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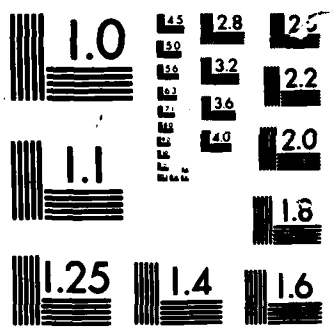

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We have used radar tracking data from NORAD to perform a sensitive search for small natural satellites of the Earth. This search would be sensitive to satellites ranging from 5 cm in diameter with perigee heights 400 km to about 40 cm with perigees 10000 km.
While a few unidentified objects were found, these were all near transfer orbits likely to contain debris from satellite launches. No objects that are unlikely to be manmade were seen.

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Final Report AFOSR-83-0128 September, 1985

An Evaluation of Existing and Prospective Air Force Data on Possible Small Natural Satellites of the Earth

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Summary

This grant was approved to fund an investigation into the feasibility of using NORAD radar tracking data to search for small natural satellites of the earth. The NORAD radar system is potentially sensitive to objects ~ 10 cm in diameter. A small natural satellite would show up as an "unknown" satellite and should appear in the NORAD tracking data. The problem is to sift through a huge amount of data to search for a natural satellite among many unidentified pieces of manmade debris already in orbit. Such a search will become more and more difficult as time goes on and the number of manmade objects in space increases.

As a result of a visit to NORAD in Colorado Springs in June, 1983, the principal investigator learned that Robert Morris (in the Directorate of Space Applications, Headquarters Spacecom) had already begun to sift through some of the NORAD data to search for unidentified objects. Conversations with Mr. Morris led to a joint effort to complete the analysis of a significant sample of the data. The result was that this grant led not to the investigation of the feasibility of a search for natural satellites, but to a very sensitive search of the space within about 10,000 km of earth. No objects that are unlikely to be manmade were found.

A paper coauthored by the principal investigator and Robert Morris, has been prepared and will be submitted for publication. This paper nicely summarizes how the search was carried out and the results; it serves as an excellent final report for this project.

A Sensitive Radar Search for Small Natural Satellites of the Earth

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We have used radar tracking data from NORAD to perform a sensitive search for small natural satellites of the Earth. This search would be sensitive to satellites ranging from 5 cm in diameter with perigee heights $\leq$ 400 km to about 40 cm with perigees $\leq$ 10000 km.

While a few unidentified objects were found, these were all near transfer orbits likely to contain debris from satellite launches. No objects that are unlikely to be manmade were seen.

The Earth seems to be unique among the planets in that it apparently has one and only one large natural satellite. The inner planets Mercury and Venus, as far as we know, have no satellites. Mars has at least two rather small ones. Jupiter and Saturn have an incredibly rich spectrum of satellites. Uranus and Neptune have ring systems as well as several large satellites, one of them almost as large as Mars. Pluto has at least one satellite.

Despite the tremendous increase in our knowledge of the solar system in the past two decades, there is still no basic understanding of this hierarchy of moons, or indeed of the planets themselves. Looking at the great diversity in sizes among the satellites of Saturn and Jupiter, one might be tempted to wonder if the Earth has small, as yet undetected natural satellites. If so, such objects would be of great interest, especially if they were in orbits from which it would be possible to retrieve them.

Despite the potential importance of such a satellite, there have been almost no published reports of searches for small natural satellites of the earth. The rapidly increasing number of artificial satellites in Earth orbit makes a search a matter of some urgency; as the clutter of manmade objects grows, it will become more and more difficult to perform a sensitive search.

The search described here became possible because of the availability of radar tracking data from the North American Aerospace Defense Command (NORAD). Analysis of a small segment of the data for "unknowns" has allowed us to make a sensitive search for natural objects with diameters as small as 5 cm.

