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Tracking the GLOMR Satellite

by

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Abstract

The task of day-to-day low orbiting satellite tracking utilizing the NAVSPASUR orbital elements is discussed and methods for improving pass time predictions are presented. Estimates are needed for preprogramming of satellite-initiated communications scheduling which requires an accuracy of approximately 30 seconds. This can be achieved by removing the variance associated with the NAVSPASUR D_2 (decay) term. Finally, the "shock" evidenced in GLOMR's orbit on February 7, 1986 is documented and attributed to a severe solar storm with immediately enhanced drag. GLOMR's life expectancy in orbit is now estimated to have dropped approximately 17% with end of orbit in early February, 1987.

Background

STS 61-A lifted off on October 30, 1985, carrying aloft DARPA's GLOMR satellite stowed in its GAS canister fixed in the port section of the cargo bay. It was a flawless launch and the DSI ground control team anxiously awaited the deployment of the 64.5 kg store/forward communications satellite, GLOMR (Global Low Orbiting Message Relay). Just south of the Fox and Shumagin Islands of the Aleutian chain, on Orbit 9, about twelve and a half hours into the mission, GLOMR bolted gracefully from its "can" into a nearly circular orbit some 326 km above the Earth. The 62 faceted nearly spherical object, with its four top-mounted antennae, prompted astronaut Sally Ride to exclaim that it looked like something from Alien or Sesame Street! Finally, on Orbit 17, the craft passed solidly within DSI's McLean, Virginia-based line of sight and we completed our first contact, and thus began the GLOMR mission which was 259 days long on July 17, 1986. Complete details of the DSI GLOMR design, fabrication, certification, and mission are contained in the 1985 GAS Experimenter's Symposium paper titled "The GLOMR Satellite, Payload G-308".

Satellite Tracking and Operations

Once successfully deployed, GLOMR's position has been obtained on a periodic basis from NAVSPASUR "one-line" orbital data elements. Our operating technique often included the requirement to initiate contact with the spacecraft at a predetermined elevation angle and not before, if possible. Additionally, we chose not to carry over the communication into the region of highest rate of Doppler change, and thus limited our contact windows to two intervals on the ascending and descending portion of each significantly elevated pass. To operate successfully in this manner required timing accuracies on the order of about 30 seconds. The Keppler problem was solved using Brown's non-iterative solution together with the J_2 perturbation and a decay term provided as the NAVSPASUR element D_2. Calculational accuracy was maintained at double precision as predictions of satellite positions were converted to terrestrial azimuth and elevation angles and slant ranges according to an ellipsoidal Earth model. With these modest tools, we set out to "track" GLOMR over a long period of time but with projections forward by approximately ten to twenty days. Since GLOMR must initiate contact with the ground control station, it must normally be "programmed" via an uplinked series of communicate orders, i.e., a schedule. Then in accordance with the onboard clock, the internal orders are carried out based on the computed communication windows generated by the orbital model.

Observed Tracking Sensitivities

It was clear that the NAVSPASUR tracking software was unsettled within the first two weeks of operation on GLOMR. No decay term was reported during this interval and some of the orbital parameters exhibited fluctuations (see the orbital eccentricity data of Figure 1 during this period). After the initial settling period, the data elements have maintained consistent quality and characteristics. After two months in orbit, GLOMR exhibited a true period of regression of the line of nodes of 79.15 days (precession of the orbital plane) and a period of elliptic axis (line of apsides) rotation of 190.0 days (in the orbital plane). However, it was learned early on that the D_2 Decay Coefficient reported in radians per Herg squared was a potential problem. Major fluctuations are evident in this term as depicted in Figure 2. An analysis of the sensitivity of the tracking timing error due solely to these fluctuations in December 1985 showed that an error of +/-1 minute could result after 10 days, increasing up to +/-3 minutes in 26 days. If, instead of directly plugging in the NAVSPASUR D_2 term one were to compute the average or "smoothed D_2-Value" and use this instead, tracking error was reduced by 84% (i.e., from -178 seconds down to -29 seconds). It is presumed that the D_2 term is a differentially derived parameter or a filter product that does not well reflect the average steady decline of the orbit. This subject will be revisited below. Given that fluctuations in the NAVSPASUR elements are typical (a presumption based only on the GLOMR observations), then further examination of other sensitivity coefficients was appropriate. Using the February 5, 1986 epoch data as a basis, the following sensitivities were computed using the orbit program:

