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# FURTHER DETERMINATIONS OF THE MAGNITUDE AND BRIGHTNESS FLUCTUATIONS OF THE PAGEOS SATELLITE

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## ABSTRACT

A passage of the PAGEOS satellite was observed electro-optically on July 13, 1966. The maximum brightness of PAGEOS reached during this pass was computed to be +1.7 magnitude and its periodic brightness fluctuations were determined to be 39 seconds. These values compare with +2.1 magnitude and 116 seconds period deduced from a passage on June 25, 1966.

The observed reflecting qualities of PAGEOS are unlike those of a perfect sphere leading to the conclusion that the satellite is deformed.

# FURTHER DETERMINATIONS OF THE MAGNITUDE AND BRIGHTNESS FLUCTUATIONS OF THE PAGEOS SATELLITE

## INTRODUCTION

A previous paper by Genatt and Moye[1] discussed a determination of the magnitude and brightness fluctuations of the PAGEOS satellite derived during the first 48 hours orbit of the satellite. In that determination, a magnitude of +2.1 was derived as the brightest that the satellite appeared to reach during its fluctuations, and a period for the variations of 116 seconds was deduced.

It was thought instructive some weeks later to attempt to see just how steady the magnitude of PAGEOS was holding and how inflexible was the period of its fluctuations. A change in observed brightness of the 100-foot balloon satellite could be interpreted in terms of deformations which affect the effective visible area. A change in its fluctuation period would be interpreted as a combination of spin rate changes and spacing of reflecting deformations over the portion of the sphere being observed.

### The Tracking Experiment

On July 13, 1966, at approximately $08^h\ 17^m$ Universal Time, the PAGEOS satellite started a pass across the horizon of the Goddard Optical Research Facility. Equipment used to track this pass was essentially that described in the aforementioned paper; i.e., the RADOT tracking telescope with the smaller Questar telescope mounted upon it and boresighted to it, the 56 TVP phototube behind the focal plane of the Questar upon which fell the light of PAGEOS and comparison stars, and a Mosely X-Y recorder which continuously recorded the brightness of PAGEOS and comparison stars.

A prediction of this passage was received from the Data Systems Division prior to the pass. Noting that the pass proceeded from the south to west to north, comparison stars of spectral types bordering that of the sun were selected as close as possible to the satellite's trajectory. These stars were to be used to determine the magnitude of PAGEOS. Since the passage was predicted to

1. "A Determination of the Magnitude and Brightness Fluctuations of the PAGEOS Satellite" by S. H. Genatt and J. E Moye, Document No. X-524-66-337, GSFC.

end near morning twilight, all comparison stars were observed and their light recorded prior to the beginning of the pass. Figure 1 illustrates the recordings obtained of the nine comparison stars observed during this trial.

The skies through which the trajectory advanced both before and during the pass were covered with thin haze and thin scattered clouds. These effects were permitted to be absorbed in the recordings since it was presumed that they would affect both satellite and stars alike, and additionally that the effects of the haze would be averaged out in the number of comparison stars employed.

PAGEOS and Comparison Stars Recordings

Figure 2, a, b, c, and d, is a reproduction of the light recording obtained of PAGEOS during this pass. In both Figures 1 and 2, the minima of the curves are the background skylight devoid of visible stars plus tube noise.

The chart recording of Pageos was run at a speed to make the x-axis have a scale of one inch equal to ten seconds of time while the y-axis scale was one inch equal to 20 millivolts.

Most of this pass was tracked automatically by the RADOT instrument locking itself upon the light of the satellite and mechanically printing out each second where its optic axis was pointing in a local X-Y coordinate system. The instances where the satellite was momentarily lost to the narrow angle six arc minutes field of view of the RADOT due to clouds or inadvertent operator mistake or by intentional ejection of the satellite to measure background skylight are indicated by the light curve dropping to a minimum and rising rapidly a few seconds later.

The PAGEOS recording for this pass is similar in several respects to the recording obtained on June 25. Both tracings show a curve which resembles that of the brightness of a point source approaching and then receding from an observer. Superimposed on this basic curve are periodic rises in intensity of the light. A visual inspection of the curve for July 13 shows the period to be somewhere between 30 and 40 seconds whereas it had been determined to be 116 seconds on June 25.

The predicted trajectory agrees quite well with the observed RADOT data considering that PAGEOS is a satellite which provides the predicting personnel with very little observed data since it is a completely passive satellite. The following table lists the predicted values at arbitrary times during the pass with the corresponding RADOT observed values after both are corrected for the same parameters.

Table 1

| Time U.T. | Predicted Data Alt. | Predicted Data Azim. | RADOT Data Alt. | RADOT Data Azim. |
|---|---|---|---|---|
| $08^h36^m00^s$ | 53°.20 | 201°.20 | 54°.47 | 201°.55 |
| 08 40 00 | 68.46 | 219.70 | 69.16 | 220.31 |
| 08 45 00 | 74.99 | 300.07 | 75.33 | 299.37 |
| 08 52 00 | 50.23 | 346.35 | 51.60 | 345.73 |
| 08 56 00 | 36.51 | 353.08 | 38.17 | 352.58 |

The Magnitude of PAGEOS

Examination of the RADOT printout reveals that the satellite reached its maximum altitude and minimum slant range somewhere between the times of $08^h\ 42^m\ 37^s$ and $08^h\ 43^m\ 45^s$. Since the portion of the sky where PAGEOS was located at $08^h\ 43^m\ 00^s$ was cloudy, the tracing of the satellite closest to that time point which showed a sharp flash was chosen to determine the magnitude of PAGEOS at its highest elevation and supposedly its greatest brightness. This flash occurred at $08^h\ 46^m\ 21^s$ and was 8.55 inches above the background sky level. RADOT was tracking at this time and indicated that it was pointing to an altitude of 71°.86.

The three comparison stars whose altitudes when they were observed were closest to that of the satellite at its peak were used to determine the magnitude of PAGEOS. These stars were $\epsilon$ Cygni, magnitude +2.64; $\zeta$ Cygni, magnitude +3.40; and 1 Pegasi, magnitude +4.27; whose respective altitudes when observed were 72°.1; 75°.4; and 68°.4. The three readings above background sky level as related to the three stars were 3.66 inches; 1.80 inches; and 0.73 inches.

When the normal magnitude formula,

$$m_1 - m_2 = -2.5 \log \frac{L_1}{L_2}$$

was employed to determine the magnitude of PAGEOS, the three equations appeared as follows,

$$(1)\ m_{PAG.} - 2.64 = -2.5 \log \frac{8.55}{3.66}$$

$$(2)\ m_{PAG.} - 3.40 = -2.5 \log \frac{8.55}{1.80}$$

$$(3)\ m_{PAG.} - 4.27 = -2.5 \log \frac{8.55}{0.73}$$

giving answers of +1.72, +1.71, and +1.60 whose mean is +1.68 or using first decimals only +1.7.

