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TDRSS Navigation Accuracy in Support of IUS Deployment Phase 1

Mission Planning and Analysis Division

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National Aeronautics and Space Administration

Lyndon B. Johnson Space Center
Houston, Texas

SHUTTLE PROGRAM

NAVIGATION FOR IUS DEPLOYMENT

TDRSS NAVIGATION ACCURACY IN SUPPORT OF IUS DEPLOYMENT PHASE 1

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NAVIGATION FOR IUS DEPLOYMENT

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SUMMARY AND INTRODUCTION

The first phase of a study has been completed to determine the navigation accuracy for tracking the Orbiter prior to interim upper stage (IUS) deployment using the tracking data relay satellite system (TDRSS). The study was performed to examine the Orbiter navigation accuracy for both one and two TDRSS satellites, for short and long data arcs, and for Doppler-only and Doppler-plus range solutions. All test cases were run with the Orbiter in a 150-n. mi. circular orbit, 28.5 degree inclination, at the time interval from the completion of the orbital maneuvering system (OMS)-2 maneuver to OMS-2 plus 2 hours (approximate time for IUS deployment). The data used were simulated by the simulation navigation (SIMNAV) program (ref. 1). The software tool used to process the TDRS data was the Shuttle Navigation Analysis Program (SNAP) (ref.1), a Kalman filter tool used to solve for the Orbiter position and velocity. Results of the study were used in a presentation to NASA Headquarters to summarize the expected navigation accuracy using the TDRS system. The study is now being continued to analyze in more detail the effects of length of data arc, type of data, and number of TDRS satellites and to examine the effects of vehicle venting, measurement noise, and TDRS ephemeris errors on navigation solutions in support of IUS deployment.

Conclusions drawn from the first phase of the TDRS navigation study are as follows.

a. Data from both TDRS satellites were essential for accurate navigation results.

b. Range data were essential for the short arc test case (Δt = 8 min) but were not needed for the long arc test case (Δt = 55 min).

c. With Doppler and range data from both TDRS satellites, the results converged to a reasonable solution after 5 to 10 minutes of data.

Further analysis in these three areas and in the effects of vehicle venting, measurement noise, and TDRS ephemeris errors is now in progress.

DESCRIPTION OF TEST CASES

Test cases were defined to determine the effects on navigation accuracy by the following:

a. Number of TDRS satellites

b. Doppler only versus Doppler plus range solutions

c. Length of tracking arc

Table I summarizes the eight test cases that were run. Four of the cases (1A to 4A) used both Doppler and range data as input; the other four cases (1B to 4B) processed only Doppler data. Cases 1A and 1B are the long data arc cases with data from both satellites. Cases 2A and 2B are the long arc, one TDRS cases. Cases 3A and 3B are the short arc cases. Cases 4A and 4B are the same as 1A and 1B, except that the position of the tracking arc is shifted to allow data from both TDRS satellites to be available early in the tracking arc.

The basic orbit used for the test cases was from the Department of Defense (DOD) geosynchronous mission, which is one of the six basic reference missions being used in IUS studies (ref. 2). The data tracking arcs were positioned between the end of the OMS-2 burn and OMS-2 plus 2 hours, which is the approximate time of the reference mission for IUS deployment. In this time frame for the DOD mission, the Orbiter is in a 150-nautical-mile orbit, 28.5-degree inclination. The two TDRS satellites are positioned at longitudes of 189 E and 319 E, which are the baseline positions now being assumed for all studies involving TDRS.

Table II summarizes the inputs for the eight test cases. Parts A through E contain the inputs common to all runs. Part F includes the parameters that varied among the eight runs.

DESCRIPTION OF ERROR MODEL

Errors applied in the study included bias and noise to the Doppler and range data, TDRS ephemeris errors, and a continuous 0.5-pound vent along the vehicle's velocity vector. Table IIb summarizes the actual values used.

FILTER WEIGHTING INPUTS

Weighting factors for SNAP program input were set to inform the filter of the known perturbations being applied in the simulation of the input data. These weighting factors include the program's uncertainty for data noise and bias, and a state noise constant (SNC) modeled into the program to allow for Orbital perturbations known to exist but not modeled into the program (such as drag perturbations, venting, etc.). The SNC value was set to allow for the propagation error due to the venting. (A 0.5 pound vent contributes to a 0.5 nautical mile downtrack propagation error after one revolution.) The filter uncertainties for Doppler noise and bias and for range noise were set to the values of the noise and bias being applied to the data. The filter uncertainty for range bias was set to allow for the range bias that was applied to the data and for the bias that was introduced by the radial position error simulated for the two TDRS satellites. The filter weighting values are summarized in table IIc.

RESULTS AND CONCLUSIONS

In this study the procedure for evaluating the navigation accuracy for each run was to set the filter weights (estimates of measurement noise and bias and the state noise constant) to account for the known errors in the data (measurement noise and bias, TDRS ephemeris errors, vehicle venting) and examine the filter output of its uncertainty in Orbiter position and velocity in the local-vertical (radial, downtrack, crosstrack) coordinate system.

Tables III and IV contain tabulations of the filter uncertainty for each component of Orbiter position and velocity for critical times in each of the eight test cases. Figures 1(a) through 8(b) show time history plots of these values for the eight runs. Tables V through VII provide interesting comparisons which have led to the following conclusions.

a. Data from both TDRS satellites were essential for accurate navigation results.

b. Range data were essential for the short arc test case (Δt = 8 min) but were not needed for the long arc test case (Δt = 55 min).

c. Short arc solutions were acceptable only when processing Doppler and range data from both TDRS satellites.

Another interesting comparison is between the results for the best geometry case (case 1A), with two TDRS satellites and Doppler and range data, against the currently documented TDRS navigation accuracy numbers obtained from reference 3. This comparison is shown in table VIII as a point of interest. Note that the in-plane results from case 1A are not as accurate as the currently documented numbers and that the out-of-plane results are an improvement to the prior results. However, case 1A results are based on simulated data and derived from an error model which is being further analyzed and should therefore be regarded as preliminary. The future results will be documented in a report to be published.

Further work is necessary prior to determining the final navigation accuracy numbers in support of IUS initialization. Test cases with orbital inclinations of 37.4 degree and 57 degree will be analyzed. Monte Carlo studies will be performed using simulated data and different error models. Finally, a review of real data results from the Apollo/Soyuz Mission will be made in an attempt to evaluate the error model being used for the simulated data results.

REFERENCES

1. Estep, Bess: Shuttle Navigation Analysis Program (SNAP). LEC Report 8868, User's Guide, June 1976.

2. Interim Upper Stage (IUS) Flight Operations/Mission Analysis: Systems Engineering Group. Boeing document no. D290-10007-1, June 6, 1977.

3. Wylie, Alan D.: Orbiter Navigation Accuracies for Initialization/Deployment of IUS. JSC Memorandum 77-FM84-173, May 3, 1977.

TABLE I.- DESCRIPTION OF TEST CASES

Case number	Type of data	Number of TDRS satellites	Length of tracking arc, min	Length of propagation interval, min
1A[a]	Doppler + range	2	55	60
2A	Doppler + range	1	49	60
3A	Doppler + range	2	7.7	60
4A[b]	Doppler + range	2	67	0
1B[a]	Doppler only	2	55	60
2B	Doppler only	1	49	60
3B	Doppler only	2	7.7	60
4B[b]	Doppler only	2	67	0

[a]Second TDRS not available until 40 min elapsed in tracking arc.

[b]Both TDRS's available within first 4 min of tracking arc.

TABLE II.- PROGRAM INPUTS

a. State vectors, RNP matrix, Greenwich hour angle

(1) Time tag for Orbiter and TDRS state vectors

G.m.t. - March 30, 1982 13 hr 44 min 45.574 sec

Get - 0 hr 44 min 45.574 sec

(2) Orbiter state vector (m and m/sec)

X	-1242.291264D + 03	$\dot{X}$	-7278.74653
Y	5838.248874D + 03	$\dot{Y}$	-2246.207141
Z	-2945.056326D + 03	$\dot{Z}$	-1382.356544

(3) TDRS state vector - longitude = 189° (m and m/sec)

X	-31134159.96	$\dot{X}$	2073.412485
Y	-28433920.33	$\dot{Y}$	-2270.336867
Z	95830.30872	$\dot{Z}$	-6.4870

(4) TDRS state vector - longitude = 319° (m and m/sec)

X	41794192.34	$\dot{X}$	406.40685
Y	-5573291.5	$\dot{Y}$	3047.67829
Z	-129746.227	$\dot{Z}$	-1.18327

(5) RNP matrix

-.993267275	-.115804370	.00307723788
.115803735	-.993272041	-.000384193237
.00310102560	-.0000252508913	.999995191

(6) Greenwich hour angle - 187.0588°

TABLE II.- Continued

b. Errors modeled into study

(1) TDRS ephemeris errors

Position:	radial	15 m[a]
	downtrack	66 m[b]
	crosstrack	61 m
Velocity:	radial	.005 m/sec[b]
	downtrack	.0005 m/sec
	crosstrack	0

(2) Measurement errors

Doppler noise	.004 Hz
Doppler bias	0
Range noise	3 m
Range bias	3 m

(3) Orbiter venting

Magnitude 0.5 pounds continuous along vehicle velocity vector

Orbiter cross-sectional area perpendicular to velocity vector 249.909 m^2

Orbiter mass 94345.30787 kg

c. Filter weights

(1)	Variance for Doppler bias	0
(2)	Variance for Doppler noise	0.16D-4 HZ^2
(3)	Variance for range bias	909 m^2
(4)	Variance for range noise	9 m^2
(5)	State noise constant	1.603D-06 m^2/sec^3
(6)	All time constants	400 sec

[a]The Earth's gravitational constant, μ_E, was changed accordingly in computing the gravitational effects on the TDRS satellites.

[b]Error introduced into the two TDRS satellites by changing the time tag of the reference state vectors by 0.021 sec.

