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Final Report

Radar Studies of Mars

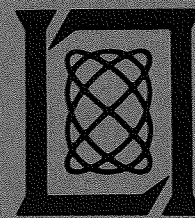
15 January 1970

Prepared for the National Aeronautics and Space Administration
under Contract NAS 9-7830 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts



ERRATA SHEET
for
RADAR STUDIES OF MARS
FINAL REPORT
15 January 1970

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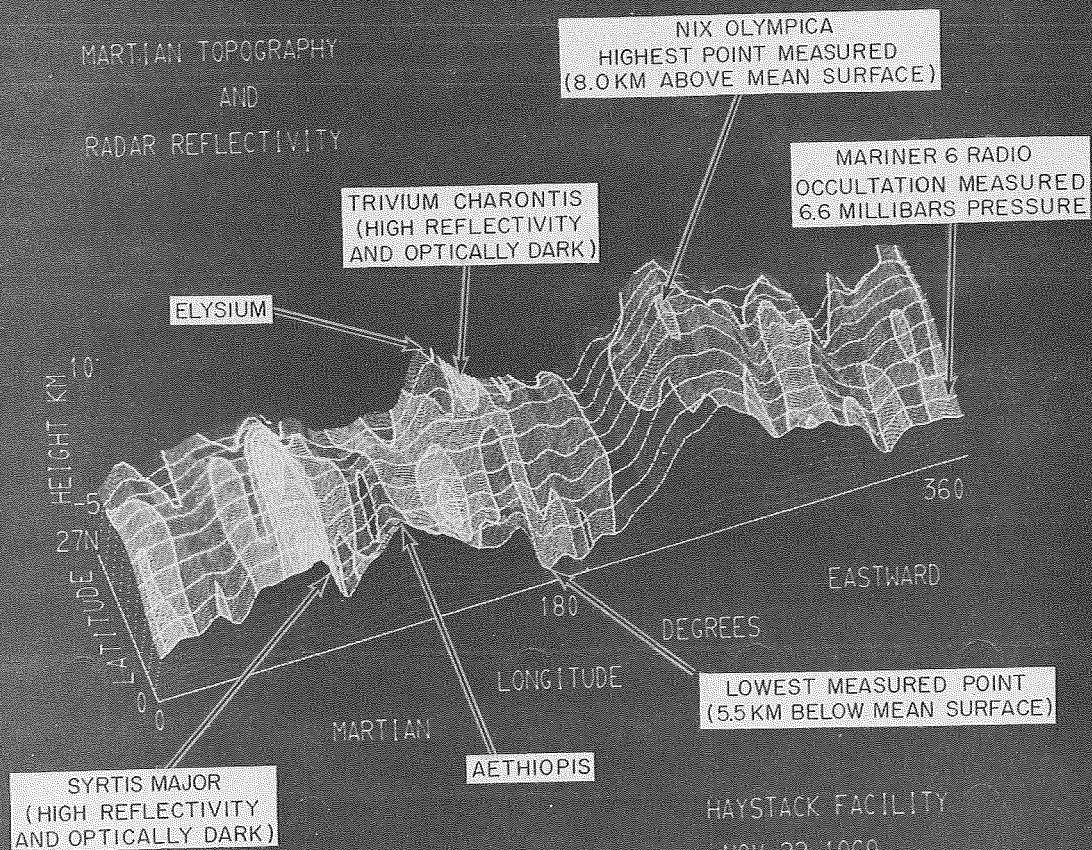
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conclusions about the functional form of the distribution as it can be fitted almost equally well with Gaussian and exponential functions. However, the rms value of the slope clearly can be taken as about 0.5° .

Since the CW spectra are observed to have a shape that is very well fitted by computed spectra using the Hagfors scattering law, it is assumed that the corresponding C value that produces the best fit represents a measure of the surface slopes in the region around the sub-radar point. These slopes must have a scale size less than 0.5° — otherwise, they would be resolved and appear as spectral features. Figure 10 shows the root-mean-square slope of the subradar region for a longitude strip centered on about 5°N latitude. The figure also shows the rms slope as derived from the best fit C values obtained from the ranging measurements. The agreement is very poor for a number of reasons. First, the regions sampled in the two types of measurement are somewhat different. The CW measurements do not have any restriction in latitude other than that self-imposed by the scattering law. Secondly, the spectral width and delay profiles are highly differentiated quantities varying rapidly with latitude and longitude so that the interpolation used on the ranging data (see Sec. V-A) may not give valid estimates of the C parameter at latitude and longitude points not sampled. Last, but most important, the noise in the estimate of the C parameter is large, particularly in the delay profile fitting when the signal is weak.

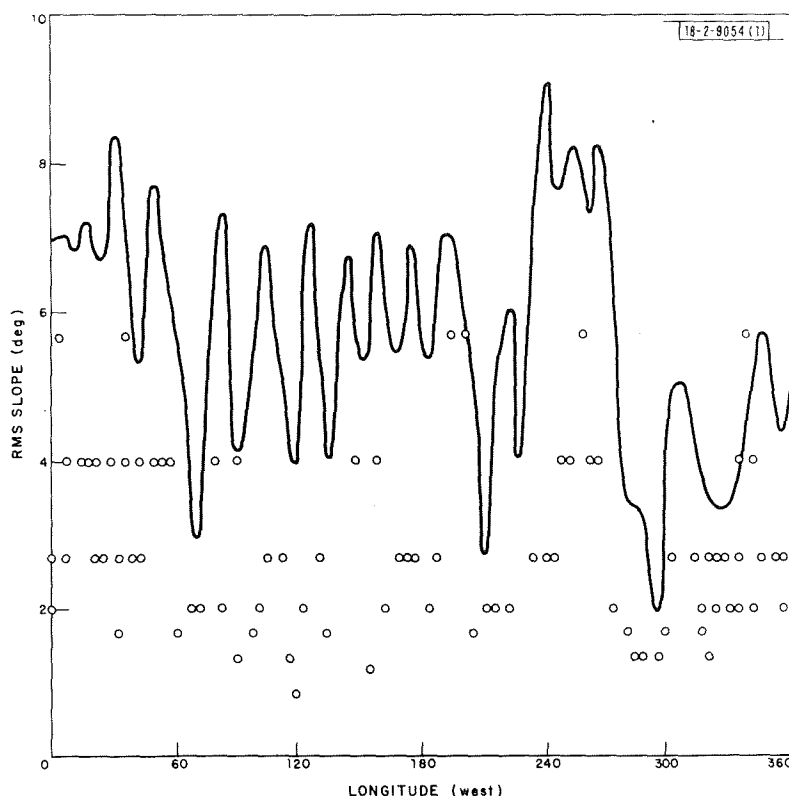


Fig. 10. Root-mean-square Martian surface slopes inferred from CW echo spectra. Smooth curve is rms slope from C values obtained in ranging measurements at 6°N .

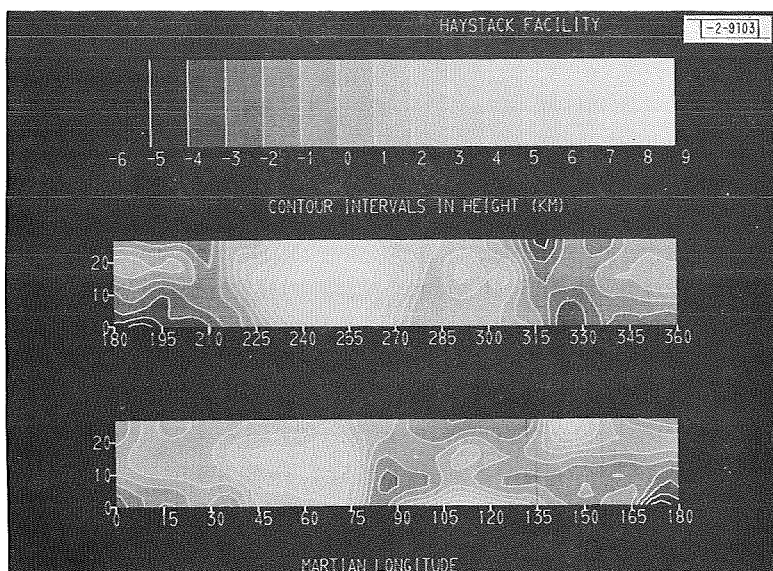


Fig.11. Contour map of height. Longitude runs eastward in two sections, and latitude runs from the equator to 27° N.

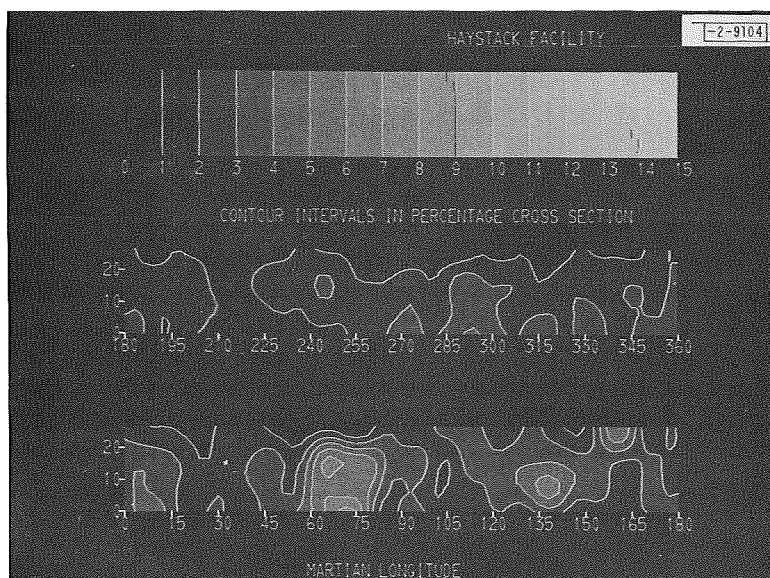


Fig.12. Contour map of cross section.

V. MARTIAN TOPOGRAPHY AND SURFACE ROUGHNESS

A. Contour Maps

The ranging data from 1967 and 1969 have been combined into contour maps of surface height, quasispecular cross section, and roughness (from C parameter value). In order to make a continuous representation of the data over all longitudes from the equator to 27°N, it was necessary to use an interpolation procedure. The interpolation was achieved by fitting the data points to a two-dimensional Fourier series and adjusting the series to fit the data in a least-squares sense. The Fourier series selected was one commensurate with the resolution in latitude and longitude. In longitude the series contained sine and cosine terms with spatial periods ranging from 360° down to 15°. The Fourier transform of the delay resolution function shown in Fig. 1 is approximately a triangular function with the 3-dB point at a spatial period of 10°. Thus, the series contains spatial frequencies well within the bandpass of the resolution but does not contain spatial frequencies that are outside the band or sufficiently far down in response that they "blow up" with the noise. In latitude the series contains spatial frequencies with periods from 54° to 13.5°.

The details of the mathematical methods used to find the coefficients of the Fourier series are given in Appendix B. The minimizing of the sum of the residuals squared produces an interpolation technique that is optimum in the sense that the value of any point is the maximum likelihood estimate.

Figures 11 through 13 show contour maps of height, cross section, and roughness. Longitude runs eastward and latitude runs from the equator to 27°N. The contour map of roughness should not be used in a quantitative manner with any high degree of confidence as the one-sigma error especially in low signal areas is of the order of a degree. However, the tendency for areas of high cross section to be smooth should be noted as it is in good agreement with the independent measurement technique of surface roughness obtained from the CW measurements described in Sec. IV-B.

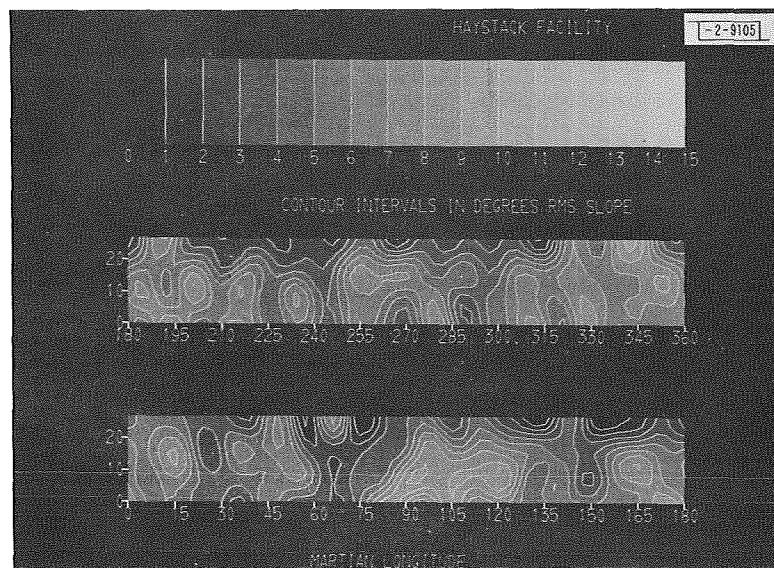


Fig. 13. Contour map of roughness or rms slope obtained from the best-fit C parameter values (Hagfors' scattering law).

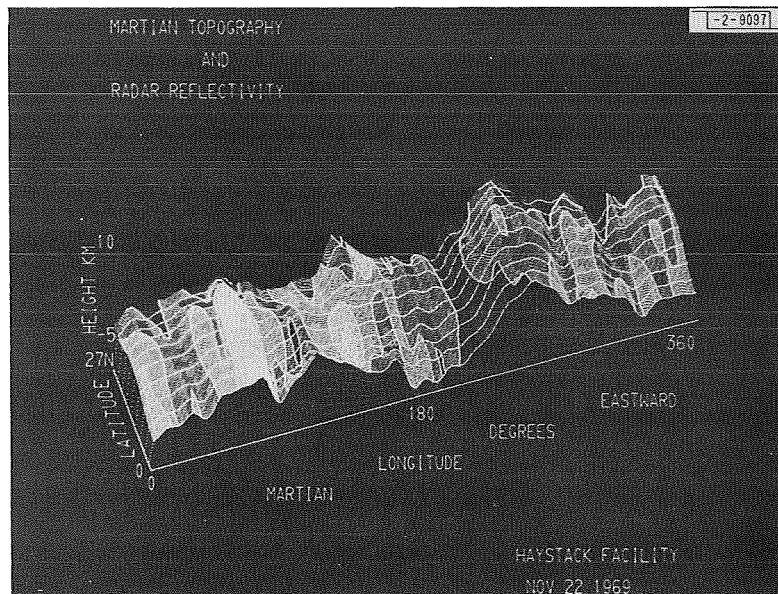


Fig. 14. "Modulated" ruled surface map. Contours of radar cross section superimposed on a topographical ruled surface.

Figure 14 is an attempt to present height and cross section simultaneously using a "modulated" ruled surface map. The presentation shows clearly the high cross section and steep slope (dropping to east) of Syrtis Major (85°E) and the high cross section on the eastern slope of Elysium (150°E , 20°N). Also see Frontispiece.

B. Surface Roughness as a Function of Scale Size

The surface roughness is a rather poorly defined term which is usually given in terms of root-mean-square slope. Its purpose is to provide some statistical information about the surface height distribution as it is obviously impossible to know the topography down to a scale of a wavelength and less. If the height were perfectly known over the surface, then the slope at each point could be obtained from the spatial derivative. However, if the height is first filtered or averaged by a filter with a spatial half-width S before the slope is determined, then the distribution of these "filtered slopes" has a scale size S .

Very small scale slopes – those with scale smaller than a wavelength (3.8 cm) – contribute mainly to the diffuse component of the radar echo. That is, they produce a scattering that is very insensitive to the angle of incidence θ . Pettengill, *et al.*,¹ measured the diffuse component of the cross section to be $0.1 \pi r^2$.

It is extremely difficult to test any specific scattering model for the diffuse component without measurements of the depolarized component of the echo and measurements of the angular dependence of the scattering. Owing to the lack of a scattering model, it is not possible to convert the observed diffuse cross section into an rms slope that has any physical meaning.

Slopes on a scale of a wavelength and larger determine the parameter C in the Hagfors scattering law. The average value of $C = 300$ (from CW measurements) corresponds to an rms slope of 3.3° . Larger scale slopes on the order of the CW resolution ($\sim 2^{\circ}$ in longitude or 120 km) are probably responsible for the offset of the CW spectrum which was observed to have an rms

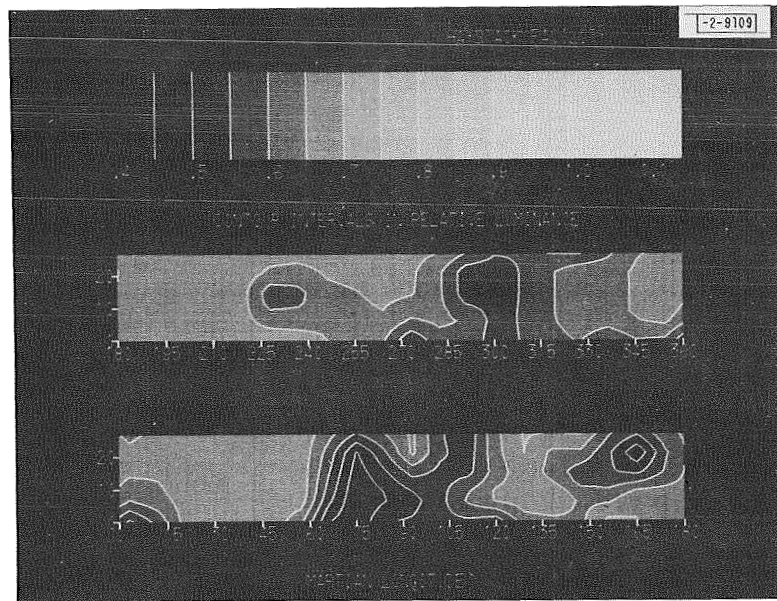


Fig. 20. Contour plot of relative luminance of Martian surface from deVaucouleurs.² Linear interpolation was used to obtain contours.

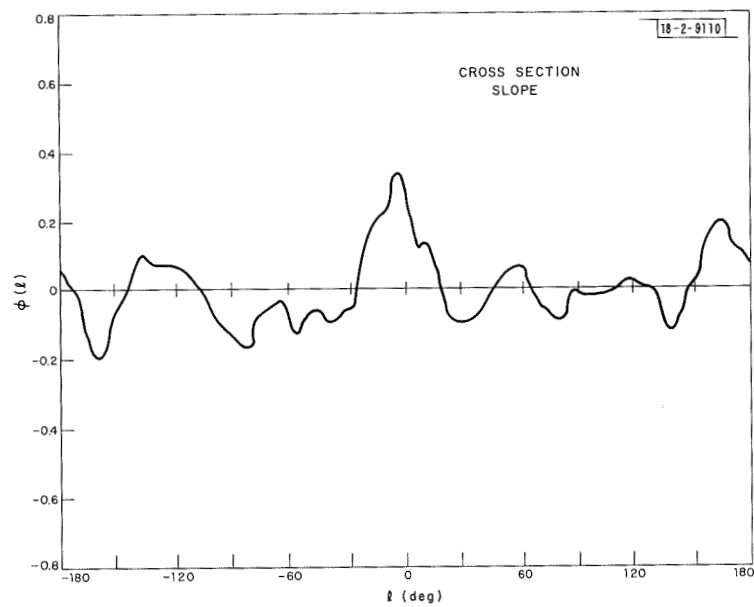


Fig. 21. Cross correlation of cross section with the derivative of topography with respect to longitude.

Final Report

Radar Studies of Mars

15 January 1970

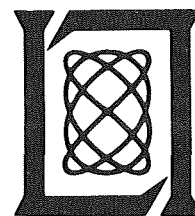
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lexington, Massachusetts



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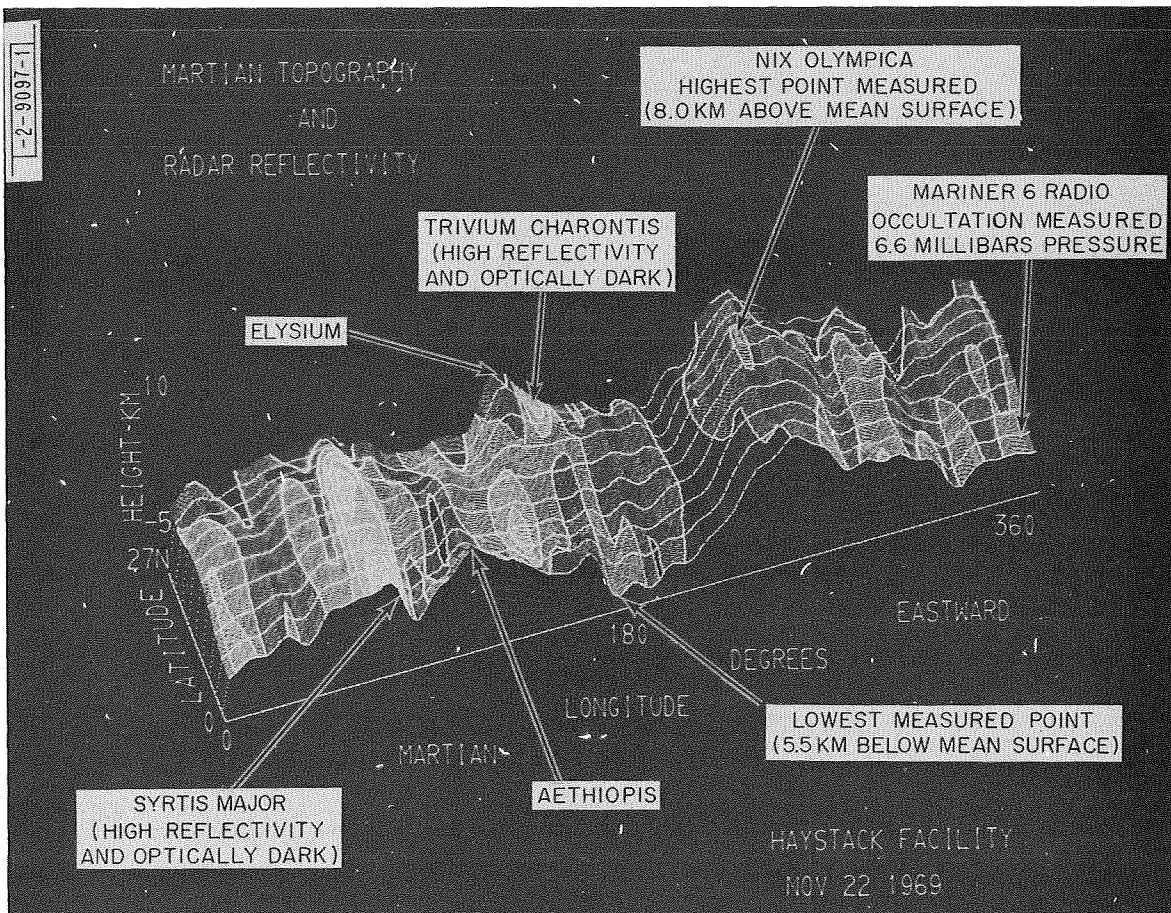
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FOREWORD

This report has been prepared as the final report required under Contract NAS 9-7830 between the National Aeronautics and Space Administration and M.I.T. Lincoln Laboratory. This investigation was conducted at the request of the National Aeronautics and Space Administration primarily to furnish information about the topography of the Martian surface useful in planning future spacecraft missions to the planet.

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RADAR STUDIES OF MARS

I. INTRODUCTION AND SUMMARY

Observations of the radar echo time delay from the planet Mars were used by Pettengill, et al.,^{1*} to derive the Martian surface topography around the 22°N parallel of latitude. These observations were made with the Haystack radar, operated at a frequency of 7840 MHz (3.8-cm wavelength) during the 1967 opposition of Mars. Pettengill, et al., found the greatest variation in elevation of the Martian surface to be about 12 km. They also found no simple correspondence between the locations of dark visible surface markings and topographic elevations or depressions.

From the distribution of echo power both as a function of time delay and frequency, Pettengill, et al., concluded that the radar reflections are predominantly quasispecular, corresponding to mean surface slopes of about 3°. The contribution of the quasispecular component to the radar cross section was found to vary considerably with longitude, showing no significant correlation with topography but having some suggested anticorrelation with visually dark regions.

Observations of the planet Mars were repeated during the 1969 opposition under contract to the National Aeronautics and Space Administration for the purpose of extending the measurements to regions closer to the equator. This report describes and evaluates the recent measurements and combines them with measurements made in 1967 by Pettengill, et al.

The geometry of the 1969 opposition was such that measurements could be made extending from the equator to a latitude of 12°N. The component of the topography that varies slowly with longitude was found to agree well with the topography measured at 22°N. The main difference in topography was found at 215°W longitude, where at 22°N there is a highland; the 1969 measurements show a lowland at the equator gradually increasing to a moderate highland at 12°N.

Measurements near the equator now suggest even more strongly that visually dark regions produce a stronger quasispecular component to the radar cross section. Also, the surface roughness as inferred from the spectral width of the echo shows that areas of high cross section are usually smoother on the average. Mean surface slopes in these areas are less than 1°.

II. RADAR ECHO TIME DELAY

A. Observations

For the time-delay measurements a 15-element pseudo-random phase-reversal code with 60-μsec baud length is transmitted. The received echo signal (plus noise) is sampled every 30 μsec and digitally decoded. Final output is limited to 8 samples of echo power at 30-μsec intervals (out of a total possible 30 such samples) because of computer processing-time limitations. The 8-sample window can be positioned arbitrarily, however, to observe the echo from the leading-edge region of the planet. The instrumental resolution (ambiguity) functions in delay and frequency are shown in Fig. 1. For the 7840-MHz operating frequency at Haystack, the full width at half power for the frequency function corresponds to a longitude interval on Mars of about 2.7° near the subradar point, and 30 μsec in delay encompasses a cap of about 5.9° in angular diameter centered on that point. Figure 2 shows the instrumental resolution functions as

* References are listed on page 40.

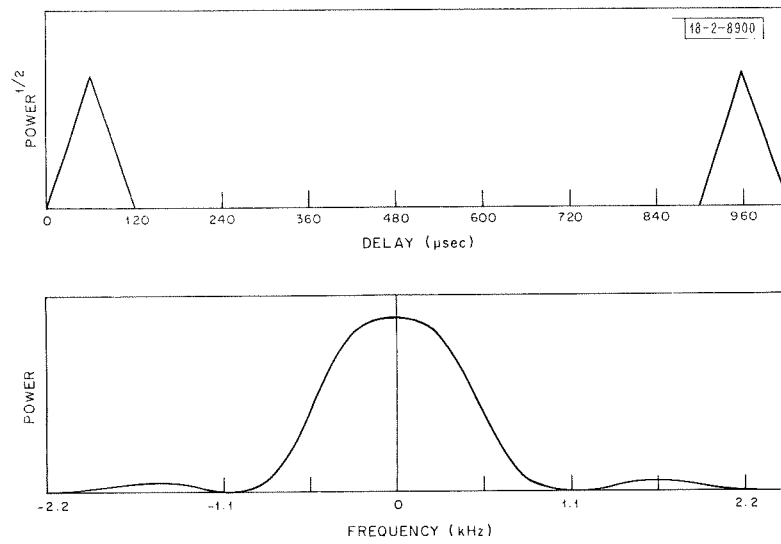


Fig. 1. Delay and frequency resolution or ambiguity functions applicable to the time-delay measurements.

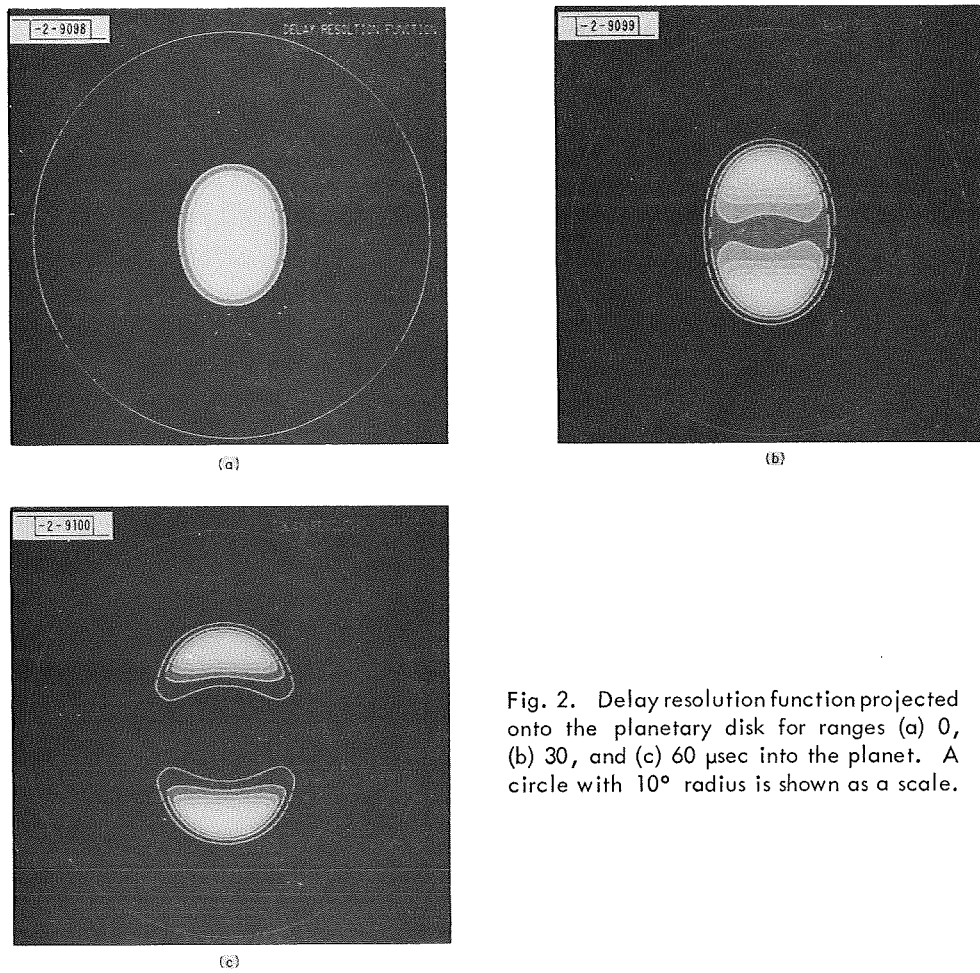


Fig. 2. Delay resolution function projected onto the planetary disk for ranges (a) 0, (b) 30, and (c) 60 μsec into the planet. A circle with 10° radius is shown as a scale.

they appear on the planetary disk. The observed distribution of echo power in delay depends on the instrumental resolution functions, and on the planetary surface scattering, in the following manner. In terms of planetocentric Cartesian coordinates (x, y, z) with the x -axis directed toward the radar and the y -axis coincident with the project apparent spin axis, the Doppler frequency, f' , and delay, d' , of the echo from any surface point (relative to the echo frequency and delay of the subradar point) are

$$f' = (z/r) f_\ell \quad , \quad (1)$$

$$d' = (2/c) [r - (r^2 - y^2 - z^2)^{\frac{1}{2}}] \quad , \quad (2)$$

where f_ℓ is the maximum center-to-limb Doppler frequency difference, r is the radius of the (assumed spherical) planet, and c is the velocity of light. If the radar cross section, S , per unit surface is assumed to depend only on the angle of incidence, θ , then the observed echo power distribution has the form

$$P(d) = \iint [S(\theta)/\cos \theta] R_F(f') R_D(d - d') dy dz \quad , \quad (3)$$

in which the integration is taken over the disk of radius r , R_F and R_D are the frequency and delay resolution functions of Fig. 4, with arguments evaluated by means of Eqs. (1) and (2), and

$$\theta = \sin^{-1} [(y^2 + z^2)^{\frac{1}{2}}/r] \quad . \quad (4)$$

If most of the energy is reflected from a small region around the subradar point, the measured power as a function of delay approaches the instrumental delay resolution function. This function is a so-called "squared-triangle" function in power, and the sampled echo power vs delay profiles obtained for Mars do indeed resemble samples of this function. The actual profiles differ sufficiently from squared-triangles, however, that the actual Martian surface scattering function, $S(\theta)$, should be considered when estimating echo delay times. A simplified method of accounting for the deviation of the Martian scattering function from that of a point target has been described by Pettengill, et al.¹ A more elaborate algorithm has been applied in the 1969 observations. The delay to the subradar point was estimated by making an (unweighted) least-squares fit of a three-parameter theoretical model of the delay profile to the measured profile. The theoretical model included the effects of both the delay and frequency resolution functions and the planet's angular scattering law, $S(\theta)$. For the latter, we used the axially symmetric expression developed by Hagfors² which contains a parameter, C , related to the root-mean-square surface slope (rms slope in radians $\approx C^{-\frac{1}{2}}$ for C large):

$$S(\theta) \propto (\cos^4 \theta + C \sin^2 \theta)^{-3/2} \quad . \quad (5)$$

This scattering law was found by Pettengill, et al., to describe accurately the Martian average echo frequency spectrum. The three parameters estimated were C , the radar cross section of the target (i. e., the over-all echo power), and the delay to the subradar point. Prior to the fit, the average of the power for the first two samples, which precede the echo signal, is taken and used as a definition of the signal-free mean noise level. Thus, only six of the eight sample points in delay are used to make this three-parameter fit for which a discrete set of trial values is used to locate the minimum. A comparison between the resultant fitted curve and data which were obtained for an average region on Mars is shown in Fig. 3. The good agreement is not surprising, considering that the measured sample values used in the fit do not number many more than the degrees of freedom of the fitted curve.

