ESTIMATING THE AREA OF ARTIFICIAL SPACE DEBRIS

R.A. Madler
Department of Aerospace Engineering, Embry-Riddle Aeronautical University,
3200 Willow Creek Rd., Prescott, AZ 86301-3720

K. Jorgensen
Colorado Center for Astrodynamics Research, Campus Box 431,
University of Colorado, Boulder, CO 80309-0431

D.B. Spencer
Phillips Laboratory/VTQ, 3550 Aberdeen SE,
Kirtland AFB, NM 87117-5776

R.D. Culp
Department of Aerospace Engineering Sciences, Campus Box 429,
University of Colorado, Boulder, CO 80309-0429

ABSTRACT

The physical characteristics of breakup debris are essential to properly estimate the orbital debris environment and its hazard to spacecraft. Direct measurements of the cross sectional area of debris fragments have not been performed in the past. This paper examines methods to determine the physical cross section of debris objects from ground based fragmentations. The results of these measurements are compared to standard models for debris. For the smaller objects, the models and measurements agree well. The measurements of objects above a certain threshold diverge from the predicted cross sectional area.

1. INTRODUCTION

There exists a need to quantify and characterize the hazard posed to orbiting assets by space debris. Currently there are approximately 8500 objects being tracked by the Department of Defense (DoD) Space Surveillance Network (SSN). The majority of these tracked objects are operational and fragmentation debris. The tracked objects in orbit as of June 1996 are categorized in Ref. 1 as follows: active payloads (6%); inactive payloads (24%); rocket bodies (18%); operational debris (11%); anomalous event debris (2%); satellite fragmentation debris (39%). A much larger population of objects below the detection threshold is known to exist from the approximately 136 on-orbit satellite breakups that have occurred to date. Hence, it is important to be able to model the fragments from these on-orbit fragmentation events. The relationships between mass, area, and size are very important because they affect the decay of resident space objects (RSOs), the expected collision rate, and the hazard to other RSOs. The relationships between mass, number, and size have been examined extensively (Refs. 2-6).

However, there has not been a concerted effort to measure the physical cross section of debris objects. This is mainly due to the difficulty of such measurements. Several researchers have examined data from on-orbit fragmentations, but great uncertainties exist in those calculations (Refs. 7-10).

A novel method to determine the cross sectional area of debris fragments at a large number of orientations, from which an average value can be determined, has been developed. This method is both fast and effective. The cross sectional area of some of the fragments has also been measured using a planimeter (a device which measures an enclosed area) to verify the results.

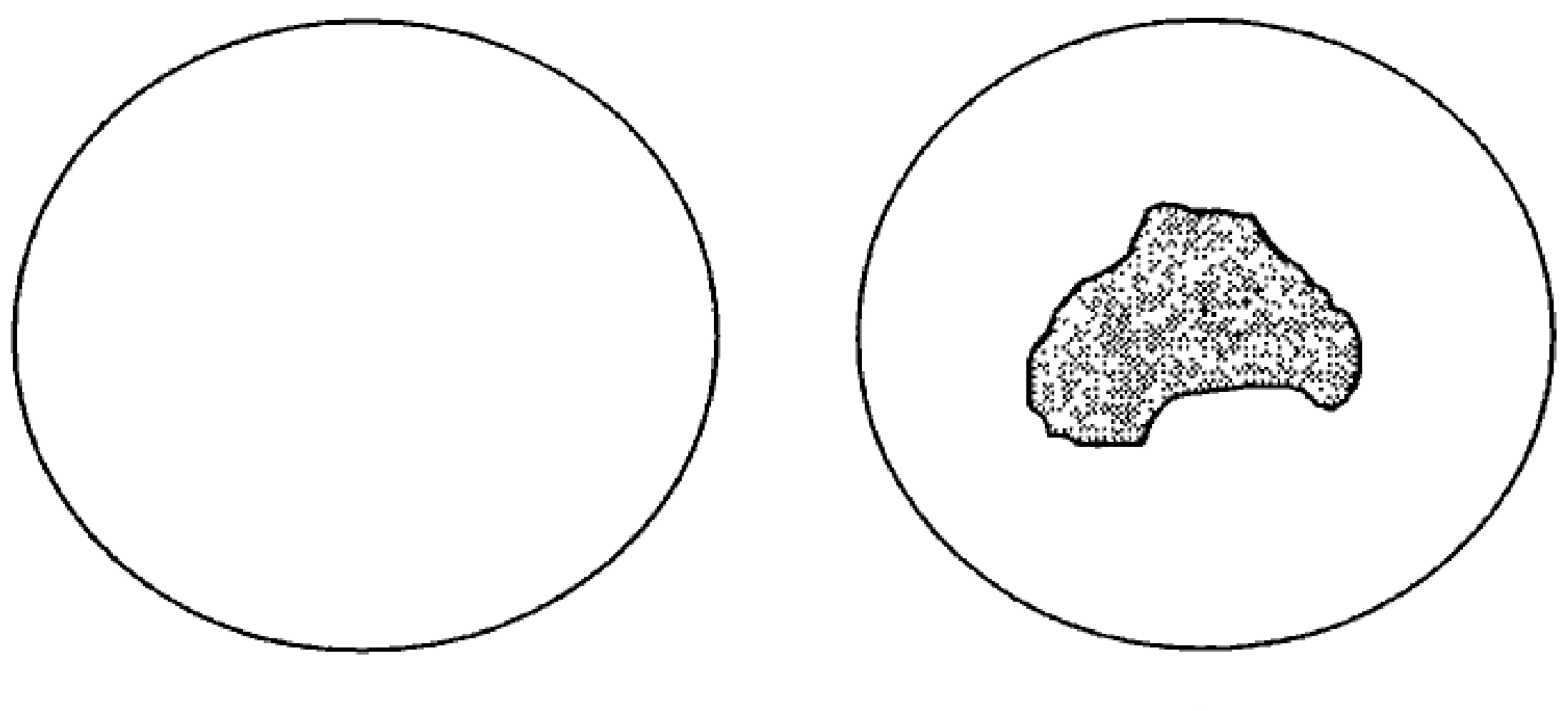
2. METHODOLOGY

Fragments from two ground-tests were obtained for this study: one a hypervelocity impact and the other an explosion event. Shot CU-6470, a hypervelocity impact conducted at the Arnold

Engineering Development Center (AEDC), was examined in cooperation with the University of Colorado and the owners of the fragments, NASA/JSC. The other set of fragments used came from an explosion test conducted by the European Space Agency/European Space Operations Center (ESA/ESOC). This explosion occurred on a downscaled ARIANE 4 H10 tank (Ref. 11).

The physical parameters: size, mass and area, were determined for a group of fragments from each event. Because many researchers have measured the mass and size, this study uses the same method for determining the characteristic dimension of fragments. Three orthogonal dimensions are measured, from which the characteristic dimension in determined. The first measurement is the longest dimension of the object; the second measurement is the longest diameter perpendicular to the first; and the third measurement is the longest dimension perpendicular to the first two. The characteristic dimension is then the mean of these three dimensions. The mass and dimensions have been measured very precisely and accurately.

