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ERROR ANALYSIS FOR APOLLO EARTH PARKING ORBITS USING RANGE RATE AND ANGLE MEASUREMENTS

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BY

A. MARLOW

JANUARY 1965

NASA

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

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SUMMARY

21662

Parametric studies are made of RMS errors in position and velocity for an Apollo Earth Parking Orbit (launch azimuth 90°, height 200 km), using uncertainties in range rate of ±0.1 m/s and ±0.03 m/s; and in angles of $\pm 2 \times 10^{-3}$ radians, $\pm 6 \times 10^{-4}$ radians, and $\pm 2 \times 10^{-4}$ radians.

Range rate and angles are measured every second by a tracking ship located at 26° 40' N and 49° 20' W in order to provide tracking during the time the spacecraft is inserted into the parking orbit. In order to compare the RMS errors in the state vector, two separate sets of error analyses are made which include and exclude the effects of an uncertainty in the tracking ship's location. For this study a total uncertainty in the tracking ship's location of approximately ±450 meters was assumed.

It was found that when range rate and angles are measured, the angles are the dominant influence; i.e., that the position and velocity errors are approximately the same whether $\delta \dot{r} = \pm 0.1$ m/s or ±0.03 m/s. For example, with optimum tracking and an angular uncertainty of $\pm 2 \times 10^{-3}$ radians, the RMS error in position is 144.2 meters when $\delta \dot{r} = \pm 0.1$ m/s and 143.8 meters when $\delta \dot{r} = \pm 0.03$ m/s. Corresponding velocity errors are 0.821 m/s and 0.819 m/s. When the angular uncertainty is $\pm 2 \times 10^{-4}$ radians, the position errors are 16.6 meters and 14.7 meters and the velocity errors are 0.097 m/s and 0.084 m/s for the respective uncertainties in range rate.

However, when station location errors are included, these become the dominant influence and even with a minimum amount of tracking, the RMS errors in position approach the level of the station location error.

Author

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ERROR ANALYSIS FOR APOLLO EARTH PARKING ORBITS
USING RANGE RATE AND ANGLE MEASUREMENTS

by
A. Marlow

The purpose of this report is to present the results of a parametric study on how the RMS errors in position and velocity are affected by varying the uncertainties in range rate and angles.

I. ORBITAL PARAMETERS

The orbit used for this study is a typical Apollo Earth Parking Orbit with a launch azimuth of 90°. It is nearly circular and has an orbital height of approximately 200 km (110 nautical miles). The following are the orbital parameters:

Epoch: 8/5/61 $0^h 5^m 0^s.6$

$a = 6625.6$ km	$X = -2725.6266$		
$e = 0.00712$	$Y = -5112.7247$	km	
$i = 28^\circ.5$	$Z = 3115.5562$		
$\Omega = 143^\circ.984$	$\dot{X} = 6.7634412$		
$\omega = 97^\circ.0$	$\dot{Y} = -3.8824499$	km/sec	
$M = 0^\circ.0$	$\dot{Z} = -0.4542630$		

II. TRACKING SYSTEM

Range rate and angles are measured every second by a tracking ship located at 26° 40' North Latitude and 49° 20' West Longitude. This location was used in order to have good tracking for the period when the spacecraft is inserted into the parking orbit. Uncertainties in range rate of ±0.1 m/s and ±0.03 m/s are assumed and combined in turn with each of three sets of angular uncertainties: $\pm 2 \times 10^{-3}$ radians, $\pm 6 \times 10^{-4}$ radians, and $\pm 2 \times 10^{-4}$ radians. Additional solutions incorporate a total tracker location uncertainty of approximately ±450 meters.

III. TRACKING MODE

Since there are variations in the length of time a radar searches before it acquires a spacecraft, this searching or acquisition mode has been simulated for the present study (see Figure 1). The actual amount of tracking time varies from the maximum (tracking during the entire interval that the spacecraft is possibly visible to the tracker), which implies immediate acquisition, to no tracking at all. Between these situations are the cases where the maximum possible tracking time is shortened by the amount of acquisition time.

Therefore, solutions were made for various acquisition times, starting with acquisition as soon as the spacecraft is first possibly visible to the tracker, and advancing the acquisition time in 30-second steps. In each case, tracking is continued to the time of last possible visibility and errors in position and velocity of the spacecraft are evaluated at that time.

The total pass over the tracker is approximately 5-1/4 minutes.

IV. SUMMARY OF RESULTS

The RMS errors in position and velocity of the spacecraft are summarized in Tables 1 and 2, respectively. Figures 2-33 compare graphically how the RMS errors in position and velocity are affected by: 1) changing the uncertainty in angles; 2) changing the uncertainty in range rate; and 3) including the uncertainty in station location.

Position RMS Errors

With optimum tracking (i.e., immediate acquisition of the spacecraft and tracking over the full 5-1/4 minutes of the pass), when $\delta \dot{r} = \pm 0.1$ m/s and $\delta\alpha = \delta\epsilon = \pm 2$ milliradians, the RMS error in position is 144.2 meters. When the angular uncertainty is decreased to ±.6 milliradians, the position error is 44.1 meters; to ±.2 milliradians 16.6 meters. Additional figures are given in Table 1 for the position errors when 1, 2, 3 or 4 minutes are needed for the radar to acquire the spacecraft. It will be noted that if the angular uncertainty is improved by a factor of 3 or 10, the position error is improved by approximately the same factor.

The RMS errors in position described above are illustrated by Figure 2, which contains three curves, one for each of the angular uncertainties, showing clearly how the angles affect the RMS errors in position.

TABLE 1

RMS ERRORS IN POSITION OF SPACECRAFT
APOLLO PARKING ORBIT (A90 H200)
(IN METERS)

ACTUAL TRACKING TIME (MIN.)	$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-3}$ radians		$\delta\alpha = \delta\epsilon = \pm 6 \times 10^{-4}$ radians		$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-4}$ radians	
	$\delta\dot{r} = \pm 0.1$ m/s	$\delta\dot{r} = \pm 0.03$ m/s	$\delta\dot{r} = \pm 0.1$ m/s	$\delta\dot{r} = \pm 0.03$ m/s	$\delta\dot{r} = \pm 0.1$ m/s	$\delta\dot{r} = \pm 0.03$ m/s
A. Not including station location errors						
1.25	1102.1	656.9	484.4	330.6	327.5	153.8
2.25	262.8	237.0	101.1	78.9	38.3	33.1
3.25	188.7	177.2	70.5	56.6	26.5	23.0
4.25	156.8	156.0	49.2	47.0	19.6	16.3
5.25	144.2	143.8	44.1	43.3	16.6	14.7
B. Including station location errors of ±452.5 meters total						
1.25	1	1	723.8	612.6	580.5	486.5
2.25	536.0	518.2	460.2	454.5	447.4	447.1
3.25	492.3	486.2	452.1	449.7	446.0	445.9
4.25	477.0	476.7	448.3	448.0	445.5	445.3
5.25	472.0	471.9	447.5	447.4	445.2	445.2

1 No solution

TABLE 2

RMS ERRORS IN VELOCITY OF SPACECRAFT
APOLLO PARKING ORBIT (A90 H200)
(IN METERS PER SECOND)

ACTUAL TRACKING TIME (MIN.)	$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-3}$ radians		$\delta\alpha = \delta\epsilon = \pm 6 \times 10^{-4}$ radians		$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-4}$ radians	
	$\delta\dot{r} = \pm 0.1$ m/s	$\delta\dot{r} = \pm 0.03$ m/s	$\delta\dot{r} = \pm 0.1$ m/s	$\delta\dot{r} = \pm 0.03$ m/s	$\delta\dot{r} = \pm 0.1$ m/s	$\delta\dot{r} = \pm 0.03$ m/s
A. Not including station location errors						
1.25	9.10	5.39	3.09	2.73	1.16	1.02
2.25	1.98	1.63	.860	.595	.324	.280
3.25	1.19	1.10	.463	.356	.176	.151
4.25	.920	.915	.291	.276	.119	.096
5.25	.821	.819	.252	.246	.097	.084
B. Including station location errors of ±452.5 meters total						
1.25	1	1	3.21	2.94	1.28	1.14
2.25	2.08	1.72	.968	.746	.513	.498
3.25	1.27	1.17	.612	.540	.430	.423
4.25	1.00	.996	.488	.480	.409	.404
5.25	.910	.908	.466	.463	.404	.401

1 No solution

Table 1 also gives the RMS errors in position when $\delta\dot{r} = \pm 0.03$ m/s and the angular uncertainties and acquisition times are as given above. Here again it is noted that the position error improves proportionately to the improvement in angular uncertainty. The accompanying illustration is Figure 3, which is similar to Figure 2.

Next we consider how the uncertainty in range rate affects the RMS error in position. The data given in Table 1 are also presented in Figures 4, 5, and 6 (one for each of the angular uncertainties), comparing this time by the uncertainty in range rate. Curve A on each figure is for $\delta\dot{r} = \pm 0.1$ m/s and curve B for $\delta\dot{r} = \pm 0.03$ m/s. These figures demonstrate very clearly that if the spacecraft can be acquired within two, or even three, minutes and tracked for two or three minutes, the position error is practically the same whether $\delta\dot{r} = \pm 0.1$ m/s or ± 0.03 m/s.

Section B of Table 1 gives the RMS errors in position when station location uncertainties totaling 450 meters are included with each of the sets of uncertainties explained above. It will be noted that the angular uncertainty does not play as important a role as in the cases where the station location uncertainty was not considered. When $\delta\dot{r} = \pm 0.1$ m/s, the RMS error in position, assuming optimum tracking, is 472.0 meters, 447.5 meters, and 445.2 meters for the three sets of angular uncertainties in decreasing order. In other words, the position error does not decrease proportionately with the decrease in angular uncertainty, as further shown in Figure 7. Similarly, when $\delta\dot{r} = \pm 0.03$ m/s, the RMS error in position is 471.9 meters, 447.4 meters, and 445.2 meters (illustrated by Figure 8). Figures 7 and 8 also demonstrate that, with even a small amount of tracking, the RMS errors approach the level of the station location error.

Figures 9, 10, and 11 are similar to Figures 4, 5, 6 and support the conclusion that no appreciable increase in accuracy is obtained by improving the range rate.

A third type of comparison which can be drawn from Table 1 is illustrated by Figures 12-17, one figure for each set of uncertainty parameters. Each figure has two curves, comparing errors with or without station location uncertainties and pointing out again that the station location uncertainty is the dominant influence.

Velocity RMS Errors

The RMS errors in velocity of the spacecraft were studied in the same manner as were the errors in position. Results were similar and are summarized in Table 2. It was found that when $\delta\dot{r} = \pm 0.1$ m/s or ± 0.03 m/s, the RMS error in velocity is .82 m/s, .25 m/s and .10 m/s for the three angular uncertainties. When station location errors are considered, these velocity errors become .91 m/s, .47 m/s, and .40 m/s, respectively. All figures here assume optimum tracking and increase only slightly for shorter periods of tracking as long as the time it takes the radar to acquire is no more than two minutes.

Figures 20-33 compare velocity errors in the same manner and order as were position errors. They are therefore self-explanatory. They also corroborate the conclusions reached above, which are restated below:

CONCLUSIONS

1. When range rate and angles are being measured, the RMS errors are more sensitive to the angles than to range rate.

2. When station location uncertainties are included, with even a small amount of tracking, the RMS errors in position approach the level of the station location uncertainty.

3. If a tracker is able to acquire a spacecraft soon enough to be able to track for approximately three minutes, the delay in acquisition does not greatly increase the RMS errors in position or velocity of the spacecraft.

ACKNOWLEDGMENT

The assistance of Thomas E. Jones in graphing all the data is gratefully acknowledged. Also Figure 1 was taken from a report by J. L. Cooley (see Reference 1 below).

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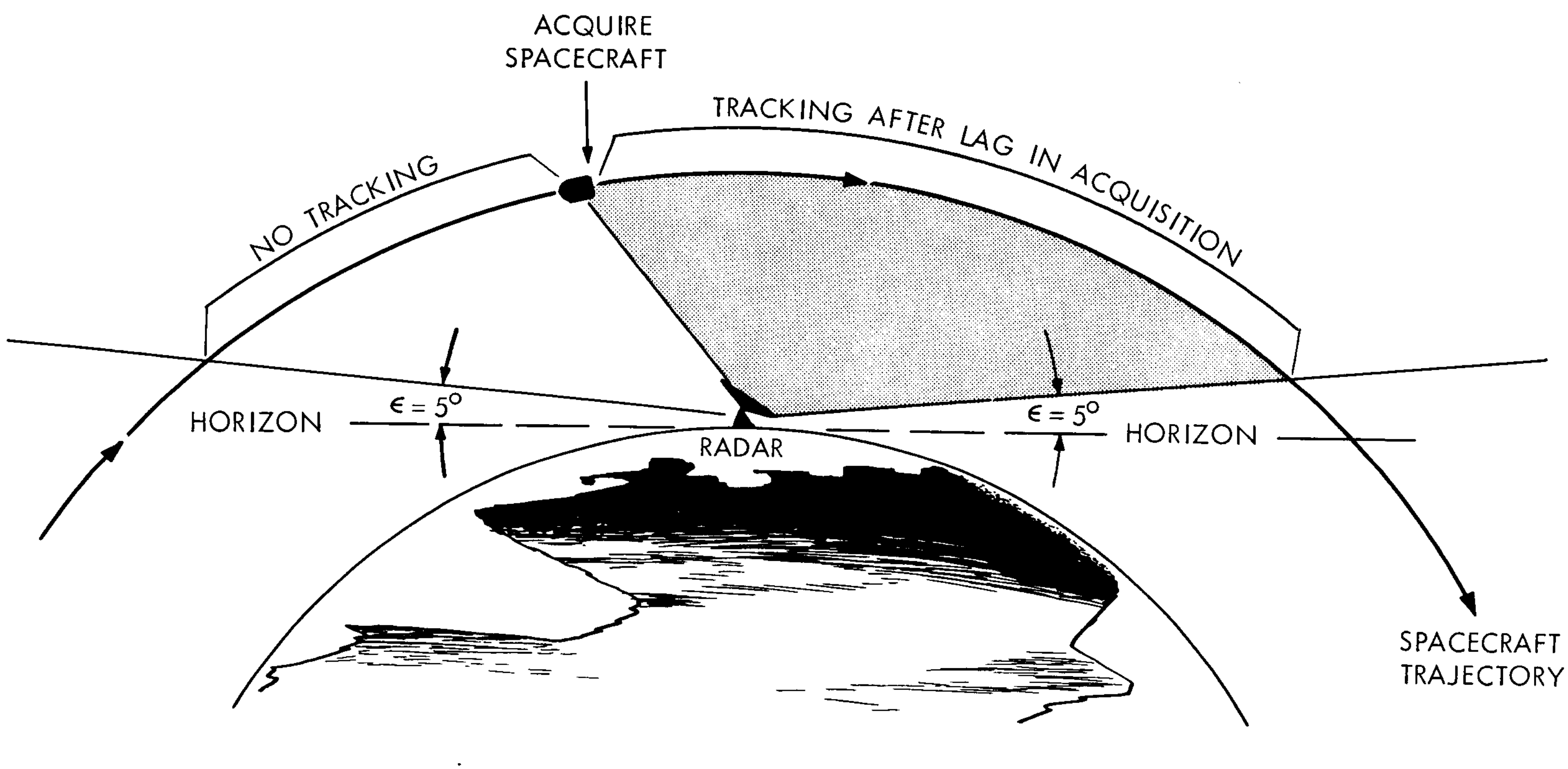
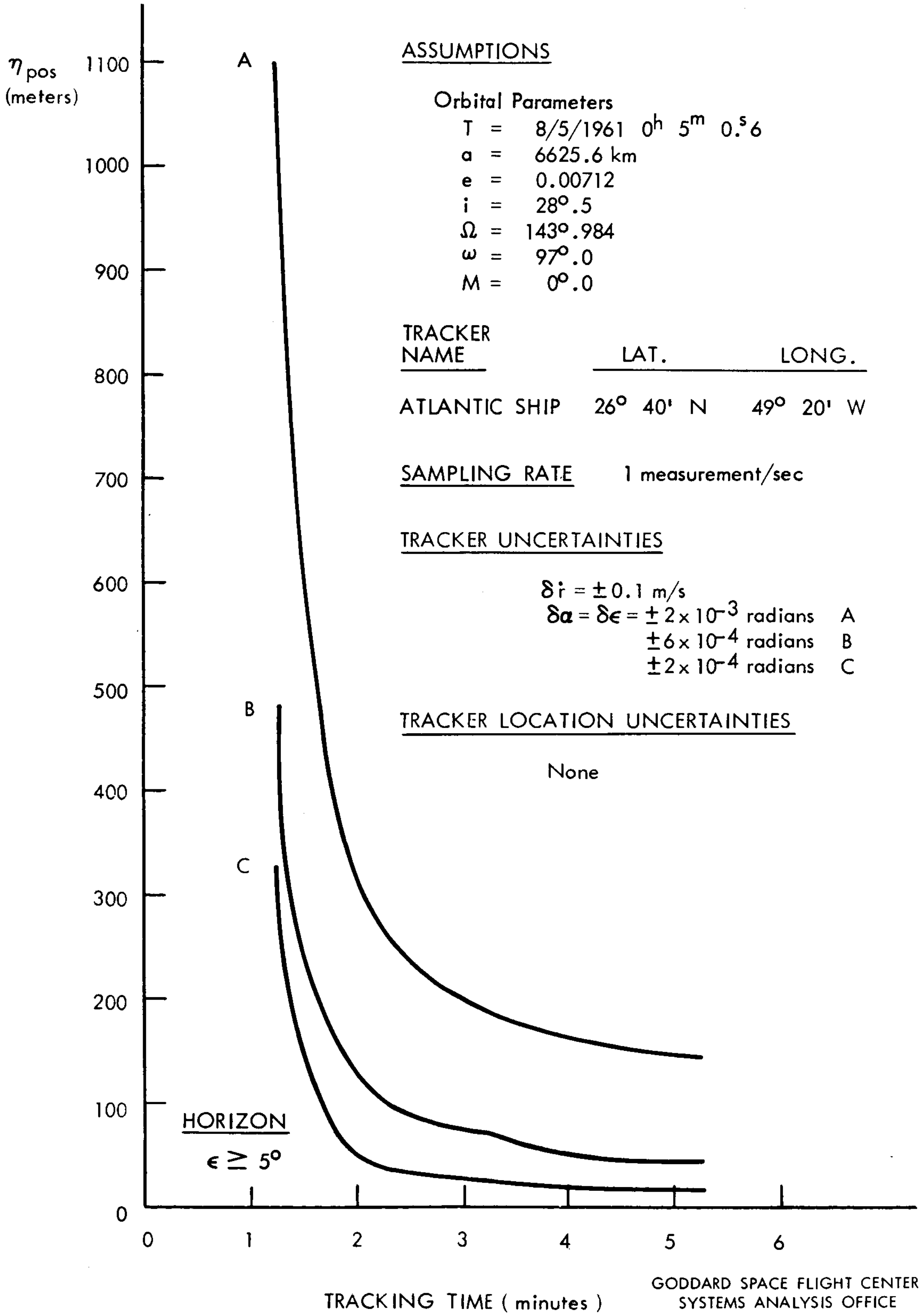


