Rings of Earth

Richard M. Goldstein and L. W. Randolph

Abstract—**We have used the planetary radar at the Jet Propulsion Laboratory's Goldstone Tracking Station to monitor small particles of orbital debris. This radar can detect metallic objects as small as 1.8 mm in diameter at an altitude of 600 km. The results of our first set of observations show a flux (at 600 km) of 6.4 objects per sq km per day, of equivalent size of 1.8 mm or larger. Forty percent of the observed particles appear to be concentrated into one or two orbits. An orbital ring with the same inclination as the radar (35.1°) is suggested. However, an orbital band with the much higher inclination of 66° is also a possibility. Neither explanation is without difficulty.**

Orbital Debris

In support of the space station Freedom's shielding design, NASA has been obtaining orbital debris information. Two experiments have been conducted by the Jet Propulsion Laboratory to obtain debris information on sizes less than 10 cm in diameter. The first experiment was conducted by Thompson *et al.*, at the Arecibo Observatory in Puerto Rico, which was able to detect debris down to 5 cm in diameter. The second experiment, which we describe here, utilized a radar of shorter wavelength, which can thereby detect smaller particles.

The Radar

The radar we used for this survey is part of the Deep Space Network, operated for the National Aeronautics and Space Administration by the Jet Propulsion Laboratory. It is located in the Mojave Desert near Goldstone, CA. An X-band transmitter connected to a 70 m parabolic dish antenna was used to illuminate the orbital particles with 3 ms pulses (with an 8 ms repetition period) of otherwise unmodulated microwave energy. A receiver was connected to a smaller antenna (26 m) located 21.6 km from the transmitter.

The antennas were pointed so that the beams intersected 600 km above the midpoint between the two antennas. Fig. 1 shows the geometry of the experiment. The cross sectional area of the antenna beam intersection was 11.6 sq. km. The layer observed was only about 40 km thick at an altitude of 600 km. Particles in near circular orbit will take 51 ms to traverse the beam intersection.

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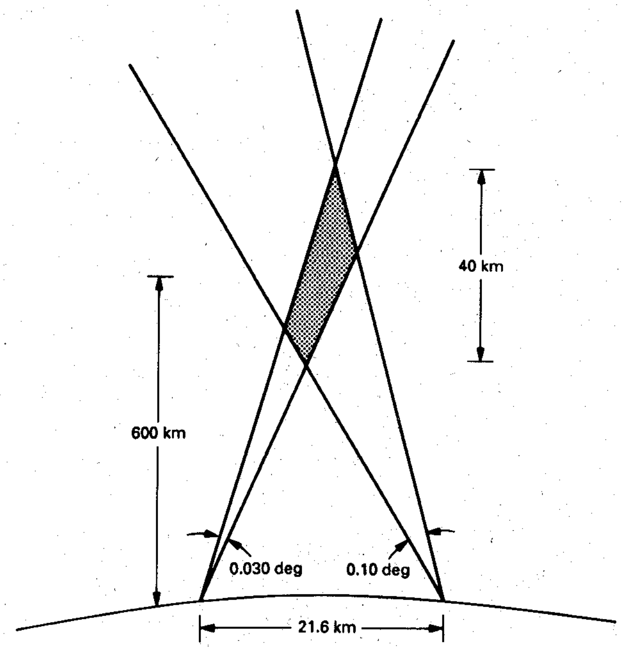

Fig. 1. Sketch of the intersection of the two antenna beams. The common area of 11.6 sq. km was centered at an altitude of 600 km.

Other radar parameters of interest were:

Transmitter power = 340 kW (peak)
Transmitter antenna gain = $2.37\ 10^7$ (over isotropic)
Receiver antenna area = 191 sq. m (effective)
System noise temperature = 24.3 K
Wavelength = 3.5 cm

Observations

Two to five hour observation periods were scheduled on an irregular basis from March 22, 1989 to October 16, 1989. Altogether, 48 hours of data were collected over 15 separate days (or nights).

Signal Processing

Received signals were filtered to a bandwidth of 10 kHz, sampled both in-phase and in-quadrature at the 10 kHz rate, and stored on digital magnetic tape. Subsequently, blocks of 3 ms duration were Fourier transformed, resulting in a resolution of 333 Hz and a bandwidth of 10 kHz. The magnitude-squared of these spectra were accumulated over 6 such send-receive cycles (48 ms). The resulting power spectra, normalized by the average power, were compared to a threshold to decide if there had been a "hit" or only noise in the data.

