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Upper-Atmosphere Studies by Ranging to Satellites

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Upper-atmosphere studies by ranging to satellites

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A satellite moving through the upper atmosphere is subjected to aerodynamic forces which may appreciably alter its orbit, and the properties of the upper atmosphere have in the past been successfully studied by determining orbits from photographic, visual and radar observations, and analysing the changes in the orbits. Laser observations of satellites in orbits with perigee height 400 km or less should allow much more accurate orbit determination, and hence improved information on the atmospheric parameters. In particular it may be possible to determine upper-atmosphere winds and scale height with a much better time resolution – perhaps daily. There seems to be a good chance of suitable satellites being launched, and the difficulties of accurate prediction for the laser tracking, though serious, should not be insuperable.

1. Introduction

A satellite in orbit at a height below 1000 km encounters significant aerodynamic forces as it ploughs its way through the rarefied upper atmosphere. These forces create orbital perturbations which are a great nuisance when determining the Earth's gravitational field, or polar motion, or Earth tides; but careful analysis of the atmospheric perturbations can given useful and unique information about the upper atmosphere. At the heights between 200 and 1000 km where the methods are most effective, the upper atmosphere is extremely complex and dynamic. The air density may vary by a factor of up to 100 over a solar cycle, by a factor of up to 6 between day and night, and irregularly by a factor of 2, or sometimes even 5, in response to solar storms (see *CIRA* 1972). This region of the atmosphere is swept by winds – perhaps hurricanes would be a better term – with speeds up to 200 m/s quite regularly, and occasionally 500 to 1000 m/s. The pattern of density and winds has been successfully studied by analysing orbits determined from photographic, radar and visual observations, and the prospect of a new technique of better accuracy is very welcome. A more accurate method for determining the winds is particularly needed, because the winds tend to control the energy balance, and are difficult or expensive to measure directly by other methods. The main use of laser observations of satellites in upper-atmosphere research seems likely to be in determining the winds; better values of scale height, and hence temperature, should also be obtained; and it is possible that improved time resolution in measurements of density may be achieved.

2. Effects of winds on orbits

Satellite orbits with perigee below about 500 km are appreciably perturbed by the rotation of the atmosphere. The aerodynamic drag on a satellite (figure 1) acts in the direction opposite to the satellite's motion relative to the air, V, which differs from the direction of motion relative to the Earth's centre, U, if the atmosphere is rotating with velocity V_a from west to east. So the drag force D can be resolved into a main component D_t tangential to the orbit, and a smaller component D_n perpendicular to the orbit, which would be zero if there were no atmospheric rotation.

The effect of D_n is to alter the inclination of the orbit to the equator. If ΔT_d is the change in the orbital period T_d (in days) and the orbit is immersed in an atmosphere rotating at Λ rev/day, the change Δi in inclination i is given in its simplest form by

$$\frac{\Delta i}{\Delta T_d} = \frac{\Lambda \sin i}{3\sqrt{F}}\left\{(1-4e)\cos^2\omega - \frac{H}{ae}\cos 2\omega + \frac{\epsilon}{e}(1-e)\sin^2 i \sin^2 2\omega + O(e^2, \epsilon^2 a^2/H^2, H^2/a^2e^2)\right\} \qquad (1)$$

if the eccentricity e is between 0.05 and 0.15 (King-Hele 1964*a*). In equation (1), ω is the argument of perigee; H is the density scale height, which is between 25 and 50 km for many of the satellites analysed in these studies; ϵ is the ellipticity of the atmosphere, taken as 0.00335; a is the semi major axis; and $\sqrt{F}$ is a factor that is usually between 0.95 and 1.0. Equations for Δi when $e < 0.05$ and $e > 0.15$ are also available (King-Hele 1964*a*; King-Hele & Walker 1976*a*), and are of basically similar form.

