N76-10186

SYSTEM DESIGN IMPACT OF GUIDANCE AND NAVIGATION ANALYSIS FOR A SEPS 1979 ENCKE FLYBY

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This is a report on a study that Martin Marietta did for Rockwell, who in turn was doing a feasibility study for the solar electric propulsion stage (SEPS). The emphasis was on system feasibility, and we tried to merge the guidance and navigation requirements into the total system. The primary emphasis was the 1979 Comet Encke flyby, which at that time was the first proposed SEPS mission. We also looked at some system requirements for other missions.

Many of the system parameters are affected by guidance and navigation requirements. The most important ones are thrust control authority (that is, how much additional control is needed in the thrust subsystem to implement trajectory corrections), thrust performance tolerances, thrust vector control, propulsion time, the additional time required for adjusting the trajectories, fuel requirements, guidance updates, and the types of earth-based navigation and communications needed. Other parameters affected are the onboard navigation subsystem (how good must it be, if it is indeed needed) and the type of trajectory and terminal errors that occur (that is, control and knowledge). Control is the dispersion of the actual about the reference, and knowledge is the dispersion of the estimated about the actual.

The baseline mission for this particular stage was a launch in March 1979 and encounter in November 1980. Figure 1 shows an ecliptic projection of the flyby.

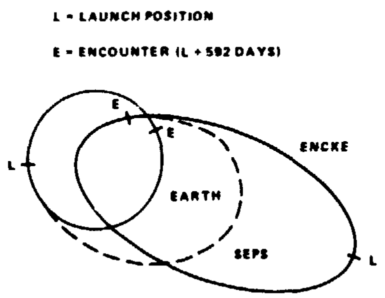

Figure 1. Ecliptic projection of the 1979 earth-to-Encke flyby.

One of the first things we did was to take the mission analysis results that Rockwell generated and produce a more realistic, optimized and targeted trajectory in which we imposed reasonable control policies. Listed below are the mission data:

- Launch date–March 25, 1979
- Arrival date–November 7, 1980
- Launch VHE–7.18 km/s
- Initial mass–1988 kg
- Initial power–21 kW
- Housekeeping power–0.650 kW
- Thruster efficiency–64 percent
- Propulsion time–523 days
- Coast time–Initial, 64 days; final, 5 days
- Arrival VHP–3.16 km/s
- Arrival RCA–1100 km
- Arrival mass–1456 kg

We employed constant cone, clock, and thrust over fixed time segments, and we imposed whatever constraints were necessary; for example, the final coast time of 5 days was the minimum acceptable for science. There was also an initial coast and a total thrust time of 523 days. We arrived at 3 km/s at 1100 km closest approach. The encounter was 30 days prior to perihelian for this particular study.

The baseline guidance and navigation strategy–and we are talking mostly about the approach phase now–assumed simultaneous or continuous coverage from three Deep Space Network (DSN) stations over the last 40 days. We assumed an onboard optical system similar to Mariner-10. Optical or onboard observations were taken twice per day starting at 30 days prior to encounter, and each optical measurement contained Encke and three identifiable stars. We estimated the vehicle state, thrust biases, and the Encke ephemeris, and we considered the process noise that is generated by the thrusters. Guidance updates were performed every 4 days, and we assumed that we could control the trajectory just by biasing the nominal thrust controls. The baseline strategy was not intended to meet all the system requirements, but it was our first try at it.