Figure 1—Acquisition Mode of Tracking

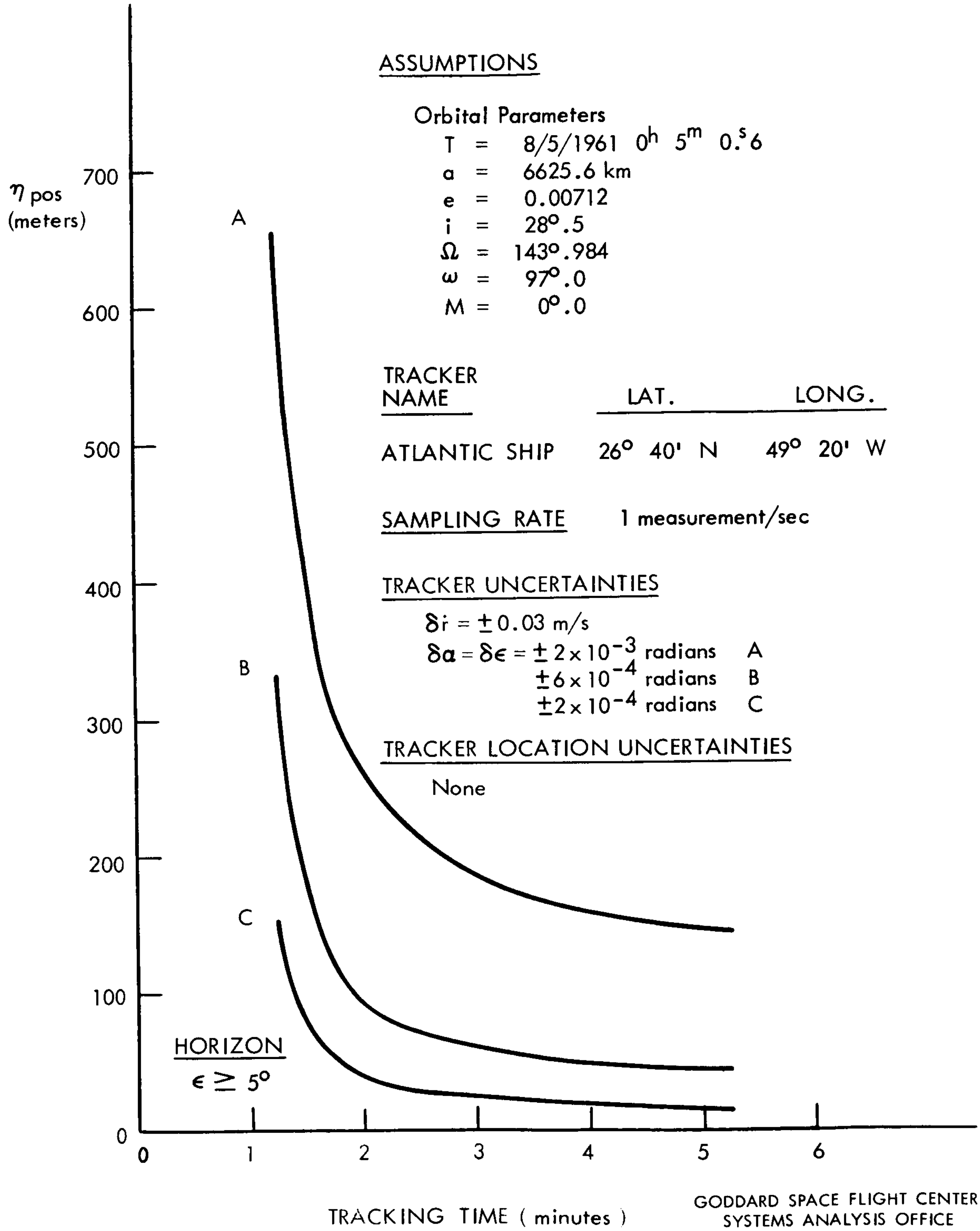
Figures 2-17

Error Propagation in Spacecraft Position Apollo Parking Orbit



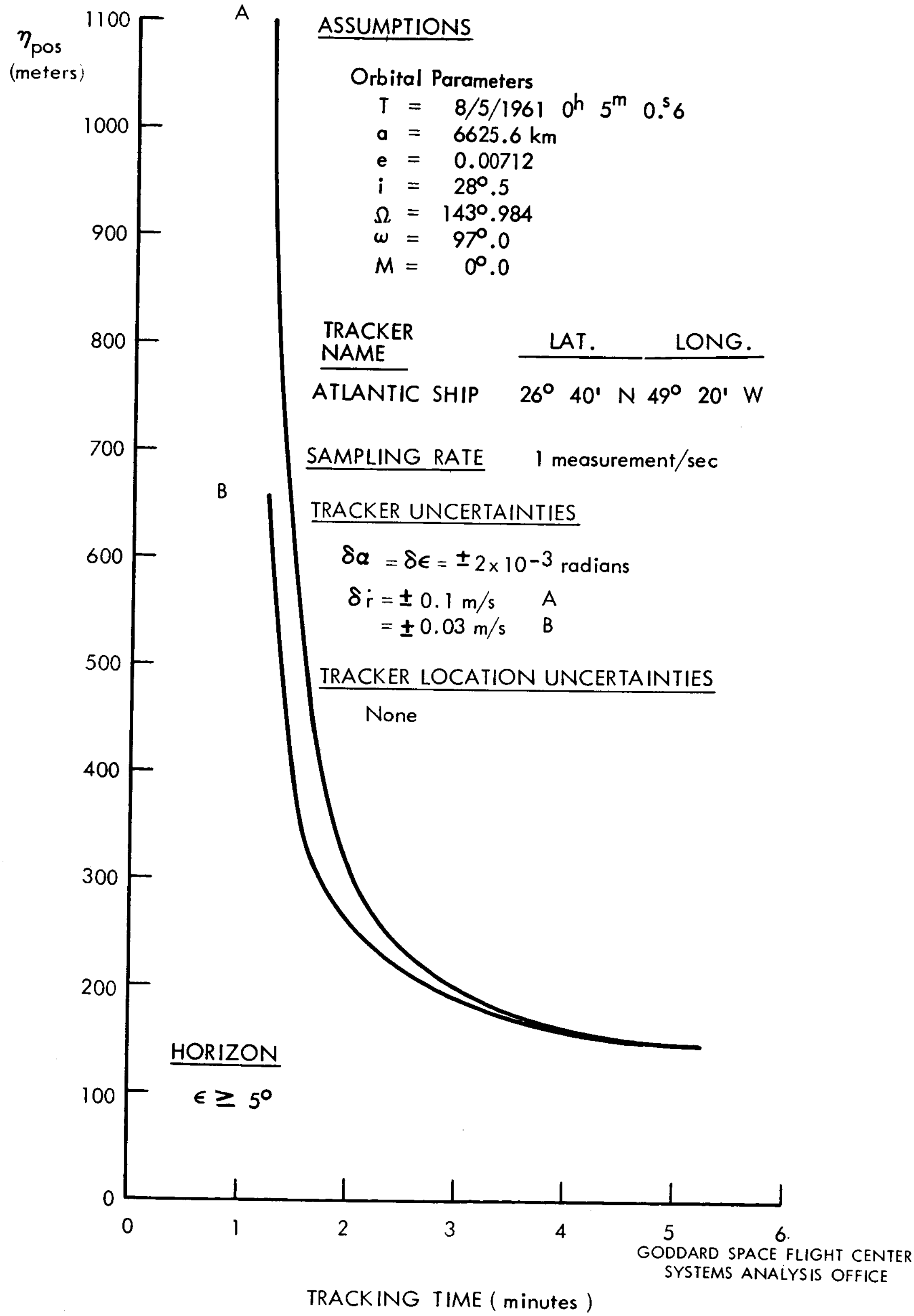
η_{pos} (meters)
0
100
200
300
400
500
600
700
800
900
1000
1100
A
B
C
HORIZON
$\epsilon \geq 5°$
0
1
2
3
4
5
6
TRACKING TIME (minutes)
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0.^s6$
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\dot{r} = \pm 0.1$ m/s
$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-3}$ radians A
$\pm 6 \times 10^{-4}$ radians B
$\pm 2 \times 10^{-4}$ radians C
TRACKER LOCATION UNCERTAINTIES
None
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 2



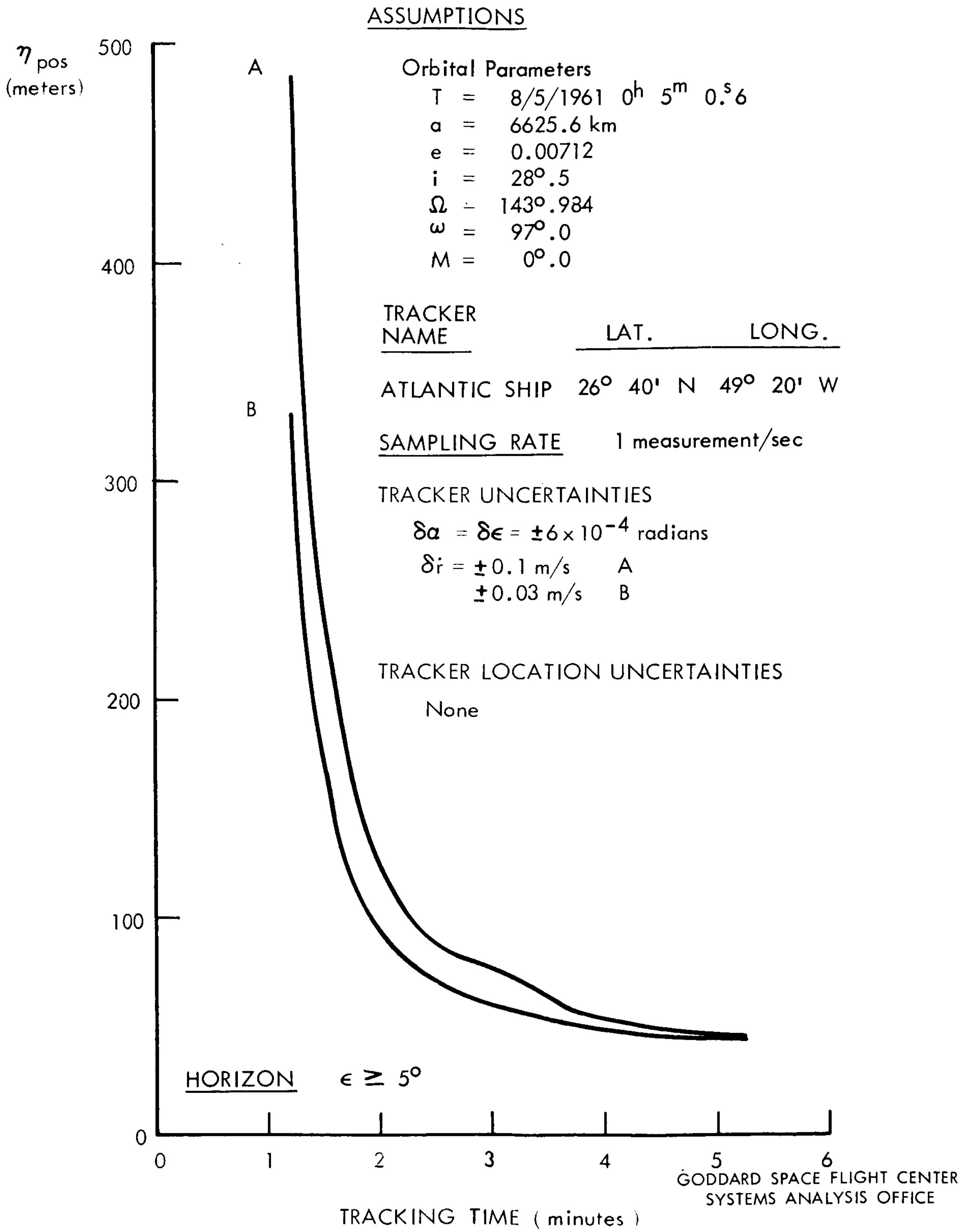
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0.^s6$
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\dot{r} = \pm 0.03$ m/s
$\delta a = \delta\epsilon = \pm 2 \times 10^{-3}$ radians A
$\pm 6 \times 10^{-4}$ radians B
$\pm 2 \times 10^{-4}$ radians C
TRACKER LOCATION UNCERTAINTIES
None
η pos (meters)
700
600
500
400
300
200
100
0
A
B
C
HORIZON
$\epsilon \geq 5°$
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 3



η_{pos} (meters)
1100
1000
900
800
700
600
500
400
300
200
100
0
A
B
ASSUMPTIONS
Orbital Parameters
$T = 8/5/1961\ 0^h\ 5^m\ 0.^s6$
$a = 6625.6$ km
$e = 0.00712$
$i = 28^\circ.5$
$\Omega = 143^\circ.984$
$\omega = 97^\circ.0$
$M = 0^\circ.0$
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-3}$ radians
$\delta\dot{r} = \pm 0.1$ m/s A
$= \pm 0.03$ m/s B
TRACKER LOCATION UNCERTAINTIES
None
HORIZON
$\epsilon \geq 5^\circ$
0
1
2
3
4
5
6
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE
TRACKING TIME (minutes)

Figure 4



ASSUMPTIONS
η_{pos} (meters)
500
400
300
200
100
0
A
B
Orbital Parameters
T = 8/5/1961 0^h 5^m $0^s.6$
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\alpha = \delta\epsilon = \pm 6 \times 10^{-4}$ radians
$\delta\dot{r} = \pm 0.1$ m/s A
± 0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
None
HORIZON $\epsilon \geq 5°$
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
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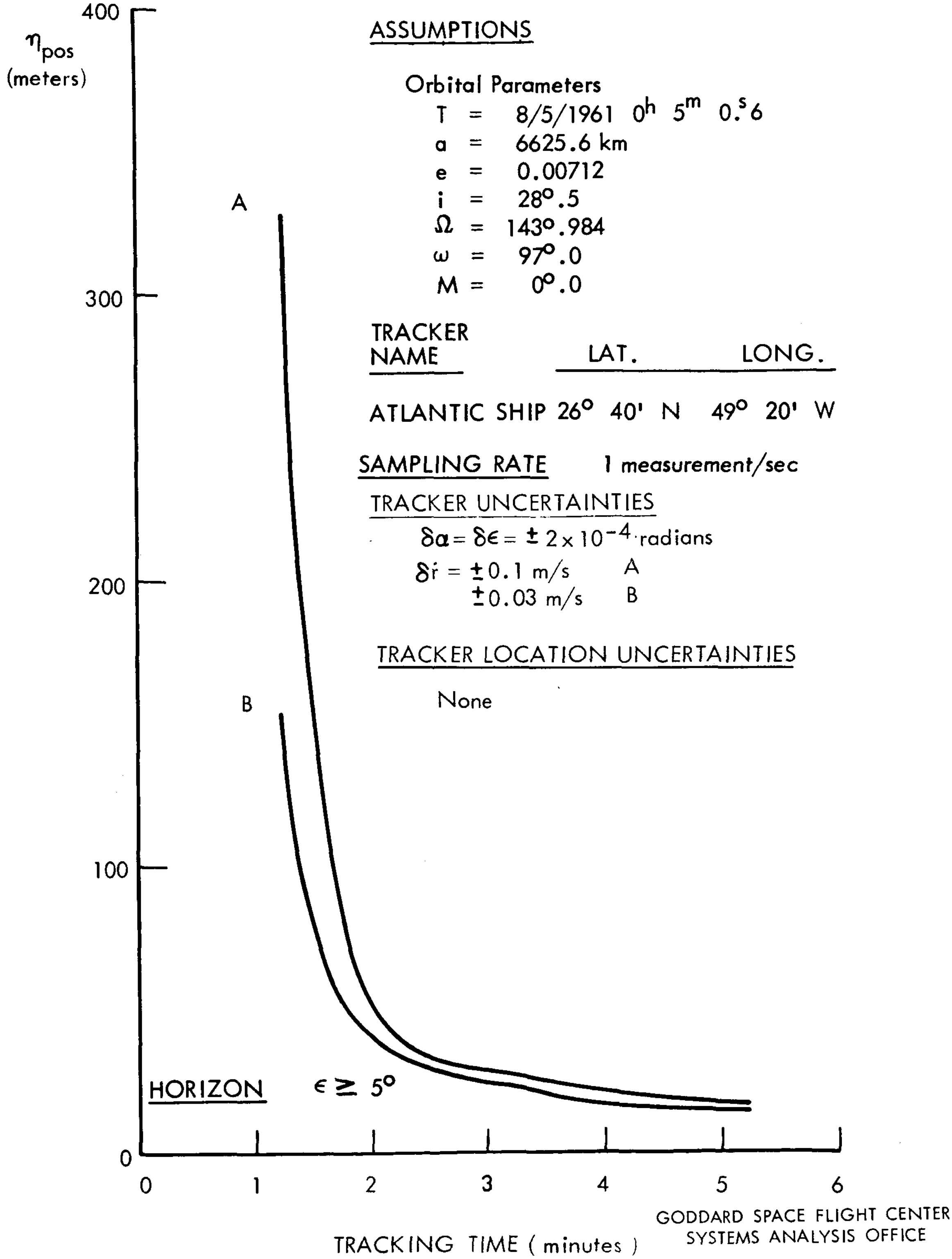
Figure 5


