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A DETERMINATION OF THE MAGNITUDE AND BRIGHTNESS FLUCTUATIONS OF THE PAGEOS SATELLITE

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ABSTRACT

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A passage of the Pageos satellite was observed with the RADOT instrument at the Goddard Optical Research Facility on June 25, 1966. By comparing the light intensity recording of the Pageos satellite with a comparison stars' recording, the magnitude of Pageos during this pass was computed to be +2.1. Analysis of the light curve of the satellite by a power spectrum routine shows a periodic fluctuation in the brightness with a period of approximately 116 seconds during the same pass.

Author

Pageos Project Objectives

The Pageos satellite of the National Aeronautics and Space Administration was launched on June 24, 1966. Among the objectives of this launching were the following:[1]

1. Place in orbit a 100-foot satellite of the Echo-1 type.

2. Encourage international participation in ground-based observations, data acquisition, and data analysis.

3. Establish an interconnected series of camera positions that will cover the entire surface of the earth, permitting geometric determination of each camera position.

4. Determine the geometric positions of the geodetic stations within 10 meters.

5. Establish a single world geometric reference system.

Balloon Inflation

The means used to inflate the balloon to its full 100-foot diameter were similar to those employed in the Echo-1 satellite. In essence, this involved placing a total of 30 pounds of subliming powders, (benzoic acid and anthraquinone) inside the folded balloon along one of its gores. When ejected from its canister into orbit over Madagascar, the residual air inside the balloon caused it to inflate to near fullness while the subliming powders accounted for the remainder of the inflation.

Since Pageos is a completely passive satellite devoid of any transmitting equipment, it is essential that its inflation be entirely favorable to present a standard optical target for observers performing various experiments around the globe.

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1. Operations Plan 6-66, Passive Geodetic Satellite (Pageos) X-513-66-229, GSFC

Requested Parameters

At the request of the Pageos Project, the Optical Systems Branch undertook an experiment to determine two desiderata.

1. The apparent visual magnitude of the satellite.

2. Periodic fluctuations in the brightness of the satellite which would tend to indicate an imperfect inflation.

The Tracking Experiment

On the morning of June 25, 1966, the Pageos satellite made a pass over the horizon of the Goddard Optical Research Facility which the Optical Systems Branch observed. Employed in this operation was a new type satellite tracking telescope known as RADOT. Installed on a two axis X-Y mount, RADOT is a Real Time Automatic Digital Optical Tracker. Consisting of a 12-inch optical Cassegrain system integrated with a modified BX-7 image orthicon network, the completed tracker can automatically find, lock on, and track satellites down to the 7th magnitude. Shaft angle encoders are employed to aid in printing out in real time the X-Y coordinates of where the optical axis is pointing.

In this experiment, a Questar telescope was attached to the optical tube of the RADOT and boresighted to its optical system (Figure 1). The Questar is a 3.5 inch aperture catadioptric telescope of 45 inches effective focal length. A diaphram was positioned in the focal plane of the Questar, with a 0.08 inch hole in its center through which the focused light of a star or satellite passed. A 14 stage Amperex 56 TVP phototube was placed behind the diaphram with its cathode surface 1.5 inches back of the hole. A Mosley X-Y recorder attached to the phototube provided a permanent continuous record of the brightness of the Pageos satellite during this passage and also of the fluctuations in its brightness.

Experiment Instrumentation

The Questar telescope in normal usage has a field of view of 55 arc minutes. However, for this experiment the field of view was limited to six arc minutes by means of a 0.08 inch hole located in the focal plane. This reduction of the Questar field was made for two reasons:

1. To limit the sky background viewing and hence increase the probability of Pageos detection.

2. To coincide with the RADOT acquisition field which is also six arc minutes.

The automatic tracking field of the RADOT system is on the order of 40 arc seconds. This then necessitated the Questar being nearly perfectly boresighted to the RADOT instrument so that its six minute field and that of Questar coincide at all pointing angles. Boresighting was accomplished using the star Polaris and checked against other stars in all four viewing quadrants.

Located 1.5 inches behind the focal plane hole was a 14 stage Amperex 56 TVP photomultiplier having an S-20 spectral response. The PM was operated at 2300 volts applied giving an overall current gain on the order of 10^8. Its output was loaded with a 10 kilohm resistor so that an increase of one microampere of output current would give rise to a voltage increase of 10 millivolts. In order to further enhance any Pageos fluctuations, the generated voltages were fed to a HP425A VTVM as shown in Figure 2.

The VTVM served both to reduce the possibility of loading on the photomultiplier output and as a X10 amplifier. It was further used as an operator's boresighting aid giving positive indications as to when a star was centered in the Questar's field. The output of the VTVM was coupled into the Mosley X-Y recorder and additionally into a CEC recorder.

The Mosely X-Y recorder was used to record and obtain a permanent record of the Pageos magnitude and fluctuations. Additionally the CEC recorder was AC coupled to the photomultiplier and was used to obtain a record of fluctuations having a period of less than 20 milliseconds. It was additionally used to record timing information for later data reduction.

Prior to the scheduled Pageos pass all of the electronic instruments were calibrated. One calibration check consisted of using an accurately known power supply voltage to calibrate the VTVM and VTVM X-Y recorder combination. The second calibration consisted of detecting various stars and recording their deflections for later Pageos comparisons. These stars, which were close to the same spectral type of the sun, then formed the basis of the Pageos magnitude determination.

Comparison Star Recording

Prior to the beginning of the pass, brightness readings were attempted on several stars. However, because of the prevailing hazy skies, only one reliable recording was obtained of the star ϵ Cygni, magnitude 2.64, spectral type KO, at $07^h\ 40^m$ U.T. The altitude, h, of the star at the time of observation was computed to be $84^\circ\!.8$ from the altitude formula,

$$\sin h = \sin\phi \sin\delta + \cos\phi \cos\delta \cos t$$

where,

$\Phi = +39° \; 01' \; 11''$

$\lambda = +76° \; 49' \; 33''$

$t = 359° \; 59\overset{'}{.}8$

$\alpha = 20^h \; 44^m \; 52^s$

$\delta = +33° \; 50' \; 24''$

Figure 3 illustrates the recordings of ϵ Cygni showing its values above the background sky level which are the minimum readings of its curve. Its average amplitude above the background sky was measured to be 5.23 inches.

Pageos Recording

Figure 4 is a reproduction of the recording obtained of the Pageos passage. The horizontal scale is one inch equals 50 seconds of time, while the vertical scale is one inch equals 20 millivolts.

Although the satellite rose above the horizon at approximately $07^h \; 47^m$ U.T. in the southeast, the sky there was too hazy to obtain dependable information until about $07^h \; 58^m$ when Pageos was at an elevation of about 27°. Tracking therefore began at $07^h \; 58^m$ and ended at $08^h \; 31^m$ when it was at an altitude of about 12° in the north.

A visual inspection of the graph makes it quite evident that what is present is a light curve with a periodic fluctuation superimposed upon it. If we draw a curve that encompasses the portion of the graph below the periodic rises, we then obtain the normal appearing curve resulting from a point source approaching and receding from an observer. This type of graph is shown in Figure 5 which is the normalized graph of $1/r^2$ for this pass, in which r is the slant range in kilometers.