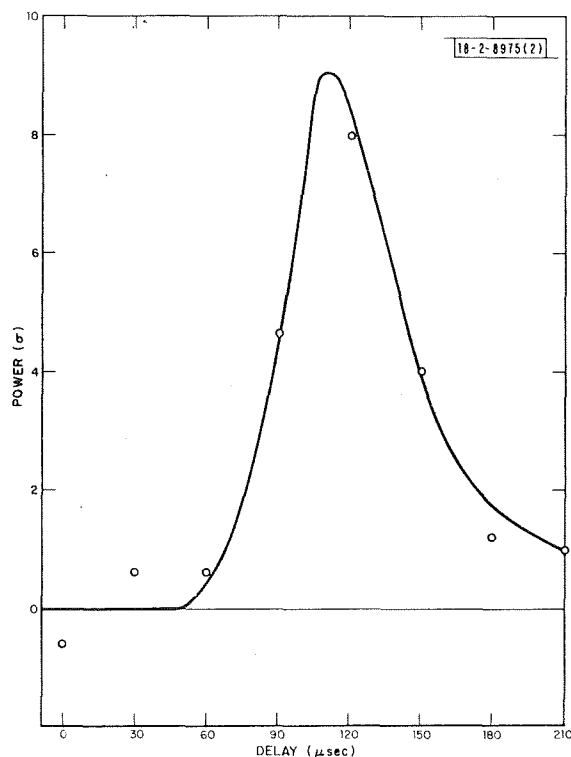


Fig. 3. Example of observed sample values of received power vs delay, with best-fitting theoretical power distribution. The unit of power is one standard deviation of background noise power, derived theoretically from measured receiving system noise temperature. The estimated subradar point delay for this case is 105 ± 15 μsec on the scale shown. This echo was observed at 23h 30m, 22 July 1969 (UT) from the Martian bright area known as Candor, at latitude 11.5°N , longitude 80°W .

This technique of delay estimation was compared for the 1969 data with the technique employed in 1967,¹ and the differences were found to be systematic with the 1969 method yielding delays for high signal-to-noise ratio measurements shorter by an average of about 5 μsec . The rms scatter about this average was also about 5 μsec , the equivalent of 750 meters one-way distance. In view of the systematic difference between the results obtained with the two techniques, all the data from both oppositions have been reduced with a common technique. The results of the delay measurements are given in Table I.

B. Orbital Fitting

The topography of Mars cannot be deduced simply by inspection of the measurements of round-trip time delays between the antenna and the subradar point on Mars. One must also know the relative orbits of both the antenna site and Mars to the requisite accuracy. Since the errors in the time-delay measurements are as low as 5 μsec when the round-trip delay is about 500 sec, uncertainties in the relative orbital distances of no more than 1 part in 10^8 will insure that orbital errors do not significantly degrade the accuracy of the topographic deductions. However, the errors in some of the planetary orbital elements as determined from classical, optical observations are about 1 part in 10^5 . Therefore, the radar data are used to determine simultaneously both the topographic and the orbital characteristics. Because of the rapid rotation of Mars compared to its synodic orbital period (ratio of about 700 to 1), the orbital and topographic

TABLE I

Table I lists the measured time delay in seconds at given UT receive time with one-sigma error in microseconds. Also listed are the height derived from ephemeris fitting residuals (see Sec. II-B), radar cross section (see Sec. III-A), the best-fitting value of parameter C, and the derived slope. The last two columns list the mean latitude and longitude of the subradar point during the receive period. For the 1967 data, no time delays are listed, since these were given in Pettengill, et al.¹ However, the new set of topographic residuals in microseconds are listed in the time-delay column. In order to obtain the timedelay measured by the least-squares fitting technique, simply take value given in Pettengill, et al., add to it the topographic correction given the same table, and subtract the new topographic correction given in this table. In addition, 1967 topographic heights have been reduced by 3.0 kilometers as a result of an attempt to place a common zero level on all the height data.

TABLE I

DATE	HRS	MIN	TIME	DELAY	+-	HEIGHT	+-	CROSS SECTION	C VALUE	SLOPE	LONGITUDE	LATITUDE
2440340.5	0	8	563.523876	4	-4.20	.6		1.80	50	8.1	182.52	3.52
2440340.5	0	28	563.453252	6	-6.45	.8		2.13	50	8.1	187.42	3.53
2440351.5	5	28	554.154207	9	6.66	1.3		.52	50	8.1	110.76	3.68
2440351.5	5	48	554.084903	0	3.96	1.3		.61	200	4.0	115.63	3.68
2440351.5	6	8	554.014007	7	3.66	1.0		1.03	200	4.0	120.51	3.68
2440351.5	6	28	553.947279	0	1.41	1.3		.56	450	2.7	125.38	3.68
2440351.5	6	48	553.874802	31	-1.29	4.0		.16	2450	1.2	130.26	3.69
2440351.5	7	8	553.810542	22	.51	3.3		.30	50	8.1	135.13	3.69
2440351.5	7	28	553.742568	12	-3.54	1.7		.26	1250	1.6	140.00	3.69
2440351.5	7	48	553.674790	13	-0.84	1.9		.49	50	8.1	144.88	3.69
2440351.5	8	8	553.607280	12	-3.99	1.7		.46	200	4.0	149.76	3.69
2440351.5	0	8	553.406074	9	-4.44	1.1		.87	50	8.1	164.37	3.69
2440351.5	0	28	553.330421	6	-4.89	.8		1.62	50	8.1	169.25	3.70
2440351.5	0	48	553.272960	0	-5.79	1.4		1.18	200	4.0	174.12	3.70
2440351.5	10	8	553.206663	6	-4.74	.8		3.34	200	4.0	179.00	3.70
2440354.5	5	34	539.971645	2	1.65	.3		1.90	800	2.0	85.48	4.13
2440354.5	5	54	539.904750	2	3.00	.3		2.44	200	4.0	90.36	4.13
2440354.5	6	14	539.844110	3	4.80	.3		2.12	450	2.7	95.22	4.13
2440354.5	6	34	539.783740	3	4.80	.3		1.64	200	4.0	100.11	4.13
2440354.5	6	54	539.721600	3	6.15	.4		.88	200	4.0	104.98	4.14
2440354.5	7	14	539.659717	3	6.30	.3		.90	200	4.0	109.86	4.14
2440354.5	7	34	539.598096	7	3.60	1.0		.44	1800	1.3	114.72	4.14
2440354.5	7	54	539.536689	6	4.50	.9		.68	200	4.0	119.60	4.14
2440354.5	8	14	539.475514	7	5.25	1.0		.64	50	8.1	124.48	4.14
2440354.5	8	34	539.414592	13	1.65	1.9		.48	50	8.1	129.36	4.15
2440354.5	8	54	539.354857	13	2.10	1.9		.21	5000	.8	134.23	4.15
2440354.5	0	14	539.294352	0	-1.35	1.4		.79	50	8.1	139.11	4.15
2440354.5	0	34	539.233031	10	.45	2.8		.73	50	8.1	143.98	4.15
2440354.5	0	54	539.172874	20	-4.95	4.3		.69	50	3.1	148.86	4.15
2440356.5	4	44	531.424539	3	1.11	.3		2.05	50	8.1	55.36	4.41
2440356.5	5	4	531.369428	3	.66	.3		2.46	50	8.1	60.23	4.41
2440356.5	5	24	531.310555	2	.66	.3		2.16	200	4.0	65.10	4.42
2440356.5	5	44	531.251024	1	1.11	.1		3.05	200	4.0	69.98	4.42
2440356.5	6	4	531.191541	2	1.71	.3		2.27	200	4.0	74.86	4.42
2440356.5	6	24	531.134415	3	1.26	.4		1.81	50	8.1	79.73	4.42
2440356.5	6	44	531.077532	1	1.71	.1		2.59	450	2.7	84.61	4.42
2440356.5	7	4	531.019844	1	2.61	.1		2.25	200	4.0	89.50	4.43
2440356.5	7	44	530.965345	4	4.86	.0		1.20	200	4.0	94.24	4.43
2440356.5	8	4	530.904421	6	6.21	.8		1.01	50	8.1	104.11	4.43
2440358.5	4	21	523.414524	3	-3.78	.3		2.48	50	8.1	32.06	4.70
2440358.5	4	41	523.354629	3	-3.33	.4		1.85	50	8.1	36.94	4.70
2440358.5	5	1	523.304962	3	-1.53	.3		2.50	50	8.1	41.81	4.70
2440358.5	5	21	523.249547	3	-1.08	.3		2.06	50	8.1	46.69	4.70
2440358.5	5	41	523.194377	2	-0.18	.3		2.13	50	8.1	51.56	4.71
2440358.5	6	1	523.141459	3	.27	.3		1.84	200	4.0	56.44	4.71
2440358.5	6	24	523.074764	2	.72	.3		2.46	200	4.0	62.05	4.71
2440358.5	6	44	523.026388	2	.72	.3		3.61	200	4.0	66.95	4.71
2440358.5	7	4	522.973256	1	1.32	.1		3.08	200	4.0	71.80	4.71
2440358.5	7	24	522.920361	3	2.67	.3		1.84	50	8.1	76.68	4.72
2440358.5	7	44	522.867727	2	.42	.3		1.81	50	8.1	81.55	4.72
2440358.5	8	4	522.815290	3	3.12	.3		3.05	50	8.1	86.43	4.72
2440358.5	8	24	522.763085	2	4.02	.3		2.75	200	4.0	91.30	4.72
2440358.5	8	44	522.711091	3	4.92	.3		2.34	200	4.0	96.18	4.72
2440358.5	0	4	522.659294	4	5.82	.0		1.96	50	8.1	101.06	4.73
2440358.5	0	24	522.607686	0	6.27	1.4		1.09	50	8.1	105.94	4.73
2440361.5	5	3	512.393240	3	-1.89	.4		2.19	50	8.1	15.45	5.14
2440361.5	5	23	512.345806	3	-1.89	.4		1.80	50	8.1	20.30	5.14
2440361.5	5	43	512.294622	3	-1.89	.3		1.90	50	8.1	25.18	5.14
2440361.5	6	13	512.224325	3	-2.64	.4		1.95	50	8.1	32.50	5.14
2440361.5	6	33	512.181770	4	-2.64	.0		1.69	50	8.1	37.37	5.14

TABLE I (Continued)

2440361.5	6	53	512.135459	3	-2.19	.4	1.51	200	4.0	42.25	5.15
2440361.5	7	13	512.080385	3	-0.84	.4	1.71	50	8.1	47.13	5.15
2440361.5	7	33	512.043551	4	.06	.6	1.93	50	8.1	52.00	5.15
2440361.5	7	58	511.986580	5	.96	.7	1.95	50	8.1	58.16	5.15
2440361.5	8	17	511.943517	4	.51	.6	1.86	200	4.0	62.74	5.15
2440361.5	8	36	511.900631	3	1.41	.3	3.49	450	2.7	67.35	5.16
2440361.5	8	58	511.851202	0	.96	1.3	.75	5000	.8	72.73	5.16
2440363.5	6	28	505.767350	2	-1.38	.3	2.56	50	8.1	18.52	5.53
2440363.5	6	47	505.727802	2	-1.38	.3	2.53	50	8.1	23.15	5.53
2440363.5	7	5	505.690542	3	-2.28	.4	1.89	50	8.1	27.52	5.53
2440363.5	7	23	505.653476	4	-3.63	.6	2.31	50	8.1	31.91	5.53
2440363.5	7	43	505.612500	3	-3.63	.3	1.77	50	8.1	36.81	5.54
2440363.5	8	3	505.571728	3	-1.23	.4	2.12	50	8.1	41.68	5.54
2440363.5	8	23	505.531176	4	-0.78	.6	1.81	50	8.1	46.57	5.54
2440363.5	8	55	505.466694	3	.57	.3	2.32	50	8.1	54.35	5.54
2440365.5	6	15	500.037444	3	.03	.3	4.24	50	8.1	357.60	5.90
2440365.5	6	51	499.971074	2	-1.77	.3	1.68	50	8.1	6.37	5.90
2440365.5	7	9	499.933175	2	-1.77	.3	1.82	50	8.1	10.77	5.90
2440365.5	7	28	499.903650	1	-1.77	.1	2.40	50	8.1	15.39	5.90
2440365.5	7	48	499.867525	3	-1.77	.4	1.89	50	8.1	20.28	5.91
2440365.5	8	8	499.831608	3	-1.17	.4	2.62	50	8.1	25.15	5.91
2440365.5	8	28	499.795906	3	-2.97	.4	2.66	50	8.1	30.02	5.91
2440365.5	8	48	499.760376	4	-2.52	.6	2.56	50	8.1	34.90	5.91
2440368.5	4	43	402.817151	2	3.27	.3	2.11	200	4.0	308.54	6.44
2440368.5	5	3	402.785314	1	2.97	.1	2.00	200	4.0	313.41	6.44
2440368.5	5	23	402.755731	2	2.07	.3	2.00	200	4.0	318.29	6.44
2440368.5	5	43	402.725405	2	.72	.3	1.74	800	2.0	323.18	6.45
2440368.5	6	3	402.695317	3	1.17	.3	1.84	200	4.0	328.05	6.45
2440368.5	6	23	402.665479	3	1.17	.3	2.01	200	4.0	332.92	6.45
2440368.5	6	43	402.635888	3	.27	.4	1.32	200	4.0	337.79	6.45
2440368.5	7	3	402.605527	2	.27	.3	2.24	200	4.0	342.68	6.46
2440368.5	7	23	402.577392	2	.27	.3	3.23	50	8.1	347.56	6.46
2440368.5	7	43	402.548477	2	-0.18	.3	3.76	200	4.0	352.44	6.46
2440368.5	8	3	402.519768	2	-0.48	.3	4.34	200	4.0	357.33	6.46
2440368.5	8	23	402.491249	2	-0.48	.3	3.26	200	4.0	362.18	6.47
2440368.5	8	43	402.462911	5	-0.93	.7	3.12	50	8.1	367.07	6.47
2440370.5	4	51	488.733479	1	2.88	.1	4.54	450	2.7	392.76	6.81
2440370.5	5	8	488.711476	1	3.78	.1	6.45	450	2.7	396.91	6.81
2440370.5	5	27	488.687114	1	2.88	.1	2.90	450	2.7	301.78	6.82
2440370.5	5	46	488.662969	3	3.33	.3	2.03	50	8.1	306.17	6.82
2440370.5	6	4	488.640307	2	2.88	.3	2.23	200	4.0	310.56	6.82
2440370.5	6	22	488.617841	3	2.88	.3	2.48	450	2.7	314.95	6.82
2440370.5	6	39	488.596815	3	.63	.4	1.93	200	4.0	319.34	6.82
2440370.5	6	58	488.573494	3	1.08	.4	1.84	450	2.7	323.73	6.83
2440370.5	7	16	488.551540	4	1.23	.6	1.83	200	4.0	328.12	6.83
2440370.5	7	34	488.529851	3	2.58	.4	2.58	50	8.1	332.51	6.83
2440372.5	3	6	485.462146	6	2.19	.9	1.59	50	8.1	249.76	7.18
2440372.5	3	24	485.442098	12	-0.06	1.8	.54	50	8.1	254.15	7.18
2440372.5	3	42	485.422227	4	-0.06	.6	.63	50	8.1	258.54	7.18
2440372.5	4	0	485.402563	4	-1.26	.6	.79	50	8.1	262.93	7.19
2440372.5	4	18	485.383093	4	-1.71	.6	1.22	50	8.1	267.30	7.19
2440372.5	4	36	485.363830	6	-2.61	.8	1.47	50	8.1	271.71	7.19
2440372.5	4	54	485.344759	2	-1.71	.3	2.12	200	4.0	276.10	7.19
2440372.5	5	12	485.325886	1	.09	.1	2.90	200	4.0	280.49	7.19
2440372.5	5	42	485.294880	2	3.69	.3	4.99	450	2.7	287.81	7.20
2440372.5	6	0	485.275562	2	3.24	.3	5.54	450	2.7	292.20	7.20
2440372.5	6	18	485.256433	1	3.69	.1	5.65	800	2.0	296.57	7.20
2440372.5	6	36	485.240502	2	3.24	.3	3.75	450	2.7	300.95	7.21
2440372.5	6	54	485.222750	4	3.69	.6	2.05	50	8.1	305.35	7.21
2440372.5	7	12	485.205183	3	3.39	.4	2.17	200	4.0	309.75	7.21
2440372.5	7	30	485.187781	3	3.84	.3	3.13	200	4.0	314.14	7.21
2440372.5	7	48	485.170550	6	2.94	.8	2.94	50	8.1	318.53	7.22

TABLE I (Continued)

2440372.5	8	6	485.15466	6	2.49	.9	2.82	50	8.1	222.92	7.22
2440375.5	3	17	481.620710	2	-1.17	.3	2.88	200	4.0	225.95	7.76
2440375.5	3	34	481.600064	1	-1.17	.1	2.66	200	4.0	230.09	7.76
2440375.5	3	52	481.594867	2	-1.17	.3	2.22	50	8.1	234.48	7.77
2440375.5	4	10	481.581869	2	-0.57	.3	2.07	50	8.1	238.86	7.77
2440375.5	4	28	481.569075	2	-0.12	.3	1.86	50	8.1	243.25	7.77
2440375.5	4	46	481.556480	3	1.23	.4	1.79	50	8.1	247.64	7.77
2440375.5	5	4	481.544098	4	1.23	.0	1.63	50	8.1	252.03	7.78
2440375.5	5	22	481.531933	3	-1.02	.4	1.40	50	8.1	256.42	7.78
2440375.5	5	40	481.519952	3	-0.57	.3	1.64	50	8.1	260.81	7.78
2440375.5	5	58	481.508176	3	-1.47	.3	2.17	50	8.1	265.20	7.78
2440375.5	6	16	481.496593	3	-2.37	.3	2.37	50	8.1	269.59	7.79
2440375.5	6	34	481.485184	1	-1.47	.1	2.78	50	8.1	273.98	7.79
2440375.5	6	52	481.473958	2	-1.02	.3	4.20	200	4.0	278.39	7.79
2440375.5	7	10	481.462884	1	2.58	.1	4.63	200	4.0	282.77	7.79
2440375.5	7	28	481.451991	2	3.48	.3	5.56	800	2.0	287.15	7.79
2440375.5	7	48	481.440079	2	3.03	.3	4.07	1250	1.6	292.03	7.80
2440375.5	8	6	481.429501	3	4.08	.4	4.94	450	2.7	296.42	7.80
2440376.5	2	17	480.724501	6	-1.89	.9	1.76	50	8.1	202.48	7.95
2440376.5	2	35	480.712655	2	-0.54	.3	2.87	200	4.0	206.87	7.95
2440376.5	2	53	480.701007	1	-1.44	.1	2.33	200	4.0	211.26	7.95
2440376.5	3	10	480.690173	2	-0.99	.3	2.88	200	4.0	215.36	7.95
2440377.5	3	2	479.924708	3	-1.26	.3	2.39	200	4.0	204.62	8.15
2440377.5	3	20	479.910517	3	-1.26	.4	2.69	50	8.1	209.01	8.15
2440377.5	3	38	479.901521	1	-0.81	.1	3.58	200	4.0	213.42	8.15
2440377.5	3	56	479.901730	2	-0.81	.3	3.43	50	8.1	217.79	8.15
2440377.5	4	14	479.893144	3	-1.11	.3	3.24	200	4.0	222.18	8.16
2440377.5	4	40	479.881097	1	-0.66	.1	3.46	200	4.0	228.52	8.16
2440377.5	4	58	479.873005	1	-0.21	.1	3.64	50	8.1	232.85	8.16
2440377.5	5	15	479.865554	3	-0.51	.3	2.89	50	8.1	237.87	8.16
2440377.5	5	32	479.854279	3	-0.51	.4	2.27	50	8.1	241.20	8.17
2440377.5	5	49	479.851175	3	-0.06	.3	2.46	50	8.1	245.35	8.17
2440377.5	6	21	479.834263	3	.84	.4	2.03	50	8.1	253.16	8.17
2440377.5	6	39	479.831263	11	-0.06	1.6	.69	50	8.1	257.55	8.18
2440378.5	1	52	479.361039	4	-2.28	.6	1.39	1250	1.6	178.73	8.33
2440378.5	2	10	479.353284	3	-1.38	.4	1.92	50	8.1	183.12	8.33
2440378.5	2	28	479.345719	3	-2.28	.3	2.16	200	4.0	187.50	8.33
2440378.5	2	46	479.338327	3	-1.38	.3	1.83	50	8.1	191.89	8.34
2440378.5	3	4	479.331138	3	-2.28	.3	1.49	50	8.1	196.28	8.34
2440379.5	4	42	478.874797	3	-0.60	.3	2.90	200	4.0	211.40	8.55
2440379.5	5	0	478.876062	2	-0.45	.3	3.26	200	4.0	215.75	8.55
2440379.5	5	18	478.872528	1	-0.45	.1	3.34	200	4.0	220.14	8.55
2440379.5	5	36	478.869193	1	-0.90	.1	3.22	200	4.0	224.47	8.55
2440379.5	6	4	478.864377	2	-0.45	.3	3.48	200	4.0	231.31	8.56
2440382.5	5	16	478.642754	3	-1.11	.4	1.87	50	8.1	193.16	9.10
2440382.5	5	33	478.645614	3	-1.56	.3	1.59	50	8.1	197.31	9.10
2440382.5	5	50	478.648637	3	-1.56	.3	1.79	50	8.1	201.45	9.10
2440382.5	6	7	478.651811	2	.39	.3	3.68	200	4.0	205.60	9.10
2440382.5	6	24	478.655155	2	-0.06	.3	3.97	200	4.0	209.74	9.11
2440382.5	6	41	478.658648	3	-0.51	.3	4.32	450	2.7	213.88	9.11
2440382.5	6	58	478.662274	3	.39	.3	5.17	50	8.1	218.04	9.11
2440382.5	7	15	478.666044	3	-0.51	.4	4.97	200	4.0	222.18	9.11
2440382.5	7	32	478.669924	5	.84	.7	5.93	50	8.1	226.32	9.11
2440384.5	0	50	479.229353	4	8.25	.6	1.72	200	4.0	110.58	9.40
2440384.5	1	7	479.233471	4	6.90	.6	1.84	200	4.0	114.73	9.40
2440384.5	1	24	479.237719	3	7.80	.4	1.98	200	4.0	118.88	9.40
2440384.5	1	41	479.242128	6	7.35	.9	.96	200	4.0	123.02	9.41
2440384.5	1	58	479.246708	4	5.10	.6	1.30	50	8.1	127.17	9.41
2440384.5	2	15	479.251446	4	3.75	.6	1.14	50	8.1	131.31	9.41
2440384.5	2	32	479.256363	5	1.05	.7	1.01	450	2.7	135.46	9.41
2440384.5	2	49	479.261438	10	.60	1.4	.53	50	8.1	139.62	9.41
2440384.5	3	6	479.266705	11	-1.95	1.6	.40	200	4.0	143.75	9.41

TABLE I (Continued)

2440384.5	3	23	479.272121	19	-0.15	2.8	.30	50	8.1	147.90	9.42
2440384.5	3	40	479.277735	3	-1.05	.4	1.15	450	2.7	152.05	9.42
2440384.5	3	57	479.283519	3	-0.15	.4	1.37	50	8.1	156.19	9.42
2440384.5	4	14	479.289507	6	-2.85	.9	1.03	50	8.1	160.33	9.42
2440384.5	4	31	479.295642	3	-0.60	.4	1.87	50	8.1	164.49	9.42
2440384.5	4	48	479.301974	2	-1.05	.3	1.96	200	4.0	168.62	9.43
2440384.5	5	5	479.308474	3	-0.60	.4	1.75	50	8.1	172.77	9.43
2440384.5	5	22	479.315145	2	-0.15	.3	2.35	50	8.1	176.91	9.43
2440384.5	5	39	479.321992	4	-1.05	.6	1.50	50	8.1	181.06	9.43
2440384.5	5	56	479.328989	3	-0.15	.4	2.53	50	8.1	185.21	9.43
2440384.5	6	13	479.336153	3	-1.05	.4	1.96	200	4.0	189.36	9.44
2440384.5	6	30	479.343460	4	-1.05	.6	2.03	50	8.1	193.51	9.44
2440384.5	6	47	479.350907	6	-1.05	.8	1.69	50	8.1	197.64	9.44
2440384.5	7	4	479.358488	7	-0.90	1.0	2.45	50	8.1	201.79	9.44
2440384.5	7	21	479.366186	5	0	.7	3.84	450	2.7	205.93	9.44
2440386.5	3	34	480.564476	4	2.91	.6	1.22	200	4.0	132.87	9.75
2440386.5	3	51	480.574043	6	2.46	.9	.78	200	4.0	137.02	9.75
2440386.5	4	25	480.593719	17	.96	2.5	.40	50	8.1	145.31	9.75
2440386.5	4	42	480.603837	11	-1.74	1.6	.54	50	8.1	140.45	9.76
2440386.5	4	59	480.614098	4	.06	.6	1.70	200	4.0	153.60	9.76
2440386.5	5	16	480.624550	9	-1.14	1.3	.92	50	8.1	157.74	9.76
2440386.5	5	50	480.645930	4	-2.04	.6	1.22	5000	.8	166.03	9.76
2440386.5	6	7	480.656840	6	-0.69	.8	1.98	50	8.1	170.19	9.77
2440386.5	6	24	480.667909	7	-1.14	1.0	1.63	50	8.1	174.32	9.77
2440386.5	6	41	480.679107	7	-0.24	1.0	2.34	50	8.1	178.47	9.77
2440386.5	6	58	480.690452	20	-2.04	3.0	.70	450	2.7	182.62	9.77
2440389.5	1	20	483.555676	4	1.65	.6	1.09	50	8.1	75.85	10.23
2440389.5	2	14	483.592562	3	4.95	.4	1.18	200	4.0	86.83	10.24
2440389.5	2	32	483.607655	4	5.85	.6	.99	50	8.1	91.20	10.24
2440389.5	2	50	483.622948	4	6.30	.6	1.13	50	8.1	95.59	10.24
2440389.5	3	8	483.638438	5	7.35	.7	.99	200	4.0	90.98	10.24
2440389.5	3	26	483.654121	25	9.60	3.7	.35	50	8.1	104.37	10.24
2440389.5	3	44	483.670025	4	8.70	.6	1.23	50	8.1	108.76	10.25
2440389.5	4	2	483.686129	3	7.80	.4	2.34	200	4.0	113.14	10.25
2440389.5	4	20	483.702426	2	7.80	.3	2.93	450	2.7	117.55	10.25
2440389.5	4	38	483.718917	3	7.80	.4	1.70	450	2.7	121.93	10.25
2440389.5	4	56	483.735610	4	6.00	.6	1.66	50	8.1	126.32	10.25
2440389.5	5	14	483.752485	3	4.65	.4	1.40	450	2.7	130.71	10.26
2440389.5	5	32	483.769542	5	2.85	.7	1.34	450	2.7	135.09	10.26
2440389.5	5	50	483.786770	16	1.05	2.3	.50	50	8.1	139.49	10.26
2440389.5	6	26	483.821710	30	-3.00	4.5	.17	5000	.8	148.27	10.26
2440389.5	6	44	483.839369	10	-0.30	1.4	1.16	200	4.0	152.66	10.27
2440393.5	2	14	489.743210	6	1.47	.8	1.48	50	8.1	50.99	10.78
2440393.5	2	34	489.768076	4	3.27	.6	1.78	50	8.1	55.86	10.78
2440393.5	2	52	489.790679	3	2.82	.4	2.31	50	8.1	60.25	10.78
2440393.5	3	10	489.813478	3	2.82	.4	2.10	200	4.0	64.64	10.78
2440393.5	3	28	489.836470	2	3.72	.3	2.48	200	4.0	69.05	10.78
2440393.5	3	48	489.862264	2	2.37	1.1	1.33	200	4.0	73.90	10.78
2440393.5	4	6	489.885673	9	2.82	1.3	.99	50	8.1	78.30	10.79
2440393.5	4	31	489.918495	5	4.62	.7	1.50	50	8.1	84.40	10.79
2440393.5	4	49	489.942350	7	5.52	1.0	1.15	50	8.1	88.77	10.79
2440393.5	5	7	489.966375	8	7.92	1.1	1.29	50	8.1	93.16	10.79
2440393.5	5	25	489.990583	6	8.37	.9	1.28	50	8.1	97.55	10.79
2440393.5	5	43	490.014964	14	7.47	2.0	.63	50	8.1	101.94	10.79
2440393.5	6	1	490.039508	12	5.07	1.8	1.12	50	8.1	106.33	10.79
2440393.5	6	19	490.064162	9	8.22	1.3	2.51	200	4.0	110.73	10.80
2440395.5	23	27	495.541597	5	2.73	.7	2.85	50	8.1	343.48	11.09
2440395.5	23	46	495.568800	4	2.28	.6	2.78	200	4.0	348.12	11.09
2440396.5	0	3	495.593276	3	2.16	.4	2.64	200	4.0	352.27	11.09
2440396.5	0	27	495.628077	4	.81	.6	2.62	200	4.0	358.11	11.09
2440396.5	0	45	495.654364	5	.81	.7	1.73	200	4.0	2.50	11.09
2440396.5	1	2	495.679348	4	1.41	.6	2.12	50	8.1	6.65	11.10