ASSUMPTIONS
Orbital Parameters
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a = 6625.6 km
e = 0.00712
i = $28^\circ.5$
Ω = $143^\circ.984$
ω = $97^\circ.0$
M = $0^\circ.0$
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-4}$ radians
$\delta\dot{r} = \pm 0.1$ m/s A
± 0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
None
η_{pos} (meters)
400
300
200
100
0
A
B
HORIZON $\epsilon \gtrsim 5^\circ$
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
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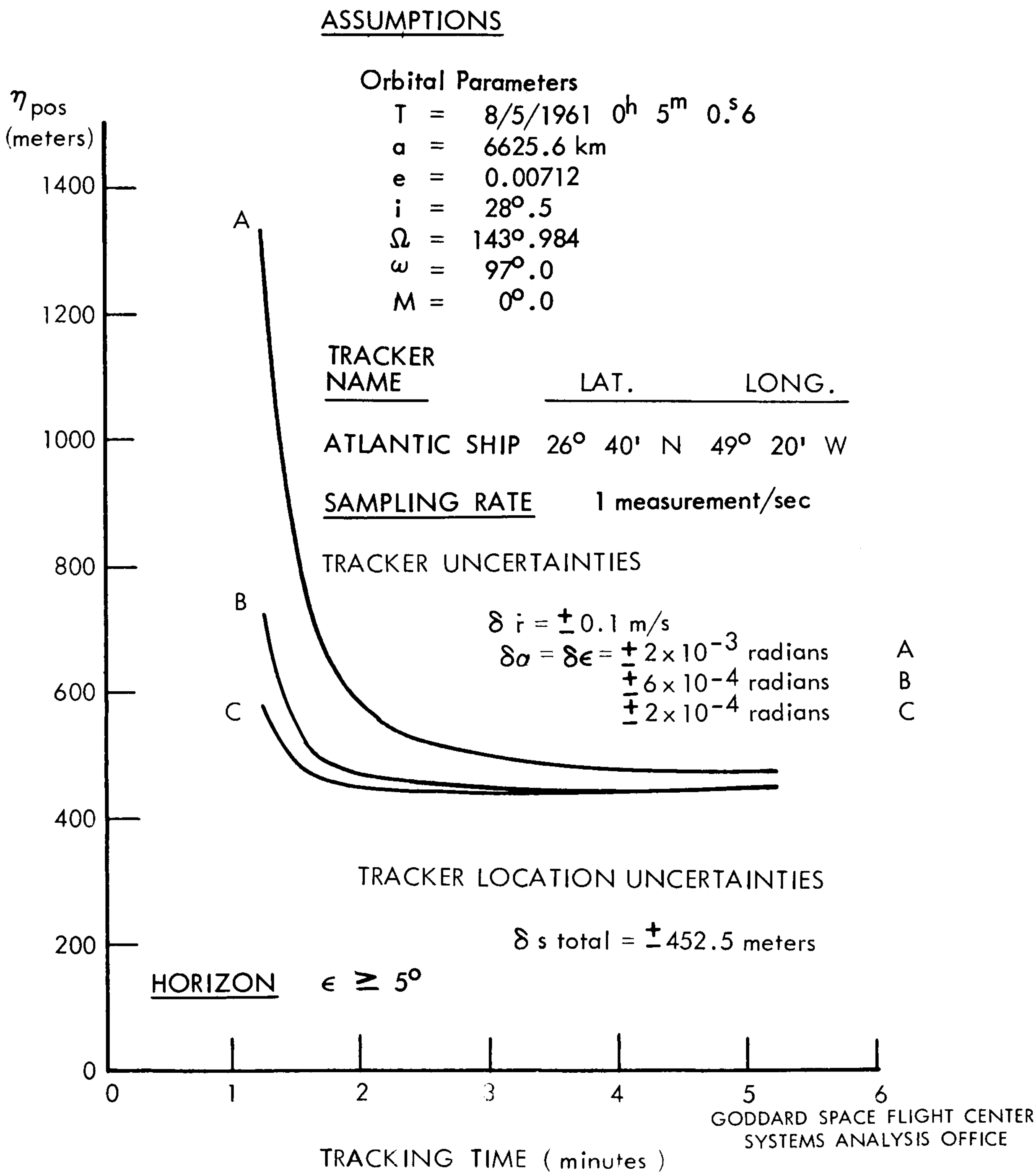
Figure 6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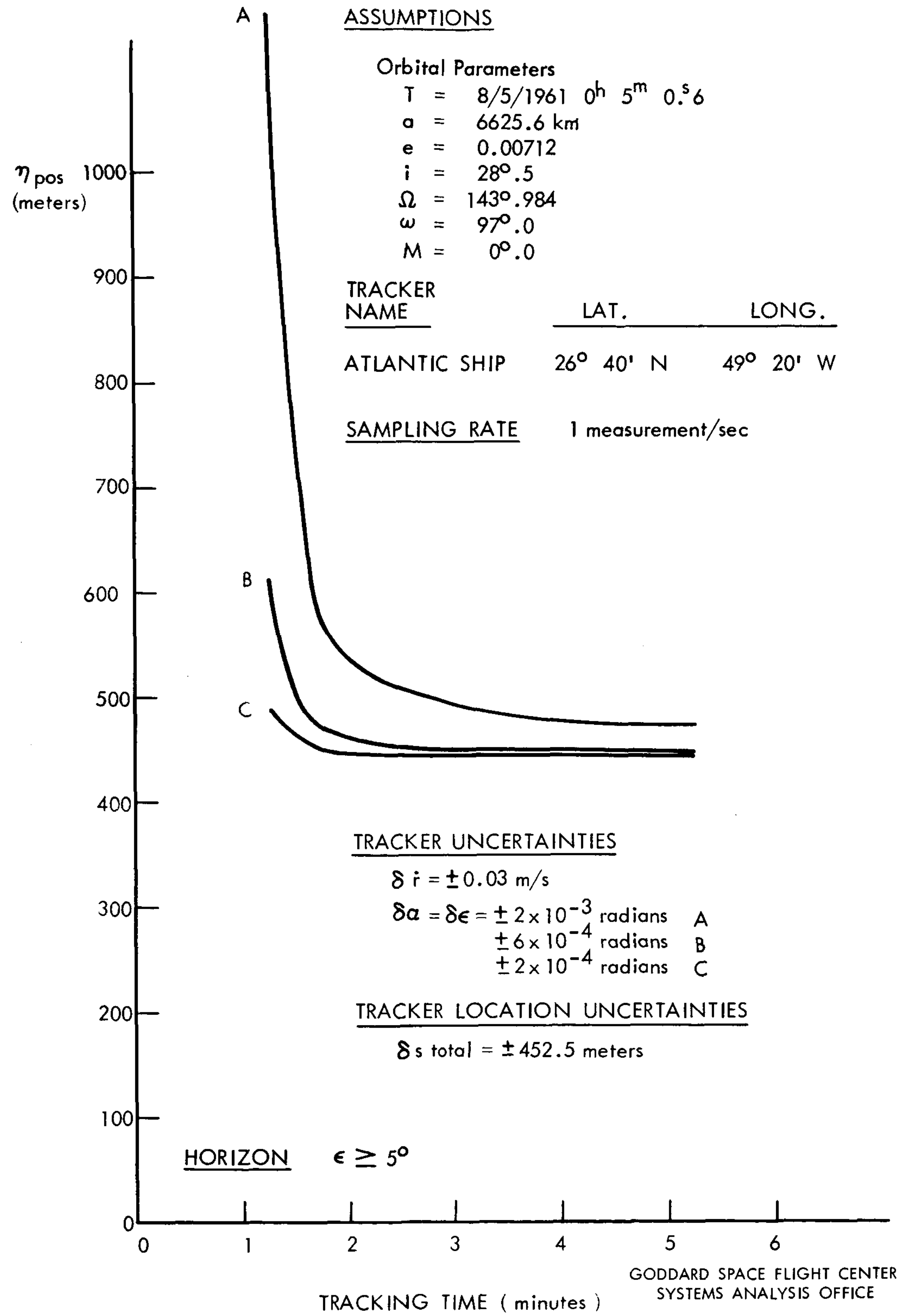
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δ ṙ = ±0.1 m/s
δα = δε = ±2 x 10^-3 radians A
±6 x 10^-4 radians B
±2 x 10^-4 radians C
TRACKER LOCATION UNCERTAINTIES
δ s total = ±452.5 meters
HORIZON ε ≥ 5°
η pos (meters)
1400
1200
1000
800
600
400
200
0
A
B
C
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 7



ASSUMPTIONS
Orbital Parameters
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a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
δ ṙ = ± 0.03 m/s
δα = δε = ± 2 x 10^-3 radians A
± 6 x 10^-4 radians B
± 2 x 10^-4 radians C
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
HORIZON
ε ≥ 5°
η pos (meters)
1000
900
800
700
600
500
400
300
200
100
0
A
B
C
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
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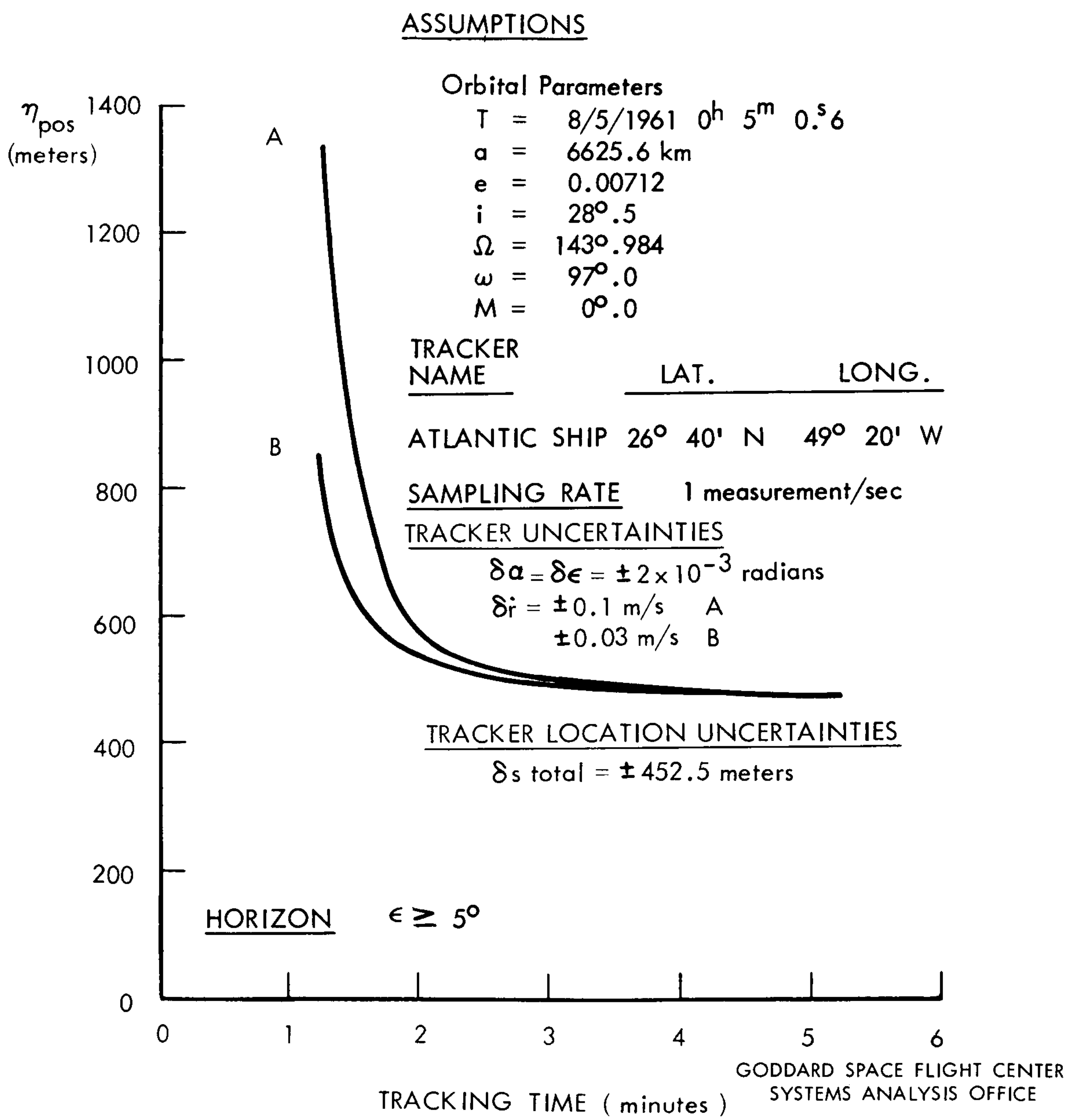
Figure 8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a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δα = δε = ±2 x 10⁻³ radians
δṙ = ±0.1 m/s A
±0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
δs total = ±452.5 meters
HORIZON ε ≥ 5°
η pos (meters)
1400
1200
1000
800
600
400
200
0
A
B
0
1
2
3
4
5
6
TRACKING TIME (minutes)
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Figure 9

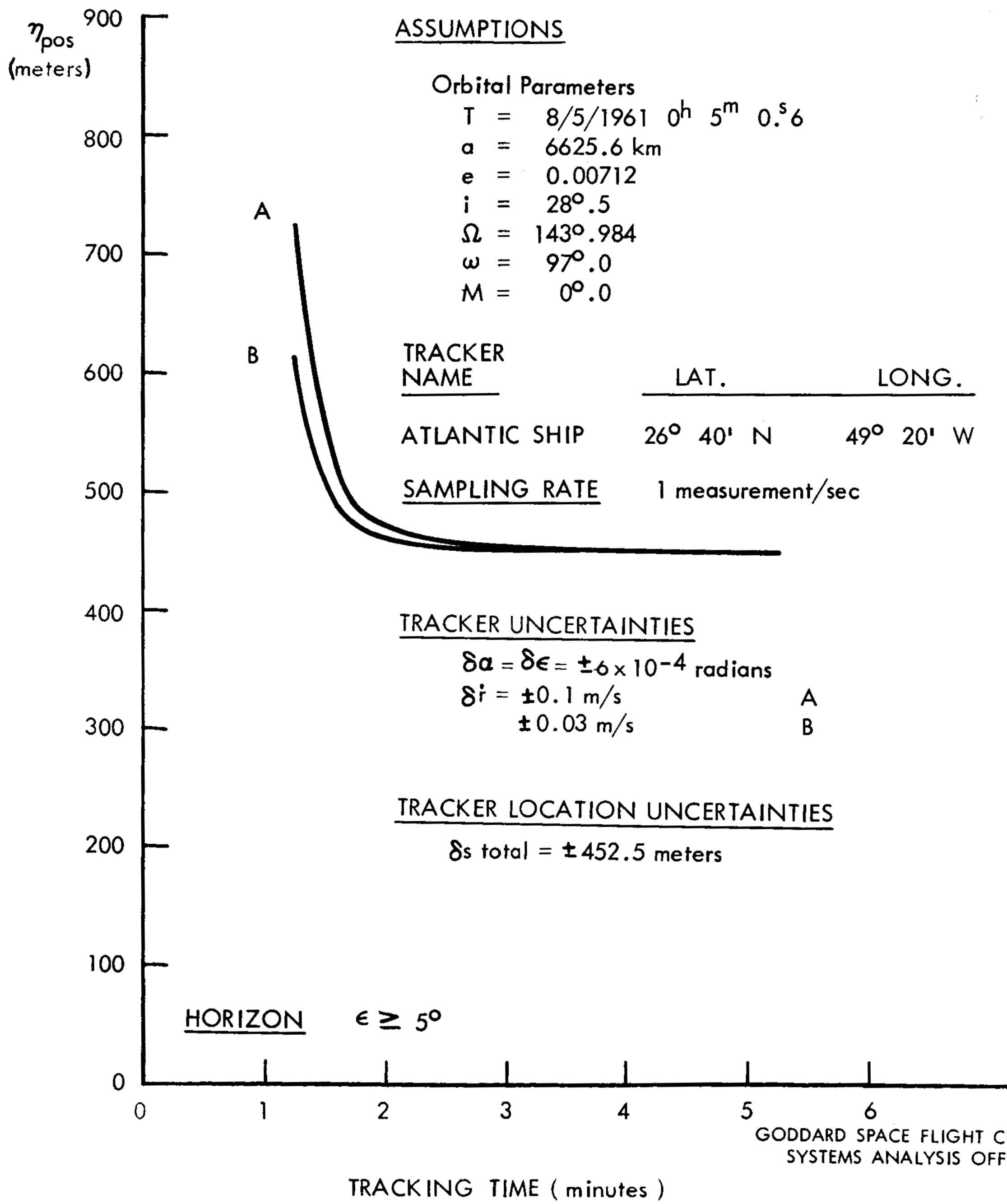

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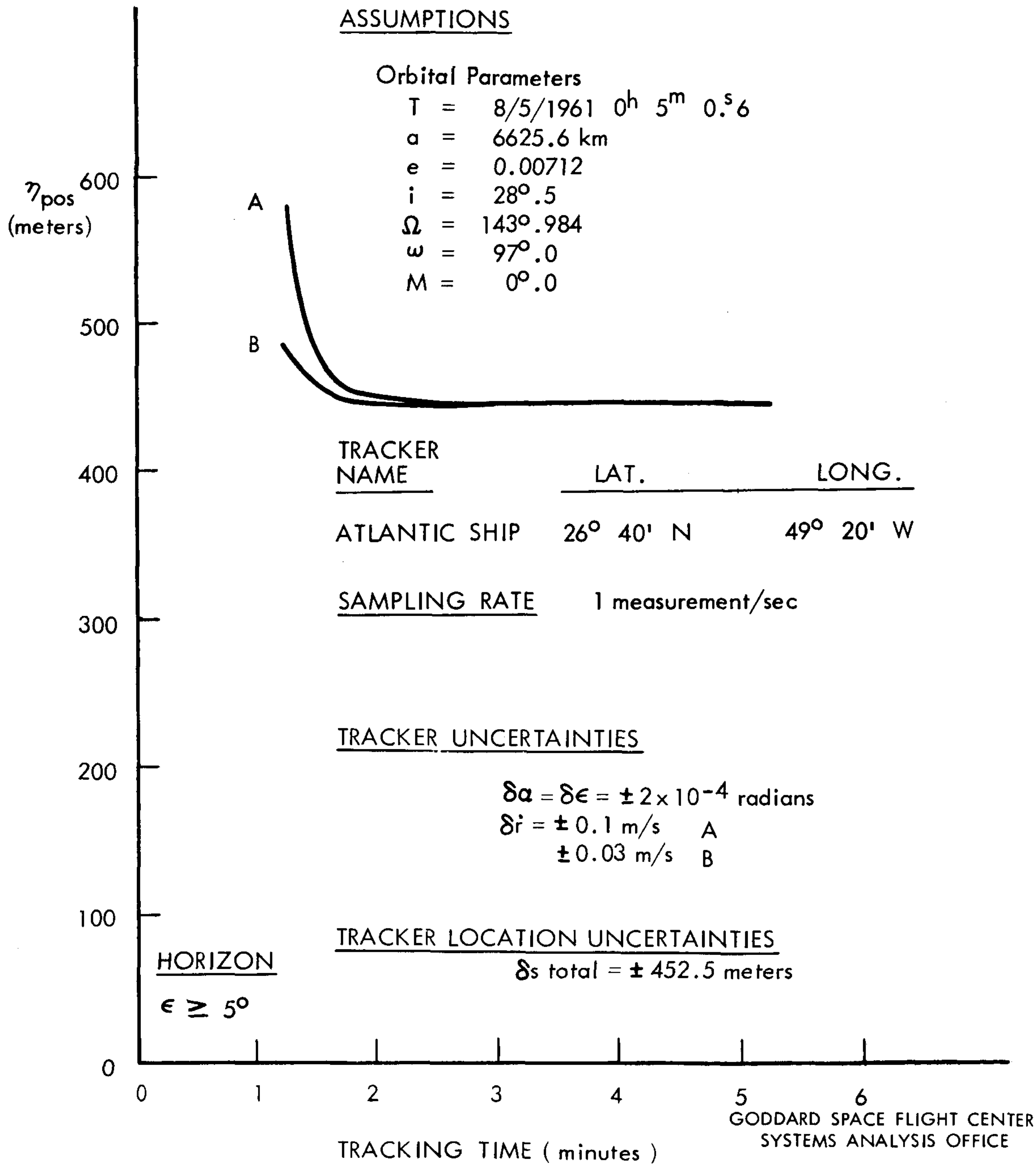
Figure 10


