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AUTONOMOUS NAVIGATION FOR ARTIFICIAL SATELLITES

Pranav S. Desai
Computer Sciences Corporation
Silver Spring, Maryland

The term "autonomous navigation" refers to the possibility of providing a satellite with the sufficient number and type of sensors, as well as computational hardware and software, to enable it to track itself. In other words, there is no ground tracking involved.

There are two classes of such autonomous navigation: passive and active. Passive means that the satellite does not get cooperation from the ground or from other satellites; active means that the satellite does get active cooperation from either the ground or from another satellite like the Trackir ... ata Relay Satellite Systen ... RSS). This active cooperation could come in the ... adio signals, laser beams, or other kinds of signals or beacons.

The basic reason for usi ... tonomous navigation is to reduce the necessity for ground tracking, thereby reducing the over... ding of ground tracking facilities and also reducing the cost. There are also other technical reasons. For example, with a fast satellite, if there is a gap in the ground tracking data set, especially if there are drag and other prominent effects present, an autonomous navigation system could increase the accuracy of prediction between the two data sets. Another reason could be that the reaction time for noticing changes in the satellite orbit would be reduced by autonomous navigation, even if it is used as a backup to ground tracking.

This work is a conceptualization effort made by Don Novak, Paul Beaudet, and the author at Computer Sciences Corporation. The literature is not exhaustive, but it should be noted that Howard Garcia's paper has a summary of sensors as well as some discussion of the new sensor interferometer landmark tracker.

The following considerations are important in such a feasibility study: First of all, it is necessary to be aware of what types of sensors are available (or could be made available) on a satellite to help in autonomous navigation. Then the observability arising from combinations or configurations of these sensors should be checked. In other words, it should be determined whether a given set of sensors is sufficient under various conditions for determination of attitude and orbit of the satellite. The accuracy of the selected system and its reliability should then be studied to determine that, should one of the components fail, the other components would be enough to back it up. The choice of sensors basically depends on the estimation algorithm, in that we might choose either a coupled attitude and orbit determination scheme or a decoupled scheme. The computational hardware is still another factor.

Some potential sensors for use in autonomous navigation are listed below, but this is by no means an exhaustive list. Some satellites that have used, or are presently using, these sensors are listed:

- Inertial measurement unit–ATS-F, OAO-2, OAO-C
- Star mapper–ATS-F, CTS, OAO-2, OAO-C, OSO-I, OSO-7, SAS-B, SAS-C, SSS-A
- Magnetometer–AE, AEROS, GEOS-C, OSO-I, OSO-7, SAS-A, SAS-B, SAS-C
- Solar sensor–SE, AEROS, ATS-F, CTS, GEOS-C, IMP-H, I, J, RAE-2, SAS-B, C, SSS-A, Nimbus
- Horizon sensors-optical–IMP-H, I, J, RAE-2, SSS-A
- Horizon sensors-infrared–AE, AEROS, ATS-F, CTS, SAS-C, TIROS, Nimbus
- Interferometer landmark tracker–ATS-F
- Scanner/camera–SMS, Nimbus, Landsat

The first is an inertial measurement unit, which is a system of gyros and accelerometers for determining inertial attitude and inertial acceleration of the spacecraft; it has been used on the Orbiting Astronomical Observatory (OAO). The star mapper is probably the most accurate of the attitude sensors for determining inertial attitude and has been used on many satellites. The magnetometer determines attitude with respect to the magnetic field of the earth, or the central body, and if there is a good model available for the magnetic field of the central body, it indirectly determines the satellite attitude. The solar sensor comes in many varieties, but basically it provides angles to the sun from the spacecraft frame. Horizon sensors can be either optical or infrared. For example, an optical horizon sensor was used on the Radio Astronomy Explorer-2 (RAE-2) mission; but infrared is more common and is used in a large number of missions. The interferometer landmark tracker (ILT), a new type of sensor, will be discussed later.

