Von R. Eshleman

THE MARINER JUPITER/SATURN RING OCCULTATION EXPERIMENT

Radio occultation measurements of the rings of Saturn constitute one of several experiments to be conducted by the Mariner Jupiter/Saturn radio science experiment team. The members are J. D. Anderson, G. Fjeldbo, and G. S. Levy of JPL, and T. A. Croft, G. L. Tyler, and myself of Stanford University. A very substantial contribution to the material I am presenting today is due to A. E. Marouf, a graduate student at Stanford.

As a spacecraft passes behind the rings of Saturn as viewed from Earth, the downlink radio signals will be affected in frequency, spectrum, and amplitude by the material in the rings. Measurements of these signal characteristics can provide information on the amount, distribution, particle size, and other characteristics of this material.

Each spacecraft will transmit two coherent signals at 13-cm (*S* band) and 3.5-cm (*X* band) wavelengths. The spacecraft antenna has a diameter of 366 cm, and ground antennas are the 64-m paraboloids of the Deep Space Network. Transmitter powers are 10 W at *S* band and 13 W at *X* band.

Gorden Pettengill Are the spacecraft transmitters solid state?

Eshleman No, they are two-level, traveling-wave-tube amplifiers. The higher power levels are 28 W at *S* band and 22 W at *X* band, but these cannot be used simultaneously at encounter because of other demands on total spacecraft power.

The radio team is particularly concerned about obtaining a flyby trajectory that includes occultation across the whole extent of the ring structure. Figure 1 is an example of some of the studies of this problem by P. Penzo and his colleagues at JPL. It shows that, for a given arrival date (September 21, 1981) and radius of closest approach (4 Saturn radii), there is a pivot point relative to where the spacecraft appears to go behind the planet as viewed from Earth. The θ angle is the one defined by Penzo previously (see contribution by Penzo).

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Figure 2 shows a closeup view of a relatively favorable condition for ring occultation on the entry side of the planet. This trajectory also provides a clear radio occultation measurement of the atmosphere (and ionosphere) at entry, so that atmospheric and ring particle effects can be separately determined. Note that at exit the atmosphere would not be seen clear of possible ring effects.

Figure 3 shows the variation with time of the inclination of the plane of the rings as viewed from Earth. The period of time for spacecraft arrival at Saturn for the defined MJS project is between late 1980 and June 1981. The inclination is small during this period—between 4.5° and 7.5°. Note that at later times this angle gets larger.

Figures 4 and 5 illustrate the potential importance of ring inclination and ring-spacecraft distance to the radio occultation experiment. The angle ψ is the ring