Orbital Parameter	CPA Timing Error (sec) Unit Parameter Change per Day
Mean Anomaly M_0	-500.0 sec/day/ΔM_0
Mean Motion M_1	-99,161.58 sec/day/ΔM_1
Decay Coefficient D_2	-1,233.33 sec/day/ΔD_2
Eccentricity e_0	+250.0 sec/day/Δe_0
Argument of Perigee ω_0	-468.33 sec/day/$\Delta \omega_0$
Long of Ascending Node λ_0	-233.33 sec/day/$\Delta \lambda_0$
Inclination i_0	+2,500.0 sec/day/Δi_0

The net timing error can be estimated as the sum of products of the above error rates times the average values of the corresponding orbital parameters. Using the most severe fluctuations of all parameters over the entire period of observation, the "worst case" scenario would result in timing errors of about a minute per day. As noted, with the "removal" of the D_2 fluctuation and use of a smoothed value, errors on the order of one second per day are often attained. Nevertheless, attention to the behavior of all the orbital elements is well justified as we shall see next.

Solar Disturbance of February 1986

At low altitudes, satellites face the unescapable force of atmospheric friction. As the altitude declines the orbital altitude decreases and the satellite speeds up in an accelerating death-spiral. As we studied GLOMR's gradual descent we reported a rate of approximately -0.11 km/day throughout the first 100 days of orbit. However, after February 7, 1986, pass timings (communications windows) began to deviate significantly from the earlier predictions used to program the satellite processors. In fact, the orbit seemed to have decayed abruptly with the result that we accumulated an error of approximately -11 sec/day. Due both to the pre-scheduling of the GLOMR contacts and to the day late arrival of the NAVSPASUR Charlie Elements, the immediate cause of the shift was unclear. Once the NAVSPASUR data became available, it appeared that a substantial "shock" occurred on February 7th (day 99 on the various graphs). Sudden enhancement of the atmospheric density at this time buffeted GLOMR and induced immediate "ringing" of the NAVSPASUR tracking filters as evidenced in the eccentricity (Figure 1) and the sharp upward jump of the decay term as shown in Figure 2. But by far more significant, yet not obvious to the casual observer, was the ramp in the mean motion curve. Using the equivalent mean altitude as depicted in Figure 3, three features are observable:

(1) The small dip on day 87 (January 26, 1986);
(2) A second dip peaked at day 104 (February 12, 1986);
(3) A sharp slope change at day 99 (February 7, 1986).

The first dip is not real since the altitude immediately recovers and follows the well established straight line behavior with a rate of -0.411 nmi/week prior to the disturbance which certainly occurred on the 7th of February. The second dip is probably NAVSPASUR tracker response to the immediate change in the derivative of the mean motion parameter. This is real since from this point on the orbit is now again on a "straight line" descent with a rate of -0.5946 nmi/week. This represents a -44.7% change in the rate of descent and clearly will affect the GLOMR mission lifetime.

Other evidence includes the decay term D_2 of Figure 2, which shows two average line fits one before and one after the disturbance:

	Smoothed Decay Term	Standard Deviation
Before:	0.01036	0.001356
After:	0.01482 (43% increase)	0.002381 (76% increase)

