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Satellite Orbital Dynamics and Observation Strategies in Support of Agricultural Applications

Although operational satellite data are generally well suited to agricultural applications, changes in observing strategy should further improve the utility of the data.

ABSTRACT: *The operational satellites (GOES, NOAA) and the proto-operational satellite (Landsat) acquire data suitable for agricultural applications representing a wide range of coverage frequencies and spatial resolution. The geosynchronous (GOES) satellites provide highly repetitive low spatial resolution data appropriate for monitoring atmospheric variability, the Landsats provide infrequent (80 m)^2 spatial resolution data appropriate for detailed study of vegetation and surface characteristics, and the NOAA series (especially the instrument Advanced Very High Resolution Radiometer—AVHRR) represent an intermediate observing regime. A discussion of satellite orbital characteristics in the context of agricultural applications suggests advantages to placing both the AVHRR and a high resolution imager (e.g., Multispectral Scanner of Landsat) on an early afternoon satellite having the capability for in-flight orbit maintenance.*

INTRODUCTION

ALTHOUGH a large number of satellites have acquired data relevant to surface phenomena and atmospheric variability (Allison *et al.*, 1980), only in the last decade have observing capabilities reached the technical quality appropriate for agricultural applications. Constraints of instrumentation and orbital geometry tend to partition Earth-observing satellites into three classes: synchronous satellites, long repeat cycle (18 day) polar orbiters, and short repeat cycle (2 to 5 day) polar orbiters. Representative satellites from these classes acquire (1) highly repetitive (½ hour) visible and thermal infrared data at relatively low spatial resolution; (2) low repetition rate (e.g., 18 days from Landsat) visible and near infrared data of very high spatial resolution; and (3) two to five day data in the visible and thermal infrared spectral intervals at intermediate spatial resolution.

Each data-coverage type has characteristic advantages for monitoring and understanding certain aspects of the general status of global agriculture. Synchronous satellite data are well suited for estimation of solar-energy input (Gautier, *et al.*, 1980) and regional scale measurements of surface temperature as it pertains to the seasonal pattern of crop growth. High spatial-resolution, low repeat cycle data (e.g., from Landsat) is helpful for field-by-field inference of crop type and land use (MacDonald and Hall, 1980). The intermediate observing regime has potential for inference of the surface temperature, surface moisture budget (Price, 1980), and regional crop stress, and is especially well suited for routinely monitoring agricultural status on a global basis. These capabilities should prove useful by promoting a more accurate assessment of global food and fiber production, and its resultant effect on commodities prices and international trade.

The general properties of data from geosyn-

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chronous satellites are first covered. Then, orbital characteristics of the Landsat series are discussed as an example of the advantages of an appropriate orbit adjustment (maintenance) strategy. The NOAA meteorological satellites lack this desirable feature. However, it appears feasible to combine the desirable characteristics of Landsat and the NOAA satellites in a single appropriately designed observing system.

GEOSYNCHRONOUS SATELLITES

The GOES (Dismachek *et al.*, 1980) satellites occupy fixed positions in the sky over the eastern and western United States, acquiring data at 30-minute intervals over the entire United States as well as much of the western hemisphere. Figure 1 illustrates the viewing perspective from geosynchronous orbit. The GOES satellites acquire visible and thermal infrared data at spatial resolutions of one kilometre and eight kilometres, respectively. During operational processing, the visible data are averaged to match the lower resolution of thermal infrared data.

The high repetition rate and large area of coverage from geosynchronous satellites is useful for inferring synoptic weather patterns, for monitoring rapidly varying atmospheric features such as severe storms, and for tracking individual cloud elements as indicators of atmospheric dynamics. These data are also well suited for estimation of two agriculturally important properties: solar radiation as affected by cloud cover, and regional scale surface temperature. A cooperative experiment between the Great Plains Regional Council on Evapotranspiration and the National Oceanic and Atmospheric Administration (Tarpley, 1979) has demonstrated the feasibility of using geosynchronous satellite data for improving radiation budget estimates in agricultural areas. Regional scale estimates of maximum and minimum surface temperature may also be inferred in order to provide an indication of growth potential (degree days), atmospheric moisture demand, etc. Surface temperature itself is especially significant in early spring for determining planting dates, and in late fall when frost may occur in cold-prone areas. In addition, work by Idso *et al* (1977) suggests the possibility of using remotely sensed surface temperatures as an indicator of yield in small grain crops.

FIG. 1. The western hemisphere as viewed from geostationary orbit.