I. Background

There seems to be no fundamental reason why the Earth cannot have small natural satellites which have escaped detection so far. All that can be said with any certainty is that their orbits cannot come too close to the Earth's atmosphere or the Moon's orbit. The evolution of orbits of large satellites with time is determined primarily by tidal interactions.[1] For very small bodies such as dust grains, radiation pressure and electromagnetic forces play major roles. None of these effects are important for satellites with sizes between say 10^{-2} and 10^{3} m. Their orbits could remain quite elliptical — which makes them hard to spot.—Their orbital life times could be arbitrarily long, if their perigees are sufficiently high. Newton's laws are time reversible so that the fact that the satellite does not escape implies that capture is also not possible without the intervention of dissipative mechanisms or rare events, such as a collision or near collision, with another body. Yet the rich hierarchy of planets with their satellites in our own solar system (and the likelihood of planets around many other stars) proves that at least during an earlier epoch efficient mechanisms for producing satellites existed.

Essentially all models of the Moon's origin postulate a swarm of material from which the Moon was formed by accretion or which was essential to reduce the angular momentum of the Earth-Moon system if the Moon was captured. It might thus seem surprising that whatever process produced our Moon left no small fragments orbiting the Earth. Any fragments in orbits with perigees $\gtrsim$ 8000 km (above the Earth's surface) should have a lifetime comparable to that of the Solar system, while any with apogees $\gtrsim$ 300000 km would probably have been swept up or driven out of orbit by the Moon.[2] This leaves a significant band between 8000 and 300000 km above the Earth's surface where primordial moonlets might still survive.

There is also a possibility that the Earth has acquired a small satellite relatively recently. O'Keefe has suggested that a spectacular train of meteors that appeared to enter the Earth's atmosphere in 1913 may have been due to the demise of a relatively short-lived natural satellite.[3]

A short-lived satellite could result when a meteor approaches the Earth on a nearly parabolic (geocentric) trajectory and just grazes the Earth's atmosphere. Occasionally this would lead to capture in an elongated elliptical orbit which gradually decays into a more circular orbit. This mechanism might give satellites with lifetimes up to a few years. Long-lived moonlets could be produced by the collision of two meteors in the Earth's vicinity. This could leave some fragments in stable Earth orbits.

Thus there seems to be sufficient justification to search for small natural satellites. Perhaps the strongest motivation is that such a search is rapidly becoming more difficult. Each year there are ~120 satellite launches, each leading to several new objects in Earth orbit.[4] Perhaps a third of these are in orbits with lifetimes exceeding 10 years. Many of the new objects are fragments from explosions or pieces jettisoned in transfer orbits. This leads to a significant number of "unknowns", particularly in and near high traffic orbits.

II. Previous Searches

A large enough natural satellite would surely have been noticed. A satellite with a diameter of 10 m would be visible to the naked eye at perhaps 2000 km on a clear moonless night.[4] One with a diameter ~2 m could be seen at that distance with 7 × 50 binoculars. At twice this distance the satellite would have to be twice as large.

To our knowledge the only systematic search for small Earth satellites was that made by Tombaugh et al.[5] Their search mainly covered the equatorial plane and the plane of the ecliptic. Even for these planes the sensitivity for highly eccentric orbits was poor. No satellites were found. Since this search is unpublished, we try to briefly summarize the search regions and limits of sensitivity here.

Several optical instruments were used in the search of Tombaugh et al. These were primarily an f/1.6 Schmidt telescope and an f/2.5 K-24 camera at Flagstaff, Arizona, and two cameras with apertures of f/1.5 and f/2.0 used at Quito, Ecuador. Visual searches were also made with small telescopes and binoculars.

The Schmidt camera search was sensitive to objects of brightness about 14^{th} magnitude. For a satellite with reflectivity of 7% in full phase illumination, this translates to a satellite about 7.5 cm diameter 1600 km above the surface of the Earth or 3 m diameter at 67000 km. This search covered orbits within about 6° of the equatorial plane with typically 40% coverage for both prograde and retrograde orbits with orbital heights between 2000 and 36000 km above the Earth. The coverage and sensitivity for highly eccentric orbits was considerably worse.

