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July 12, 1968

EFFECTS OF GUIDANCE AND NAVIGATION SYSTEM ERRORS ON THE APOLLO 7 MISSION

By Melvin R. Rother

Guidance and Performance Branch

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MISSION PLANNING AND ANALYSIS DIVISION

MANNED SPACECRAFT CENTER
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PROJECT APOLLO

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Guidance and Performance Branch

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MISSION PLANNING AND ANALYSIS DIVISION
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

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EFFECTS OF GUIDANCE AND NAVIGATION SYSTEM ERRORS ON THE APOLLO 7 MISSION

By Melvin R. Rother

SUMMARY

A study was made to determine the effects of guidance and navigation (G&N) system errors, i.e., gyrodrift, accelerometer bias, and accelerometer scale factor errors on the powered maneuvers of the Apollo 7 mission. Dispersions resulting from G&N errors of -70 to +70 standard deviations were calculated for inertial velocity and flight-path angle, altitude above a spherical earth, geocentric latitude, longitude, weight of vehicle, apogee and perigee altitude above a spherical earth, argument of perigee, and length of SPS burn.

The study was designed primarily to assist the Flight Control Division in designing trajectories for the Ground Simulation Support Computer (GSSC), but can also be used to analyze the effects of the G&N errors on the orbital parameters.

INTRODUCTION

This note documents the results of a study to determine the effects of G&N system errors during the powered maneuvers on Apollo 7 (Mission C). The study was requested by the Flight Control Division (ref. 1) and supplements the preliminary dispersion analysis for Apollo 7. The powered maneuvers that are analyzed are described in the spacecraft reference trajectory for Mission C (refs. 2 and 3) since the operational trajectory (refs. 4 and 5) was not available when the data for this study was generated. Even though the results presented are based on the reference trajectory, they are applicable to the powered maneuvers scheduled in the operational trajectory since the maneuvers are similar to those in the reference trajectory.

The study is designed to aid the Mission Simulation Section of the Flight Control Division in simulating cases on the GSSC, but can also be used to analyze the effects of G&N errors on the various orbital parameters. The GSSC drives various displays during mission simulations which are used to train both the flight control personnel and the crew. The data in this note are presented in parametric plots of dispersions in the

various trajectory parameters as functions of the G&N system errors and can be used to design trajectories on the GSSC that will cause the different displayed parameters to violate their limits. The violations will cause flight controller action in Houston which, in turn, will cause the crew to take action in the simulator at the Kennedy Space Center (KSC).

ANALYSIS

Since the GSSC can only simulate gyro drift errors, accelerometer bias errors, and accelerometer scale factor errors, these are the only G&N system errors considered. The magnitude of the errors were taken from the Guidance System Operations Plan (GSOP) for Mission C (ref. 6). Error sources from 0 to 70 standard deviations were used to generate a large range of dispersions and to show linearities in the dispersed parameters.

The Guidance Analysis High Speed (GAHS) Program (ref. 7) was used to calculate the powered-flight dispersions due to the G&N errors. The GAHS program is a three-degree-of-freedom, point-mass trajectory program that contains a standard G&N error model. Each of the service propulsion system (SPS) maneuvers scheduled in the Mission C reference trajectory, except the two minimum impulse burns, were modeled in the following manner: assume platform alignment 30 minutes prior to ullage ignition, execute a 15 second ullage, and burn the SPS engine until the nominal external ΔV targets have been achieved. A coast phase to 400 000 ft was added to the deorbit maneuver.

The platform alignment used was a preferred alignment that set the platform X-axis (X_{SM}) along the desired velocity-to-be-gained vector (V_g), the Y-axis (Y_{SM}) along the cross-product of V_g and the vehicle radius vector, and the Z-axis (Z_{SM}) along the cross-product of X_{SM} and Y_{SM}. Hence, the Z_{SM} - X_{SM} plane is the pitch plane for the maneuver and the X_{SM} - Y_{SM} plane is in the yaw plane for the maneuver. Since X_{SM} is aligned along V_g, all of the acceleration sensed during a nominal maneuver is in X_{SM}. Hence, gyro drift errors about the X_{SM} and scale factor errors in the Y_{SM} and Z_{SM} have no effects on the powered flight maneuvers.

RESULTS

Results of the nominal maneuver simulations are presented in table I.

The trajectory parameters are tabulated at ullage ignition and SPS burn cutoff for each of the maneuvers and at entry interface (400 000 ft) for the deorbit maneuver. These results are used as the nominal points for figures 1 through 7. Table II presents the external ΔV targets that were used to define the platform alignments for the SPS maneuvers. The information can be used to determine whether the maneuvers are in-plane or out-of-plane and, hence, will help in analyzing the effects of G&N errors on the maneuvers. The table shows that SPS burns 1, 2, and 8 are strictly in-plane maneuvers while burns 4, 5, and 7 are out-of-plane by different angles.

Figures 1 through 7 present parametric plots of the following trajectory parameters as functions of the G&N errors considered in this analysis: inertial velocity and flight-path, altitude above a spherical earth, geocentric latitude, longitude, weight of the vehicle, apogee and perigee altitudes above a spherical earth, true anomaly, argument of perigee, and length of the SPS burn. The range of errors considered is from -70 to +70 standard deviations.

Since the external ΔV maneuvers have been set up with a preferred alignment having the X_{SM} along V_g, all accelerations sensed during a nominal maneuver are along X_{SM}. Therefore, scale factor errors in the Y_{SM} and Z_{SM} have no effect on the maneuvers since their sensed accelerations are zero. Scale factor errors in X_{SM} cause the actual velocity achieved during a maneuver to be more or less than the nominal, but the velocity is achieved in the nominal direction. Hence, the most significant dispersions caused by scale factors in X_{SM} are in the length of the SPS burn and related parameters such as latitude, longitude, and weight at cutoff. The effects on the trajectory parameters of the scale factor errors in X_{SM} are linear.

Like the Y_{SM} and Z_{SM} scale factor errors, gyro drift errors about the X_{SM} produce no effect on the maneuvers since the Y_{SM} and Z_{SM} accelerations are nominally zero. Gyro drift errors about the Y_{SM} cause the thrust direction to be misaligned in the pitch plane for the maneuver since the navigation system attempts to drive the sensed accelerations in Y_{SM} to zero. Likewise, gyro drift errors about the Z_{SM} cause the thrust to be misaligned in the yaw plane.

The biggest dispersions in the orbit parameters such as apogee altitude, perigee altitude, true anomaly, and argument of perigee for in-plane maneuvers are caused by the misalignment of the thrust in the pitch plane and, hence, result from the gyro drift about the Y_{SM}. For out-of-plane maneuvers, the gyro drift about Y_{SM} is no longer the dominant contributor

to the orbit parameter dispersions. Gyro drift errors about Z_{SM} gain significance as the out-of-plane angle increases for the maneuvers. The effects of gyro drift errors are generally not linear, but are linear enough to approximate results from the figures.

An accelerometer bias error in X_{SM} produces orbit parameter dispersions similar to the X_{SM} scale factor error but of a larger magnitude. The dispersions caused by X_{SM} bias errors are linear. A bias error in the Y_{SM} causes the navigation system to change the thrust direction in the yaw plane until the Y_{SM} sensed acceleration is zero. The same thing happens for a bias error in the Z_{SM} except the thrust direction is changed in the pitch plane. Hence, biases in Z_{SM} are the dominant contributors to dispersions for in-plan maneuvers, while biases in Y_{SM} become significant for out-of-plane maneuvers.

CONCLUDING REMARKS

The above discussion indicates that this study can be used not only to assist the Flight Control Division in designing trajectories for the GSSC, but also in analyzing the effects of G&N errors on the different orbital parameters. Even though the SPS maneuvers scheduled for the C mission in the operational trajectory are different from those in the reference trajectory, the dispersions presented in this document are applicable to the operational trajectory maneuvers since the scheduled maneuvers are so similar. Furthermore, the results will be applicable to any new SPS maneuvers that may be scheduled that utilize the G&N system external ΔV mode and are similar to those used in this analysis.

TABLE I.- TRAJECTORY PARAMETERS FOR THE NOMINAL APOLLO 7 MANEUVERS

Event	Inertial velocity, ft/sec	Inertial flight-path, deg	Altitude, ft	Geocentric latitude, deg	Longitude, deg	Weight, lb	Apogee altitude, n. mi.	Perigee altitude, n. mi.	True anomaly, deg	Argument of perigee, deg	Length of SPS maneuver or coast, sec
SPS-1 Ignition	25299.4	-0.173	980854	-29.199	107.840	32607.3	161.87	121.96	212.71	78.70	-
SPS-1 Cutoff	25352.0	-0.573	977796	-28.843	109.496	32028.8	191.96	119.83	265.72	27.26	8.780
SPS-2 Ignition	25455.4	-0.554	885479	-21.279	109.249	32029.3	194.32	120.00	289.85	26.34	-
SPS-2 Cutoff	25379.9	-0.243	880008	-20.660	110.630	31526.9	151.93	116.39	238.47	79.23	7.582
SPS-4 Ignition	25582.9	-0.092	719258	28.303	-80.526	31353.8	157.00	114.96	343.97	131.23	-
SPS-4 Cutoff	25696.5	0.029	717913	27.764	-78.431	30393.0	220.84	115.61	2.05	116.12	14.957
SPS-5 Ignition	25700.6	-0.019	706233	21.179	-80.777	30394.5	220.28	114.70	358.68	138.20	-
SPS-5 Cutoff	25647.3	0.920	715906	19.014	-76.415	26776.3	225.96	86.05	56.63	87.77	56.800
SPS-7 Ignition	25835.9	-0.350	548824	33.861	-81.423	26738.2	214.51	82.96	340.15	114.84	-
SPS-7 Cutoff	25845.2	-0.155	544151	33.699	-78.676	25451.7	214.57	85.25	351.18	104.61	19.916
SPS-8 Ignition	25422.7	-0.997	889662	13.659	-134.602	25453.7	213.76	88.25	273.78	111.25	-
SPS-8 Cutoff	25236.0	-1.618	876077	14.622	-133.077	24612.7	205.74	-16.80	242.28	144.61	12.900
400 000 feet	25810.2	-1.772	400000	31.373	-93.400	12842.0	205.37	-21.10	283.29	145.68	619.902

TABLE II.- EXTERNAL ΔV TARGETS

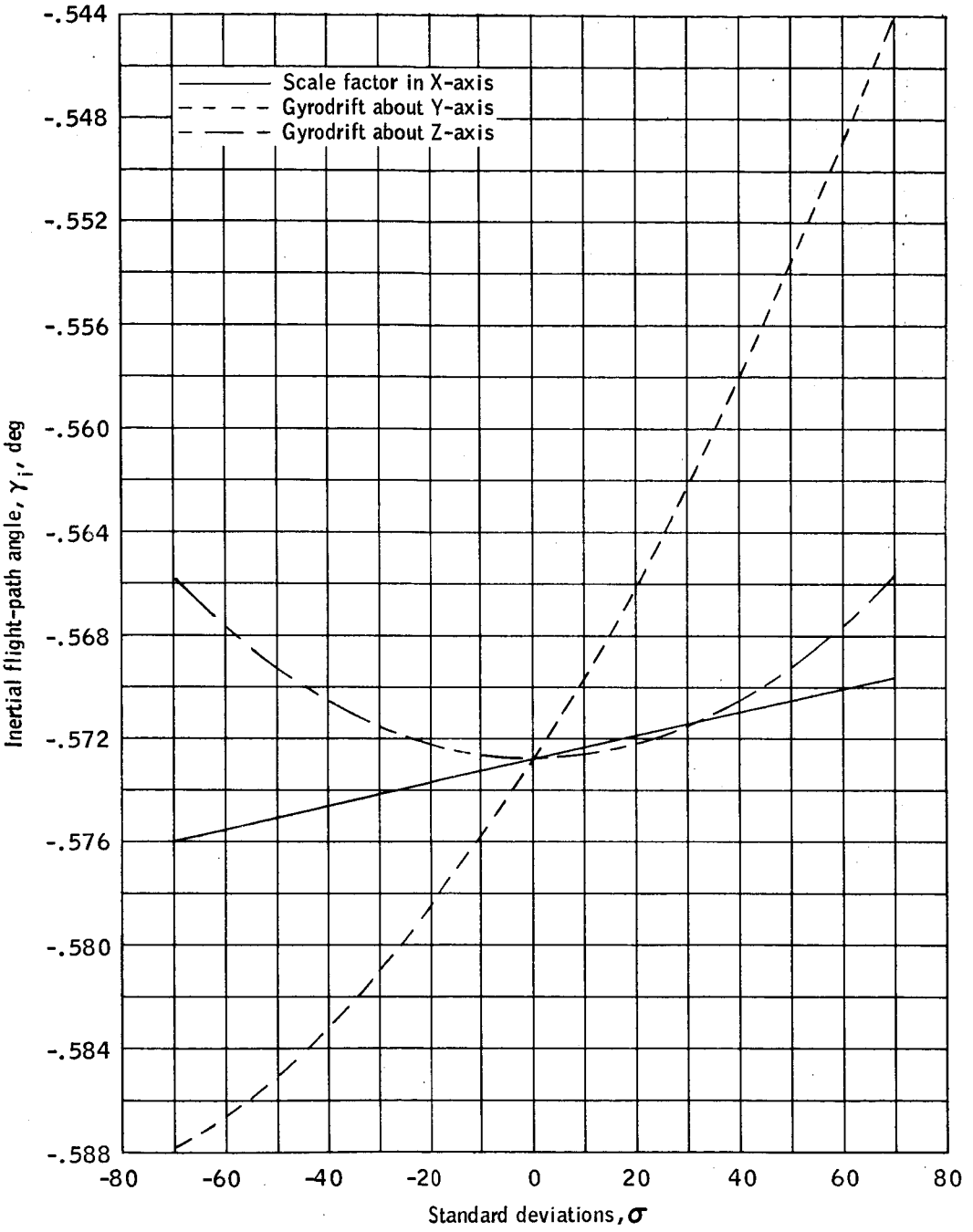
Maneuver	External ΔV Components*		
	ΔX, ft/sec	ΔY, ft/sec	ΔZ, ft/sec
SPS-1	45.25	0.00	174.65
SPS-2	-78.30	0.00	-138.69
SPS-4	111.47	290.74	-45.79
SPS-5	-66.63	1219.48	-394.78
SPS-7	0.78	-493.59	-69.28
SPS-8	-213.39	0.00	263.52

*Components are in the local vertical system which is defined as follows:

the Z-axis is a unit vector along the radius vector of the vehicle, but is opposite in sign;

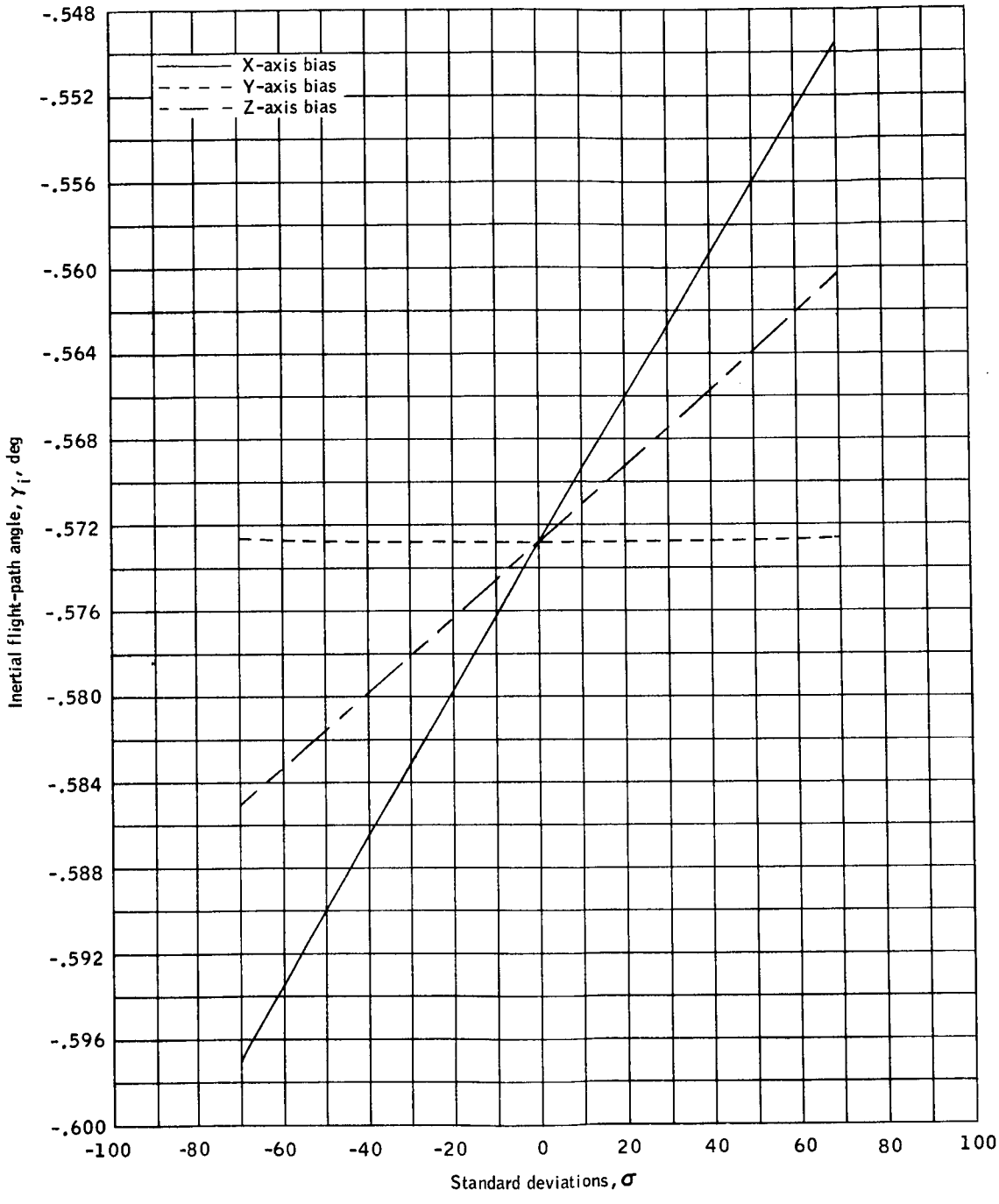
the Y-axis is a unit vector along the vehicle velocity vector crossed into the vehicle radius vector and so it is perpendicular to the orbit plane; and

the X-axis is unit vector along the Y-axis crossed into the Z-axis and so it is in the orbit plane, perpendicular to the radius vector, and positive in the direction of motion.



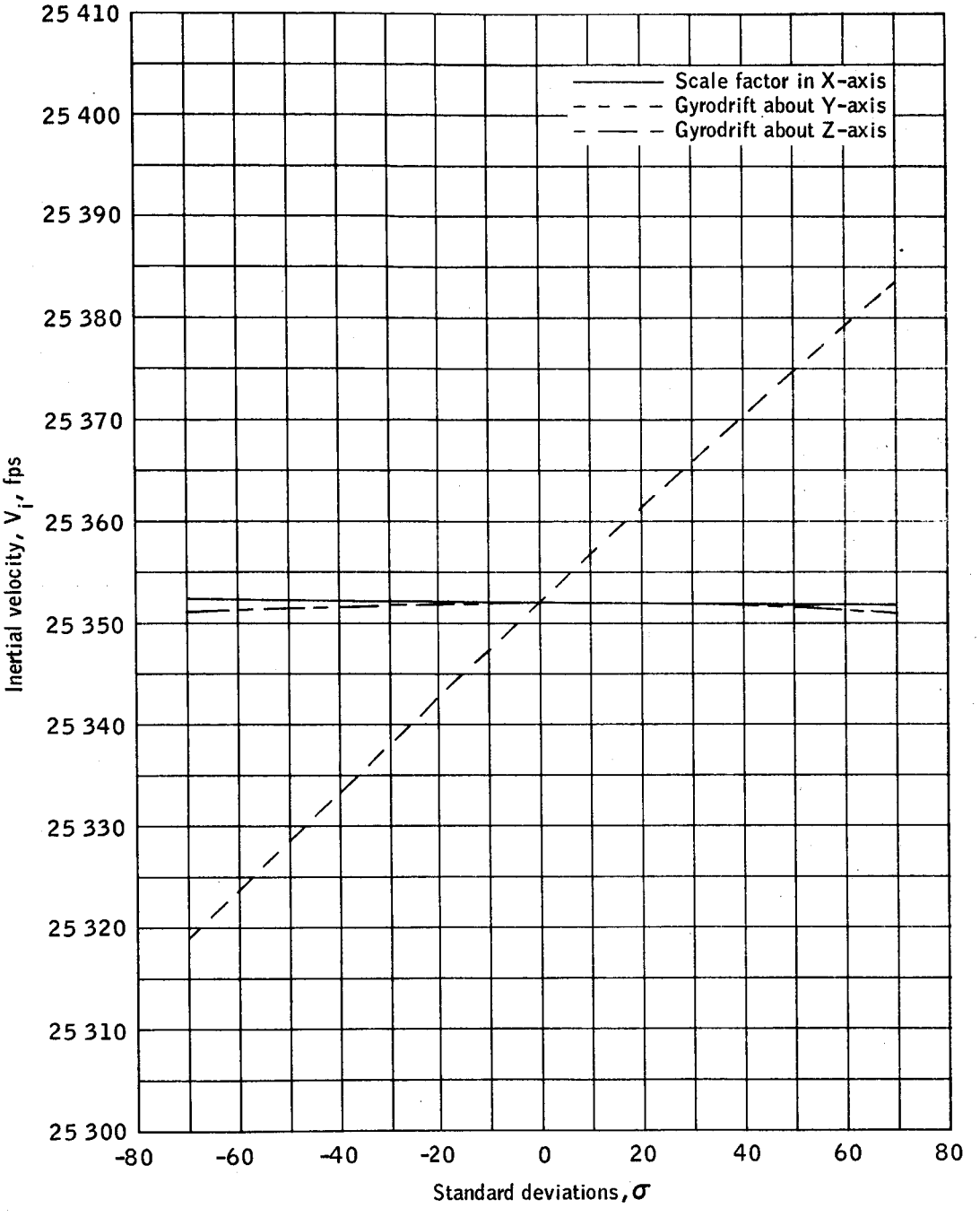
(a) Inertial flight-path angle versus scale factor and drift errors.

Figure 1.- Mission C dispersion at the end of the first SPS burn due to accelerometer bias, accelerometer scale factor and gyrodrift errors.



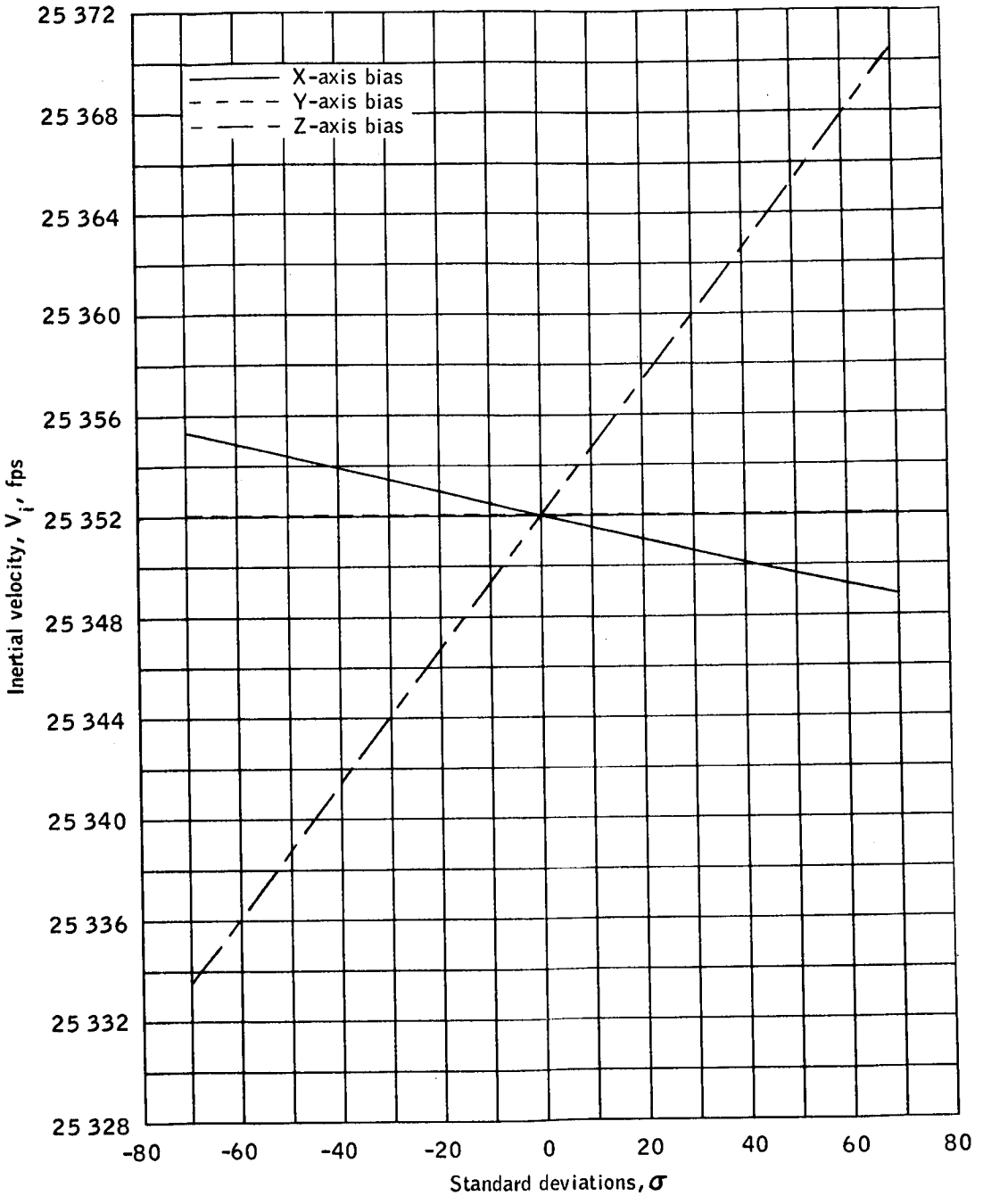
(b) Inertial flight-path angle versus bias errors.

Figure 1.- Continued.



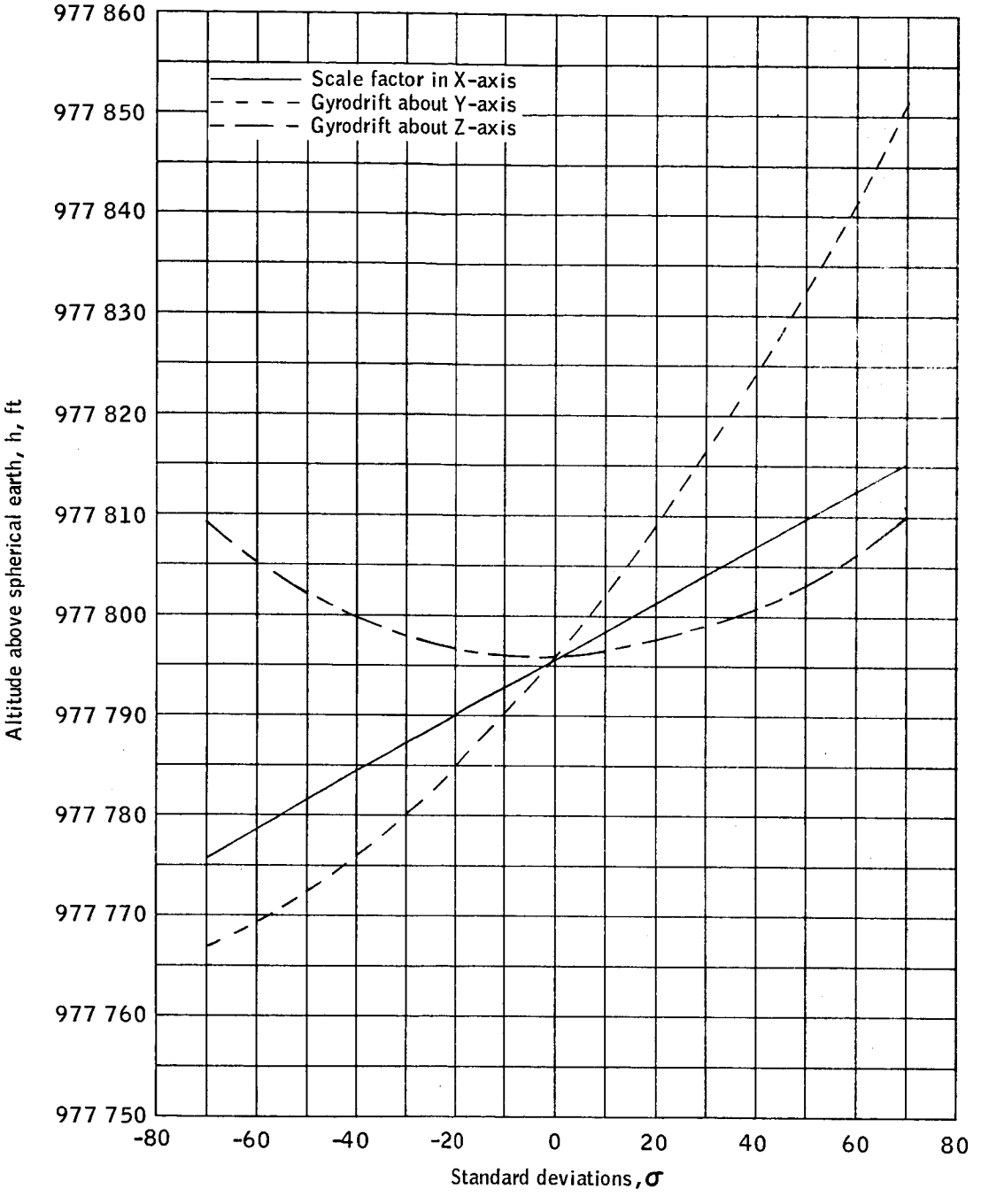
(c) Inertial velocity versus scale factor and drift errors.

Figure 1.- Continued.



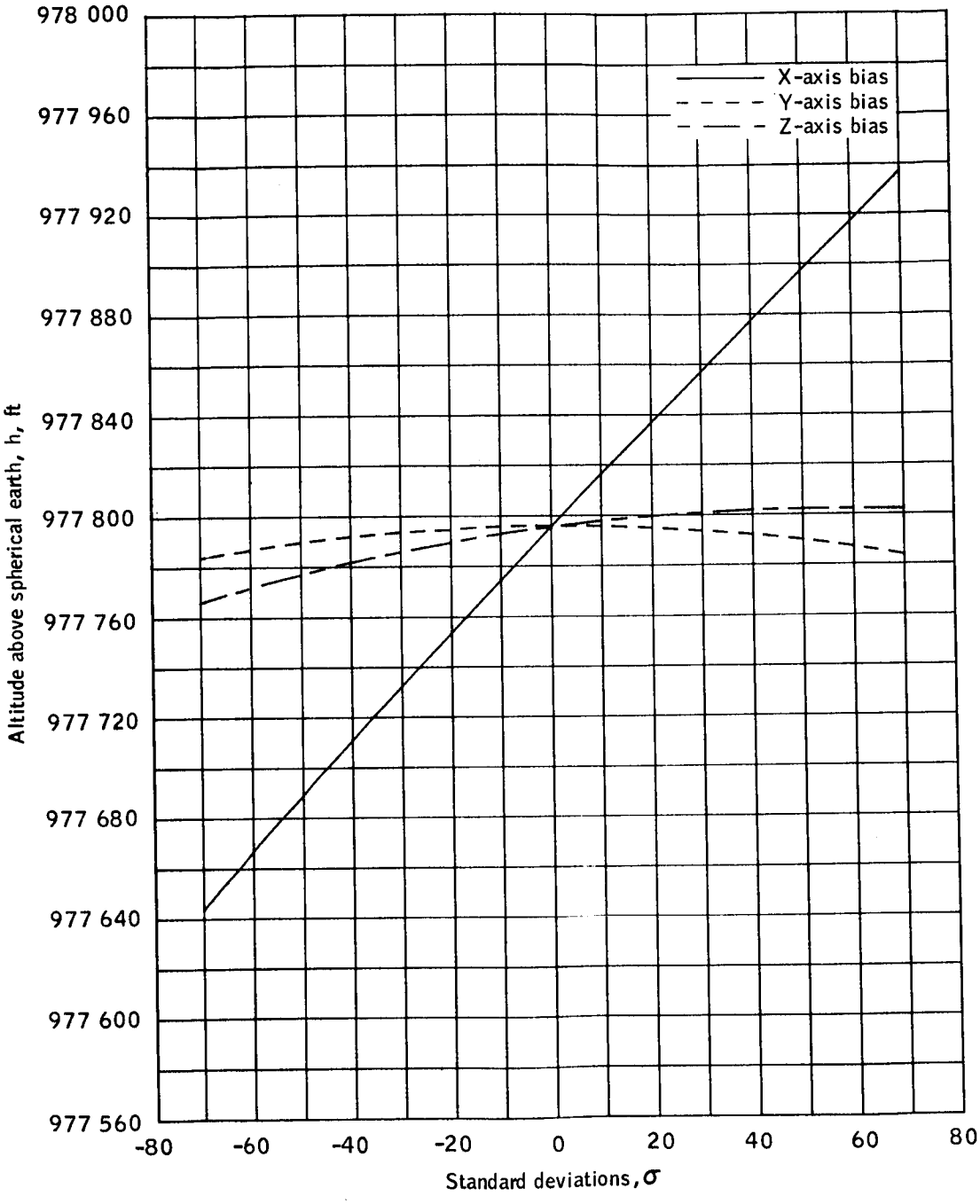
(d) Inertial velocity versus bias errors.

Figure 1.- Continued.



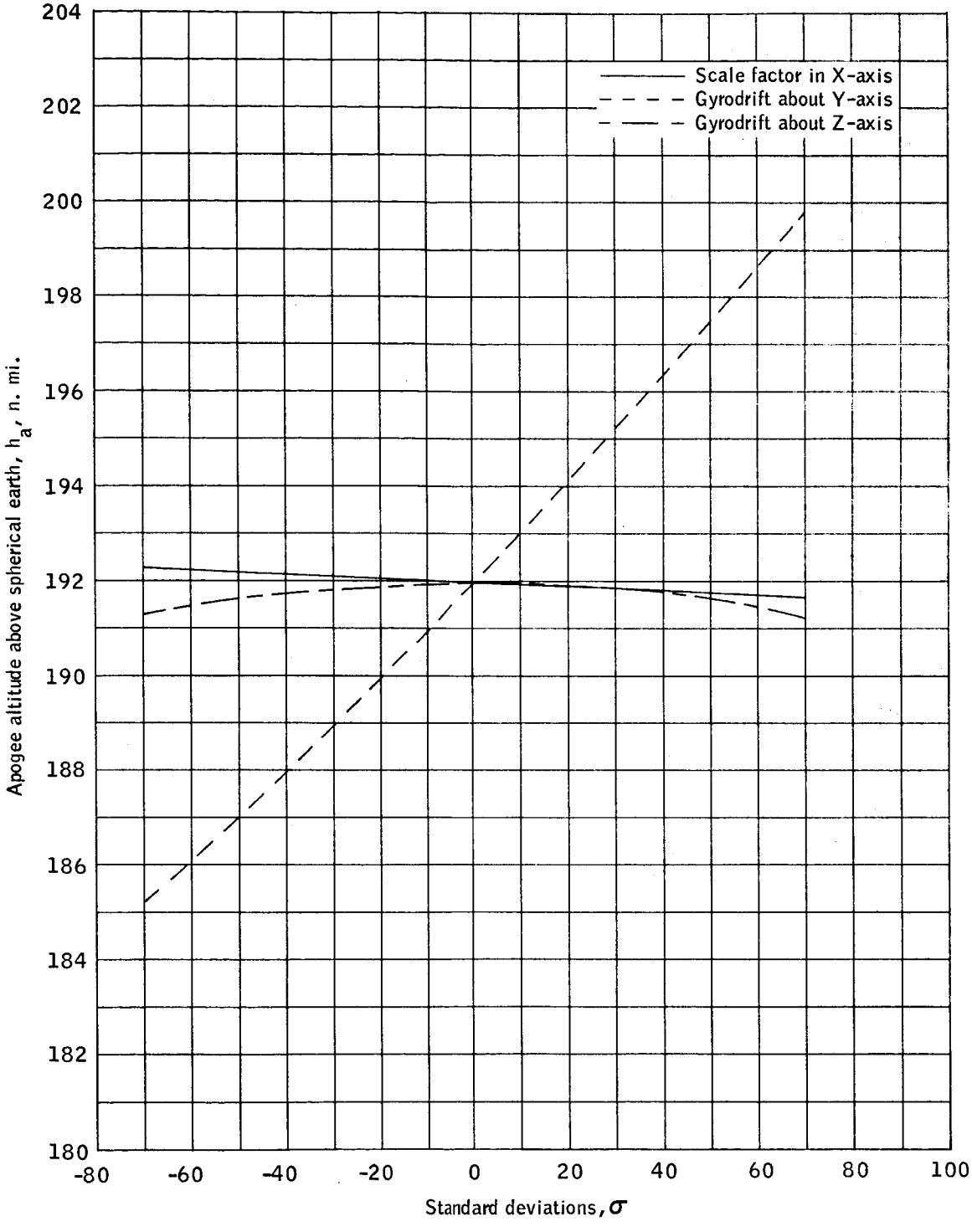
(e) Altitude above spherical earth versus scale factor and drift errors.

Figure 1.- Continued.



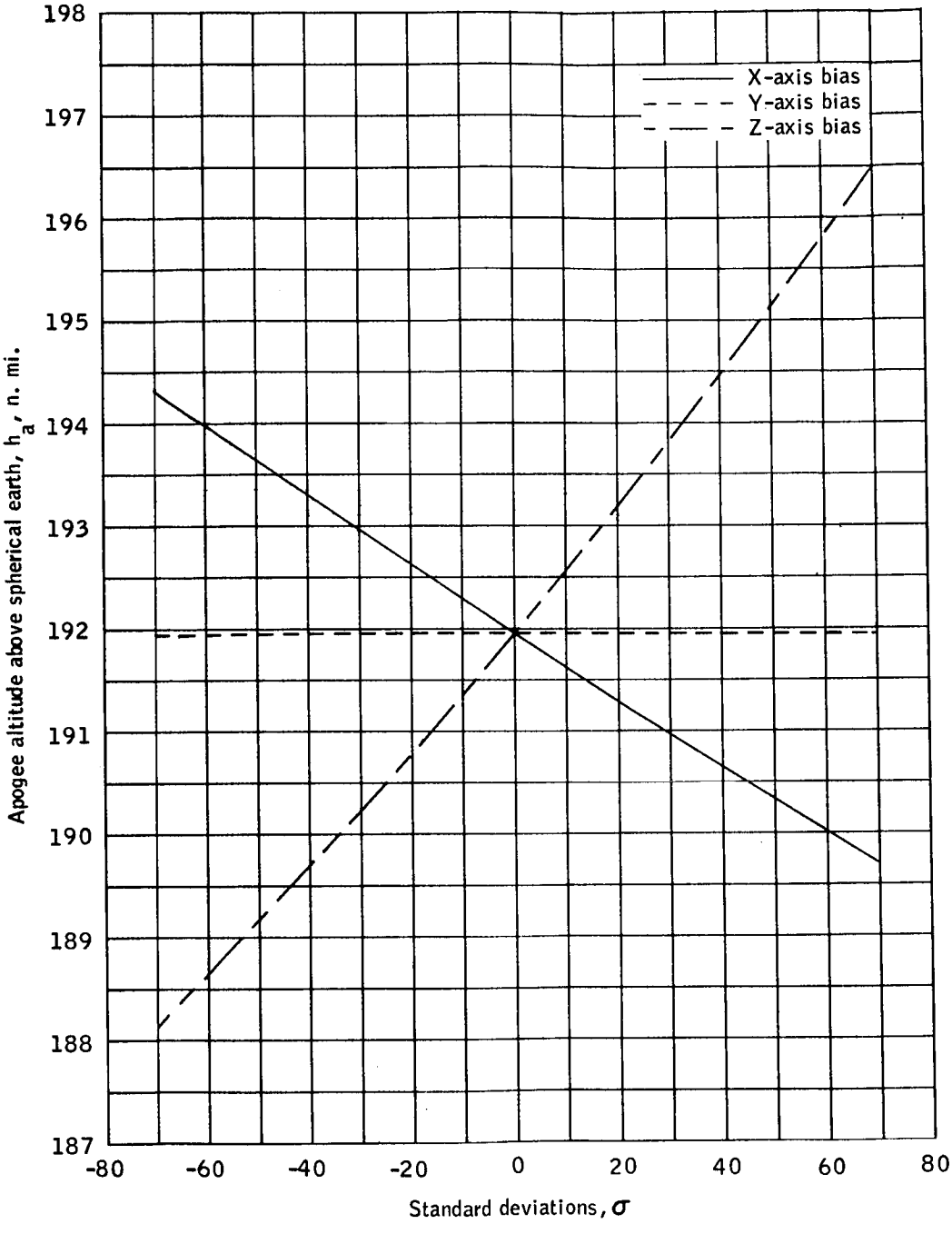
(f) Altitude above spherical earth versus bias errors.

Figure 1.- Continued.



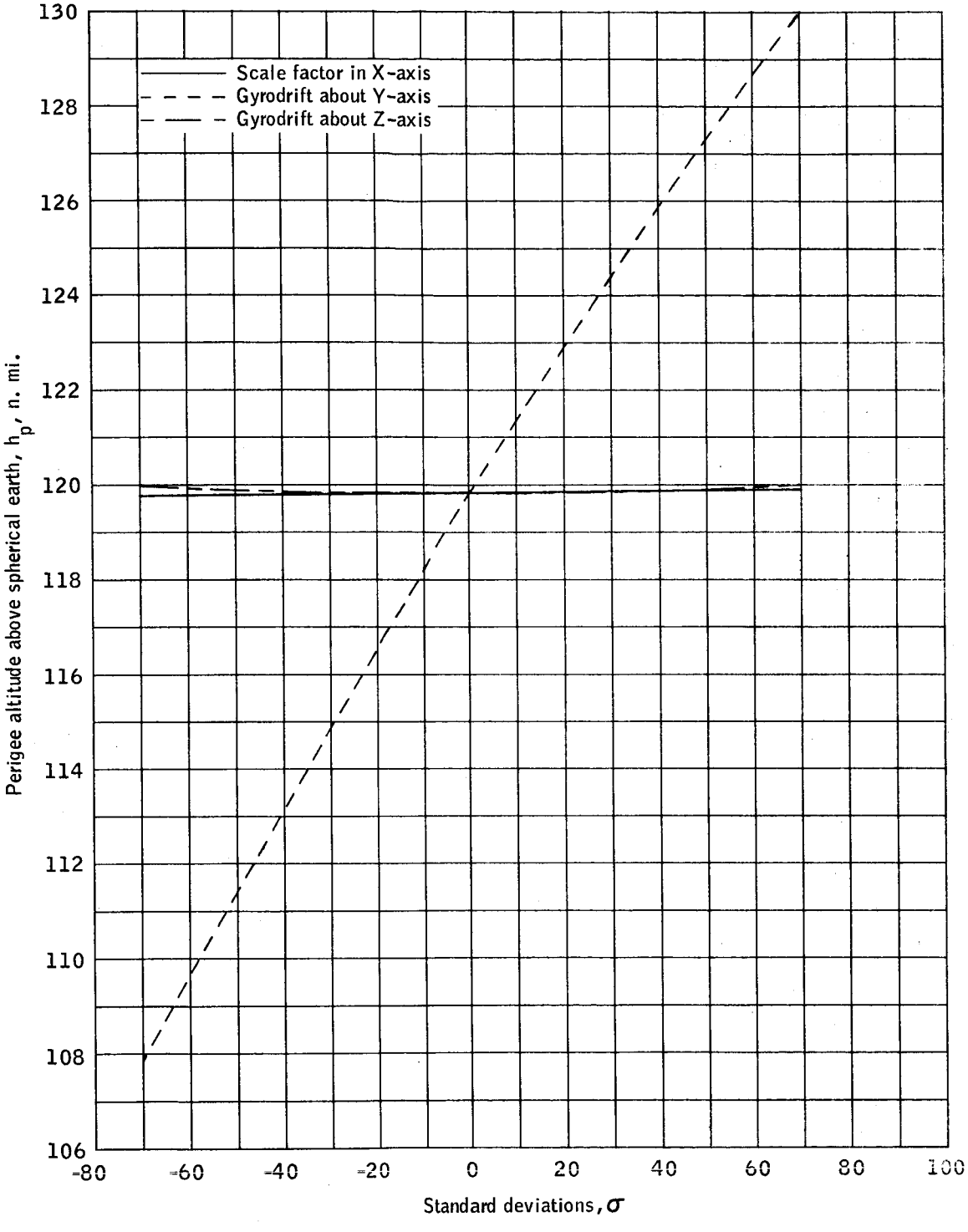
(g) Apogee altitude above spherical earth versus scale factor and drift errors.

Figure 1.- Continued.



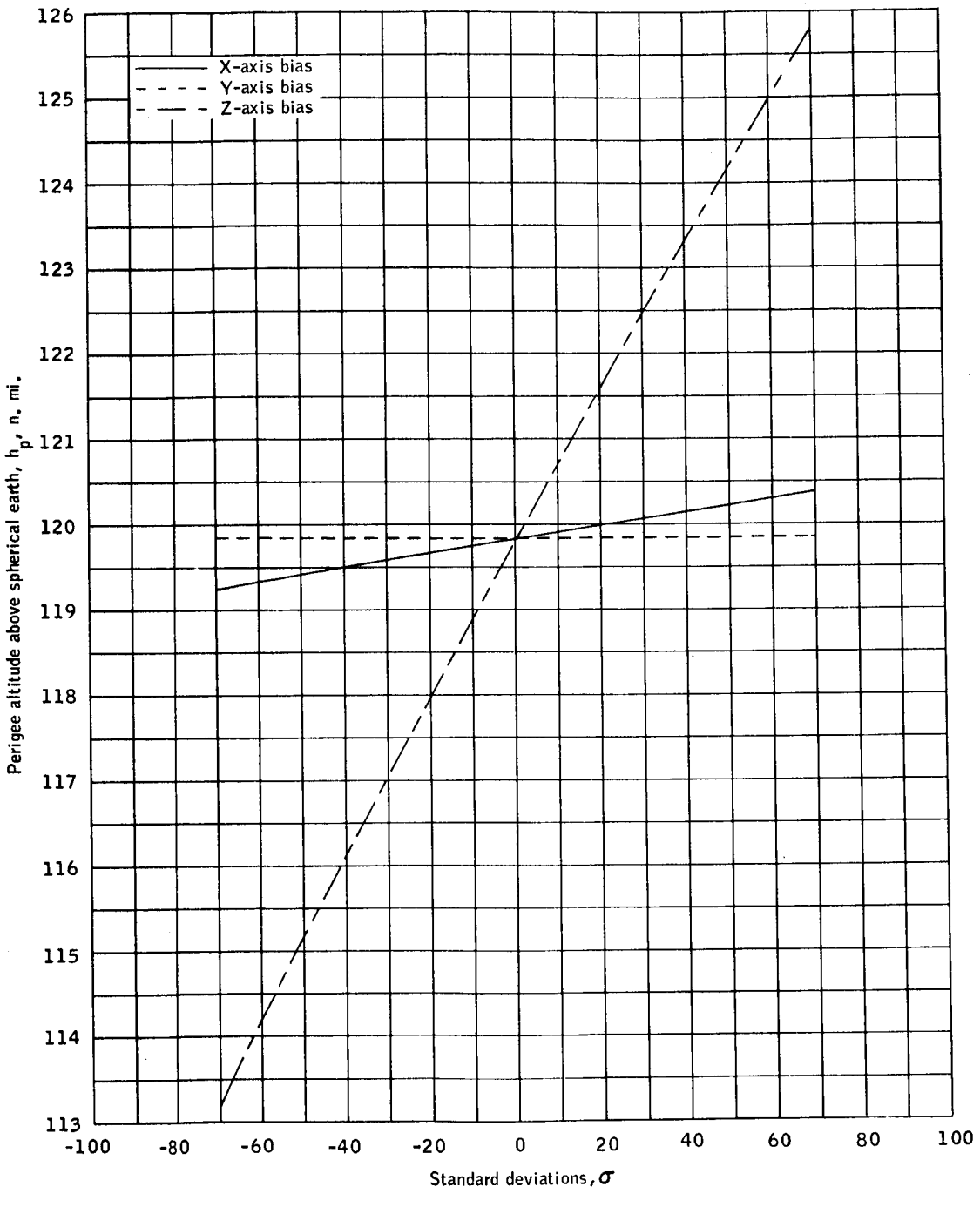
(h) Apogee altitude above spherical earth versus bias errors.

Figure 1.- Continued.



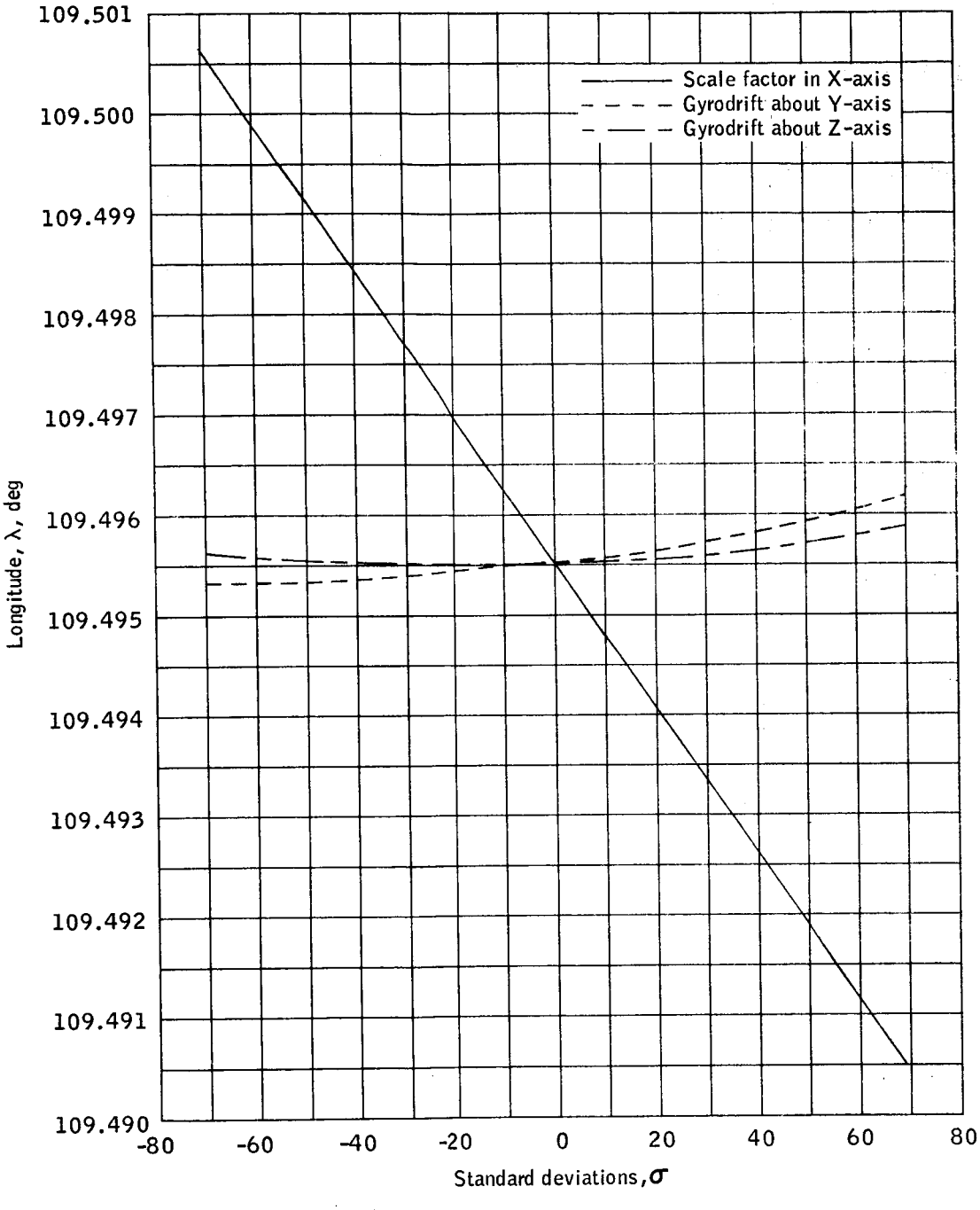
(i) Perigee altitude above spherical earth versus scale factor and drift errors.

Figure 1.- Continued.



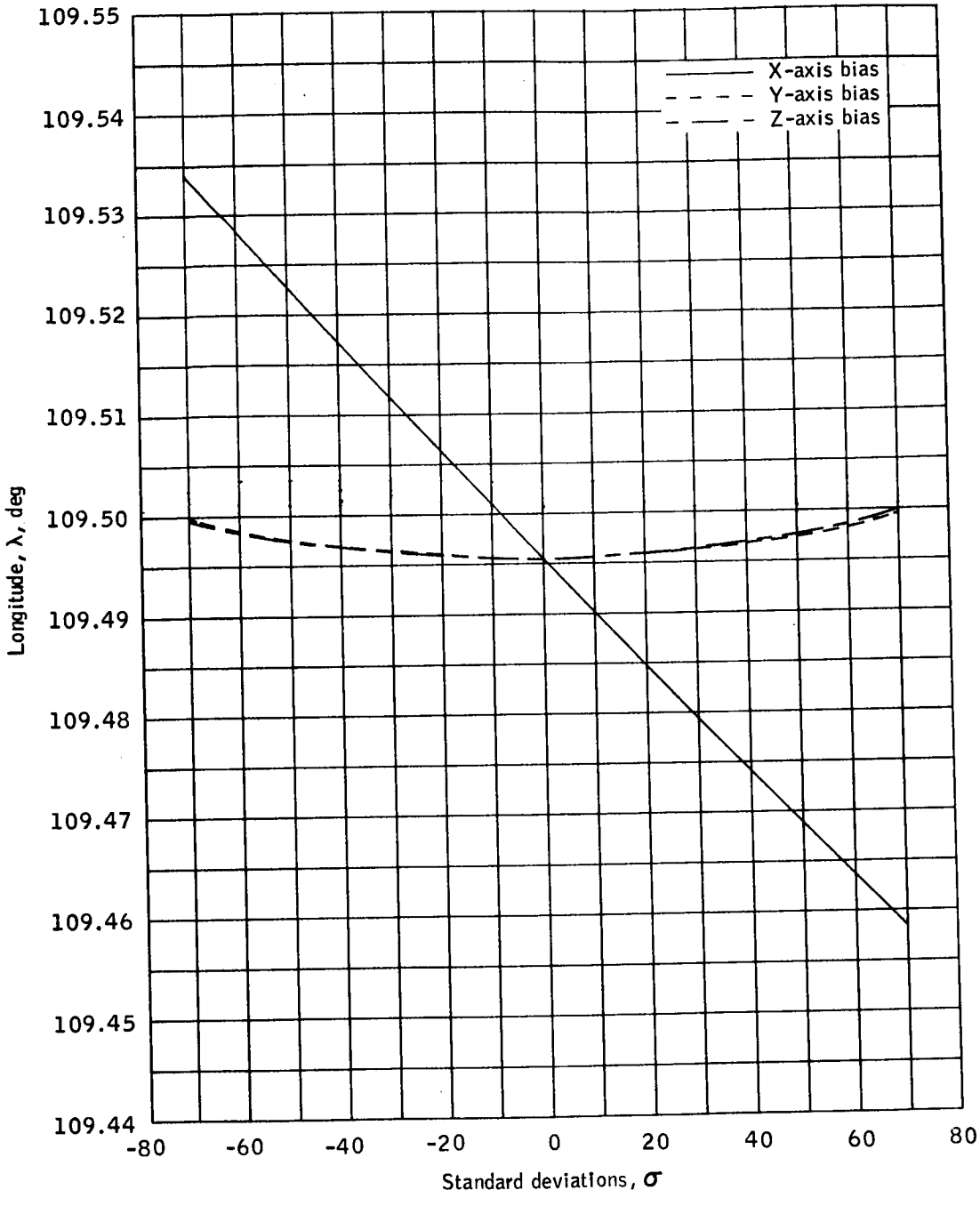
(j) Perigee altitude above spherical earth versus bias errors.

Figure 1.- Continued.



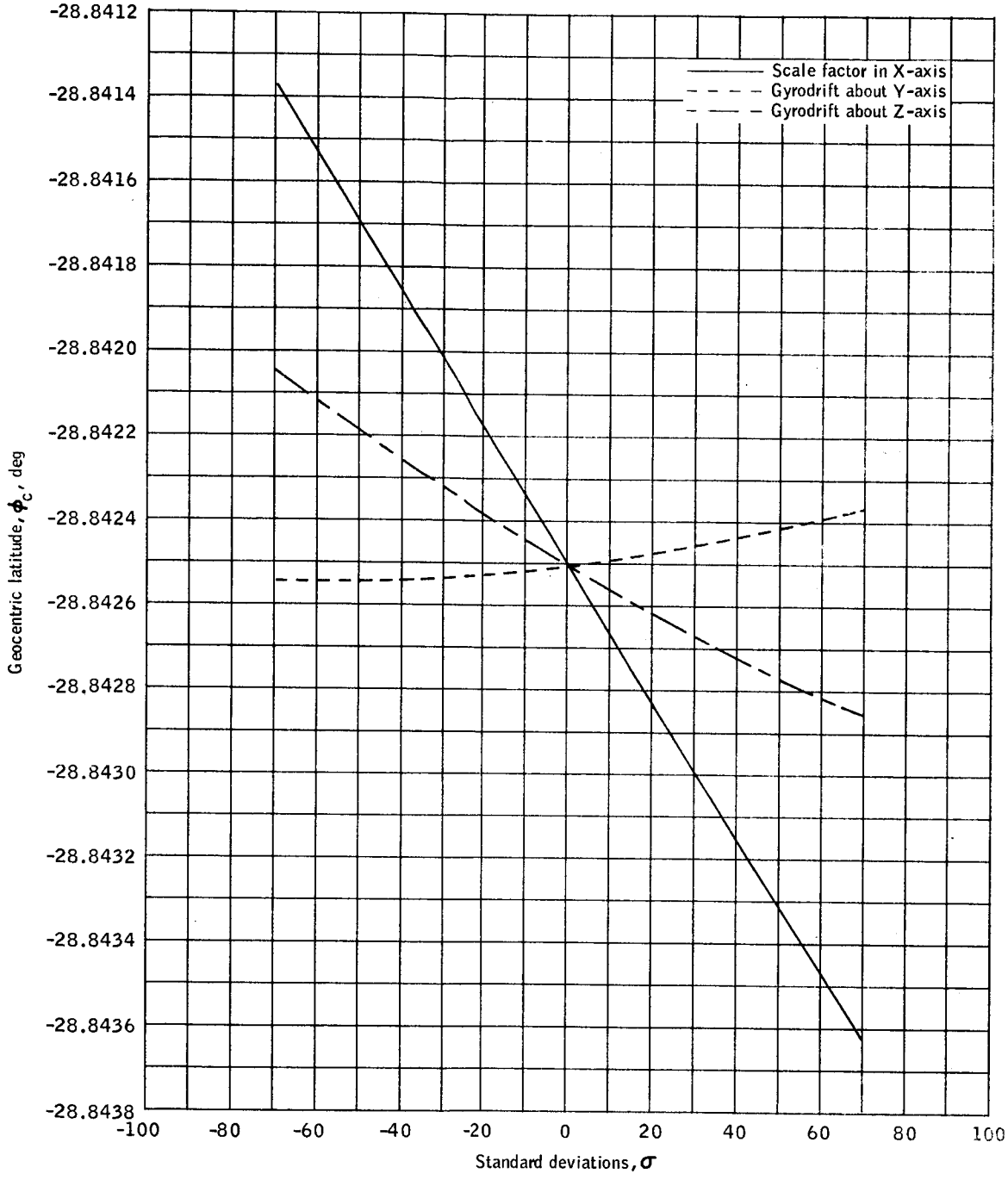
(k) Longitude versus scale factor and drift errors.

Figure 1.- Continued.



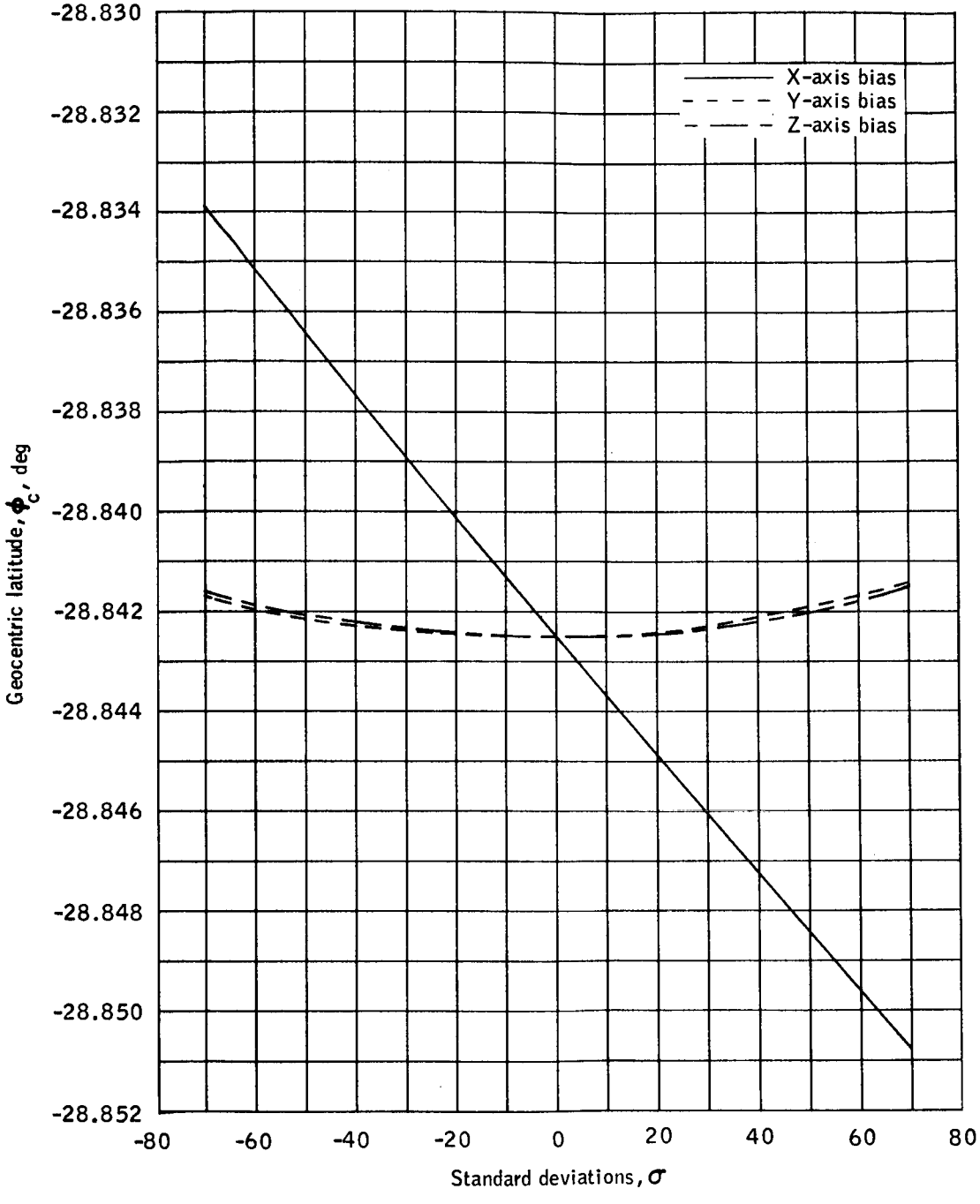
(l) Longitude versus bias errors.