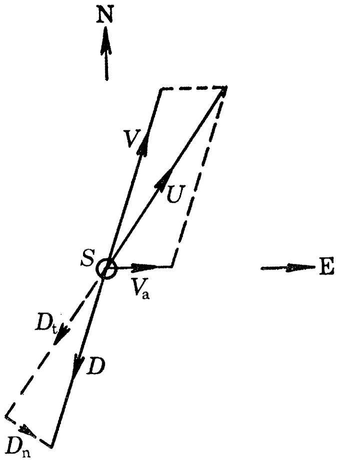

Figure 1. Kinematics of spherical satellite S moving in an atmosphere rotating from west to east at velocity V_a. The symbols are defined in the text.

Equation (1) shows that the effect of atmospheric rotation is greatest when the satellite perigee is near the equator ($\cos^2\omega \simeq 1$), and becomes very small when perigee is at maximum latitude ($\cos^2\omega = 0$), since ae/H usually exceeds 10 if $e > 0.05$. If the argument of perigee runs through many cycles during the satellite's lifetime, as is usual, the mean value of $\cos^2\omega$ is 0.5, and the effects build up, with the inclination decreasing appreciably towards the end of the satellite's life, when the orbital period has decreased from its initial value to near 88 min. For a satellite with an initial orbital period of 102 min, $\Delta T_d = 0.01$ day, and the total decrease in i during the lifetime for a high-inclination orbit is equivalent to a distance of about 10 km on the Earth's surface ($\Delta i \simeq 0.09°$).

So atmospheric rotation produces a steadily accumulating change in inclination, which can be analysed to determine the mean atmospheric rotation rate over a specified time interval, and hence the mean zonal wind. For an orbit with $e > 0.05$, the drag effects are concentrated within an arc extending for about 20° on each side of perigee, and the region of the atmosphere in which the winds are being sampled can be described as 'near perigee'. Also, since the effects of atmospheric rotation on the orbit are greater when perigee is near the equator, the winds determined from analysis of orbits over a cycle or more of the argument of perigee are biased towards the equatorial regions: even near-polar orbits give the atmospheric rotation rate averaged over latitudes between 0 and about 55°.

Meridional (north-to-south) winds also produce changes in inclination, which depend on $\cos i \cos \omega$ rather than $\sin i \cos^2 \omega$ (King-Hele & Walker 1976*a*). Consequently, the effect of meridional winds tends to cancel out as ω runs through many cycles; but if ω is confined within a range of, say, 30°, the meridional winds are likely to have just as much effect as zonal winds.

Figure 2 shows the decrease in inclination, expressed as metres on the Earth's surface, as the orbital period decreases by 0.1 min for an orbit with perigee on the equator and $e \simeq 0.1$, produced by:

(*a*) an atmosphere rotating with the Earth (solid line);

(*b*) a west-to-east rotation of 0.2 rev/day (broken line), equivalent to a west-to-east wind of about 80 m/s at latitude 30° (or 100 m/s on the equator);

(*c*) a meridional (south-to-north) rotation rate μ of -0.2 rev/day, equivalent to a north-to-south wind of about 100 m/s (dot-dash line).

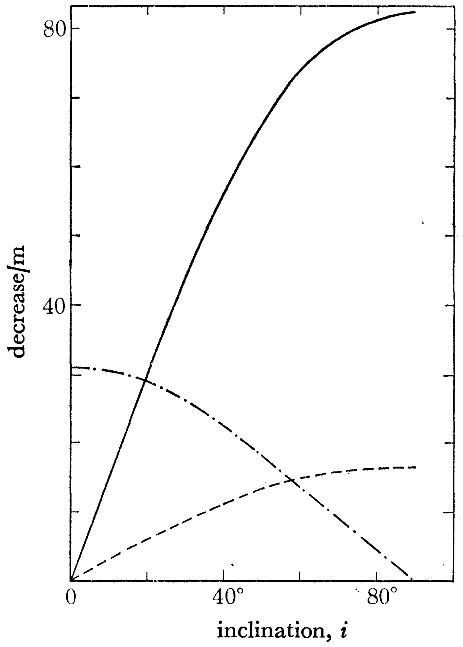

FIGURE 2. Decrease in inclination (in metres) as orbital period decreases by 0.1 min for an orbit with perigee on equator and $e \simeq 0.1$. ——, $\Lambda = 1$; – – –, $\Lambda = 0.2$; —·—, $\mu = -0.2$.