The point on the basic PAGEOS curve, (the curve devoid of the flashes) directly below the peak flash had a reading of 6.70 inches above the background sky level. When this value was inserted into the above three equations, the resulting magnitudes were +1.98, +1.97, and +1.86 or an average of +1.94. One observation here is that when the PAGEOS satellite fluctuated in brightness during this pass, the individual flashes appeared to be one-quarter of a magnitude brighter than what the satellite would be at that point if it did not exhibit flashing effects.

The probable reasons that PAGEOS appeared brighter during this pass than the earlier one are the following:

1. On July 13, 1966, the minimum slant range distance to the satellite was approximately 4480 kilometers whereas on June 25, 1966, the minimum range was 4844 kilometers. When these two values of distance are inserted into the slant range term, ($5 \log \frac{\rho}{a_v}$), in the formula for specular reflection, Fig. IV, the difference in magnitude due to the different distances only is 0.17.
2. Practically the entire pass of July 13 took place west of the meridian. As a result, a much larger area of the satellite was visible to view than during the June 25 pass which took place east of the horizon, since in each pass the sun was below the horizon in the east.

We may compute the increased brightness of the 12% diffuse reflectivity portion due to phase angle, P, in the following manner.

In the June 25 pass, the time under consideration was $08^h\ 11^m$ U.T. At this time, the celestial coordinates of the sun and PAGEOS were approximately as follows:

$$GHA_{SUN} = 302^\circ\ 08' \qquad GHA_{PAG} = 29^\circ\ 48'$$

$$DEC_{SUN} = +23^\circ\ 24' \qquad DEC_{PAG} = +37^\circ\ 36'$$

The angular distance, d, between the sun and PAGEOS, was therefore,

$$\cos d = \sin DEC_{PAG} \sin DEC_{SUN} + \cos DEC_{PAG} \cos DEC_{SUN} \cos (GHA_{SUN} - GHA_{PAG})$$

$$d = 74\overset{\circ}{.}2$$

Substituting the computed value of d, $74\overset{\circ}{.}2$, from above into the formula for phase, P, we get,

$$P = \frac{1 - \cos d}{2}$$

$$P = 0.364$$

Repeating the same equations with the parameters of the July 13 pass, at $08^h\ 46^m$ U.T., which were,

$$GHA_{SUN} = 310^\circ\ 06' \qquad GHA_{PAG} = 96^\circ\ 30'$$

$$DEC_{SUN} = +21^\circ\ 53' \qquad DEC_{PAG} = 49^\circ\ 48'$$

we obtain,

$$d = 102\overset{\circ}{.}4$$

$$P = 0.607$$

In other words, if PAGEOS were a perfect sphere, 36.4% of its surface would have been illuminated during the time of concern in the June 25 pass while 60.7% of its surface would have been illuminated during the corresponding time in the July 13 pass.

The difference in magnitude due to the change in phase only between the two passes would have been,

$$\Delta m = -2.5 \log \frac{60.7}{36.4}$$

$$\Delta m = 0.55$$

The difference in brightest magnitude reached between the two passes was approximately 0.4. Of this, 0.17 magnitude can be explained by a difference in distance, while the remainder 0.23 magnitude is only half of the expected magnitude change due to the difference in phase. Because of this latter fact, it appears that PAGEOS is deformed sufficiently so that it definitely does not reflect light as does a perfect sphere.

The Normalized $1/r^2$ Curve

Figure 3 is a curve of $1/r^2$ plotted against time during the pass, where r is the predicted slant range of the satellite in kilometers. The purpose of the curve was to show how the brightness of the satellite would vary during this pass if distance alone were the sole cause of its varying brightness. As may be seen, the intensity falls off a little more rapidly as the satellite moves away from RADOT than as it approaches. This is exactly what the recorded curve of PAGEOS shows when it is examined in its entirety.

Specular Reflection Magnitude

Since the material making up the body of the satellite reflects light in a specular manner and has an albedo which is 88% specular approximately, a curve of how the magnitude might vary during the pass was plotted using the predicted slant ranges and the assumed reflectance, Figure 4. The formula employed for the magnitude was one given by Koskela[1], i.e.,

$$m_v = m_{\odot} + \log \frac{\rho}{a_v} - 2.5 \log \gamma + 1.505 + A$$

where the individual parameters are defined on Figure 4. This curve resembles the $1/r^2$ curve in that the brightness drops more rapidly as the satellite moves away from the observer than as it rises when it approaches.

1. Contribution to Astrodynamics "A Dynamic Analysis and Preliminary Design of Guidance for Lunar Vehicles" Vol. IV, Stellar Magnitudes by P. E. Koskela, Aeronutronic Publication C-590, September, 1959.

The brightest magnitude reached on this curve is +2.44 while the average greatest brightness computed earlier was +1.68 giving a difference of +0.76 magnitude. On the June 25, 1966 pass, it was also noticed that this specular reflectance formula gave a magnitude about 0.6 fainter than the satellite reached.

In an attempt to determine if changing the constant, 1.505, would make the theoretical curve resemble true conditions more closely, the curve was redrawn substituting +0.75 for the constant, +1.505, (dashed graph). Points were taken from the PAGEOS recording where periodic flashes occurred and their magnitudes computed using as a basis the magnitude +1.68 for a deflection above background sky of 8.55 inches. The circled points are the resulting magnitudes.

The difference between the dashed line graph and an imaginary curve drawn through the dots appears to be a timing error. If the imaginary curve were moved to the left an amount equal to about 5 minutes of time, there would be a fair agreement between the new formula and observed magnitudes.

The Power Spectrum Analysis

As in the earlier discussion of the June 25 pass of PAGEOS, an attempt was made here to determine the period in the fluctuating brightness by a more rigorous method than manually measuring from peak-to-peak. A power spectrum analysis on the data was thereby performed. A brief explanation of this technique was given in the previous paper mentioned.

Values were taken from the PAGEOS recording at each five seconds of time between the interval $08^h\ 31^m\ 50^s$ and $09^h\ 00^m\ 00^s$. At those five second points where the record had dropped to a minimum, an extrapolated smooth value was used. They were taken at this interval because it was obvious by a visual inspection of the record that the period was somewhere over 30 seconds. A power spectrum analysis does not extract periods which are shorter than twice the interval between points.

Figure 5 shows the relative power of two graphs derived using two different frequency resolutions. The lower graph has twice the frequency resolution of the upper and this fact is reflected in the greater number of periods exhibited.

Figure 6 illustrates the two curves of Figure 5 after each curve had undergone a numerical filtering. The top curve of Figure 6 is the effective frequency response of the filter. The X-axis reads both the frequency in cycles per second and the period. Relative power is on the Y-axis. As may be seen, the period of the fluctuations averages out to 39 seconds.

Conclusions

1. PAGEOS is definitely deformed which explains it not behaving as a perfect sphere in its reflecting qualities. The passes on June 25 and on July 13 bear this out both from the standpoint of expected brightness against observed and also from the fluctuations in its brightness.