TABLE I (Continued)

2440396.5	1	19	495.704496	3	1.41	.4	2.39	50	8.1	10.79	11.10
2440396.5	1	36	495.729815	4	.51	.6	2.84	50	8.1	14.94	11.10
2440396.5	1	53	495.755301	5	.06	.7	2.13	50	8.1	19.08	11.10
2440396.5	2	10	495.780956	5	.06	.7	2.01	50	8.1	23.22	11.10
2440396.5	2	27	495.806795	3	-1.29	.4	2.06	200	4.0	27.37	11.10
2440396.5	2	44	495.832801	3	-1.29	.5	2.17	50	8.1	31.51	11.10
2440396.5	3	1	495.858980	3	-0.84	.4	2.01	50	8.1	35.66	11.11
2440396.5	3	18	495.885344	5	-1.74	.7	1.22	50	8.1	39.81	11.11
2440396.5	3	35	495.911873	3	-1.29	.5	2.18	50	8.1	43.95	11.11
2440396.5	3	53	495.940154	6	-1.29	.8	1.32	50	8.1	48.33	11.11
2440396.5	4	12	495.970190	7	2.01	1.0	1.99	50	8.1	52.97	11.11
2440396.5	4	33	496.003650	3	2.01	.4	2.39	450	2.7	58.09	11.11
2440396.5	5	5	496.056090	5	2.91	.7	2.02	200	4.0	65.89	11.11
2440396.5	5	22	496.082633	3	3.36	.4	3.46	200	4.0	70.03	11.12
2440396.5	5	40	496.111956	12	2.46	1.7	1.49	50	8.1	74.42	11.12
2440396.5	5	57	496.139789	12	1.11	1.8	.69	5000	.8	78.57	11.12
2440396.5	6	14	496.167720	11	3.36	1.6	2.09	200	4.0	82.71	11.12
2440398.5	0	53	500.311373	3	1.77	.4	2.68	50	8.1	86.60	11.31
2440398.5	1	10	500.339382	3	2.22	.4	3.49	50	8.1	90.73	11.31
2440398.5	1	28	500.369228	3	1.32	.4	3.00	200	4.0	95.12	11.31
2440398.5	1	46	500.399262	3	.42	.5	2.59	200	4.0	99.51	11.32
2440398.5	2	4	500.429481	3	1.02	.5	2.37	50	8.1	103.89	11.32
2440398.5	2	22	500.459900	2	.57	.5	1.96	50	8.1	108.28	11.32
2440398.5	2	40	500.490513	3	.57	.5	2.21	50	8.1	112.67	11.32
2440398.5	2	58	500.521326	3	.12	.5	2.29	200	4.0	117.06	11.32
2440398.5	3	16	500.552330	2	.12	.5	2.28	50	8.1	121.45	11.32
2440398.5	3	34	500.583532	3	-0.33	.5	2.13	50	8.1	125.84	11.32
2440398.5	3	51	500.613172	3	-0.33	.5	2.11	50	8.1	130.08	11.33
2440398.5	4	9	500.644739	3	-0.78	.4	2.21	50	8.1	134.37	11.33
2440398.5	4	27	500.676491	5	-1.68	.7	1.55	50	8.1	138.77	11.33
2440398.5	4	45	500.708404	6	-0.33	.8	1.14	50	8.1	143.15	11.33
2440398.5	5	3	500.740493	7	-0.33	1.0	1.11	50	8.1	147.53	11.33
2440398.5	5	21	500.772724	6	2.37	.8	1.96	50	8.1	151.92	11.33
2440398.5	5	39	500.805123	8	2.37	1.1	1.73	200	4.0	156.31	11.33
2440398.5	5	57	500.837668	6	1.92	.9	2.73	200	4.0	160.71	11.33
2440400.5	2	22	505.592528	2	2.28	.5	3.10	50	8.1	165.44	11.54
2440400.5	2	40	505.626106	3	.93	.5	2.93	200	4.0	169.83	11.54
2440400.5	2	58	505.659866	3	1.38	.5	2.97	50	8.1	174.21	11.54
2440400.5	3	16	505.693829	3	.48	.5	2.48	50	8.1	178.59	11.54
2440400.5	3	34	505.727980	6	.03	.9	1.54	50	8.1	182.99	11.54
2440400.5	3	52	505.762316	5	.03	.7	1.63	50	8.1	187.38	11.54
2440400.5	4	10	505.796834	5	.03	.7	2.15	50	8.1	191.77	11.54
2440400.5	4	28	505.831529	6	.03	.8	1.62	50	8.1	196.15	11.54
2440400.5	4	46	505.866403	5	-1.32	.7	1.55	50	8.1	200.54	11.55
2440400.5	5	4	505.901431	6	-1.32	.9	2.19	50	8.1	204.93	11.55
2440400.5	5	22	505.936625	8	-3.12	1.1	1.03	800	2.0	209.32	11.55
2440400.5	5	40	505.971945	12	-2.22	1.8	1.39	50	8.1	213.71	11.55
2440402.5	23	8	513.725238	3	-0.21	.4	2.52	450	2.7	218.12	11.71
2440402.5	23	26	513.761008	3	1.14	.3	4.23	200	4.0	222.46	11.71
2440402.5	23	46	513.800920	2	3.84	.5	3.66	450	2.7	226.83	11.71
2440403.5	0	4	513.837016	2	5.22	.3	4.88	800	2.0	231.23	11.71
2440403.5	0	38	513.905676	2	5.22	.5	5.07	800	2.0	235.61	11.72
2440403.5	0	57	513.944327	3	4.32	.4	1.52	450	2.7	240.05	11.72
2440403.5	1	15	513.981125	3	4.92	.3	2.13	450	2.7	244.43	11.72
2440403.5	1	33	514.018114	3	4.92	.3	2.59	50	8.1	248.81	11.72
2440403.5	1	52	514.057373	2	4.02	.3	2.21	200	4.0	253.19	11.72
2440403.5	2	11	514.096838	3	4.32	.3	2.10	200	4.0	257.57	11.72
2440403.5	2	30	514.136525	5	3.87	.7	1.56	50	8.1	261.95	11.72
2440403.5	2	49	514.176428	3	3.42	.4	1.96	200	4.0	266.33	11.72
2440403.5	3	8	514.216544	4	3.12	.6	1.31	450	2.7	270.71	11.72
2440403.5	3	27	514.256871	3	2.67	.5	2.05	200	4.0	275.09	11.72
2440403.5	3	46	514.297400	5	2.67	.7	2.36	50	8.1	279.47	11.72

TABLE I (Continued)

2440403.5	4	5	514.338132	4	2.22	.6	2.45	50	8.1	348.46	11.72
2440403.5	4	24	514.379050	5	2.67	.7	2.85	50	8.1	353.09	11.72
2440403.5	4	43	514.420157	4	2.22	.6	3.42	50	8.1	357.72	11.72
2440403.5	5	2	514.461439	6	1.92	.8	2.75	50	8.1	2.35	11.72
2440403.5	5	21	514.502893	7	.12	1.0	2.01	50	8.1	6.98	11.72
2440403.5	5	40	514.544487	13	.12	1.9	2.31	50	8.1	11.63	11.72
2440404.5	22	50	519.862337	27	-1.65	4.0	.23	5000	.8	253.62	11.79
2440404.5	23	13	519.911179	28	-1.20	4.2	.37	50	8.1	259.22	11.79
2440404.5	23	31	519.949563	4	.15	.6	2.66	50	8.1	263.61	11.79
2440404.5	23	49	519.988111	2	.15	.3	3.17	200	4.0	268.00	11.79
2440405.5	0	7	520.026825	3	-0.27	.3	2.57	200	4.0	272.38	11.79
2440405.5	0	28	520.072202	3	.18	.3	3.81	450	2.7	277.47	11.79
2440405.5	2	57	520.401440	3	4.38	.4	2.68	50	8.1	313.79	11.80
2440405.5	5	3	520.689757	6	2.28	.8	2.48	200	4.0	344.52	11.80
2440405.5	5	41	520.778188	5	2.28	.7	5.89	50	8.1	353.77	11.80
2440409.5	23	21	537.036097	4	2.10	.6	2.61	200	4.0	215.72	11.99
2440409.5	23	40	537.082887	2	2.10	.3	2.47	200	4.0	220.36	11.99
2440410.5	0	26	537.196961	3	.48	.4	2.68	50	8.1	231.56	12.00
2440410.5	0	50	537.256937	3	.48	.4	2.23	200	4.0	237.41	12.00
2440410.5	1	9	537.304646	2	1.23	.3	2.91	50	8.1	242.04	12.00
2440410.5	1	58	537.428679	3	.78	.3	2.29	50	8.1	253.99	12.00
2440410.5	2	17	537.477150	3	1.23	.4	1.87	50	8.1	258.62	12.00
2440410.5	2	36	537.525841	3	.33	.3	2.85	50	8.1	263.24	12.00
2440410.5	2	55	537.574733	2	.33	.3	3.11	200	4.0	267.88	12.00
2440410.5	3	26	537.654940	1	.03	.1	3.85	450	2.7	275.44	12.00
2440410.5	3	45	537.704347	2	.93	.3	6.46	200	4.0	280.06	12.00
2440410.5	4	11	537.772236	1	5.13	.1	5.70	450	2.7	286.40	12.00
2440410.5	4	30	537.822069	2	5.58	.3	6.80	1250	1.6	291.03	12.00
2440424.5	21	46	599.400603	6	4.50	.8	3.33	50	8.1	54.53	11.42
2440424.5	22	7	599.466074	8	.60	1.1	1.30	2450	1.2	59.61	11.42
2440424.5	22	28	599.531700	6	1.95	.9	2.64	200	4.0	64.73	11.42
2440424.5	22	49	599.597533	3	3.30	.4	3.48	200	4.0	69.84	11.42
2440424.5	23	10	599.663605	7	1.35	1.0	2.04	50	8.1	74.96	11.42
2440424.5	23	31	599.729895	8	.90	1.1	.94	800	2.0	80.07	11.42
2440424.5	23	52	599.796401	9	3.60	1.3	1.52	200	4.0	85.18	11.42
2440425.5	0	13	599.863163	9	4.53	1.4	1.20	50	8.1	90.30	11.41
2440425.5	0	34	599.930175	15	4.98	2.1	.75	200	4.0	95.41	11.41
2440425.5	0	55	599.997422	10	7.68	1.4	1.24	50	8.1	100.53	11.41
2440425.5	1	16	600.064977	18	1.98	2.6	.35	3200	1.0	105.64	11.41
2440425.5	1	37	600.132710	6	6.93	.8	1.94	200	4.0	110.76	11.41
2440425.5	1	58	600.200721	8	6.93	1.1	1.07	450	2.7	115.87	11.41
2440425.5	2	19	600.268973	6	6.93	.8	2.04	450	2.7	120.99	11.41
2440425.5	2	40	600.337479	6	3.78	.8	1.19	2450	1.2	126.10	11.41
2440425.5	3	1	600.406187	3	3.78	.4	1.92	3200	1.0	131.22	11.40
2440425.5	3	22	600.475102	5	4.68	.7	2.75	50	8.1	136.33	11.40
2440425.5	3	43	600.544235	18	2.88	2.6	.97	450	2.7	141.45	11.40
2440425.5	4	4	600.613610	22	-7.32	3.3	.55	50	8.1	146.57	11.40
2440427.5	23	2	613.678732	8	-3.51	1.1	1.47	4050	.9	44.96	11.16
2440427.5	23	24	613.750159	9	-0.36	1.4	1.21	450	2.7	50.31	11.15
2440427.5	23	46	613.821850	6	1.89	.8	2.48	50	8.1	55.67	11.15
2440428.5	0	8	613.893822	6	2.07	.8	1.86	200	4.0	61.03	11.15
2440428.5	0	30	613.966060	4	2.97	.6	3.08	50	8.1	66.39	11.15
2440428.5	0	52	614.038576	3	2.97	.4	3.50	200	4.0	71.75	11.15
2440428.5	1	14	614.111372	9	2.07	1.3	1.68	50	8.1	77.12	11.15
2440428.5	1	36	614.184428	10	2.97	1.4	1.09	50	8.1	82.46	11.15
2440428.5	1	58	614.257746	8	4.32	1.1	1.52	50	8.1	87.82	11.15
2440428.5	2	20	614.331315	9	7.02	1.3	1.45	50	8.1	93.20	11.14
2440428.5	2	42	614.405144	9	7.92	1.4	1.33	50	8.1	98.54	11.14
2440428.5	3	26	614.553522	11	7.02	1.6	2.11	50	8.1	109.26	11.14
2440428.5	3	48	614.628012	9	9.27	1.4	2.31	50	8.1	114.63	11.14
2440430.5	21	33	627.792991	9	-0.42	1.4	1.78	200	4.0	355.49	10.90
2440430.5	21	55	627.865360	9	.03	1.4	1.51	200	4.0	.84	10.90

TABLE I (Continued)

2440430.5	22	17	627.937947	9	-0.27	1.3	1.25	50	8.1	6.21	10.90
2440430.5	22	39	628.010749	6	1.08	.8	2.05	50	8.1	11.56	10.89
2440430.5	23	1	628.083810	6	-0.27	.9	1.70	50	8.1	16.92	10.89
2440430.5	23	23	628.157107	6	.63	.9	1.66	50	8.1	22.28	10.89
2440430.5	23	45	628.230695	8	-2.97	1.1	.85	450	2.7	27.64	10.89
2440431.5	0	7	628.304517	5	-1.59	.7	2.08	50	8.1	33.00	10.89
2440431.5	0	29	628.378624	0	-2.49	1.4	1.03	50	8.1	38.36	10.89
2440431.5	0	51	628.452995	12	-2.04	1.7	.89	50	8.1	43.71	10.89
2440431.5	1	13	628.527631	10	-0.69	1.4	.86	50	8.1	49.07	10.89
2440431.5	1	35	628.602536	10	.66	1.4	1.16	50	8.1	54.43	10.88
2440431.5	1	57	628.677704	5	2.01	.7	1.91	200	4.0	59.79	10.88
2440431.5	2	19	628.753129	6	3.06	.8	1.56	50	8.1	65.15	10.88
2440431.5	2	41	628.828799	5	3.96	.7	2.49	50	8.1	70.51	10.88
2440431.5	3	3	628.904744	18	-1.44	2.7	.56	2450	1.2	75.86	10.88
2440431.5	3	25	628.980842	17	2.61	2.5	1.22	200	4.0	81.22	10.88
2440432.5	21	18	637.530162	26	2.79	3.8	.52	5000	.8	833.03	10.63
2440432.5	21	41	637.606903	11	-0.36	1.6	.60	5000	.8	838.62	10.63
2440432.5	22	3	637.680479	9	2.34	1.4	1.24	50	8.1	843.97	10.62
2440432.5	22	25	637.754300	6	1.44	.9	1.94	50	8.1	849.34	10.62
2440432.5	22	50	637.838479	6	-0.36	.9	1.23	800	2.0	855.45	10.62
2440432.5	23	12	637.912810	5	-0.21	.7	2.22	50	8.1	.78	10.62
2440432.5	23	34	637.987402	6	-0.66	.8	1.47	50	8.1	6.14	10.61
2440432.5	23	56	638.062247	9	.69	1.3	1.12	50	8.1	11.51	10.61
2440433.5	0	19	638.140800	6	-0.63	.8	1.97	50	8.1	17.11	10.61
2440433.5	0	41	638.216210	8	-1.08	1.1	1.04	450	2.7	22.45	10.61
2440433.5	1	3	638.291885	6	-0.63	.9	1.92	50	8.1	27.82	10.60
2440434.5	22	18	647.659822	13	-0.30	1.9	.94	200	4.0	328.92	10.34
2440434.5	22	41	647.738294	9	1.50	1.4	.62	1250	1.6	334.29	10.34
2440434.5	23	4	647.817044	9	2.10	1.3	1.25	200	4.0	339.89	10.34
2440434.5	23	26	647.892647	6	.30	.8	1.64	50	8.1	345.48	10.34
2440434.5	23	50	647.975410	6	.30	.8	10.39	800	2.0	351.09	10.33
2440435.5	0	13	648.055028	5	-0.27	.7	2.12	200	4.0	356.69	10.33
2440435.5	0	36	648.134932	5	.63	.7	2.12	50	8.1	2.29	10.33
2440435.5	0	59	648.215142	6	.18	.9	1.52	50	8.1	7.90	10.33
2440435.5	1	22	648.295650	7	-1.17	1.0	1.29	200	4.0	13.49	10.33
2440435.5	1	44	648.372911	5	-0.27	.7	1.89	200	4.0	19.07	10.32
2440435.5	2	8	648.457495	7	-0.72	1.0	1.53	50	8.1	24.69	10.32
2440435.5	2	31	648.538833	7	-2.07	1.0	1.73	50	8.1	30.30	10.32
2440435.5	2	53	648.616853	9	-0.72	1.4	2.04	50	8.1	35.88	10.32
2440435.5	3	17	648.702230	16	-1.92	2.3	1.02	200	4.0	41.49	10.31
2440435.5	3	39	648.781694	30	-2.37	4.4	1.12	50	8.1	47.07	10.31
2440437.5	21	17	662.587090	6	3.54	.8	3.34	450	2.7	285.75	9.93
2440437.5	21	41	662.669972	10	4.44	1.4	1.81	450	2.7	291.58	9.93
2440437.5	22	5	662.754107	3	5.34	.4	5.03	450	2.7	297.43	9.93
2440437.5	22	29	662.836526	12	4.44	1.7	1.47	450	2.7	303.26	9.93
2440437.5	22	53	662.920229	9	4.44	1.4	2.32	50	8.1	309.10	9.92
2440437.5	23	17	663.004236	10	4.14	1.4	2.39	450	2.7	314.99	9.92
2440437.5	23	41	663.088546	7	5.04	1.0	2.01	200	4.0	320.80	9.92
2440438.5	0	5	663.173200	9	1.92	1.4	1.79	450	2.7	326.66	9.92
2440438.5	0	29	663.258158	12	1.47	1.8	1.01	1800	1.3	332.51	9.92
2440438.5	0	53	663.343440	13	.57	1.9	1.33	800	2.0	338.34	9.91
2440438.5	1	17	663.429014	10	3.27	1.4	2.16	50	8.1	344.17	9.91
2440438.5	1	41	663.514935	5	.57	.7	2.65	800	2.0	350.02	9.91
2440438.5	2	5	663.601133	6	1.02	.8	3.33	200	4.0	355.87	9.91
2440439.5	20	47	672.724010	36	1.20	5.4	1.25	200	4.0	359.74	9.66
2440439.5	21	11	672.807644	9	-1.95	1.3	2.50	50	8.1	365.58	9.66
2440439.5	21	41	672.912492	7	-2.85	1.0	1.39	1250	1.6	372.90	9.65
2440439.5	22	5	672.996641	3	-1.05	.4	3.82	450	2.7	378.74	9.65
2440439.5	22	53	673.165768	3	4.35	.3	3.92	800	2.0	390.41	9.65
2440439.5	23	17	673.251795	2	4.80	.3	4.34	450	2.7	396.27	9.64
2440439.5	23	41	673.336140	8	4.35	1.1	2.03	200	4.0	302.09	9.64
2440440.5	0	5	673.421795	7	5.28	1.0	2.40	50	8.1	307.93	9.64

TABLE I (Continued)

2440440.5	0	29	673.507787	6	3.48	.9	2.05	450	2.7	213.78	9.64
2440440.5	0	53	673.594088	6	3.48	.9	2.25	200	4.0	219.63	9.64
2440440.5	1	18	673.684333	8	1.23	1.1	1.16	2450	1.2	225.72	9.63
2440440.5	1	41	673.767637	8	1.68	1.1	1.49	450	2.7	231.34	9.63
2440440.5	2	5	673.854855	6	1.68	.9	2.18	50	8.1	237.15	9.63
2440440.5	2	29	673.942360	17	.78	2.5	2.62	50	8.1	243.02	9.63
2440440.5	2	53	674.030127	15	.33	2.3	1.54	450	2.7	248.88	9.62
2440444.5	21	52	698.813896	6	-1.95	.8	2.96	5000	.8	213.53	8.80
2440444.5	21	17	698.903352	9	-0.45	1.3	2.54	200	4.0	219.59	8.79
2440444.5	21	49	699.015262	6	-1.35	.8	2.66	450	2.7	227.40	8.79
2440444.5	22	13	699.104750	6	-0.90	.8	2.48	50	8.1	233.21	8.78
2440444.5	22	37	699.191524	6	-0.45	.9	2.12	50	8.1	239.08	8.78
2440444.5	23	1	699.271603	6	-0.90	.9	1.76	50	8.1	244.93	8.78
2440444.5	23	25	699.365966	9	-2.25	1.4	1.52	50	8.1	250.77	8.78
2440444.5	23	49	699.453689	21	-1.35	3.1	.79	50	8.1	256.61	8.77
2440445.5	0	13	699.541703	6	-1.02	.8	2.55	50	8.1	262.44	8.77
2440445.5	0	39	699.637417	5	-1.47	.7	2.25	50	8.1	268.78	8.77
2440445.5	1	3	699.726091	6	-1.47	.8	2.21	200	4.0	274.62	8.76
2440445.5	1	27	699.815068	3	-1.02	.3	4.68	450	2.7	280.45	8.76
2440445.5	1	51	699.904308	3	4.38	.3	4.51	200	4.0	286.31	8.76
2440445.5	2	15	699.993870	4	3.63	.6	4.50	800	2.0	292.16	8.75
2440445.5	2	39	700.083688	5	4.08	.7	3.96	450	2.7	297.99	8.75
2440445.5	3	3	700.173759	18	3.03	2.7	1.68	50	8.1	303.85	8.75
2440445.5	3	27	700.264045	27	3.03	4.0	2.01	5000	.8	309.69	8.75
2440448.5	20	46	720.065644	24	-0.18	3.5	.68	5000	.8	174.32	8.07
2440451.5	22	40	736.641364	10	-3.24	1.4	1.52	50	8.1	173.54	7.51
2440451.5	23	5	736.734630	8	-3.69	1.1	1.89	50	8.1	179.63	7.50
2440451.5	23	30	736.824224	8	-2.79	1.1	1.29	800	2.0	185.71	7.50
2440451.5	23	55	736.922153	12	-0.99	1.8	1.43	50	8.1	191.79	7.50
2440452.5	0	21	737.020218	28	-1.41	4.2	.76	200	4.0	197.95	7.46
2440452.5	0	59	737.164191	13	-0.96	1.9	1.66	200	4.0	207.18	7.45
2440452.5	1	24	737.250337	6	-3.21	.9	1.36	5000	.8	213.29	7.45
2440452.5	1	49	737.354764	6	-0.96	.9	3.05	50	8.1	219.37	7.44
2440452.5	2	14	737.450502	7	-1.41	1.0	3.16	200	4.0	225.46	7.44
2440452.5	2	39	737.546505	11	-0.96	1.6	2.90	200	4.0	231.54	7.44
2440453.5	22	1	747.348877	14	-2.43	2.0	1.30	50	8.1	144.88	7.04
2440453.5	22	27	747.445935	11	-1.08	1.6	1.45	50	8.1	151.21	7.04
2440453.5	22	53	747.543376	36	-4.68	5.3	.86	50	8.1	157.54	7.03
2440453.5	23	19	747.641137	12	-1.98	1.7	1.19	50	8.1	163.87	7.03
2440453.5	23	45	747.739295	10	-3.78	1.4	1.47	200	4.0	170.19	7.03
2440454.5	1	56	748.239276	13	-3.15	1.9	.91	200	4.0	202.08	7.01
2440454.5	2	22	748.339500	13	-1.80	1.9	1.71	200	4.0	208.41	7.00
2440454.5	2	48	748.440020	9	-2.70	1.3	2.00	5000	.8	214.74	7.00
2440454.5	3	14	748.540787	12	-2.70	1.8	7.28	50	8.1	221.07	6.99
2440455.5	20	19	757.874949	12	7.08	1.8	2.39	50	8.1	101.07	6.62
2440455.5	20	45	757.975377	36	4.83	5.3	1.17	50	8.1	107.40	6.61
2440455.5	21	11	758.072059	12	5.13	1.8	.79	5000	.8	113.70	6.61
2440455.5	21	37	758.169038	20	5.58	3.0	1.08	50	8.1	120.05	6.61
2440455.5	22	3	758.266358	15	2.88	2.1	1.33	50	8.1	126.38	6.60
2440455.5	23	21	758.560382	35	-2.07	5.2	.22	5000	.8	145.37	6.59
2440455.5	23	47	758.659100	15	-1.17	2.1	.94	50	8.1	151.69	6.59
2440456.5	0	40	758.861502	10	-4.29	1.4	.97	1800	1.3	164.59	6.58
2440456.5	1	6	758.961318	21	-2.94	3.0	.83	50	8.1	170.92	6.58
2440456.5	1	32	759.061472	7	-1.14	1.0	3.26	50	8.1	177.25	6.57
2440456.5	1	58	759.161981	13	-4.29	1.9	1.94	200	4.0	183.58	6.57
2440456.5	2	24	759.262744	11	-0.24	1.6	3.68	50	8.1	189.90	6.56
2440458.5	20	29	774.378005	9	1.92	1.4	3.14	200	4.0	74.77	5.96
2440458.5	20	56	774.479038	16	.12	2.3	1.80	50	8.1	81.36	5.96
2440458.5	21	23	774.580347	10	3.27	1.4	2.23	50	8.1	87.92	5.95
2440458.5	21	50	774.681993	10	6.42	1.4	1.82	50	8.1	94.50	5.95
2440458.5	22	17	774.784020	10	6.27	1.4	1.98	50	8.1	101.07	5.95
2440458.5	22	44	774.885423	13	6.27	1.9	1.51	50	8.1	107.64	5.94

TABLE I (Continued)

2440458.5	23	11	774.984217	11	5.82	1.6	1.69	50	8.1	114.21	5.94
2440458.5	23	38	775.092401	12	6.27	1.8	1.72	50	8.1	120.79	5.93
2440459.5	0	5	775.196017	19	1.50	2.8	1.80	50	8.1	127.35	5.93
2440459.5	1	26	775.500072	12	2.40	1.8	2.21	50	8.1	147.08	5.92
2440459.5	1	53	775.614177	11	-2.10	1.6	1.56	1250	1.6	153.64	5.91
2440460.5	20	42	785.465673	17	4.08	2.5	1.77	50	8.1	58.97	5.52
2440460.5	21	9	785.567383	6	.48	.9	2.25	800	2.0	65.53	5.52
2440460.5	21	36	785.669387	7	1.83	1.0	2.47	450	2.7	72.10	5.52
2440460.5	22	3	785.771763	27	.18	4.0	.85	50	8.1	78.67	5.51
2440460.5	22	30	785.874473	9	3.78	1.3	2.01	50	8.1	85.25	5.51
2440460.5	22	57	785.977588	8	4.23	1.1	1.70	800	2.0	91.82	5.50
2440460.5	23	24	786.081081	10	6.93	1.4	1.88	50	8.1	98.39	5.50
2440460.5	23	51	786.184997	24	5.58	3.6	.89	200	4.0	104.96	5.49
2440461.5	0	18	786.286290	6	6.81	.9	2.70	50	8.1	111.53	5.49
2440461.5	0	45	786.393058	27	9.96	4.0	.72	200	4.0	118.10	5.49
2440461.5	1	12	786.495018	27	10.41	4.0	1.03	50	8.1	124.67	5.48
2440461.5	1	39	786.604466	32	9.06	4.8	1.22	50	8.1	131.24	5.48
2440462.5	20	48	796.574989	10	-2.61	1.4	2.94	200	4.0	41.22	5.03
2440462.5	21	16	796.685068	21	-3.06	3.0	.73	5000	.8	48.03	5.03
2440462.5	21	44	796.791480	21	.99	3.1	.79	450	2.7	54.85	5.02
2440462.5	22	12	796.894308	10	.54	1.4	1.80	200	4.0	61.65	5.02
2440462.5	22	40	797.005528	6	1.89	.8	3.37	50	8.1	68.46	5.01
2440462.5	23	6	797.113189	12	.09	1.0	.79	5000	.8	75.29	5.01
2440462.5	23	36	797.221253	12	1.44	1.8	1.99	50	8.1	82.11	5.00
2440463.5	0	4	797.326746	12	2.37	1.7	1.26	1250	1.6	88.92	5.00
2440463.5	0	32	797.438466	13	5.07	1.9	1.28	200	4.0	95.74	4.99
2440463.5	1	0	797.547070	17	5.52	2.5	1.46	50	8.1	102.54	4.99
2440463.5	1	28	797.657674	15	7.32	2.3	1.29	450	2.7	109.36	4.98
2440466.5	21	42	819.123375	16	-2.34	2.3	1.26	5000	.8	15.96	4.03
2440466.5	22	10	819.231269	19	-2.34	2.0	1.64	5000	.8	22.77	4.03
2440466.5	22	38	819.334570	20	-2.34	3.0	2.30	50	8.1	29.58	4.02
2440466.5	23	34	819.557423	13	-0.39	1.9	2.03	200	4.0	43.20	4.02
2440467.5	0	30	819.776976	13	-0.06	1.9	2.55	200	4.0	56.82	4.01
2440467.5	0	58	819.887347	15	3.09	2.1	4.02	50	8.1	63.65	4.00
2440467.5	1	26	819.994131	15	2.34	2.1	2.06	5000	.8	70.46	4.00
2440467.5	21	24	824.671119	13	-2.16	1.9	2.83	50	8.1	2.04	3.79
2440467.5	21	52	824.779031	10	-2.61	1.4	2.62	450	2.7	8.83	3.78
2440467.5	22	20	824.887331	18	-1.71	2.7	1.75	50	8.1	15.64	3.78
2440467.5	22	48	824.996055	14	-2.61	2.0	1.78	50	8.1	22.47	3.78
2440467.5	23	16	825.105202	12	-3.51	1.8	2.17	50	8.1	29.29	3.77
2440467.5	23	44	825.214780	27	-5.31	4.0	1.14	50	8.1	36.10	3.77
2440468.5	0	12	825.326740	8	-1.23	1.1	5.89	50	8.1	42.91	3.76
2440468.5	0	40	825.435126	36	1.02	5.4	1.89	50	8.1	49.72	3.76
2440468.5	1	8	825.545022	13	1.47	1.9	2.06	50	8.1	56.54	3.75
2440468.5	1	36	825.657100	15	1.02	2.1	1.76	450	2.7	63.36	3.75
2440468.5	2	4	825.768624	9	1.02	1.4	3.58	450	2.7	70.16	3.74
2440468.5	20	46	830.154404	20	-1.98	3.0	1.56	200	4.0	343.21	3.55
2440468.5	21	14	830.262066	10	-1.08	1.4	3.12	50	8.1	350.04	3.54
2440468.5	21	43	830.374969	11	-1.53	1.6	2.81	50	8.1	357.10	3.54
2440468.5	22	12	830.486281	12	-0.18	1.7	1.73	50	8.1	4.16	3.53
2440468.5	22	41	830.594062	12	-3.33	1.7	1.91	50	8.1	11.19	3.53
2440468.5	23	10	830.712264	21	-1.98	3.1	1.29	50	8.1	18.27	3.53
2440468.5	23	30	830.825931	18	-1.98	2.6	1.86	50	8.1	25.33	3.52
2440469.5	0	8	830.940075	15	-5.55	2.1	2.55	50	8.1	32.38	3.52
2440469.5	0	37	831.054612	24	-1.50	3.6	.65	5000	.8	39.46	3.51
2440469.5	1	6	831.169576	18	2.40	2.6	2.40	50	8.1	46.48	3.51
2440469.5	2	4	831.400741	15	2.55	2.3	3.50	200	4.0	60.64	3.49
2440469.5	20	56	835.834425	17	.75	2.5	1.92	50	8.1	336.13	3.30
2440469.5	21	25	835.946351	12	-0.15	1.8	1.96	50	8.1	343.18	3.29
2440469.5	21	54	836.058674	9	.30	1.4	2.77	200	4.0	350.25	3.29
2440469.5	22	23	836.171440	9	-1.50	1.4	2.52	200	4.0	357.30	3.28
2440469.5	22	52	836.284643	8	-1.95	1.1	3.38	50	8.1	4.35	3.28