The dynamic and measurement error sources that we assumed are listed below:

- Dynamic error sources
  a. Launch error – Position, 3 km; velocity, 5 m/s; mass, 1 kg
  b. Thrust bias – Magnitude, 2.2 percent; direction, 0.035 rad

c. Thrust noise – Magnitude, 3.5 percent; correlation time, 5 days; direction: 0.010 rad; correlation time, 3 hours

d. Encke – Position, 10,000 km; velocity, 1000 km/day

- Measurement error sources

  a. DSN station location – Spin radius, 1.5 m; longitude, 3.0 m; height, 10.0 m

  b. Doppler noise – Two-way, 1 mm/s; three-way, 0.1 mm/s

  c. Range noise – Two-way, 3 m; three-way, 10 m

  d. Optical – Resolution, 30 arc-seconds; center finding, 10 km

SEPS is launched with the Titan-Centaur, so we had typical insertion uncertainties. The thrust uncertainties consisted of both bias and noise. We estimated the bias and the noise, which has a time-varying component, hence the correlation times associated with them were considered. The values listed are for a single thruster; there are eight operating thrusters for this vehicle. The a priori error for Encke was assumed to be very pessimistic, although at that time it was a reasonable uncertainty of 10,000 km and 1000 km per day, or about 10 m/s.

Typical station location uncertainties were assumed. Since we used simultaneous range and range rate data from earth to the spacecraft, we also included three-way uncertainties. Our onboard optical uncertainties consisted of an error or 30 arc-seconds noise and an uncertainty of 10 km to approximate the uncertainty between the comet's center of brightness and the center of gravity.

One of the first things we studied was the approach geometry, to see if we could get an idea of what was happening. Figure 2 is a view of the last 30 days prior to encounter. It can be seen that the thrust vector is almost retrograde, which means that it is on a flat trajectory relative to Encke, and there is very little curvature. There is also the possibility of the thrust plume interfering with any instruments that are sensing as Encke is approached. However, cutoff occurs at 5 days prior to encounter. The position of the earth is changing very rapidly both in direction and in declination, which would indicate that earth-based tracking of the spacecraft would be very good. On the other hand, because of the flatness of the trajectory, the onboard optics probably will not be as good.

Figure 3 is a plot of the inertial position uncertainties due to the estimation of both Encke and SEPS. Because simultaneous data are employed, we get near-ballistic results for the spacecraft. However, our onboard optics just barely get below the a priori level.

Most of this is along-track error. However, a 6000-km along-track error is about 10 minutes uncertainty, and that would seriously affect pointing and slewing rates. Because the stage and Encke are dynamically uncoupled, the Encke relative uncertainty is basically the RSS of these two, which is then dominated by the Encke uncertainties.

