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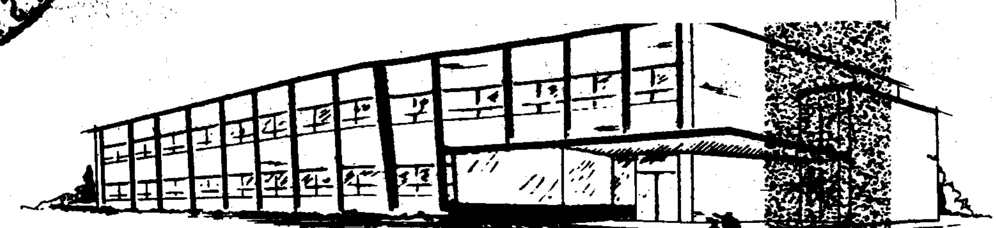

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FINAL REPORT

VOLUME II

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SECTION 9

DATA UTILIZATION

Figure 9-1 shows the mission analysis which precedes the use of the Lunar Navigation Study performance data. The mission phase, exploration system phase, and navigation system phase yield the general parameters which simulate the lunar roving vehicle navigation mission. The system designer at this point in the study can specify selenographic region, mission era, vehicle constraints, traverse data, and navigation state variable requirements. The preceding planning data can be decomposed into the parameters of the Lunar Navigation Study to attain the necessary commonality level for data utilization.

The selenographic region eventually specifies the critical variables and relative geometry of the position fixing, dead reckoning, and homing functions.

The vehicle constraints such as vehicle total range, velocity, and acceleration characteristics, specify mission duration and range. In addition, conservation of vehicle expendables might limit the amount of astronaut time to effect a position or heading fix.

Traverse specification data permit calculation of initial vehicle location, the target location, and great circle or straight path range.

The definition of mission era enables the navigation sensor, lunar knowledge technological era to be defined. Since navigation instrumentation technological advances are created in areas other than lunar surface exploration missions, the Technology SOA (available accuracy type systems) and mission era must be correlated.

The above conditions fix the mission parameters, and the navigation state variable requirements must be satisfied as a function of the fixed mission conditions.

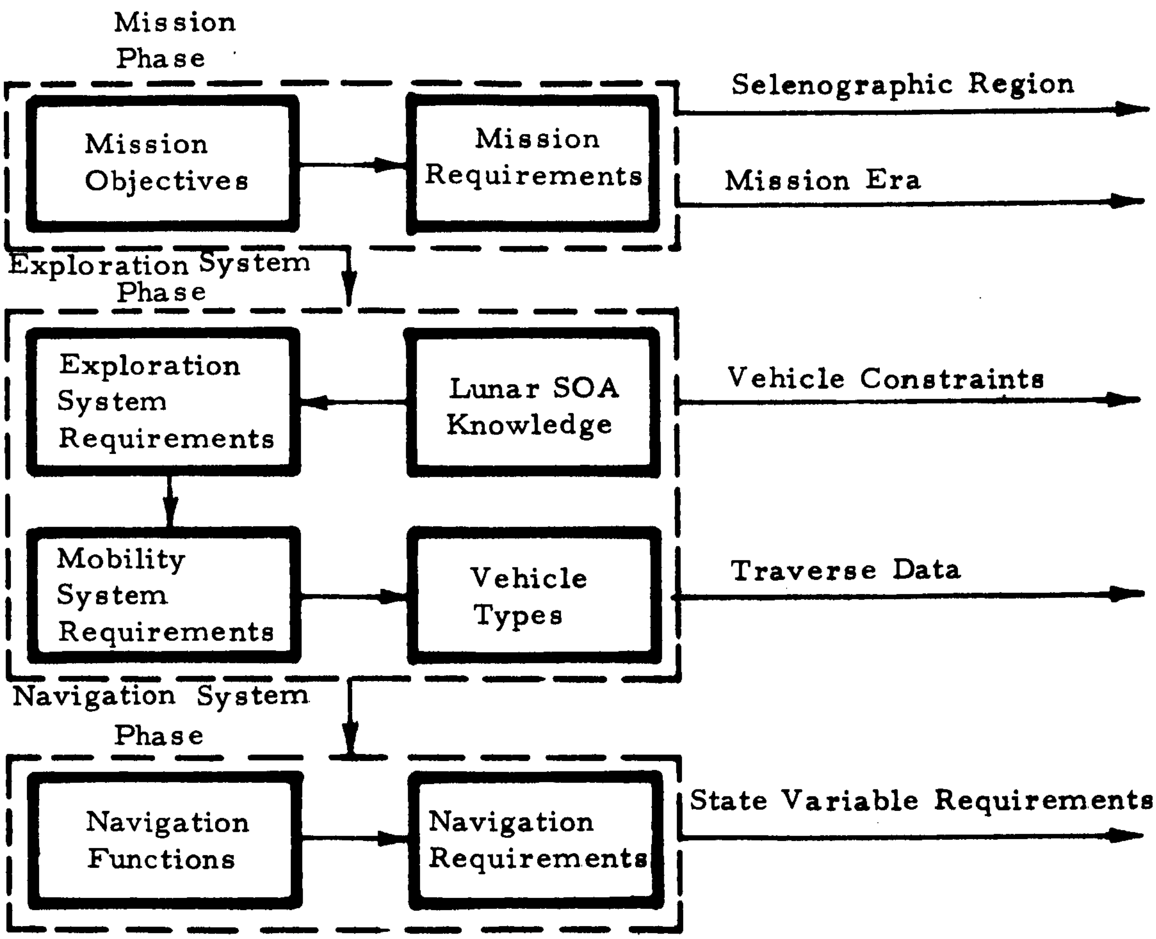


Figure 9-1 Mission Definition/Navigation Requirement Evolution

The comparison of position fix and dead reckoning performance data and the navigation requirements enables the system or mission analyst to specify the accuracy requirements of the sensors or support aids comprising the navigation concept, providing the navigation requirements and mission parameters are reduced to the commonality of the study parameters.

An overall objective of the Lunar Navigation Study is the generation of a parametric performance handbook which details navigational concept performance as a function of navigational sensor accuracy. The performance trade-offs are necessarily a function of standardized traverse parameters which can be interpreted by the user of the handbook to determine sensor requirements for a typical mission postulated by the catalog user.

Outlined in this section is the general analytical procedure that is applied in the analyis of a conceptual navigation system where the preliminary constraint imposed upon the system is the navigation accuracy requirement.

The procedure should be reviewed and instituted prior to the use of the data handbook. The use of the handbook is not limited to the prescribed format, but application of the procedure will initially orient the user to the handbook organization and supply insight to the utility of the data.

9.1 PROCEDURE FOR DATA UTILIZATION

Figure 9-2 shows the functional flow diagram that outlines the procedure for use of the handbook. Phase I orients the user with the handbook organization, and Phase II outlines a step-by-step procedure of data utilization to reach objectives 1, 2, and 3. The handbook orientation introduces the error model formulation, the matrix of components, subconcepts, mission parameters, and navigation requirements. The section number of each topic is identified in the flow diagram, Figure 9-2.

Completing the orientation process, the objectives of the data analysis should be considered and selected.

Objective 1: Define acceptable subconcept for a fixed mission and fixed navigation requirements.

Objective 2: Define recommendations for technology research and developments

Objective 3: Evaluate subconcept performance for fixed subconcept accuracy design point; define sensitivity of fixed design to changing: (1) technology, (2) lunar knowledge, and (3) mission conditions.

The remaining flow diagram of Figure 9-2 shows the sequence necessary to achieve the analytical objectives by applying the performance data. The flow diagram delineates the mission parameter transformation, navigation requirement transformation, error allocation routines, and application of the functional component group, concept, and component error data.

The examples of Section 9.3 apply the procedure.

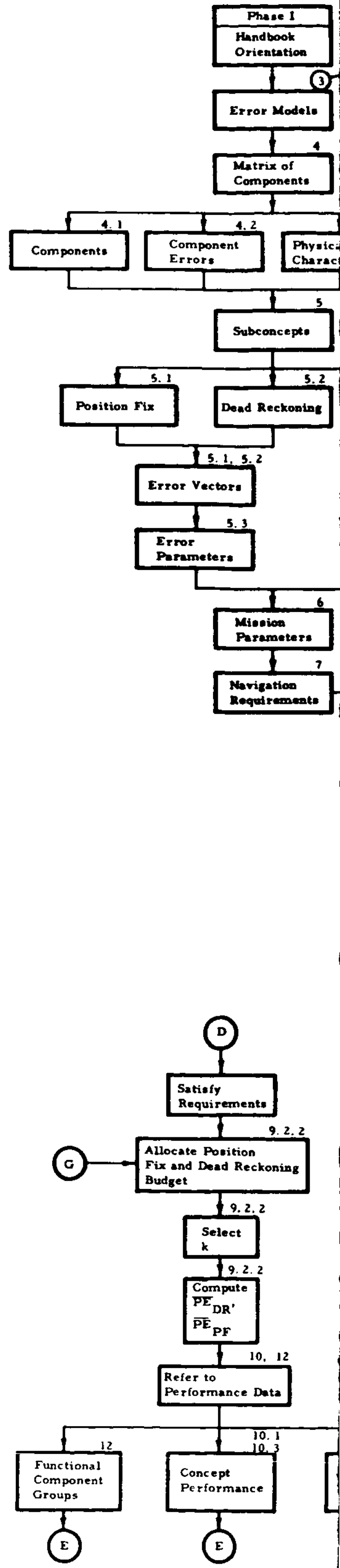
9.2 REQUIREMENT BUDGETING

To evaluate fully the impact of a stringent requirement upon the navigational technology, methods of error allocation, error budgeting, and error reduction to relax stringent accuracy requirements should be considered.

9.2.1 Position Fix Updating

Stringent dead reckoning accuracy requirements can be relaxed by varying the frequency of position fixing. Generally, two criteria exist for taking a position fix:

1. Every T hours
2. Every R kilometers.



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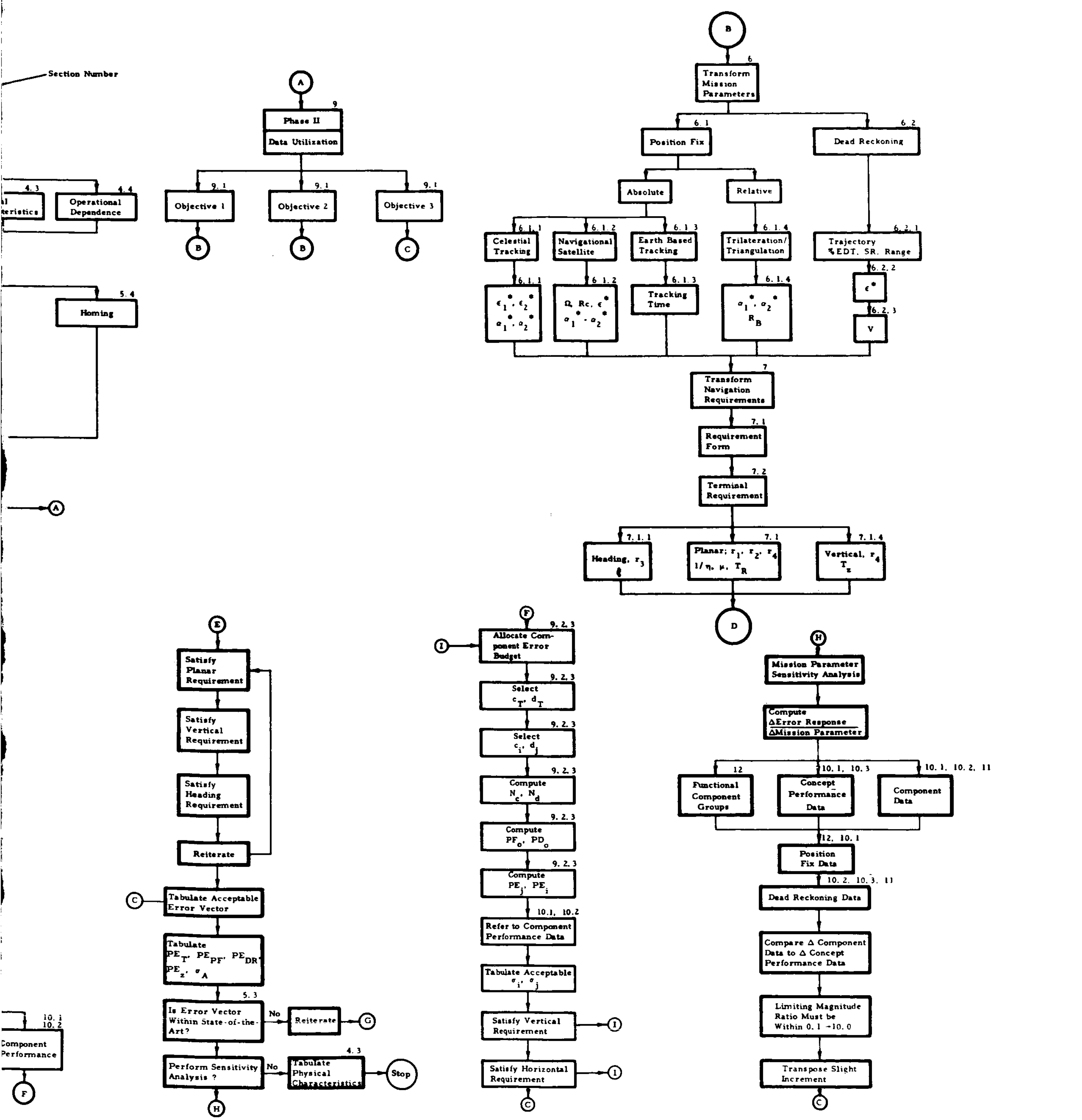


Figure 9-2A Data Utilization

FOR REFERENCE, SEE PAGE 12-27/12-28

9-2B

The criteria are not entirely separable but depending on whether the vehicle dead reckoning concept is operationally dependent upon time or distance, the selection criteria critically affect total concept performance. Thus, if the comparison of the performance data with specified requirements does not satisfy state-of-the-art component development, the stringent component accuracy constraint might be relaxed by altering the T and R position fix criteria. The constraint is imposed upon the position fix subconcept to satisfy the given position fix requirement; i.e., if the 3σ position fix error ellipsoid is unsatisfactorily large, updating certainly is not a navigational aid. Therefore the technique of updating actually reduces the stringent dead reckoning accuracy requirements.