2. The satellite rotates but the period is indeterminate as of now. It appears to be a multiple of approximately 39 seconds.

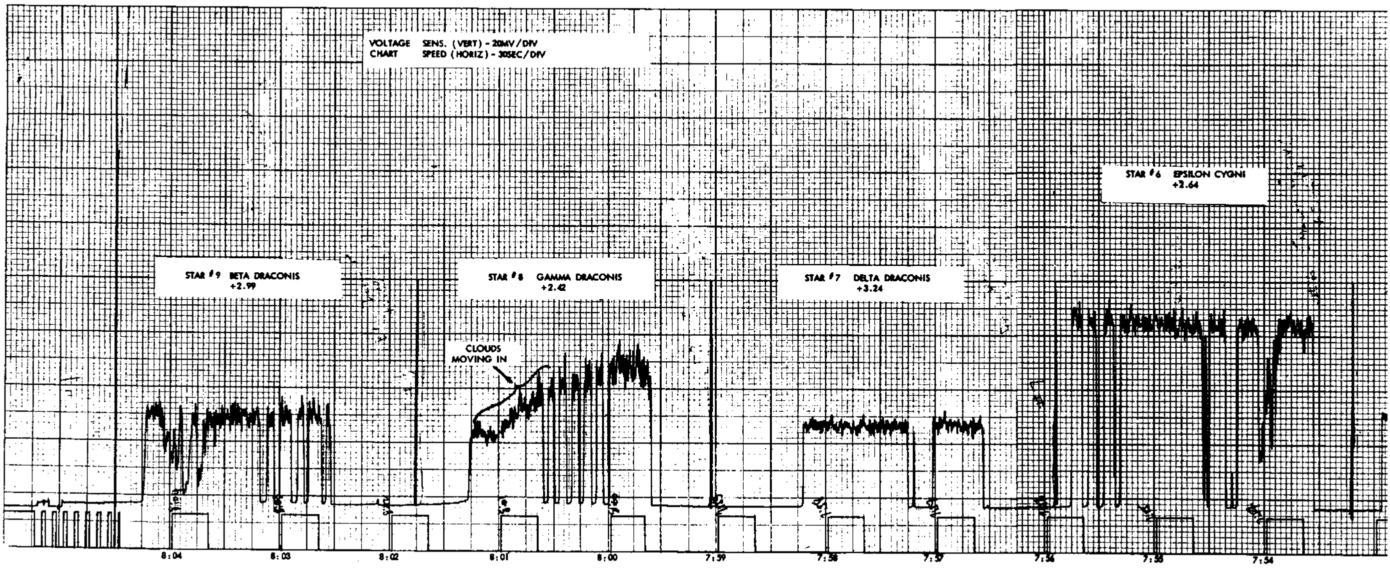
3. Since the probability of the rotation rate of the balloon changing between June and July is extremely small, it seems that there are deformed areas on the satellite equally spaced along the surface. These areas cause glints of sunlight to be given off and result in fluctuations in the brightness of the satellite. The periods of these observed fluctuations were 116 seconds on June 25 and 39 seconds on July 13.

4. The specular reflection formula quoted by Koskela appears to represent observed brightnesses somewhat better when the constant +0.75 is employed in the formula instead of +1.505.

ACKNOWLEDGMENTS

The authors wish to thank Messrs. J. R. Cook and J. D. Stewart of Scientific Data Systems and Bendix Field Engineering respectively for operating the RADOT instrument during the passage and Mr. B. J. Conrath of the Planetary Radiations Branch for performing the power spectrum analysis on the data.

10-1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CLOUDS
MOVING IN
STAR #7 DELTA DRACONIS
+3.24
STAR #6 EPSILON CYGNI
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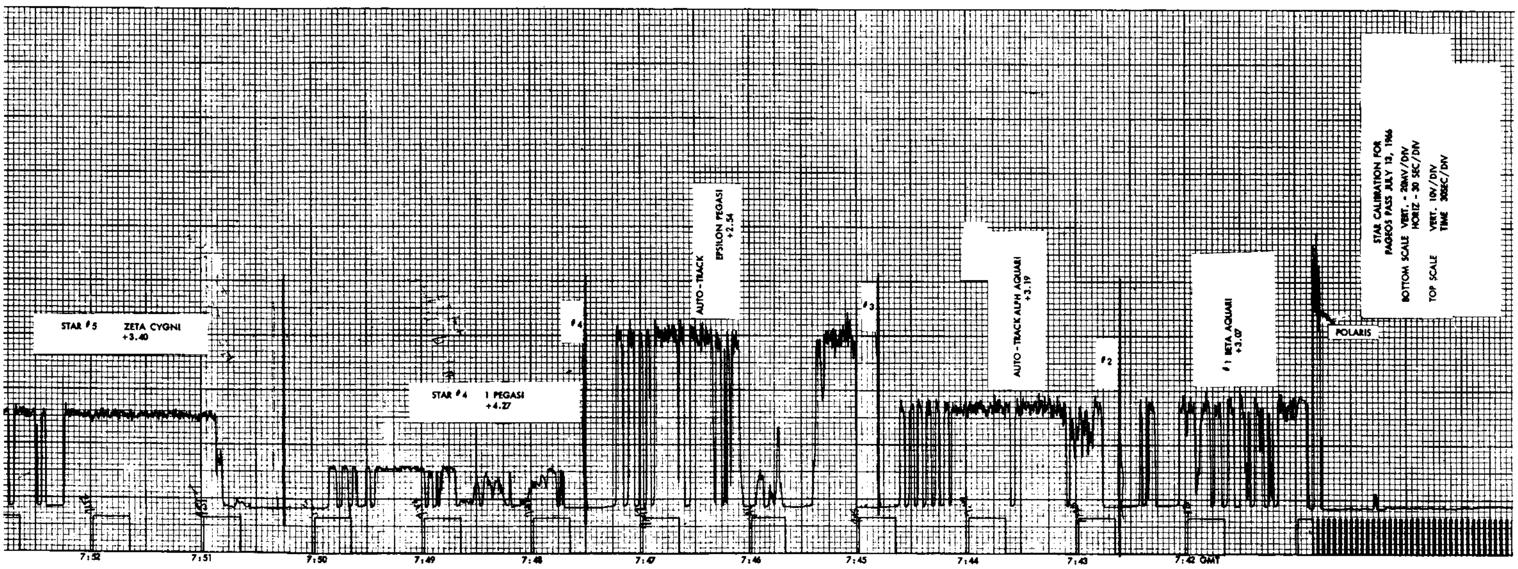
10-2




igure 1. The Comparison Stars Recording.