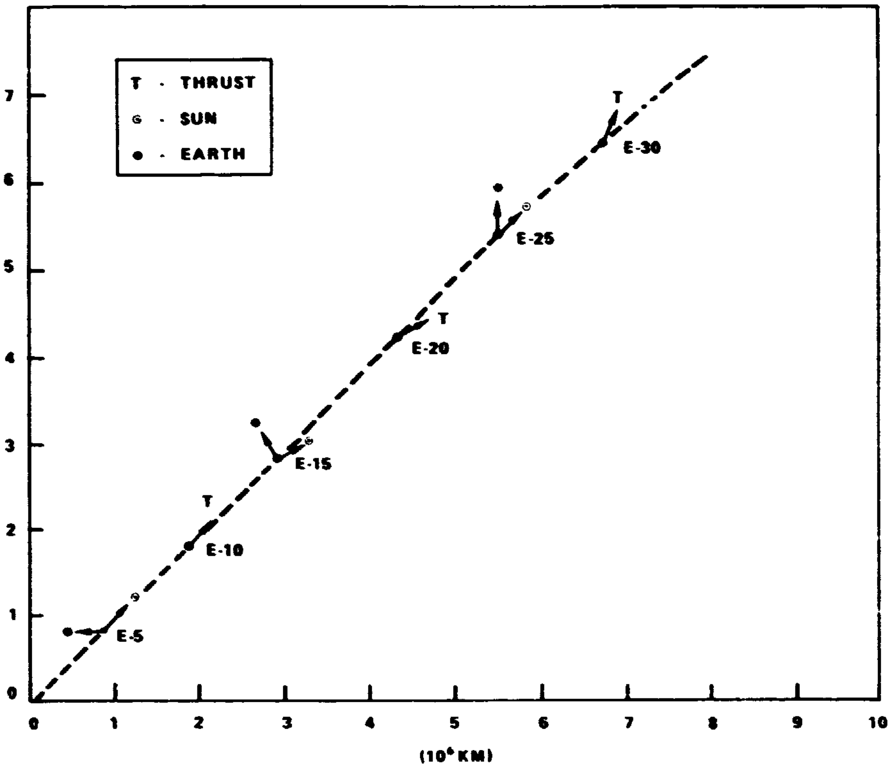

Figure 2. Encke flyby relative approach geometry for last 30 days prior to encounter.

As shown in figure 4, the velocity shows only fair improvement. It is still not very good, either that of Encke or of the stage.

Since we found that the Encke relative uncertainties are dominated by the a priori ephemeris error, we looked at a number of different a prioris and found that Encke relative uncertainties are a priori sensitive, primarily in the velocity component (figure 5). For example, we found that, if we have no velocity uncertainty, we will get very good estimation errors. However, if we have any reasonable amount of a priori velocity uncertainty, the optics cannot compensate, which means that the comet's relative uncertainty remains unchanged. We did take some covariances from Bob Farquhar and used them as our a priori. They looked more like our zero velocity case, although not quite as good, or about 400 km terminal uncertainty.

Figure 6 illustrates the magnitude of the thrust guidance corrections, that is, biases to the nominal thrust control policy. The biases never exceed more than 3 percent in thrust magnitude and are irregularly shaped because of our strategy. The curve could have been smoothed out by placing the guidance updates at different intervals and by employing a different control policy. But in magnitude, the bias is not more than 3 percent, and in pointing, it is less than 2°, 1σ.

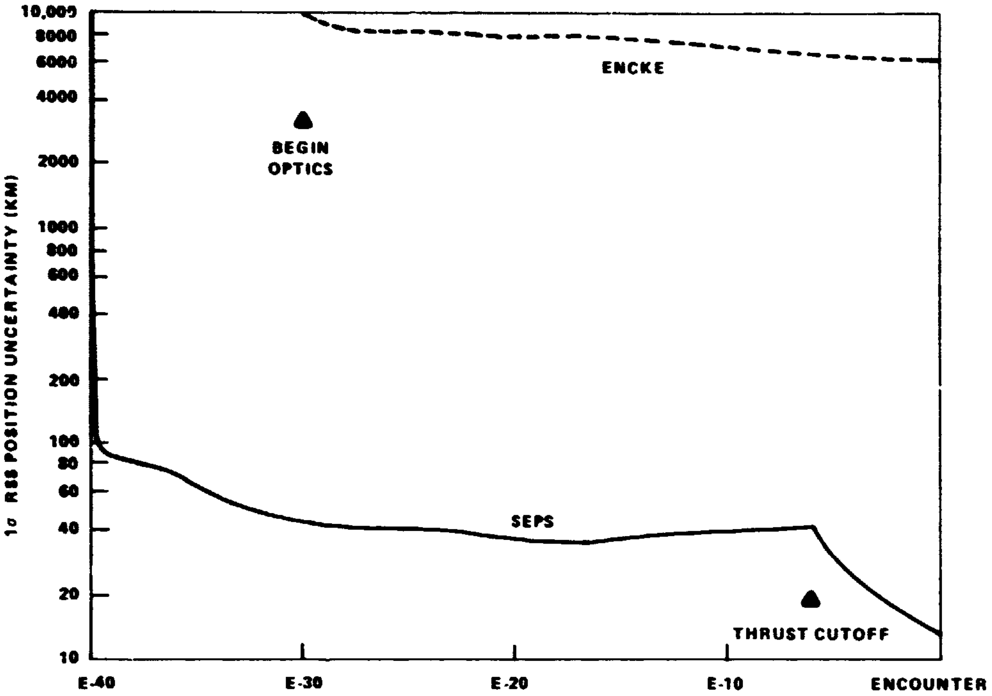

Figure 3. Encke flyby approach phase baseline position uncertainties.