9.2.2 Subconcept Error Allocation

An alternate technique of relaxing stringent accuracy requirements upon either the position fix or dead reckoning subconcepts is allocation of weighting factors to the given error budget.

In general the navigation requirement is satisfied if the following inequality holds,

$$\text{Requirement} \geq \left[\overline{PE}^2_{PF} + \overline{PE}^2_{DR} \right]^{1/2} \qquad (9\text{-}1)$$

where

$\overline{PE}_{PF}$ = Allowable 3σ position fix error

$\overline{PE}_{DR}$ = Allowable 3σ dead reckoning error

For convenience the following terminology is used:

$\mu \triangleq$ Navigation Requirement (planar, vertical, directional).

Also two assumptions are required:

1. μ is given for a defined set of mission parameters
2. The error random variables are statistically independent.

If independence does not exist for the error random variables, then the results will give an excellent first-order approximation.

The error weighting which relates the position fix and dead reckoning requirement is defined by the following expression:

$$k = \frac{\overline{PE}_{PF}}{\overline{PE}_{DR}} \tag{9-2}$$

where $0.1 \leq k \leq 10$.

Thus given the requirement μ, the dead reckoning and position error budgets can be computed as a function of the subconcept error budget ratio k.

$$\overline{PE}_{DR} = \mu / \sqrt{1 + k^2} \tag{9-3}$$

$$\overline{PE}_{PF} = k\, \overline{PE}_{DR} \tag{9-4}$$

$$\overline{PE}_{PF} = k\mu / \sqrt{1 + k^2} \tag{9-5}$$

9.2.3 Component Error Allocation

The method of error budgeting and error allocation which is used to distribute the total error among the concept components is considered. A simple allocation routine is described which can be applied to the sensor performance data to generate tables of functional component groups. The resultant component group would be capable of meeting a representative accuracy requirement.

The position fix and dead reckoning requirements can be approximated by the following expressions

$$\overline{PE}_{PF} = \left(\sum_{i=1}^{n} PE_i^2 \right)^{1/2} \tag{9-6}$$

where

n = number of position fix elements

PE_i = allowable position error contribution of i^{th} position fix sensor

$$\overline{PE}_{DR} = \left(\sum_{j=1}^{m} PE_j^{\,2} \right)^{1/2} \qquad (9\text{-}7)$$

where

m = number of dead reckoning elements

PE_j = allowable position error contribution of j^{th} dead reckoning sensor.

And, to specify a weighting coefficient to each error term, the requirements take the following form.

For the position fix sensors

$$\overline{PE}_{PF} = PF_o \left(\sum_{i=1}^{n} c_i^{\,2} \right)^{1/2} \qquad (9\text{-}8)$$

and similarly for the dead reckoning sensors,

$$\overline{PE}_{DR} = PD_o \left(\sum_{j=1}^{m} d_j^{\,2} \right)^{1/2} \qquad (9\text{-}9)$$

The coefficients c_i give the weighting of the position fix sensor error contributions relative to the base position error value PE_o, and the coefficients d_j weight the dead-reckoning sensor error requirements. The relative coefficient weightings of the elements are constrained by the relations:

$$0.1 \leq \frac{c_i}{c_k} \leq 10 \qquad 1 \leq i,\ k \leq n \tag{9-10}$$

and

$$c_T = c_1 + c_2 + \ldots + c_i + \ldots + c_n \tag{9-11}$$

Expressions 9-10 and 9-11 hold for both the dead reckoning and position fix elements. If the error weighting factors, d_j and c_i, and the error budget ratio k have been defined, the base position error values can be computed.

$$PF_o = \left(\sum_{i=1}^{n} c_j^{2} \right)^{-1/2} \overline{PE}_{PF} \tag{9-12}$$

$$PD_o = \left(\sum_{j=1}^{m} d_j^{2} \right)^{-1/2} \overline{PE}_{DR} \tag{9-13}$$

Letting the summation of coefficients be defined by N_c and N_d respectively, and applying Equations 9-3 and 9-5 gives

$$PF_o = \frac{k\mu}{N_c\sqrt{1 + k^2}} \tag{9-14}$$

$$PD_o = \frac{\mu}{N_d\sqrt{1 + k^2}} \tag{9-15}$$

When the base position error values are determined, the independent position fix component requirements can be calculated:

Component #1

$$PE_1 = c_1 PF_o$$

Component #2

$$PF_2 = c_2 PF_o$$

$$\vdots \qquad (9\text{-}16)$$

Component i

$$PE_i = c_i PF_o$$

$$\vdots$$

Component n

$$PE_n = c_n PF_o$$

The similar procedure follows for the dead reckoning components.

Thus, the application of Equation 9-16 will define the sensor, aid, or navigational element position error component. The performance data curves can be referred to, and the appropriate element 3σ error σ_j, σ_i selected.

For convenience, sample weighting sequences are shown in Table 9-1.

TABLE 9-1

ERROR WEIGHTINGS

	$c_T = 12$						N	$1/N$
	c_1	c_2	c_3	c_4	c_5	c_6		
w_1	1	1	1	1	1	7	7.3	0.14
w_2	1	1	1	1	2	6	6.6	0.15
w_3	1	1	1	1	3	5	6.2	0.16
w_4	1	1	1	1	4	4	6.0	0.17
w_5	1	1	1	2	2	5	6.0	0.17
w_6	1	1	1	2	3	4	5.7	0.18
w_7	1	1	1	3	3	3	5.5	0.18
w_8	1	1	2	2	2	4	5.5	0.18
w_9	1	1	2	2	3	3	5.3	0.19
w_{10}	1	2	2	2	2	3	5.1	0.20

	$c_T = 12$						
	c_1	c_2	c_3	c_4	c_5	N	$1/N$
w_1	1	1	1	1	8	8.2	0.12
w_2	1	1	1	3	6	7.5	0.13
w_3	1	1	1	3	6	6.9	0.14
w_4	1	1	1	4	5	6.6	0.15
w_5	1	1	2	2	6	6.8	0.15
w_6	1	1	2	3	5	6.3	0.16
w_7	1	1	2	4	4	6.2	0.16
w_8	1	1	3	3	4	6.0	0.17
w_9	1	2	2	2	5	6.2	0.17
w_{10}	1	2	2	3	4	5.8	0.18

Table 9-1.A

	c_1	c_2	c_3	c_4	c_5	N	1/N
w_{11}	[illegible]	[illegible]	2	2	4	5.7	0.18
w_{12}	2	2	2	3	3	5.5	0.18

	$c_T = 10$						
	c_1	c_2	c_3	c_4	c_5	N	1/N
w_1	1	1	1	1	6	6.3	0.16
w_2	1	1	1	2	5	5.7	0.18
w_3	1	1	1	3	4	5.3	0.19
w_4	1	1	2	2	4	5.1	0.20
w_5	1	1	2	3	3	4.9	0.20
w_6	1	2	2	2	3	4.7	0.21
w_7	2	2	2	2	2	4.5	0.22

	$c_T = 12$					
	c_1	c_2	c_3	c_4	N	1/N
w_1	1	1	1	9	9.2	0.11
w_2	1	1	2	8	8.4	0.12
w_3	1	1	3	7	7.7	0.13
w_4	1	1	4	6	7.4	0.14
w_5	1	1	5	5	7.2	0.14
w_6	1	2	2	7	7.6	0.13
w_7	1	2	3	6	7.1	0.14
w_8	1	2	4	5	6.8	0.15
w_9	1	3	3	5	6.6	0.15
w_{10}	1	3	4	4	6.5	0.15
w_{11}	2	2	2	6	6.9	0.14
w_{12}	2	2	3	5	6.5	0.15
w_{13}	2	2	4	4	6.3	0.16
w_{14}	2	3	3	4	6.2	0.16
w_{15}	3	3	3	3	6.0	0.17

	$c_T = 12$				
	c_1	c_2	c_3	N	1/N
w_1	1	1	10	10.1	0.10
w_2	1	2	9	9.3	0.11
w_3	1	3	8	8.6	0.12
w_4	1	4	7	8.1	0.12
w_5	1	5	6	7.9	0.13
w_6	2	2	8	8.5	0.12
w_7	2	3	7	7.9	0.13
w_8	2	5	5	7.4	0.14
w_9	2	5	5	7.4	0.14
w_{10}	3	3	6	7.4	0.14
w_{11}	3	4	5	8.1	0.14
w_{12}	4	4	4	6.9	0.14

	$c_T = 12$			
	c_1	c_2	N	1/N
w_1	1	11	11.0	0.09
w_2	2	10	10.2	0.10
w_3	3	9	9.5	0.11
w_4	4	8	8.9	0.11
w_5	5	7	8.6	0.12
w_6	6	6	8.5	0.12

ILMED.
9-13

TABLE 9-13

9.3 EXAMPLE - OBJECTIVE 1

The following postulated mission provides an example of a typical lunar surface navigation mission where the objective (Objective 1) of the analysis is to derive a suitable subconcept for fixed mission and navigation requirements.

The postulated mission task is to conduct an exploratory traverse in the vicinity of the ray system of Copernicus. Specifically, the mission task is to traverse from the rim of the crater Milichius, across the moderately smooth maria, to the northwest rim of the crater Hortensius. The lunar terrain during the traverse is probably typical of the moderately smooth maria, since the traverse intersects the termination of the Copernicus ray system, and the area is probably strewn with rubble from the formation of Copernicus.

The postulated navigation functions require monitoring of vehicle position in absolute coordinates, selenographic latitude, and longitude. The assumed tasks imposed upon the navigation system are: (1) to fix the absolute location of a suitable lunar landmark midway between Milichius and Hortensius, (2) to measure bearing to north during the deployment of a scientific experimental package at the midpoint, and (3) to maintain cognizance and control over vehicle expendables by limiting the vehicle altitude errors and absolute position errors to fixed magnitudes.

Assume that the associated navigation requirements of the navigation functions are to: (1) fix the landmark absolute location to 3 km (3σ), (2) measure bearing to 0.1° (3σ), and (3) monitor absolute position to 3 km (3σ) and altitude error to 0.1 km (3σ).

IN THE FOLLOWING ANALYSIS, CONTINUALLY REFER TO FIGURE 9-2 AND NOTE THE SEQUENTIAL PROGRESS THROUGH THE FLOW DIAGRAM AS THE ANALYSIS PROCEEDS THROUGH THE DATA HANDBOOK.

9.3.1 Mission Parameters, Ⓑ

The above problem statement can be summarized:

Initial Point

Milichius

Latitude $x_o \cong 10^\circ$

Longitude $y_o \cong -30^\circ$

Destination Point

Hortensius

Latitude $x_D \cong 6.5^\circ$

Longitude $y_D \cong -28^\circ$

Slant Range $\cong$ 120 km

Vehicle Velocity $\cong$ 8 km/hr

Slant Range to Intermediate Destination $\cong$ 60 km

9.3.1.1 Position Fix Mission Parameters

In the following analysis, the position fix parameters have been arbitrarily selected to provide the example mission details.

9.3.1.1.1 Celestial Tracking

Given: (1) the vehicle position at $x = 10^\circ$, $y = -30^\circ$, (2) the specific time of mission occurrence, and (3) the lunar based ephemeris—the true elevation, ϵ^*, and true heading, a_t^*, of the candidate stars can be computed by Equations 6-1 and 6-2, or approximated by refering to Figure 6-2.

Table 9-2 shows the brightest available navigational stars which can be observed and the true angles ϵ^* and a_t^* to the stars. (Assume the time of mission occurrence is such that the moon right ascension is 17° and declination 0°, relative to the earth. Then the transformation equations of Appendix C, Reference 1, (Vol. I) were used to compute the star positions in Table 9-2.)

TABLE 9-2

CANDIDATE STARS

Star	Magnitude	u (deg)	w (deg)	ϵ^* (deg)	a_t (deg)
Canopus	-0.9	-53	259	3	214
Sirius	-1.6	-17	264	15	248
Procyon	0.5	5	277	38	267
Regulus	1.3	12	315	75	277
Acrux	1.1	-63	349	20	168
Spica	1.2	-11	4	50	120
Hadar	0.9	-60	13	15	155

The selection of the candidate stars is based on the minimization of position error, i.e., azimuthal separation near 90°. Choose stars Hadar and Sirius.

Thus,

$$\alpha_1^* - \alpha_2^* = 93^\circ$$

$$\epsilon_1^* = 15^\circ$$

$$\epsilon_2^* = 15^\circ$$

9.3.1.1.2 Navigational Satellite

From Section 6.1.2, arbitrarily select the mission parameters:

$$R_c = 2038 \text{ km}$$

and

$$\Omega = -60^{\circ}$$

$$(\Omega = -50^{\circ}, \text{ absolute, with vehicle at } y = -30^{\circ})$$

Then

$$\epsilon^{*} \cong 30^{\circ} \text{ (Ranging, Range Rate Figure 6-9)}$$

and

$$\left|\alpha_1^{*} - \alpha_2^{*}\right| \cong 50^{\circ} \text{ (Angle Tracking Figure 6-10).}$$

9.3.1.1.3 Earth Based RF Tracking

Assume that the vehicle is on station at Milichius for 24 hr to conduct scientific measurements. Thus, allowable tracking time, the mission parameter critical to the performance of the sc 5, sc 6 subconcepts, would be 24 hr.