The K-24 camera would only have been sensitive to a satellite about 5 times as large as the Schmidt, but it covered orbits within about 15° of the equator and the ecliptic. Coverage in these planes was reasonably complete for prograde orbits between 200 and 36000 km, but was less complete for retrograde orbits.

The sensitivity of the camera used at Quito was probably comparable to that of the K-24 camera, but coverage there was much less complete. The major addition there was about 25% coverage of closer in orbits down to about 800 km above the Earth for prograde orbits only.

The visual telescope search gave almost complete coverage of both prograde and retrograde orbits between 1000 and 4000 km of the Earth for orbital inclinations $\leq 10'$ of the equatorial plane. The search would have been sensitive to satellites ≥ 0.3 m diameter at 1000 km and ≥ 0.9 m at 4000 m.

Tombaugh et al. also report limits for more distant satellites based on an earlier search for trans-Saturnian planets. This had essentially complete coverage in the plane of the ecliptic for satellites $\geq$ 60 m in diameter out to the distance of the Moon.

By comparision the radar search described here had a sensitivity comparable to or better than that of the Schmidt cameras but the coverage was essentially complete out to a range $\sim 10^4$ km with all orbital inclinations covered. The sensitivity of the radar search is also less dependent on the eccentricity; the coverage is related to the ratio of orbital period to the search period.

III. General Description of the Present Search

A. The NORAD Tracking System

The data used for this search were radar observations from the Space Detection and Tracking system of the North American Aerospace Defense Command (NORAD). Most of the data came from the phased-array radar system at Eglin Air Force Base in Florida. This radar is continuously active and is capable of tracking multiple satellites simultaneously.

As a satellite rises over the horizon it is acquired by the radar, which begins a series of observations. Each observation consists of a measurement of the range, the azimuth and elevation angles, and the time. The information from several such observations is compared with the orbital position of known objects. If the new acquisition is correlated with a known object and the site has not been tasked to observe that satellite, the system will stop tracking the object; otherwise it will continue tracking until it collects a track of suitable length for orbit determination. Observations which cannot be correlated with known objects are called uncorrelated tracks (UCT's). These are most often due to debris from satellite break-ups, misidentification of known objects, deviations of known objects from their predicted orbits, or new launches. These UCT's are the basic data used for this search. These were collected over a period of time and analyzed as described below.

B. Manmade Objects in Earth Orbit

Manmade objects in Earth orbit already constitute a serious background to a search for small natural satellites. Fortunately most of this background is confined to rather well-defined orbital bands. This is illustrated by the distributions in orbital inclination I for identified satellites shown in Figure 1(a) for orbits with perigee heights < 1000 km and in Fig. 1(b) for perigee heights > 1000 km. These data were compiled from the NORAD Satellite Catalog compilations ("CLASSY") dated May 1, 1983.[6] These distributions show strong peaks which reflect the latitudes of the usual launch sites and land masses of the USA and the USSR, as well as the fact that certain orbital inclinations have very desirable properties.

The peak at inclinations near 0° for perigee heights (H_p) greater than 1000 km is due to geosynchronous satellites in equatorial orbits with $H_p \cong 36000$ km. The peak near I = 28.5° results from U.S. satellites launched from Cape Canaveral at latitude approx. 28.5°. (The minimum energy launch is due eastward which gives an orbital inclination equal to the latitude of the launch site.)

The peaks between I = 60° and 85° are due to satellites launched by the USSR; the high inclinations reflect the high latitude of the Soviet land mass. In the 1960's and 1970's the most common inclination was 65°; in the 1980's the band 81-83° became dominant.[4] The Russian Molniya communications satellites have highly eccentric orbits with inclinations of 63°, initial perigee heights of about 400 km, and apogee heights near 36000 km, with the orbit arranged so that the satellite spends most of the time high above the

Russian land mass. A significant number of objects with I near 65° are fragments from a few satellites which exploded in orbit; in one case 462 objects resulted from a single launch.

