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THE EFFECTS OF TRACKING STATION LOCATION UNCERTAINTY AND MEASUREMENT BIAS ERRORS DURING PHASES OF THE APOLLO MISSION

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ABSTRACT

The results of a study to evaluate the influence of measurement noise, measurement bias, and station location uncertainties on the capabilities of the ground navigation system during the earth orbital, translunar, lunar orbital, and transearth phases of the Apollo mission are presented. Primary emphasis is placed upon the relative effects of measurement bias and station location uncertainties on the spacecraft position and velocity errors during each phase of the mission. Thus the relative importance of measurement bias and station location uncertainties may be evaluated.

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List of Illustrations

SUMMARY

The relative influence of measurement noise, measurement bias, and station location uncertainties on the tracking capabilities of the Manned Space Flight Network during the earth orbital, translunar, lunar orbital, and transearth phases of the Apollo mission is studied for the station switching type of tracking mode. It is found that the station location uncertainty influences the spacecraft position and velocity errors significantly more than does the measurement bias during the earth orbital phase after a third station has tracked (and then, by factors of 5 to 10). For example, with station location uncertainties included, the 3σ uncertainties in position and velocity at the time of translunar injection increase from 200 feet to 1200 feet and .2 ft/sec. to 1.3 ft/sec. respectively. The measurement bias dominates the station location uncertainty in the early phase of the earth orbit by factors of 4 to 10. Also the measurement bias dominates the station location uncertainty during much of the translunar phase by factors of 2 to 4, during the lunar orbit phase by factors of 3 to 6, and during much of the transearth phase by factors of 2 to 3. For example, with measurement bias errors included, the 3σ uncertainties in position and velocity increase from 10,000 feet to 23,000 feet and from 4.8 ft/sec to 10.8 ft/sec at the time of lunar orbit insertion, from 90 feet to 350 feet and from .16 ft/sec to .56 ft/sec at the time of transearth injection, and from 3,000 feet to 6,000 feet and from 2.7 ft/sec to 5.7 ft/sec at the time of earth reentry. Thus the measurement bias is a larger error source than station location uncertainties during much of the Apollo mission; however, smaller station location uncertainties would decrease the position and velocity errors during the terminal portion of the earth orbital phase.

THE EFFECTS OF TRACKING STATION LOCATION UNCERTAINTY AND MEASUREMENT BIAS ERRORS DURING PHASES OF THE APOLLO MISSION

INTRODUCTION

A study was made of the effects of measurement noise, station location uncertainty, and measurement bias on the spacecraft position and velocity errors along typical Apollo orbits. It was initiated in order to evaluate the relative influence of the various error sources on the tracking capabilities of the Manned Space Flight Network (MSFN).

The study is divided into four phases. Tracking of the Apollo spacecraft is simulated during the earth orbital, translunar, lunar orbital, and transearth phases of the Apollo mission. The trajectories used are based upon the September 17, 1969 integrated trajectory state vector given in an Apollo Navigation Working Group (ANWG) document "Apollo Missions and Navigation Systems Characteristics" (see reference 1). The statistical values used for the error sources (the measurement noise, measurement bias, and station location uncertainties) are taken from the same document. These values are given on each of the graphs included. The tracking schedules and sampling rates are based upon studies presented in the document "Apollo Navigation, Ground and Onboard Capabilities," (see reference 2). The station switching type of tracking mode, whereby only one station at a time tracks, is considered here. Abbreviations are used for the station names on the graphs included—these are as follows:

Call Letters	Station Name
BDA	Bermuda
BRA	Canberra, Australia
CRO	Carnarvon, Australia
CYI	Grand Canary Island
GWM	Guam
HAW	Hawaii
MAD	Madrid, Spain
ODS	Goldstone, California
USC	Ascension Island
WHS	White Sands, New Mexico

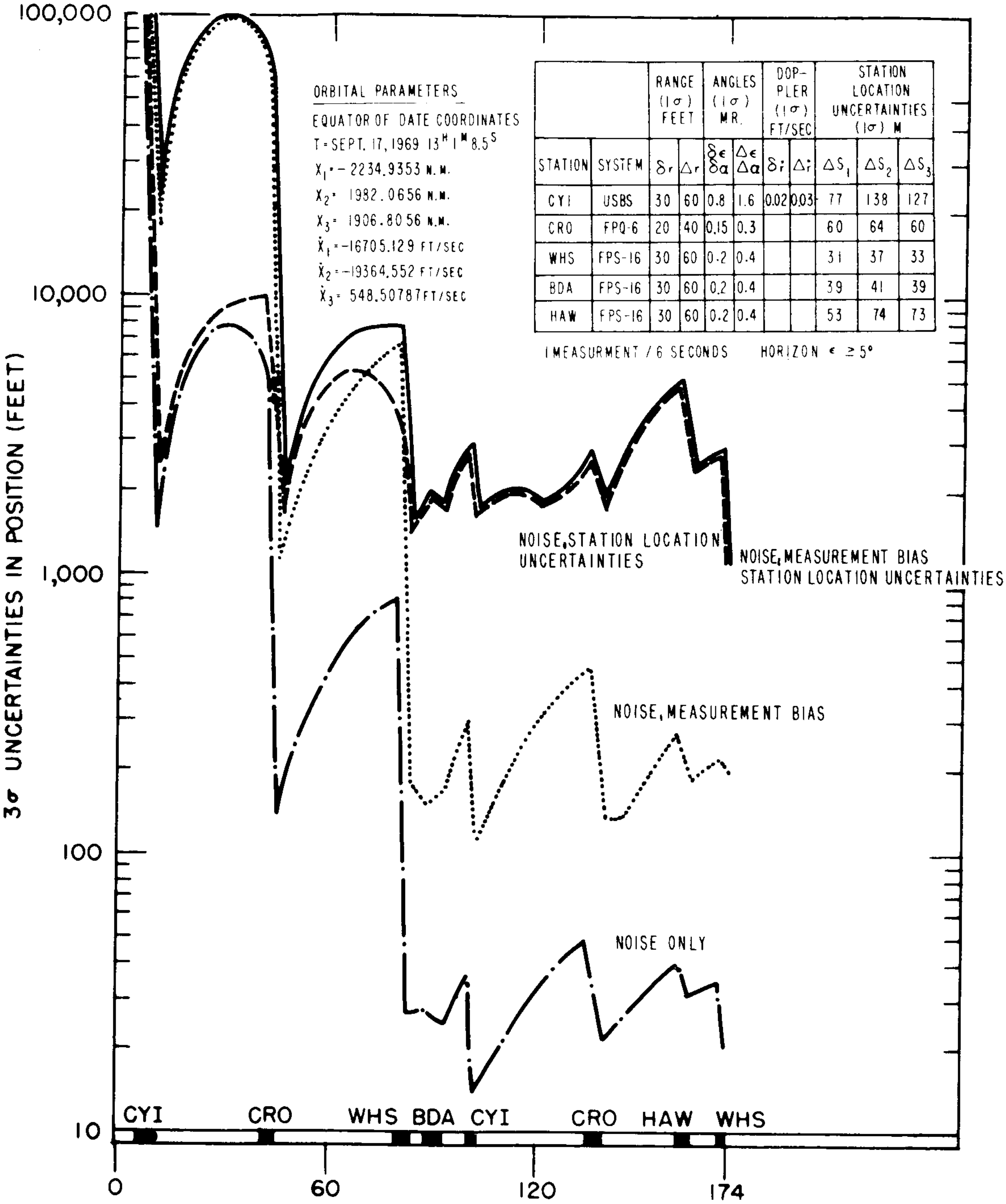
A linear error analysis computer program based on the minimum variance statistical filter (Kalman-Schmidt filter) was used for the study (see reference 3). This filter treats the assumed biases in station location and the measurement biases as if they were neglected in an orbit determination program; this is done on the assumption that the error model biases are not to be accounted for in the orbit determination process.