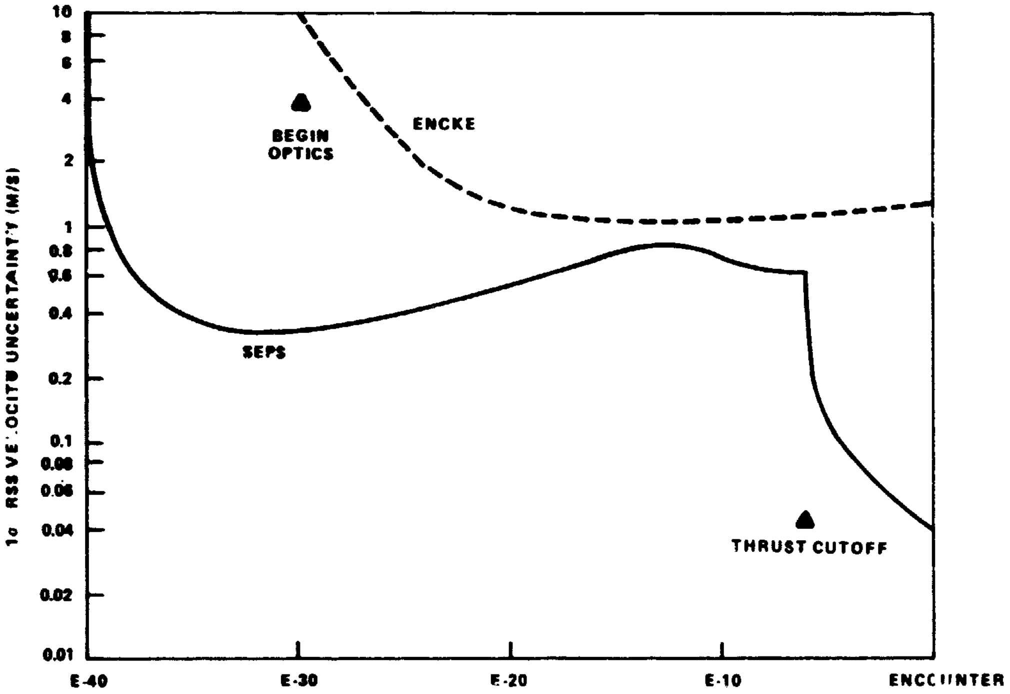

Figure 4. Encke flyby approach phase baseline velocity uncertainties.