The basic orbital constraint for all Earth-fixed satellites is the balance between gravitational attraction and the centrifugal force tending to produce straight line motion away from the Earth. A circular, or nearly circular, orbit is assumed because a variable satellite-to-Earth distance would cause an undesirable varying spatial scale in image data products. The minor effects of orbital eccentricity and the flattened shape of the Earth are discussed in the section on Orbit Selection: Minimizing the Effect of Eccentricity. For a circular orbit, the balance of forces is expressed as

$$\frac{GMm}{a^2} = ma\omega^2 \qquad (1)$$

where GM is the Earth's gravitational attraction, $3.99 \times 10^5 \text{km}^3/\text{sec}^2$, m is the satellite mass, a is the distance from the Earth's center to the satellite, and $\omega = 2\pi/(\text{period } T)$ is defined in this section as the angular velocity of the satellite about the Earth's center. Dividing out the satellite mass yields a simple relation between the orbital period and the Earth-to-satellite distance (Kepler's third law—White, 1948).

Geosynchronous satellites are of interest because they maintain constant surveillance over an unvarying portion of the Earth. Setting the orbital period equal to that of the Earth's rotation and solving for a:

$$a = \left(\frac{GMT^2}{4\pi^2} \right)^{1/3} \qquad (2)$$

one finds a geosynchronous satellite distance of 42,200 km from the center of the Earth (42,200 − 6,400 = 35,800 km from the Earth's surface).

In order to avoid an apparent daily north-south movement in the sky, the geosynchronous satellites are stationed above the Earth's equator. A negative, but unavoidable, consequence is the fact that areas at the limbs of observation (north and south poles, and far east and west of the subsatellite point along the equator) are observed obliquely. For such areas, this results in a lower effective spatial resolution and an increased atmospheric influence as the atmospheric path length increases.

Although highly repetitive measurements of multispectral reflectivity characteristics and high resolution mapping/land-use classification are feasible from geosynchronous altitude, such possibilities are largely of academic interest because surface properties such as land use, vegetation cover, crop status, etc., do not change on an hour-to-hour basis. In addition, for geosynchronous observation, expensive and highly sophisticated instrumentation would be required to provide the high spatial resolution which is readily obtainable from satellites closer to Earth.

LONG REPEAT CYCLE SATELLITES

The Landsat satellites, which are planned to become operational in the next several years, represent low-observing frequency polar orbiters which acquire extremely high spatial resolution multispectral data (U.S. Geological Survey, 1979). This type of data has a demonstrated utility for land-use evaluation, crop discrimination, crop-area mensuration, and potentially, for crop-stress and crop-yield estimation. Practical considerations, especially design and cost of the observing instrument, data transmission rates, and cost of data processing, all tend to restrict high spatial resolution sensors to a narrow swath of data acquisition. Thus, the Landsat Multispectral Scanner with 80-metre resolution acquires data in a swath 185 kilometres wide. As a consequence, a long revisit time results, i.e., 18 days in the case of Landsat. If shorter repeat cycles, e.g., 6 days, were selected without a widened swath, then the two-thirds of the Earth between coverage strips would not be observed from such an orbit. Such a coverage pattern appears quite unacceptable, while a widened coverage pattern for complete coverage from a 6-day cycle would increase data acquisition by a factor of three. (The data rate from the Landsat D Thematic Mapper will be 8×10^7 bits/second.)

In order to clarify the options regarding coverage patterns for near-Earth polar orbiting satellites, Equation 2 is solved for the orbital period T: i.e.,

$$T = 2\pi \left(\frac{a^3}{GM} \right)^{1/2} \tag{3}$$

The radius of the Earth is approximately 6,400 km; thus, for low-Earth orbiters, $a \approx 7{,}000$ and the period is approximately 100 minutes. To a very good approximation, one may regard the satellite's orbital plane as fixed in space while the Earth rotates under it. If the orbital period is 96 minutes, corresponding to an altitude of 570 kilometres, then the Earth will rotate under the satellite (1.6 hours) × (360° of longitude/24 hours) = 24° of longitude while the satellite completes one orbit. Such a satellite would trace out the same ground track day after day, with no passes over the intermediate area between successive ground tracks. (Note that 24° divides exactly into 360°; 360°/24° = 15.) This hypothetical satellite is a one-day repeater, with the undesirable characteristic that points midway between adjacent orbits (separated by 2,700 km at the equator) must be observed at large nadir angles from the satellite. The result is poor spatial resolution at large nadir angles as well as the increasing atmospheric influence as the slant path through the atmosphere becomes longer.