No equation of motion biases (such as uncertainties in the earth and lunar gravitational constants, and the earth and lunar harmonics) were considered in this study. Thus the uncertainties in spacecraft position and velocity are smaller in certain cases than should be expected. The principal emphasis of the report is on the comparison of the relative effects of station location uncertainty with measurement bias.

EARTH ORBIT PHASE

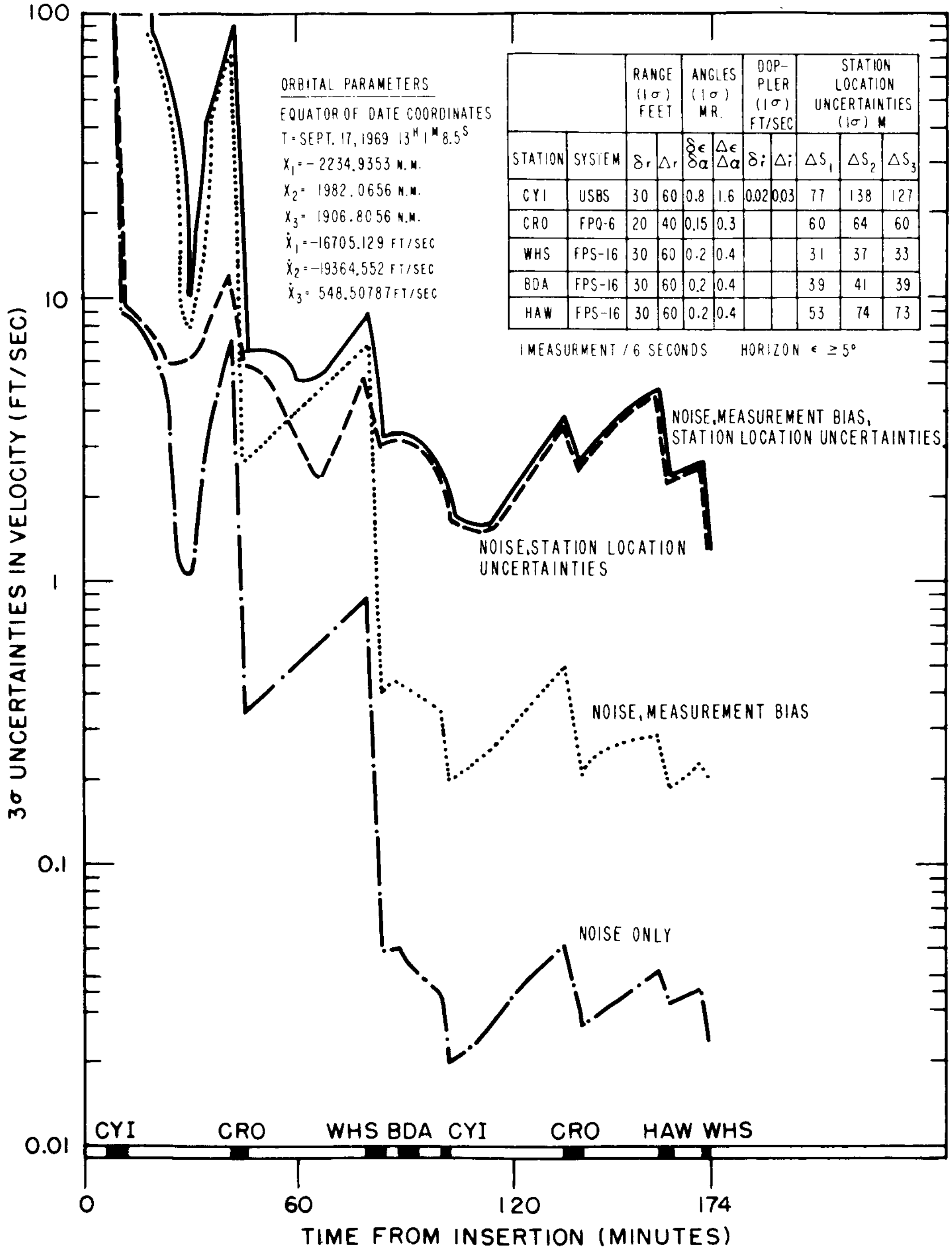
The nominal trajectory for this phase is given in the ANWG document No. 65-AN-1.1 (reference 1), on page 3-17. The trajectory is a 100 nautical mile (185 kilometer) circular earth parking orbit. Translunar injection was assumed at the end of the second parking orbit; the study for the earth orbital phase covers 2 hours and 54 minutes. The tracking network considered for the study consists of 5 stations, of which 4 use C-band radar tracking and 1 uses the USBS tracking system. The tracking times are shown on each figure presented. The C-band data, consisting of range, azimuth, and elevation measurements, and the S-band data consisting of range, range rate and angular measurements, are obtained at a sampling rate of 10 measurements per minute. The tracking mode is similar to that used in reference 2 (chapter 4.0).

Figures 1 and 2 show the 3σ uncertainties in spacecraft position and velocity as a function of time from insertion for combinations of error sources. The lower curves give the uncertainties in position and velocity when measurement noise is the only error source considered. The upper curves give the errors in spacecraft position and velocity when measurement noise, measurement bias, and station location uncertainties are included. The intermediate curves consider only station location uncertainty or measurement bias along with measurement noise. It is seen that, with poor a priori knowledge about the uncertainties in position and velocity and with tracking by one station only, the measurement bias has a far greater effect on the errors in spacecraft position and velocity than does the station location uncertainty. Until tracking begins for the second station, Carnarvon, station location uncertainty has only a slight effect on the errors in spacecraft position and velocity. After tracking by the second station, the effects of measurement noise and measurement bias are reduced and the



		RANGE (1σ) FEET		ANGLES (1σ) MR.		DOPPLER (1σ) FT/SEC		STATION LOCATION UNCERTAINTIES (1σ) M		
STATION	SYSTEM	δ_r	Δ_r	$\delta\epsilon$ $\delta\alpha$	$\Delta\epsilon$ $\Delta\alpha$	$\delta_{\dot{r}}$	$\Delta_{\dot{r}}$	ΔS_1	ΔS_2	ΔS_3
CYI	USBS	30	60	0.8	1.6	0.02	0.03	77	138	127
CRO	FPQ-6	20	40	0.15	0.3			60	64	60
WHS	FPS-16	30	60	0.2	0.4			31	37	33
BDA	FPS-16	30	60	0.2	0.4			39	41	39
HAW	FPS-16	30	60	0.2	0.4			53	74	73