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The threshold was determined from a chi-squared distribution of 12 degrees of freedom such that, on average, there would be one false alarm per 5 hours (375 000 spectra). The resulting threshold (3.87) corresponds to a radar cross section of 5.8 10^{-3} sq. mm, which we take to be our detection limit. At our wavelength, a metallic sphere of 1.8 mm diameter has this radar cross section.

The radar cross section, σ, is computed from the signal-to-noise ratio by the radar equation:

$$\text{SNR} = \frac{\text{Power Gain } \sigma \text{ Area}}{(4\pi)^2 R^4 k \text{ Temp Bandwidth}}$$

where R is the range and k is Boltzman's constant (1.3 10^{-23}), and bandwidth is 333 Hz.

Rayleigh scattering theory is appropriate for a metallic sphere when the diameter is small compared to the wavelength, i.e.,

$$\pi d < 0.6\lambda.$$

In such cases, the radar cross section is

$$\sigma = \frac{\pi^5 d^6}{\lambda^4}.$$

We have reduced the number of reported events by the expected number of false alarms. Thus the reported flux is a lower limit; there must have been undetected small particles.

DATA

The spectrograms for a representative event are shown in Fig. 2. Five spectrograms are plotted in a time sequence separated by 48 ms, the approximate time for a particle to remain within the beam intersection. Line-of-sight velocity is the abscissa; relative power density the ordinate. A line-of-sight component of velocity of ± 88 m/s corresponds to a frequency range of ± 5 kHz. The signal to noise ratio for this event was 6.5, somewhat over the threshold and corresponding to a metallic sphere of 1.9 mm diameter.

Fig. 3 is a cumulative distribution of all of the particles detected in the survey, plotted according to radar cross section. Also marked along the abscissa is the size of the equivalent metallic sphere of the same radar cross section. We note that the actual particles can be larger than this if they are not made of metal.

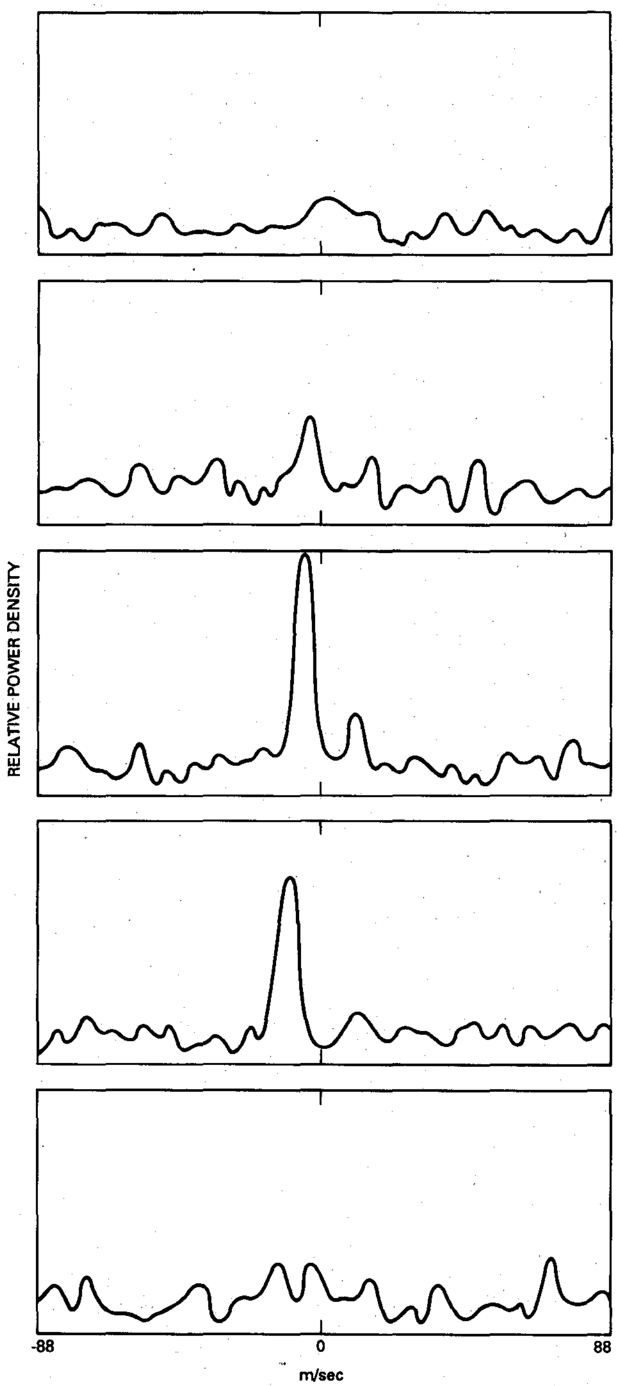

Fig. 2. Spectrograms separated in time by 48 ms. An object of equivalent diameter of 1.9 mm appears to have passed through the intersection of the two antenna beams.