9.3.1.1.4 Triangulation/Trilateration

The relative position measurements are not applicable under mission definition.

9.3.1.2 Dead Reckoning Mission Parameters

Again, the mission parameters are selected, in some instances, to provide the example mission details. As the example continues, constantly refer to Figure 9-2.

9.3.1.2.1 Trajectory Data

Since the traverse is in a moderately smooth maria, the terrain characterizations are:

$$A_{max} = 90^{\circ}.$$

Then from Figure 6-14,

$$\% \text{ EDT} = 15\%.$$

(Or inversely, the ELMS model specifies 7% EDT for the smooth maria)

Slant Range to Destination = 60 km

Range to Destination = 60 (1 + 0.15)

= 69 km.

9.3.1.2.2 Vehicle Velocity

Assume the estimated average velocity is V = 8 km/hr.

9.3.1.2.3 Selenographic Region

Assume true elevation angle ϵ^* to the earth is 60°, the true elevation angle to the sun is 30°. (Given the earth and sun subpoint, Figure 6-2 can be used to approximate ϵ^*.)

9.3.2 Navigational Requirements

Note the progress of the analysis in Figure 9-2. The mission parameters have been transformed, and the navigational requirements must be transformed.

9.3.2.1 Requirement Form

From Section 7.1, the mapping requirement, r_1, and homing requirement, r_2, are identical:

$$r_1: \quad 1/\eta = \frac{3.0}{69} = 1/23$$

or

$$r_2: \quad T_R = 3 \text{ km}.$$

The direction limit, r_3 (Section 7.1), at the destination is:

$$\zeta = 0.1^{\circ}.$$

The position limit requirement, r_4, is:

$$T_R = 3 \text{ km}$$

$$T_Z = 0.1 \text{ km}.$$

9.3.2.2 Terminal Requirement

Due to the mission definition, the terminal requirement T_R is given by r_1, r_2, or r_4.

9.3.3 Error Allocation, (D)

The error allocation procedure is initiated at point (D) in Figure 9-2. Assume equal weighting between the dead reckoning and position fix subconcept errors. From Section 9.2.2,

$$k = 1, \text{ hence}$$

$$\overline{PE}_{DR} = \frac{T_R}{\sqrt{2}} = 2.1 \text{ km}$$

$$\overline{PE}_{PF} = 2.1 \text{ km}$$

and

$$1/\eta = \frac{2.1}{69} = 1/33, \text{ the dead reckoning linear requirement.}$$

Since altitude is measured relative to Milichius, the origin,

$$(\overline{PE_Z})_{PF} = 0.0$$

$$(\overline{PE_Z})_{DR} = 0.1 \text{ km.}$$

That is,

$$k = 0.0, \text{ from Section 9.2.2.}$$

Assume the weighting of the heading requirement to be 1 part to 5 parts. (Usual ratios are less than 10 and greater than 0.1).

$$k = \frac{(\sigma_A)_{PF}}{(\sigma_A)_{DR}} = 1/5, \text{ then}$$

$$(\zeta)_{DR} = \frac{0.1^\circ}{\sqrt{1 + (0.2)^2}} = 0.098^\circ$$

$$(\zeta)_{PF} = (0.2)(0.1^\circ) = 0.02^\circ$$

9.3.4 Functional Component Group Performance Data

For the commonality requirements above, and the fixed mission conditions, the performance data are consulted.

9.3.4.1 Position Fix

Section 12, as a quick response aid to the analyst, lists position fix functional component groups which satisfy given navigation requirements as a function of fixed mission conditions. Refer to Table 5-1 for the position fix error vectors. Then, from the tables of Section 12, the approximate accuracy design points which satisfy the mission and navigation requirements are:

Celestial Tracking, scl:

$$\begin{bmatrix} \sigma_{\epsilon} \\ \sigma_{r} \\ \sigma_{p} \\ \sigma_{R} \\ \sigma_{D} \\ \sigma_{t} \\ \sigma_{\gamma} \end{bmatrix} = \begin{bmatrix} 0.024^{\circ} \\ 0.024^{\circ} \\ 0.030^{\circ} \\ 0.03^{\circ} \\ 0.03^{\circ} \\ 0.03 \text{ hr} \\ 0.0043^{\circ} \end{bmatrix}$$

(Table 12-1, Case 1)

Ranging Navigational Satellite, sc 2:

$$\begin{bmatrix} \sigma_{\rho} \\ \sigma_{u} \\ \sigma_{w} \\ \sigma_{Rnc} \end{bmatrix} = \begin{bmatrix} 0.33 \text{ km} \\ 0.33 \text{ km} \\ 0.33 \text{ km} \\ 0.10 \text{ km} \end{bmatrix}$$

(Table 12-2, Case 2)

Angle Tracking Navigational Satellite, sc 3:

$$\begin{bmatrix} \sigma_\rho \\ \sigma_u \\ \sigma_w \\ \sigma_\epsilon \\ \sigma_p \\ \sigma_r \\ \sigma_\gamma \end{bmatrix} = \begin{bmatrix} 0.19 \text{ km} \\ 0.19 \text{ km} \\ 0.19 \text{ km} \\ 0.01^\circ \\ 0.01^\circ \\ 0.01^\circ \\ 0.002^\circ \end{bmatrix}$$

(Table 12-3, interpolate between Case 1 and Case 2)

Range Rate Navigational Satellite, sc 4:

$$\begin{bmatrix} \sigma_\rho \\ \sigma_u \\ \sigma_w \\ \sigma_{\dot\rho} \\ \sigma_{\dot u} \\ \sigma_{\dot w} \\ \sigma_{\dot r} \end{bmatrix} = \begin{bmatrix} 1.0 \text{ km} \\ 1.0 \text{ km} \\ 1.0 \text{ km} \\ 1.0 \text{ km/hr} \\ 1.0 \text{ km/hr} \\ 1.0 \text{ km/hr} \\ 2.8 \text{ km/hr} \end{bmatrix}$$

(Table 12-4, Case 2)

Earth Based RF Tracking sc 5, sc 6:

DSIF Ranging: $PE_{PF} = 8$ km (Table 10-24)

DSIF Range Rate: $PE_{PF} = 20$ km.

9.3.4.2 Dead Reckoning

The dead reckoning functional component groups, Tables 12-6 to 12-16, list the design point accuracy subconcepts that will meet representative requirements. Approximate the requirement, 1/33 at 69 km, by 1/50 at 75 km. Considering the distance elements to be the most critical, the functional component groups that meet the requirement with maximum component errors are:

1. Odometer, sc 12, III-2 (Table 12-6)

2. Doppler Radar, sc 16, III-3 (Table 12-7)

3. Accelerometer, sc 20, III-4 (Table 12-8).

Refer to Table 5-2 and the error parameters of Table 5-3. The 3σ error vectors of the subconcepts are:

$$\begin{bmatrix} \sigma_o \\ \sigma_{GA} \\ \sigma_{gD} \\ \sigma_r \\ \sigma_p \\ \sigma_{pD} \\ \sigma_{rD} \end{bmatrix} = \begin{bmatrix} 2\% \\ 0.1 \\ 0.08^\circ/hr \\ 0.1^\circ \\ 0.1^\circ \\ 0.05^\circ/hr \\ 0.05^\circ/hr \end{bmatrix}$$

sc 16, III-3:

The sc 16 vector, with the exception of the doppler radar term σ_V, is identical to the subconcept sc 12 error vector.

$$\sigma_V = 0.1 \text{ km/hr}.$$

sc 20, III-4:

The sc 20 vector, with the exception of the accelerometer term σ_{Ax}, is identical to the subconcept sc 12 error vector.

$$\sigma_{Ax} = 10^{-7} \text{ earth g}$$

$$K_{A3} = 10^{-4} \%$$

9.3.5 Concept Performance Data

Section 10 presents concept performance data in greater detail than does Section 12. A correspondingly higher amount of effort is necessary to obtain the problem solution.

9.3.5.1 Position Fix

Celestial Tracking, sc 1:

Apply Table 10-2, and refer to Table 10-1 for the sensor errors.

Requirement = 2.1 km.

The major error source is the vertical anomaly, and this allowable error term requires trade-offs to minimize equipment sophistication. The trade-off is based on maximizing the allowable vertical anomaly such that equipment sophistication is minimized and the position fix requirement is satisfied.

From Table 10-2, Case 1 with equipment and aid errors at the nominal level (NOM), and $\sigma_\gamma = 0.0$, the position fix error is:

$$PE_{PF} = 0.75 \text{ km}.$$

To solve for the allowable vertical anomaly and to meet the 2.1-km requirement,

$$\sigma_\gamma \cong \left[(2.1)^2 - (0.75)^2\right]^{1/2} \quad \frac{(0.05)}{1.5}$$

$$\cong 0.065^\circ.$$

Thus, the error vector of sc 12 from Table 10-1 is:

$$\begin{bmatrix} \sigma_\epsilon \\ \sigma_r \\ \sigma_p \\ \sigma_R \\ \sigma_D \\ \sigma_t \\ \sigma_\gamma \end{bmatrix} = \begin{bmatrix} 0.01^\circ \\ 0.01^\circ \\ 0.01^\circ \\ 0.01^\circ \\ 0.01^\circ \\ 0.003 \text{ hr} \\ 0.065^\circ \end{bmatrix}$$

where the sophistication of ephemeris and equipment errors is evident since the allowable anomaly term has increased. Also, from Table 10-6, for the above error vector $\sigma_A = 0.02^\circ$, which equals the position fix bearing requirement.

The remaining position fix subconcepts can be treated in a similar fashion. See Tables 10-7 and 10-9 (Ranging), Tables 10-12 and 10-13 (Angle Tracking), Tables 10-18 and 10-20 (Range Rate), and Table 10-24 (Earth Based Tracking). Thus,

Ranging, sc 2:

$$\sigma_{Rnc} = 0.1 \text{ km}$$
$$\sigma_{\rho} = \sigma_{u} = \sigma_{w} = 0.28 \text{ km}$$

Angle Tracking, sc 3:

$$\sigma_{\epsilon} = 0.01^{\circ}$$
$$\sigma_{p} = \sigma_{r} = 0.01^{\circ}$$
$$\sigma_{u} = \sigma_{w} = \sigma_{\rho} = 0.1 \text{ km}$$
$$\sigma_{\gamma} = 0.0$$

Range Rate, sc 4:

$$\sigma_{\dot{\rho}} = \sigma_{\dot{u}} = \sigma_{\dot{w}} = 1 \text{ km/hr}$$
$$\sigma_{\rho} = \sigma_{u} = \sigma_{w} = 1 \text{ km}$$
$$\sigma_{\dot{r}} = 2.9 \text{ km/hr}$$

The earth based tracking position error capability does not change, since the allowable tracking duration does not vary.

9.3.5.2 Dead Reckoning

Refer to Section 10.3 to locate the dead reckoning concept data. Consider the odometer subconcepts, since the functional group data indicate highly sophisticated accelerometers and velocity sensors are necessary. Again consider the odometer as the initial error source. Locate the error response curves in Section 10.3 that satisfy the requirement of 2.1 km at 69 km.

The accuracy design point concepts which fullfill the requirements are:

1. Odometer, sc 9, III-2 (Figure 10-212)

2. Odometer, sc 10, III-2 (Figure 10-221)

3. Odometer, sc 11, II-2 (Figure 10-235)

4. Odometer, sc 12, II-2 (Figure 10-264).

The variation in the accuracy design point of sc 12 from the III-2 of Section 9.3.4.2 to II-2 above, reflects the fact that the functional component group data of Section 12 hold for fixed mission conditions. The concept data of Section 10.3 are more flexible in that a wider choice of mission conditions are available to the user of the data. Thus, the more precise mission definition specifies the II-2 vector.

The odometer sc 12 subconcept is selected from the above subconcepts, since the allowable odometer error is greater. The error vector is:

$$\begin{bmatrix} \sigma_{o} \\ \sigma_{GA} \\ \sigma_{gD} \\ \sigma_{r} \\ \sigma_{p} \\ \sigma_{pD} \\ \sigma_{rD} \end{bmatrix} = \begin{bmatrix} 2\% \\ 0.5^{\circ} \\ 0.25^{\circ}/hr \\ 0.5^{\circ} \\ 0.5^{\circ} \\ 0.1^{\circ}/hr \\ 0.1^{\circ}/hr \end{bmatrix}$$

From Table 5-2 and Table 5-4.

9.3.5.2.1 Vertical Requirement

Restrict the ensuing analysis to the dead reckoning subconcept sc 12 at the accuracy design point II-2. This restriction is based on maximizing the allowable errors. Refer to the dead reckoning concept altitude data of Section 10.3.2. For the II-2 subconcept, the altitude error at the destination is:

$$PE_z = 0.8 \text{ km.} \qquad \text{(Figure 10-346)}$$

This value exceeds the requirement, and an alternative solution is required.