An orbit suitable for this type of analysis might have an initial orbital period of 108 min, initial eccentricity 0.12, and a lifetime of perhaps 2 years. For such an orbit, the period decreases by about 0.1 min per week (until near the end of the life).

So figure 2 can be regarded as giving a rough idea of the weekly change in inclination for a typical satellite, caused by typical zonal or meridional winds of order 100 m/s. For a satellite at inclination 50° the change is about 15 m, that is about 2 m/day. Orbits used for determining upper-atmosphere winds have hitherto been derived from photographic, radar and visual observations: the best nominal cross-track accuracy achieved has been 2 m on an unusual occasion when four Hewitt camera plates were available for one orbit determination (Walker 1975). The great majority of the orbits so far determined for these studies have cross-track accuracies of order 100 m (e.g. Hiller 1975). Consequently, it has not usually been possible to derive wind speeds accurate to 50 m/s over time intervals less than about 100 days. The inclusion of laser observations would greatly improve the accuracy of the orbit analysis and allow much more frequent measurements of winds.

3. MEASUREMENTS OF WINDS FROM ORBITAL CHANGES

Despite the limitations in accuracy, a general picture of upper-atmosphere winds has been obtained from orbital analysis. The first studies of Sputnik 2 in 1958 indicated the possibility that the upper atmosphere at heights near 250 km might be rotating faster than the Earth (Merson, King-Hele & Plimmer 1959), and this was confirmed by analysis of a number of satellite orbits in the early 1960s (King-Hele 1964*b*) which suggested west-to-east winds of order 150 m/s in the height range 200–300 km. Subsequent studies showed an increase of rotation rate with height up to 350 km (King-Hele, Scott & Walker 1970), and then a decrease above 450 km (Gooding 1971). It has also been possible to distinguish variations with local time, because the variation of the local time at the satellite's perigee is often quite slow, perhaps only an hour or two per month, and values over two or three months in real time may be confined to a fairly small range of local time.

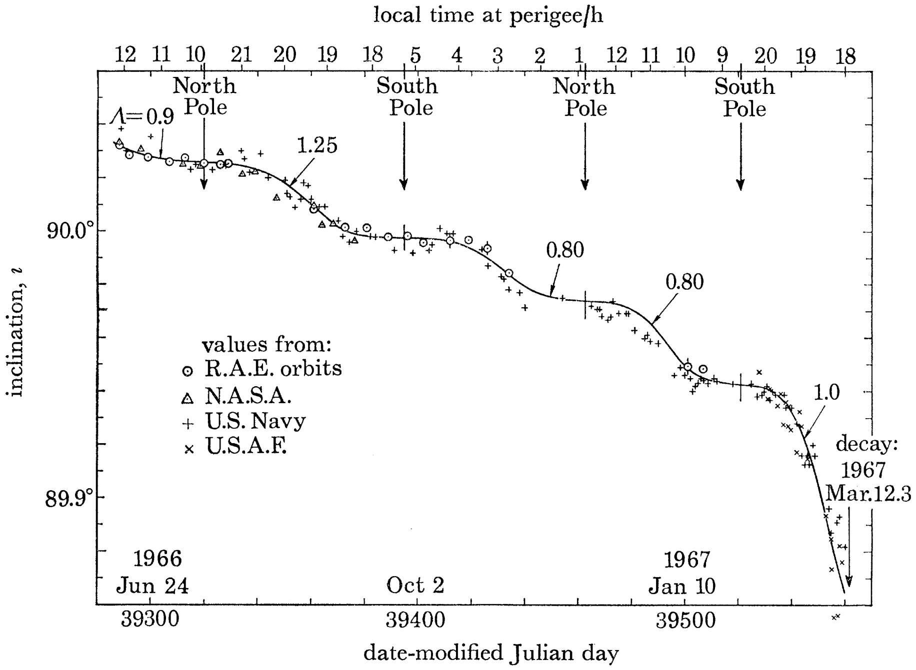

FIGURE 3. Orbital inclination of 1966-51C, ORS 2, from June 1966 to March 1967.