The 43% increase in the decay term matches the 44% drop in the rate of descent noted above since the rate of descent is approximately related to the decay term as:

$$da/dt = -(4/3)E\text{-}5 * D_2 * a^{2.5}$$

where a is the semi-major axis. Using the pre-disturbance D_2 -value (smooth) of 0.10362, the computed rate of change of altitude is -0.402 nmi/week which agrees with the curve fit value of -0.411 reported above. Likewise, the post-disturbance value is computed to be -0.5755 nmi/week which compares nicely with the previous value of -0.5946. At least in terms of "smoothed" D_2-values, there is agreement between the orbital parameters and the documented observances. It is suggested that a "long-term" fit to the rate of descent curve to get da/dt (nmi/wk) inserted into the following equation will produce an optimum smooth D_2-value:

$$D_2\ (\text{smooth}) = 0.029051 * (da/dt) * [(3444 + ALT)/3444]^{-2.5}$$

In this expression ALT is the current mean altitude in nmi. The approximation presumes a nearly circular orbit.

NAVSPASUR reported to us that the storm was the worst in its history and that the Geomagnetic Index (which had been in the 30-40 range) jumped to 89, 236, and 98 for February 7, 8, and 9, respectively. Further evidence included a jump in the Exospheric Temperature from the 700s up to 997, 1164, and 1001. Now that the storm effects on the orbital parameters were established, the ramifications to GLOMR's lifetime were explored.

GLOMR Orbital Life Expectancy

Assuming a nearly circular orbit and further that 145 km marks the essential "terminal" altitude, the orbital lifetime is approximated by:

$$L = -\int_{ALT_0}^{145\ \text{km}} \frac{d(ALT)}{(C_d * A/m) * \rho(ALT) * (M*G*ALT)^{-0.5}}$$

where M is the mass of the Earth, G is the Universal Gravitation Coefficient, m is the satellite mass (64.5 kg), A is the satellite projected area (0.162 m^2), C_d is the drag coefficient, and ρ is the atmospheric density. The CIRA 1972 Mean Reference Atmosphere was used (see Figure 4) via curve fit in the 90 to 400 km regime:

$$\log \rho(\mathrm{kg/m^3}) = -8.384 * (1+\mathrm{ALT} * 9.079795\mathrm{E}{-4}) * (1-(67.75/\mathrm{ALT})^3)$$

ALT is expressed in km. The lifetime integral L was evaluated for the two situations: before and after the large storm of February, 1986. Figure 5 presents these results. The drag coefficient was empirically fitted to data in the two regimes so that the altitude dynamic matched the computed values. The use of an emperical value also allows for the fact that the orbit is slightly eccentric. The before and after values for C_d are, respectively, 0.43455 and 0.52513. If C_d is approximately constant, then this is equivalent to an increase of 21% in atmospheric density. GLOMR's lifetime has thus been reduced by about 17.3% and, according to the model, should fall to Earth 365 days past the date of the storm or about February 7, 1987. This assumes no further change in drag between the GLOMR altitude of 290 km on July 17, 1986 and the 145 km value which should occur six months from now.

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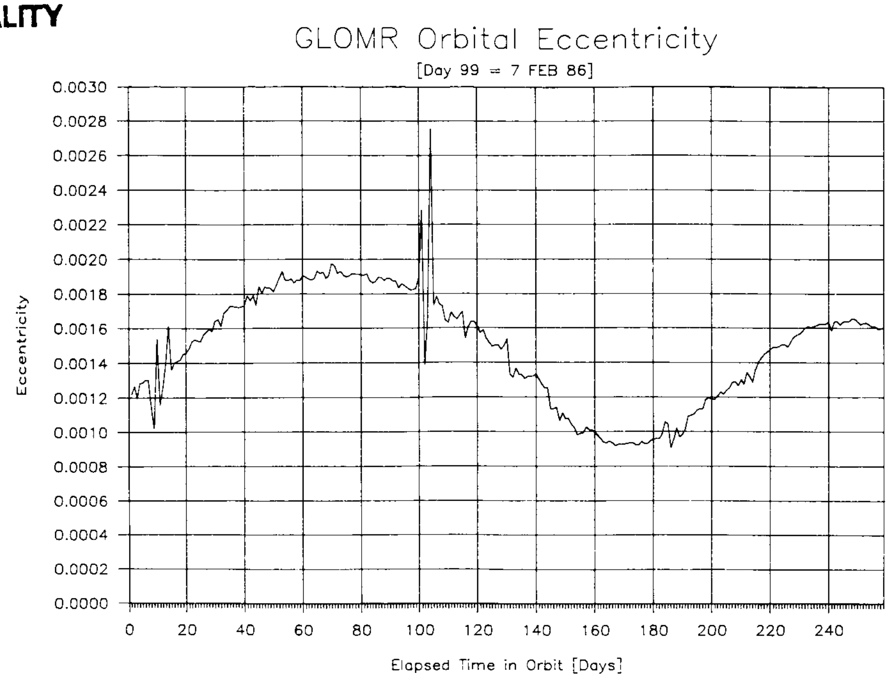