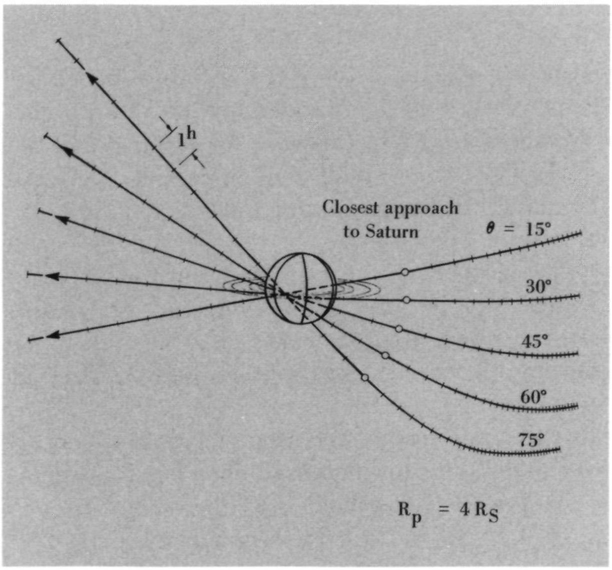

FIGURE 1.—*Saturn trajectories viewed from Earth on September 21, 1981.*

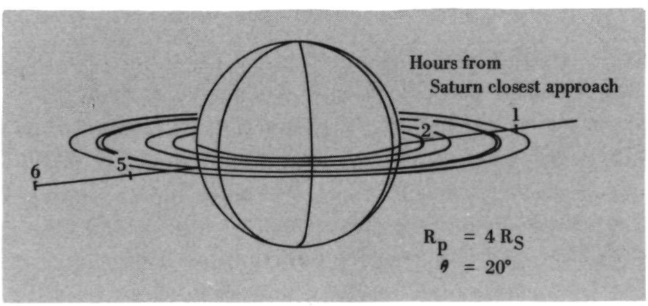

FIGURE 2.—*Ring occultation trajectory of September 21, 1981 arrival date.*

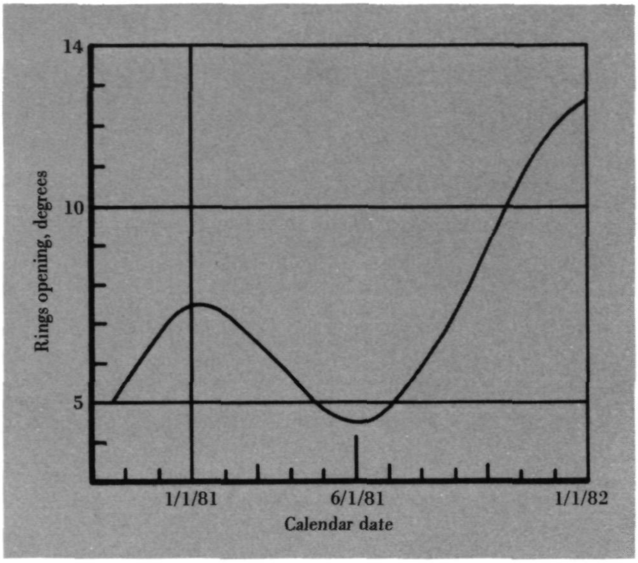

FIGURE 3.—*Ring inclination as viewed from Earth for the period around MJS Saturn encounter.*

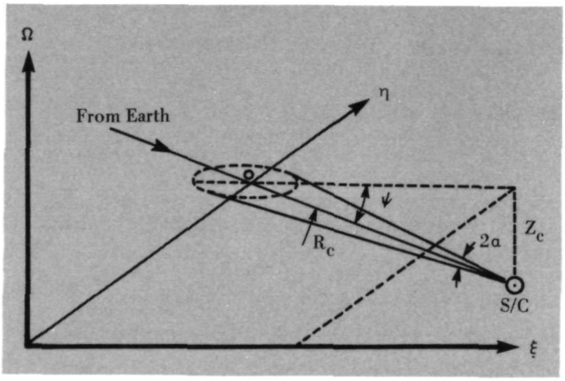

FIGURE 4.—*Spacecraft antenna ring viewing geometry.*

inclination, R_c is the distance from the spacecraft to the intersection point in the ring plane ($\xi-\eta$ plane) of a line from the spacecraft to Earth, and α is the half-width of the spacecraft antenna beam. For an inclination angle of 8° and several different (relatively small) values of R_c, figure 5 illustrates the area in the ring plane illuminated by the antenna for values of α of 0.5°, 1.5°, and 3°. This figure also shows the disk of Saturn and the relative light intensity of the rings as a function of radius.

Under certain conditions discussed below, the resolution of the radio occultation experiment would be limited by the illuminated area of figure 5. The X-band beam illumination of the ring plane would be an ellipse somewhat smaller than