ASSUMPTIONS
Orbital Parameters
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a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
η pos (meters)
600
500
400
300
200
100
0
A
B
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
δα = δε = ± 2 x 10^-4 radians
δṙ = ± 0.1 m/s A
± 0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
HORIZON
ε ≥ 5°
0
1
2
3
4
5
6
TRACKING TIME (minutes)
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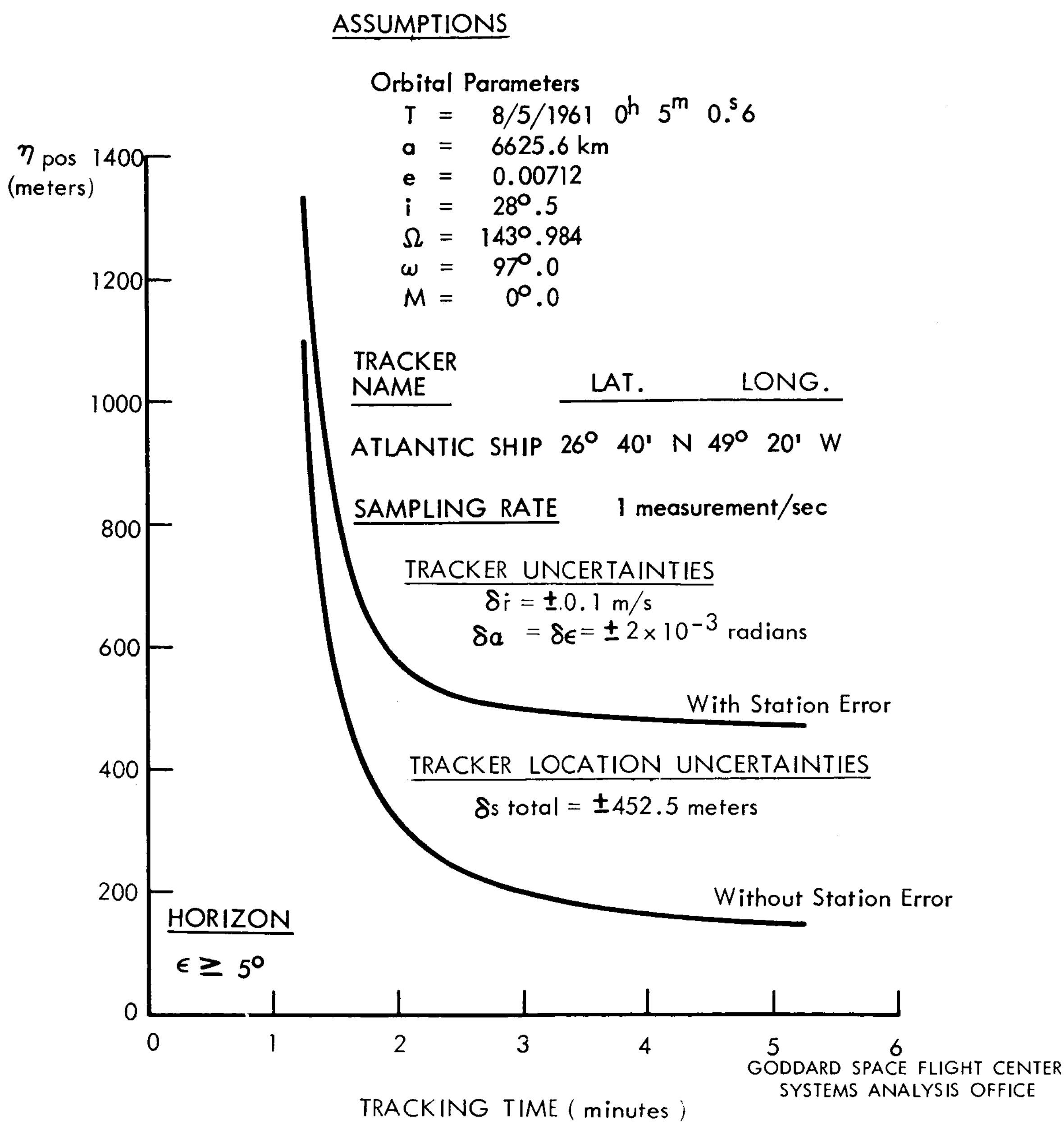
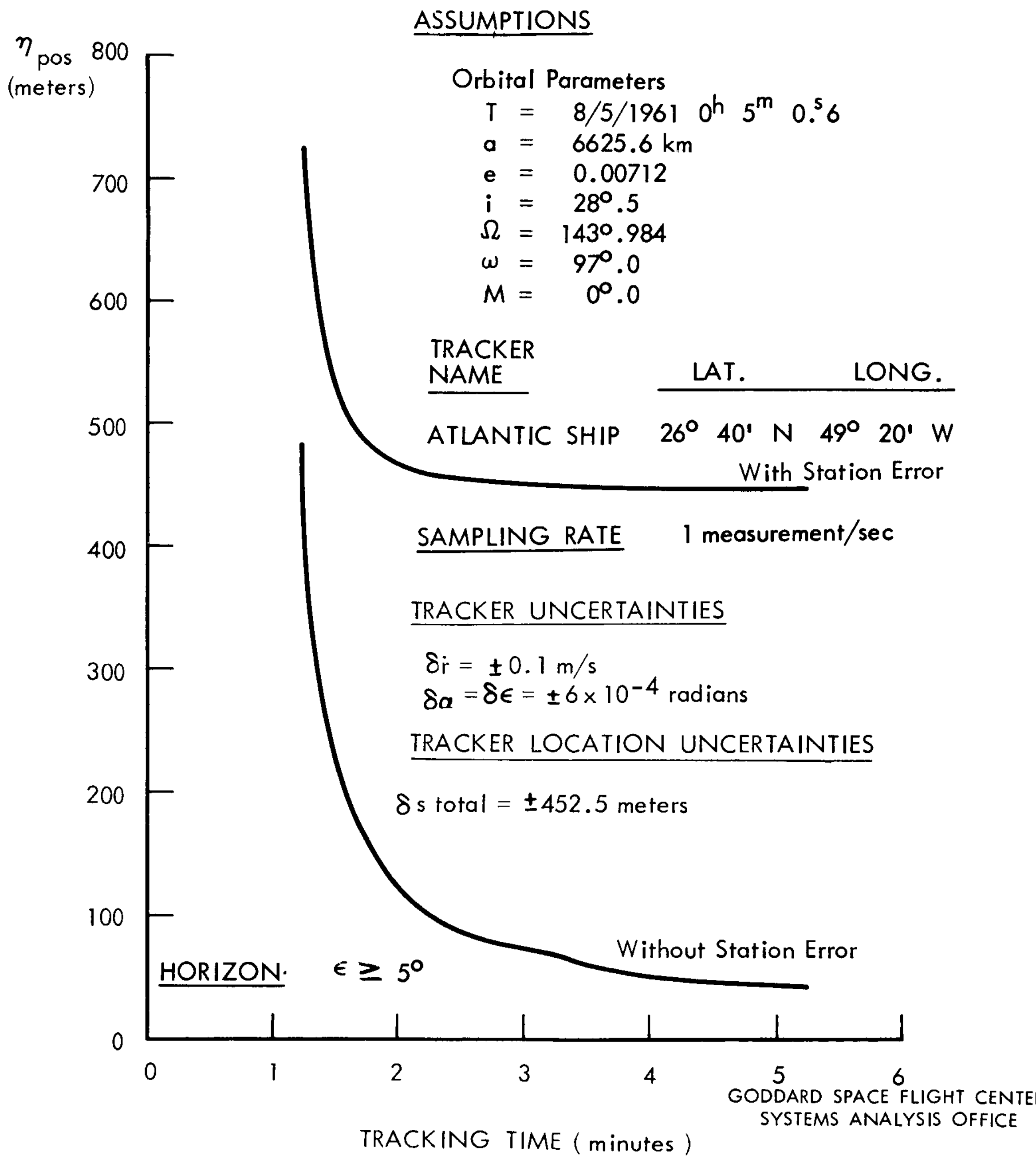
SYSTEMS ANALYSIS OFFICE

Figure 11



ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0^s.6$
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\dot{r} = \pm 0.1$ m/s
$\delta a = \delta\epsilon = \pm 2 \times 10^{-3}$ radians
With Station Error
TRACKER LOCATION UNCERTAINTIES
δs total = ±452.5 meters
Without Station Error
HORIZON
$\epsilon \geq 5°$
η pos (meters)
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 12



ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
With Station Error
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ±0.1 m/s
δα = δε = ±6 x 10^-4 radians
TRACKER LOCATION UNCERTAINTIES
δs total = ±452.5 meters
Without Station Error
HORIZON· ε ≥ 5°
η pos (meters)
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 13

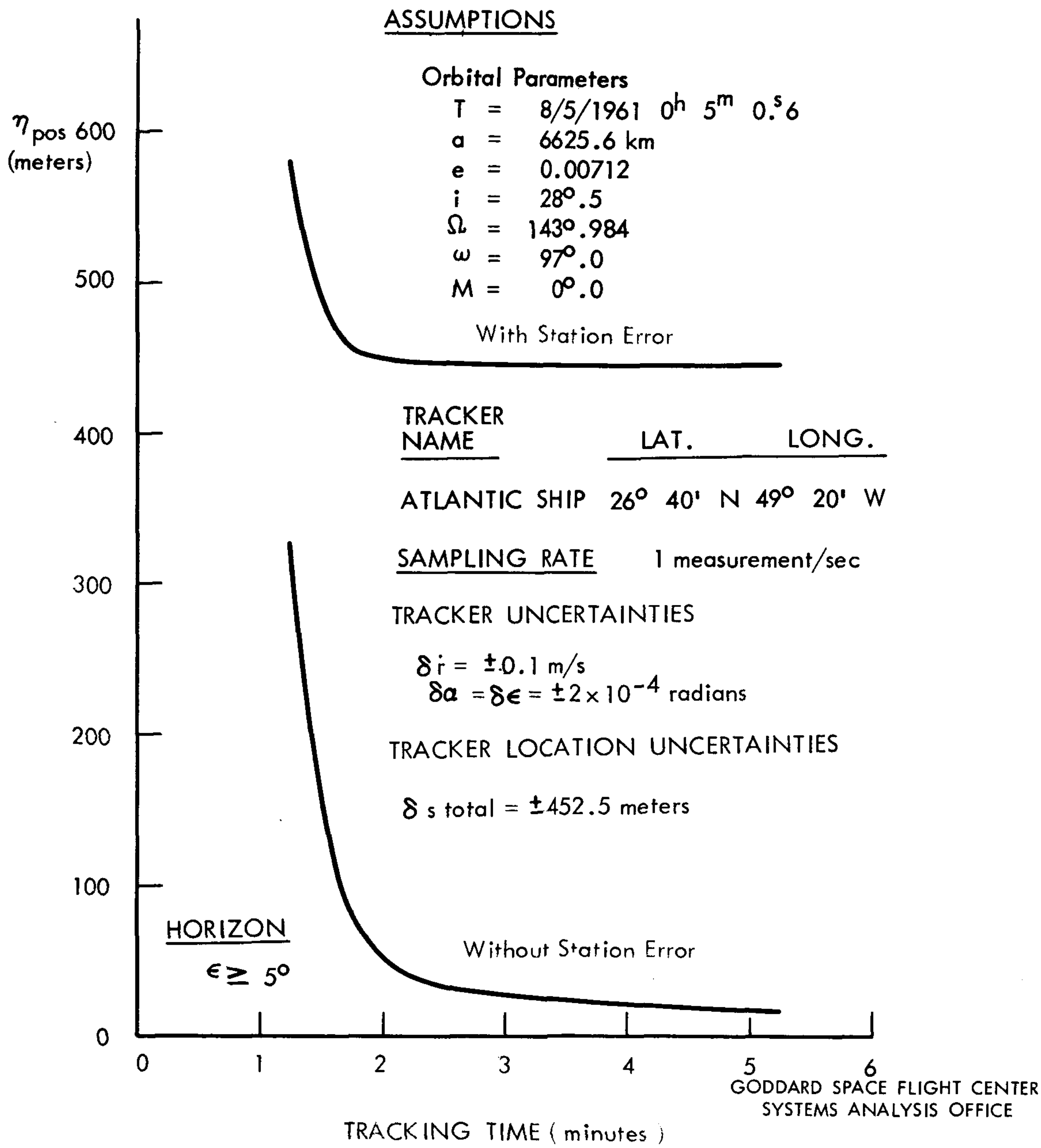
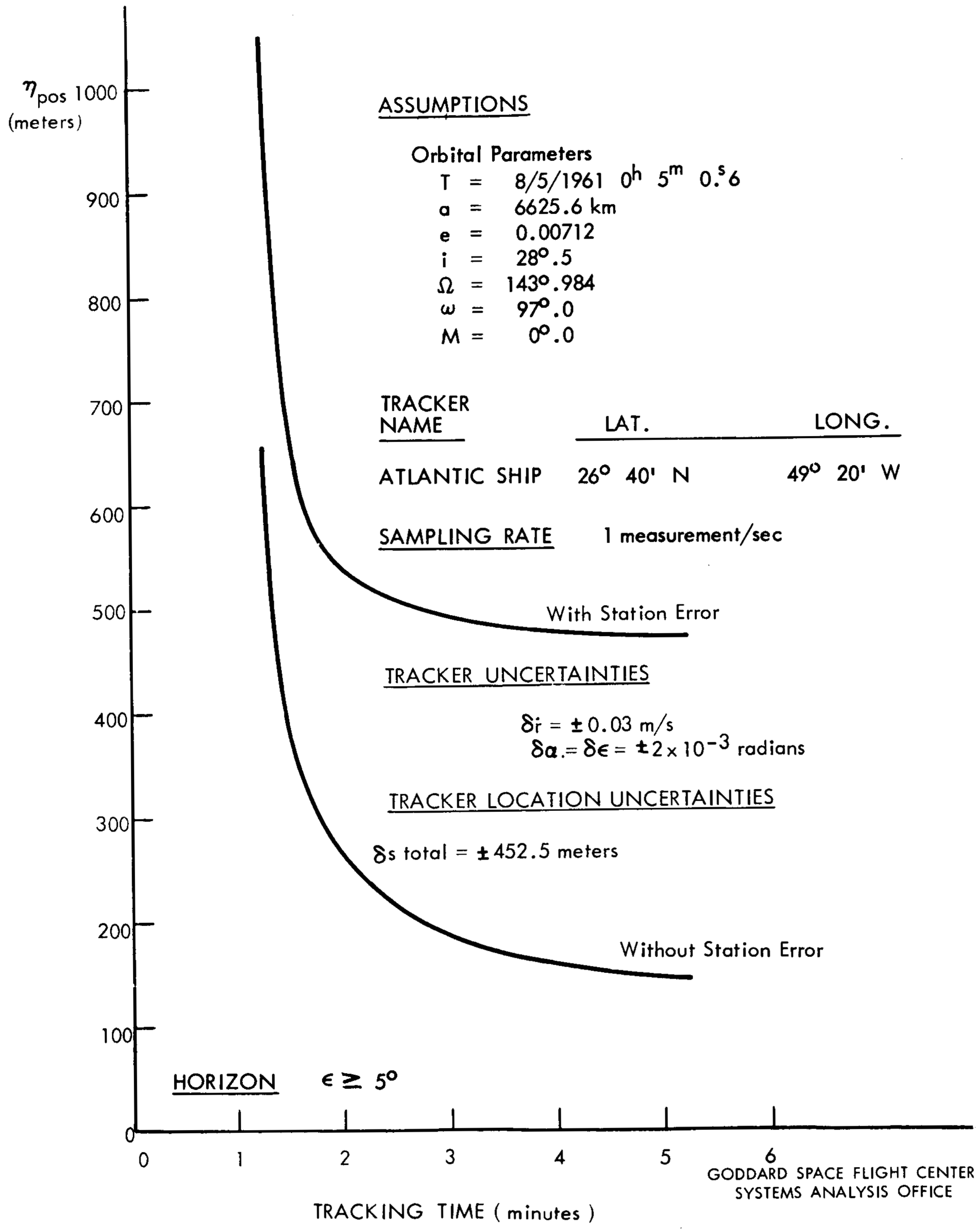

ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
With Station Error
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ±0.1 m/s
δa = δε = ±2 x 10^-4 radians
TRACKER LOCATION UNCERTAINTIES
δ s total = ±452.5 meters
HORIZON
ε ≥ 5°
Without Station Error
η pos (meters)
600
500
400
300
200
100
0
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 14



η pos (meters)
1000
900
800
700
600
500
400
300
200
100
0
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
With Station Error
TRACKER UNCERTAINTIES
δṙ = ± 0.03 m/s
δα = δε = ± 2 x 10⁻³ radians
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
Without Station Error
HORIZON
ε ≥ 5°
0
1
2
3
4
5
6
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE
TRACKING TIME (minutes)