FIGURE 1

LONG TERM BEHAVIOR OF THE GLOMR ORBITAL ECCENTRICITY

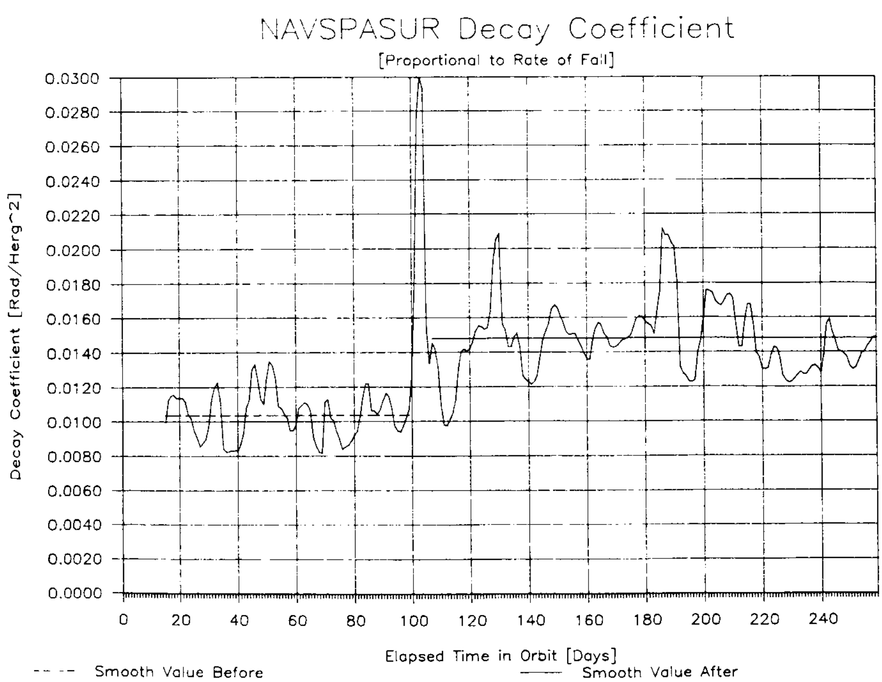

FIGURE 2

NAVSPASUR D_2 DECAY COEFFICIENT WITH SUPERIMPOSED LMS LINE FITTED BEFORE AND AFTER THE SOLAR STORM

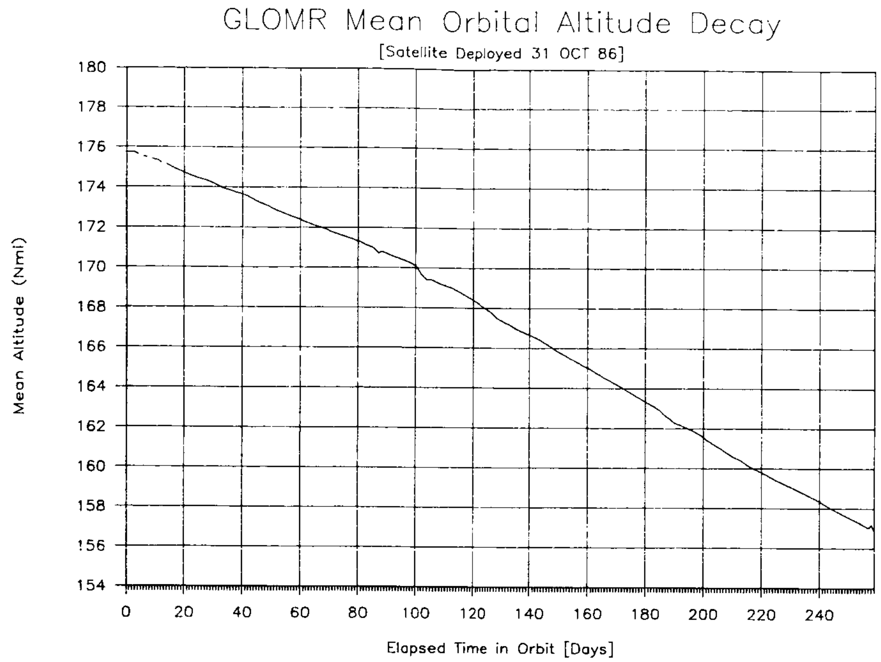

FIGURE 3

GLOMR'S DESCENT IS CHARTED HERE. THE SLOPE CHANGE AT DAY 99 CAN EASILY BE SEEN