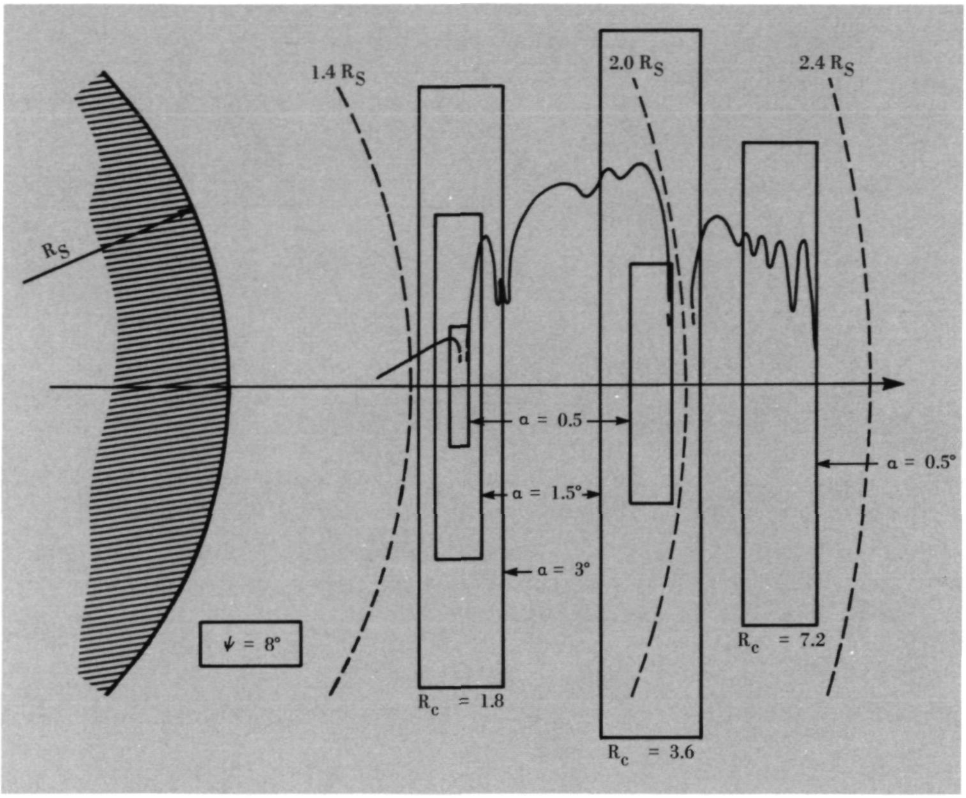

FIGURE 5.—*Antenna patterns superimposed on ring system for specific spacecraft-ring-Earth geometry.*

would fit in the $\alpha = 0.5°$ rectangle of figure 5, while the S-band ellipse would be a bit smaller than the corresponding $\alpha = 1.5°$ rectangle.

Pettengill The smaller rectangle is for the X band?

Eshleman The smallest one ($\alpha = 0.5$) is actually larger than the X-band pattern, since the half-power beamwidths correspond to $\alpha = 0.34°$ at X band and $\alpha = 1.23°$ at S band.

Note that if the antenna beamwidth limits resolution, it will be difficult to obtain reasonable discrimination of changes of ring characteristics with radius unless the ring inclination is relatively large and the flyby distance is small.

The next sequence, figures 6 through 9, shows a view looking perpendicularly down on the ring plane. These examples are for Earth being 30° above the plane, so that the spacecraft at occultation is 30° below the ring plane. In figure 6 the spacecraft is shown quite close to the planet, only $2R_S$, or one Saturn radius from the surface of the planet. It is moving perpendicular to the Earth-spacecraft line at 10 km/sec. Figures 7, 8, and 9 show the spacecraft on this path at successively later times. For these conditions, the contours shown are loci of constant doppler shift (in kilohertz at S band or 11/3 times this value at X band) for scattering from ring particles at the indicated positions. That is, for a ray from the spacecraft to the ring particle and then to Earth, the doppler shift due to particle and spacecraft motion would be the value indicated at that position. (There are, of course, some areas where the ray from the spacecraft to a ring particle or from a particle to Earth would be shadowed by the planet.)

These doppler contours can be used to determine theoretical radio-frequency spectra for rings with various radial distributions and particles with different assumed scattering properties. The inverse problem is also being studied (i.e., we wish to know how to determine ring and particle properties from measured spectra).