Figure 1.- Continued.



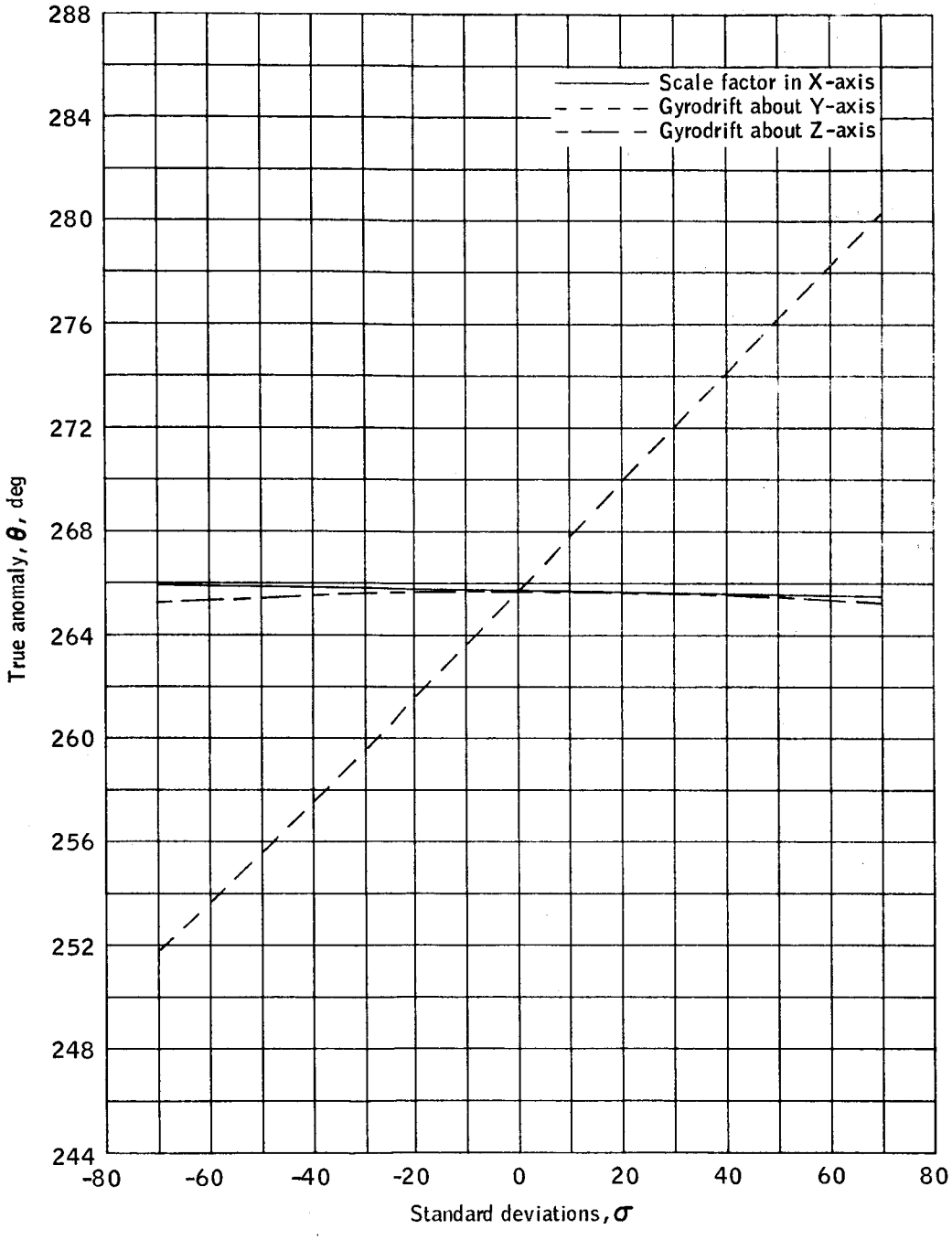
(m) Geocentric latitude versus scale factor and drift errors.

Figure 1.- Continued.



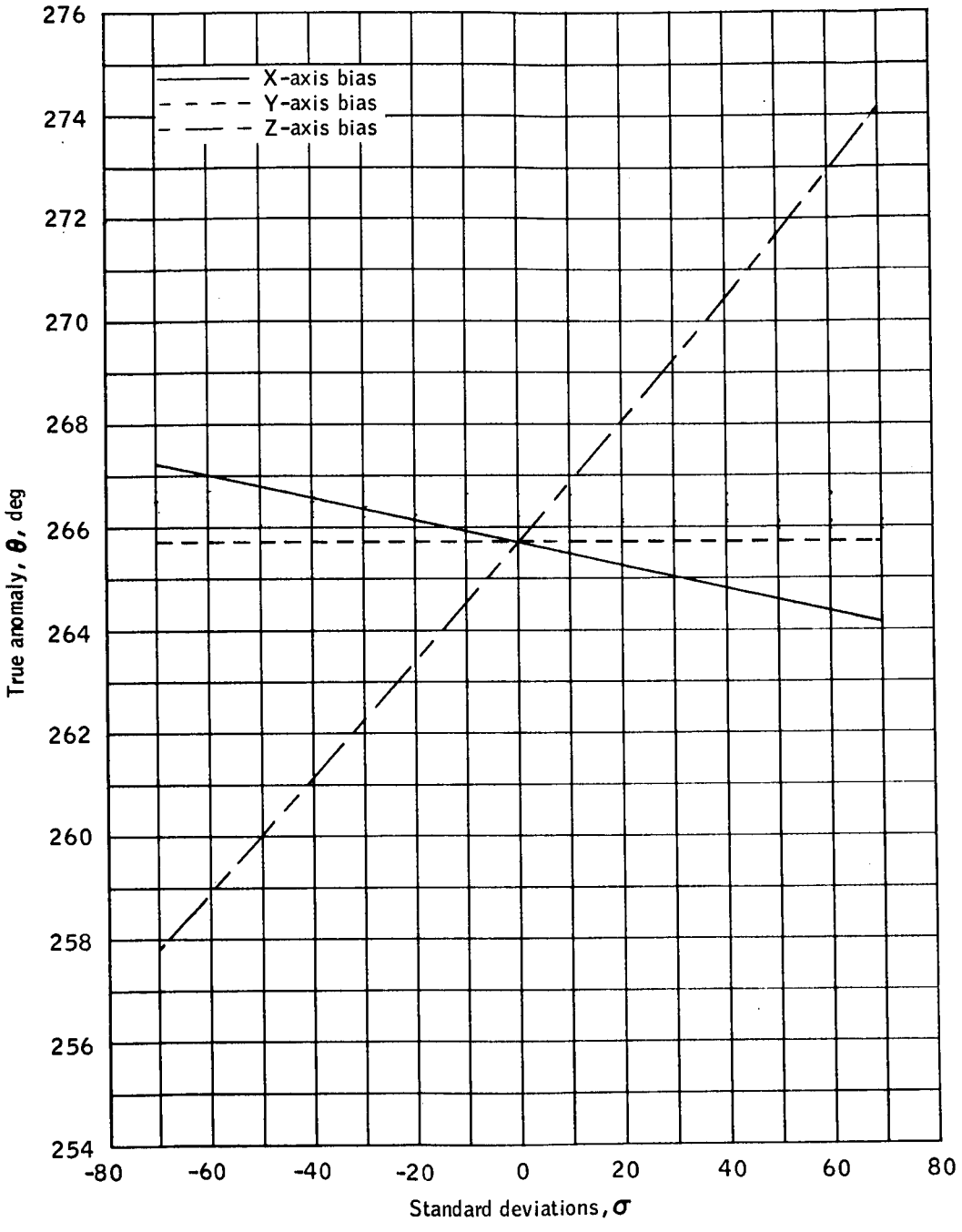
(n) Geocentric latitude versus bias errors.

Figure 1.- Continued.



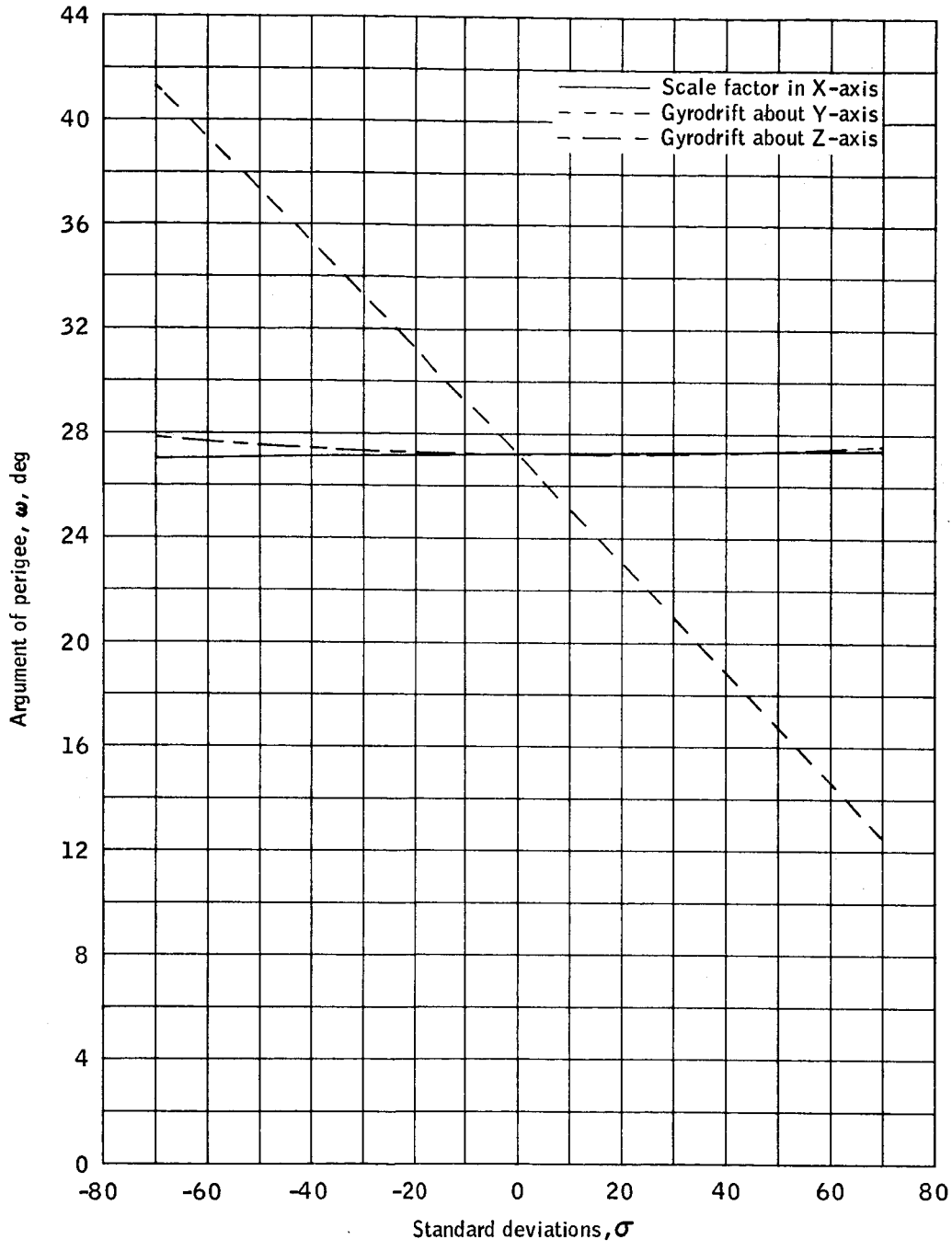
(o) True anomaly versus scale factor and drift errors.

Figure 1.- Continued.



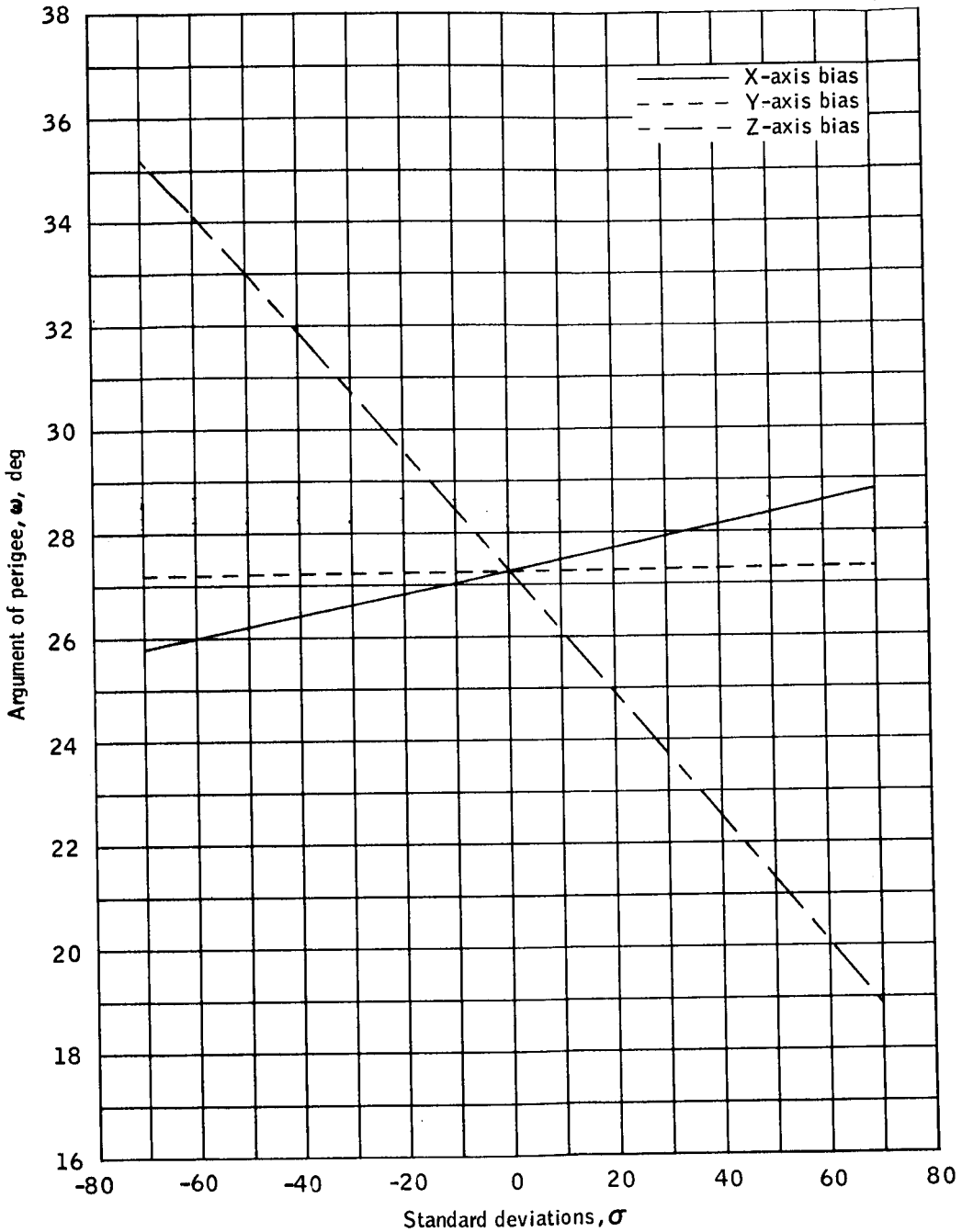
(p) True anomaly versus bias errors.

Figure 1.- Continued.



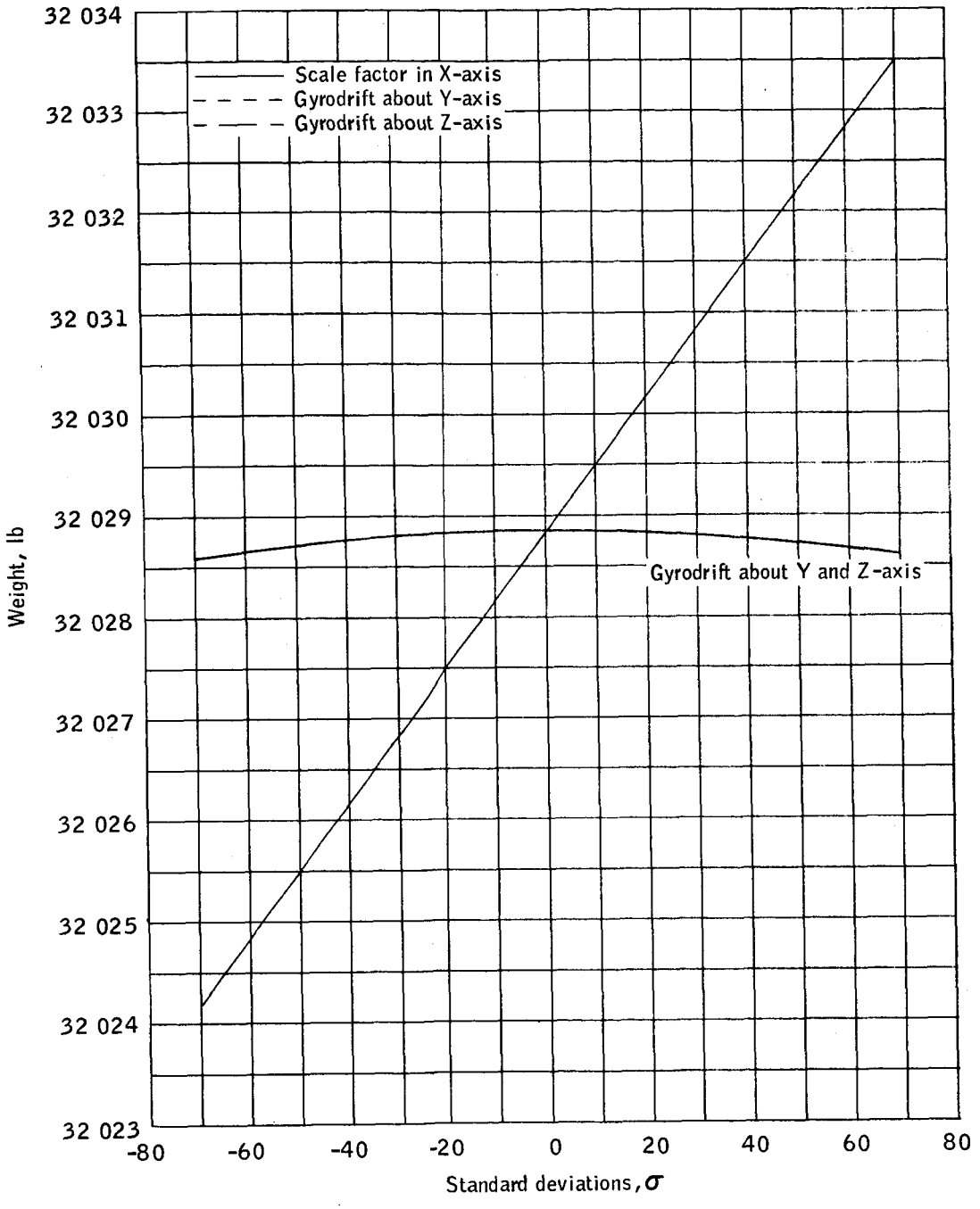
(q) Argument of perigee versus scale factor and drift errors.

Figure 1.- Continued.



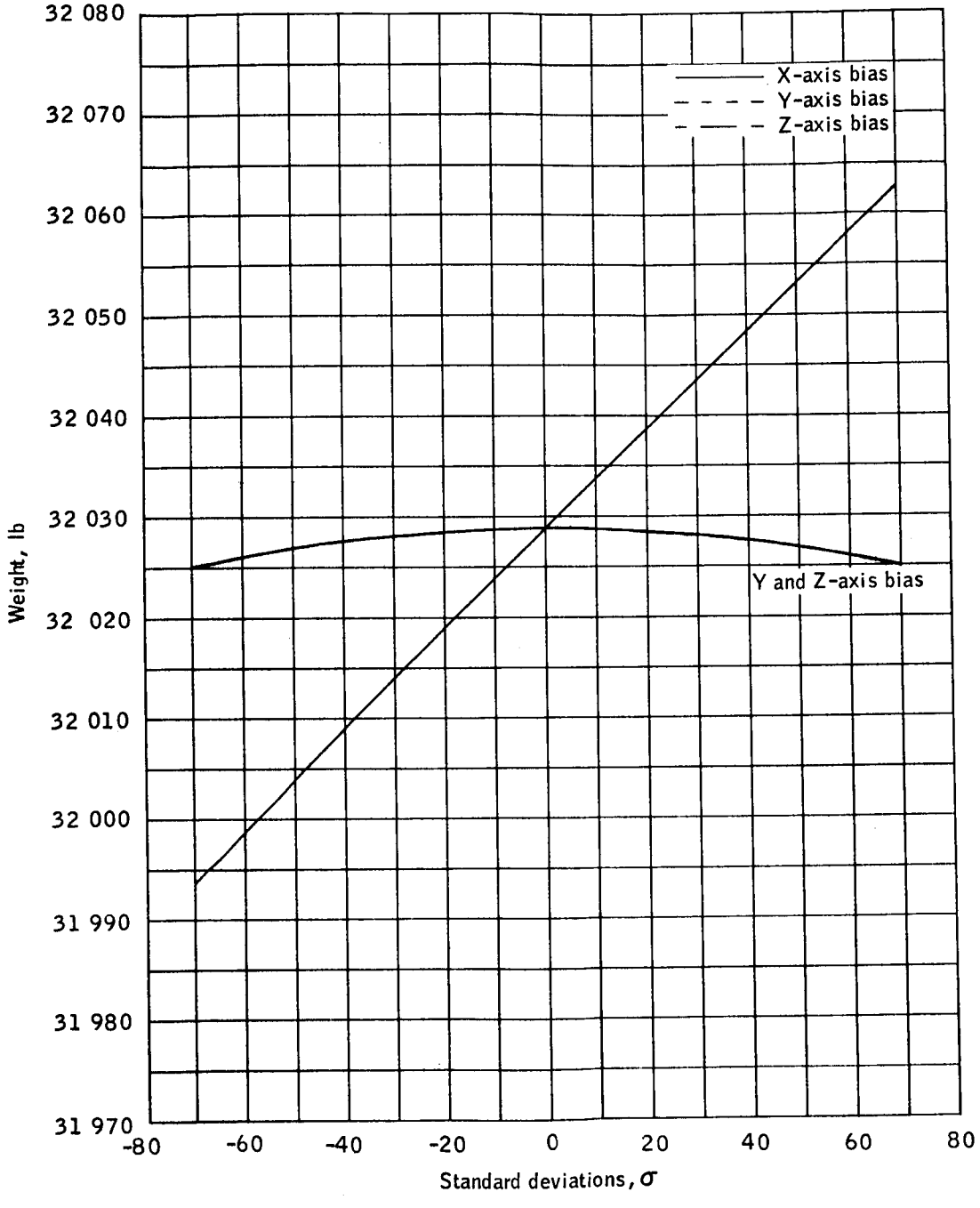
(r) Argument of perigee versus bias errors.

Figure 1.- Continued.



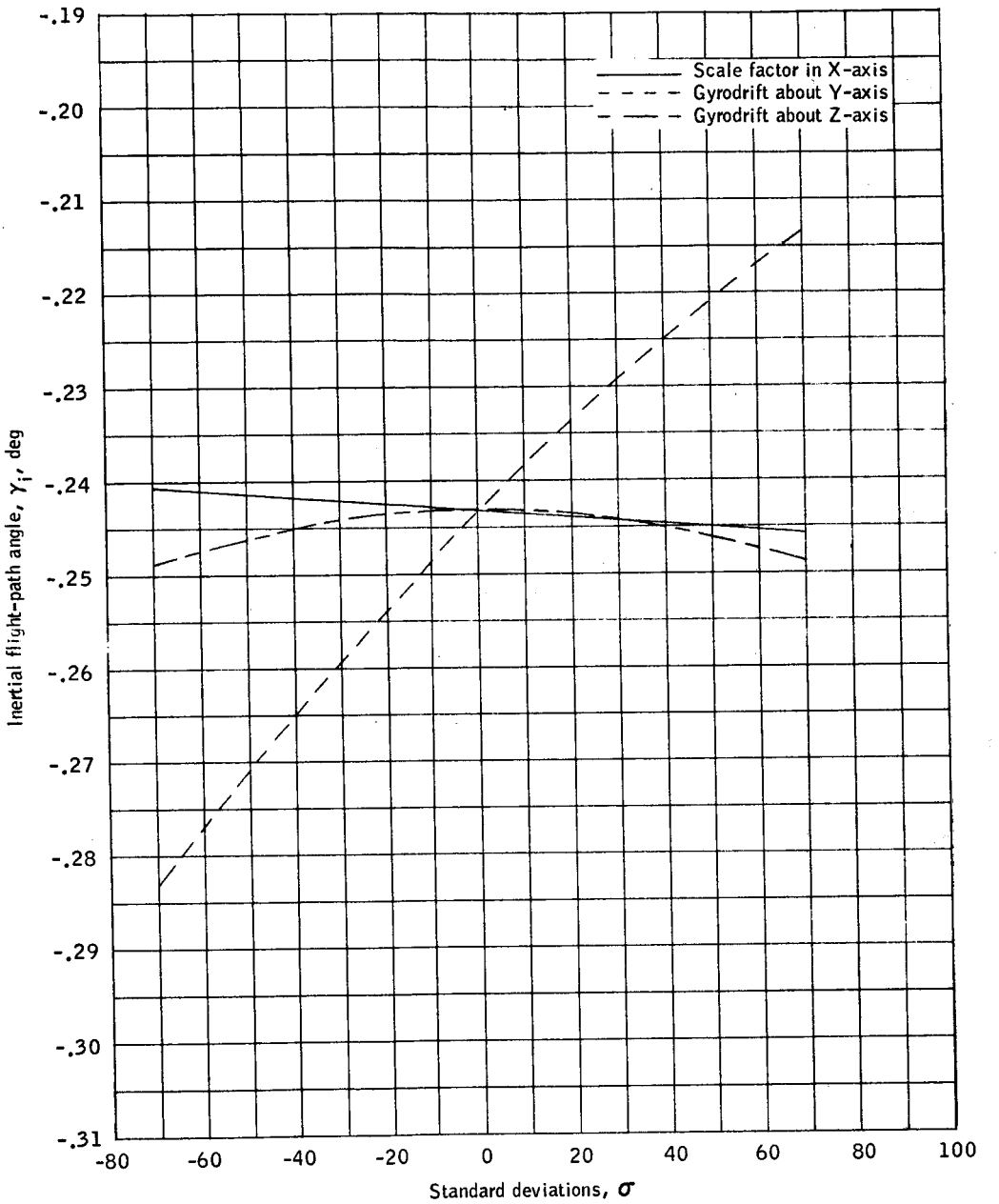
(s) Weight versus scale factor and drift errors.

Figure 1.- Continued.



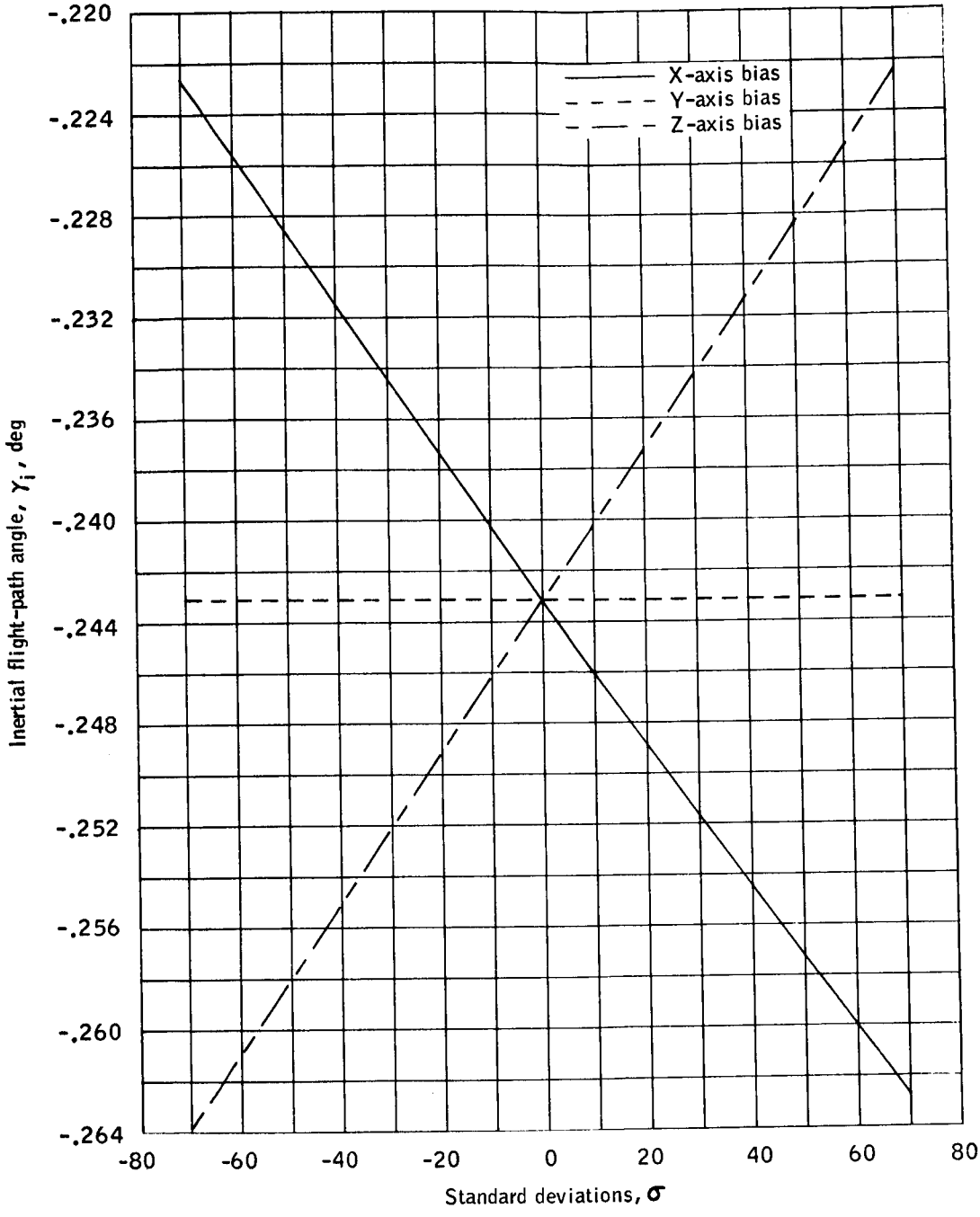
(t) Weight versus bias errors.

Figure 1.- Concluded.



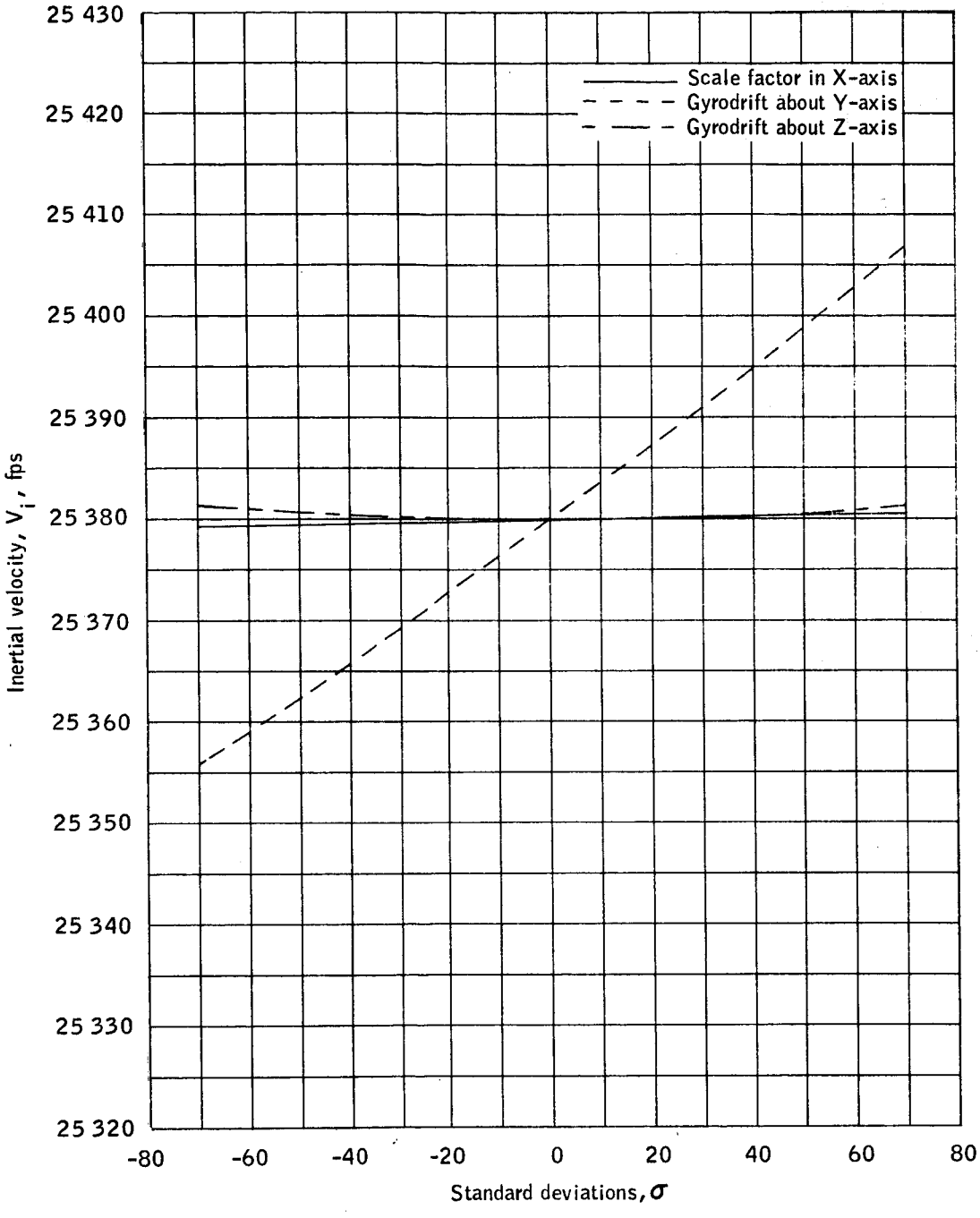
(a) Inertial flight-path angle versus scale factor and drift errors.

Figure 2.- Mission C dispersions at the end of the second SPS burn due to accelerometer bias, accelerometer scale factor and gyrodrift errors.



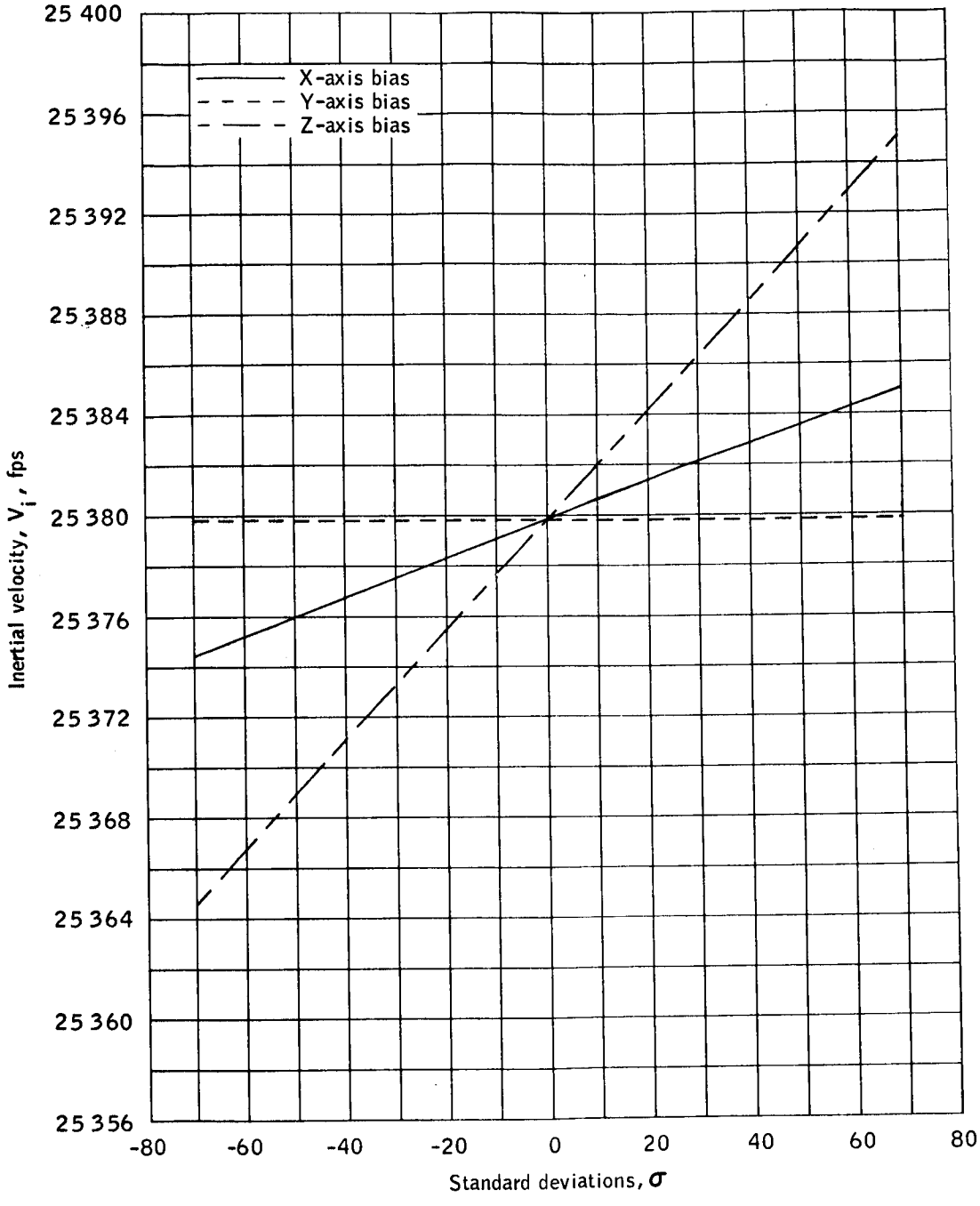
(b) Inertial flight-path angle versus bias errors.

Figure 2.- Continued.



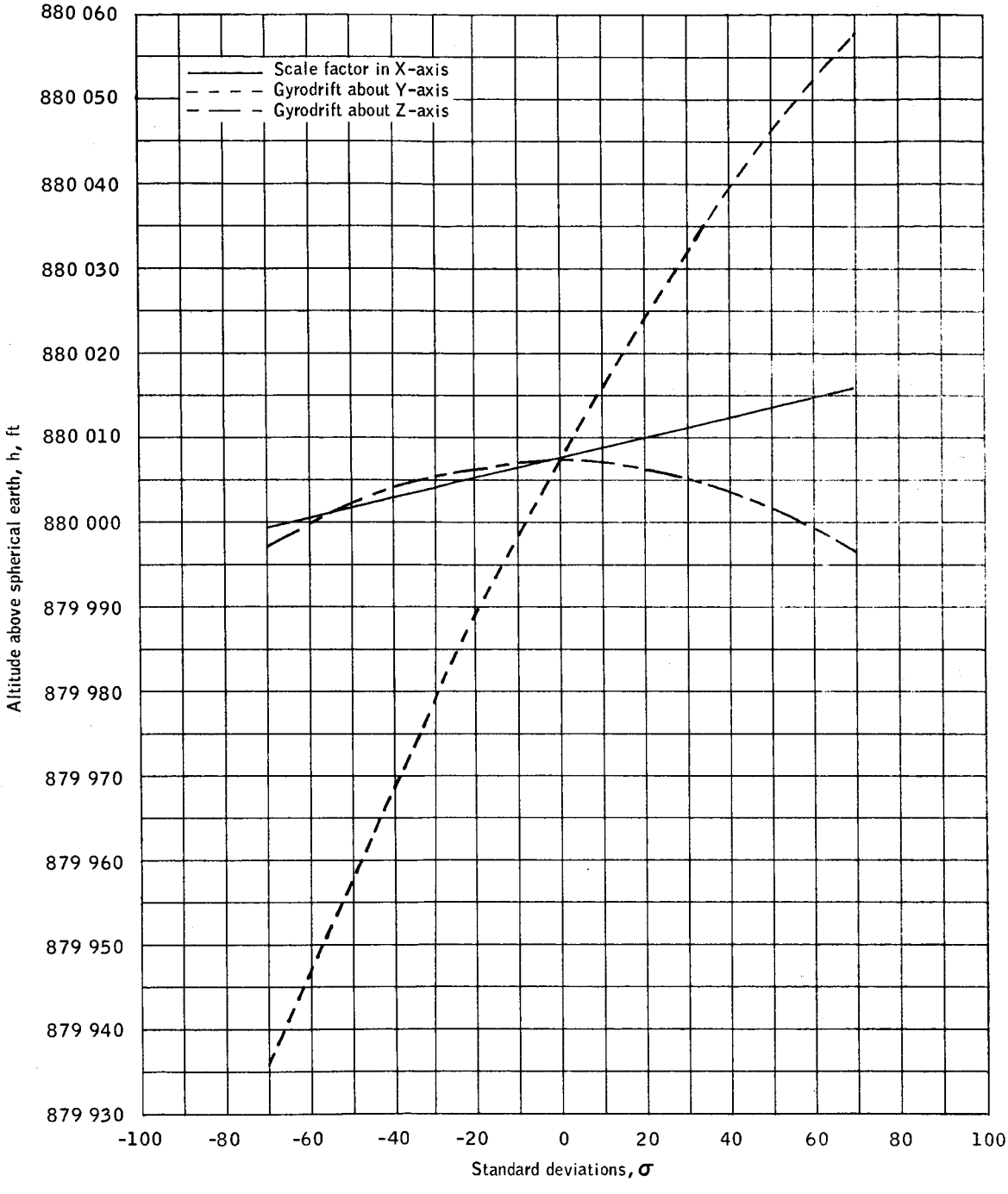
(c) Inertial velocity versus scale factor and drift errors.

Figure 2.- Continued.



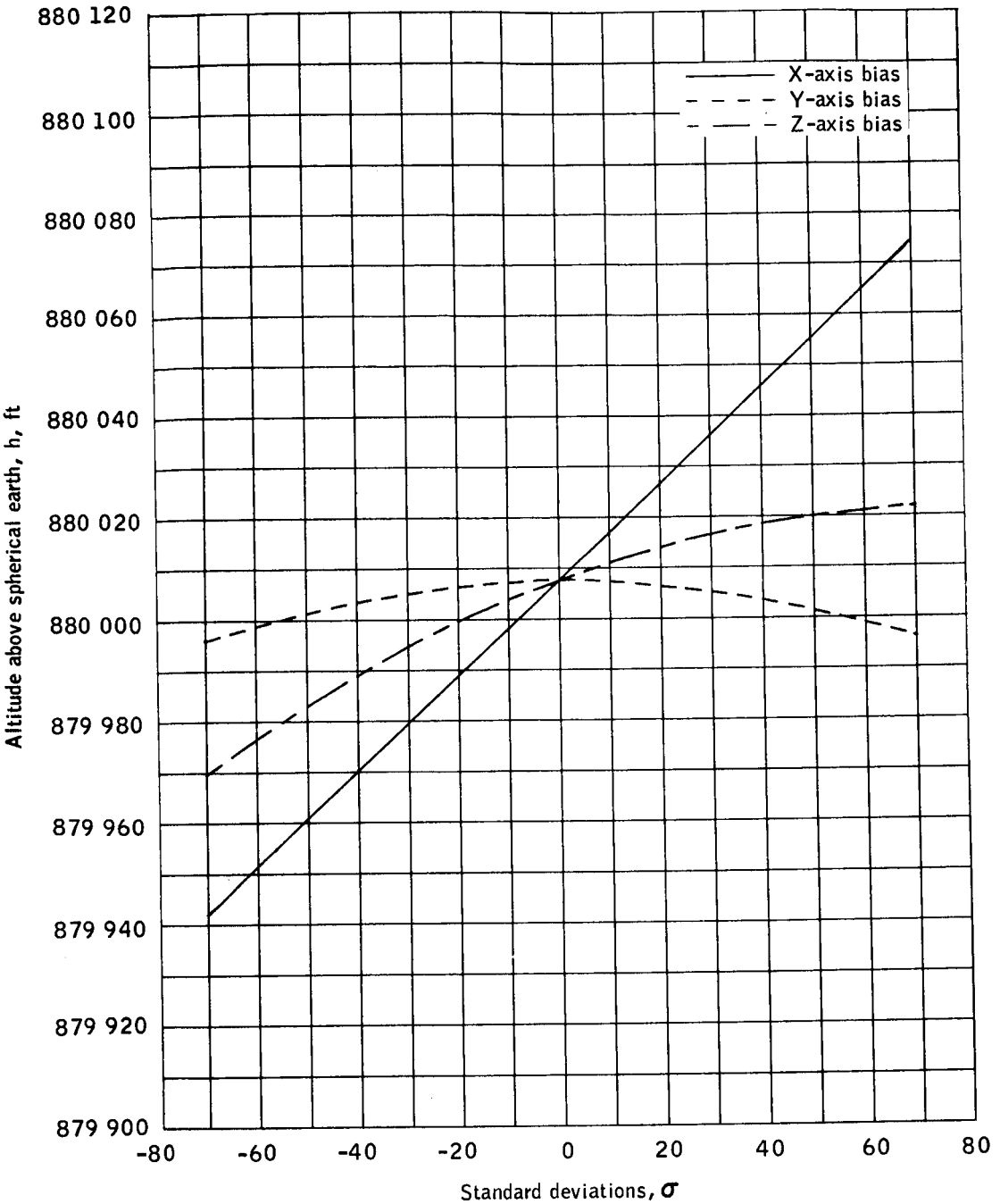
(d) Inertial velocity versus bias errors.

Figure 2.- Continued.



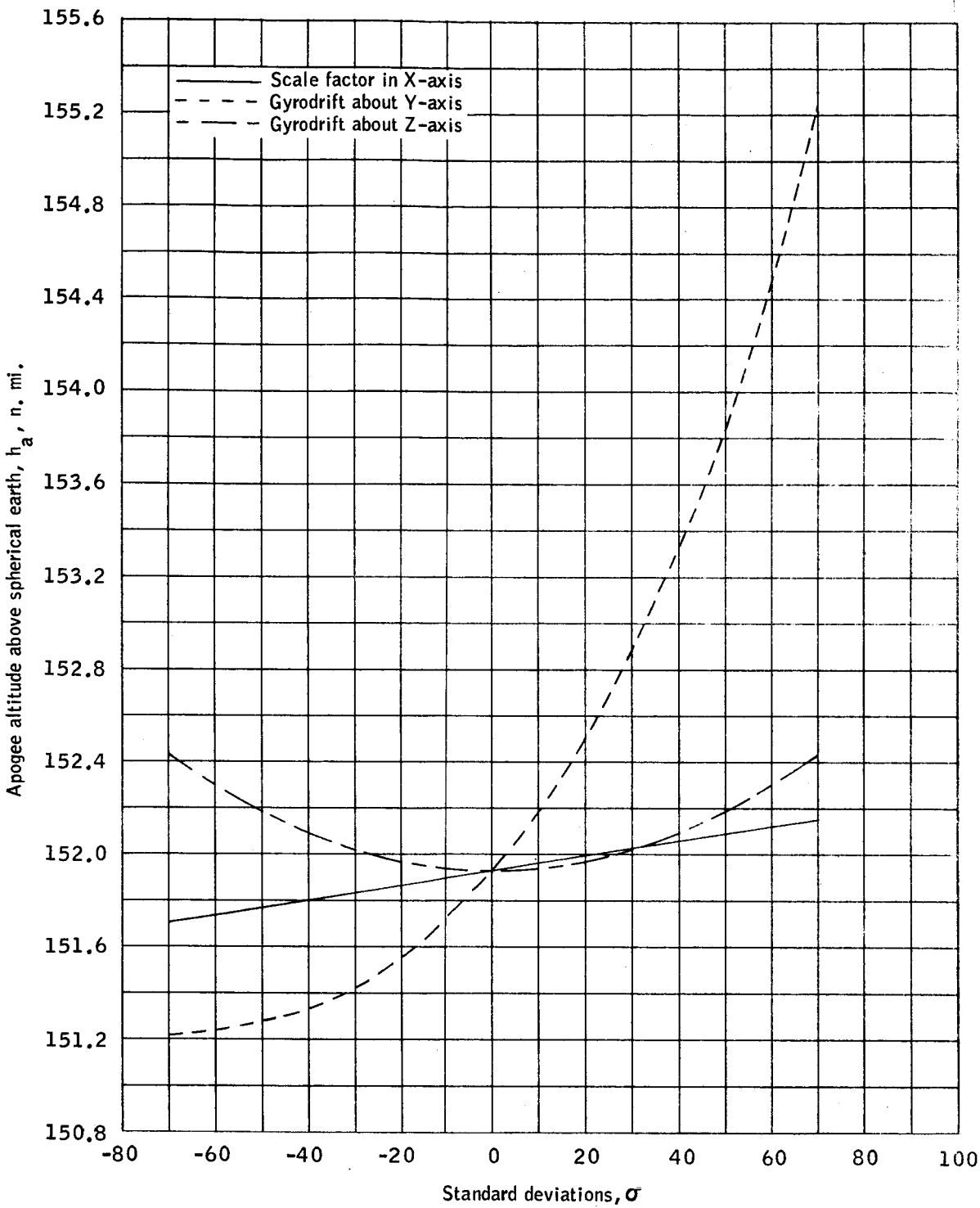
(e) Altitude above spherical earth versus scale factor and drift errors.

Figure 2.- Continued.



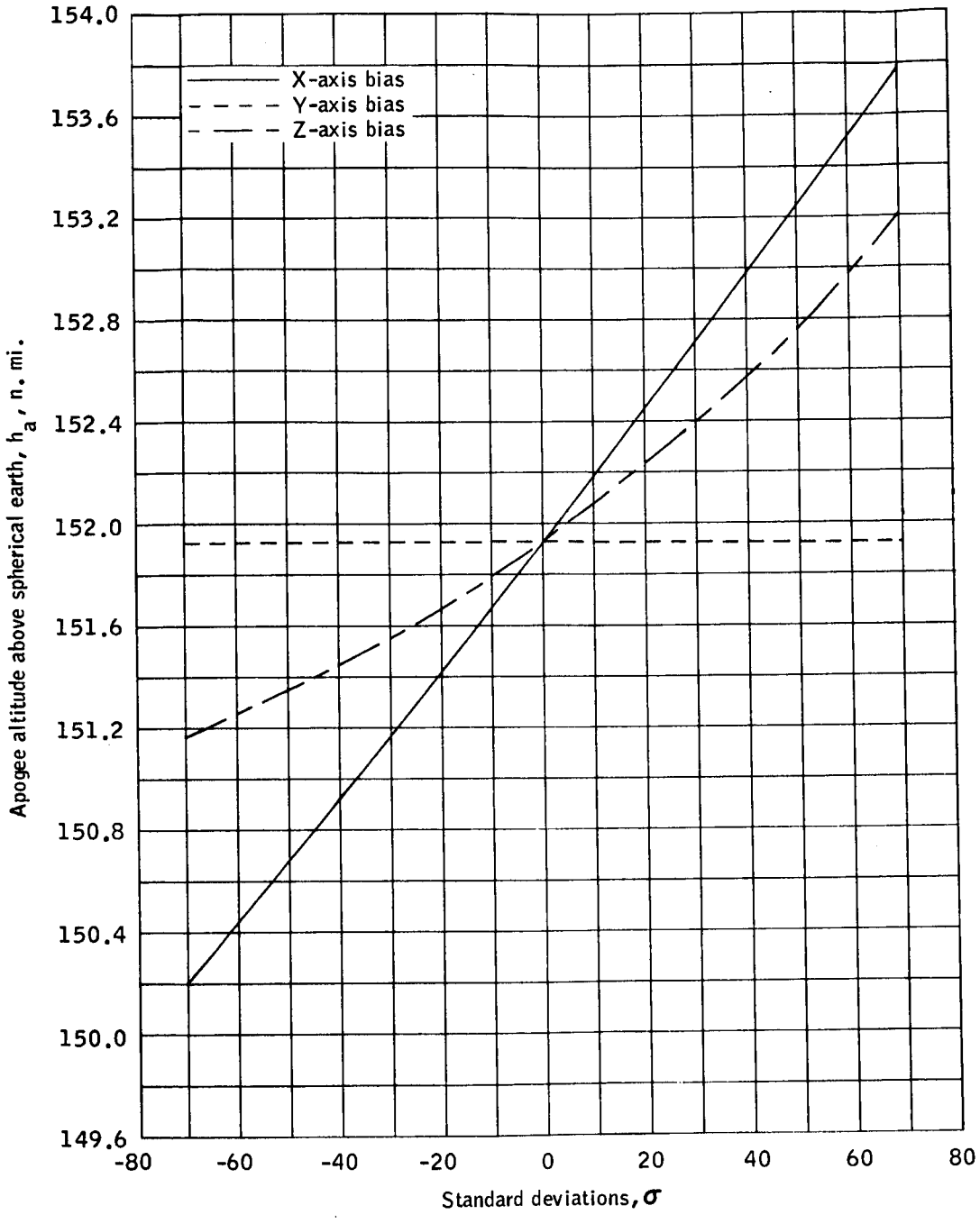
(f) Altitude above spherical earth versus bias errors.

Figure 2.- Continued.



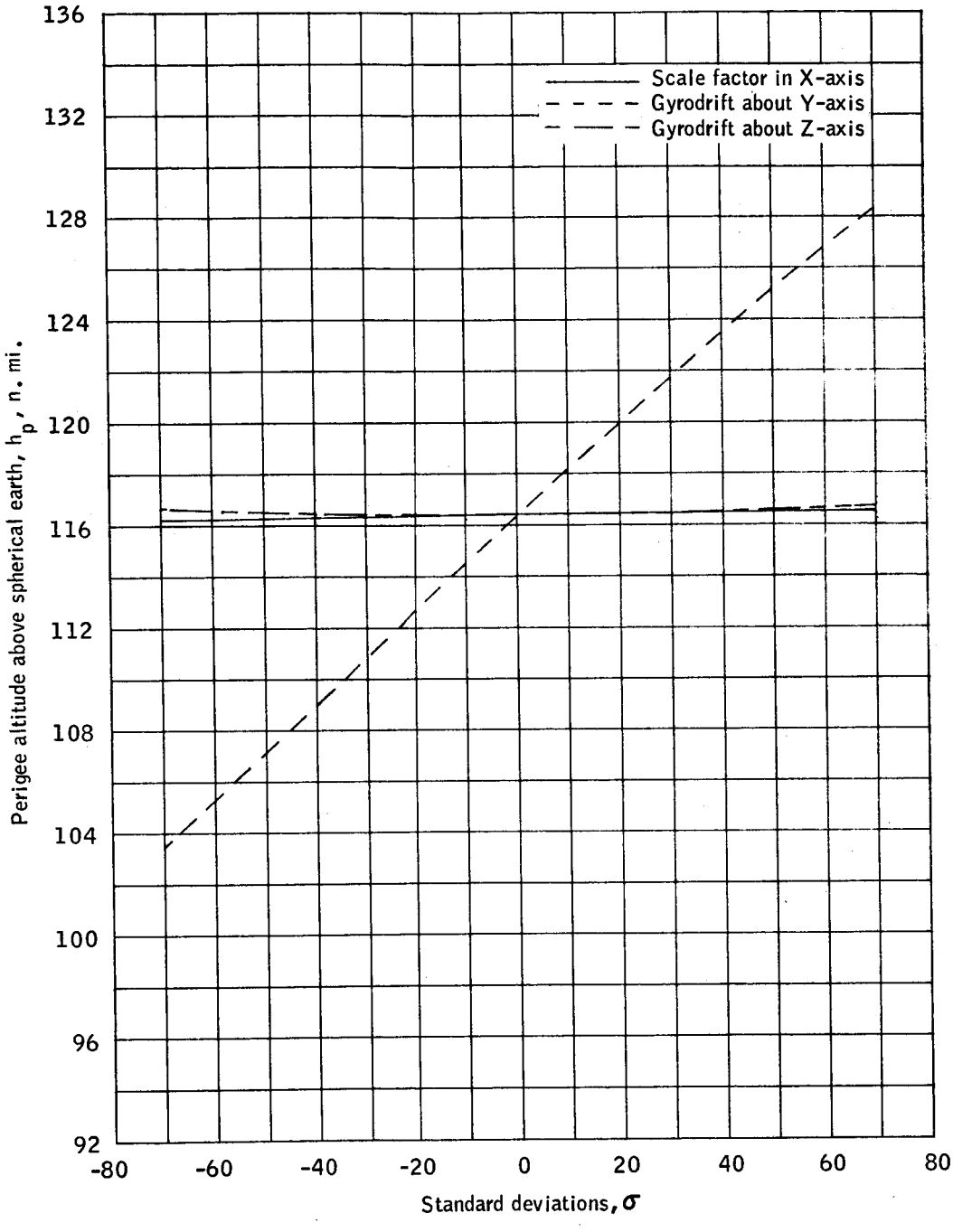
(g) Apogee altitude above spherical earth versus scale factor and drift errors.

Figure 2.- Continued.



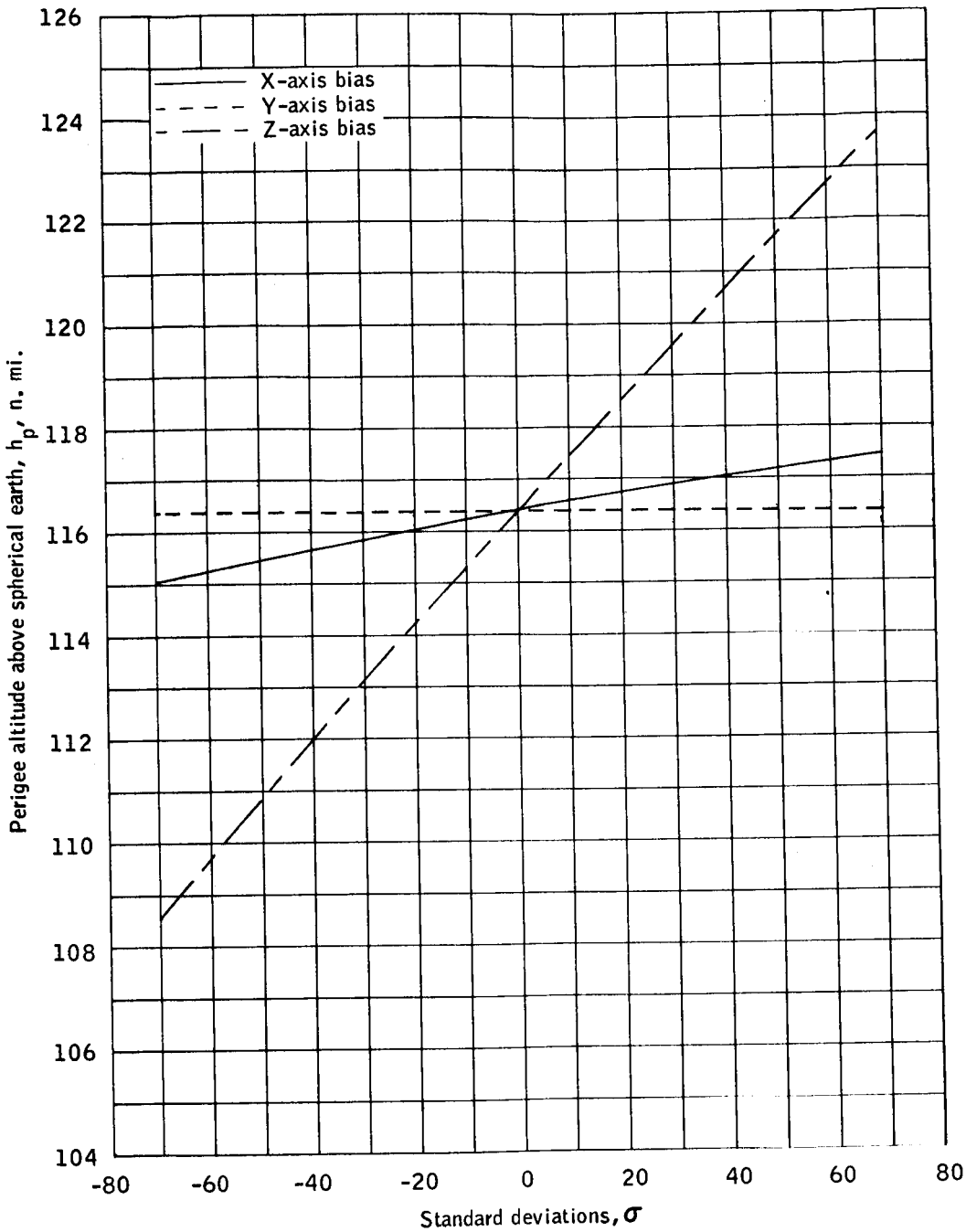
(h) Apogee altitude above spherical earth versus bias errors.

Figure 2.- Continued.