So far the discussion has been limited to attitude-type sensors; however, they are by no means the only sensors that could be used for autonomous navigation. We could consider using non-attitude- or non-navigational-type sensors, including meteorological cameras and scanners that could be used in a landmark determination scheme, in which there is currently an interest.

There are two other sensors to be considered: the one-way Doppler and the image correlator (IC); however, the image correlator has not yet been put on board. The one-way Doppler would determine range rate to known radio stations on the ground or to a tracking satellite. The image correlator is an advanced version of the landmark determination-type scheme where a computer would determine, through pattern recognition, the direction cosines in the spacecraft axes to a known landmark.

It is also necessary to decide how to combine the sensors for autonomous navigation, and a decision has to be made as to whether attitude and orbit should be determined in a coupled or decoupled scheme. There is an argument in favor of a decoupled scheme because orbital parameters, on the whole, vary less rapidly than attitude parameters. Therefore, longer spans of data can be used for orbit determination than for attitude. A coupled scheme would not take into account this difference in the memory span requirement of the two. However, an initial determination could very well be coupled, so perhaps the best method would be to first determine a coarse orbit and attitude in a coupled determination, followed by fine attitude determination, followed by fine orbit determination. So, for this discussion, it is assumed that we are going to determine attitude first, then orbit.

The ILT (figure 1a) has a pair of antennas (at A and B), and its function is to determine the phase difference between the received signals that arrive at the antennas. The ILT must be initialized as to what radio signal frequency it is looking for, which means that the approximate position in orbit must be known. If the satellite is geosynchronous, orbit determination does not have to be done continuously.

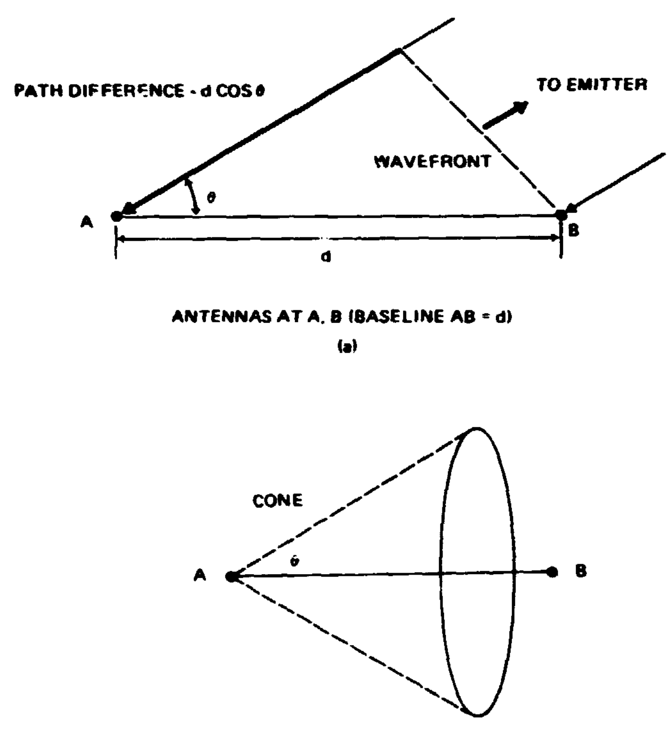

Figure 1. Interferometer landmark trackers phase shift geometry and circle of ambiguity. (a) ILT phase shift geometry; (b) ILT circle of ambiguity.

We determine the path difference, d cos θ, by determining the phase difference, because the two are proportional, and this gives us the angle θ between the direction line to the emitter and the baseline of the ILT. However, as seen in figure 1b, there is a conical ambiguity left in the direction to the emitter, because that angle is all that is known. To reduce ambiguity, we also have another pair of antennas (not shown in figure) where the baseline is perpendicular to the first baseline; we will have an intersection of two cones and, therefore, will reduce the ambiguity to just two lines. A little further analysis, perhaps over a period of time or using multiple landmark determination, might reduce the twofold ambiguity as well.