(7) Weighting factor control nonlinearities in the measurement incorporation equations — 1.2

(8) Minimum elevation above Earth horizon for processing TDRS measurements — 0.2° (79.5 n. mi.)

d. Initial errors in Orbiter state vector

(1) Position:

	radial	4571.65 m (15 000 ft)
	downtrack	14 635.57 m (48 000 ft)
	crosstrack	3354.10 m (11 000 ft)

(2) Velocity:

	radial	16.16 m/sec (53 ft/sec)
	downtrack	3.96 m/sec (13 ft/sec)
	crosstrack	3.35 m/sec (11 ft/sec)

e. Initial filter state covariance matrix

(1) Position:

	radial	3×10^4 m
	downtrack	3×10^4 m
	crosstrack	3×10^4 m

(2) Velocity:

	radial	31.6 m/sec
	downtrack	31.6 m/sec
	crosstrack	31.6 m/sec

f. Start and stop times

(1)

Filter processing	Cases 1A, 1B	Cases 2A, 2B	Cases 3A, 3B	Cases 4A, 4B
Start	13:44:45.574	13:44:45.574	13:44:45.574	13:44:45.574
Stop	15:44:45.574	15:44:45.574	15:44:45.574	15:44:45.574
Delta, min	120	120	120	120

TABLE II.- Concluded

(2)

Data interval	Cases 1A, 1B	Cases 2A, 2B	Cases 3A, 3B	Cases 4A, 4B
Start	13:49:52.7	14:10:50	14:36:48	14:36:48
Stop	14:44:45.574	14:44:45.574	14:44.45.574	15:44:45.574
Delta, min	55	34	7.7	67.7

(3)

Orbiter venting interval	Cases 1A, 1B	Cases 2A, 2B	Cases 3A, 3B	Cases 4A, 4B
Start	13:44:45.574	13:44:45.574	13:44:45.574	13:44:45.574
Stop	15:44:45.574	15:44:45.574	15:44:45.574	15:44:45.574
Delta, min	120	120	120	120

TABLE III.- TABULATION OF FILTER COVARIANCE OUTPUT

AT TIMES OF INTEREST; INPUT DATA - DOPPLER AND RANGE

Time, sec	Comment	σ_u, ft	σ_v, ft	σ_w, ft	$\sigma_{\dot{u}}$, fps	$\sigma_{\dot{v}}$, fps	$\sigma_{\dot{w}}$, fps
Run 1a - Two TDRS satellites; best geometry							
52025	Prior to acquisition of second TDRS	286	2976	16 074	3.3	0.14	13.47
52055	After acquisition of second TDRS	90	63	271	0.16	0.08	0.17
53085	End of data arc	66	57	104	0.09	0.09	0.15
56685	End of propagation	648	1866	186	2.07	0.55	0.23
Run 2a - One TDRS satellite only; poor geometry							
52815	End of data arc	377	1449	8 968	1.45	0.20	3.01
56685	End of propagation	729	5750	832	6.28	0.68	10.83
Run 3a - Two TDRS satellites; short data arc							
53085	End of data	97	107	238	0.54	0.49	0.81
56685	End of propagation	1591	4949	662	5.22	1.39	0.44
Run 4a - Two TDRS satellites; data available from both satellites early in tracking arc							
52815	TDRS 1 LOS (after 3 min of data)	168	95	305	1.9	0.75	2.2
54965	TDRS 2 LOS	220	86	264	0.37	0.07	0.19
55615	TDRS 1 AOS	430	403	174	0.79	0.32	0.26
56685	End of tracking arc	75	125	172	0.10	0.13	0.20

TABLE IV.- TABULATION OF FILTER COVARIANCE OUTPUT

AT TIMES OF INTEREST; INPUT DATA - DOPPLER ONLY

Time, sec	Comment	σ_u, ft	σ_v, ft	σ_w, ft	$\sigma_{\dot{u}}$, fps	$\sigma_{\dot{v}}$, fps	$\sigma_{\dot{w}}$, fps
Run 1b - Two TDRS satellites; best geometry							
52025	Prior to TDRS 2 AOS	464	5 612	34 965	5.69	0.18	21.93
52055	After TDRS 2 AOS	477	1 138	7 995	0.98	0.19	3.30
53085	End of data	102	84	168	0.12	0.11	0.24
56685	End of propagation	650	1 936	200	2.15	0.55	0.32
Run 2b - One TDRS satellite; poor geometry							
52615	End of data	2 086	18 064	93 153	20.85	1.06	19.91
56685	End of propagation	2 962	37 401	2 666	42.87	1.98	110.25
Run 3b - Two TDRS satellites; short data arc							
53085	End of data	1 972	1 743	5 440	2.36	2.41	3.24
56685	End of propagation	11 332	58 234	4 907	61.83	8.53	4.17
Run 4b - Two TDRS satellites; data available from both satellites early in tracking arc							
52815	TDRS 1 LOS (after 3 min of data)	4 741	2 432	13 094	8.90	3.42	11.54
54965	TDRS 2 LOS	294	413	946	0.72	0.15	0.55
55615	TDRS 1 AOS	109	355	867	0.35	0.06	0.47
56685	End of tracking arc	117	129	198	0.13	0.14	0.29

TABLE V.- TWO TDRS VERSUS ONE TDRS SOLUTIONS

(LONG TRACKING ARC)

Component	Doppler plus range		Doppler only	
	Two TDRS results	One TDRS results	Two TDRS results	One TDRS results
σ_u, ft	648	729	650	2962
σ_v, ft	1866	5750	1936	37 401
σ_w, ft	186	[a]832	200	2666
$\sigma_{\dot{u}}$, fps	2.07	6.28	2.15	42.87
$\sigma_{\dot{v}}$, fps	0.55	0.68	0.55	1.98
$\sigma_{\dot{w}}$, fps	0.23	10.83	0.32	110.25

[a]Not stable.

Conclusions:

(1) For Doppler plus range data, two TDRS's are necessary to get good plane estimate.

(2) For Doppler only, two TDRS's are necessary for both in-plane and out-of-plane estimates.

TABLE VI.- DOPPLER PLUS RANGE VERSUS DOPPLER ONLY (TWO TDRS'S) SOLUTIONS

Component	Long tracking arc (Δt = 55 min)		Short tracking arc (Δt = 8 min)	
	Doppler only	Doppler plus range	Doppler only	Doppler plus range
σ_u, ft	650	648	11 332	1591
σ_v, ft	1936	1866	58 234	4949
σ_w, ft	200	186	4907	662
$\sigma_{\dot{u}}$, fps	2.15	2.07	61.83	5.22
$\sigma_{\dot{v}}$, fps	0.55	0.55	8.53	1.39
$\sigma_{\dot{w}}$, fps	0.32	0.23	4.17	0.44

Conclusions:

(1) Doppler only sufficient for the long tracking arc.

(2) Range data essential for the short tracking arc.

TABLE VII.- LONG ARC VERSUS SHORT ARC SOLUTIONS (TWO TDRS'S)

Component	Doppler plus range		Doppler only	
	Long arc results, (Δt = 55 min)	Short arc results, (Δt = 8 min)	Long arc results, (Δt = 55 min)	Short arc results (Δt = 8 min)
σ_u, ft	648	1591	650	11 332
σ_v, ft	1866	4949	1936	58 234
σ_w, ft	186	662	200	4907
$\sigma_{\dot{u}}$, fps	2.07	5.22	2.15	61.83
$\sigma_{\dot{v}}$, fps	0.55	1.39	0.55	8.53
$\sigma_{\dot{w}}$, fps	0.23	0.44	0.32	4.17

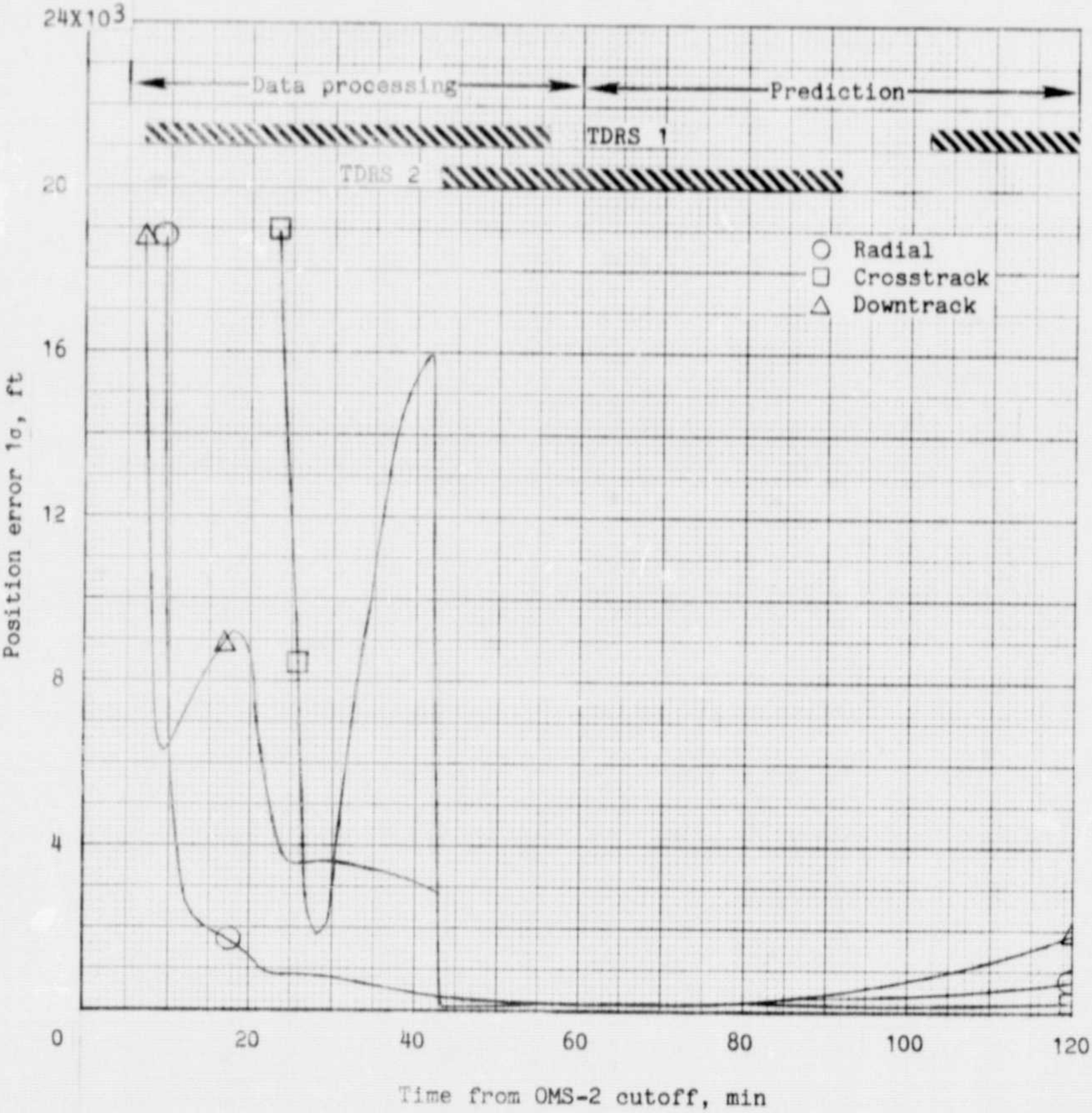
Concluding remark:

Short arc solution sufficient only when processing Doppler plus range from two TDRSS satellites.