One of the best examples of the satellites used for such analyses is 1966-51C, the Octahedron Research Satellite 2, launched on 9 June 1966 into a polar orbit with perigee height 180 km, and apogee 3600 km. The orbital inclination decreased by 0.16° during the 9-month life time. Figure 3 shows the values of inclination, after removal of relevant perturbations. The orbits come from four different sources, those indicated by the circles being the most accurate. The local time at perigee changes by 12 h whenever perigee passes the north or south pole, but only by about 2–3 h while the perigee is at latitudes less than 45°, where the main effects of atmospheric winds occur. So results for a short span of local time can be obtained by dividing the lifetime at each polar passage of perigee. The orbits are well fitted by theoretical curves, which give $\Lambda = 1.25 \pm 0.1$ for 18–21 h local time on the first full pole-to-pole journey of perigee, and $\Lambda = 0.80 \pm 0.06$ on the next two sections, where the local time is 02–04 and 09–12 h.

Figure 4 gives the picture of upper-atmosphere winds that has emerged as a result of such analyses. The values are divided into three categories of local time: 18–24 h (evening), shown by upward-pointing triangles and ⅄-symbols; 04–12 h (morning), shown by downward-pointing triangles and Y symbols; and average values, shown by circles. This picture, from King-Hele & Walker (1976*b*), utilizes three values obtained by Blum & Schuchardt (1976), two obtained by Forbes (1975) and three by Slowey (1975).