Figure 1—Uncertainties in Position During Earth Orbit Phase



		RANGE (1σ) FEET		ANGLES (1σ) MR.		DOPPLER (1σ) FT/SEC		STATION LOCATION UNCERTAINTIES (1σ) M		
STATION	SYSTEM	δr	Δr	$\delta\epsilon$ $\delta\alpha$	$\Delta\epsilon$ $\Delta\alpha$	$\delta\dot{r}$	$\Delta\dot{r}$	ΔS_1	ΔS_2	ΔS_3
CYI	USBS	30	60	0.8	1.6	0.02	0.03	77	138	127
CRO	FPQ-6	20	40	0.15	0.3			60	64	60
WHS	FPS-16	30	60	0.2	0.4			31	37	33
BDA	FPS-16	30	60	0.2	0.4			39	41	39
HAW	FPS-16	30	60	0.2	0.4			53	74	73

Figure 2–Uncertainities in Velocity During Earth Orbit Phase

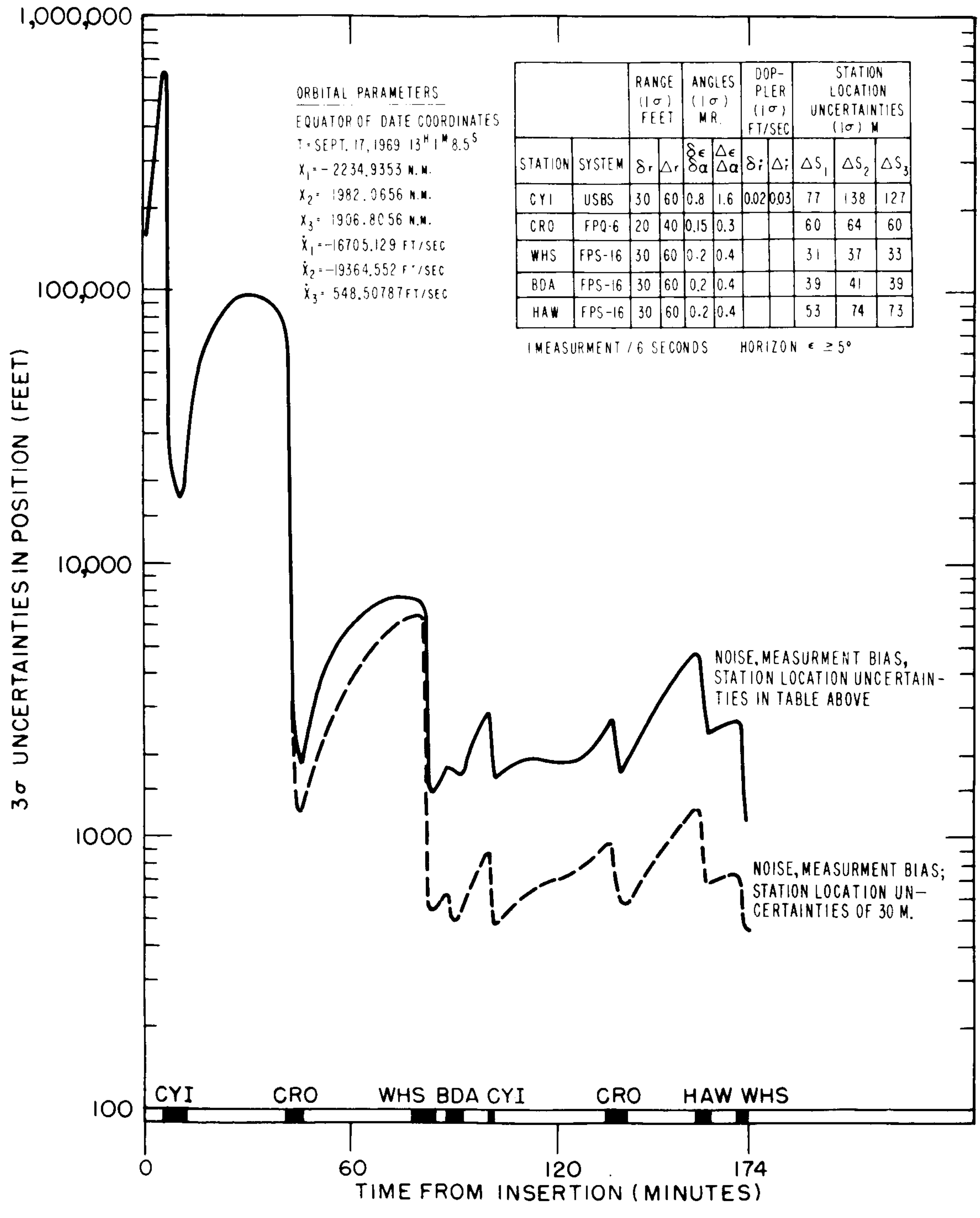
effects of measurement bias and station location uncertainties become approximately equal. After tracking by the third station, White Sands, the effect of station location uncertainty outweighs that of measurement bias. In fact, thereafter to translunar injection at 2 hours and 54 minutes, the station location uncertainties contribute a factor of 5 to 10 as much as measurement bias to the 3σ uncertainty in spacecraft position and velocity.

Figures 1 and 2 show that the station location uncertainties contribute most to the errors in spacecraft position and velocity at the time of translunar injection. The station location uncertainties used are those given in the ANWG document AN-1.1 (see reference 1). Further studies were made where the station location uncertainty in each component for each station was reduced to 30 meters in order to find the resulting decrease in spacecraft position and velocity uncertainty. Figures 3 and 4 show the comparison between the spacecraft position and velocity uncertainty when the ANWG (reference 1) station location uncertainties are used (upper curves) and when the station location uncertainty in each component for each station is reduced to 30 meters (lower curves). It is seen that at translunar injection the 3σ position uncertainty can be reduced from 1,150 feet to 450 feet, and the 3σ velocity uncertainty from 1.3 feet/second to 0.5 feet/second. Note that the noise and measurement bias curves on Figures 1 and 2 give the case of no station location uncertainty; then the 3σ position uncertainty is 200 feet and the 3σ velocity uncertainty is 0.2 feet/second.

In summary, for the earth orbit phase the measurement bias is predominant on the first parking orbit until the second station tracks, the measurement bias and station location uncertainties are then approximately equal until the third station begins tracking, and thereafter the station location uncertainty is predominant. Thus the measurement bias most influences the errors in spacecraft position and velocity for one station tracking, but the station location uncertainties most influence the errors in spacecraft position and velocity at translunar injection.