The cross sectional area has never before been determined through direct measurements. The average area and area distribution was determined using a quick and direct method which measured the cross sectional area of objects at a number of orientations. A uniform light field was created which the debris pieces were suspended in front of to block a certain percentage of light, creating a shadowgraph. The view seen by the sensor is presented in Figure 1. The measured light level with and without the debris object in place can be used along with the known view area to determine the area of the debris object. This is represented by Equations 1 and 2. The distribution of areas and an average area are determined by taking measurements at a number of evenly spaced orientations, usually 20 to 25.



L_{ref} and A_{ref}

L_{deb} and A_{deb}

Figure 1: View down sensor tube as seen from sensor point of view

$$\frac{I * A_{ref}}{L_{ref}} = \frac{I * (A_{ref} - A_{deb})}{L_{deb}} \qquad (1)$$

$$A_{deb} = A_{ref} * \left(1 - \frac{L_{deb}}{L_{ref}}\right) \qquad (2)$$

where: I=light field intensity; A_{ref}=reference area; A_{deb}=debris area; L_{ref}=measured reference light; and L_{deb}=measured light with debris piece.

The measurements were taken at a special facility in the Laboratory for Atmospheric and Space Physics (LASP) of the University of Colorado, Boulder. The lab had a unique black coating to the walls to prevent extraneous light from interfering with the measurements. The setup is shown in Figure 2 and explained in the following paragraphs.

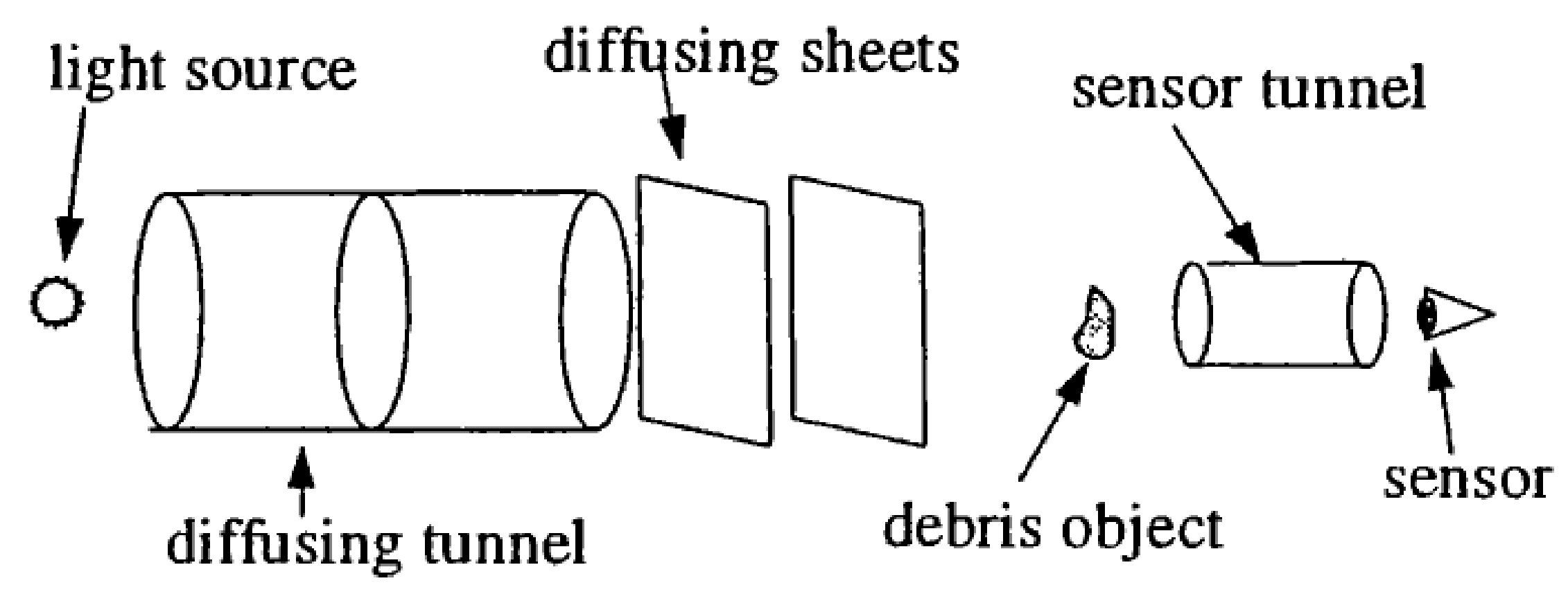


Figure 2: Laboratory Setup

The light source was a 500-Watt "Sun Gun" with a reflective backplate to direct light down the "diffusing tunnel." The diffusing tunnel was a roughened, white cardboard tube designed to produce an even light at the end. A plastic photographic light diffuser was positioned midway down the four-foot, twelve inch diameter tube. At the end of the tube, two photographic Mylar sheets provided the final diffusing elements to obtain an even light field that acted as a "light box," similar to ones used to view negatives or x-rays. This setup was selected after many attempts to get a bright, even light field. Measurements of the light field showed that it was uniform to within 5 or 10 percent, with the main variations occurring towards the edge of the light field, which had a lower intensity. Due to this effect, the viewed region was limited to the inner portion of the light field, which was more uniform. It was thought that this may cause us to overestimate the area of the debris objects. This did not appear to be the case after analyzing and verifying the data. The sensor measured the amount of light at the end of an eight-inch, light-baffled tube. The sensor tube was baffled to prevent any forward scattering of light, which could corrupt the data. Eye observations confirmed that little unwanted light was reaching the sensor. On the other end of the sensor tube, several cutouts of known dimension and area were placed to serve as a reference area. These different templates were used to minimize the reference area so that the ratio A_{deb}/A_{ref} was as high as possible to reduce error.

Measurements of two known objects, a black Ping-Pong ball and a floor-hockey ball, were taken before each piece was examined over the 20 to 25 orientations. Since the areas of these balls were well known, they were used to verify/correct the area estimates. The debris objects were viewed at various orientations by suspending them with sewing thread and changing the orientation between each reading. Though a device was created to aid in uniformly changing the orientation of the objects, it was found that having one person suspend the object at different orientations while another recorded the readings was more efficient. Multiple (usually two) runs were performed for each object. Due to limited lab time, 15 pieces from CU-6470 and 8 pieces from ESOC-2 were analyzed.

3. RESULTS

The area at many different orientations was measured for a large number of objects using the shadowgraph method. A smaller number of objects were imaged and measured with a planimeter. An area distribution and an average area can be found from this data.

3.1 Relative area frequency distribution

The relative area frequency distribution for each individual object in the CU-6470 shot has been determined. A non-dimensional relative area is found by dividing each area measured at various orientations by the average area for that piece. The relative area distribution can then be compared for all pieces regardless of the actual area. These distributions are compared with the relative area distributions calculated by physically measuring the area of several digital images of debris pieces with a planimeter.

Figures 3 and 4 show the relative area distribution for pieces 2 and 6, and 4 and 8, respectively, from CU-6470 using the shadow method. Figures 5 and 6 represent the planimeter data for those same pieces. Ian Gravseth of the University of Colorado has contributed area measurements for pieces 4 and 8 from CU-6470. The other pieces were measured by Prof. Madler and Jonathan Rustick at Embry-Riddle Aeronautical University.