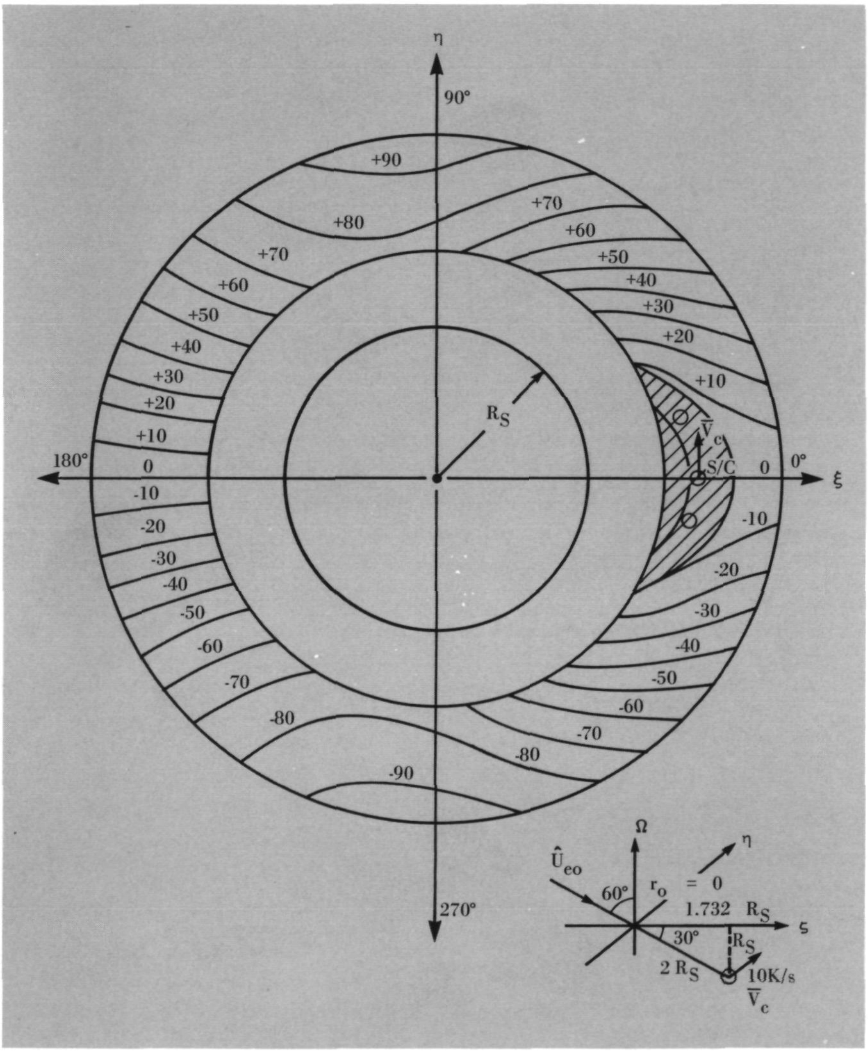

FIGURE 6.—*Doppler contours for the visible ring system illuminated by the spacecraft with* $r_o/R_S = 0.0$.

Pettengill Did you say these were drawn for an inclination of 30°?

Eshleman Yes. Thus they are not exactly representative, since smaller angles are expected at encounter, although they do illustrate the important characteristics.

You might think of the full range of contours in these figures as representing doppler effects if the spacecraft antenna were omnidirectional. With the actual high-gain antenna, only those elliptical illumination regions discussed earlier would contribute to the spectrum. The spacecraft antenna could be pointed in directions other than directly toward Earth in order to study a wider range of

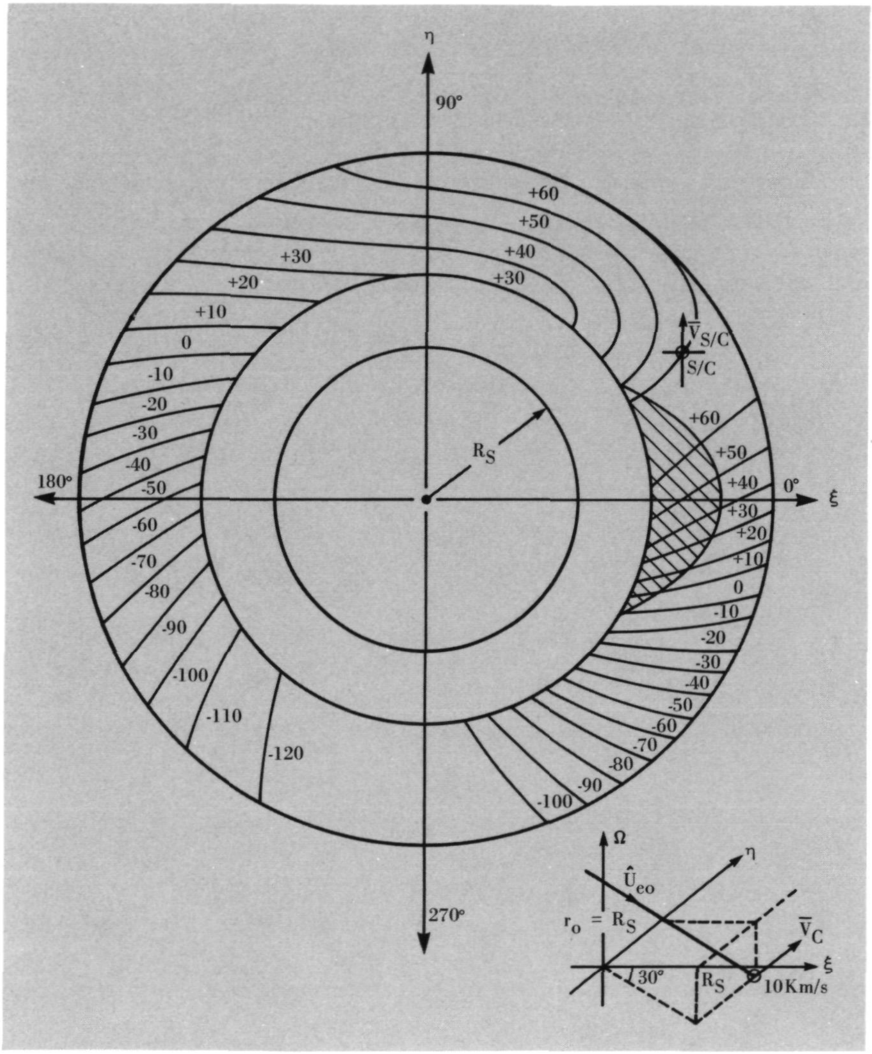

FIGURE 7.—*Doppler contours for the visible ring system illuminated by the spacecraft with* $r_o/R_s = 1.0$.

particle scattering angles. In principle, it would be possible to study scattering angles from direct backscatter to direct forward scatter.

