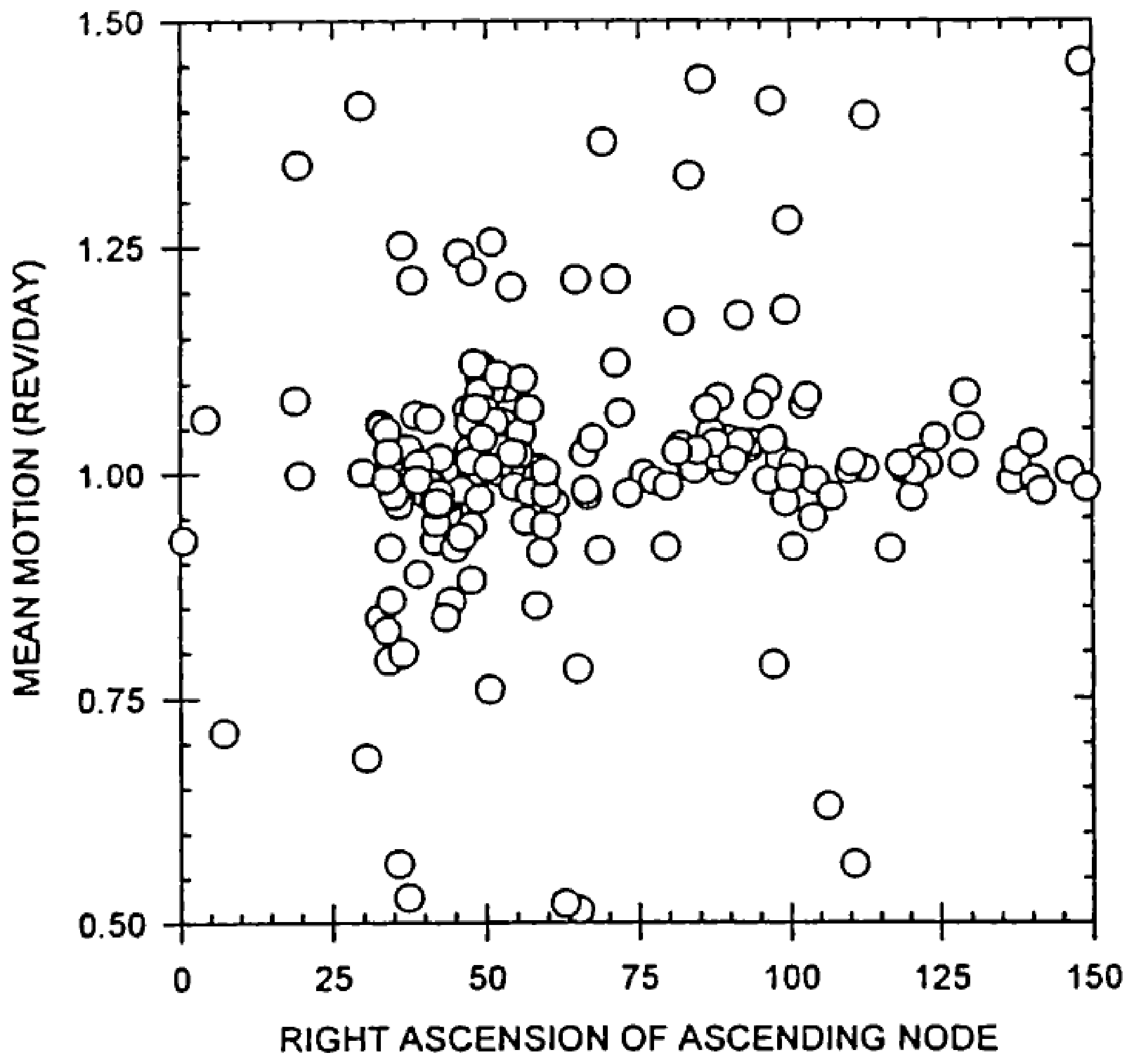

Figure 1. UCT Mean Motions vs. RAAN.