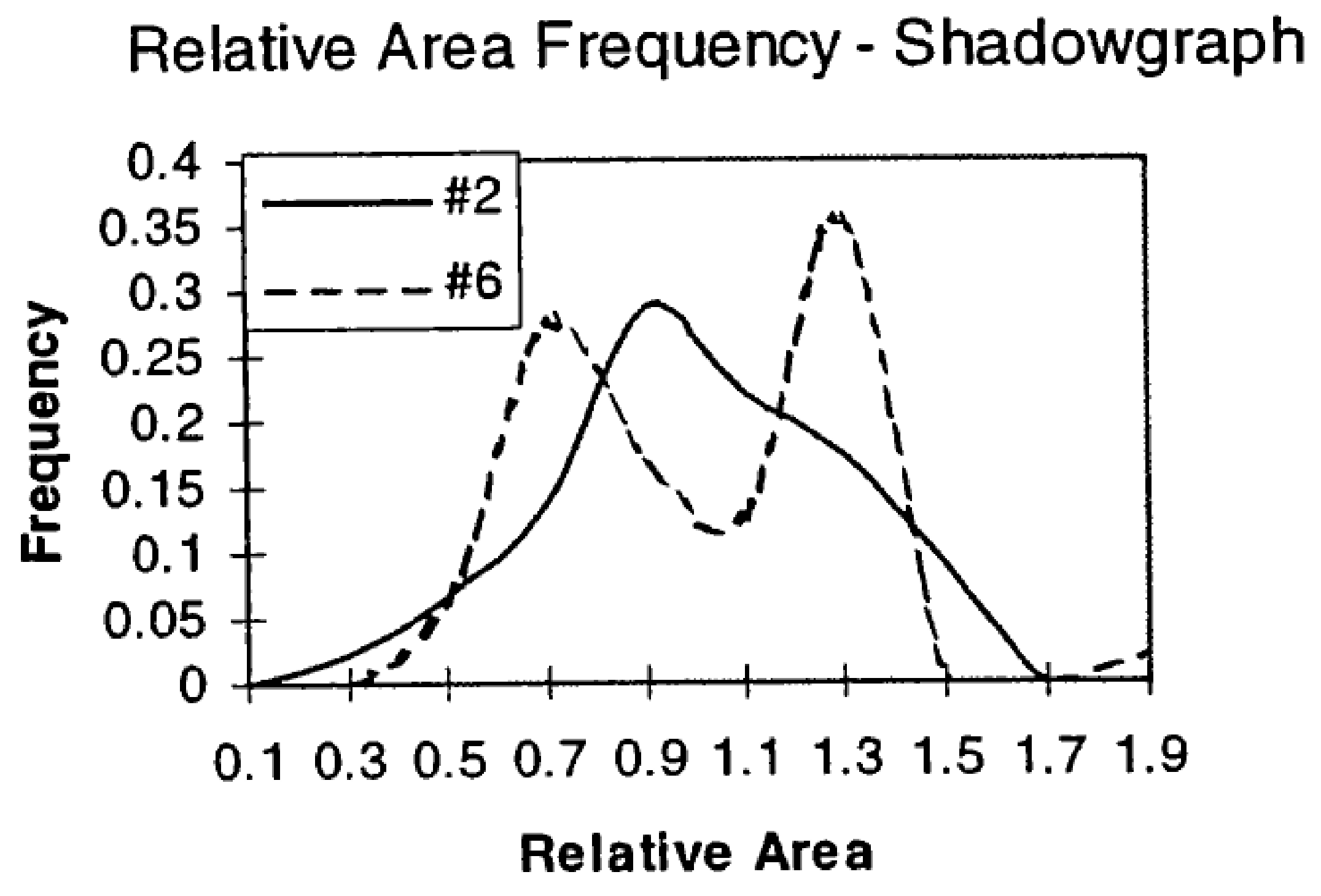


Figure 3: Shadow method for determining area for pieces 2 and 6 from shot CU-6470. A bi-modal distribution is apparent for one of the pieces.

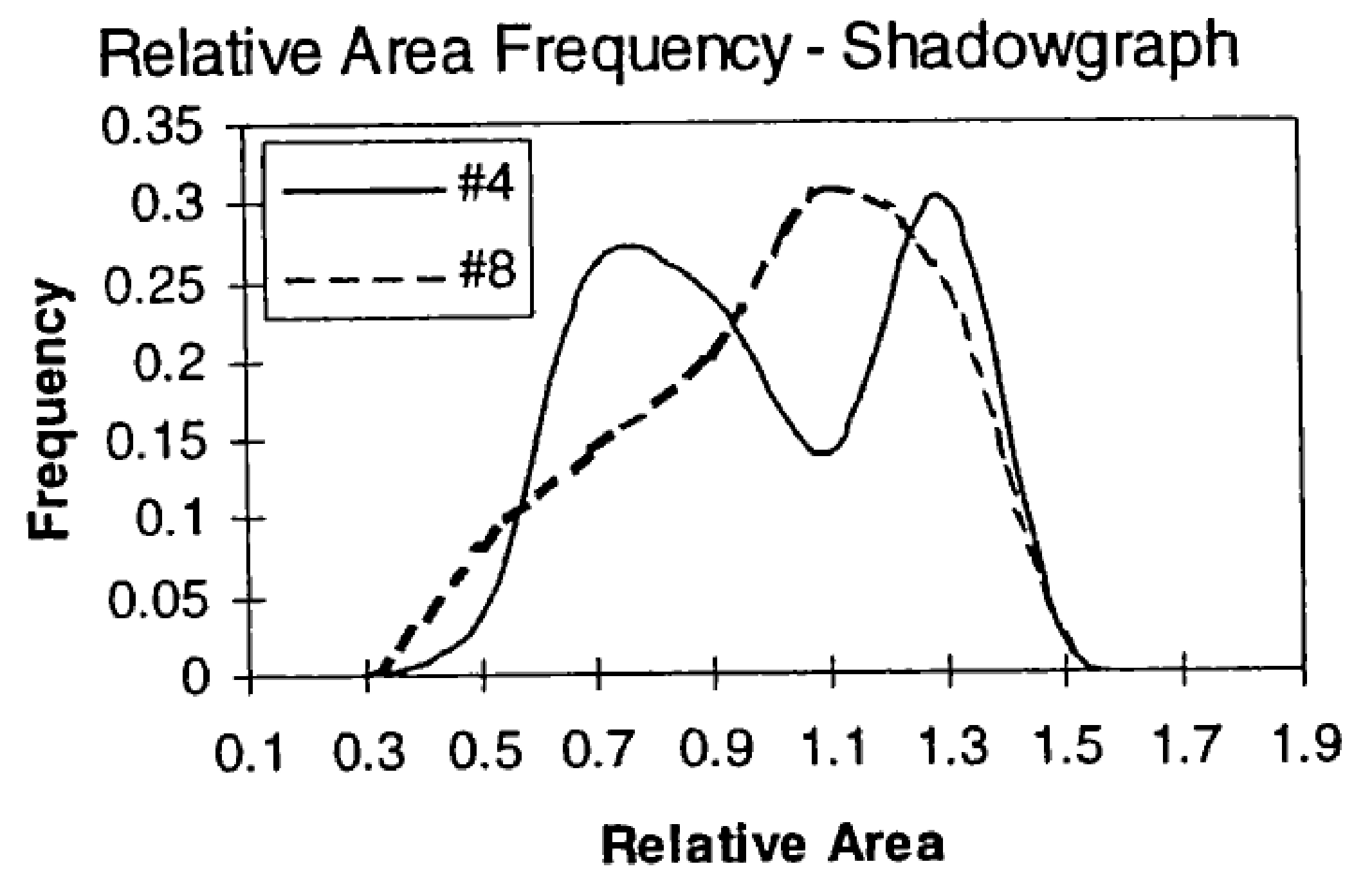


Figure 4: Shadow method for determining area for pieces 4 and 8 from shot CU-6470. A bi-modal distribution is apparent for one of the pieces.