The major source of altitude error is the vertical sensor. However, the vertical sensor contributes negligible planar errors. Refer to the component data of Section 10.2 to select the necessary vertical requirement error. For sc 12, V = 8 km/hr, and from Figures 10-91 and 10-93,

$$\sigma_p = \sigma_r = 0.05^\circ \quad PE_z = 0.06 \text{ km and}$$
$$\sigma_{pD} = \sigma_{rD} = 0.01^\circ/\text{hr} \quad PE_z = 0.06 \text{ km}$$

The revised error vector is:

$$\begin{bmatrix} \sigma_o \\ \sigma_{GA} \\ \sigma_{\dot{g}D} \\ \sigma_p \\ \sigma_r \\ \sigma_{pD} \\ \sigma_{rD} \end{bmatrix} = \begin{bmatrix} 2\% \\ 0.5^\circ \\ 0.25^\circ/\text{hr} \\ 0.05^\circ \\ 0.05^\circ \\ 0.01^\circ/\text{hr} \\ 0.01^\circ/\text{hr} \end{bmatrix} \quad \text{for subconcept sc 12.}$$

9.3.5.2.2 Heading Requirement

A similar analysis leads to the revised directional errors. From Figure 10-96, if

$\sigma_{gD} = 0.01^\circ/\text{hr}$, then $\sigma_A = 0.08^\circ$ and from Table 10-36, if

$\sigma_{pD} = \sigma_{rD} = 0.01^\circ/\text{hr}$, $\sigma_A = 0.017^\circ$, and if

$\sigma_{GA} = 0.017^\circ$, then total heading error is

$\sigma_A = 0.098^\circ$ which equals the dead reckoning bearing requirement. Thus, the revised sc 12 error vector is

$$\begin{bmatrix} \sigma_o \\ \sigma_{GA} \\ \sigma_{gD} \\ \sigma_p \\ \sigma_r \\ \sigma_{pD} \\ \sigma_{rD} \end{bmatrix} = \begin{bmatrix} 2\% \\ 0.02^\circ \\ 0.01^\circ/hr \\ 0.05^\circ \\ 0.05^\circ \\ 0.01^\circ/hr \\ 0.01^\circ/hr \end{bmatrix}.$$

Thus, the altitude and heading requirements significantly decrease allowable altitude errors, and the major source of planar position error becomes the odometer error. The definition of the above error vectors, which fulfill the navigation requirements, indicates that the analysis has progressed to point Ⓒ in Figure 9-2. The next step is to determine the error response and correlate the error vector to the state of the art.

9.3.5.2.3 Error Response

Given the above accuracy design point error vector for dead reckoning subconcept, sc 12, the error vector component magnitudes can be correlated to the state of the art by referring to Table 5-3.

Odometer, σ_O; II

Directional Gyro, σ_{GA}; less than IV

Directional Gyro, σ_{gD}; IV

Vertical Gyro, $\sigma_p = \sigma_r$; IV

Vertical Gyro, $\sigma_{pD} = \sigma_{rD}$; V

Thus, this error vector is identified as Odometer, sc 12, IV-2. This identification infers that all sc 12 component errors are equal to the IV design point (since the planar position error component contributed by the vertical gyro drift is a second-order effect, the design point is approximated by the IV level) while the odometer error is equal to the II (2) design point.

Refer to Figure 10-264 for the accuracy design point error response. The response IV-2 is not plotted because of the relationship between the concept performances data and component performance data. Locate the independent odometer error response on Figure 10-78 for $\sigma_o = 2\%$. Then locate the error response of the design point IV- on Figure 10-264.

The accuracy design point IV- signifies negligible odometer error, $\sigma_o \cong 0.0$, and all other subconcept errors are fixed at the IV accuracy design point. Thus the curve IV- is the error response where the only navigational component errors are the attitude errors. Now, compare the response $\sigma_o = 2\%$ of the Figure 10-78 to the response IV- of Figure 10-264. The former is an order of magnitude greater. Thus, the odometer error response, $\sigma_o = 2\%$, completely dominates the sc 12 dead reckoning subconcept errors and is the error response PE_{DR} of dead reckoning subconcept sc 12, Odometer IV-2.

The altitude error response PE_z is given by the curve IV-5, Vertical Gyro, Figure 10-346. Since the vertical sensors dominate the altitude error, the Vertical Gyro IV-5 was selected. IV-5 implies navigational component errors at the IV accuracy design point, and the vertical gyro drift at the V (5) level.

The heading error response σ_A, characterized principally by the heading sensor can be located in Figure 10-362, the Directional Gyro, sc 12, IV-4.

Thus, the dead reckoning errors, as a function of distance travelled, have been determined, the navigational requirements fulfilled, and as the flow diagram of Figure 9-2 dictates, the error vector components have been compared to the state of the art given in Table 5-3 and found to be intermediate (IV) to the nominal (NOM) and state-of-the-art (SOA) design points.

9.3.6 Component Performance Data

Return to point Ⓕ in Figure 9-2, and apply the component performance data for the dead reckoning subconcepts.

The use of the component performance data is demonstrated, considering the error allocation routine for the dead reckoning subconcept sc 12. An identical process can be used for the position fix subconcepts.

In review, the dead reckoning requirements are:

$T_R = 2.1$ km

$T_Z = 0.1$ km

$\zeta = 0.1^{\circ}$

To solve this problem, errors are allocated to the components of subconcept sc 12. (Subconcept sc 12 was arbitrarily chosen to provide an example of the error allocation routine.)

The error vector of dead reckoning subconcept sc 12 is comprised of five error terms:

1. Odometer, σ_o
2. Directional Gyro, σ_{GA}
3. Directional Gyro, σ_{gD}
4. Vertical Gyro, $\sigma_p = \sigma_r$
5. Vertical Gyro, $\sigma_{pD} = \sigma_{rD}$.

Now enter the component error allocation routine of Figure 9-2.

9.3.6.1 Planar Requirement

$\overline{PE}_{DR} = 2.1$ km

The number of dead reckoning error sources m is five.

m=5

$d_1 \Rightarrow$ Odometer weighting

$d_2 \Rightarrow$ Directional gyro alignment weighting

$d_3 \Rightarrow$ Directional gyro drift weighting

$d_4 \Rightarrow$ Vertical gyro alignment weighting

$d_5 \Rightarrow$ Vertical gyro drift weighting.

$$d_T = \sum_{j=1}^{5} d_j$$

Arbitrarily let $d_T = 12$. Then select the weighting elements to be

$$d_1 = 8 \quad d_2 = 1 \quad d_3 = 1 \quad d_4 = 1 \text{ and } d_5 = 1.$$

The odometer error is heavily weighted (d_1) since it is the major error source.

Then, from Table 9-1, use weighting sequence for $d_T = 12$ (c_T in Table 9-1), w_1:

$$N = N_d = 8.2, \quad 1/N_d = 0.12$$

So

$$PD_o = (0.12)(2.1) = 0.25 \text{ km}.$$

The allowable dead reckoning component position errors are:

1. Odometer: (0.25) (8) = 2.0 km

2. DG Alignment: (0.25) (1) = 0.25 km

3. DG Drift: (0.25) (1) = 0.25 km

4. VG Alignment: (0.25) (1) = 0.25 km

5. VG Drift: (0.25) (1) = 0.25 km

The above error budget must be equaled for the mission parameters, V = 8 km/hr, and distance travelled, 69 km.

Refer to the dead reckoning component data, Section 10.2, and linearize:

$$\sigma_o = \left(\frac{2.0\%}{1.1\ km}\right)(2\ km) = 3.6\% \qquad \text{(Figure 10-78)}$$

$$\sigma_{GA} = \left(\frac{0.1^o}{0.1\ km}\right)(0.25\ km) = 0.25^o \qquad \text{(Figure 10-81)}$$

$$\sigma_{gD} = \left(\frac{0.25^o/hr}{1.0\ km}\right)(0.25\ km) = 0.063\ ^o/hr \qquad \text{(Figure 10-83)}$$

$$\sigma_r = \sigma_p = \left(\frac{1^o}{0.073\ km}\right)(0.25\ km) = 3.4^o \qquad \text{(Figure 10-86)}$$

$$\sigma_{pD} = \sigma_{rD} = \left(\frac{0.1\ ^o/hr}{0.03\ km}\right)(0.25) = 0.83\ ^o/hr \qquad \text{(Figure 10-88)}$$

9.3.6.2 Altitude Requirement

In Figure 9-2, the analysis has progressed to point (I).

The altitude component of the vehicle position error originates from the vertical gyro and odometer errors. Thus, three sources of altitude error are present in the dead reckoning subconcept sc 12:

1. Odometer, σ_o
2. Vertical Gyro, $\sigma_p = \sigma_r$
3. Vertical Gyro, $\sigma_{pD} = \sigma_{rD}$.

Enter the component error allocation of Figure 9-2.

$\overline{PE}_{DR}$ = 0.1 km, the altitude requirement

$m = 3$

d_1 = odometer weighting

d_2 = VG alignment weighting

d_3 = VG drift weighting

$$d_T = \sum_{j=1}^{3} d_j$$

let

$$d_T = 12.$$

Use weighting sequence w_4 for $c_T = d_T = 12$, Table 9-1.

$$d_1 = 1$$

$$d_2 = 4$$

$$d_3 = 7.$$

Then

$$N_d = 8.1, \quad 1/N_d = 0.12$$

And,

$$PD_o = (0.12)(0.1) = 0.012 \text{ km}.$$

The allowable dead reckoning component altitude errors are:

1. Odometer: (1) (0.012) = 0.012 km
2. VG Alignment: (4) (0.012) = 0.048 km
3. VG Drift: (7) (0.012) = 0.084.

Refer to the dead reckoning altitude component error data of Section 10.2.

Thus,

$$\sigma_o \tilde{=} 0.8\% \qquad \text{(Table 10-35)}$$

$$\sigma_p = \sigma_r = \left(\frac{0.05^\circ}{0.060 \text{ km}}\right)(0.048 \text{ km}) = 0.04^\circ, \qquad \text{(Figure 10-91)}$$

$$\sigma_{pD} = \sigma_{rD} = \left(\frac{0.01\ ^\circ/\text{hr}}{0.070 \text{ km}}\right)(0.084 \text{ km}) = 0.012\ ^\circ/\text{hr} \qquad \text{(Figure 10-93)}$$

9.3.6.3 Directional Requirement

The analysis, in Figure 9-2, will reiterate, starting at point ①.

The heading error of the dead reckoning concept sc 12 is due to errors in the vertical gyro and directional gyro. Thus, the four sources of error are:

1. DG Alignment, σ_{GA}
2. DG Drift, σ_{gD}
3. VG Alignment, $\sigma_p = \sigma_r$
4. VG Drift, $\sigma_{pD} = \sigma_{rD}$.

Use the component error allocation of Figure 9-2.

$$\overline{PE}_{DR} \cong 0.1^{\circ}$$

$$m = 4$$

let

$$d_T = 12\,.$$

The weighting sequence is chosen from Table 9-1: Sequence w_8 is chosen because the dominant errors are from the directional gyro:

$d_1 = 4$, DG Alignment

$d_2 = 5$, DG Drift

$d_3 = 1$, VG Alignment

$d_4 = 2$, VG Drift

$$N_d = 6.8 \text{ and } \frac{1}{N_d} = 0.15$$

So,

$$PD_o = (0.15)(0.1^{\circ}) = 0.015^{\circ}$$

Then the allowable bearing error of each navigation component is:

1. DG Alignment: 0.060°
2. DG Drift: 0.080°
3. VG Alignment: 0.015°
4. VG Drift: 0.030°.

Refer to the dead reckoning heading error data of Section 10.2.

Thus,

$$\sigma_{GA} = 0.06^\circ, \text{ directly}$$

$$\sigma_{gD} = \left(\frac{0.1\ ^\circ/hr}{0.8^\circ}\right)(0.08^\circ) = 0.01\ ^\circ/hr, \qquad \text{(Figure 10-96)}$$

$$\sigma_r = \sigma_p \cong 0.1^\circ, \qquad \text{(Table 10-36)}$$

$$\sigma_{rD} = \sigma_{pD} \cong 0.04\ ^\circ/hr, \qquad \text{(Table 10-36)}$$

9.3.6.4 Total Concept Error Vector Requirement Ⓒ

Refer to Figure 9-2 and note the location of point Ⓒ

Selecting the maximum allowable component error from the planar, altitude, and heading requirements defines the acceptable error vector:

$$\begin{bmatrix} \sigma_o \\ \sigma_{GA} \\ \sigma_{gD} \\ \sigma_p \\ \sigma_r \\ \sigma_{pD} \\ \sigma_{rD} \end{bmatrix} = \begin{bmatrix} 0.8\% \\ 0.06^\circ \\ 0.04\ ^\circ/hr \\ 0.04^\circ \\ 0.04^\circ \\ 0.01\ ^\circ/hr \\ 0.01\ ^\circ/hr \end{bmatrix}$$

Given the above error vector terms, the component errors can be correlated to the state of the art by referring to Table 5-3:

1. Odometer, σ_o; less than III
2. Directional Gyro Alignment, σ_{GA}; approximately IV
3. Directional Gyro Drift, σ_{gD}; approximately IV
4. Vertical Gyro Alignment, $\sigma_p = \sigma_r$; less than IV
5. Vertical Gyro Drift, $\sigma_{pD} = \sigma_{rD}$; V.

The total error response can be calculated by taking the root sum square (RSS) of the independent errors at each point of slant range, or approximated by the following design point subconcepts:

Planar PE_{DR}: sc 12, Odometer, IV-3; (Figure 10-264)

Altitude PE_z: sc 12, Vertical Gyro, IV-5; (Figure 10-346)

Heading σ_A: sc 12, Directional Gyro Drift, IV-4; (Figure 10-361)

In the case of the planar response, the curve σ_o = 1% of sc 12 Figure 10-78 will suffice, since the odometer errors dominate the dead reckoning error response. i.e. Compare curve σ_o = 1% of Figure 10-78 to the curve IV of 10-264. (IV-, implies the odometer error is negligible.) Since the former is nearly an order of magnitude greater than the latter, the σ_o = 1% curve of Figure 10-78 is the error response of the concept:

sc 12 Odometer IV-3.

