OUTER PLANET PROBE NAVIGATION
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MR. FRIEDMAN: We have been conducting a series of navigation studies in conjunction with the outer planet Pioneer missions that Byron Swenson has just discussed.* These missions are described in Figure 3-7. What I am going to describe is a brief summary of these results and some of the major conclusions from the studies. I will also discuss the more recent work that has been performed in conjunction with the Mariner-Jupiter-Uranus mission and make some overall conclusions as far as navigating probes to the outer planets.

The point of our studies has been to determine navigation requirements for these potential atmospheric probe missions and in particular, to look at proposed measurement systems in order to target probes into the outer planets and Titan. The study work is described in Figure 3-8 and 3-9.

To estimate maneuver sizes and strategy for such missions, we have been interacting with the mission designers with items such as separation times, strategy for making measurements, and finally of course the navigation implementation.

Figure 3-10 shows some of the basic assumptions. The Titan III E/Centaur/TE 364 is the planned launch vehicle for all the missions this implies about an eighty meter per second to correct injection dispersions (that is a mean plus three sigma number). This dictates pretty much the entire cruise requirement for delta-V since the subsequent navigation maneuvers are quite small.

Radio accuracies are more or less traditional as to what has been assumed. In our navigation studies, we have deweighted the range data so as to account for the effect of process noise and we have also investigated both conventional Doppler and ranging and differenced Doppler and ranging.

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*This report describes work by Jordan Ellis, Frank Jordan, Charles Paul, Kent Russell and Gary Sherman, in addition to myself at JPL.

FIGURE 3-7

ADVANCED PIONEER

OUTER PLANET PROBE MISSION

	S '79	SU '80	JU '80	TITAN
LAUNCH	11-23-79	11-25-80	12-9-80	1-6-84
ARRIVALS	4-16-83	1-5-84 11-9-87	3-25-82 4-2-86	1-11-87
V_∞ (KM/SEC)	9.1	10.5(S), 13.8(U)	15.1(J), 15.8(U)	11.6
R_P (RADII)	2.6	2.8(S), 4.0(U)	14.7(J), 3.0(U)	13.8 R_S
PROBE				
B (RADII)	3.5	1.5	1.3	0.0 R_T
γ_E (DEG)	-30	-40	-40	-90
$R_{SEP.}$ (RADII)	300	700/1000/1300	600/800/1200	
T_{SEP} (DAYS FROM PERI.)	506	14/20/26	12/16/24	27
ΔV (M/SEC) - EARTHLINE	104	45/30/18	56/43/28	37
- NORMAL	0	66/46/36	60/36/30	3

FIGURE 3-8
OUTER PLANET PIONEER NAVIGATION STUDIES

o DETERMINES NAVIGATION REQUIREMENTS
   o MEASUREMENTS
      o RADIO TRACKING
      o ON-BOARD OPTICAL

   o MANEUVER SIZES AND STRATEGY

o CONTRIBUTES TO MISSION DESIGN

o DESCRIBES NAVIGATION IMPLEMENTATION
   o SINGLE AND MULTI-MISSIONS

o DEFINES TARGETTING ACCURACIES

FIGURE 3-9
MAJOR TASKS IN STUDY

o REDUCTION OF V-SLIT SENSOR DATA TO NAVIGATIONAL INFO.
   o NO ASSESSMENT OF SENSOR
   o NO ANALYSIS OF INSTRUMENT ACCURACY

o STATISTICS OF THE PIONEER MANEUVER EXECUTION
   o PRECESSION MANEUVER MODEL (HISTORICAL)
   o RESTRICED DIRECTION MANEUVER MODEL (NEW)

o ORBIT DETERMINATION PARAMETRIC STUDIES
   o RADIO (INCL. EPHEMERIS)
   o OPTICAL
   o SEPARATION DISTANCES AND COORDINATES

o COMBINED MANEUVER EXECUTION AND ORBIT DETERMINATION
   NAVIGATION RESULTS

FIGURE 3-10

ASSUMPTIONS

o   TITAN III E/CENTAUR/TE 364-4 INJECTION REQUIRES ∿80 M/SEC
    ALLOWANCE FOR 1ST MIDCOURSE

o   RADIO ACCURACIES
    DOPPLER: 100 MM/SEC (CONV), 2.8 MM/SEC (DIFF.)
               10 KM   (CONV), 8.4 M   (DIFF.)
           (ALLOWS EFFECT OF PROCESS NOISE)

o   TRACKING
        1 PT/MIN DOPPLER, 1 PT/6 HR RANGE, OVERLAP
        E - 120 DAYS TO E
        STATION LOCATIONS CONSIDERED (TIGHT: 1 x 2 x 15 M
                                      LOOSE: 3 x 5 x 15 M)

o   EPHEMERIS
        JUPITER: 400KM
        SATURN: 1000KM
        URANUS: 10000KM

I won't go through the other details depicted on the figure, but note the ephemeris accuracies we assumed in the basic study. These are one sigma ephemeris accuracies that we have assumed for the post-MJS time period. The Uranus ephemeris error, 10,000 kilometers, is quite a bit out of line with the other planets. There is reason for that, but that is a subject being separately studied, and will be discussed more later.

We also, in addition to the radio tracking assumptions, have analyzed the V-slit optical navigation sensor which was proposed by TRW as part of the same series of mission studies. In principle, it is to work on the Pioneer spacecraft by taking advantage of the spin to sweep out a region of the sky, and thereby get a cone and clock angle measurement of the satellite and of a star. By being able to determine the angle between them, it then is possible to obtain a satellite-star angle measurement. Its operation is shown in Figure 3-11.

We have worked through various geometries for the various missions and analyzed the star background. It appears adequate. A sample star background is shown in Figures 3-12 and 3-13 for the S/U mission at Saturn and Uranus respectively. The accuracies assumed by TRW in proposing this particular sensor were fifteen arc/seconds in cone and twenty-five arc/seconds in clock (one-sigma).

This is the only concept we have investigated in our studies although it is applicable to other concepts if you parameterize those other concepts in terms of cone and clock angle errors. Thus, our results generalize to any kind of optical system.

The V-slit sensor can only work when the object is bright enough but also when it is less than the slit diameter. The proposal is to acquire it at a certain magnitude and then, as you get closer to the spacecraft, when it gets larger than twenty arc/ seconds, you no longer use the measurement. Figure 3-14 shows these cut-offs for various satellites of the outer planets, and lists