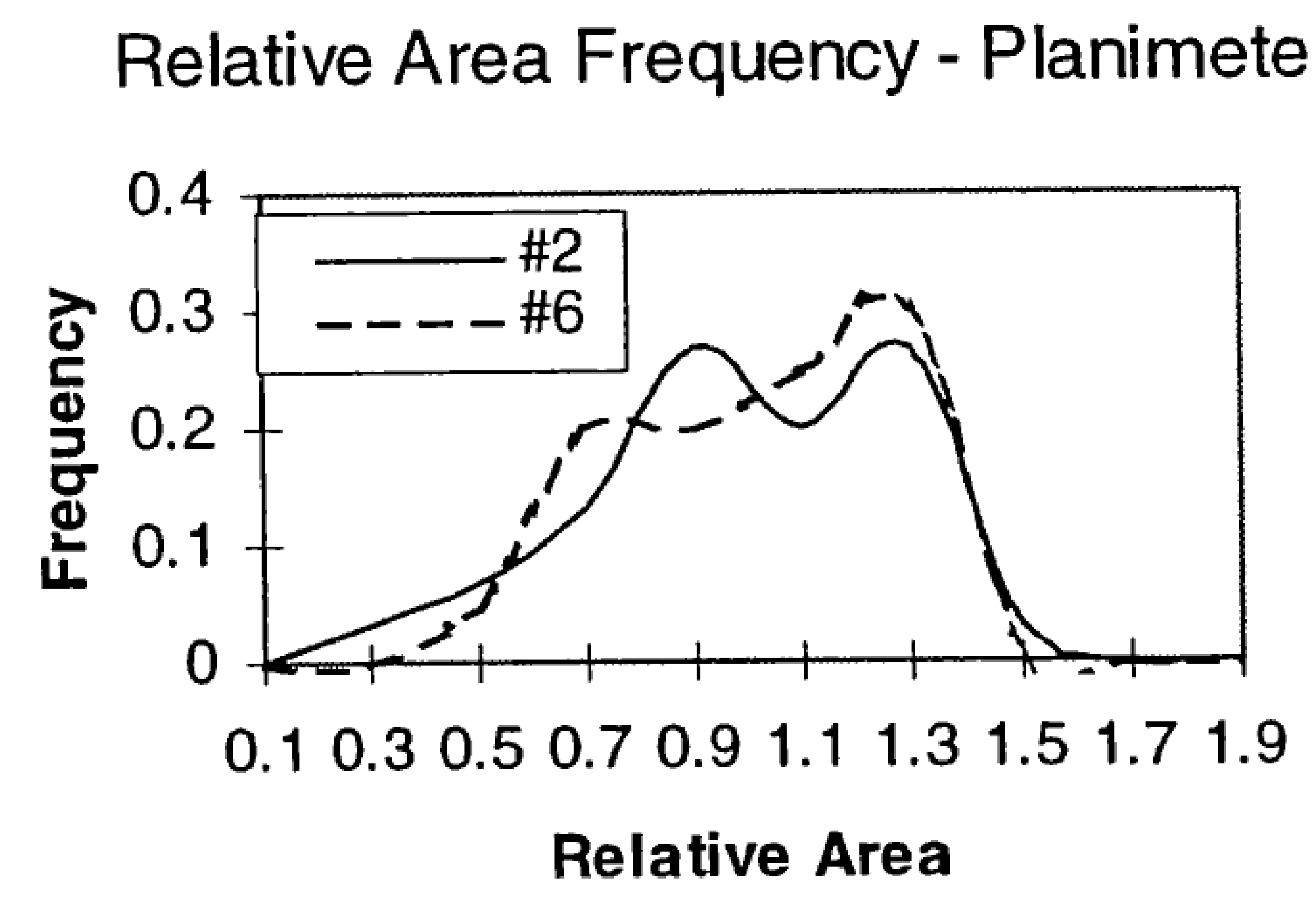


Figure 5: Relative area frequency distribution for pieces 2 and 6 from shot CU-6470.