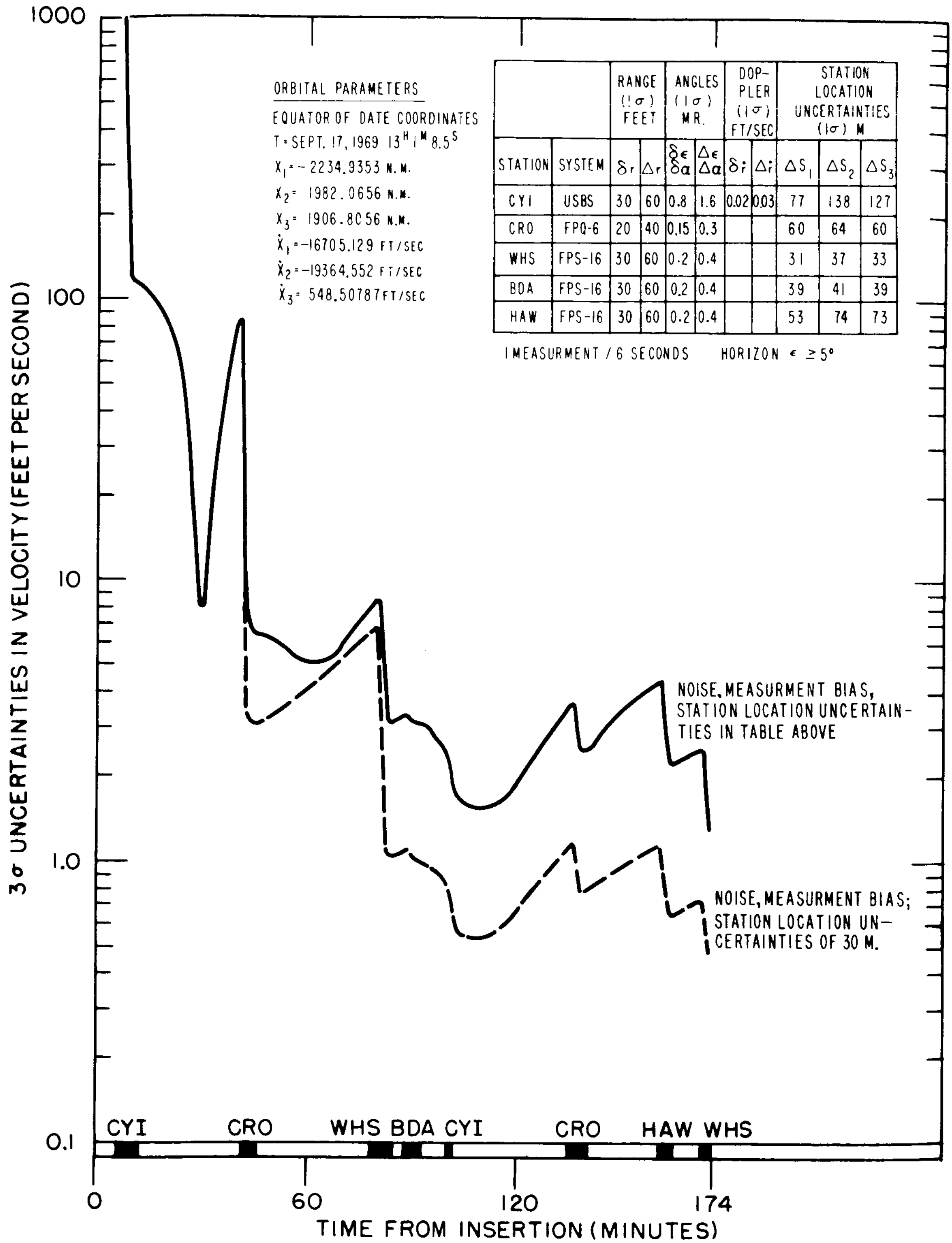
TRANSLUNAR PHASE

The nominal trajectory for the translunar phase, taken from reference 2 (chapter 5.0, page 5-8), covers approximately 66 hours. The tracking network chosen for this phase consists of 7 USBS stations using the two-way Doppler tracking mode; range rate measurements were taken from a specified tracking station at a sampling rate of one measurement per minute. Values used for the range rate noise and bias are the same as those given in reference 1. The tracking schedule is similar to that used in reference 2.



		RANGE (1σ) FEET		ANGLES (1σ) MR.		DOPPLER (1σ) FT/SEC		STATION LOCATION UNCERTAINTIES (1σ) M		
STATION	SYSTEM	δ_r	Δ_r	$\delta\epsilon$ $\delta\alpha$	$\Delta\epsilon$ $\Delta\alpha$	$\delta_{\dot{r}}$	$\Delta_{\dot{r}}$	ΔS_1	ΔS_2	ΔS_3
CYI	USBS	30	60	0.8	1.6	0.02	0.03	77	138	127
CRO	FPQ-6	20	40	0.15	0.3			60	64	60
WHS	FPS-16	30	60	0.2	0.4			31	37	33
BDA	FPS-16	30	60	0.2	0.4			39	41	39
HAW	FPS-16	30	60	0.2	0.4			53	74	73

Figure 3–Uncertainities in Position During Earth Orbit Phase
(Reduced Station Location Uncertainty)



		RANGE (1σ) FEET		ANGLES (1σ) MR.		DOPPLER (1σ) FT/SEC		STATION LOCATION UNCERTAINTIES (1σ) M		
STATION	SYSTEM	δ_r	Δ_r	$\delta\epsilon$ $\delta\alpha$	$\Delta\epsilon$ $\Delta\alpha$	$\delta_{\dot{r}}$	$\Delta_{\dot{r}}$	ΔS_1	ΔS_2	ΔS_3
CYI	USBS	30	60	0.8	1.6	0.02	0.03	77	138	127
CRO	FPQ-6	20	40	0.15	0.3			60	64	60
WHS	FPS-16	30	60	0.2	0.4			31	37	33
BDA	FPS-16	30	60	0.2	0.4			39	41	39
HAW	FPS-16	30	60	0.2	0.4			53	74	73

Figure 4–Uncertainties in Velocity During Earth Orbit Phase (Reduced Station Location Uncertainty)

Figures 5 and 6 show the 3σ uncertainties in spacecraft position and velocity as a function of time from translunar injection. For the first hour, during which time the two stations at Grand Canary Island and Ascension Island are tracking one at a time, the station location uncertainties dominate and measurement bias is insignificant. Note that very poor a priori information was assumed. Then with one station tracking at a time, the effect of measurement bias increases until the measurement bias is dominant after 4 hours. With either measurement bias or station location uncertainty considered, the uncertainties in position steadily increase (before the lunar sphere of influence is reached) as the spacecraft's distance relative to the earth increases while the uncertainties in velocity first decrease and then increase as the effect of measurement bias is felt. From 4 hours until lunar orbit insertion the measurement bias contributes approximately twice as much to the 3σ uncertainties in spacecraft position and velocity as does the station location uncertainties. Note that the 3σ uncertainty in velocity increases within the lunar sphere of influence (LSOI) as does the actual velocity on the nominal trajectory.

Thus, for tracking during the translunar phase, the measurement bias most influences the 3σ uncertainties in spacecraft position and velocity at the time of lunar orbit insertion.