In figure 2, we begin examining some sensor configurations from the point of view of observability. Suppose we were trying to determine the satellite inertial attitude using a star sensor that determines the direction to one star only, and then supplement that with a landmark determination scheme. In other words, the direction cosines in the spacecraft axis to one landmark on the central body are determined using either the ILT or some other means such as a scanner or a camera.

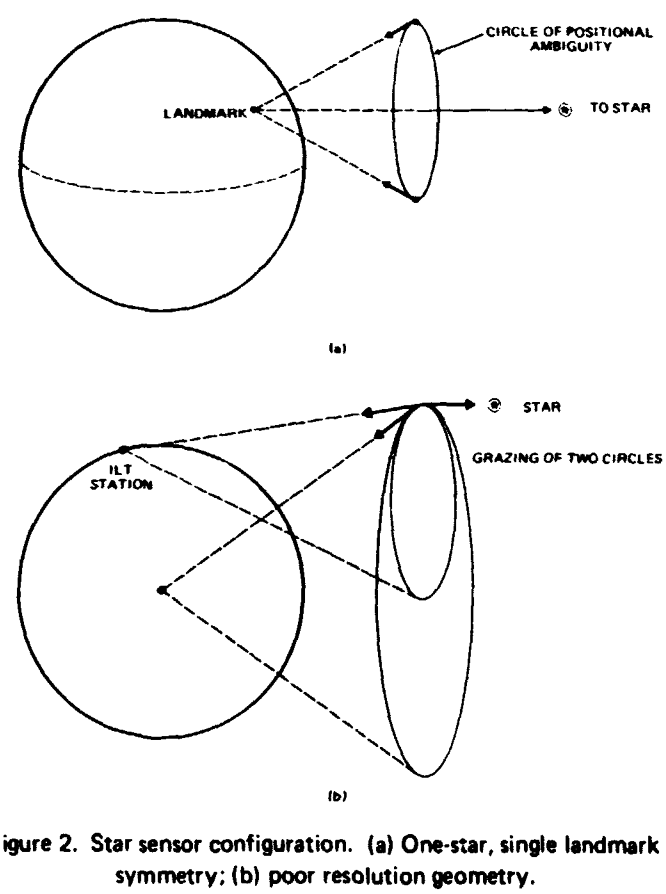

Figure 2. Star sensor configuration. (a) One-star, single landmark symmetry; (b) poor resolution geometry.

In a scheme like this, the star determines the satellite attitude ambiguous to the roll around the axis from the satellite to the star. Normally, the roll ambiguity is further reduced by having a second star, but suppose that second star is replaced by a landmark. In that case, all that is known is the angle between the star direction and the landmark direction, and that does not give the absolute attitude of the spacecraft unless its position is known. Spacecraft position can be ambiguous to within that circle (figure 2a), in fact, to within the whole cone, which indirectly results in ambiguity in the attitude. That would be considered an untenable or unobservable condition.

Suppose we tried to reduce the ambiguity by looking at the central body horizon and obtaining indirectly the direction to the center of the central body. This could remove the ambiguity, but occasionally there is a situation where the resolution is poor, because we are now on two circles that graze, and as can be seen in figure 2b, the graze is quite large. If the ILT station was not placed in the plane formed by the line to the center of the central body and the line to the star, then the circles would intersect at two points instead of grazing, and that would be a better resolution geometry.