Since the satellite is fabricated of 0.5-mil thick mylar film with a vapor deposited aluminum on the outside surface, its reflected light is mainly specular, about 88% so. A graph, Figure 6, was therefore plotted of the formula given by Koskela,[2]

$$m_v = m_o + 5 \log \frac{\rho}{a_v} - 2.5 \log \gamma + 1.505 + A$$

relating the magnitude, m_v, of a specular reflecting balloon with its slant range ρ, radius a_v, albedo γ, atmospheric abosrption in magnitudes A, and where the magnitude of the sun, m_o, equals -26.7. The intention was to see how closely a graph of magnitude due mainly to specular reflection versus time would approximate the curve obtained for Pageos. There is a definite similarity to the portion of the Pageos curve below the periodic rises. However there is a difference of approximately one-third of a magnitude between the brightness observed of Pageos on its average curve and this predicted curve at their maxima. There is a difference of approximately 0.6 magnitude between the maxima of the predicted curve and the brightest flash sequence of Pageos as will be brought out in the next section.

Figure 7 is a plot of the atmospheric absorption formula,

$$\text{Absorption} = 0^{m}.21 \sec Z$$

where Z is the zenith distance of a point source. The times listed upon the graph cover that portion of the pass which underwent an analytical treatment.

Magnitude of Pageos

The recorded Pageos brightness graph shows that at about $08^{h}\ 11^{m}\ 35^{s}$ U.T. the light of the satellite reached a maximum. RADOT output reveals that at

2. 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

$08^h11^m13^s$ U.T. the satellite reached a maximum elevation of 52°94. At the former time, the readings on the graph for the peak of the periodic flare-up and for the normal curve below it are respectively 8.30 and 6.80 inches above background sky.

Applying the usual brightness, l, formula for the difference in magnitude of two point sources,

$$m_1 - m_2 = -2.5 \log \frac{l_1}{l_2}$$

and using the companion star, ε Cygni, magnitude 2.64, reading of 5.23 inches at 84°8 altitude, we obtain,

$$m_{PAG.} - 2.64 = -2.5 \log \frac{8.30}{5.23}$$

$$m_{PAG.} = +2.14$$

at the peak of its flashes, and

$$m_{PAG.} - 2.64 = -2.5 \log \frac{6.80}{5.23}$$

$$m_{PAG.} = +2.36$$

at the top of its normal curve.

Since the difference in atmospheric absorption for zenith distances of 5°2 and 37°1 is 0.05 magnitude from Figure 7, we apply this difference to each of the two computed magnitudes. Doing this gives a final rounded magnitude of +2.1 for the peak magnitude reached during this pass and +2.3 for the brightest magnitude of the average curve of Pageos devoid of periodic flashes.

Periodic Fluctuations

A visual inspection of the graph shows that the periodic fluctuation in the brightness of Pageos is approximately two minutes of time. A more rigorous solution was desired and a power spectrum analysis was attempted. Since this procedure required data equally spaced in time, only that portion of the graph between $08^h\ 02^m$ and $08^h\ 20^m$ was used. Values on the graph were selected at each 5 seconds of time and where the satellite temporarily went out of the tracking field for more than 5 seconds, an interpolated value of the brightness was used.

The standard technique of autocorrelation spectral density analysis was used to determine the fluctuation period. The formulas used for the analysis were the following; i.e. the autocorrelation function being

$$C(\tau) = \frac{1}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} F(t)F(t-\tau)dt$$

where τ = lag time

$\tau = 0 - \tau_{max}$ $\tau_{max} = 50\Delta t$

T = Entire interval of time $\Delta t = 5$ sec.

The autocorrelation function gives an indication of the existence of a period inherent in the data. To confirm the presence of such a periodicity, it is necessary to evaluate the spectral density function. This is readily obtained by taking the Fourier transform of the autocorrelation function; that is, the Fourier transform of the above integral is expressed as follows:

$$P(f) = \int_{0}^{\tau_{max}} C(\tau)\cos 2\pi f\tau d\tau$$

where

$f = n\Delta f$ Δf = resolution

max freq $f_n = \frac{1}{2\Delta t}$ $\Delta f = 0.002$ cps

and the power spectrum, P(f) will peak at the suspected period.

On Figure 9, the power spectrum peaks at $n = 4.3$ which corresponds to a frequency of 8.6×10^{-3} cycles per second or a period of approximately 116 seconds.

Figure 8 is the power spectrum of the raw data before filtering out the effect of the mean light curve of Pageos, i.e., the light curve devoid of the flashes of light. Figure 9 illustrates the effect of filtering out from the data the mean light curve of the satellite. The periods other than 116 seconds indicated on Figure 9 are questionable due to being introduced by the polynomial filter used.

ACKNOWLEDGEMENTS

The authors wish to thank the following persons for assistance in this experiment, their colleagues in the Optical Systems Branch, the Messrs. D. A. Premo, E. G. Reid and H. E. Walker for assembling and operating the recording apparatus herein used; the Messrs. J. R. Cook and J. D. Stewart of Scientific Data Systems and Bendix Field Engineering respectively for operating the RADOT instrument during the pass and Mr. B. J. Conrath of the Planetary Radiations Branch for performing the power spectrum analysis on the observed data.