TABLE I (Continued)

2440460.5	23	21	836.398290	15	-1.05	2.1	2.42	50	8.1	11.40	3.28
2440460.5	23	50	836.512407	12	-2.40	1.7	2.36	50	8.1	18.46	3.27
2440470.5	0	48	836.741962	11	-2.37	1.6	2.77	50	8.1	32.58	3.26
2440470.5	1	17	836.857385	15	-3.57	2.3	1.15	5000	.8	39.64	3.26
2440470.5	1	46	836.973179	30	-1.77	4.4	2.16	50	8.1	46.70	3.25
2440472.5	21	31	852.967298	15	.54	2.3	1.36	5000	.8	315.56	2.51
2440472.5	22	0	853.080504	23	-2.46	3.4	1.27	3200	1.0	322.64	2.51
2440472.5	22	29	853.194121	15	-2.01	2.3	1.91	5000	.8	329.69	2.50
2440472.5	22	58	853.308177	9	-0.21	1.4	1.55	5000	.8	336.75	2.49
2440472.5	23	56	853.537676	12	-0.21	1.8	4.07	200	4.0	350.86	2.48
2440473.5	0	54	853.768977	28	-4.38	4.2	.81	5000	.8	4.98	2.47
2440474.5	22	59	864.702431	10	1.65	1.4	1.83	200	4.0	317.83	1.95
2440474.5	23	29	864.821441	15	-0.60	2.1	.76	5000	.8	325.13	1.95
2440474.5	23	54	864.931922	10	.75	1.4	2.24	200	4.0	332.18	1.94
2440475.5	0	28	865.056872	16	-1.02	2.3	.69	5000	.8	339.47	1.94
2440475.5	0	57	865.173250	9	-1.47	1.4	3.29	450	2.7	346.55	1.93
2440475.5	1	27	865.294077	10	-3.72	1.4	2.59	800	2.0	353.84	1.93
2440475.5	1	57	865.415293	30	-4.62	4.4	1.65	50	8.1	1.14	1.92
2440475.5	2	27	865.536842	10	-1.62	2.8	8.99	50	8.1	8.42	1.92
2440475.5	20	52	869.014201	23	-1.92	3.4	1.51	50	8.1	277.32	1.71
2440475.5	21	22	870.031434	4	1.68	.6	5.53	200	4.0	284.61	1.70
2440475.5	22	0	870.180587	5	2.43	.7	5.24	450	2.7	293.89	1.70
2440475.5	22	30	870.298873	6	1.98	.8	3.16	1250	1.6	301.17	1.69
2440475.5	23	0	870.417640	8	1.68	1.1	3.22	450	2.7	308.49	1.68
2440475.5	23	30	870.536890	12	1.68	1.8	1.94	50	8.1	315.77	1.68
2439594.5			3.000000	4	-2.55	.6	1.35	5000	.8	161.34	22.00
2439594.5			12.000000	5	-1.20	.8	.87	50	8.1	167.20	22.00
2439594.5			.000000	11	-3.00	1.6	.51	800	2.0	172.56	22.00
2439594.5			12.000000	5	-1.20	.7	1.34	450	2.7	177.93	22.00
2439594.5			6.000000	3	-2.10	.4	2.14	1800	1.3	183.30	22.00
2439594.5			12.000000	5	-1.20	.7	1.28	200	4.0	188.66	22.00
2439594.5			18.000000	1	-0.30	.2	2.86	1250	1.6	194.03	22.00
2439594.5			24.000000	1	.60	.1	4.93	5000	.8	199.40	22.00
2439594.5			30.000000	1	1.50	.2	3.27	5000	.8	204.76	22.00
2439594.5			48.000000	2	4.20	.3	2.01	1250	1.6	213.55	22.00
2439594.5			36.000000	5	2.40	.8	.89	450	2.7	218.91	22.00
2439594.5			24.000000	1	.60	.2	3.02	1800	1.3	224.28	22.00
2439594.5			3.000000	3	-2.55	.4	1.89	450	1.2	229.65	22.00
2439594.5			18.000000	2	-0.30	.3	2.21	200	4.0	235.01	22.00
2439594.5			15.000000	3	-0.75	.4	1.31	200	4.0	240.38	22.00
2439594.5			15.000000	4	-0.75	.6	1.45	50	8.1	245.75	22.00
2439594.5			12.000000	4	-1.20	.6	1.72	200	4.0	251.11	22.00
2439594.5			6.000000	5	-2.10	.7	1.80	450	2.7	256.48	22.00
2439594.5			18.000000	5	-0.30	.7	1.33	50	8.1	261.85	22.00
2439594.5			18.000000	5	-0.30	.7	1.18	50	8.1	267.21	22.00
2439594.5			18.000000	4	-0.30	.6	1.86	800	2.0	272.58	22.00
2439601.5			28.000000	11	1.20	1.6	.44	450	2.7	88.84	22.00
2439601.5			37.000000	19	2.55	2.8	.32	800	2.0	94.20	22.00
2439601.5			55.000000	7	5.25	1.0	.63	200	4.0	99.57	22.00
2439601.5			61.000000	4	6.15	.6	1.15	200	4.0	105.18	22.00
2439601.5			64.000000	5	6.60	.8	1.00	200	4.0	110.55	22.00
2439601.5			64.000000	3	6.60	.4	1.25	200	4.0	115.91	22.00
2439601.5			43.000000	6	3.45	.9	.92	200	4.0	121.28	22.00
2439601.5			46.000000	5	3.90	.7	1.11	450	2.7	126.65	22.00
2439601.5			37.000000	16	2.55	2.5	.33	50	8.1	143.24	22.00
2439601.5			7.000000	17	-1.95	2.6	.32	5000	.8	148.60	22.00
2439601.5			1.000000	7	-2.85	1.1	.94	5000	.8	153.97	22.00
2439601.5			10.000000	5	-1.50	.8	.99	200	4.0	159.34	22.00
2439601.5			7.000000	6	-1.95	.9	.83	50	8.1	164.70	22.00
2439601.5			10.000000	6	-1.50	.9	.63	50	8.1	170.80	22.00
2439601.5			4.000000	7	-2.40	1.0	.75	200	4.0	176.17	22.00
2439601.5			13.000000	2	-1.05	.3	2.82	1250	1.6	181.54	22.00

TABLE I (Continued)

2439601.5	10.000000	3	-1.50	.4	1.83	800	2.0	186.90	22.00
2439601.5	13.000000	3	-1.05	.4	1.76	800	2.0	192.27	22.00
2439601.5	22.000000	1	.30	.2	4.22	2450	1.2	197.64	22.00
2439601.5	28.000000	2	1.20	.3	2.65	2450	1.2	203.00	22.00
2439600.5	7.000000	3	-1.95	.4	1.08	1800	1.3	30.12	22.00
2439600.5	7.000000	5	-1.95	.7	.72	50	8.1	35.49	22.00
2439600.5	1.000000	6	-2.85	.9	.64	200	4.0	40.86	22.00
2439600.5	-5.000000	6	-3.75	.9	.78	800	2.0	46.22	22.00
2439600.5	13.000000	4	-1.05	.6	1.09	450	2.7	51.59	22.00
2439600.5	22.000000	4	.30	.6	1.25	800	2.0	56.95	22.00
2439600.5	37.000000	5	2.55	.7	1.09	200	4.0	62.32	22.00
2439600.5	31.000000	4	1.65	.6	1.14	200	4.0	67.69	22.00
2439600.5	31.000000	7	1.65	1.0	.61	200	4.0	73.05	22.00
2439600.5	52.000000	6	4.80	.9	.74	5000	.8	97.20	22.00
2439600.5	58.000000	6	5.70	.9	.69	200	4.0	102.57	22.00
2439600.5	61.000000	6	6.15	.9	.65	1250	1.6	107.93	22.00
2439600.5	64.000000	4	6.60	.6	1.38	5000	.8	113.30	22.00
2439600.5	64.000000	5	6.60	.8	.90	450	2.7	118.66	22.00
2439600.5	40.000000	7	3.00	1.1	.78	4050	.9	124.03	22.00
2439614.5	37.000000	5	2.55	.7	1.20	450	2.7	297.84	22.00
2439614.5	40.000000	6	3.00	.9	.82	200	4.0	303.21	22.00
2439614.5	28.000000	5	1.20	.8	.95	1250	1.6	308.57	22.00
2439615.5	34.000000	3	2.10	.4	1.24	200	4.0	317.60	22.00
2439615.5	16.000000	1	-0.60	.2	2.00	200	4.0	.76	22.00
2439615.5	16.000000	2	-0.60	.3	1.69	450	2.7	6.13	22.00
2439615.5	22.000000	5	.30	.7	1.06	50	8.1	11.49	22.00
2439615.5	13.000000	4	-1.05	.6	.97	50	8.1	16.86	22.00
2439615.5	4.000000	6	-2.40	.9	.94	50	8.1	22.22	22.00
2439615.5	7.000000	3	-1.95	.4	1.09	50	8.1	27.59	22.00
2439615.5	10.000000	4	-1.50	.6	1.27	50	8.1	32.95	22.00
2439615.5	-2.000000	2	-3.30	1.4	.65	200	4.0	38.32	22.00
2439615.5	10.000000	7	-0.15	1.1	.58	800	2.0	61.48	22.00
2439615.5	31.000000	7	1.65	1.1	.99	450	2.7	66.85	22.00
2439621.5	8.000000	11	-1.80	1.7	.67	5000	.8	232.82	22.00
2439621.5	5.000000	7	-2.25	1.0	1.37	5000	.8	238.43	22.00
2439621.5	11.000000	5	-1.35	.7	2.22	200	4.0	244.04	22.00
2439622.5	5.000000	9	-2.25	1.4	1.27	5000	.8	264.27	22.00
2439622.5	25.000000	10	.90	1.5	.86	50	8.1	269.64	22.00
2439622.5	35.000000	13	2.25	2.0	.72	5000	.8	288.41	22.00
2439622.5	41.000000	11	3.15	1.7	1.01	50	8.1	294.02	22.00
2439622.5	20.000000	17	1.35	2.6	.54	5000	.8	299.62	22.00
2439622.5	38.000000	21	2.70	3.2	.47	1250	1.6	305.23	22.00
2439622.5	38.000000	8	2.70	1.2	.72	50	8.1	310.84	22.00
2439622.5	38.000000	4	2.70	.6	1.42	200	4.0	316.45	22.00
2439622.5	20.000000	5	1.35	.7	1.37	2450	1.2	322.05	22.00
2439622.5	32.000000	5	1.80	.7	1.19	200	4.0	327.66	22.00
2439622.5	26.000000	6	.90	.9	.92	450	2.7	333.27	22.00
2439622.5	26.000000	5	.90	.8	.96	200	4.0	339.36	22.00
2439628.5	-7.000000	13	-4.05	2.0	.52	5000	.8	162.01	22.00
2439628.5	11.000000	4	-1.35	.6	1.19	200	4.0	178.83	22.00
2439628.5	11.000000	4	-1.35	.6	1.57	200	4.0	184.44	22.00
2439629.5	14.000000	3	-0.90	.4	2.29	200	4.0	192.97	22.00
2439629.5	20.000000	1	.0	.1	5.66	4050	.9	198.82	22.00
2439629.5	26.000000	1	.90	.1	3.94	5000	.8	204.67	22.00
2439629.5	44.000000	5	3.60	.8	.63	5000	.8	210.52	22.00
2439629.5	44.000000	7	3.60	1.0	.58	50	8.1	216.37	22.00
2439629.5	29.000000	4	1.35	.6	1.66	1250	1.6	222.22	22.00
2439629.5	5.000000	2	-2.25	.3	2.99	450	2.7	246.10	22.00
2439629.5	5.000000	2	-2.25	.3	3.53	1800	1.3	251.95	22.00
2439629.5	11.000000	3	-1.35	.4	2.05	200	4.0	257.80	22.00
2439629.5	5.000000	4	-2.25	.6	1.89	3200	1.0	263.65	22.00
2439629.5	17.000000	4	-0.45	.6	1.99	800	2.0	269.50	22.00

TABLE I (Continued)

2439629.5	23.000000	3	.45	.4	2.09	450	2.7	275.35	22.00
2439629.5	26.000000	11	.90	1.7	.67	800	2.0	281.20	22.00
2439630.5	24.000000	9	.60	1.4	.90	200	4.0	59.27	22.00
2439639.5	36.000000	8	2.40	1.2	.89	800	2.0	65.61	22.00
2439639.5	30.000000	14	1.50	2.1	.39	450	2.7	71.94	22.00
2439640.5	60.000000	7	6.00	1.0	1.09	800	2.0	115.80	22.00
2439640.5	48.000000	5	4.20	.7	1.62	5000	.8	122.13	22.00
2439640.5	39.000000	8	2.85	1.2	1.01	200	4.0	128.46	22.00
2439640.5	18.000000	34	-0.30	5.1	.38	5000	.8	134.80	22.00
2439640.5	21.000000	18	.15	2.7	.36	5000	.8	141.13	22.00
2439640.5	-6.000000	37	-3.90	5.6	.24	5000	.8	147.47	22.00
2439640.5	12.000000	12	-1.20	1.8	.70	50	8.1	153.80	22.00
2439642.5	2.000000	12	-2.70	1.8	.55	50	8.1	38.76	22.00
2439642.5	-10.000000	13	-4.50	2.0	.79	5000	.8	45.34	22.00
2439642.5	17.000000	8	-0.45	1.2	.76	200	4.0	51.67	22.00
2439643.5	50.000000	8	4.50	1.2	.84	450	2.7	91.38	22.00
2439643.5	50.000000	13	4.50	1.9	.70	200	4.0	97.71	22.00
2439643.5	56.000000	10	5.40	1.5	.75	50	8.1	104.05	22.00
2439643.5	62.000000	8	6.30	1.2	.89	450	2.7	110.38	22.00
2439643.5	53.000000	9	4.95	1.4	1.02	1800	1.3	116.71	22.00

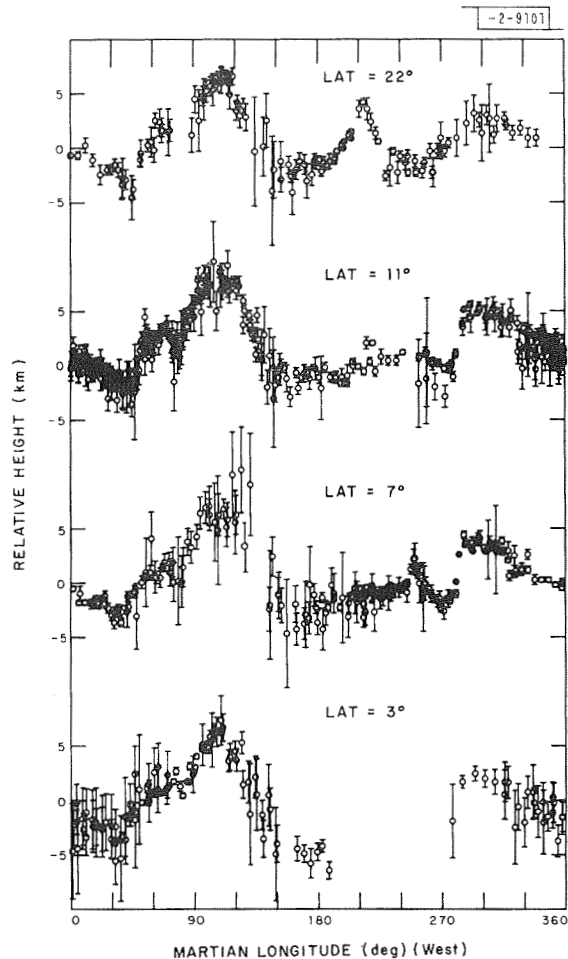


Fig. 4. Martian surface height variation with longitude (West) in four latitude steps ranging from 1.6°N to 5.0°N in first band, 5.0°N to 8.8°N in the second, 9.1°N to 12.0°N in the third, and 20°N to 24°N in the top band. The error bars represent $\pm$ one sigma (standard deviation). In the cases when the peak signal is greater than ten sigma, agreement between successive days' measurements for corresponding longitudes and latitudes is usually within 200 meters. The numerical values from which this plot was made are listed in Table 1.

effects are only weakly correlated when the subradar points of the observations are distributed reasonably well over Martian longitude for each narrow band of latitude observed. (For this reason, one can obtain useful, although not optimum, estimates of the topography without actually determining a new orbit simultaneously; for discussion of this point see Pettengill, *et al.*⁴) In any event, aside from topography, there are only 14 (partially) unknown parameters associated significantly with the earth-Mars radar measurements — six orbital elements each for the earth and Mars, the mean radius of Mars, and the light-second equivalent of the astronomical unit — whereas the number of Mars radar measurements is about 500. Moreover, there exist over 1000 accurate radar measurements of earth-Venus and earth-Mercury round-trip time delays that can be used to determine with sufficient accuracy the earth's orbit and the astronomical unit. The Mars radar data need, in effect, only be used to determine the Martian orbit and mean radius in addition to the topographic variations. The "out-of-plane" orbital elements are not determined well by these data but, by the same token, these elements do not affect significantly the topographic interpretation. All the data — radar and optical — should be employed simultaneously to estimate the entire set of unknown parameters, and we have in fact followed this procedure: 8839 optical and radar observations of the inner planets were treated simultaneously to estimate by weighted least squares the values of 38 parameters including, in addition to those mentioned above, the orbital elements and radii of Mercury and Venus, the mass of Mercury, the earth-moon mass ratio, and eight parameters associated with the influence of phase effects on the optical observations of Mercury and Venus. General relativity was the underlying gravitational theory employed. The masses of Venus, the earth, Mars, and the outer planets were taken from independent determinations which were more accurate than could have been obtained from the set of data we employed. For similar reasons, the orbits of the moon and outer planets, and the motion of the radar site with respect to the earth's center of mass, were taken from other sources. The errors thereby introduced into our present results are quite negligible. In particular, the errors in the orbital positions and masses of the outer planets have only a second-order influence on the interpretation of the earth-Mars radar data. Effects of the propagation medium on the signal delay are substantially less than 1 μ sec for all Mars observations near opposition and hence are also negligible.

The residual obtained by subtracting the theoretical value for each earth-Mars time-delay measurement from the relevant observed value yields the altitude for the corresponding latitude and longitude of the subradar point observed. (To obtain the altitude from the delay residual, one multiplies by minus one-half the velocity of light, or -0.15 km/sec.) The results of reduction of the entire set of Mars data — 1967 and 1969 — are shown in Fig. 4, where the altitudes with respect to the mean surface are shown as a function of longitude for separate bands of latitude, centered at 3°N , 7°N , 11°N and 22°N .

The mean radius obtained for Mars was 3393 ± 8 km (three times the formal standard error), in excellent agreement with the result of 3394 ± 4 km obtained from Mariner IV. The formal standard error was multiplied by three to yield what is felt from experience to be a more reliable bound on the actual error in the radius determination. The estimate of the mean radius, in contrast to the topographical deductions, is highly correlated with the estimates of certain of Mars' orbital parameters, since the data extend over such a relatively short arc of the Martian orbit. For example, when only one month's 1969 data was included, the estimated radius was 3383 ± 8 km (formal standard error). As the arc over which data are collected is extended, the radius estimate obtained increases in reliability.

C. Interpretation

The striking similarities between the four topographic profiles measured at latitudes 3°N, 7°N, 12°N, and 22°N are not unexpected as the topographic autocorrelation function computed by Pettengill, *et al.*,¹ for 22°N showed a correlation coefficient of 0.5 between relative heights at points 15° apart. The normalized autocorrelation function computed for the topographic variation for 7°N latitude decreases to 0.5 at a longitude separation of 22°. That is, the Martian topographic variation, although large in magnitude, changes only slowly with latitude or longitude.

The correlation between the topographic and white-light luminance variations measured by de Vaucouleurs² at 6°N latitude were computed by the same method employed by Pettengill, *et al.*, in 1967, and again there appears to be no significant correlation (correlation coefficient -0.126 at 6°N; +0.068 at 22°N). More complete correlation of the data with white-light luminance measurements is performed in Sec. V after the data have been assembled in two-dimensional form.

III. RADAR CROSS SECTION

A. Observations

The radar cross section is defined as the effective target size of the planet based on an equivalent perfect isotropic scattering. The received echo power for a target of cross section A is

$$\left(\frac{P_T G_T L_T L_A}{4\pi R^2} \right) \times \left(\frac{A}{4\pi R^2} \right) \times (A_R L_R L_A) \quad , \quad (6)$$

where

P_T = transmitted power,

G_T = antenna gain,

L_T = transmitter waveguide attenuation,

R = distance to planet,

A = cross section,

A_R = antenna receiving aperture,

L_R = waveguide attenuation in receiver,

L_A = atmospheric attenuation,

which is compared with the receiver noise power

$$KT_s B_{eff} \quad , \quad (7)$$

where

K = Boltzmann's constant,

T_s = system temperature,

B_{eff} = effective receiver bandwidth.

A list of the values of these parameters is included in the Appendix. The atmospheric attenuation is included in an empirically determined elevation dependence of antenna gain and aperture during fine weather; however, an attempt was made to take out the increase in atmospheric attenuation brought about by poor weather. Since it is known that the receiver system temperature remains relatively constant with time, any change of atmosphere attenuation from L_A to $L_A(\Delta L_A)$ produces an increase of system temperature

$$\begin{aligned}\Delta t &\approx (1 - \Delta L_A) \times \text{the atmosphere temperature} \quad , \\ &\approx 300 \times (1 - \Delta L_A) \quad .\end{aligned}\tag{8}$$

Thus, the observed changes in system temperature at a given elevation can be used to estimate the added atmospheric attenuation brought about mainly by low-altitude water vapor.

The effective bandwidth is given by

$$B_{\text{eff}} = \int_{-\infty}^{+\infty} R_F(f) df / R_F(0) \quad ,\tag{9}$$

which in the CW case is summed over each frequency channel. Cross-section measurements obtained from the coded ranging observations are listed in Table I and plotted in Fig. 5, while those obtained from CW measurements are listed in Table II and plotted in Fig. 6.

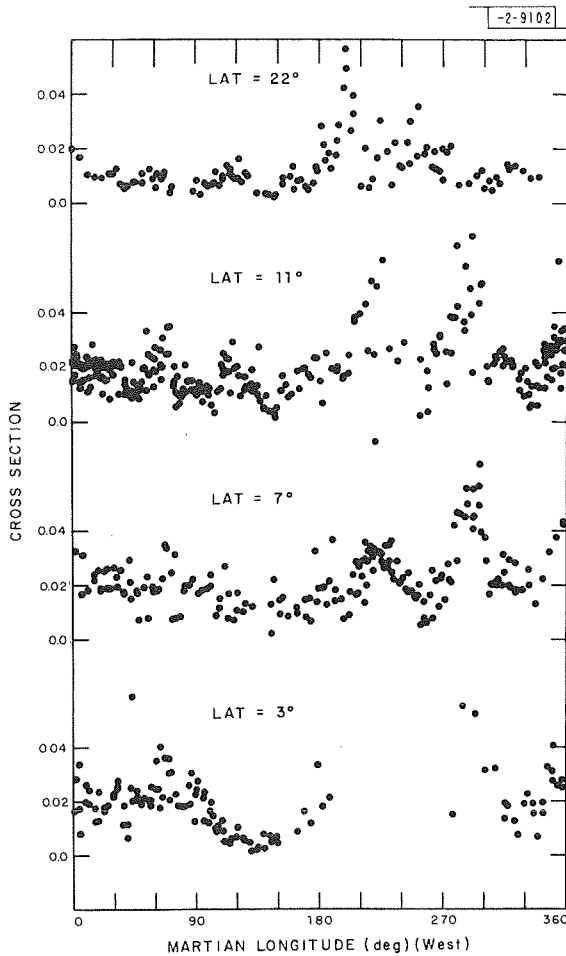


Fig. 5. Martian radar cross section inferred from phase-coded (ranging) measurements expressed as a fraction of the geometric area (πr^2). The echo power contributing to these cross-section estimates comes from only a small surface region surrounding the subradar point (see Sec. IV-B).

TABLE II

Tabulation of the data from CW transmissions. The cross section is listed as a percentage of the geometric area (πr^2). Also listed are the C value for the best fit, the rms slope in degrees derived from this C value (see Sec. IV-B), and the frequency offset from the ephemeris predicted value.

TABLE II

JULIAN DATE	HOURS	MIN	CROSS SECTION	C VALUE	SLOPE	FREQ	OFFSET HZ	LONGITUDE	LATITUDE
2440349.5	4	14	2.522	450	2.7		120	110.85	3.51
2440351.5	4	7	4.984	1800	1.4		150	91.13	3.68
2440351.5	4	27	3.128	1250	1.6		-60	95.94	3.68
2440351.5	4	47	2.213	800	2.0		90	100.80	3.68
2440351.5	5	7	2.199	450	2.7		150	105.66	3.68
2440354.5	3	20	6.928	200	4.1		-30	52.85	4.06
2440354.5	3	40	4.257	200	4.1		-120	57.60	4.06
2440354.5	3	59	4.368	1250	1.6		0	62.38	4.06
2440354.5	4	19	7.074	800	2.0		-30	67.25	4.06
2440354.5	4	39	4.961	800	2.0		0	72.11	4.06
2440356.5	2	58	5.487	200	4.1		60	29.85	4.40
2440356.5	3	17	5.091	200	4.1		-180	34.44	4.40
2440356.5	3	38	3.336	450	2.7		60	39.52	4.41
2440356.5	3	58	6.594	200	4.1		-30	44.39	4.41
2440356.5	4	17	6.476	200	4.1		0	49.07	4.41
2440358.5	3	36	3.003	450	2.7		-60	21.17	4.69
2440358.5	3	55	3.460	450	2.7		-60	25.76	4.69
2440361.5	2	22	1.161	800	2.0		-30	336.33	5.12
2440361.5	2	42	3.195	200	4.1		300	341.12	5.12
2440361.5	3	23	4.852	450	2.7		180	351.11	5.13
2440361.5	3	42	4.527	800	2.0		270	355.74	5.13
2440361.5	4	3	3.696	800	2.0		-90	.79	5.13
2440361.5	4	22	1.874	200	4.1		-90	5.63	5.13
2440363.5	2	42	3.460	450	2.7		30	323.53	5.50
2440363.5	3	3	2.586	450	2.7		-60	328.76	5.50
2440363.5	3	22	4.100	200	4.1		90	333.27	5.50
2440363.5	3	42	3.947	100	5.7		240	338.13	5.50
2440364.5	2	29	4.690	450	2.7		-60	311.45	5.68
2440364.5	2	47	4.130	800	2.0		0	315.84	5.68
2440364.5	3	7	3.707	450	2.7		-90	320.72	5.69
2440364.5	3	27	3.310	800	2.0		0	325.59	5.69
2440364.5	5	30	6.550	450	2.7		180	355.61	5.70
2440364.5	5	49	6.008	450	2.7		0	.22	5.71
2440364.5	6	7	4.096	100	5.7		-240	4.62	5.71
2440364.5	6	25	3.231	450	2.7		90	8.98	5.71
2440364.5	6	43	5.218	200	4.1		180	13.51	5.71
2440364.5	7	2	4.830	200	4.1		-60	18.00	5.71
2440364.5	7	22	4.956	200	4.1		90	22.90	5.72
2440364.5	7	42	4.955	200	4.1		-90	27.72	5.72
2440364.5	8	3	4.340	450	2.7		-120	32.93	5.72
2440364.5	8	22	4.773	100	5.7		-150	37.52	5.72
2440364.5	8	42	4.336	450	2.7		0	42.42	5.73
2440368.5	3	2	7.651	1800	1.4		90	284.06	6.43
2440368.5	3	22	6.543	1800	1.4		0	288.90	6.43
2440368.5	3	42	5.947	1800	1.4		90	293.78	6.43
2440368.5	4	2	6.474	1250	1.6		-60	298.65	6.43
2440368.5	4	22	3.942	450	2.7		-150	303.53	6.44
2440370.5	1	49	5.556	200	4.1		0	248.50	6.79
2440370.5	2	9	5.189	200	4.1		-120	253.39	6.79
2440370.5	2	28	3.543	100	5.7		-90	258.25	6.79
2440370.5	2	49	3.823	200	4.1		30	263.13	6.80
2440370.5	3	9	5.203	200	4.1		-120	268.00	6.80
2440370.5	3	33	3.531	800	2.0		90	273.86	6.80
2440370.5	4	6	7.496	1250	1.6		150	281.90	6.81
2440372.5	2	7	4.604	450	2.7		30	235.34	7.17
2440372.5	2	24	3.688	450	2.7		30	239.64	7.17
2440372.5	2	42	3.835	450	2.7		-150	244.03	7.18
2440375.5	2	23	3.443	800	2.0		180	212.89	7.75
2440375.5	2	40	3.025	800	2.0		90	217.04	7.76
2440375.5	2	58	3.965	800	2.0		90	221.45	7.76

TABLE II (Continued)

2440379.5	3	39	2.604	100	5.7	-240	106.15	8.54
2440379.5	3	57	2.733	100	5.7	240	200.52	8.54
2440379.5	4	15	3.829	1250	1.6	30	204.90	8.54
2440382.5	0	56	3.530	450	2.7	0	129.91	9.10
2440382.5	1	15	2.103	1250	1.6	-30	124.33	9.10
2440382.5	2	5	1.111	200	4.1	-60	146.72	9.11
2440382.5	2	39	1.979	2450	1.2	-30	155.01	9.08
2440382.5	2	56	2.055	200	4.1	90	159.15	9.08
2440382.5	3	13	2.019	800	2.0	210	163.30	9.08
2440382.5	3	30	4.328	450	2.7	30	167.44	9.09
2440382.5	3	47	3.060	450	2.7	30	171.58	9.09
2440382.5	4	4	3.132	450	2.7	90	175.74	9.09
2440382.5	4	39	2.581	800	2.0	60	184.08	9.09
2440382.5	4	55	3.089	450	2.7	-30	188.17	9.10
2440386.5	2	14	2.236	1800	1.4	-30	113.51	9.74
2440386.5	2	31	2.742	5000	.8	30	117.64	9.74
2440386.5	2	50	2.019	800	2.0	-30	122.27	9.74
2440391.5	2	52	3.368	200	4.1	180	78.51	10.57
2440391.5	3	9	2.838	800	2.0	-120	82.65	10.57
2440391.5	3	45	2.143	200	4.1	-150	81.33	10.58
2440393.5	0	43	2.920	200	4.1	0	28.93	10.77
2440393.5	1	1	1.128	1250	1.6	180	23.31	10.77
2440400.5	0	3	1.170	1250	1.6	0	316.67	11.52
2440400.5	0	21	1.367	1800	1.4	-180	321.10	11.53
2440400.5	0	39	1.384	800	2.0	0	325.50	11.53
2440400.5	0	57	2.580	800	2.0	60	329.79	11.53
2440400.5	1	15	2.527	450	2.7	120	324.35	11.53
2440400.5	1	42	2.957	800	2.0	90	340.80	11.53
2440400.5	1	60	3.759	450	2.7	-60	345.17	11.53

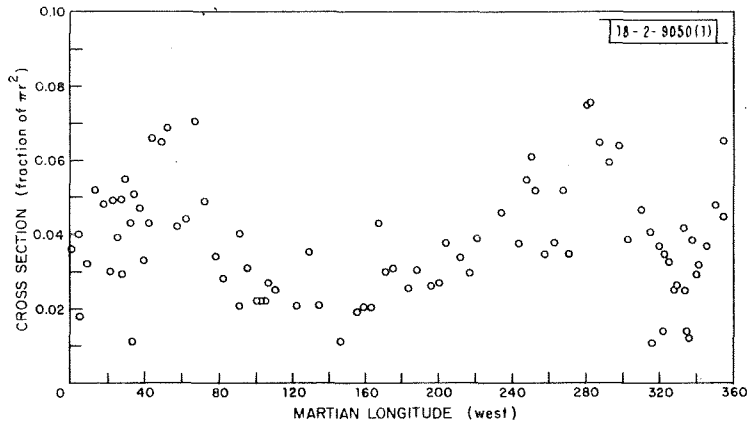


Fig. 6. Martian radar cross section inferred from CW echo spectra (bandwidth 4.8 kHz at 7840 MHz).