FIGURE 3-11
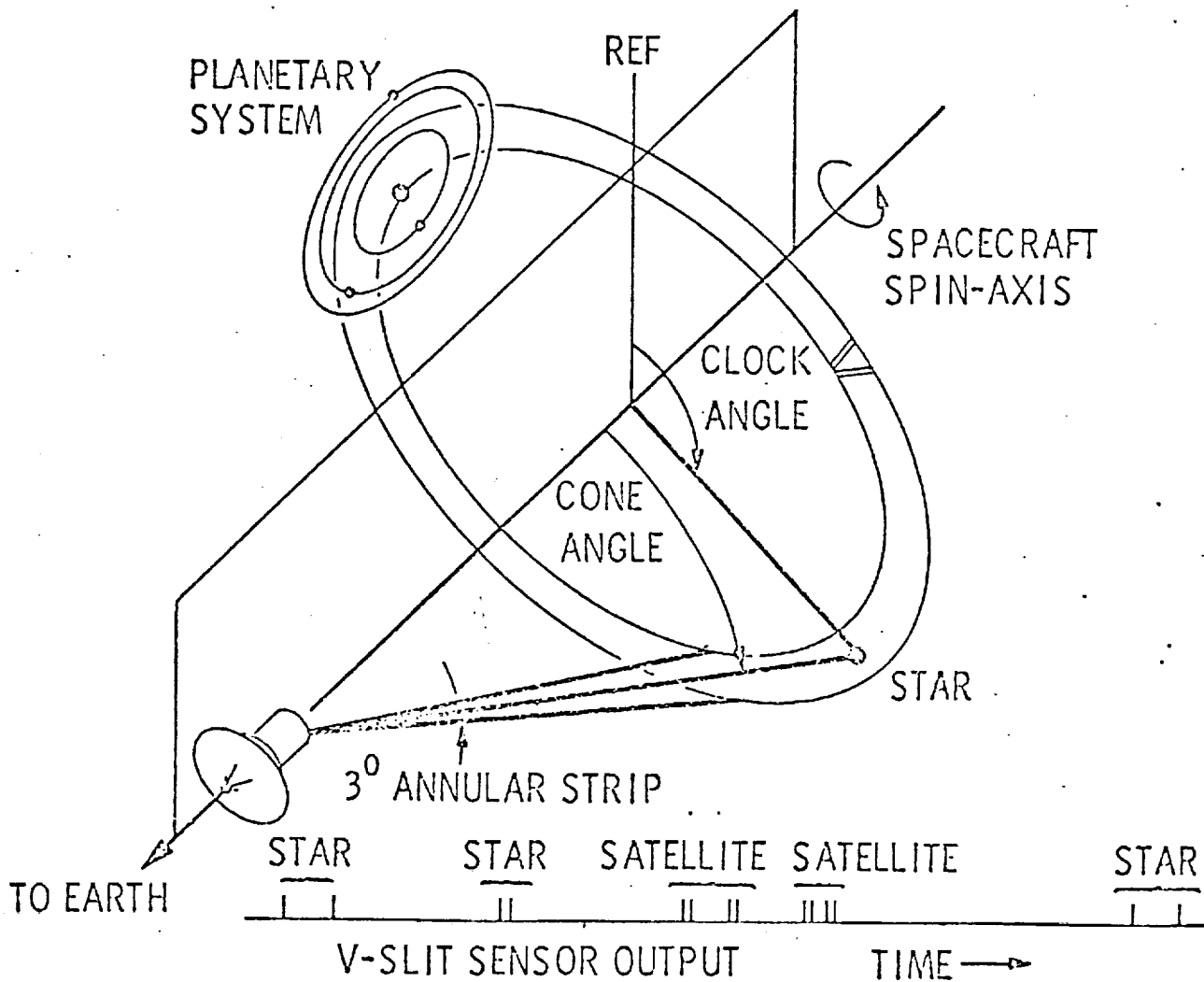
V-Slit Sensor Geometry

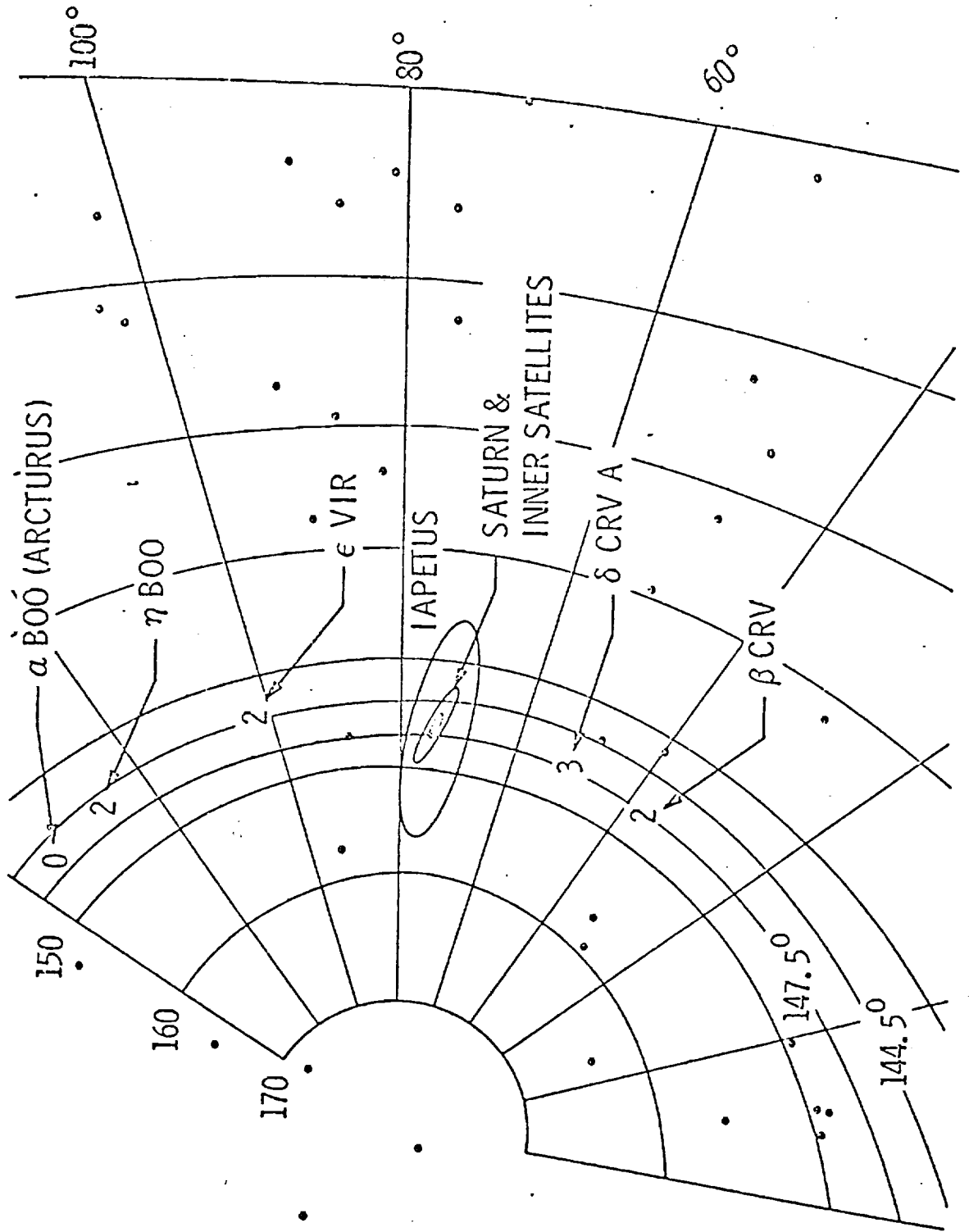ASSUMED ACCURACY, 1σ

CONE 15" (75 RAD)

CLOCK 25" (125 RAD)

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FIGURE 3-12.

Star Visibility at Saturn
S/U 80
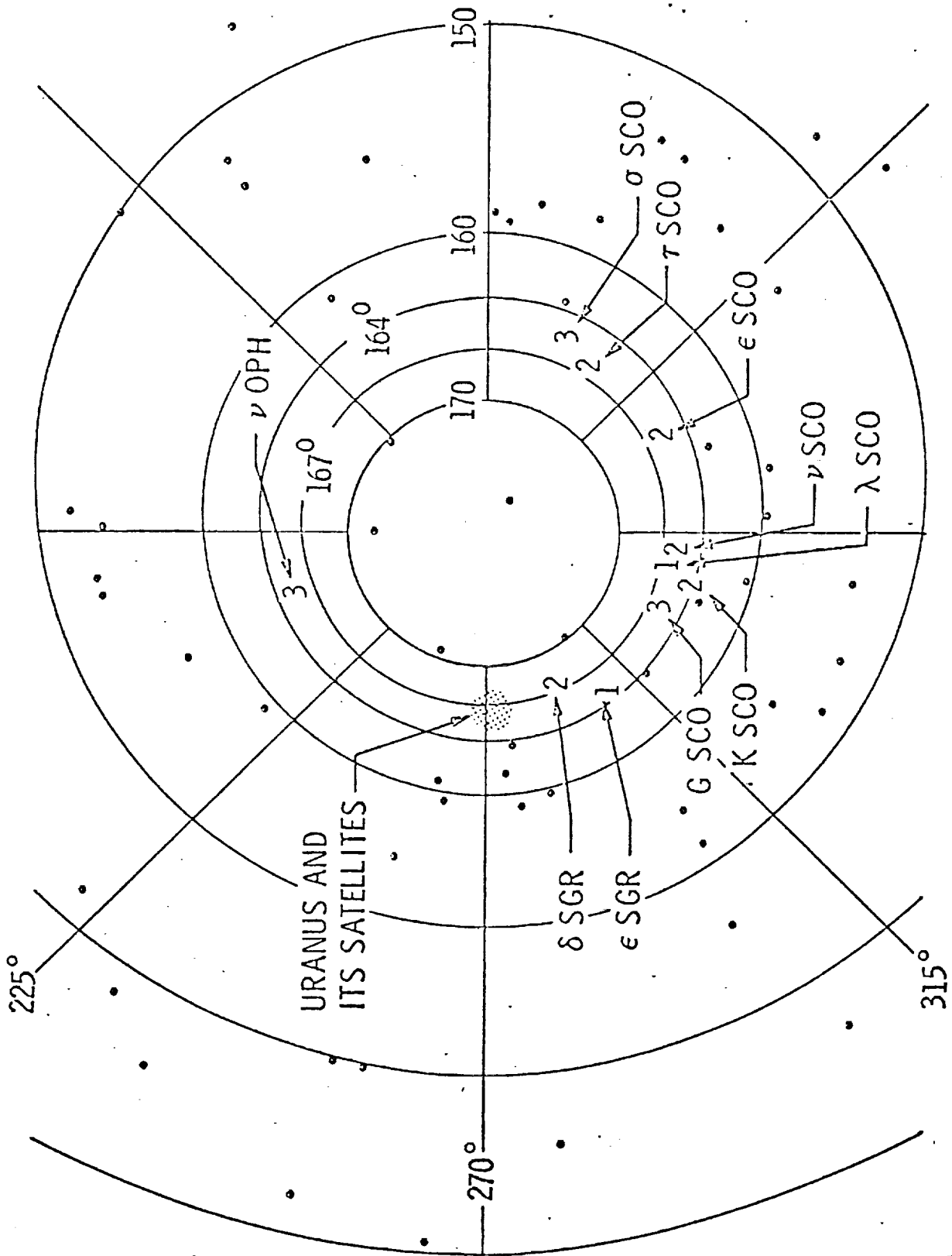
FIGURE 3-13

Star Visibility at Uranus

S/U 80

URANUS AND
ITS SATELLITES

ν OPH
164°
167°
170
160
150
σ SCO
τ SCO
ε SCO
ν SCO
λ SCO
G SCO
K SCO
δ SGR
ε SGR

