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ATMOSPHERIC DENSITIES AND TEMPERATURES FROM THE DRAG
ANALYSIS OF THE SAN MARCO SATELLITE

by

Luigi G. Jacchia and Franco Verniani

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ATMOSPHERIC DENSITIES AND TEMPERATURES FROM THE DRAG
ANALYSIS OF THE SAN MARCO SATELLITE¹

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Luigi G. Jacchia² and Franco Verniani³

13840
Abstract.--Atmospheric densities have been obtained from the drag analysis of the San Marco Satellite in the interval from December 19, 1964, to February 11, 1965. Temperatures have been computed from the densities using Jacchia's 1964 atmospheric model. The analysis is based on field-reduced Baker-Nunn observations and on Mini-track observations.

Author

Introduction

The San Marco Satellite (1964-84a) was launched on December 15, 1964, in an orbit with an eccentricity of 0.045, an inclination of 37.8, and a mean perigee height close to 200 km. It is a nearly spherical object with a diameter of 66 cm and a mass of 115 kg. According to information received from the National Aeronautics and Space Administration, the area-to-mass ratio is 0.032 cm²/g.

The San Marco Satellite was launched with the primary purpose of measuring atmospheric density through a dynamometer. Therefore, the densities obtained from the analysis of the atmospheric drag on this satellite are presented here for comparison with those obtained from the measurements. The results are based on the field-reduced Baker-Nunn observations and on Minitrack observations. The analysis covers the period from December 19, 1964, to February 11, 1965, a date close to the end of the active life of the satellite.

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Densities and temperatures

The methods used to determine orbital accelerations and then to arrive at values of the atmospheric density are essentially those described by Jacchia and Slowey (1962). Densities were computed by numerical integration of Sterne's integral in a form that includes the effect of atmospheric rotation (1959); the value of the drag coefficient C_D was taken, as before, to be 2.2. Jacchia's last atmospheric model (1964) was used for the integration. The results of the analysis are given in Table 1, which contains the following quantities:

- MJD : time in Modified Julian Days. $MJD = JD - 2400000.5$.
The tabulation is ordinarily at 0.5-day intervals, except during magnetic storms (0.2-day intervals). In the 5-day interval from MJD 38793 to MJD 38798, which was poorly covered by observations, the tabulation is at 1-day intervals.
- \dot{P} : the observed rate of change of the anomalistic period P .
Since this satellite has very low perigee heights, the effect of radiation pressure on P is completely negligible compared to atmospheric drag.
- $\log \rho_{\pi}$: the decimal logarithm of the atmospheric density in g/cm^3 at perigee height.
- $\log \rho_s$: the decimal logarithm of the atmospheric density in g/cm^3 at a standard height of 200 km.
- T_{π} : the exospheric temperature in $^{\circ}K$ at the perigee, computed from Jacchia's 1964 model.
- z : the height of the perigee in km.
- $\alpha_{\pi} - \alpha_{\odot}$: the difference in degrees between the right ascension α_{π} of the perigee and the right ascension α_{\odot} of the sun.
- $\delta_{\pi} - \delta_{\odot}$: the difference in degrees between the declination δ_{π} of the perigee and the declination δ_{\odot} of the sun.
- T_N : the nighttime exospheric temperature in $^{\circ}K$ computed from T_{π} and Jacchia's 1964 model.

The logarithm of the observed atmospheric density at the standard height of 200 km, the logarithm of the density computed from Jacchia's 1964 model, and the residuals $\log \rho_{\text{obs}} - \log \rho_{\text{comp}}$ are plotted as functions of time in Figure 1, together with the smoothed geomagnetic indices \bar{K}_p and \bar{a}_p , the solar decimetric flux $F_{10.7}$, and the theoretical curve of the diurnal variation.

The standard deviation of 1 observation is 0.022 in $\log \rho$. If we had assumed that all the scatter in the residuals is due to random errors in the determination of the atmospheric density, this figure would correspond to a probable error of 3.5 percent in our determinations. This is obviously not the case: the density variations of the atmosphere could not possibly have been taken into account without error, so the actual relative precision of our density determinations must be greater.