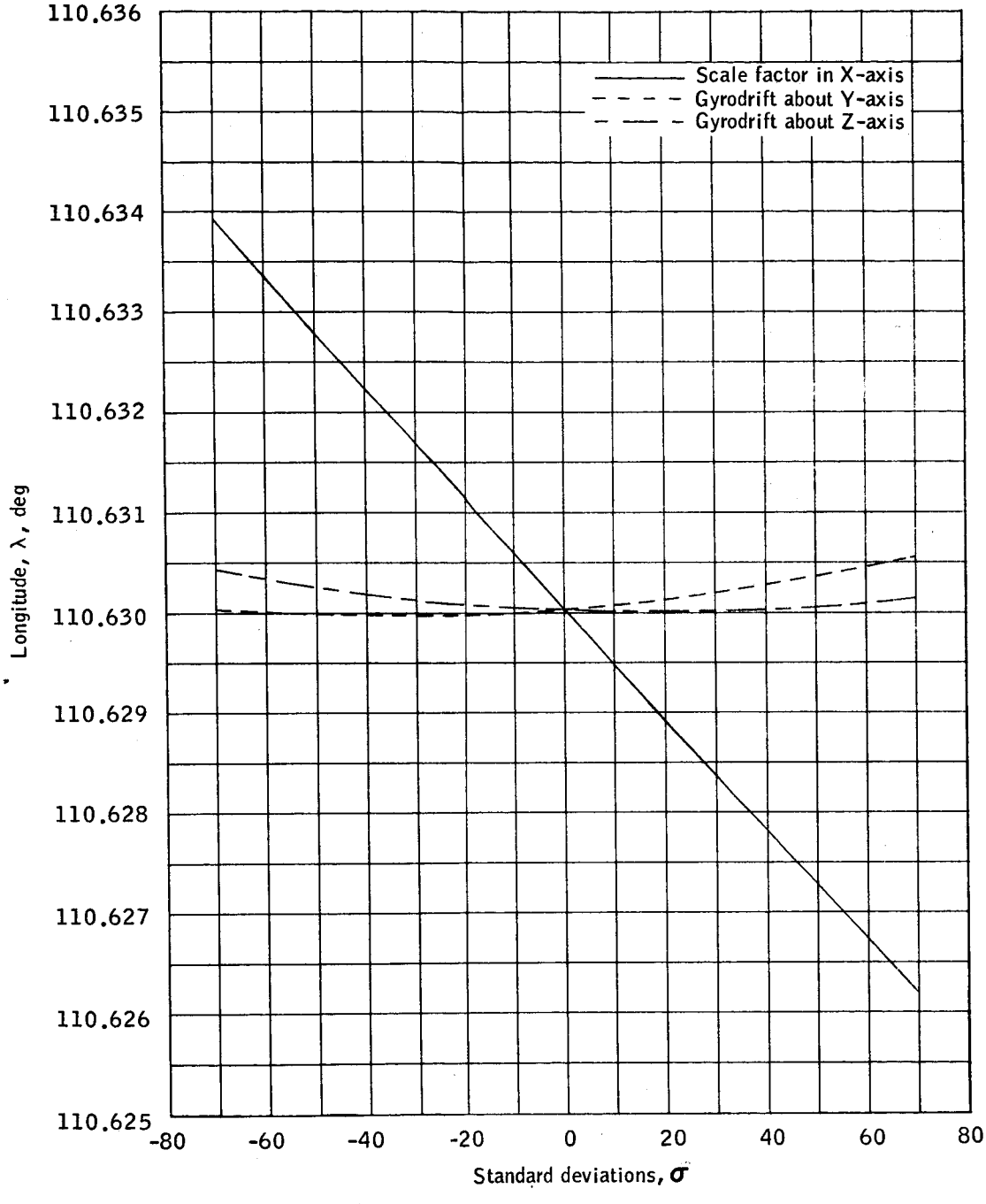
(i) Perigee altitude above spherical earth versus scale factor and drift errors.

Figure 2.- Continued.



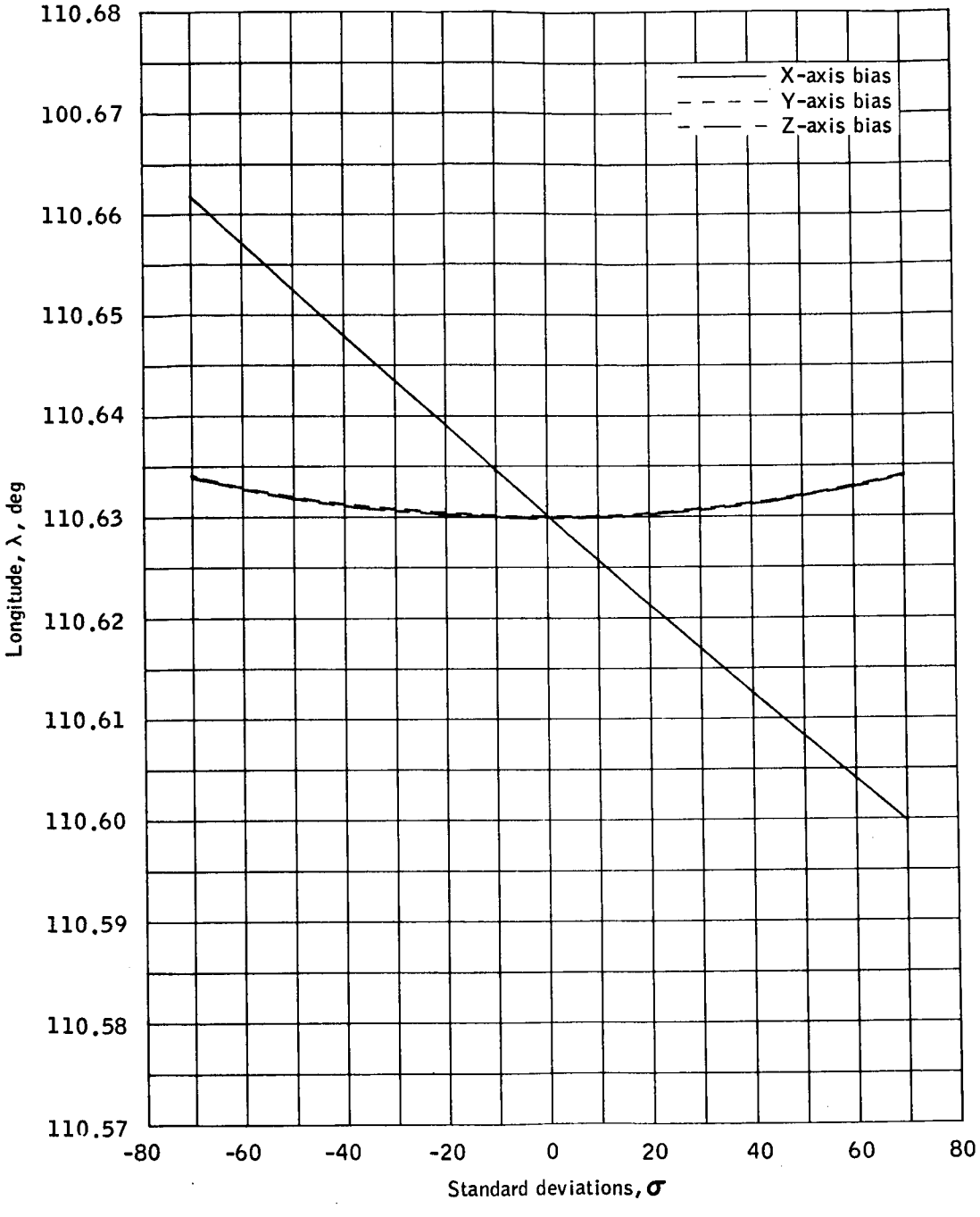
(j) Perigee altitude above spherical earth versus bias errors.

Figure 2.- Continued.



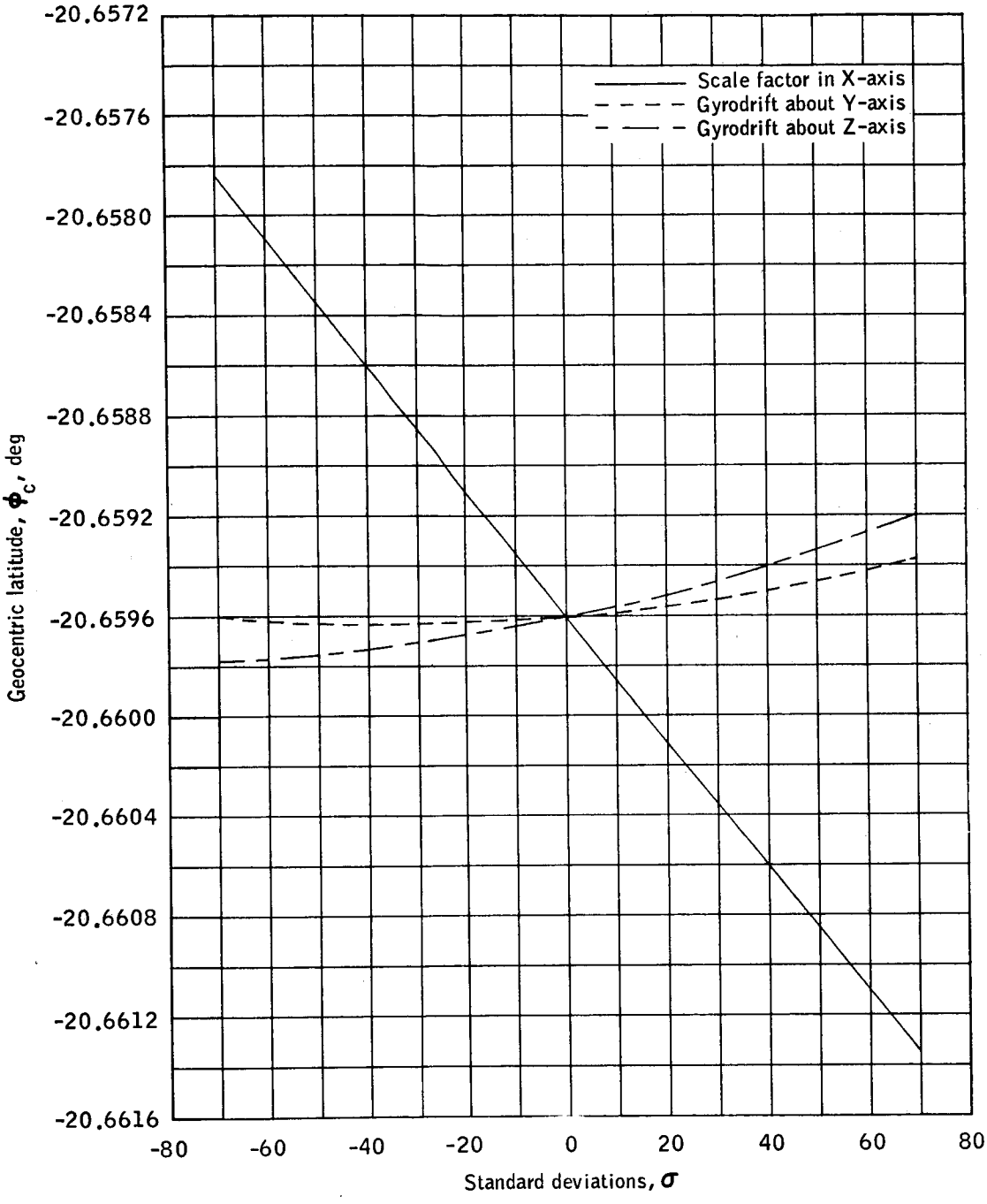
(k) Longitude versus scale factor and drift errors.

Figure 2.- Continued.



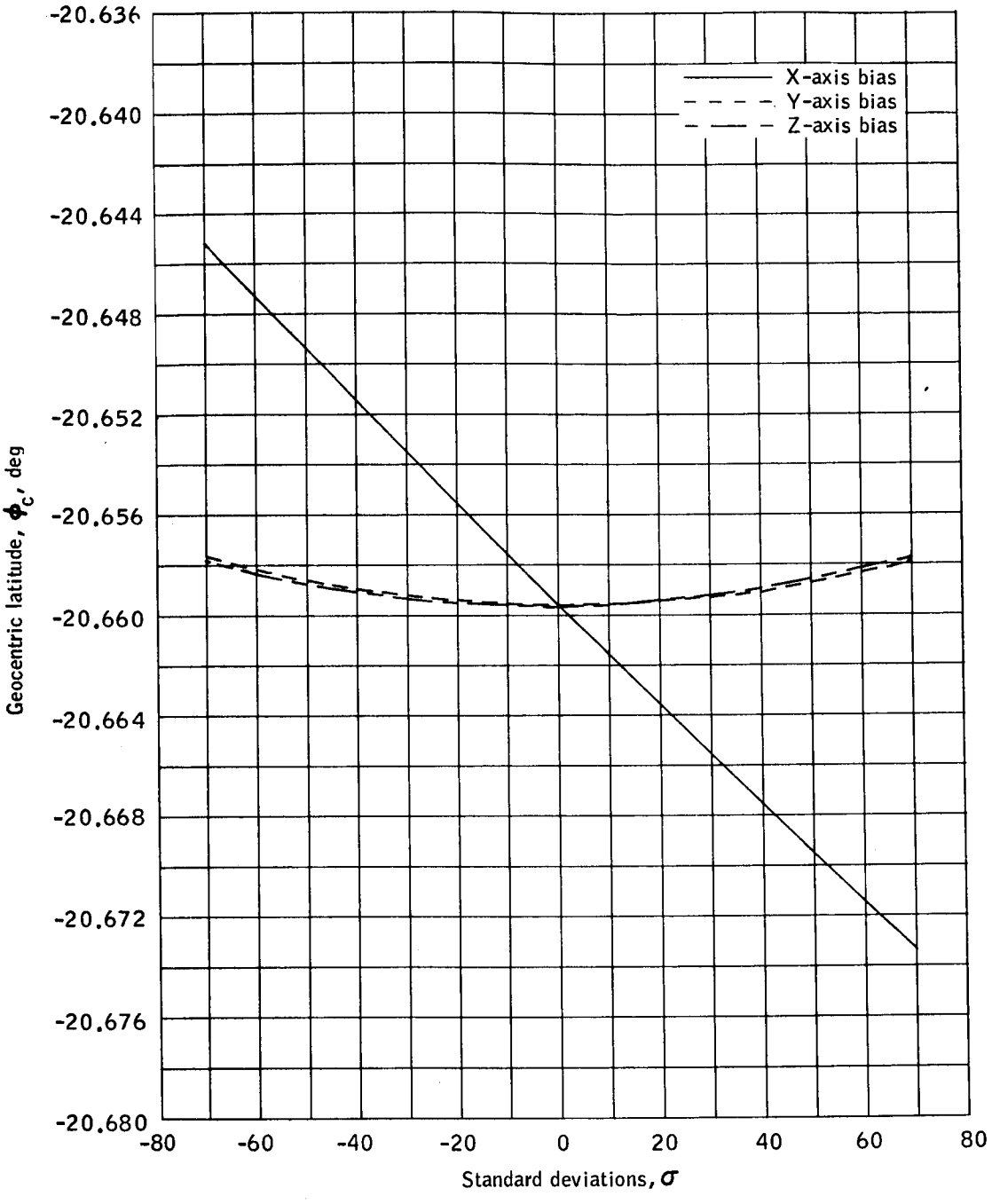
(l) Longitude versus bias errors.

Figure 2.- Continued.



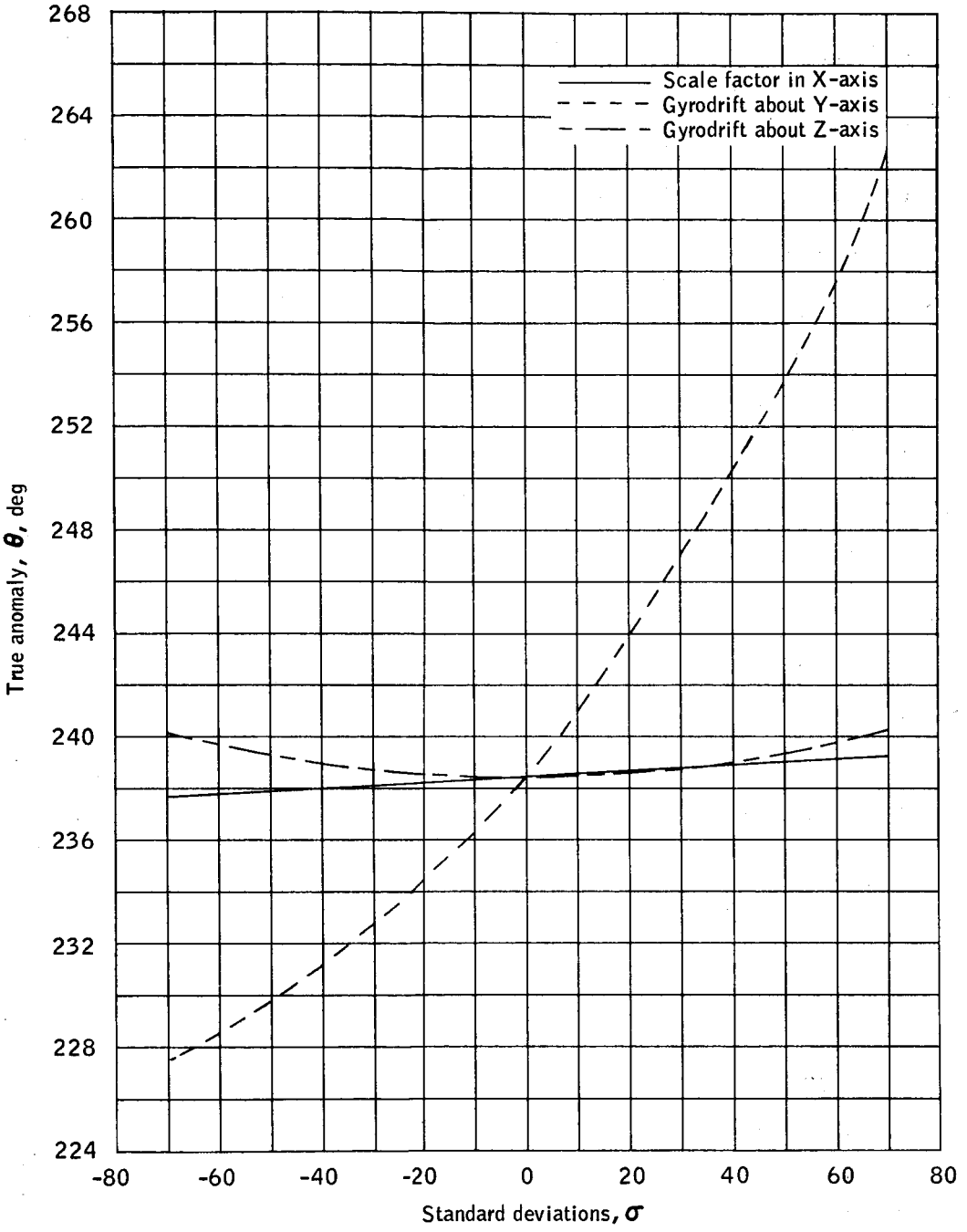
(m) Geocentric latitude versus scale factor and drift errors.

Figure 2.- Continued.



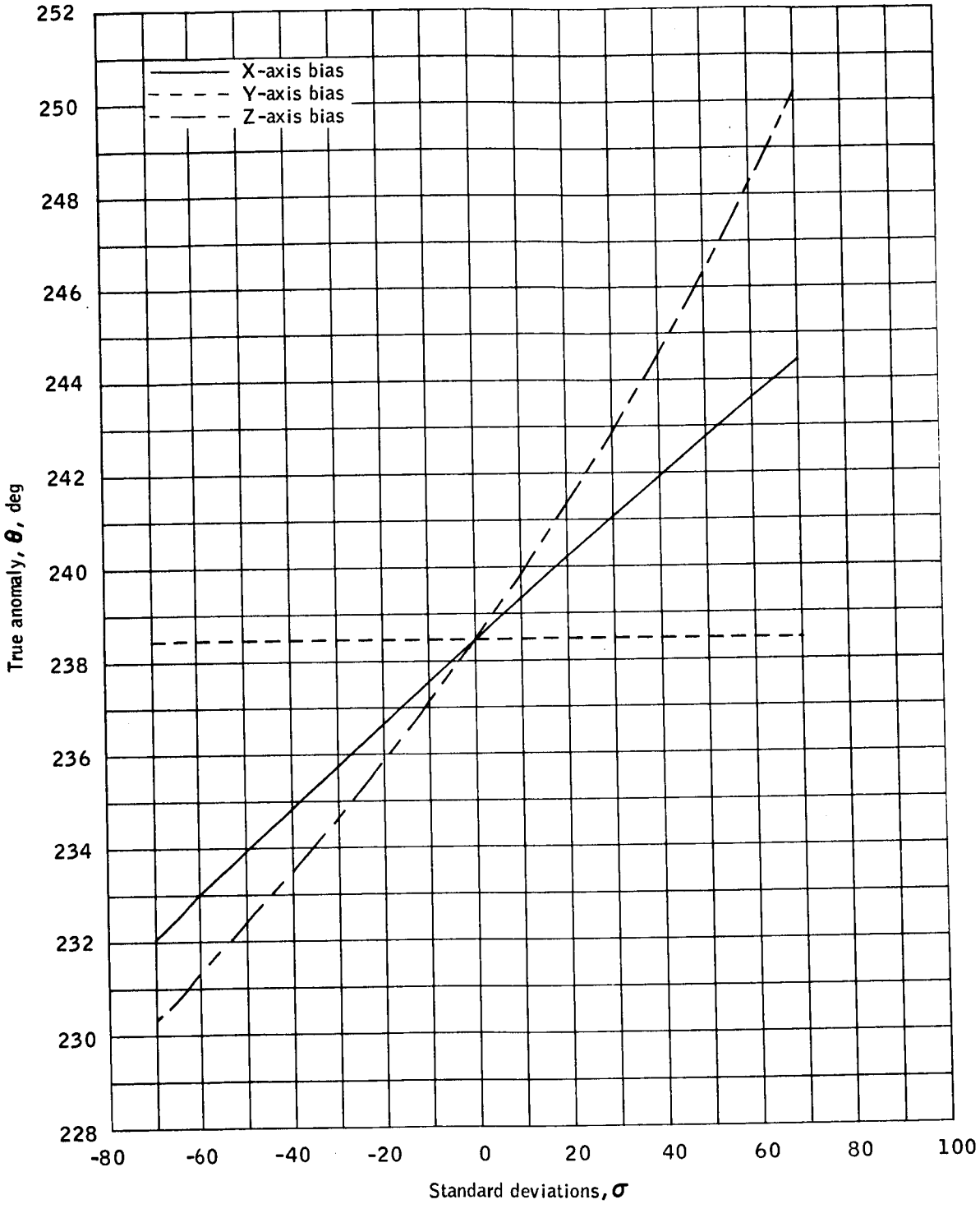
(n) Geocentric latitude versus bias errors.

Figure 2.- Continued.



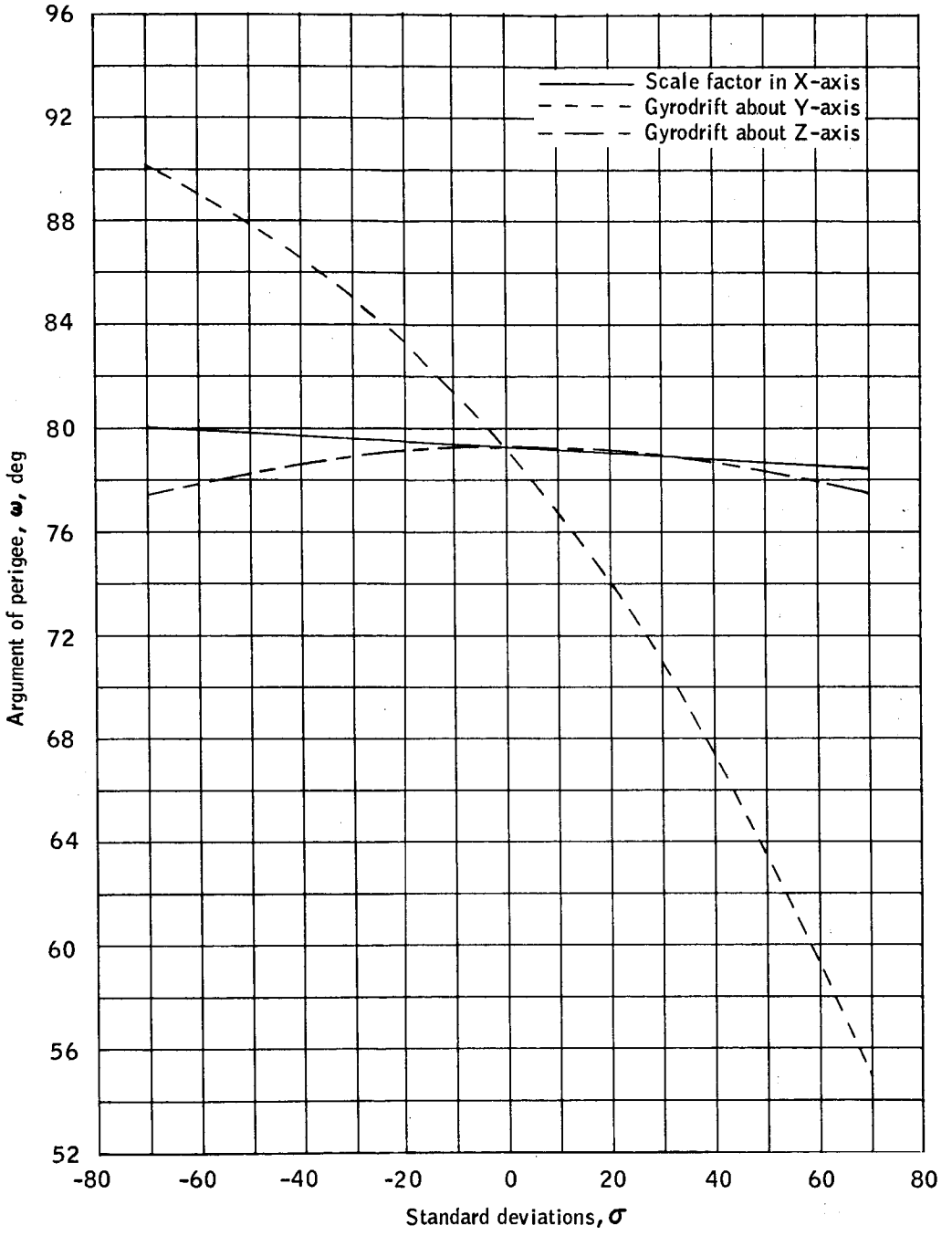
(o) True anomaly versus scale factor and drift errors.

Figure 2.- Continued.



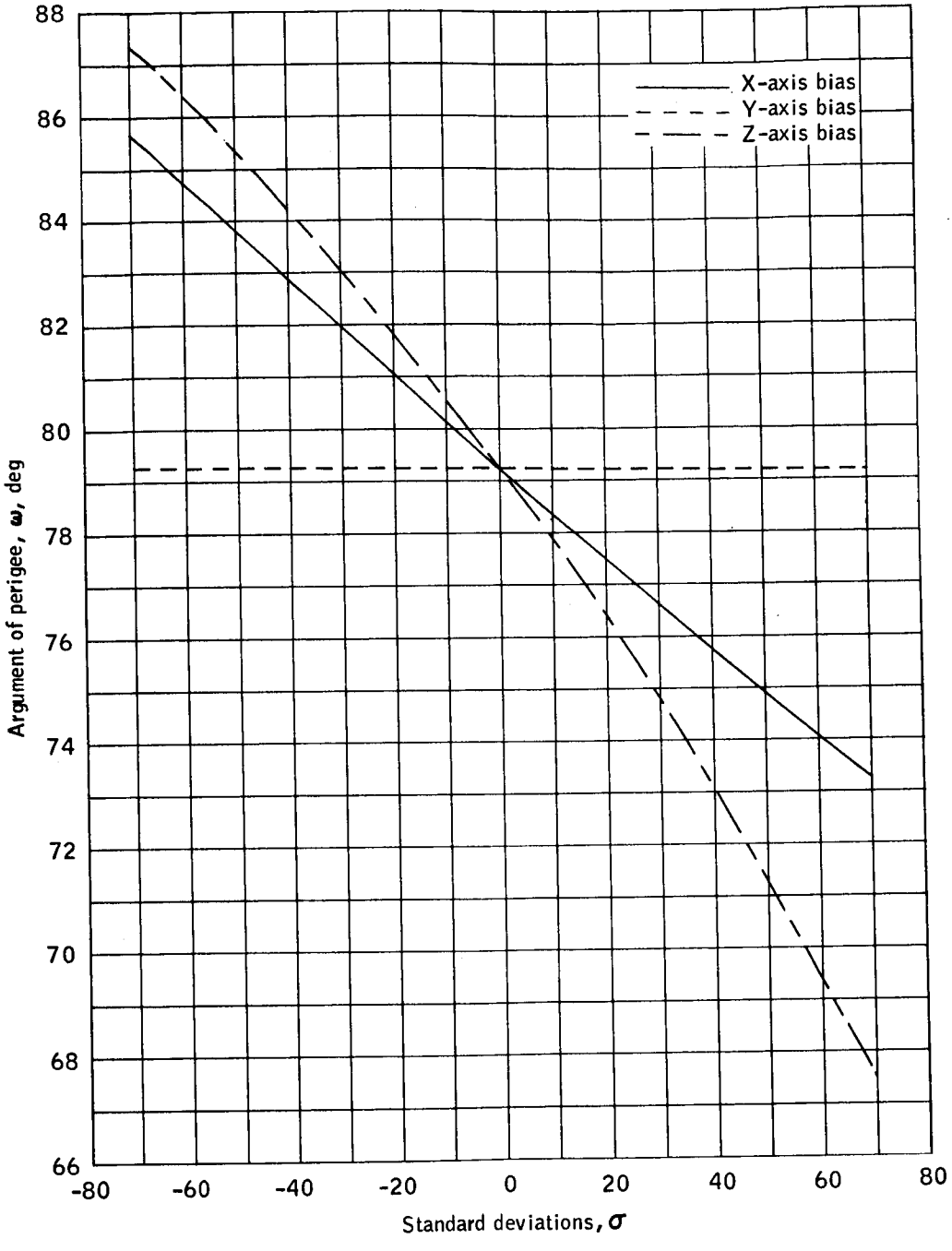
(p) True anomaly versus bias errors.

Figure 2.- Continued.



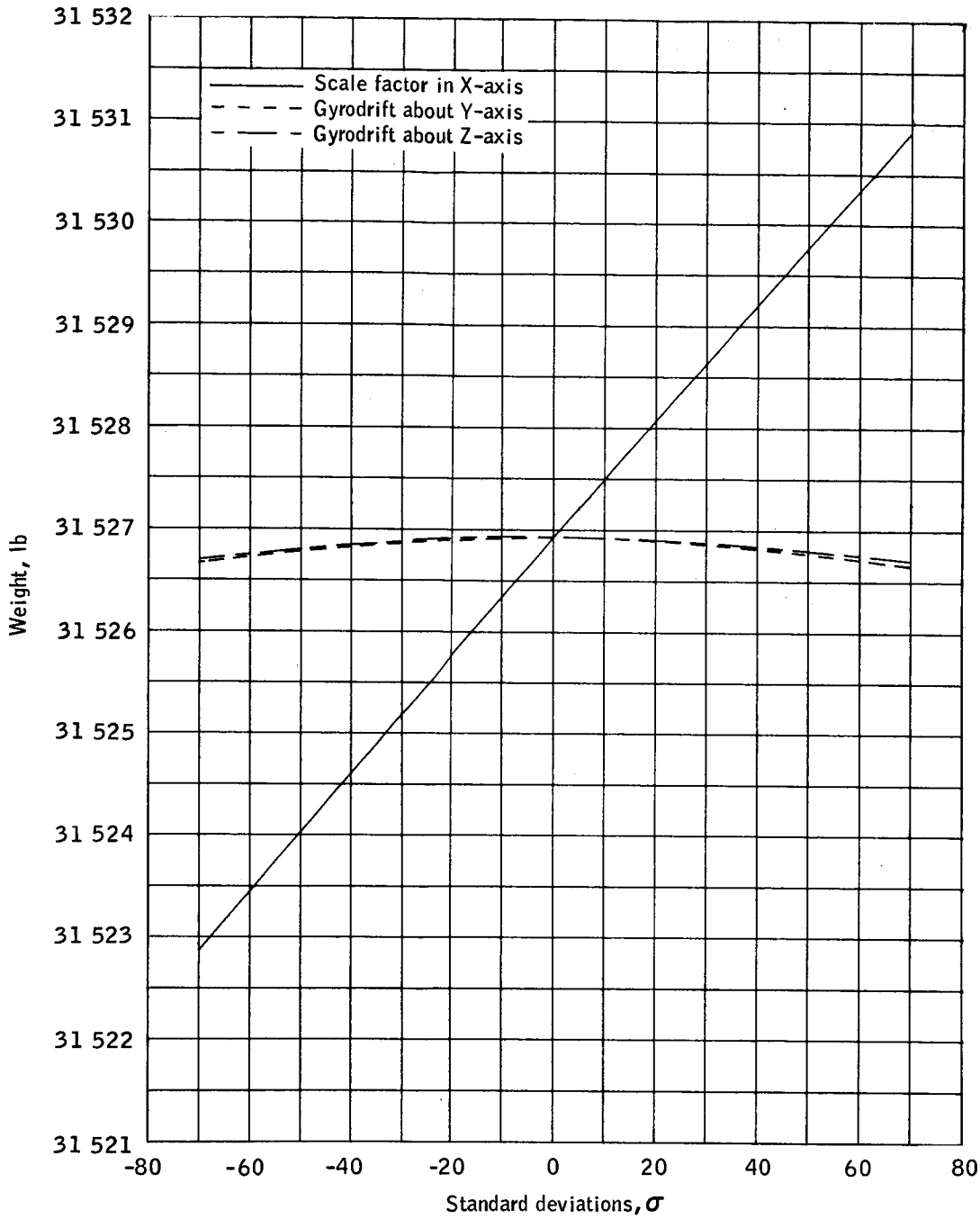
(q) Argument of perigee versus scale factor and drift errors.

Figure 2.- Continued.



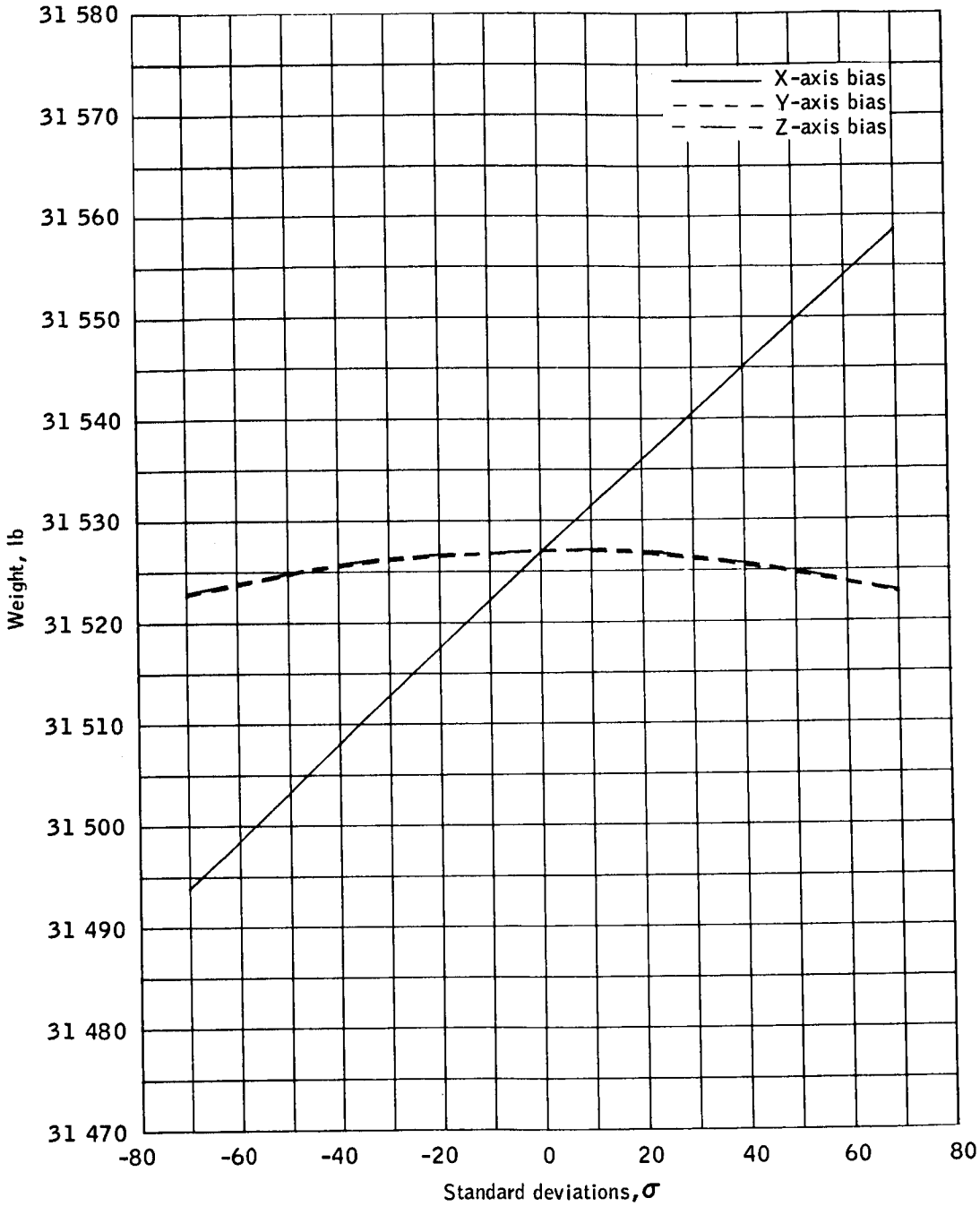
(r) Argument of perigee versus bias errors.

Figure 2.- Continued.



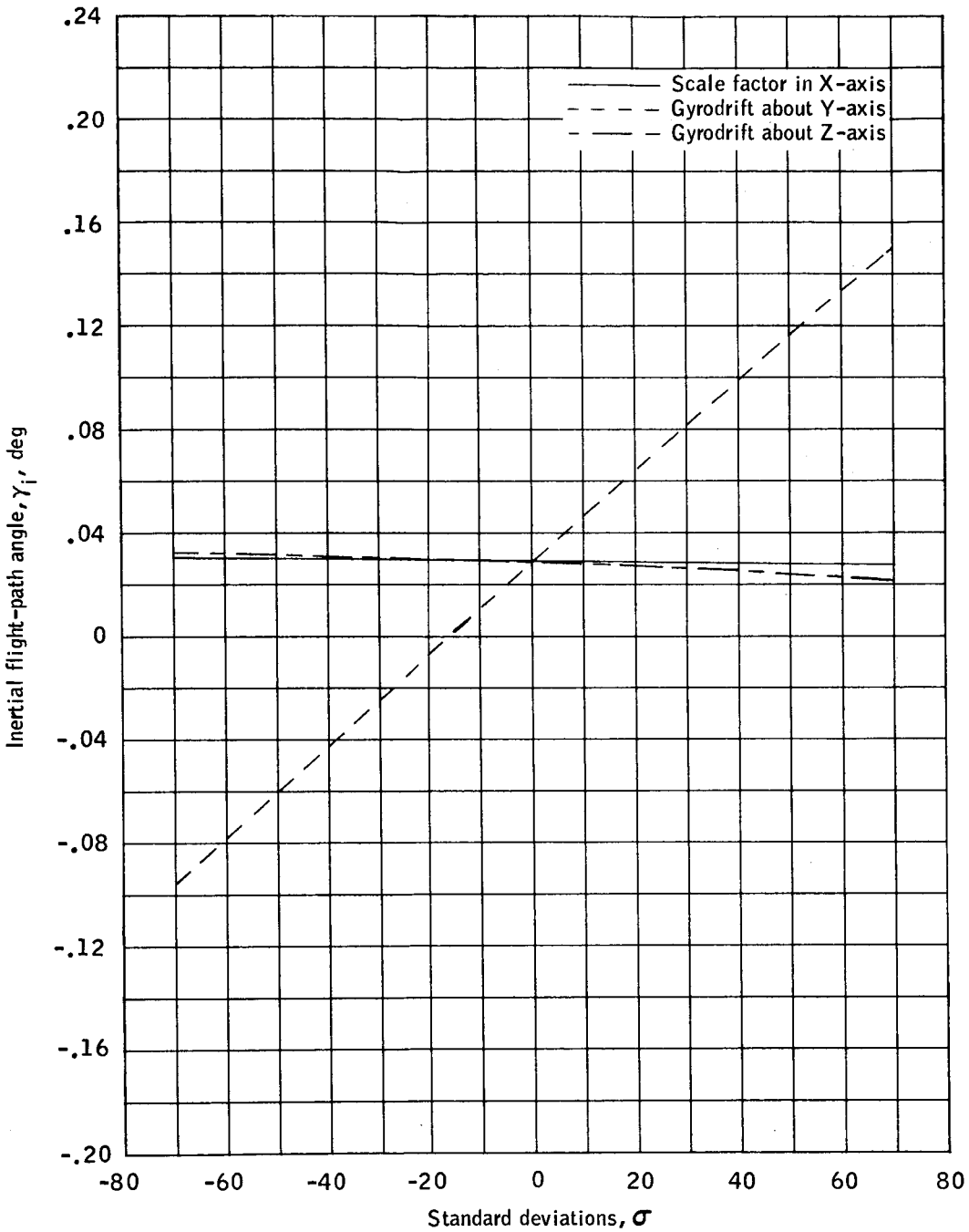
(s) Weight versus scale factor and drift errors.

Figure 2.- Continued.



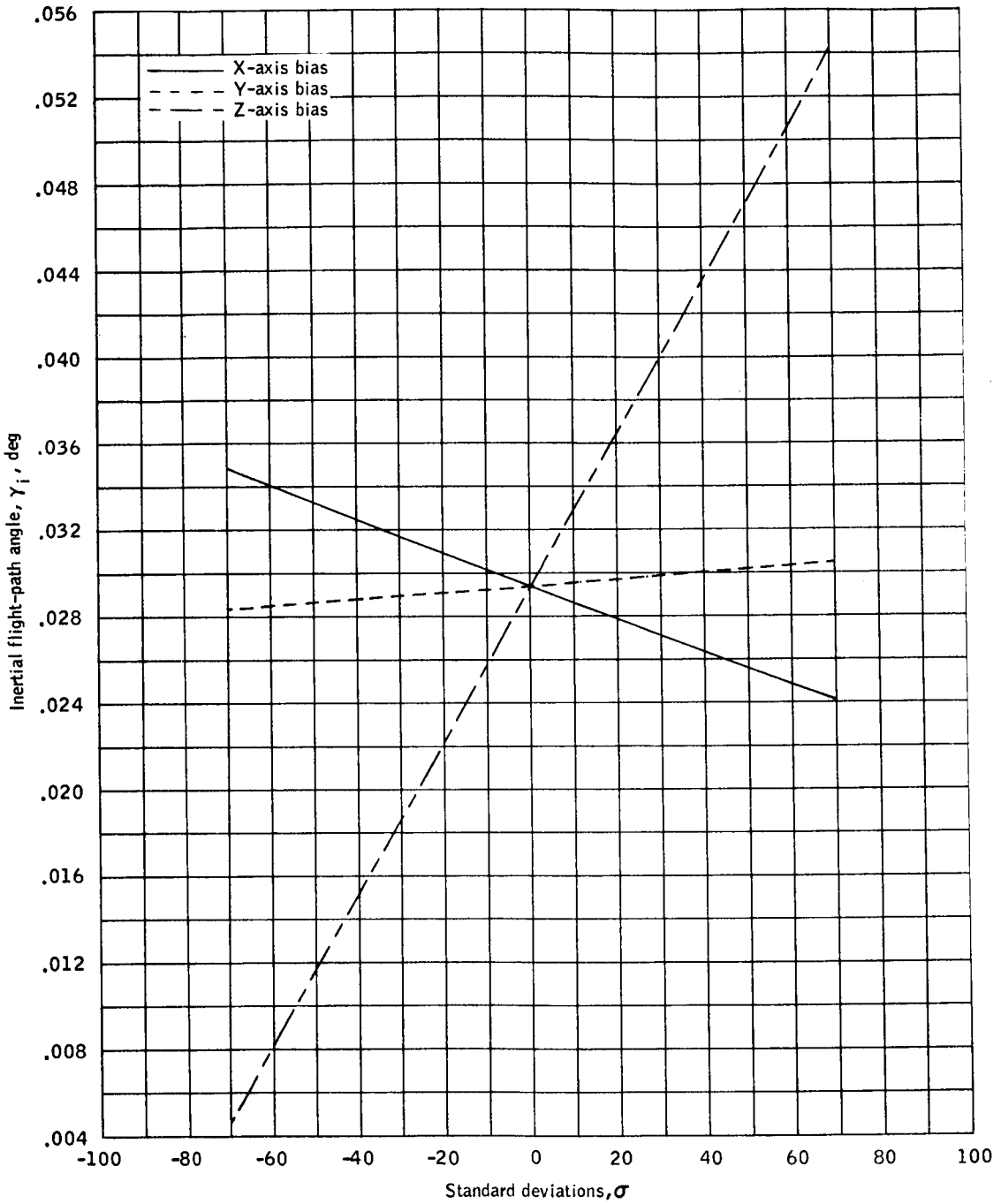
(t) Weight versus bias errors.

Figure 2.- Concluded.



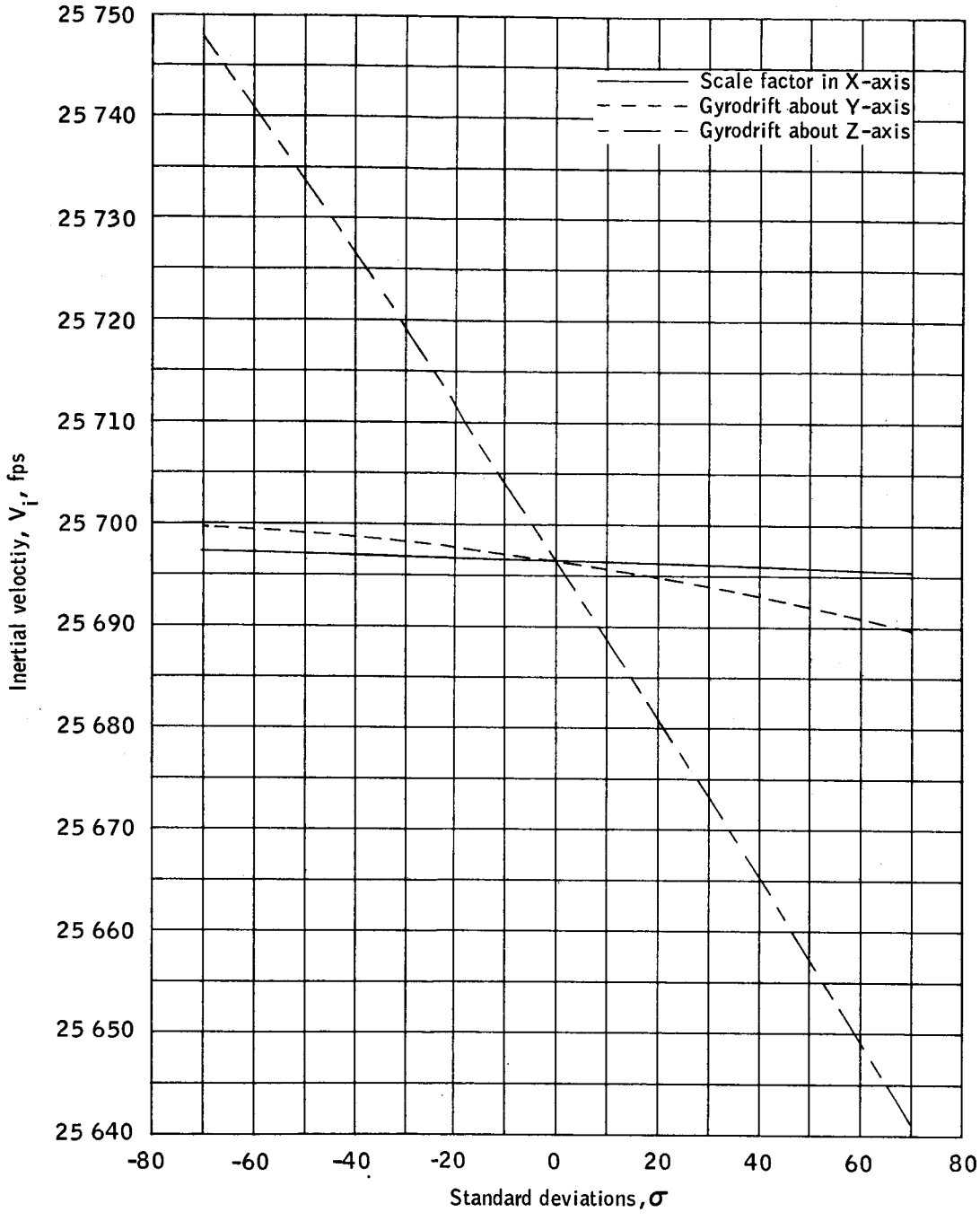
(a) Inertial flight-path angle versus scale factor and drift errors.

Figure 3.- Mission C dispersions at the end of the fourth SPS burn due to accelerometer bias, accelerometer scale factor and gyrodrift errors.



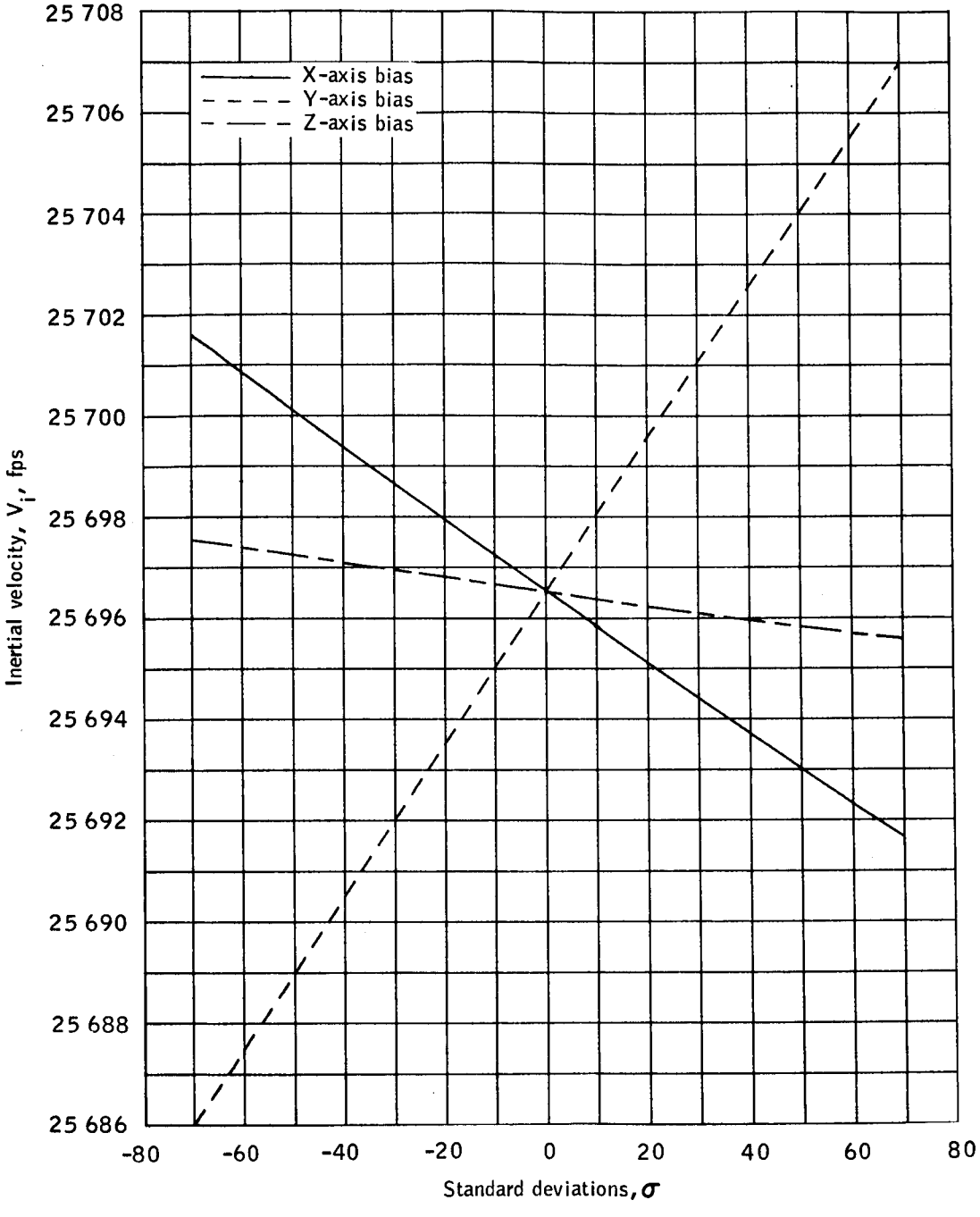
(b) Inertial flight-path angle versus bias errors.

Figure 3.- Continued.



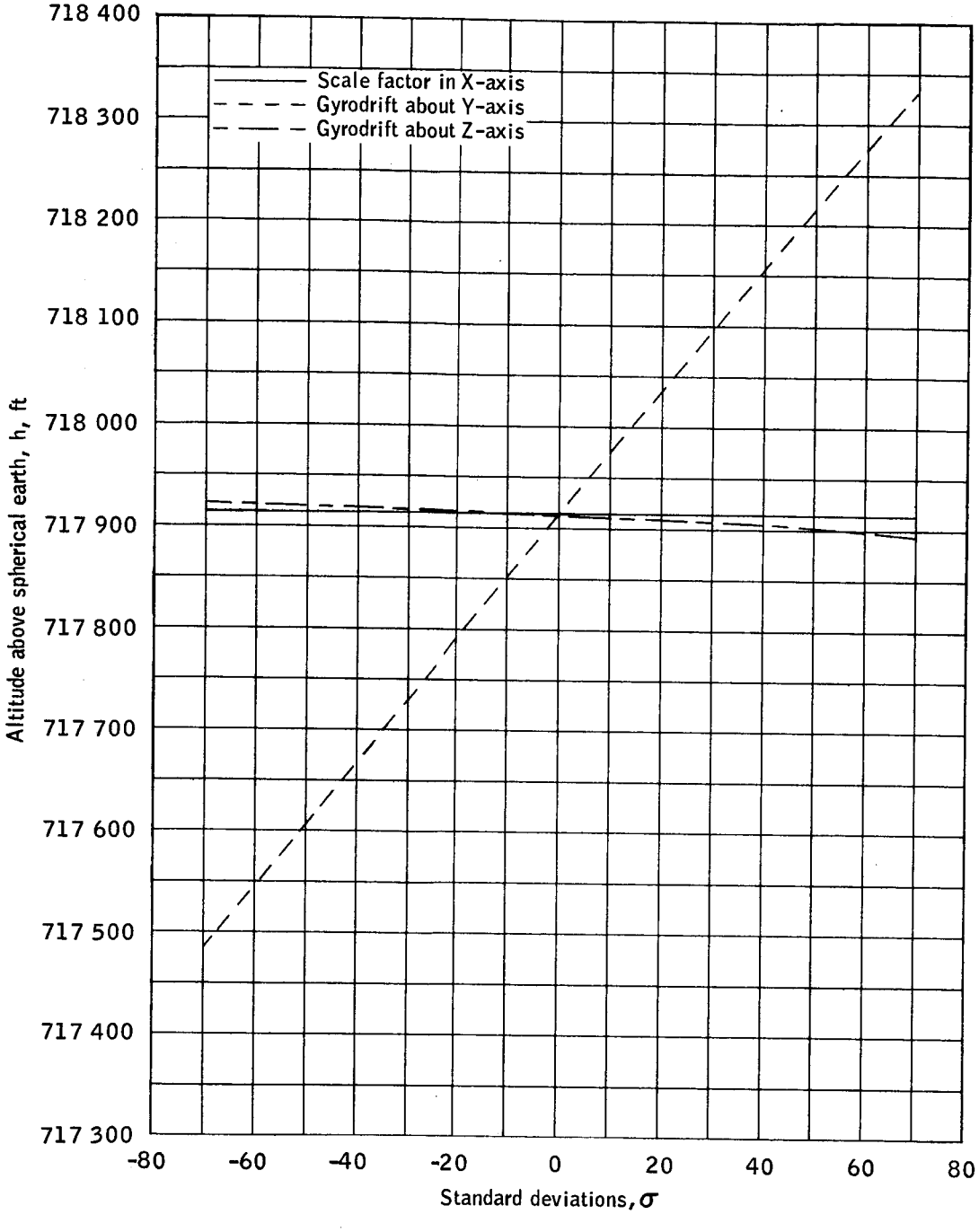
(c) Inertial velocity versus scale factor and drift errors.

Figure 3.- Continued.



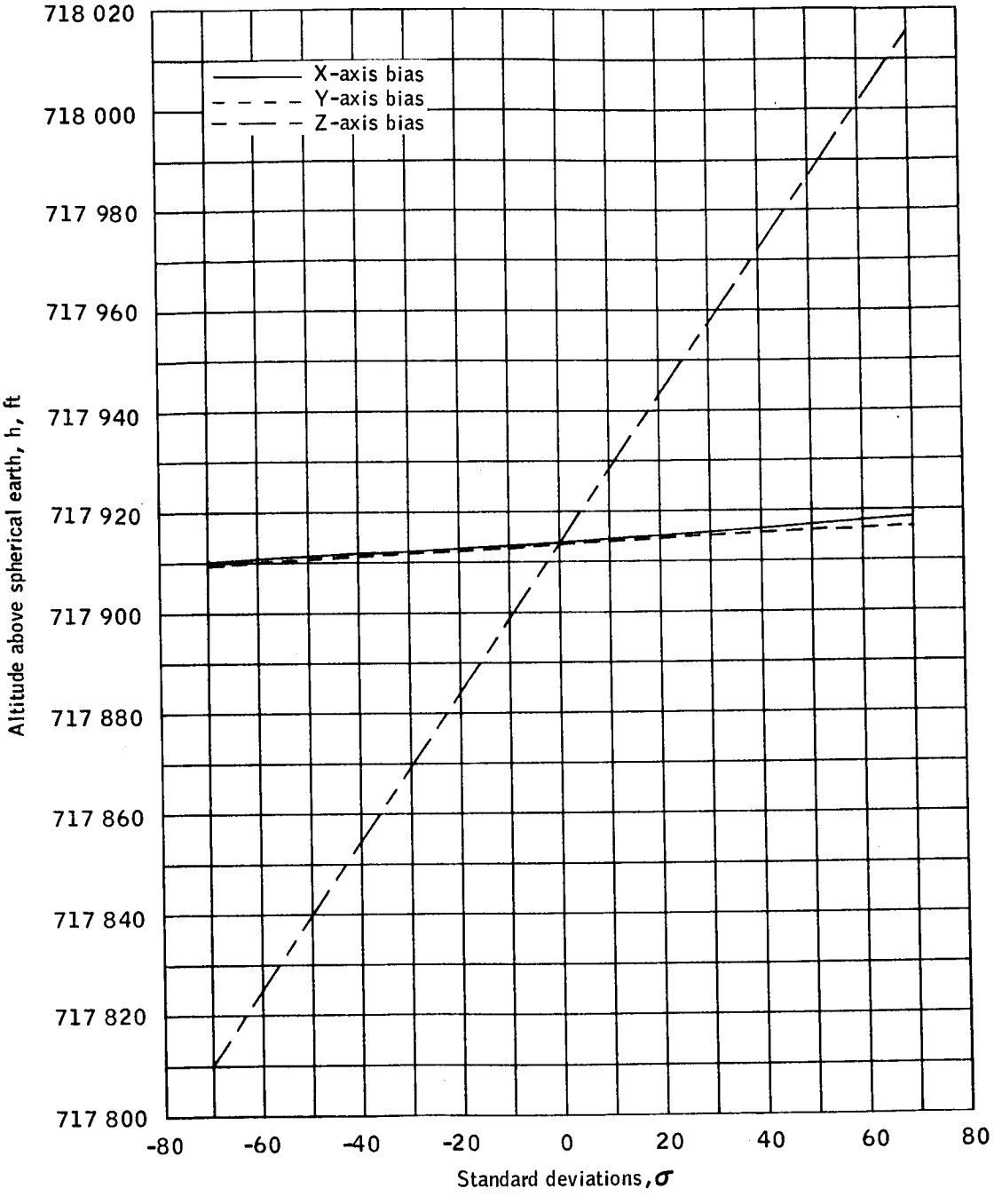
(d) Inertial velocity versus bias errors.

Figure 3.- Continued.



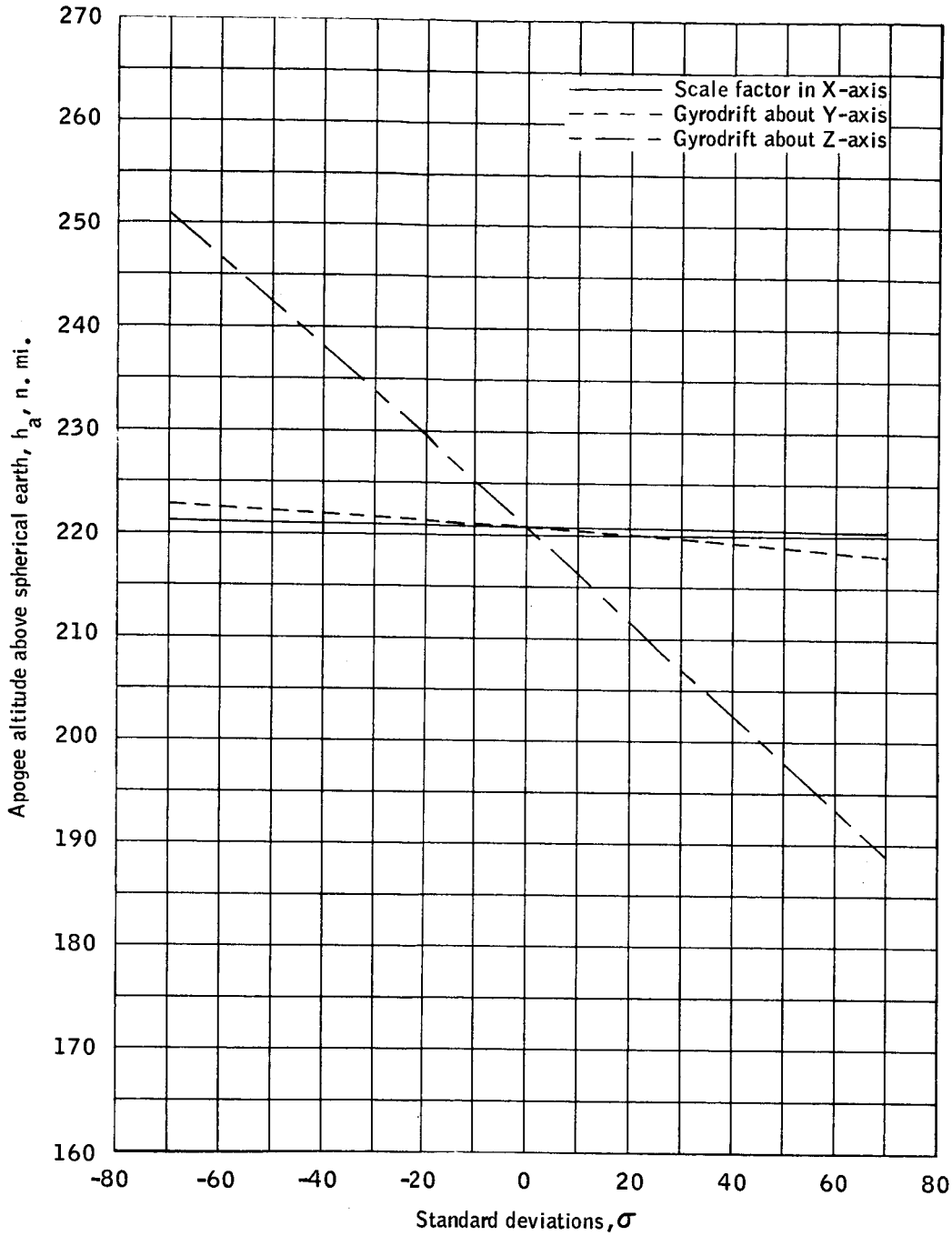
(e) Altitude above spherical earth versus scale factor and drift errors.

Figure 3.- Continued.