11-1

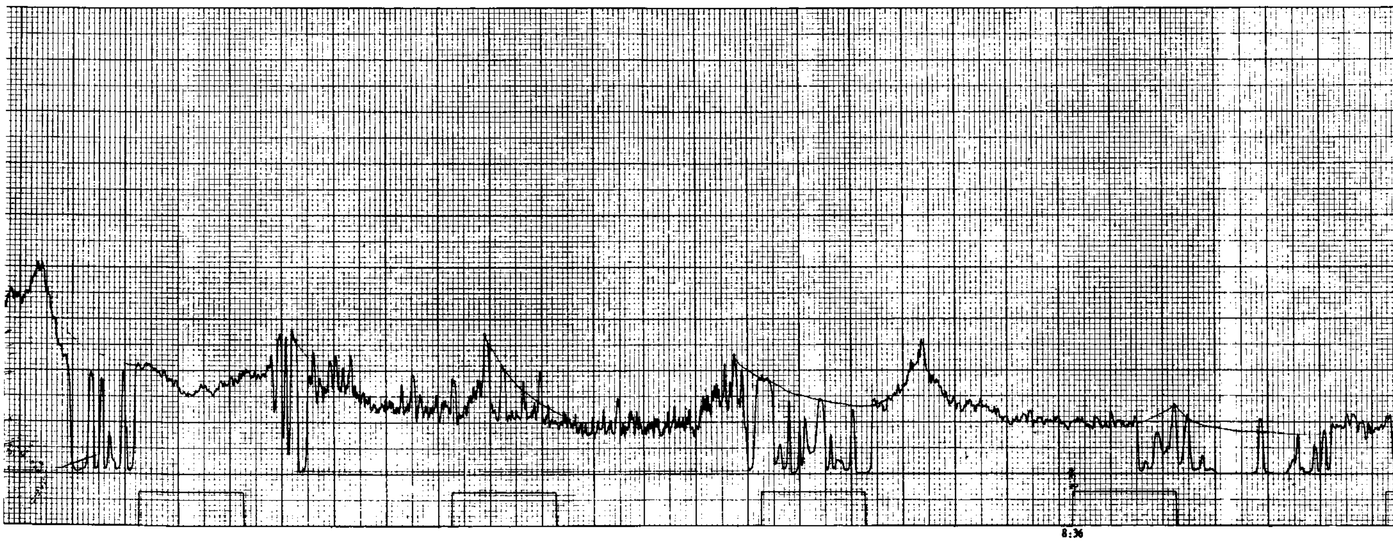
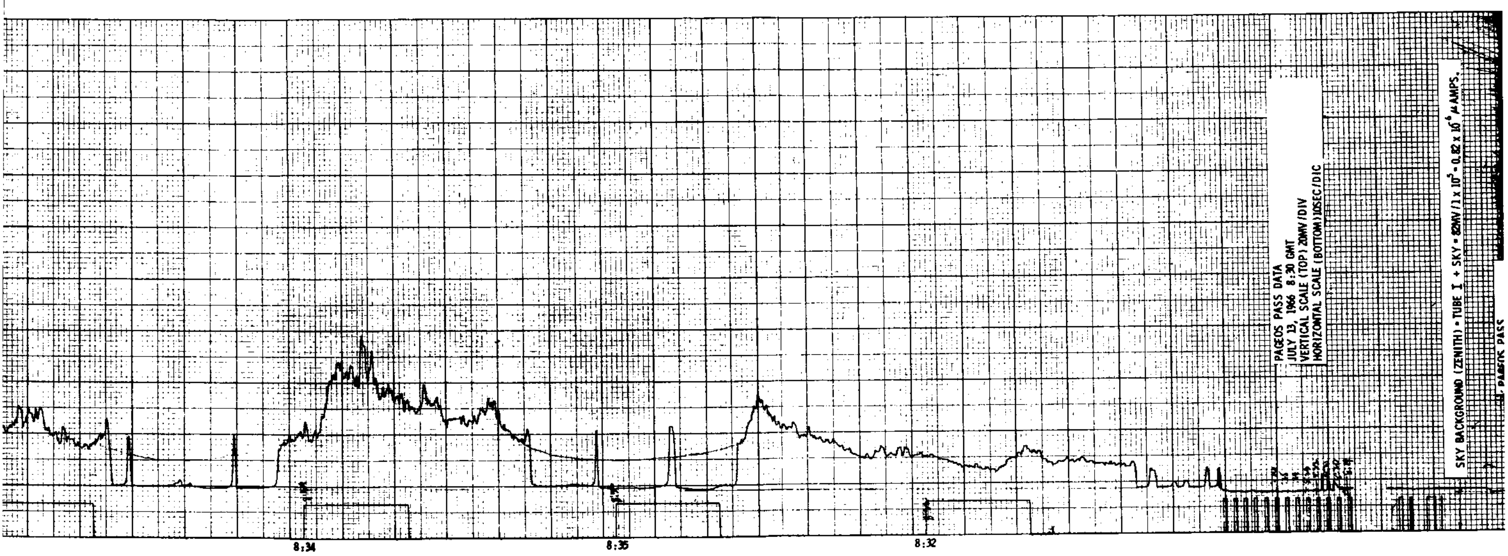



FIGURE 2a ...