According to our information, experiments involving the extrusion of an antenna should have been performed on the satellite on January 29 (MJD 38789). These experiments may have had the effect of altering the presentation area of the satellite. If so, the effect must have been a minor one because our data do not show any discontinuity on that day.

Density variations with geomagnetic activity

During the period covered by this analysis there were several enhancements of geomagnetic activity as shown by the values of \bar{K}_p and \bar{a}_p (see Fig. 1). As usual, similar variations can be recognized in the density curve. In order to determine the time lag between the increase in the magnetic activity and the subsequent increase of the atmospheric density, we have plotted the 3-hour values of K_p and a_p and then drawn a smoothed curve directly comparable with the curve of the density, where the actual resolution in time is generally smaller than 3 hours. To increase the accuracy of the detection of the time of occurrence of the density peaks, we took these times directly from the mean anomaly curve and compared them with the times of occurrence of peaks in the smoothed curve for K_p . The result is an average time lag

(at the height of 200 km and at low latitudes) of 9 hours with a probable error of 1 or 2 hours. This lag is a little larger than the 5-hour lag determined by Jacchia and Slowey (1964) from a precision analysis of the Explorer IX Satellite and confirmed by Roemer (1965) on the basis of an extension of the analysis for the same satellite. But since the lag was derived from very limited data, the difference should not be taken too seriously. A more extensive survey of the time lag is in progress, involving satellites of different perigee heights and inclinations.

The mean of the residuals in $\log \rho$ is -0.035 ; in other words, the "observed" densities are systematically smaller than those of Jacchia's 1964 model by 8 percent. Since this discrepancy is within the margin of error caused by the uncertainties in the assumed drag coefficient and the area-to-mass ratio of the satellite, it should not necessarily be taken to indicate a real departure from the model atmosphere.

Orbital elements

As a preliminary step in the determination of the atmospheric drag, orbital elements were computed for the satellite from 4-day arcs at 1-day intervals. The time lapse covered by the observations was then divided into 2 intervals of the length of 33 and 32 days, respectively, with a 12-day overlap, and analytical functions were fitted by least squares to the elements within the 2 intervals. Table 2 gives the results of these least-squares fittings. It should be remembered that, while the expressions for ω , Ω , i , and e can be considered as representing the elements without systematic residuals, the same is not true of M , in which systematic residuals up to 10^{-3} revolutions are tolerated.