At this point on Figure 9-2, the error vector can be assessed with respect to the state of the art and the above analysis reiterated (point Ⓖ), or since the error vector of sc 12 (as an example) is within the state of the art, the analysis could progress to the mission sensitivity analysis (see the example of Section 9.5) or terminate with the definition of the subconcept physical characteristics (Table 4-3).

9.4 EXAMPLE - OBJECTIVE 2

The application of the data handbook to reach Objective 2, definition of recommendations for technology research and developments, for fixed mission and requirement conditions, proceeds in the fashion of the analysis of Example 1. However, rather than terminating the analysis with the defined subconcept error vector, comparison of navigational component error requirements and the state of the art is made by referring the dead reckoning error vector to Table 5-3 or the position fix error vector to Table 5-4.

The analytical procedure, initiated in Figure 9-2 with the mission parameter transformation Ⓑ, and terminated by defining an acceptable error vector and the position, altitude, and heading error response as a function of the fixed mission conditions, point Ⓒ in Figure 9-2, is identical to that of Objective 1. In addition, assume the error allocation routines (point Ⓖ and point Ⓕ of Figure 9-2) have been reiterated to maximize the allowable equipment errors.

Thus, assume the analysis has progressed to point Ⓒ shown in Figure 9-2, and a comparison of the error vector with the state of the art is the remaining task. Consider the acceptable error vector of the position fix subconcept to be:

sc 2, Ranging Navigational Satellite:

$$\begin{bmatrix} \sigma_\rho \\ \sigma_u \\ \sigma_w \\ \sigma_{Rnc} \end{bmatrix} = \begin{bmatrix} 0.10 \text{ km} \\ 0.10 \text{ km} \\ 0.10 \text{ km} \\ 0.10 \text{ km} \end{bmatrix} .$$

Comparing the error sources of the error vector to the tabulations of Table 5-4, it is found: Satellite Ephemeris σ_ρ (σ_u, σ_w) = 0.1 km is typical of the projected state of the art. However, the necessary ranging measurement is acceptable with σ_{Rnc} = 0.10 km, the MAX value.

Consider the dead reckoning analysis to conclude with the acceptable error vector,

For subconcept sc 9:

$$\begin{bmatrix} \sigma_o \\ \sigma_a \\ \sigma_p \\ \sigma_r \\ \sigma_{RE} \\ \sigma_{DE} \\ \sigma_t \end{bmatrix} = \begin{bmatrix} 0.01\% \\ 0.01^o \\ 0.01^o \\ 0.01^o \\ 0.001^o \\ 0.001^o \\ 0.0003 \text{ hr} \end{bmatrix}$$

Comparing this error vector to the error magnitudes in Table 5-3, the correlation to the design point range is:

Odometer $\sigma_o = 0.01\ \%$; VII

Celestial Tracker $\sigma_a = 0.01^o$; V

Vertical Sensor $\sigma_p = \sigma_r = 0.01^o$; V

Ephemeris $\sigma_{RE} = \sigma_{DE} = 0.001^o$; V

Timer $\sigma_t = 0.0003$ hr;

which is identified as sc 9, Odometer V-7. The odometer parameter is typical of a projected-state-of-the-art (PSOA) magnitude, while the remaining elements are characterized by the state of the art (SOA).

Proceeding one step further, from Table 5-3 it is noted that the suitable elements for the celestial tracker are:

1. s 3 IR Earth Tracker

2. s 4 RF Earth Tracker

3. s 20 Sun Tracker.

Since $\sigma_a = 0.01^{\circ}$ was the acceptable 3σ error for the celestial tracker and was denoted as SOA, Table 4-2 should be consulted for the particular sensor parameter range. Thus, it is found from Table 4-2 that the following accuracy design point components are necessary:

- IR earth tracker exceeding the state of the art (SOA)

- RF earth tracker exceeding the projected state of the art (PSOA)

- Sun tracker equaling the state of the art.

The above example demonstrates the analysis process to be applied to the state-of-the-art assessment irrespective of the specific subconcept or navigational component.

The analysis has progressed to either point Ⓖ in Figure 9-2, or the mission analysis, depending upon the needs of the analyst. See the example in Section 9.5 for the mission sensitivity analysis, or terminate the above analysis by cataloging the physical characteristics of the error vector components (Table 4-3).

9.5 EXAMPLE-OBJECTIVE 3

Figure 9-2 shows that achievement of Objective 3 requires transferral to point Ⓒ. Thus, the error vector is fixed, and it is desired through a mission analysis to evaluate subconcept sensitivity to varying conditions.

9.5.1 Position Fix Subconcept

Consider the fixed error vector to be,

Celestial tracking subconcept, sc 1:

$$\begin{bmatrix} \sigma_{\epsilon} \\ \sigma_{r} \\ \sigma_{p} \\ \sigma_{R} \\ \sigma_{D} \\ \sigma_{t} \\ \sigma_{\gamma} \end{bmatrix} = \begin{bmatrix} 0.01^{\circ} \\ 0.01^{\circ} \\ 0.01^{\circ} \\ 0.01^{\circ} \\ 0.01^{\circ} \\ 0.003 \text{ hr} \\ 0.065^{\circ} \end{bmatrix}$$

For this error vector and the mission conditions of Section 9.3,

$$PE_{PF} = 2.1 \text{ km}.$$

The object of the analysis is to determine the sensitivity of the output position fix errors, for the fixed vector, and varying mission conditions. See point Ⓗ in Figure 9-2.

The critical mission variable of the celestial tracking subconcept is the azimuthal separation between the observables, $\alpha_1^* - \alpha_2^*$. In the example of Objective 1,

$$\alpha_1^* - \alpha_2^* = 93^{\circ}.$$

To assess the effect of varying the mission conditions, select stars Acrux and Spica, Table 9-2.

Thus,

$$\alpha_1^* - \alpha_2^* = 48^{\circ}$$
$$\epsilon_1^* = 20^{\circ}$$
$$\epsilon_2^* = 50^{\circ}.$$

Consider the component performance data of Section 10.1 for each component of the error vector:

1. Celestial Tracker, σ_ϵ: PE_1 = 0.61 km, (Figure 8-1)

2. Vertical Sensor, $\sigma_r = \sigma_p$: PE_2 = 0.66 km, (Figure 8-2)

3. Ephemeris, $\sigma_R = \sigma_D$: PE_3 = 0.51 km, (Figure 8-3)

4. Timer, σ_t: $PE_4 = \left(\frac{0.016 \text{ km}}{0.001 \text{ hr}}\right)$ (0.003 hr), (Figure 8-4)

   PE_4 = 0.048 km

5. Anomaly, σ_γ: $PE_5 = \left(\frac{0.48 \text{ km}}{0.01^\circ}\right)$ (0.065°), (Figure 8-5)

   = 3.1 km.

Taking the RSS, PE_{PF} = 3.3 km,

or a 57% increase in position fix error due to changing mission conditions.

The sensitivity of the position error for subconcepts sc 1... sc 8 to variations in the mission factors is evaluated in a similar fashion by applying the data of Sections 10.1 or 12.

9.5.2 Dead Reckoning Subconcept

For this example, an error vector is given, the error response is obtained, and variations in the error response are found as a function of mission parameters.

Given for sc 9, the odometer, celestial tracking elements, the following error data.

sc 9

Odometer	σ_o = 0.5%
Sun Tracker	$\sigma_a = 1^\circ$
Pendulous Vertical	$\sigma_r = \sigma_p = 1.0^\circ$

Ephemeris $\sigma_{RE} = \sigma_{DE} = 0.03^{o}$

Timer $\sigma_t = 0.03$ hr

The error vector is:

$$\begin{bmatrix} \sigma_o \\ \sigma_a \\ \sigma_p \\ \sigma_r \\ \sigma_{RE} \\ \sigma_{DE} \\ \sigma_t \end{bmatrix} = \begin{bmatrix} 0.5\% \\ 1^{o} \\ 1.0^{o} \\ 1.0^{o} \\ 0.03^{o} \\ 0.03^{o} \\ 0.03 \text{ hr} \end{bmatrix}$$

9.5.2.1 Component Data

The independent planar position errors, from the component data Section 10.2 at 69 km, V = 8 km/hr, and true elevation angle to the Sun, $\epsilon^* = 30^{o}$, are:

1. Odometer, σ_o: $PE_1 = 0.28$ km, Figure 10-23
2. Sun Tracker, σ_a: $PE_2 = 1.0$ km, Figure 10-27
3. Pendulous Vertical, $\sigma_p = \sigma_r$: $PE_3 = 0.60$ km, Figure 10-32
4. Ephemeris, $\sigma_{RE} = \sigma_{DE}$: $PE_4 = 0.036$ km, Figure 10-56
5. Timer, σ_t: $PE_5 = 0.0055$ km, Figure 10-63.

Taking the RSS, $PE_{DR} = 1.2$ km.

Including the vertical anomaly term increases the position error; if $\sigma_\gamma = 1.6$,

$$PE_6 = 0.96 \text{ km (Figure 10-32)}.$$

Thus,

$$PE_{DR} = 1.5 \text{ km}.$$

The altitude position error can be calculated:

1. Odometer, σ_o: 0.01 km, Table 10-31

2. Pendulous Inclinometer $\sigma_p = \sigma_r$: 1.2 km, Figure 10-64.

Thus,

$$PE_z = 1.2 \text{ km}.$$

The bearing error can be calculated:

1. Sun Tracker, σ_a: 1.07^o, Table 10-32

2. Pendulous Inclinometer, $\sigma_r = \sigma_p$: 0.69^o, Table 10-32.

The ephemeris, timer, and odometer heading errors are less than 0.1^o. Thus,

$$\sigma_A = 1.3^o.$$

9.5.2.2 Concept Performance Data

The total response of planar position error vs. distance travelled can be obtained from the concept performance data of Section 10.2.

Note the correlation of the error vector elements to the state of the art as given by Table 5-3. Also note that the ephemeris and timer contribute negligible errors.

Hence, if

$$\sigma_o = 0.5\% \Rightarrow \text{IV} \quad PE_1 = 0.28 \text{ km}$$
$$\sigma_a = 1^o \Rightarrow \text{II} \quad PE_2 = 1.0 \text{ km}$$
$$\sigma_p = \sigma_r = 0.1^o \Rightarrow \text{III} \quad PE_3 = 0.06 \text{ km}$$

Compare position error magnitudes of each term. The dominating terms are due to the sun tracker and the odometer. Thus, characterize the error type or accuracy design point as: sc 9 Celestial Tracker III-2 (i.e. sc 9, with all errors at the III level and the celestial tracker at the II (2) level of Table 5-3.)

The approximate error response is found in Figure 10-214, curve III-2. The response is given for $\epsilon^* = 77^o$; therefore, compare the component error response of Figures 10-27 and 10-214 to arrive at the composite response.

The heading error response is given in Figure 10-345, curve III-2. Again the parametric data are given for $\epsilon^* = 77^o$, and the reduction factors of Table 10-32 must be considered.

Since the altitude position error is completely dominated by the vertical sensor term, the concept altitude error response is given in Figure 10-64.

9.5.3.3 Sensitivity to Mission Parameters

The component data of 9.5.2.1 give the position error components for the basic mission. The mission parameters are now varied but the mission length, 69 km (60 km slant range), remains constant.

9.5.3.4 Vehicle Velocity

If V = 16 km/hr,
Odometer, σ_o: $PE_1 = 0.40$ km (Figure 11-1).

9.5.3.5 % EDT

If percent extra distance travelled equals 30%, the vehicle altitude error at the destination is:

$PE_z = 1.4$ km, Figure 11-10, since the vertical sensor errors dominate.

9.5.3.6 Selenographic Region

If the true elevation angle ϵ^* is 77^o, the celestial tracking position error component increases to:

$$PE_2 = 1.6 \text{ km (Figure 11-12)},$$

and the vertical sensor position error component increases to

$$PE_3 = 4.6 \text{ km (Figure 11-12)}.$$

The ephemeris error component increases to

$$PE_4 = 0.15 \text{ km (Figure 11-13).}$$

Thus, the total position error is:

$$PE_{DR} = 4.9 \text{ km.}$$

9.5.3.7 Elimination of Vertical Reference

Elimination of the local vertical reference for relative dead reckoning increases the error component:

$$PE_3 = 2.4 \text{ km (Figure 11-18) for } \epsilon^* = 30^\circ.$$

9.5.3.8 Elimination of Ephemeris Data

The mode of dead reckoning using the celestial heading reference without ephemeris updating leads to position errors

$$PE_4 = 0.46 \text{ km (Figure 11-20).}$$

Thus, the above sensitivity data show the variation of output errors as a function of changing or uncertainty in mission parameters, for a fixed error vector. The mission parameter sensitivity analysis (point Ⓗ, Figure 9-2), for this example, is concluded, and the point of the analytical procedure in Figure 9-2 is point Ⓒ, where reiteration as given in Sections 9.3 and 9.4 might be required, or the analysis is terminated at "STOP".

SECTION 10

PERFORMANCE DATA

The performance data of the dead reckoning and position fix components exhibit steady-state 3σ position error, altitude error, and heading error of the lunar roving vehicle navigation concept about a true point on the lunar surface as a function of:

1. Navigational sensor technology and lunar physical knowledge (Section 4, Vol. I)

2. Subconcept configuration (Section 5, Vol I)

3. Mission parameters (Section 6, Vol I).

Position fix navigational component technology is analyzed in conjunction with the subconcepts sc 1, sc 2, ... sc 8, as a function of the critical mission parameters that affect the magnitude of the position error ellipse, or the heading error.

The dead reckoning component technologies, formulated into functional component groups, sc 9, sc 10, ..., sc 20 are evaluated over the ensemble of lunar surface trajectories and the associated critical parameters of the lunar surface mission.