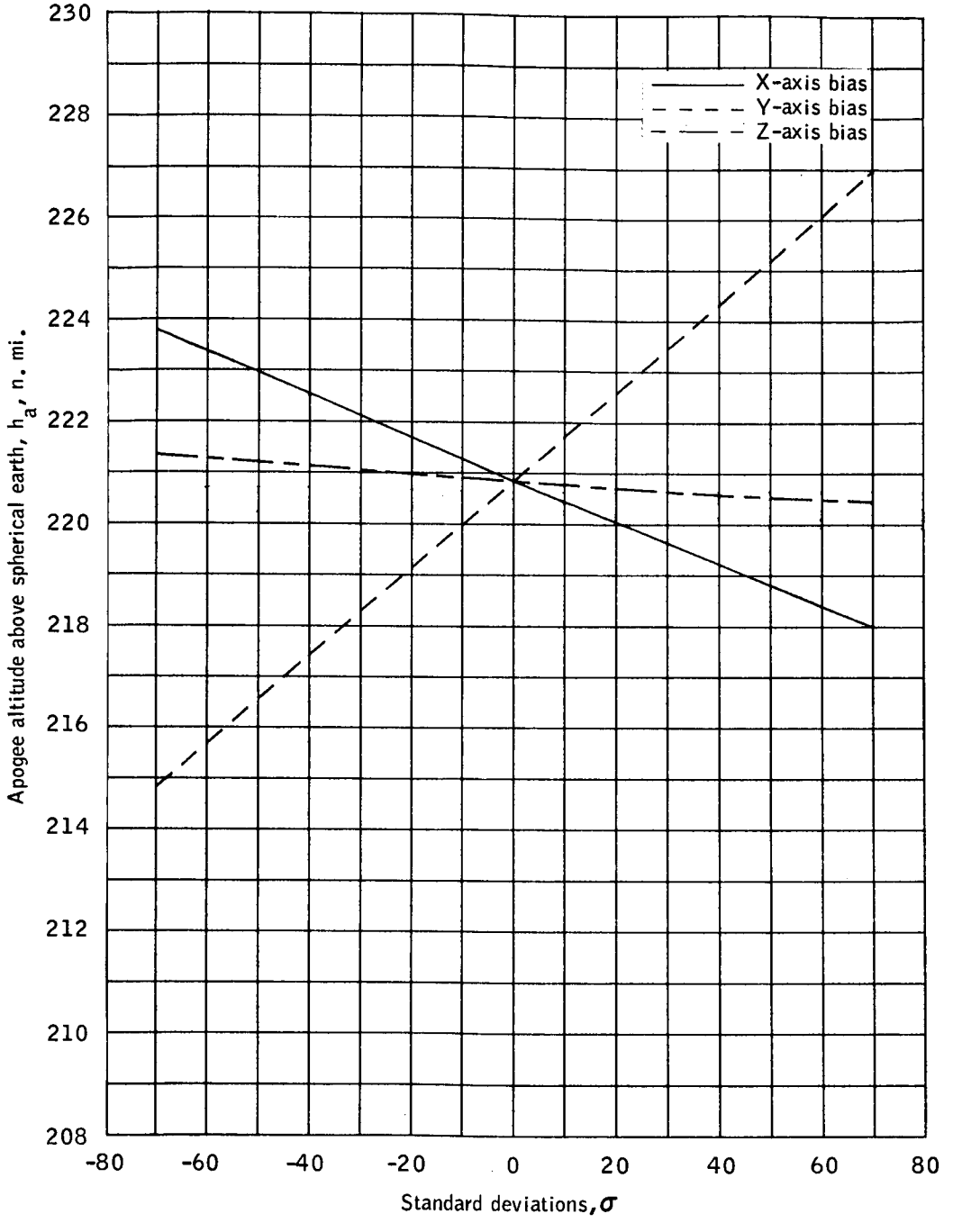
(f) Altitude above spherical earth versus bias errors.

Figure 3.- Continued.



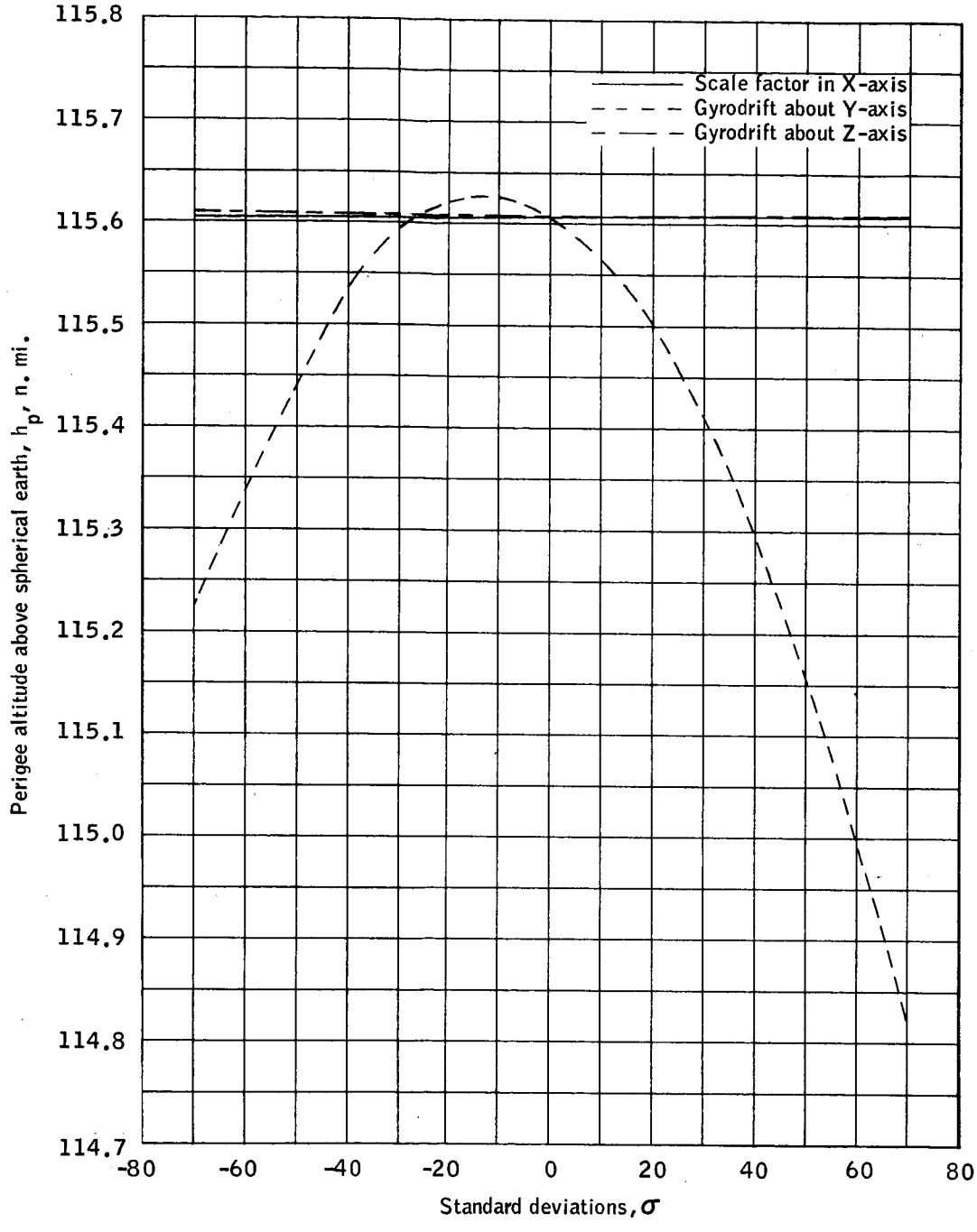
(g) Apogee altitude above spherical earth versus scale factor and drift errors.

Figure 3.- Continued.



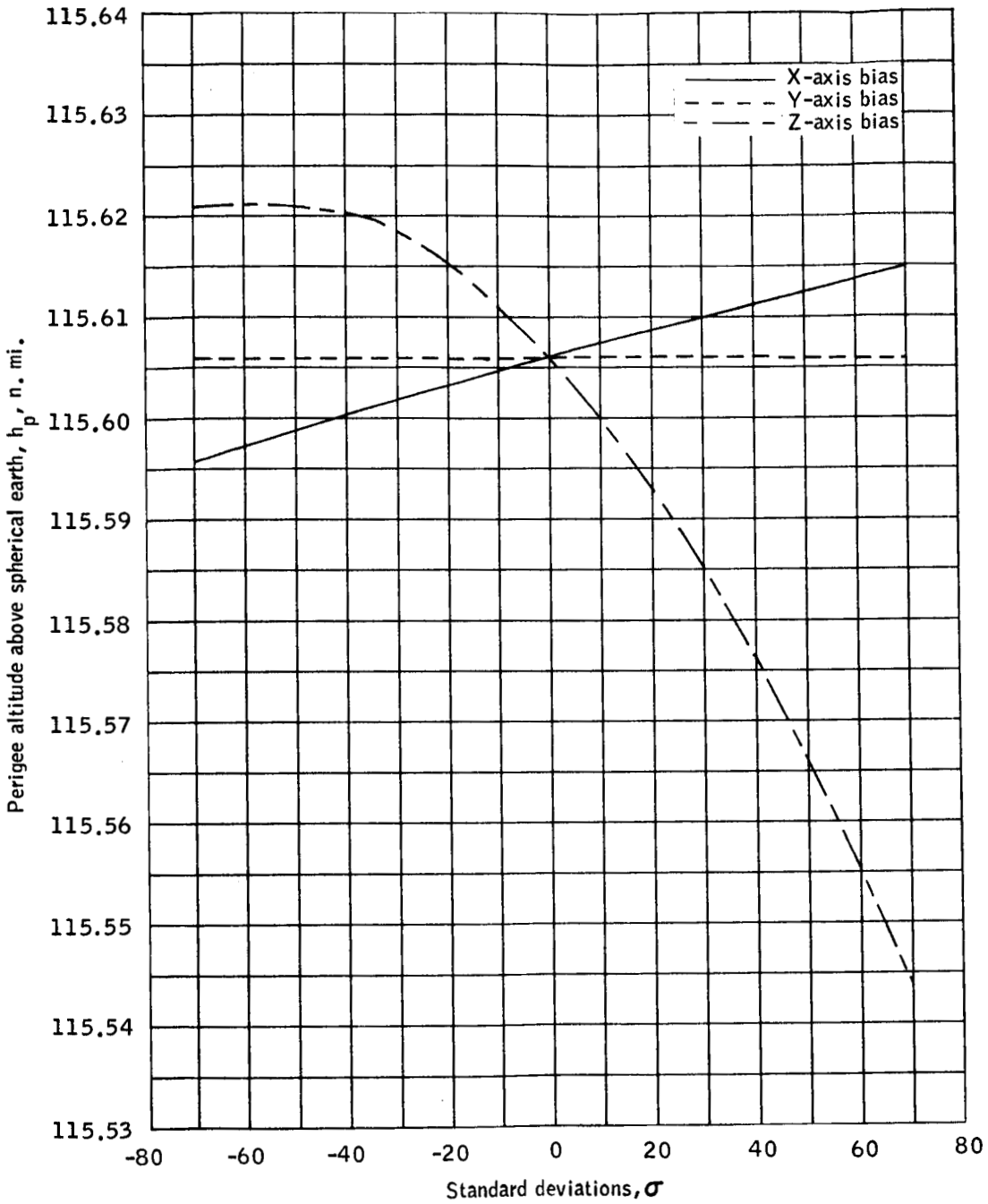
(h) Apogee altitude above spherical earth versus bias errors.

Figure 3.- Continued.



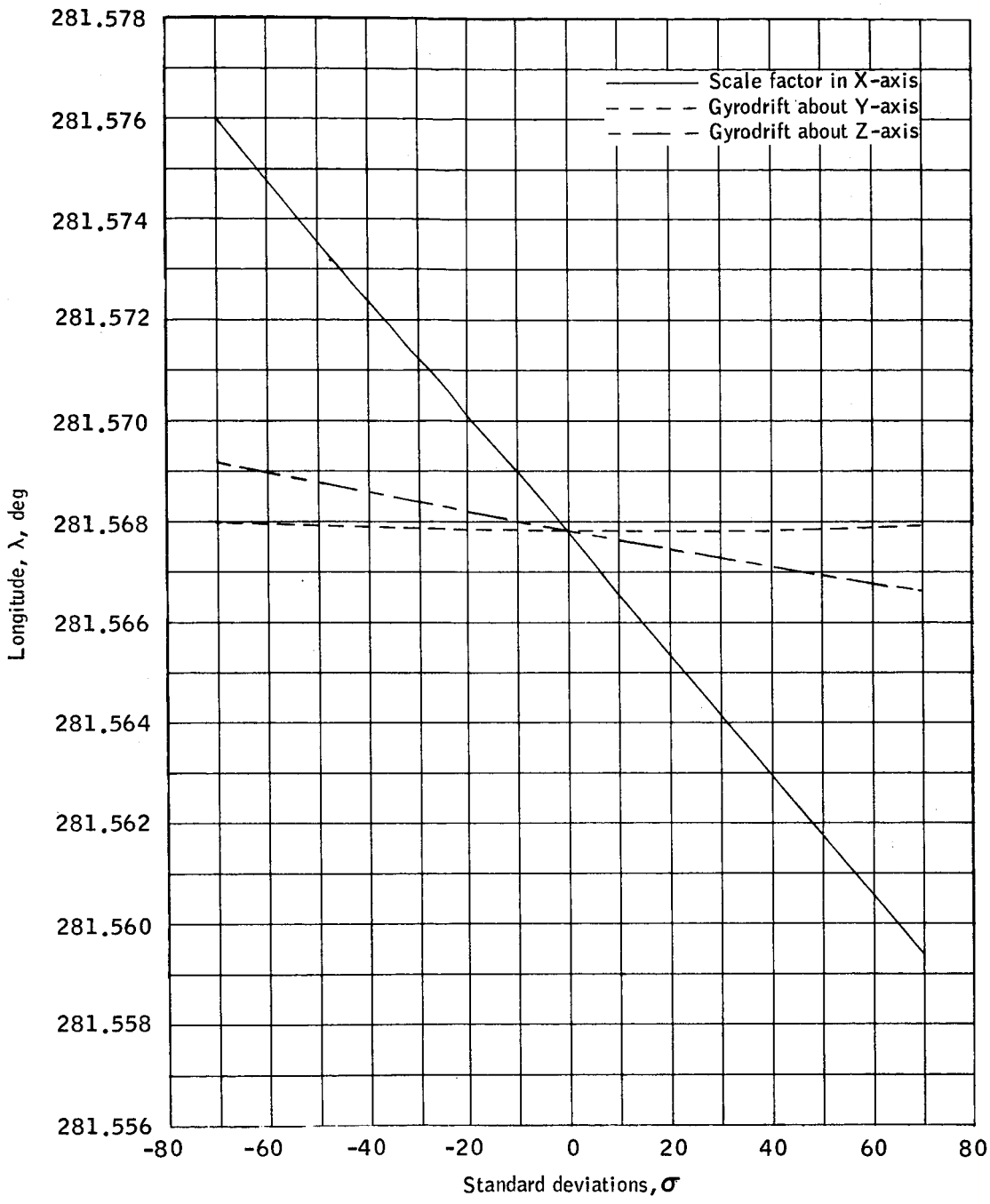
(i) Perigee altitude above spherical earth versus scale factor and drift errors.

Figure 3.- Continued.



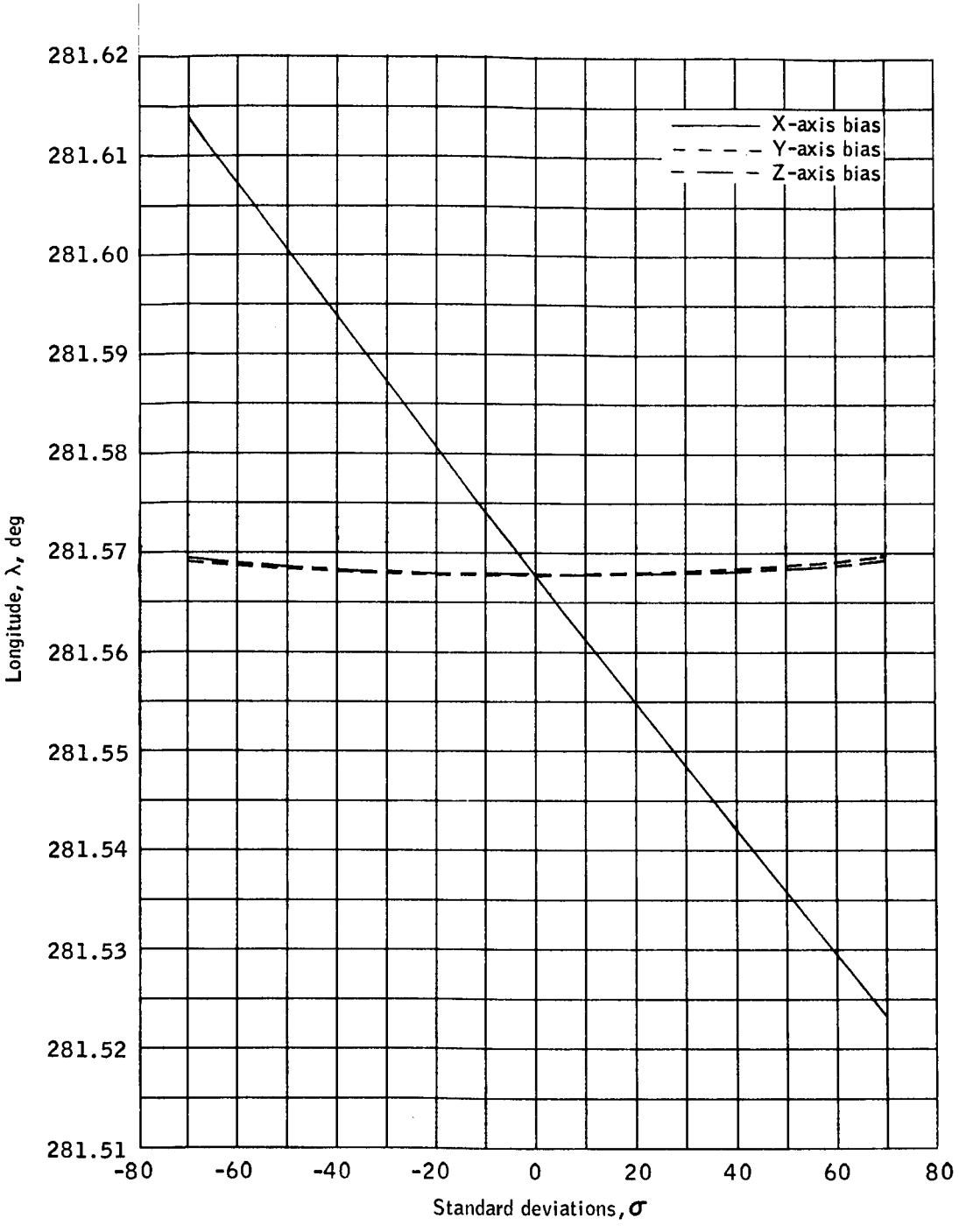
(j) Perigee altitude above spherical earth versus bias errors.

Figure 3.- Continued.



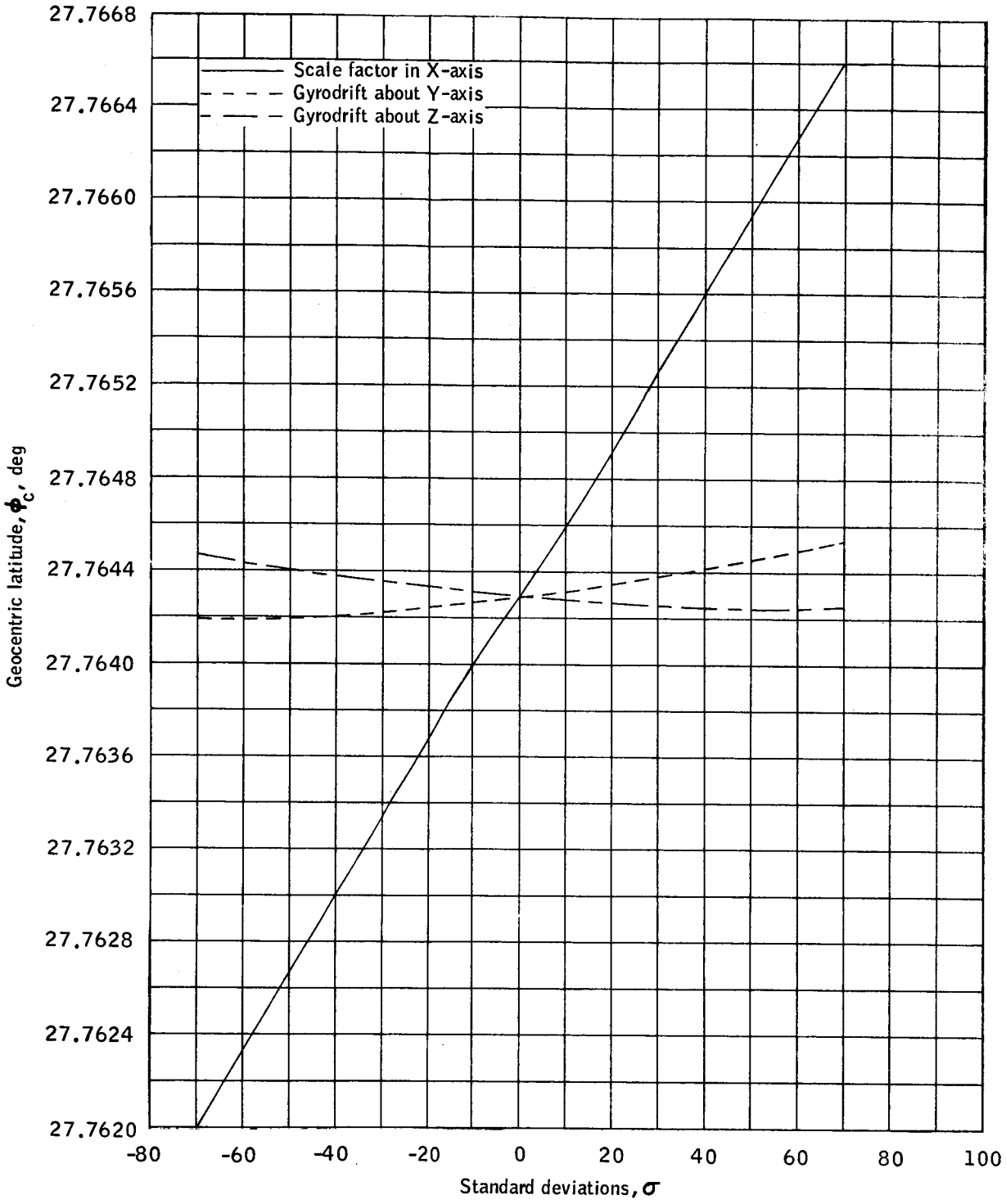
(k) Longitude versus scale factor and drift errors.

Figure 3.- Continued.



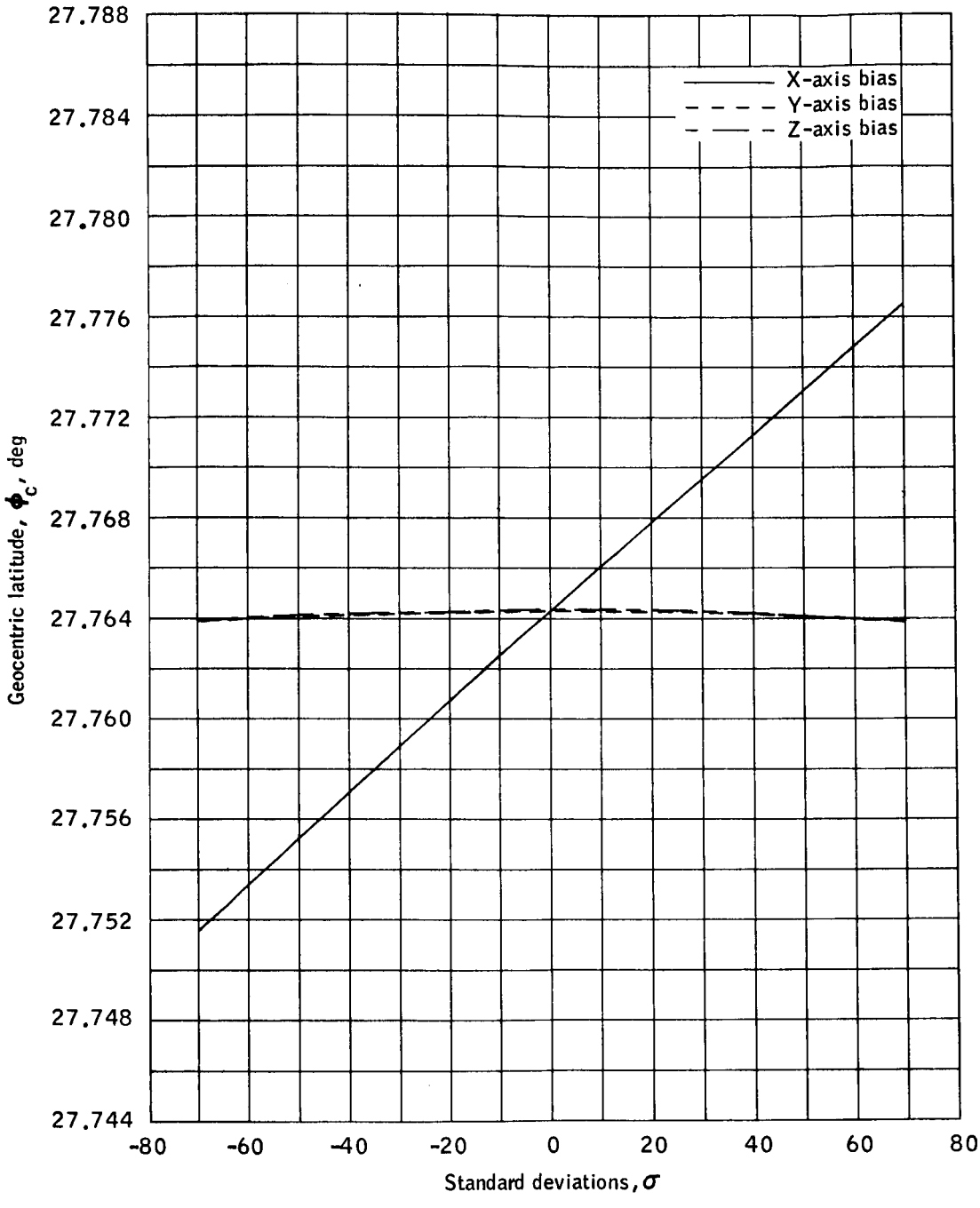
(l) Longitude versus bias errors.

Figure 3.- Continued.



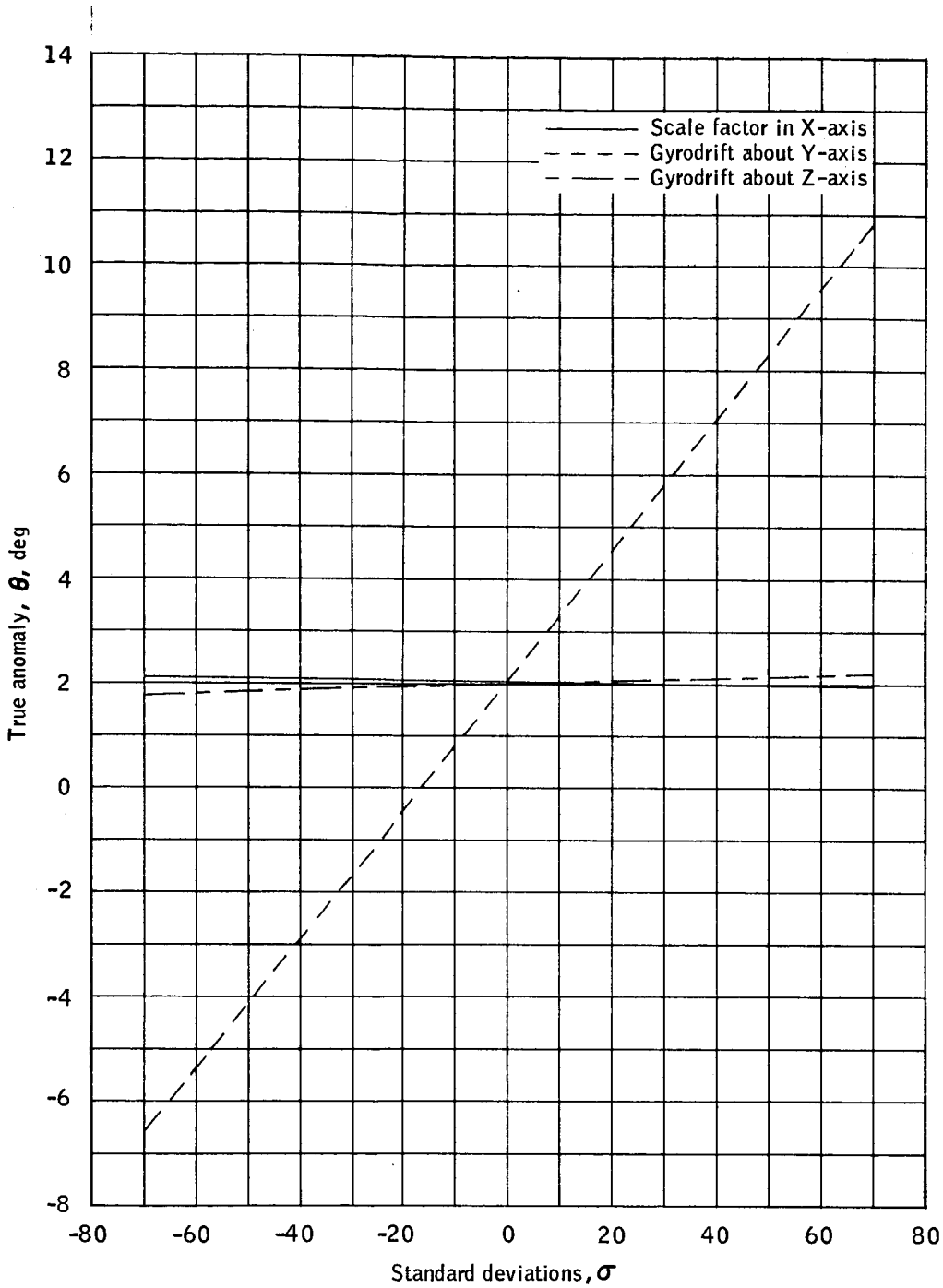
(m) Geocentric latitude versus scale factor and drift errors.

Figure 3.- Continued.



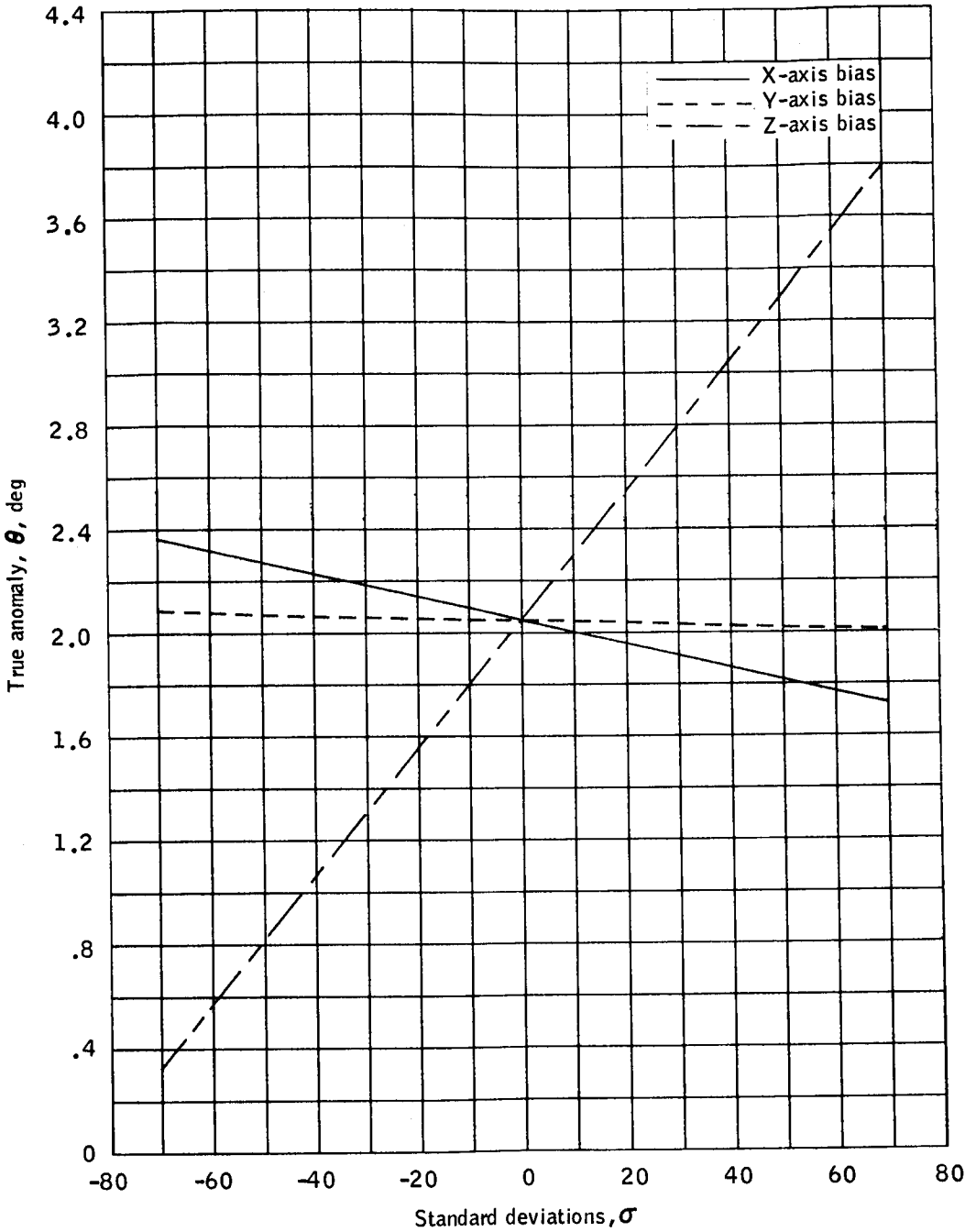
(n) Geocentric latitude versus bias errors.

Figure 3.- Continued.



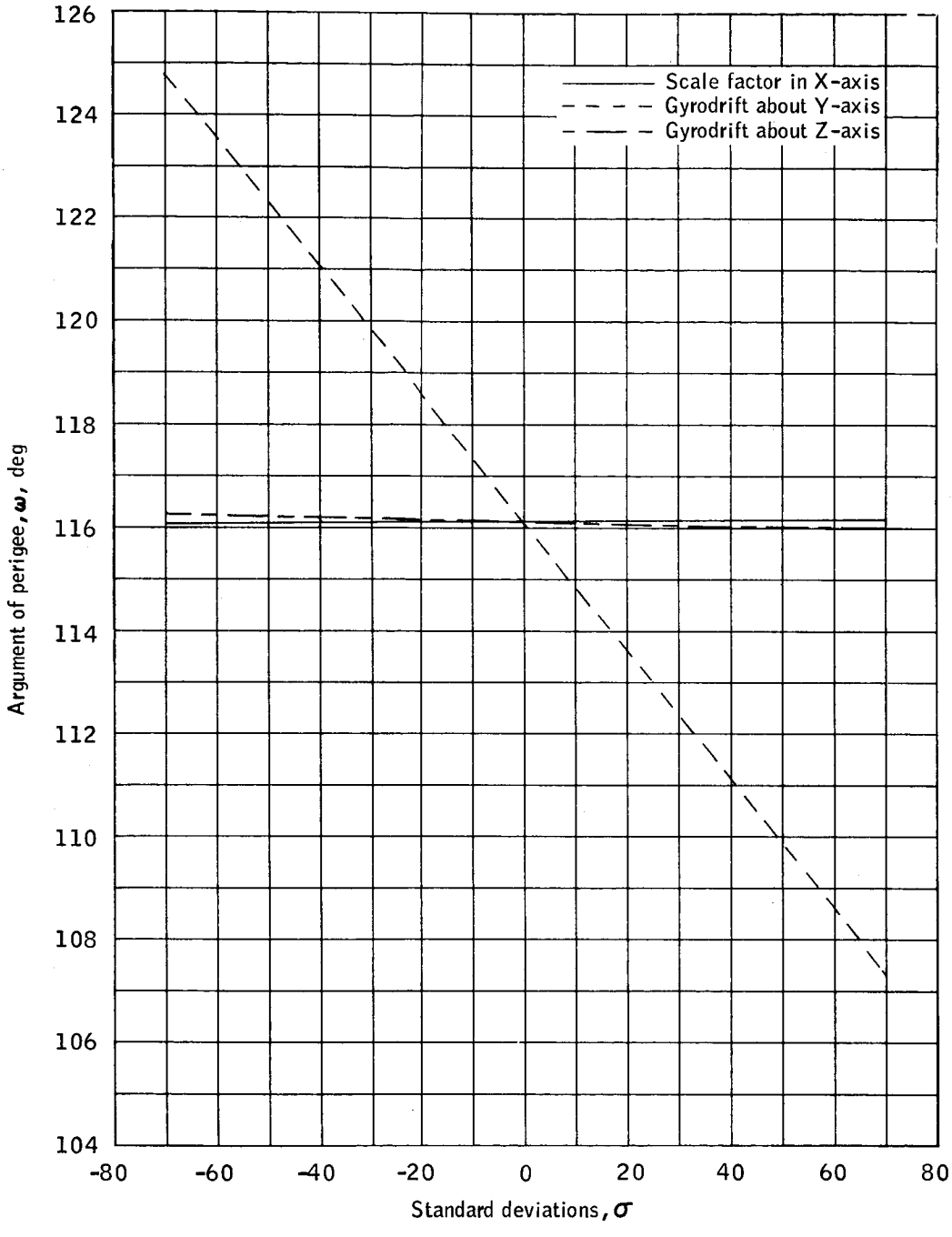
(o) True anomaly versus scale factor and drift errors.

Figure 3.- Continued.



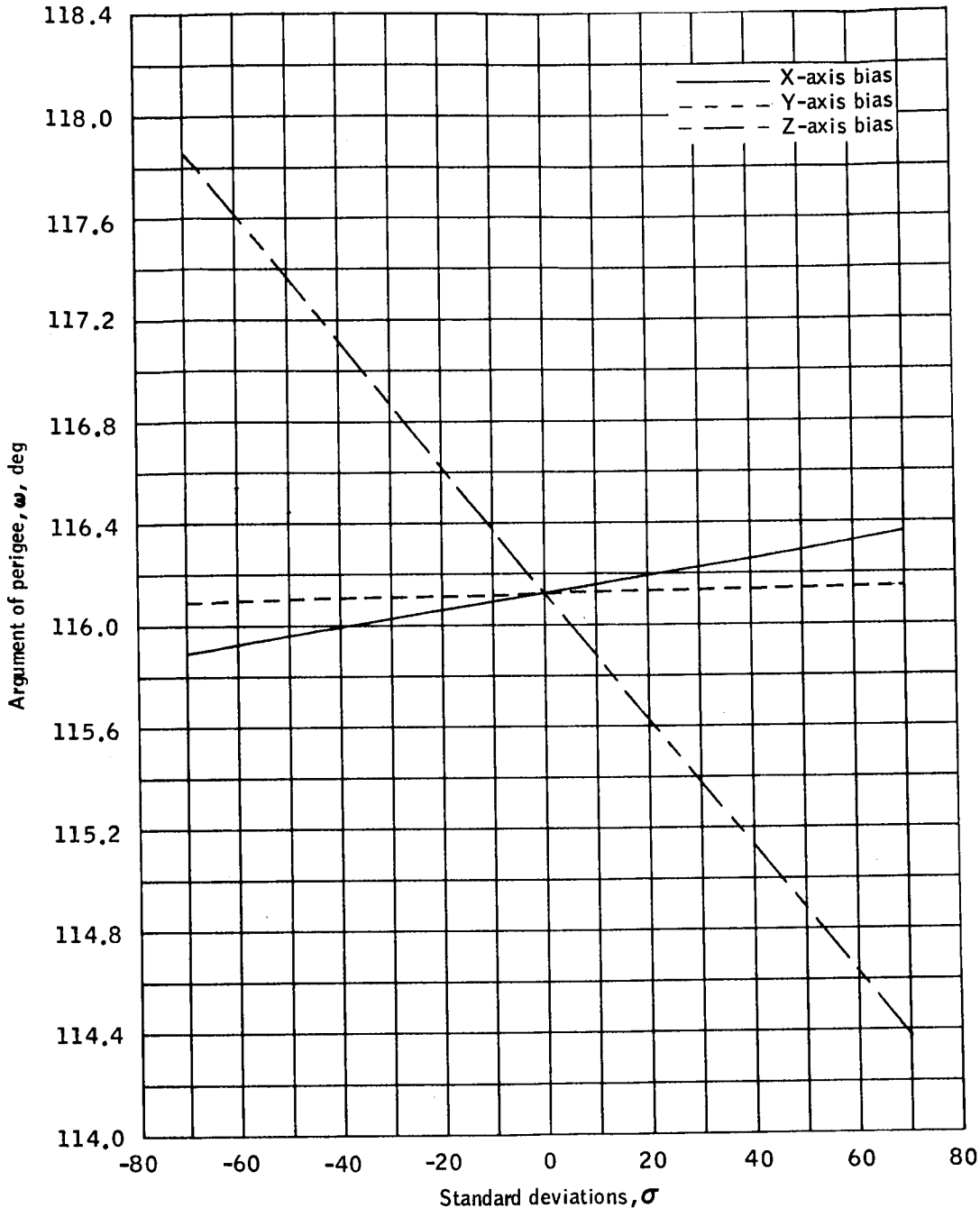
(p) True anomaly versus bias errors.

Figure 3.- Continued.



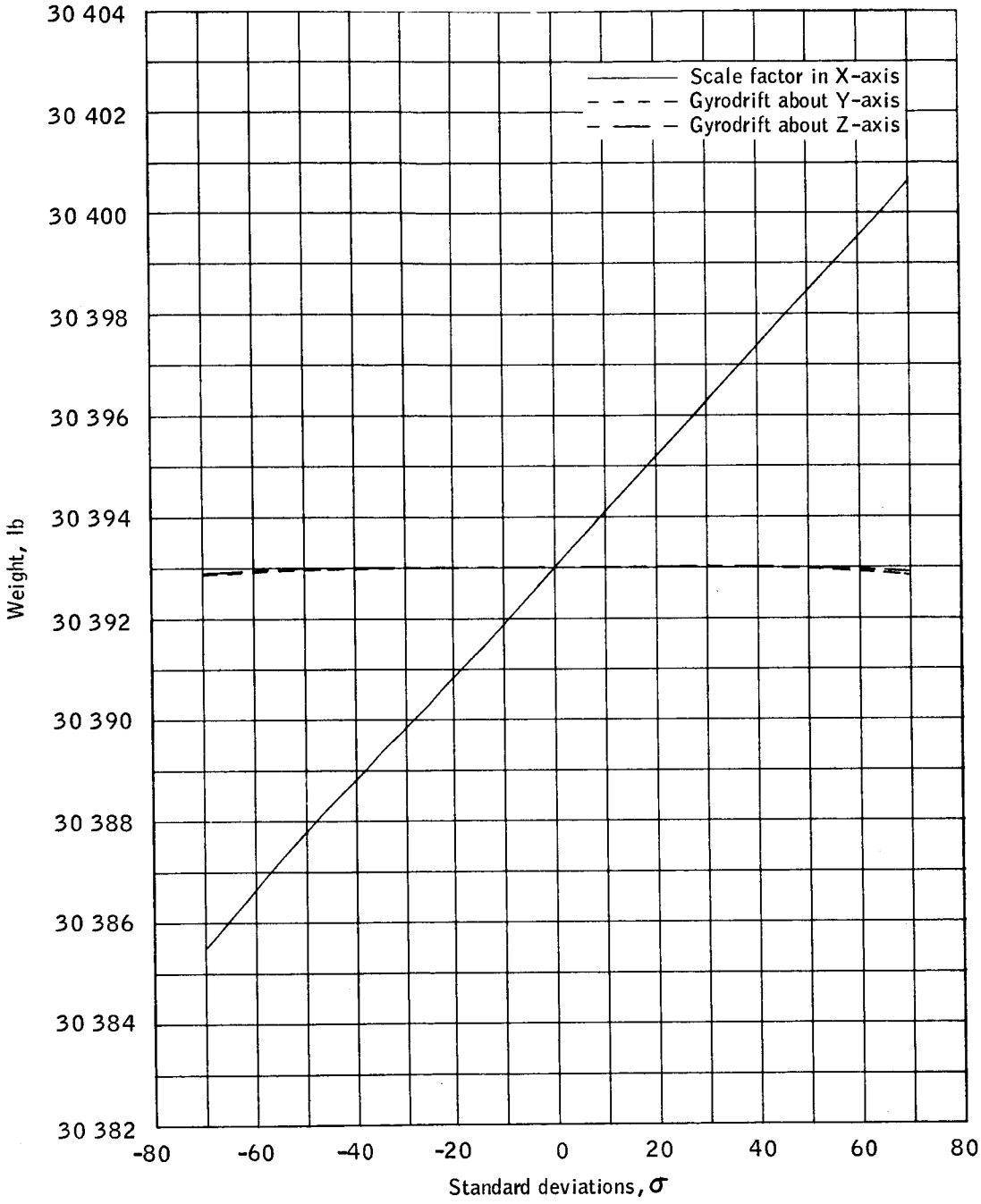
(q) Argument of perigee versus scale factor and drift errors.

Figure 3.- Continued.



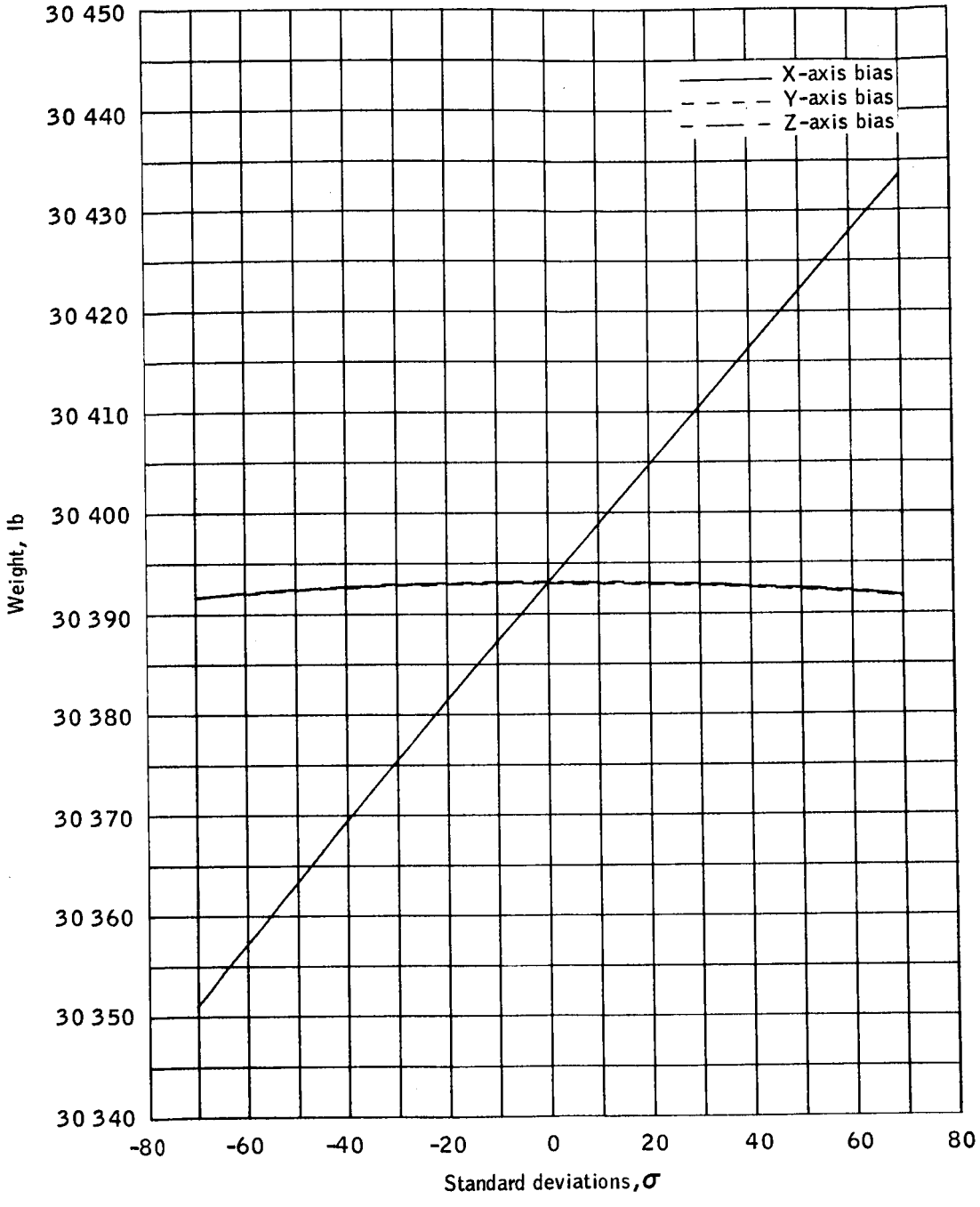
(r) Argument of perigee versus bias errors.

Figure 3.- Continued.



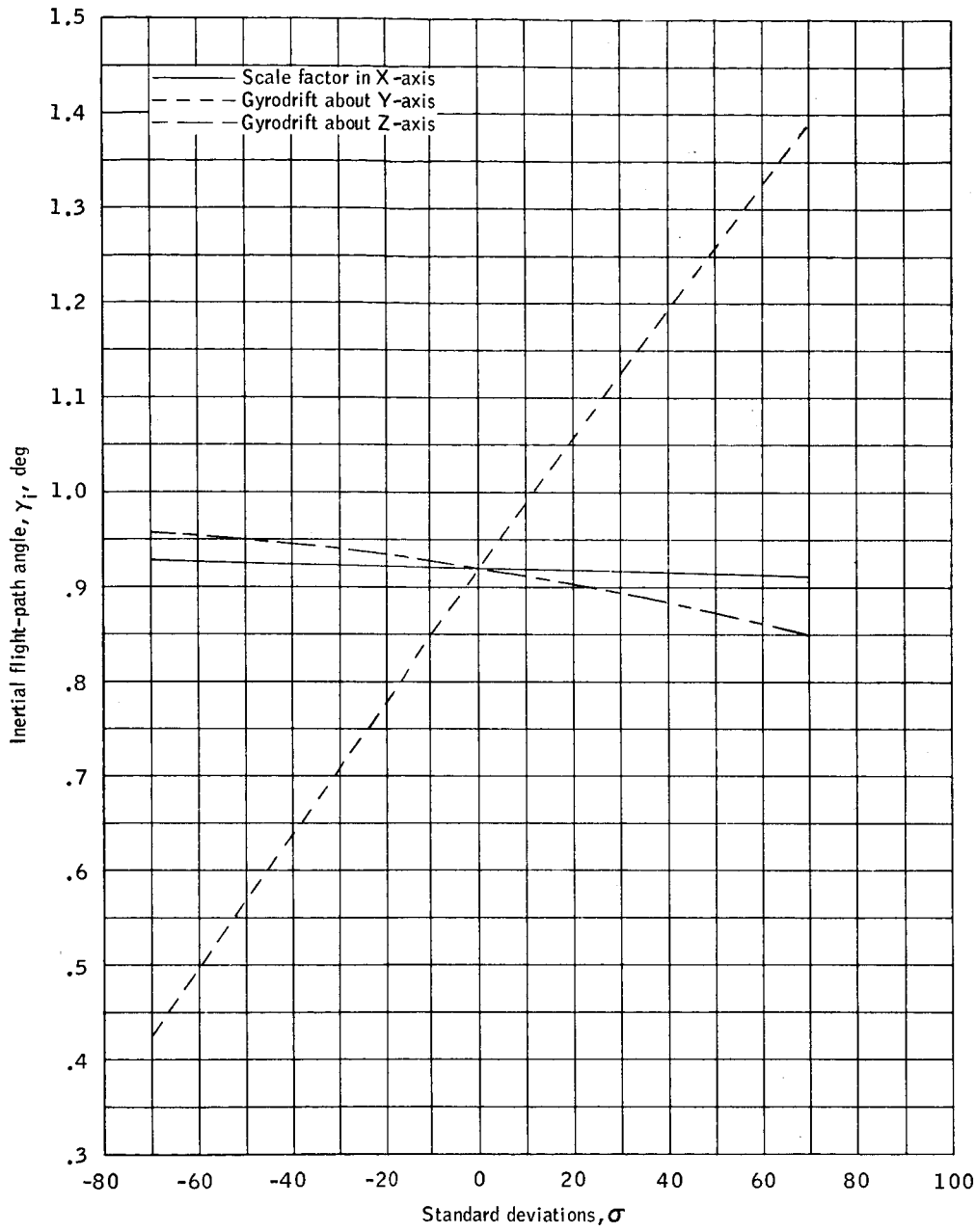
(s) Weight versus scale factor and drift errors.

Figure 3.- Continued.



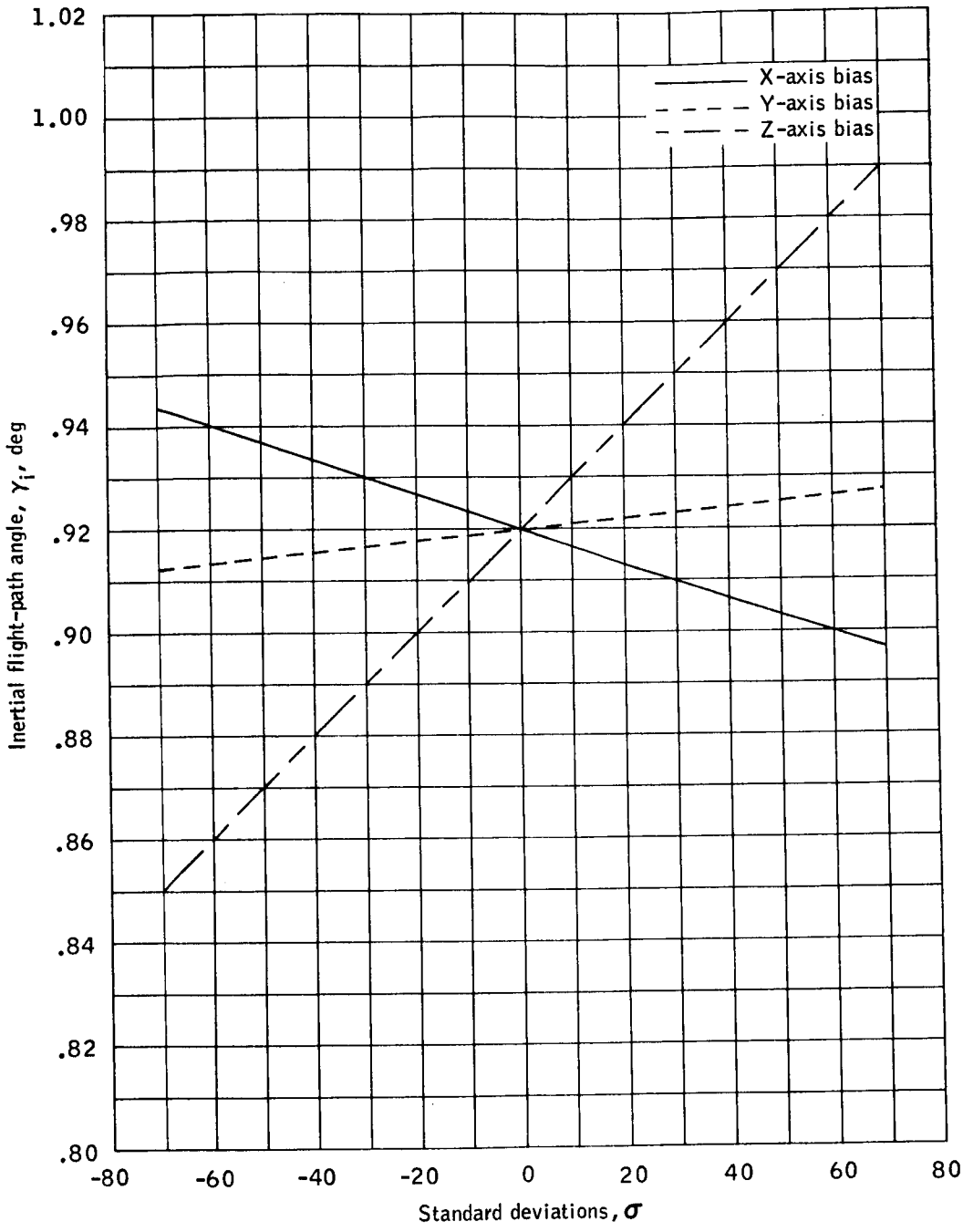
(t) Weight versus bias errors.

Figure 3.- Concluded.



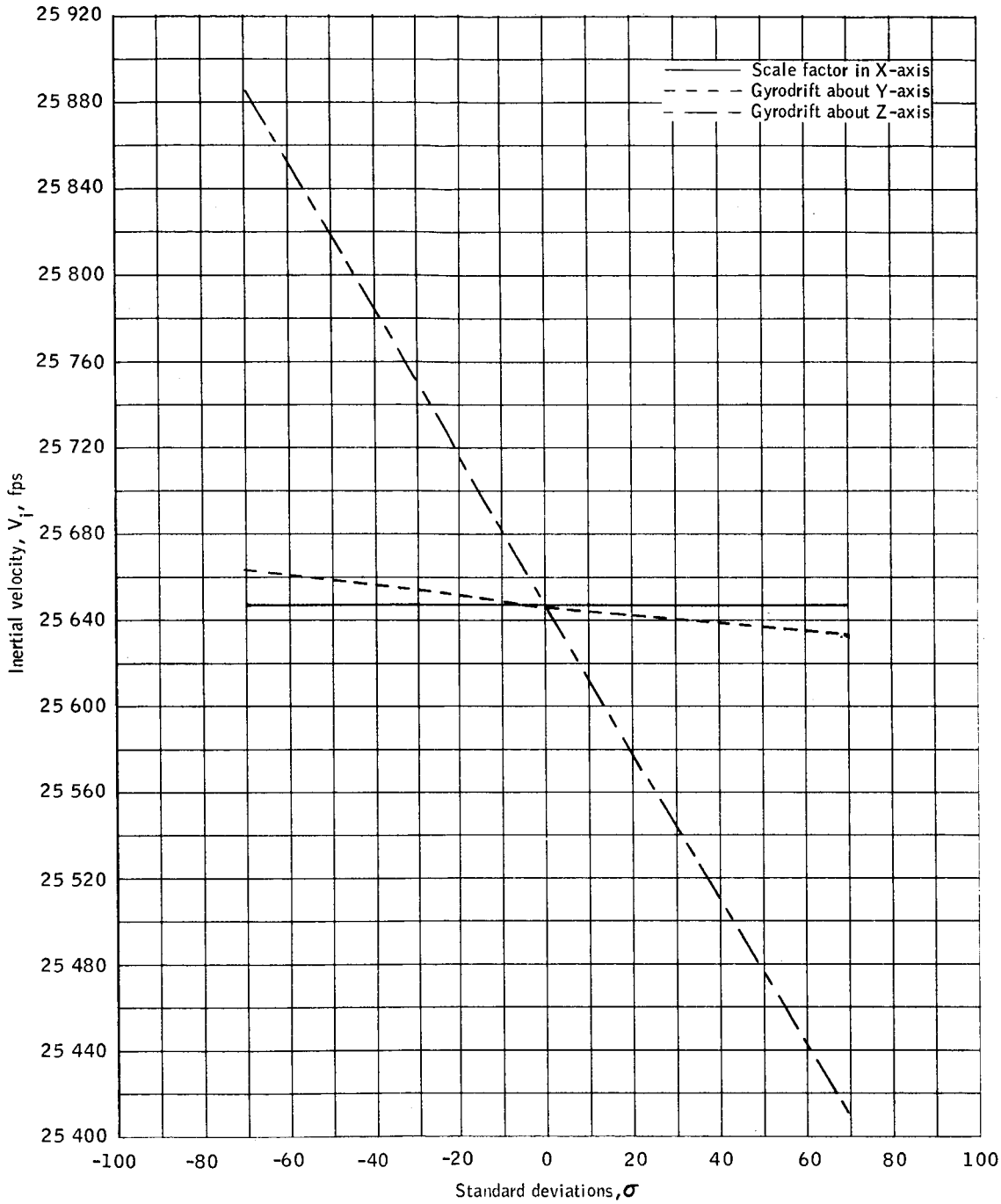
(a) Inertial flight-path angle versus scale factor and drift errors.

Figure 4.- Mission C dispersions at the end of the fifth SPS burn due to accelerometer bias, accelerometer scale factor and gyrodrift errors.



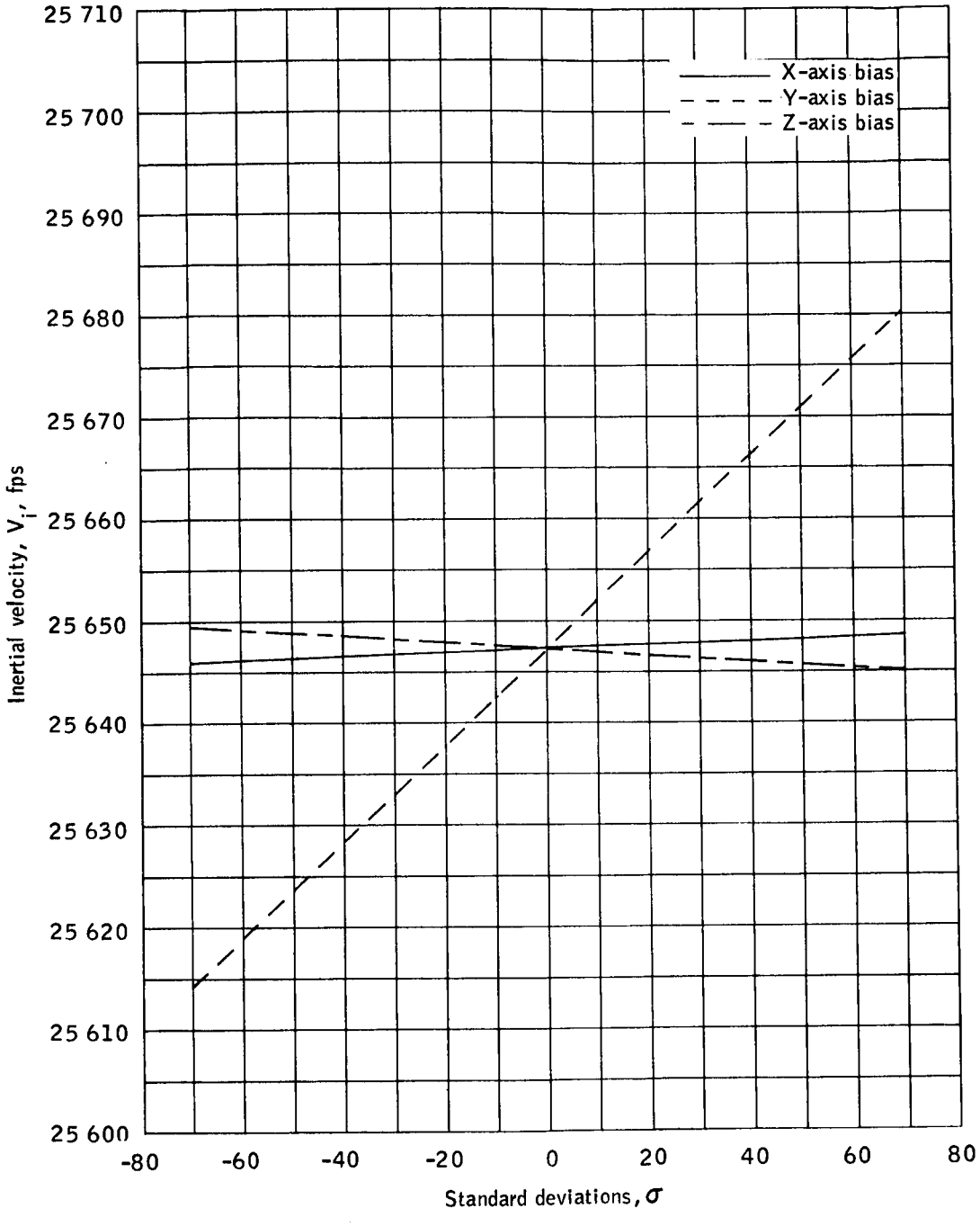
(b) Inertial flight-path angle versus bias errors.