Figure 15

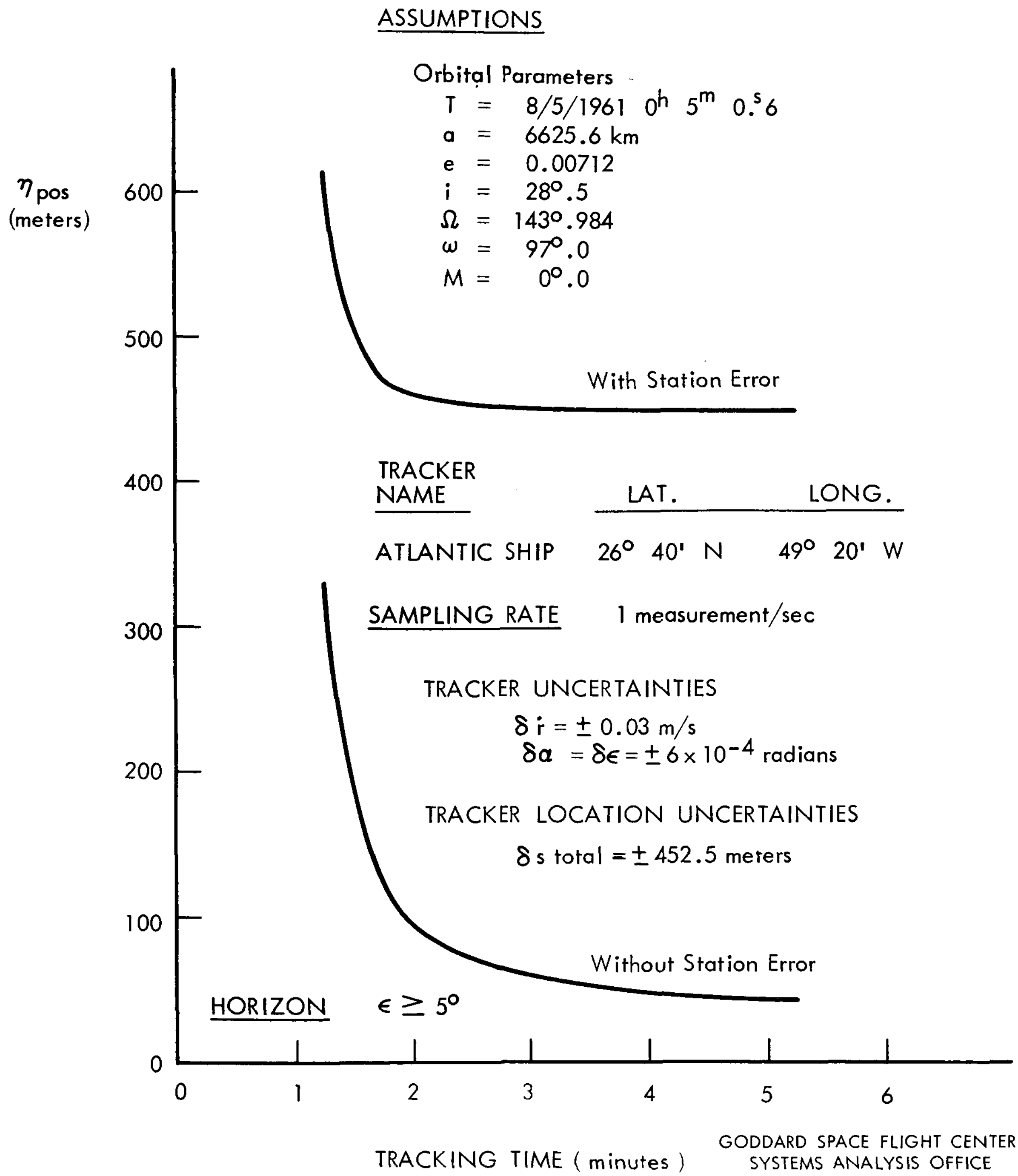
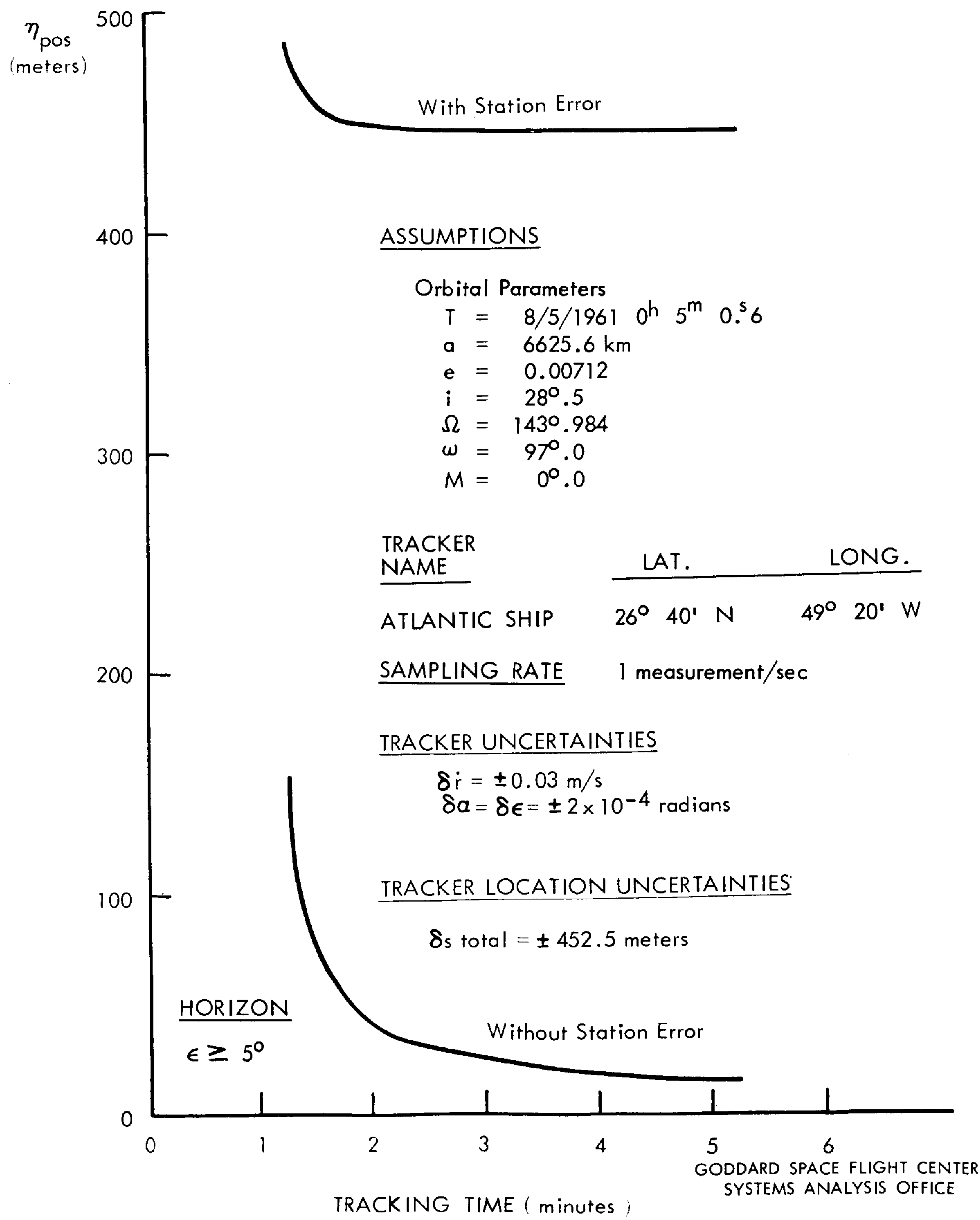

ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
With Station Error
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ± 0.03 m/s
δα = δε = ± 6 x 10⁻⁴ radians
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
Without Station Error
HORIZON ε ≥ 5°
η pos (meters)
600
500
400
300
200
100
0
0 1 2 3 4 5 6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 16

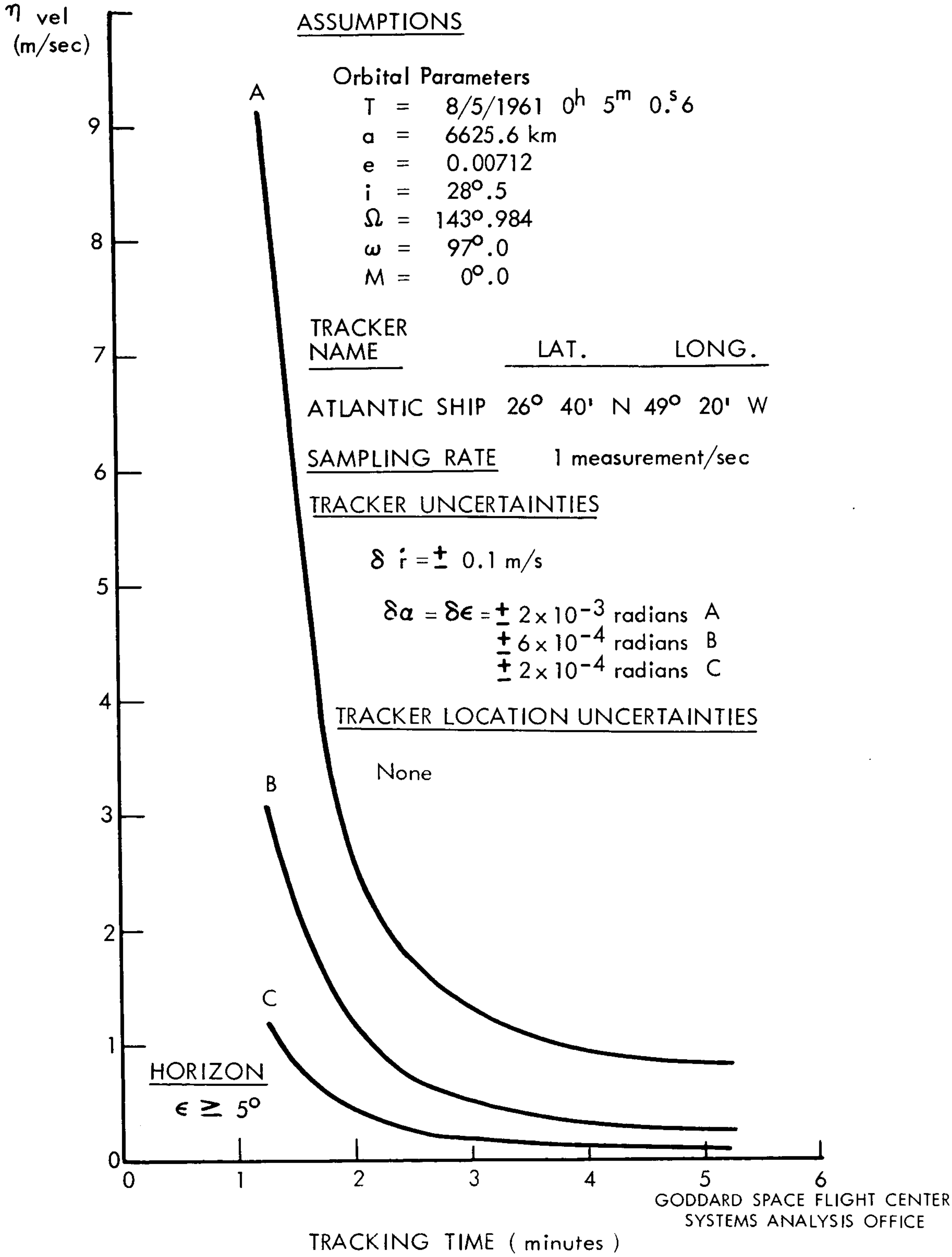


η_{pos} (meters)
500
400
300
200
100
0
With Station Error
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0.^s6$
a = 6625.6 km
e = 0.00712
i = $28^\circ.5$
Ω = $143^\circ.984$
ω = $97^\circ.0$
M = $0^\circ.0$
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\dot{r} = \pm 0.03$ m/s
$\delta a = \delta\epsilon = \pm 2 \times 10^{-4}$ radians
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
HORIZON
$\epsilon \geq 5^\circ$
Without Station Error
0
1
2
3
4
5
6
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE
TRACKING TIME (minutes)

Figure 17

Figures 18-33

Error Propagation in Spacecraft Velocity Apollo Parking Orbit



η vel (m/sec)
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δ ṙ = ± 0.1 m/s
δα = δε = ± 2 x 10⁻³ radians A
± 6 x 10⁻⁴ radians B
± 2 x 10⁻⁴ radians C
TRACKER LOCATION UNCERTAINTIES
None
A
B
C
HORIZON
ε ≥ 5°
0
1
2
3
4
5
6
7
8
9
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE
TRACKING TIME (minutes)

Figure 18

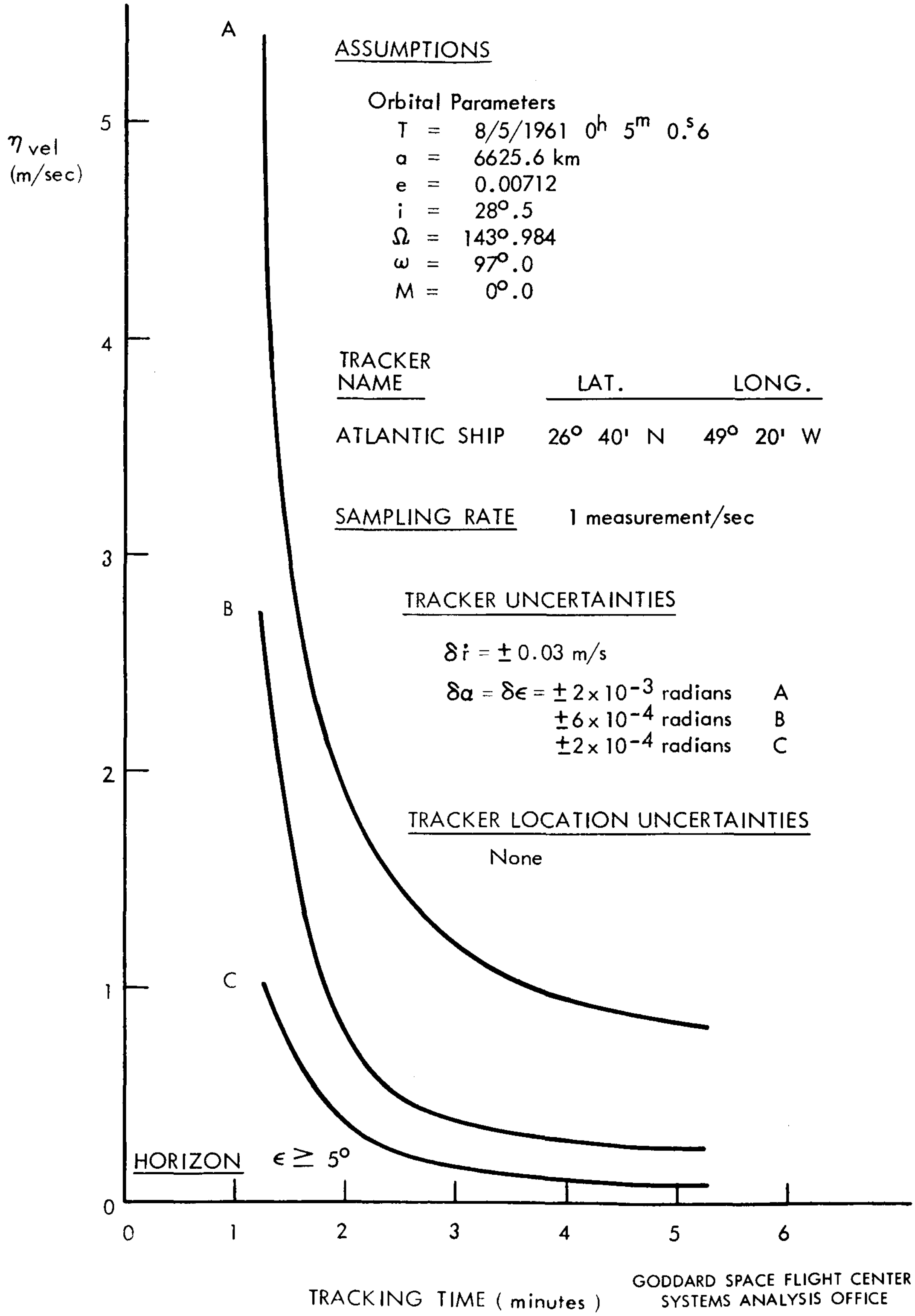

A
B
C
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0^s.6$
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta \dot{r} = \pm 0.03$ m/s
$\delta a = \delta \epsilon = \pm 2 \times 10^{-3}$ radians A
$\pm 6 \times 10^{-4}$ radians B
$\pm 2 \times 10^{-4}$ radians C
TRACKER LOCATION UNCERTAINTIES
None
η_{vel}
(m/sec)
0
1
2
3
4
5
6
HORIZON $\epsilon \geq 5°$
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 19