James Pollack I'm sorry, I'm confused here. Are you speaking of an experiment you actually plan to do where you shine the antenna at the rings and look at the signal that gets bounced off the rings?

Eshleman We will be concerned primarily with the angles very near forward scattering, but we also hope to be able to orient and move the spacecraft so that the antenna will look in directions well away from the direct line to Earth, in order to gain more complete information on the scattering properties of the particles.

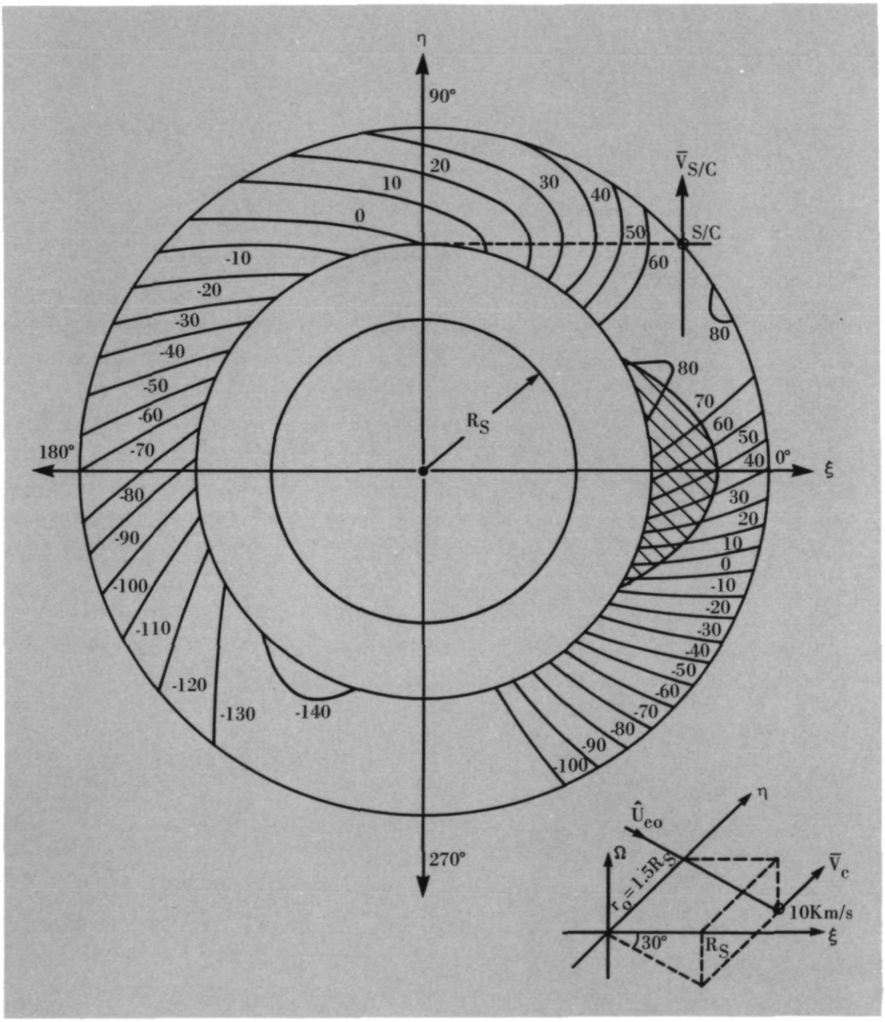

FIGURE 8.—*Doppler contours for the visible ring system illuminated by the spacecraft with* $r_o/R_S = 1.5$.

Now I would like to outline briefly several characteristics of radio wave scattering from particles. The size of the particles is of particular interest. Table I illustrates five different particle size scales that delineate six regions where the scattering characteristics would differ in this experiment. The inverse wave number at X band, k_X^{-1}, is about 0.5 cm. The inverse wave number at S band, k_S^{-1}, is about 2 cm. The radius of the spacecraft antenna, R, is about 180 cm. The radius of the principal Fresnel zone at X band, F_X, is about 2 km if the spacecraft distance from the ring intersection point described earlier is 4 Saturn radii, and the corresponding scale at S band, F_S, is about 4 km. These five scale sizes are boundaries to the six size regions specified as $A, B, \ldots, F$ in table I.