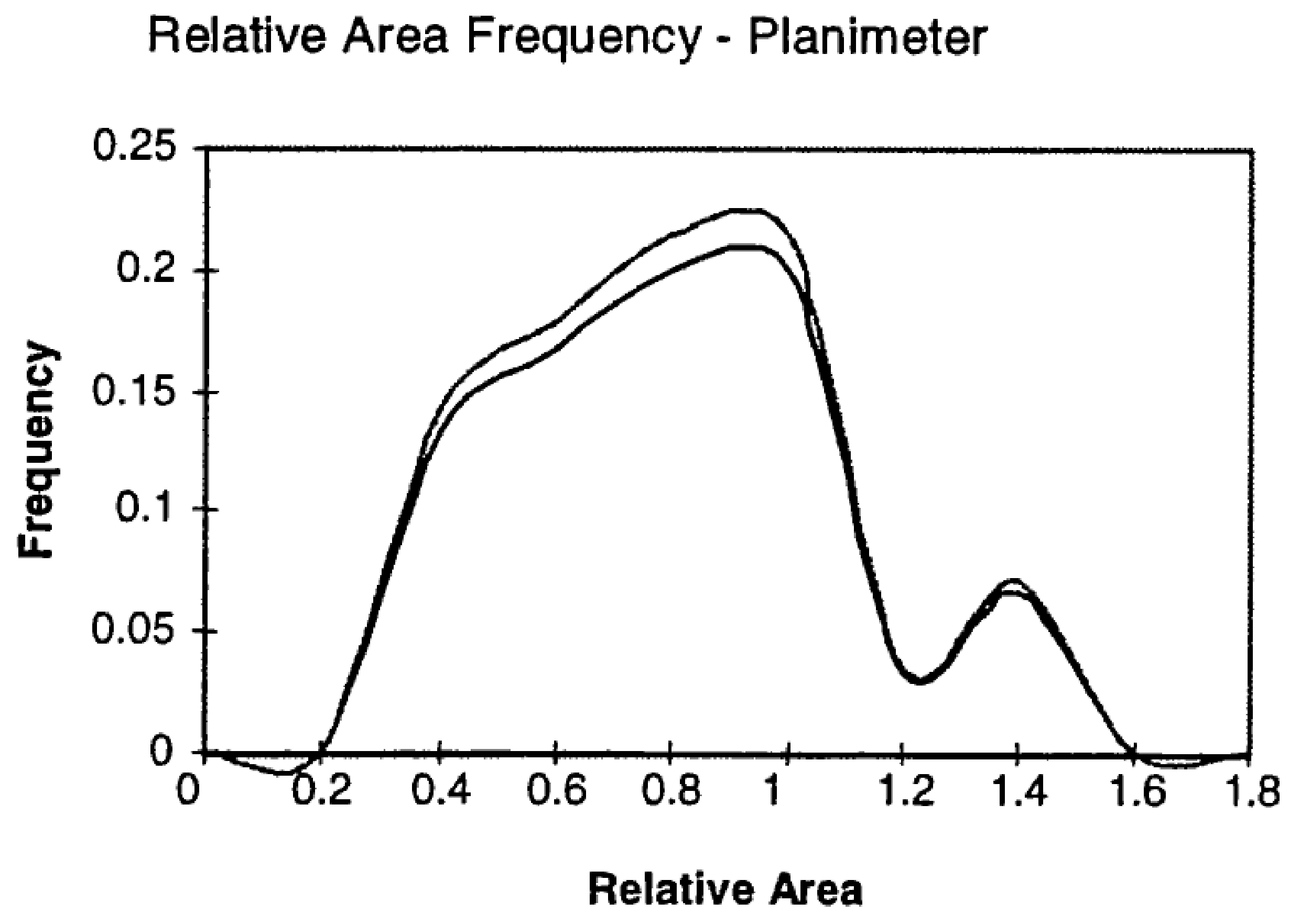


Figure 6: Relative area frequency distribution for pieces 4 and 8 from shot CU-6470. (courtesy of Ian Gravseth).

The relative area frequency (RAF) distributions are interesting in that they appear to depend on the "shape" of the object. Figure 7 compares the RAF for pieces which had highly twisted shapes (such at 2, 4, 6, and 8) with those pieces which were more plate-like (pieces 3, 9, 12, 20, and 39). Both show a slight bi-modal distribution, but have quite different shapes. This makes sense compared with the relative area frequency one would see with a sphere or a flat plate.

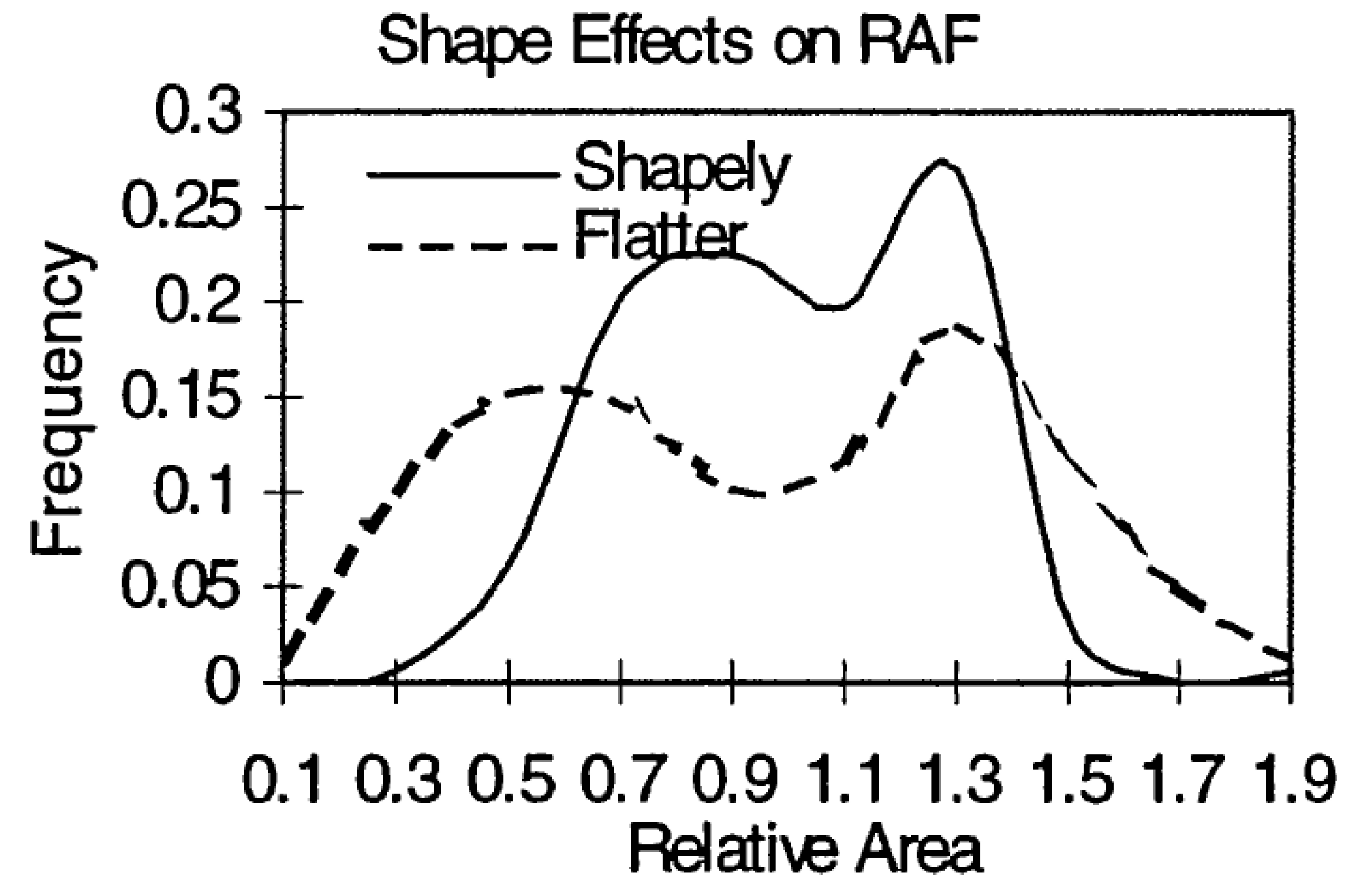


Figure 7: Comparison of "Shapely" and "Flatter" objects.

By combining all of the relative area frequency distributions for the CU-6470 pieces, one gets a generic RAF figure for debris objects. This is shown in Figure 8. This type of figure could be used to estimate the general range of cross sections expected for a piece of debris. This could possibly be useful in debris penetration studies or when estimating debris size given a number of metric observations.