Sun-synchronous orbits with inclinations near 98° are favorites for weather satellites so that the local time of photographs remains the same over a long period of time.

Note that there are very few manmade objects in orbits with I > 105°. This makes it possible to do a very sensitive search for natural satellites in retrograde orbits with I > 105°.

C. Sensitivity of the Search

The smallest-sized natural satellite to which this search would be sensitive is determined mainly by the height of the perigee of the orbit above the Earth's surface H_p. A good idea of the sensitivity of our search can be obtained by looking at the objects that are regularly tracked. For $H_p \cong 350$ km, objects with radar cross sections $\sigma \sim 10^{-4}$ m^2 are tracked. For $H_p \sim 3000$ km, the smallest objects have radar cross sections $\sim 10^{-1}$ m^2. Because radar detection involves the emission of microwave radiation by the transmitting antenna and the subsequent reemission by the detected object, the minimum detectable cross section varies as the fourth power of the range. Thus we expect

$$\sigma_{min} = C \, H_p^4 \qquad (1)$$

where the constant C depends on the transmitter parameters, etc.

Figure 2 shows a scatter plot of radar cross sections vs. perigee height for a sample of the objects in the CLASSY catalog, plotted on a log-log scale. Only objects with $\sigma < 10^{-1}$ m^2 are shown. A plot of Eq. 1 would be a straight line ascending to the right on Fig. 2. Objects to the right of this line would be invisible to the radar. Since many of the objects that are tracked are fragments from the breakup of satellites or rocket bodies, or pieces jetissoned, we can assume the smallest objects tracked are at the limits of detection. A reasonable estimate of this limiting sensitivity, which has the form of Eq. (1), is the straight line shown on Fig. 2. The equation of this line can conveniently be written:

$$\sigma_{min} = 8 \times 10^{-4} (H_p/1000)^4 \qquad (2)$$

where σ_{min} is in m^2 and H_p is in km.

Assuming Eq. (2) is a good estimate of the minimum detectable cross section, we can now proceed to an estimate of the minimum size "rock" that could be detected by our search. Most of the radar data are taken in the UHF band, or 442 MHz. [The radar cross sections in CLASSY are at this frequency.] This corresponds to a wavelength $\lambda = 0.68$ m and a wave number $k = 2\pi/\lambda = 9.26\ m^{-1}$. Since we are generally interested in objects with dimensions << 1 meter the objects will be small compared to λ. This corresponds to the Rayleigh scattering region. Fortunately in this regime the radar cross section is not strongly dependent on the details of the shape or electrical properties.[7]

For an approximately spherical object of radius a and index of refraction m, where $m = \sqrt{\epsilon_R \mu_R}$ with ϵ_R and μ_R the relative permittivity and permeability respectively,[7]

$$\sigma \cong 4\pi a^2 \left|\frac{m^2 - 1}{m^2 + 2}\right|^2 (ka)^4 \qquad (3)$$

if $ka \lesssim 1$. Some data are available on ϵ_R for chondrite meteorites. For frequencies around 420 MHz, ϵ_R ranges from 12 to 37.[8] If we take $\mu_R \cong 1$, then from Eq. (3), $\sigma/4\pi a^2$ ranges from 0.62 to 0.90 $(ka)^4$. We shall use a middle value,

$$\sigma/(4\pi a^2) \cong 0.75\ (ka)^4 \qquad (4)$$

or at 442 MHz

$$\sigma \cong 6.9 \times 10^4 a^6 \qquad (5)$$

Combining Eqns. (2) and (5),

$$6.9 \times 10^4 a^6 > 8 \times 10^{-4} (H_p/1000 \text{ km})^4$$

or

$$a_{min} > 0.0475 (H_p/1000 \text{ km})^{2/3} \qquad (6)$$

Table I gives some numerical values of the minimum detectable radius as a function of perigee height.