B. Interpretation

If the instrumental resolution functions do not exclude substantial echo power from the limbs of the planet, the cross section can be related to the dielectric constant of the surface provided the planet is homogenous (i. e., provided the planet is more or less uniformly rough and does not have, for example, a smooth region at the subradar point that is not compensated by other such smooth areas at small angles of incidence). The dielectric constant k , under the assumption of uniformity, is related to the total cross section ρ_o expressed as a fraction of the geometric disk area if conductivity and permeability effects are ignored by

$$k = \left[\frac{1 + (\rho_o)^{\frac{1}{2}}}{1 - (\rho_o)^{\frac{1}{2}}} \right]^2 \quad (10)$$

By using a wideband CW window, Pettengill, *et al.*,¹ measured the total cross section to be 0.0915 and corresponding dielectric constant of 3.5.

Owing to the small bandwidth window used in both CW and coded observation (4.8 kHz for CW measurements and ~ 1 kHz for phase-coded measurements) compared with the limb-to-limb Doppler spread of 23.5 kHz, the cross section measured is almost entirely due to the quasispecular component of the echo. This means that only regions close to the subradar point contribute to the echo power. The cross section is observed to change abruptly with latitude and longitude. These changes can be due to variations in local surface roughness and dielectric constant. It is now not possible to separate the two effects because changes in surface roughness in the subradar region will alter the "quasispecular" component of the echo and hence alter the measured cross section. However, measurement of the spectrum of the echo and delay profile can yield more information to aid in the understanding of the cross-section changes. This is discussed in Sec. IV-B.

IV. RADAR SPECTRUM

A. Observations

Analysis of the echo from CW (continuous-wave, i. e., monochromatic) transmissions used the same one-bit autocorrelation technique employed in 1967. The sampling frequency was

reduced, however, providing a window only 4.8 kHz wide but yielding 120-Hz resolution in contrast to the 1-kHz resolution obtained in 1967. The higher resolution is necessary to resolve the narrow-band quasispecular echo. The expected CW echo power spectral density $P(f)$ is proportional to

$$\int \frac{S(\theta)}{\cos \theta} R_F(f' - f) dy dz \quad (11)$$

The frequency resolution function R_F for those measurements resembles that shown in Fig. 1 for the time-delay measurements, the main difference being in scale: R_F has an approximately Gaussian shape with half-power width equal to 120 Hz or about 0.5° in longitude on Mars near the subradar point. In addition, however, the resolution in longitude was smeared from 0.5° half-width to about 2° half-width as the data were averaged over the receive period (~ 10 minutes) during which Mars rotates by about 2° . Attempts to analyze the data on a shorter period were not fruitful owing to the poor signal-to-noise ratio obtained on shorter integration periods and the lack of evidence of much variation of the spectrum within one receive period. A three-parameter fit, again using Hagfors' scattering law [Eq. (5)] and using a discrete set of trial values to locate those yielding the minimum sum of squares of residuals, was made to each spectrum. The three parameters adjusted to this fit were C , the radar cross section, and the frequency offset of the spectrum from the ephemeris predicted value.

Results of the CW measurements are given in Table II. In computing the radar cross section, the data were corrected for atmospheric absorption in the same manner as described in Sec. III.

B. Interpretation

Hagfors³ has worked out a theory of scattering from slowly undulating surfaces that is observed to be in good agreement with experimental data provided that some minor modifications are made to the theory. Hagfors has shown that for an exponential distribution of surface slopes the scattering function $S(\theta)$ is given by

$$S(\theta) \propto (\cos^4 \theta + C \sin^2 \theta)^{-3/2} \quad (12)$$

where C is a parameter related to the root-mean-square surface slope (rms slope $\approx C^{-1/2}$ radians). However, the theory assumes a perfectly homogeneous surface. If for example, the subradar region is tilted, or has a significantly different roughness or dielectric constant from the average properties of the planet, then the echo will be significantly affected especially in the case of Mars where the scattering function is sharply peaked at $\theta = 0$. The observed spectra do approximate Eq. (11) with Hagfors' scattering law provided that an allowance is made for a frequency offset from the ephemeris predicted "zero Doppler shift." An example of a spectrum with best fit is shown in Fig. 7. This frequency offset is interpreted as the effect of a tilted subradar region. A tilt in the subradar region effectively displaces the specular point ($\theta = 0$) producing a frequency shift Δf of

$$\Delta f = \frac{2f_0}{c} \frac{dr(t)}{dt} \quad (13)$$

where f_0 is the radar center frequency and c is the velocity of propagation. $r(t)$ is the distance of the subradar point from the center of mass of Mars which is a function of time t owing to the

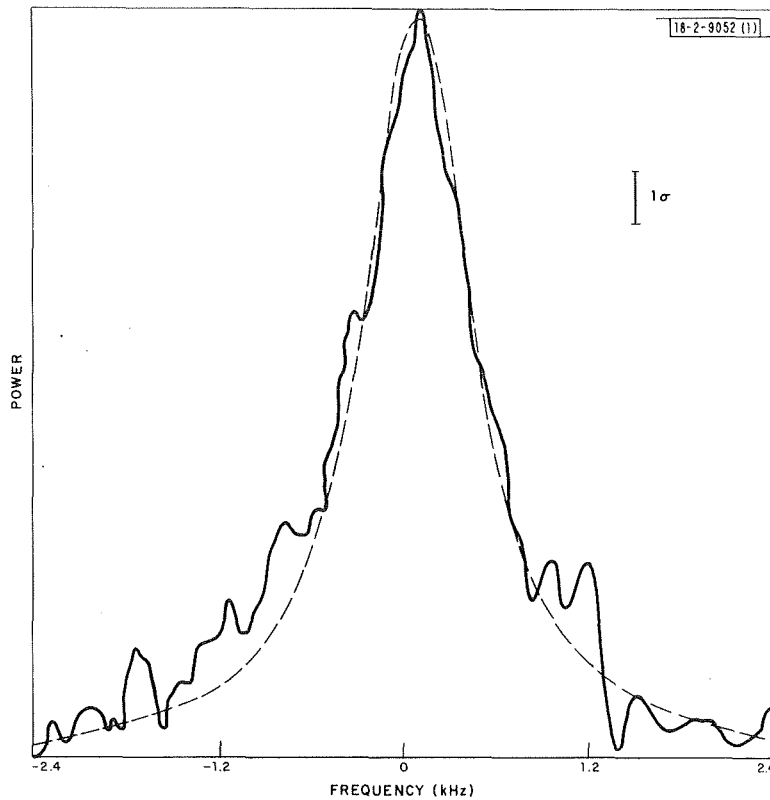


Fig. 7. Example of measured spectral power density of echo from continuous-wave (monochromatic) transmission, with best-fitting theoretical spectrum (dashed curve) based on Hagfors' scattering model. This observation was made at 3h 33m on 29 May 1969. The best-fit spectrum has a value of $C = 800$ and a frequency offset of 90 Hz.

planet's spin angular velocity Ω . $r(t)$ can be expanded into a constant plus the topographic height h so that

$$\Delta f = \frac{2f_o \Omega}{c} \frac{dh}{dL}, \quad (14)$$

where L denotes longitude.

The variation of height with longitude has been derived from the ranging measurements described in Sec. II. After fitting a smooth curve through the ranging data (see Sec. V), it can be differentiated with respect to longitude to derive a frequency offset which then can be compared with the measured frequency offset. Figure 8 shows the measured frequency offsets and those from Eq. (10). The agreement is poor except in certain cases (e. g., Syrtis Major region $\sim 275^\circ W$) probably because the resolution of the ranging measurements is about 4° in longitude (after least-square fitting a smooth curve) compared with 2° or less for the CW measurements. Also, the frequency offset measurements have one-sigma errors of 100 Hz in the cases of weak signal.

If it is assumed that the frequency offsets are produced by topographic structure unresolved in the coded measurements, a measure of the slopes of this structure can be derived from the histogram plot shown in Fig. 9. From such a small sample, it is not possible to draw any real

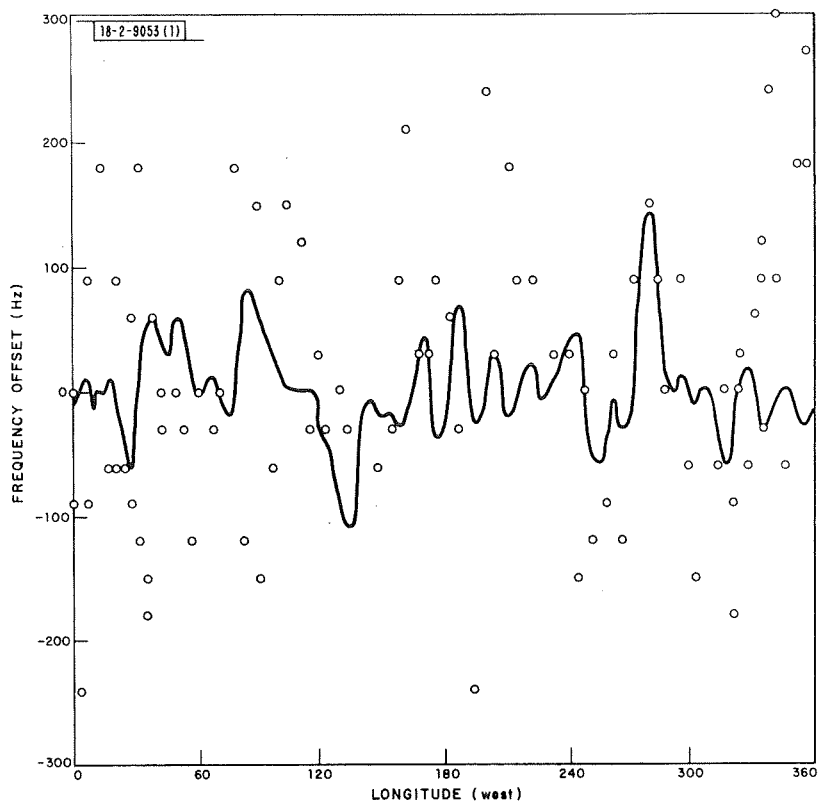


Fig. 8. Frequency offset derived from differential topography (smooth curve) and measured frequency offset of CW echo as a function of Martian longitude.

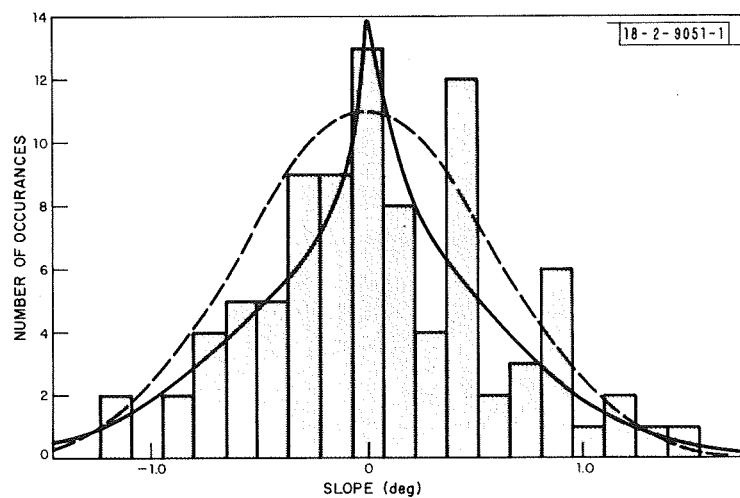


Fig. 9. Histogram of equivalent slope from frequency offset of CW measurements compared with a Gaussian with sigma of 0.6° , and an exponential with sigma of 0.5° .

conclusions about the functional form of the distribution as it can be fitted almost equally well with Gaussian and exponential functions. However, the rms value of the slope clearly can be taken as about 0.5° .

Since the CW spectra are observed to have a shape that is very well fitted by computed spectra using the Hagfors scattering law, it is assumed that the corresponding C value that produces the best fit represents a measure of the surface slopes in the region around the sub-radar point. These slopes must have a scale size less than 0.5° — otherwise, they would be resolved and appear as spectral features. Figure 10 shows the root-mean-square slope of the subradar region for a longitude strip centered on about 5°N latitude. The figure also shows the rms slope as derived from the best fit C values obtained from the ranging measurements. The agreement is very poor for a number of reasons. First, the regions sampled in the two types of measurement are somewhat different. The CW measurements do not have any restriction in latitude other than that self-imposed by the scattering law. Secondly, the spectral width and delay profiles are highly differentiated quantities varying rapidly with latitude and longitude so that the interpolation used on the ranging data (see Sec. V-A) may not give valid estimates of the C parameter at latitude and longitude points not sampled. Last, but most important, the noise in the estimate of the C parameter is large, particularly in the delay profile fitting when

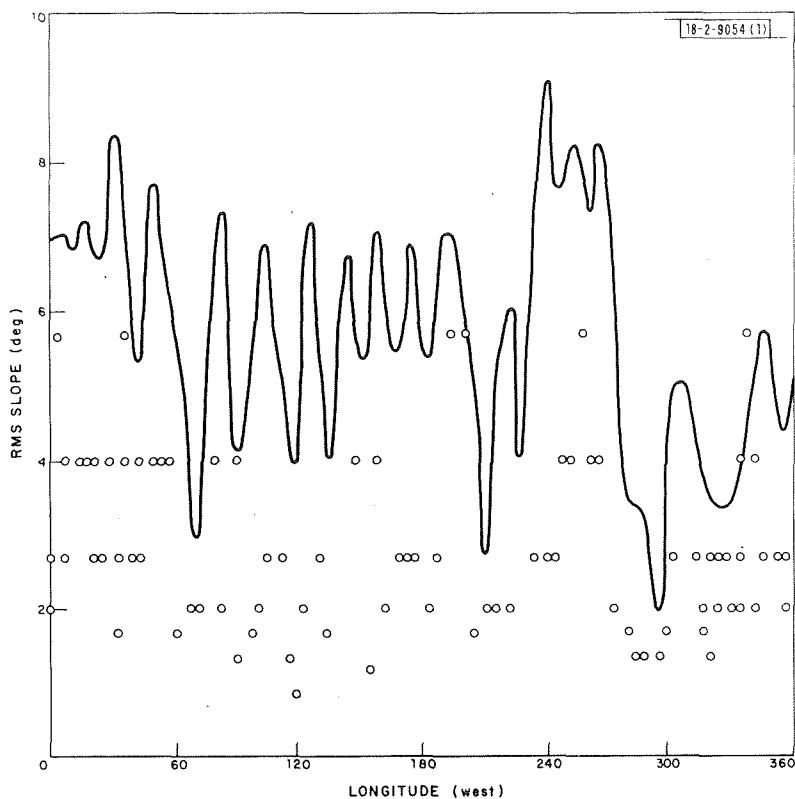


Fig. 10. Root-mean-square Martian surface slopes inferred from CW echo spectra. Smooth curve is rms slope from C values obtained in ranging measurements at 6°N .

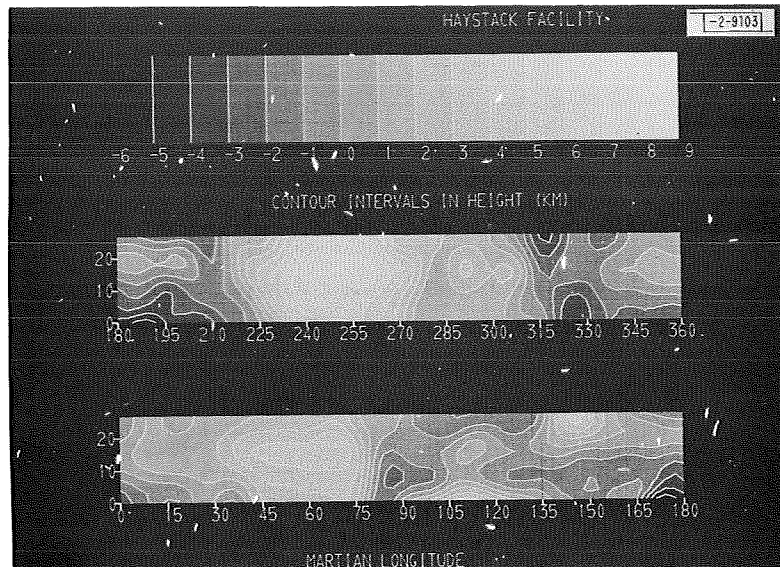


Fig.11. Contour map of height. Longitude runs eastward in two sections, and latitude runs from the equator to 27° N.

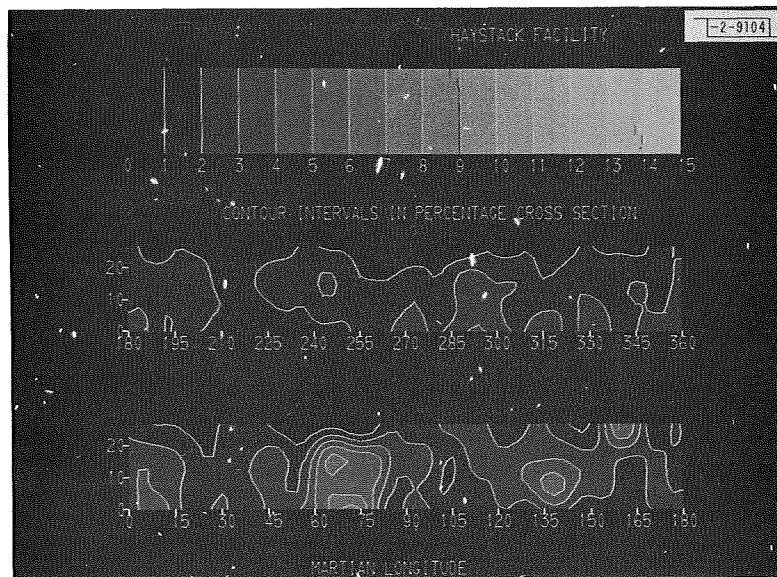


Fig.12. Contour map of cross section.

V. MARTIAN TOPOGRAPHY AND SURFACE ROUGHNESS

A. Contour Maps

The ranging data from 1967 and 1969 have been combined into contour maps of surface height, quasispecular cross section, and roughness (from C parameter value). In order to make a continuous representation of the data over all longitudes from the equator to 27°N, it was necessary to use an interpolation procedure. The interpolation was achieved by fitting the data points to a two-dimensional Fourier series and adjusting the series to fit the data in a least-squares sense. The Fourier series selected was one commensurate with the resolution in latitude and longitude. In longitude the series contained sine and cosine terms with spatial periods ranging from 360° down to 15°. The Fourier transform of the delay resolution function shown in Fig. 1 is approximately a triangular function with the 3-dB point at a spatial period of 10°. Thus, the series contains spatial frequencies well within the bandpass of the resolution but does not contain spatial frequencies that are outside the band or sufficiently far down in response that they "blow up" with the noise. In latitude the series contains spatial frequencies with periods from 54° to 13.5°.

The details of the mathematical methods used to find the coefficients of the Fourier series are given in Appendix B. The minimizing of the sum of the residuals squared produces an interpolation technique that is optimum in the sense that the value of any point is the maximum likelihood estimate.

Figures 11 through 13 show contour maps of height, cross section, and roughness. Longitude runs eastward and latitude runs from the equator to 27°N. The contour map of roughness should not be used in a quantitative manner with any high degree of confidence as the one-sigma error especially in low signal areas is of the order of a degree. However, the tendency for areas of high cross section to be smooth should be noted as it is in good agreement with the independent measurement technique of surface roughness obtained from the CW measurements described in Sec. IV-B.

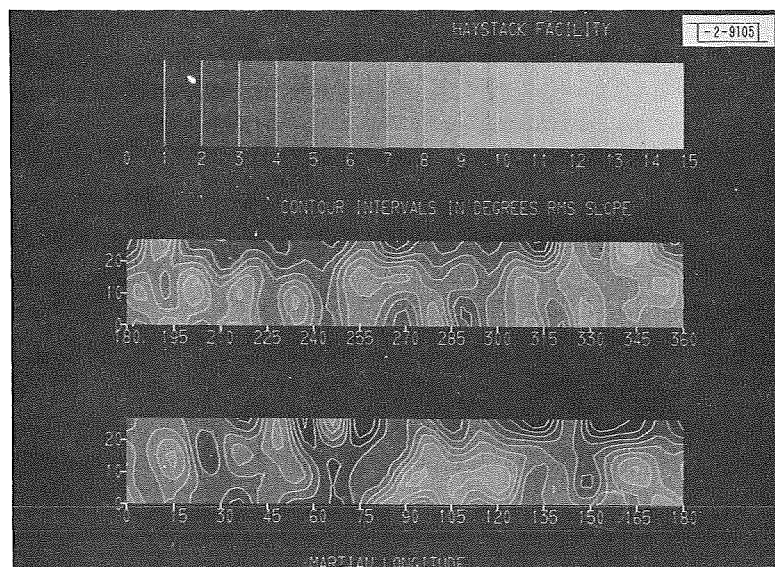


Fig.13. Contour map of roughness or rms slope obtained from the best-fit C parameter values (Hagfors' scattering law).

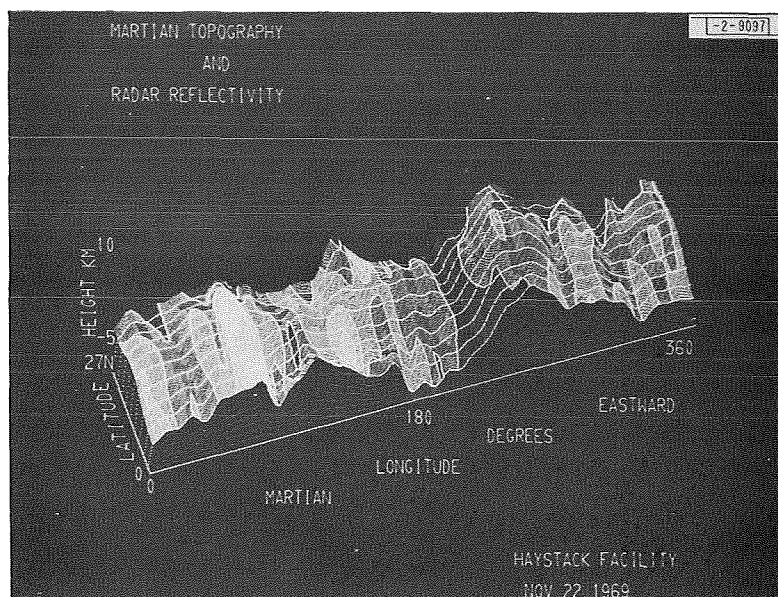


Fig. 14. "Modulated" ruled surface map. Contours of radar cross section superimposed on a topographical ruled surface.

Figure 14 is an attempt to present height and cross section simultaneously using a "modulated" ruled surface map. The presentation shows clearly the high cross section and steep slope (dropping to east) of Syrtis Major (85°E) and the high cross section on the eastern slope of Elysium (150°E, 20°N). Also see Frontispiece.

B. Surface Roughness as a Function of Scale Size

The surface roughness is a rather poorly defined term which is usually given in terms of root-mean-square slope. Its purpose is to provide some statistical information about the surface height distribution as it is obviously impossible to know the topography down to a scale of a wavelength and less. If the height were perfectly known over the surface, then the slope at each point could be obtained from the spatial derivative. However, if the height is first filtered or averaged by a filter with a spatial half-width S before the slope is determined, then the distribution of these "filtered slopes" has a scale size S .

Very small scale slopes – those with scale smaller than a wavelength (3.8 cm) – contribute mainly to the diffuse component of the radar echo. That is, they produce a scattering that is very insensitive to the angle of incidence θ . Pettengill, *et al.*,¹ measured the diffuse component of the cross section to be $0.1 \pi r^2$.

It is extremely difficult to test any specific scattering model for the diffuse component without measurements of the depolarized component of the echo and measurements of the angular dependence of the scattering. Owing to the lack of a scattering model, it is not possible to convert the observed diffuse cross section into an rms slope that has any physical meaning.

Slopes on a scale of a wavelength and larger determine the parameter C in the Hagfors scattering law. The average value of $C = 300$ (from CW measurements) corresponds to an rms slope of 3.3°. Larger scale slopes on the order of the CW resolution ($\sim 2^\circ$ in longitude or 120 km) are probably responsible for the offset of the CW spectrum which was observed to have an rms

value equivalent to 0.5° . On a still larger scale, that of the ranging measurements ($\sim 3^\circ$ in longitude or 180 km), the rms slope can be obtained directly from the derivative of the height. An rms value of 0.3° was obtained by differentiation of the height in Fig. 11.

Combining these three measures of rms slope, the average surface properties of Mars can be represented by Fig. 15.

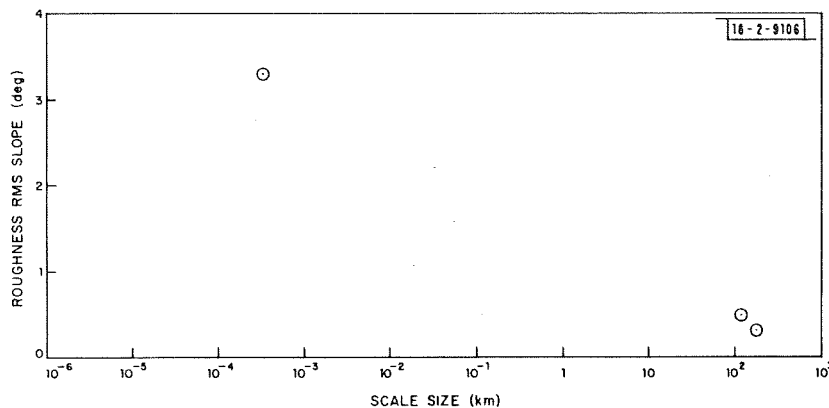


Fig. 15. Average surface slopes as a function of scale size.

An alternate method of describing the surface roughness is in terms of the spectrum of height. Direct Fourier transform of the topography yields the Fourier components for each spatial harmonic up to the spatial frequency cutoff of the measurements. Figure 16 shows the square root of the height spectrum up to the 10th spatial harmonic. This figure can be directly compared with similar figures by Pettengill, *et al.*¹ Higher harmonics can be obtained by Fourier transformation of the derivative of topography as obtained from the CW frequency offset measurements, using the transform relation

$$\frac{dx(t)}{dt} \leftrightarrow i\omega x(\omega) \quad (15)$$

to correct for the filtering produced by differentiation. Figure 17 shows spatial harmonics of height up to the 100th spatial harmonic. Information about higher spatial harmonics is contained in the spectral width and delay profile measurements to the extent that the C parameter of Hagfors' scattering function is a measure of the height spectrum integrated over spatial harmonics with periods approximately ranging from a wavelength to 100 km. An exponential correlation function

$$\rho(r) = \exp[-r/d] \quad (16)$$

was assumed by Hagfors³ and Hagfors⁴ in the derivation of the scattering function of Eq. (5). The height power spectrum $H(\omega)$ is given by

$$H(\omega) = \int_0^\infty \langle h^2 \rangle \exp[-r/d] r J_0(r\omega) dr \quad (17)$$

$$= \frac{\langle h^2 \rangle d^2}{(1 + d^2 \omega^2)^{3/2}} \quad (18)$$

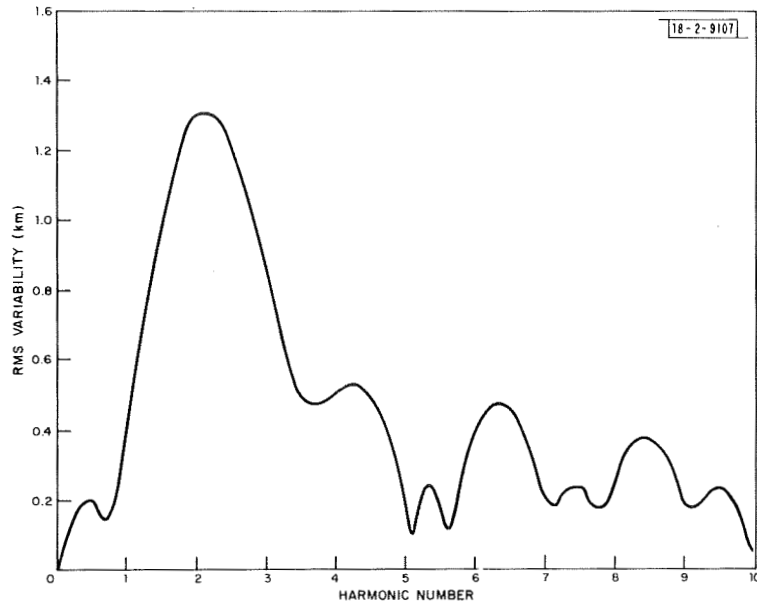


Fig. 16. Square root of height spectrum as a function of spatial harmonic number.