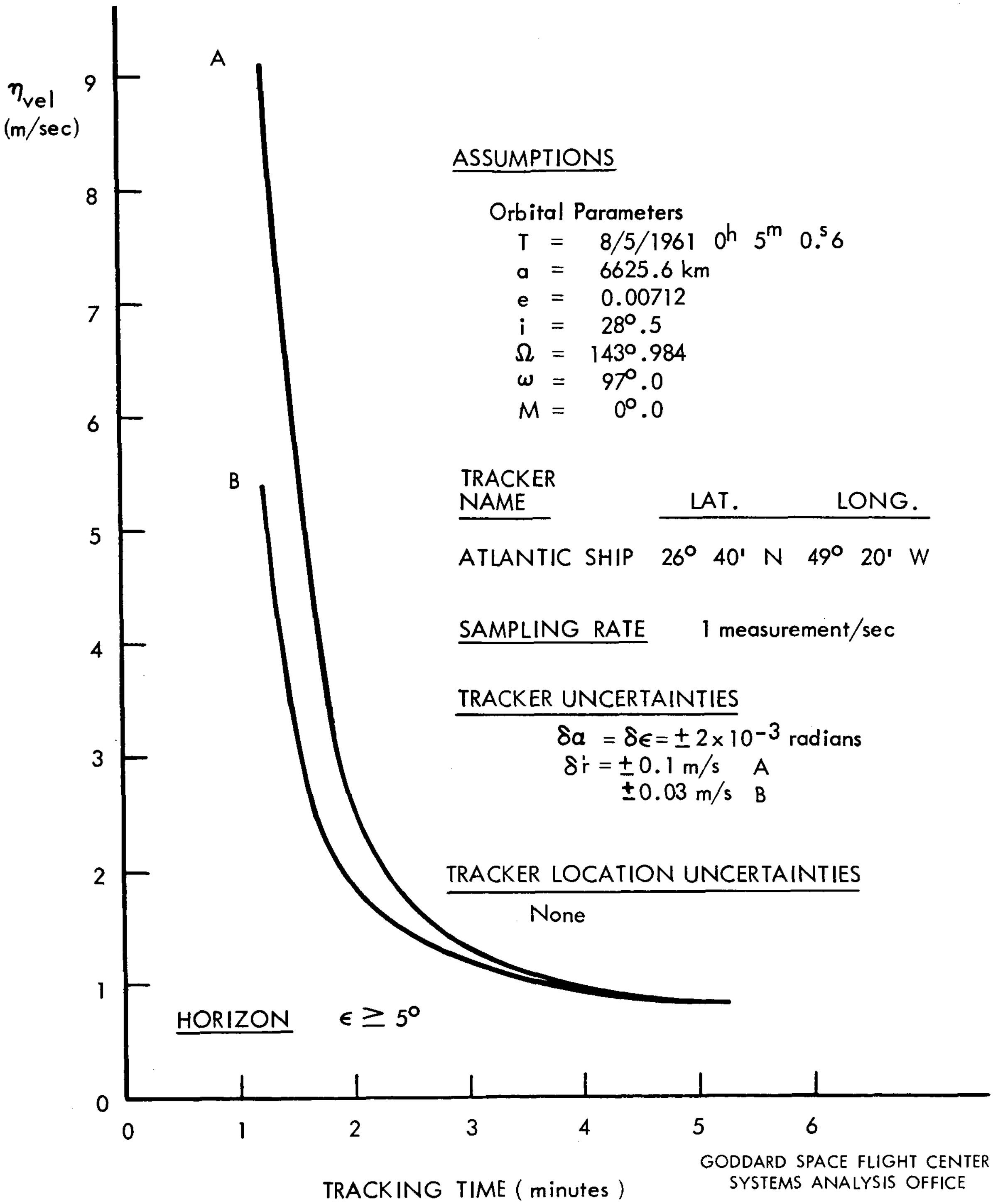
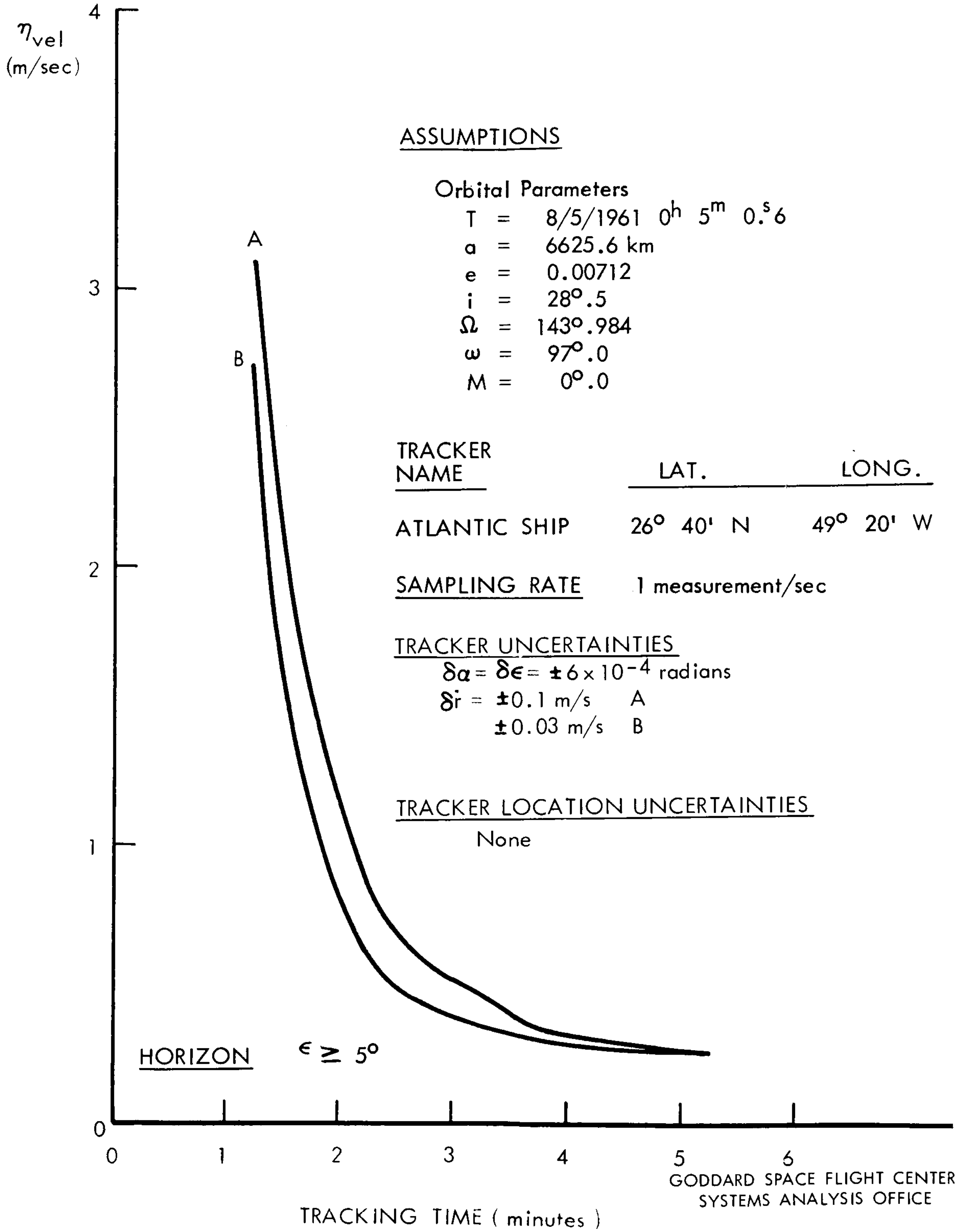

η_{vel} (m/sec)
9
8
7
6
5
4
3
2
1
0
A
B
ASSUMPTIONS
Orbital Parameters
$T = 8/5/1961\ 0^h\ 5^m\ 0.^s6$
$a = 6625.6$ km
$e = 0.00712$
$i = 28^\circ.5$
$\Omega = 143^\circ.984$
$\omega = 97^\circ.0$
$M = 0^\circ.0$
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\alpha = \delta\epsilon = \pm 2 \times 10^{-3}$ radians
$\delta\dot{r} = \pm 0.1$ m/s A
± 0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
None
HORIZON $\epsilon \geq 5^\circ$
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 20



η_{vel} (m/sec)
4
3
2
1
0
A
B
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\alpha = \delta\epsilon = \pm 6 \times 10^{-4}$ radians
$\delta\dot{r} = \pm 0.1$ m/s A
± 0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
None
HORIZON
$\epsilon \geq 5^\circ$
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 21

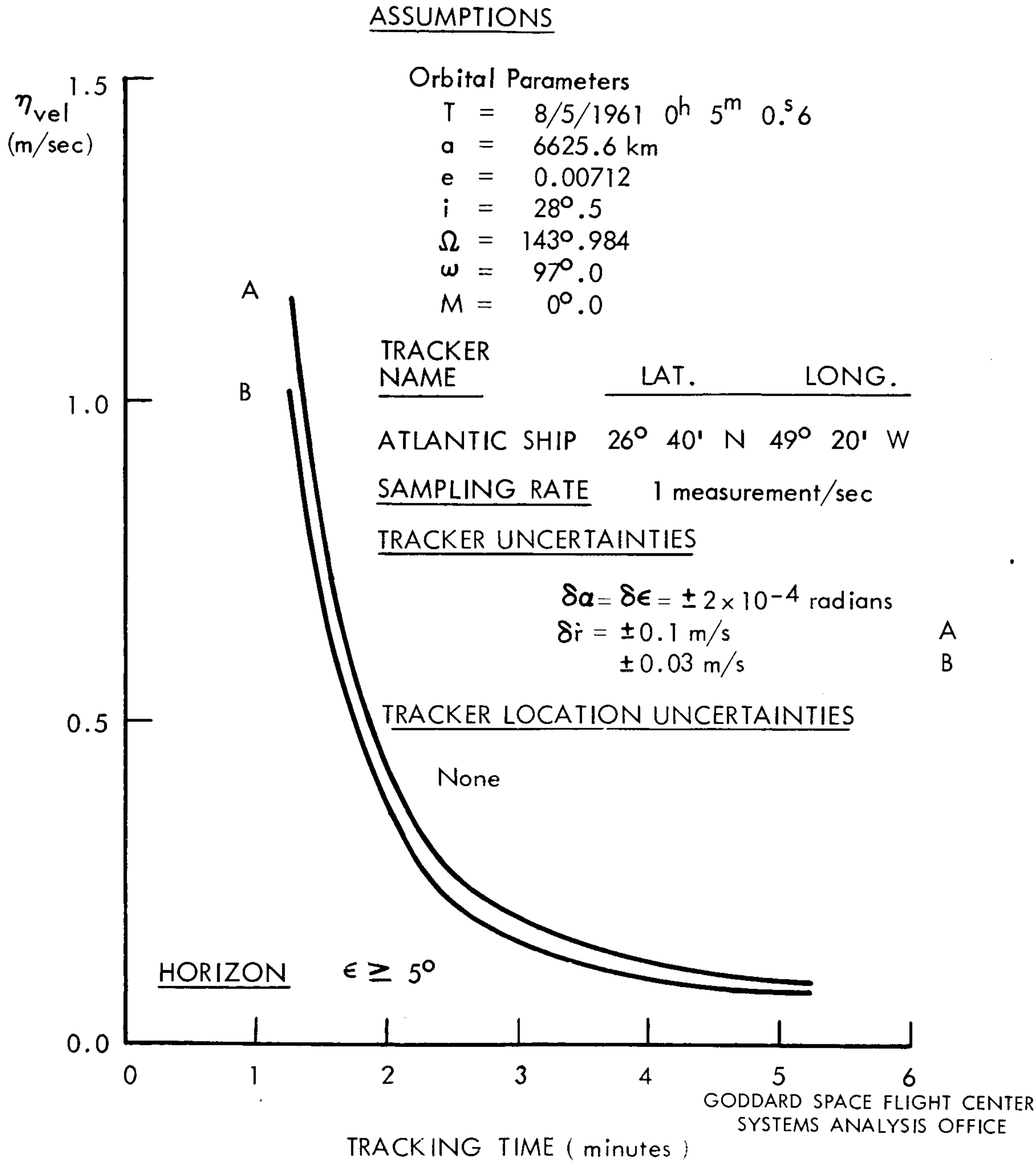

ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δα = δε = ± 2 x 10⁻⁴ radians
δṙ = ±0.1 m/s A
±0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
None
HORIZON ε ≥ 5°
ηvel (m/sec)
1.5
1.0
0.5
0.0
A
B
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 22

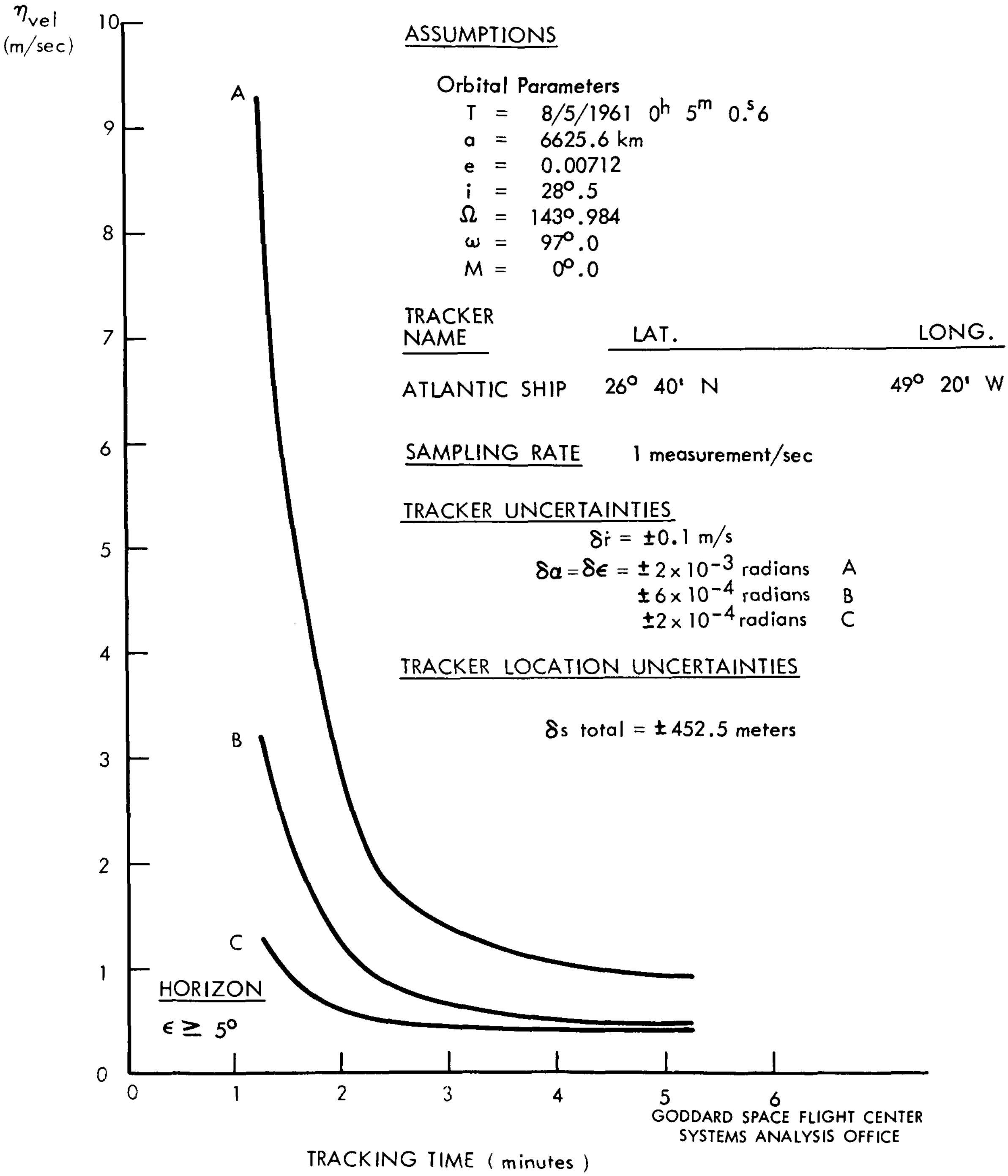

η_{vel} (m/sec)
0 1 2 3 4 5 6 7 8 9 10
A
B
C
HORIZON
$\epsilon \geq 5°$
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0.^s6$
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
$\delta \dot{r} = \pm 0.1$ m/s
$\delta a = \delta \epsilon = \pm 2 \times 10^{-3}$ radians A
$\pm 6 \times 10^{-4}$ radians B
$\pm 2 \times 10^{-4}$ radians C
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
0 1 2 3 4 5 6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 23