225°
270°
315°
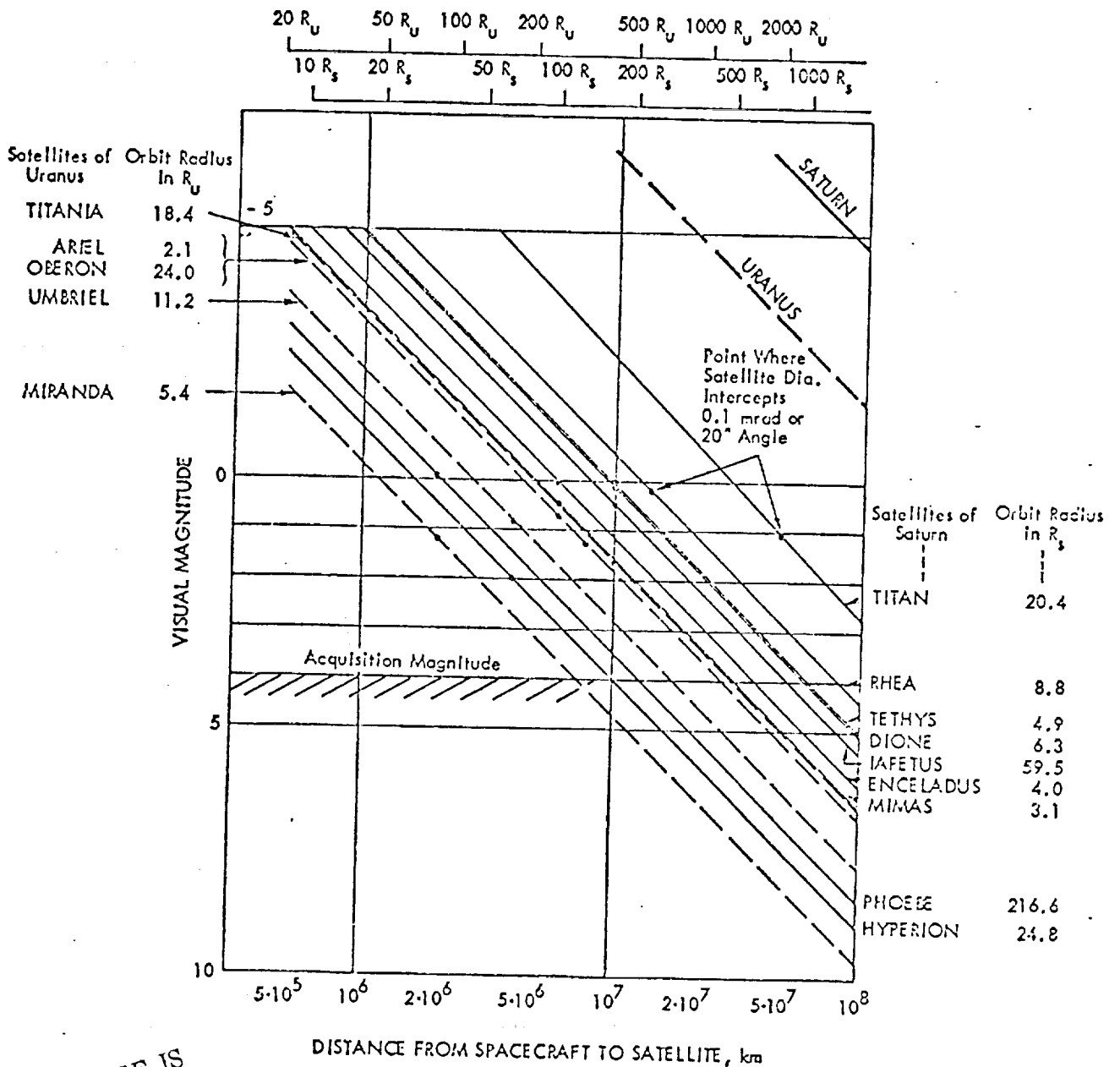
FIGURE 3-14

Visual Magnitudes of Satellites of Saturn and Uranus

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how the magnitude and diameters vary with range of the space-
craft, hence when you can use those satellites as observables.
This becomes very important as you can see here for Titan. Quite
far away from Titan we are prevented from obtaining useful meas-
urements, and so that either the time of getting measurements must
be extended or some other scheme for measurements must be found.

As a brief description of some of the results, areas listed
on Figure 3-15 will be covered.

For Jupiter, which is only an intermediate target, we looked
at radio only navigation first and found out that the accuracy
was sufficient so that the size of the post-Jupiter maneuver could
be kept to reasonable levels so that the mission could be carried
out; that is, go on to Uranus. We assumed two levels of tracking
accuracy - shown in Figure 3-16. The solid line represents what
we call loose stations (cf Figure 3-10). The dotted line repre-
sents what we call tight station accuracies.

We studied different lengths of tracking arcs and let them
go to near encounter. Presumably, tracking is cut off around four
days before encounter when a final maneuver is made. Even at four
days, we obtained very reasonable post-Jupiter Delta-V require-
ments. Either the eight meters per second or the thirteen meter
per second are acceptable. That is no problem and hence at Ju-
piter, radio-only navigation suffices.

In Figure 3-17 we show what happens when you try radio-only
tracking at Uranus. Here we have to live with the ephemeris
error. Shown are three components of position error and because
of the geometry, you transfer errors in one component to an error
in the other component. Basically, the ephemeris error is near
seven thousand kilometers and can not be much improved. However,
optical navigation at Uranus offers significant improvement to
these resutls. As an example, Figure 3-18 shows navigation accuracy
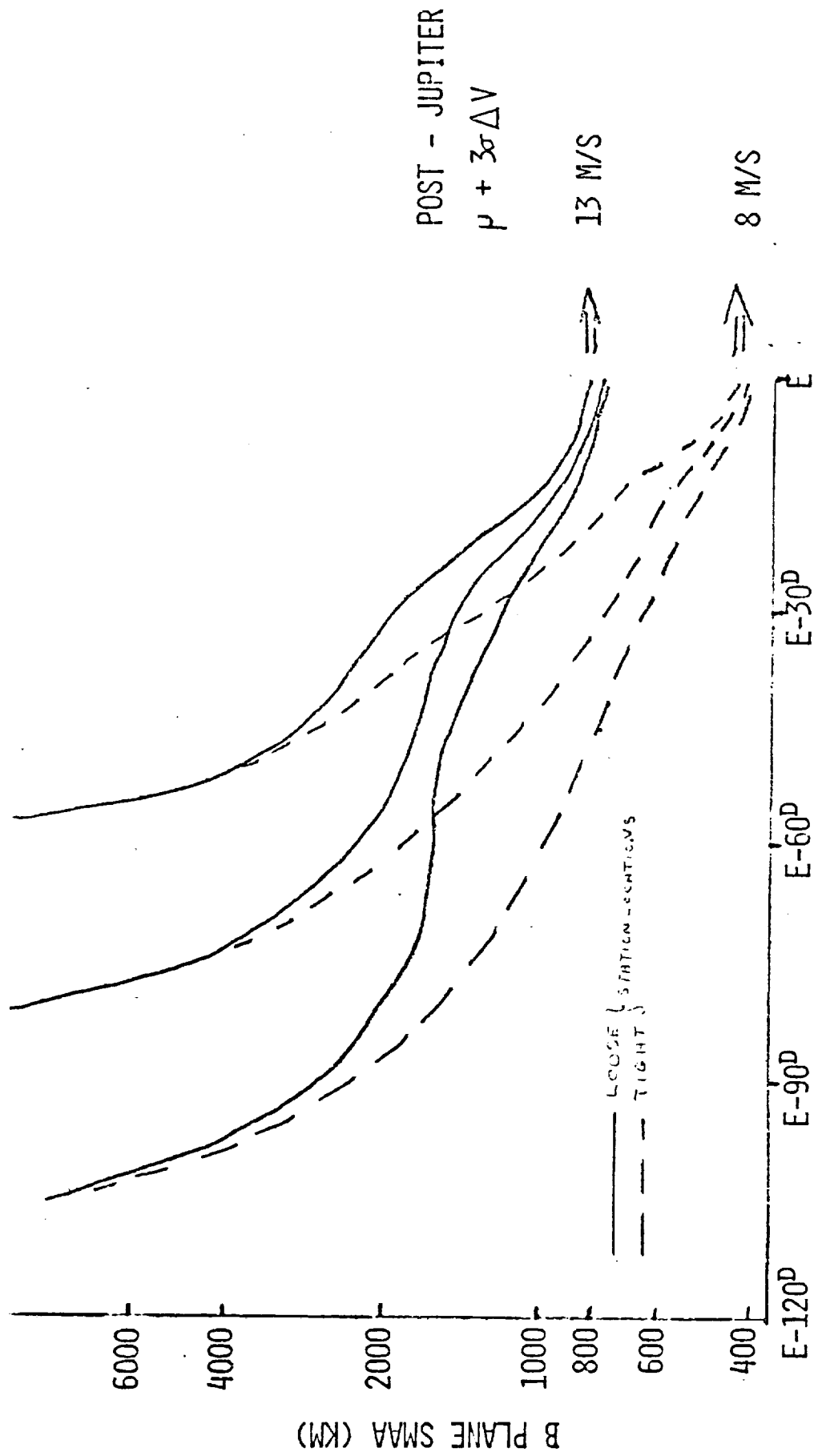
FIGURE 3-15

SAMPLE RESUTLS

- JUPITER RADIO-ONLY RESULTS

- URANUS BUS POSITION ERROR COORDINATES
  (RADIO ALONE)