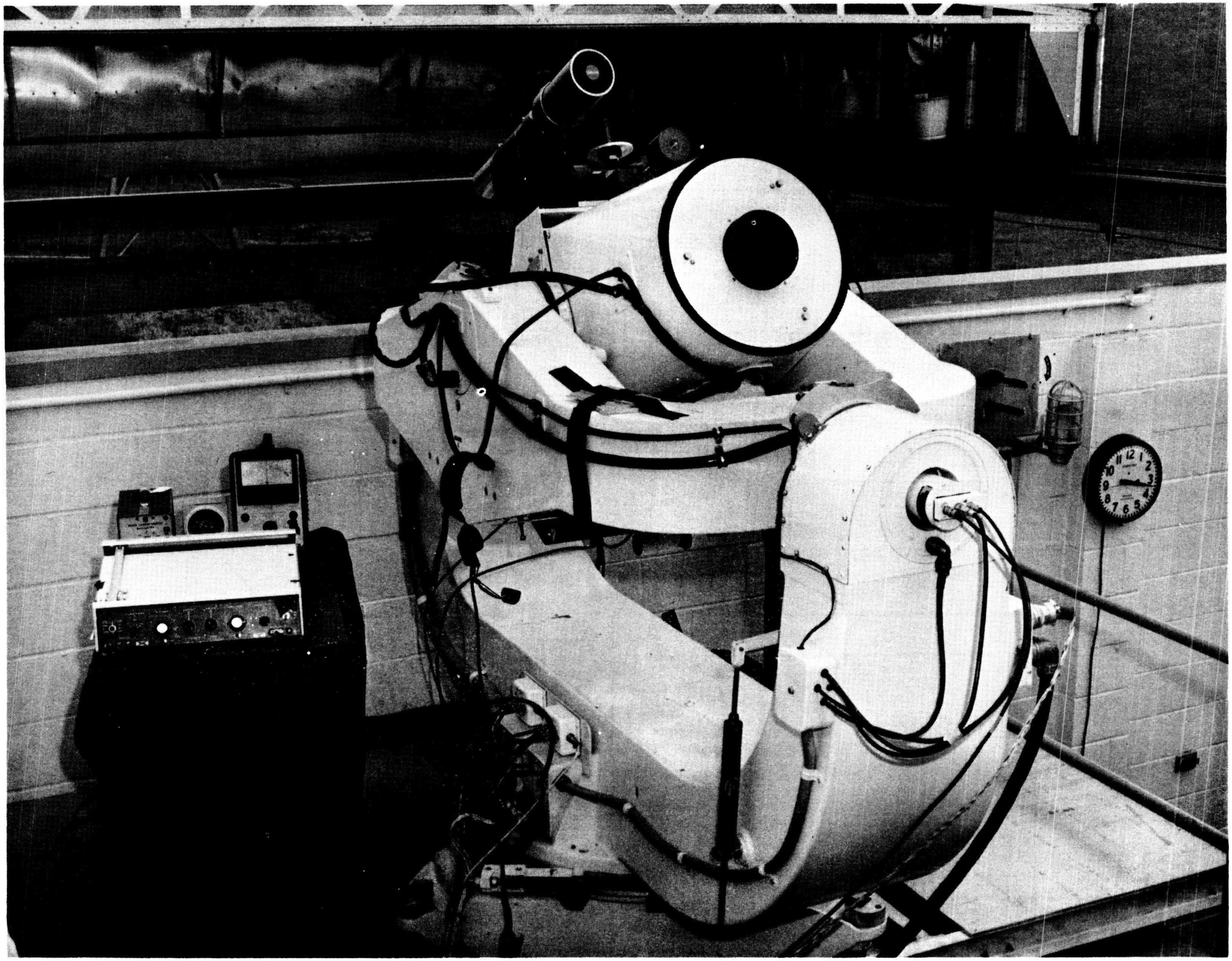


FIGURE 1. THE RADOT INSTRUMENT PLUS RECORDING APPARATUS USED TO TRACK PAGEOS.

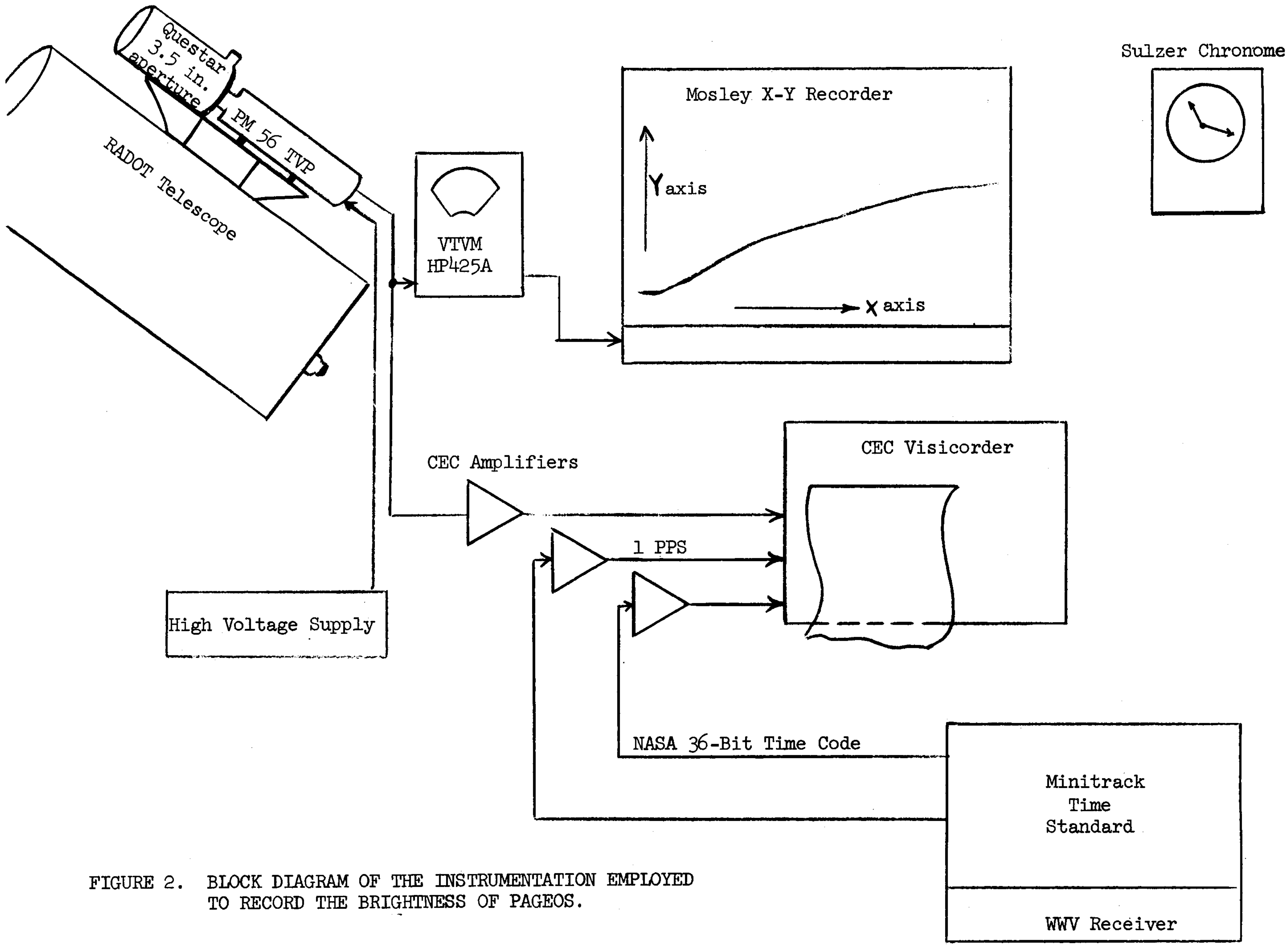


FIGURE 2. BLOCK DIAGRAM OF THE INSTRUMENTATION EMPLOYED TO RECORD THE BRIGHTNESS OF PAGEOS.