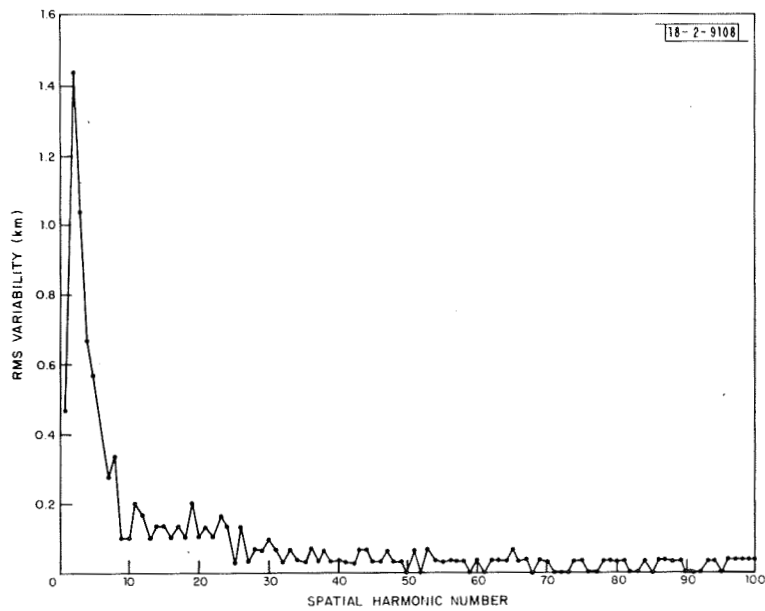


Fig. 17. Spatial harmonics of height as obtained from CW frequency offset measurements.

where d is the correlation length, ω is the spatial frequency, and $\langle h^2 \rangle$ is the mean square height. The correlation length d is related to the C parameter by

$$C^{-\frac{1}{2}} = \frac{2(2\pi/\lambda) \langle h^2 \rangle}{d}, \quad (19)$$

and the root mean square slope is $C^{-\frac{1}{2}}$ on a scale Δ where

$$\Delta \cong \frac{\lambda C^{\frac{1}{2}}}{4\pi}. \quad (20)$$

The scale size Δ is essentially fixed by the "filtering action" of the integral (4-24) of Hagfors.⁴

VI. CORRELATION OF RADAR MEASUREMENTS WITH OTHER DATA

A. Correlation with Ground-Based Optical Measurements

The radar measurements of topography, cross section, and roughness in the Fourier series interpolated form have been correlated with the photometric measurements (linearly interpolated) of deVaucouleurs.² The method used is similar to that used by Pettengill, *et al.*¹ Owing to the relatively small latitude range covered in the radar measurements, the two-dimensional correlation function was explored in only one dimension. The correlation function $\varphi_{ij}(\ell)$ is defined as

$$\varphi_{ij}(\ell) = \frac{\int \int f_i(\ell', x) f_j(\ell' + \ell, x) d\ell' dx}{\left(\int \int f_i^2(\ell', x) d\ell' dx \int \int f_j^2(\ell', x) d\ell' dx \right)^{\frac{1}{2}}}, \quad (21)$$

where $f_i(\ell, x)$ is the function of longitude ℓ and latitude x . $i = 1, 2, 3, 4$ correspond to cross section, topography, relative luminance, and roughness (in rms slope), respectively. The functions have been normalized to zero mean before correlation. Figures 18 and 19 show the auto- and cross-correlation functions in a form that can be compared directly with those of Pettengill, *et al.*¹ Figure 20 shows a contour plot of the luminance data of deVaucouleurs.² A linear interpolation was applied to obtain these contours as deVaucouleurs gives equally spaced data points every 9° in longitude and 7° in latitude.

The autocorrelation of topography shows a correlation of 0.5 for points 18° apart. Cross section has 50 percent correlation at points 10° apart and roughness has 50 percent correlation at points 8° apart. The two-dimensional Fourier series fitting process produces a half-power correlation half-width of 4° on noise alone which, when taken out in a sum of squares manner, yields corrected half-widths of 17° , 9° , and 7° , respectively. These correlation widths show that topography is predominantly a slowly varying global quantity, while cross section and roughness are both more highly differentiated functions not fully resolved by the radar measurements.

Cross correlations show clearly that topography is not correlated with cross section [$\varphi_{1,2}(0) = 0.04$] or luminance [$\varphi_{2,3}(0) = 0.0$]. Topography is probably not correlated with roughness [$\varphi_{2,4}(0) = -0.26$] either as $|\varphi_{2,4}(\ell)|$ is not a maximum at $\ell = 0$. On the other hand, cross section is anticorrelated with luminance [$\varphi_{1,3}(0) = -0.48$], making a stronger case for the suggestion made by Pettengill, *et al.*,¹ that optically dark regions produce a stronger quasispecular radar echo. Also, cross section is anticorrelated with roughness [$\varphi_{1,4}(0) = -0.38$], suggesting that regions of high cross section are smoother on the average than their environs.

While topography is not directly correlated with cross section, there is a tendency of slopes rising to the West to be associated with high cross section. This suggestion is borne out by the

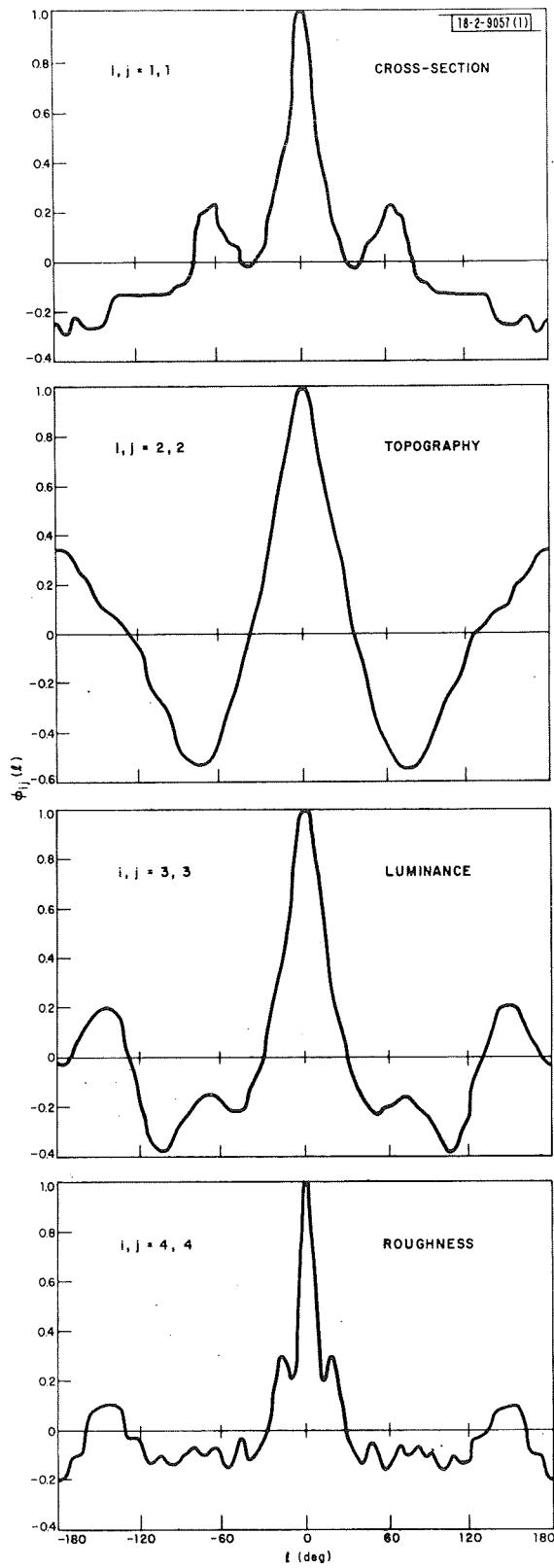
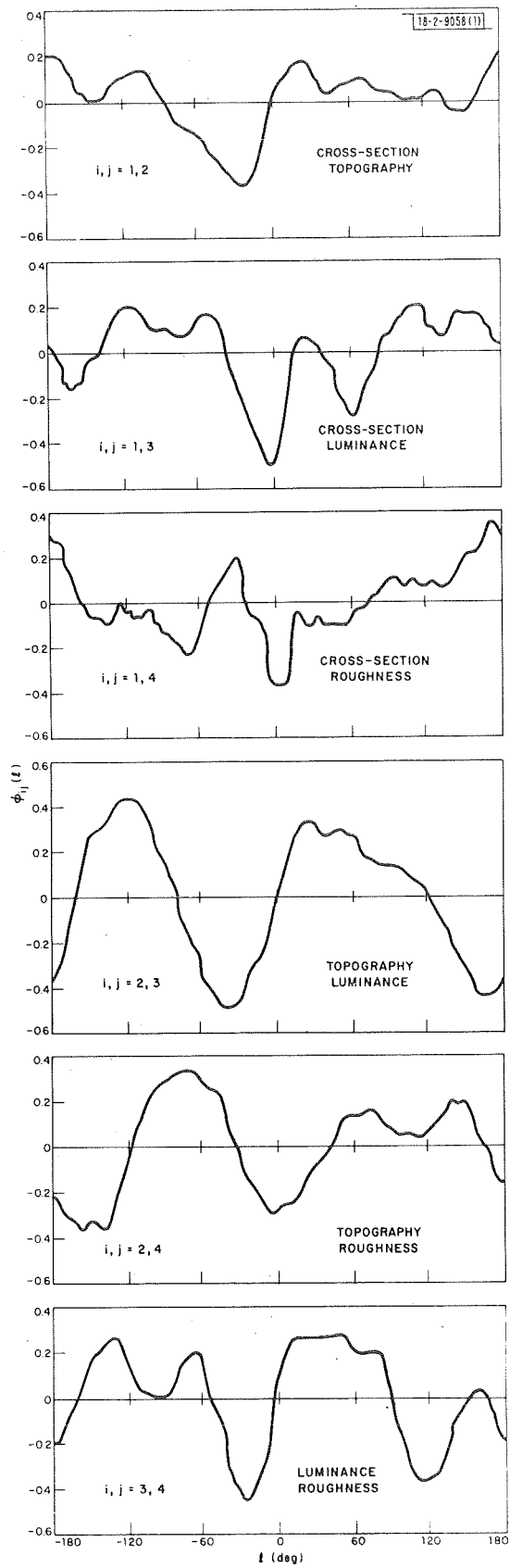


Fig. 18. Autocorrelation of the four continuous representations: Martian radar cross section, surface topography, luminance, and roughness.

Fig. 19. Cross correlations of the four continuous representations: Index 1 = cross section, 2 = topography, 3 = luminance, and 4 = roughness.



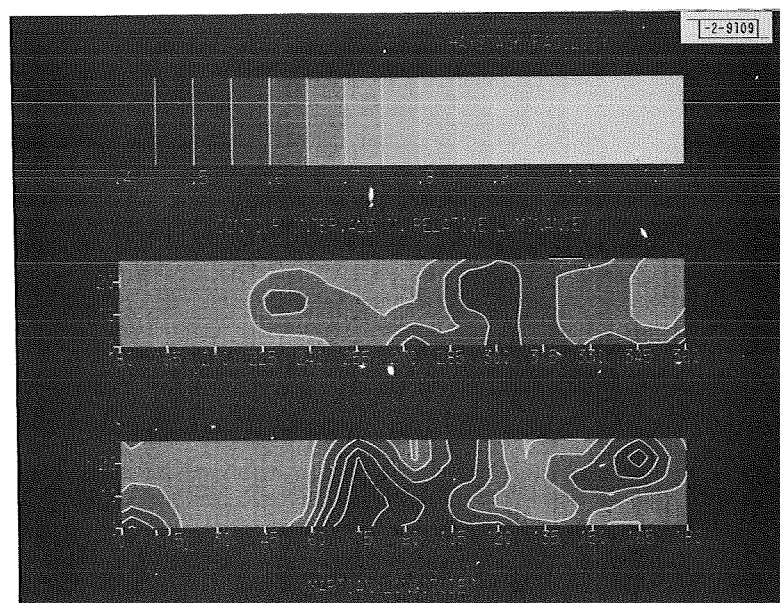


Fig. 20. Contour plot of relative luminance of Martian surface from deVaucouleurs.² Linear interpolation was used to obtain contours.

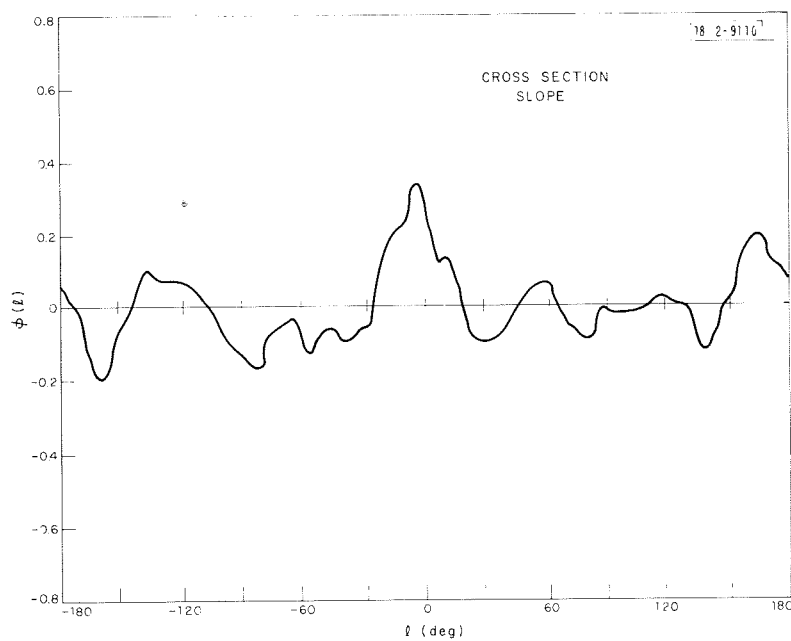


Fig. 21. Cross correlation of cross section with the derivative of topography with respect to longitude.

large positive derivative of $\phi_{1,2}(\ell)$ at $\ell = 0$. However, this result may be dominated by Syrtis Major and Trivium Charontis, the only large cross section regions in the region mapped, both of which rise to the West. Figure 24 shows the cross correlation of radar cross section with the derivative (with respect to longitude) of topography. The figure shows a correlation of 0.3 between cross section and slopes rising to the West. A similar correlation carried out on the 1967 radar data alone shows a correlation of only 0.14.

B. Correlation with Mariner Results

The radio occultation measurements of the Martian atmosphere recently reported by Kliore, *et al.*,⁵ indicate a variation in topography of about 5 to 6 kilometers over the four points of measurement. This is consistent with the radar measurements of topography. Unfortunately, only

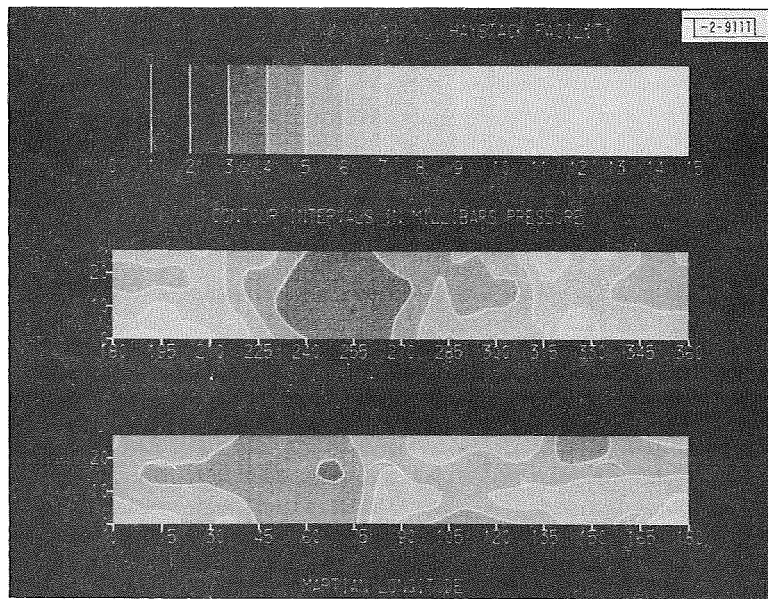


Fig. 22. Contours of atmospheric pressure at surface of Mars obtained from topography using Mariner 6 entry at 4°N, 355°E as a calibration pressure of 6.6 millibars.

one Mariner entry or exit occurred within a latitude range measured by radar. This was the Mariner 6 entry at 4°N and 355°E for which a pressure of 6.6 millibars was measured. Using this point as a calibration, and a pressure scale height of 12.7 km, the radar topography contours can be converted to pressure contours shown in Fig. 22.

VII. CONCLUSION

The analysis of the radar measurements of Mars contained in this report may shed more light on the nature of the Martian surface. By correlating the radar results with optical observations, it is clear that the optically dark areas have a significantly higher intrinsic radar reflectivity and are somewhat smoother on the scale of the 3.8-cm radar wavelength than other regions. Also, there is a tendency for optically dark areas to lie on the eastern slopes of the radar measured topographic highlands at least in the radar probed strip extending from the equator to 22°N. These results are consistent with a model of dark areas being bare rock producing a high radar reflectivity and other areas being dust covered surfaces of low radar reflectivity. The tendency

of bare rock areas to be on the eastern slopes of Martian highlands may be due to a prevailing wind pattern on Mars.

Conclusions arising from the radar study that might be considered most important for the landing of a spacecraft on Mars are:

- Mean small scale surface slopes are sufficiently small that there is a high probability that a spacecraft would rest on the surface oriented to within a few degrees of the zenith.
- Martian highlands have an atmospheric pressure of about 3 millibars compared with about 9 millibars for the lowlands.

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The contributions of all members of Group 21, Surveillance Techniques, which operates the Haystack Facility under the leadership of P. B. Sebring, are gratefully acknowledged, as is also the support of the U. S. Air Force in the operation of this facility.

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APPENDIX A

RADAR SYSTEM

I. PERFORMANCE PARAMETERS

The basic Haystack performance parameters for 1967 and 1969 are given in Table A-1. The improvement in antenna performance from 1967 to 1969 was the result of a readjustment of the parabolic surface.

TABLE A-1 HAYSTACK RADAR PARAMETERS APPLICABLE TO OBSERVATIONS OF MARS IN 1967 AND 1969		
	1967	1969
Frequency	7840 MHz	7840 MHz
Wavelength	3.824 cm	3.824 cm
Antenna Diameter	120 ft	120 ft
Antenna Gain (G_T)	65.7 dB	66.1 dB
Antenna Effective Area (A_R) (includes waveguide attenuation L_R)	26.35 dB $> m^2$	26.7 dB $> m^2$
Beamwidth	$\sim 0.07^\circ$	$\sim 0.07^\circ$
Average Power (P_T)	150 – 350 kW	150 – 350 kW
Transmit Polarization	Right circular	Right circular
Transmitter Waveguide Losses (L_T)	0.5 dB	0.5 dB
Receiver	Single maser	Dual maser
Receive Polarization	Left circular	Left and right circular
System Temperature	$\sim 65^\circ$	$\sim 50^\circ$
Data Processing Computer	CDC-3300	CDC-3300
Station Standard	Hydrogen maser (5 parts in 10^{12} stability)	Hydrogen maser (5 parts in 10^{12} stability)

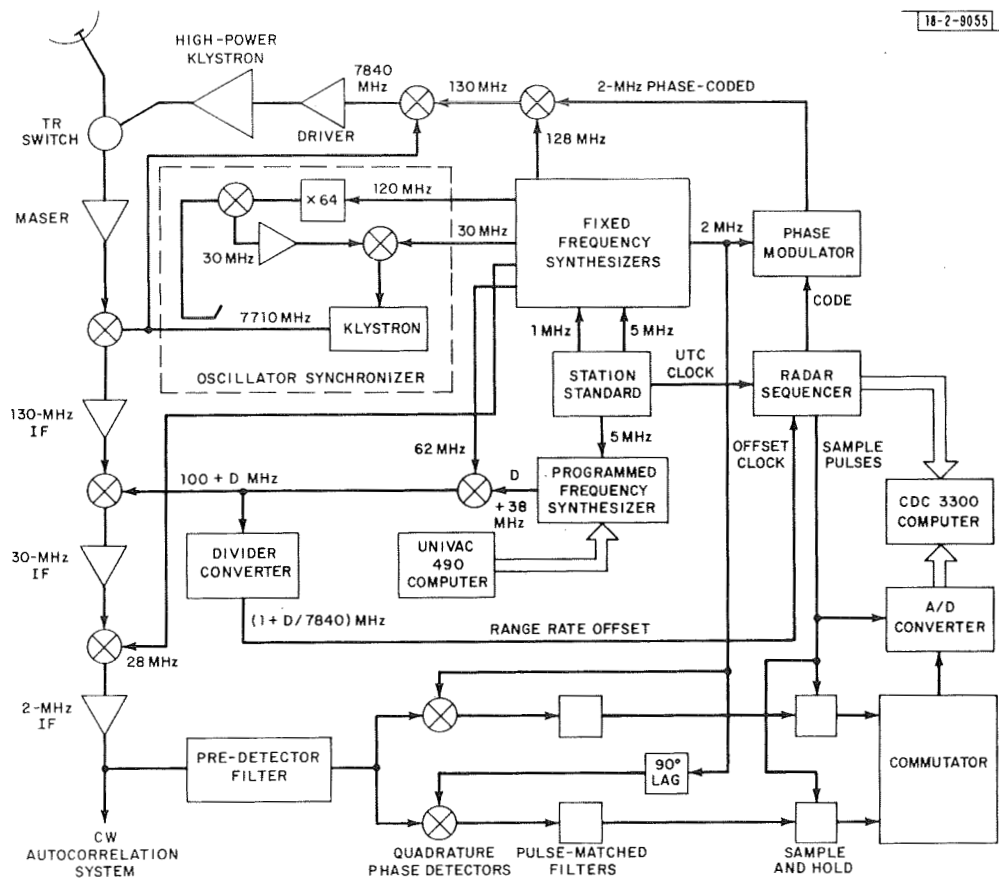


Fig. A-1. Block diagram of radar system used for observations of Mars.

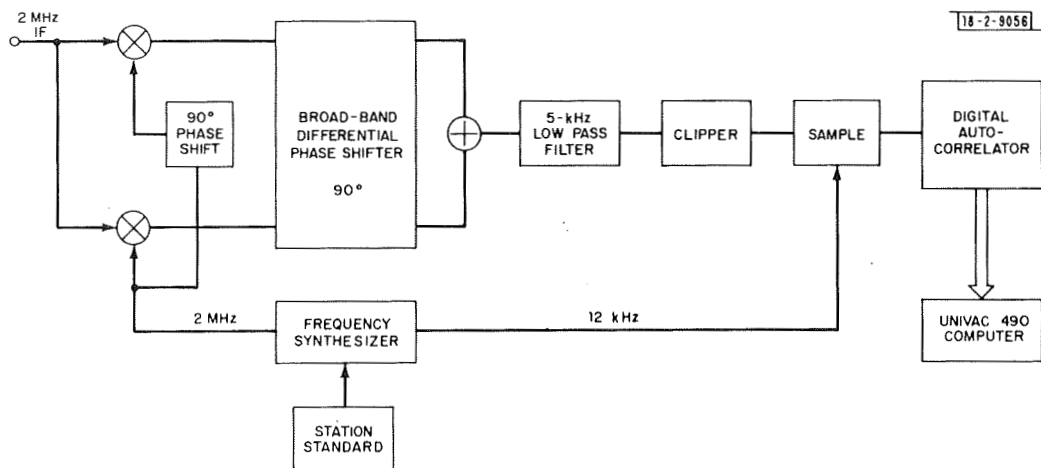


Fig. A-2. Block diagram of frequency conversion system for high frequency resolution of CW echoes in 1969.

II. RADIO-FREQUENCY EQUIPMENT

The radio-frequency hardware configuration for ranging measurement used in 1969 is shown in Fig. A-1. The system is similar to that used by Pettengill, et al., in 1967. Figure A-2 shows the single-sideband conversion system used to make high-resolution CW measurements. The system used in 1967 was not suited to high frequency resolution and had many "free running" local oscillators.

III. MODE PARAMETERS

The ranging measurements (excluding certain test modes) were made using code, sampling, and filter parameters.

Number of code elements	15
Number of code elements processed	8 (6 in 1967)
Baud length	60 μ sec
Sample period	30 μ sec
Signal code	4-3-0
Predetection filter	2 MHz center, 110 kHz bandwidth
Pulse matched filter	60 μ sec
Instrumental delay	75 μ sec (test pulse in range box 3.5)

Some observations were made with longer baud lengths to ensure that no range ambiguity was present.

The CW measurements made in 1969 used the following parameters:

Sampling frequency	12 kHz
Window width analyzed	4.8 kHz
Spectral resolution	120 Hz

APPENDIX B

MAXIMUM LIKELIHOOD PARAMETER ESTIMATION THEORY

I. MAXIMUM LIKELIHOOD ESTIMATE

If measurements are made of a physical quantity, it can be assumed in many cases that the measurement differs from the physical quantity by a random error or noise. Let the i^{th} measured data point be d_i of the physical quantity S_i . Then

$$d_i = S_i + n_i \quad ,$$

where n_i is the noise in the i^{th} measurement. Or if we choose to represent all data points by the vector $\vec{d}$ (with as many dimensions as data points),

$$\vec{d} = \vec{S} + \vec{n} \quad .$$

In most cases (for example, radar delay measurement) the noise has Gaussian statistics. Each noise component is independent of the others. A meaningful criteria in data analysis is to maximize the probability that the estimates $\vec{S}$ of the physical quantity equals that actual quantity $\vec{S}_0$ given that the data $\vec{d}$ are measured, i.e.,

$$\text{Maximize Prob}(\vec{S} = \vec{S}_0 | \vec{d})$$

by Bayes' rule

$$\text{Prob}(\vec{S} = \vec{S}_0 | \vec{d}) = \frac{\text{Prob}(\vec{d} | \vec{S} = \vec{S}_0) \text{Prob}(\vec{S} = \vec{S}_0)}{\text{Prob}(\vec{d})} \quad .$$

Now $\text{Prob}(\vec{d})$ is independent of our choice of $\vec{S}$ and $\text{Prob}(\vec{S} = \vec{S}_0)$ might as well be a constant given that we have no a priori knowledge of $\vec{S}_0$. Thus, maximizing

$$\text{Prob}(\vec{d} | \vec{S} = \vec{S}_0)$$

will have the same effect. If the noise is Gaussian, the probability density $p(\vec{n})$ is given by

$$\begin{aligned} p(\vec{n}) &\propto \prod_i \exp[-n_i^2/2\sigma_i^2] \\ &\propto \exp\left[-\sum_i n_i^2/2\sigma_i^2\right] \end{aligned}$$

so that

$$\text{Prob}(\vec{d} | \vec{S} = \vec{S}_0) \propto \exp\left[-\sum (d_i - S_i)^2/2\sigma_i^2\right] dd_1 dd_2 \dots dd_I \quad ,$$

which is clearly maximized by choosing $\vec{S}$, to minimize

$$\sum_{i=1}^I \frac{(d_i - S_i)^2}{2\sigma_i^2} \quad .$$

That is, a "weighted least-squares fit" is equivalent to a maximum likelihood estimate in the case of Gaussian error statistics with zero means.

II. TWO-DIMENSIONAL LEAST-SQUARES FITTING

Let $f(x, y)$ be a real function of two variables x and y . Assume that f can be first expanded in x , i. e.,

$$f(x, y) = \sum_{k=1}^N A_K(y) \Psi_K(x) \quad ,$$

where $\Psi_K(x)$ is an element of a set of functions of x . For example, $\Psi_K(x)$ could be one trigonometric function out of a Fourier series. Now, assume that each $A_K(y)$ can be expanded as a series,

$$A_K(y) = \sum_{\ell=1}^L B_{\ell} \Theta_{\ell}(y) \quad ,$$

where $\Theta_{\ell}(y)$ is an element of a set of functions. Combining the two equations above,

$$f(x, y) = \sum_{k=1}^N \sum_{\ell=1}^L A_K B_{\ell} \Psi_K(x) \Theta_{\ell}(y) \quad .$$

In order to make $f(x, y)$ the "best" function in a least-squares sense, one requires that

$$\sum_{i=1}^I [f(x_i, y_i) - d_i(x_i, y_i)]^2 = \Delta$$

be a minimum. In general, this can be done by solving the set of equations produced by setting the partial derivative of Δ with respect to A and B equal to zero. However, this procedure leads to a computationally difficult problem of solving for a large number of unknowns by a matrix inversion process. A simpler method is to first quantize y in units Δy and consider all data points such that

$$(j-1) \Delta y < y_i \leq j \Delta y$$

for each $j = 1, 2, \dots, J$. For each j find

$$f_j(x) = \sum_{K=1}^N A_K(j) \Psi_K(x)$$

so that

$$\Delta_j = \sum_i [f_j(x_i) - d_i(x_i)]^2$$

where the sum is over all i such that $(j-1) \Delta y < y_i \leq j \Delta y$ is a minimum. This is now a one-dimensional problem which can be solved by solving the set of equations given by

$$\frac{\partial \Delta_j}{\partial A_z(j)} = \sum_i 2 \left\{ \sum_k A_K(j) \Psi_K(x_i) - d_i(x_i) \right\} \Psi_z(x_i) = 0$$

for all $1 \leq z \leq K$. Rewriting the above equation in the form

$$A_z(j) \sum_i \Psi_z^2(x_i) + \sum_{k \neq z} A_k(j) \sum_i \Psi_k(x_i) \Psi_z(x_i) = \sum_i d_i(x_i) \Psi_z(x_i) \quad ,$$

it is often possible to solve the equations by an iterative process:

$$\begin{aligned} A_z^0(j) &= \sum_i d_i(x_i) \Psi_z(x_i) / \sum_i \Psi_z^2(x_i) \quad , \\ A_z^1 &= - \sum_{k \neq z} A_k^0(j) \sum_i \Psi_k(x_i) \Psi_z(x_i) / \sum_i \Psi_z^2(x_i) + A_z^0(j) \quad , \\ &\vdots \\ A_z^N(j) &= - \sum_{k \neq z} A_k^{N-1}(j) \sum_i \Psi_k(x_i) \Psi_z(x_i) / \sum_i \Psi_z^2(x_i) + A_z^0(j) \quad , \end{aligned}$$

where N is the N th iteration. This process converges rapidly if

$$\sum_i \Psi_k(x_i) \Psi_z(x_i) \ll \sum_i \Psi_z^2(x_i) \quad \text{for } k \neq z \quad ,$$

which is almost always the case when data points are almost equally spaced and Ψ are a set of orthonormal functions since

$$\begin{aligned} \int \Psi_k(x) \Psi_z(x) dx &= 1 & k = z \quad , \\ &= 0 & k \neq z \quad . \end{aligned}$$

Having derived $f_j(x)$ for all $1 \leq j \leq J$ and corresponding sets of $A_K(j)$, it is now possible to find a new set of $A_K(y)$, i. e.,

$$A_k(y) = \sum_{\ell=1}^L B_{\ell} \Theta_{\ell}(y) \quad ,$$

in the following manner. Changing $A_k(j)$ to $A_k(y_i)$ alters Δ_j by an amount

$$\frac{\partial^2 \Delta_j}{\partial A_k(j)^2} [A_k(j) - A_k(y_i)]^2$$

by expansion of Δ_j in a Taylor series about its minimum point. Since

$$\Delta = \sum_j \Delta_j \quad ,$$

Δ is minimized by minimizing

$$\sum_j \frac{\partial^2 \Delta_j}{\partial A_k(j)^2} [A_k(j) - A_k(y_i)]^2$$

for each value of k , which is another one-dimensional problem — that of a weighted least-squares fit weight $W_k(j)$ and is given by

$$W_k(j) = \frac{\partial^2 \Delta_j}{\partial A_k(j)^2} = 2 \sum_i \Psi_k^2(x_i)$$

where the summation is carried over all i such that $(j-1) \Delta y \leq y_i \leq j \Delta y$.