- OPTICAL TRACKING AT URANUS

- ENTRY ANGLE ERROR AT URANUS

- SATURN/URANUS VELOCITY REQUIREMENT

- TITAN ORBIT DETERMINATION RESULTS

- TITAN GUIDANCE POLICY

FIGURE 3-16

JUPITER PHASE RADIO ONLY
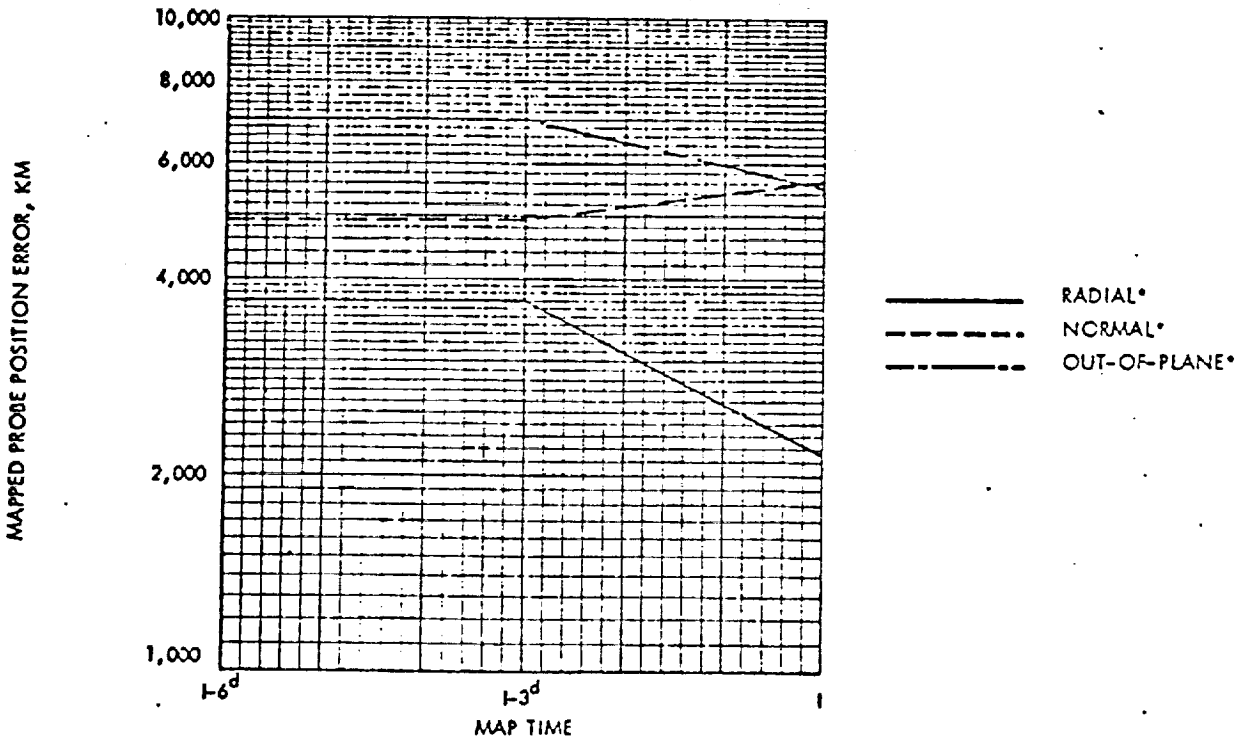

POST – JUPITER
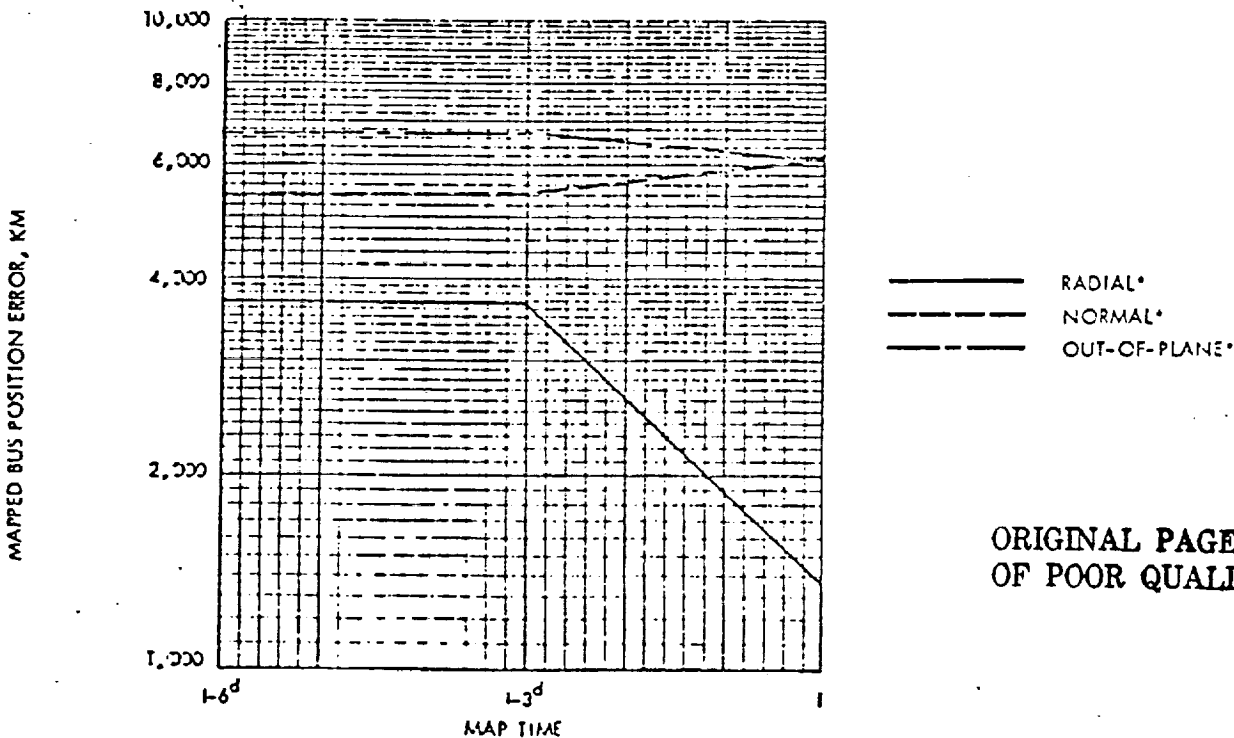
$\mu + 3\sigma\Delta V$

13 M/S

8 M/S

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URANUS BUS - RADIO ALONE

*ALL RESULTS THE SAME FOR "TIGHT" OR "LOOSE" STATION LOCATION A PRIORI

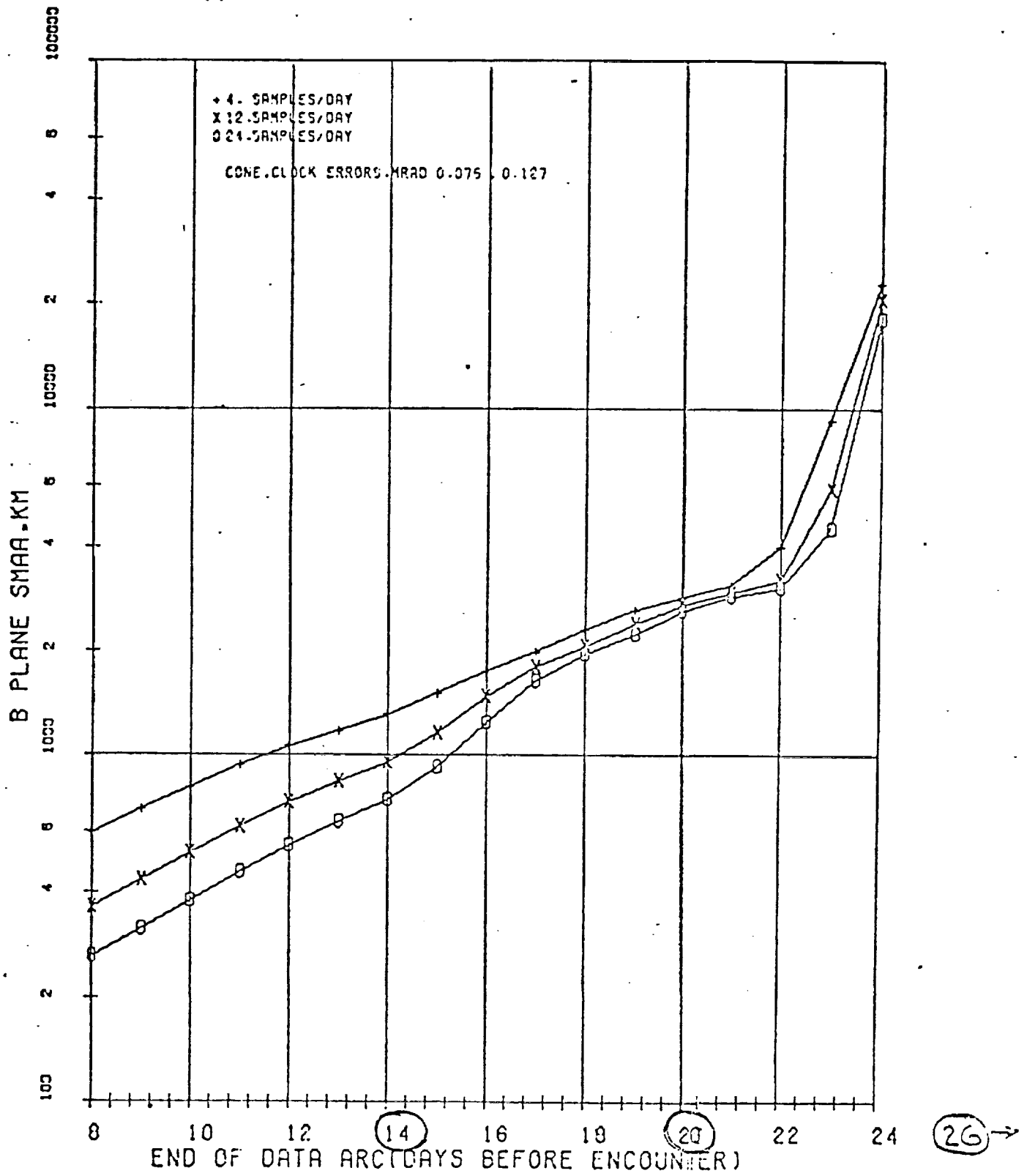Mapped Probe Position Error vs Map Time

*ALL RESULTS THE SAME FOR "TIGHT" OR "LOOSE" STATION LOCATION A PRIORI

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FIGURE 3-17

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V-Slit Sensor Accuracy Satellite Titania

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5-21

FIGURE 3-18

III-25

obtained using the satellite Titania. More results are in the
report that we have given to Ames. We have run many more simu-
lations and these can be checked in more detail.