The following discussion would apply ideally to cases where the particles are

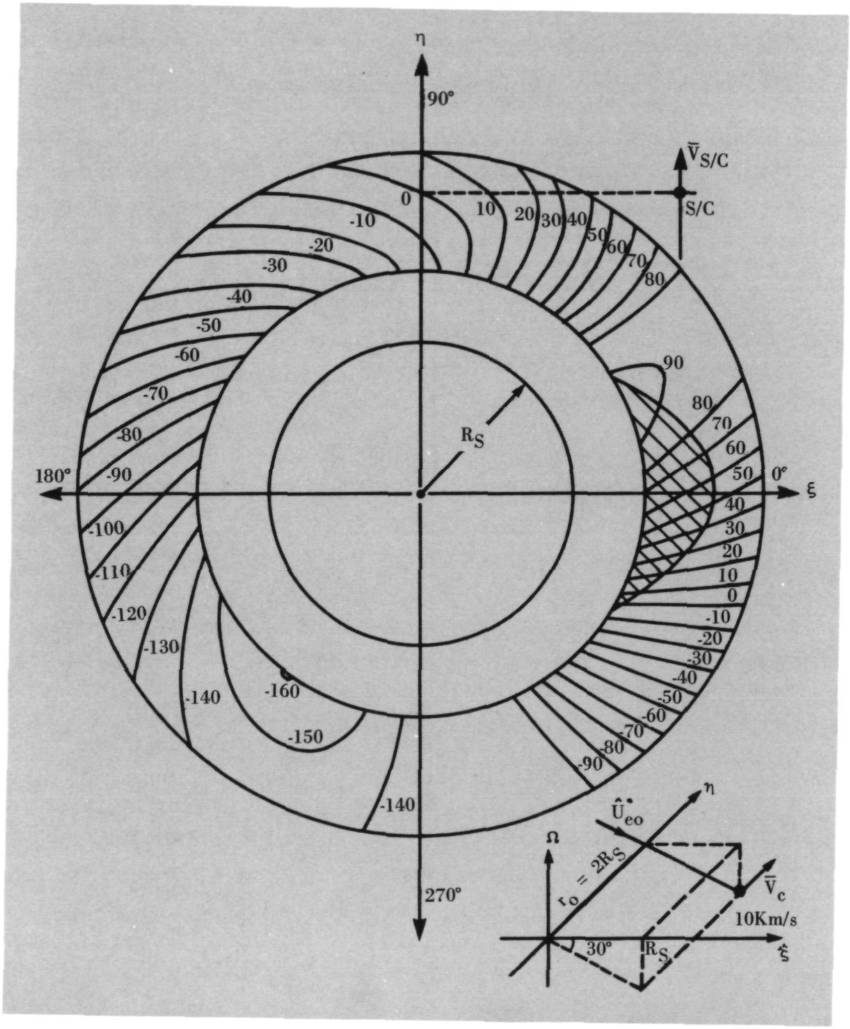

FIGURE 9.—*Doppler contours for the visible ring system illuminated by the spacecraft with* $r_o/R_s = 2.0$.

TABLE I.—*Scales which determine regions of different particle scattering behavior.*

Scale, cm	
k_x^{-1}	0.5
k_s^{-1}	2
R	180
F_X	$2 \cdot 10^5$
F_S	$4 \cdot 10^5$

A	$a < k_x^{-1}$
B	$k_x^{-1} < a < k_s^{-1}$
C	$k_s^{-1} < a < R$
D	$R < a < F_X$
E	$F_X < a < F_S$
F	$F_S < a$

all of the same size, but if there is a narrow range of sizes it would still be applicable. Important information on the size distribution would also be available based on these same scales if there were a wide spectrum in size, but this condition is not analyzed here.

Consider first region A, where all particles are smaller than the smallest size (0.5 cm) in the table. (The Earth-based radar measurements of the rings indicate that this size regime is not to be expected.) Figure 10 outlines some features of this case. In the absence of ring particles, the received signal would be an impulse in the frequency domain, as illustrated by the dashed line. In general, particles could cause a frequency shift (f) of the impulse, a reduction of power in the coherent signal to P_c, and an incoherent signal of power P_i and spectral width Δf. For case A it is expected that the incoherent signal would be too weak for detection, so P_i and Δf would not be measurable. Because there are two coherent wavelengths, the wavelength dependence of the loss of coherent power could be measured. For lossless particles this change would be due to scattering and would be proportional to λ^{-4}, while for lossy particles it would vary as λ^{-1}.