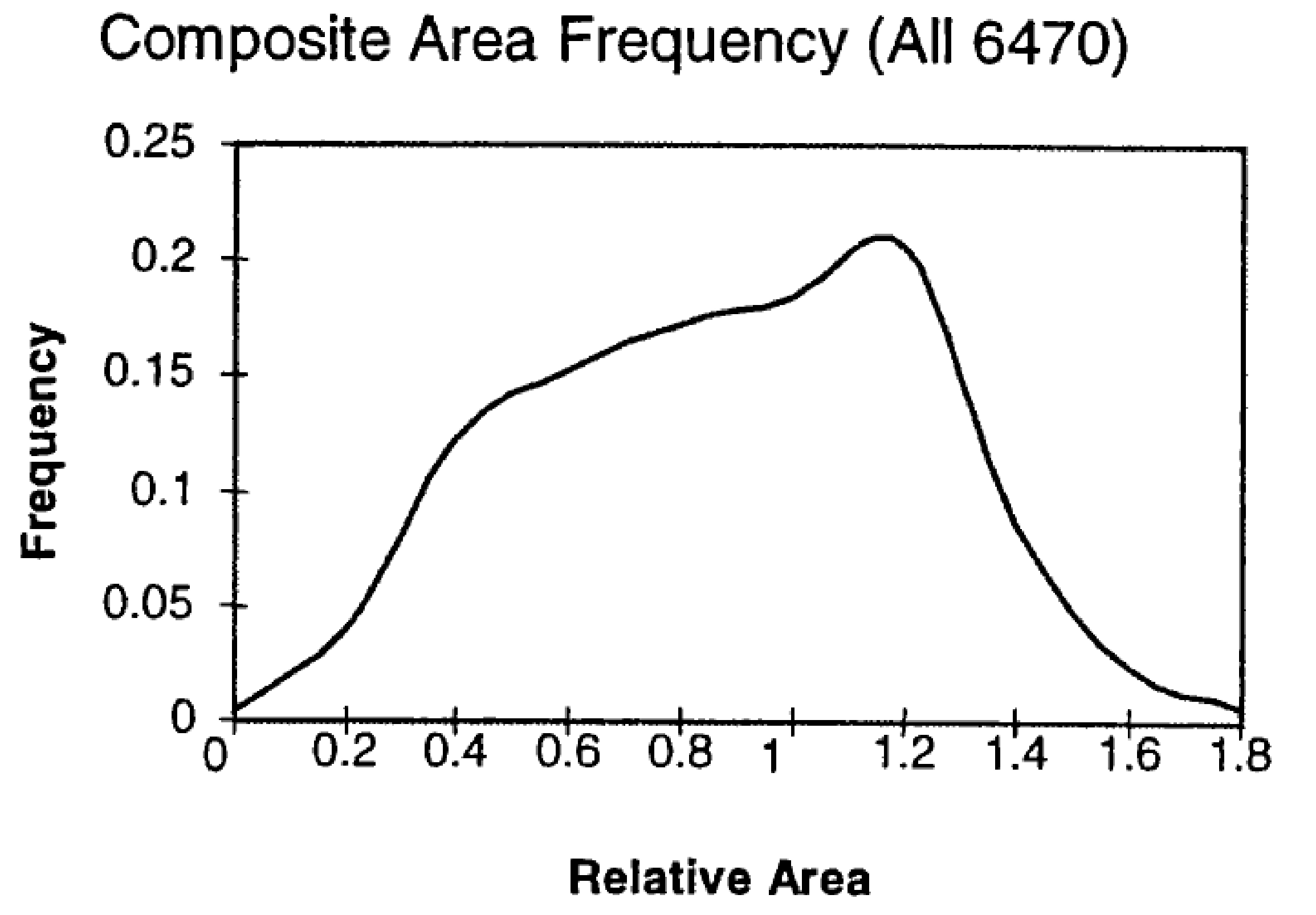


Figure 8: Composite relative area frequency for all CU-6470 pieces.

3.2 Average area distribution

Figures 9 and 10 show the measured and estimated area versus mass for the two ground tests examined. The estimated area comes from a commonly used method of assuming the object to be a sphere with the characteristic dimension as the diameter. It can be seen that the measured and estimated values diverge at larger masses. The mass range is significantly different between the two tests due to the difference in object thickness. The diameter versus area comparisons follow a similar pattern as seen in Figures 11 and 12.

Figure 9: Area versus mass for CU-6470 objects. Estimated and measured values diverge at a certain point. There are two measured values for each piece.

These results appear to imply that a common method of estimating cross sectional area may actually overestimate the area. This may have implications for debris models and measurements. A lower area would mean longer lifetimes for fragments and hence a more severe future environment. The lower area may also mean that optical measurements are actually seeing more massive objects than presently estimated. Both of these effects would make us believe the environment is less hazardous than it actually is. Further investigation is necessary to clarify this point since this analysis is based on a small database.

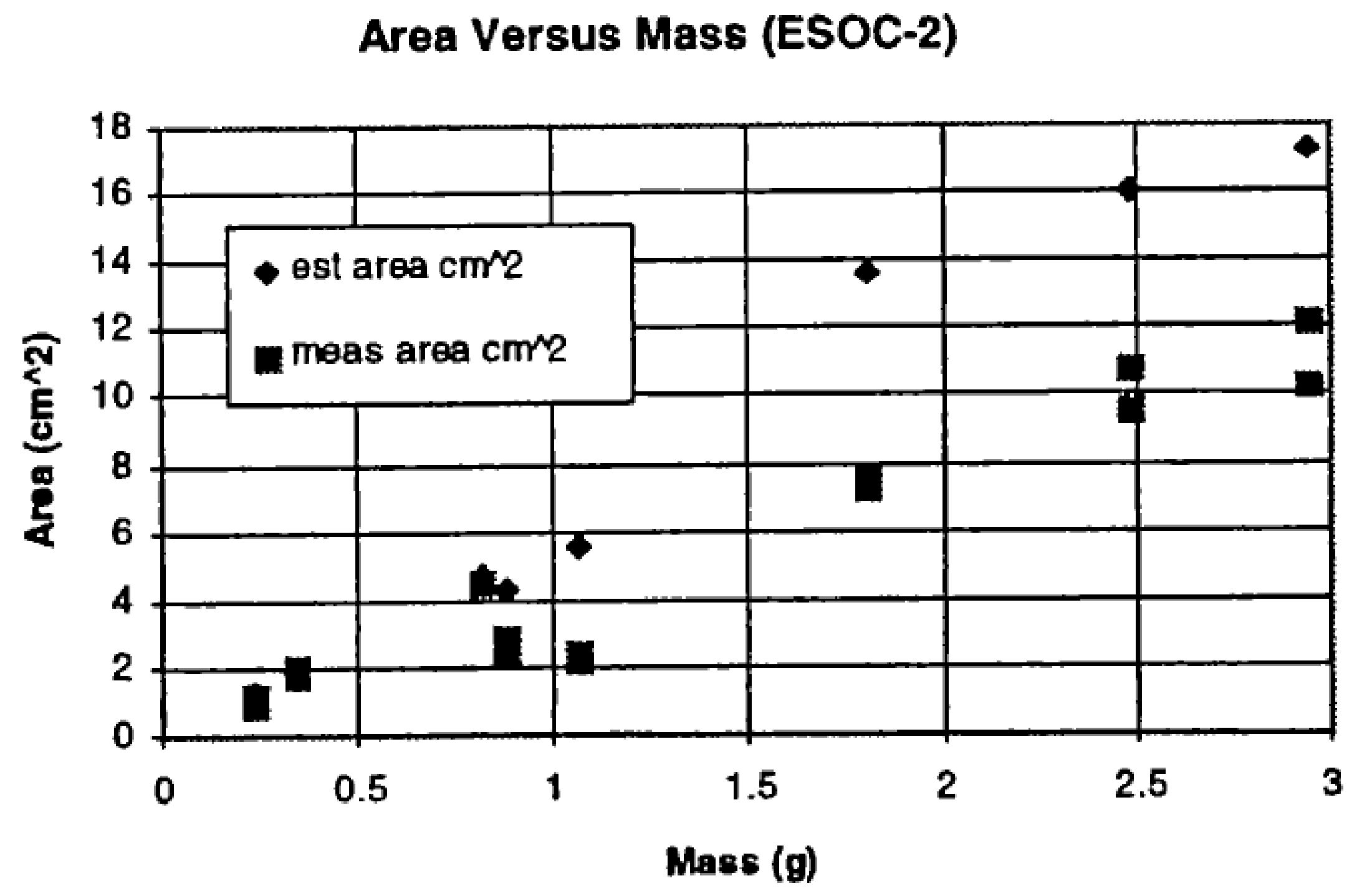


Figure 10: Area versus mass for ESOC-2 objects. Estimated and measured values diverge at a certain point. There are two measured values for each piece.