The point here is that this is navigation accuracy using
the V-slit sensor to image the satellite Titania with respect to
the star background. Shown is the one-sigma semi-major axis in
the B plane versus the end of the data arc in days before encounter.
The longer you track the better you can do, but you can't track
beyond the time of separation of the probe.

In one concept it was proposed to separate the probe at
27 days, but this is seen as insufficient to bring the errors
down from the almost 10,000 kilometer level. If we wait a little
longer, we can then bring the errors to below a few thousand
kilometers.

Certainly, errors of about a thousand kilometers or somewhat
larger are acceptable and so it seems indicated that separation
should be made somewhere around twenty days at least. Figure 3-19
relates to the required accuracy in the B plane to the entry
angle error. A thousand kilometers at a forty degree entry angle
leaves a 2.7 degree entry angle error, which is quite acceptable.
And even two thousand would be out around five degrees.

So roughly, as long as we can keep errors within this region,
that is track up to about twenty days (using satellite Titania)
optical navigation used with this V-slit sensor at assumed levels
of accuracy was quite satisfactory.

Looking at the Saturn-Uranus mission, we also sized the Delta-V
requirements according to the strategy of Figure 3-20. We looked
at the case of radio-only navigation at Saturn just like we did
at Jupiter and found that the post-Saturn maneuver would have to
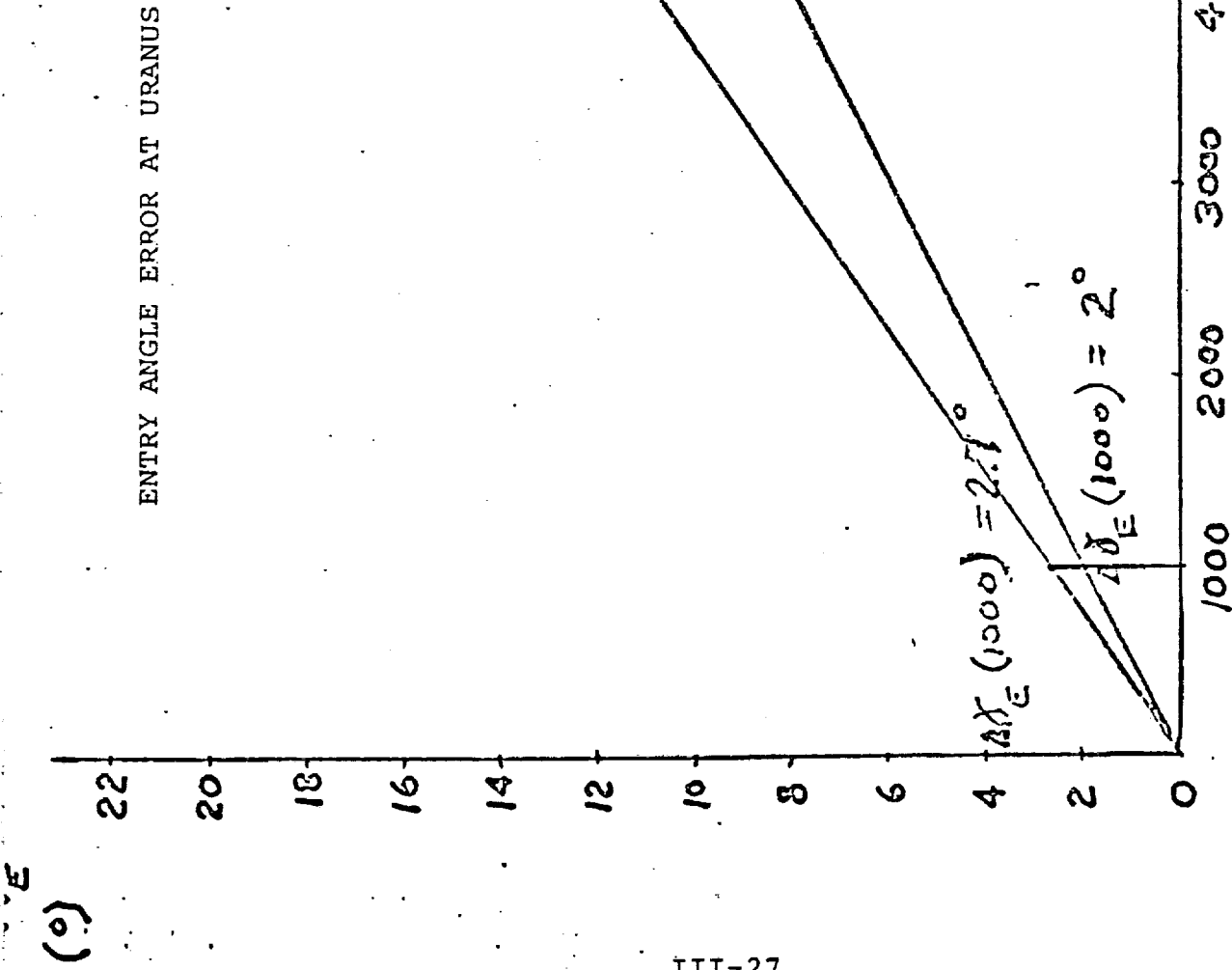be 140 meters per second in the case of radio-only navigation, far

ENTRY ANGLE ERROR AT URANUS

FIGURE 3-19

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FIGURE 3-20

Saturn/Uranus Mission

Description	Time
Earth launch	I
1st velocity correction	I + 5 days
2nd velocity correction	S - 200 days
Initiation of radio and optical tracking	S - 150 days
Termination of radio and optical tracking	S - 5 days
3rd velocity correction	S - 5 days
Saturn encounter	S
4th velocity correction	S + 50 days
5th velocity correction	U - 200 days
Initiation of radio tracking	U - 150 days
Initiation of optical tracking	U - 25 days
Pre-separation velocity correction	SEP* - 1 day
Termination of radio and optical tracking	SEP - 1 day
Bus separation maneuver	SEP
Probe entry	U
Bus periapsis	U + 1 hr

*SEP: separation

too large to be acceptable, given amount of fuel that is planned
to be carried on the Pioneer mission. However, using the optical
V-slit sensor and imaging the satellites at Saturn, that number
can be reduced to about 22 meters per second. That is quite
satisfactory. The Delta-V values are summarized in Figure 3-21.
We assumed this optical navigation would be required on the way
past Saturn on to Uranus.

Now, to consider the Titan probe mission we recently conducted
a study and on Figure 3-22 depict again the navigation accuracy in
the B plane, one sigma, semi-major axis versus the end of the
tracking arc. We now remember the time of the separation is
somewhere around 27 days, so we stopped all the simulation right
at that point and see what kind of accuracies we can get.

We examined four cases. One is a 15 and 25 arc seconds
which is consistent with the V-slit sensor type of numbers that
I mentioned earlier. We considered first improving those num-
bers (hypothetically) by a factor of 2, and then used values now
being quoted for the Mariner TV or vidicon type of system that
would be used in the outer planets, which is 2 and 3.3 arc seconds.

Finally, we considered radio alone navigating, starting
tracking at E minus 150 days.

The radio-alone navigation is out just where we expected it,
at about 8,000 kilometers. Titan's ephemeris is not significantly
improved. It has a fairly large ephemeris error, since it hasn't
been well observed.

Examining the 15-25 arc/seconds sytem, we find that it can
yield about 700 kilometers of B plane error going into Titan. If
we can improve by a factor of 2, we can get the errors to less
than 500 kilometers. It is about this level of accuracy, 500 to
600 kilometers, that is required in order to target to Titan;
that is to achieve a reasonable entry angle dispersion. These
results are related to entry angle errors on Figure 3-23. The radio-

Saturn/Uranus Mission Midcourse Velocity Requirements

Event	Velocity Correction Number	Mean Velocity $\mu + 3\sigma$ (m/sec)	Along Earth-line Component $\mu + 3\sigma$ (m/sec)	Normal to Earth line $\mu + 3\sigma$ (m/sec)
2	1	80.1	29.2	79.6
3	2	14.0	12.0	10.7
4	3	7.0	6.4	4.5
6[a]	4	139.3, 23.2	38.6, 11.4	138.9, 22.4
7	5	18.7, 2.9	3.9, .9	18.7, 2.8
8[b]	6	110.4	44.6	65.8

[a]The first value of each pair pertains to radio-only navigation at Saturn while the second value pertains to the optical V-slit sensor.

[b]Maximum deflection maneuver considered at 700 Uranus radii.