WITH A RULER: INITIAL RATE =-0.411 NMI/WEEK WITH A VALUE OF -0.5946 NMI/WEEK AFTER THE DISTURBANCE ON THAT DATE.

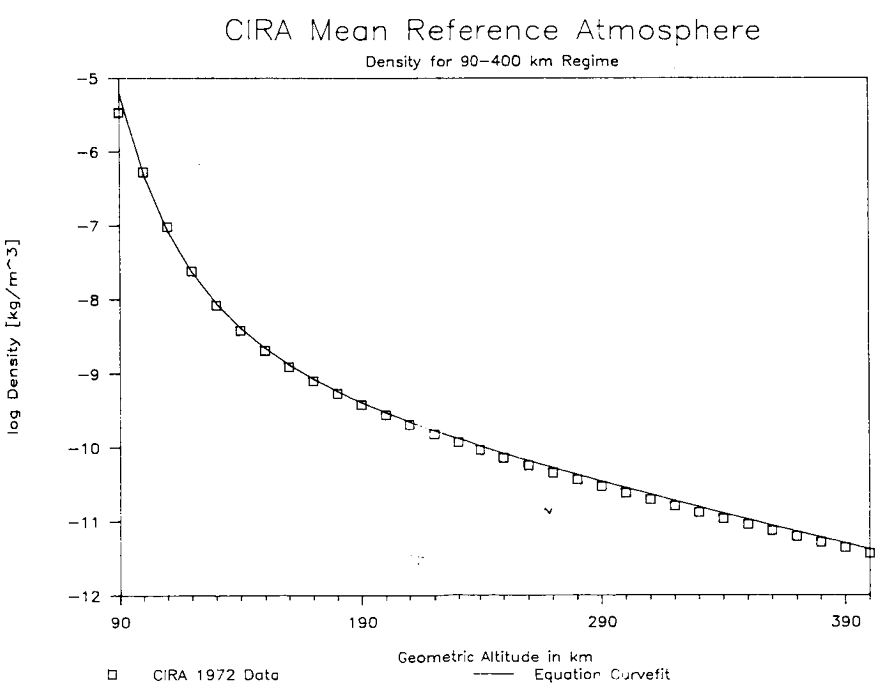

FIGURE 4

COSPAR INTERNATIONAL REFERENCE ATMOSPHERE (CIRA) 1972 ATMOSPHERIC DENSITY IN THE GLOMR OPERATIONAL REGIME WITH EMPERICAL FUNCTIONAL CURVEFIT USED IN GLOMR ORBITAL LIFETIME MODEL.