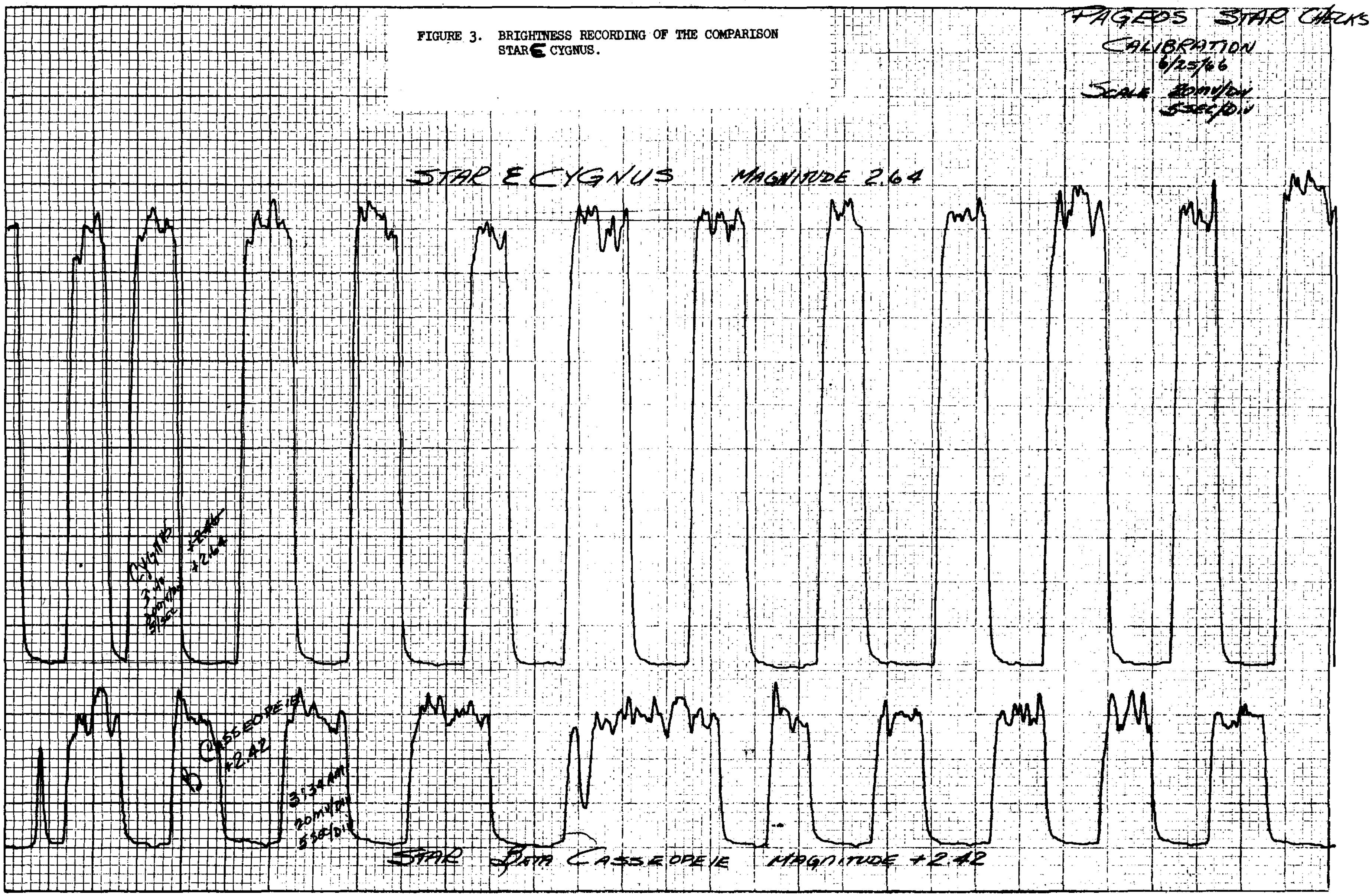


FIGURE 3. BRIGHTNESS RECORDING OF THE COMPARISON STAR € CYGNUS.

FIGURE 4A. BRIGHTNESS RECORDING OF THE PAGEOS SATELLITE.

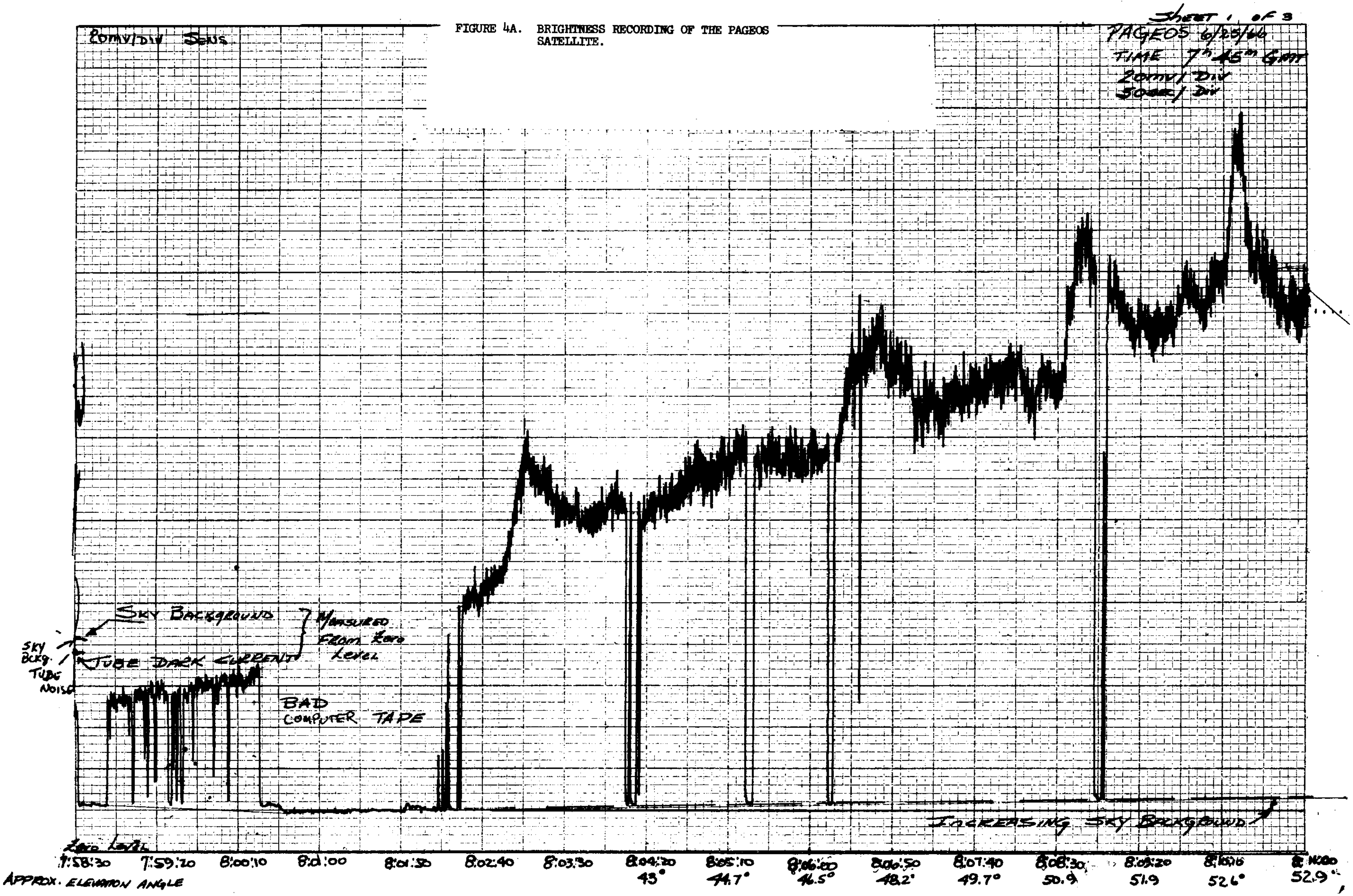


FIGURE 4B. BRIGHTNESS RECORDING OF THE PAGEOS SATELLITE (CONTINUED)