Table I - Minimum "radius" natural satellite detectable in this search

a_{min}	Perigee Height
2.6 cm	400 km
3.3	600
4.8	1000
7.5	2000
13.9	5000
22.	10000

Note that we have taken $\mu_R \cong 1$ so this estimate is slightly conservative for possible satellites with properties like iron meteorites.

Our search therefore has a sensitivity comparable to that of Tombaugh et al. using the Schmidt camera, their most sensitive instrument. However, theirs was limited to orbits within about 6° of the equator for orbital heights between about 200 and 36000 km. Their coverage was ~ 40% for circular orbits but decreased quickly with increasing orbital eccentricity. Our search was sensitive to all orbital inclinations and orbital heights ≤ 10000 km. The main requirement in our search is that the orbital period be short enough to allow at least 4 observations by the Eglin AFB radar during the 3-month search period.

IV. Treatment of Data

UCT radar observations over a three-month period during the summer of 1982 were collected. Each separate track was used to determine an orbit which best fit the observations. The resulting orbits were then compared to each other, and similar ones matched up into groups. Each group was examined for temporal consistency: that is, did the time history of orbital position match that suggested by the orbit elements of the group? Any inconsistent tracks would be rejected, and if 4 or more consistent tracks remained, that group would be considered to define a candidate debris orbit.

V. Results

The total sensitive time of the search was approximately 5.8 days for objects with orbital periods < 200 min. and approximately 160 days for longer periods. The analysis of the data yielded a total of 140 candidate orbits, each corresponding to 4 or more temporally consistent observations as described in Sect. IV. These all had inclinations I between 13.5° and 103°.

Most of the candidate orbits had parameters close to those of routinely tracked satellites listed in CLASSY.[6] Candidates with inclination within 0.6° and perigee heights H_p within 12% of an orbit in CLASSY were discarded on the grounds that they were probably debris associated with a launch. This left 32 candidate orbits. All of these had inclination between 13.5° and 28°.

All except one of these 32 candidates had apogee heights between 20000 and 41000 km and perigee heights between approximately 200 and 1000 km. These are consistent with debris left in transfer orbits from near-Earth orbits to geosynchronous orbit. The remaining candidate had I = 17.85°, an apogee height of 8100 km, and a period of 181 min. This and some of the other candidates at similar inclinations are probably debris from the launch of an Ariane upper stage rocket from French Guiana which blew up in 1980.

VI. Conclusions

Though our search found some "unidentified" objects in orbit, all of these have a high probability of being manmade, i.e. - they are in orbits that are very close to those of known objects or in orbital bands likely to contain debris from launches. Thus we conclude that it is unlikely that the Earth has small natural satellites with sizes $\gtrsim$ 20 cm (see Table 1), perigee heights $\lesssim$ 10000 km, and orbital periods $\lesssim$ 1 month. This still leaves an interesting region between about 10000 and 300000 km which could contain stable orbits. The optical search of Tombaugh et al. gave partial coverage of this region, mostly within ~ 10° of the equator and the ecliptic, which would be sensitive to satellites $\gtrsim$ 1 m diameter at distances ~ 10^5 km and ~ 60 m diameter at 3×10^5 km.