Based on this discussion, we can eliminate as untenable those configurations for attitude determination which use only one star and one landmark and such other combinations which are conceptually equivalent, for example:

- One star–ILT/IC (single station)
- Sun–ILT/IC (single station)
- One star–central body horizon
- Sun–central body horizon
- Moon horizon–central body horizon
- Moon ILT–central body ILT (single station)

The following are weakly-orbit-coupled configurations for attitude determination:

- One star–central body horizon–ILT/IC (single station)
- Sun–central body horizon–ILT/IC (single station)
- Moon horizon–central body horizon–ILT/IC (single station)
- One star–ILT/IC (multiple stations)
- Sun–ILT/IC (multiple stations)
- Moon horizon–ILT/IC (multiple stations)
- Moon ILT–central body ILT (multiple stations)

We are still speaking of attitude determination, and we would like it to be orbit decoupled, but these configurations are weakly orbit coupled in the sense that the ILT, for example, would need to be initialized with an approximate knowledge of orbit so that we would know which station to tune to. This list includes a one star/central body horizon/one landmark configuration as well as a one-star/multiple station configuration for the same reason. In summary, to have orbit decoupled attitude determination, perhaps two star sensors would be needed, and they could have an associated inertial measurement unit to back them up.

We will now examine the information that can be derived by determining the direction to the landmark in the spacecraft frame. Figure 3 shows the spacecraft position, the line from the spacecraft to a known landmark, and θ and γ, which are the latitude and longitude of the landmark. The unknown subpoint of the satellite is $(\theta_\theta, \gamma_0)$, the distance of the satellite is r, and the satellite-to-landmark range is ρ. The following equations are based on the fact that this line intersects this sphere, and they show that the direction cosines of that line ought to be $1_x, 1_y, 1_z$, in the earth frame of reference:

$$\cos\theta \cos\gamma = \rho \ell_x + r\cos\theta_0 \cos\gamma_0 \tag{1}$$

$$\cos\theta \sin\gamma = \rho \ell_y + r\cos\theta_0 \sin\gamma_0 \tag{2}$$

$$\sin\theta = \rho \ell_z + r\sin\theta_0 \tag{3}$$

$$\rho = -r\left[\hat{\ell}\cdot\hat{r} + \sqrt{(\hat{\ell}\cdot\hat{r})^2 - (1 - 1/r^2)}\right]$$

where

$$\hat{\ell}\cdot\hat{r} \equiv \ell_x \cos\theta_0 \cos\gamma_0 + \ell_y \cos\theta_0 \sin\gamma_0 + \ell_z \sin\theta_0 .$$

Equations 1 to 3 can be solved to get the range explicitly; therefore, for every landmark, the three equations reduce to two equations. If θ and γ, the position of the landmark on the earth, are known, then there are three unknowns: r, θ_θ, and γ_0. If we are interested in orbit determination, and the attitude is already determined, then we have three unknowns and two equations per landmark, so that we need at least two landmarks for orbit or position determination.

If we could determine the subpoint $(\theta_\theta, \gamma_0)$ on a continuous basis, then, by studying a history of the subpoint, we could get a track of the satellite on the ground and its characteristics would suggest a period. By using Kepler's Third Law, for example, the semimajor axis could be derived indirectly from the period. In that case, even one landmark is, in principle, sufficient for orbit determination.

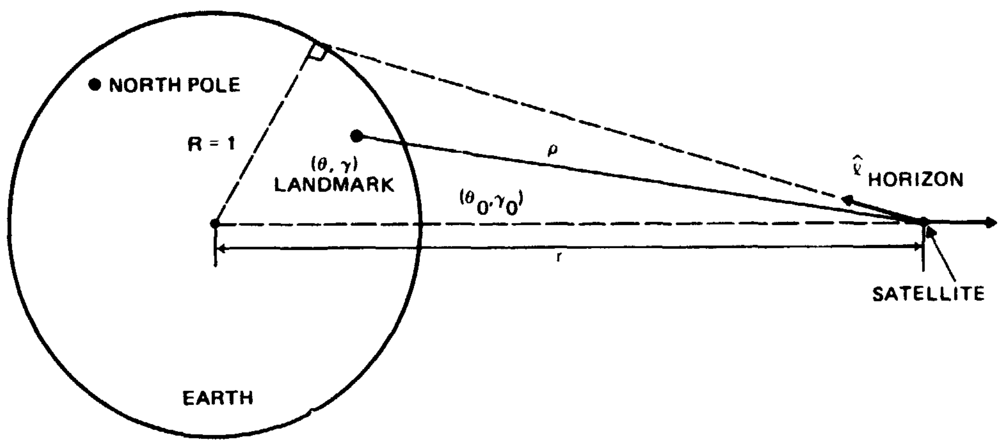

Figure 3. Spacecraft/landmark geometry.