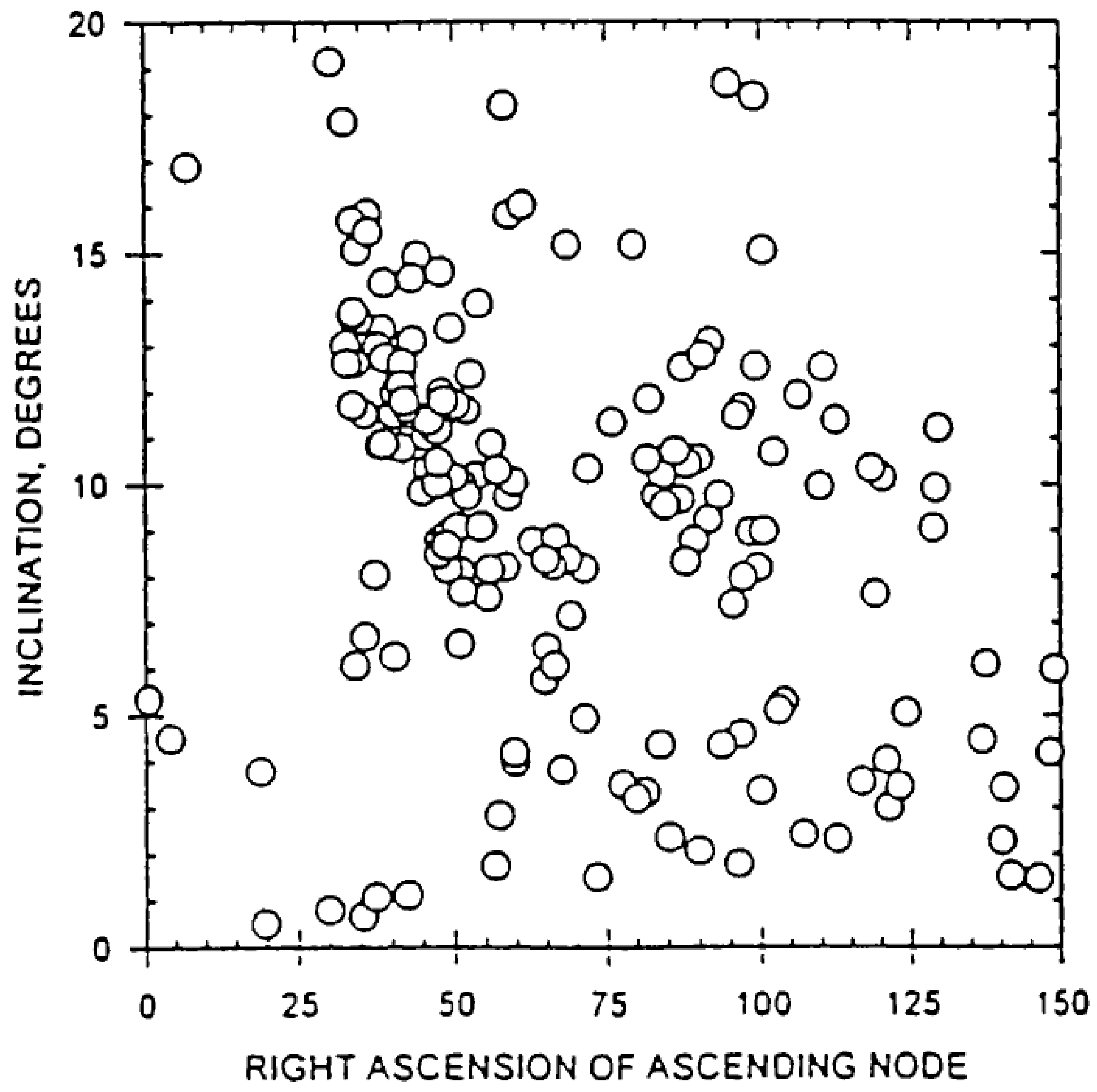

Figure 2. UCT Inclinations vs. RAAN.