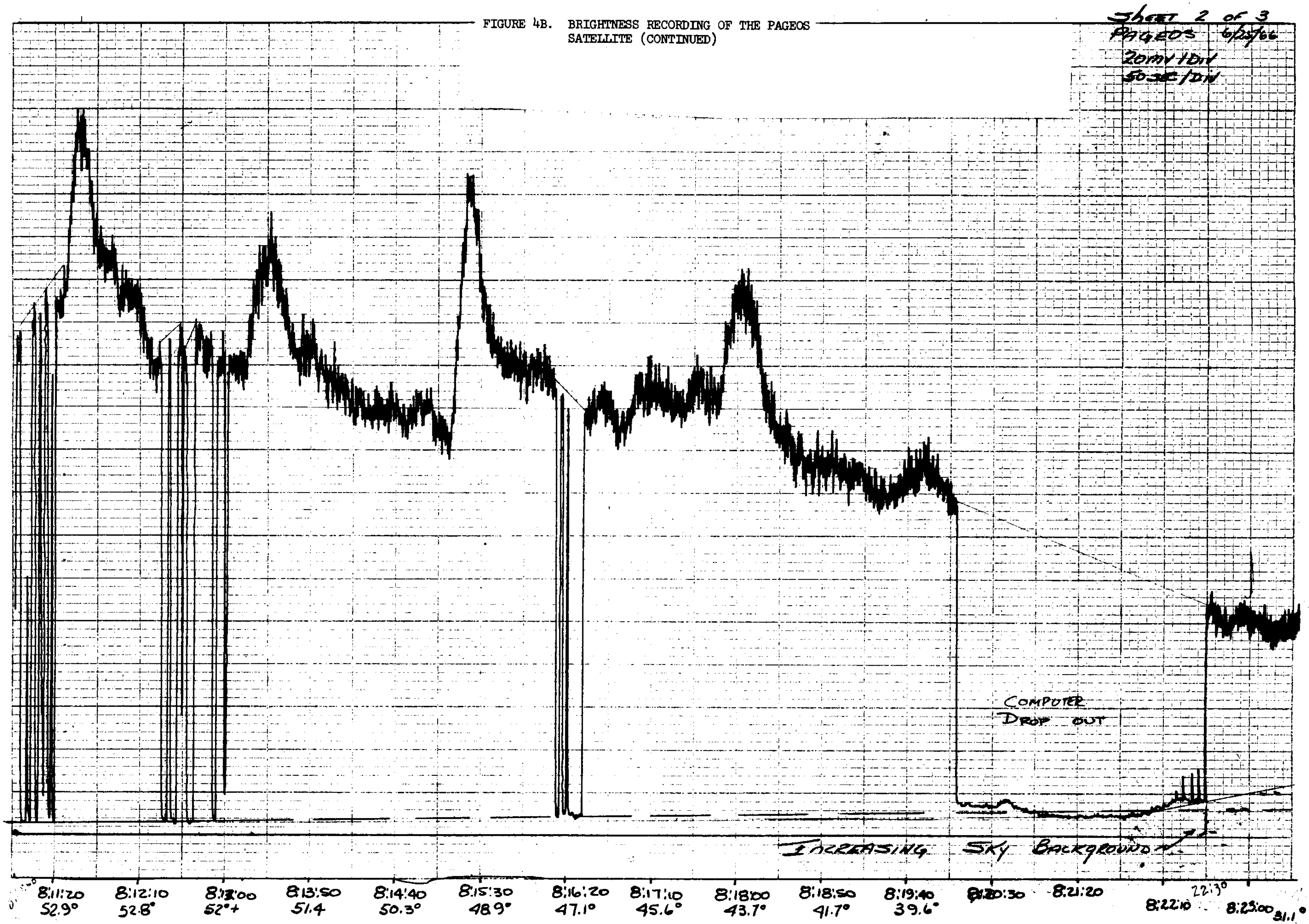
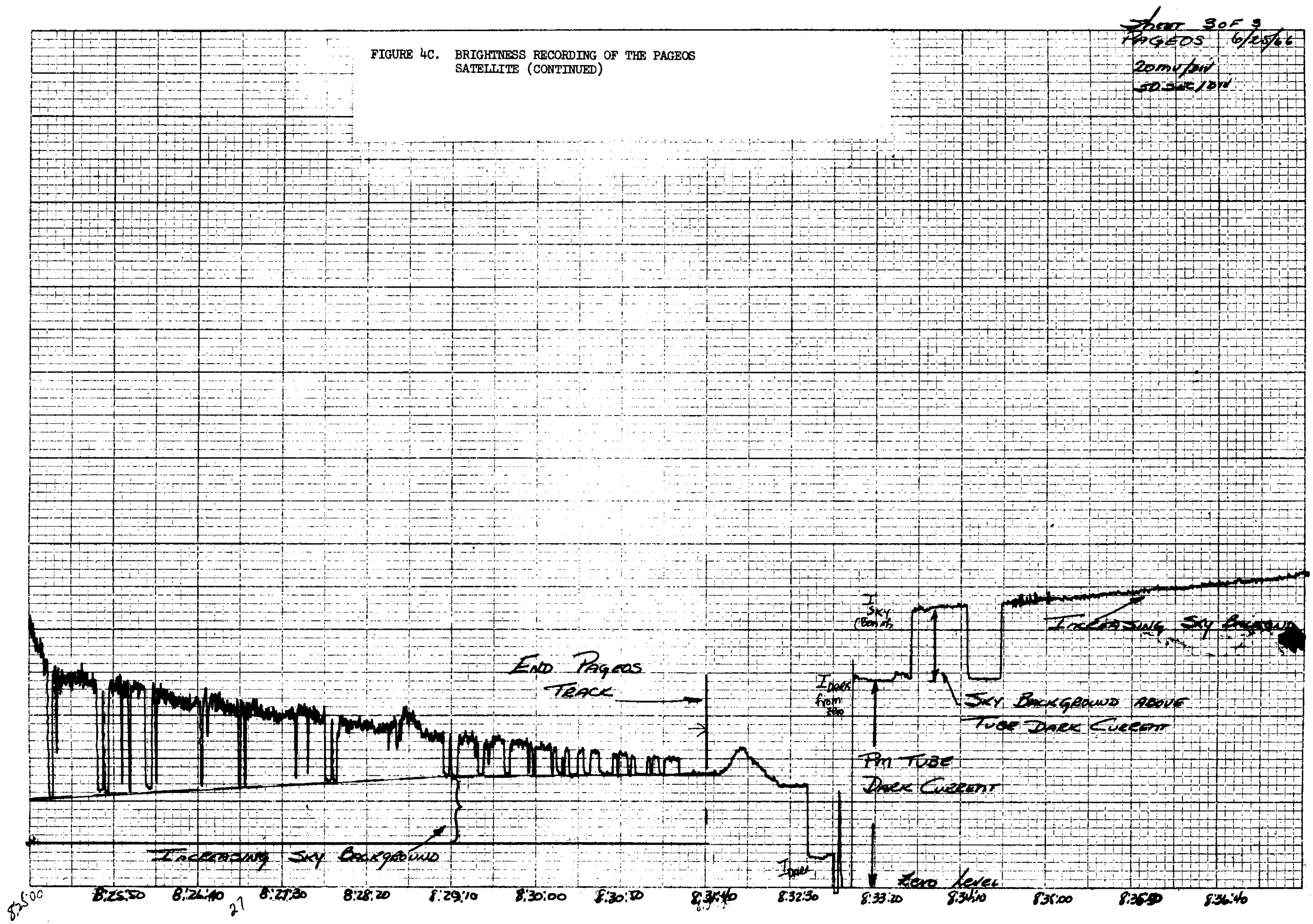