We have assumed that attitude was already known, but suppose we were trying to use this ILT for a coupled attitude and orbit determination, perhaps in a coarse way, for preliminary locking on. How many unknowns would then be had?

In figure 3, we have these directional cosines to the landmark, which are supposed to be in the geographic frame. What we really would know from the satellite instruments would be the direction cosines in the satellite frame of reference. Therefore, indirectly there are three unknowns involved here which represent the transformation from the satellite frame to the geographic frame, which essentially means the satellite attitude, that is, the three attitude angles of the satellite. We then have six unknowns–the three satellite attitude angles plus three positional unknowns–and two equations per landmark, so we still would need only three landmarks. If we had strategically located a sufficient number of landmarks, accounting for possible cloud cover, even then perhaps just a few would be enough for a coupled attitude and orbit determination. (Expressions for the sensitivity of this kind of determination have been developed in our report and are available for anyone interested in performing their error analysis.)

In summary, it seems that by using a variety of sensors it is conceptually possible to have autonomous navigation. However, the details would have to be worked out for each type of orbit. For example, a geosynchronous orbit would require a different type of configuration, perhaps, than the 2-hour satellite, so we do not have a general conclusion or recommendation valid for all types of satellites.

The second part of this paper presents a standardized autonomous navigation system (figure 4) which was designed by Computer Sciences Corporation personnel for possible future use in a standardized type of satellite. In the base are the computer, electronics, and some gyro hardware. On the two sides of that base are two gimbal units. The right-hand gimbal unit is a two-star sensor, located near the beam splitter, which would determine the satellite's inertial attitude. The main navigational unit (lower left) consists of a gimbal unit with three arrays of infrared detectors arranged conically at the tip of the unit. One small section of that array is high resolution, and two outside sections are low resolution. This is supposed to determine three directions to three points on the horizon of the central body.