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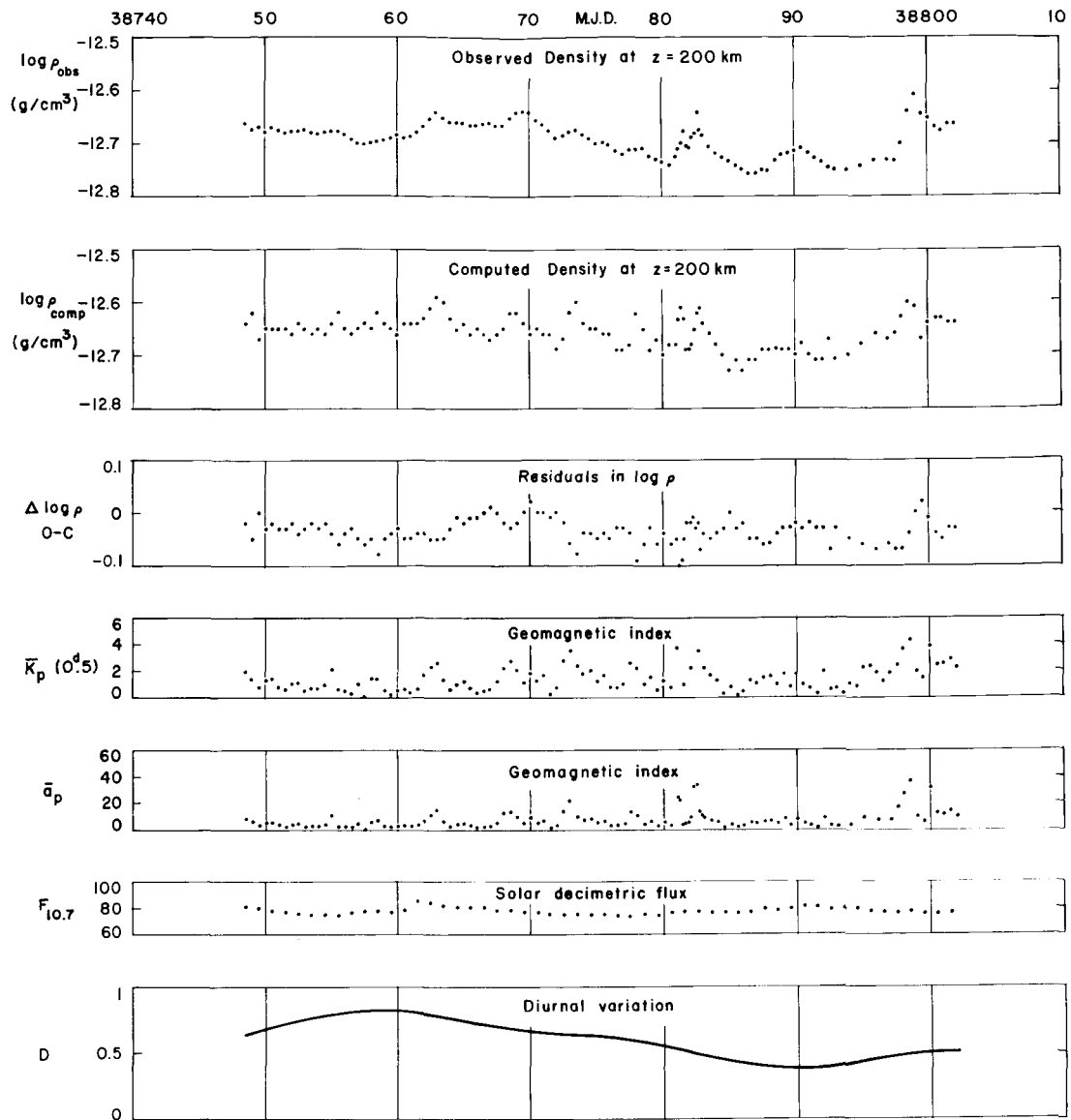


Figure 1.--Atmospheric densities determined from the orbital drag of Satellite 1964-84A (San Marco). Observed densities (top section) are compared with densities computed from Jacchia's 1964 model, taking into account the observed values of the geomagnetic index and the 10.7-cm solar flux, the diurnal factor, and the semiannual effect; residuals are plotted in the third section. MJD is the Modified Julian Day (JD minus 2,400,000.5). The half-day mean of the 3-hourly K_p index is $\bar{K}_p(0.5)$. The mean of the 3-hourly a_p index is \bar{a}_p taken over an interval equal to the resolution in the drag. The 10.7-cm solar flux $F_{10.7}$ is in units of 10^{-22} watts/m²/cycle/sec bandwidth.

Table 1.--Accelerations, atmospheric densities, atmospheric temperatures, and geometric parameters (see text for full explanation of the symbols)