More nearly vertical coverage in the region between adjacent satellite passes may be achieved by selecting a satellite altitude for which the coverage swath fills in over a number of days the gaps between successive orbits on a particular day. For example, a satellite with a 96-minute period completes 24 hours/(1.6 hours) = 15 orbits per day, at intervals of 24° of longitude. If the period is changed to 2 days/(29 orbits) = 99.3 minutes, then passes on alternate days fall midway between those of the day before, and the separation of ground tracks is 360°/29 = 12.4° of longitude. By varying the ratio (days per repeat cycle)/(number of orbits), any desired spacing between ground tracks may be achieved. In general, one obtains the orbital period for a pattern that repeats every m days, after n orbits spaced at intervals of $360°/n$, by equating n × (orbital period) with m × (24 hours). For a given repeat cycle and approximate distance between coverage tracks, several choices of satellite altitude are possible, depending on the interleaving characteristics of the orbital tracks over a period of days (King, 1976). Several of these options are discussed in the section on Short Revisit Polar Orbiters. For Landsat 3, the repeat cycle is 18 days and 251 revolutions, with the orbital track on a given day 360°/251 = 1.43° to the west of the track for the orbit about 24 hours earlier.

Over a long time interval, perturbing forces modify the satellite orbit, so that data acquisition tracks tend to diverge from the regular repeating pattern. The repeating characteristic is not essential for meteorological observations where the intention is to monitor cloud cover and storm systems, even at rather oblique viewing angles. Thus, the NOAA satellites, including Tiros-N and NOAA-6 and -7, are not maintained in a repeating orbit. As a result, long-term accurate predictions of the NOAA coverage patterns are not possible due to the slow, but steady, decay of the satellite orbit.

In contrast, precise repetition of coverage is necessary for many geologic and agricultural applications, as a ground observer must be able to schedule field activities days or weeks in advance with certain knowledge that a satellite overpass will occur. This requires a strategy of orbit maintenance in order to maintain the desired coverage pattern.

For most applications, analysis is greatly simplified through data acquisition under relatively constant viewing conditions. In particular, the satellite orbit should pass overhead at a fixed time rather than at varying times during the day and night. Such orbits are termed sun synchronous, as the satellite appears at a fixed time with respect to the sun. By definition, the orbital plane of such an orbit makes a fixed angle with the radius vector from the sun to the Earth. The requirement that the orbital plane precess once per year (to match the Earth's revolution around the sun) corresponds to a constraint on orbital inclination (i) with respect to the altitude of the satellite, where inclination is defined as the angle between the satellite motion as it crosses the equatorial plane from south to north and a vector parallel to the equator and pointed east (see Appendix, Figure 6). Orbital precession results from the nonspherical nature of the Earth's gravitational field. The precession is determined by the equation (see Appendix and Escobal, 1965)

$$\dot{\Omega} = \frac{3}{2} J_2(GM/a^3)^{1/2} \left[\frac{R_e}{a} \right]^2 \cos \mathrm{i} \qquad (4)$$

Where

$\dot{\Omega}$ = rate of motion of the orbital plane; = 360°/(365.24 days) for sun synchronous observations;
J_2 = the quadrupole correction (Brower and Clemence, 1961) to the Earth's gravity field; = −0.0011; and
R_e = Earth radius = 6378 km.

For orbiters in the altitude range 400 to 1000 km, the required inclination is between 95° and 100°, indicating that the satellites ascending motion crosses the equatorial place headed in a northwest direction, reaching maximum latitude excursions at approximately 80° north and south latitudes. Note that the Landsats acquire data during the descending pass (northeast to southwest). The constraint fixed time of observation <=> orbital inclination causes Earth-observing satellites to go nearly over the poles, i.e., "polar orbiters."

ORBIT MAINTENANCE—GROUND TRACK

In the absence of perturbing forces, a satellite at a properly selected altitude and orbital inclination will cross a given location at a fixed time of day at regular intervals, e.g., every 18 days. In fact, atmospheric drag, the sun's influence, and the nonsymmetric nature of the earth's gravitational field all slowly modify the idealized orbital geometry, leading to an increasing divergence with time between the desired observing conditions and the actual. This slow divergence may be eliminated, provided an orbit adjustment system is carried on the satellite. Because the current NOAA satellites are subject to this gradual drift, a discussion of the evolution of the ground track is appropriate.

From Equation 3, one finds the change in satellite period for a small change in mean orbital radius, i.e.,

$$\delta T = \frac{3}{2} \frac{T}{a} \delta a \qquad (5)$$

Thus, for a period change δT, the longitudinal separation $\Delta\lambda$ between successive ground tracks is changed by $\delta(\Delta\lambda)$ (per orbit) = $\omega_{\mathrm{Earth}}\ \delta T = (2\pi/24$ hours) × $[3T/(2a)]\delta a$. A satellite at higher than nominal altitude (δa positive) will trace paths increasingly to the west [$\delta(\Delta\lambda)$ positive] of its nominal track, and a satellite at lower than nominal altitude will appear to be deflected to the east.