LUNAR ORBIT PHASE

The CSM/LM (Command and Service Modules/Lunar Excursion Module) spacecraft is to be inserted into a circular lunar parking orbit with an altitude above the lunar surface of approximately 80 nautical miles. The September 17, 1969 nominal trajectory from reference 1 was used here. The CSM/LM separation occurs at approximately 3 hours and 43 minutes after insertion, and the beginning of CSM/LM rendezvous occurs at approximately 40 hours and 58 minutes after insertion. Finally, transearth injection occurs at approximately 44 hours and 49 minutes after insertion for this reference trajectory. The complete period is considered here. The tracking network consists of 3 USBS stations using the two-way Doppler tracking mode. Tracking times are given on each graph presented. A range rate measurement from one of the stations is obtained at a sampling rate of 1 measurement minute during the period that the spacecraft is not occulted by the moon.

Figures 7 and 8 show the uncertainties in spacecraft position and velocity as a function of time from lunar orbit insertion for the entire 44-hour and 49-minute period. It is seen that measurement bias outweighs the effect of station location uncertainties on the spacecraft 3σ position and velocity uncertainties by factors of 3 to 6 after the initial measurements are processed. The nature

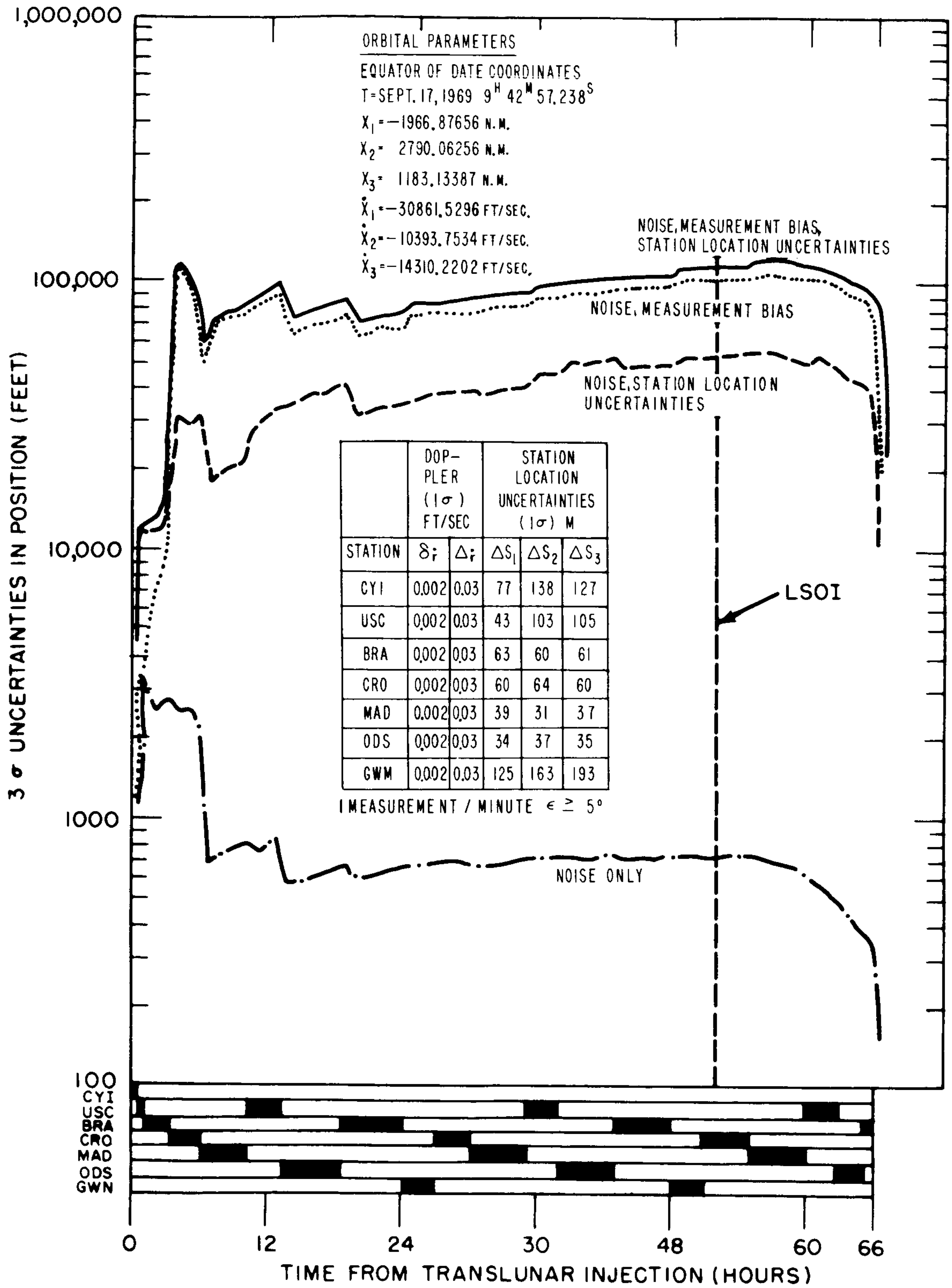
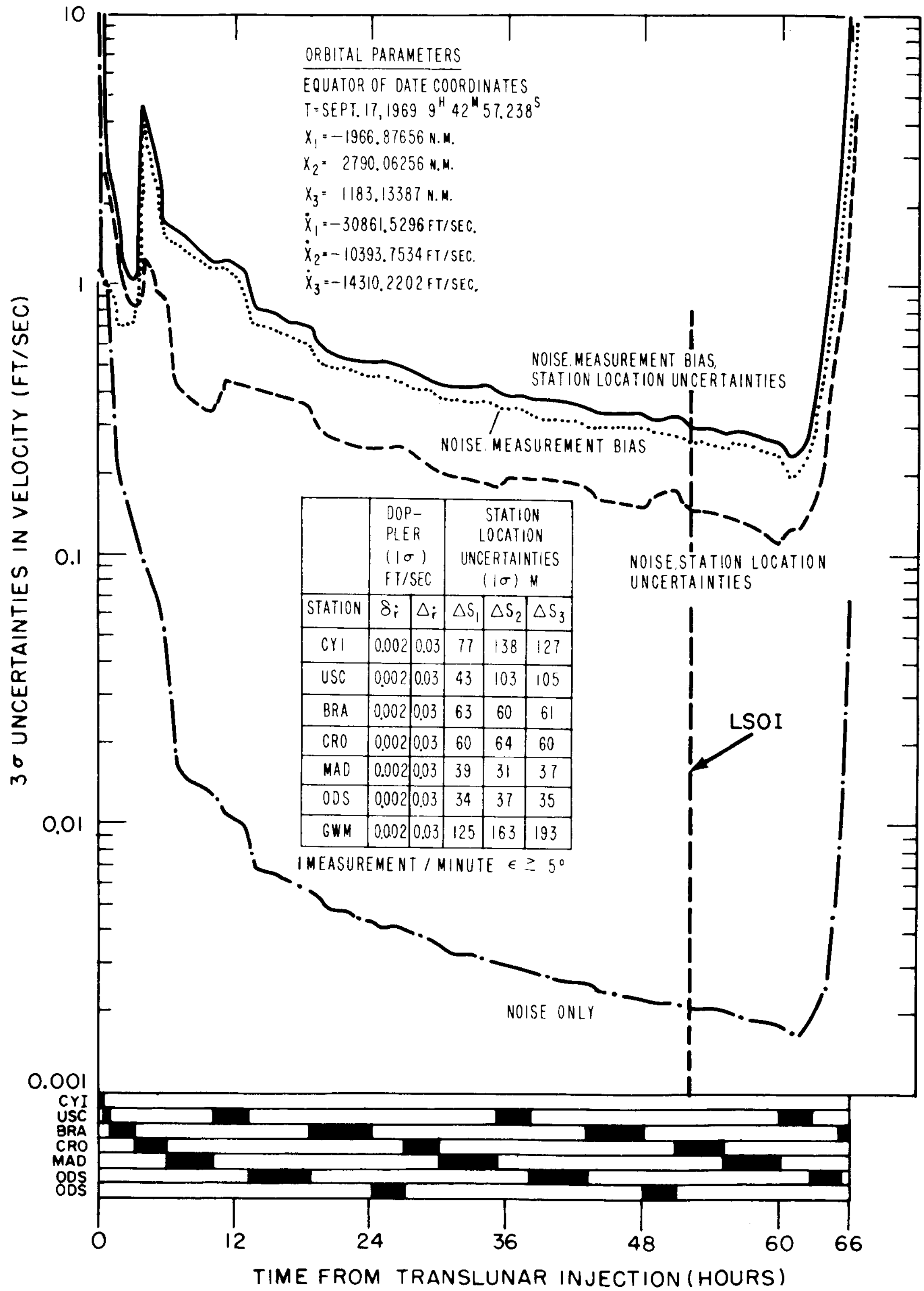