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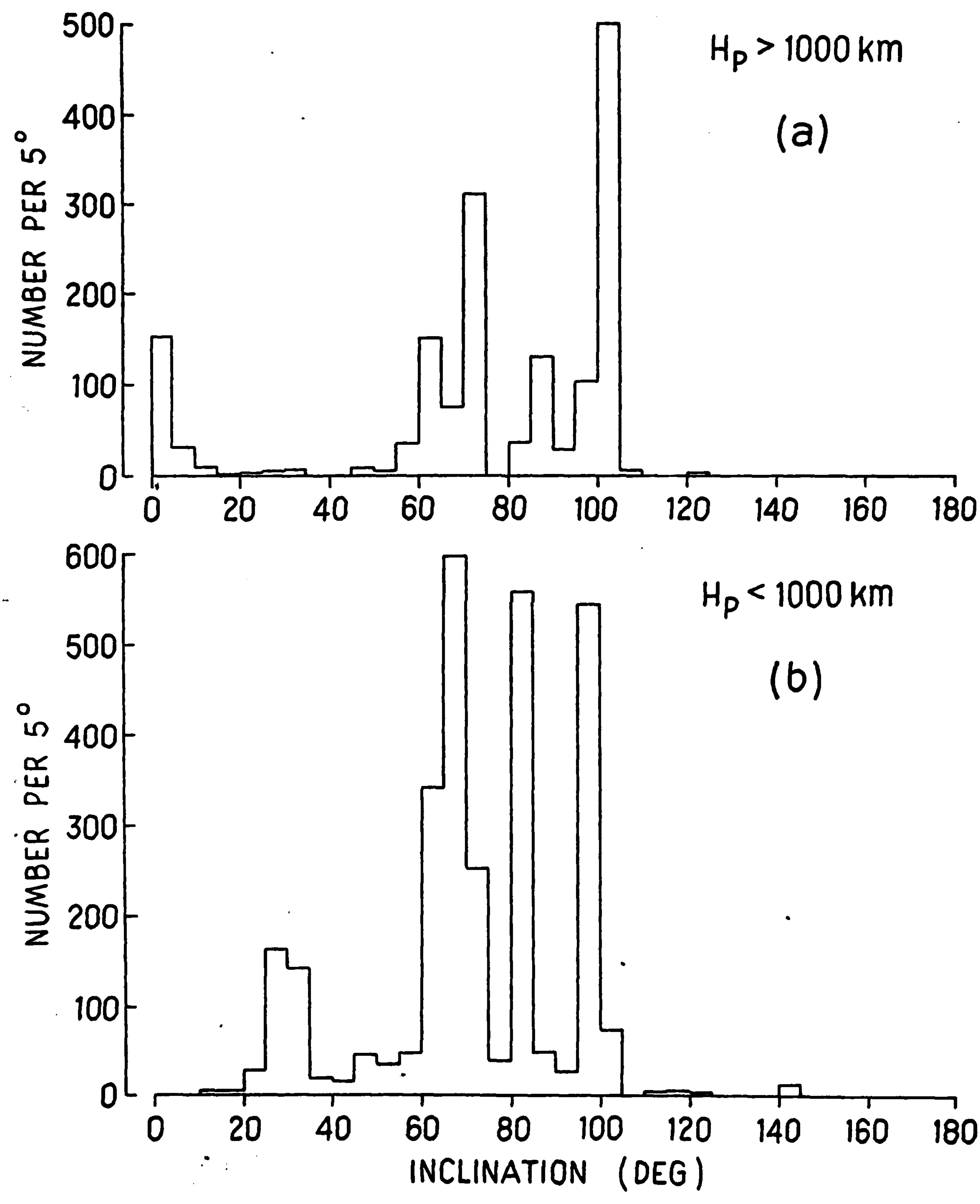
1. (a) Distribution of manmade satellites as a function of orbital inclination I for perigee heights greater than 1000 km.

   (b) Same for perigee heights < 1000 km.

   [Data from CLASSY, May 1, 1983.]

2. Scatter plot of radar cross section vs perigee height for a sample of objects in CLASSY catalog. The line is an estimate of the limiting sensitivity as a function of perigee height. Objects to the right of the line are likely to escape detection.