SWARMS

For most days of observations, one or two events per hour were recorded. On some hours, however, the rate was as high as 15. What happened on those days to produce swarms of events?

Fig. 4 gives the results of one such day. Time for each event is plotted against line-of-sight velocity. The velocities are measured from the spectrograms and represent the Doppler shifts generated by the (small) radial velocities of the objects when they cross the antenna beam. The signal to noise ratio of each event is marked on the figure. Two of the events show relatively large amounts of power, but the equivalent sphere is still smaller than the wavelength.

To within the accuracy of the velocity estimates, one straight line goes through almost all of the points. These separate events are therefore strongly related; they must have a common origin. However, during the hour long life time of such a swarm, the Earth has rotated 15 degrees. How is it possible for this family of objects to remain so long in an antenna beam of only 315 m width at altitude?

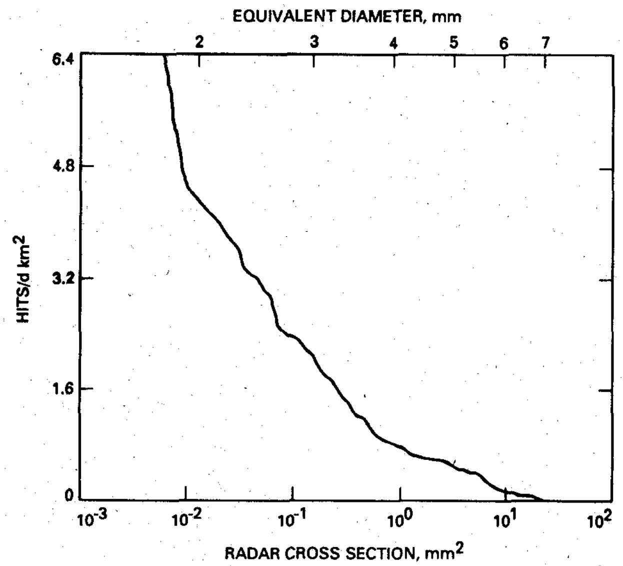

Fig. 3. Cumulative distribution for the flux of orbital debris. For each radar cross section, the plot gives the flux of particles of that cross section or larger.

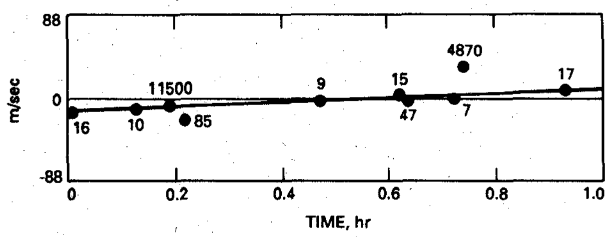

Fig. 4. Record of events during 1 hour on Sept. 4, 1989. One straight line fits the data so well that the events must be related. Numbers indicate the signal to noise ratio.

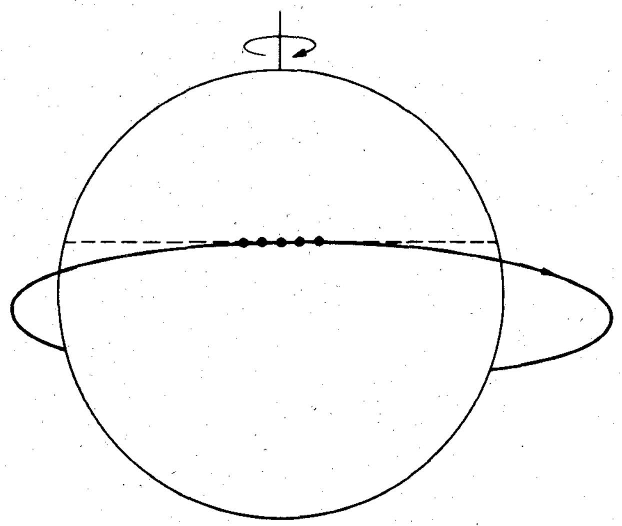

Fig. 5. Diagram showing how an antenna fixed to the rotating Earth can illuminate an orbital ring for an extended period of time.