Because of atmospheric drag, the orbit decays according to

$$\dot{a} = -(GMa)^{1/2} \frac{A\rho}{m} \qquad (6)$$

where A is the appropriate cross section of the satellite, ρ is the atmospheric density at satellite height, and m is the satellite mass. Although atmospheric density is affected by solar variations (especially sunspots), one may treat the right side of Equation 6 as constant over time intervals of weeks to months, so that by integration $a(t) = a(t_0) - [GMa(t_0)]^{1/2} A\rho(t-t_0)/m$ where t_0 is the initial time. Substituting this expression into that for $\delta(\Delta\lambda)$, and integrating with respect to time:

$\delta(\Delta\lambda)$ (degrees of longitude per day)

$$= 540 \times \frac{\delta a(t_0)}{a(t_0)} (t - t_0) - 270\,[GMa\ (t_0)]^{1/2} A\rho\ (t - t_0)^2/m \qquad (7)$$

where t is in seconds.

To maintain a desired coverage pattern over a long period of time, it is necessary to initialize the orbit at a slightly higher than nominal altitude, leading to a slow drift to the west (first term on the right). As time goes on, the small but steady effect of drag forces brings the satellite down, leading to an increasing deflection to the east (second term). When the deviation to the east has reached the maximum permissable value, the onboard propulsion system is used to kick the satellite into a higher orbit, leading again to the westward drift. The deviation of ground track from nominal is thus a series of parabolas (Figure 2). If orbit adjustments are not carried out, the coverage pattern continually shifts to the east as compared to a drag-free satellite. Unfortunately, atmospheric density, ρ, at satellite altitudes is not constant over many months, so that Equation 7 may not be used to describe the satellite location accurately over a long time interval: periodic orbital adjustments are needed if this predictability is required.

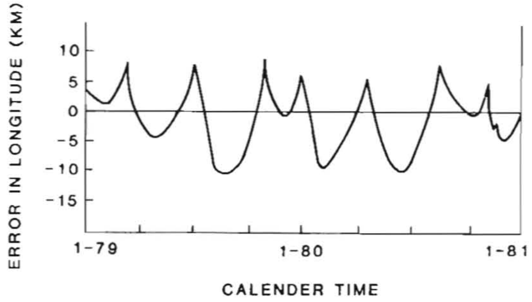

FIG. 2. East-west variation of the Landsat 3 ground track. Cusps represent orbit adjustment maneuvers.

ORBIT MAINTENANCE—CROSSING TIME

As Figure 3 illustrates, even a "sun synchronous" satellite will suffer a slow change from its predicted overpass time due to perturbing forces. This occurs because the sun exerts a small but steady effect on the orbit, tending to change the inclination angle. The force is essentially a tidal force, with the sun's attraction being greater on the day half of the orbit than on the night half. The effect is described by (Wells, 1965)

$$\dot{i} = \frac{3}{16} \times (a_e^3/M_eG)^{1/2}\,(M_sG/a_s^3)\,(\cos i_s + 1)^2 \sin i \sin(2\Omega_s) \qquad (8)$$

where M_e and M_s are the mass of Earth and sun, a_e and a_s are the radius of satellite motion of the satellite about the Earth and the Earth about the sun, i_s is the obliquity or the angle between the equatorial plane and the plane of the Earth's motion about the sun ($i_s = 23.5°$), and Ω_s is the angle between the ascending node of the satellite orbit and the Earth-sun line. An analysis similar to that for the ground track pattern shows that, as i increases linearly with time for Equation 8, the result is a quadratic falloff of the time of overpass from the desired sun synchronous condition (Equation 4). Figure 3 also illustrates the effect of the decision to adjust the Landsat-3 orbital inclination in December of 1977, leading to a return toward the desired 9:30 crossing time.

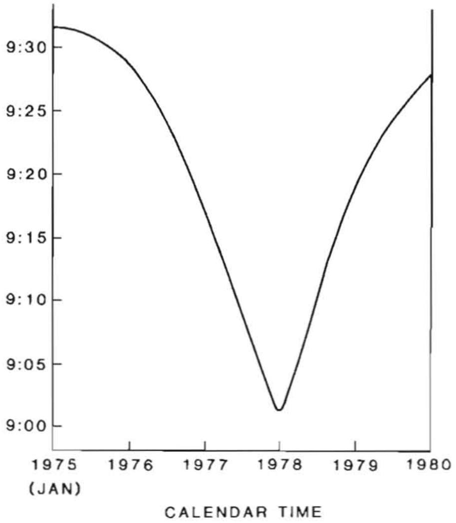

FIG. 3. Landsat 2 Time of descending node (equatorial crossing), illustrating the effect of orbit adjustment in late 1977.