Input error vectors for the position fix and dead reckoning subconcepts are identified, and elements of the error vectors, exercised over the range of mission parameters, are transformed by the error models to derive:

1. Component performance data

2. Concept performance data.

The component data display the error response for a set of mission conditions, and a single, independent sensor error.

These baseline performance data provide the maximum flexibility for the analyst considering variations in the mission conditions, but lengthy computations are required for calculation of the total subconcept error.

The concept performance data present the total dead reckoning or position fix error response for fixed mission conditions and selected accuracy design points of the navigational components. Fixing the mission conditions decreases the flexibility for the data utilization, but the availability of the total subconcept error data offsets the disadvantage.

10.1 POSITION FIX ERROR ANALYSIS

The error analysis of the position fix components yields the performance data of navigational components and physical uncertainties for position fix subconcepts sc 1, sc... sc 8. Position fix and heading fix errors are given as a function of subconcept configuration, independent component errors, total concept errors, and a spectrum of lunar mission parameters.

The presentation of subconcept errors takes two forms:

1. Component Performance Data
2. Concept Performance Data.

The following constraints are imposed upon the component performance data:

1. Component performance data show the transformed output errors, 3σ position fix and heading fix errors, of a single element of the input error vector. The input error vector is:

$$3\sigma \text{ Input Error Vector} = \begin{bmatrix} 0 \\ 0 \\ \sigma_1 \\ 0 \\ 0 \end{bmatrix}$$

where σ_1 is the only non-zero error input and is the error term of the navigational element under study.

2. The independent error contributions are plotted and tabulated for selected error parameter values. If the position fix or heading fix errors are desired for values of element errors other than those designated, the following approximation is sufficient for identical mission conditions:

$$PE = \frac{\sigma \text{ Desired}}{\sigma \text{ Given}} \; PE_{\text{Given}} \qquad (10\text{-}1)$$

or

$$\sigma_A = \frac{\sigma \text{ Desired}}{\sigma \text{ Given}} \; \sigma_{A \text{ Given}} \qquad (10\text{-}2)$$

where "given" implies the plotted or tabulated data.

3. The total position fix and heading fix errors for a given set of input data can be approximated by the root-sum-square of the independent errors.

$$PE = \left[(PE_1)^2 + (PE_2)^2 + \ldots (PE_n)^2 \right]^{1/2} \qquad (10\text{-}3)$$

where $PE_1 \ldots PE_n$ are the 3σ error components of sensor errors $\sigma_1 \ldots \sigma_n$.

4. Orthogonal error pairs are equated: $\sigma_r = \sigma_p$, $\sigma_R = \sigma_D$ etc.

The constraints and guidelines of the concept performance data are:

1. The concept performance data show the error transform of the input error vector where:

$$3\sigma \text{ Input Error Vector} = \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \vdots \\ \sigma_n \end{bmatrix}$$

and $\sigma_1 \ldots \sigma_n$ are non-zero and selected with respect to the state-of-the-art parameter range.

2. Generally, four mission conditions are specified for the presentation of the concept data.

Table 5-1, Vol I shows the configuration, instrumentation, and error vectors of subconcepts sc 1 . . . sc 8.

Table 5-4, Vol I shows the magnitudes and error correlation of the navigational components to the state of the art.

Mission parameters are introduced in Section 6, Vol I.

10.1.1 Celestial Tracking Subconcept sc 1

The error sources, sensors, and error magnitudes of the celestial tracking elements are shown in Table 10-1.

10.1.1.1 Component Performance Data

The independent position error and independent heading fix errors are shown in Figures 10-1 through 10-5. The position error and heading error is shown for each independent error source. The 3σ errors are plotted as a function of the critical variable, azimuthal separation between sightings $|\alpha_1^* - \alpha_2^*|$. The heading alignment error is dependent principally upon the true elevation angle ϵ^* to the observable. The conditions for minimizing error propagation are seen to be:

1. 90° azimuthal separation of observables

2. Low true elevation angle ϵ^* of observable.

The latter condition is specified only for the heading fix since the position fix error is independent of the observable true elevation angle ϵ^*.

Total position fix error and heading fix errors can be calculated by taking the root-sum-square (RSS) of the component errors. Also, the linearity condition can be used to approximate position fix and heading fix errors for non-tabulated errors.

10.1.1.2 Concept Performance Data

The performance data of the celestial tracking subconcept sc 1 are tabulated in Tables 10-2 to 10-5. Shown are the 3σ position fix errors of the accuracy design point celestial tracking subconcepts and the component of position fix error attributable to a given sensor or navigational aid. The entries of the tables are the 3σ position fix error PE_{PF} in km. Table 10-6 shows the celestial tracking heading fix error.

Several operating points which define the parameterized lunar surface navigation mission are given by azimuthal separation between celestial observations. The four cases of the azimuthal separation are:

Case	$\lvert \alpha_1^* - \alpha_2^* \rvert$
1	90^o
2	120^o or 60^o
3	135^o or 45^o
4	150^o or 30^o

The minimum error propagation conditions are given in Case 1 and the maximal conditions by Case 4.

The total position fix error for the designated accuracy design point is given by the row PE_{PF}. For example, the total position fix error of the maximum accuracy design point (MAX) is 7.9 km. The table entries below the single line show total position fix error with the component error held at a specific magnitude. For example, the total position fix error for the nominal design point concept (NOM) with the vertical anomaly σ_Y equal to the state-of-the-art magnitude, and the ephemeris uncertainty σ_R equal to the NOM value is 0.93 km 3σ. Treat the remaining table entries in a similar fashion.

An analysis of the position fix error tables leads to the following conclusions:

1. For optimal mission conditions, state-of-the-art errors, and a negligible vertical anomaly, the position fix error is minimum at 0.075 km 3σ. As the design point celestial tracking subconcept is relaxed from the state-of-the-art value to the intermediate field operational level NOM, the position fix error increases to 0.75 km.

The upper bound of the position fix sensors is 6.2 km 3σ. However the practical capability of the celestial tracking technique yields a minimum position error range of 0.075 km 3σ to 0.75 km 3σ.

2. The minimum error range, limited by the NOM and state-of-the-art design points, depends on the lunar vertical anomaly, the ephemeris uncertainty, and the sighting geometry.

3. Including the vertical anomaly error term increases the minimum capability. The increased minimum range is 0.17 km 3σ to 1.7 km 3σ.

4. Fixing the ephemeris uncertainty at the state-of-the-art value changes the minimum range. The minimum capability is then 0.075 km to 0.61 km, without the vertical anomaly, and 0.17 km to 1.6 km with the anomaly. However, if the NOM value of the lunar ephemeris is typical, the minimum range is 0.44 km to 0.75 km, without the vertical anomaly term.

5. As the geometry of the sightings is varied from optimal, the upper bound of the practical minimum position error range is increased to the values, 0.075 km 3σ to 1.4 km 3σ.

6. Considering the maximum geometrical condition, and a negligible vertical anomaly, the practical position fix error range is 0.14 km to 1.4 km 3σ.

7. Assuming a NOM vertical anomaly increases the upper bound 3σ position fix error to 4.1 km.

8. The celestial tracker and vertical sensor errors are the major contributors of position fix error. Ephemeris errors can be of equal importance if the design point constraints are maintained.

9. The vertical anomaly term will dictate the design point of the position fix concept, if the anomaly term is equal to or greater than the NOM value of $\sigma \gamma = 0.05^{\circ}$, since the position error component due to this source of error ranges from 1.5 km 3σ, for optimal sighting, to 3.9 km 3σ for the fourth case. Thus the accuracy design point would range from 0.15 km to 0.39 km.

10. Initial heading alignment error σ_{AO}, shown in Table 10-6 for the above position fix conditions, is less than or equal to 0.2° for the entire set of parametric conditions.

10.1.2 Ranging Navigational Satellite Subconcept sc 2

The lunar surface navigation technique of position fixing using a lunar orbiting navigational satellite in conjunction with ranging equipment is analyzed. The error analysis of the ranging navigation satellite technique is performed with the objective of generating performance data of the initial position fix 3σ error ellipsoid as a function of vehicle/satellite geometry, instrumentation errors, and technology state of the art.

The 3σ error table, Table 10-7, of the ranging navigational satellite position fix technique contains the sources of concept error and the 3σ range of values from maximum, MAX, to projected state-of-the-art. The input error components are produced by satellite ephemeris and ranging measurement errors. The instrumentation concepts practical for the ranging technique are the laser, optical, and RF units, sc 9, sc 10 and sc 15, respectively.

10.1.2.1 Component Performance Data

Figures 10-6 and 10-7 show the position fix error for the input 3σ error sources, ephemeris error σ_{ρ}, and ranging error σ_{Rnc}. Owing to statistical independence of the error inputs, the independent position error component from each source is shown. To obtain the total vehicle position errors, the independent error contributions can be combined by the RSS procedure.

The position error is plotted for parametric variations of the input error source. If position error components are desired for other than indicated error parameter values, the linear relationship should be applied.

The position error components, plotted as a function of satellite ascending node, and indirectly true elevation angle ϵ^* (see Section 6, Vol. I) increase as the satellite altitude increases, and approach infinity as the satellite nears the observer's zenith. The position error is given for the sightings specified by the vertical hash marks. Encircled sighting points increase the vehicle position error by 120%. See the dashed position error curves of Figures 10-6 and 10-7.

10.1.2.2 Concept Performance Data

The position fix error components of the ranging navigational satellite subconcept sc 2 are tabulated in Tables 10-8 to 10-11. The selected mission parameters are satellite orbital radius R_c and nominal satellite true elevation angle ϵ^* relative to the lunar roving vehicle. The two orbital radii are 2038 km and 2738 km, or 300-km and 1000-km satellite altitude. The true elevation angles are nominally 60^o and 45^o.

The position error increases as satellite altitude increases, but decreases as the angular separation between sightings approaches 45^o: three sightings are required. These conditions hold for all error components, and the total effect is to decrease PE_{PF} by increasing satellite altitude, and maintaining ϵ^* fixed.

Shown in the tables are the position fix errors attributable to the ranging errors and the satellite ephemeris errors. The component errors are classified by a parameter range of state-of-the-art sophistication MAX, NOM, etc. The entries in the table are the vehicle position fix error PE_{PF} in km. An analysis of the position fix error tables leads to the following conclusions:

1. The minimum position fix error within the state-of-the-art error range is 2.2 km 3σ. This position fix error occurs in Case 4, and the dominant error source is satellite ephemeris error. The ranging measurement error can equal the maximum value $\sigma_{R_{nc}} = 0.100$ km, and the final position fix error is constant at 2.2 km.

2. The minimum intermediate or nominal (NOM) position fix error is 4.5 km, and constant for all values of ranging error.

3. Reducing satellite ephemeris data to the projected state of the art attains the position fix error of 0. 45 km, 3σ.

4. As the sighting and orbital geometry changes, the minimum position fix error increases from 2. 2 km to 5. 3 km. The minimum intermediate or NOM values will range from 4. 5 km to 10. 5 km, 3σ.

5. The major, completely dominant error term is the satellite ephemeris error which defines the position fix error range within practical state of the art as 2. 2 km to 4. 5 km. For the ranging position fix subconcept to become a feasible competitive position fixing technique, the critical uncertainty, the satellite ephemeris error, must be reduced to the projected state-of-the-art magnitude.

10. 1. 3 Angle Tracking Navigational Satellite Subconcept sc 3

The lunar surface navigation position fixing technique of angle tracking a navigational satellite is analyzed. Performance data show the initial 3σ position fix error ellipsoid as a function of instrumentation errors, physical uncertainties, and vehicle/satellite relative sighting geometry.

Since initial bearing of the vehicle can be computed if the vehicle position and a satellite tracking angle are known, initial heading alignment error is also given.

The input 3σ error vector to the angle tracking navigational satellite technique contains ephemeris, instrumentation, and vertical vector uncertainties.

The error components and 3σ magnitudes, classified by accuracy type, are defined in Table 10-12.

10. 1. 3. 1 Component Performance Data

Application of the above input error vector results in the 3σ position error $(PE)_T$ performance data shown in Figures 10-8 to 10-10. Position fix error and heading fix error are plotted as a function of orbital/ vehicle geometry. The fix errors are due to the independent contributions of the sensor errors.

If the position fix error or heading fix error is desired for a sensor error parameter other than the indicated value, the linear relationship should be applied.

If the position or heading fix error is desired for combinations of the input 3σ error vector, than the independent contributions of the position error can be combined in an RSS manner.

The error coefficients of the angle tracking position fix error model are more sensitive to azimuthal separation of the sighting points than the elevation angle of the sightings. Initial heading alignment error propagation is more sensitive to the elevation angle of the sighting, but since the heading alignment fix error is a function of position fix error and since position fix error approaches large values for 180° azimuthal separation, the heading error is substantially influenced by the azimuthal separation angle of the sightings. Of course, if position is fixed through independent means (celestial tracking, DSIF, etc.) then only one sighting is required to fix heading, and the error is independent of the second measurement.

The conditions for minimizing error propagation are:

$$\left|\alpha_1^* - \alpha_2^*\right| \rightarrow 90^\circ$$

$$\epsilon_1^* = \epsilon_2^* \leq 60^\circ$$

10.1.3.2 Concept Performance Data

The position fix error components of the angle tracking navigational satellite are shown in Tables 10-13 to 10-16. Position fix errors of sc 3 are tabulated as a function of parametric mission conditions, and subconcept error components, which are correlated to the state-of-the-art parameter range. The 3σ position fix error PE_{PF} is also given for the total concept with component errors set at specified values.