TABLE VIII.- CASE 1A RESULTS VERSUS

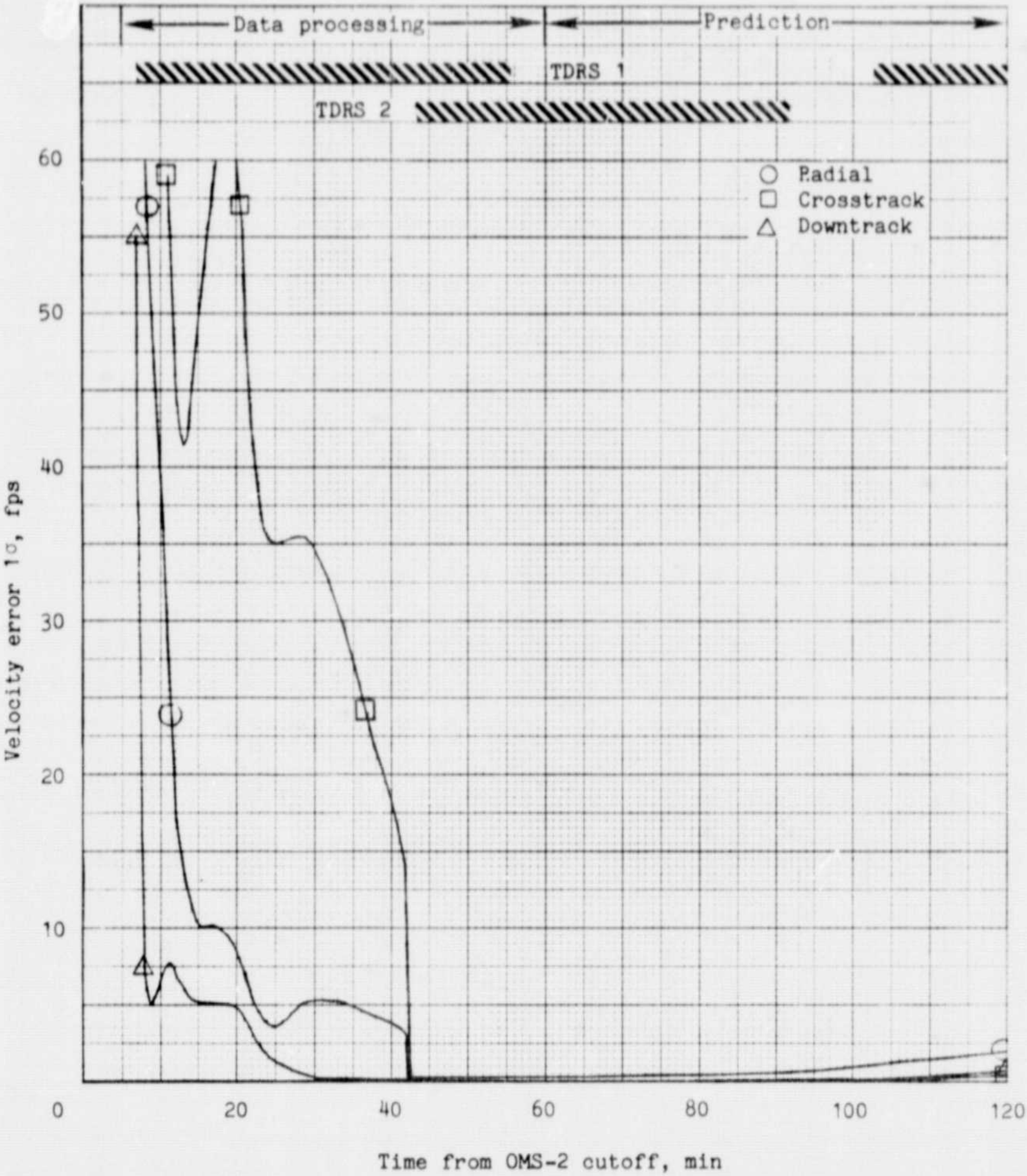
CURRENT OFFICIAL TDRS NAVIGATION ACCURACIES (3σ)

Component	Current TDRS accuracy numbers	Case 1A results
u, ft	1000	1950
v, ft	3000	5600
w, ft	3000	560
$\dot{u}$, fps	3.0	6.0
$\dot{v}$, fps	1.0	1.6
$\dot{w}$, fps	3.0	.7



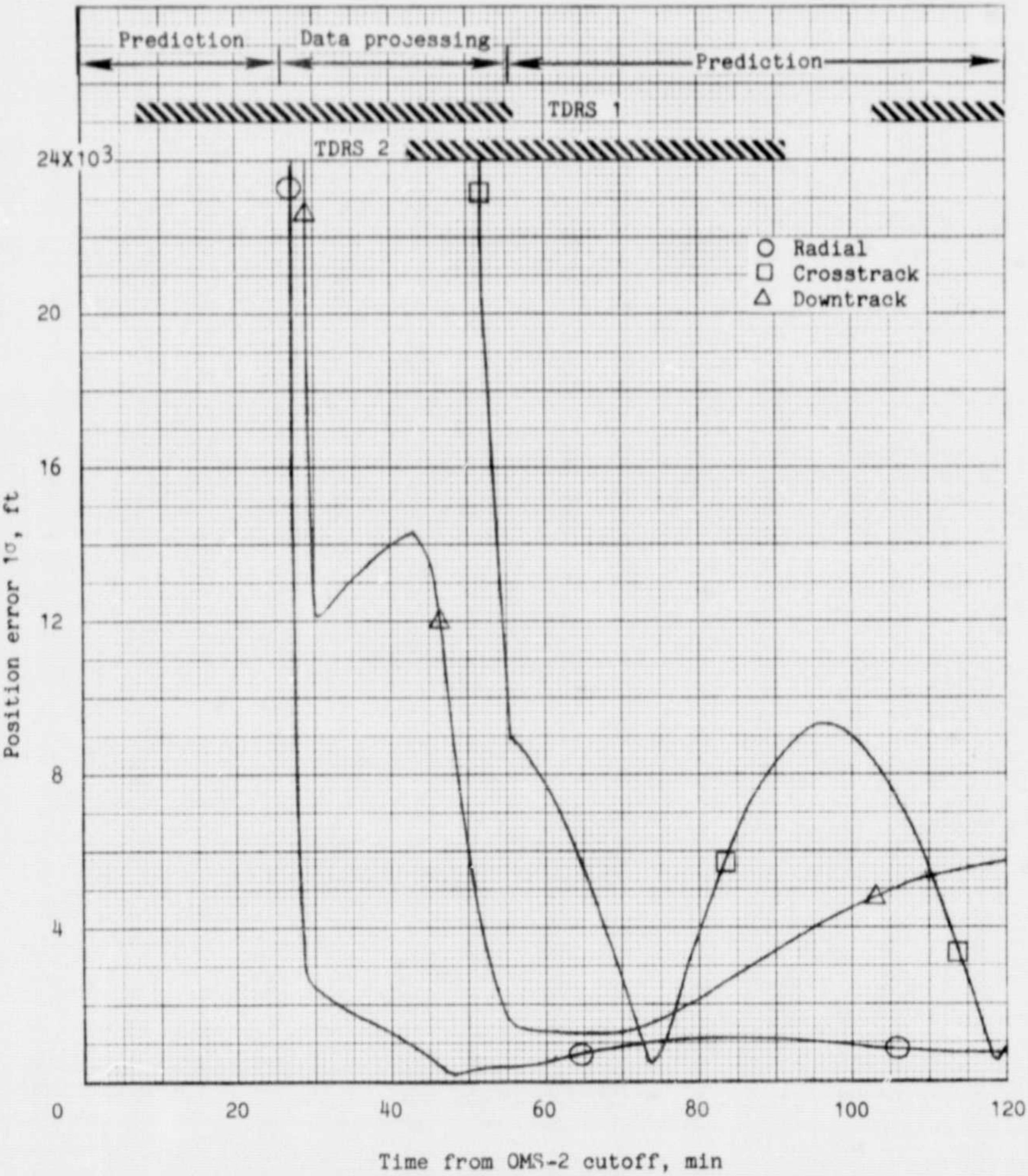
(a) Position.

Figure 1.- Navigation accuracy with TDRS, case 1A.