In the two-dimensional least-squares fitting used to make the contour maps described in Sec. V-A, longitude was taken as x and latitude as y . The latitude was quantized in 3° intervals (i. e., $\Delta y = 3^\circ$). Fifty functions were used for Ψ (sines and cosines) and ten functions for Θ . Only five iterations were required to bring the function within 1 percent of the converged value at all points.

APPENDIX C
DATA REDUCTION PROGRAM LISTINGS

LISTING 1

Compass listing of the real time data processing program. This program decodes the signal into up to 8 range boxes without any loss of data. Incoherent averages are written out onto magnetic tape every 10 seconds. At the end of the receive period an average is printed out on a high speed printer.

```

;SEQUENCE,4
;JOB,4LMAR110,BROCK,05
;COMPASS,L,R,P
      IDENT      MARS
      TITLE      MARS, 4-3-0 DECODING PROGRAM
      ENTRY      MAIN,CINIT,RUN
      EXT        INPUT,ENDRUN
      EXT        CIT,CST,ABNORMAL
MAIN   UJP        **
LOC0   EQU        0
      SJ5        **2          SSWTCH 5 ON MAKE BOOTSTRAP TAPE
      UJP        START
      LDA        *-1
      STA        LOC0
      CON        6,0
      UJP        *-1
      SEL        8,0
      UJP        *-1
      ENA,S      0
      ENI        7,1
      STA        CST,1          CLEAR CST
      IJD        *-1,1
      OUTW       0,0,77740B
      UJP        *-2
      EXS        2,0
      UJP        *-1
      EXS        2400B,0        CHECK FOR ERRORS
      HLT        **1
      SEL        13,0
      UJP        *-1
      EINT       0
      HLT        77740B
START  RTJ        INPUT
RESTART RTJ        CINIT
      RTJ        RUN
      RTJ        ENDRUN
      SJ2        START          SSWITCH 2 ON = RE-INITIALIZE
      UJP        RESTART
      EJECT

*
*   CINIT CLEARS ARRAYS AND SETS UP INTERRUPT LOCATIONS
*   -----
CINIT  UJP        **
      ENA,S      1
      STA        INT1-1          POWER FAILURE HALT
      ENI        ABNORMAL,1      SET UP STOP INABNORMAL
      STA        1,1
      ENA,S      0
      STA        IND
      STA        INDCT
      STA        ICNT
      STA        OUTBUF
      STA        FCNT
      STA        ZAQ
      ENI        59,1
      STA        ICOH,1          CLEAR INCOHERENT INTEGRATION
      STA        ITIME1,1
      STA        ITIME2,1
      IJD        *-3,1
      ENI        8191,1
      LDA        BIAS
      STA        BUF0,1          CLEAR BUFFERS
      IJD        *-1,1
      LDA        KR
      INA        4048

```

```

        SWA      I.2I      INITIAL SETTING OF B2
        STA      INDEX2
        LDA      KR
        INA,S    -2
        SHA      1
        SWA      I.1      B1 = 2*(KR-2)
        LDA      KR
        INA,S    -32
        SWA      I.2      B2 STEP = -(32-KR)
*   NOTE / KR MUST BE EVEN SINCE TWO SAMPLES ARE DECODED FOR EACH PASS.
*   KR MAY BE ANY EVEN NUMBER FROM 2 TO 30 DEPENDING ON THE BAUD INTERVAL
*   FOR 60 MICROSEC. KR = 6, FOR 126 MICROSEC. KR = 16
        ENI      21,1
        LDA      CIT,1
        STA      CITSAVE,1      SAVE CIT TABLE
        IJD      *-2,1
        UJP,I    CINIT
        EJECT

*
*   RUN CONNECTS INTERFACE AND OUTPUT DEVICES
*   -----
RUN      UJP      **
        SJ1      *      SSW 1 ON, WAIT FOR INTERFACE
        SSIM     17B
        CON      2000B,3
        UJP      *-1
        EXS      1,3      TEST FOR READY
        UJP      **2
        UJP      *-2
        SEL      5,3      CLEAR CH3 INT.
        UJP      *-1
        IOCL     5      CLEAR CHAN 0 AND 2
        CON      2,0      CONNECT UNIT 2 TO CH 0
        UJP      *-1
        SEL      6,0      SET 800 BPI UNIT 2
        UJP      *-1
        ENI      12,1
        ENA,S    MANUAL
        STA      CIT,1
        ENI      17,1
        ENA,S    CH3
        STA      CIT,1
        ENA      WAIT
        SWA      WAIT
        SEL      3,3      ENABLE/START WRITE CORE
        UJP      *-1
        EXS      4,3      TEST FOR WRITE CORE
        UJP      **2
        UJP      *-2
        ENA      0
        TAM      22B
        STA      TIMER
        SEL      12B,3      READ TIME FUNCTION
        UJP      *-1
        INPW     3,TIME1,TIME1+2      READ IN START TIME
        UJP      *-2
        PAUS     10B
        UJP      **1
        OUTW     0,ITITLE,KR+1
        UJP      *-2
        EXS      2,0
        UJP      *-1
        EINT     0
        UJP      WAIT
PROCESS  ENA      WAIT

```

	SWA	WAIT	
	ENA	I.1	
	SWA	WHERE	
	ENI	134,3	
*	DECODE 135 (OR LESS) OF THE 136 CODE INTERVALS PER BUFFER		
I.2I	ENI	**,2	
*	B2 SET TO 4048+KR+(0 OR 4096 DEPENDING ON BUFFER)		
I.1	ENI	**,1	B1=2*(KR-2) MODIFIED IN CINIT
DECODE	LDAQ	BIAS	BIAS=01770177
	ADAQ	DATA+8,2	BIAS+1=01770177
	ADAQ	DATA+10,2	
	ADAQ	DATA+12,2	
	ADAQ	DATA+16,2	
	ADAQ	DATA+18,2	
	ADAQ	DATA+24,2	
	ADAQ	DATA+28,2	
	STAQ	SAVEN	SAVEN=SUM SUBTRACTS
	LDAQ	DATA,2	
	ADAQ	DATA+2,2	
	ADAQ	DATA+4,2	
	ADAQ	DATA+6,2	
	ADAQ	DATA+14,2	
	ADAQ	DATA+20,2	
	ADAQ	DATA+22,2	
	ADAQ	DATA+26,2	
	SBAQ	SAVEN	
	TAM	70B	
	TQM	71B	
	ANA,S	60000B	
	STA	ZA	
	MUA	ZA	
	STQ	ZAQ+1	
	TMA	70B	(R1A,I1A,)=A
	SHA	12	(I1A,R1A)=A
	ANA,S	60000B	
	STA	ZA	
	MUA	ZA	
	ENA	0	
	ADAQ	ZAQ	
	ADAQ	ICOH,1	
	STAQ	ICOH,1	
	TMA	71B	
	ANA,S	60000B	
	STA	ZA	
	MUA	ZA	
	STQ	ZAQ+1	
	TMA	71B	
	SHA	12	
	ANA,S	60000B	
	STA	ZA	
	MUA	ZA	
	ENA	0	
	ADAQ	ZAQ	
	ADAQ	ICOH+2,1	
	STAQ	ICOH+2,1	
	TIA	1	
	AZJ,NE	**,4	
I.2	INI	**,2	JUMP B2 BY -(30-KR)
WHERE	IJD	I.1,3	B3 COUNTS 136 CODE INTERVALS
	UJP	**,4	
	INI	-2,2	
	INI	-4,1	
	UJP	DECODE	
	ENA	0	
	STA	IND	
	LDI	ICNT,2	

	TMA	22B	
	ISG	100,2	
	STA	ITIME1,2	
	EXS	4,3	CORE WRITE TEST
WAIT	UJP	*	TO PROCESS OR WAIT
*		END OF RECEIVE PERIOD	SENSED IN PROCESS
ENDREC	IOCL	10B	
	EXS	2,0	WAIT FOR TAPE WRITE
	UJP	*-1	
	SEL	13,0	END FILE TAPE 2
	UJP	*-1	
	SJ6	*+2	SSW6 ON=EOF,REWIND AND UNLOAD
	UJP	*+5	
	SEL	13,0	END FILE
	UJP	*-1	
	SEL	9,0	REWIND AND UNLOAD
	UJP	*-1	
	ENI	21,1	
	LDA	CITSAVE,1	
	STA	CIT,1	RESTORE CIT TABLE
	IJD	*-2,1	
	ENI	7,1	
	ENA,S	0	
	STA	CST,1	CLEAR CST
	IJD	*-1,1	
	SEL	5,0	
	UJP	*-1	CLEAR
	UJP,I	RUN	RETURN TO MAIN PROGRAM
	EJECT		
* CH3 INTERFACE INTERRUPT PROCESSOR			
* -----			
* CH3			
	UJP	**	DDI INTERRUPT PROCESSOR
	ENA	CH3	RESTORE INT ADDRESS
	SWA	CIT,1	RESTORE INT ADDRESS
	LDA	IND	
	AZJ,EQ	*+3	
	ENA,S	1	
	RAD	INDCT	
	ENA	77777B	
	STA	IND	
	COPY	3	COPY STATUS OF CH 3
	TAM	77B	
	ANA,S	2100B	
	AZJ,NE	FAULT	
EOBTEST	TMA	77B	
	ANA,S	60B	
	AZJ,EQ	NOTE0B	
	LDI	INDEX2,2	
	ASE	20B	
	INI	4096,2	
	STI	1,21,2	
	LDI	ICNT,2	
	TMA	22B	
	ISG	100,2	
	STA	ITIME2,2	
	INI	1,2	
	STI	ICNT,2	UP BUFFER COUNT
	ENQ	10000	
	ADA	TIMER	
	AQJ,GE	RECORD	
	STA	TIMER	
	ENA	0	
RESET	TAM	22B	
	ENA	PROCESS	
	SWA	WAIT	SET RETURN TO PROCESS

NOTE0B	SWA	WHERE	TERMINATE INTEGRATION
	SEL	10B,3	CLEAR INTERRUPT
	UJP	*-1	
	UJP,I	CH3	
RECORD	OUTW	0,ICNT,ICOH+60	
	UJP	*-2	
	ENA	0	
	STA	TIMER	
	UJP	RESET	
TIMER	BSS	1	
INDEX2	BSS	1	
FAULT	ENA,S	1	
	RAD	FCNT	COUNT FAULTS
	RAD	SAVEQ	NOTIFY PHASEII
	SEL	11B,3	CLEAR FAULT
	UJP	*-1	
	UJP	EOBTST	ACCEPT IF EOB TO MAINTAIN TIMING
ERR	UJP	**	
	LDA	INT1+1	
	LDQ	INT1	
	HLT	*+1	
	UJP,I	ERR	
	REM	TEMPORARY HALT WITH LOCS 4 AND 5 IN Q AND A	
MANUAL	UJP	**	MANUAL INT ROUTINE
	SEL	4,3	DISABLE WRITE CORE
	UJP	*-1	
	UCS	0	STOP
	SJ1	ENDREC	SENSE SWITCH 1 ON, GO TO END
	IOCL	10B	OFF CLEAR INTERFACE,
	UJP	RESTART	RESTART
	EJECT		
SAVEQ	OCT	0	
INT1	EQU	4	
BUF0	EQU	8192	
BUF1	EQU	12288	
BIAS	OCT	01770177	
	OCT	01770177	
OUTBUF	BSS	1	
CITSAVE	BSS	22	
ZA	BSS	1	
ZAQ	BSS	2	
SAVEN	BSS	2	
DATA	EQU	BUF0-30	
IND	BSS	1	
	DATA		
ICNT	BSS	1	
FCNT	BSS	1	
INDCT	BSS	1	
ICOH	BSS	100	
	COMMON		
KR1	BSS	1	
KR2	BSS	1	
ITITLE	BSS	18	
IRUN	BSS	1	
TIME1	BSS	1	
TIME2	BSS	1	
KR	BSS	1	
ITIME1	BSS	100	
ITIME2	BSS	100	
SP	BSS	60	
	END	MAIN	
	FINIS		
FORTRAN,L,P			
	SUBROUTINE INPUT		
	COMMON KR1,KR2,ITITLE(18),IRUN,ITIM1,ITIM2,KR,ITIME1(100),ITIME2(1		
	100),SP(30)		

```

      DO 1 I=1,30
1    SP(I)=0.0
      IRUN=1
      WRITE(59,1006)
1006  FORMAT(14H TYPE IN TITLE)
      READ(58,200) (ITITLE(I),I=1,18)
      200  FORMAT(18A4)
33    WRITE(59,202)
202   FORMAT(53H TYPE IN NUMBER OF RANGES, FORMAT I2, AN EVEN NUMBER )
      READ(58,201) KR
201   FORMAT(I2)
203   FORMAT(20H NUMBER OF RANGES = , I7)
      WRITE(59,203) KR
      IF(KR.GT.30.OR.KR.LT.2) GO TO 33
      KR1=2*(KR-2)
      KR2= -2*(30-KR)
      RETURN
      END

      SUBROUTINE ENDRUN
      TYPE DOUBLE(2) ICOH,TIME
      COMMON KR1,KR2,ITITLE(18),IRUN,ITIM1,ITIM2,KR,ITIME1(100),ITIME2(1
100),SP(30)
      COMMON/DATA/ ICNT,IFCNT,INDCT,ICOH(30)
      DIMENSION POWER(30),X(30)
      EQUIVALENCE (TIME,ITIM1)
      DO 1 I=1,KR
      POWER(I)=ICOH(I)
      X(I)=I
1    SP(I)=SP(I)+POWER(I)
      WRITE(61,200) (ITITLE(I),I=1,18)
200  FORMAT(18A4)
      IMASK=77B
      ITIM1=AND(IMASK,ITIM1)
      FTIME=TIME
      IHR=FHR=FTIME/3.6E7
      IMIN=FMIN=(FHR-IHR)*60.0
      ISEC=(FMIN-IMIN)*60.0
      WRITE(61,3000) IHR,IMIN,ISEC
3000  FORMAT(7H TIME =,I3,1H-,I2,1H-,I2,4H GMT)
      WRITE(61,100) IRUN,ICNT,IFCNT,INDCT
100  FORMAT(5X,11H RUN NUMBER,I5,/,5X,17H NO. OF BUFFERS =,I8,16H NO. 0
1F FAULTS =,I4,8H INDCT =,I7)
      WRITE(61,101) (I,POWER(I),I=1,KR)
101  FORMAT(5(I5,2X,E16.7))
      CALL SKETCH(X,POWER,KR)
      GO TO (300,890) SSWTCHF(3)
300  WRITE(61,301)
301  FORMAT(14H1 SUM OF RUNS )
      WRITE(61,101) (I,SP(I),I=1,KR)
      CALL SKETCH(X,SP,KR)
890  AV1=AV2=0.0
      NT=100
      IF(ICNT.LT.100) NT=ICNT-1
      DO 5 I=3,NT
      AV1=AV1+ITIME1(I)
5    AV2=AV2+ITIME2(I)
      AV1=AV1/(NT-2)$AV2=AV2/(NT-2)
      WRITE(61,6) AV1,AV2
6    FORMAT(27H AVERAGE PROCESSING TIME = ,F6.1,6H MSEC. /
1    27H AVERAGE BUFFER INTERVAL = ,F6.1,6H MSEC. )
888  GO TO(2,3)SSWTCHF(6)
2    WRITE(59,102)
102  FORMAT(55H RELEASE SENSE SWITCH 6 WHEN NEW TAPE MOUNTED AND READY)
4    GO TO(4,3)SSWTCHF(6)
3    IRUN=IRUN+1
      RETURN
      END
      FINIS

```

LISTING 2

Fortran listing of program which analyzes the output of the previous program. This program determines the least-squares fit delay, cross section, and C value.

```

;SEQUENCE,6
;JOB,4LABC133,ROGERS,13,ND
;FORTRAN,L,X
      PROGRAM MARSRN2
      CHARACTER CH
      DIMENSION IPWR(63),IDATA(25),PWR(30),APWR(30),AAPWR(30),PWR2(30)
      1,INFO(200),CH(72),RA(20),DECS(20),KDAY(20)
      2,ALON(20),P(10,130),C(50,10,10)
      EQUIVALENCE (IDATA,CH)
      PI=3.1415926536
      DO 205 M=1,130
      DO 205 L=1,10
205  P(L,M)=0.0
      DO 200 M=1,130
      DO 200 L=1,10
      AC=L*L*50.0
      DO 200 NN=1,130
      N=NN-80
      IF(N) 201,201,202
202  PA=1.0+2.0*AC*(N+0.0)/7500.0
      PA=1.0/PA
      PA=PA*PA*PA
      PA=SQRT(PA)*(SQRT(N+0.0)-SQRT(N-1.0))
      GO TO 203
201  PA=0.0
203  IDFF=IABS(NN-M)
      IF(IDFF-20) 204,200,200
204  P(L,M)=P(L,M)+PA*(1.0-IDFF/20.0)*(1.0-IDFF/20.0)
200  CONTINUE
      IDAYC=0
      IDAYCK=0
      STIME=0.0
      DO 71 I=1,20
      READ 72,HRS,AMIN,SECS,DEGS,DMINS,DSEC,ALON(I),KDAY(I)
72  FORMAT(7F10.7,I3)
      RA(I)=HRS*PI/12.0 +AMIN*PI/720.0+SECS*PI/43200.0
71  DECS(I)=DEGS*PI/180.0+SIGN((DMINS*PI/10800.0+DSEC*PI/648000.0
1),DEGS)
      1 BUFFER IN(30,1)(IDATA(1),IDATA(22))
      2 GO TO (2,3,400,3),UNITSTF(30)
      3 PRINT 4, (CH(I),I=1,72)
      4 FORMAT(1X,72R1)
      PRINT 5, IDATA(19)
      5 FORMAT(1X,10HRUN NUMBER,4X,I7)
      TIME((((CH(80)+0)*64.+CH(81))*64.+CH(82))*64.+CH(83))*64.+CH(84)
1)/36000000.0
      PRINT 6, TIME
      6 FORMAT(1X,4HTIME,4X,F10.6)
      KERR=LENGTHF(30)
      IF(KERR-22) 400,301,400
301 IF(IDATA(19)-50) 302,400,400
302 IF(IDATA(19)) 400,400,303
303 CONTINUE
      IF(IDAYCK) 304,304,39
304 NBOX=8
      IDAYCK=1
      IDA=0
      DO 19 I=2,72
      IF(IDA.EQ.0)11,19
11 IF(CH(I).LE.9)13,19
13 IF(CH(I).GE.0)14,19
14 IF(CH(I+1).LE.9)15,17
15 IF(CH(I+1).GE.0)16,17
16 IDAY=CH(I)*10+CH(I+1)
      GO TO 18

```

```

17 IDAY=CH(I)
18 IDA=I
19 CONTINUE
   DO 39 I=IDA,72
   IF(CH(I).EQ.1RM)20,23
20 IF(CH(I+1).EQ.1RA)21,23
21 MOIS=120
   GO TO 39
23 IF(CH(I).EQ.1RJ)24,27
24 IF(CH(I+1).EQ.1RU)25,27
25 IF(CH(I+2).EQ.1RN)26,27
26 MOIS=151
   GO TO 39
27 IF(CH(I).EQ.1RJ)28,31
28 IF(CH(I+1).EQ.1RU)29,31
29 IF(CH(I+2).EQ.1RL)30,31
30 MOIS=181
   GO TO 39
31 IF(CH(I).EQ.1RA)32,35
32 IF(CH(I+1).EQ.1RU)33,35
33 MOIS=212
   GO TO 39
35 IF(CH(I).EQ.1RS)36,39
36 IF(CH(I+1).EQ.1RE)37,39
37 MOIS=243
39 CONTINUE
   NDAY=MOIS+IDAY
   IF(NDAY-215)900,901,900
901 NDAY=216
900 IF(NDAY-220)902,903,902
903 NDAY=230
902 CONTINUE
   DTIME=TIME-STIME
   STIME=TIME
   IF(DTIME) 510,511,511
510 IDAYC =1
511 NDAY=NDAY+IDAYC
   PRINT 40,NDAY
40 FORMAT(1X,3HDAY,4X,I7)
   CALL LIMITS(-20.0,+80.0,-20.0,+100.0)
   DO 60 I=1,30
   ICOUNT=0
   AAPWR(I)=0.0
60 APWR(I)=PWR2(I)=0.0
41 BUFFER IN (30,1)(IPWR(1),IPWR(63))
42 GO TO(42,50,100,43),UNITSTF(30)
43 PRINT 44
44 FORMAT(1X,12HPARITY ERROR)
50 DO 51 I=1,NBOX
   J=2*I+2
   K=J+1
   IPWRA=IPWR(K)/2
   IPWRA=AND(37777777B,IPWRA)
51 PWR(I)=IPWR(J)*16777216.0+IPWRA*2.0
   DO 52 I=1,NBOX
52 APWR(I)=APWR(I)+PWR(I)-PWR2(I)
   A=(ICOUNT-20)
   AB=PWR(1)+PWR(2)-PWR2(1)-PWR2(2)
   B=(2.0*(PWR(4)-PWR2(4))-AB)*500.0/AB+20.0
   CALL POINTS(A,B,1R4,1)
   B=(2.0*(PWR(5)-PWR2(5))-AB)*500.0/AB+20.0
   CALL POINTS(A,B,1R5,1)
   B=(2.0*(PWR(6)-PWR2(6))-AB)*500.0/AB+20.0
   CALL POINTS(A,B,1R6,1)
   B=(2.0*(PWR(7)-PWR2(7))-AB)*500.0/AB+20.0
   CALL POINTS(A,B,1R7,1)

```

```

DO 53 I=1,NBOX
J=2*I+2
K=J+1
IPWRA=IPWR(K)/2
IPWRA=AND(37777777B,IPWRA)
53 PWR2(I)=IPWR(J)*16777216.0+IPWRA*2.0
ICOUNT=ICOUNT+1
GO TO 41
100 TIME=TIME+ICOUNT/(12.0*60.0)
SAM=ICOUNT*11111.1
AAP=0.0
DO 101 I=1,2
101 AAP=AAP+APWR(I)
AAP=AAP/2.0
DO 102 I=1,NBOX
102 AAPWR(I)=(APWR(I)-AAP)*SQRT(SAM)/AAP
PRINT 112
112 FORMAT(1X,2HI ,10X,10HAPWR(I) ,10X,10HPWR(I) ,10X,10HAAPWR(I)
1 ,10X,10HAAP )
DO 110 I=1,NBOX
110 PRINT 111,I,APWR(I),PWR(I),AAPWR(I),AAP
111 FORMAT(1X,I2,10X,E10.3,10X,E10.3,10X,F10.2,10X,F16.2)
ENCODE(800,103,INFO) NDAY,ICOUNT,TIME
103 FORMAT(4HDAY ,I7,1X,6HCOUNT ,I7,3X,5HTIME ,F7.2)
DMAX=0.0
DO 105 I=1,NBOX
IF(AAPWR(I)-DMAX) 105,106,106
106 DMAX=AAPWR(I)
IDMAX=I
105 CONTINUE
NNBOX=10*NBOX
AAPWR1=AAPWR(IDMAX)
IF(AAPWR(IDMAX+1)-AAPWR(IDMAX-1)) 155,155,156
155 AAPWR2=AAPWR(IDMAX+1)
AAPWR3=AAPWR(IDMAX-1)
AAPWR4=AAPWR(IDMAX-2)
AAA=SQRT(AAPWR3)-SQRT(AAPWR4)
AAN=AAA*(IDMAX-2)-SQRT(AAPWR4)
BBB=SQRT(AAPWR2)-SQRT(AAPWR1)
BBN=BBB*(IDMAX)-SQRT(AAPWR1)
ABN=(10.0*AAN-10.0*BBN)/(AAA-BBB)
IABOX=ABN+0.5
GO TO 157
156 AAPWR2=AAPWR(IDMAX-1)
AAPWR3=AAPWR(IDMAX+1)
AAPWR4=AAPWR(IDMAX+2)
AAA=SQRT(AAPWR1)-SQRT(AAPWR2)
AAN=AAA*(IDMAX-1)-SQRT(AAPWR2)
BBB=SQRT(AAPWR4)-SQRT(AAPWR3)
BBN=BBB*(IDMAX+1)-SQRT(AAPWR3)
ABN=(10.0*AAN-10.0*BBN)/(AAA-BBB)
IABOX=ABN+0.5
157 CONTINUE
DO 602 I=1,50
DO 602 J=1,10
DO 602 K=1,10
C(I,J,K)=0.0
DO 602 L=3,8
M=L*10-I+81-30
602 C(I,J,K)=C(I,J,K)+(AAPWR(L)-DMAX*(1.0+(K-2.0)/10.0)*P(J,M)/P(J,81)
1)**2
AMIN=1000000.0
DO 604 I=1,50
DO 604 J=1,10
DO 604 K=1,10
IF(AMIN-C(I,J,K)) 604,605,605

```

```

605 AMIN=C(I,J,K)
   IBOX=I+30
   INS=K
   JBOX=J
604 CONTINUE
   ADL=AMIN+10.0
   ICCR=0
   DO 600 I=1,50
     III=IBOX+I-40
     DO 600 J=1,10
       DO 600 K=1,10
         IF(C(I ,J,K)-ADL ) 606,600,600
606 IF(ICCR) 607,607,608
607 IRBOX1=III
   ICCR=1
608 IRBOX2=III
600 CONTINUE
   IRBOX=IRBOX2-IRBOX1
   PRINT 208
208 FORMAT(1X,28HLEAST SQUARES FIT PARAMETERS)
   PRINT 206,IBOX,AMIN,IABOX ,INS,JBOX,IRBOX
206 FORMAT(1X,I8,10X,F10.2,10X,I8,3I8)
   DO 350 K=1,3
     KKK=INS-2+K
     PRINT 351
351 FORMAT(1X,20HSHIFT DOWN,AC ACROSS)
   DO 350 I=1,10
     III=IBOX+I-35
350 PRINT 352,(C(III,J,KKK),J=1,10)
352 FORMAT(1X,10F10.2)
   DAY      =NDAY
   TIM      =TIME
   IF(DMAX-10.0) 240,240,241
240 AMULT=10.0
   PRINT 243
243 FORMAT(1X,14HSCALE EXPANDED)
   GO TO 242
241 AMULT=1.0
242 CONTINUE
   DO 209 L=1,NBOX
     A=L*10
     B=AAPWR(L)*AMULT
209 CALL POINTS(A,B,1RD,1)
     XSECT=0.0
     NNNBOX=IBOX+49
     DO 220 L=1,NNNBOX
       A=L
       M=L-IBOX+81
       B=AMULT*DMAX*(1.0+(INS-2.0)/10.0)*P(JBOX,M)/P(JBOX,81)
       XSECT=XSECT+B/(SQRT(SAM)*AMULT)
220 CALL POINTS (A,B,1R*,1)
     CALL LABELS(3HDEL,1,3HPOW,1)
     CALL GRIDS (-20.0,10.0,-20.0,20.0)
     CALL GRAPHS(INFO,15,200,1)
     THETA=PI/2.0-PI*53.0/180.0
     OMEGA=24.0/24.0+37.0/(24.0*60.0)+22.6689/(24.0*60.0*60.0)
     OMEGA=1.0/OMEGA
     DO 401 K=1,20
       IF(KDAY(K)-DAY ) 401,402,402
402 IF(KDAY(K)-9-DAY ) 403,403,401
403 KA=K
     KB=K-1
401 CONTINUE
     A1=PI/2.0+RA(KB)-PI*317.0/180.0
     A2=PI/2.0+RA(KA)-PI*317.0/180.0
     AE1=SIN(THETA)*SIN(DECS(KB))-SIN(A1)*COS(DECS(KB))*COS(THETA)

```

```

      AE2=SIN(THETA)*SIN(DECS(KA))-SIN(A2)*COS(DECS(KA))*COS(THETA)
      BE1=COS(A1)*COS(DECS(KB))
      BE2=COS(A2)*COS(DECS(KA))
      AN1=ATAN(AE1/BE1)+(0.5-SIGN(0.5,BE1))*SIGN(PI,AE1)
      AN2=ATAN(AE2/BE2)+(0.5-SIGN(0.5,BE2))*SIGN(PI,AE2)
      AL1=(180.0/PI)*ASINF(-COS(THETA)*SIN(DECS(KB))-SIN(THETA)*SIN(A1)*
1COS(DECS(KB)))
      AL2=(180.0/PI)*ASINF(-COS(THETA)*SIN(DECS(KA))-SIN(THETA)*SIN(A2)*
1COS(DECS(KA)))
      ALATR=AL1+(AL2-AL1)*(DAY -KDAY(KB)+(TIM /24.0))/10.0
      ANG=(AN2-AN1)*(DAY -KDAY(KB)+(TIM /24.0))/10.0
      ALOGR=OMEGA*(DAY -KDAY(KB)+(TIM /24.0))+ANG/(2.0*PI)+ALON(KB)
1/360.0
      LOGR=ALOGR
      ALOGR=(ALOGR-LOGR)*360.0
      PRINT 404,ALOGR,ALATR,IBOX,JBOX,TIM,DAY,IRBOX,XSECT
404  FORMAT(1X,2F12.2,10X,2I8,2F12.2,10X,I8,F12.2)
      PUNCH 841,ALOGR,ALATR,IBOX,JBOX,TIM,DAY,IRBOX,XSECT
841  FORMAT(2F10.3,2I10,2F10.3,I10,F10.3)
      GO TO 1
400  GO TO (411,412)SSWTCF(2)
412  PAUSE
411  PRINT 413
413  FORMAT(1X,13HPAUSE ON TAPE)
      STIME=0.0
      IDAYC=0
      IDAYCK=0
      GO TO(1,410) SSWTCF(1)
410  END
      FINIS
;EQUIP,30=MTCEOU03
;LOAD,56
;RUN