FIGURE 3-21

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5-21

FIGURE 3-722

TITAN PROBE O.D. ERROR ON APPROACH

B PLANE, SMAA (GM)

10
8
6
4

2

1

.7

.5
.4

.3

.2

.1

E-150^D E-80^D E-60^D E-37^D E-27^D

RADIO + OPTICAL

LOOSE

TIGHT

RADIO ONLY

OPTICAL DATA
OBSERVING TITAN
─────── 15, 25 SEC
─ ─ ─ ─ 7.5, 12.5 SEC
─ ─ ─ 2, 3.3 SEC

EXECUTION ERROR
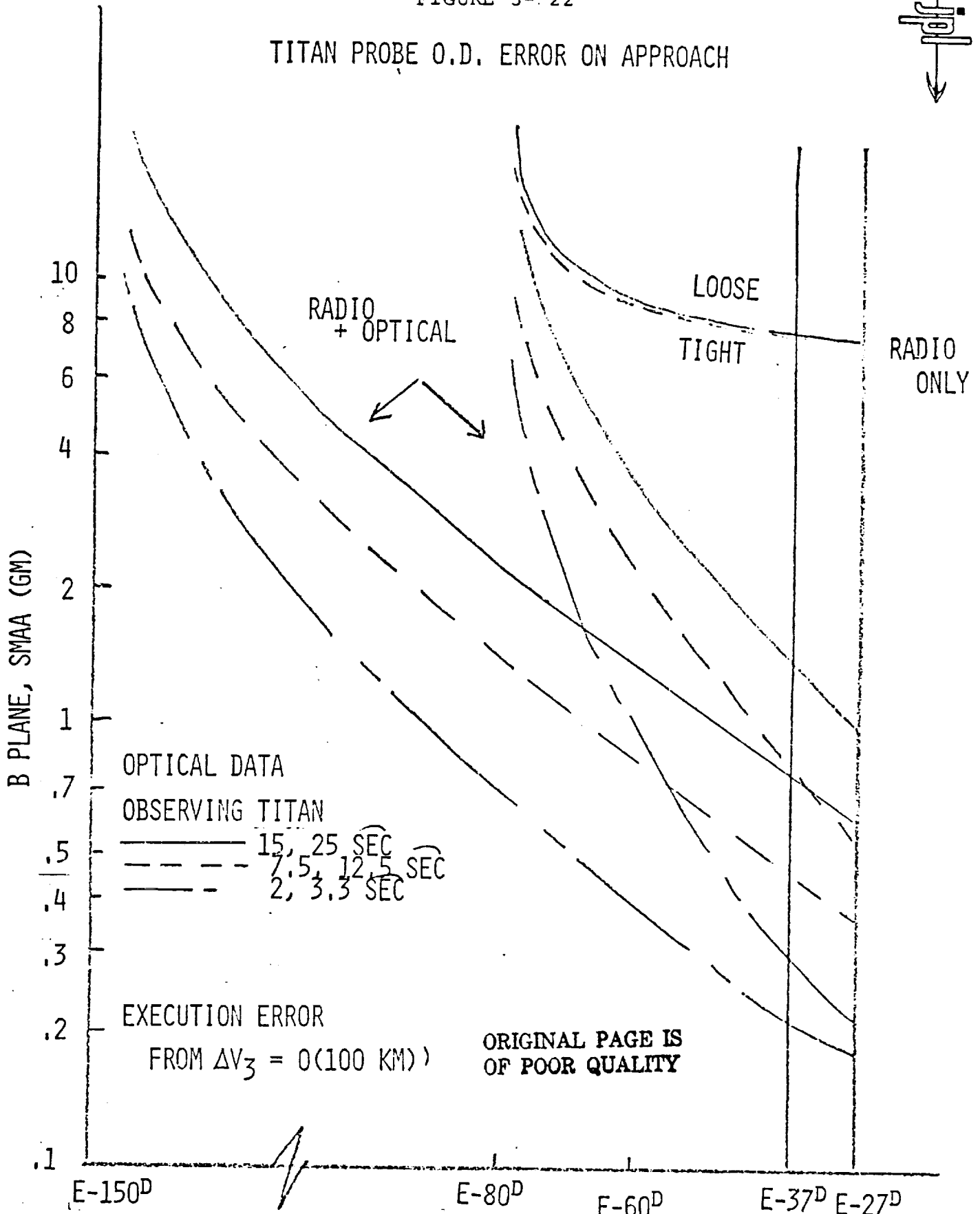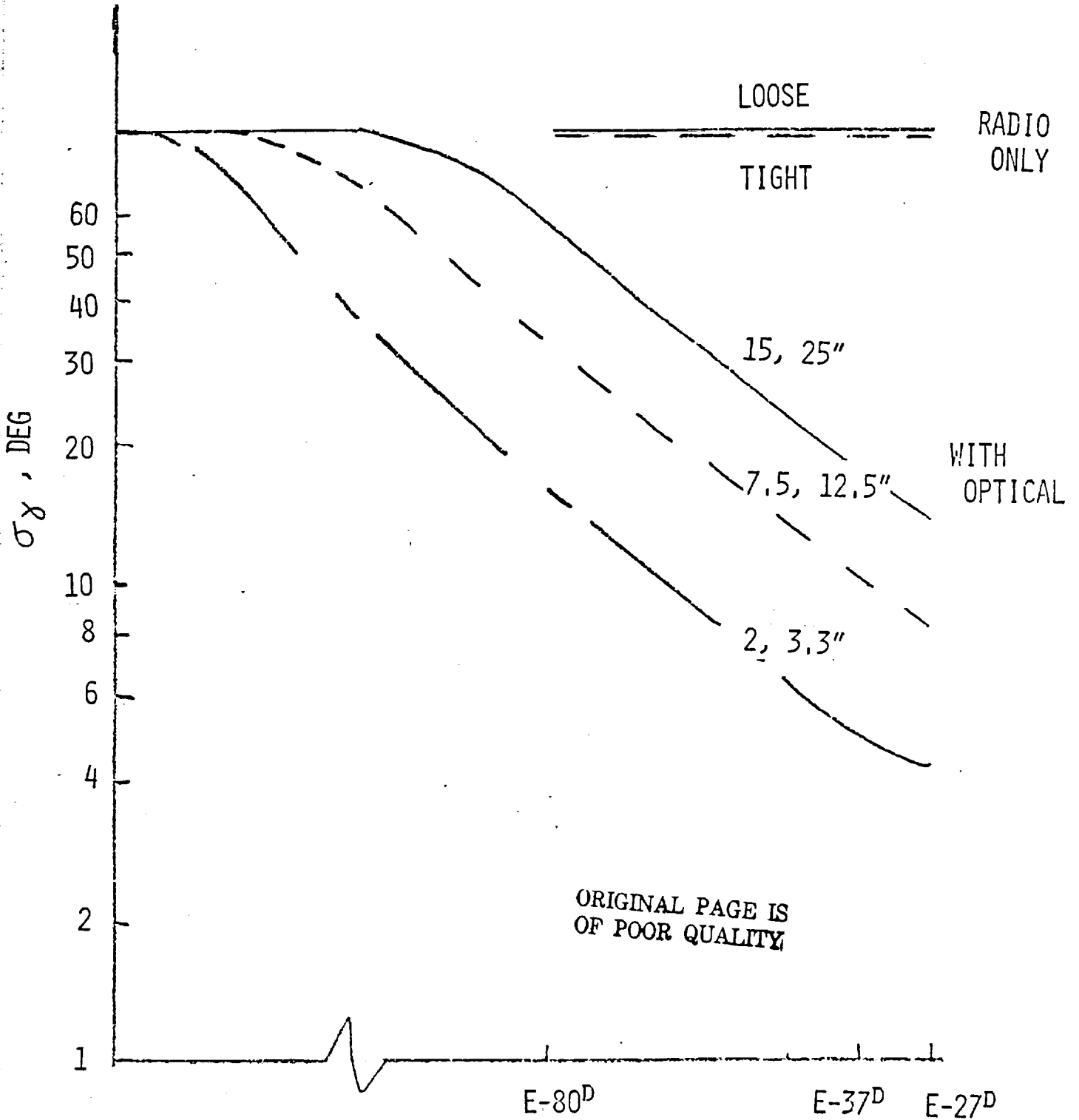   FROM $\Delta V_3 = 0(100$ KM$))$

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OF POOR QUALITY

LDF - 16

FIGURE 3-23

TITAN PROBE ENTRY ANGLE ERRORS

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III-32

alone, the errors would be out around 90 degrees. This is the
one sigma entry angle error. Obviously it is unacceptable: you
might miss the planet.

The optical navigation errors are also shown. The 15-25 arc/
seconds system gives about 15 degrees of entry angle error. That
is a one sigma error, so the three sigma error would be around
45 degrees and that is pretty risky.

If we can improve the accuracy, there is a tremendous pay-
off as shown on the figure. One thing to be noted is that the gain
from improving accuracy is far more significant than the gain from
tracking longer.

There are two limitations to the V-slit sensor concept.
One was the fact that it couldn't track once the object became
big enough to fill the slit; and the other was that it wasn't
quite as accurate as we hoped. It looks from these results like
the payoff is in improving accuracy, not in making it track
longer.

In Figure 3-24 the Delta-V requirements for the Titan probe
mission are summarized. Our basic conclusions from the study of
the outer planet Pioneer missions, that is, the direct Saturn
mission, the Saturn-Uranus mission, the Jupiter-Uranus mission,
and the Titan probe mission, are kind of summarized on Figure 3-25.
We did find a great advantage in using differenced data,
i.e. quasi-very-long-baseline-interferometry. If we delay sepa-
ration a little bit, we have very acceptable errors in navigating
to Saturn on the Saturn probe mission.

On Saturn-Uranus 80, the radio-alone navigation with tight
station locations and with the QVLBI data and some other assump-
tions, might barely be sufficient at Saturn. But there was sig-
nificant improvement by incorporating optical navigation there.
And it was absolutely necessary at Uranus due to the pathologically
poor Uranus ephemeris.