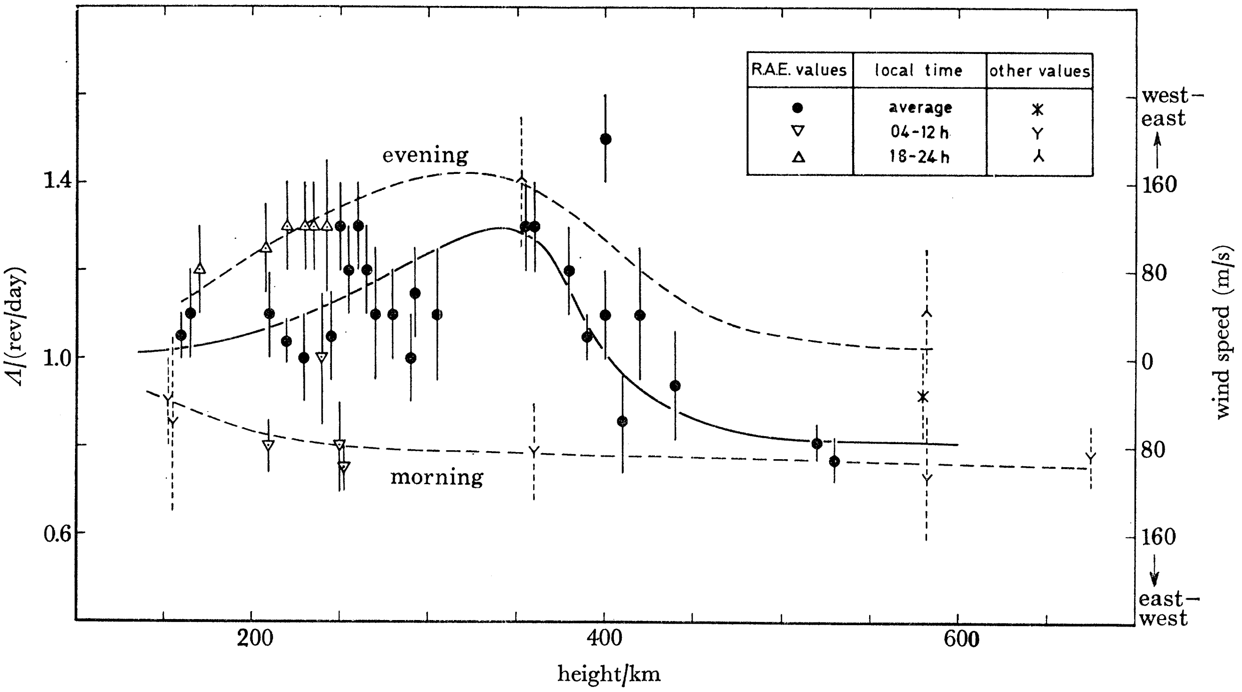

FIGURE 4. Atmospheric rotation rate, Λ, versus height.

In figure 4 three curves have been drawn through the points, to give an impression of the variation of wind speed with height for the three categories of local time. The solid curve, through the points averaged over local time, shows that the rotation rate (in rev/day) increases from near 1.0 at 150 km to 1.3 near 350 km (corresponding to an average west-to-east wind of 120 m/s), and then declines to 1.0 at 400 km, and probably to about 0.8 at greater heights. The upper broken curve shows that the wind is from west to east in the evening, increasing from about 50 m/s at 150 km height to a maximum of about 150 m/s near 350 km. Above that the data are sparse, but a decline to near zero by 600 km seems probable. The lower broken curve shows consistent east-to-west winds in the morning, of magnitude of 50–100 m/s above 200 km.

These results, though they are of value in giving a general impression, refer to winds averaged over all conditions of solar activity and geomagnetic disturbance, and it is very likely that there are wide day-to-day variations from these average values, because the studies of upper-atmosphere density and temperature have indicated large and irregular variations on a short time-scale. The values are also somewhat biased towards latitudes less than 45°, and it is probable that there are considerable variations with latitude; there is already some indication that the rotation rate is greater near the equator than at higher altitudes, for heights above 350 km. Also it is well known that upper-atmosphere winds are greatly enhanced at times of geomagnetic disturbance, when there is heating in the auroral zones as a result of the inflow of particles from the solar wind. During geomagnetic storms, winds in the auroral zones of up to 500 m/s, have been measured by Rees (1971), using vapour-trail methods, and by Brekke, Doupnik & Banks (1974), from radar backscatter techniques. Winds of up to 1000 m/s have been recorded by Feess (1973) with accelerometers on a satellite; and Forbes (1975) has measured winds of up to 350 m/s, using satellite orbit analysis. These winds connected with auroral heating are short-term, and last for a few days at most, like the geomagnetic disturbance itself. But they have a profound effect on the upper atmosphere, and need to be evaluated.

4. THE PROMISE OF LASER TRACKING

Successful laser tracking of corner-reflector satellites having perigee heights lower than 400 km should lead to frequent measurements of atmospheric winds – perhaps every day, perhaps every 2 or 3 days. There are, however, three possible problems which will delay such researches: the absence of suitable satellites; difficulties in tracking; and difficulties in orbit determination.

The last of these three problems is the easiest to overcome. Although it will be more difficult to determine orbits accurately when the drag is so much higher, experience with the Hewitt camera observations suggests that, even with high drag, the cross-track errors need not be more than about 5 times greater than the error of the most accurate tracking instrument, provided there is adequate backing from less accurate tracking stations in other parts of the world. With the Hewitt camera, the accuracy is equivalent to about 5 m, and orbits accurate to about 25 m cross-track have been obtained even when the perigee is as low as 200 km (Hiller 1972; Walker 1974). Wind speeds have also been successfully measured by analysing the orbit of a satellite (1970–114F) with a perigee height of 110 km, and an apogee height that decreased from 7000 km to 1000 km in 20 days: it was shown that the meridional winds near perigee increased from 40 ± 30 m/s in a geomagnetically quiet period, to 150 ± 30 m/s during a 10-day period of geomagnetic disturbance (King-Hele 1976). So there seems a possibility that laser observations might be used to determine accurate orbits for satellites with perigee heights down to about 250 km, though an orbital model better than those now in use will be needed.