```

LISTING 3

Fortran program to perform two-dimensional least-squares fitting of data.

```

;SEQUENCE,6
;JOB,4LABC133,ROGERS,13,ND
;FORTRAN,L,X
PROGRAM MARSCON
DIMENSION F(50),F1(50),F2(50),D(900),Y(900),DC(121),F3(50,50)
1,W(900)
COMMON DA( 900),X( 900),YA( 900),IARR(121,10)
1,ARR(50,10),ARW(50,10)
PI=3.1415926536
NP=25
I=1
703 READ 700,LBOX,SIGMA,TIM,DAY,ALOGR,ALATR,HGT,ERR
700 FORMAT(I10,7F10.2)
IF(DAY-1966.0) 952,951,951
952 HGT=HGT+(DAY-128.0)*3.0/100.0
GO TO 953
951 HGT=HGT-3.0
953 CONTINUE
DA(I)=HGT
X(I)=ALOGR
YA(I)=ALATR
IF(LBOX) 701,702,701
701 I=I+1
GO TO 703
702 III=I-1
PRINT 704, III
704 FORMAT(1X,I10)
DO 100 IQ=1,10
XMAX=(IQ-1)*3.0+5.0
XMIN=XMAX-10.0
IKK=1
DO 200 I=1,III
IF(YA(I)-XMIN) 200,101,101
101 IF(YA(I)-XMAX) 102,102,200
102 D(IKK)=DA(I)
Y(IKK)=X(I)*2.0*PI/360.0
W(IKK)=1.0
IKK=IKK+1
200 CONTINUE
II=IKK-1
IF(II) 100,100,202
202 CALL DATAFT(II,D,W,Y,DC,NP,F,F3)
DO 201 IM=1,121
201 IARR(IM,IQ)=DC(IM)*1000
DO 400 IC=1,50
ARR(IC,IQ)=F(IC)
400 ARW(IC,IQ)=F3(IC,IC)
100 CONTINUE
NP=5
II=10
DO 500 IC=1,50
DO 501 IQ=1,10
D(IQ)=ARR(IC,IQ)
Y(IQ)=(IQ-1)*2.0*PI/20.0
501 W(IQ)=ARW(IC,IQ)
CALL DATAFT(II,D,W,Y,DC,NP,F,F3)
DO 502 IQ=1,10
IQQ=(IQ-1)*5+1
502 ARR(IC,IQ)=DC(IQQ)
500 CONTINUE
DO 800 IQ=1,10
DO 504 K=1,121
504 DC(K)=0.0
DO 800 K=1,121
DO 600 J=1,25

```

```

      THETA=(J-1)*(K-1)*2.0*PI/120.0
      C1=COS(THETA)
      C2=SIN(THETA)
      JJ=J+25
600 DC(K)=DC(K)+ARR(J,IQ)*C1+ARR(JJ,IQ)*C2
800 IARR(K,IQ)=DC(K)*1000
      DO 300 I=1,121
      PUNCH 302, (IARR(I,J),J=1,10)
300 PRINT 301, (IARR(I,J),J=1,10)
302 FORMAT(10I8)
301 FORMAT(1X,10I10)
      END

      SUBROUTINE DATAFT(II,D,W,Y,DC,NP,F,F3)
      DIMENSION F(50),F1(50),F2(50),D(900),Y(900),DC(121),F3(50,50)
1,W(900)
      PI=3.1415926536
      DO 600 J=1,50
      F1(J)=0.0
      F2(J)=0.0
      F(J)=0.0
      DO 600 K=1,50
600 F3(J,K)=0.0
      DO 1 I=1,II
      DO 1 K=1,NP
      THETA=(K-1)*Y(I)
      C1=COS(THETA)
      C2=SIN(THETA)
      F1(K)=F1(K)+C1*D(I)*W(I)
      KK=K+NP
      F1(KK)=F1(KK)+C2*D(I)*W(I)
      DO 1 J=1,NP
      THET=(J-1)*Y(I)
      C3=COS(THET)
      C4=SIN(THET)
      F3(J,K)=F3(J,K)+C3*C1*W(I)
      F3(J,KK)=F3(J,KK)+C3*C2*W(I)
      JJ=J+NP
      F3(JJ,K)=F3(JJ,K)+C4*C1*W(I)
1 F3(JJ,KK)=F3(JJ,KK)+C4*C2*W(I)
      DO 900 L=1,5
      NPP=NP*2
      DO 2 K=1,NPP
      AA=0.0
      DO 101 J=1,NPP
      IF(J-K) 100,101,100
100 AA=AA+F(J)*F3(K,J)
101 CONTINUE
      IF(F3(K,K)) 200,2,200
200 F(K)=(F1(K)-AA)/F3(K,K)
2 CONTINUE
900 CONTINUE
      AMAX=-1000000.0
      AMIN=+1000000.0
      DO 300 I=1,121
300 DC(I)=0.0
      DO 3 K=1,121
      DO 3 J=1,NP
      THETA=(J-1)*(K-1)*2.0*PI/120.0
      C1=COS(THETA)
      C2=SIN(THETA)
      JJ=J+NP
3 DC(K)=DC(K)+F(J)*C1+F(JJ)*C2
      DO 7 K=1,121
      IF(DC(K)-AMAX) 10,10,11
11 AMAX=DC(K)

```

```

10 IF(DC(K)-AMIN) 12,7,7
12 AMIN=DC(K)
7 CONTINUE
  DO 17 K=1,II
    IF(D(K)-AMAX)20,20,21
21 AMAX=D(K)
20 IF(D(K)-AMIN) 22,17,17
22 AMIN=D(K)
17 CONTINUE
  CALL LIMITS(1.0,121.0,AMIN,AMAX)
  DO 4 I=1,II
    A=Y(I)*120.0/(2.0*PI)+1.0
    B=D(I)
4 CALL POINTS(A,B,1RD,1)
  DO 5 K=1,121
    A=K
    B=DC(K)
5 CALL POINTS(A,B,1R+,1)
  CALL GRAPHS(0,0,0,1)
  RETURN
END
  FINIS
;LOAD,56

```

LISTING 4

Fortran program to analyze CW data. Program determines best-fit
C value cross section and frequency offset.

```

PROGRAM MAKSCW
DIMENSION IHEAD(4),T(161),RA(20),DECS(20),KDAY(20),ALON(20),
1 SCAT(161),DELTA(10,10,41)
PI=3.1415926536
DO 71 I=1,20
  READ 72,HRS,AMIN,SECS,DEGS,DMINS,DSEC,ALON(I),KDAY(I)
72 FORMAT(7F10.7,I3)
  RA(I)=HRS*PI/12.0 +AMIN*PI/720.0+SECS*PI/43200.0
71 DECS(I)=DEGS*PI/180.0+SIGN((DMINS*PI/10800.0+DSEC*PI/648000.0
  1),DEGS)
  1 READ(30) IHEAD,TIME,T
  GO TO (410,2),EOFCKF(30)
  2 PRINT 3,IHEAD,TIME
  3 FORMAT(1X,4I8,10X,F10.2)
  NDAY=IHEAD(4)
  DAY      =NDAY
  TIM      =TIME/3600.0 +0.05
  PRINT 5, NDAY,TIM
  5 FORMAT(1X,I8,F10.2)
  ANL=0.0
  DO 4 I=1,20
    II=162-I
  4 ANL=ANL+T(I)+T(II)
    ANL=ANL/40.0
    TMAX=0.0
    DO 7 I=1,161
      T(I)=T(I)-ANL
      IF(TMAX-T(I)) 6,6,7
  6 TMAX=T(I)
  7 CONTINUE
  DO 9 I=1,10
    DO 9 J=1,10
      DO 9 K=1,41
  9 DELTA(I,J,K)=0.0
    DO 20 IC=1,10
      C=IC*IC*50.0
      DO 10 IY=81,161
        Y=(IY-81)*30.0/12500.0
        ZMAX=SQRT(1.0-Y*Y)
        IZMAX=ZMAX*100.0
        SCAT(IY)=0.0
        DO 8 IZ=1,IZMAX
          Z=(IZ-1.0)/100.0
          R=SQRT(Z*Z+Y*Y)
          R2=1.0-R*R
          R1=R2*R2+C*R*R
  8 SCAT(IY)=SCAT(IY)+SQRT(1.0/(R1*R1*R1*R2))
  10 CONTINUE
  DO 11 I=1,81
    II=162-I
  11 SCAT(I)=SCAT(II)
    DO 14 IH=1,10
      DO 14 I=41,121
        DO 14 IS=1,41
          ISS=I+IS-21
          SCATB=TMAX*IH*SCAT(ISS)/(SCAT(81)*5.0)
  14 DELTA(IC,IH,IS)=DELTA(IC,IH,IS)+(T(I)-SCATB)*(T(I)-SCATB)
  20 CONTINUE
  DELTM=10.0**6
  DO 24 IC=1,10
    DO 24 IH=1,10
      DO 24 IS=1,41
        IF(DELTM-DELTA(IC,IH,IS)) 24,24,23
  23 DELTM=DELTA(IC,IH,IS)
  ICC=IC
  IHH=IH
  ISH=IS

```

```

24 CONTINUE
C=ICC*ICC*50.0
DO 110 IY=81,161
Y=(IY-81)*30.0/12500.0
ZMAX=SQRT(1.0-Y*Y)
IZMAX=ZMAX*100.0
SCAT(IY)=0.0
DO108 IZ=1,IZMAX
Z=(IZ-1.0)/100.0
R=SQRT(Z*Z+Y*Y)
108 SCAT(IY)=SCAT(IY)+SQRT(1.0/((((1.0-R*R)**2+C*R*R)**3)*(1.0-R*R)))
110 CONTINUE
DO 111 I=1,81
II=162-I
111 SCAT(I)=SCAT(II)
SCATB=SCAT(81)
DO 114 I=1,161
114 SCAT(I)=TMAX*(1.0+(IHH-5.0)/5.0)*SCAT(I)/SCATB
PRINT 25,SCATB,ICC,IHH,ISH
25 FORMAT(1X,F10.6,3I12)
CALL LIMITS(1.0,161.0,0.0,TMAX)
B22=0.0
DO 26 I=1,161
A=I
B1=T(I)
ISS=I+ISH-21
B2=SCAT(ISS)
B22=B22+SCAT(I)
26 CALL POINTS(A,B1,1R*,1)
CALL POINTS(A,B2,1R*,1)
CALL GRIDS(1.0,10.0,0.0,TMAX)
CALL GRAPHS(0,0,0,1)
XSECT      =B22*30.0
JC          =ICC
THETA=PI/2.0-PI*53.0/180.0
OMEGA=24.0/24.0+37.0/(24.0*60.0)+22.6689/(24.0*60.0*60.0)
OMEGA=1.0/OMEGA
DO 401 K=1,20
IF(KDAY(K)-DAY ) 401,402,402
402 IF(KDAY(K)-9-DAY ) 403,403,401
403 KA=K
KB=K-1
401 CONTINUE
A1=PI/2.0+RA(KB)-PI*317.0/180.0
A2=PI/2.0+RA(KA)-PI*317.0/180.0
AE1=SIN(THETA)*SIN(DECS(KB))-SIN(A1)*COS(DECS(KB))*COS(THETA)
AE2=SIN(THETA)*SIN(DECS(KA))-SIN(A2)*COS(DECS(KA))*COS(THETA)
BE1=COS(A1)*COS(DECS(KB))
BE2=COS(A2)*COS(DECS(KA))
AN1=ATAN(AE1/BE1)+(0.5-SIGN(0.5,BE1))*SIGN(PI,AE1)
AN2=ATAN(AE2/BE2)+(0.5-SIGN(0.5,BE2))*SIGN(PI,AE2)
AL1=(180.0/PI)*ASINF(-COS(THETA)*SIN(DECS(KB))-SIN(THETA)*SIN(A1)*
1COS(DECS(KB)))
AL2=(180.0/PI)*ASINF(-COS(THETA)*SIN(DECS(KA))-SIN(THETA)*SIN(A2)*
1COS(DECS(KA)))
ALATR=AL1+(AL2-AL1)*(DAY -KDAY(KB)+(TIM /24.0))/10.0
ANG=(AN2-AN1)*(DAY -KDAY(KB)+(TIM /24.0))/10.0
ALOGR=OMEGA*(DAY -KDAY(KB)+(TIM /24.0))+ANG/(2.0*PI)+ALON(KB)
1/360.0
LOGR=ALOGR
ALOGR=(ALOGR-LOGR)*360.0
PRINT 404,ALOGR,ALATR,JC ,XSECT ,TIM ,DAY ,ISH
404 FORMAT(1X,2F12.2,10X, I8,3F12.2,10X,I10)
PUNCH 841,ALOGR,ALATR,JC ,XSECT ,TIM ,DAY ,ISH
841 FORMAT (2F10.3, I10,3F10.3,I10)
GO TO 1
410 END
;EQUIP,30=MTCE0EU03

```


APPENDIX D
DISPLAY PROGRAM LISTINGS

LISTING 1

Program that produces contour map displays.

```

;SEQUENCE,6
;JOB,4LABC133,ROGERS,13,ND
;FORTRAN,L,X
  PROGRAM MRSDSP1
  DIMENSION IARR(10,121),INFO1(20),INFO2(200),INFO3(200),INFO4(200)
  1,X(2),Y(2) ,IA(20,121),IAR(10,61)
  1, IBUFFER(200),XA(16,16),YA(16,16),ZMA(16,16)
  1,ZMASTOR(16),ZMASTOT(16)
  DO 1 I=1,121
  IZ=I
  IZ=122-I
  1 READ 2,(IARR(J,IZ),J=1,10)
  2 FORMAT(10I8)
603 CONTINUE
  ITEMPMAX=0
  ITEMPMIN=0
  DO 900 J=1,121
  DO 900 I=1,10
  IF(IARR(I,J)-ITEMPMAX) 901,901,902
902 ITEMPMAX=IARR(I,J)
901 IF(IARR(I,J)-ITEMPMIN) 903,900,900
903 ITEMPMIN=IARR(I,J)
900 CONTINUE
  CALL RESETD(-6,-10)
  CALL SCALE(.0,1023.0,0.0,1023.0,0,0,0,0)
  DO 300 L=1,9
  DO 201 N=1,2
  DO 200 I=1,13
  X(1)=(I-1)*80.0+30.0
  X(2)=X(1)
  Y(1)=190.0 +(N-1.0)*300.0
  Y(2)=200.0 +(N-1.0)*300.0
  DO 200 J=1,20
200 CALL PLOT(2,2,X,Y,1,1,0)
  DO 201 I=1,3
  X(1)=20.0
  X(2)=30.0
  Y(1)=(I-1)*160./3.0+200.0+(N-1.0)*300.0
  Y(2)=Y(1)
  DO 201 J=1,20
201 CALL PLOT(2,2,X,Y,1,1,0)
  ENCODE(800,100,INFO1)
100 FORMAT(17HHAYSTACK FACILITY)
  CALL TEXT(600,1000,INFO1,64,2,1,0,0,0)
  ENCODE(800,101,INFO2)
101 FORMAT(16HMARTIAN LATITUDE)
  ENCODE(800,102,INFO3)
102 FORMAT(17HMARTIAN LONGITUDE)
  CALL TEXT(350,100,INFO3,64,2,1,0,0,0)
  ENCODE(800,202,INFO4)
202 FORMAT(1H0)
  CALL TEXT(16,200,INFO4,64,2,1,0,0,0)
  CALL TEXT(16,500,INFO4,64,2,1,0,0,0)
  ENCODE(800,203,INFO4)
203 FORMAT(2H10)
  CALL TEXT(00,254,INFO4,64,2,1,0,0,0)
  CALL TEXT(00,554,INFO4,64,2,1,0,0,0)
  ENCODE(800,204,INFO4)
204 FORMAT(2H20)
  CALL TEXT(00,308,INFO4,64,2,1,0,0,0)
  CALL TEXT(00,608,INFO4,64,2,1,0,0,0)
  ENCODE(800,205,INFO4)
205 FORMAT(62H0 15 30 45 60 75 90 105 120 135 150 16
15 180)
  CALL TEXT(30,180,INFO4,68,2,1,0,0,0)

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      ENCODE(800,215,INFO4)
215 FORMAT(63H180 195 210 225 240 255 270 285 300 315 330 3
      145 360)
      CALL TEXT(14,480,INFO4,68,2,1,0,0,0)
      ENCODE(800,216,INFO4)
216 FORMAT(62H0 1 2 3 4 5 6 7 8 9 10 11 12 13
      114 15)
      CALL TEXT(30,780,INFO4,68,2,1,0,0,0)
      ENCODE(800,217,INFO4)
217 FORMAT(45HCONTOUR INTERVALS IN PERCENTAGE CROSS SECTION)
      CALL TEXT(200,700,INFO4,50,2,1,0,0,0)
300 CONTINUE
      ITEMPMIN=-5000
      ITEMPMAX=10000
      DO 700 J=1,61
      DO 700 K=1,10
      JJJ=(J-1)/4
700 IAR(K,J)=JJJ*1000
      CALL IGRA3(IAR,30.0,800.0)
      DO 500 J=1,61
      DO 500 K=1,10
500 IAR(K,J)=IARR(K,J)
      CALL IGRA3(IAR,30.0,200.0)
      DO 501 J=1,61
      DO 501 K=1,10
      JJ=J+60
501 IAR(K,J)=IARR(K,JJ)
      CALL IGRA3(IAR,30.0,500.0)
      CALL ADVFILM(0,1)
      PAUSE
      END

      SUBROUTINE IGRA3(IAR,XSTART,YSTART)
      DIMENSION IAR(10,61),IBUFFER(200),XA(16,16),YA(16,16),ZMA(16,16)
      1,ZMASTOR(16),ZMASTOT(16)
      DO 1 I=1,60
      DO 1K=1,9
      X1=(I-1.0)*16.+XSTART
      Y1=(K-1.0)*16.0+YSTART
      ZM1=IAR(K,I)
      ZM2=IAR(K+1,I)
      ZM3=IAR(K+1,I+1)
      ZM4=IAR(K,I+1)
      II=I-1
      KK=K-1
      IF(II) 980,980,981
980 II=1
981 IF(KK) 982,982,983
982 KK=1
983 CONTINUE
      ZM5=IAR(K,II)
      ZM6=IAR(K+1,II)
      ZM7=IAR(KK,I)
      ZM8=IAR(KK,I+1)
      ZAS=ZM5+(ZM1-ZM5)*15.0/16.0
      ZBS=ZM6+(ZM2-ZM6)*15.0/16.0
      DO 2 IXX=1,16
      ZA=ZM1+(ZM4-ZM1)*(IXX-1.0)/16.0
      ZB=ZM2+(ZM3-ZM2)*(IXX-1.0)/16.0
      ZAT=ZM7+(ZM8-ZM7)*(IXX-1.0)/16.0
      ZMASTOT(IXX)=ZAT+(ZA-ZAT)*15.0/16.0
      DO 2 IYY=1,16
      XA(IXX,IYY)=X1+(IXX-1.0)
      ZMASTOR(IYY)=ZAS+(ZBS-ZAS)*(IYY-1.0)/16.0
      ZMA(IXX,IYY)=ZA+(ZB-ZA)*(IYY-1.0)/16.0
      2 YA(IXX,IYY)=Y1+(IYY-1.0)

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```

DO 1 IXX=1,16
DO 1 IYY=1,16
X=XA(IXX,IYY)
Y=YA(IXX,IYY)
IYYY=IYY-1
IME=ZMA(IXX,IYYY)/1000.0
IF(IYYY) 985,985,986
985 IME=ZMASTOT(IXX)/1000.0
986 IMF=ZMA(IXX,IYY)/1000.0
IXXX=IXX-1
IMG=ZMA(IXXX,IYY)/1000.0
IF(IXXX) 990,990,991
990 IMG=ZMASTOR(IYY)/1000.0
991 IF(IME-IMF)992,993,992
993 NST=IMF
IF(IMG-IMF) 992,996,992
992 NST=20
996 IF(NST) 1,1,3
3 CALL PLOTA(X,Y,NST)
1 CONTINUE
RETURN
END

SUBROUTINE PLOTA(X,Y,NST)
DIMENSION IBUFFER(200)
COMMON IDUMMY(10),ISELECT1,ISELECT2,IBUFFAD
IBUFFER(1)=60004000B
IBUFFER(2)=00010000B
IBUFFER(3)=10000B*AND(IBUFFAD,1777B)+3020B
IBUFF=4
IX=X
IY=Y
DO 1 I6=1,NST
IBUFFER(IBUFF)=10000B*AND(IX,1777B)+AND(IY,1777B)
1 IBUFF=IBUFF+1
IBUFFER(IBUFF)=ISELECT1
IBUFFER(IBUFF+1)=ISELECT2
IBUFF=IBUFF-1
CALL PUTPUT(IBUFFER,IBUFF,IBUFF-3)
RETURN
END
FINIS

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LISTING 2

Program for generating modulated ruled surface.

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;SEQUENCE,6
;JOB,4LABC133,ROGERS,13,ND
;FORTRAN,L,X
  PROGRAM MRSDSP2
  DIMENSION IH(33,122),IP(33,122),INFO1(20),INFO2(200),INFO3(200),IN
1F04(200),IBUFFER(200),IPP(11,122),IHH(11,122)
  1,XA(8,8),YA(8,8),ZMA(8,8)
  1,ZMASTOR(8),ZMASTOT(8)
  DO 10I=1,121
    IZ=123-I
10  READ 20,(IHH(J,IZ),J=2,11)
20  FORMAT(10I8)
    READ 21,ICLK
21  FORMAT(I10)
    DO 11 I=1,121
      IZ=123-I
11  READ 20,(IPP(J,IZ),J=2,11)
      CALL RESETD(-6,-10)
      CALL SCALE(.0,1023.0,0.0,1023.0,0,0,0,0)
      DO 200 LL=1,10
        ENCODE(800,100,INFO1)
100  FORMAT(17HHAYSTACK FACILITY)
        CALL TEXT(723,100,INFO1,64,2,1,0,0,0)
        ENCODE(800,101,INFO1)
101  FORMAT(17HNOV 22 1969 )
        CALL TEXT(739, 50,INFO1,64,2,1,0,0,0)
        ENCODE(800,102,INFO2)
102  FORMAT(7HMARTIAN)
        CALL TEXT(300,200,INFO2,64,2,1,0,0,0)
        ENCODE(800,103,INFO2)
103  FORMAT(9HLONGITUDE)
        CALL TEXT(490,250,INFO2,64,2,1,0,0,0)
        ENCODE(800,104,INFO2)
104  FORMAT(7HDEGREES)
        CALL TEXT(680,300,INFO2,64,2,1,0,0,0)
        ENCODE(800,105,INFO2)
105  FORMAT(8HEASTWARD)
        CALL TEXT(870,350,INFO2,64,2,1,0,0,0)
        ENCODE(800,106,INFO2)
106  FORMAT(8HLATITUDE)
        CALL TEXT( 20,260,INFO2,64,2,1,0,0,1)
        ENCODE(800,107,INFO2)
107  FORMAT(18HMARTIAN TOPOGRAPHY)
        CALL TEXT( 50,950,INFO2,64,2,1,0,0,0)
        ENCODE(800,108,INFO2)
108  FORMAT(3HAND)
        CALL TEXT(200,900,INFO2,64,2,1,0,0,0)
        ENCODE(800,109,INFO2)
109  FORMAT(18HRADAR REFLECTIVITY)
        CALL TEXT( 50,850,INFO2,64,2,1,0,0,0)
        ENCODE(800,110,INFO2)
110  FORMAT(9HHEIGHT KM)
        CALL TEXT( 1,464,INFO2,64,2,1,0,0,1)
        ENCODE(800,111,INFO3)
111  FORMAT(1H0)
        CALL TEXT(100,220,INFO3,64,2,1,0,0,0)
        ENCODE(800,112,INFO3)
112  FORMAT(3H180)
        CALL TEXT(540,330,INFO3,64,2,1,0,0,0)
        ENCODE(800,113,INFO3)
113  FORMAT(3H360)
        CALL TEXT(980,444,INFO3,64,2,1,0,0,0)
        ENCODE(800,111,INFO3)
        CALL TEXT( 80,240,INFO3,64,2,1,0,0,0)
        ENCODE(800,114,INFO3)

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114 FORMAT(2H27)
    CALL TEXT( 10,420,INFO3,64,2,1,0,0,0)
    ENCODE(800,115,INFO3)
115 FORMAT(2H-5)
    CALL TEXT( 20,460,INFO3,64,2,1,0,0,0)
    ENCODE(800,116,INFO3)
116 FORMAT(2H10)
    CALL TEXT( 20,610,INFO3,64,2,1,0,0,0)
200 CONTINUE
    XSTART=100.0
    YSTART=300.0
    ALPHA=0.3
    THETA=1.0
    SCA=8.0
    SCA=12.0
    CA=COS(ALPHA)
    SA=SIN(ALPHA)
    CT=COS(THETA)
    ST=SIN(THETA)
    DO 900 I=1,122
    DO 900 J=1,20
    K=(J-2)/2+2
    IH(J,I)=IHH(K,I)+(IHH(K+1,I)-IHH(K,I))*(J-K*2+2.0)/2.0
    IP(J,I)=IPP(K,I)+(IPP(K+1,I)-IPP(K,I))*(J-K*2+2.0)/2.0
    IP(1,I)=0
    IP(J,1)=0
    IH(1,I)=-6000
900 IH(J,1)=-6000
    X1=0.0
    X2=-SCA*SA
    X3=8.0*CA-SCA*SA
    X4=8.0*CA
    Y1=0.0
    Y2=SCA*CA*ST
    Y3=8.0*SA*ST+SCA*CA*ST
    Y4=8.0*SA*ST
    SCF=X1*(Y4-Y2)/2.0+X2*(Y1-Y3)/2.0+X3*(Y2-Y4)/2.0+X4*(Y3-Y1)/2.0
    SCF0=SCF
    DO 1 I=1,121
    DO 1 K=1,19
    X1=(I-1.0)*8.0*CA-(K-1.0)*SCA*SA+XSTART
    X2=(I-1.0)*8.0*CA-(K-0.0)*SCA*SA+XSTART
    X3=(I-0.0)*8.0*CA-(K-0.0)*SCA*SA+XSTART
    X4=(I-0.0)*8.0*CA-(K-1.0)*SCA*SA+XSTART
    Y1=(I-1.0)*8.0*SA*ST+(K-1.0)*SCA*CA*ST+IH(K,I)/100.+YSTART
    Y2=(I-1.0)*8.0*SA*ST+(K-0.0)*SCA*CA*ST+IH(K+1,I)/100.+YSTART
    Y3=(I-0.0)*8.0*SA*ST+(K-0.0)*SCA*CA*ST+IH(K+1,I+1)/100.+YSTART
    Y4=(I-0.0)*8.0*SA*ST+(K-1.0)*SCA*CA*ST+IH(K,I+1)/100.+YSTART
    SCF=X1*(Y4-Y2)/2.0+X2*(Y1-Y3)/2.0+X3*(Y2-Y4)/2.0+X4*(Y3-Y1)/2.0
    SCF=SCF/SCF0
    ZM1=IP(K,I)
    ZM2=IP(K+1,I)
    ZM3=IP(K+1,I+1)
    ZM4=IP(K,I+1)
    II=I-1
    KK=K-1
    IF(II) 980,980,981
980 II=1
981 IF(KK) 982,982,983
982 KK=1
983 CONTINUE
    ZM5=IP(K,II)
    ZM6=IP(K+1,II)
    ZM7=IP(KK,I)
    ZM8=IP(KK,I+1)
    ZAS=ZM5+(ZM1-ZM5)*7.0/8.0

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ZBS=ZM6+(ZM2-ZM6)*7.0/8.0
DO 2 IXX=1,8
ZA=ZM1+(ZM4-ZM1)*(IXX-1.0)/8.0
ZB=ZM2+(ZM3-ZM2)*(IXX-1.0)/8.0
ZAT=ZM7+(ZM8-ZM7)*(IXX-1.0)/8.0
ZMASTOT(IXX)=ZAT+(ZA-ZAT)*7.0/8.0
YAA=Y1+(Y4-Y1)*(IXX-1.0)/8.0
YBB=Y2+(Y3-Y2)*(IXX-1.0)/8.0
XAA=X1+(X4-X1)*(IXX-1.0)/8.0
XBB=X2+(X3-X2)*(IXX-1.0)/8.0
DO 2 IYY=1,8
XA(IXX,IYY)=XAA+(XBB-XAA)*(IYY-1.0)/8.0
ZMASTOR(IYY)=ZAS+(ZBS-ZAS)*(IYY-1.0)/8.0
ZMA(IXX,IYY)=ZA+(ZB-ZA)*(IYY-1.0)/8.0
2 YA(IXX,IYY)=YAA+(YBB-YAA)*(IYY-1.0)/8.0
DO 1 IXX=1,8
DO 1 IYY=1,8
NGS=0
X=XA(IXX,IYY)
Y=YA(IXX,IYY)
IYYY=IYY-1
IME=ZMA(IXX,IYYY)/1000.0+1.0
IF(IYYY) 985,985,986
985 IME=ZMASTOT(IXX)/1000.0+1.0
IKQK=1-(K-(K/2)*2)+(1-1SIGN(1,K*K-2))/2
NGS=10*IKQK
986 IMF=ZMA(IXX,IYY)/1000.0+1.0
IXXX=IXX-1
IMG=ZMA(IXXX,IYY)/1000.0+1.0
IF(IXXX) 990,990,991
990 IMG=ZMASTOR(IYY)/1000.0+1.0
IKQI=1-(I-(I/2)*2)+(1-1SIGN(1,I*I-2))/2
IKQI= (1-1SIGN(1,I*I-2))/2
NGS=10*IKQI
991 IF(IME-IMF) 992,993,992
993 SCFF=SCF*(IMF+NGS)+0.5
ICF=SCFF
NST=ICF
IF(IMG-IMF) 992,996,992
992 NST=20
996 IF(I-1) 910,911,910
911 NST=2+NGS
910 IF(K-1) 912,913,912
913 NST=2+NGS
912 IF(NST) 1,1,3
3 CALL PLOTA(X,Y,NST)
1 CONTINUE
CALL ADVFILM(0,1)
PAUSE
END

SUBROUTINE PLOTA(X,Y,NST)
DIMENSION IBUFFER(200)
COMMON IDUMMY(10),ISELECT1,ISELECT2,IBUFFAD
IBUFFER(1)=60004000B
IBUFFER(2)=00010000B
IBUFFER(3)=10000B*AND(IBUFFAD,1777B)+3021B
IBUFF=4
IX=X
IY=Y
DO 1 I6=1,NST
IBUFFER(IBUFF)=10000B*AND(IX,1777B)+AND(IY,1777B)
1 IBUFF=IBUFF+1
IBUFFER(IBUFF)=ISELECT1
IBUFFER(IBUFF+1)=ISELECT2
IBUFF=IBUFF-1
CALL PUTPUT(IBUFFER,IBUFF,IBUFF-3)
RETURN
END
FINIS
;LOAD,56

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