| MJD | $10^{-6} \ddot{P}$ | $\log \rho_{\pi}$ | $\log \rho_s$ | T_{π} | z | $\alpha_{\pi} - \alpha_{\odot}$ | $\delta_{\pi} - \delta_{\odot}$ | T_N |
|---------|--------------------|-------------------|---------------|-----------|-------|---------------------------------|---------------------------------|-------|
| 38748.5 | 11.01 | -12.700 | -12.664 | 761 | 202.1 | 85.2 | 45.9 | 645 |
| 49.0 | 10.76 | .704 | .675 | 749 | 201.7 | 85.3 | 43.8 | 633 |
| 49.5 | 11.02 | .693 | .670 | 754 | 201.3 | 85.3 | 41.6 | 635 |
| 50.0 | 10.74 | .699 | .681 | 742 | 201.0 | 85.2 | 39.3 | 623 |
| 50.5 | 11.11 | .686 | .672 | 752 | 200.8 | 85.0 | 37.0 | 630 |
| 51.0 | 10.98 | .688 | .677 | 746 | 200.6 | 84.8 | 34.6 | 623 |
| 51.5 | 10.83 | .691 | .682 | 741 | 200.5 | 84.5 | 32.2 | 617 |
| 52.0 | 10.97 | .686 | .678 | 746 | 200.5 | 84.2 | 29.8 | 619 |
| 52.5 | 10.93 | .687 | .678 | 746 | 200.6 | 83.9 | 27.3 | 617 |
| 53.0 | 10.92 | .688 | .676 | 748 | 200.7 | 83.5 | 24.8 | 617 |
| 53.5 | 10.67 | .697 | .680 | 743 | 201.0 | 83.1 | 22.3 | 611 |
| 54.0 | 10.46 | .705 | .683 | 740 | 201.3 | 82.8 | 19.8 | 607 |
| 54.5 | 10.37 | .710 | .681 | 742 | 201.7 | 82.4 | 17.3 | 607 |
| 55.0 | 10.27 | .716 | .679 | 744 | 202.1 | 82.1 | 14.8 | 608 |
| 55.5 | 10.13 | .724 | .678 | 746 | 202.7 | 81.8 | 12.3 | 608 |
| 56.0 | 9.69 | .743 | .685 | 738 | 203.3 | 81.6 | 9.9 | 601 |
| 56.5 | 9.20 | .765 | .694 | 728 | 204.0 | 81.5 | 7.5 | 592 |
| 57.0 | 8.74 | .787 | .702 | 720 | 204.7 | 81.5 | 5.2 | 585 |
| 57.5 | 8.52 | .800 | .702 | 720 | 205.4 | 81.5 | 2.9 | 584 |
| 58.0 | 8.31 | .814 | .702 | 720 | 206.1 | 81.7 | 0.7 | 585 |
| 58.5 | 8.18 | .824 | .698 | 724 | 206.9 | 81.9 | -1.4 | 588 |
| 59.0 | 8.08 | .833 | .694 | 728 | 207.7 | 82.3 | -3.4 | 591 |