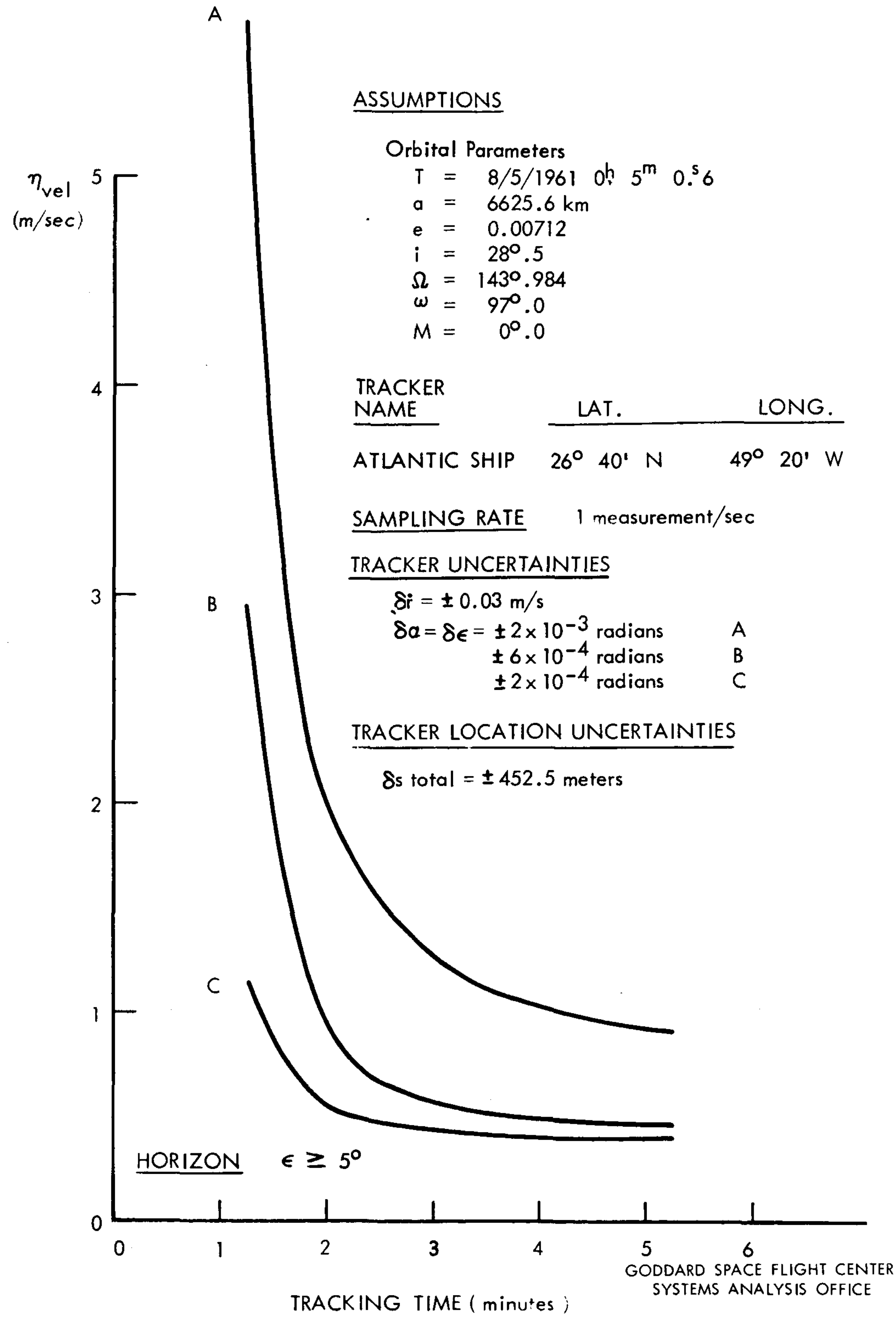
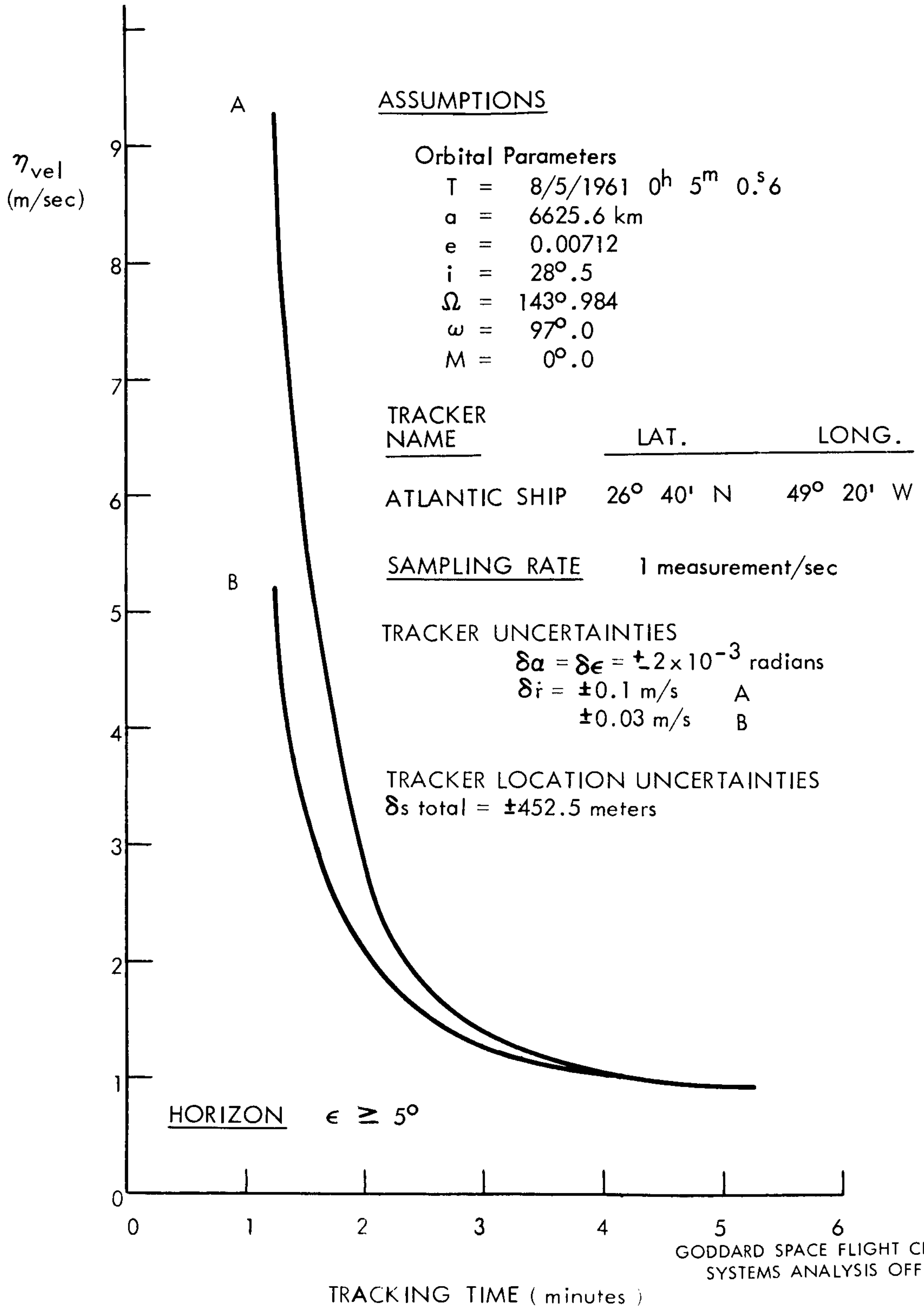
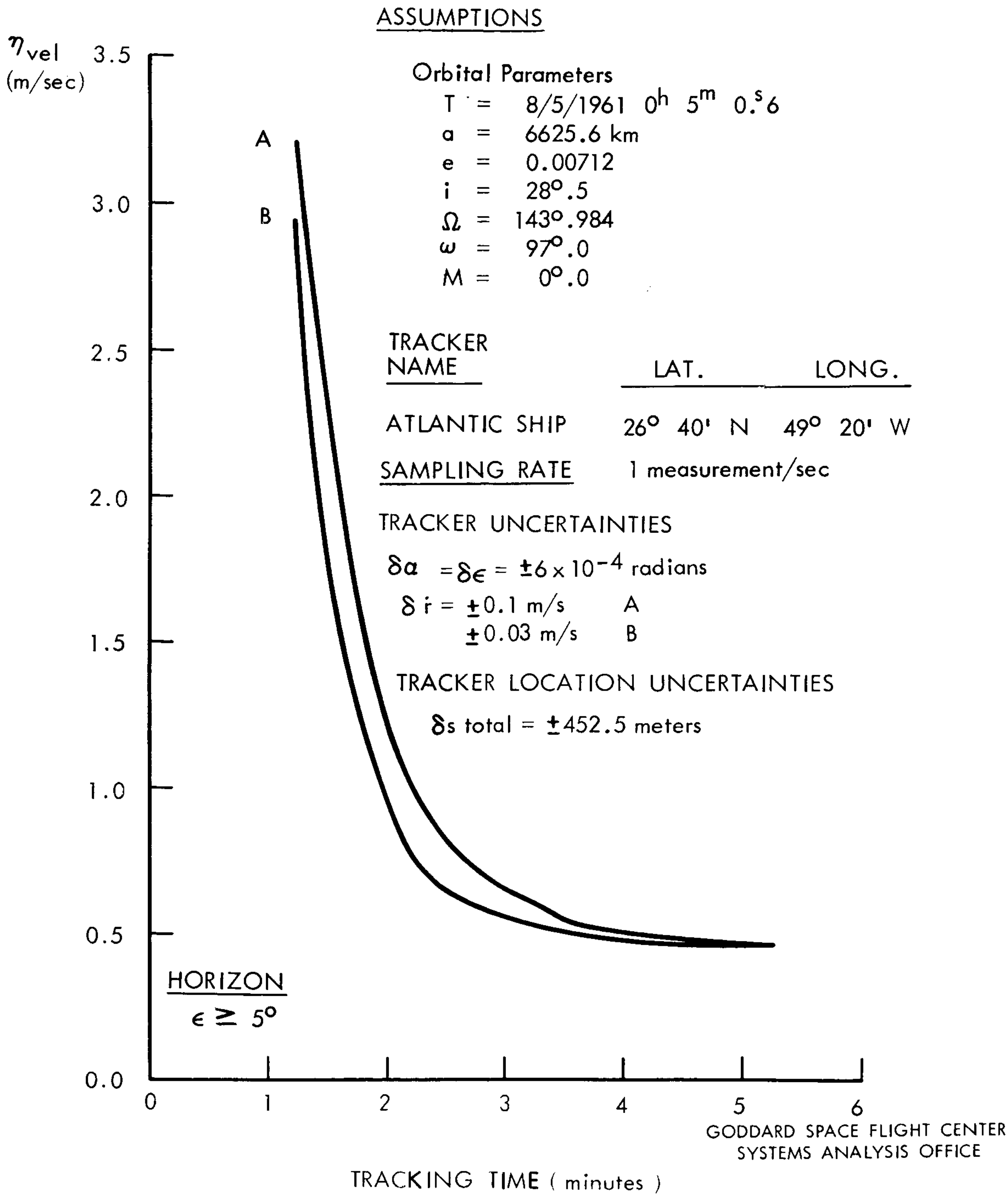

A
B
C
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ± 0.03 m/s
δα = δε = ± 2 x 10^-3 radians A
± 6 x 10^-4 radians B
± 2 x 10^-4 radians C
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
HORIZON ε ≥ 5°
η_vel (m/sec)
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 24



GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 25



ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
δα = δε = ±6 x 10^-4 radians
δ ṙ = ±0.1 m/s A
±0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
δs total = ±452.5 meters
η vel (m/sec)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
A
B
HORIZON
ε ≥ 5°
0
1
2
3
4
5
6
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE
TRACKING TIME (minutes)

Figure 26

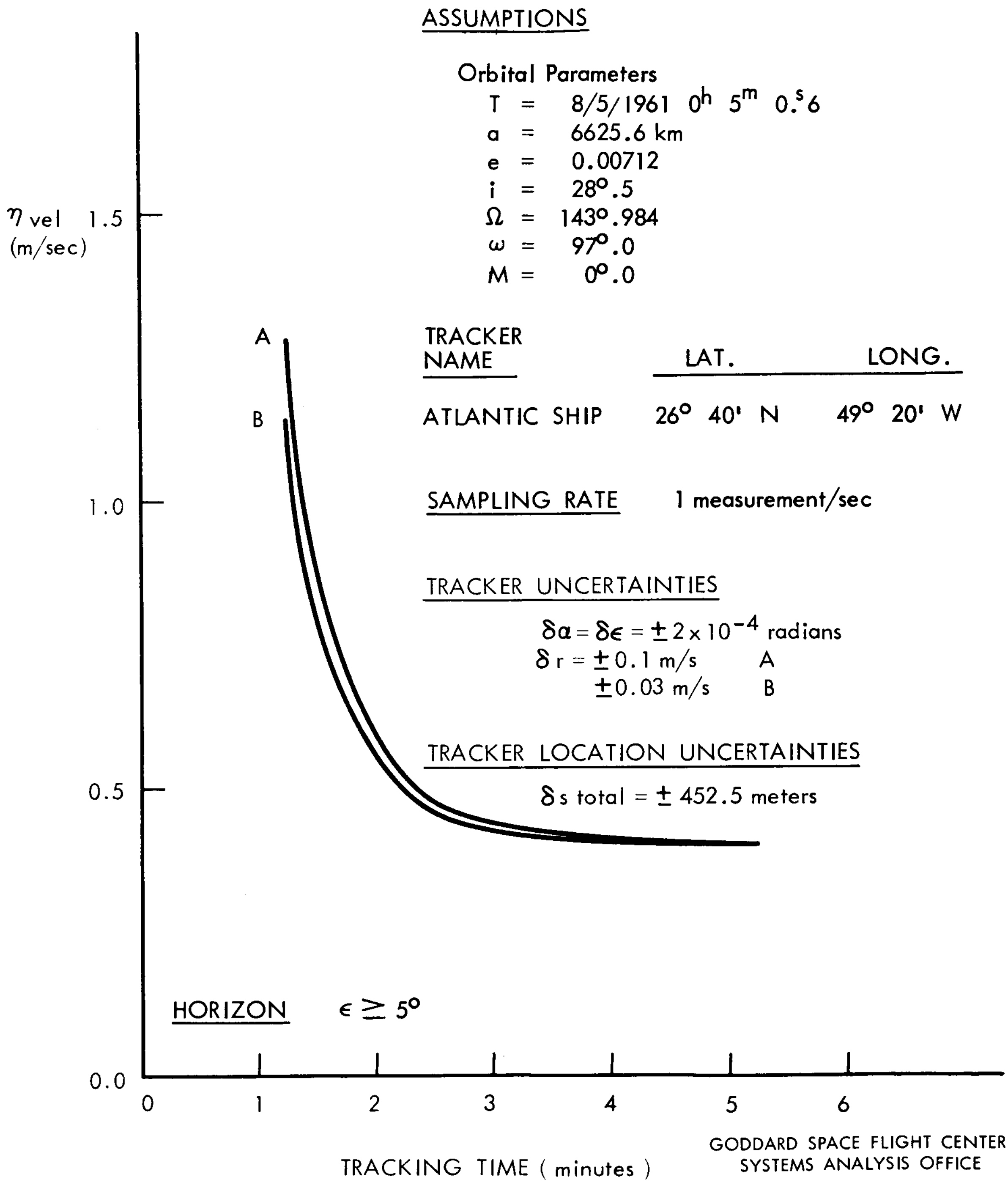
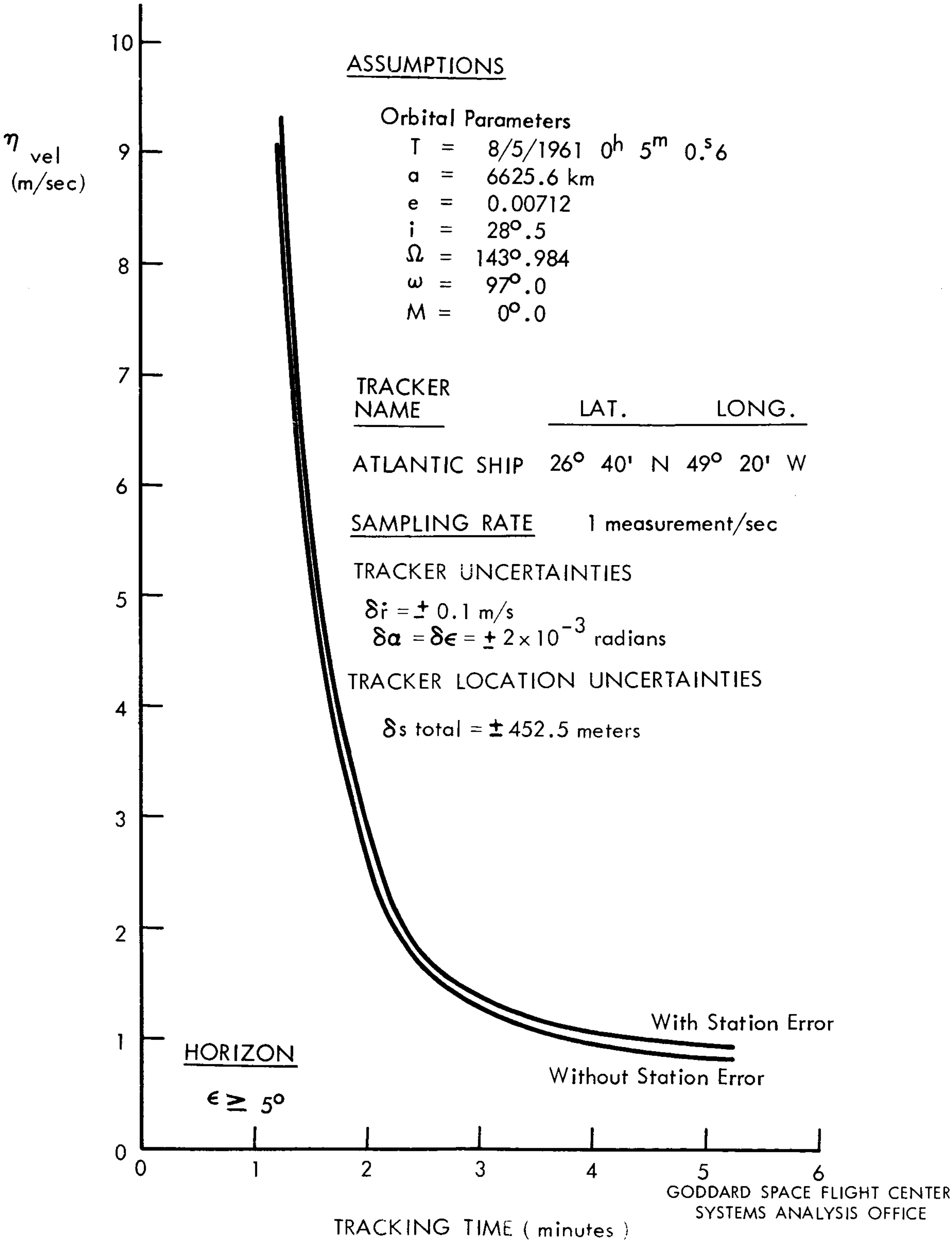

ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
δα = δε = ± 2 x 10^-4 radians
δr = ± 0.1 m/s A
± 0.03 m/s B
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
η vel (m/sec)
1.5
1.0
0.5
0.0
A
B
HORIZON
ε ≥ 5°
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 27



η_{vel} (m/sec)
10
9
8
7
6
5
4
3
2
1
0
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0.^s6$
a = 6625.6 km
e = 0.00712
i = $28^\circ.5$
Ω = $143^\circ.984$
ω = $97^\circ.0$
M = $0^\circ.0$
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta \dot{r} = \pm 0.1$ m/s
$\delta \alpha = \delta \epsilon = \pm 2 \times 10^{-3}$ radians
TRACKER LOCATION UNCERTAINTIES
δs total = $\pm$ 452.5 meters
With Station Error
Without Station Error
HORIZON
$\epsilon \geq 5^\circ$
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 28

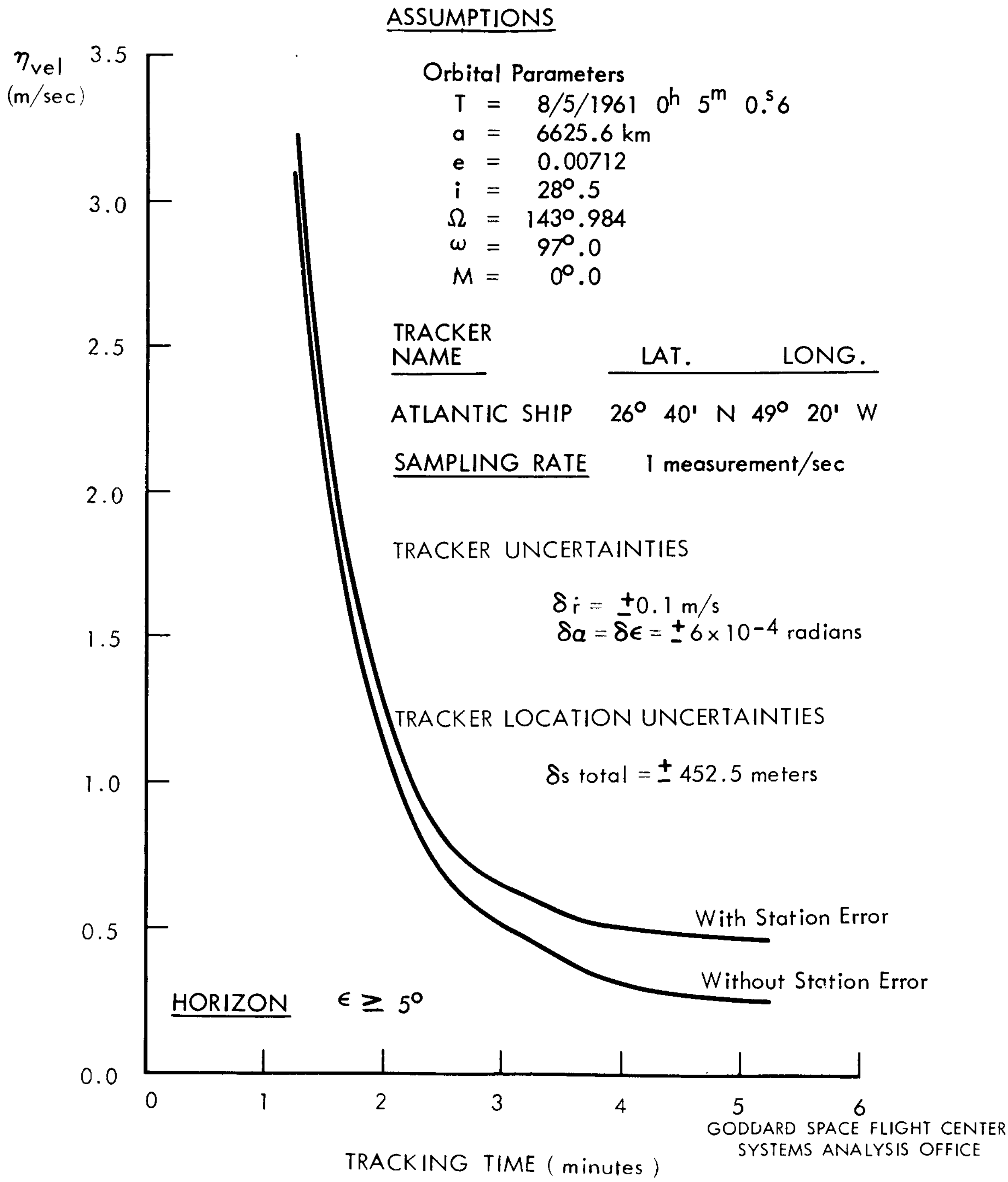

ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ±0.1 m/s
δα = δε = ±6 x 10^-4 radians
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
With Station Error
Without Station Error
HORIZON ε ≥ 5°
η vel (m/sec)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 29