11-2




E PAGEOS RECORDING

12-1

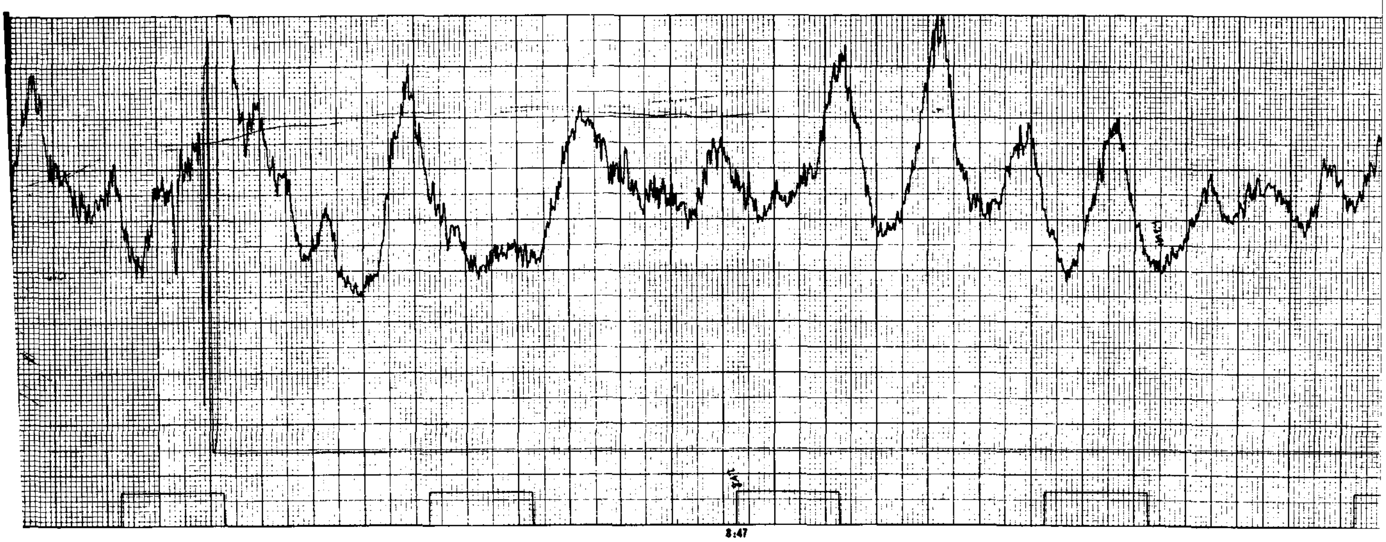
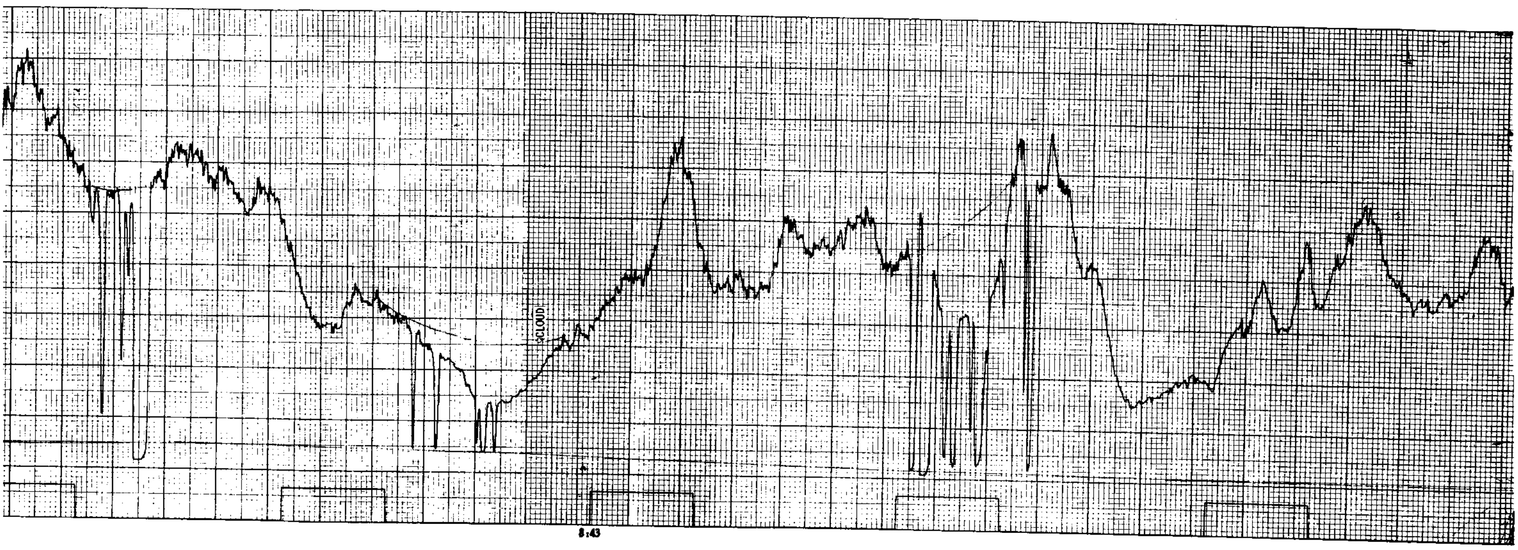



FIGURE 2b

12-2




THE PAGEOS RECORDING

13-1

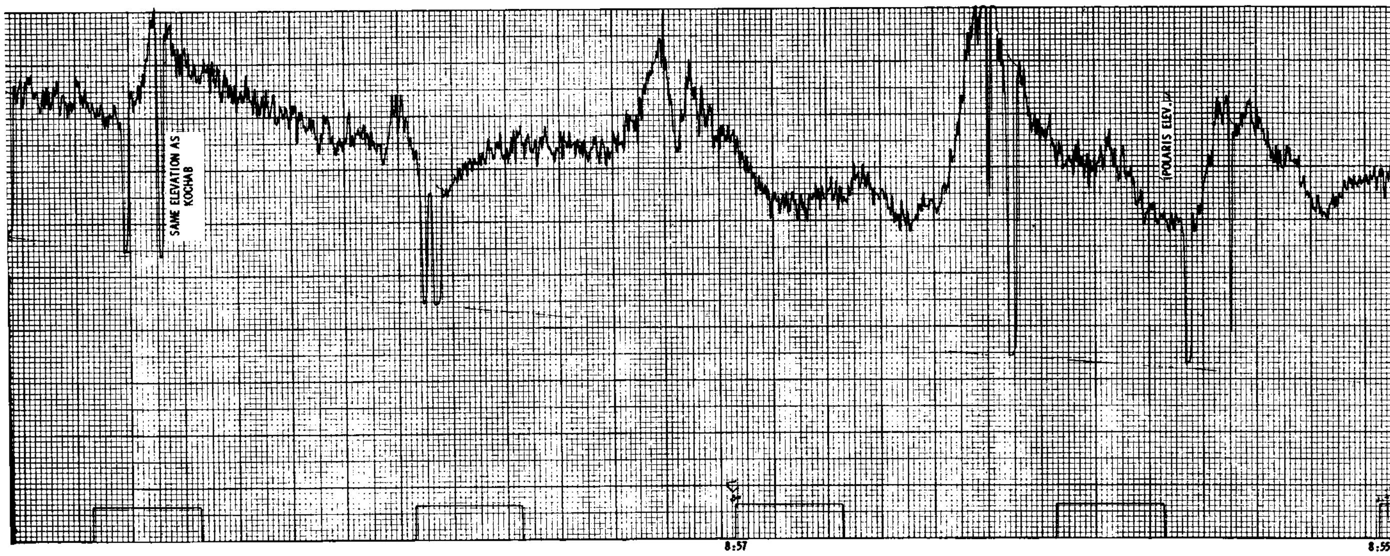
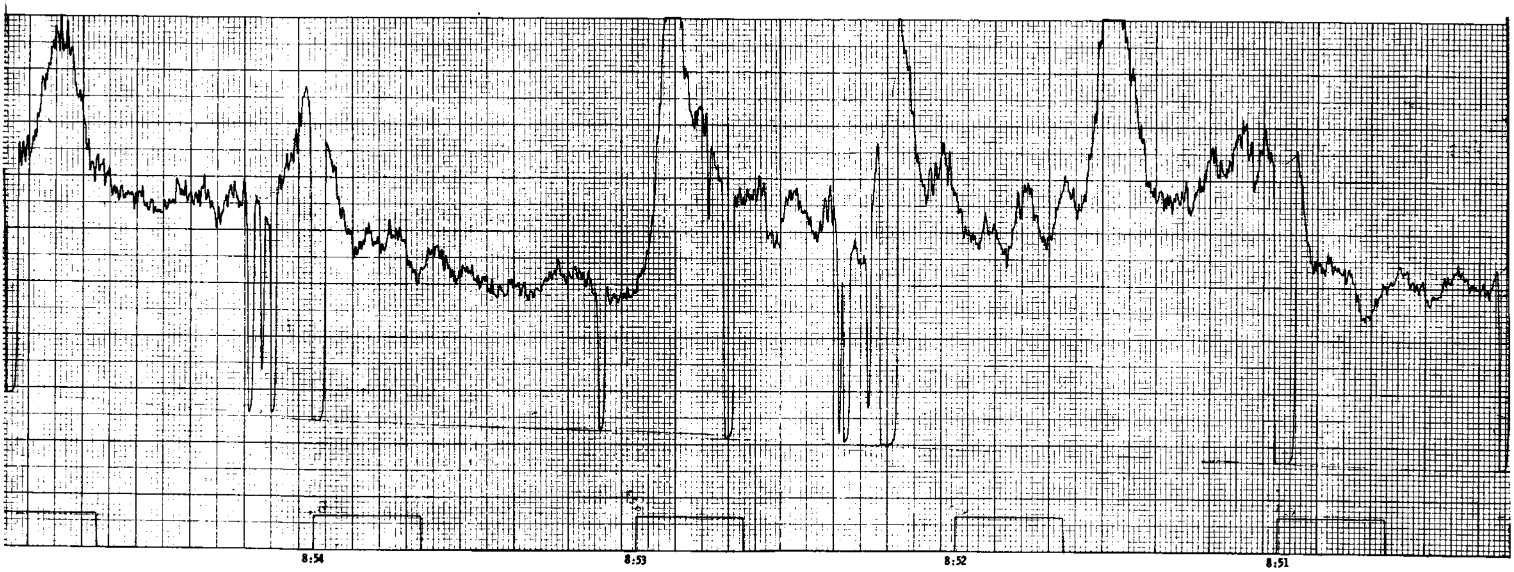