The pertinent parameters describing the position fix mission are the satellite altitude R_c, and the azimuthal angular separation between sightings $\left|\alpha_1^* - \alpha_2^*\right|$. Since all position error components decrease with increasing satellite altitude, the total position error is minimized for greater satellite altitude. However the angular separation between the sightings is required to be fixed. Fixing the altitude and varying the angular separation between the two necessary points of sighting defines the minimum error transmission condition to be approximately 90^{o}. Maximum uncertainty occurs at 180^{o}, obviously, but the propagation effect is still minimal to nearly 30^{o}.

Analysis of the position fix error tables leads to the following conclusions:

1. The minimum 3σ position fix error that is attainable over the spectrum of possible missions and with the state-of-the-art parameter range, is 0. 70 km.

2. The minimum position fix error range which is achieveable with the practical parameter ranges of state of the and NOM is 0. 70 km to 1. 6 km, 3σ.

3. As the mission geometry changes, the minimum position error attainable with the practical equipments and data varies from 0. 70 km to 11 km, 3σ.

4. The major error component is the satellite ephemeris error and accounts for the high minimum values. Reduction of ephemeris error to the projected state of the art fixes the minimum error of 0. 16 km.

5. The lunar vertical anomaly is an insignificant contributor with the ephemeris error maintained at the state-of-the-art value since the minimum error range is 0. 72 km to 12 km, 3σ. However, if the satellite ephemeris data attain the projected state of the art, the vertical anomaly term is a major error and the minimal range is from 0. 24 km to 5. 4 km, 3σ.

6. The accuracy attainable in the heading alignment mode is restricted to 0.1^{o} by the limit of the ephemeris uncertainty (Table 10-17). Again the contribution of output error is mainly because of satellite ephemeris uncertainty. The vertical anomaly term has a second-order effect.

10.1.4 Range Rate Navigational Satellite Subconcept sc 4

The lunar surface navigation position fixing technique of determining vehicle position using the doppler, range-rate navigational satellite technique is analyzed. The range-rate navigational satellite error model is evaluated to determine the magnitude of the vehicle position error ellipsoid as a function of the satellite orbital parameters and instrumentation state of the art.

The error inputs of the doppler, range-rate navigational satellite error model are tabulated in Table 10-18. The error sources arise because of ephemeris errors σ_{ρ}, ephemeris rate errors $\sigma_{\dot{\rho}}$, and instrumentation range rate errors $\sigma_{\dot{r}}$. The 3σ values of the error sources are tabulated with respect to accuracy type classification, and range from a maximum value (MAX) to projected state of the art.

10.1.4.1 Component Performance Data

The error input vector was applied to the conditions of the orbit and vehicle geometry discussed in Section 6, Vol. I. The total vehicle position error $(PE)_T$ as a function of satellite ascending node Ω (and indirectly ϵ^*) is shown in Figures 10-11 to 10-13. The position error given is the independent position error component from each specified sensor parameter with the remaining error inputs identically zero.

The total position error is minimized for low altitude orbits and overhead passes (i.e., $\epsilon^* \rightarrow 90^o$).

10.1.4.2 Concept Performance Data

The total concept capability of the range-rate navigation satellite position fix subconcept sc 4, is shown in Tables 10-19 to 10-22. Position fix error PE_{PF} is displayed as a function of navigational aid and sensor error magnitude and state of the art. In addition, the total position error for selected accuracy design points is tabulated.

Four typical mission conditions were selected to cover the spectrum of position fix geometrical environments. The mission parameters are the satellite radius R_c and true elevation angle ϵ^* at mid-satellite passage. The final position is relatively invariant of ϵ^* since the major error source is the satellite ephemeris error which transforms into constant vehicle position errors as a function of ϵ^*. However, the final position fix error is also relatively independent of satellite altitude. Although the position error owing to ephemeris errors decreases with respect to increasing satellite altitude, the range-rate position fix errors increase. Thus, the net effect is to maintain a relatively constant position fix error. Observation of the data tabulated in the position fix error tables leads to the following conclusions:

1. The minimum position fix error within the state-of-the-art parameter range is 1. 2 km, 3σ.

2. Relaxing the input errors to the nominal parameter range increases the minimum range to 8. 2 km, 3σ.

3. If the range-rate error is restricted to the state-of-the-art magnitude, then the practical capability, and minimum error magnitudes range from 1. 2 km, 3σ to 1. 8 km, 3σ.

4. As stated, the geometrical variations impose relatively insignificant variations upon the vehicle position fix error.

5. The major error components depend upon the design point concept. The range-rate error $\sigma_{\dot{r}}$, dominates at the MAX and NOM magnitudes. The state-of-the-art and projected-state-of-the-art design points are influenced considerably by the ephemeris errors σ_ρ and at these exotic magnitudes, the ephemeris error virtually limits the capability.

6. Limiting satellite ephemeris errors to the nominal magnitude σ_ρ requires that range-rate instrumentation achieving the state-of-the-art magnitude of $\sigma_{\dot{r}} = 2$ km/hr be available to maintain position fix error to 5. 3 km or less.

10.1.5 Earth Based Tracking: Ranging sc 5, Range Rate sc 6

The tracking capability of the Deep Space Instrumentation Facility is shown in Table 10-23 (Ref. 1, Vol. I) as a function of the ranging sc 5 and doppler sc 6 mode of operation. A vehicle mounted S-band transponder is tracked. Shown is the tracking time in days required to reduce the position error ellipsoid to the specified magnitudes. Computation is also earth based.

The position fix concept accuracy is significantly dependent upon allowable tracking and data smoothing time, and time dissipated on lunar surface is an extreme penalty function.

If subconcepts sc 5 and sc 6 are to be used, then time sharing of mission functions (navigation, experimentation, etc.) is advisable. Also, since the subconcepts are earth dependent, earth based tracking is suitable only for near-side missions.

For the optimal conditions:

1. One full day (24 hours) of tracking and data smoothing is necessary to fix vehicle absolute position to within 3 km.

2. Approximately 2.5 days are needed to halve the position error to 1.5 km.

3. Nearly 3 days (72 hours) are required to achieve a position fix accurate to 0.75 km

4. At least 5 days of tracking are necessary to fix vehicle position within 0.3 km.

5. Table 10-24 summarizes the 3σ position fix error.

10.1.6 Triangulation Subconcept sc 7

The error inputs to the triangulation model are defined in Table 10-25. Also tabulated are the 3σ error ranges from projected state of the art to an arbitrary maximum value MAX.

The initial position of the origin and heading of the base line are fixed by alternate subconcepts such as celestial tracking, DSIF, navigational satellite, etc. (sc 1 ... sc 6). These subconcepts give rise to the errors σ_{xo}, σ_{yo} and σ_A. The instrumentation required for the triangulation technique are the laser, optical, or RF units, s_9, s_{10} and s_{15} respectively. The vertical reference can be a quality vertical gyro s_5, a pendulous vertical sensor s_{12}, or a precision static inclinometer s_{19}. See Appendix F, Vol. I for the error sensitivity coefficient analysis and Section 6, Vol. I for the definition of triangle geometry.

10.1.6.1 Component Performance Data

Target position error is shown in Figures 10-14 to 10-16. Triangle geometry is varied by changing the triangle vertex angles. The target position error is given as a function of the sensor 3σ errors σ_a, σ_A, σ_p, and σ_{RB}. The independent position error component from each sensor contribution is plotted as a function of the origin to target vertex angle. The remaining sensor error parameters are identically zero.

The position fix error components are not shown since the transformation is 1:1.

Sensitivity of the total position error to a change in the base line length R_B is given by

$$(PE)_T \cong PE_o \frac{R_B}{R_{Bo}} \qquad (10\text{-}4)$$

where

$$PE_o = (PE)_T \Big|_{R_B = R_{Bo}}$$

Therefore target position error data, computed for the prototype triangle, can be converted to the position error for a similar triangle with modified base line distance.

10.1.6.2 Concept Performance Data

Typical target position error components from each sensor are tabulated in Table 10-26. The accuracy type classification (i.e., MAX, NOM...) correspond to the sensor error parameters of Table 10-24. The triangle selected for a nominal comparison is a 60°, 70° triangle which maximizes the ratio of triangle area to maximum line of sight.

The principal sources of target position error are the angular resolution errors σ_a of the sighting instrument. Since the maximum line of sight is approximately 1.5 km (R_B = 1 km), the accuracy requirement which can be met by the maximum to projected state-of the-art technology is 1:25 to 1:6000. Reduction of the attainable state-of-the-art linear rate to 1:2500 is possible if a projected state-of-the-art sighting instrument were available.

An important conclusion to be noted is that generally the translation of the position fix absolute coordinates and the initial position error are independent of the triangulation subconcept errors. Only in the instance when the 3σ position error is less than 0.5 km will the triangulation sensors affect the target position error.

However, the error contributions are noticeable when triangulation is treated as an extension of a relative set of control points or an extension of an established homing range.

Figure 10-17 shows a typical set of control points establishing a selenodetic survey net. The planar projection of east and north coordinates is shown for eight target points $T_1 \ldots T_8$ extending over a slant range of about 10 km.

The target altitude error σ_{hT} and position error $(PE)_T$ are plotted as a function of the target sequence.

The following 3σ sensor parameters form the input error vector. The instrumentation accuracy type is a NOM system with the exception that the sighting angle component accuracy approaches a state-of-the-art sensor.

$\sigma_A = 0.1^\circ$

$\sigma_{RB} = 0.0005$ km

$\sigma_\alpha = \sigma_\epsilon = 0.06^\circ$

$\sigma_p = 0.1^\circ$

The initial position fix error is zero, i.e., $\sigma_{xo} = \sigma_{yo} = 0$.

The final position error as a function of slant range is approximately 1.5%, or about 1:70 of the slant range.

Thus the propagation of error through the net increases the linear requirement from less than 1:60 (Table 10-26) to 1:70.

10.1.7 Trilateration Subconcept sc 8

Table 10-27 defines the trilateration error inputs, the 3σ error magnitudes, and groups specific accuracy type sensors according to the state-of-the-art level, MAX, NOM, state-of-the-art, projected-state-of-the-art.

Instrumentation sufficient for initial position fixing and heading fixing are subconcepts sc 1 ... sc 6, the celestial tracking, navigation satellites, DSIF subconcepts.

Instrumentation of the trilateration technique for defining the three coordinates of target position requires a vertical sensor such as a quality vertical gyro s_5, a pendulous vertical s_{12}, or static pendulous inclinometer s_{19}. Also necessary are the distance sensing elements, the laser, optical, and RF units, s_9, s_{10} and s_{15} respectively, which also sense the target inclination angle ϵ^*. The 3σ error sources imposed upon the sensed variables are tabulated in Table 10-27. See Appendix F, Vol. I for the trilateration sensitivity analysis, and Section 6, Vol. I for the definitions of triangle geometry.

10.1.7.1 Component Performance Data

Figures 10-18 to 10-20 show trilateration position error for selected triangle cases. The independent position error contributions from each sensor are plotted. Several broad conclusions can be made if a single error source is analyzed with respect to the total target position error:

1. The total position error $(PE)_T$ is independent of the base line heading A.

2. Initial position error is transmitted on a 1:1 basis.

3. The sensitivity of total position error to angular errors σ_A, σ_{ϵ}^* is given by:

$$(PE)_T \cong \frac{R_B}{R_{B_o}} PE_o \qquad (10\text{-}5)$$

where

$$PE_o = (PE)_T \Big|_{R_B = R_{B_o}}$$

This condition implies that the magnitudes of angular resolution error coefficients, computed for the prototype triangle, are easily transformed for a triangle of arbitrary base line distance. Thus, the sensitivity of total position to parametric changes in the base line distance R_B is given by Equation 10-5 in conjunction with the data of Figures 10-18 to 10-20.

However, the preceding statement holds only for angular resolution errors. The total position error is insensitive to base line parametric variations for a distance error source, i.e., σ_{RB}, σ_{ROT}, σ_{RBO}. Generally the independence arises due to similar triangle factors such as

$$\text{constant} \cong \frac{R_{BT}}{R_B} \text{ or } \frac{R_{OT}}{R_B} \text{ etc., for fixed vertex angles}$$

a_1^*, a_2^*.

10.1.7.2 Concept Performance Data

Table 10-28 shows the summarized 3σ total position error $(PE)_T$ components for each accuracy type sensor. The total achievable accuracy for the selected accuracy type concepts ranges from 1:70 to 1:70,000.

The major error contributor is the base line alignment error, but owing to the extremely low linear requirements which are achievable with the NOM and state-of-the-art accuracy type concepts, the base line error source is not a major problem area. The results indicate trilateration is an order of magnitude more accurate than the current state-of-the-art triangulation techniques.

Figure 10-17 shows a typical survey net with which the error propagation effects of the triangulation and trilateration NOM accuracy type concepts have been evaluated. Figure 10-21 shows altitude error σ_{hT} and total position error $(PE)_T$ as a function of control point sequence.

The linear requirement for the entire net is 1:50, an increase from the 1:700 attainable over a single triangle. Thus, total capabilities and sensor requirements of trilateration techniques require consideration of the typical expected mission net.

If the elevation angle resolution error σ_ϵ is reduced to the SOA level ($\sigma_\epsilon = 0.06^\circ$), the linear requirement which can be achieved is 1:170, a substantial increase in concept capabilities.

10.2 DEAD RECKONING COMPONENT ERROR ANALYSIS

The baseline parametric performance data of the dead reckoning sensors, components, and navigational aids are the 3σ steady-state error response of the vehicle position error ellipsoid to an independent error source of the input error vector. The independent steady-state 3σ position error, 3σ altitude error, and 3σ heading errors of the dead reckoning components are evaluated as a function of subconcept configuration, sensor technology, and lunar physical knowledge, over the ensemble of lunar surface trajectories and the range of lunar mission parameters. The mission parameters include selenographic region, vehicle velocity, mission range, and mission duration.