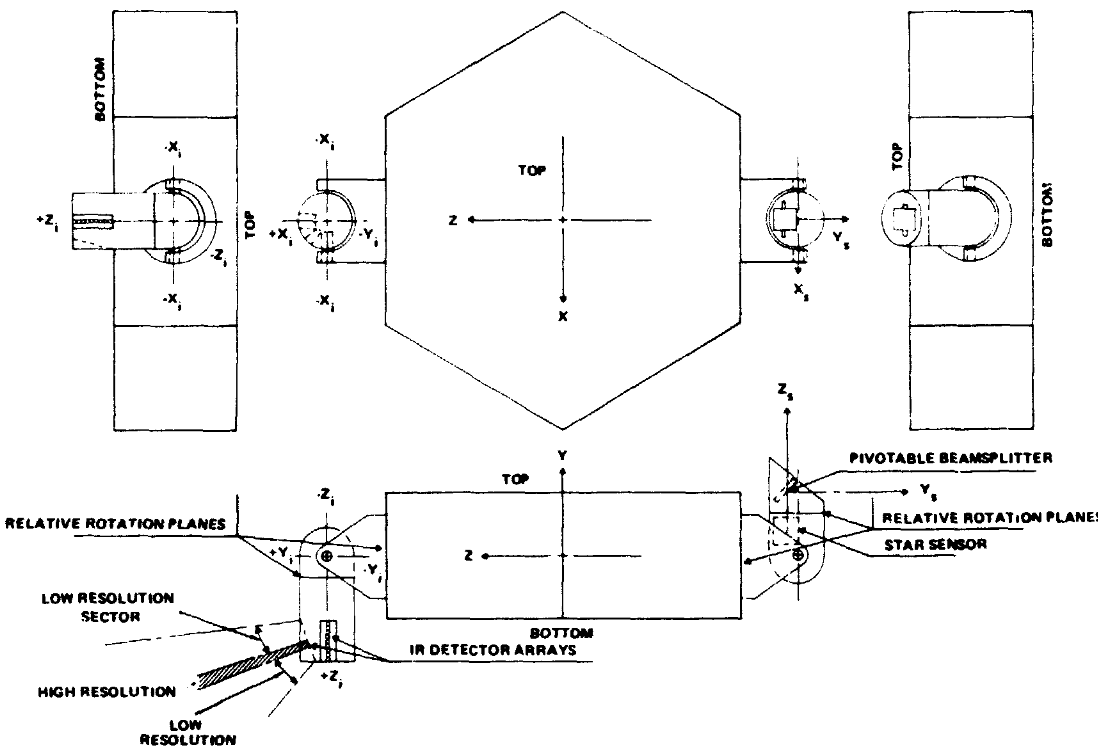

Figure 4. Possible configuration for the proposed standardized autonomous navigation system.

As seen in figure 5, three lines of sight to the central body horizon determine a unique cone, so that the satellite position is known. The following are the equations for x_i, y_i, z_i, the central body coordinates in the spacecraft axes:

$$h_{11}x_i + h_{12}y_i + h_{13}z_i = (r^2 - R^2)^{1/2}$$

$$h_{21}x_i + h_{22}y_i + h_{23}z_i = (r^2 - R^2)^{1/2}$$

$$h_{31}x_i + h_{32}y_i + h_{33}z_i = (r^2 - R^2)^{1/2}$$

By using the information from the star sensors, the equations can be transformed into inertial coordinates.

Figures 6 and 7 show the degree of accuracy we can get from this system. Depending on the angular accuracy of the IR detectors, different errors are obtained at different altitudes. At 1000 km altitude, and with a 0.1° angular precision, we have less than a 10-km error, in fact, close to a 5-km error in altitude (figure 7). In figure 6, the horizontal component error, the curves are flatter, but again we have the same order of magnitude accuracy.

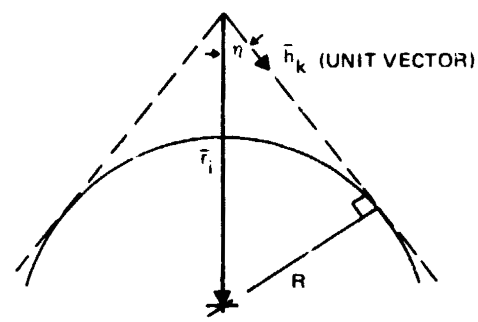

Figure 5. Three lines of sight to the central body horizon determine a unique cone.