FIGURE 2c TH

13-2

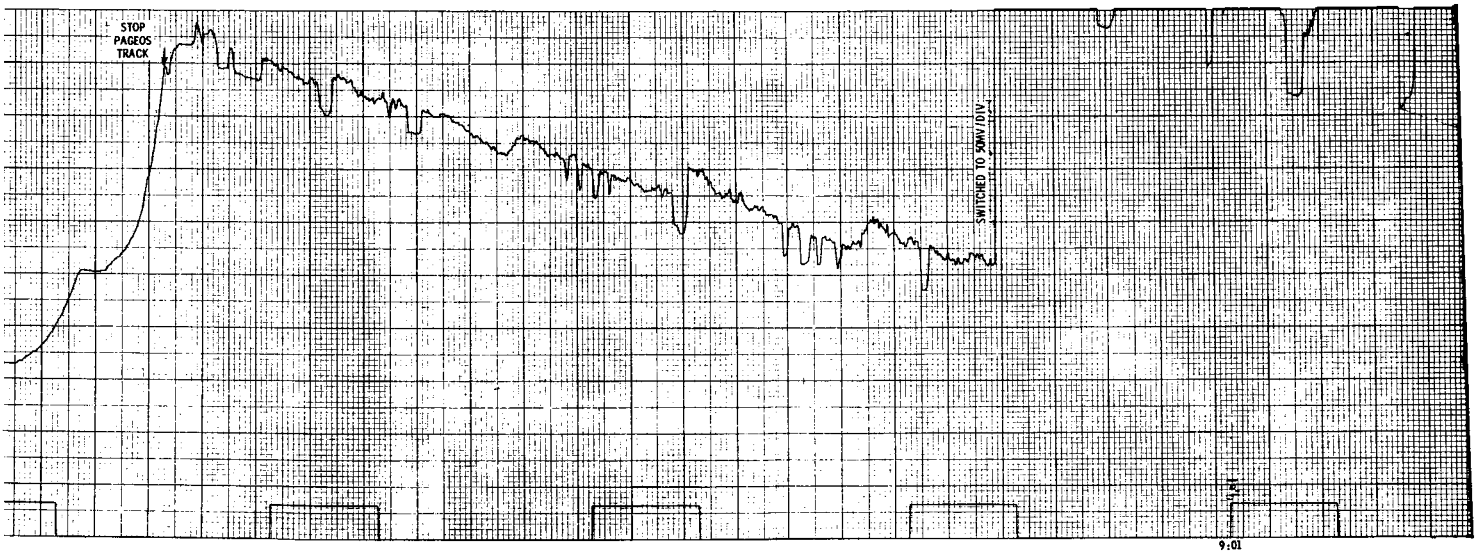



: PAGEOS RECORDING

14-1


FIGURE 2d THE PAGEOS R

14-2




CORDING

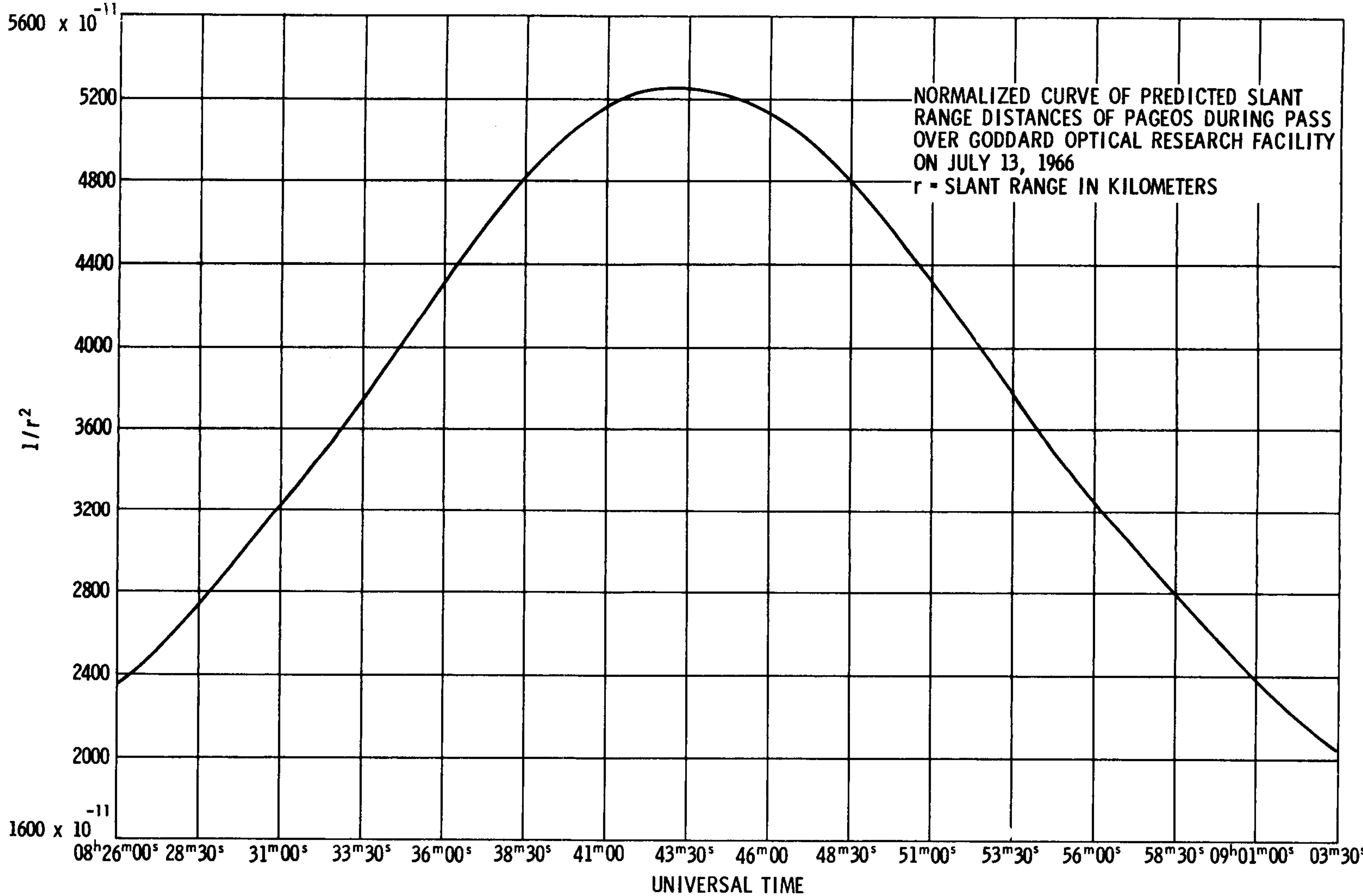



FIGURE 3 THE $1/r^2$ CURVE