FIGURE 3-24

TITAN PROBE STUDY
GUIDANCE POLICY

MANEUVER	TIME		WHAT IT CORRECTS	ΔV	$\Delta V + 3\sigma \Delta V$
ΔV_1	$L + 5^D$	$O(3 \times 10^6)$ KM	INJECTION ERRORS	32 M/S	77 M/S
ΔV_2	$E-200^D$	$O(4 \times 10^4)$ KM	EXECUTION ERRORS IN ΔV_1	4 M/S	9 M/S
ΔV_3	$E-30^D$	$O(1000)$ KM	EXECUTION ERRORS IN ΔV_2	3 M/S	10 M/S
		$O(1500)$ KM	O.D. UNCERTAINTY AT $E-200^D$		
		$O(5000)$ KM	TITAN EPH. $E-200^D$		

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5-21

FIGURE 3-25

CONCLUSIONS

• SATURN '79

    ◦ QVLBI DATA PROVIDES DRAMATIC IMPROVEMENTS

    ◦ LATER SEPARATION REDUCES ERRORS

• S/U '80

    ◦ RADIO ALONE MAY BE SUFFICIENT AT SATURN -
      HOWEVER THIS DEPENDS ON "TIGHT STATION
      LOCATIONS

    ◦ RADIO/OPTICAL NAVIGATION OFFERS SIGNIFICANT
      ADVANTAGE AT SATURN AND

    ◦ IS ABSOLUTELY NECESSARY AT URANUS
      (DUE TO PATHOLOGICALLY POOR URANUS EPHEMERIS)

• J/U '80

    ◦ RADIO ALONE AT JUPITER IS SUFFICIENT

    ◦ URANUS CONCLUSION IS SAME AS ABOVE

FIGURE 3-25

CONCLUSION (CONT'D)

• TITAN '84

  • RADIO ALONE DOES NOT GUARANTEE ENTRY

  • V-SLIT SENSOR ADVERTISED CAPABILITY IS MARGINAL
    • ACCURACY
    • EXTENDED OBJECT

  • BIGGEST PAYOFF IS IMPROVING ACCURACY OF OPTICAL
    NAVIGATION SENSOR

  • TITAN OCCULTATION BY BUS MAY BE MISSED:
    OPTICAL NAV ERROR RANGES FROM 50-115 SEC
    (700-1600 KM)

Jupiter-Uranus '80 mission yielded basically the same kinds of conclusions except that radio-alone is certainly adequate at Jupiter.

On the Titan '84 mission, the radio-alone navigation does not guarantee entry. The V-slit sensor advertised capability - realizing this is only a concept and so it might be better than presently advertised, or it might be worse - is marginal. The problem is accuracy and viewing an extended object. The major benefit is in improving accuracy.

Finally, we did look at the question of Titan occultation, which was discussed earlier. With the basic sensor levels here that we are talking about, there is a chance you would miss a Titan occultation. The optical navigation error range is from 50 to 115 seconds, that is about 700 to 1600 kilometers. Titan itself is 2400 kilometers in radius. The chances for occultation actually depend on the geometry as to how you pass by that occultation region whether or not this is sufficient accuracy.

Moving now to the Mariner-Jupiter-Uranus mission study that has been underway, we have been looking at navigation requirements at Uranus in somewhat more depth and somewhat more connected to the Mariner questions.

The situation is a little different than with the Pioneer study because we are not only concerned about the delivery of the entry probe, but we are concerned about imaging the satellites of Uranus on the way in (Figure 3-26). It turns out, not too sur-prisingly, that we can do a better job than we could in the Pioneer-Jupiter-Uranus study of delivering the entry probes simply because the Mariner vidicon yields far better accuracy. We also looked a little more into the question of the Uranus ephemeris and will modify our conclusions about that. Imaging of the satellites for scientific purposes yields an additional requirement on the navi-gation system which turns out to be the tighter one rather than delivery accuracy for the probes.

FIGURE 3-26

NAVIGATION REQUIREMENTS AT URANUS

1. DELIVERY OF THE ENTRY PROBE

2. CONTROL OF THE SATELLITE IMAGING
   FIELD OF VIEW

In Figure 3-27 the relation of required accuracy on approach (in the B plane) to entry angle error is shown. Again, 40 degrees is nominal plus or minus a probable requirement of ten degrees. This is three sigma accuracy, so one sigma accuracy requirement is about 2,000 kilometers.

The second requirement, for navigation follows from noting that a trajectory knowledge error can result in a missed satellite image (cf Figure 3-28). This turned out to be an important requirement.

The optical navigation that we studied used the 1,500 mm focal length TV camera. The characteristics are shown in Figures 3-29 & 3-30 for the two types of requirements mentioned above. We investigated two types of imaging systems, one based on the Mariner-Jupiter-Saturn vidicon and one based on a proposed CCD, Charge Coupled Detector; and they have slightly different properties by a factor of two in terms of pixel size.

The conclusions of the study are shown in Figure 3-31. Optical navigation is not required for the entry probe if you improve the Uranus ephemeris. Now we pointed out when we did the Pioneer-Jupiter-Uranus study that we were basically stuck with this 8,000 to 10,000 kilometer level of ephemeris uncertainty. Some recent investigation has suggested that this is true, but that probably with a modest expenditure - modest in terms of project ephemeris development - the Uranus ephemeris, over a number of years could be improved. This would involve collecting all the old observations and incorporating the new observations over this next five-year period. This could bring Uranus ephemeris to the level of about 2,000 kilometers. Recall that 2,000 kilometers is about the level we needed.
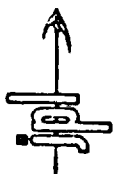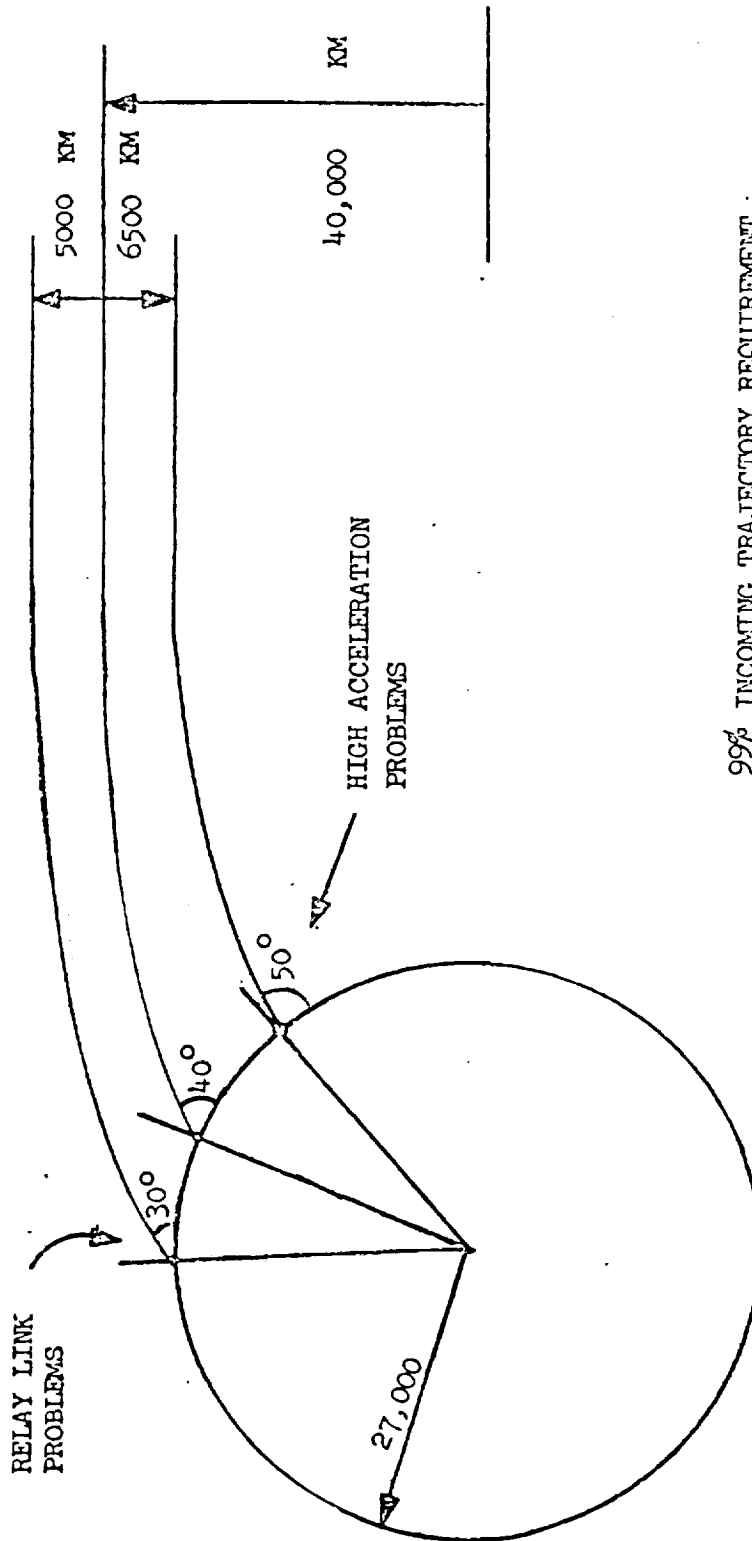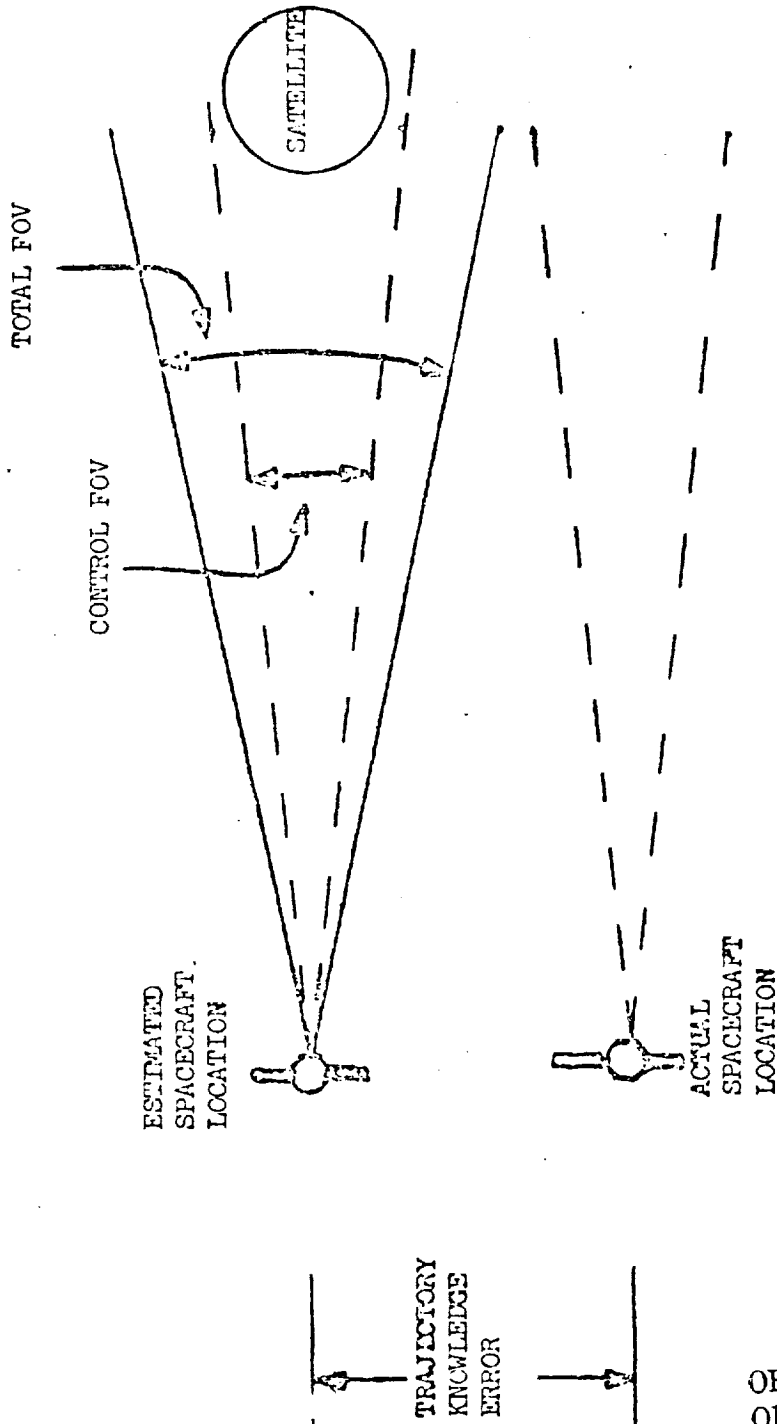
FIGURE 3- 27