FIGURE 4C. BRIGHTNESS RECORDING OF THE PAGEOS SATELLITE (CONTINUED)



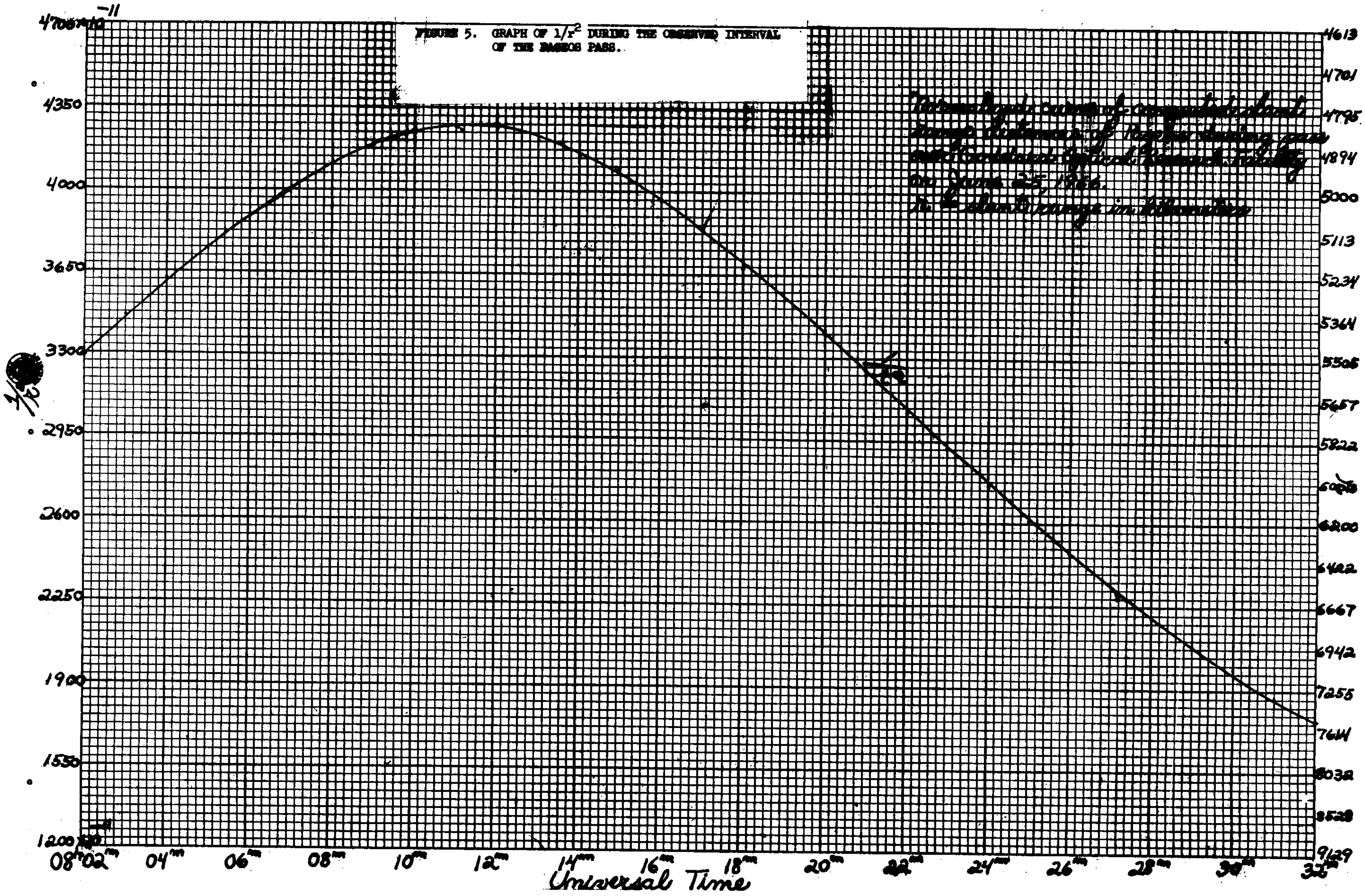
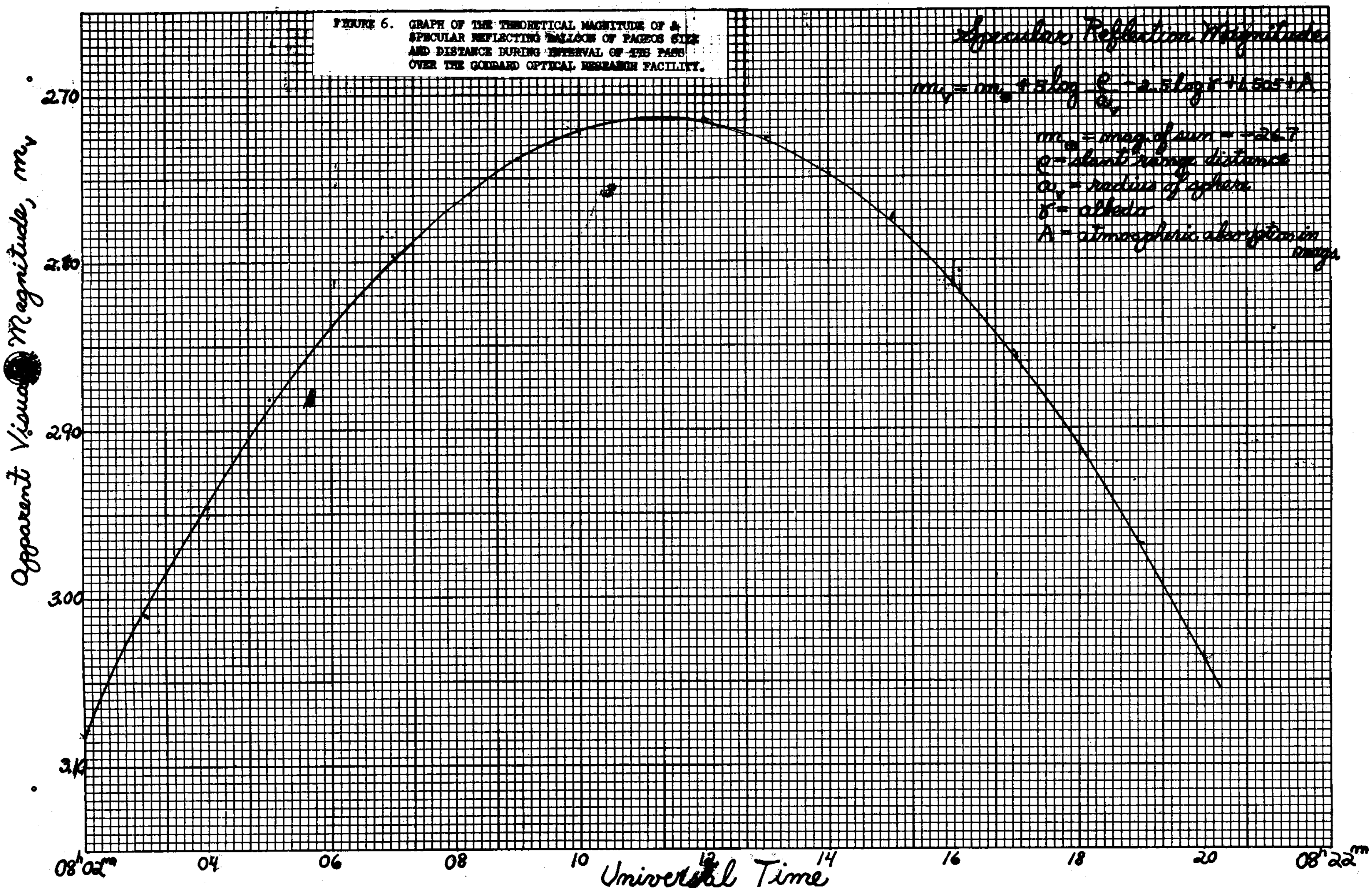