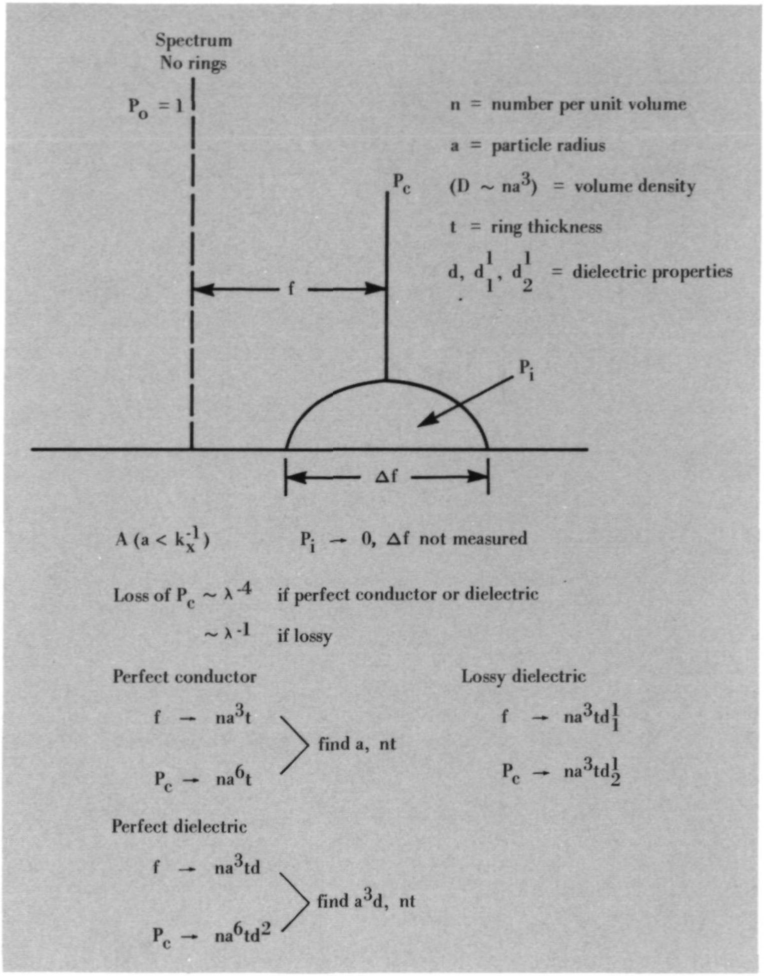

FIGURE 10.—*Illustration of spectral information in case* A.

Pollack Any real particles will show λ^{-1} dependence if they are small compared to the wavelength.

Eshleman It does take only a very small loss to do that, I agree.

Pollack A metal ball, if it is large compared to the wavelength, is a perfect reflector; if it is small compared to the wavelength, it is a perfect absorber.

Eshleman Well, if it were lossless, it would not be an absorber.

Pollack Yes, but it isn't.

Eshleman I am giving illustrations in terms of lossless and lossy particles, not in terms of real metals and real dielectrics but rather perfect conductors and perfect dielectrics as compared with lossy particles.

The loss in coherent power will represent different measures of ring and particle properties, as shown in figure 10, for lossless and lossy materials. Similarly, the frequency shift of the coherent signal will represent other combinations of these properties.

Under certain conditions some of these properties are separable, but in general one might characterize the results as being important mainly when combined with the results of other experiments for a more complete description of ring and particle properties. Obtaining resolution in radius from signal characteristics in this case (*A*) is determined by Fresnel zone size (i.e., very fine resolution) and not by the antenna illumination area illustrated in figure 5.

Cases *C* and *D* are illustrated in figure 11. Case *D* is for particle sizes larger than the spacecraft antenna but smaller than the *X*-band Fresnel zone; that is, for particles having radii between 180 cm and 2 km. Consider, for example, the case where these large particles are dense. That is, they are either perfectly absorbing, or they are reflecting if multiple scattering is not important in total signal characteristics. For this case there would be no frequency shift of the coherent signal.

