ABSTRACT

A simple expression for the go, no-go criterion is derived in analytical form. This provides a better understanding of the problems involved which is lacking when large computer programs are used. A comparison between "slide rule" results and computer results is indicated on Figure 3.

An example is given using a 185 km near circular parking orbit. It is shown that a 3σ speed error of 6 m/s and a 3σ flight path angle error of 4.5 mrad result in a 3σ perigee error of 30 km which is tolerable when a 5 day orbital life time of the Apollo (SIVB + Service + Command Module) is required.
GO, NO-GO FOR THE APOLLO SPACECRAFT -
AN ANALYTICAL SOLUTION

INTRODUCTION

The purpose of this paper is to derive, in simple form, an analytical expression of the go, no-go criterion for the insertion of the Apollo spacecraft into an earth parking orbit. This means in essence the determination of the maximum perigee height error \( \sigma h_p \) which can be allowed when a certain orbital lifetime is required after insertion. By doing so, a better understanding of the important physical parameters involved can be obtained, which is normally lacking when large computer programs are used.

Considering only the safety of the astronauts, one can state that the inclination of the parking orbit is of no influence; and only the spacecraft orbital lifetime, which is independent of the inclination, is of importance. The lifetime, on the other hand, is directly related to the perigee height \( h_p \) as shown in References 1 and 2.

In brief, if the injection height \( h \) is assumed to be 185 km (100 nm), the minimum perigee height \( h_p \) can be determined providing a certain orbital lifetime is assumed (see references 1 and 2). Please note that all the considerations here are made for near circular parking orbits, which are required for the Apollo spacecraft.
This analysis can be accomplished by deriving an expression for the variational equation of the perigee height (equation (13)), and in addition, it can be used to derive a simple error equation as expressed by (14).

I. VARIATIONAL EQUATION FOR THE PERIGEE HEIGHT \( h_p \).

Since the go, no-go decision depends on the perigee height variation \( \Delta h_p \) and ultimately its error \( \sigma_{h_p} \), this value will be derived. Knowing this quantity as a function of the insertion parameters, \( p, v, \) and \( \gamma \) as shown in Figure 1, the go, no-go criterion can be established; or the errors in \( p, v, \) and \( \gamma \), can be determined for a certain error \( \sigma_{h_p} \) of the perigee height \( h_p \) corresponding to a given or previously established orbital lifetime.

Three quantities, insertion radius \( p \), insertion speed \( v \), and insertion flight path angle \( \gamma \) determine the ellipse of the parking orbit and thus the perigee radius \( p_p \) that is:

\[
p_p = f(v, p, \gamma) \quad \text{(1)}
\]
No perturbing forces will be considered since only the error in $h_p$ (or $h_p$) is of interest and this error is almost independent of the perturbations.

Varying equation (1) results in:

$$
\Delta h_p = \frac{\partial^2 \rho}{\partial v} \Delta v + \frac{\partial^2 \rho}{\partial \rho} \Delta \rho + \frac{\partial^2 \rho}{\partial \gamma} \Delta \gamma
$$

where $\Delta h_p$ and $\Delta h$ have replaced the values $\Delta \rho_p$ and $\Delta \rho$ as derived from $\rho = (R + h)$ and $\rho_p = (R + h_p)$.

Starting with the fundamental equations for the ellipse, which can be found in all basic textbooks (see References 1, 3, 4, and 5) on orbits, one can write:

a. The equation for the eccentricity

$$
(1 - e^2) = \left(\frac{\nu \rho \cos \gamma}{\mu}\right)^2
$$
b. The equation for the perigee radius

\[ r_p = a(1 - e) \]  \hspace{1cm} (4) \hspace{1cm} \rho = \rho_0

c. The vis viva integral

\[ v^2 = \mu \left( \frac{\sqrt{r}}{\rho} - \frac{i}{\mu} \right) \]  \hspace{1cm} (5) \hspace{1cm} h = m\mu \hspace{1cm} \rho = \rho_0

d. The polar equation

\[ \rho = \frac{a(1 - e^2)}{1 + e \cos \phi} \]  \hspace{1cm} (6) \hspace{1cm} \phi = \theta \hspace{1cm} \rho = \rho_0

where \( \mu = 3.986\times10^5 \text{km}^3/\text{sec}^2 \) is the gravitational parameter of the earth (see References 1 and 6), and \( \phi \) is the true anomaly of the elliptic orbit under consideration.