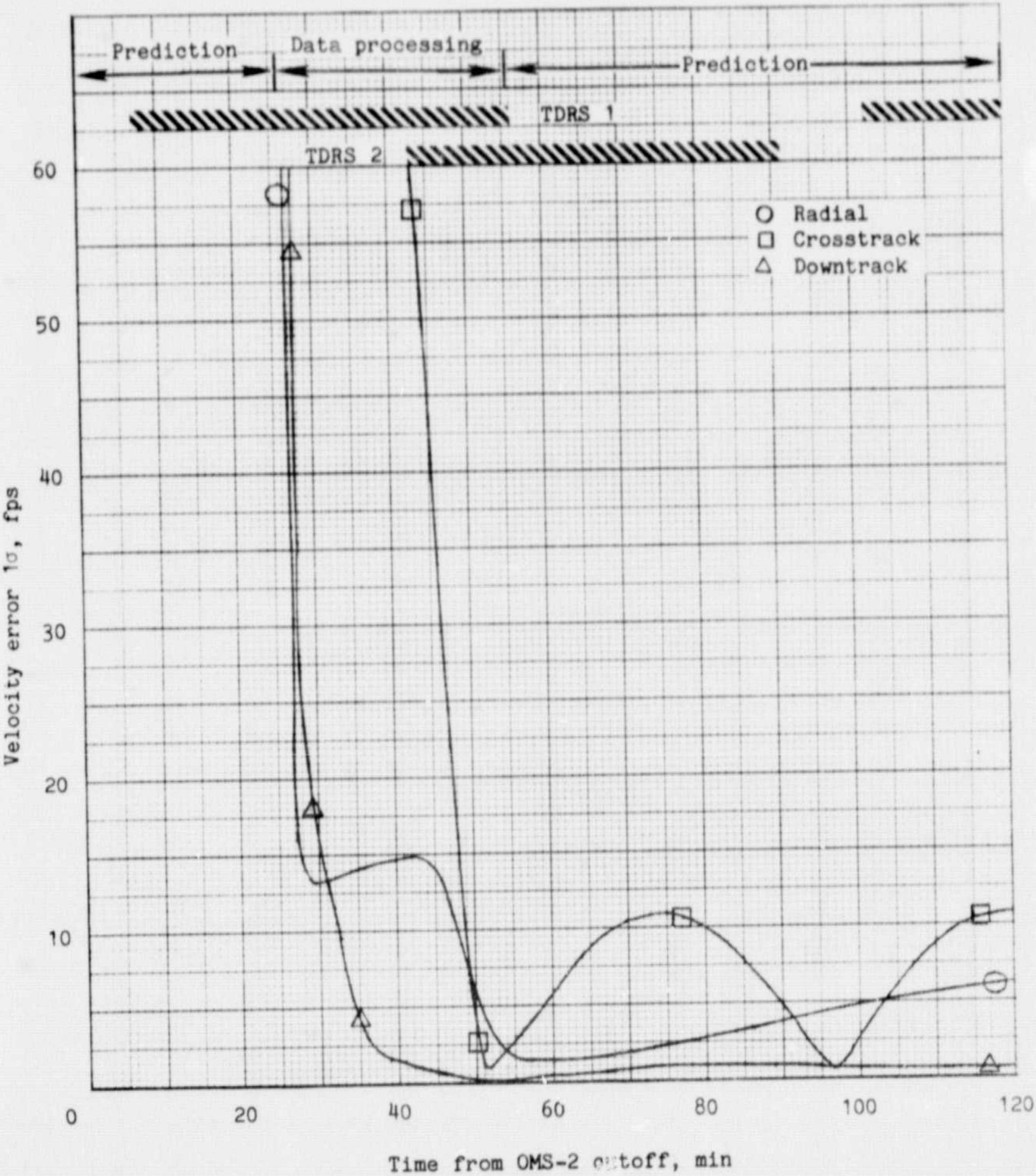
(b) Velocity.

Figure 1.- Concluded.



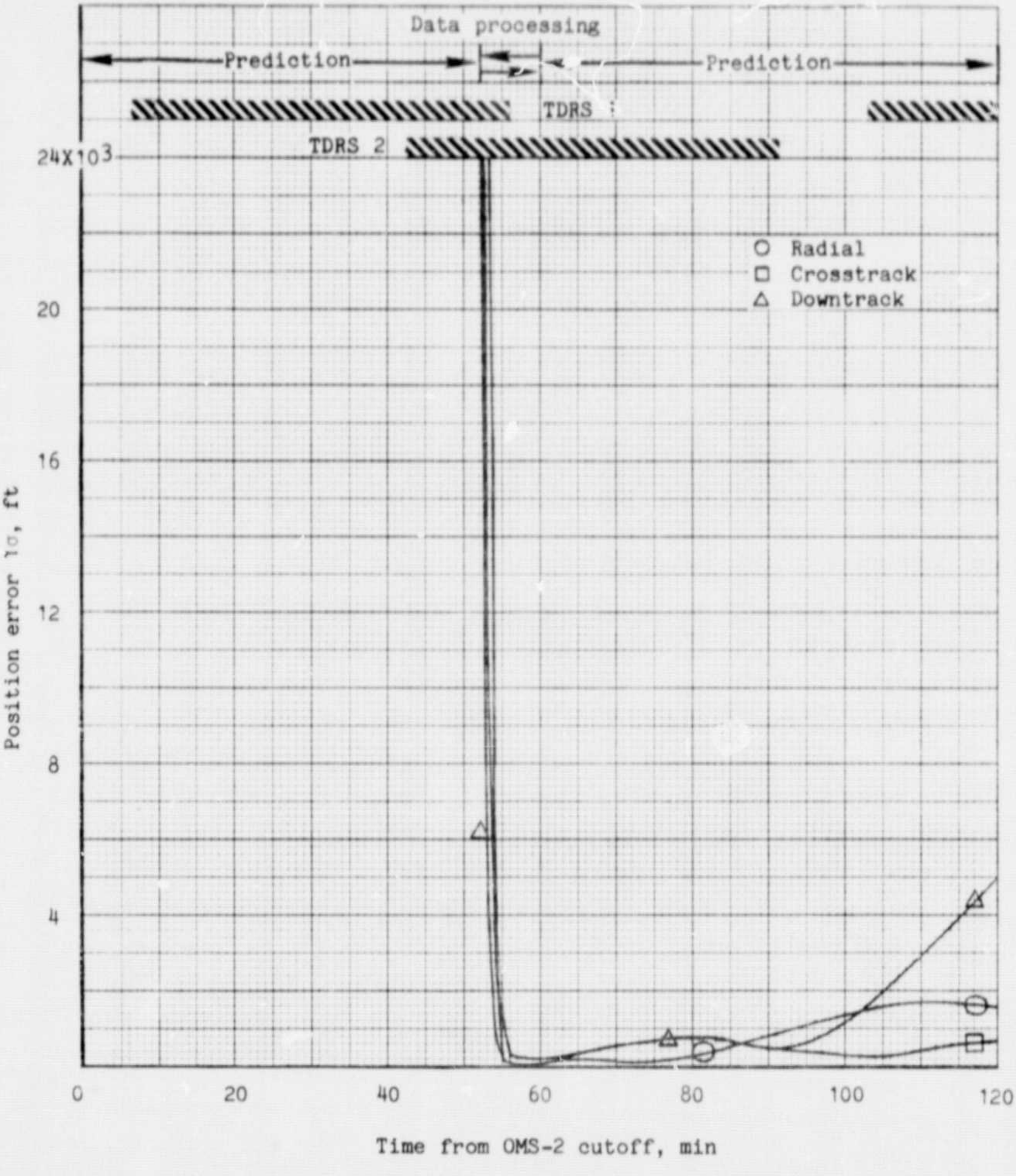
(a) Position.

Figure 2.- Navigation accuracy with TDRS, case 2A.



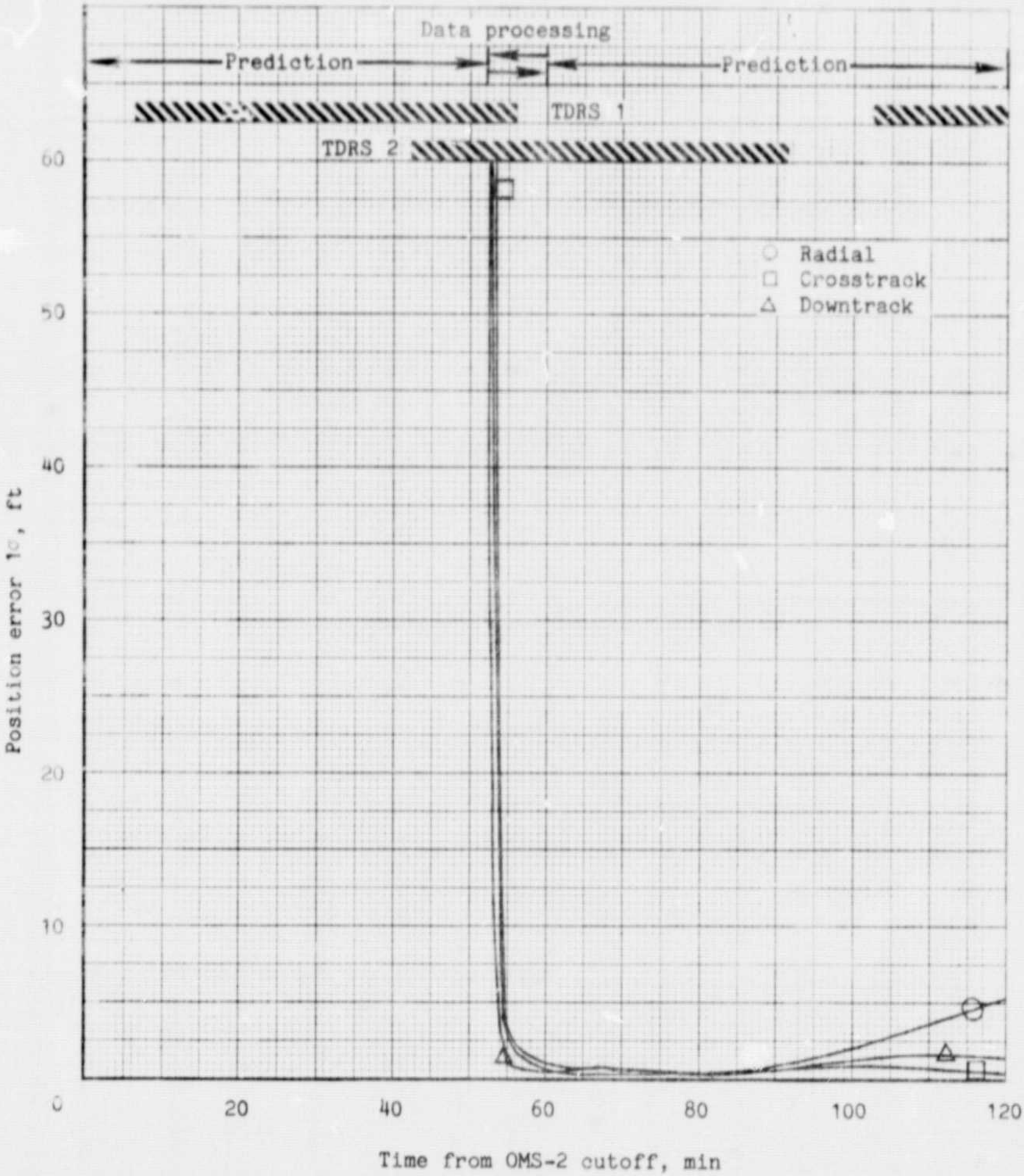
(b) Velocity.