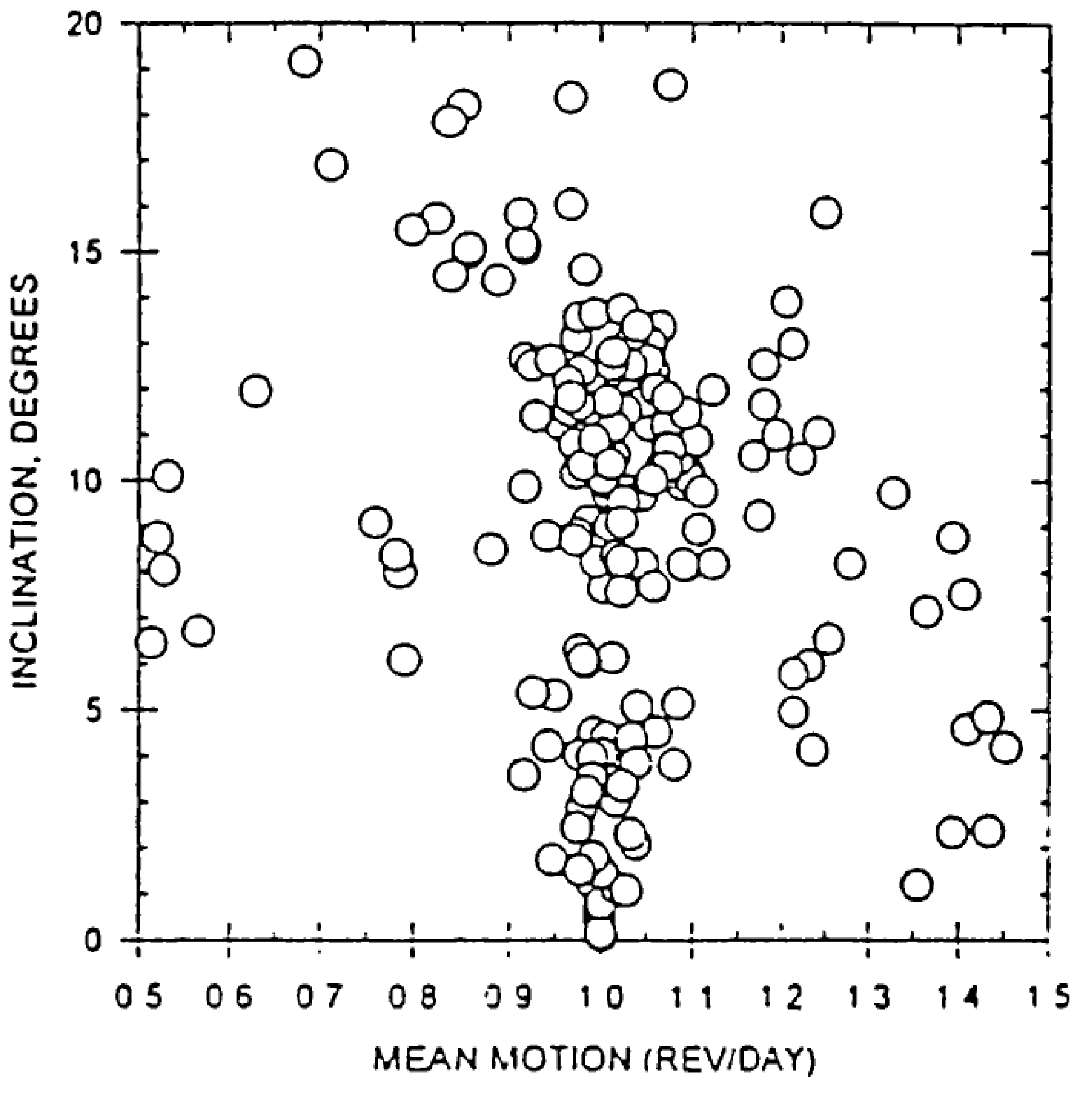

Figure 3. UCT Inclinations vs. Mean Motion.

phase angles were between 10° and 15°. A histogram showing the distribution of sizes is given as Figure 4.