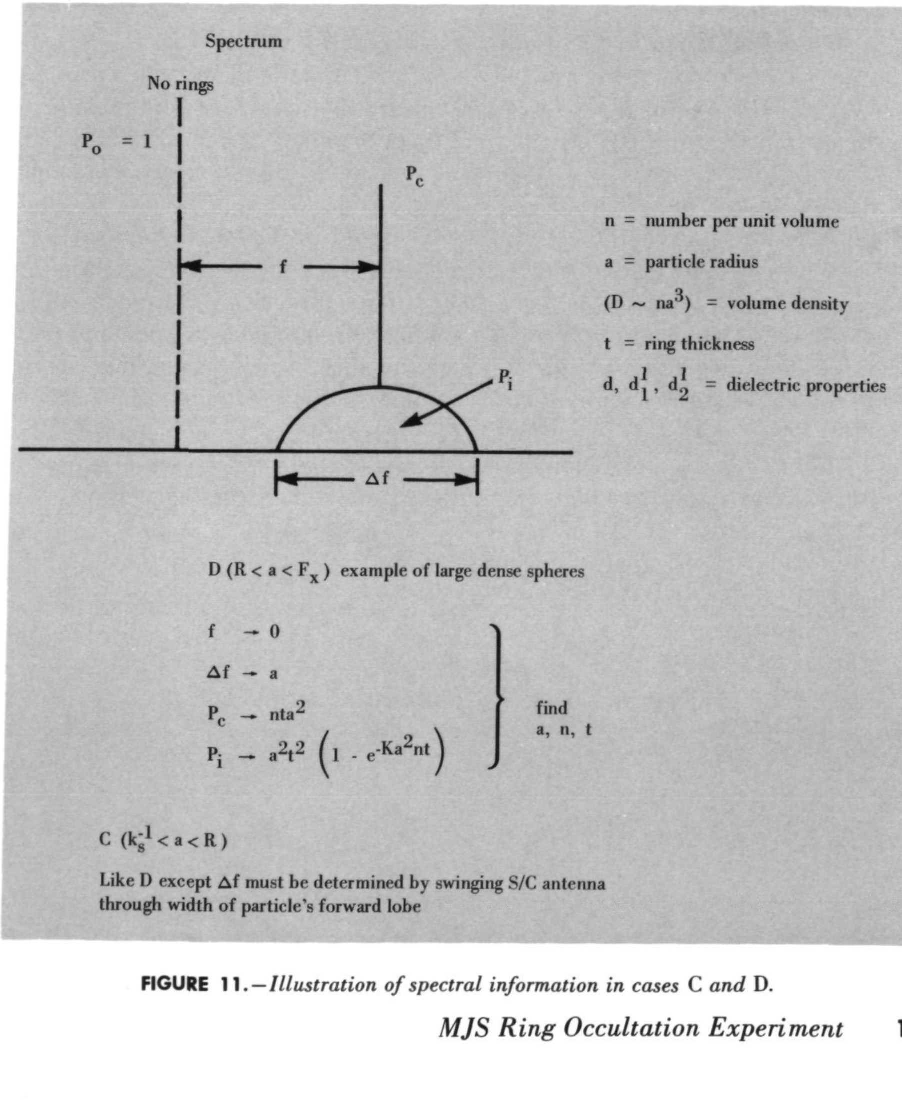

FIGURE 11.—*Illustration of spectral information in cases* C *and* D.

The spectral width of the incoherent signal would be a direct measure of particle size. Measurements of coherent and incoherent power would give other combinations of ring and particle parameters which would make possible the separate determination of particle size, ring thickness, and the number of particles per unit volume, all as a function of radius in the ring plane. Resolution for case *D* would not depend on the illuminated area in the ring plane but would be a smaller area determined by particle size.

Case *C* is for particles smaller than the spacecraft antenna but larger than the *S*-band inverse wave number, or between 2 and 180 cm. Here the results would be the same as in *D*, except that it would be necessary to swing the spacecraft antenna beam somewhat away from the direction to Earth in order to measure the spectral width of the incoherent signal, Δf. This is because the main forward lobe of scattering from these particles is wider than the antenna beam width, since the particles are smaller than the antenna. Resolution in the ring plane for this case is set by the illuminated area.

For case *B*, signal properties would be as in *A* at *S* band and like *C* at *X* band.

For case *F*, where the ring particles are larger than both Fresnel zones, signal strengths at both wavelengths would be reduced in a characteristic manner when a particle passed across the line of sight from the spacecraft to Earth, yielding a measure of particle size. For *E*, this reduction would be much more pronounced at *X* band than at *S* band.

There are other features that will be considered in future studies, such as the effects of an ionized gas that might accompany the ring particles. Also, there is work remaining to be done in theoretical studies of scattering from particles of various characteristics and in inversion studies to relate measurements to particle properties. However, at this time I would say that these are not the most vital considerations relative to gaining maximum information about the rings of Saturn from the radio occultation experiment. The most critical problems are related to such matters as instrument capabilities, details of the geometry and timing of the trajectories, and the ability and agreement to maneuver the spacecraft for radio beam swinging purposes. All of the above considerations will require much attention from radio team members from now until the experiment is conducted in 1980 or 1981.