Figure 2.- Concluded.



(a) Position.

Figure 3.- Navigation accuracy with TDRS, case 3A.



(b) Velocity.

Figure 3.- Concluded.

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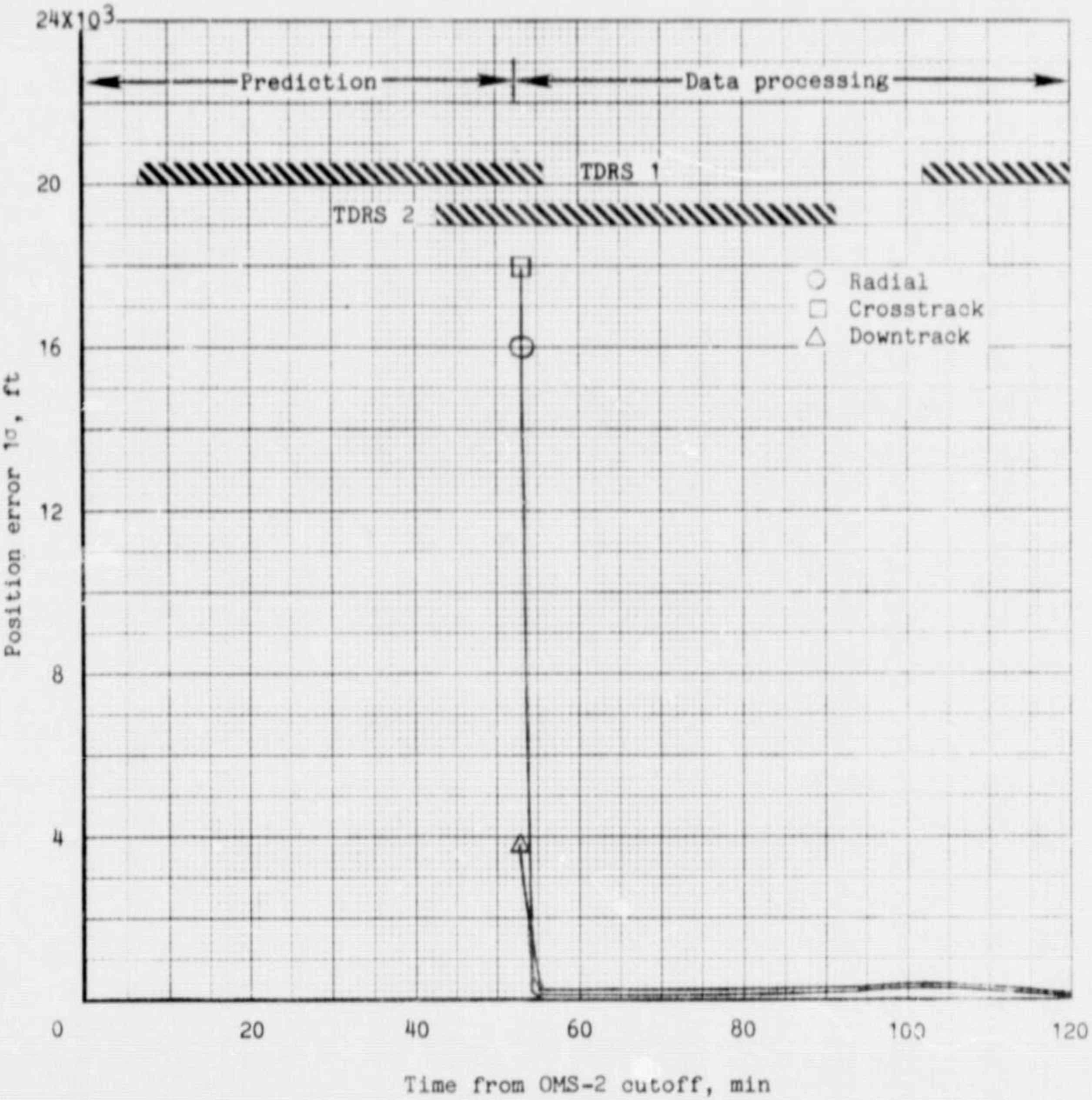
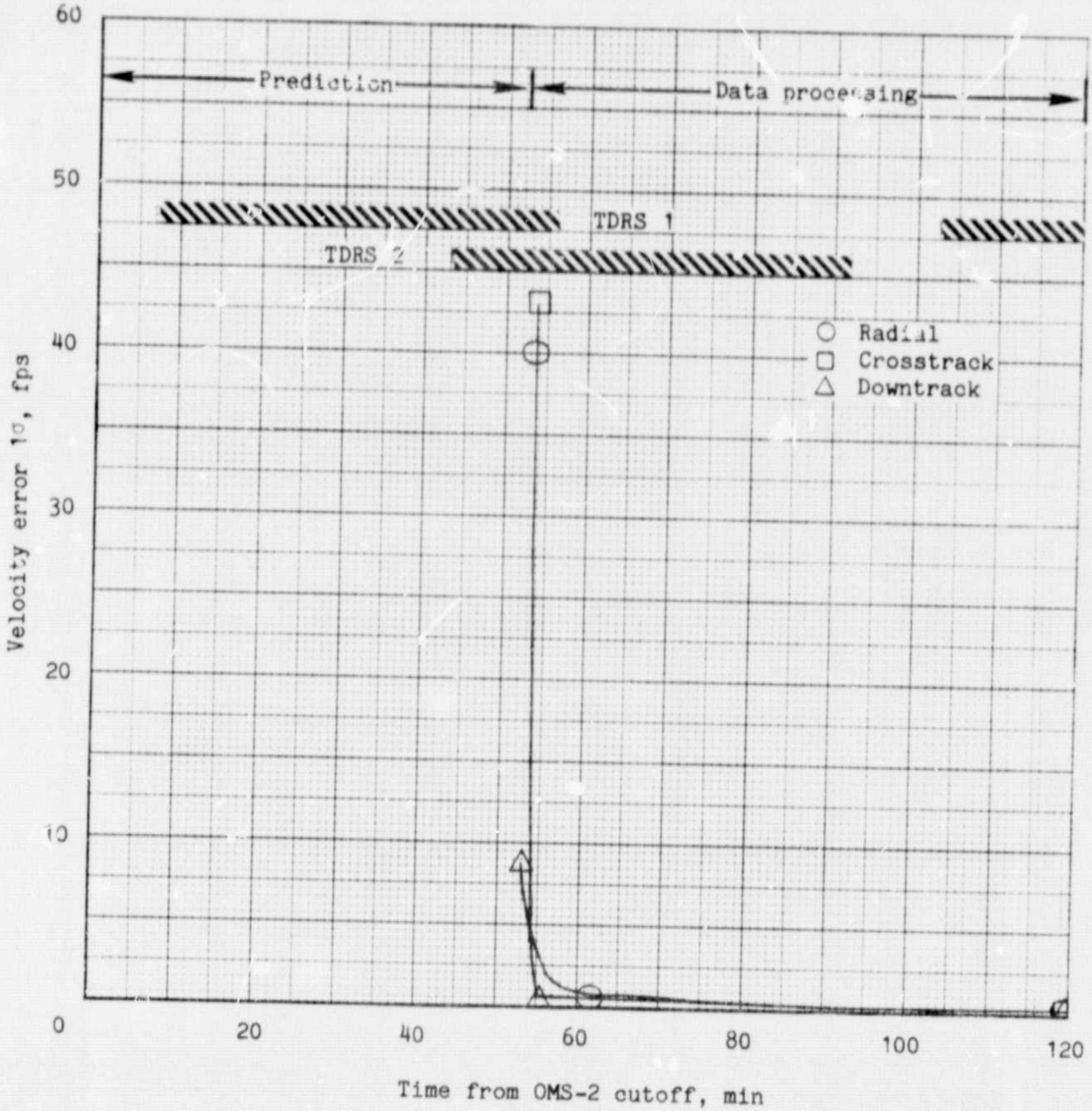


(a) Position.

Figure 4.- Navigation accuracy with TDRS, case 4A.



(b) Velocity.

Figure 4.- Concluded.