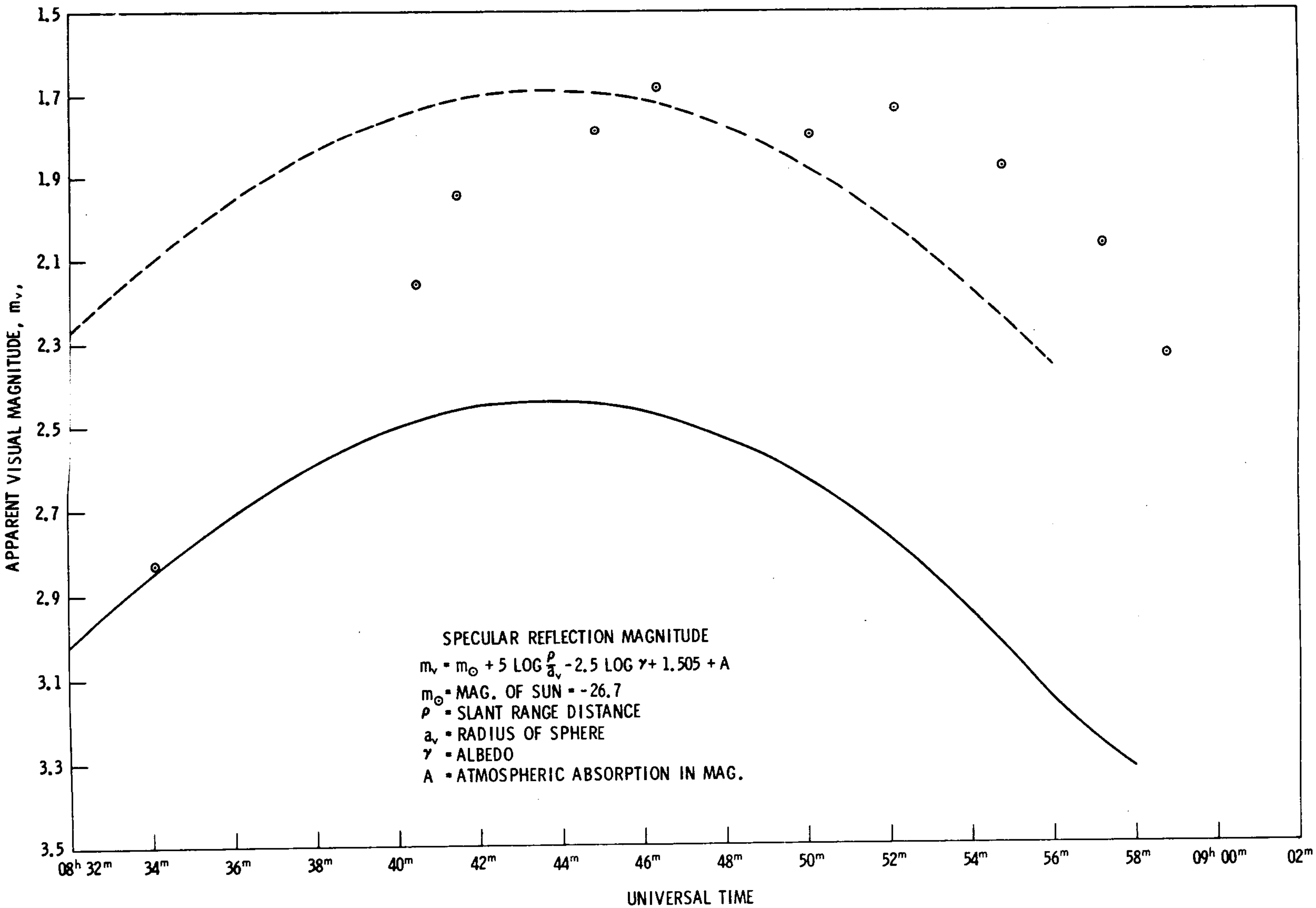



FIGURE 4 CURVES OF SPECULAR REFLECTANCE

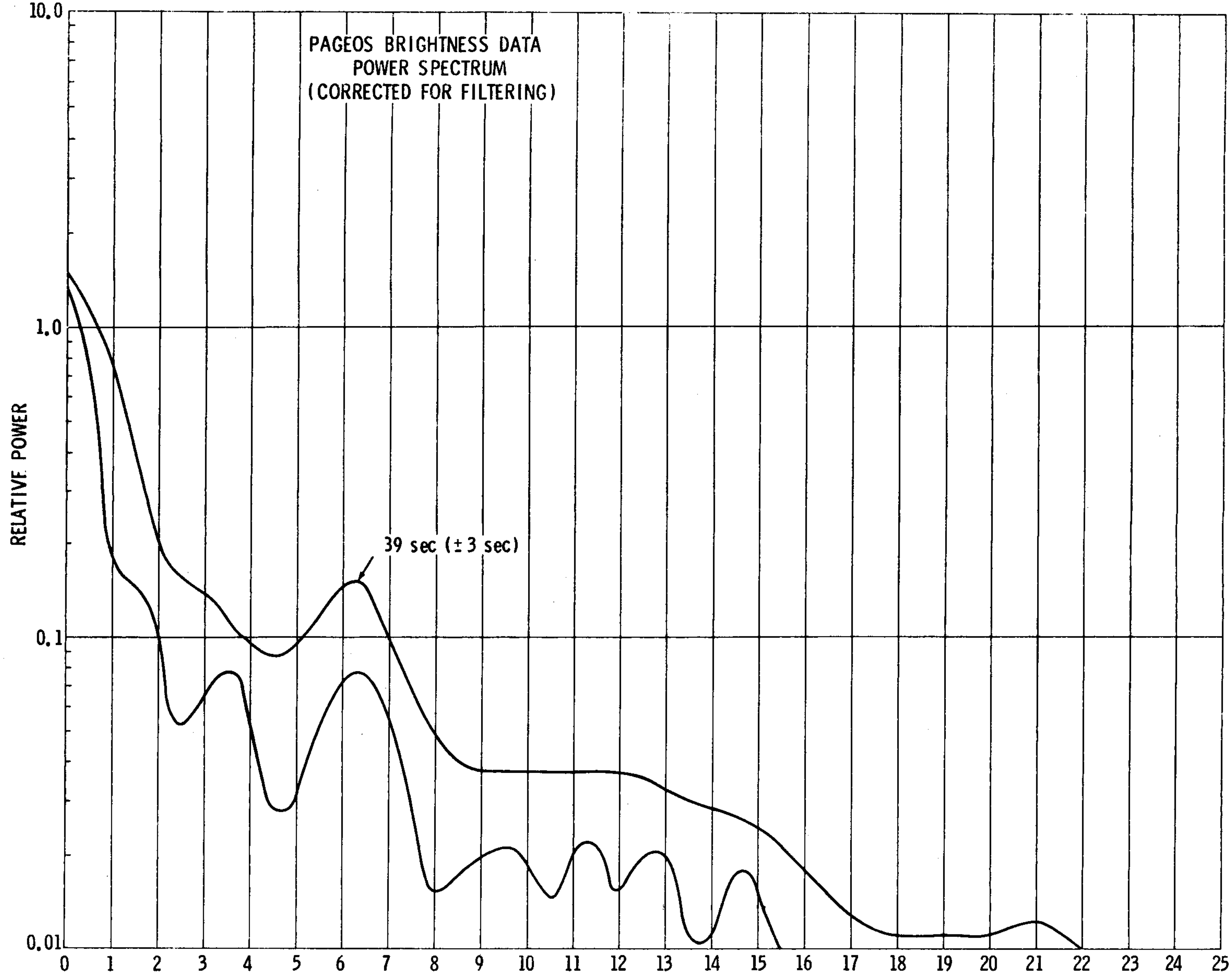



FIGURE 5 THE POWER SPECTRUM CURVE INCORPORATING TWO DIFFERENT