FIGURE 5. GRAPH OF $1/r^2$ DURING THE OBSERVED INTERVAL OF THE PAGEOS PASS.

FIGURE 6. GRAPH OF THE THEORETICAL MAGNITUDE OF A SPECULAR REFLECTING BALLOON OF PAGEOS SIZE AND DISTANCE DURING INTERVAL OF THE PASS OVER THE GODDARD OPTICAL RESEARCH FACILITY.



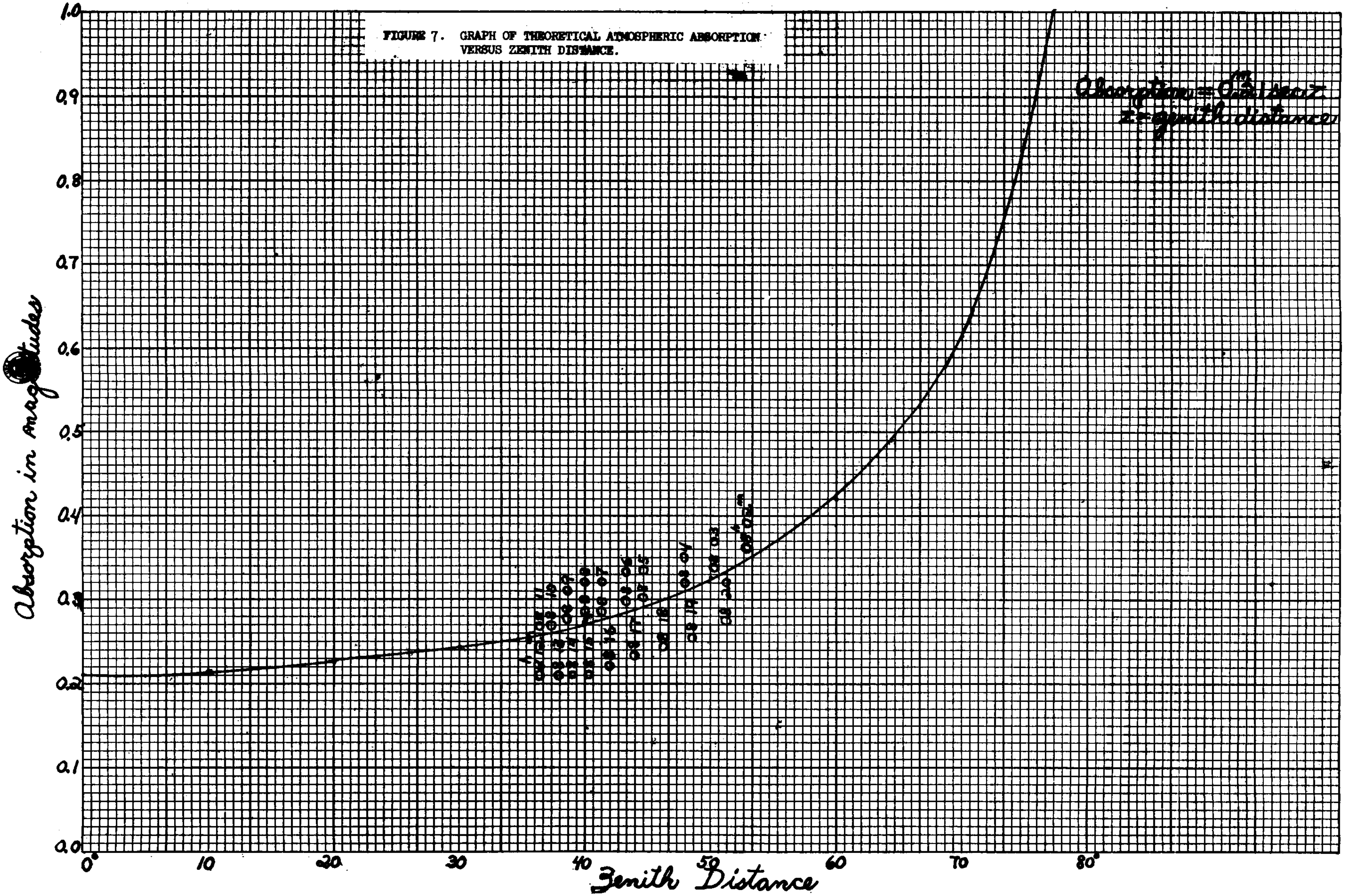


FIGURE 7. GRAPH OF THEORETICAL ATMOSPHERIC ABSORPTION VERSUS ZENITH DISTANCE.