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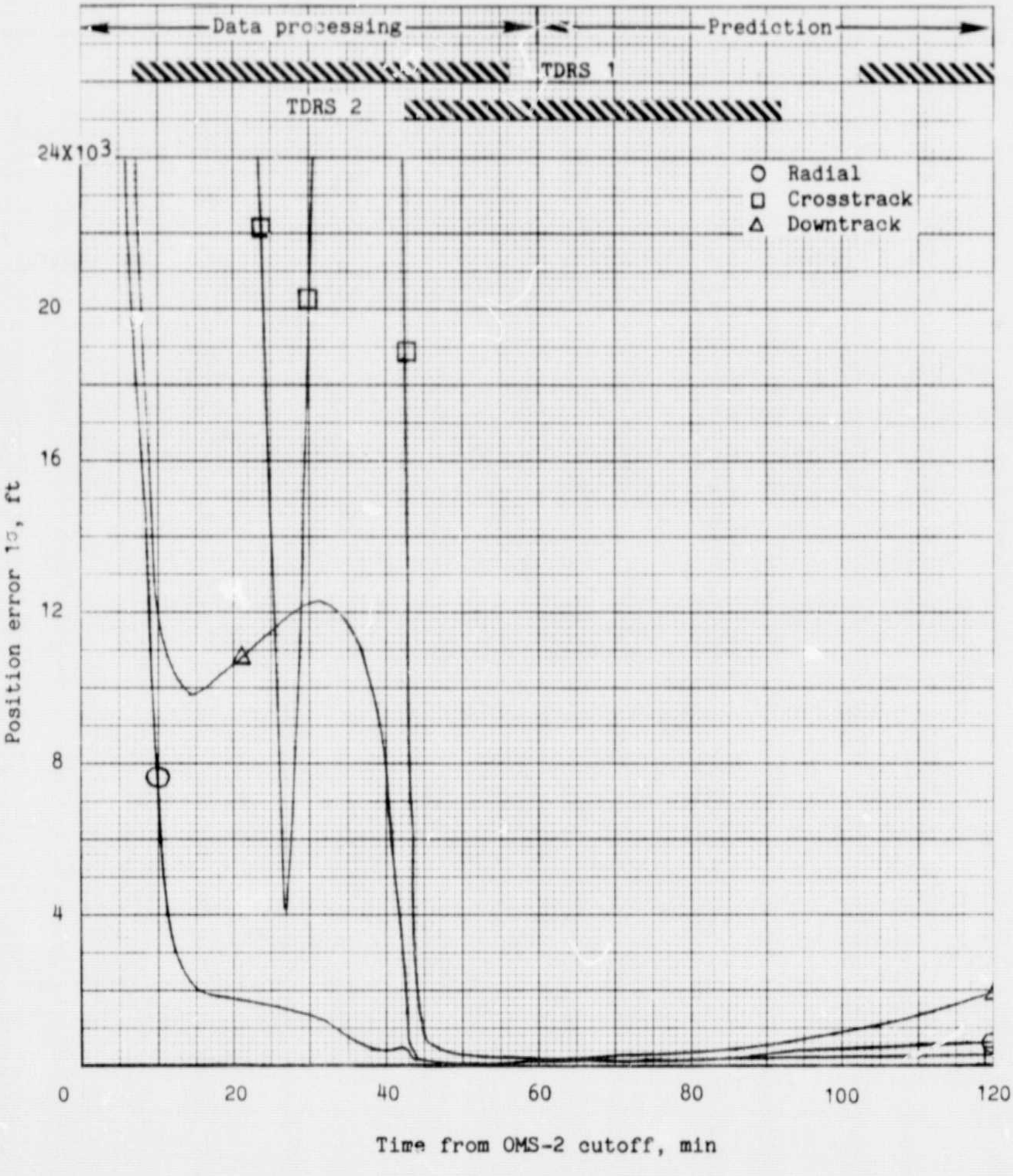
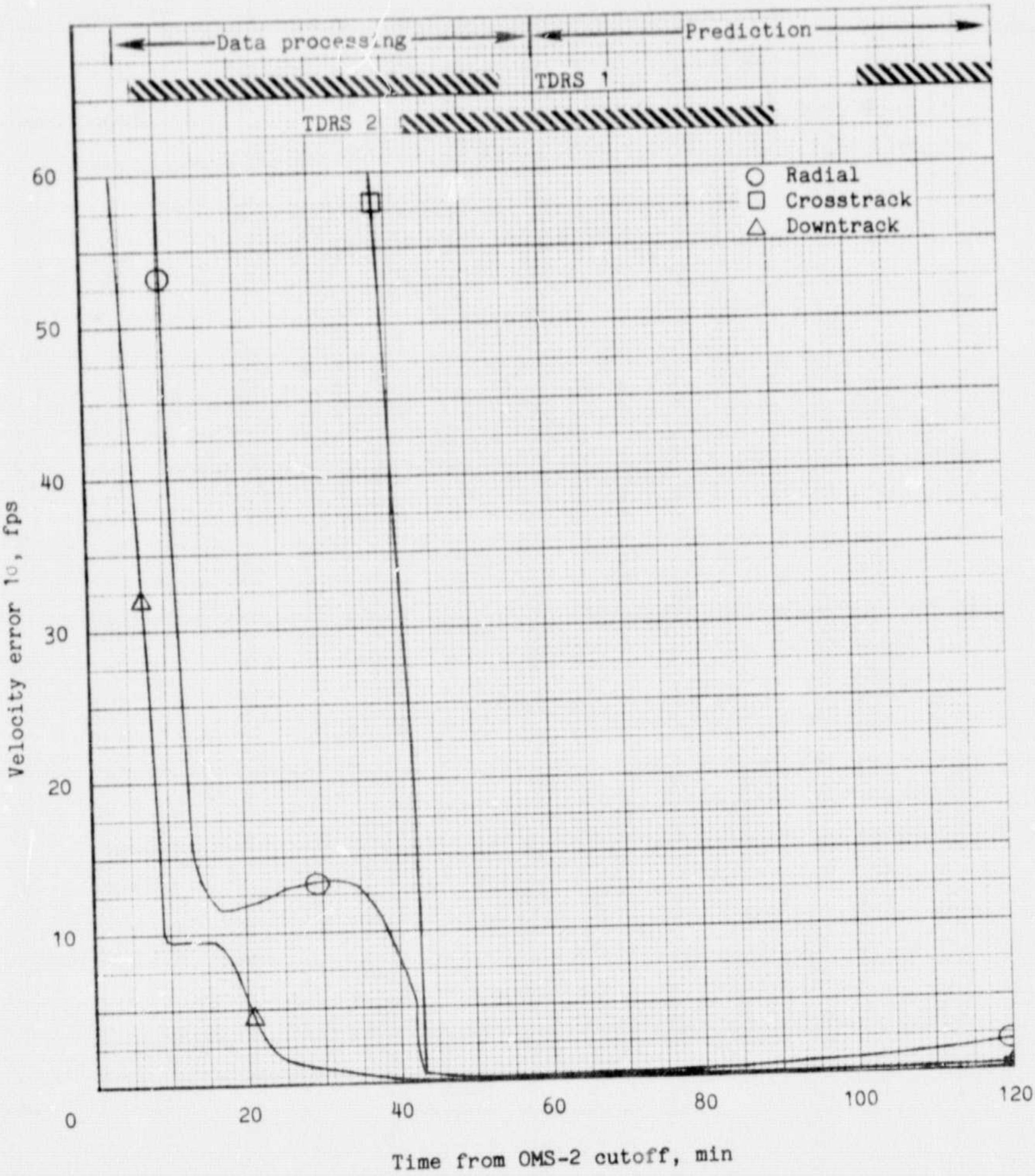


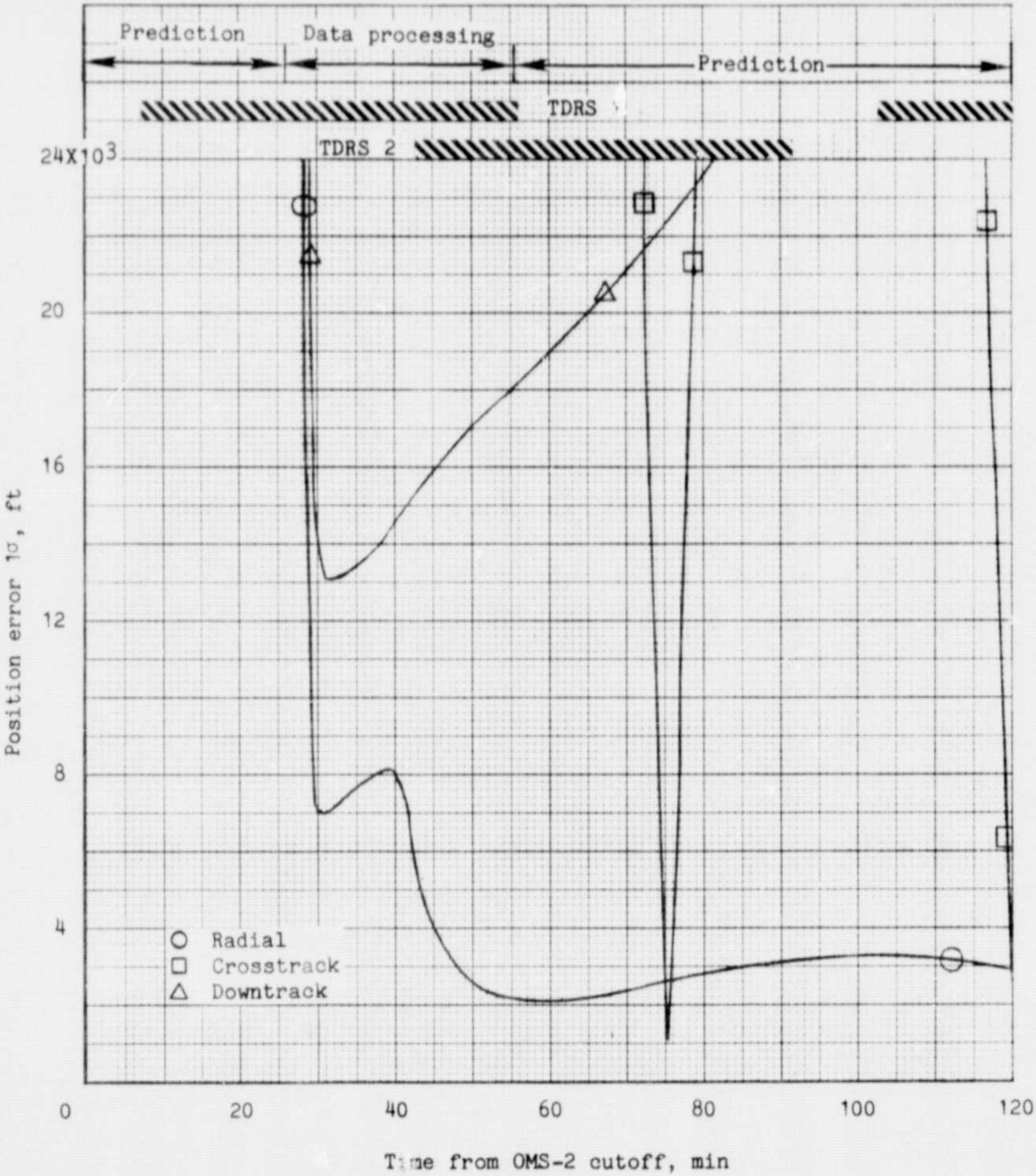
(a) Position.