FREQUENCY RESOLUTIONS, (PRIOR TO FILTERING)

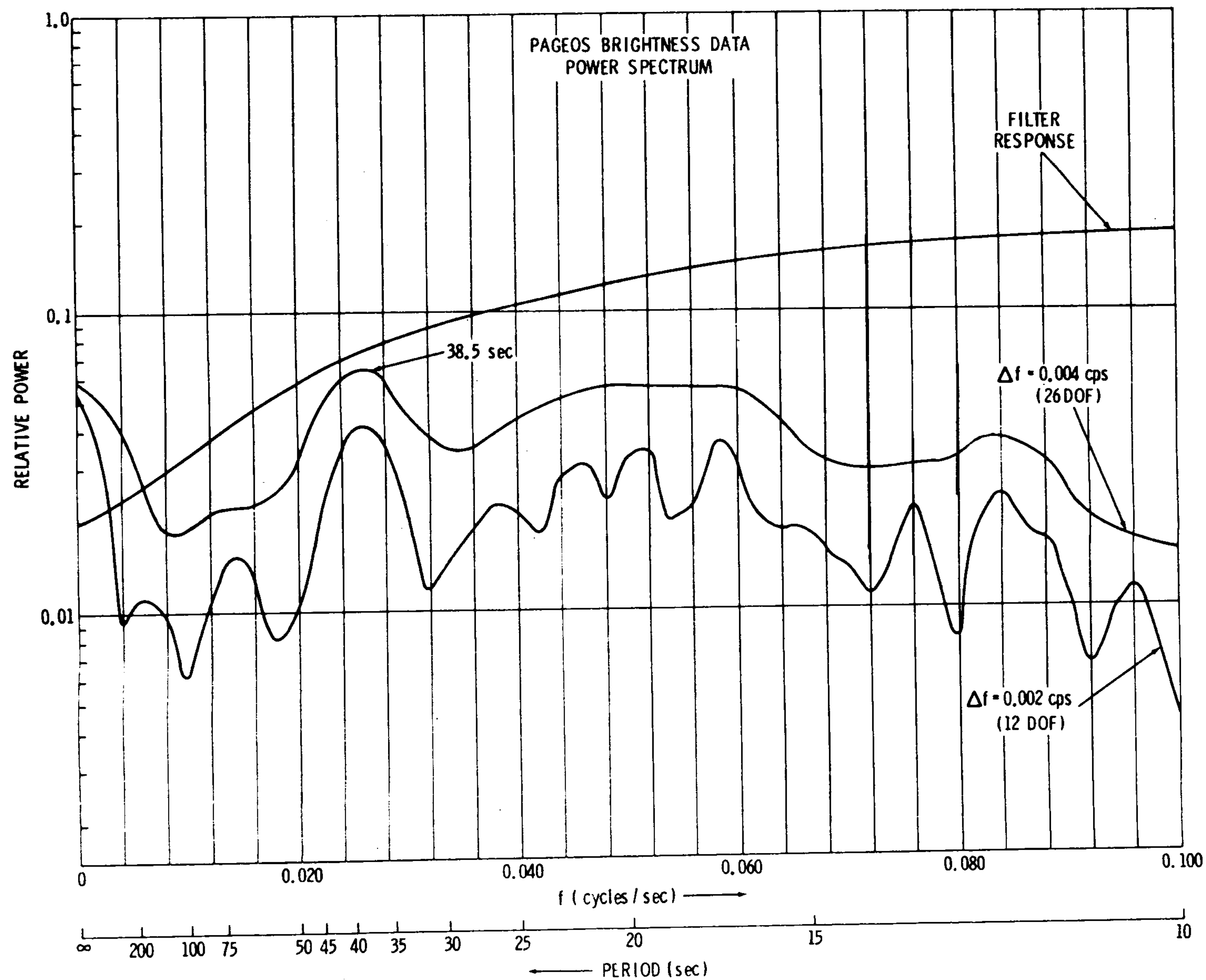



FIGURE 6 THE POWER SPECTRUM CURVES, INCORPORATING THE TWO DIFFERENT FREQUENCY RESOLUTIONS, (AFTER FILTERING)