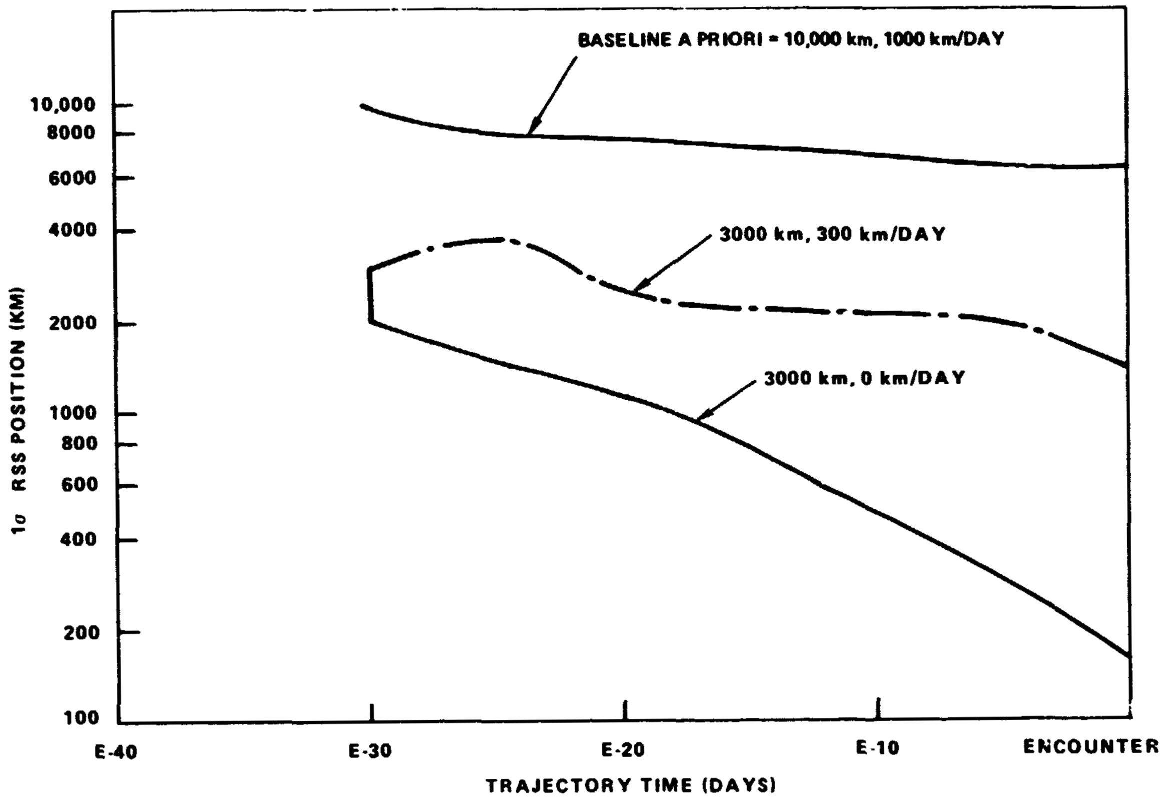

Figure 5. Encke ephemeris uncertainty.

Figure 7 illustrates the terminal control error; that is, the error obtained after all the orbit determination and guidance have been employed. The shaded area is the inertial spacecraft uncertainty, and the total bar is the Encke relative uncertainty. We chose 1000 km as a guidance success zone, which is our maximum acceptable error for a successful mission. Obviously our baseline missed that by quite a bit. If we look at the effect of a priori ephemeris uncertainties, we could get within the success zone if we have zero velocity uncertainty in Encke. However, that is not a realistic case. If we assume some currently reasonable error, we will probably just barely make the guidance success zone. Because of the dominance of the ephemeris uncertainty, even if we eliminated earth-based ranging of the stage, the Encke relative uncertainty would not be affected, but the stage uncertainty would be. If we ever do reduce the ephemeris error down to some low level, we will still need earth-based ranging, and the same thing goes for simultaneous range and range rate data from the earth.

The conclusions for this particular study are as follows: Cruise guidance and navigation requirements (not discussed) were minimal compared to the approach phase. The Encke relative approach error was dominated by the ephemeris uncertainties, particularly the