Figure 5.- Navigation accuracy with TDRS, case 1B



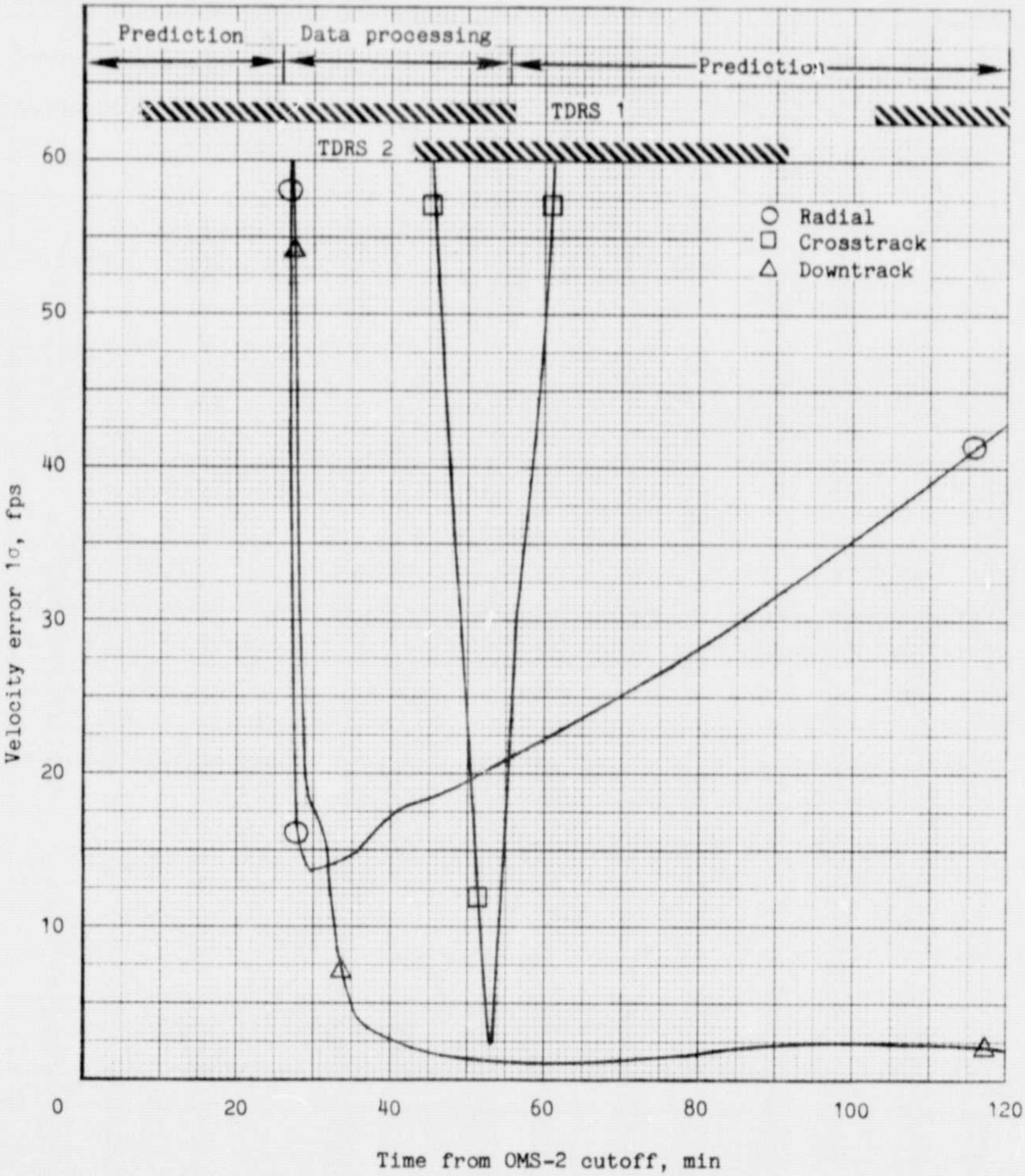
(b) Velocity.

Figure 5.- Concluded.



(a) Position.

Figure 6.- Navigation accuracy with TDRS, case 2B.



(b) Velocity.

Figure 6.- Concluded.

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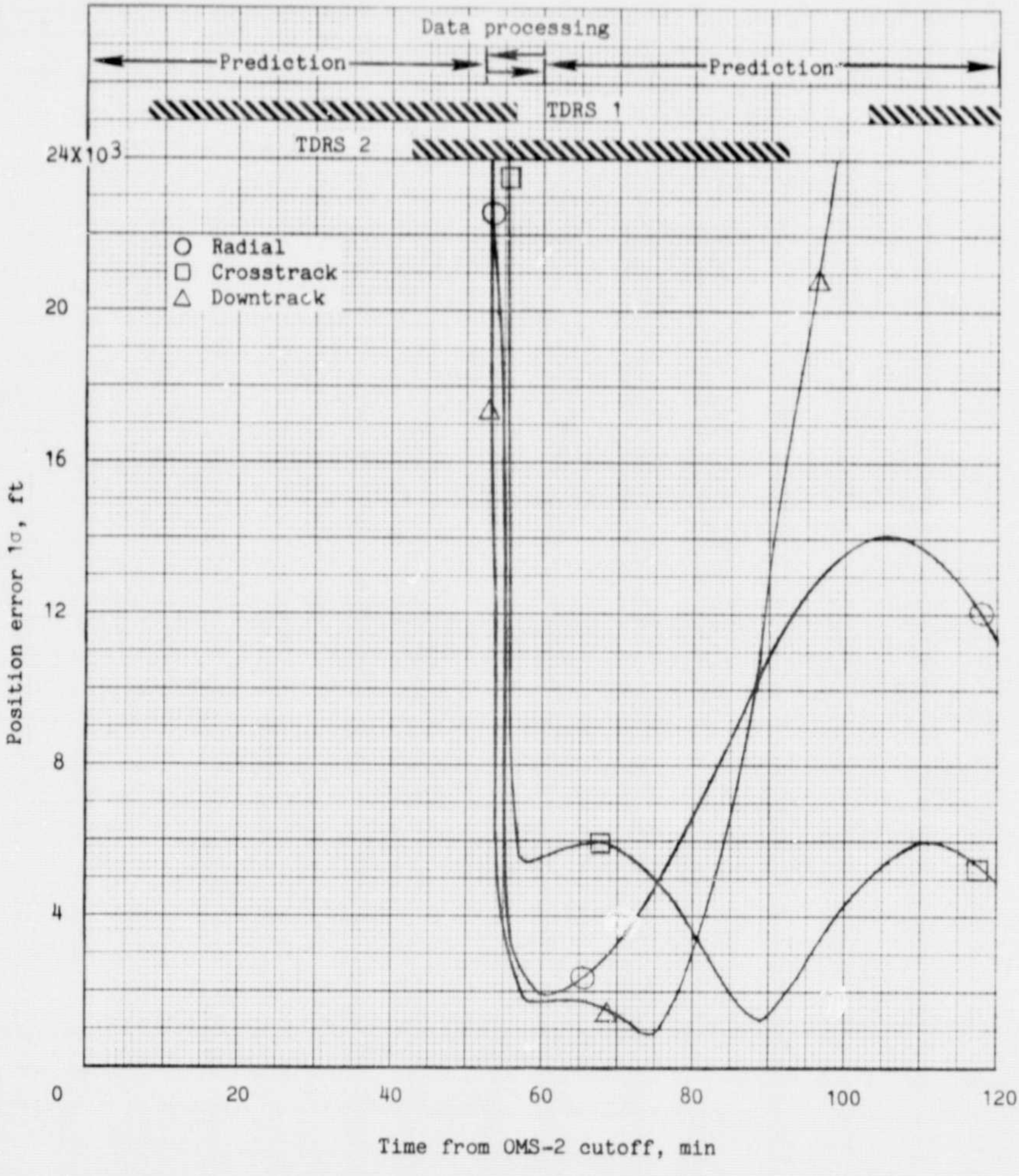
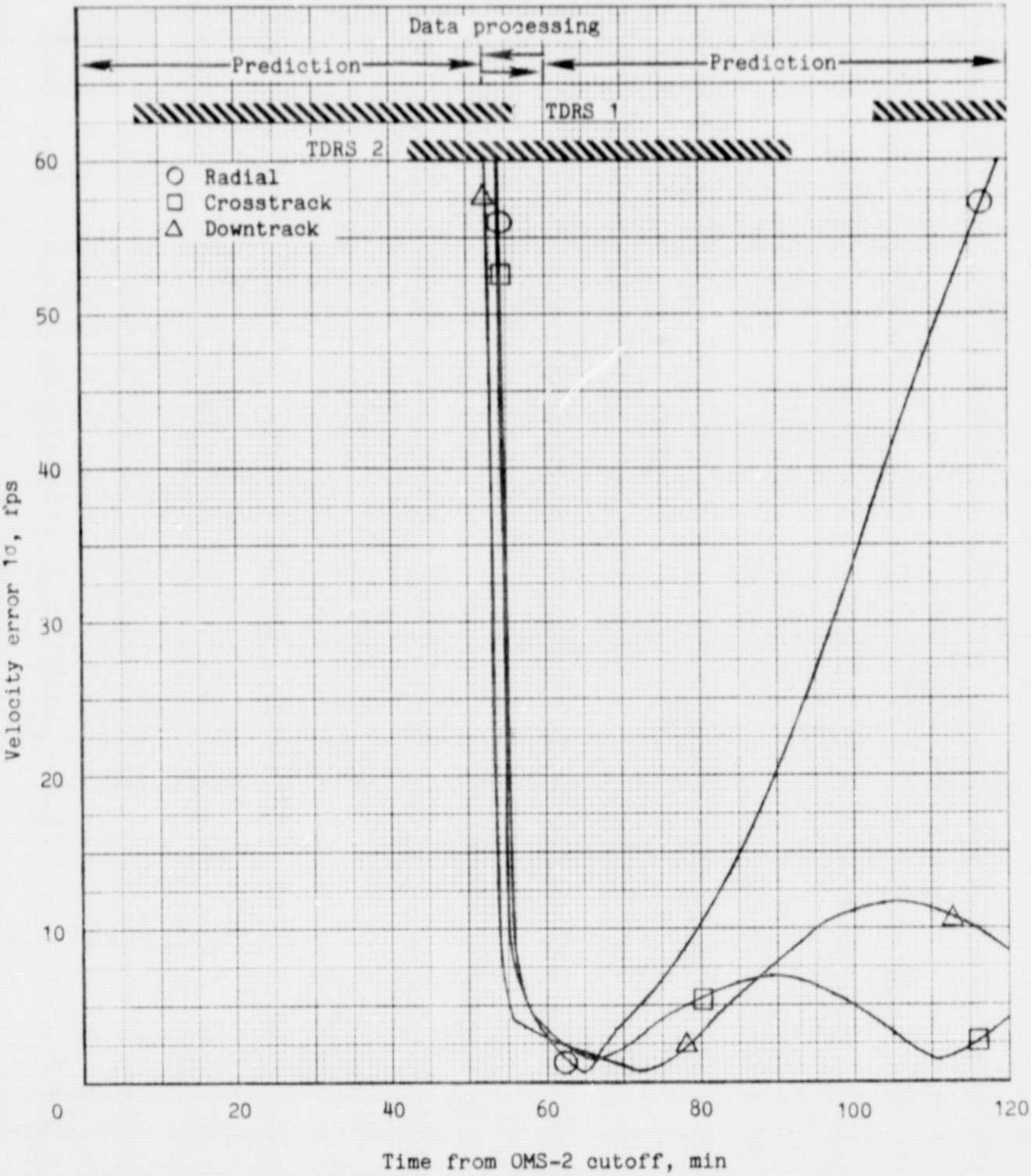