| 59.5 | 7.97 | .842 | .690 | 732 | 208.4 | 82.9 | -5.3 | 595 |
| 60.0 | 7.87 | .851 | .687 | 736 | 209.1 | 83.6 | -7.1 | 598 |
| 60.5 | 7.63 | .866 | .689 | 734 | 209.8 | 84.4 | -8.7 | 597 |
| 61.0 | 7.50 | .876 | .687 | 735 | 210.4 | 85.4 | -10.2 | 599 |
| 61.5 | 7.55 | .877 | .680 | 742 | 210.9 | 86.5 | -11.5 | 606 |
| 62.0 | 7.74 | .871 | .670 | 754 | 211.4 | 87.8 | -12.6 | 617 |
| 62.5 | 8.09 | .859 | .655 | 770 | 211.8 | 89.2 | -13.5 | 631 |
| 63.0 | 8.45 | .846 | .642 | 785 | 212.0 | 90.7 | -14.2 | 645 |
| 63.5 | 8.07 | .863 | .653 | 774 | 212.2 | 92.3 | -14.7 | 636 |
| 64.0 | 7.76 | .877 | .662 | 763 | 212.3 | 93.9 | -15.0 | 629 |
| 64.5 | 7.80 | .876 | .661 | 764 | 212.3 | 95.5 | -15.0 | 631 |
| 65.0 | 7.82 | .874 | .662 | 763 | 212.2 | 97.1 | -14.9 | 632 |
| 65.5 | 7.76 | .876 | .666 | 758 | 212.0 | 98.7 | -14.5 | 629 |
| 66.0 | 7.89 | .868 | .665 | 759 | 211.7 | 100.2 | -13.8 | 632 |
| 66.5 | 8.07 | .859 | .663 | 761 | 211.3 | 101.6 | -13.0 | 635 |
| 67.0 | 8.26 | .848 | .662 | 763 | 210.8 | 102.8 | -11.9 | 637 |
| 67.5 | 8.36 | .841 | .664 | 760 | 210.2 | 104.0 | -10.7 | 636 |
| 68.0 | 8.53 | .831 | .665 | 759 | 209.6 | 105.0 | -9.3 | 637 |
| 68.5 | 9.24 | .800 | .650 | 776 | 208.9 | 105.8 | -7.8 | 652 |
| 69.0 | 9.83 | .775 | .641 | 788 | 208.2 | 106.5 | -6.1 | 663 |
| 69.5 | 10.17 | .760 | .638 | 791 | 207.4 | 107.0 | -4.3 | 666 |
| 70.0 | 10.32 | .750 | .641 | 787 | 206.6 | 107.4 | -2.4 | 664 |
| 70.5 | 10.09 | .753 | .655 | 771 | 205.8 | 107.7 | -0.3 | 651 |
| 71.0 | 10.10 | .748 | .662 | 763 | 205.1 | 107.8 | 1.8 | 645 |
| 71.5 | 9.95 | .748 | .674 | 749 | 204.3 | 107.9 | 3.9 | 634 |
| 72.0 | 9.78 | .750 | .688 | 735 | 203.6 | 107.8 | 6.2 | 623 |