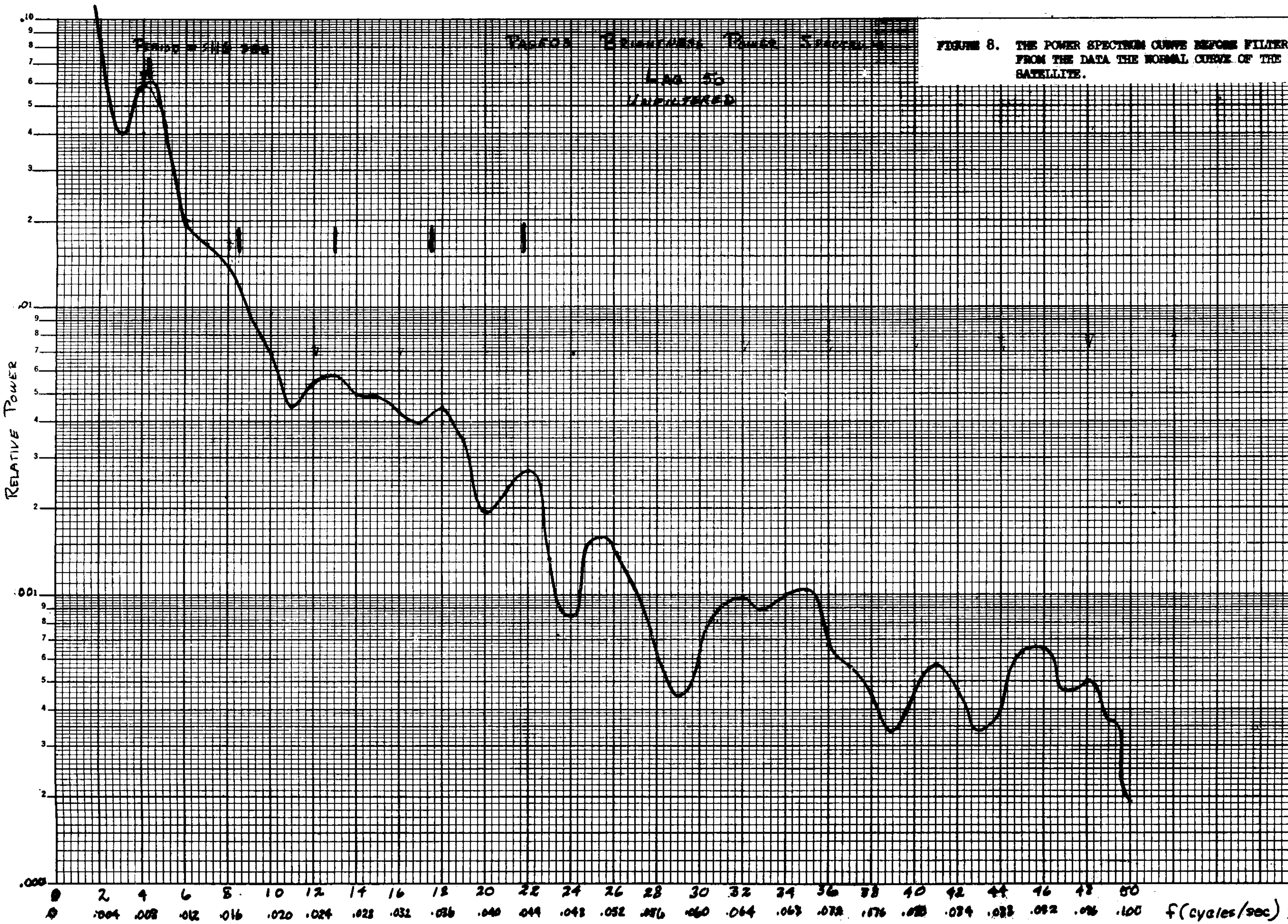


FIGURE 8. THE POWER SPECTRUM CURVE BEFORE FILTERING FROM THE DATA THE NORMAL CURVE OF THE PAGEOS SATELLITE.

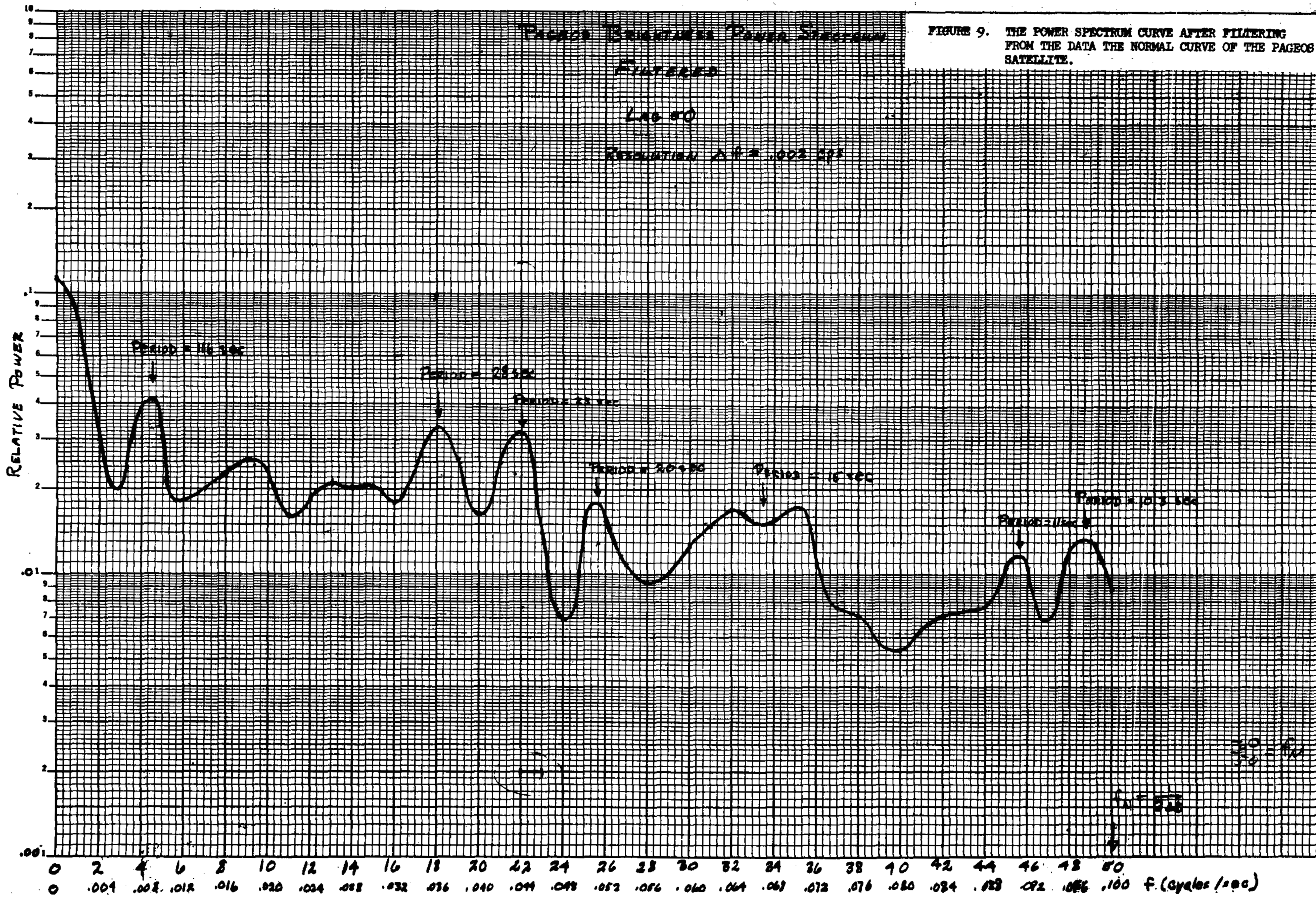


FIGURE 9. THE POWER SPECTRUM CURVE AFTER FILTERING FROM THE DATA THE NORMAL CURVE OF THE PAGEOS SATELLITE.