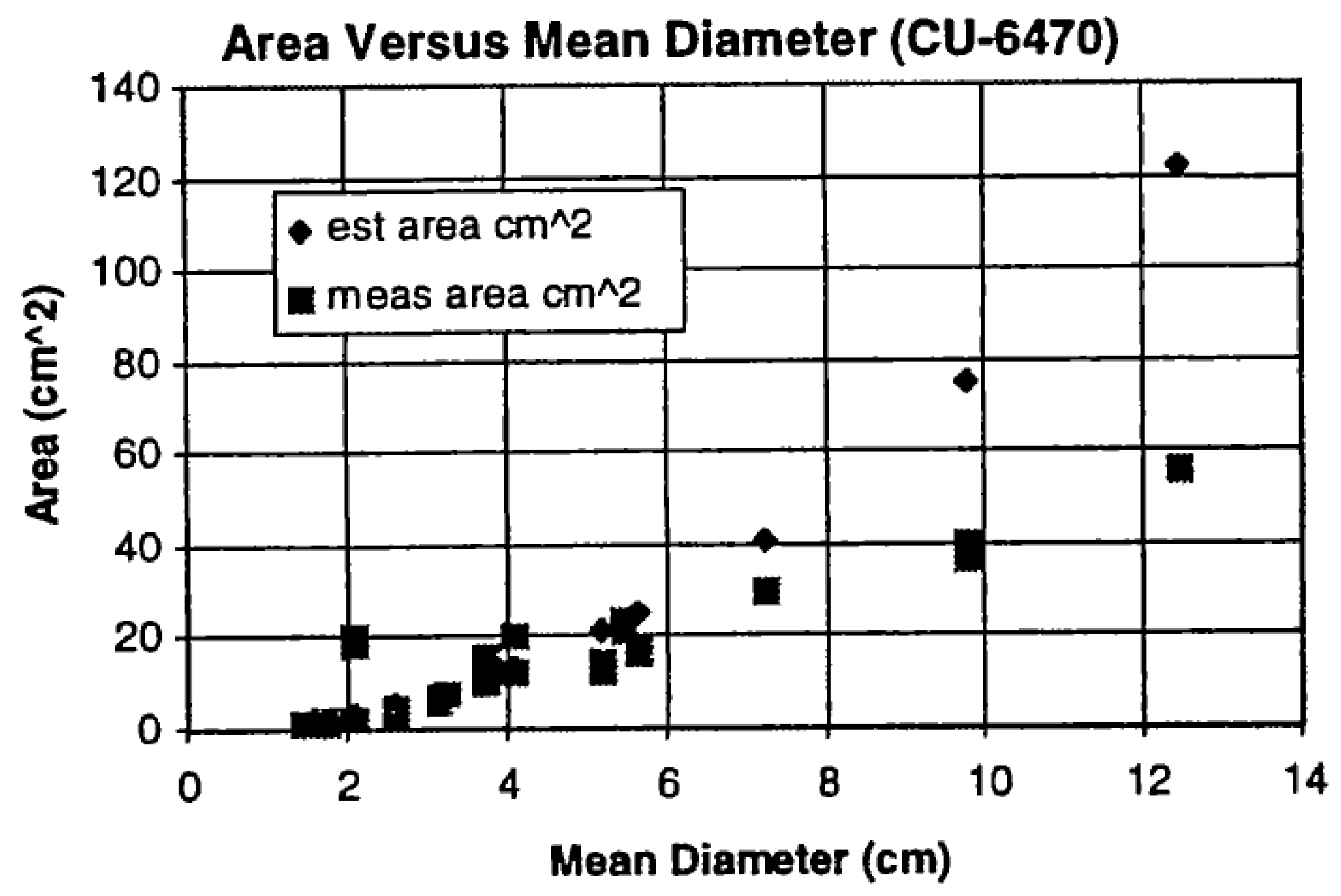


Figure 11: Area versus mean diameter for CU-6470 objects. Estimated and measured values diverge at a certain point. There are two measured values for each piece.