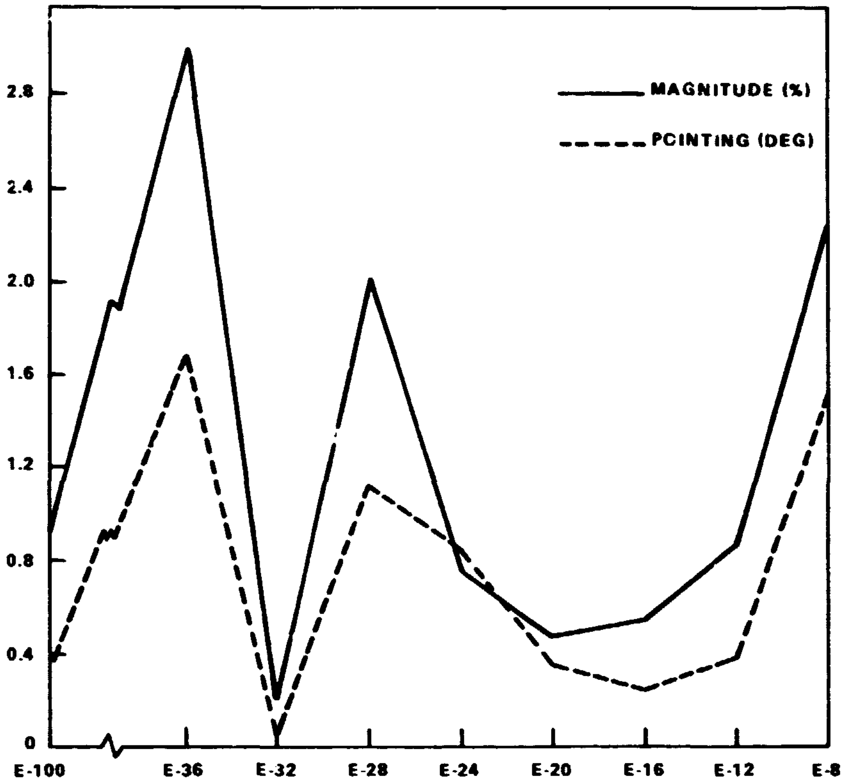

Figure 6. Encke flyby thrust guidance corrections.

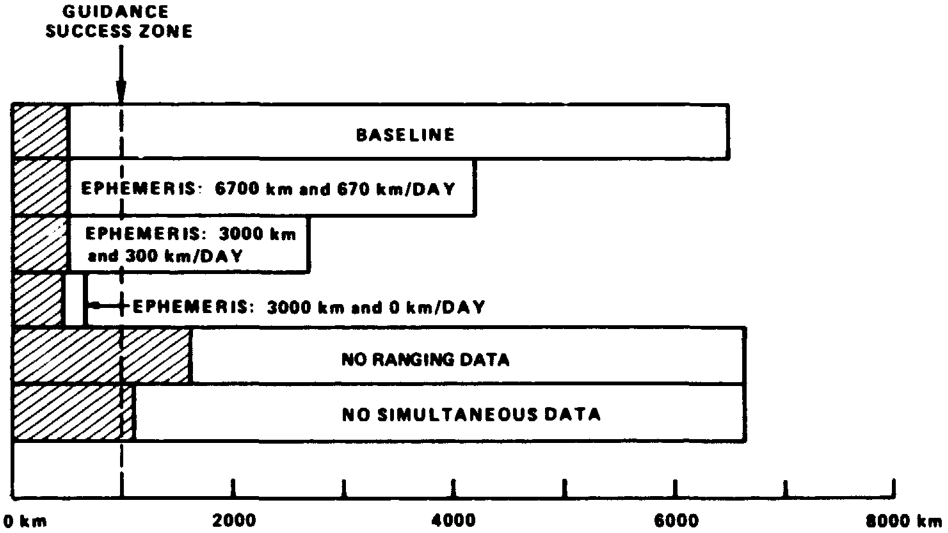

Figure 7. Encke encounter uncertainties (1σ).

velocity components. The earth-based tracking was very good; however, quality three-way data are still needed from the DSN stations. Optical navigation was only fair, due primarily to the flat trajectory. Finally, the thrust control authority, that is, the thrust updates, were within acceptable tolerances.

Table 1 lists some other missions which might drive the design of this stage, which is supposed to be a multimission spacecraft, and we identified a few missions which might drive the guidance and navigation subsystem design. One was the Encke flyby, because that was the first proposed SEPS mission. The next was an earth-orbital mission, because of its unique characteristics. The Encke rendezvous was chosen primarily because it might place great demands on an onboard sensor and also because it was the second interplanetary mission. The Mercury orbiter was chosen because it had a high thrust acceleration at approach, which meant that the process noise in the thrust would dominate this particular mission. Finally, we chose an outer planet mission, or an outbound mission, in this case a Phobos/Deimos rendezvous. The data in the table are just guesses as to what the impact might be on these subsystems.