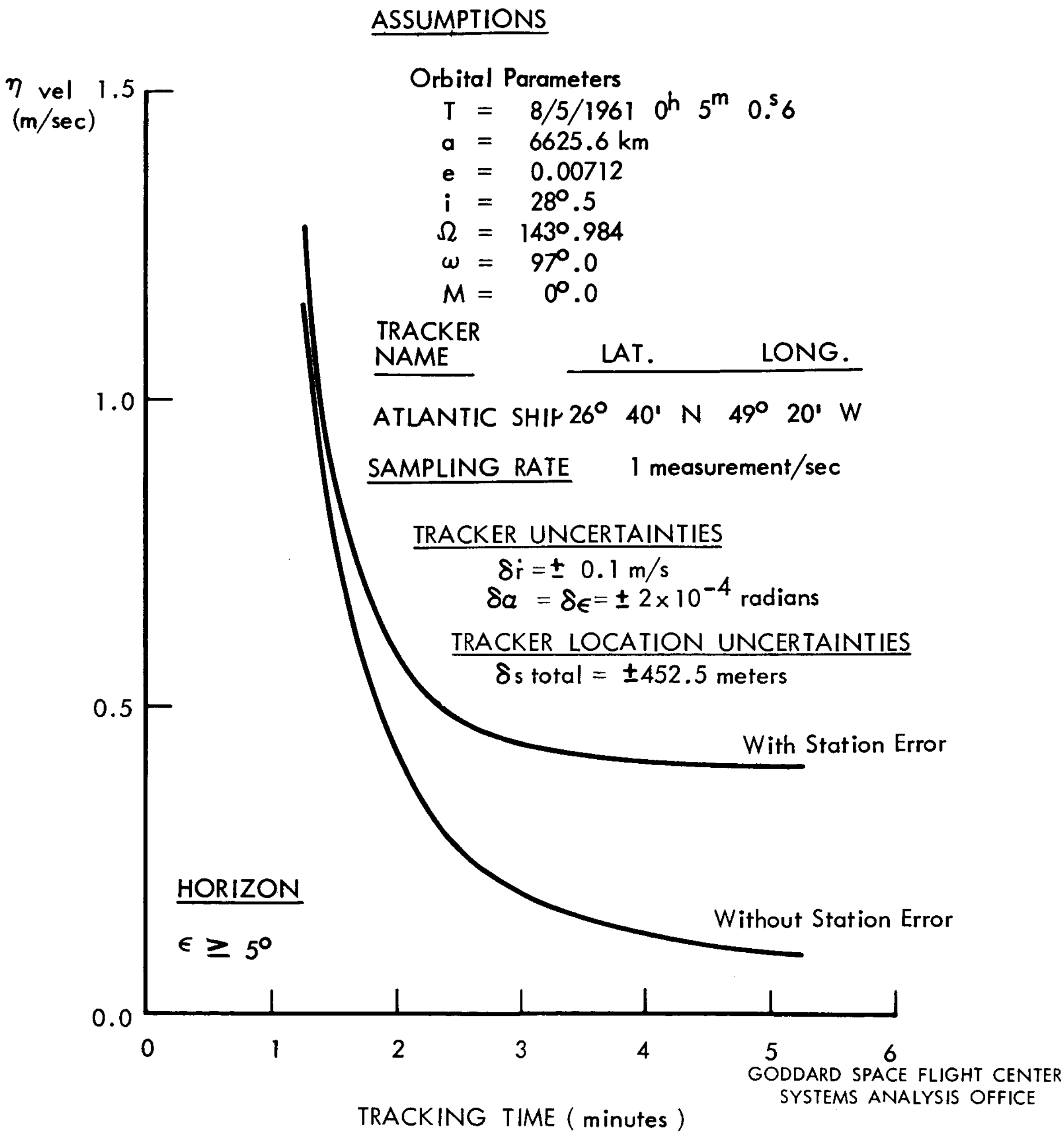

ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ± 0.1 m/s
δα = δε = ± 2 x 10^-4 radians
TRACKER LOCATION UNCERTAINTIES
δs total = ±452.5 meters
With Station Error
Without Station Error
HORIZON
ε ≥ 5°
η vel (m/sec)
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 30

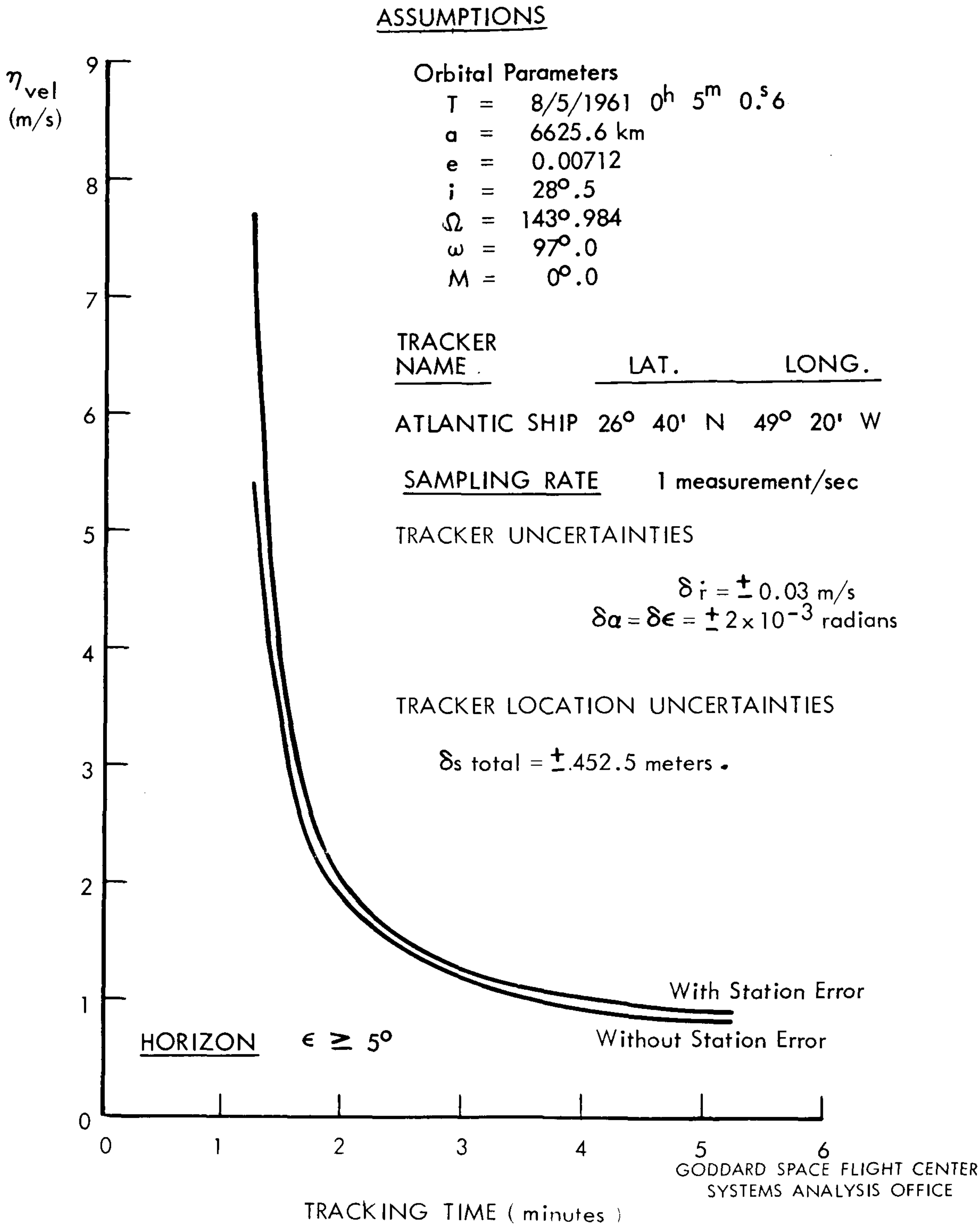

ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ± 0.03 m/s
δα = δε = ± 2 x 10^-3 radians
TRACKER LOCATION UNCERTAINTIES
δs total = ±.452.5 meters
η vel (m/s)
With Station Error
Without Station Error
HORIZON ε ≥ 5°
TRACKING TIME (minutes)
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE

Figure 31

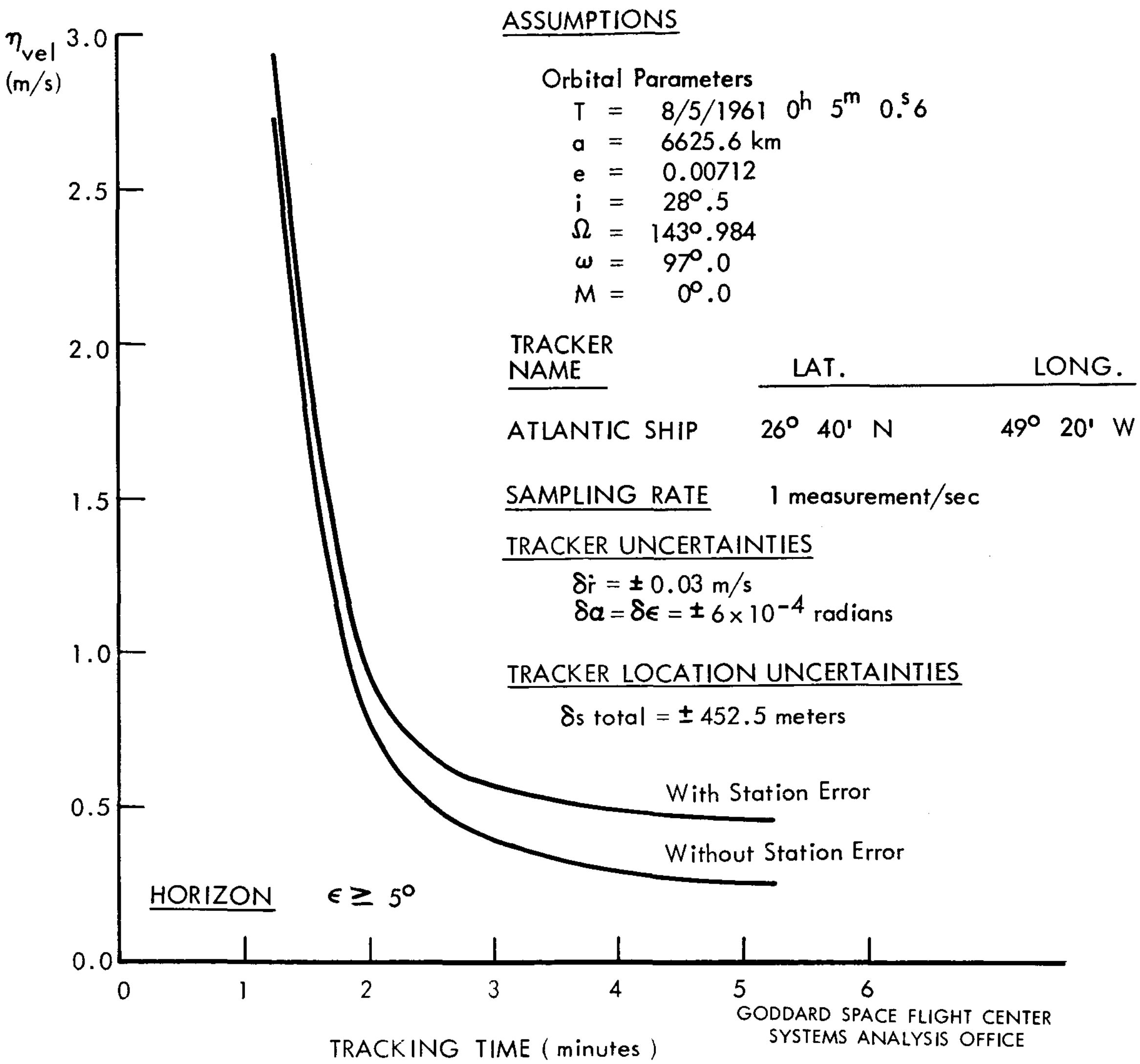

η_{vel} (m/s)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
TRACKING TIME (minutes)
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0^h 5^m $0.^s6$
a = 6625.6 km
e = 0.00712
i = $28^\circ.5$
Ω = $143^\circ.984$
ω = $97^\circ.0$
M = $0^\circ.0$
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP
26° 40' N
49° 20' W
SAMPLING RATE
1 measurement/sec
TRACKER UNCERTAINTIES
$\delta\dot{r} = \pm 0.03$ m/s
$\delta\alpha = \delta\epsilon = \pm 6 \times 10^{-4}$ radians
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
With Station Error
Without Station Error
HORIZON
$\epsilon \geq 5^\circ$
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Figure 32

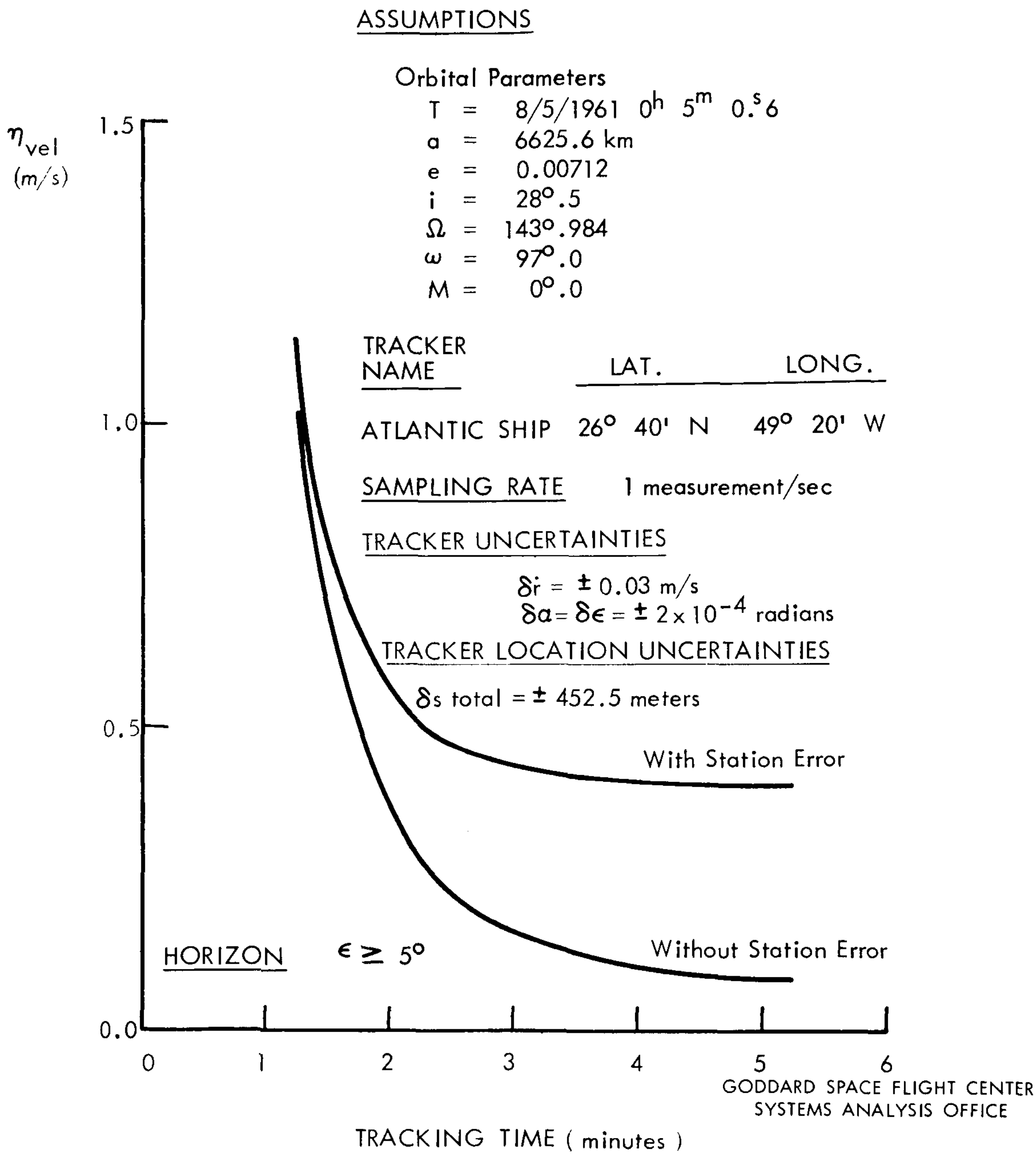
ASSUMPTIONS
Orbital Parameters
T = 8/5/1961 0h 5m 0.s6
a = 6625.6 km
e = 0.00712
i = 28°.5
Ω = 143°.984
ω = 97°.0
M = 0°.0
TRACKER NAME
LAT.
LONG.
ATLANTIC SHIP 26° 40' N 49° 20' W
SAMPLING RATE 1 measurement/sec
TRACKER UNCERTAINTIES
δṙ = ± 0.03 m/s
δa = δε = ± 2 x 10^-4 radians
TRACKER LOCATION UNCERTAINTIES
δs total = ± 452.5 meters
With Station Error
Without Station Error
HORIZON ε ≥ 5°
η vel (m/s)
1.5
1.0
0.5
0.0
0
1
2
3
4
5
6
GODDARD SPACE FLIGHT CENTER
SYSTEMS ANALYSIS OFFICE
TRACKING TIME (minutes)

Figure 33