Figure 5–Uncertainties in Position During Translunar Phase



STATION	DOPPLER (1σ) FT/SEC $\delta_{\dot r}$	$\Delta_{\dot r}$	STATION LOCATION UNCERTAINTIES (1σ) M ΔS_1	ΔS_2	ΔS_3
CYI	0.002	0.03	77	138	127
USC	0.002	0.03	43	103	105
BRA	0.002	0.03	63	60	61
CRO	0.002	0.03	60	64	60
MAD	0.002	0.03	39	31	37
ODS	0.002	0.03	34	37	35
GWM	0.002	0.03	125	163	193

Figure 6–Uncertainties in Velocity During Translunar Phase

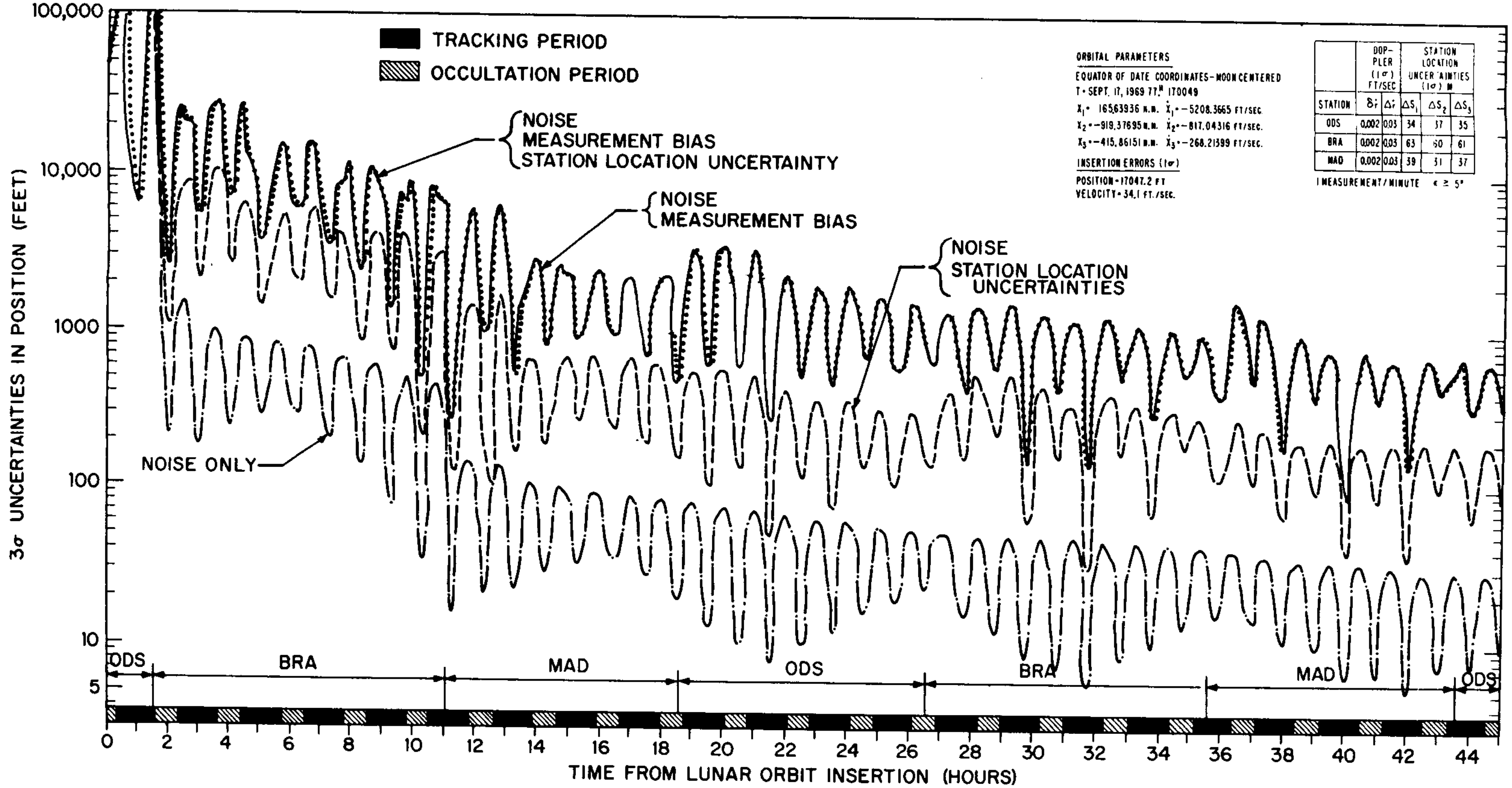


Figure 7—Uncertainties in Position During Lunar Orbit Phase

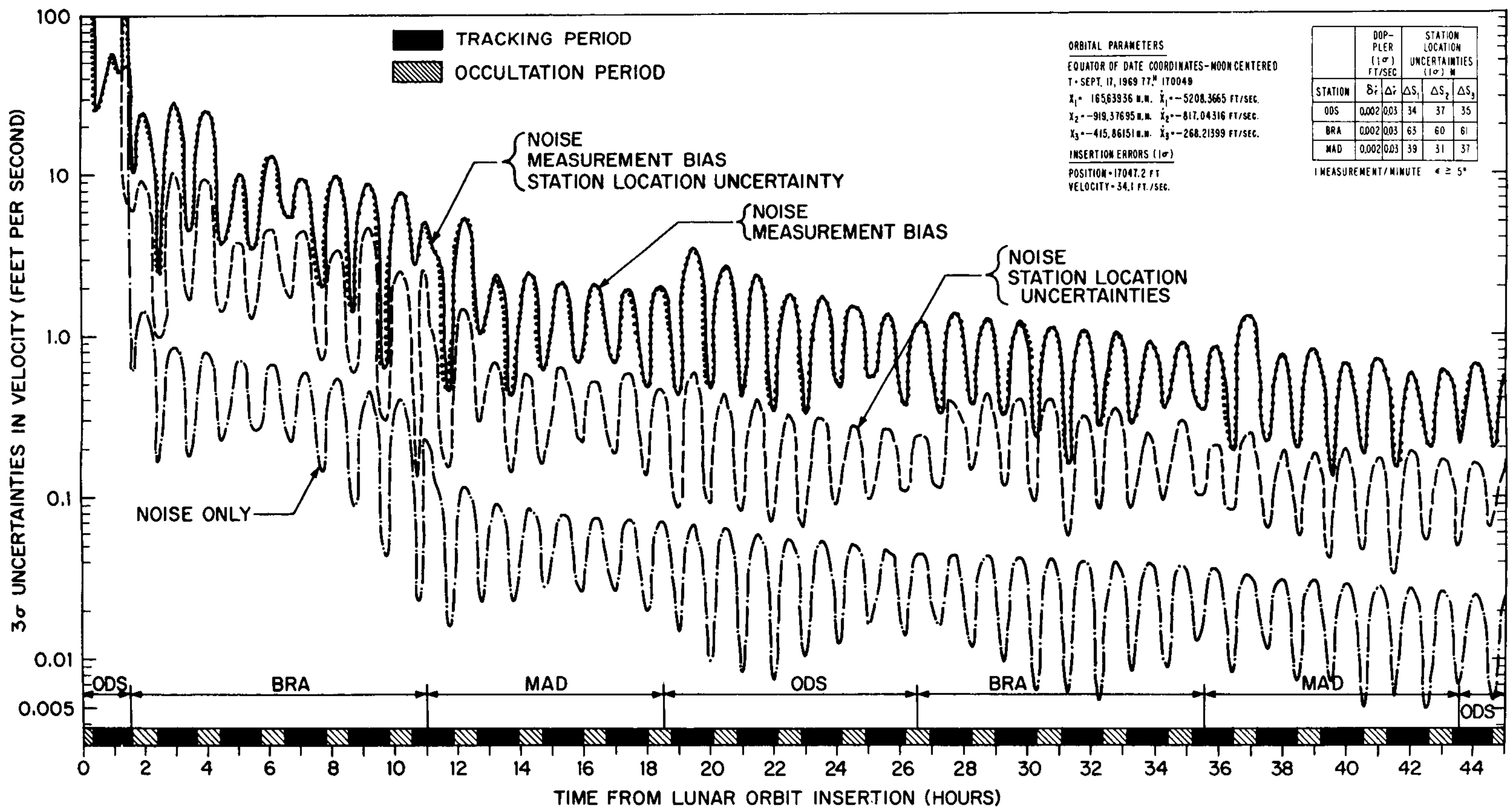


Figure 8—Uncertainties in Velocity During Lunar Orbit Phase

of the curves is due to the fact that the in-plane parameters are estimated well but the out of plane parameters, giving information about the orientation of the spacecraft's orbital plane, are poorly estimated with earth tracking only. It should be pointed out that the equation of motion biases, such as the uncertainties in the gravitational constants for the moon and earth, are very significant on this phase. Thus the magnitudes of the 3σ uncertainties in spacecraft position and velocity will be increased when equation of motion biases are considered.

For tracking during the lunar orbital phase, the measurement bias contributes more than the station location uncertainties to the 3σ uncertainties in spacecraft position and velocity at critical event times at which CSM/LM separation, CSM/LM rendezvous, and transearth injection occur.

TRANSEARTH PHASE