PROBE DELIVERY

RELAY LINK PROBLEMS

30°

40°

50°

HIGH ACCELERATION PROBLEMS

27,000

5000 KM

6500 KM

40,000 KM

99% INCOMING TRAJECTORY REQUIREMENT IS 6000 KM

JFJ
5/7/74

FIGURE 3-28

A TRAJECTORY KNOWLEDGE ERROR CAN RESULT
IN A MISSED SATELLITE IMAGE

SATELLITE

TOTAL FOV

CONTROL FOV

ESTIMATED
SPACECRAFT
LOCATION

ACTUAL
SPACECRAFT
LOCATION

TRAJECTORY
KNOWLEDGE
ERROR

JFK
5/10/74

CHARACTERISTICS OF OPTICAL NAVIGATION AND ITS CAPABILITY
FOR ENTRY PROBE DELIVERY

1. USE 1500 mm CAMERA

2. OPERATE BETWEEN E-130 DAYS AND E-25 DAYS
   (< 1000 PICTURES)

3. OBSERVE THE URANUS SATELLITES AGAINST 5th to 10th
   MAGNITUDE STAR BACKGROUND

4. MJS VIDICON CAPABILITIES: 300 km ~ $\Delta\alpha = 1/2^{\circ}$

5. CCD CAPABILITIES: 600 km ~ $\Delta\alpha = 1^{\circ}$

6. POSSIBILITY OF REDUCING THE SHIELD/STRUCTURE WEIGHT
   FROM THAT OF THE CURRENT DESIGN

FIGURE 3-29

CHARACTERISTICS OF OPTICAL NAVIGATION AND ITS CAPABILITIES

FOR CONTROL OF SATELLITE IMAGING FIELD OF VIEW

1. USE 1500 MM CAMERA

2. OPERATE BETWEEN E-15d and E-5d (< 300 PICTURES)

3. OBSERVE SATELLITES AGAINST STAR BACKGROUND

4. MJS VIDICON CAPABILITIES: SPACECRAFT TRAJECTORY AND SATELLITE
   EPHEMERIDES ACCURATE TO 150 KM

5. CCD VIDICON CAPABILITIES: SPACECRAFT TRAJECTORY AND SATELLITE
   EPHEMERIDES ACCURATE TO 300 KM

FIGURE 3-30

URANUS NAVIGATION SUMMARY

1. OPTICAL NAVIGATION NOT REQUIRED FOR ENTRY PROBE

2. IMPROVED URANUS EPHEMERIS IS REQUIRED: COST 250K

3. OPTICAL NAVIGATION MAY ALLOW REDUCED PROBE WEIGHT

4. SATELLITE IMAGING REQUIREMENTS CANNOT BE MET WITH RADIO-ONLY NAVIGATION

5. OPTICAL NAVIGATION ALLOWS SATELLITE IMAGING RE-QUIREMENTS TO BE MET

FIGURE 3-31

Thus, improving the Uranus ephemeris, if it can be done, would allow use of radio-alone navigation, albeit somewhat marginally, to target the entry probe. There is considerable payoff from use of optical navigation, in reducing the entry angle errors.

However, the satellite imaging requirements cannot be met with radio-alone navigation. Several different schemes were investigated and it was found that either too many pictures or too much data rate was required or it took too long to get back all the pictures with radio-only navigation errors (even in the case of the improved Uranus ephemeris). Hence, optical navigation was incorporated to allow the satellite imaging requirements to be met. The requirements could be met with either a vidicon or CCD imaging system.

In summary, we have done a number of outer planet probe studies and found some particular cases where optical navigation is important and some cases where radio-alone navigation will suffice. We have estimated maneuver sizes that are acceptable to the mission designs.

MR. DAN HERMAN: How long does it take to get an orbit determination update after a V-slit sensor observation of one of those satellites? What is the time, approximately?

MR. FRIEDMAN: You mean the time involved in the real mission?

MR. HERMAN: Yes, including observation and including the time it takes to get an alternate determination.

MR. FRIEDMAN: Basically, of course, you are going to be limited by the round-trip light time. Above and beyond that, this problem hasn't really been factored into the simulation. I have heard estimates through other studies that we have been doing, estimating about a couple of hours once you get the data back to Earth. But, of course, you have to live with the round-trip light time.

MR. HERMAN: The question I was alluding to was have you done any work yet on developing the ground software to accommodate the optical data as well as the radio data?

MR. FRIEDMAN: Yes. For the Mariner system, we tested experimental use of this data; on Mariner 1971 and on Mariner 1969. It is being further developed and used on the Viking mission and it will be completely operational on the MJS mission. By that time we will have operational navigation software to include optical navigation measurements.

MR. HANS MEISSINGER: With regard to making sure that you are aiming the camera at the fast-moving satellite during the short encounter, you can use the camera system and the feedback system and try to correct it as you go; namely, the field of view is large enough to encompass the satellite in a very small area and you can keep it centered that way by autonomous feedback without ...

MR. FRIEDMAN: In actual operation, that might be done but it requires early commitment to do it. I don't think it is an easy job. If that was a requirement, and I am not sure it is, I think that could be put on the thing.

MR. SEIFF: What is a representative number for the uncertainty in the position of one of the satellites relative to the planet?

MR. FRIEDMAN: I think it is about 5,000 to 6,000 km, at present. However, the Galilean satellites are quite a bit less than that.

MR. SEIFF: So that is right at the limit of what you want to allow in terms of entry flight path angle. I notice you were reporting 6,000 km and the desired uncertainty in the B plane for Uranus and the uncertainty in the position of the satellite is comparable to that.

MR. FRIEDMAN: Well, it is even worse than that because for 5,000 or 6,000 km for Titan, that is one sigma, and the uncertainty in the entry angle that you want is three sigma.

That has been factored in. That was basically why radio-alone navigation at Titan did not suffice to meet the entry angle requirements. It wasn't even marginal; it just missed. Is that fair, Kent?

MR. KENT RUSSELL: Yes

DR. W. DIXON: The point should be made, though, that if you use a satellite as your navigation target, then the process of navigating also refines your knowledge of the ephemeris of that satellite, in addition to figuring out what the safest entry angle is.

MR. FRIEDMAN: Oh yes, that is correct. That has been completely factored in, too, in the optical navigation. But we just didn't quote the ephemeris improvements.

DR. DIXON: So If you aim a probe at Titan and you use Titan as the target for navigating, then you also refine where it is as well as where the spacecraft is. It is possible to hit it even if you didn't know where it was to begin with.

MR. FRIEDMAN: That's right, yes, but only with the optical navigation. But that has been factored into the optical navigation results. The results are quoted in terms of spacecraft state relative to Titan, implicit in that is the fact that Titan's ephemeris, relative to earth is improved. It just isn't quoted in those terms.