Figure 4.- Continued.



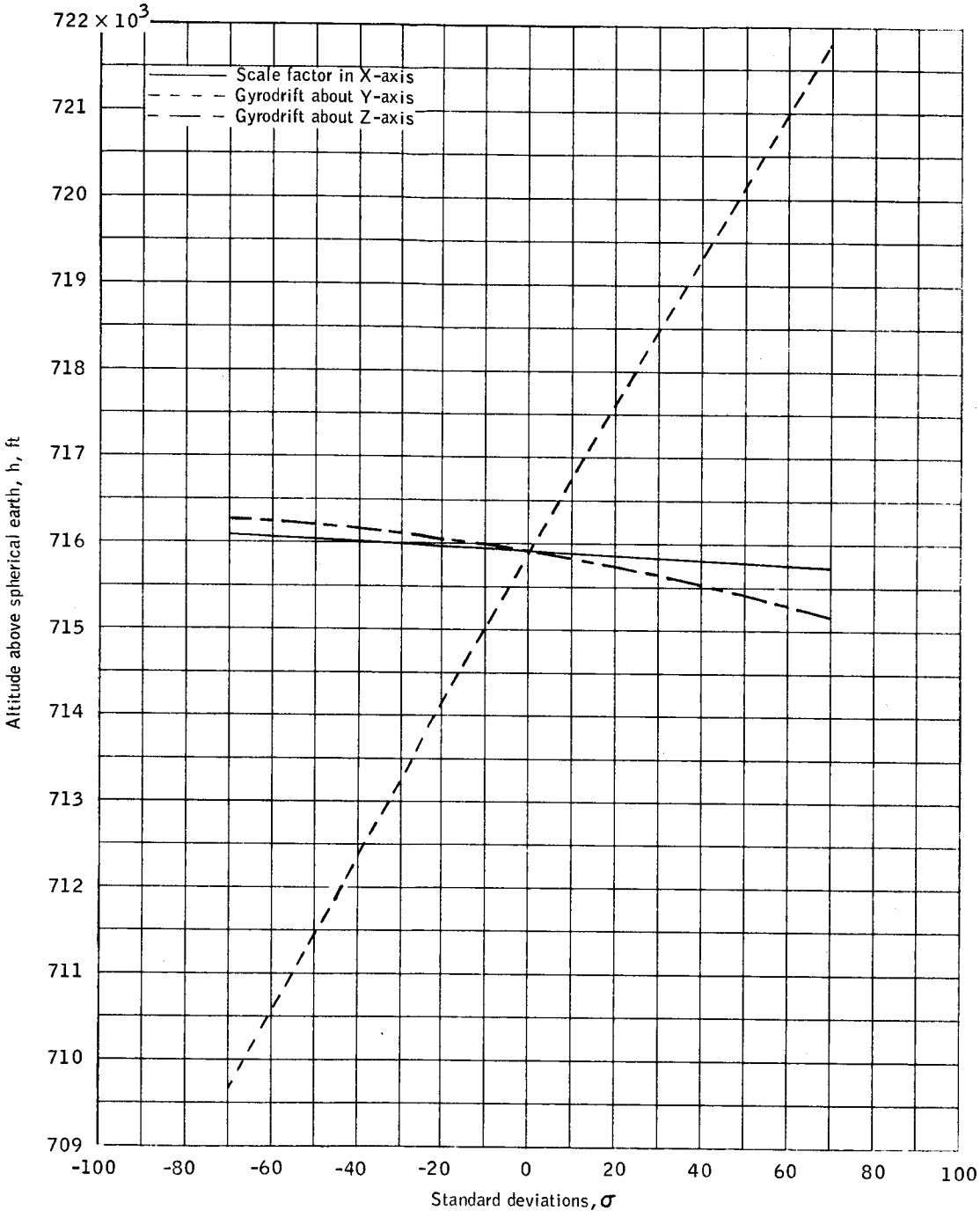
(c) Inertial velocity versus scale factor and drift errors.

Figure 4.- Continued.



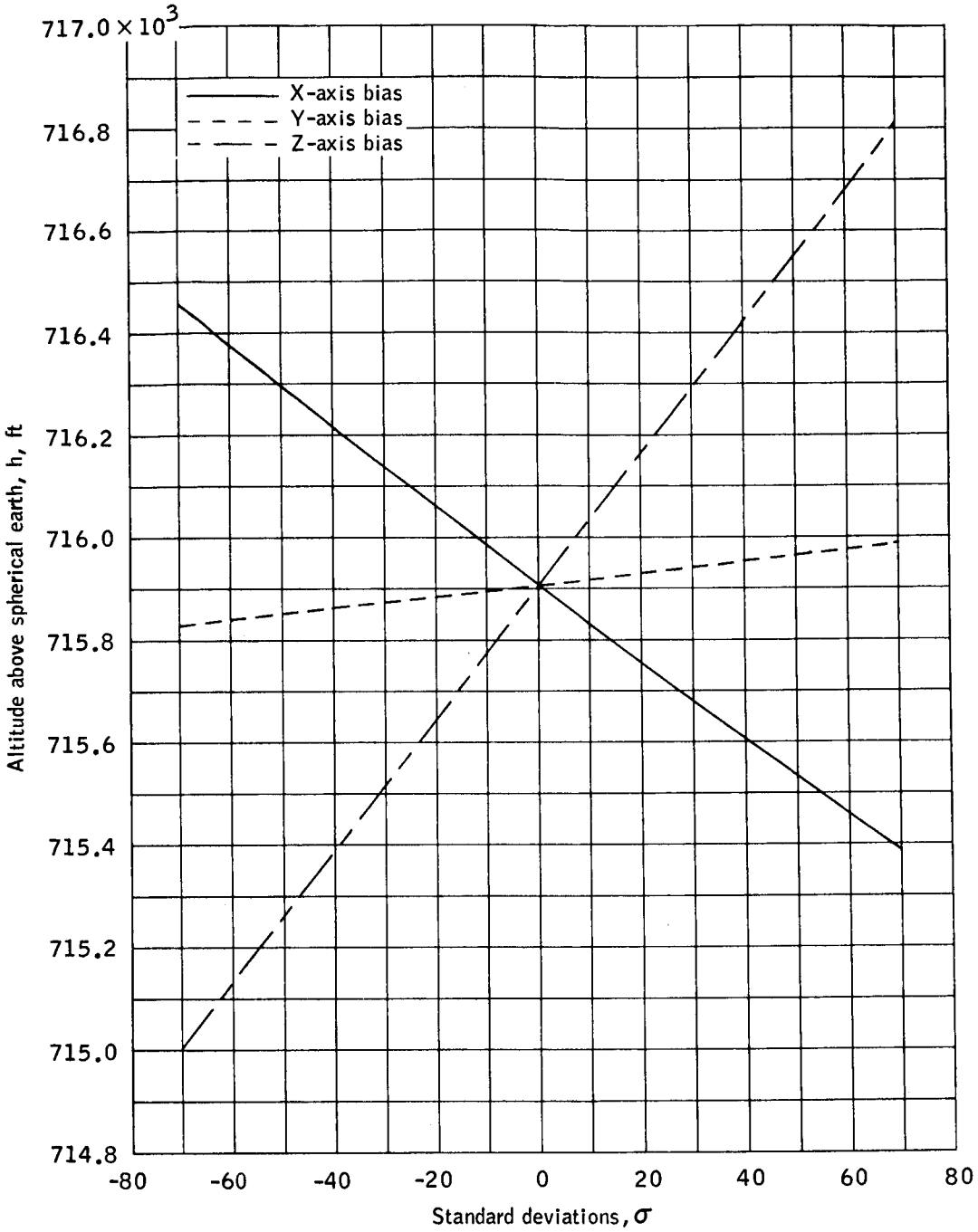
(d) Inertial velocity versus bias errors.

Figure 4.- Continued.



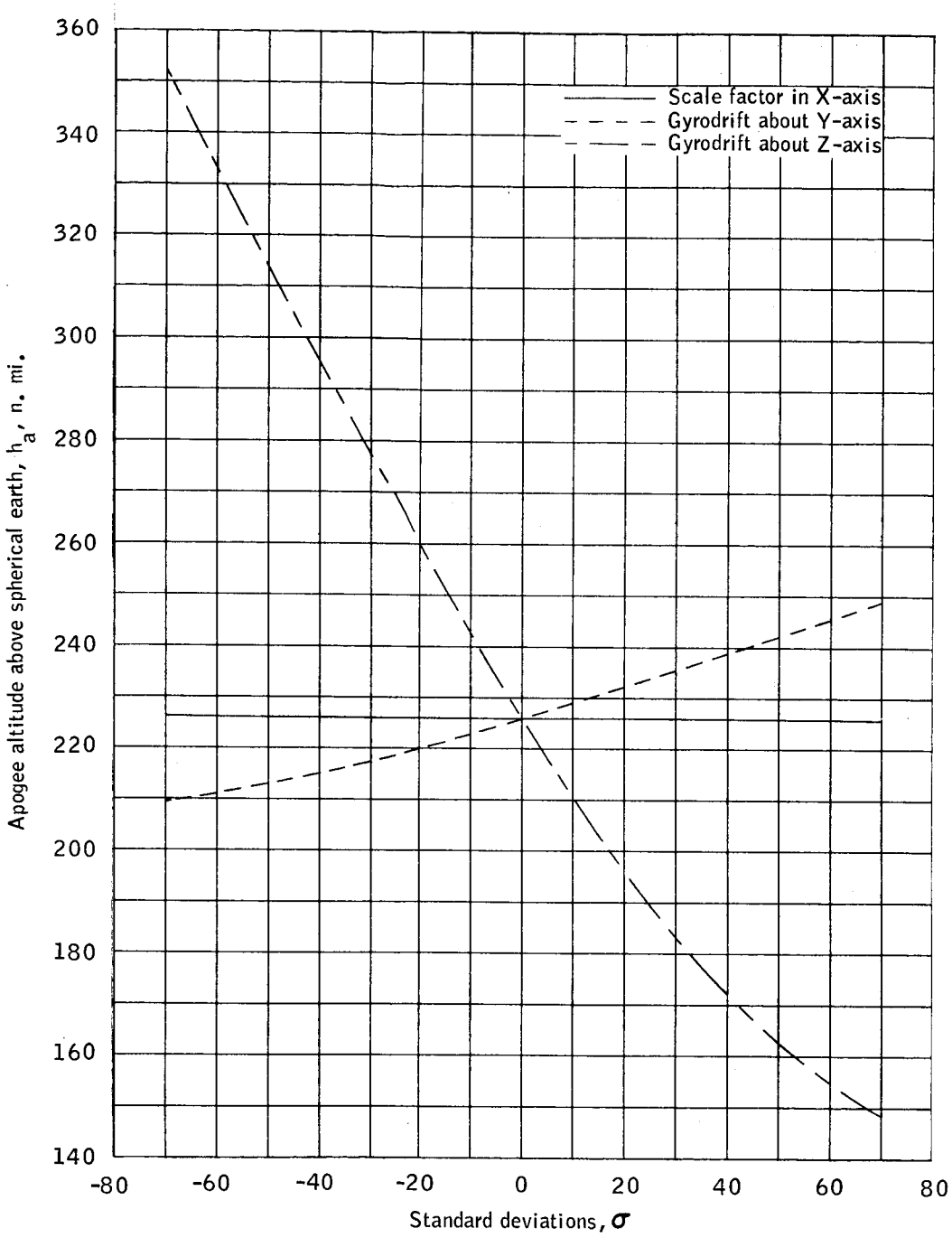
(e) Altitude above spherical earth versus scale factor and drift errors.

Figure 4.- Continued.



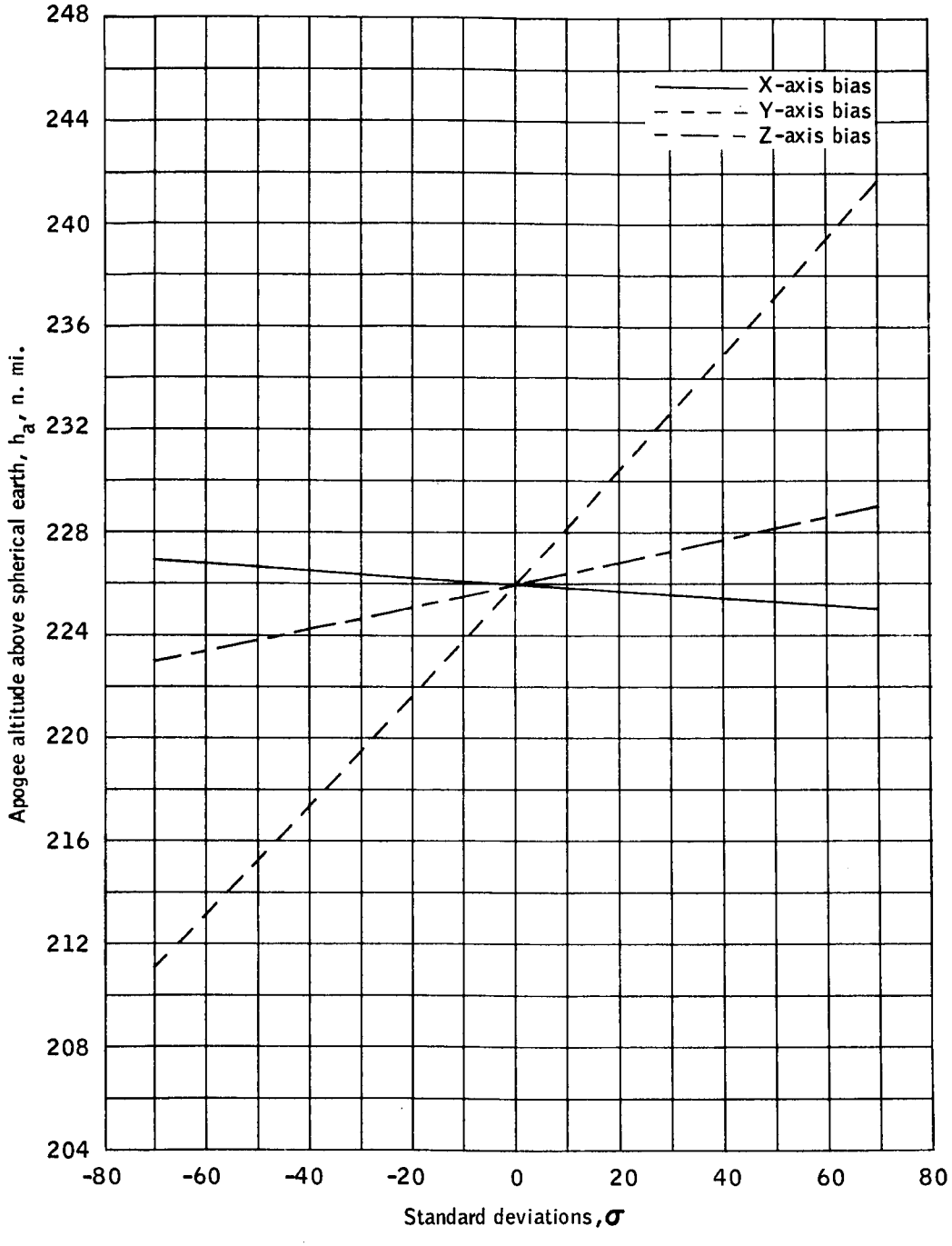
(f) Altitude above spherical earth versus bias errors.

Figure 4.- Continued.



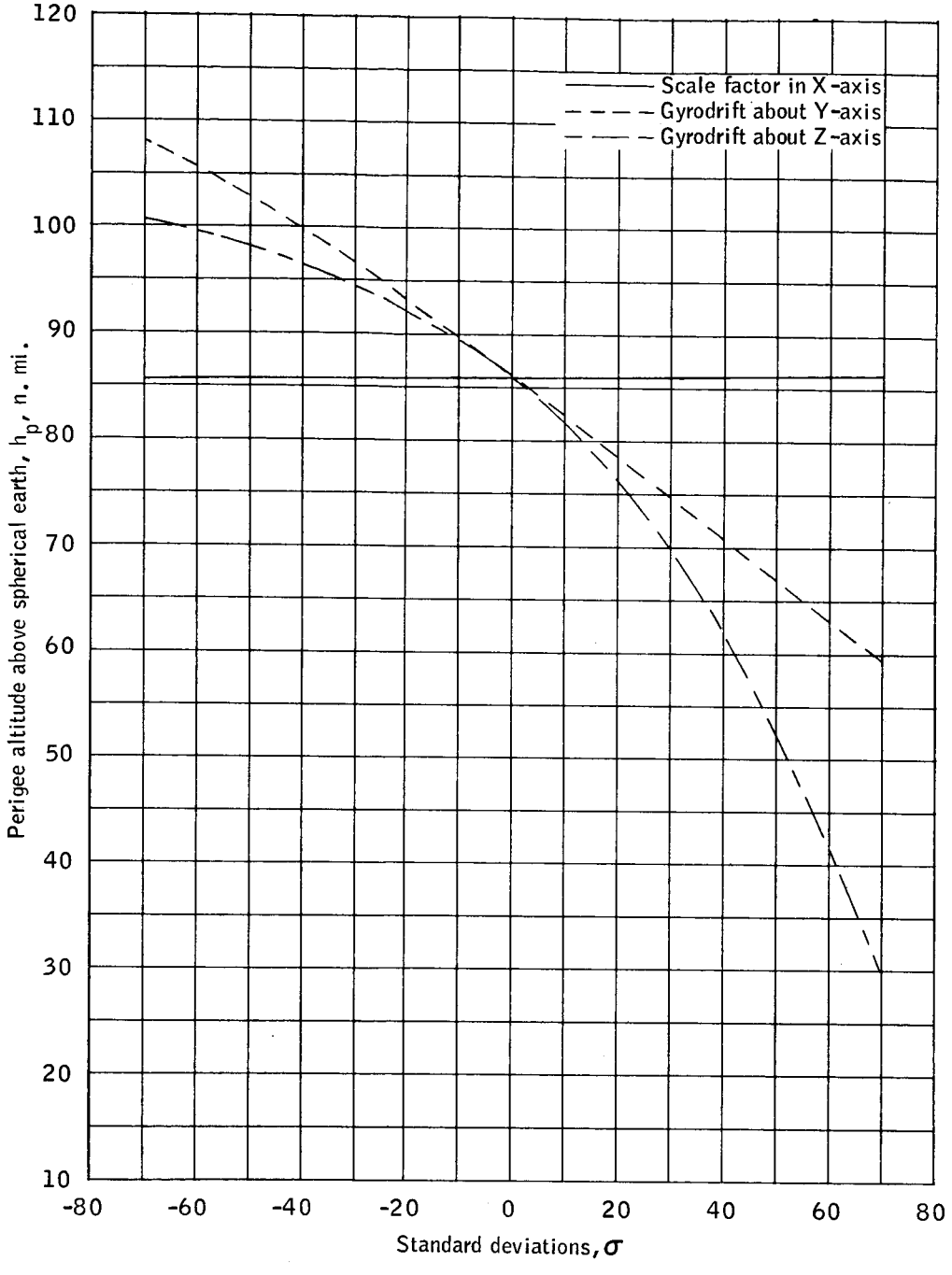
(g) Apogee altitude above spherical earth versus scale factor and drift errors.

Figure 4.- Continued.



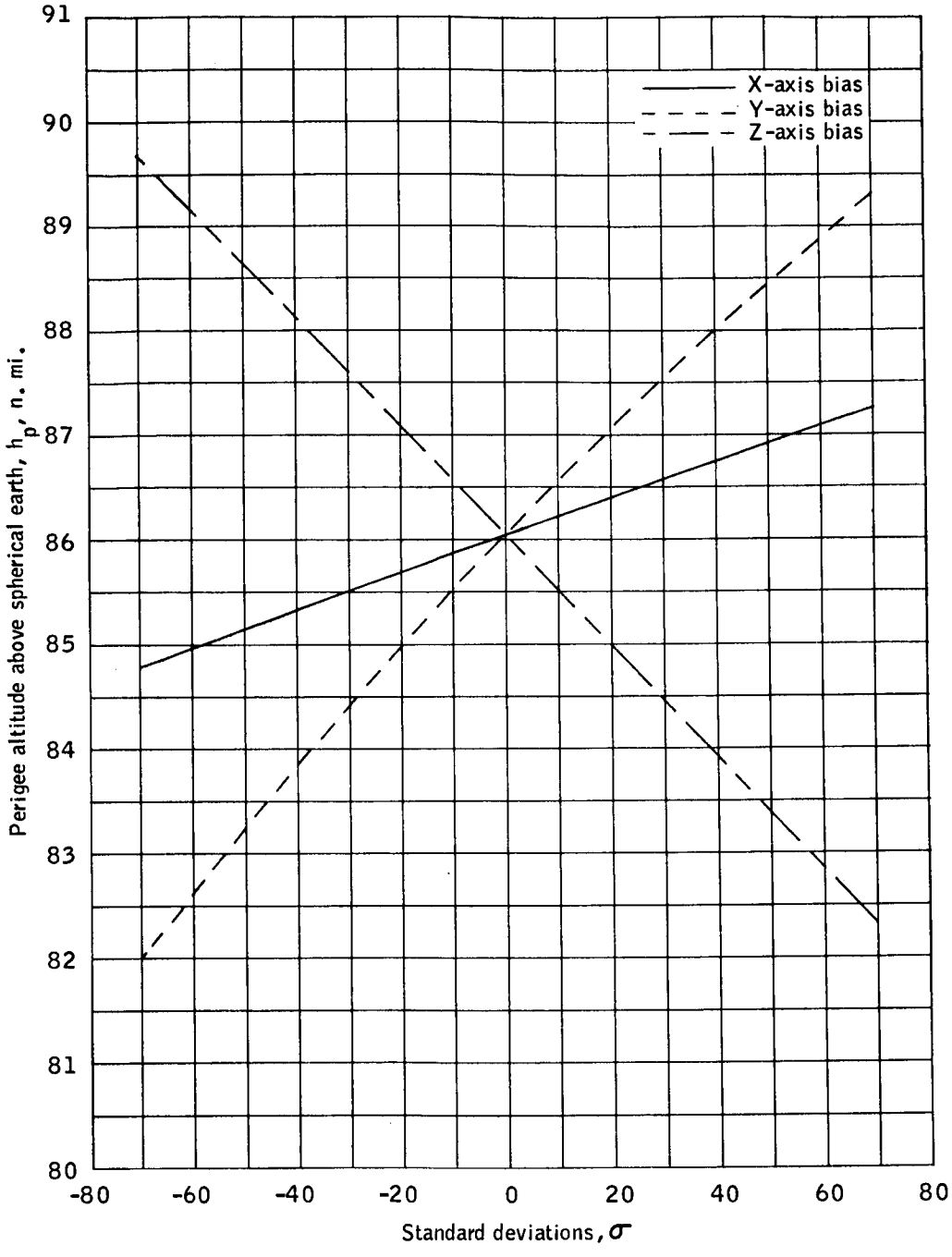
(h) Apogee altitude above spherical earth versus bias errors.

Figure 4.- Continued.



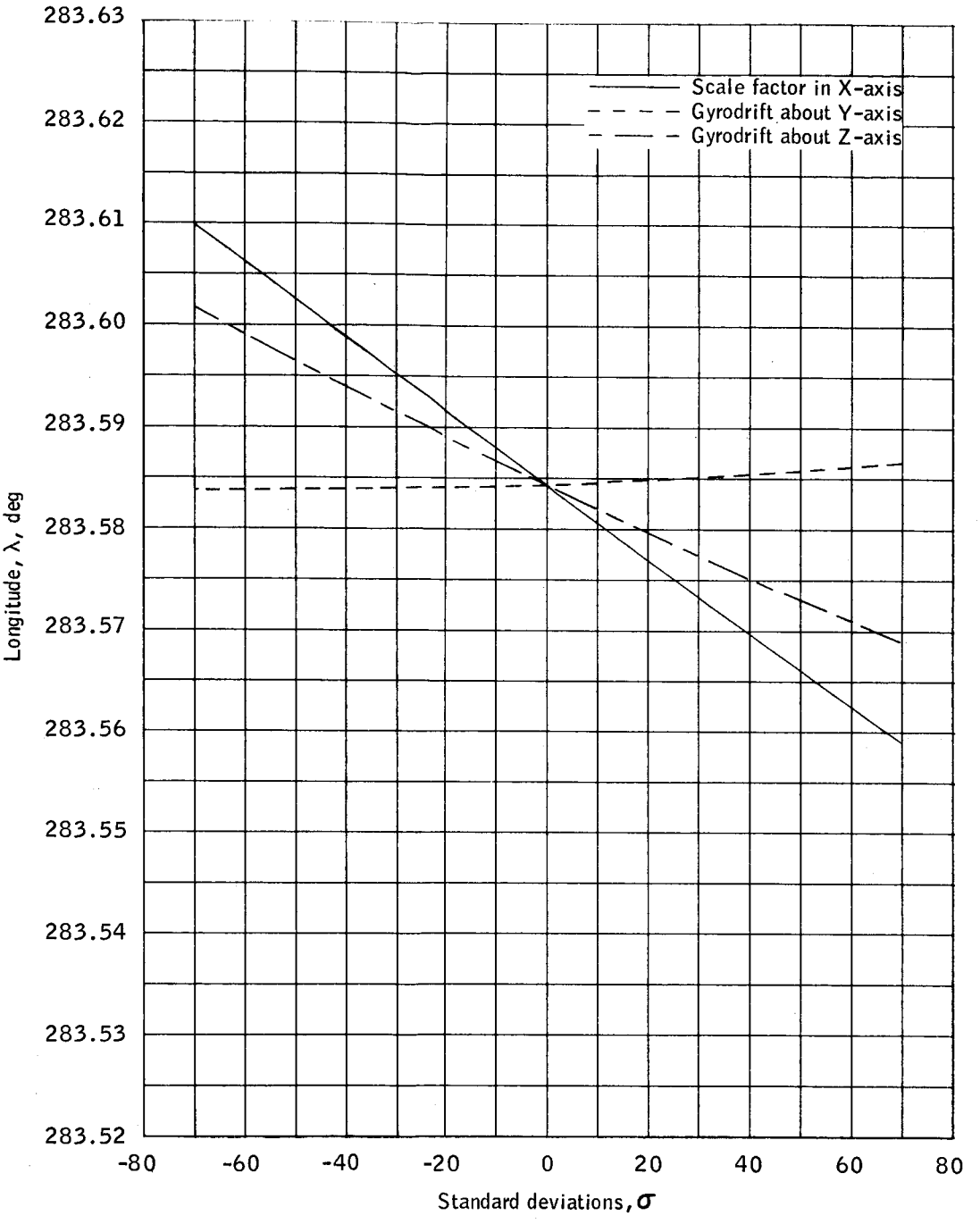
(i) Perigee altitude above spherical earth versus scale factor and drift errors.

Figure 4.- Continued.



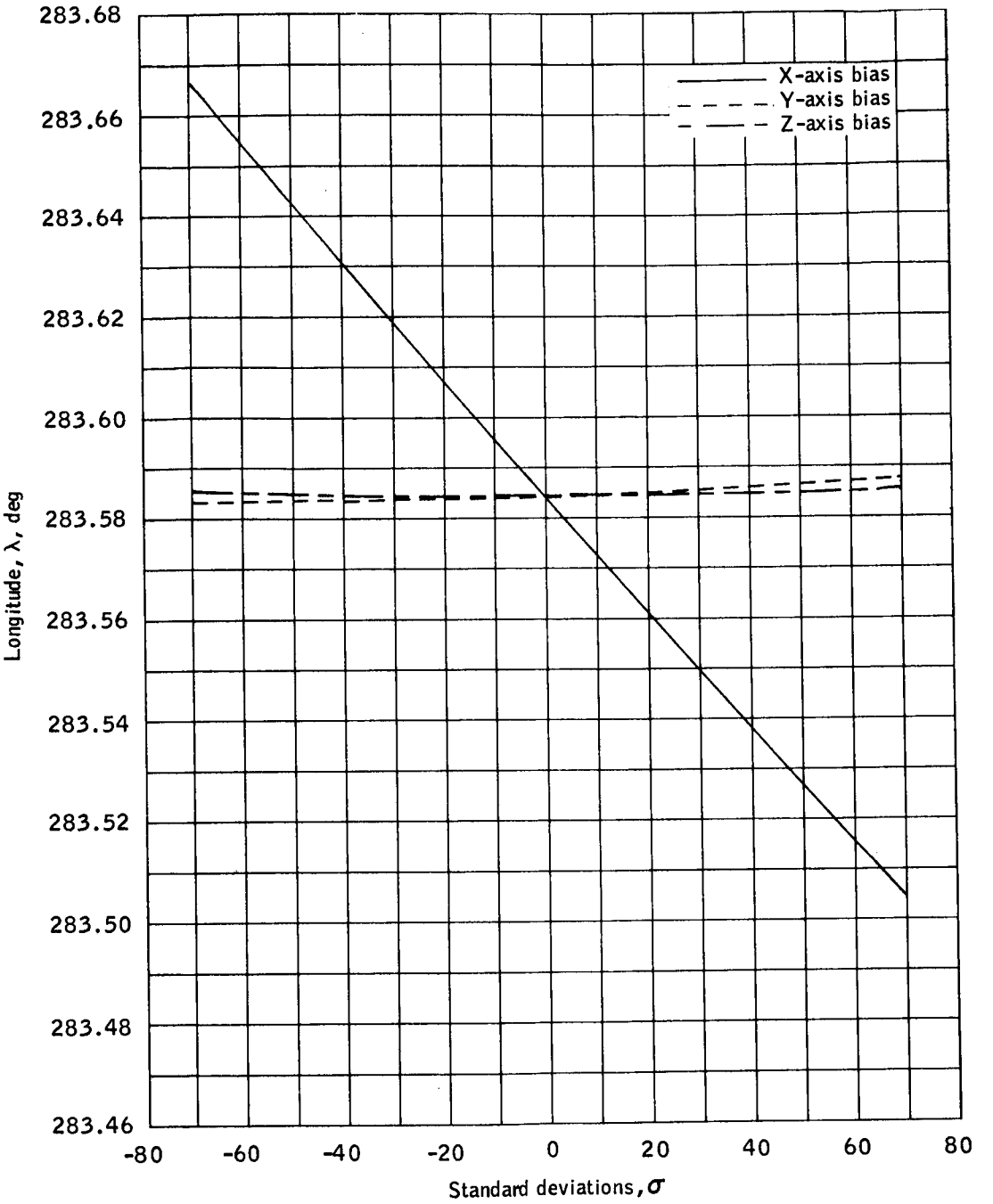
(j) Perigee altitude above spherical earth versus bias errors.

Figure 4.- Continued.



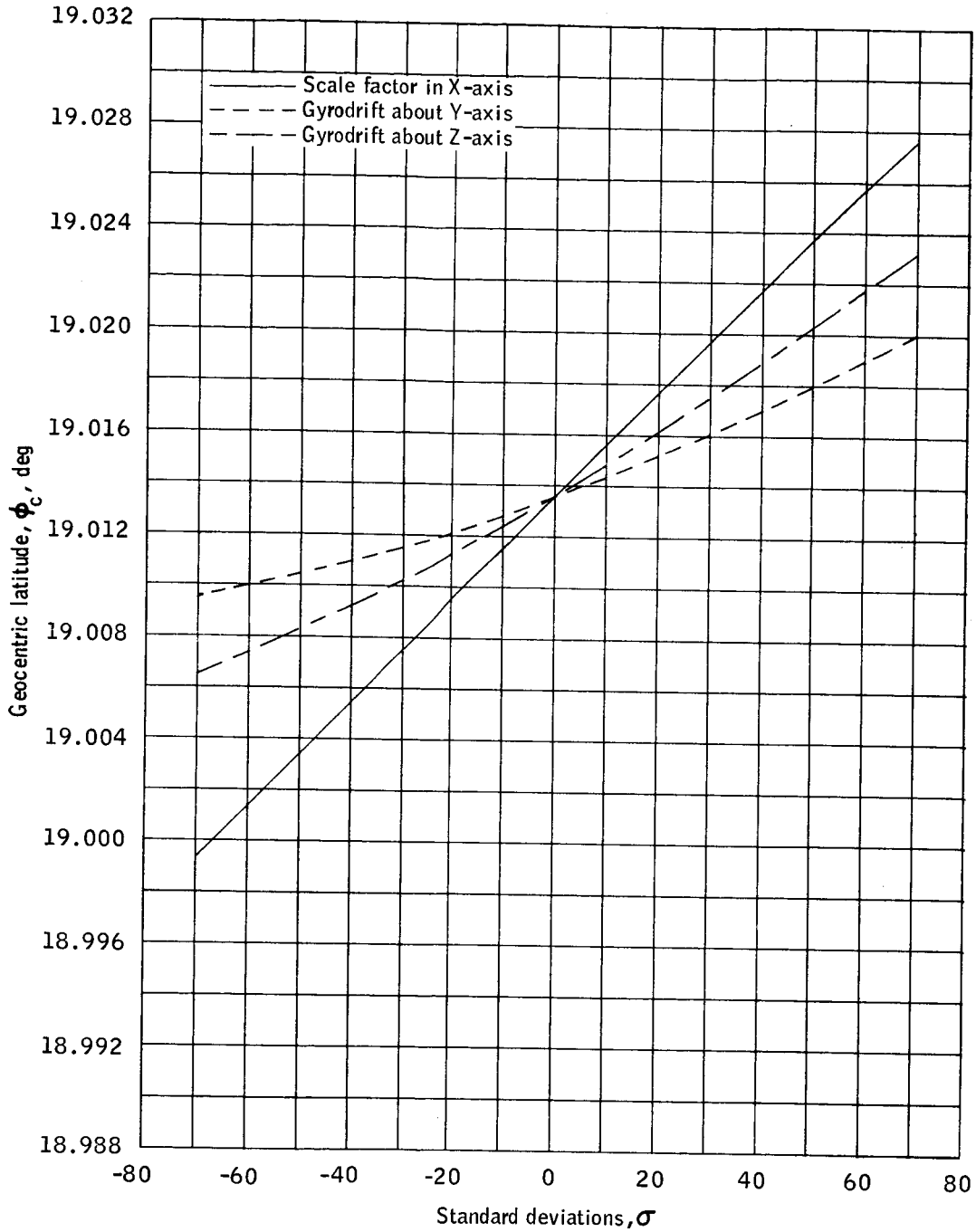
(k) Longitude versus scale factor and drift errors.

Figure 4.- Continued.



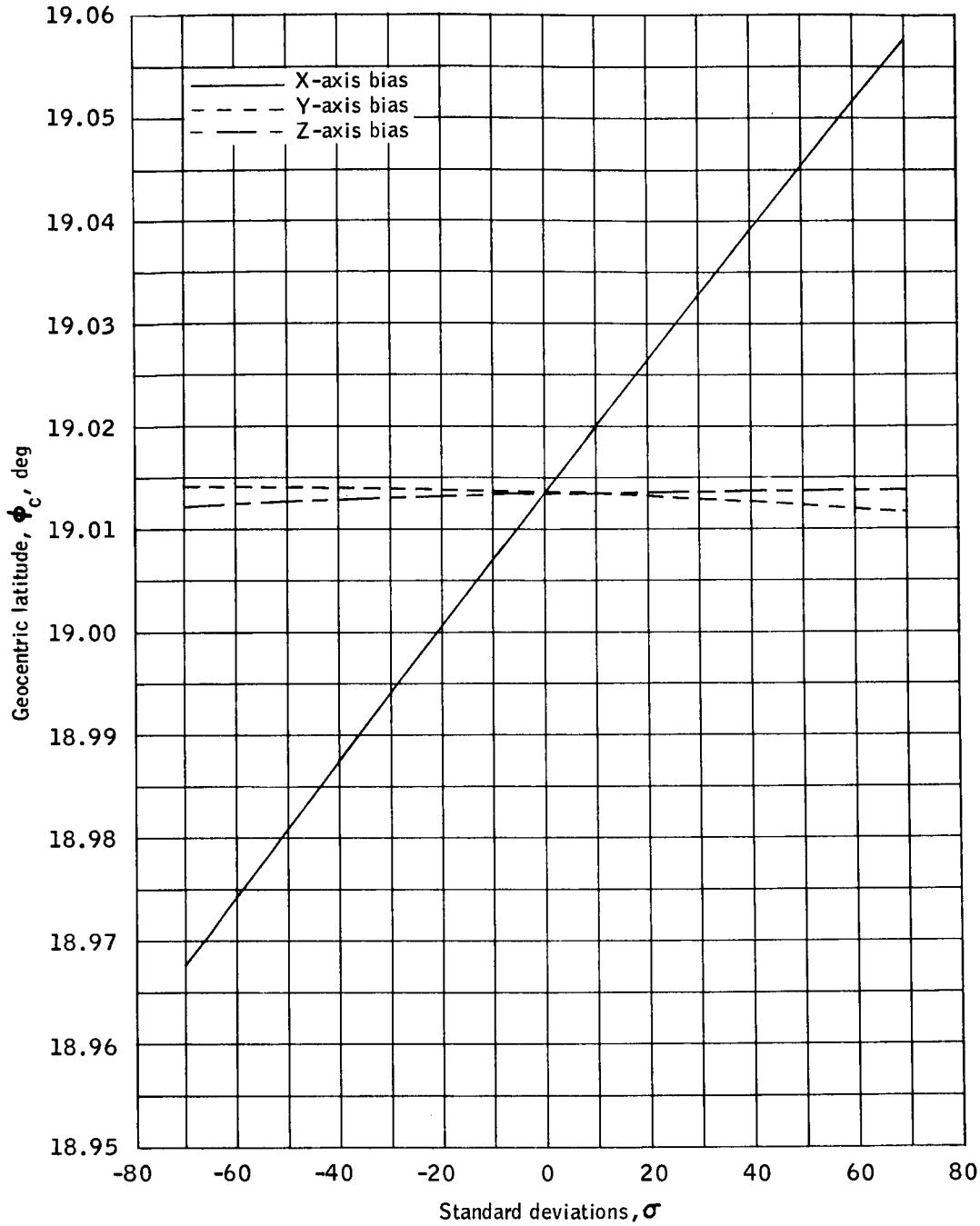
(l) Longitude versus bias errors.

Figure 4.- Continued.



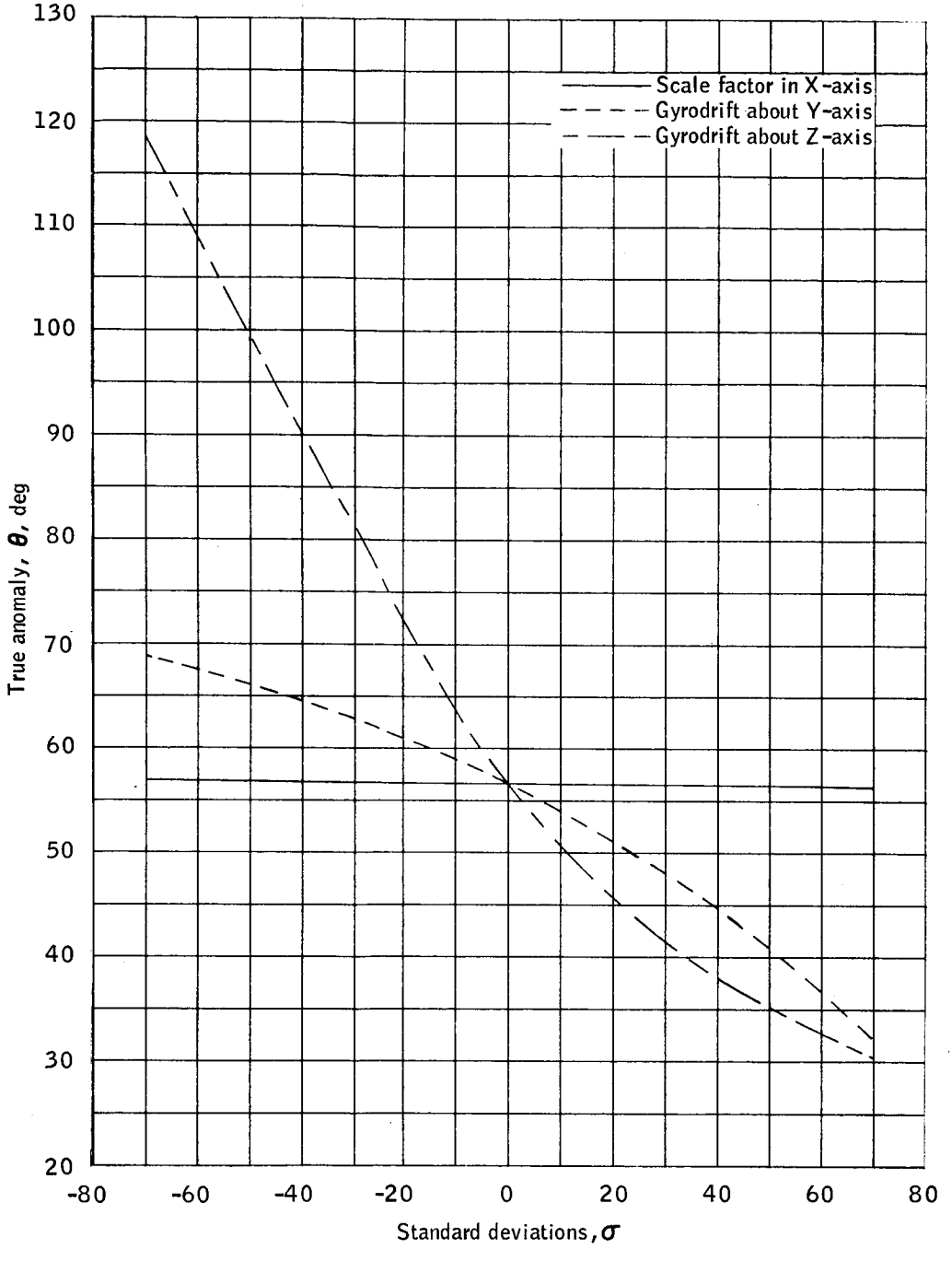
(m) Geocentric latitude versus scale factor and drift errors.

Figure 4.- Continued.



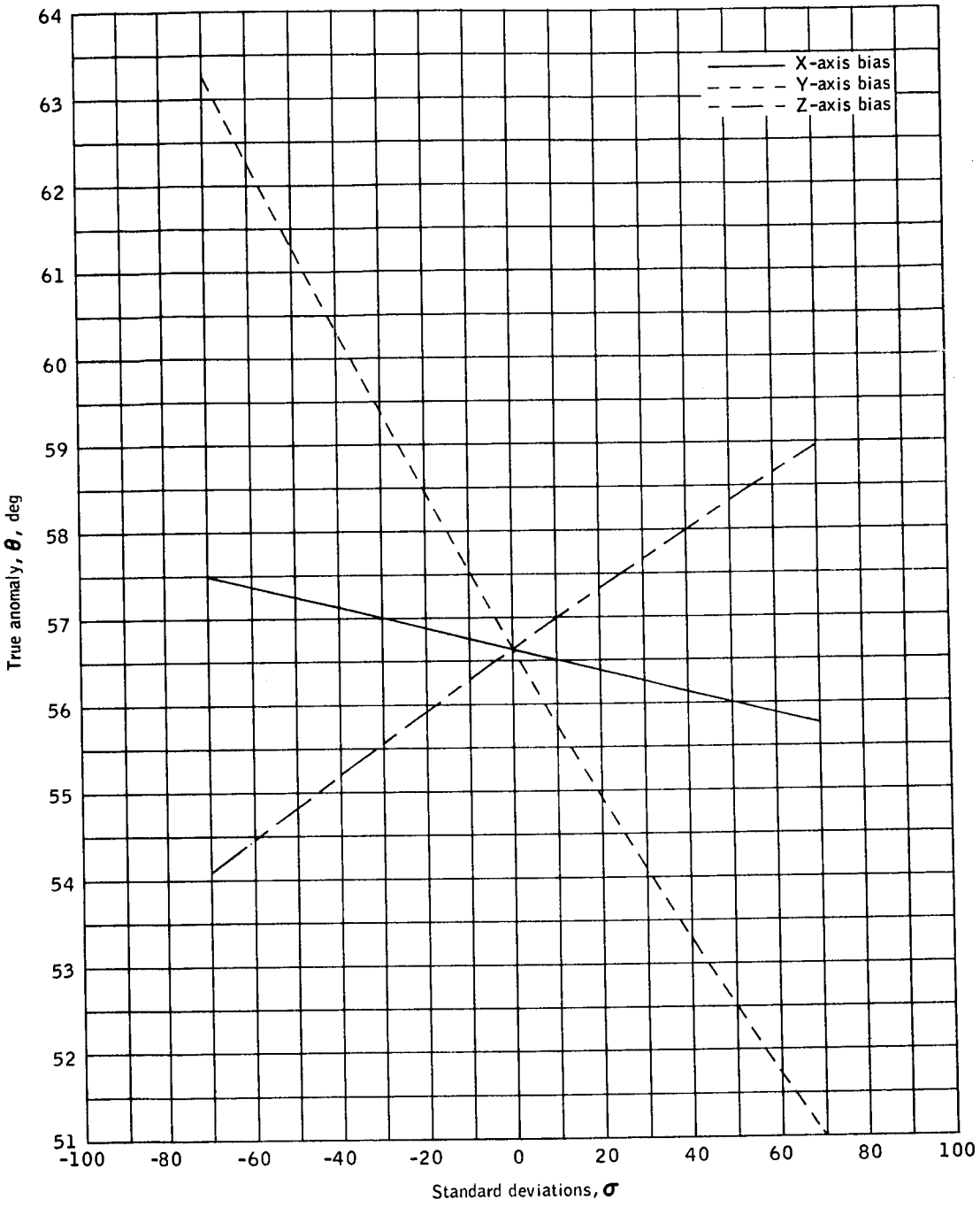
(n) Geocentric latitude versus bias errors.

Figure 4.- Continued.



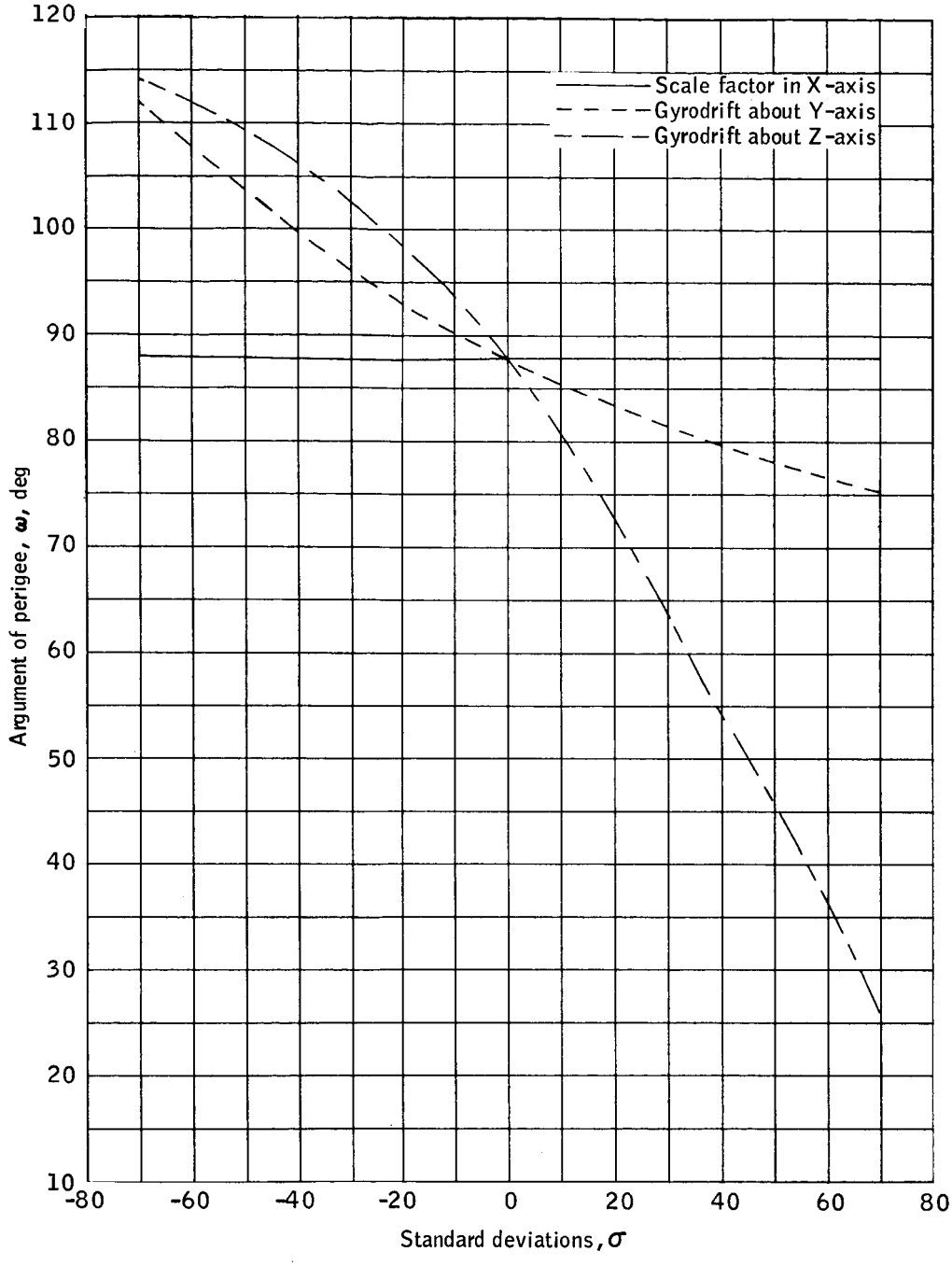
(o) True anomaly versus scale factor and drift errors.

Figure 4.- Continued.



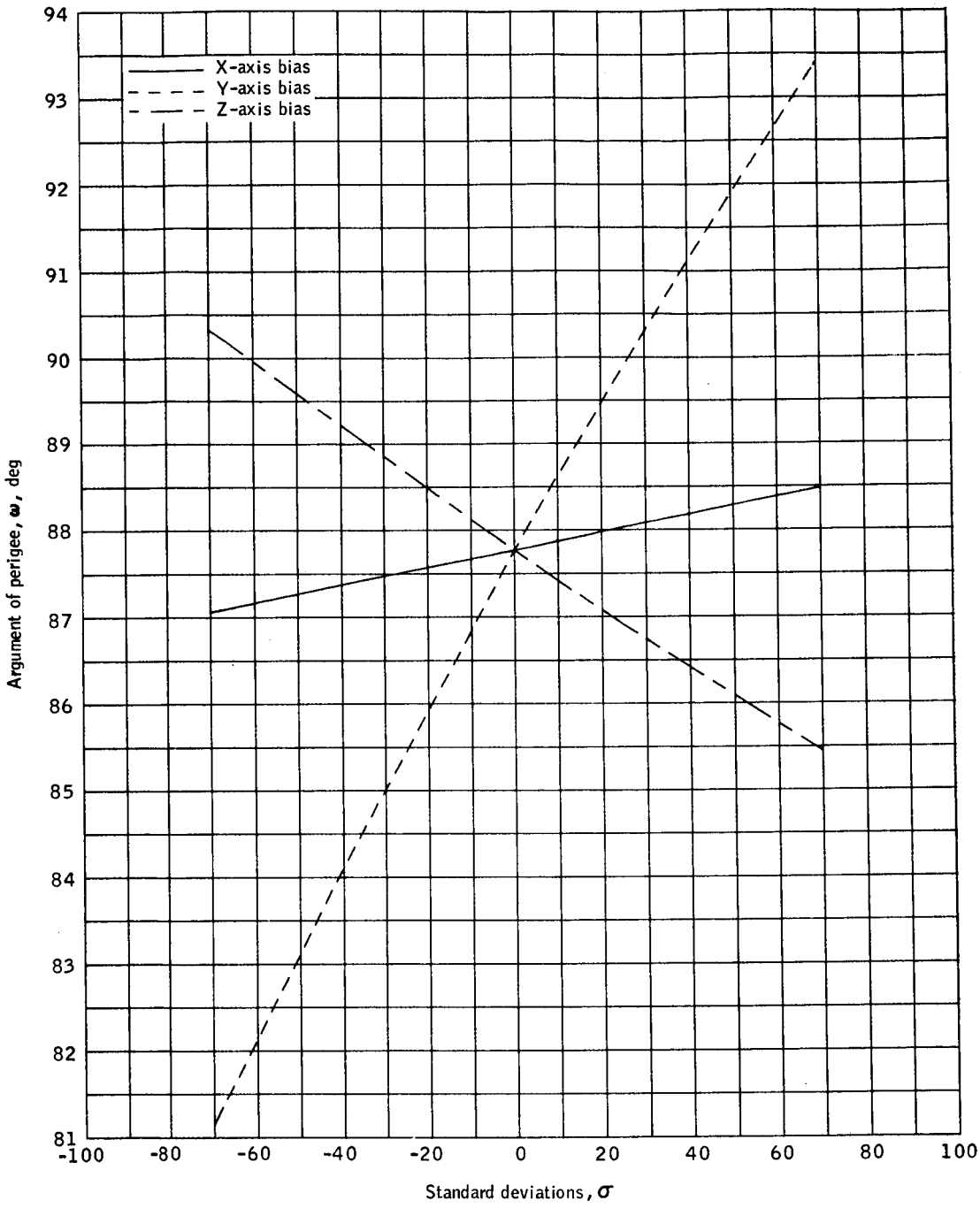
(p) True anomaly versus bias errors.

Figure 4.- Continued.



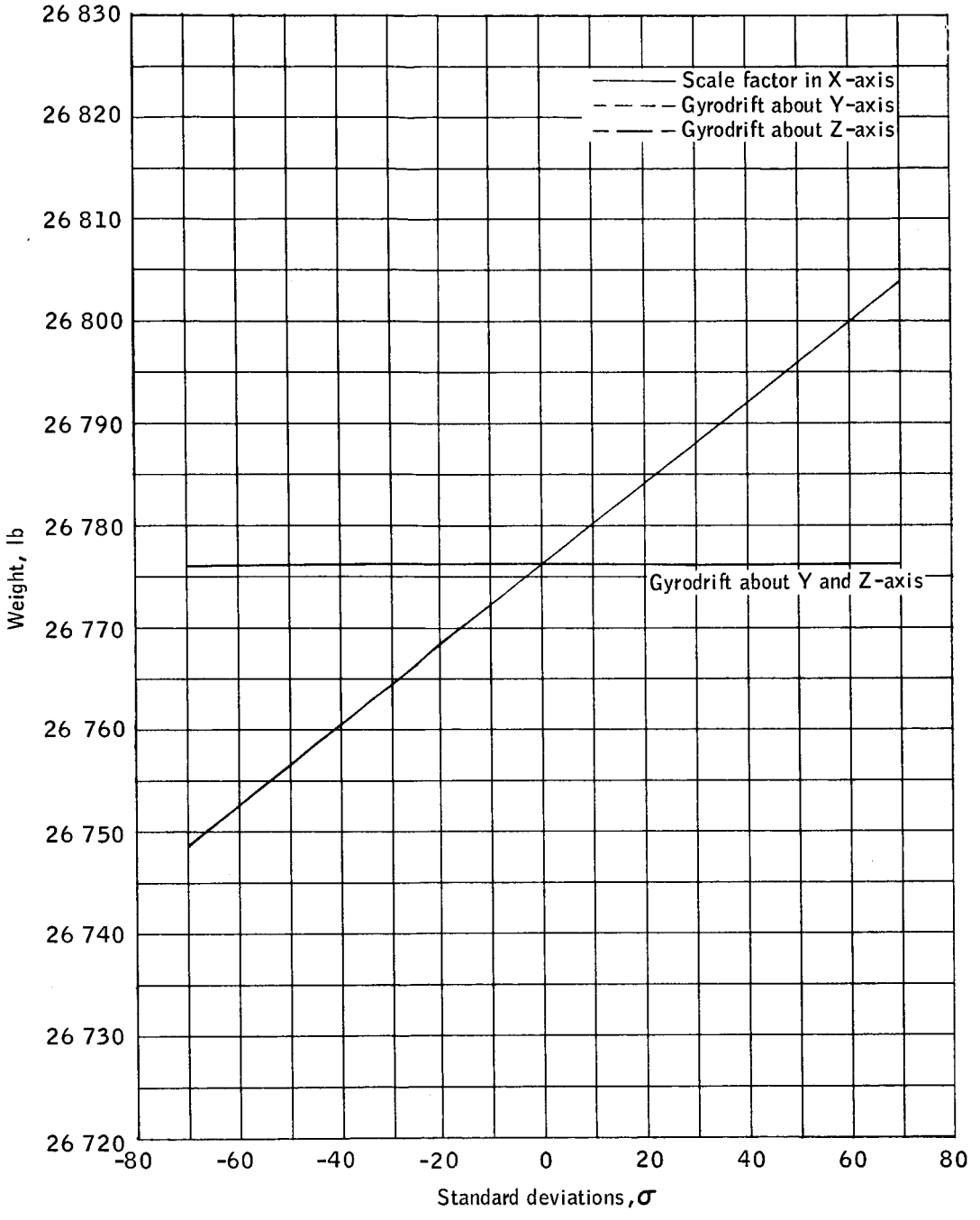
(q) Argument of perigee versus scale factor and drift errors.

Figure 4.- Continued.



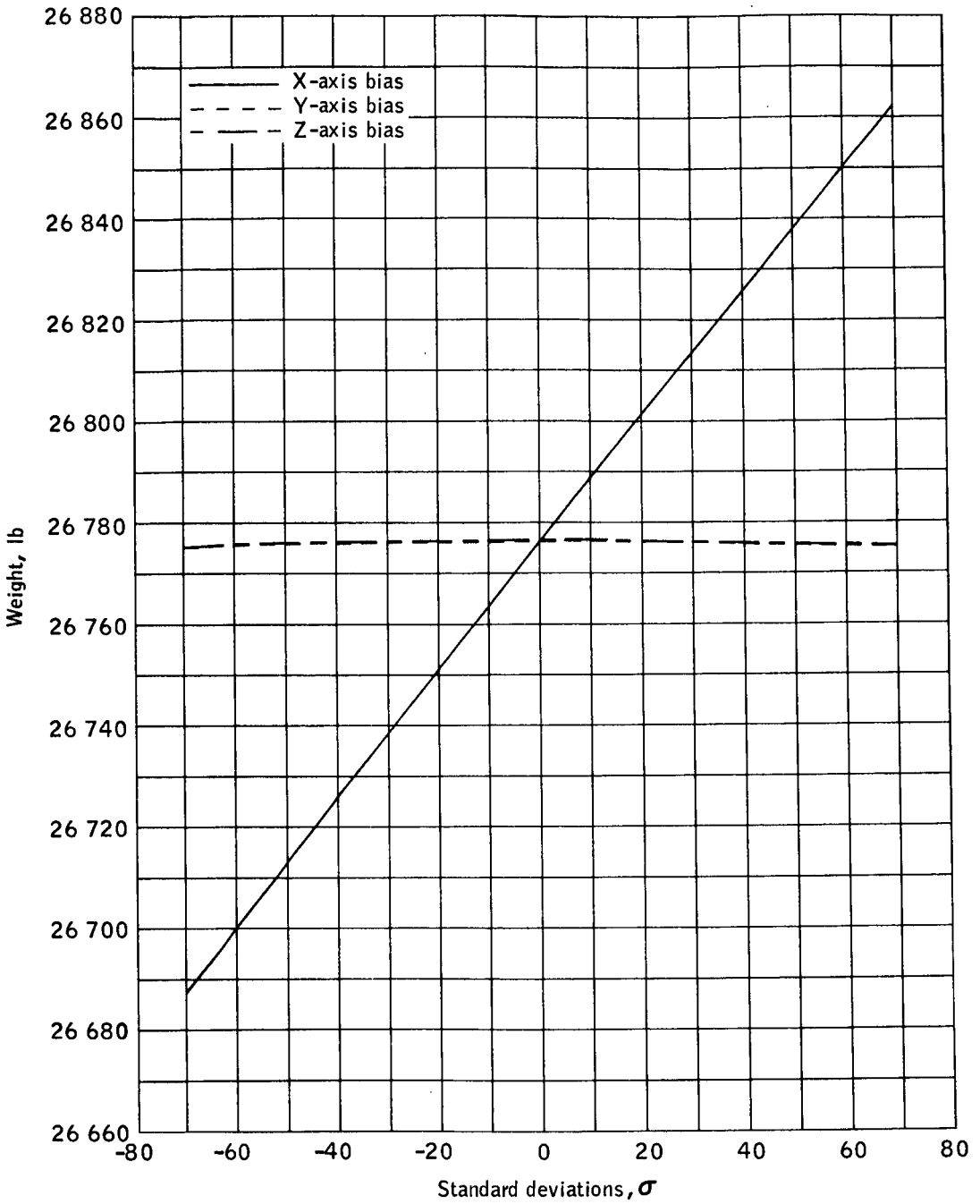
(r) Argument of perigee versus bias errors.

Figure 4.- Continued.