In this phase of the study injection into the transearth trajectory is assumed to occur from the lunar parking orbit on the back side of the moon. The spacecraft is not visible to the earth for the first 20 minutes after termination of the transearth injection burn. The transearth trajectory covers the portion of the Apollo Mission from transearth injection to the point of reentry into the earth's atmosphere (i.e., 400,000 feet). The time period covered is approximately 89 hours. The tracking network assumed in the study consists of 6 USBS stations; range rate measurements are taken from a specified tracking station at a rate of one measurement a minute. Values used for the range rate noise and bias are the same as those given in reference 1; the tracking schedule is similar to that used in reference 2. In this phase a priori information is assumed at injection (see reference 2, chapter 8.0) based upon tracking in the lunar orbit phase.

Figures 9 and 10 show the 3σ uncertainties in spacecraft position and velocity as a function of time from transearth injection. It is seen that station location uncertainties and measurement bias have approximately the same effect on the spacecraft position uncertainty for the first 15 hours after injection. The station location uncertainties and measurement bias also have approximately the same effect on the spacecraft velocity uncertainty at 15 hours after injection. Thereafter, to earth reentry, the measurement bias dominates the station location uncertainties and contributes from 2 to 3 times as much to the 3σ uncertainties in spacecraft position and velocity. Note that the uncertainty in position decreases as the spacecraft distance relative to the earth decreases, while the uncertainties in velocity increase within the earth sphere of influence as the actual velocity on the nominal trajectory increases.