ORBIT SELECTION: MINIMIZING THE EFFECT OF ECCENTRICITY

Although a circular orbit may be regarded as optimum for Earth observations, such orbits do not persist in the Earth's asymmetric gravitational field. As orbital eccentricity builds up, the result is a varying satellite-to-Earth distance, i.e., the satellite altitude changes slightly from one overpass to the next. This produces an apparent change of scale of image products unless resampling of the image data is carried out.

Landsat-3, still operating at this time, has a typical eccentricity in the range 0.0011 to 0.0014, corresponding to an altitude variation of approximately ±10 kilometres over the orbit. Because the location of closest approach, or perigee, gradually moves, with a period of approximately 300 days, the scale of imagery over a particular location changes by approximately ±1 percent over this time interval. Although the 21-km difference between the Earth's equatorial and polar radii also causes an apparent scale change in satellite imagery, this variation is a function of location only, while a temporal variation of satellite altitude produces a time varying scale change at a given location. This temporal variability may be reduced to a negligible value if desired. The eccentricity, e, of the orbit changes according to

$$\dot{e} = -b \cos \omega$$

where

$$b = 3/2(GM_e)^{1/2} R_e^3 J_3 \sin i \,(1\text{-}5/4 \sin^2 i)/a^{3/2}$$

in which ω is the angle between the satellite perigee and the equatorial plane, and J_3 is the third order correction to the Earth's gravitational field = 2.5×10^{-6}, corresponding to a small assymetry between the northern and southern hemispheres. The eccentricity may be held at a fixed value ($\dot{e} = 0$) by setting $\cos \omega = 0$, i.e., $\omega = 90°$, so that the apogee-perigee line coincides with the Earth's axis of rotation. In order for this condition to persist, one must also have $\dot{\omega} = 0$, where

$$\dot{\omega} = \frac{3J_2R_e^2}{a^2}\left(\frac{GM_e}{a^3}\right)^{1/2}\left(1 - \frac{5}{4}\sin^2 i\right) \cdot \left[1 + \frac{R_eJ_3 \sin i}{2J_2ae}\right]$$

Setting the bracketed quantity equal to zero results in a value for the eccentricity of approximately 10^{-3}. The resulting deviation from a circular orbit is not large. However, the resulting exact reproducibility of the orbit is an advantage when satellite data are to be processed for maximum geometric fidelity. This benefit accrues both from the unvarying height of observation over each specific location on Earth, but also because satellite attitude (orientation with respect to the Earth's surface) tends to be coupled to satellite altitude through the horizon sensors used for attitude control on most satellites.

SHORT REVISIT POLAR ORBITERS—METEOROLOGICAL SATELLITES

Meteorological satellites such as NOAA 6 (Kidwell, 1979) provide a spatial scale and frequency of observations falling nicely between those of the geostationary satellites and the Landsat's. The observing instrument, the Advanced Very High Resolution Radiometer (AVHRR), acquires multispectral data (five channels on NOAA-7) every few days, depending on the swath width acceptable to the user (horizon-to-horizon data are acquired). The data are well suited for monitoring the general status of agriculture on a global basis because:

- The visible/near infrared channels acquire data which are indicative of crop canopy cover, and, if Landsat is a guide, to crop stress as it affects near infrared reflectance; and
- The thermal infrared channels yield surface temperature, which may provide an indication of surface moisture conditions, owing to the pronounced cooling effect of surface evaporation.

Although the spatial resolution of the AVHRR is somewhat coarse (1.1 km), the broad coverage swath represents an advantage over Landsat by increasing greatly the probability of acquiring cloud-free data. In addition, a three- to six-day coverage frequency is well suited for monitoring surface variability induced by weather effects, including need for irrigation, mapping of surface temperatures as a key to spring planting time, and in the fall as an indicator of susceptibility to freezing due to microclimatological variability. The afternoon passes of Tiros-N (2:30 P.M. at northern mid-latitudes) are reasonably well placed for inference of surface moisture conditions, although a slightly earlier crossing time (1 to 2 P.M.) would provide temperature data less affected by the diurnal temperature wave, and crop stress could be detected more readily in the visible/near infrared data because higher radiation levels induce higher leaf temperatures and thus a greater evaporative tendency.