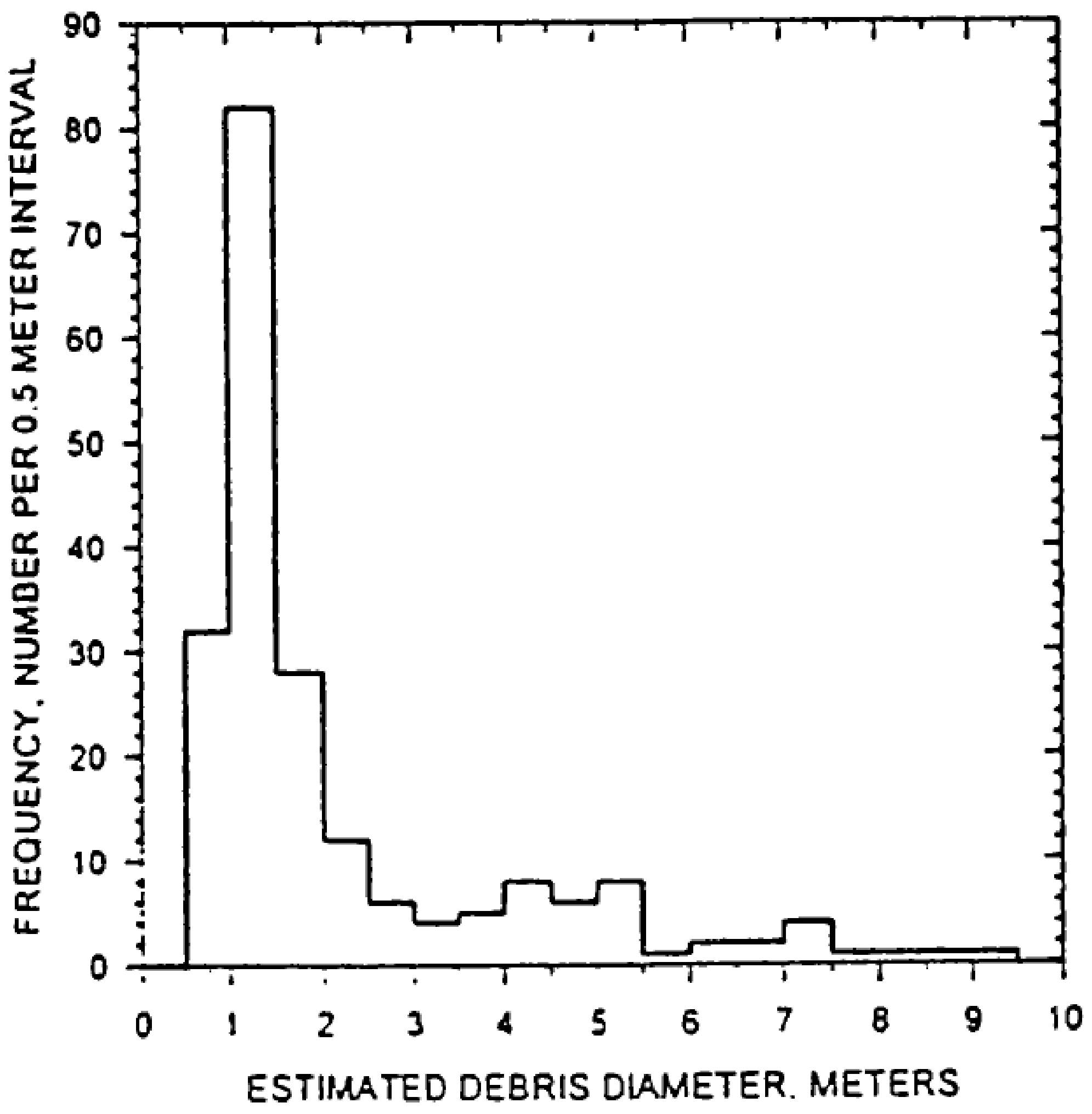

Figure 4. Histogram of Derived UCT Diameters.

Objects that were sub-meter in size were clearly observed and the apparent peak in the distribution shows that most of the UCTs were between 1.0-m to 1.5-m in characteristic dimension -- clearly debris-size pieces. But a word of caution is required in that the peak in this distribution probably reflects detectability limits more than it reflects population characteristics. The existence of sub-meter debris is indicated, but the sampling should not be expected to be complete. Surveys with greater sensitivity should improve the sampling of smaller debris objects in GEO.

An important point is that the UCT population we found is well within the detection capability of existing optical tracking facilities. These facilities generally do not have a field of view large enough to permit search and survey, as was done in this work. They have to know approximately where to look for the object of interest. However, once found by a survey program, most of the debris objects could be tracked to provide accurate orbital elements using existing optical facilities.

6.5 Identification of the Sources of GE0 Debris

There are suggestions of groupings of objects in Figure 2. It is tempting to try to ascribe these groupings to historic GEO fragmentations. However, all objects in GEO will drift in inclination once they are released from station-keeping control, until an inclination of about 15 degrees is reached. There is no way to determine the initial inclination of the UCT objects without knowledge of the time elapsed since they were generated. More detailed analysis and more accurate orbital element data may eventually permit probable origins to the debris we observed, but this is not possible at present.

7. CONCLUSIONS

The principal conclusions of this study are:

1. A measurable debris population exists in and near the geosynchronous environment.

2. Approximately 27% of all objects in GEO observable to a magnitude limit of 17.1 are not currently tracked and maintained as catalogued objects by USSPACECOM.

3. The objects we found were sufficiently bright that they could be tracked by existing facilities to provide accurate orbits.

8. REFERENCES

1. Grissom, I.W., et. al., *History of On-Orbit Satellite Fragmentations*, Teledyne-Brown Engineering, Colorado Springs, Co., 1994.

2. Pensa, A.F., et al., Debris in Geosynchronous Orbit, *SPACE FORUM*, Vol. 1, 23-27, 1996.

3. Kasimenko, T.V., Mikisha, A.M., Rykhlova, L.V. and Smirnov, M.A. "Explosions on the Geostationary Orbit", in *Collisions in the Surrounding Space (Space Debris)*, A.G. Massevitch, ed., Moscow, 1995, 159-168. See also Rykhlova, L, Smirnov, M., Mikisha, A., and Barabanov, S., "Explosions on GEO", *13-th IADC Meeting, Darmstadt, Germany, 27 Feb-1 Mar., 1996* and

4. Bagrov, A.V., Smirnov M.A., and Smal., S.Yu, Observations of a Small Fragment" in *Collisions in the Surrounding Space (Space Debris,* A.G. Massevitch, ed., Moscow, 1995, 307-311.

5. Friesen, L. et. al., Results in Orbital Evolution of Objects in the Geosynchronous Region, AIAA 90-1362, *AIAA /NASA/DOD Orbital Debris Conference: Technical Issues and Future Directions,* Baltimore, Maryland, April 16-19, 1990.

6. Mulrooney, M., *M.S. Thesis*, Department of Space Physics and Astronomy, Rice University, Houston, Texas, 1993.