Table 1.--Continued.

| MJD | $10^{-6} \dot{p}$ | $\log \rho_{\pi}$ | $\log \rho_s$ | T_{π} | z | $\alpha_{\pi} - \alpha_{\odot}$ | $\delta_{\pi} - \delta_{\odot}$ | T_N |
|---------|-------------------|-------------------|---------------|-----------|-------|---------------------------------|---------------------------------|-------|
| 38772.5 | 10.08 | -12.736 | -12.686 | 737 | 202.9 | 107.7 | 8.5 | 625 |
| 73.0 | 10.57 | .717 | .678 | 745 | 202.2 | 107.5 | 10.8 | 633 |
| 73.5 | 10.83 | .706 | .676 | 748 | 201.8 | 107.2 | 13.2 | 636 |
| 74.0 | 10.79 | .704 | .683 | 740 | 201.2 | 106.9 | 15.6 | 629 |
| 74.5 | 10.72 | .704 | .691 | 731 | 200.8 | 106.6 | 18.0 | 623 |
| 75.0 | 10.57 | .708 | .701 | 721 | 200.4 | 106.2 | 20.4 | 615 |
| 75.5 | 10.77 | .700 | .699 | 723 | 200.1 | 105.9 | 22.8 | 618 |
| 76.0 | 10.60 | .706 | .708 | 714 | 199.9 | 105.5 | 25.2 | 611 |
| 76.5 | 10.43 | .711 | .716 | 706 | 199.7 | 105.2 | 27.6 | 605 |
| 77.0 | 10.36 | .714 | .720 | 702 | 199.7 | 104.9 | 30.0 | 602 |
| 77.5 | 10.58 | .708 | .714 | 708 | 199.7 | 104.6 | 32.3 | 608 |
| 78.0 | 10.64 | .708 | .712 | 710 | 199.8 | 104.4 | 34.6 | 611 |
| 78.5 | 10.68 | .709 | .711 | 711 | 199.9 | 104.3 | 36.8 | 614 |
| 79.0 | 10.21 | .727 | .725 | 698 | 200.1 | 104.2 | 39.0 | 603 |
| 79.5 | 10.00 | .737 | .730 | 693 | 200.4 | 104.3 | 41.1 | 600 |
| 80.0 | 9.76 | .749 | .736 | 687 | 200.7 | 104.4 | 43.1 | 597 |
| 80.5 | 9.57 | .759 | .740 | 683 | 201.0 | 104.7 | 45.1 | 595 |
| 81.0 | 9.88 | .751 | .726 | 696 | 201.3 | 105.1 | 46.9 | 608 |
| 38781.2 | 10.32 | -12.737 | -12.711 | 711 | 201.5 | 105.3 | 47.6 | 622 |
| 81.4 | 10.62 | .729 | .700 | 722 | 201.6 | 105.5 | 48.3 | 631 |
| 81.6 | 11.35 | .708 | .678 | 745 | 201.8 | 105.7 | 48.9 | 653 |
| 81.8 | 10.36 | .740 | .706 | 716 | 201.9 | 106.0 | 49.6 | 628 |
| 82.0 | 10.23 | .745 | .709 | 713 | 202.0 | 106.3 | 50.2 | 626 |
| 82.2 | 10.85 | .727 | .689 | 733 | 202.2 | 106.6 | 50.8 | 645 |
| 82.4 | 11.05 | .722 | .682 | 741 | 202.3 | 106.9 | 51.4 | 652 |
| 82.6 | 12.42 | .684 | .644 | 783 | 202.4 | 107.2 | 51.9 | 690 |
| 82.8 | 11.22 | .719 | .675 | 748 | 202.6 | 107.6 | 52.4 | 660 |
| 38783.0 | 10.80 | -12.733 | -12.686 | 736 | 202.7 | 108.0 | 52.9 | 650 |
| 83.5 | 10.06 | .759 | .706 | 716 | 203.0 | 109.1 | 54.0 | 634 |
| 84.0 | 9.60 | .777 | .719 | 703 | 203.2 | 110.3 | 55.0 | 625 |
| 84.5 | 9.30 | .790 | .727 | 696 | 203.4 | 111.6 | 55.7 | 619 |
| 85.0 | 9.09 | .798 | .733 | 690 | 203.6 | 113.0 | 56.2 | 616 |
| 85.5 | 8.80 | .810 | .742 | 681 | 203.7 | 114.5 | 56.5 | 610 |
| 86.0 | 8.60 | .819 | .749 | 675 | 203.7 | 116.1 | 56.6 | 605 |
| 86.5 | 8.43 | .826 | .755 | 669 | 203.7 | 117.6 | 56.5 | 601 |
| 87.0 | 8.42 | .825 | .756 | 668 | 203.7 | 119.2 | 56.1 | 601 |
| 87.5 | 8.60 | .817 | .751 | 673 | 203.5 | 120.7 | 55.5 | 606 |
| 88.0 | 8.66 | .814 | .751 | 673 | 203.3 | 122.1 | 54.7 | 607 |
| 88.5 | 9.23 | .790 | .733 | 690 | 203.1 | 123.4 | 53.7 | 623 |
| 89.0 | 9.62 | .774 | .723 | 700 | 202.8 | 124.6 | 52.5 | 632 |
| 89.5 | 9.84 | .764 | .719 | 704 | 202.5 | 125.7 | 51.1 | 636 |
| 90.0 | 10.05 | .754 | .715 | 707 | 202.2 | 126.6 | 49.6 | 639 |
| 90.5 | 10.34 | .742 | .710 | 712 | 201.8 | 127.4 | 47.9 | 644 |
| 91.0 | 10.17 | .744 | .718 | 704 | 201.4 | 128.1 | 46.0 | 635 |
| 91.5 | 9.98 | .748 | .728 | 694 | 201.1 | 128.6 | 44.0 | 626 |
| 92.0 | 9.89 | .748 | .735 | 688 | 200.7 | 129.0 | 41.9 | 620 |
| 92.5 | 9.70 | .751 | .745 | 679 | 200.3 | 129.3 | 39.7 | 611 |

Table 1.--Continued.