Within the U.S. Department of Agriculture, the Foreign Agricultural Service is using AVHRR data operationally to augment Landsat data in assessing the status of global agriculture. Efforts within the Agricultural Research Service are directed toward increasing the utility of these data. Possible failure of Landsats 2 and 3 before launch of Landsat D would leave only the data from NOAA satellites for evaluation of visible/near infrared reflectance measurements of vegetation. (At press—Landsat 2 has failed, Landsat 3 is marginally functional, Landsat D has been launched successfully.)

POSSIBLE IMPROVEMENT OF COVERAGE PATTERNS FROM POLAR-ORBITING SATELLITES

In many respects, the Landsat orbit is well suited to observations of global agriculture. The orbit maintenance strategy for assuring ground tracks and time of overpass is very desirable for coordination of satellite data with ground observations. The suggested freezing of overpass altitude at each location provides only a minor improvement to data quality. However, it is "free," i.e., no penalties result in other performance characteristics.

Although the observing characteristics of NOAA satellites are less favorable, this is consistent with the historical mission of the National Earth Satellite Service (formerly the National Environmental Satellite Service). The new responsibility coincides with increasing quality and potential applications of data from the AVHRR. Obviously, data utilization would be facilitated through well defined data coverage characteristics, such as those of Landsat. An additional improvement could be obtained by placing a high resolution instrument (e.g., the Multispectral Scanner) and a wide swath instrument (AVHRR) on a single satellite. This would facilitate

- Intercomparisons of radiometric calibration, inasmuch as the instrumental spectral bands contain similar information, because Landsat bands 4 and 5 represent the spectral interval 0.5 to 0.7 micrometres, which is equivalent to AVHRR band 1 (0.56 to 0.69), and Landsat bands 6 and 7 span the interval 0.7 to 1.1 micrometres, which is equivalent to AVHRR channel 2 (0.7 to 1.09). Such a comparison would add to the relatively meager information available concerning calibration of satellite radiometers (Williamson, 1977).
- Extrapolation of inferences drawn from a narrow strip of high resolution data to the broader swath of lower spatial resolution data. In regions deficient in surface observations, the high resolution data could be used for a better understanding of the spatial variability of AVHRR data.

If, in addition, the two instruments were placed in an early afternoon orbit, this would render reflectance measurements less susceptable to topographic effects, including shadowing. While this would provide less sensitivity to crop cover in the early season, as there would be less shadowing of the soil surface compared to midmorning observations, it would tend to provide a better definition of crop growth stage at midseason when canopy cover reaches maximum values. In addition, observations in the noon to 2:30 P.M. time frame facilitate interpretation of thermal infrared data as they pertain to evapotranspiration and near-surface moisture. Finally, it should be noted that early afternoon observations will be affected somewhat adversely by mid-day growth of cumulus clouds.

It is not apparent that the possibility of frequent satellite observations, as afforded by the broad coverage pattern of the AVHRR, is consistent with the slowly stepping pattern of the narrow swath Landsat coverage (see Figure 4). From the Landsat orbit, a typical ground location could be observed at small nadir angles for 4 to 8 days, then only at highly oblique angles until the 18-day repeat cycle crossed the region again.

However, other coverage selections are possible (King, 1976). For example, patterns exist which combine the long period repeat cycle needed for narrow-swath observations with the large day-to-day longitudinal variation which is appropriate so that all areas are observed frequently at nearly vertical (<30°) nadir angles. An example is the repeating orbit at approximately 800 km, which is essentially an 18-day and a 3 1/2-day repeater. Such a coverage pattern appears well suited to agricultural observations, both domestic and global (Figure 5). Clearly, a thorough understanding of current satellite data is needed before tradeoffs in observing strategies may be evaluated with confidence. However, it is also clear that both an orbit maintenance strategy for the NOAA satellites and placement of a narrow- and wide-swath instruments on a single satellite would both tend to facilitate agricultural utilization of remotely sensed data.

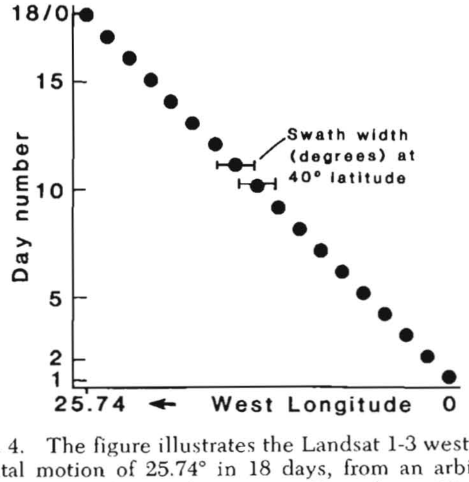

FIG. 4. The figure illustrates the Landsat 1-3 westward orbital motion of 25.74° in 18 days, from an arbitrary starting point (longitude 0). At midlatitudes, a 30 to 40 percent coverage overlap occurs on successive days.