Equation (1) can be obtained in a straightforward manner using equations 3, 4, and 5, that is:

\[ 2 \rho_p - 2 \frac{\rho_p v^2}{\mu} + \frac{\rho_p v^2}{\mu} = \frac{1}{\mu} v^2 \rho^2 \cos \gamma \]  \hspace{1cm} (7) \hspace{1cm} \rho = \rho_0 \hspace{1cm} \mu = m\mu \hspace{1cm} \gamma = \gamma_0 \\ \\ \ \ \ \ \ \ (8) \hspace{1cm} \rho = \rho_0

In order to obtain a variational expression for \( \rho_p \) or \( h_p \), equation (7) has to be varied, resulting in:
where proper terms have been collected as shown in equation (8). Please note that \( \Delta \rho = \Delta h \) and \( \Delta h_p = \Delta \rho \), because their relationship is linear. In the following, it is shown how the coefficients in equation (8) can be evaluated. In order to simplify these, it is assumed that the orbit eccentricities are within \( 0 \leq e \leq 0.15 \), which includes all of the ranges of the parking orbits under consideration for the Apollo spacecraft.

Considering only terms up to the second order in \( e \), that is \( e^2 \neq 0 \) (all higher terms of \( e \) are considered small compared to other terms involved), one obtains the following results for the coefficients of equation (8):

\[
\Delta h \left[ 1 - 2 \frac{\rho_p}{e} + \frac{\gamma^2 \rho_p}{\mu} \right] = \left[ \frac{(\nu \rho \cos \gamma)^2}{\mu} - \frac{\rho_p}{\mu} \right] \frac{\Delta h}{e} \\
+ \left[ \frac{(\nu \rho \cos \gamma)^2}{\mu} - \frac{\gamma^2 \rho_p}{\mu} \right] \frac{\Delta v}{v} - \left[ \frac{(\nu \rho \cos \gamma)^2}{\mu} \right] \Delta \gamma 
\]

(8)
First, for $\Delta h$:

$$
\left( 1 - 2 \frac{\rho_p}{\lambda} + \frac{v^2 \rho_p^2}{\mu} \right) = e \quad (9)
$$

using equation (6) with the assumption that $\phi$ is small making $\cos \phi = 1$. This is justified since the normal insertion conditions are $\gamma = 0$ or $\phi = 0$ which means that $\rho_p = \rho$ and $\frac{v^2 \rho_p}{\mu} = (1 + e)$

Second, for $\left( \frac{\Delta \rho}{\ell} \right) = \left( \frac{\Delta h}{\ell} \right)$:

$$
\left[ \frac{(v \rho \cos \gamma)^2}{\mu} - \frac{\rho_p^2}{\ell} \right] = e \rho \quad (10)
$$

using equation (1), introducing $\frac{\rho_p^2}{\rho^2} = (1 + e)$ and neglecting terms of $e^3$ and higher.

Third, for $\left( \frac{\Delta V}{V} \right)$:

$$
\left[ \frac{(v \rho \cos \gamma)^2}{\mu} - \frac{v^2 \rho_p^2}{\mu} \right] = 2 \rho a = 2 \rho (1 + e) \quad (11)
$$
using (1), (4), and (5) and setting \( 1 - \frac{\rho}{\mu} = e \).