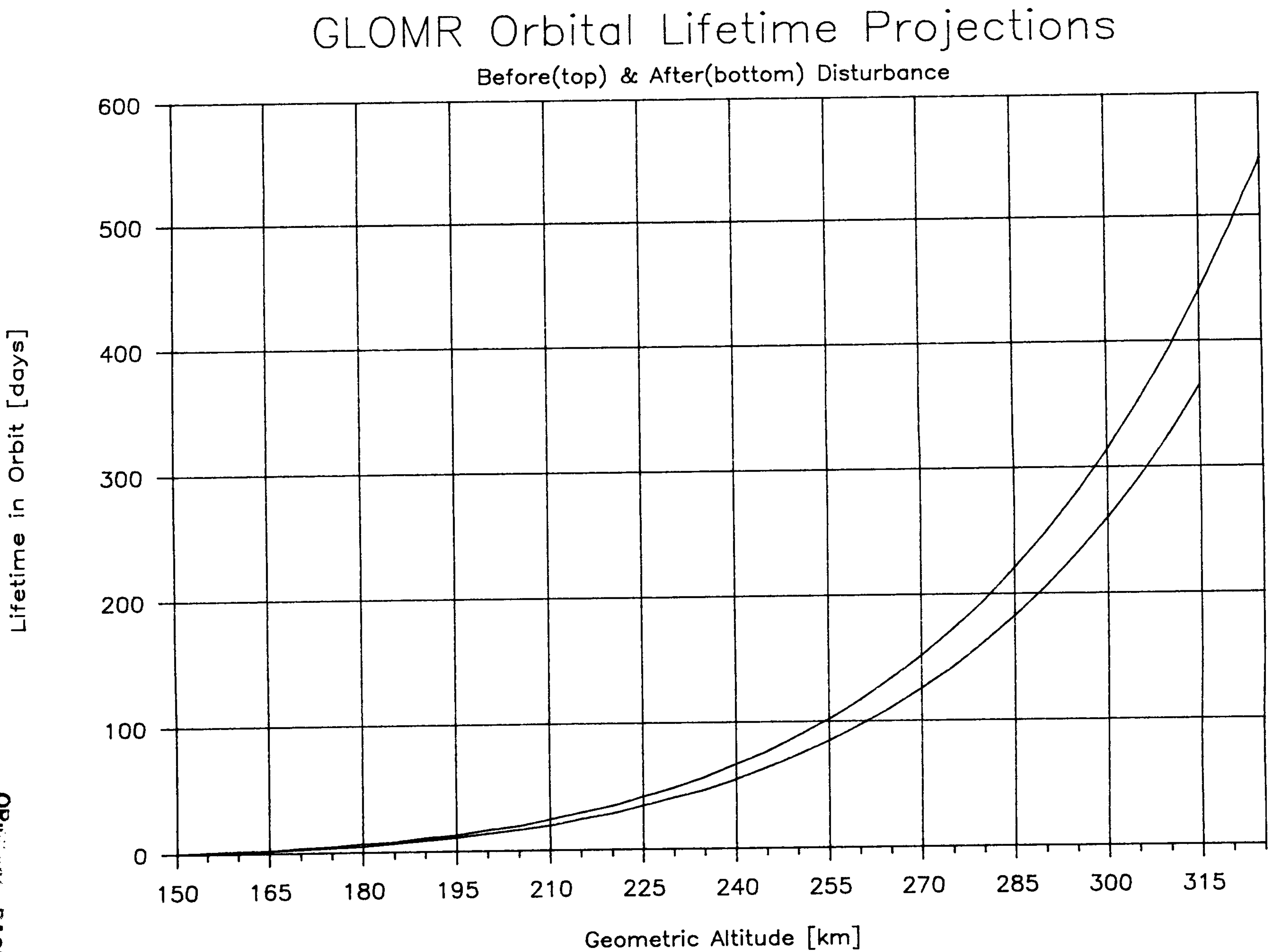

FIGURE 5 ESTIMATED GLOMR LIFE EXPECTANCY AS A FUNCTION OF [illegible] ALTITUDE BEFORE (TOP CURVE) AND AFTER (BOTTOM CURVE) THE SEVERE SOLAR STORM OBSERVED ON FEBRUARY 7, 1986.