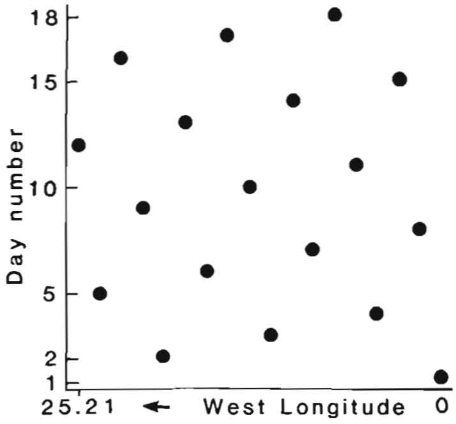

FIG. 5. Ground track sequence for a hypothetical satellite at 800 km. Path-to-path overlap occurs at seven-day intervals.

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APPENDIX

The description of satellite motion represents a straightforward application of classical mechanics, the present consideration being selection of approximations so that the relation between orbital parameters and ground observations is readily understood. Although powerful numerical solution methods are available (Cappellari *et al.*, 1976), they leave options and constraints for typical Earth observation missions relatively obscure because of their great generality.

Figure A-1 illustrates orbital geometry and the definition of the angles, i, the north-south tendency of the orbit with respect to the Earth's equatorial plane, Ω, the angle between the ascending node and a fixed direction in space (the vernal equinox), and ω, the angle within the orbit plane between the ascending node and the point of closest approach (perigee). This last is significant only for an eccentric (non-circular) orbit. Unfortunately, an initially circular orbit will not remain so due to the third moment or egg-shaped tendency of the Earth's gravitational field. Figure A-2 illustrates geometry within the orbit plane.

Expressions for the rate of change of a, e, ω, i, and Ω due to a small deviation from the field of a joint mass are given in Escobal (1965), with appropriate formulas being utilized in this paper.

One should note, in addition, that even with an orbit maintenance strategy, the satellite motion is not truly sun synchronous over the course of a year. This effect occurs, not because of any imperfection in satellite motion, but because of the apparent non-uniform motion of the sun with respect to the rotation of the Earth. The equation of time, which is usually presented graphically, describes the apparent deflection of the sun in the sky from that expected by civil time. Thus, the sun may appear to cross the north-south line more than 15 minutes early in late November.

The effect arises principally from two causes, which may be closely approximated as

(1) The non-uniform motion of the earth about the sun. From conservation of angular momentum (i.e., Kepler's second law)

$$r^2\dot{\theta} = \text{constant} \qquad \text{(A-1)}$$

where r is the Earth-sun distance $= a_s[1 - e\cos(\theta - \theta_0)]$, as is the Earth-sun semimajor axis, e is the eccentricity, and θ_0 is the phase with respect to perihelion, which occurs on 2 January, so that $\theta_0 = (2\pi)\cdot(2 \text{ days}/365 \text{ days})$. Because e is small ($e \sim 1/60$), a simple expansion and integration of Equation A-1 is possible, leading to the time correction due to the non-uniform angular motion of the Earth about the sun; i.e.,

$$\begin{aligned} \delta t_1 &= -2e \sin[2\pi(\text{Day} - 2)/365] && \text{(radians)} \\ &\sim 8 \sin[2\pi(\text{Day} - 2)/365] && \text{(minutes)} \end{aligned}$$

(2) The second contributing factor is the solar obliquity ($\alpha = 23.5°$), which corresponds to the apparent north-south motion of the sun as the seasons change. For this computation, the Earth's

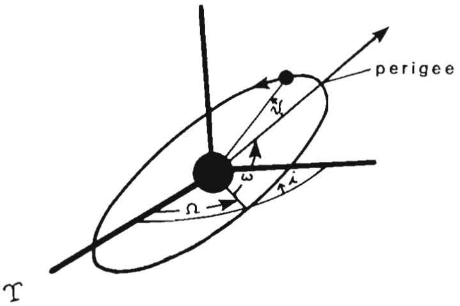

FIG. A-1. Conventional illustration of orbital angles (Escobal, 1965).