| MJD | $10^{-6} \dot{P}$ | $\log \rho_{\pi}$ | $\log \rho_S$ | T_{π} | z | $\alpha_{\pi} - \alpha_{\odot}$ | $\delta_{\pi} - \delta_{\odot}$ | T_N |
|---------|-------------------|-------------------|---------------|-----------|-------|---------------------------------|---------------------------------|-------|
| 38793.0 | 9.67 | -12.750 | -12.749 | 675 | 200.0 | 129.4 | 37.4 | 607 |
| 94.0 | 9.78 | .741 | .750 | 674 | 199.5 | 129.4 | 32.6 | 604 |
| 95.0 | 10.06 | .728 | .743 | 681 | 199.2 | 129.1 | 27.5 | 607 |
| 96.0 | 10.34 | .717 | .733 | 690 | 199.2 | 128.6 | 22.3 | 613 |
| 97.0 | 10.22 | .722 | .733 | 690 | 199.4 | 128.0 | 16.9 | 611 |
| 38797.5 | 10.12 | -12.727 | -12.733 | 690 | 199.7 | 127.7 | 14.2 | 610 |
| 98.0 | 10.97 | .702 | .702 | 720 | 200.0 | 127.4 | 11.6 | 635 |
| 98.5 | 13.07 | .647 | .641 | 788 | 200.4 | 127.1 | 8.9 | 694 |
| 99.0 | 14.19 | .624 | .611 | 825 | 200.9 | 126.9 | 6.2 | 726 |
| 99.5 | 12.52 | .668 | .646 | 782 | 201.4 | 126.7 | 3.6 | 687 |
| 38800.0 | 12.02 | -12.685 | -12.653 | 773 | 202.0 | 126.6 | 1.0 | 678 |
| 00.5 | 11.35 | .709 | .666 | 759 | 202.6 | 126.5 | -1.6 | 665 |
| 01.0 | 10.74 | .732 | .677 | 746 | 203.2 | 126.6 | -4.1 | 654 |
| 01.5 | 10.95 | .730 | .665 | 759 | 203.9 | 126.7 | -6.5 | 665 |
| 02.0 | 10.69 | .743 | .667 | 758 | 204.5 | 127.0 | -8.8 | 664 |

Table 2.--Least-squares fitting of orbital elements for the San Marco Satellite; t = time in MJD; ω = argument of perigee; Ω = right ascension of the node; i = inclination; e = eccentricity; M = mean anomaly in node revolutions; $\tau = t - t_0$.

Section 1: MJD 38747 to 38780 (December 18, 1964, to January 20, 1965)

$$T_0 = 38747$$

$$\omega = 129.834 + 8.10353 \tau + 0.001555 \tau^2 + 0.738 \sin (226.97 + 8.19 \tau)$$

$$\Omega = 214.0175 - 6.053164 \tau - 8.402 \times 10^{-4} \tau^2 - 2.01 \times 10^{-6} \tau^3$$

$$i = 37.7970$$

$$e = 0.044696 - 1.1747 \times 10^{-4} \tau + 7.14 \times 10^{-7} \tau^2 + 4.16 \times 10^{-4} \sin (144.39476 + 8.194 \tau)$$

$$M = 0.5972 + 15.187150 \tau + 1.7866 \times 10^{-3} \tau^2 - 4.7484 \times 10^{-5} \tau^3 + 1.1727 \times 10^{-6} \tau^4 - 9.30 \times 10^{-9} \tau^5$$

Section 2: MJD 38768 to 38802 (January 8, 1965, to February 11, 1965)

$$T_0 = 38768$$

$$\omega = 301.015 + 8.1103 \tau + 3.071 \times 10^{-3} \tau^2 + 0.765 \sin (15.94 + 8.19 \tau)$$

$$\Omega = 86.5132 - 6.09070 \tau - 1.0134 \times 10^{-3} \tau^2 - 4.41 \times 10^{-7} \tau^3$$

$$i = 37.7963$$

$$e = 0.042866 - 1.132 \times 10^{-4} \tau + 5.12 \times 10^{-7} \tau^2 + 6.55 \times 10^{-4} \sin (297.50361 + 8.194 \tau)$$

$$M = 0.06515 + 15.232844 \tau + 1.22202 \times 10^{-3} \tau^2 + 6.0678 \times 10^{-6} \tau^3 - 4.4200 \times 10^{-7} \tau^4 + 7.0482 \times 10^{-9} \tau^5.$$

Errata to Special Report No. 193

Table 2. The fourth line of the heading should read
"e = eccentricity; M = mean anomaly in revolutions;"
In the table under Section 1 and Section 2
"T₀" should read "t₀."