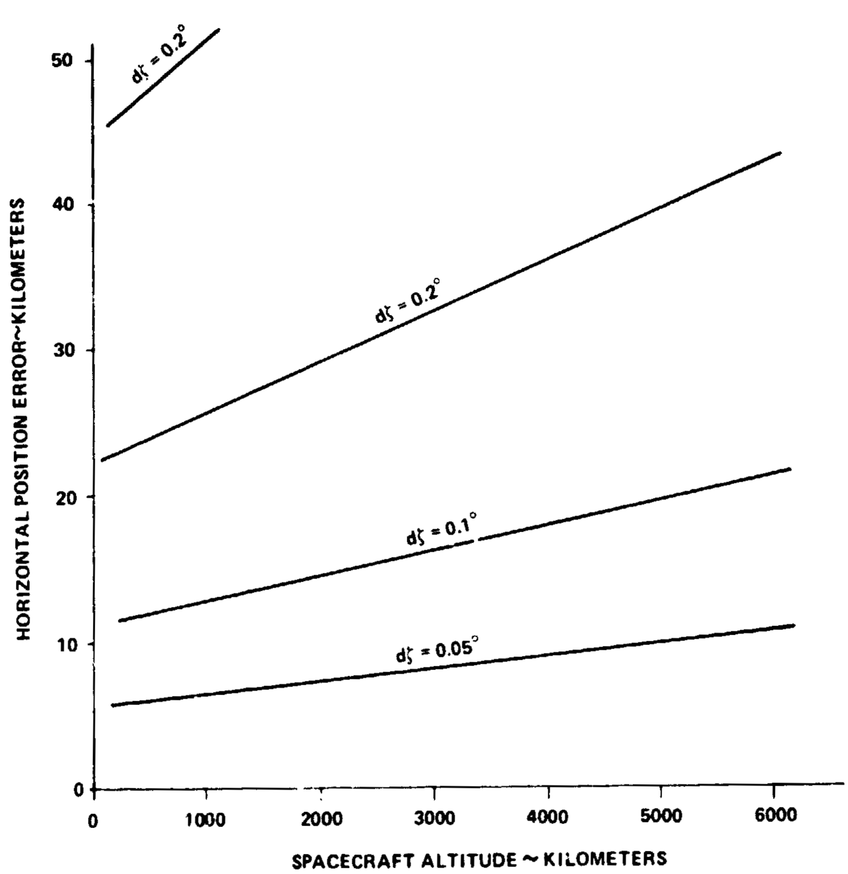

Figure 6. Variation of the position horizontal component error.

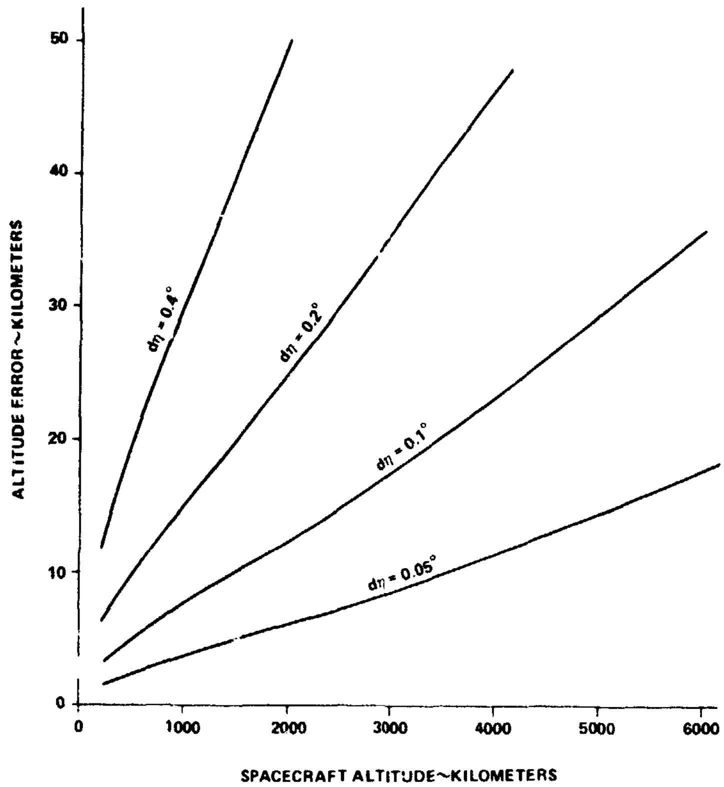

Figure 7. Variations in altitude error as a function of altitude.

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IDEAL ELEMENTS FOR PERTURBED KEPLERIAN MOTIONS

A. Deprit
University of Cincinnati
Cincinnati, Ohio

The motion is referred to Hansen's ideal frame, its attitude being defined by its Eulerian parameters. The parameters selected to determine the motion in the orbital plane cause no singularities or indeterminacies for small eccentricities; they have been chosen with a view of making the right-hand members of the equations as simple to program as possible.