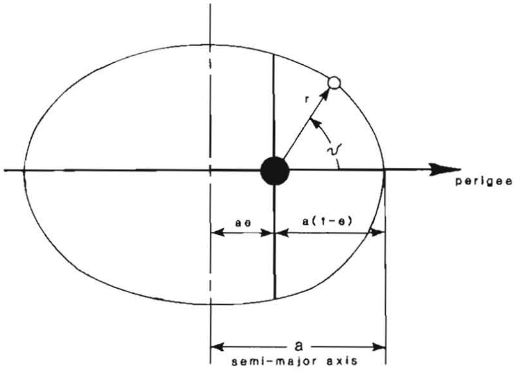

FIG. A-2. Within-plane orbital geometry for an Earth orbiting satellite.

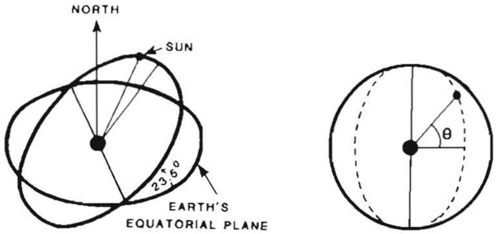

FIG. A-3. The solar obliquity produces an apparent variation in the angular velocity of the Earth about the sun.

orbit about the sun may be considered to be circular. As illustrated in Figure A-3, uniform motion along the orbital path results in an apparent motion of the sun in the ecliptic plane of

$$\dot{\lambda} = \frac{d}{dt}\left[\tan^{-1}\left(\frac{\sin\theta}{\cos\theta\,\cos\alpha}\right)\right]$$

$$= \frac{\dot{\theta}\,\cos\alpha}{1 + (\cos^2\alpha - 1)\cos^2\theta}$$

By rearranging and using a double angle formula $\dot{\lambda} =$

$$\frac{\dot{\theta}}{(1 + \cos^2\alpha)/(2\cos\alpha) + (1 - \cos^2\alpha)\,\cos 2\theta/(2\cos\alpha)},$$

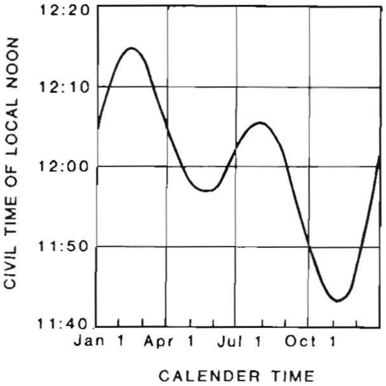

FIG. A-4. The difference between civil time and that from a sundial—the equation of time.

or a difference between $\dot{\lambda}$ and $\dot{\theta}$ of approximately 0.087 cos 2θ. The phase difference $(\lambda - \theta)$ is the time integral or 0.043 sin 2θ, where θ is measured from the winter solstice, day 355, in the Earth's equatorial plane. The difference in minutes due to this effect is thus.

$$\delta t_2 = 0.043\,\sin\left[\frac{4\pi\,(\text{Day} - 355)}{365}\right]\,(\text{radians})$$

$$\sim 10\,\sin\left[4\pi\,(\text{Day} - 355)/365\right]\,(\text{minutes})$$

The sum of δt_1 and δt_2 describes to within approximately one minute the variability in the apparent sun with respect to mean solar time (Figure A-4).

Errata

A number of changes and additions to the July 1982 Yearbook Issue of *Photogrammetric Engineering and Remote Sensing* have been brought to our attention.

On page 1148, in the "Roster of Honorary Members," the name JOHN T. SMITH, JR. 1981 should be added, and the dates after the names CLIFFORD J. CRANDALL and ARTHUR J. MCNAIR should be changed to 1982.

On page 1163, the "1982 Roster of Members Emeritus" should include the name SPERO KAPELAS.

In the organization chart on page 1192 the name of the 2nd Deputy of the Geological Sciences Committee should be ADERBAL C. CORREA.

On page 1033, in the list of "Officers of the Technical Commissions and Chairmen of Working Groups, 1980-1984" of the International Society for Photogrammetry and Remote Sensing, the following additions should be made:

Commission IV

TOPOGRAPHIC AND CARTOGRAPHIC APPLICATIONS
W.G. IV/1 *Cost Models in the Mapping Process*
Prof. Dr. H. G. Jerie
ITC
350 Boulevard 1945
NL 7511 Enschede, Netherlands

W.G. IV/2 *Mapping Technology and Applications for Developing Countries*
General G. C. Agarawal
Surveyor General
Post Box 37
Dehra Dun (U.P.), India

W.G. IV/3 *Mapping from Space Borne Imagery*
Mr. Raymond Batson