The other two problems – the absence of suitable satellites and the difficulty of tracking – go together. The orbits of geodetic satellites intended for laser tracking are chosen to avoid drag, and none has a perigee below 500 km. Satellites with perigee heights in the neighbourhood of 400 km, as required, are difficult to predict accurately enough for automatic laser tracking, because the atmospheric density suffers irregular variations. At present there are no suitable satellites in orbits with a perigee height near 400 km. There is, however, one satellite with corner reflectors in an orbit with much lower perigee. This is the French satellite D5B (1975–39B), for which the perigee height is near 270 km, and the apogee height was originally 1250 km, but is rapidly decreasing. The inclination of its orbit to the equator is 30°, which is too low an inclination for many of the laser tracking stations. Because of its low inclination and high drag, the D5B is like a prophet who comes before the world is ready: apart from the low inclination, its orbit is excellent for studies of wind speeds, but it seems unlikely that the satellite will be intensively tracked with lasers before its decay, which will probably be in 1978.

Another planned satellite which may be useful in atmospheric studies is an Intercosmos satellite carrying corner-cube reflectors, which is intended to be launched in 1978 into a near circular orbit at 83° inclination and 500 km height (Klokočnik *et al.* 1975). If the orbit is too nearly circular, the values of rotation rate obtained would be too heavily averaged; but even a small eccentricity would suffice to confine the measurements in local time, and to some extent in latitude.

Satellites suitable for atmospheric studies could also emerge as a result of persuading launching authorities to fit corner reflectors on satellites being launched for other purposes. Here the danger is that the launching authority may regard the extra experiment as too cheap to be valuable; but common sense may occasionally prevail. Alternatively the rocket left in transfer orbit after the launch of a geodetic satellite might be fitted with corner reflectors: the Lageos rocket (1976–39B), with perigee 300 km and apogee 6000 km, would have been ideal. Another possibility is that a geodetic satellite designed for laser ranging may fail to reach its intended orbit and become stuck in a transfer orbit with a perigee near 300 km. Relying on failures may seem chancy or cynical, but many of the best satellites for orbit analysis in the past have been those which failed to reach their planned orbits, e.g. 1970–65D, which was intended to go to Venus (Walker 1974).

So there seems a fairly good prospect of satellites suitable for laser tracking and with low enough perigee for atmospheric studies. But the problem of tracking still remains.

Fully automatic tracking, as with geodetic satellites, seems unlikely to be possible with low-perigee satellites, because the irregular day-to-day variations in air density make accurate prediction so difficult. One possibility is to acquire the satellite by visual tracking on a transit when it is illuminated by the Sun against a dark sky, and to control the direction of the laser by that of the visual tracking instrument. The azimuth and elevation of the visual observations could be used to update the orbit, so that the satellite might be acquired by automatic prediction on the next transit, when it is in eclipse and invisible to the visual observer, though still available for laser tracking. The technicalities of this and other modes of operation would have to be carefully considered, and so would the psychology of the operation, because observers may feel that failure to acquire the satellite is discreditable to them, and they may prefer to track the easier satellites, using the automatic methods. The best plan might be to begin with one observing team specializing in the laser tracking of low-perigee satellites. The observations made by this team alone would be valuable, and the team might also pass on the skills acquired to observers at other stations.

5. Improvements in determination of air density

The evaluation of air density from the rate of contraction of satellite orbits determined from photographic and other observations is a well-established technique, but the time resolution of the method has so far been not less than one revolution and, more often, several revolutions. For a non-circular orbit with eccentricity greater than about 0.02, the drag is concentrated in an arc each side of perigee, and observations well away from perigee are unlikely to reveal any information about the air density on that part of the orbit. Laser tracking of satellites in non-circular orbits with fairly low perigee will certainly give improved orbits, but the time resolution achieved is likely to depend more on the frequency of observations than on their accuracy.