Table 1
Mission/Subsystem Impact*

Mission	Launch	Flight Time (days)	Approach Guidance	Thrust	Thrust Vector and Attitude Control	Earth-based Tracking	Operations and Communications	Science
Encke Flyby	1979	630	M	L	L	M	L	H
Earth Orbital	1980	50-100†	H	H	H	H	H	–
Encke Rendezvous	1981	1100	H	H	M	M	M	H
Mercury Orbiter	1984	400	–	H	H	H	M	M
Phobos/Deimos Rendezvous	1984	260	H	M	M	M	H	H

*(L = low, M = moderate, H = high).

†Per one-way trip.

If we dismiss ephemeris uncertainties for the time being, the limiting factor is the thrust uncertainty; that is, the noise or uncertainty in the performance of the engines. Figure 8 shows the closest approach uncertainty. The Encke flyby is relatively insensitive to thrust magnitude uncertainties, primarily because of the good tracking from the earth, which can minimize the effect of the thrust uncertainties. The Encke rendezvous in 1981, which is a 1984 encounter, does not do as well, because the earth geometry relative to the spacecraft and Encke is not as good. The Mercury orbiter, because of the high acceleration at approach, is very sensitive to thrust error. Of course, this means that if we have a 1000-km guidance success zone, we had better reduce the thrust errors considerably for the Mercury orbiter.

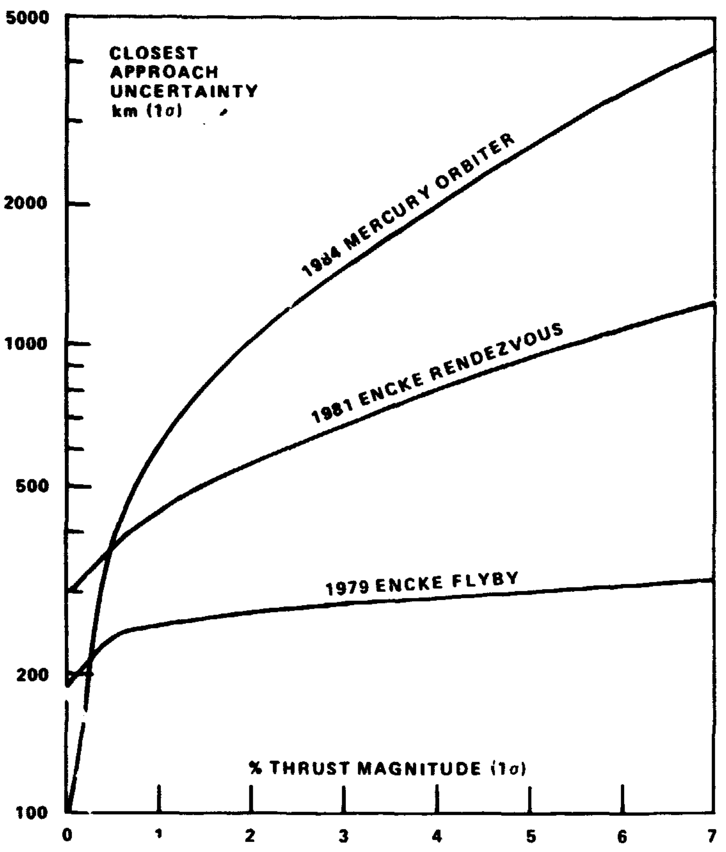

Figure 8. Sensitivity of encounter error to thrust error.

The following recommendations were made and will probably be conducted in a follow-on study:

- Improve the small body, both comet and astroid, ephemeris determination. Part of this involves integrating the earth-based telescope observations of Encke with the DSN and onboard optics measurements.
- Reduce thrust noise level, either through hardware changes or through better orbit determination and measurement.
- Continue development of the simultaneous and/or differenced data types, that is, the quality earth-based three-way data.
- Investigate the impact of other missions and combine their requirements into a common spacecraft.
- Study alternate mission strategies. For example, since we do have thrust at the end, we might shape the trajectory and possibly get some curvature to minimize the along-track error.