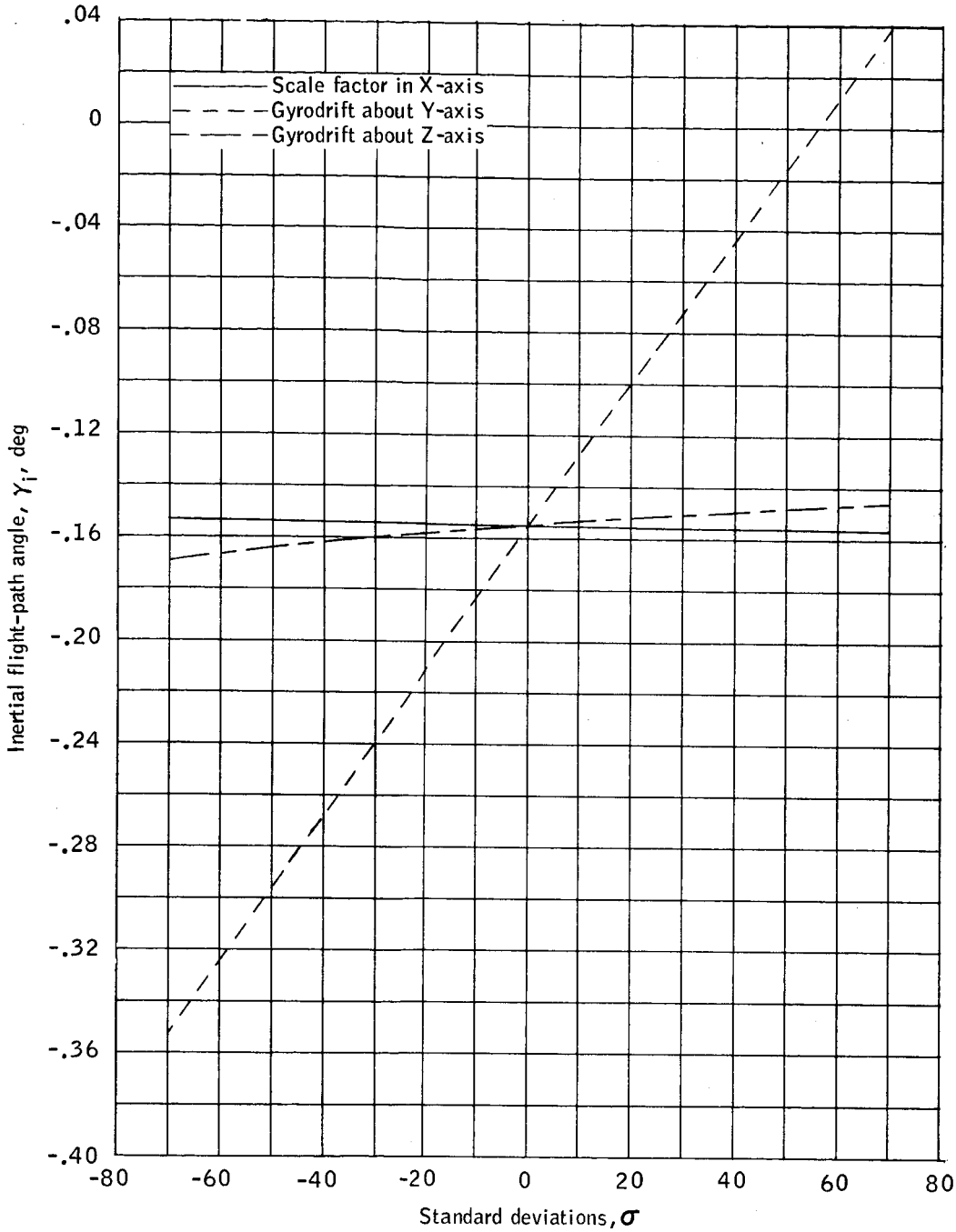
(s) Weight versus scale factor and drift errors.

Figure 4.- Continued.



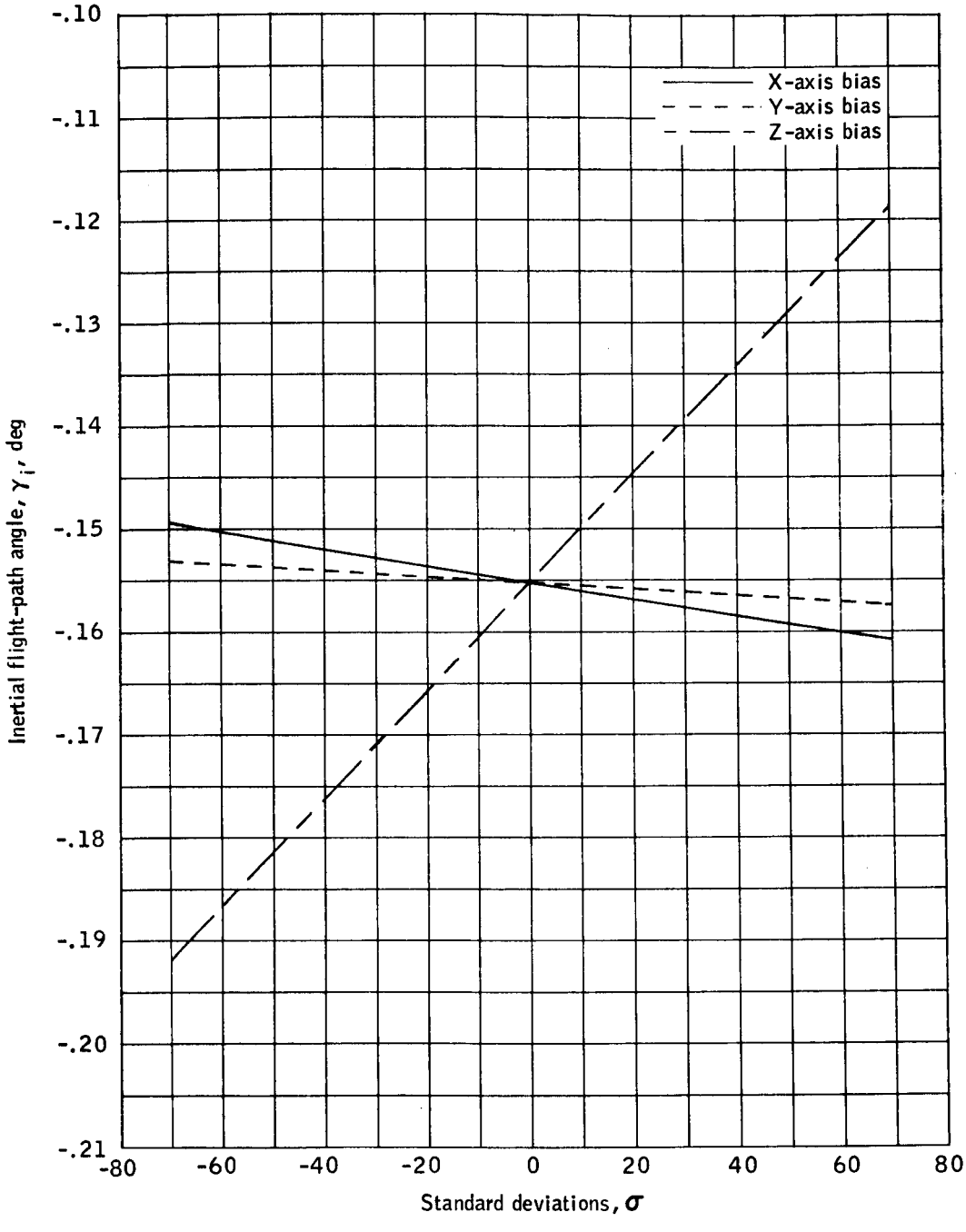
(t) Weight versus bias errors.

Figure 4.- Concluded.



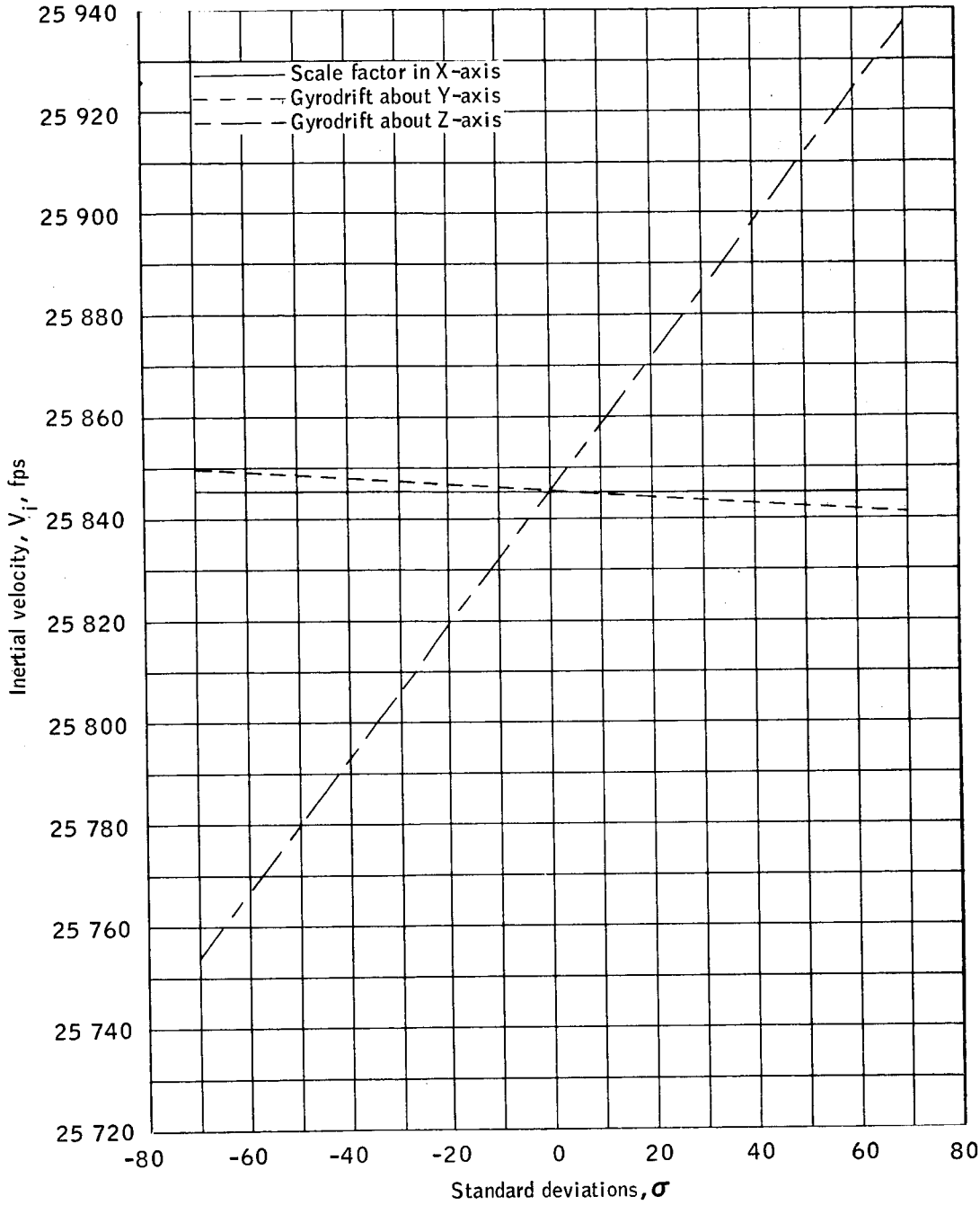
(a) Inertial flight-path angle versus scale factor and drift errors.

Figure 5. - Mission C dispersions at the end of the seventh SPS burn due to accelerometer bias, accelerometer scale factor and gyrodrift errors.



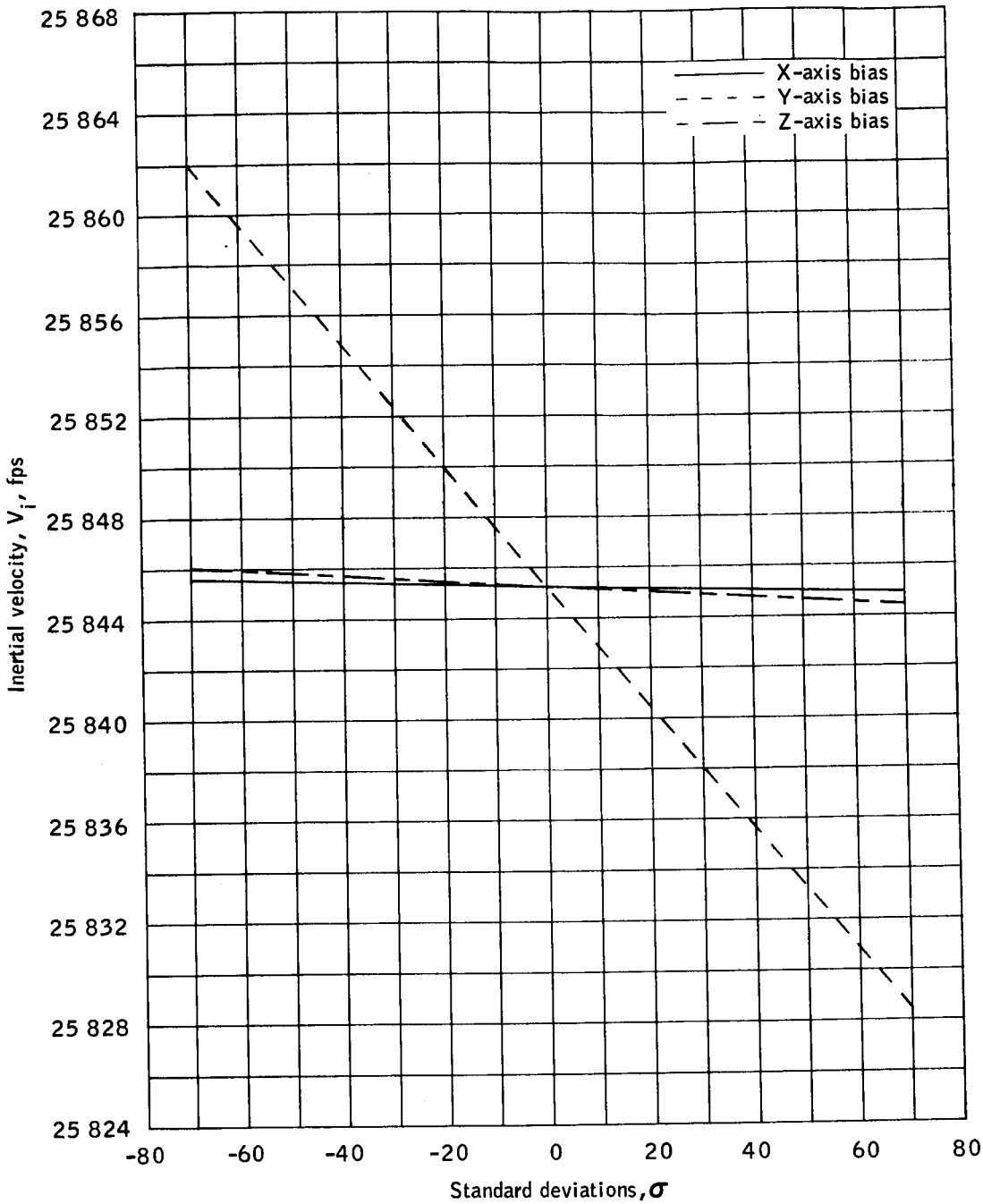
(b) Inertial flight-path angle versus bias errors.

Figure 5. - Continued.



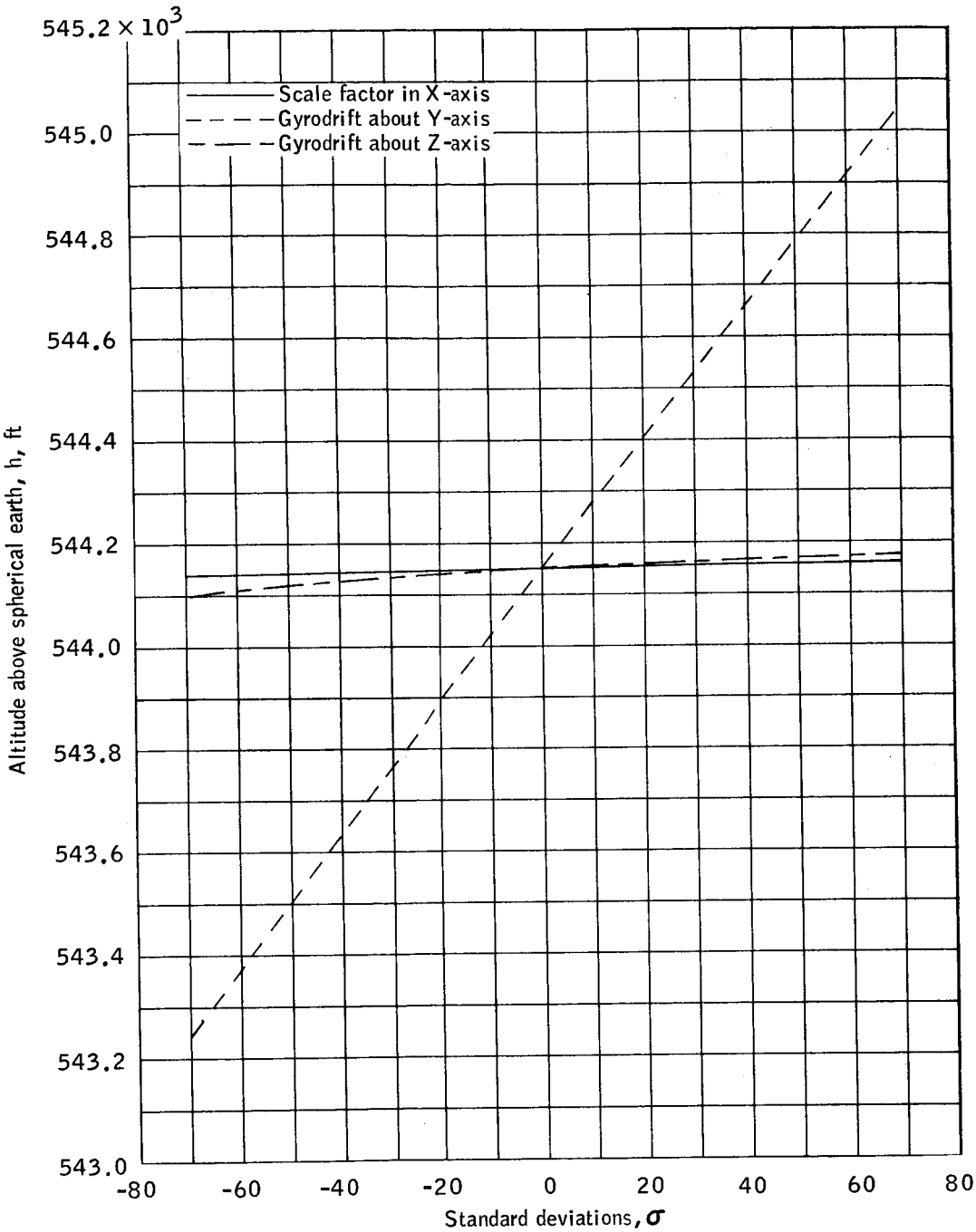
(c) Inertial velocity versus scale factor and drift errors.

Figure 5. - Continued.



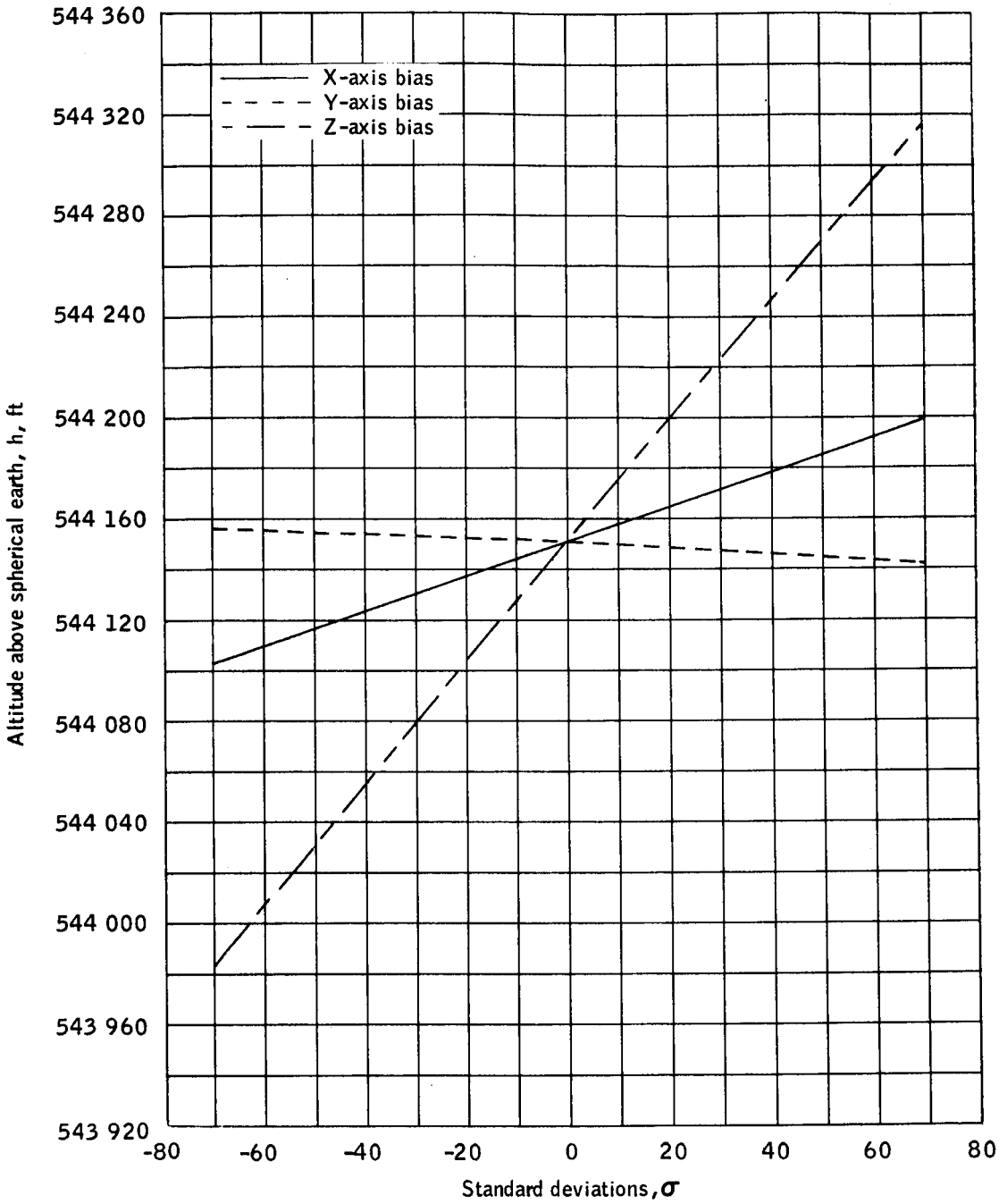
(d) Inertial velocity versus bias errors.

Figure 5. - Continued.



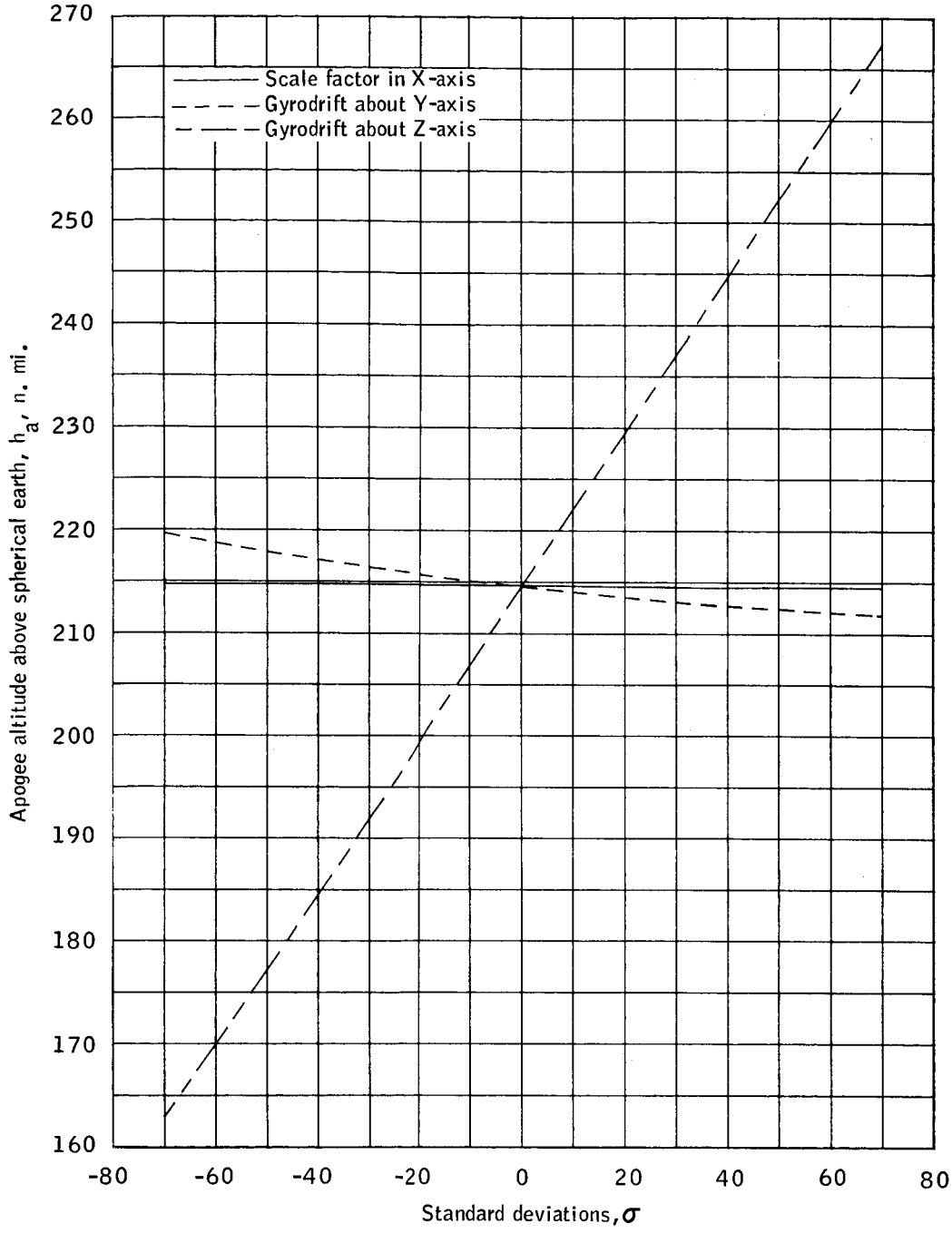
(e) Altitude above spherical earth versus scale factor and drift errors.

Figure 5. - Continued.



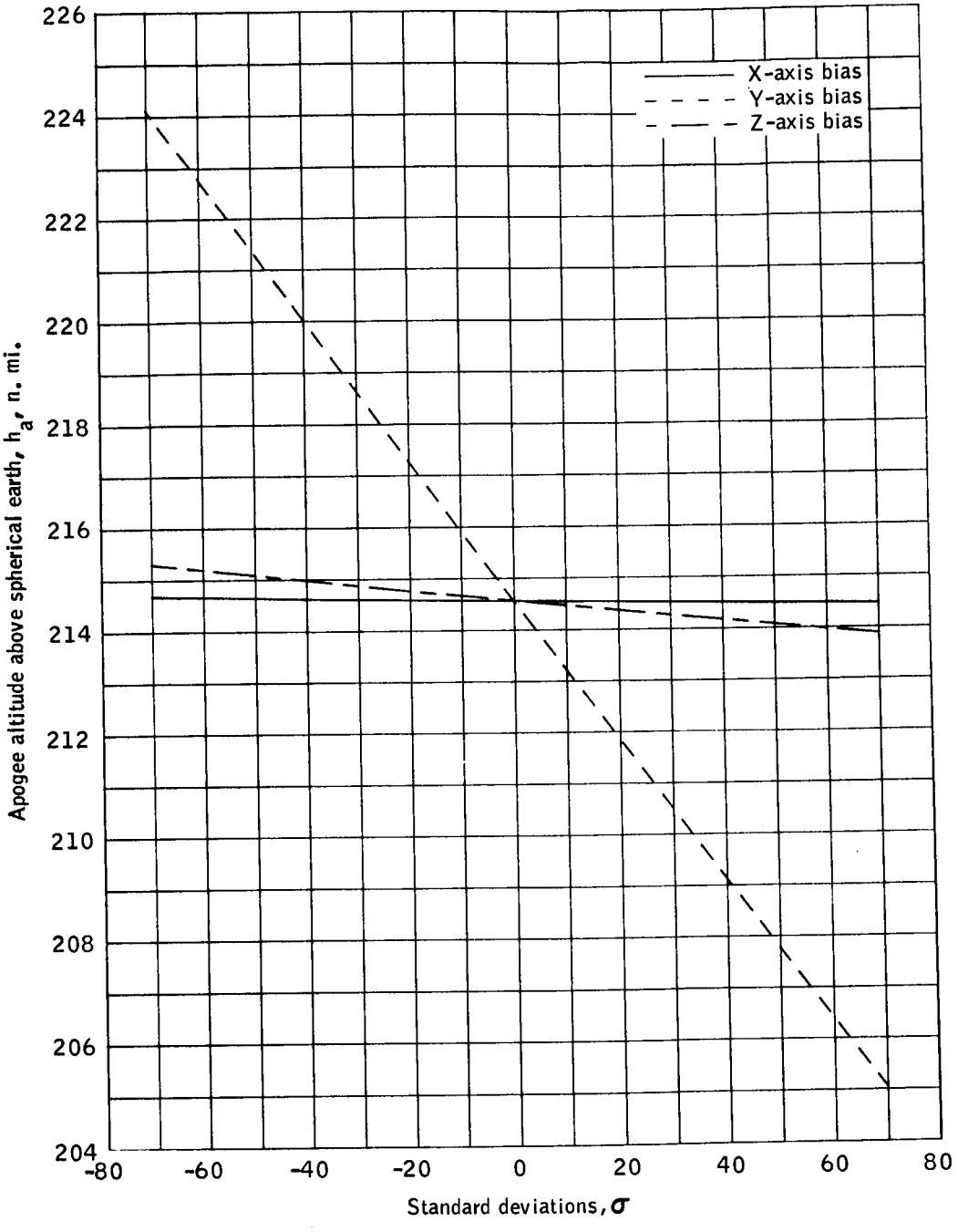
(f) Altitude above spherical earth versus bias errors.

Figure 5. -Continued.



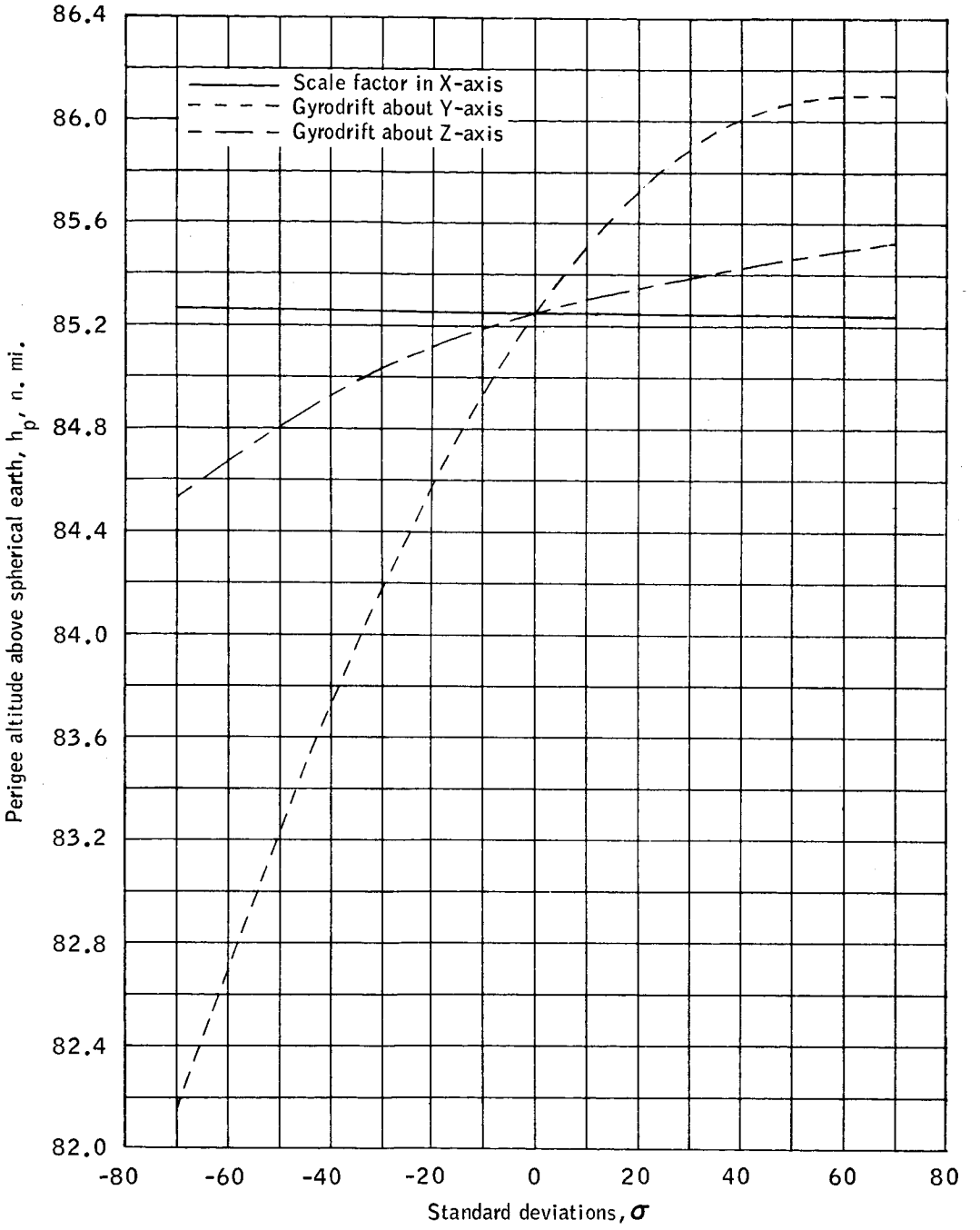
(g) Apogee altitude above spherical earth versus scale factor and drift errors.

Figure 5. - Continued.



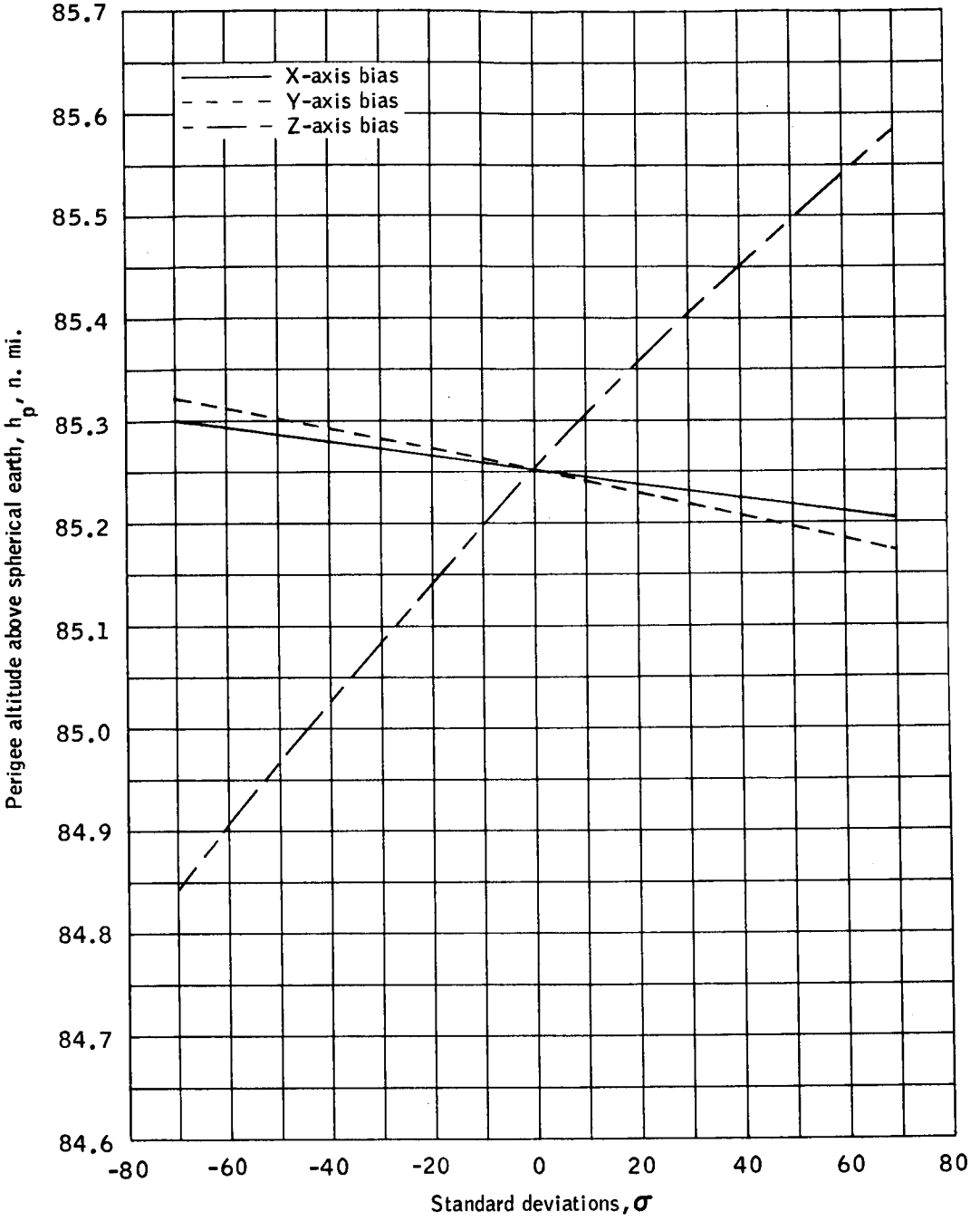
(h) Apogee altitude above spherical earth versus bias errors.

Figure 5.- Continued.



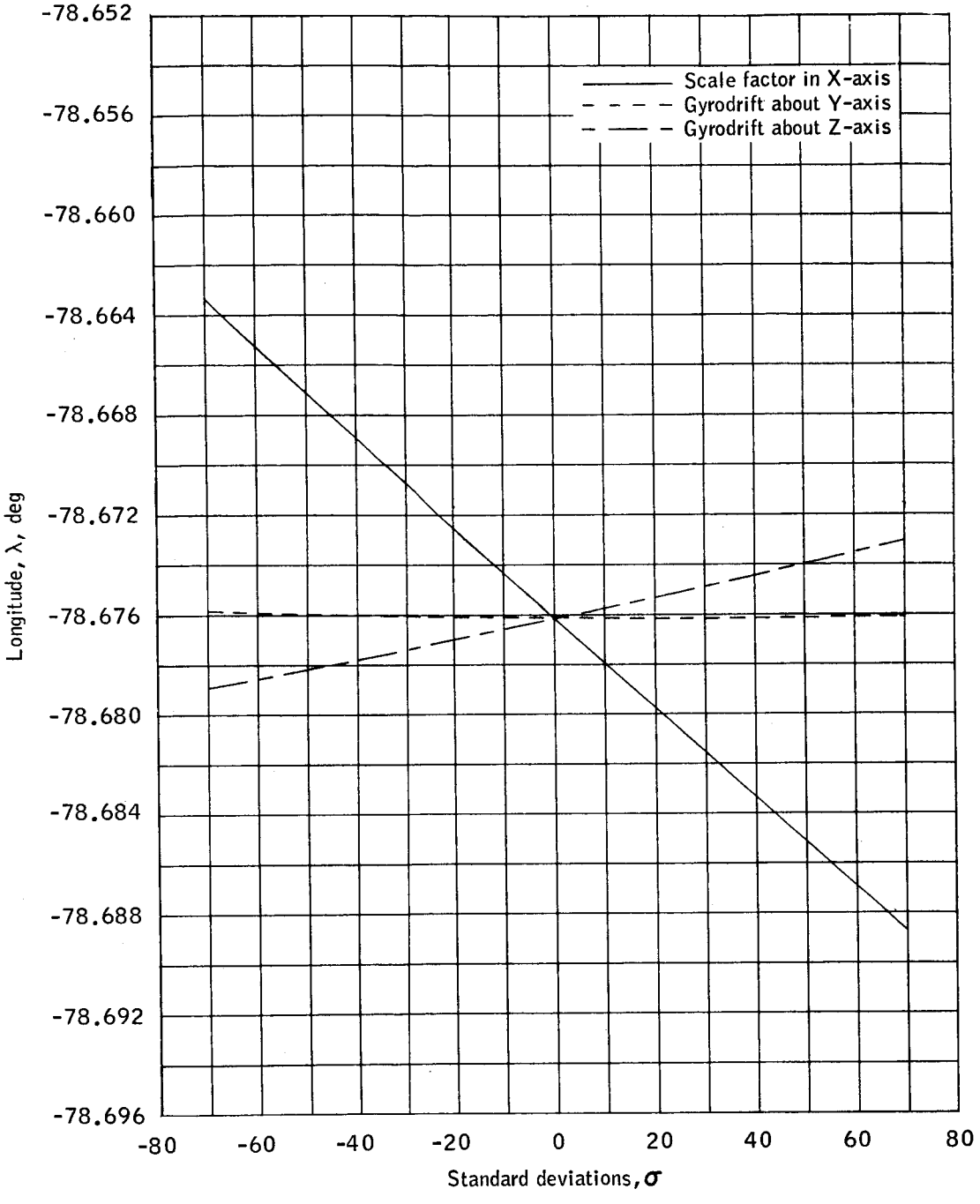
(i) Perigee altitude above spherical earth versus scale factor and drift errors.

Figure 5. - Continued.



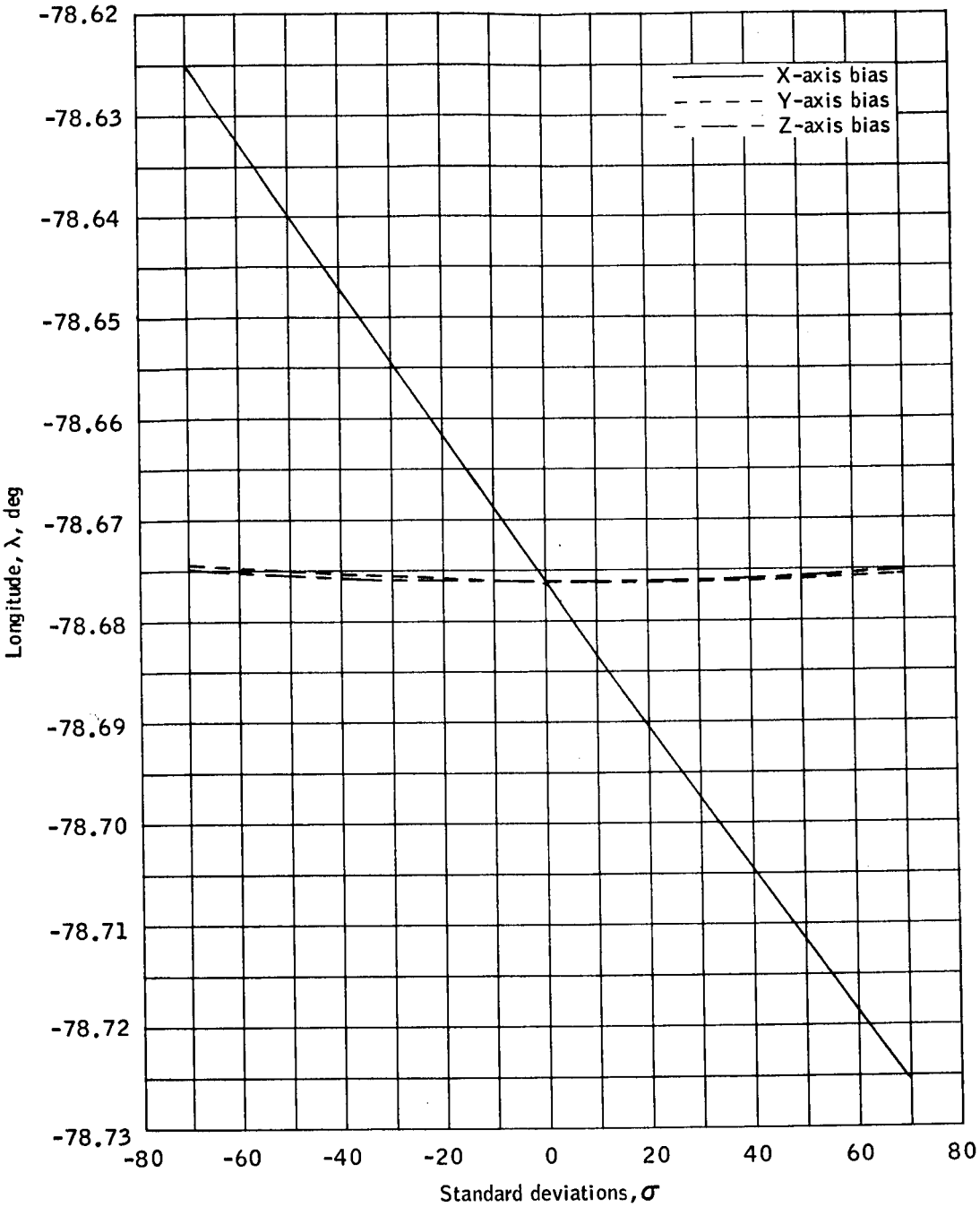
(j) Perigee altitude above spherical earth versus bias errors.

Figure 5. - Continued.



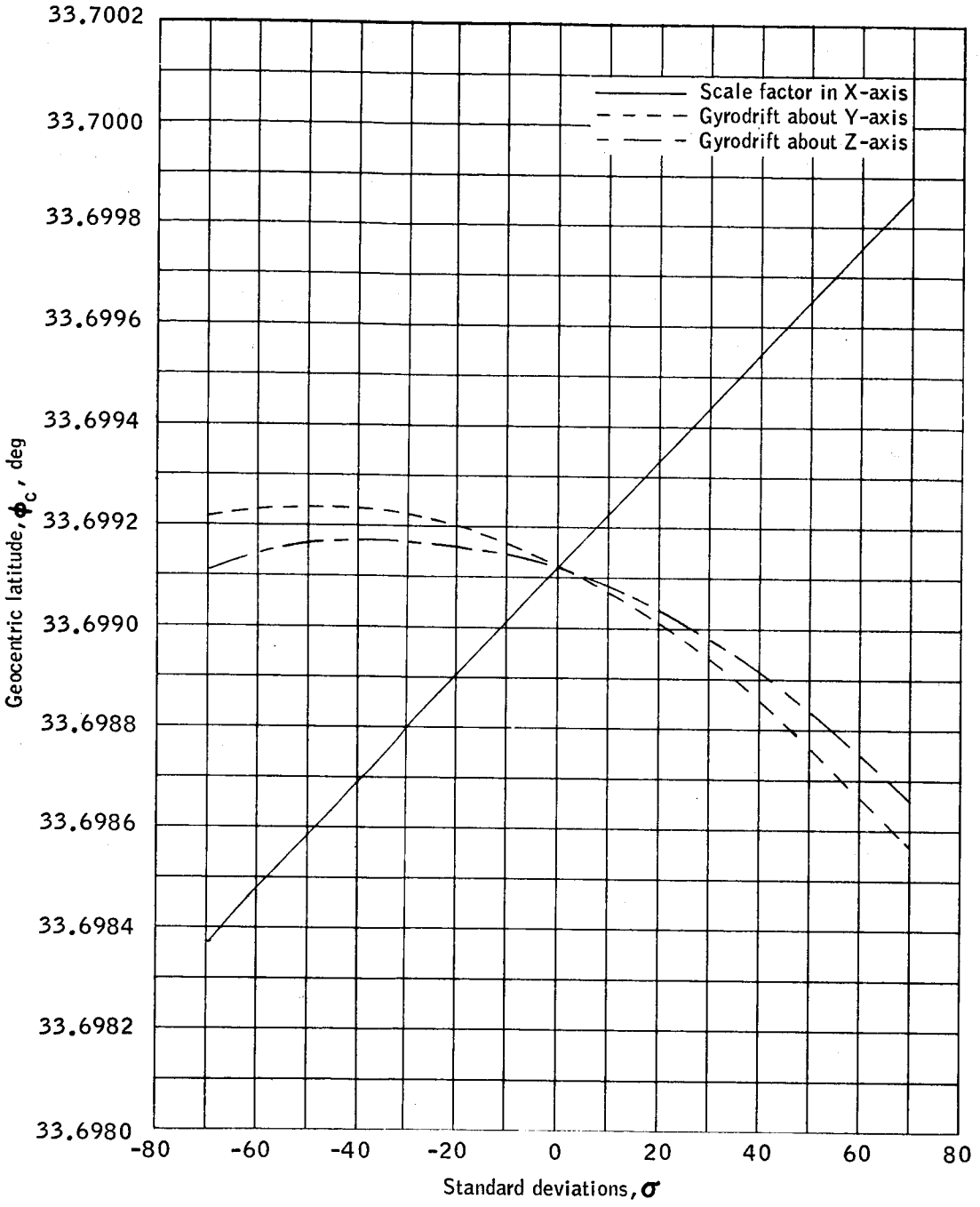
(k) Longitude versus scale factor and drift errors.

Figure 5. - Continued.



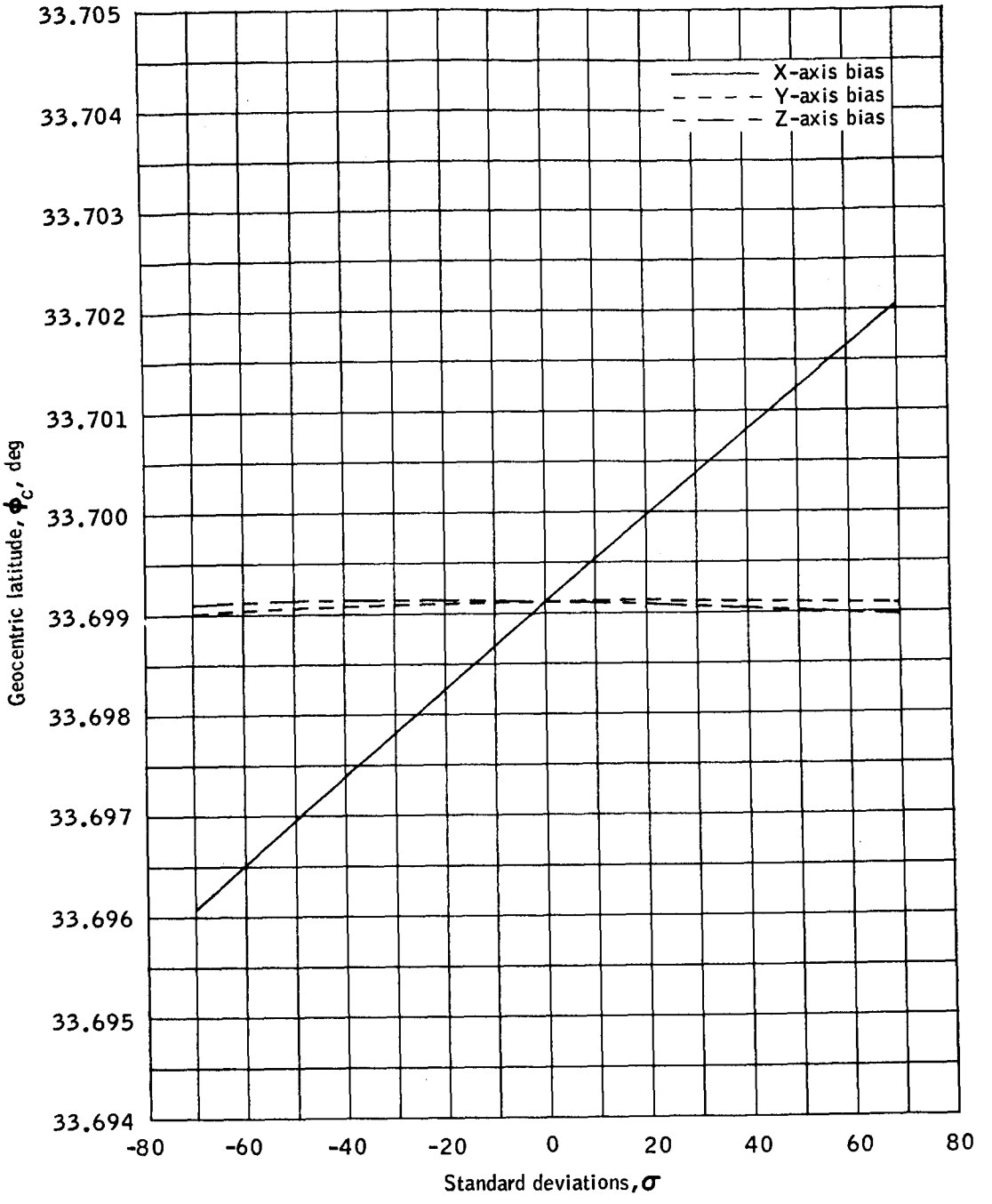
(l) Longitude versus bias errors.

Figure 5. - Continued.



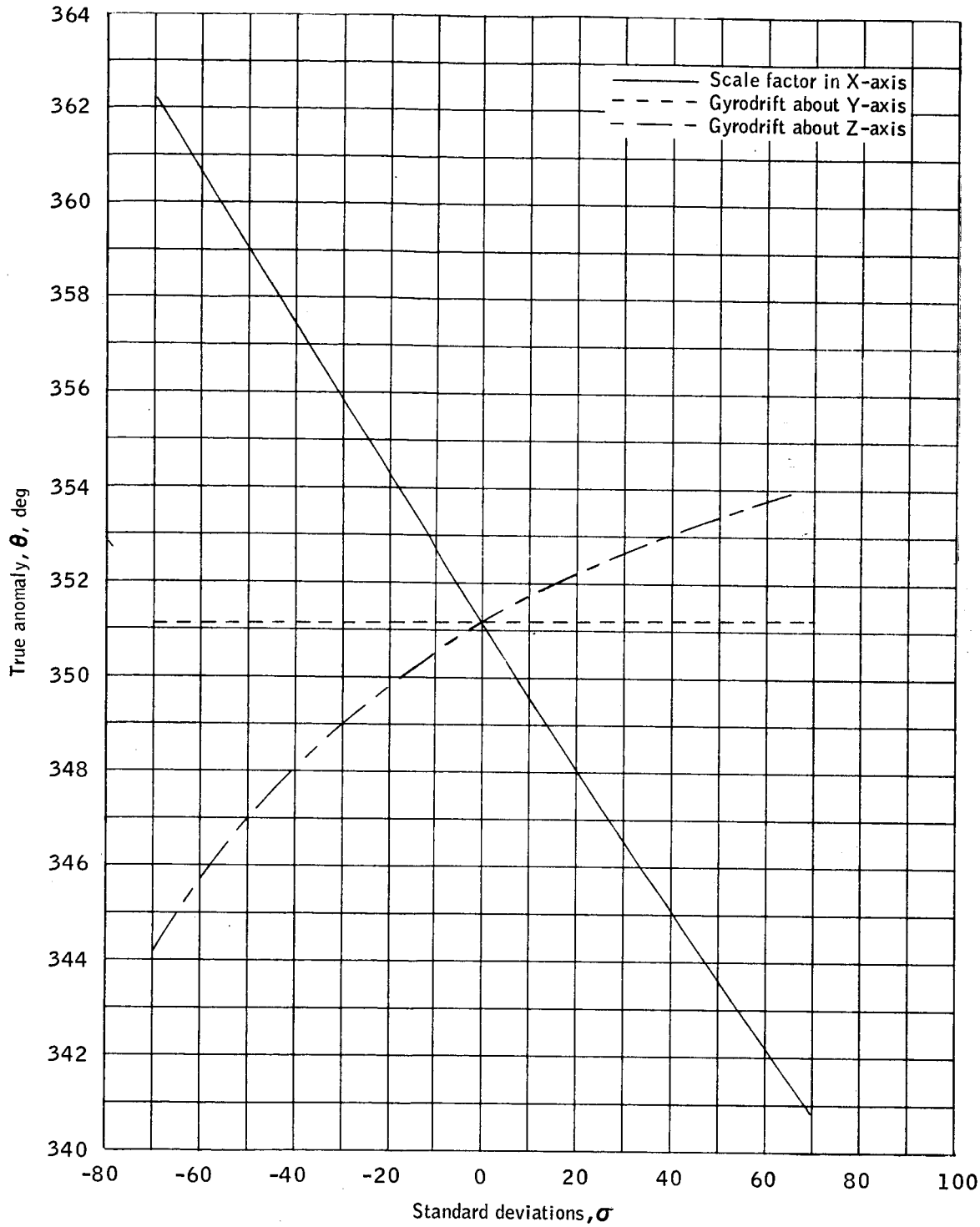
(m) Geocentric latitude versus scale factor and drift errors.

Figure 5. - Continued.



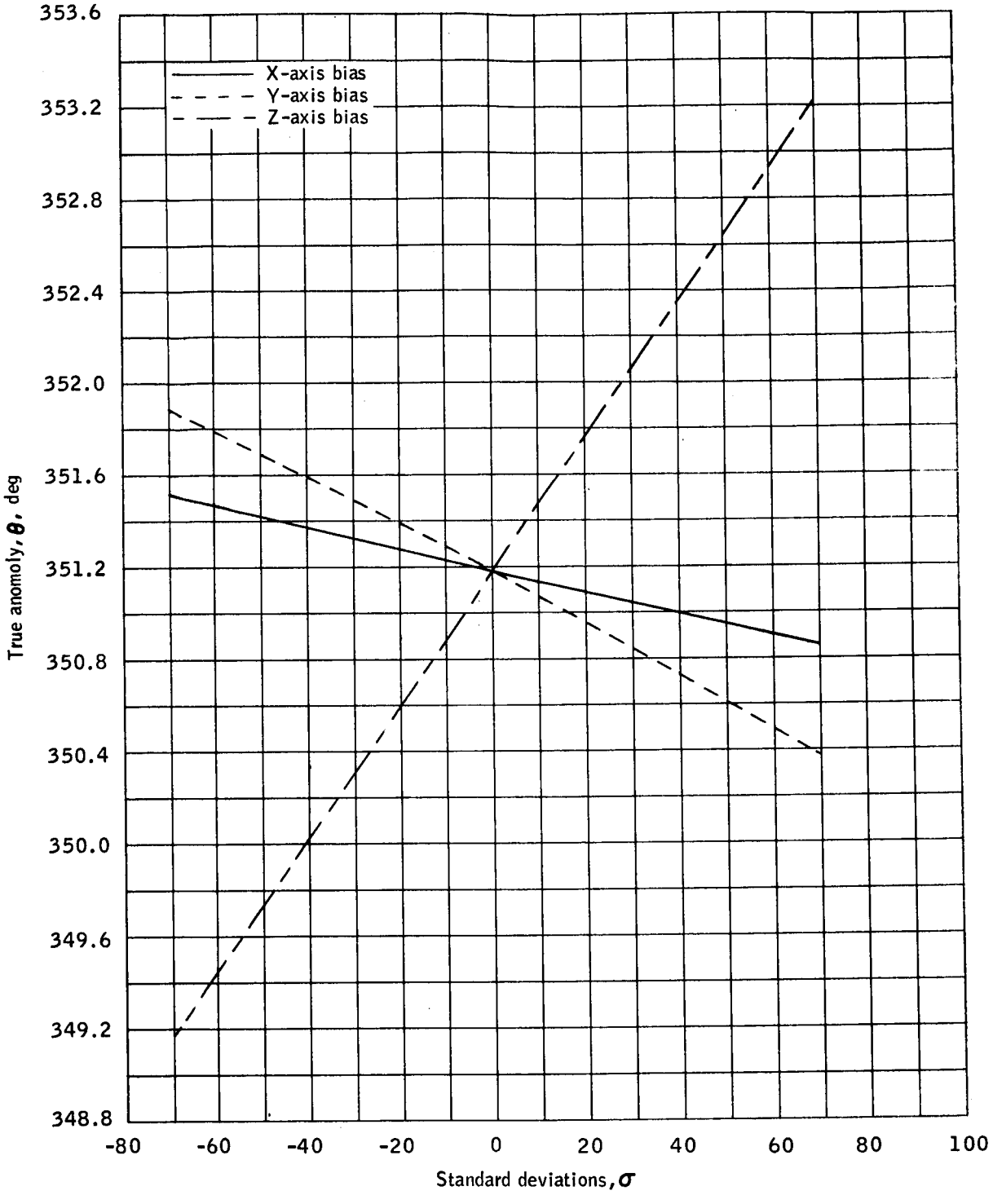
(n) Geocentric latitude versus bias errors.

Figure 5. - Continued.



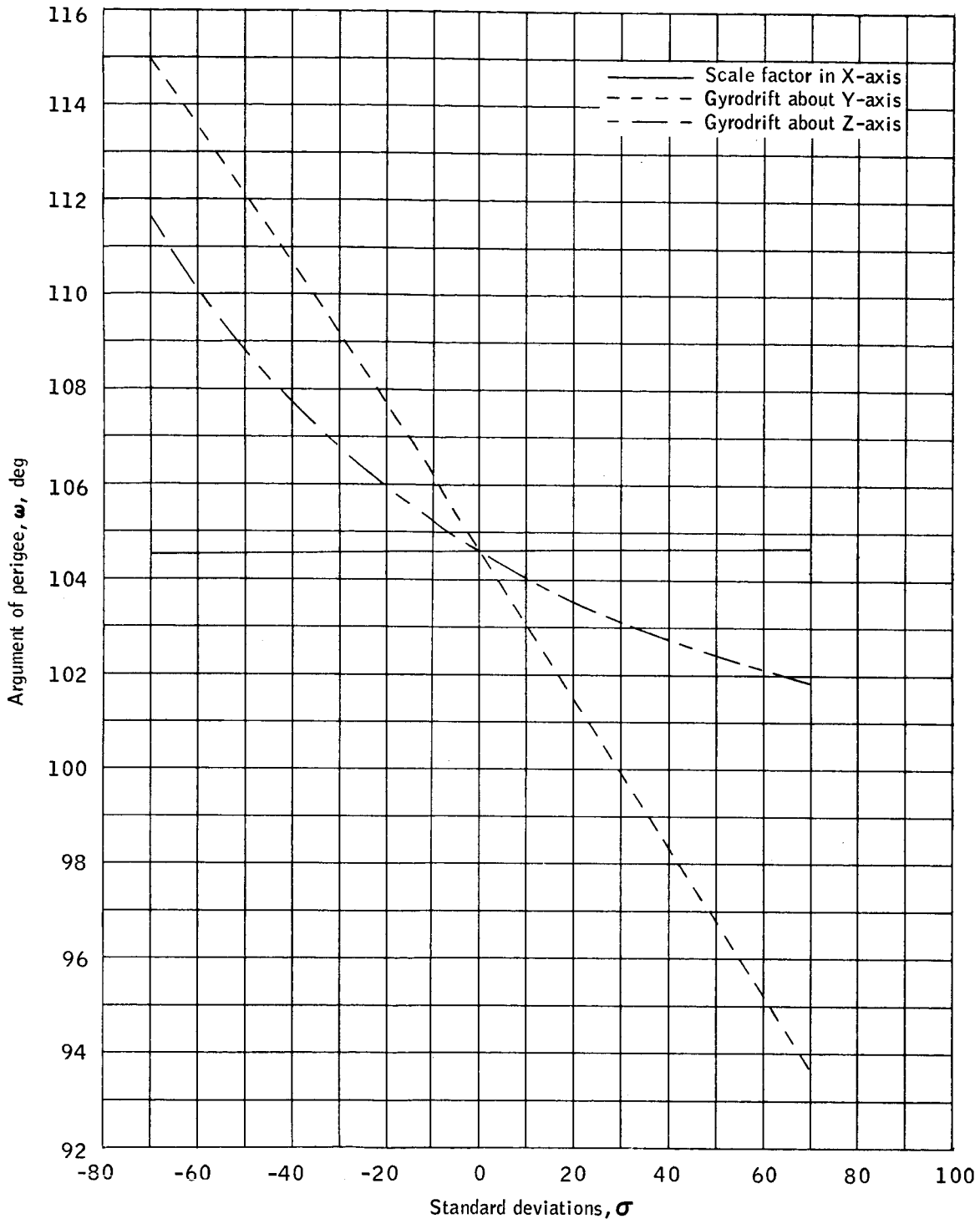
(o) True anomaly versus scale factor and drift errors.