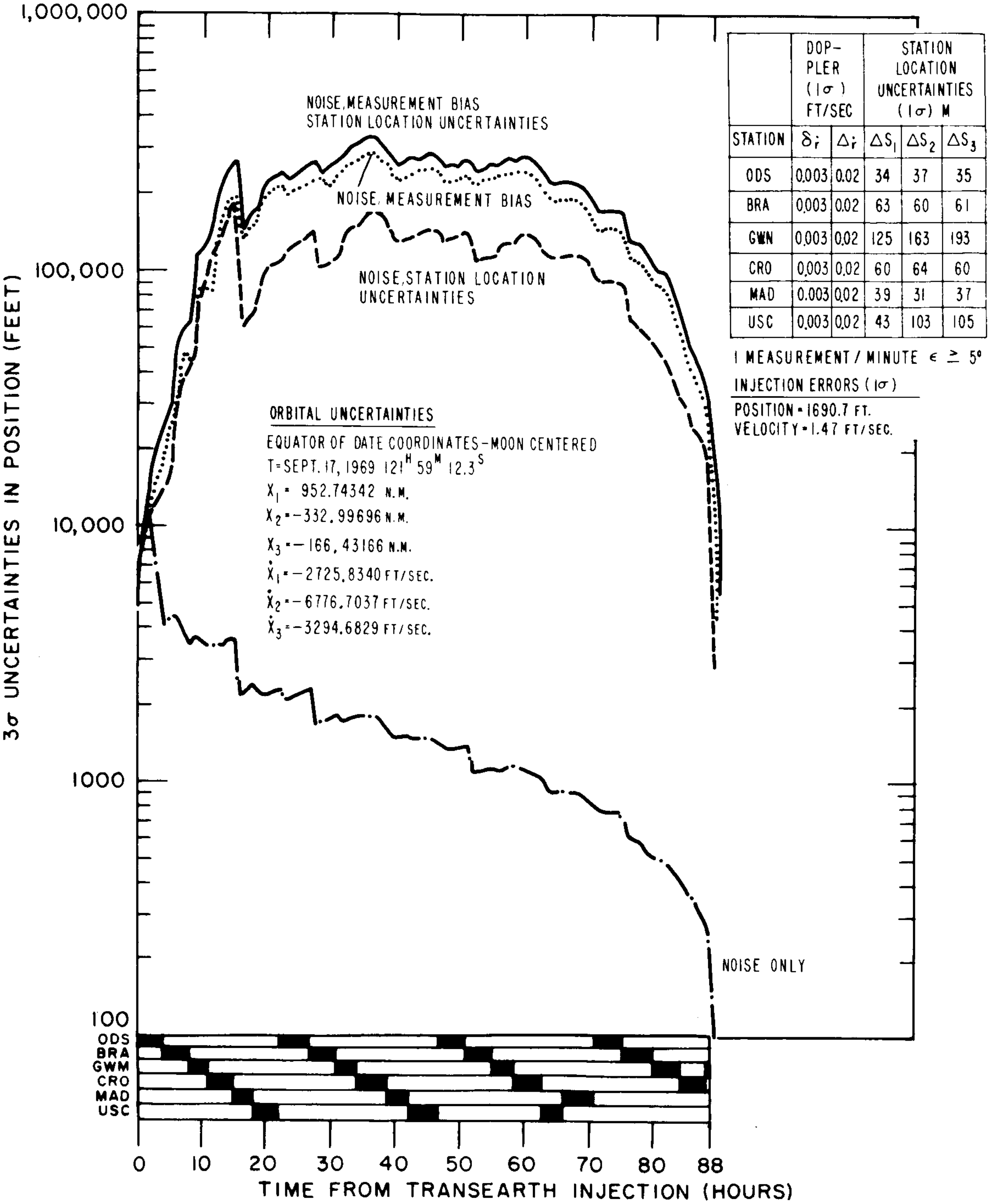
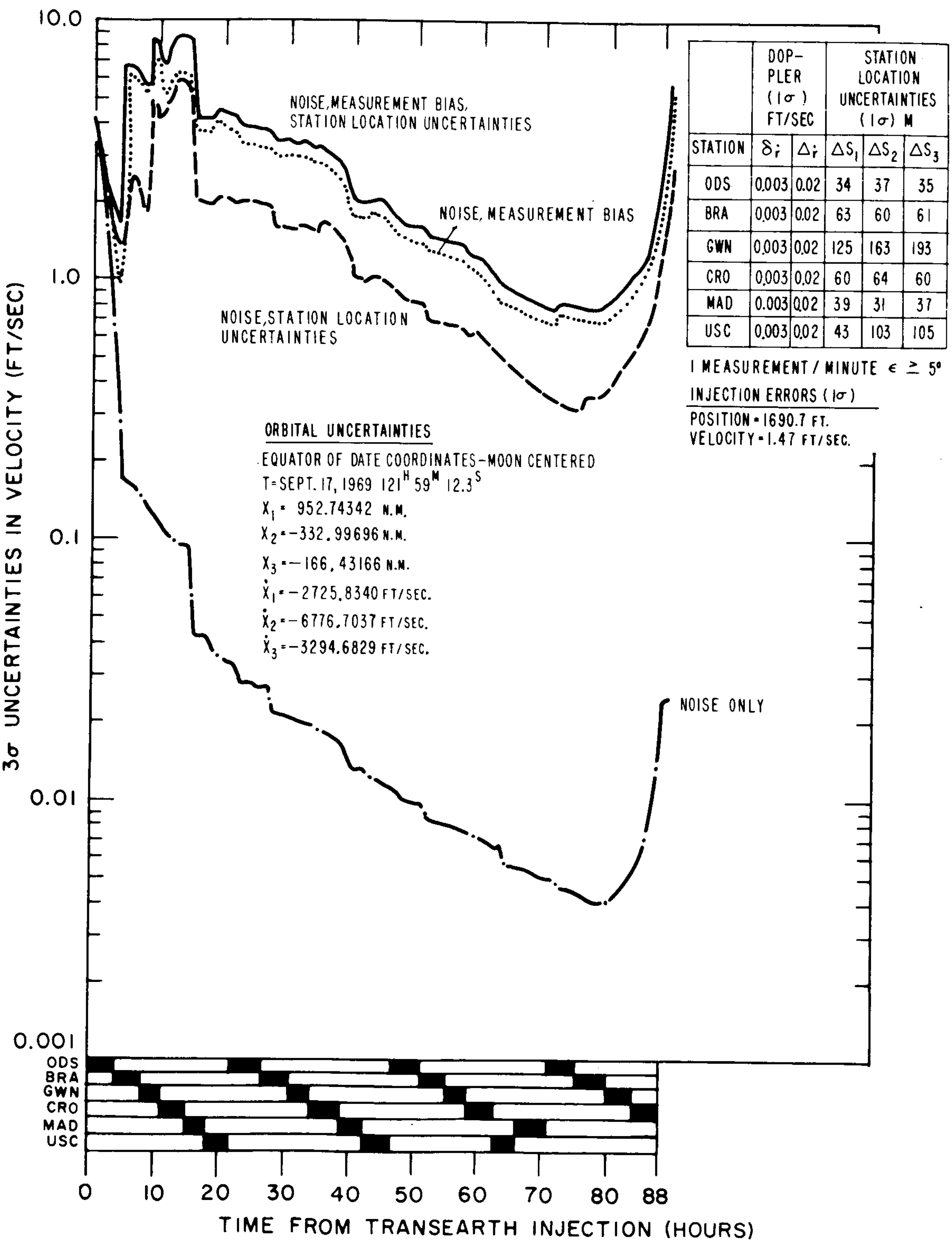


Figure 9—Uncertainties in Position During Transearth Phase



	DOPPLER (1σ) FT/SEC		STATION LOCATION UNCERTAINTIES (1σ) M		
STATION	δ_i	Δ_i	ΔS_1	ΔS_2	ΔS_3
ODS	0.003	0.02	34	37	35
BRA	0.003	0.02	63	60	61
GWN	0.003	0.02	125	163	193
CRO	0.003	0.02	60	64	60
MAD	0.003	0.02	39	31	37
USC	0.003	0.02	43	103	105

Figure 10–Uncertainties in Velocity During Transearth Phase

Thus, for tracking during the transearth phase, the measurement bias most influences the uncertainties in spacecraft position and velocity at earth reentry.

CONCLUSION

For the station switching type of tracking mode considered here, the station location uncertainty influences the 3σ spacecraft position and velocity uncertainty more than does the measurement bias during the earth orbital phase, after the second station has tracked. The measurement bias dominates the station location uncertainties during the early phase of the earth orbit, during the entire CM lunar parking orbit phase, and during the translunar and transearth orbits after about 5 and 15 hours respectively. Thus the station location uncertainties are the dominating error source up to the time of translunar injection; the measurement bias has more effect at the time of CSM/LM lunar orbit insertion, CSM/LM separation, CSM/LM rendezvous, transearth injection, and earth reentry.

ACKNOWLEDGMENTS

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