Fourth, for \( \Delta y \):

\[
\left[ \frac{\left( v \rho \cos \gamma \right)^2}{\mu} + \tan \gamma \right] = a \left( 1 - e^2 \right) \tan \gamma
\]  

(12)

These coefficients, represented by the equations (9), (10), (11), and (12), can now be introduced into equation (8), which leads to the final variational equation for the perigee height, that is

\[
\Delta h_{\rho} = \Delta h + 2 \left( 1 + e \right) \left( R + h \right) \left( \frac{\Delta v}{v} \right) - \left( 1 + e \right) \left( R + h \right) \Delta y
\]  

(13)

where the value \( \left( \frac{\tan \gamma}{e} \right) = 1 \leq \) (limit case for \( e \to o \) and \( \gamma \to 0 \)) and \( \rho = \left( R + h \right) \) were introduced.

Equation (13) can be used to determine the necessary "maneuvers" to change the perigee height \( h_{\rho} \), by a certain amount \( \Delta h_{\rho} \), by changing \( \Delta h \), \( \Delta v \) or \( \Delta y \) as deemed necessary. This is graphically illustrated in Figure 2. It can be seen from this graph that inadequate insertion speed (\( \Delta v \) negative) can be compensated for by a negative \( \Delta y \), etc. For example, using \( \Delta h = 0.5 \) km, a flight path angle variation of \(-1.5\) mrad and a velocity variation of \(-5\) m/s results in a zero variation of the perigee height, as indicated in Figure 2. Also, this can be seen by inspecting equation (13).
II. THE ERROR IN THE ORBITAL PERIGEE HEIGHT $\Delta h_p$.

Assuming zero covariances, the error in perigee height $\Delta h_p$ can be written as the sum of the squares of the variational expressions, (13), that is

$$
\Sigma^2 \Delta h_p = (R + \gamma) \left[ \left( \frac{\sigma h}{R + \gamma} \right)^2 + \frac{1}{2} \left( 1 + e \right) \left( \frac{\sigma \gamma}{\gamma} \right)^2 + \left( 1 + e \right) \sigma \gamma \right] \sqrt{\gamma} \tag{14}
$$

This equation is presented in graph form in Figure 3, for a typical Apollo parking orbit, $e \approx 0$, $h = 185$ km. It is shown in References 7 and 8, that the neglect of the covariances always gives conservative estimate of the errors volume.

The corresponding values obtained with a computer program in conjunction with a Monte Carlo approach are shown in Figure 3. This substantiates what was mentioned in the previous paragraph.
III. CRITERION FOR GO, NO-GO IN SIMPLE FORM.

The Apollo spacecraft has a weight of approximately 91,000 kg at the time of insertion into the earth parking orbit, and a frontal area of about 35 m².

Using data as given in References 1 and 2, one obtains a lifetime of approximately 30 days for a 185 km (100 nmi) orbit, which corresponds to the area previously mentioned. For a 160 km (88 nmi) orbit, the lifetime is approximately 9 days (respectively). See Figures 4 and 4a.

As an example, assume that for a go, no-go decision a 5-day orbital lifetime is required. Using a 185 km (100 nmi) circular orbit as the nominal parking orbit, one could tolerate a 3σh_p error of approximately 30 km from the lifetime considerations. (See Figure 4.) Using Figure 3, one finds that a 3σ speed error up to 6 m/s and a 3σ flight path angle error up to 4.5 mrad are tolerable; or a 3σ speed error of 12 m/s and a 3σ flight path angle error of 3 mrad are also within the 3σh_p error bounds. In all the cases, the perigee height error of 3σh_p was assumed to be 1.5 km. The value for the insertion height can be easily obtained as shown in Reference 9 (1σh = 500 m). Inspection of Figure 3 shows that the error in insertion height does not play an
Important role: $3\sigma_n = 1.5 \text{ km}$ or $3\sigma_n = 2 \text{ km}$ does not alter the conclusions reached. In Reference 9 the velocity errors $1\sigma_v$ are presented for different noise, bias and station locations (ships) using one tracking sample per second without a priori knowledge of the orbit.