The best hope of exploiting the accuracy of laser tracking directly seems to be with near-circular orbits ($e < 0.001$), in which the drag has an important effect all round the orbit. A satellite like the proposed Intercosmos, with a 500 km circular orbit and a lifetime of 10 years, will suffer a reduction in height of about 10 km per year, or about 2 m per revolution. In an ideal situation, with such a satellite in an equatorial orbit about an isolated spherical Earth, and with numerous equatorial laser tracking stations making range measurements accurate to 10 cm, it is possible to envisage a time resolution down to about 0.1 rev (10 min). In practice, with an Earth having a complex gravitational field, non-equatorial orbits subject to lunisolar perturbations, and tracking stations on a spinning Earth having different geometries on each revolution, it is not clear whether the numerous perturbations could be adequately removed from the orbit to yield density measurements several times per revolution. The technique is worthy of further investigation.

6. MEASUREMENT OF SCALE HEIGHT

If as a first approximation the density ρ at height y in the upper atmosphere is assumed to vary exponentially with height above a reference height y_0, so that

$$\rho = \rho_0 \exp\{-(y-y_0)/H\}, \tag{2}$$

where H is constant, the quantity H is called the density scale height, and is the height in which the density falls off by a factor of 2.7. (If the variation is not exponential, H may be defined as $-\rho/(\mathrm{d}\rho/\mathrm{d}y)$.) The value of H is most significant in upper-atmosphere studies, because it is proportional to the thermospheric temperature τ, which is given by

$$\tau = \frac{MgH}{R}\{1 + O(\mathrm{d}H/\mathrm{d}y)\}, \tag{3}$$

where M is the mean molecular mass of the air molecules, g is the acceleration due to gravity and R is the gas constant (8.31 J K^{-1} mol^{-1}).

The value of H can be determined from the rate of decrease of the perigee distance Q of a satellite, after removal of zonal harmonic and lunisolar perturbations, since $\dot{Q}$ is a linear function of H, being given by (King-Hele & Walker 1973)

$$\dot{Q} = -\frac{H\dot{n}}{3ne}\left\{1 - 2e + \frac{H}{4ae} - \frac{2\epsilon}{e}\sin^2 i \cos 2\omega + O(e^2, H^2/a^2e^2)\right\} \tag{4}$$

for an orbit with eccentricity between 0.05 and 0.15 in an oblate atmosphere of constant H; similar though lengthier expressions are available if H varies with height. The values of e, the mean motion n, and its time derivative $\dot{n}$ are accurately known; so the accuracy with which H can be calculated depends entirely on the accuracy of $\dot{Q}$.

This method has been used in the past to obtain values of H accurate to about 10 % over time intervals of a few weeks or months (King-Hele & Walker 1973; Walker 1974). The greatly improved accuracy of orbits determined from laser observations should provide much more accurate values of Q, and so it should be possible to obtain values of H, and hence the temperature, every few days, or possibly even daily: for an orbit with perigee height near 250 km, initial eccentricity 0.12 and lifetime 2 years, the decrease in perigee distance due to drag is about 20 m/day; so $\dot{Q}$ could be measured daily, accurate to 5 %, if Q was accurate to 1 m. Such a frequent monitoring of upper-atmosphere temperature would be a valuable addition to the research techniques available for studying the upper atmosphere, because the temperature is the atmospheric parameter most directly correlated with the influx of solar radiation and particles.

7. Conclusions

Laser tracking of satellites in orbits with perigee height 400 km or lower will allow much more accurate orbit determinations. Subsequent analysis of changes in inclination and perigee distance of non-circular orbits should yield far better values – either more accurate or with a finer resolution in time – of upper-atmosphere wind speeds and scale height, with the possibility of daily determinations of both. Better time resolution in density measurements may also be possible, using satellites in circular orbits.

There are at present no corner-reflector satellites in orbits suitable for such studies, but there is a good chance of suitable satellites in the future. Laser tracking of low-perigee satellites is difficult, because day-to-day irregularities in air density make accurate predictions impracticable; but these difficulties should not be insuperable.

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