Fig. 5 presents a possible answer; the objects are in a common orbit (a ring) that has the same inclination as the latitude of the radar. Then, the Earth's rotation would carry the radar in a direction that is parallel to the putative

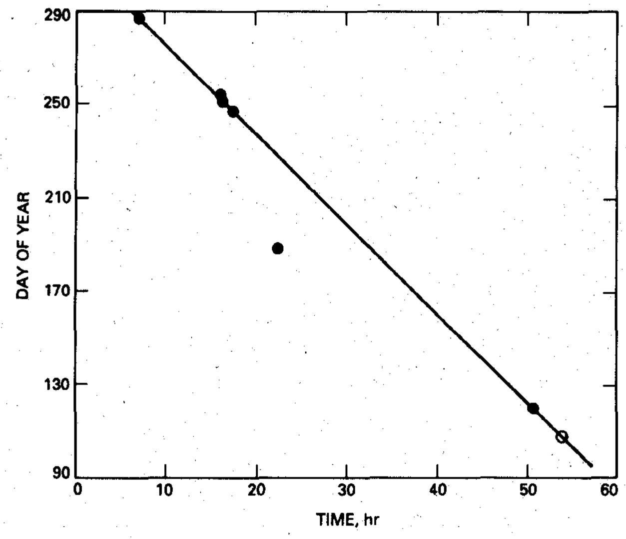

Fig. 6. Day of year versus time of day plot show that 5 of the 6 observed swarms were repeat observations of the same orbital ring, precessed by 4.0 degrees per day.

ring. Such a hypothesis should be easy to test. All one needs to do is to repeat the experiment the next sidereal day, when the radar has rotated back again under the ring. Unfortunately, our observation schedule was too irregular, averaging only two tracks per month.

During the survey, we found six occasions where the velocity-time plots could be essentially connected by one straight line. For each of these occasions, we have plotted the time of the zero crossing of the straight line against the day of year on which it occurred. The result is given in Figure 6.

A single straight line connects 5 of the 6 points. We conclude that the same orbit was observed 5 times. The slope of the line represents the precession of the orbit, which was 3.0 degrees per day faster than a stationary orbit. The orbit is prograde. The sixth point of Fig. 6 represents a second orbit, one observed only once. The velocity-time line for that swarm had the opposite slope from the other five.

The observed precession rate seems too low for an orbit of 35 degrees inclination. It matches, instead, what one would expect for 66 degrees.

A second possibility is that of a satellite at the higher inclination that broke (or was broken) up in orbit. The debris might then spread into a band which could be in the Goldstone beam for the required hour. The breakup must have been rather violent, since so many small particles were produced. Such a process would tend to randomize the Doppler shifts, which is contrary to the linear relationship which we found.

The open circle on Fig. 6 represents one day when observations were made at the correct time to see the swarm, but no swarm was seen. On that day, the receiver's circular polarization was reversed. Large, irregular objects and flake or wire shapes can reverse the sense of circular polarization. The observed swarm evidently was not composed of any of these.

Conclusion

From the observed flux of 6.4 events per sq km per day, the expected time for an astronaut to be hit is 214 years. The danger, however, appears to depend on location. Within the ring volume, the expected time drops to 59 years. And at the convergence point (if it exists) of the orbital band, the expected time is only 1.5 months.

In any case, the situation is continually deteriorating as more and more debris is deposited into orbit. Furthermore, there is an undetermined, but apparently larger, flux of particles smaller than 1.8 mm that could pose a hazard.

Acknowledgment

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References

[1] T. W. Thompson, R. M. Goldstein, D. B. Campbell, E. G. Stansbery, and A. E. Potter, Jr., "Radar detection of centimeter-sized orbital debris: preliminary arecibo observations at 12.5-cm wavelength," *Geophysical Research Letters*, vol. 19, no. 3, pp. 257–259, Feb. 7, 1992.

Richard M. Goldstein was born on April 11, 1927, in Indianapolis, IN. He received the B.S. degree in electrical engineering from Purdue University and the Ph.D. degree in radar astronomy from the California Institute of Technology.

He joined the staff at the Jet Propulsion Laboratory in 1958, where his research includes telecommunications systems, radio ranging of spacecraft, and radar observations and mapping of the planets and occasional asteroids and comets. His current work is in radar interferometric measurements of Earth's topography and displacements, ocean currents and ocean wave spectra.

L. W. Randolph, photograph and biography not available at the time of publication.