Figure 5. - Continued.



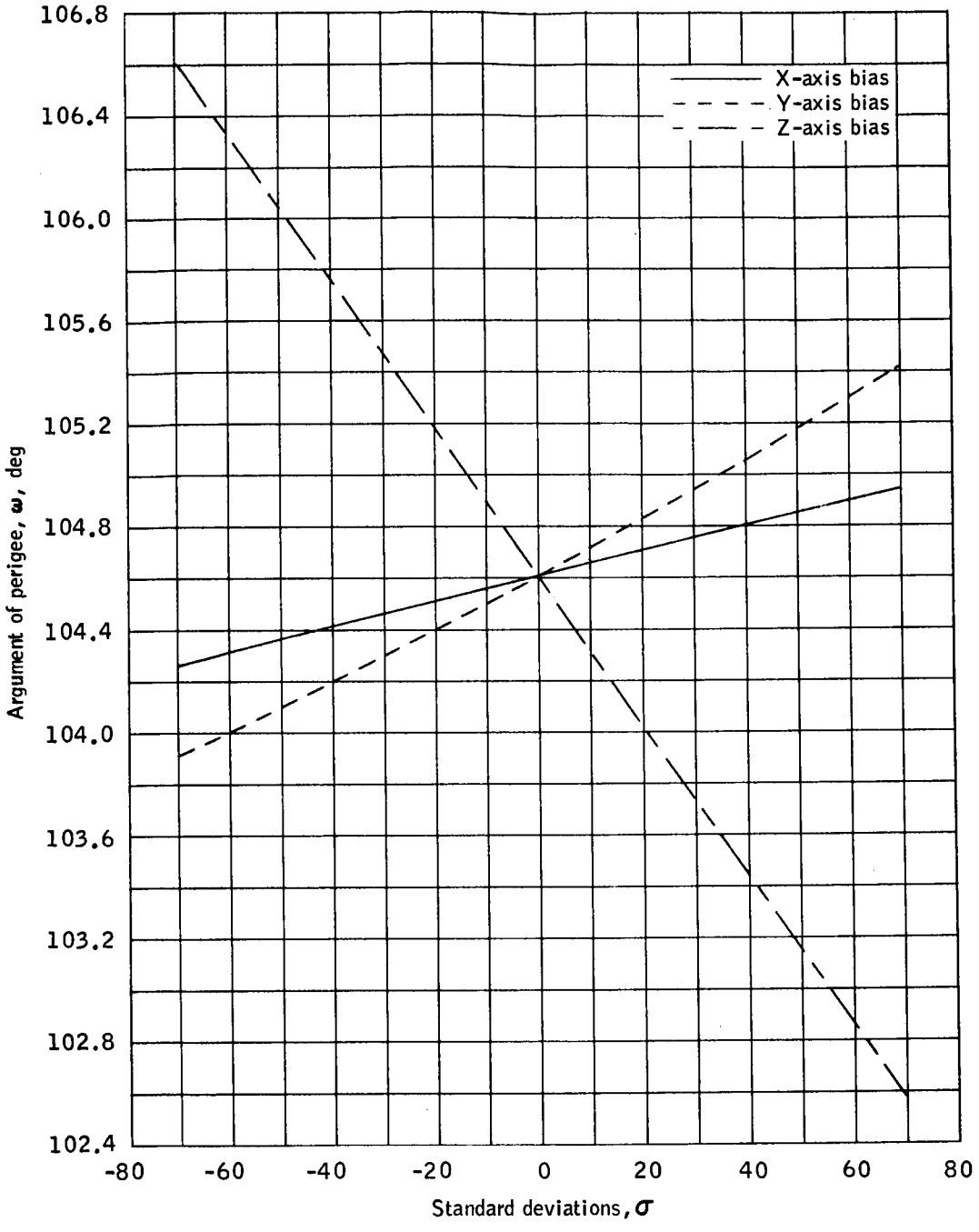
(p) True anomoly versus bias errors.

Figure 5. - Continued.



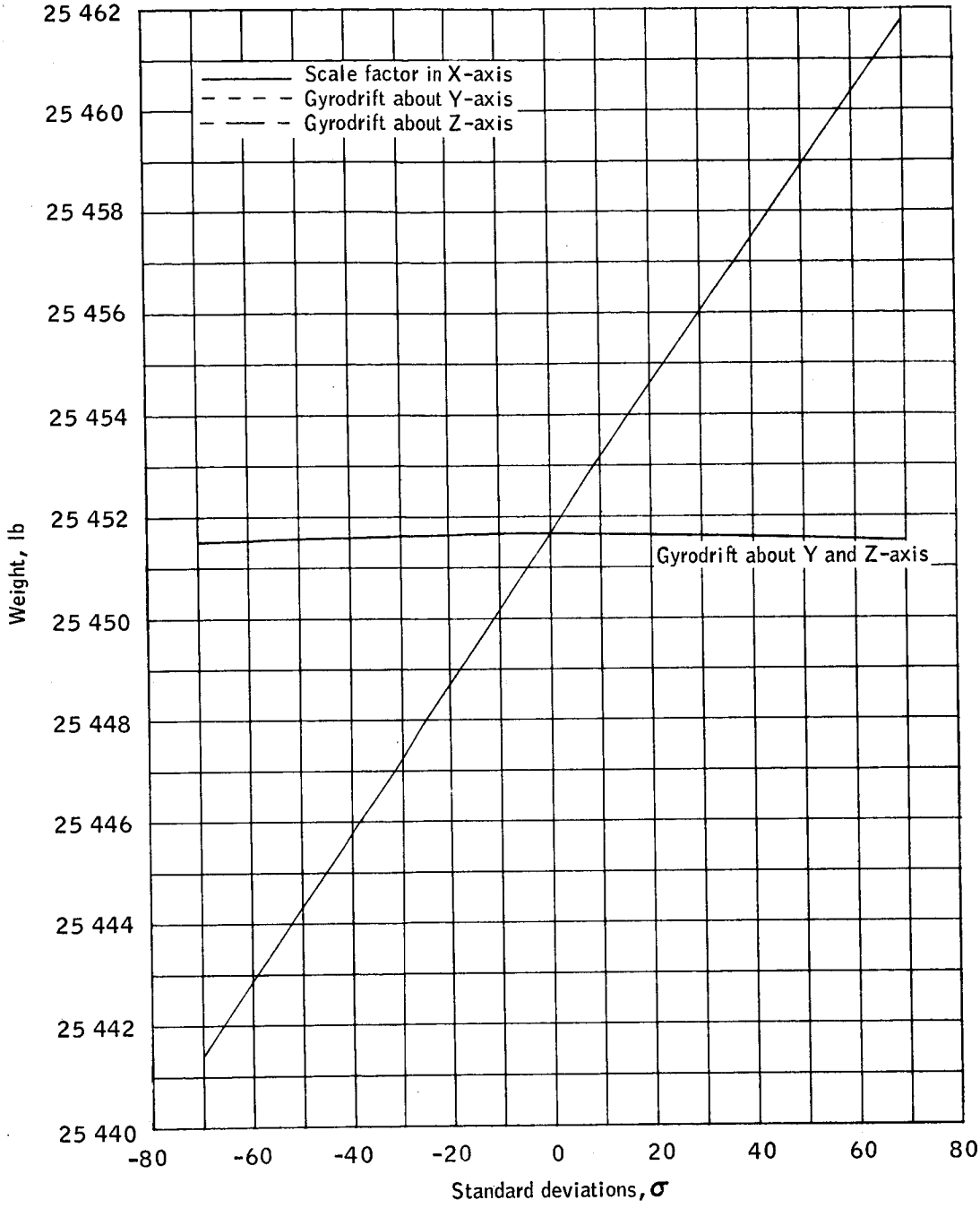
(q) Argument of perigee versus scale factor and drift errors.

Figure 5. - Continued.



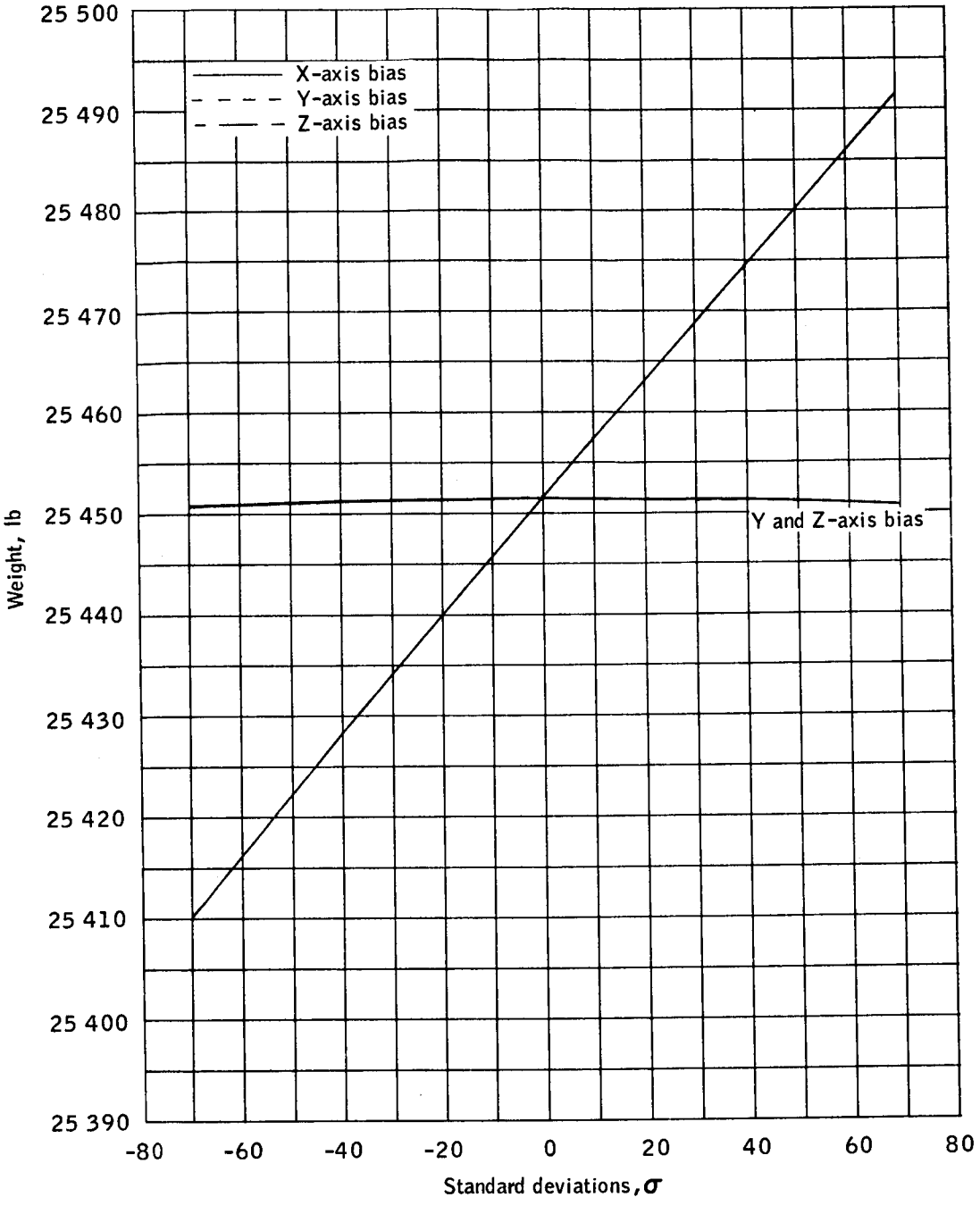
(r) Argument of perigee versus bias errors.

Figure 5. - Continued.



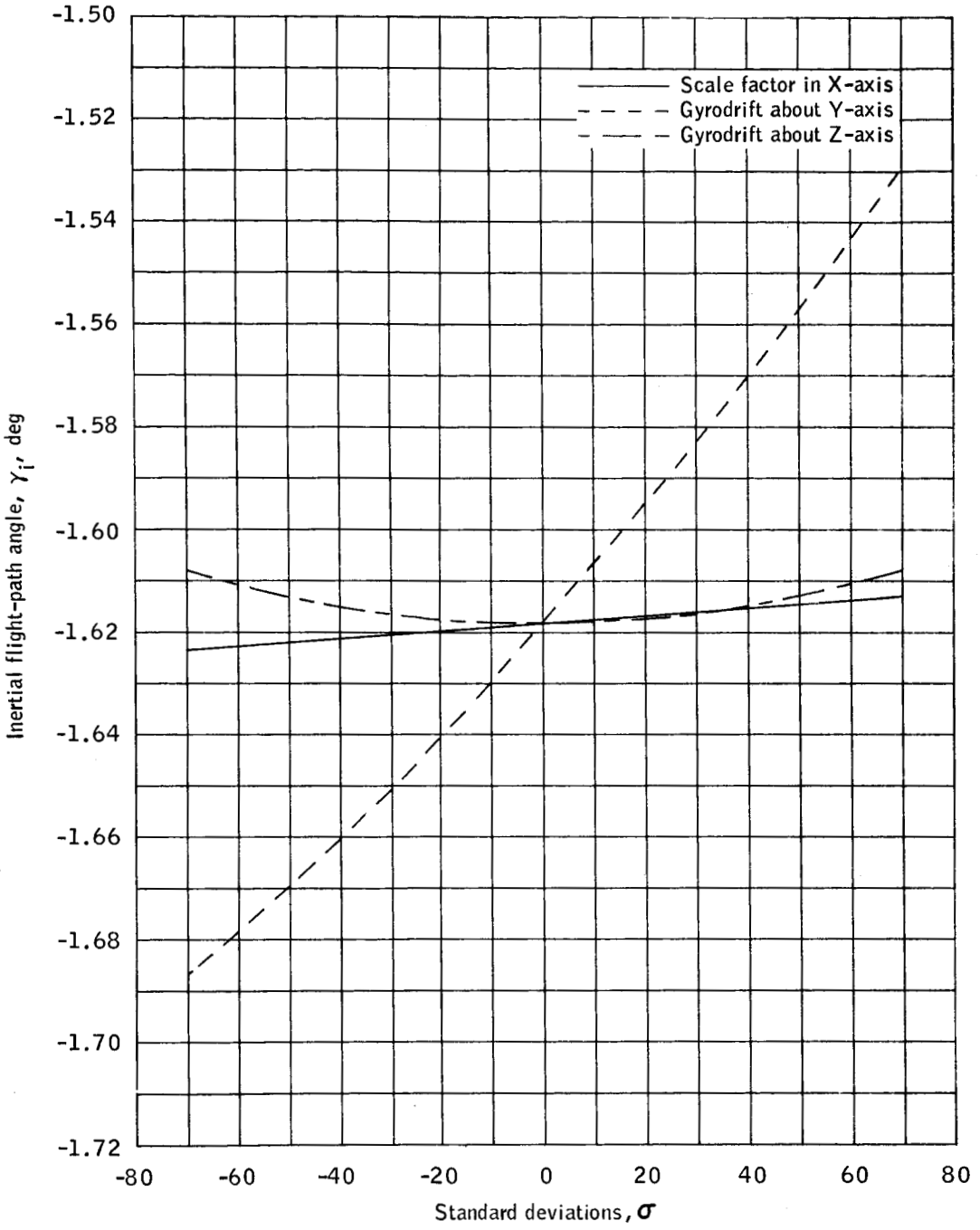
(s) Weight versus scale factor and drift errors.

Figure 5. - Continued.



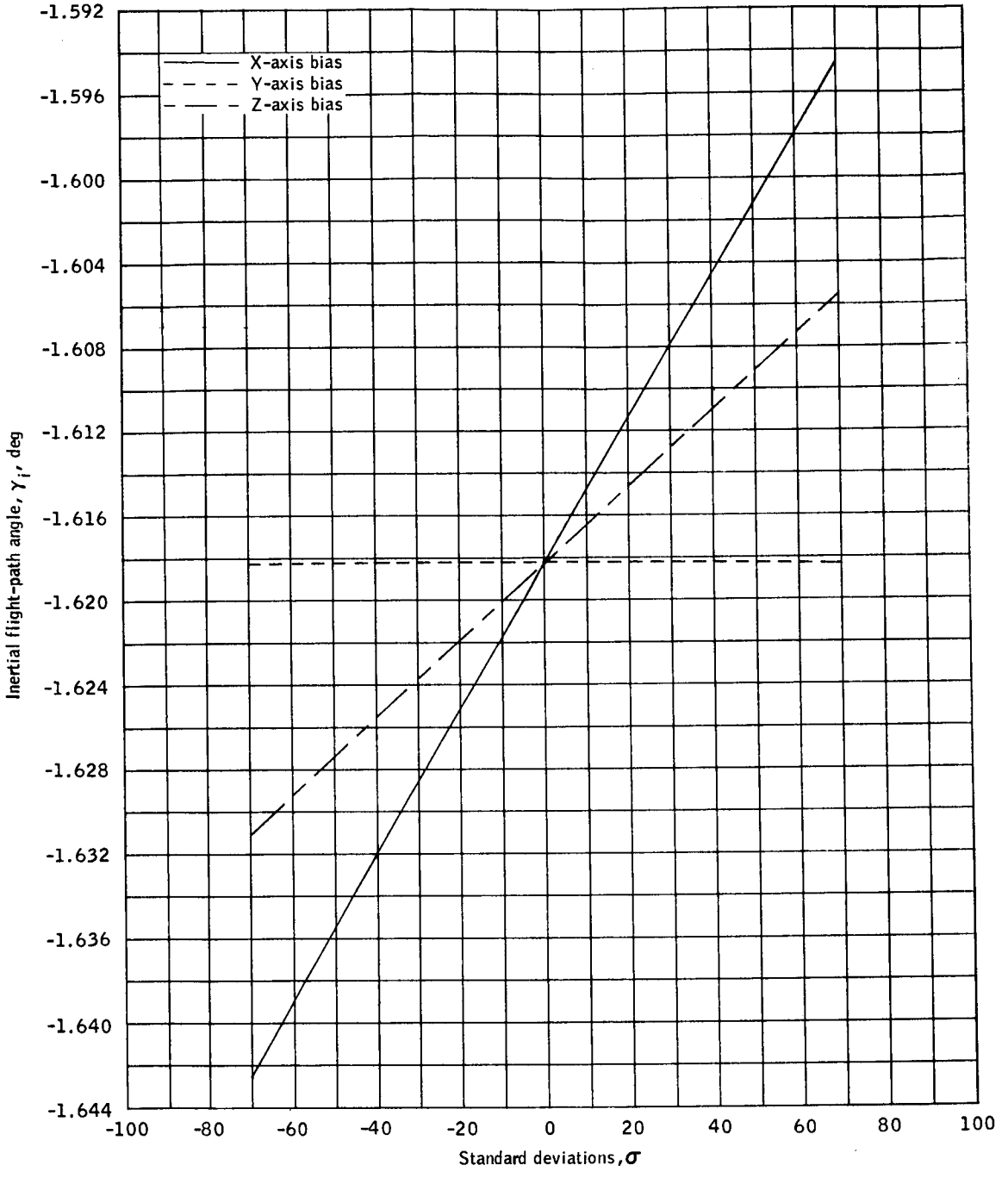
(t) Weight versus bias errors.

Figure 5. - Concluded.



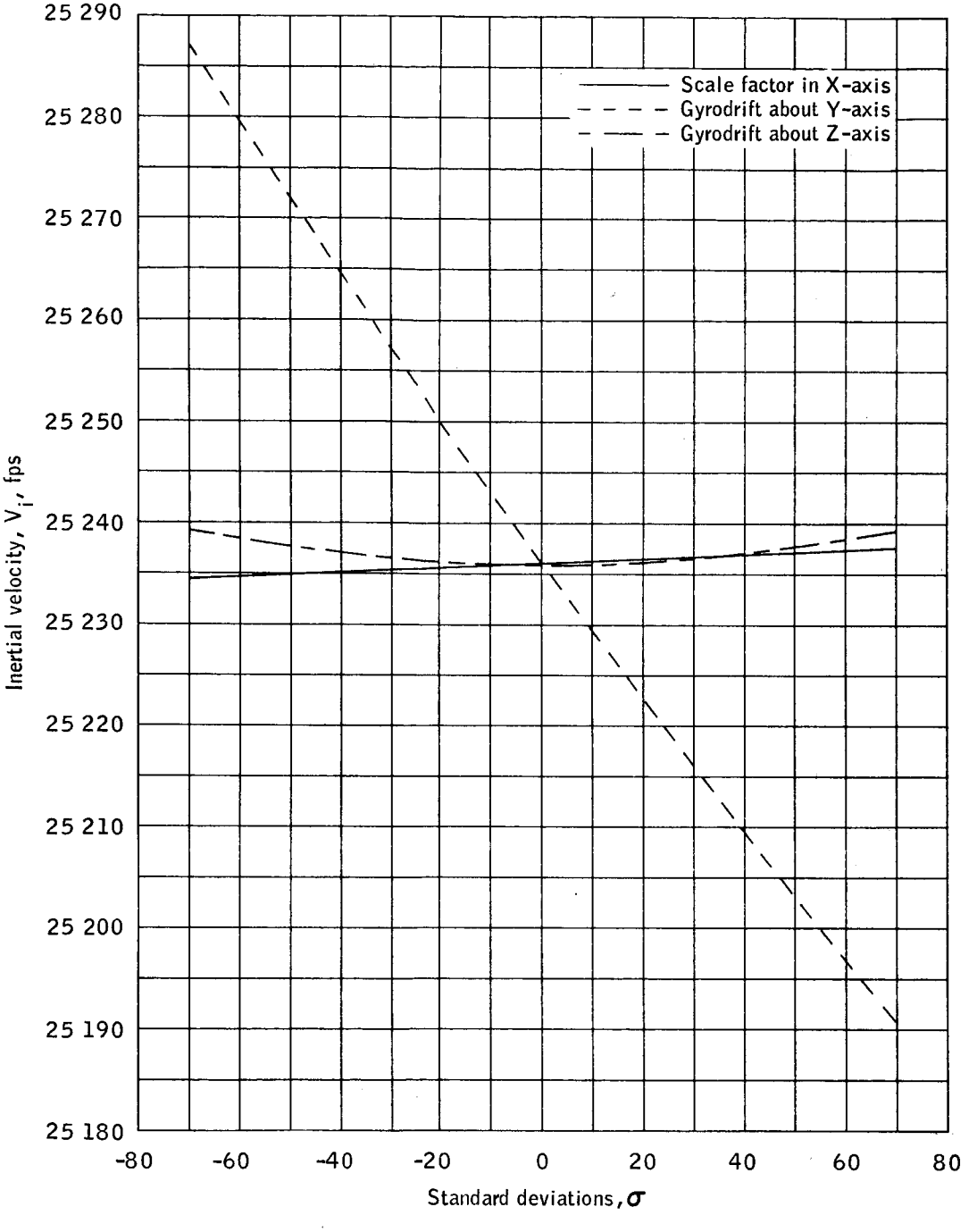
(a) Inertial flight-path angle versus scale factor and drift errors.

Figure 6.- Mission C dispersions at the end of the eighth SPS burn due to accelerometer bias, accelerometer scale factor and gyrodrift errors.



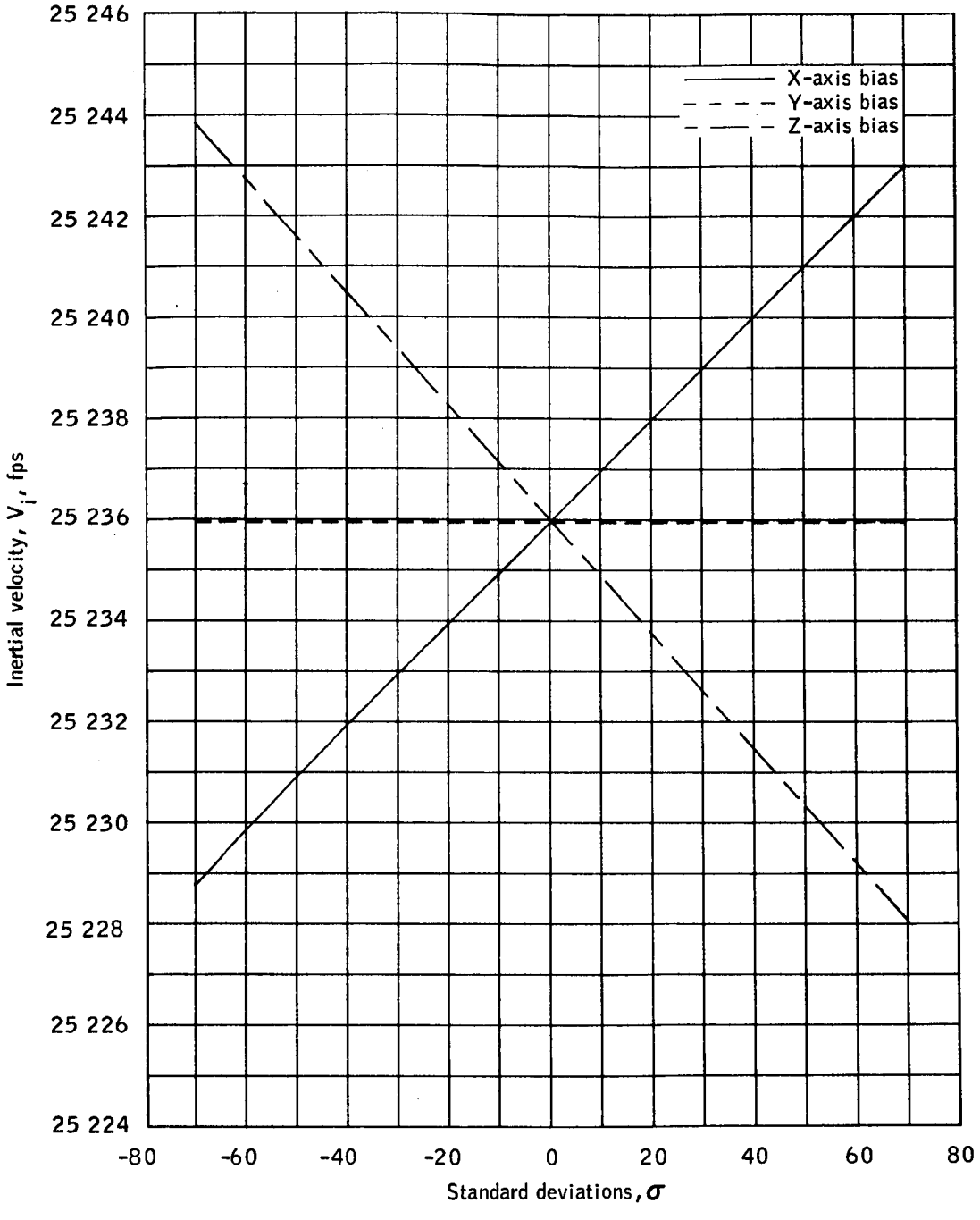
(b) Inertial flight-path angle versus bias errors.

Figure 6. - Continued.



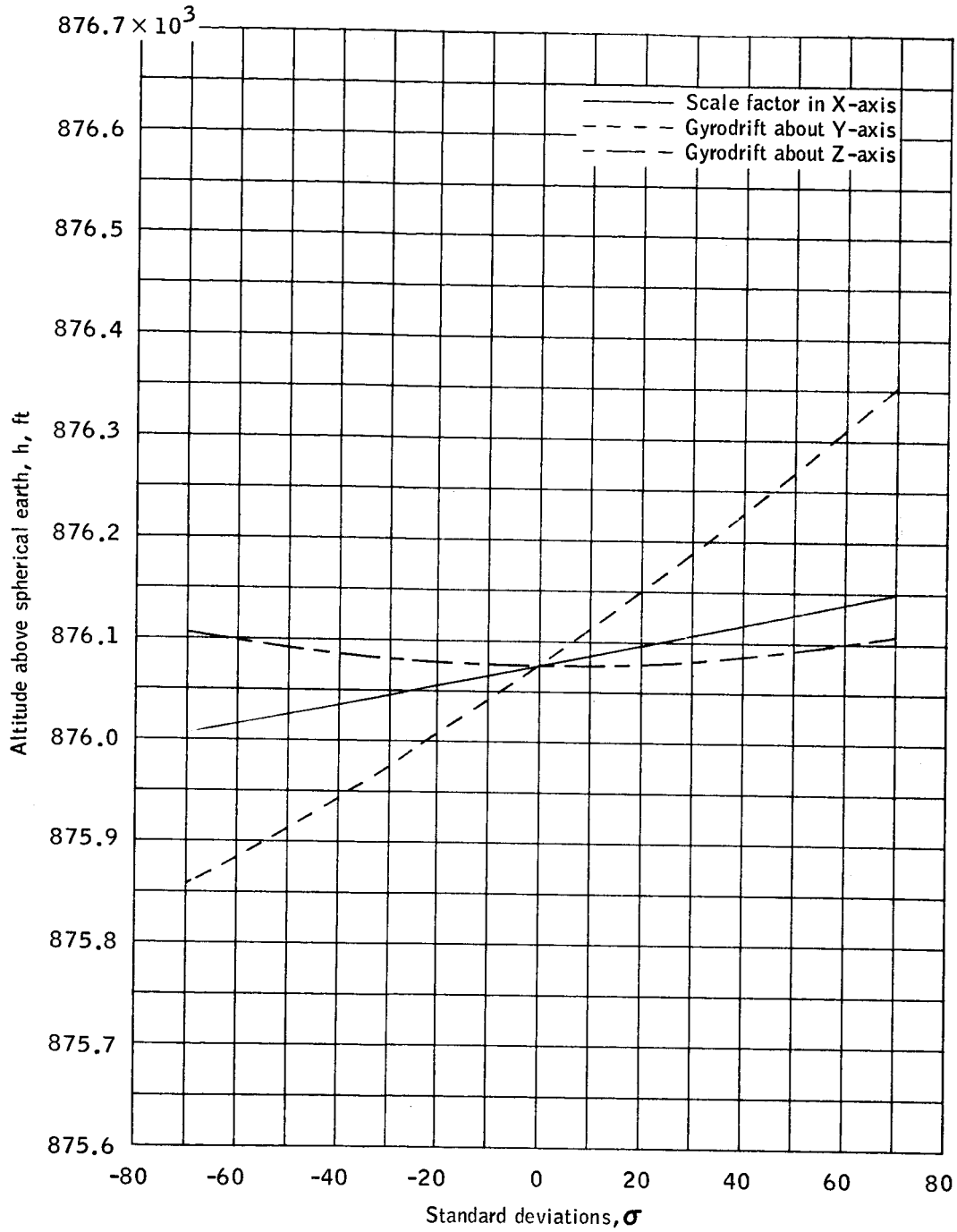
(c) Inertial velocity versus scale factor and drift errors.

Figure 6.- Continued.



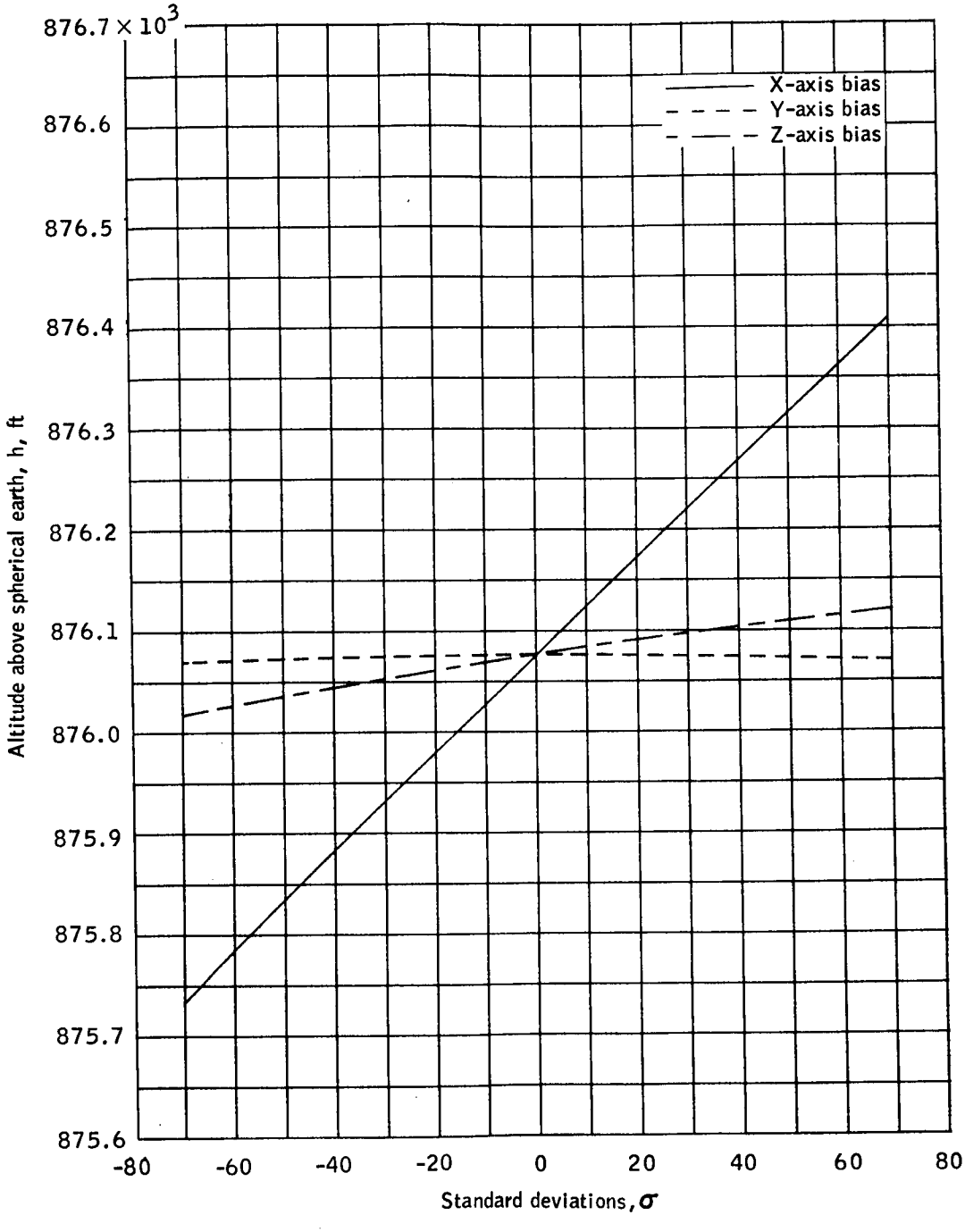
(d) Inertial velocity versus bias errors.

Figure 6.- Continued.



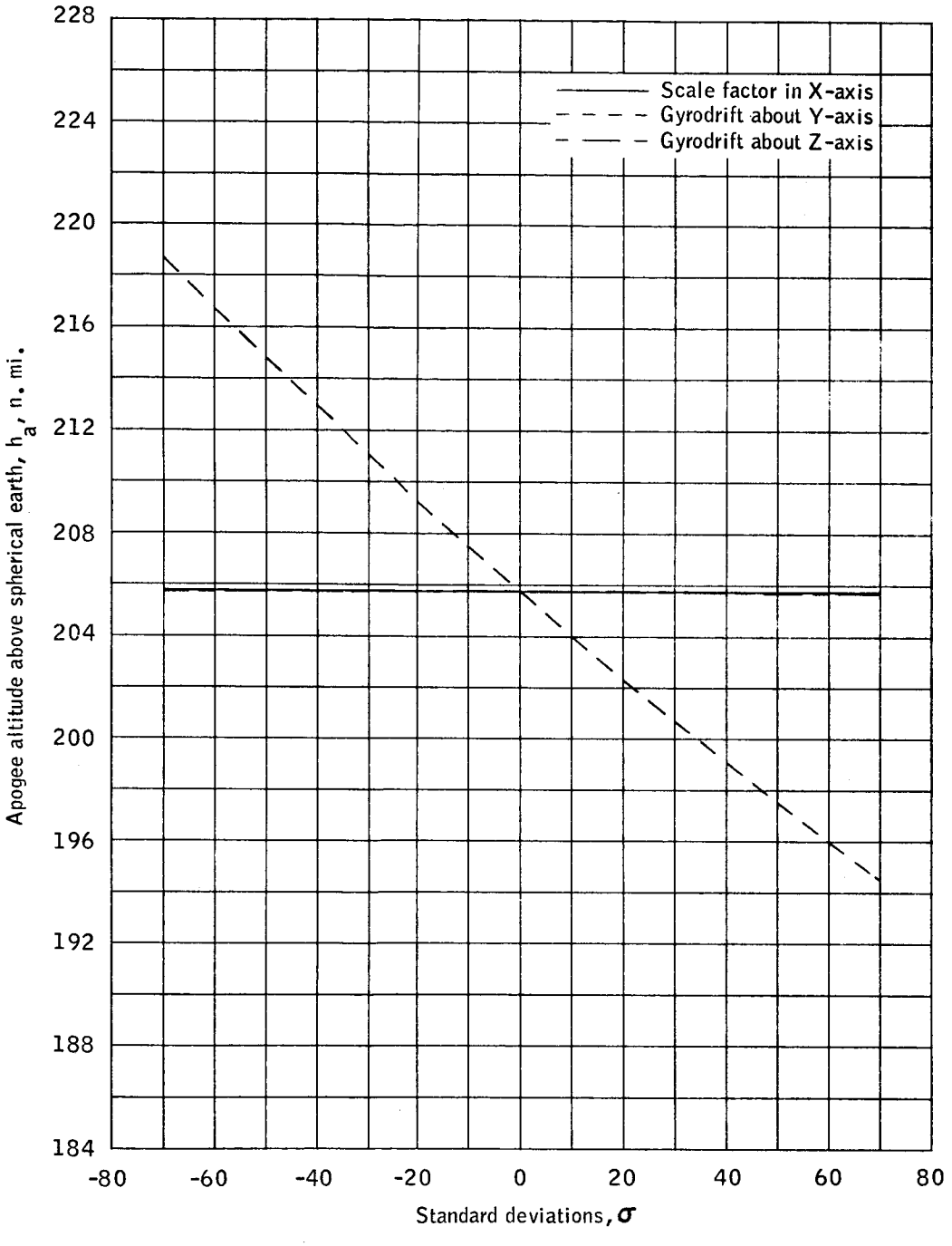
(e) Altitude above spherical earth versus scale factor and drift errors.

Figure 6.- Continued.



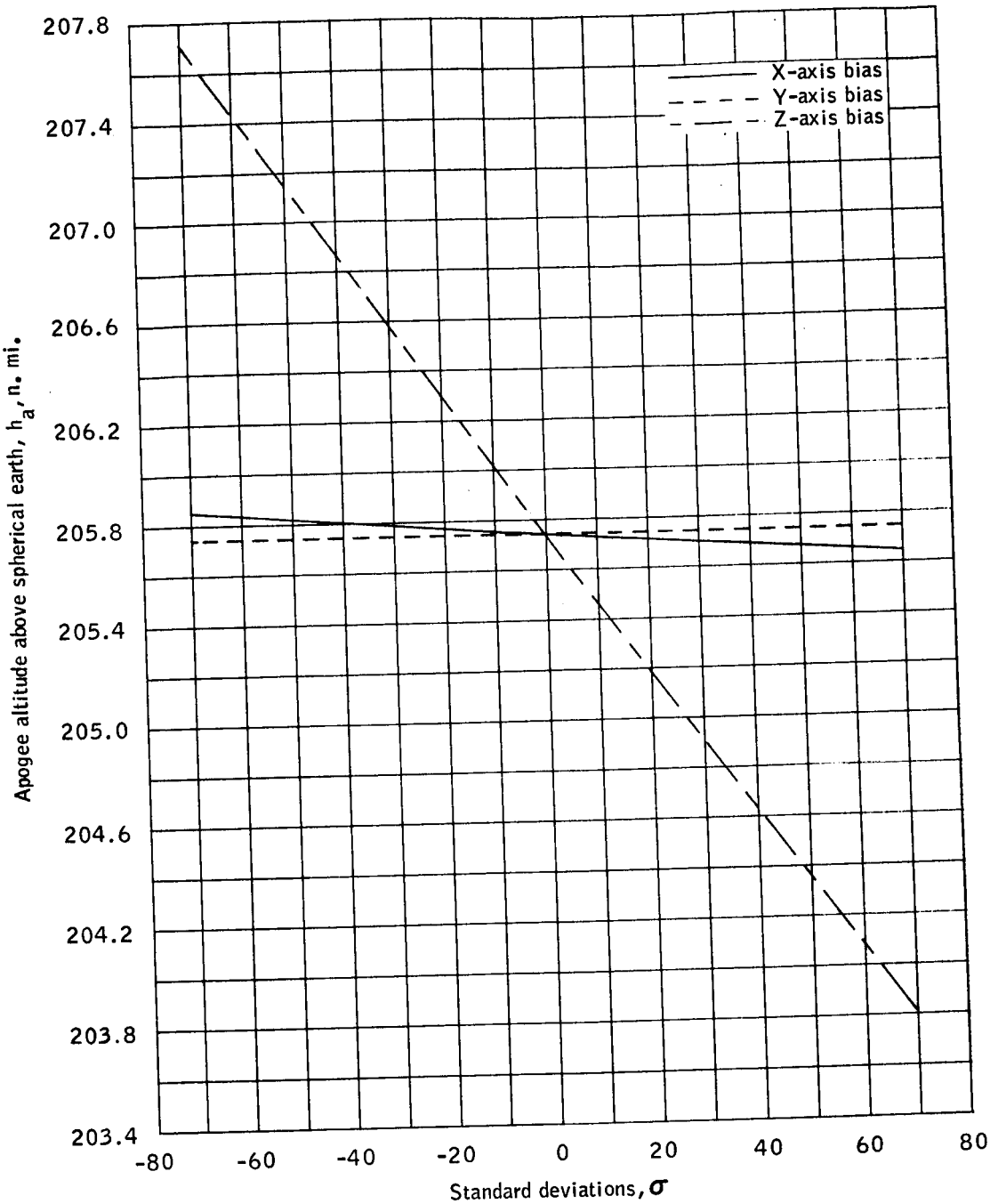
(f) Altitude above spherical earth versus bias errors.

Figure 6.- Continued.



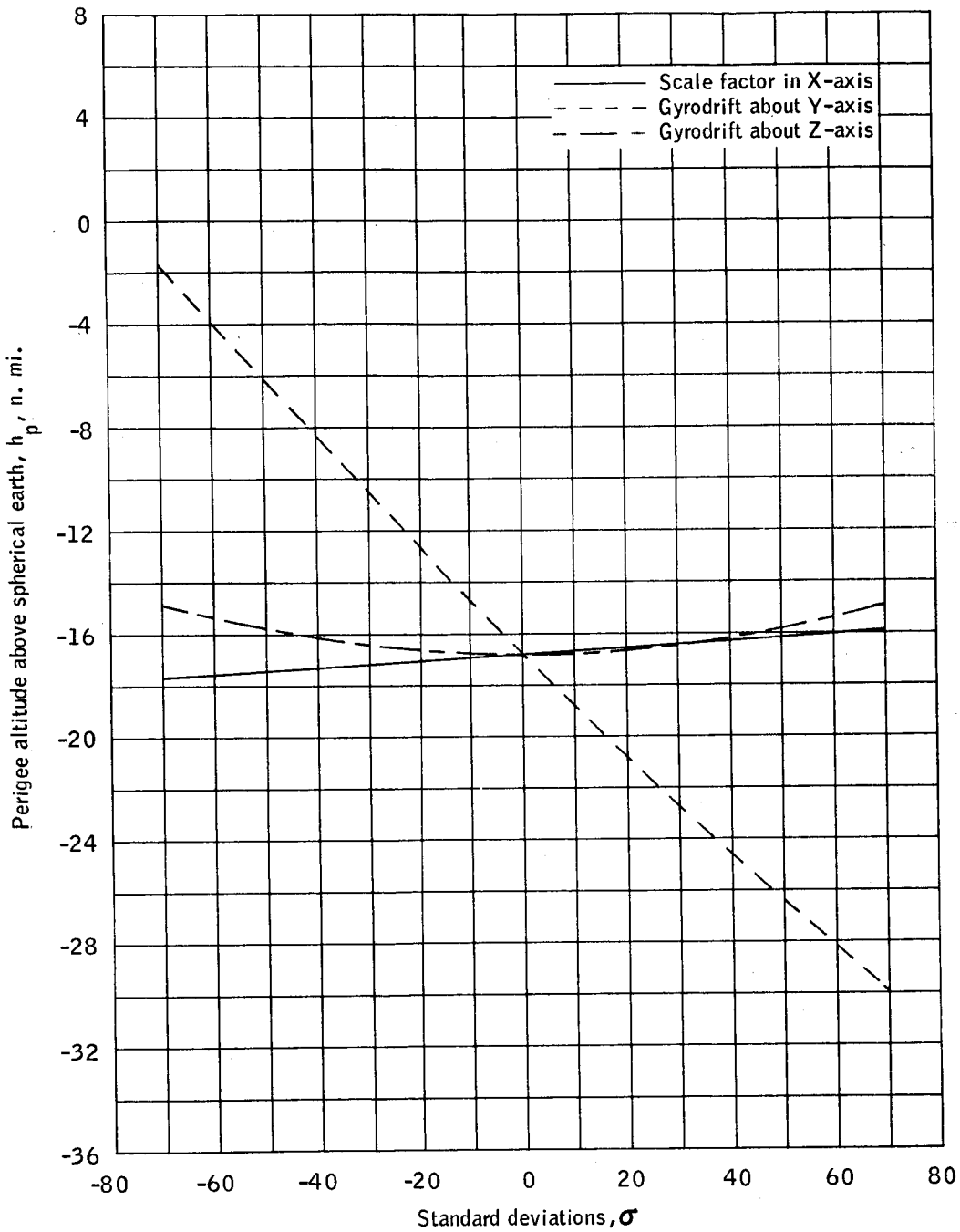
(g) Apogee altitude above spherical earth versus scale factor and drift errors.

Figure 6.- Continued.



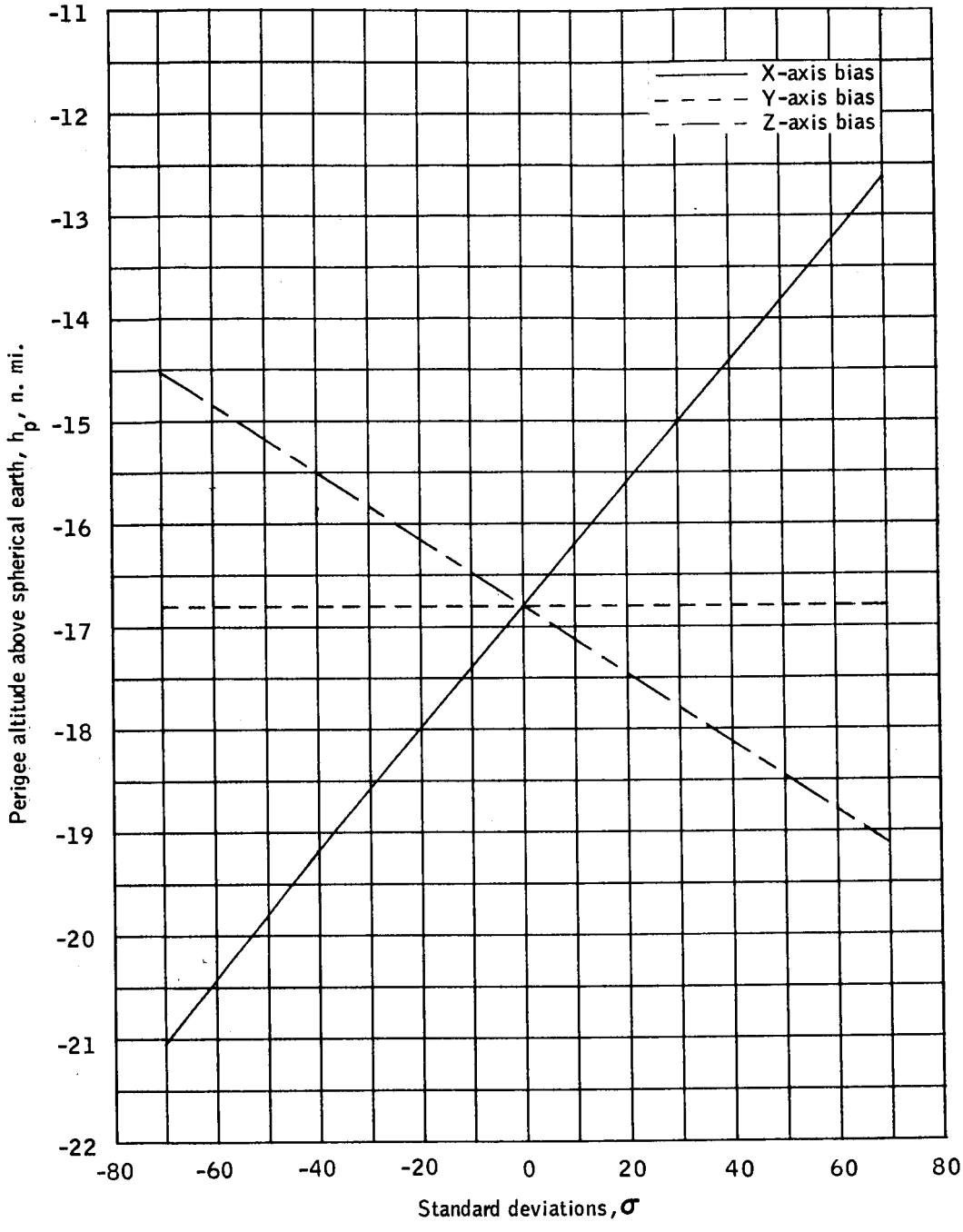
(h) Apogee altitude above spherical earth versus bias errors.

Figure 6.- Continued.



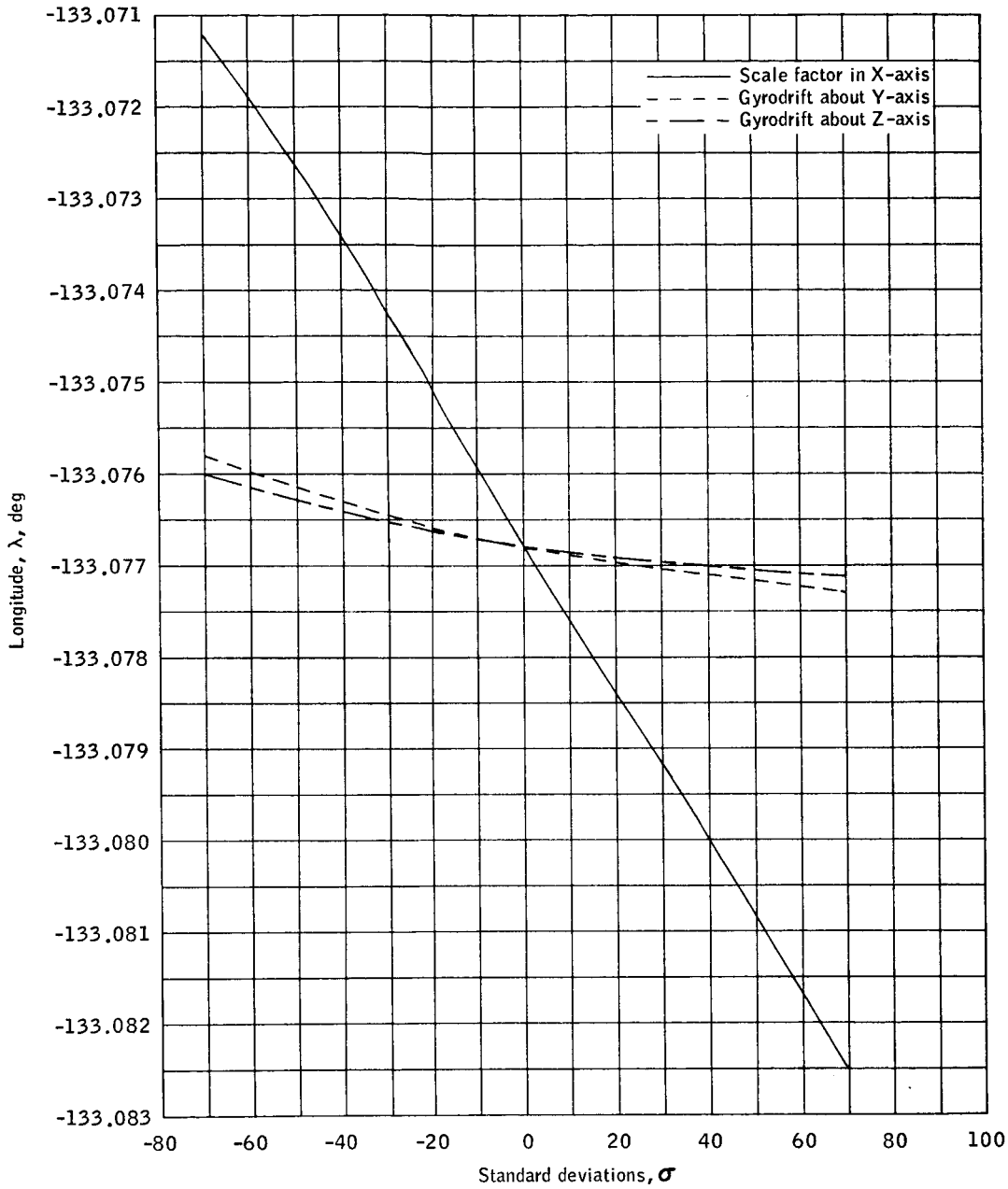
(i) Perigee altitude above spherical earth versus scale factor and drift errors.

Figure 6.- Continued.



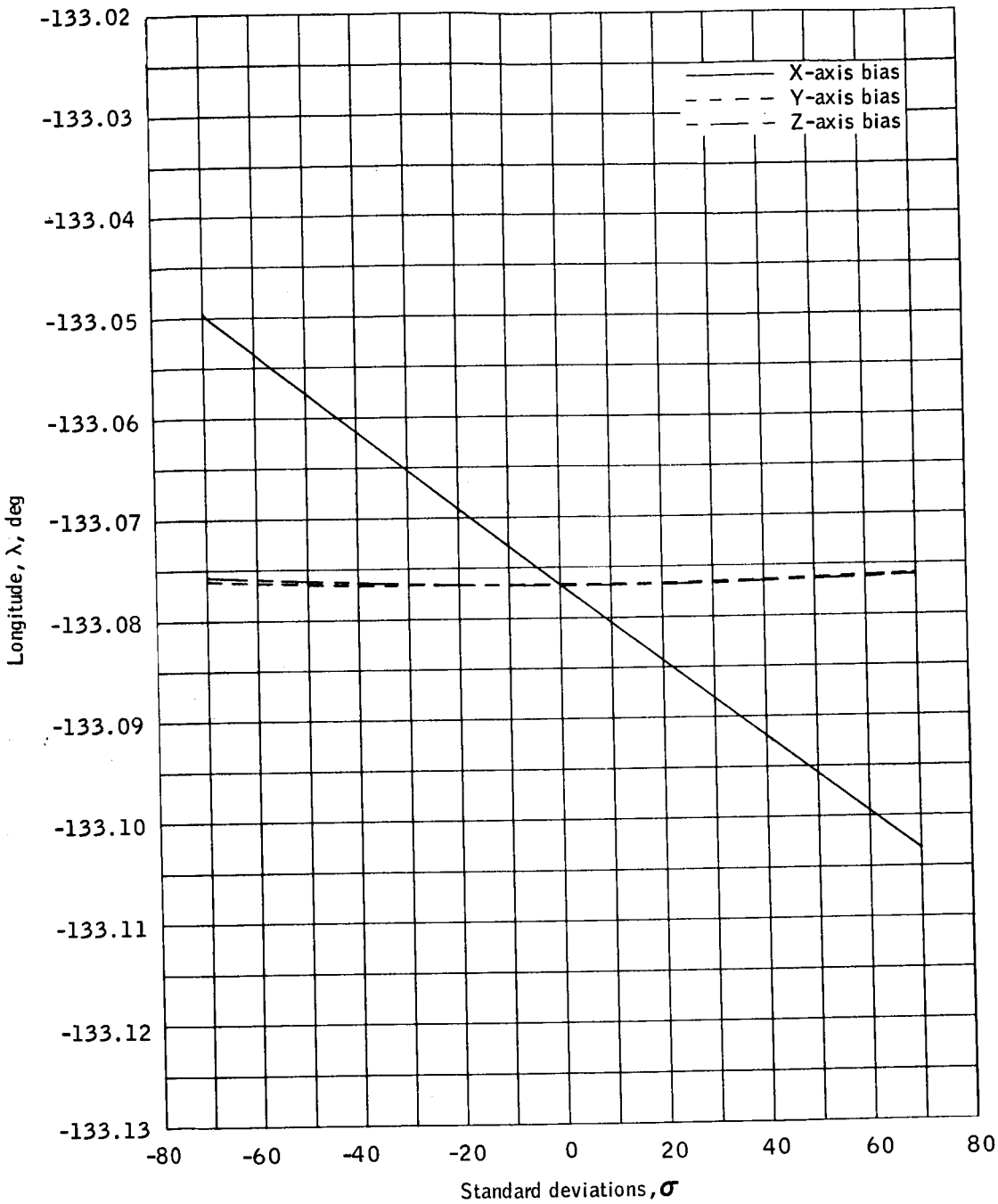
(j) Perigee altitude above spherical earth versus bias errors.

Figure 6. -Continued.



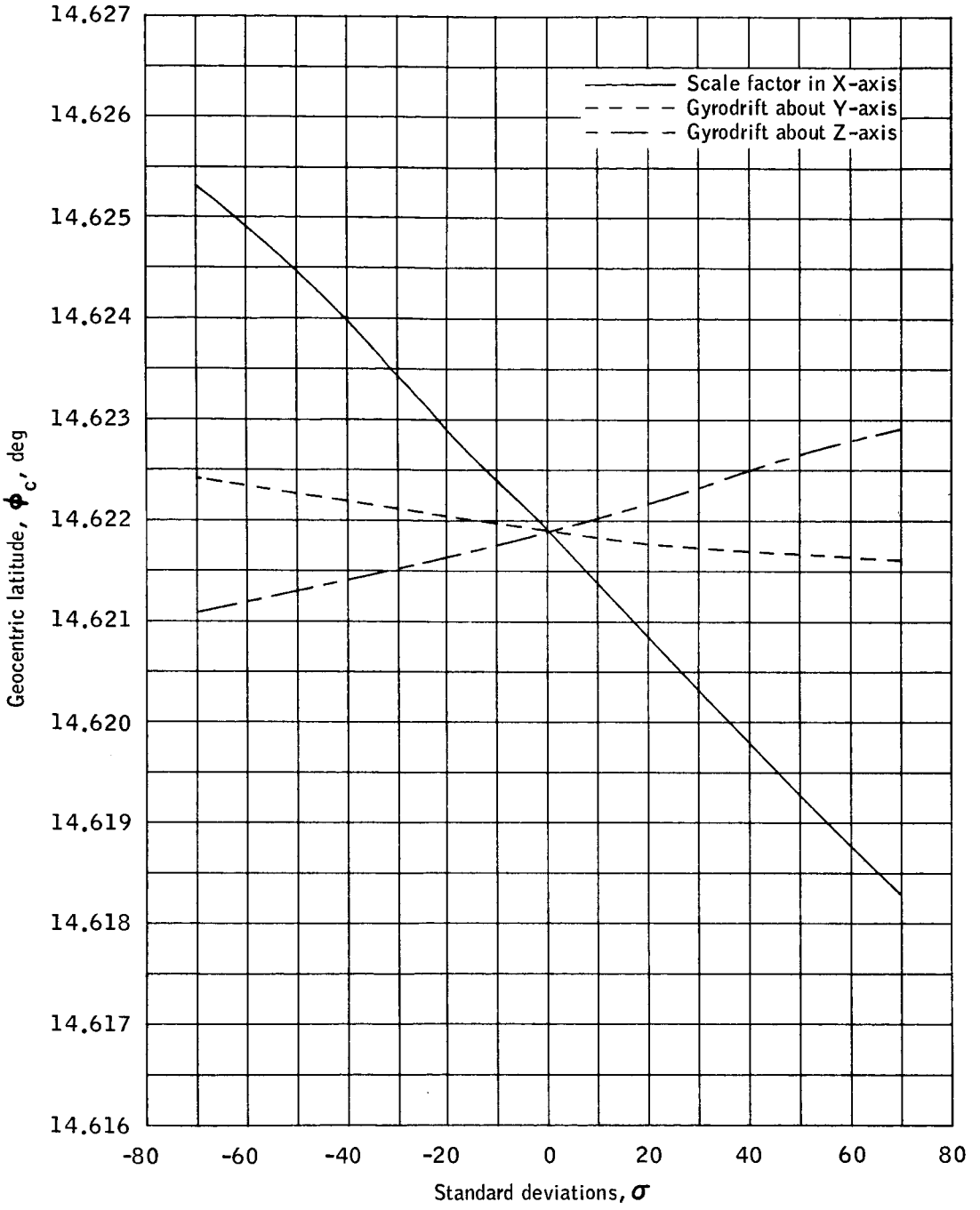
(k) Longitude versus scale factor and drift errors.

Figure 6.- Continued.