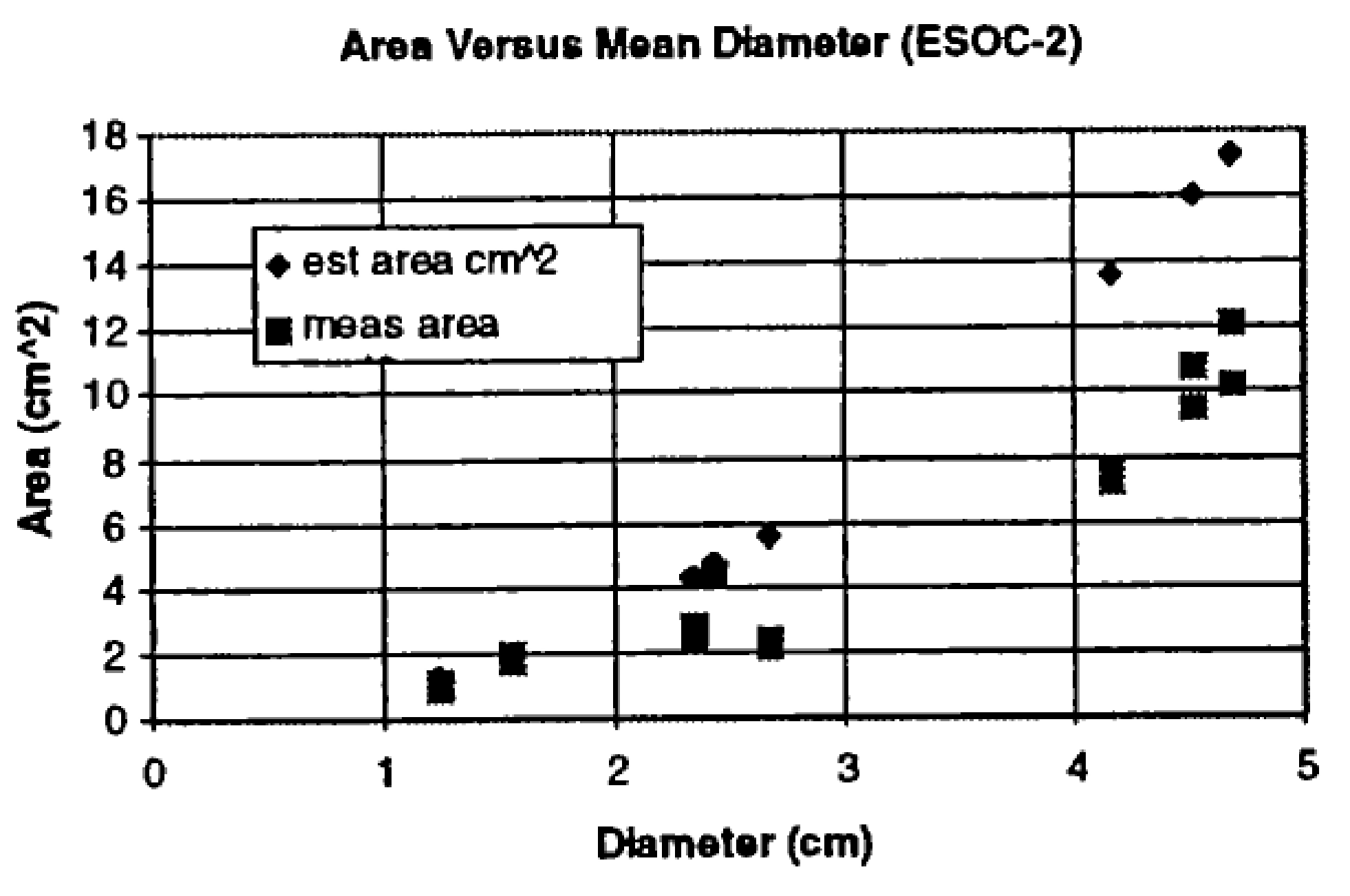


Figure 12: Area versus mean diameter for ESOC-2 objects. Estimated and measured values diverge at a certain point. There are two measured values for each piece.

4. SUMMARY

The purpose of this research has been to examine methods for determining the cross sectional area of debris objects. For laboratory pieces, the area can be measured using several different techniques. The most straightforward method is to measure the projected area of the piece from several different orientations. This has been done using a planimeter (a device to measure area). This will give an area distribution as well as an average area, but is **extremely** tedious and time consuming.

This research has developed a new, quick method for determining the cross sectional area of small debris objects. Objects are placed in front of a light source of known area and constant intensity. The lighting level is measured before and after the object is placed in front of the light source. The area of the object at that orientation can then be estimated. The main advantage of this method is that the area at each orientation can be determined very quickly and fairly accurately.

5. CONCLUSIONS

The results show that the actual cross sectional area is less than the estimated cross sectional area for the larger fragments. This could have implications for our estimates of the debris environment. Further study is required to clarify this observation.

Also it was shown that the relative area frequency distribution appears to depend upon the "shape" of a debris object. This may be the first step in trying to define a "shape" for debris objects that could be used in penetration analysis and reduction of observational data.

6. ONGOING WORK

A promising method that could be quick and does not require any specialized laboratory facilities uses digital imagery. Many images are taken of debris pieces from different orientations, and the images are analyzed to determine the cross sectional area. The image analysis software has not been completed at this time. It appears to be a promising method due to the emerging popularity of digital cameras. Figure 13 shows the image of a debris object and a reference object. Though the figure is black and white, it is actually a color image. The color is important because the background is a unique color (red in this case) so that the image has high contrast when examined in color. This allows the edges of the objects to be readily determined. As one can see from the figure, it would be difficult to distinguish the edges in a black and white image.

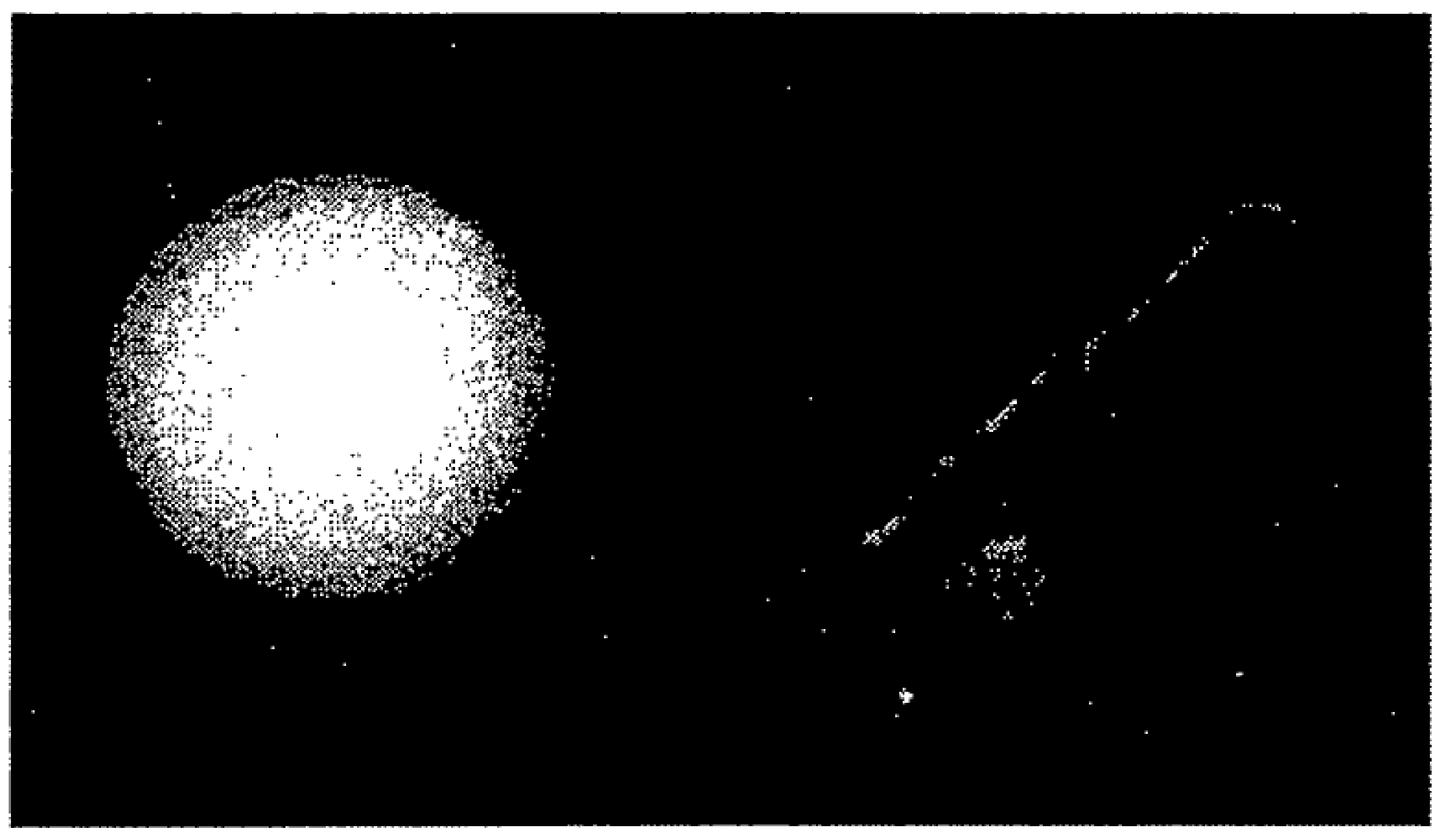


Figure 13: A debris piece and a reference area imaged. Though in black and white it is hard to see the boundaries, the color image shows a red background, yellow ball, and dark debris object; making it relatively easy to distinguish the edges of the object.

Further work is needed to determine a methodology to characterize the shape of debris objects. The shape of a fragment is necessary for determining the coefficient of drag (C_d) as well as the lethality of debris objects from on-orbit collision

7. ACKNOWLEDGEMENTS

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