NUMBER PER 5°
$H_P > 1000$ km
(a)
0
100
200
300
400
500
0
20
40
60
80
100
120
140
160
180
NUMBER PER 5°
$H_P < 1000$ km
(b)
0
100
200
300
400
500
600
0
20
40
60
80
100
120
140
160
180
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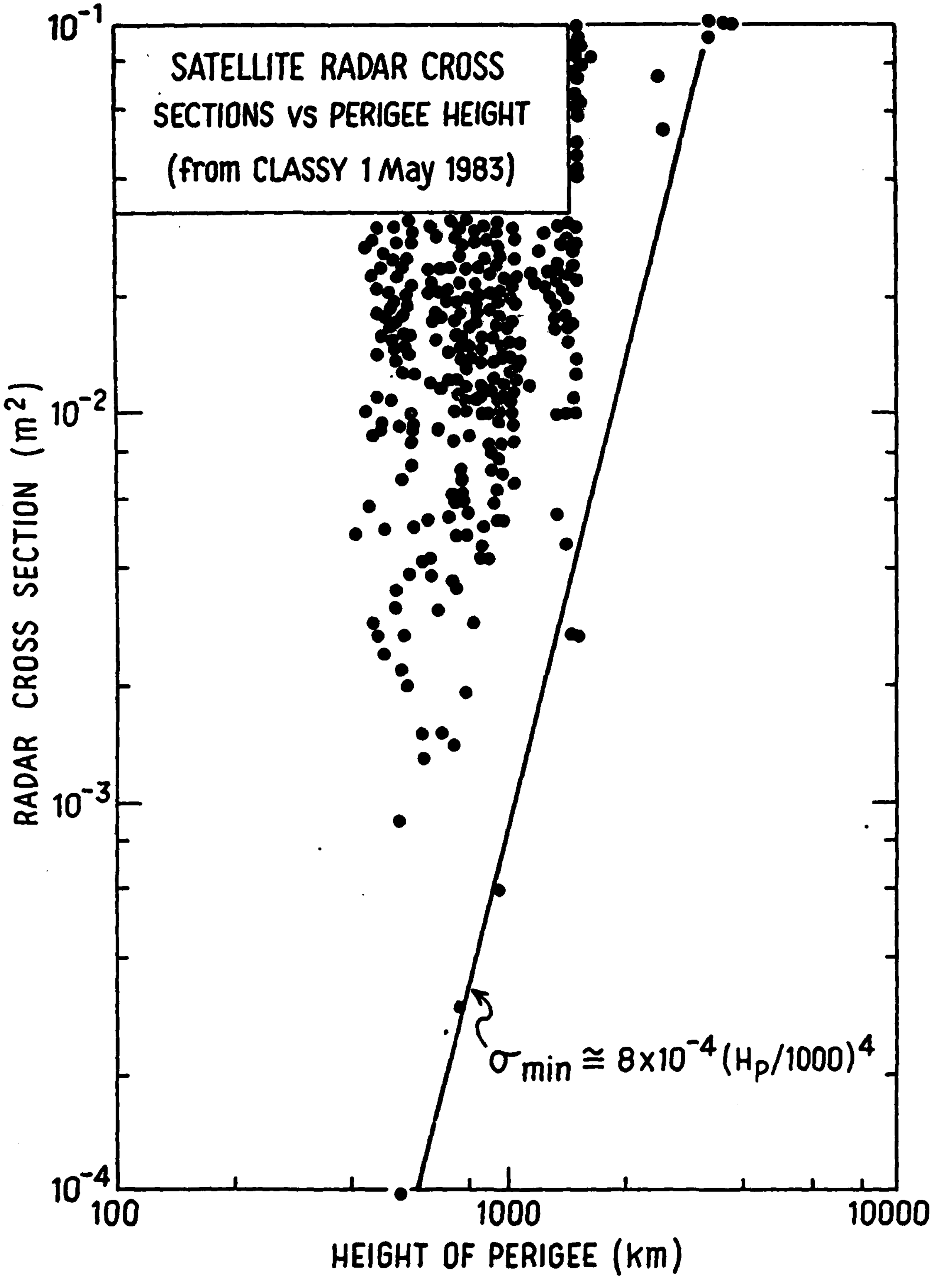

SATELLITE RADAR CROSS SECTIONS vs PERIGEE HEIGHT (from CLASSY 1 May 1983)
RADAR CROSS SECTION (m^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
100
1000
10000
HEIGHT OF PERIGEE (km)
$\sigma_{min} \cong 8 \times 10^{-4} (H_p/1000)^4$

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