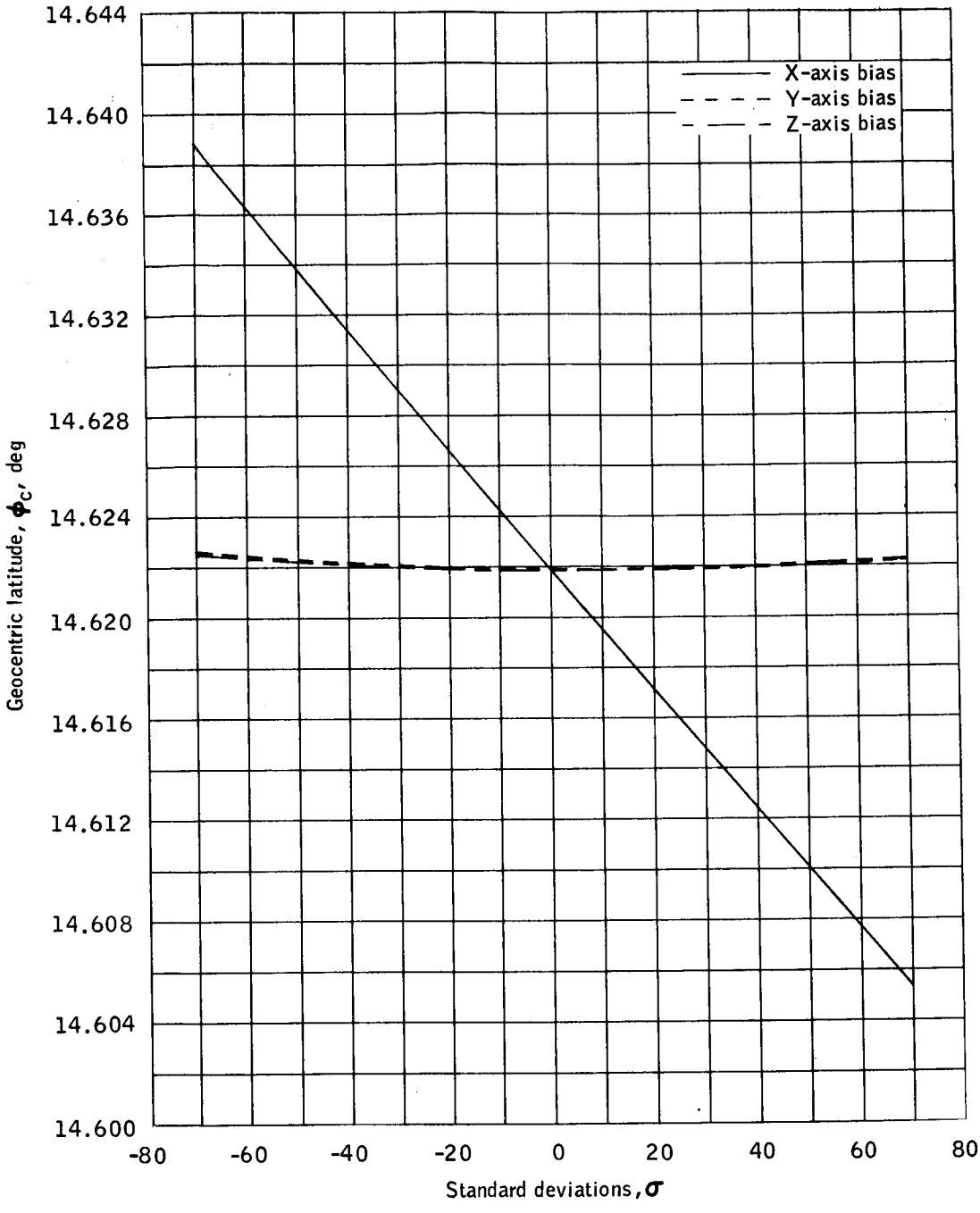
(l) Longitude versus bias errors.

Figure 6. - Continued.



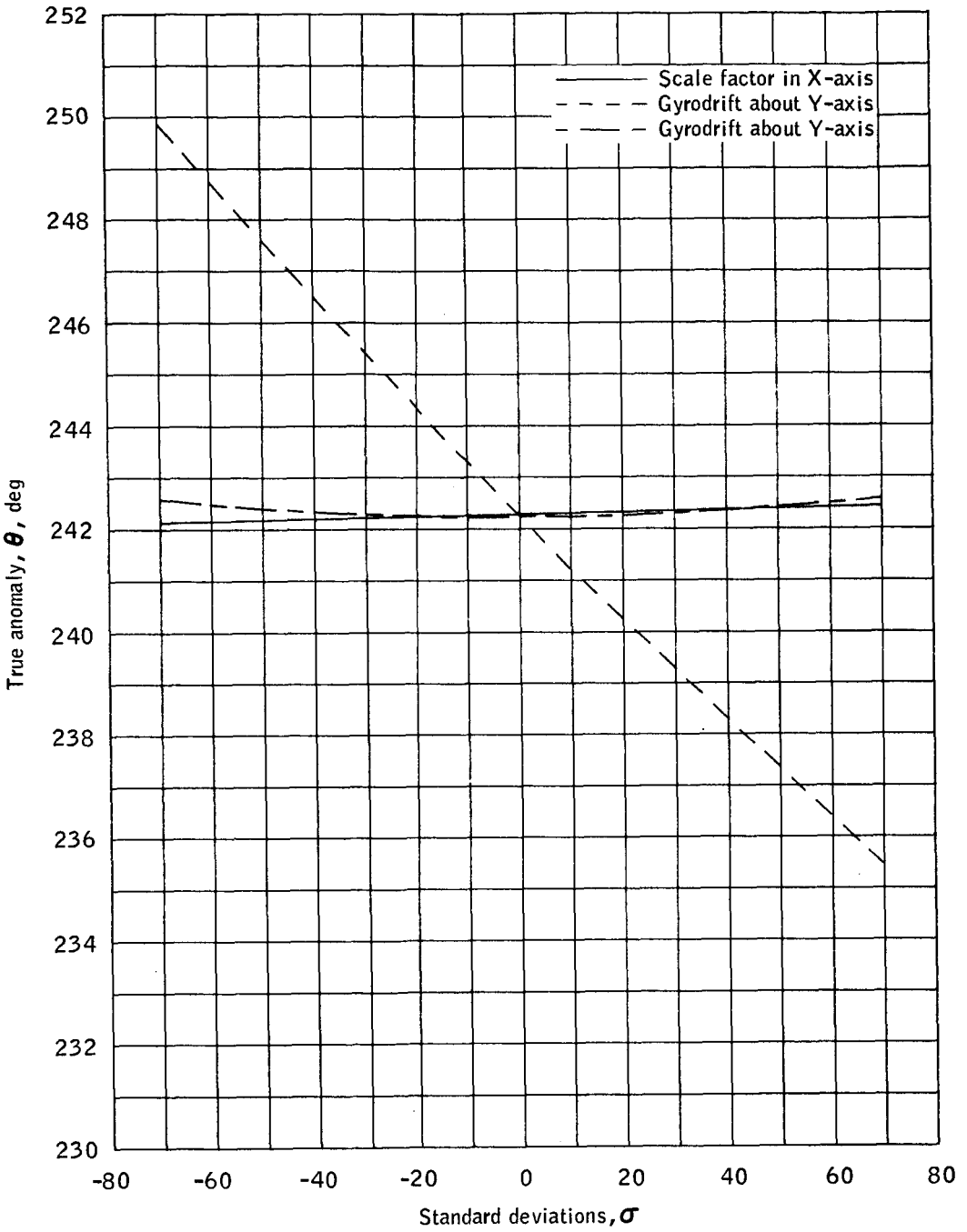
(m) Geocentric latitude versus scale factor and drift errors.

Figure 6.- Continued.



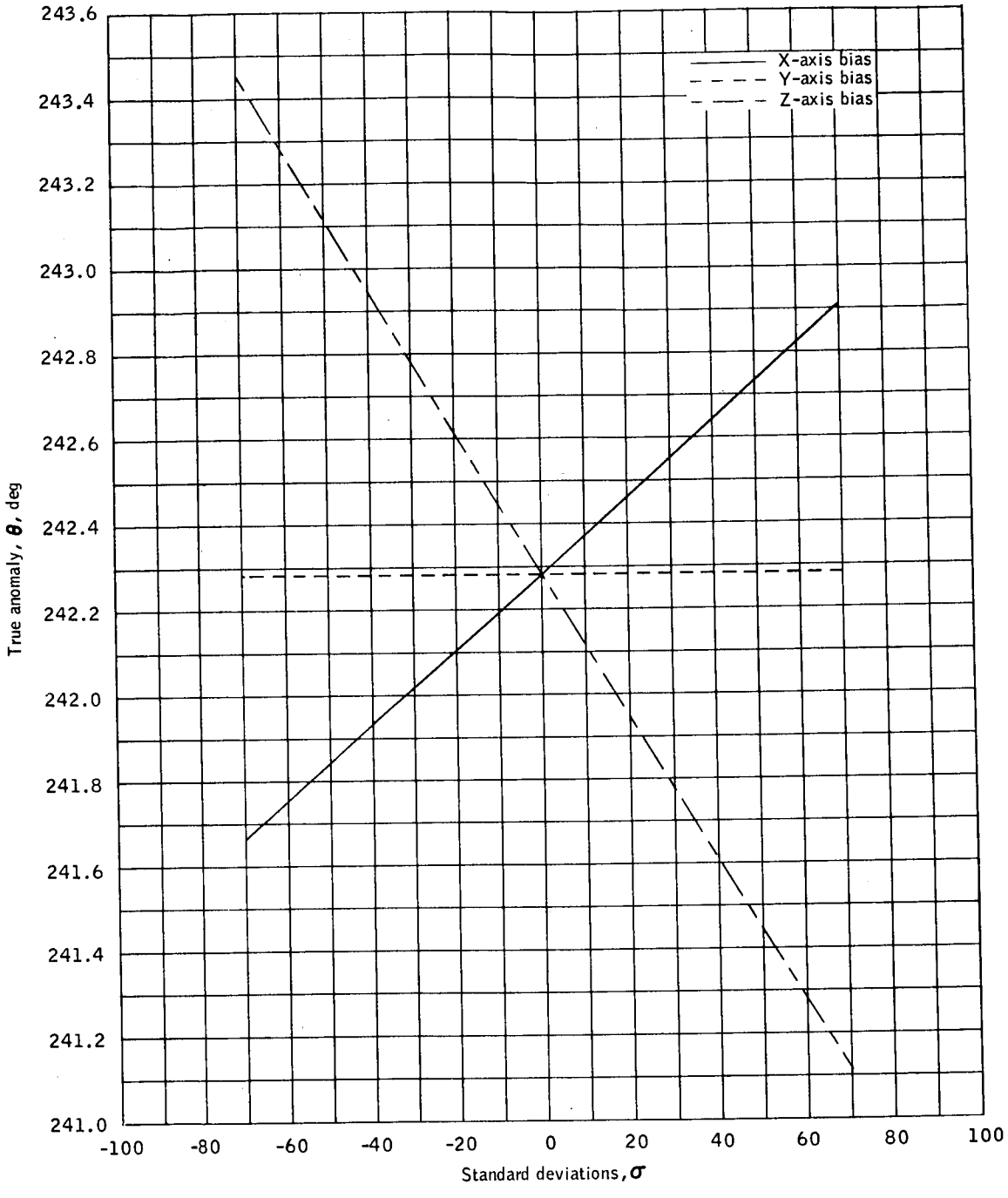
(n) Geocentric latitude versus bias errors.

Figure 6. -Continued.



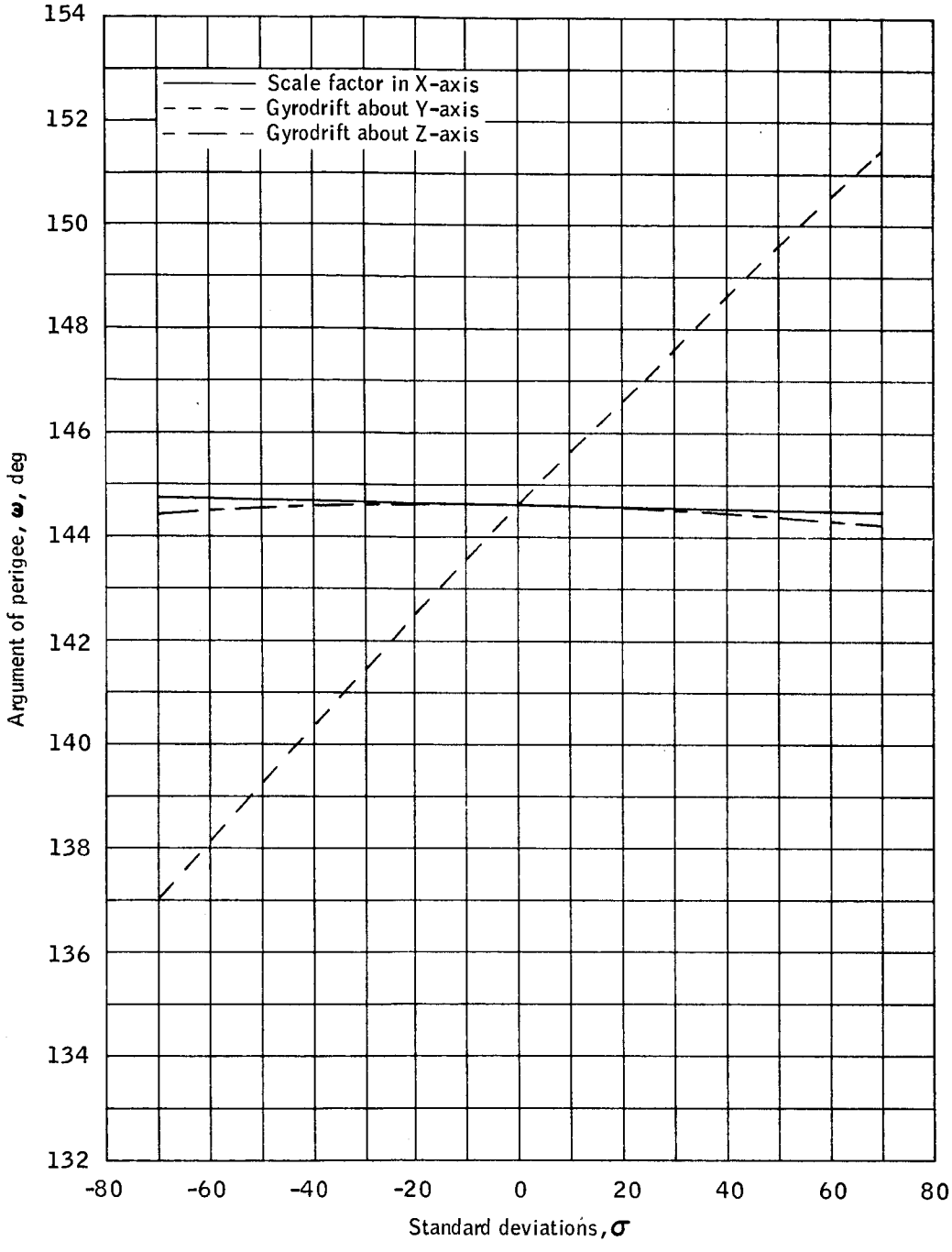
(o) True anomaly versus scale factor and drift errors.

Figure 6.- Continued.



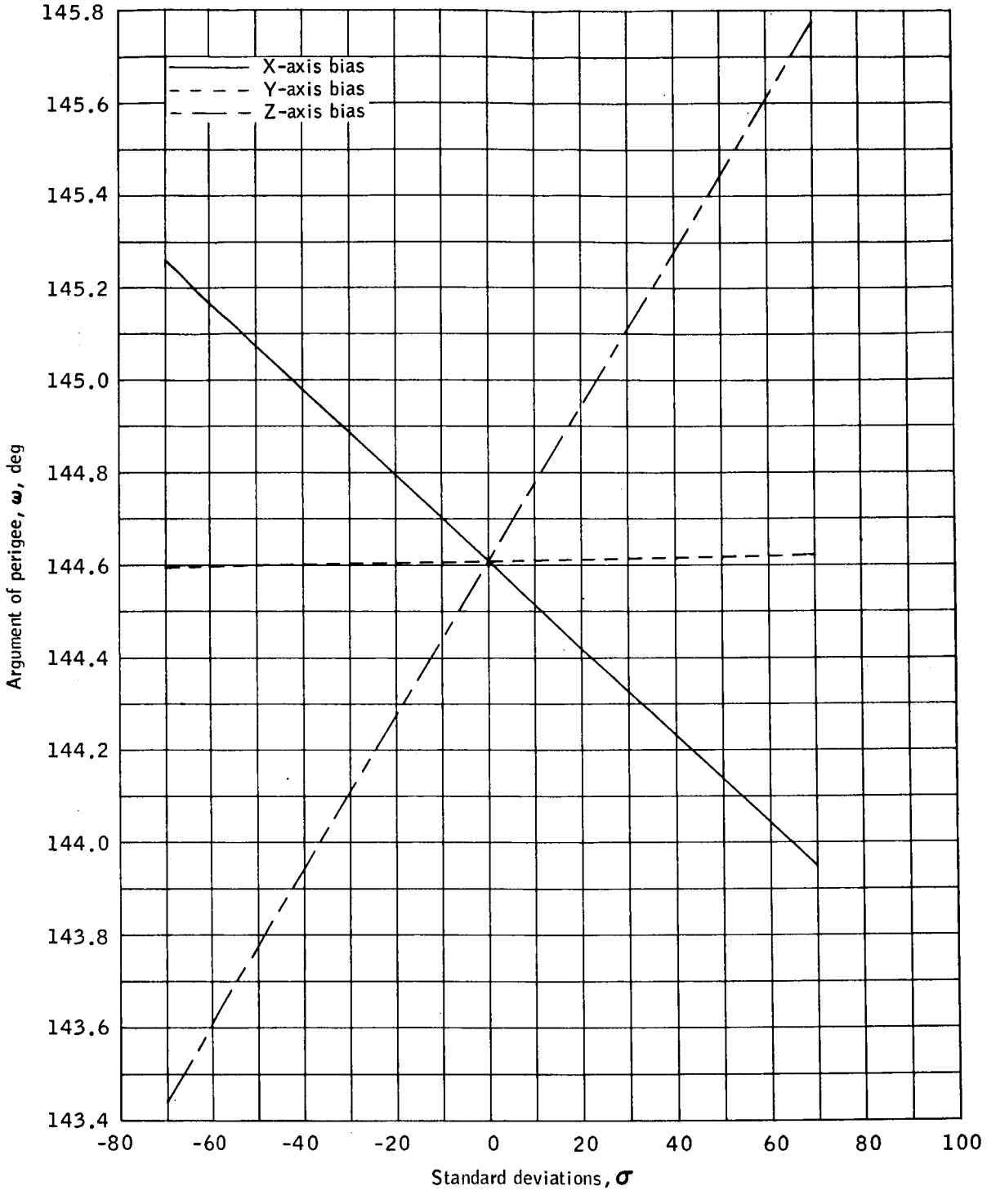
(p) True anomaly versus bias errors.

Figure 6. -Continued.



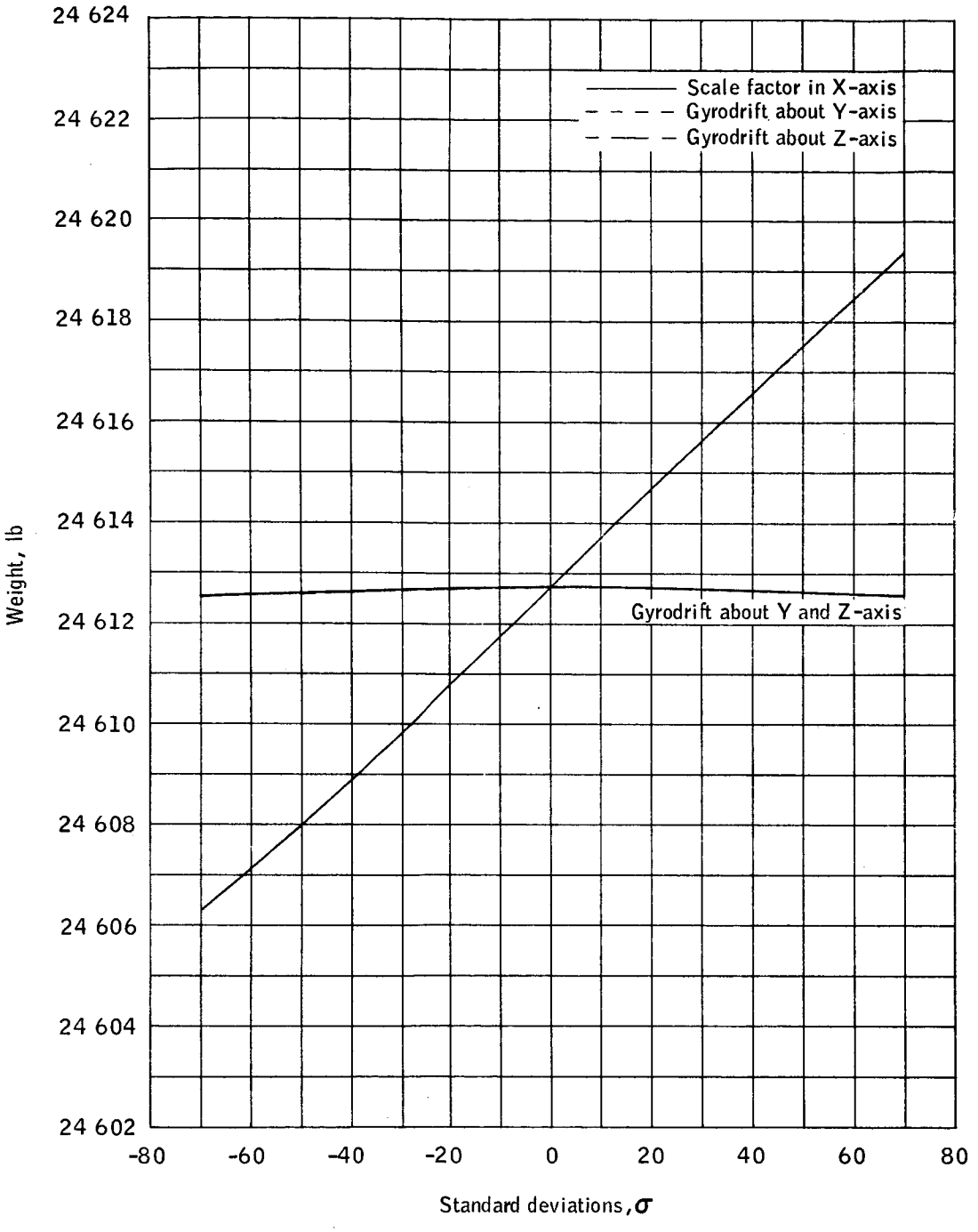
(q) Argument of perigee versus scale factor and drift errors.

Figure 6.- Continued.



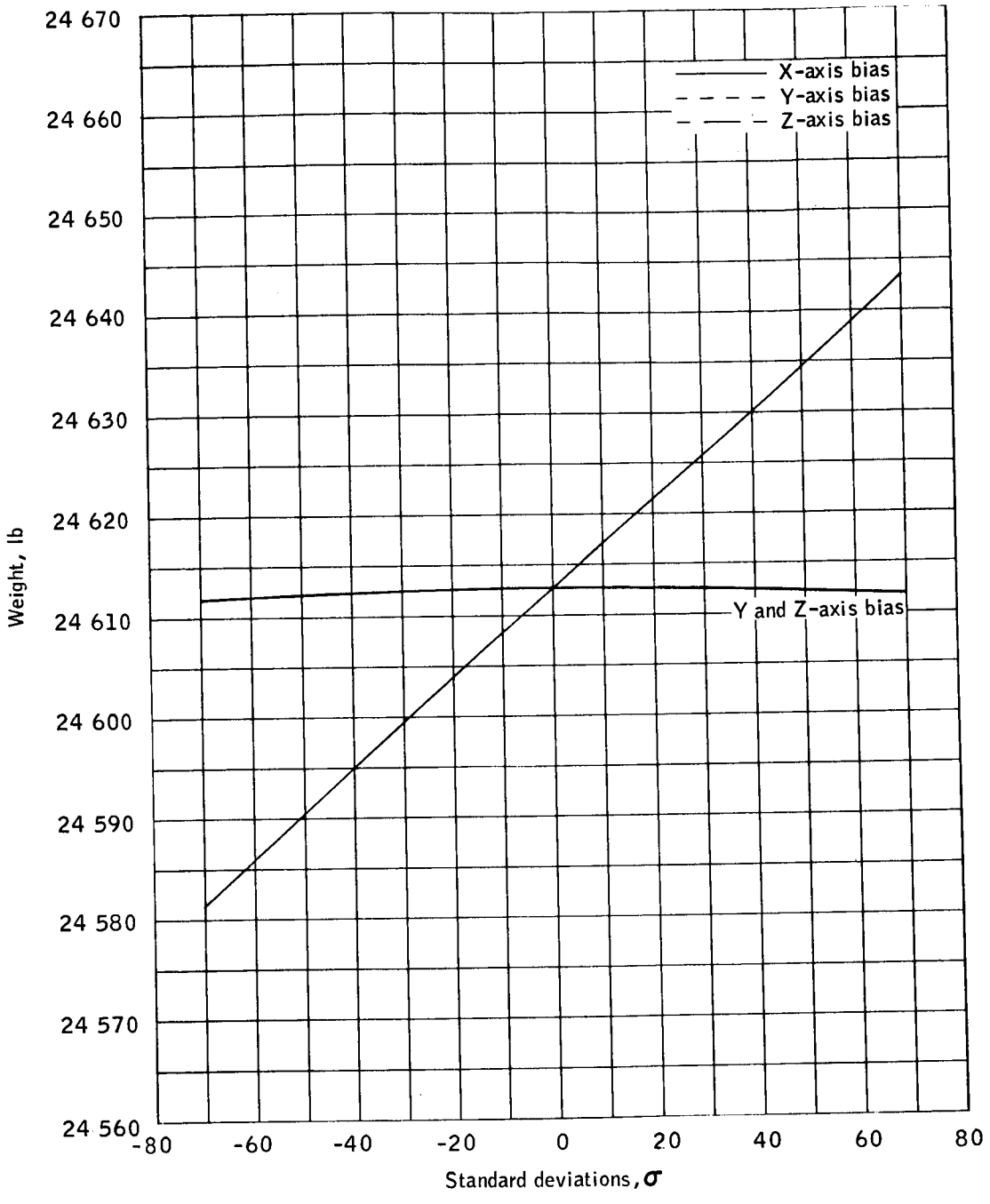
(r) Argument of perigee versus bias errors.

Figure 6.- Continued.



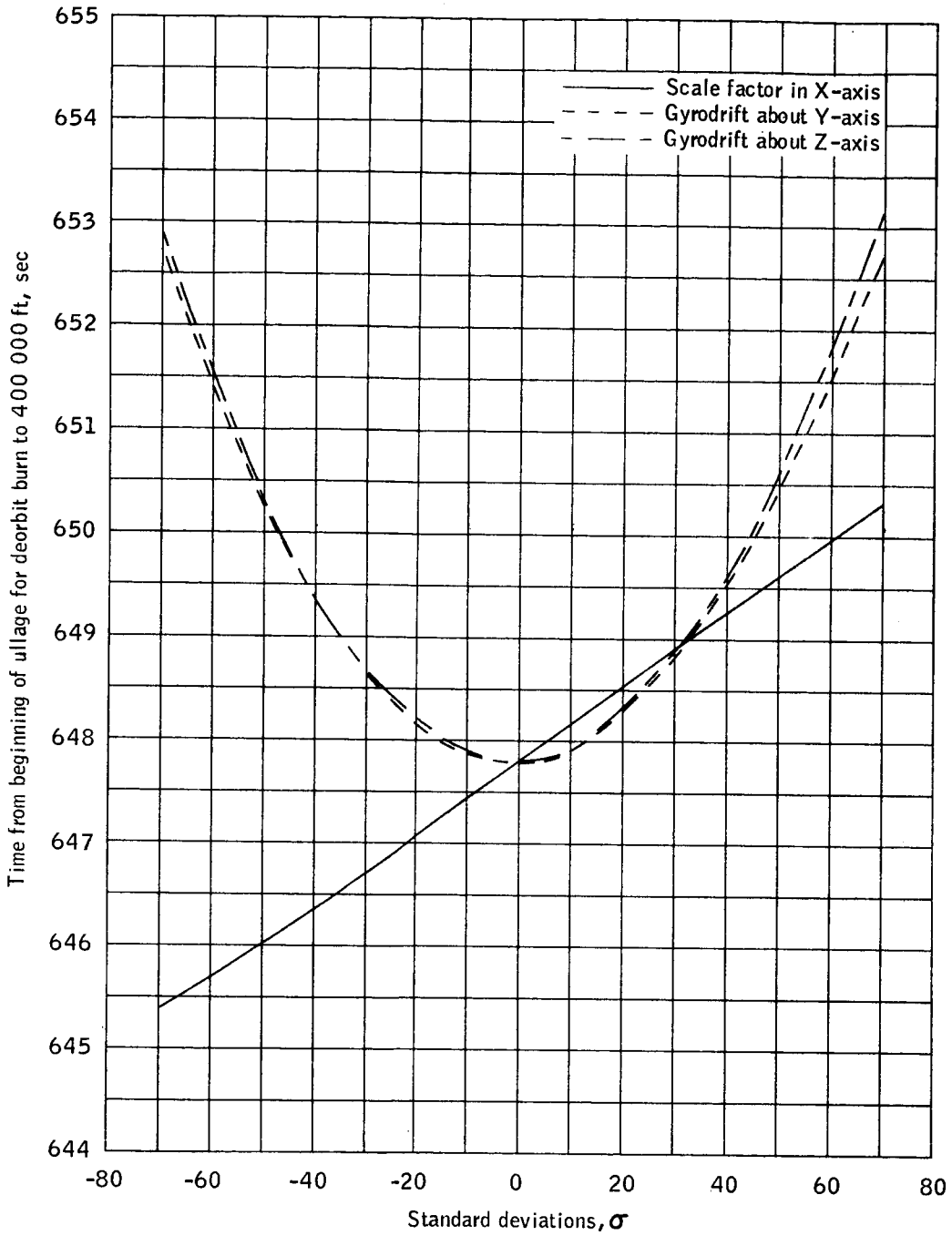
(s) Weight versus scale factor and drift errors.

Figure 6.- Continued.



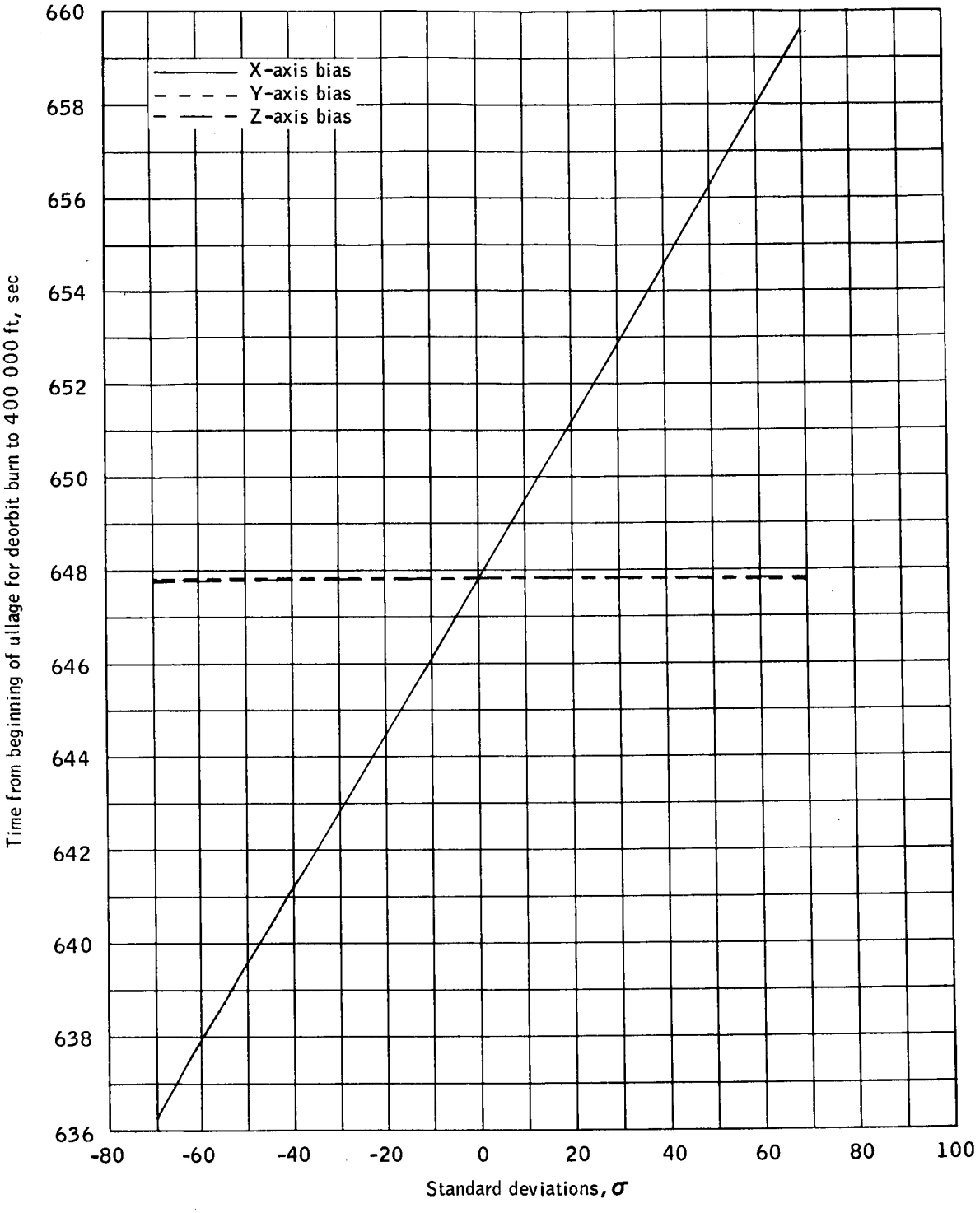
(t) Weight versus bias errors.

Figure 6.- Concluded.



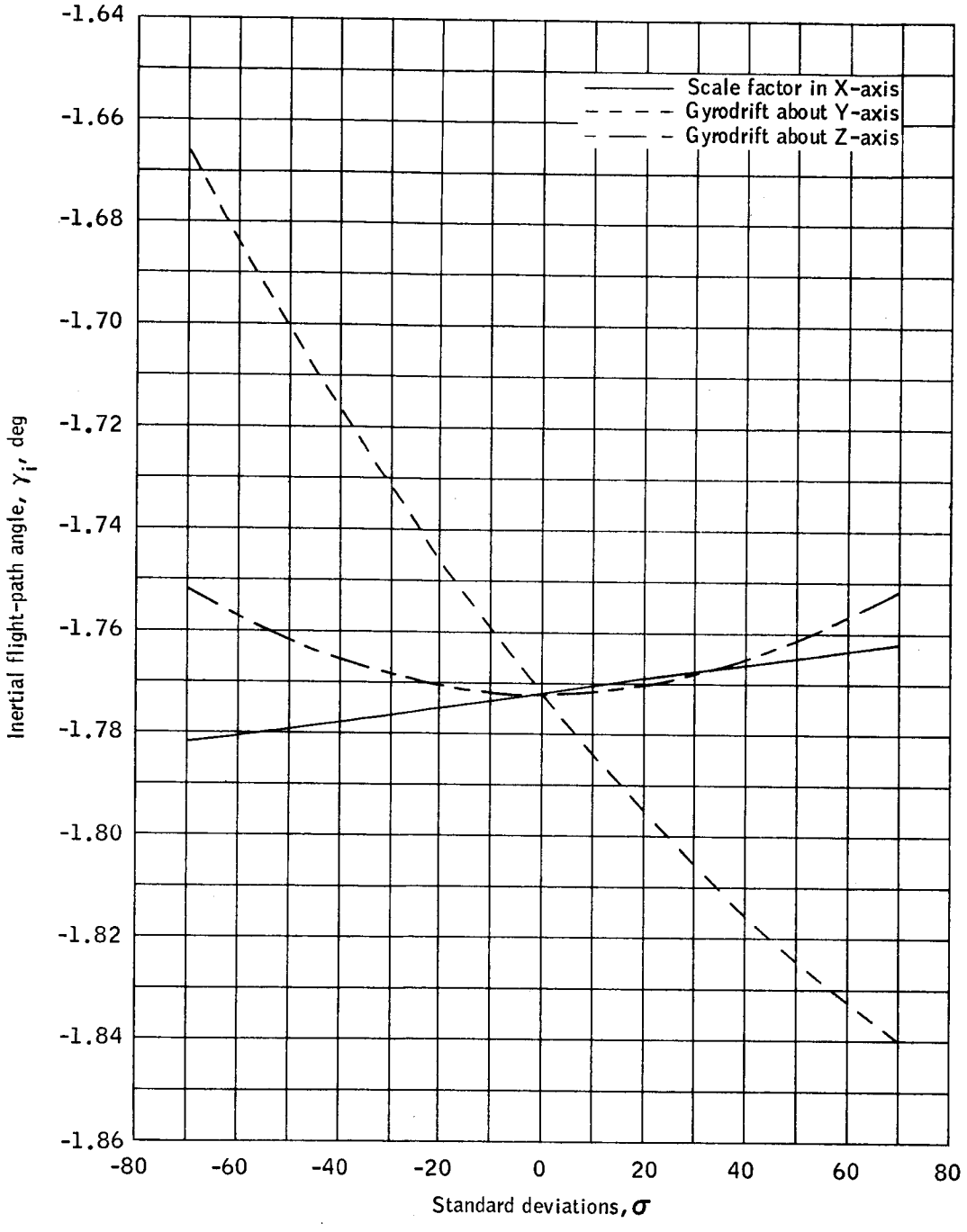
(a) Time versus scale factor and drift errors.

Figure 7.- Mission C dispersions at entry interface (400 000 ft) due to accelerometer bias and scale factor errors and gyrodrift errors during the eighth SPS burn.



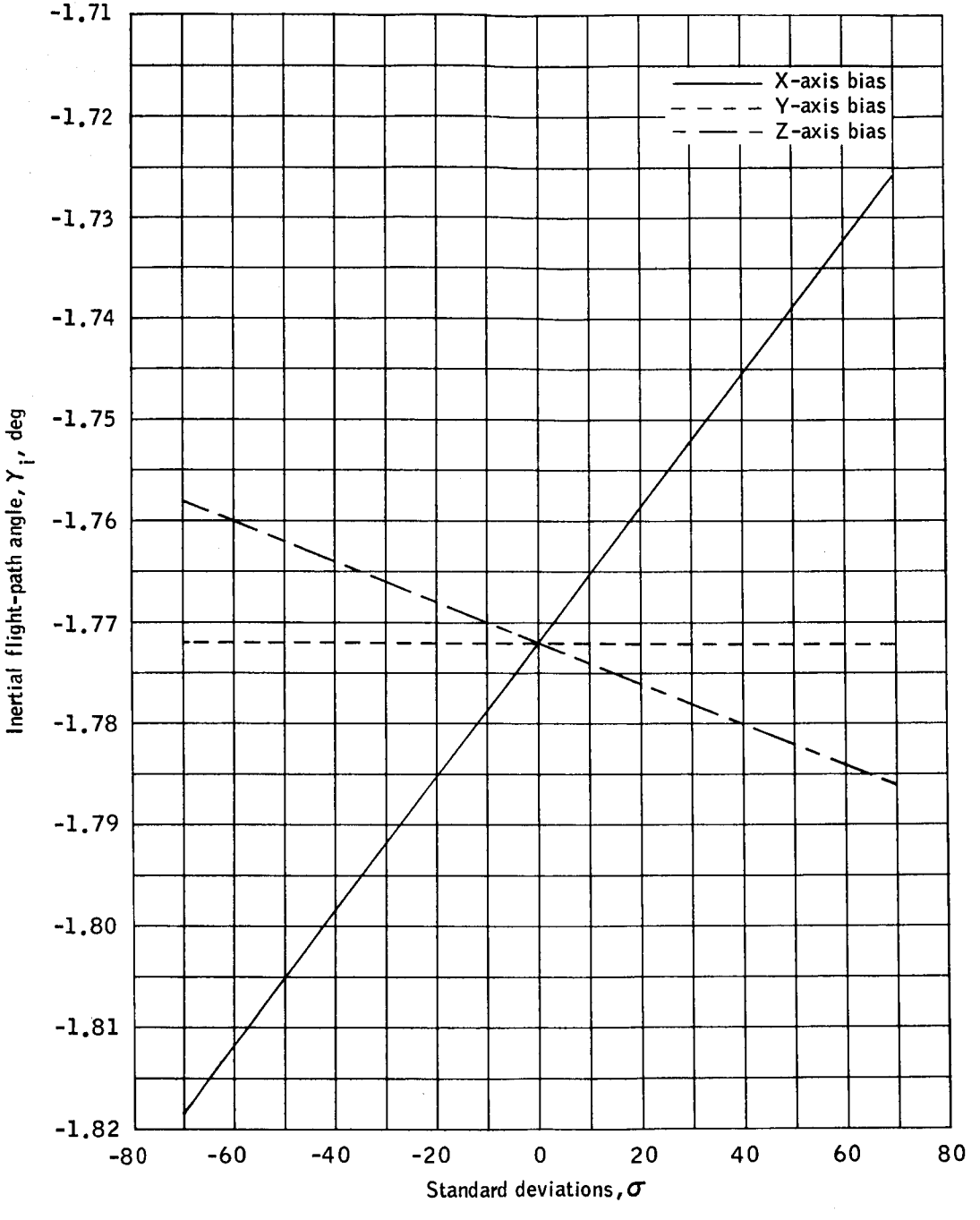
(b) Time versus bias errors.

Figure 7.- Continued.



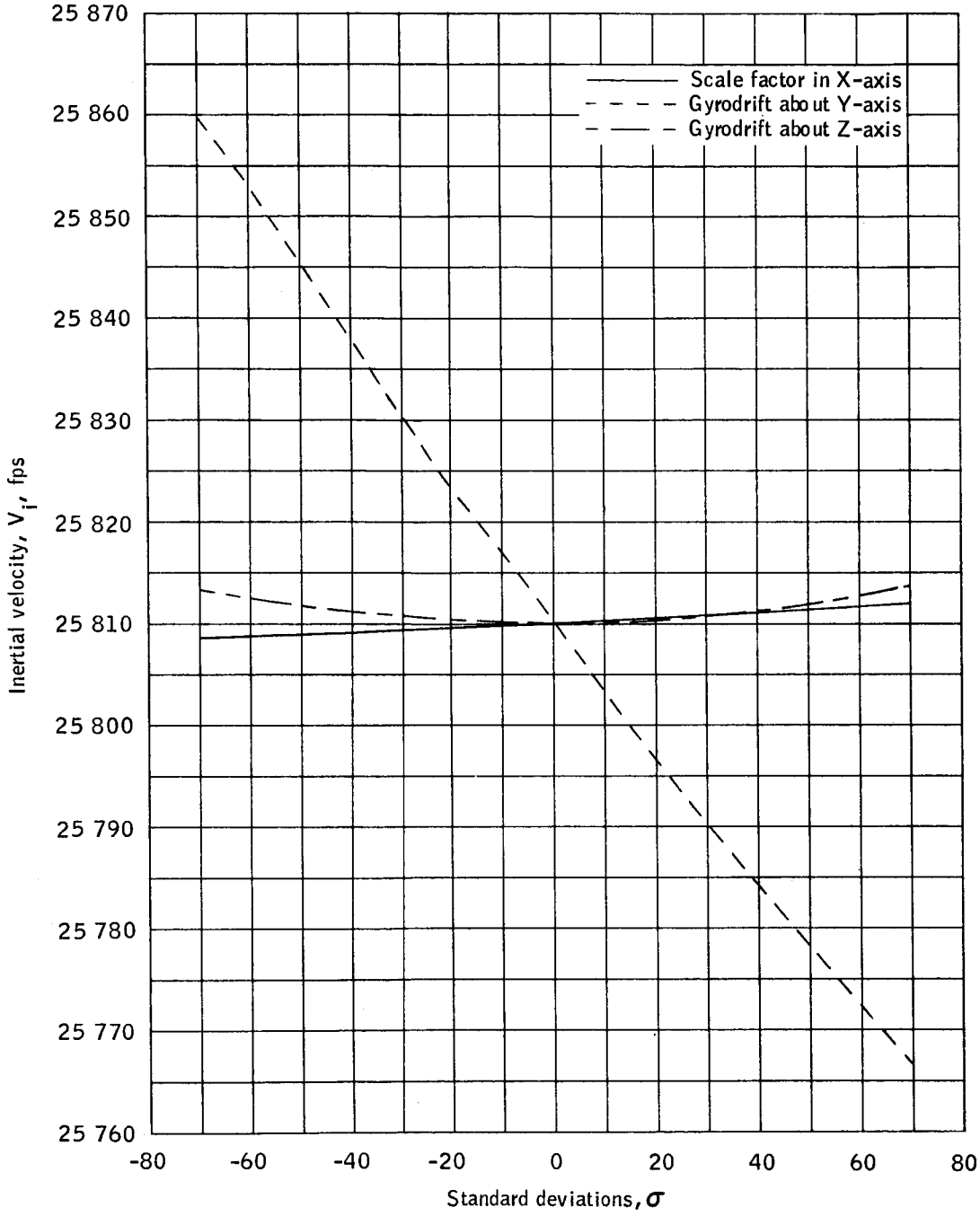
(c) Inertial flight-path angle versus scale factor and drift errors.

Figure 7.- Continued.



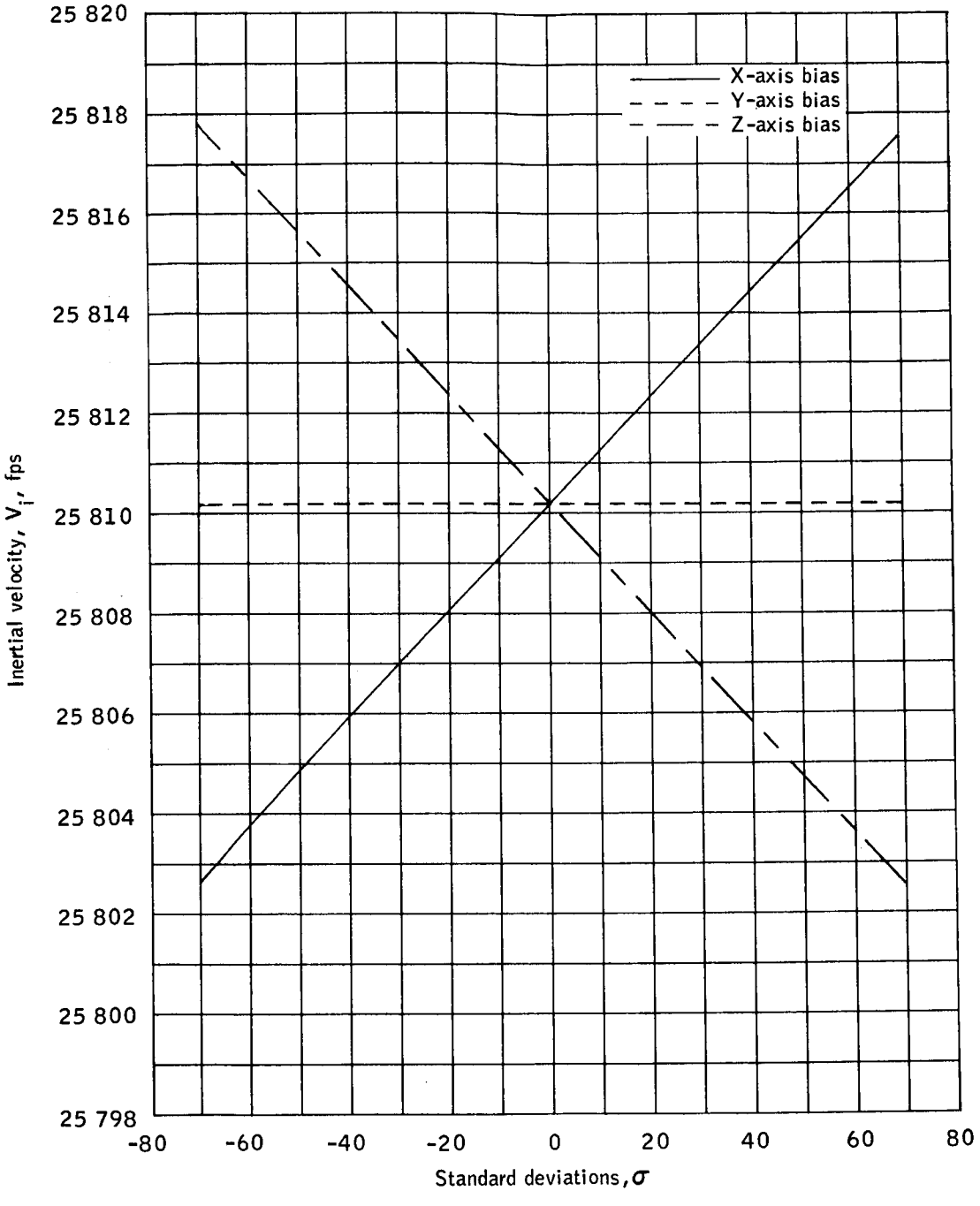
(d) Inertial flight-path angle versus bias errors.

Figure 7.- Continued.



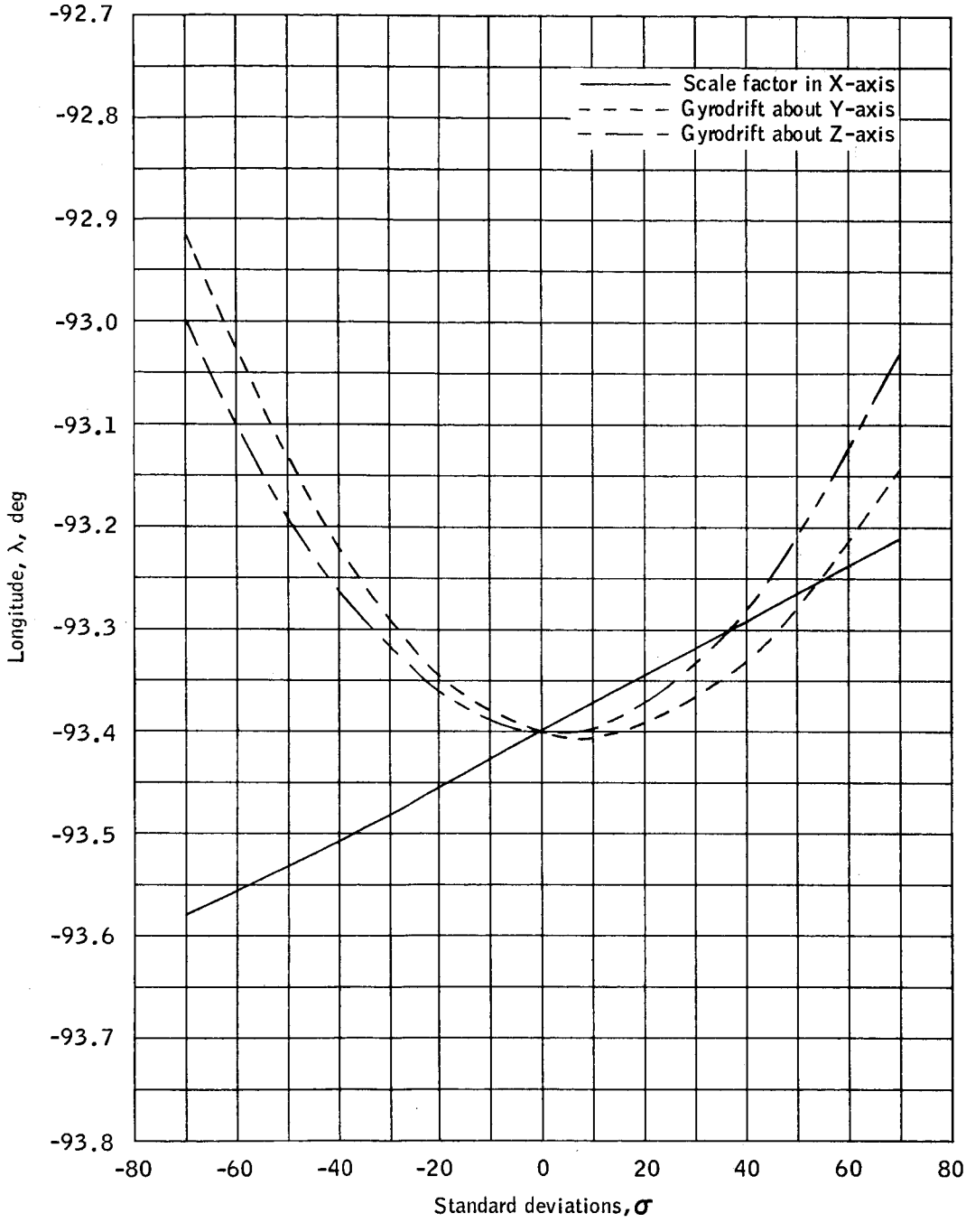
(e) Inertial velocity versus scale factor and drift errors.

Figure 7.- Continued.



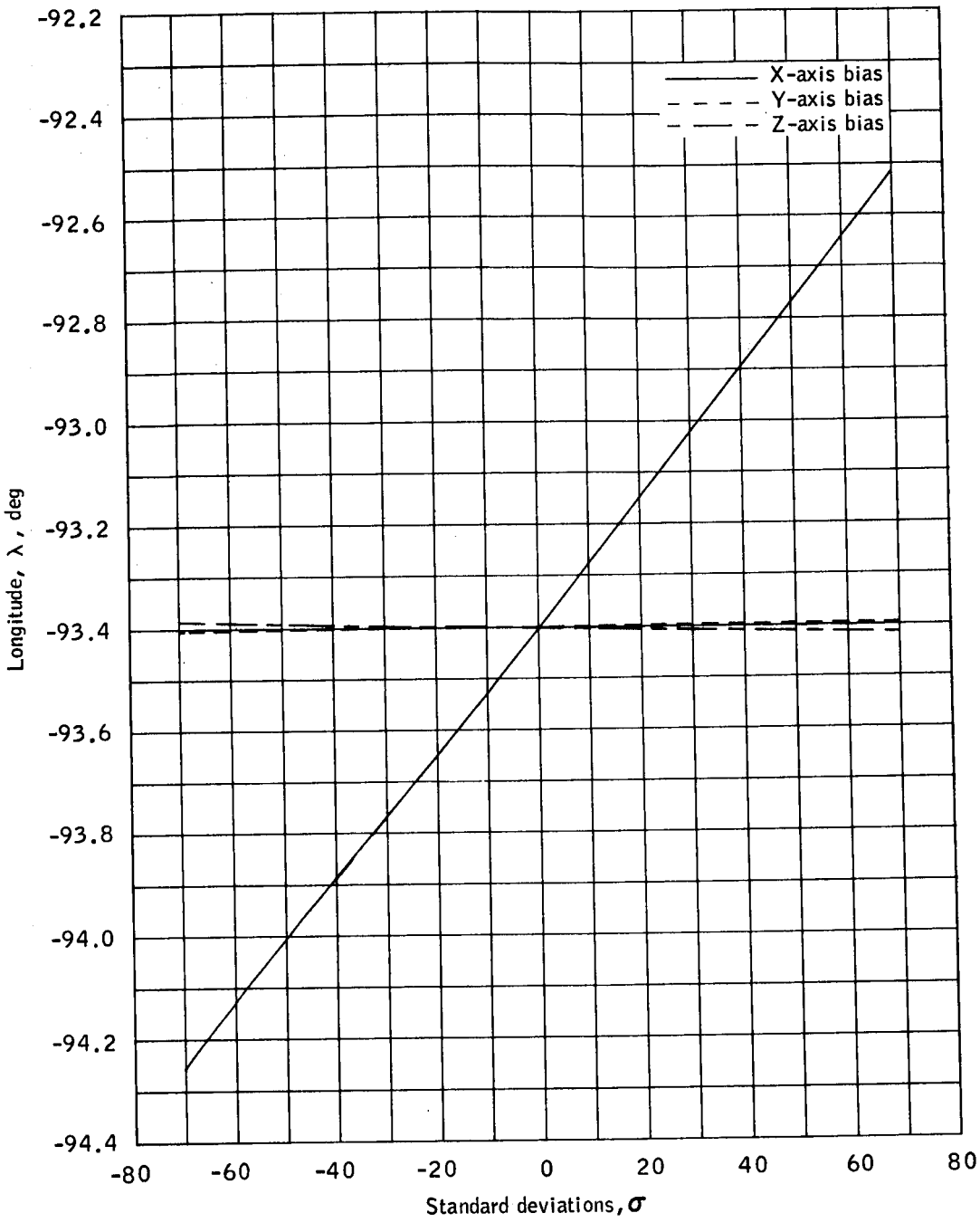
(f) Inertial velocity versus bias errors.

Figure 7.- Continued.



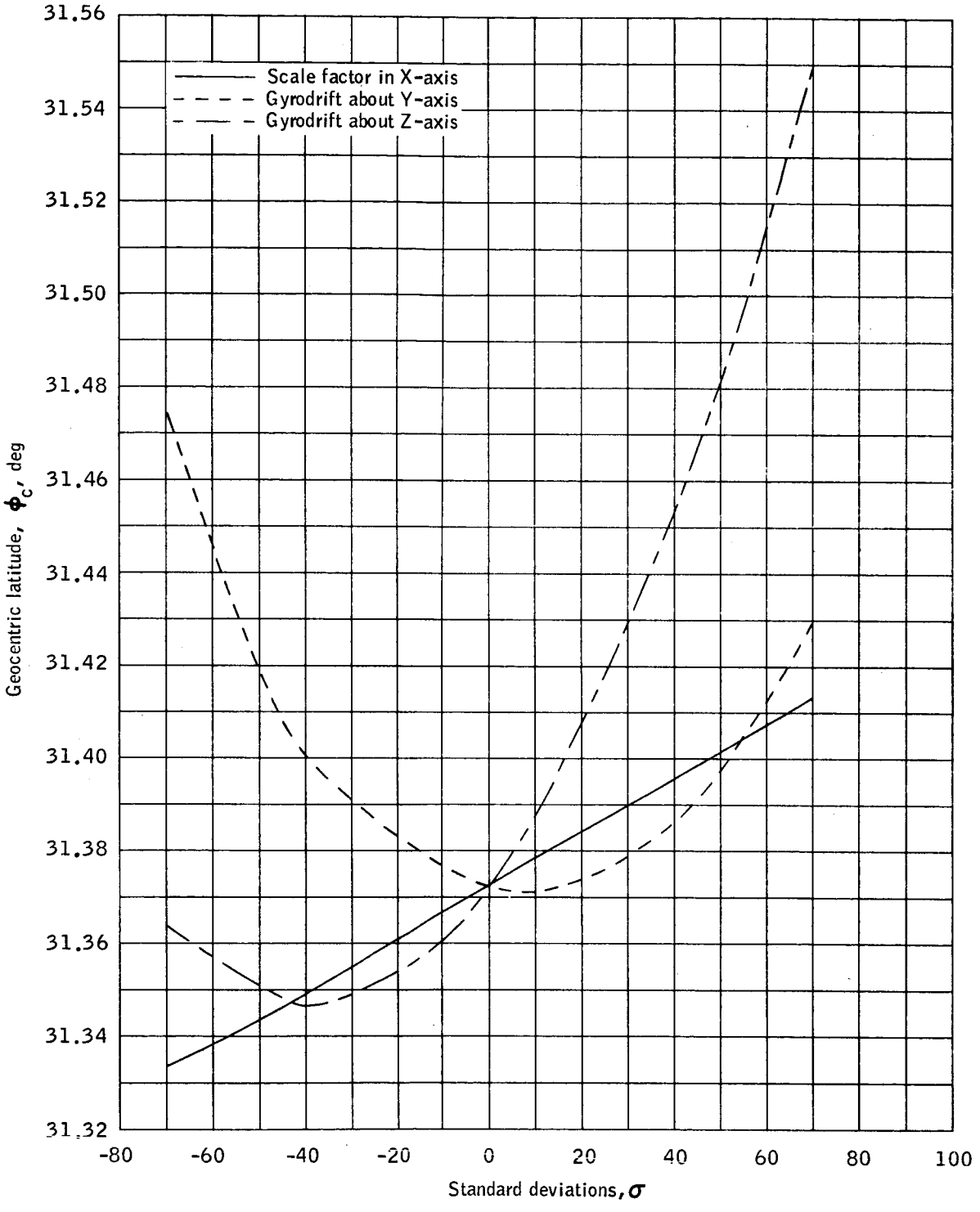
(g) Longitude versus scale factor and drift errors.

Figure 7.- Continued.



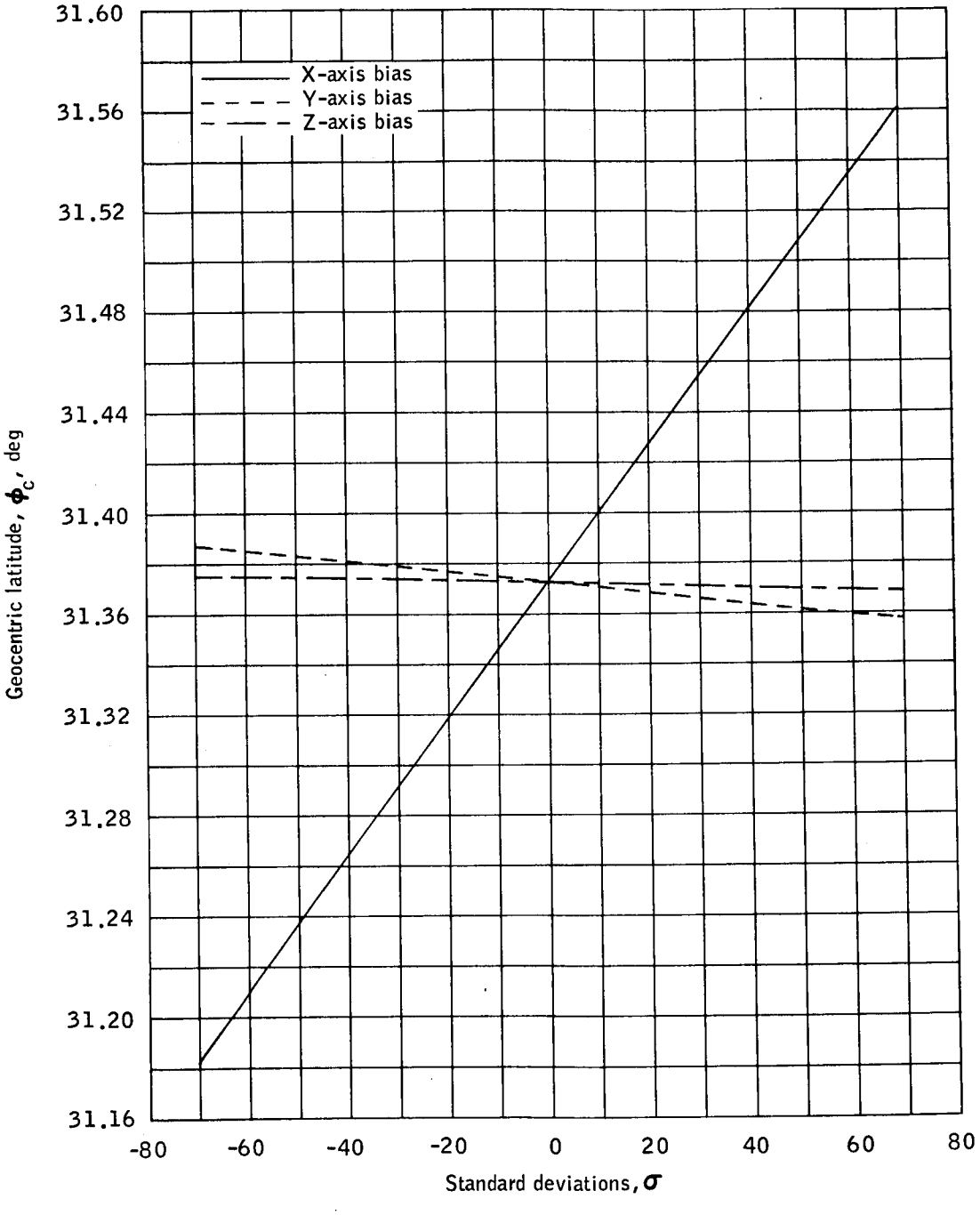
(h) Longitude versus bias errors.

Figure 7.- Continued.



(i) Geocentric latitude versus scale factor and drift errors.

Figure 7.- Continued.



(j) Geocentric latitude versus bias errors.

Figure 7.- Concluded.

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