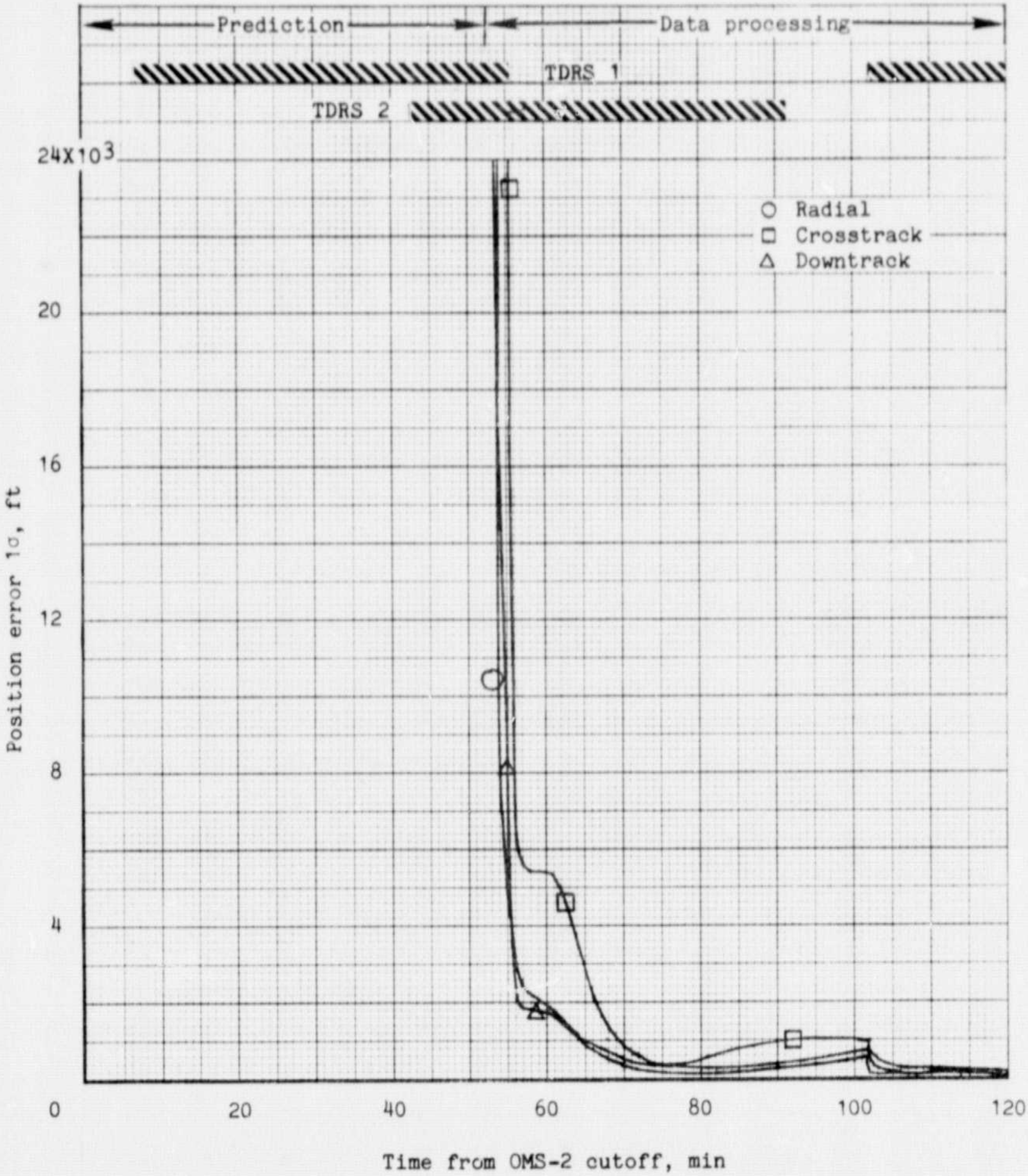
(a) Position.

Figure 7.- Navigation accuracy with TDRS, case 3B.



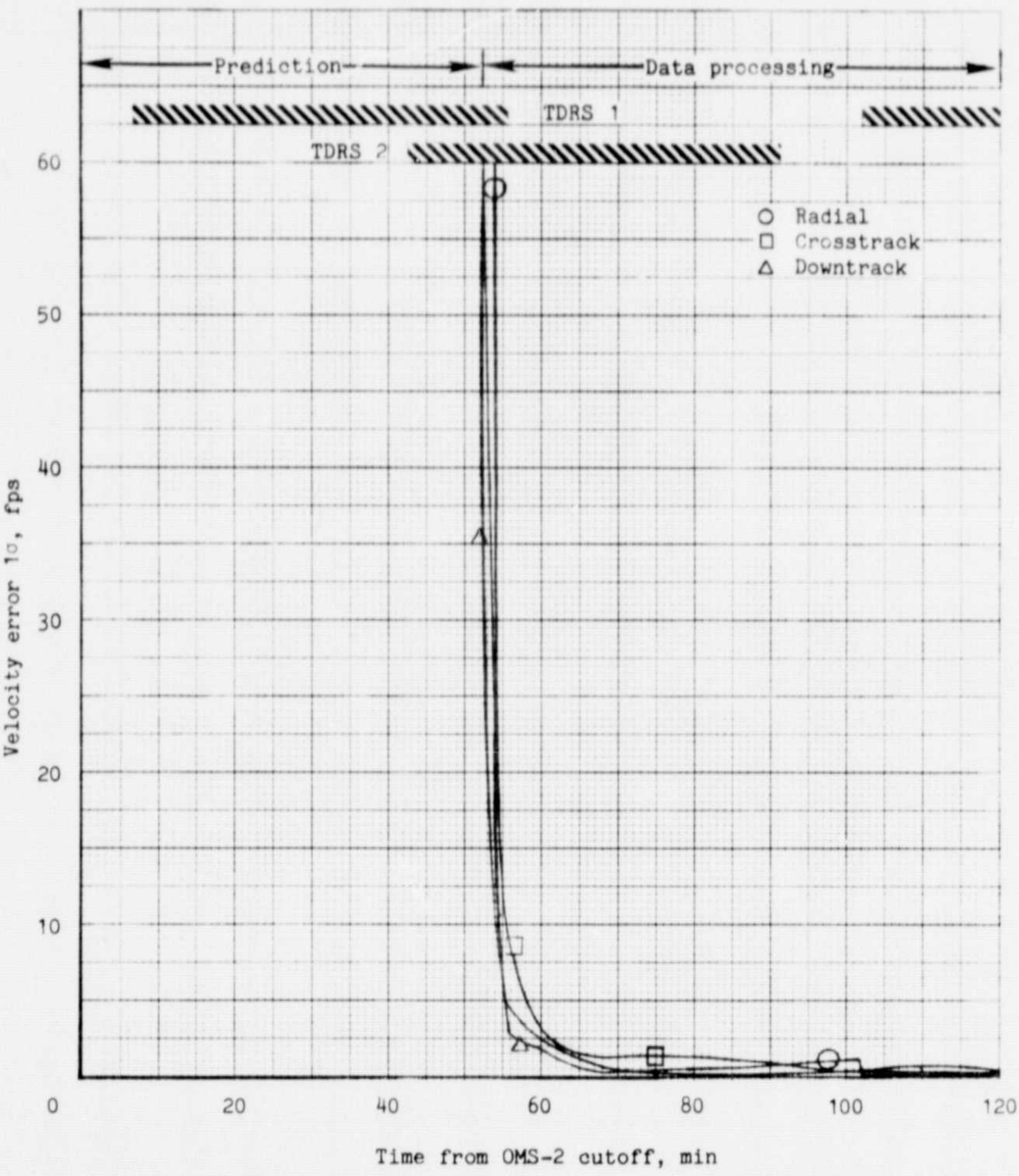
(b) Velocity.

Figure 7.- Concluded.



(a) Position.

Figure 8.- Navigation accuracy with TDRS, case 4B.



(b) Velocity.

Figure 8.- Concluded.

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