Using the $3\sigma$ error analysis results just mentioned, for speed and flight path angles given in Reference 10, for a 40 second tracking interval and 5 tracking samples per second, that is $4 \text{ m/s}$ and $2 \text{ mrad}$, shows that the associated $3\sigma$ error in perigee height is well within the assumed limits. Therefore, a safe go, no-go can be made using a tracking time of approximately 40 seconds with 5 tracking samples per second. The values stated are based upon radar measurements with a range noise error of $1\sigma_r = 10 \text{ m}$ and angular noise errors of $1\sigma_\alpha = 1\sigma_\epsilon = 0.4 \text{ mrad}$ combined with bias errors twice the stated noise values respectively. A detailed table on the tracking errors used for Apollo is presented in Reference 11, the Apollo Navigation Working Group Report.

It is interesting to note that the location errors for the tracker (a ship in case of Apollo, see References 9 and 10) do not influence the velocity and flight path angle, which are the
vital parameters for this decision. As clearly stated in Table
3.4 of Reference 10, speed, flight path angle and altitude
errors are not affected much by the station location error. A
numerical example is given for better understanding. Assume
the insertion ship tracks the spacecraft with its C-band radar
using the errors quoted before and in addition has a navigational
error of $3\sigma = 4$ km (in N and E direction). The corresponding error
in spacecraft speed $3\sigma_V \approx 2$ m/s and that in flight path angle
$\sigma_\gamma \approx 1$ mrad after 2 minutes of tracking. This can also be seen
from Figures 5 and 6 in Reference 9, which show that the navigation
accuracies needed for the Apollo insertion ship (References 9 and
10) are only moderate.
REFERENCES


hp --- PERIGEE HEIGHT
h --- INSERTION HEIGHT
v --- INSERTION SPEED
γ --- INSERTION FLIGHT PATH ANGLE
R --- EARTH RADIUS
ρ --- (R+h)
ρ_p --- (R+h_p)
θ --- TRUE ANAMOLI

Figure 1

ORBITAL INSERTION GEOMETRY
PERIGEE VARIATIONS FOR APOLLO PARKING ORBITS

Figure 2

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October 1965
PERIGEE ERROR FOR APOLLO PARKING ORBITS
(e = 0, \( h_0 = 185 \) km)

Figure 3

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Mission Analysis Office
October 1965
INITIAL HEIGHT, $h_0 = 185 \text{ km}$
INITIAL ECCENTRICITY, $e_0 = 0$
INITIAL AIR DENSITY, $\rho_0 = 2.42 \times 10^{-10} \text{ kg/m}^3$
FRONTAL AREA, $A_1 = 35 \text{ m}^2$
WEIGHT IN ORBIT, $W = 91,000 \text{ kg}$
DRAG COEFFICIENT, $C_D = 2$.

$$\frac{C_D A_1}{W} = 0.769 \times 10^{-3} \text{ m}^2/\text{kg}$$

HEIGHT OF THE APOLLO PARKING ORBIT AFTER INSERTION
(Perkins, Ref. 2).

Figure 4

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Mission Analysis Office
November 1965
INITIAL HEIGHT, \( h_0 = 185 \text{ km} \)

INITIAL ECCENTRICITY, \( e_0 \approx 0 \)

INITIAL AIR DENSITY, \( \rho_0 = 2.42 \times 10^{-10} \text{ kg/m}^3 \)

FRONTAL AREA, \( A_1 = 35 \text{ m}^2 \)

WEIGHT IN ORBIT, \( W = 91,000 \text{ kg} \)

DRAG COEFFICIENT, \( C_D = 2 \)

\[ \frac{C_D A_1}{W} = 0.769 \times 10^{-3} \text{ m}^2/\text{kg} \]

HEIGHT RATES FOR THE APOLLO PARKING ORBIT
(Perkins, Ref. 2)

Figure 4a

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