The output position and heading errors, a transform of the input error vectors, are given for dead reckoning subconcepts sc 9 to sc 20 and the sensor and physical uncertainty error inputs.

Table 5-2, Vol. I defines the configuration, instrumentation, and 3σ error input vector for subconcepts sc 9 through sc 20, and Table 5-3, Vol. I correlates the elements of the error vector to technology state of the art by showing the error magnitudes.

The constraints and operating point conditions of the independent error data are summarized:

1. The dead reckoning 3σ error is the response to an independent error source. Although a total 3σ input error vector contains several components, e.g.,

$$3\sigma \text{ Input Error Vector} = \begin{bmatrix} \sigma_{v} \\ \sigma_{GA} \\ \sigma_{gD} \\ \sigma_{r} \\ \sigma_{p} \\ \sigma_{rD} \\ \sigma_{pD} \\ \sigma_{\gamma} \\ PE_{PF} \\ \sigma_{a0} \end{bmatrix}$$

the data are presented as a function of an independent error. The error vector thus has the form:

$$3\sigma \text{ Input Error Vector} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \sigma_p \\ \sigma_r \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

where only the sensor under study has the non-zero error term

2. The dead reckoning error response is relative to an arbitrary origin and heading. The initial position fix error PE_{PF} and heading fix error σ_{a0} are identically zero.

3. The magnitude of orthogonal and cross axis error inputs are equated:

$$\sigma_r = \sigma_p, \ \sigma_{RE} = \sigma_{DE}, \ \sigma_{rD} = \sigma_{pD},$$

and the error response shown for an orthogonal error pair are the results of the two-axis input. The effect of the lunar vertical anomaly upon the absolute dead reckoning position error can be computed by applying the position error curves of the vertical sensor; i.e.,

$$\sigma_r = \sigma_p = \sigma_\gamma$$

4. The odometer and doppler radar errors are treated as described in Section 3.

5. The independent output error response is given for an ensemble of lunar surface trajectories. Generally -

$$\begin{aligned} A \max &= 90^\circ \\ h \max &= 0.45 \text{ km} \\ r \max &= 13^\circ \\ D_j &= 2 \text{ km} \\ h_o &= h_D = 0.0 \end{aligned}$$

6. Table 5-2, Vol. I references all subconcept technical and error vector data.

7. Table 5-3, Vol. I identifies error magnitudes and correlates the values to state of the art.

8. The data are organized in the following manner:

   a. Subconcept: sc 9, sc 10, ... sc 20

   b. Error Component: Position Error, Altitude Error, Heading Error

   c. Navigational Component: Odometer, ...

   d. Selenographic Region: $\epsilon^* = 10^{\circ}$, ...

   e. Vehicle Velocity: V = 4 km/hr, ...

   f. Distance Traveled: 1 km ... 116 km

To generate total dead reckoning subconcept performance data, the total position error ellipsoid can be approximated by taking the root-sum-square (RSS) of the independent error contributors for identical mission conditions.

$$PE_{DR} = \left[\left(PE_1\right)^2 + \left(PE_2\right)^2 + \left(PE_3\right)^2 + \ldots \left(PE_n\right)^2 \right]^{1/2} \qquad (10\text{-}6)$$

where:

$PE_1 \ldots PE_n$ imply the 3σ position error components from errors $\sigma_1, \sigma_2 \ldots \sigma_n$.

Also, since linearity holds, an approximation to any output error for a non-plotted input error is given by using the linear expression:

$$PE = \frac{\sigma_{Desired}}{\sigma_{Given}} PE_{Given} \qquad (10\text{-}7)$$

where "given" implies a plotted parametric value.

The treatment is the same for the heading and altitude independent error data.

Variations of independent position error data with changing mission parameters are discussed in Section 11, Vol. II.

Total vehicle position error is computed by taking the RSS of the position fix and dead reckoning errors.

10.2.1 Odometer - Celestial Heading Subconcepts sc 9, sc 10

Table 5-2, Vol. I defines the configuration, instrumentation, and input error vector of the odometer - celestial heading subconcepts sc 9 and sc 10. Tables 10-29 and 10-30 summarize the navigational elements and 3σ errors of sc 9 and sc 10 respectively.

The performance data of the dead reckoning subconcepts sc 9 and sc 10 are the 3σ vehicle position error, 3σ vehicle altitude error, and the 3σ vehicle heading error. The three components of vehicle error are given in the following figures and tables as a function of:

1. Independent navigational element errors defined by the input error vectors
2. Vehicle range of traverse
3. Vehicle velocity, V
4. Relative vehicle/celestial observable position denoted by the true celestial elevation angle ϵ^*.

The curves in Figures 10-22 to 10-63 apply to both subconcept sc 9 and sc 10. The proper choice of the sensor error and subconcept are dictated by the user of the curves (e.g., all curves apply to sc 10, but error curves as a function of σ_{pD} do not pertain to sc 9.)

10.2.1.1 Dead Reckoning Component 3σ Position Error sc 9, sc 10

The parametric curves, Figures 10-22 to 10-63, show the 3σ vehicle dead reckoning position error as a function of distance travelled on the lunar surface. This dead reckoning performance data is the planar 3σ position error due to independent error inputs. The error response is given for the single error input shown.

10.2.1.2 Dead Reckoning Component 3σ Altitude Error sc 9, sc 10

The independent altitude error response caused by each navigational element error input is shown in Figures 10-64 to 10-68 and Table10-31. Unlike the planar position error response which is primarily distance travelled dependent, the altitude error derived from the distance sensing element, the odometer, is principally path dependent. Thus Table 10-31 shows the maximum 3σ altitude error experienced between the traverse origin and traverse destination. The maximum value occurs at any point during the traverse and is not constrained to occurring at the destination.

The altitude error as a function of celestial tracker, ephemeris, and timer errors is zero.

The steady-state altitude error responses of the vertical sensors and vertical gyros are shown in Figures 10-64 to 10-68.

10.2.1.3 Dead Reckoning Component 3σ Heading Error sc 9, sc 10

The steady-state 3σ heading error of the lunar vehicle navigation concepts sc 9, sc 10 is shown in Figures 10-69 to 10-76. The 3σ heading error σ_A is the independent bearing error from each of the sensor errors. If heading performance data are desired for other than the given input errors, linearity will give a sufficient approximation.

As in the case of the vehicle altitude error, in some instances, the vehicle bearing error is path dependent. The maximum heading error which occurs during a traverse is given in Table 10-32 for the celestial tracker, and vertical sensor error inputs.

10.2.2 Odometer - Inertial Heading Subconcepts sc 11, sc 12

Table 5-2, Vol. I defines the configuration, instrumentation, and input 3σ error vector of the odometer - inertial heading subconcepts sc 11 and sc 12. The elements of the 3σ error vectors are delineated in Tables 10-33 and 10-34 for the subconcepts sc 11 and sc 12 respectively. The correlation of the error parameters to state-of-the-art technology is given in Table 5-3 of Section 5. 3.

The steady-state 3σ dead reckoning position, altitude, and heading errors of subconcepts sc 11 and sc 12 are given as a function of:

1. Independent navigational component errors
2. Distance travelled
3. Vehicle velocity, V.

The principal sensitivity of the vehicle 3σ errors is given by the mission duration. Selenographic dependencies exist, because of traverses in a lunar polar region, but this is simply a geometric coordinate transformation and is not considered here.

The independent error data of sc 11 and sc 12 are identical; therefore, only one set of curves is required. However, the error curves as a function of vertical gyro drift do not apply to sc 11.

If the vertical anomaly effects are desired, the user should refer to the vertical sensor curves. In instances where a two-axis error is analyzed, the identities in Tables 10-33 and 10-34 should be observed.

10.2.2.1 Dead Reckoning Component 3σ Position Error sc 11, sc 12

The lunar vehicle dead reckoning planar position error is given in the following curves as a function of vehicle distance travelled, vehicle velocity, and sensor error. (Figures 10-77 to 10-90.)

10.2.2.2 Dead Reckoning Component 3σ Altitude Error sc 11, sc 12

The vertical component of the steady-state 3σ error ellipsoid is shown in Figures 10-91 to 10-95 as a function of traverse range. The altitude position error shown is the error response due to independent error inputs of the subconcept navigational elements.

Since the vertical position error is a path function when the source of input error is the odometer, the odometric altitude error is shown in Table 10-35. The magnitudes of the altitude error shown can occur at any point along the vehicle trajectory and are the maximum value reached at an arbitrary point of the traverse.

The altitude position errors are independent of the heading channel as is noted by:

$$PE_z = 0 \text{ for all } \sigma_{gA}, \sigma_{gD}$$

The vertical position error component, for vertical sensor and vertical gyro errors, is shown in Figures 10-91 to 10-95.

10.2.2.3 Dead Reckoning Component 3σ Heading Error sc 11, sc 12

The lunar roving vehicle dead reckoning heading error is shown in Table 10-36 and Figure 10-96 for the subconcepts sc 11, sc 12. The tabulations show the path dependent maximum heading error components which occur at any point of the traverse.

In the case of the heading error as a function of directional gyro drift error, linearity can be applied to calculate an excellent approximation of heading error for any desired drift error.

Also, gyro alignment error σ_{gA} completely dominates other correlated sources of vehicle heading error such that

$$\sigma_A = \sigma_{gA} \text{ for all } \sigma_{gA}.$$

Table 10-36 lists the maximum heading errors as a function of instrument error.

$$\sigma_A \cong 0 \text{ for all } \sigma_o$$

10.2.3 Velocity - Celestial Heading Subconcepts sc 13, sc 14

The configuration, instrumentation, and 3σ input error vectors of the velocity-celestial heading subconcepts sc 13 and sc 14 are defined in Table 5-2, Vol. I. Table 10-37 summarizes the error vector elements of sc 13, and Table 10-38 tabulates the input errors of sc 14.

The steady-state 3σ dead reckoning position errors, altitude errors, and heading errors are given as a function of several sensitivity parameters:

1. Component quality or independent error source

2. Vehicle distance travelled

3. Relative vehicle/celestial region, ϵ^*

4. Vehicle velocity, V.

Table 5-3, Vol. I correlates error magnitude to technology state of the art.

10.2.3.1 Dead Reckoning Component Position Error sc 13, sc 14

The total planar position error of the doppler celestial subconcepts is displayed in the curves of Figure 10-97 to 10-123 as a function of lunar vehicle distance travelled, and independent sensor error input.

10.2.3.2 Dead Reckoning Component 3σ Altitude Error sc 13, sc 14

The 3σ altitude component of the lunar vehicle position is shown in Figures 10-124 to 10-128 and also in Table 10-39. The altitude error component, as a function of velocity error, is path dependent, and Table 10-39 shows the maximum 3σ altitude error PE_z that occurs during traverse.

In addition to the tabulated and plotted data, the following condition holds:

$$PE_z = 0 \text{ for all } \sigma_a, \sigma_{RE}, \sigma_t.$$

10.2.3.3 Dead Reckoning 3σ Heading Error sc 13, sc 14

The baseline performance data displaying independent vehicle heading error as a function of the 3σ input error vectors are shown in Figures 10-129 to 10-134. Table 10-40 shows the path dependent heading error for the celestial tracker and vertical sensor. The remaining heading error data are plotted as a function of vehicle distance travelled.

10.2.4 Velocity-Inertial Heading Subconcepts sc 15, sc 16

The configuration, instrumentation, and 3σ input error vector of the velocity-inertial heading subconcepts sc 15 and sc 16 are shown in Table 5-2. Tables 10-41 and 10-42 summarize the input error vector data of subconcepts sc 15 and sc 16. Correlation of the error parameters and the error magnitudes to current and projected technology is given in Table 5-3 .

The dead reckoning subconcepts sc 15 and sc 16 steady-state 3σ error ellipsoid position error components and lunar vehicle heading error are given as a function of:

1. Independent error input

2. Vehicle distance travelled

3. Vehicle velocity, V.

10.2.4.1 Dead Reckoning Component 3σ Position Error sc 15, sc 16

The dead reckoning 3σ planar position errors, or the output transform of the input error vectors of sc 15 and sc 16 are shown in Figures 10-135 to 10-148. The planar error ellipsoid is plotted as a function of lunar vehicle distance travelled, and parametric values of vehicle velocity (mission duration) and sensor error input.

10.2.4.2 Dead Reckoning Component Altitude Error sc 15, sc 16

The 3σ altitude error component of the vehicle position error ellipsoid is given in Figures 10-149 to 10-153 as a function of the input error vector components for sc 15 and sc 16. Table 10-43 shows the path dependent maximum altitude error PE_z as a function of doppler radar error σ_v.

The following condition completes the definition of the altitude error spectrum:

$$PE_z = 0 \text{ for all } \sigma_{GA}, \sigma_{gD}.$$

10.2.4.3 Dead Reckoning Component 3σ Heading Error sc 15, sc 16

The 3σ heading error of the dead reckoning navigation subconcept sc 15 and sc 16 is given by Tables 10-44 and 10-45 and Figures 10-154 to 10-157. This baseline performance data apply to both the subconcepts sc 15 and sc 16. The vertical gyro drift does not apply to sc 15.

10.2.5 Acceleration–Celestial Heading Subconcepts sc 17, sc 18

Table 5-2, Vol. I defines the configuration, instrumentation and 3σ input error vector of the acceleration celestial heading subconcepts sc 17, sc 18. Tables 10-46 and 10-47 summarize the input error vector terms of sc 17 and sc 18. The magnitude of the error terms and the correlation to state-of-the-art technology are given by Table 5-3 .

The input error vectors of sc 17 and sc 18 have been transformed into output error responses. The steady-state 3σ vehicle position error, altitude error, and heading error are given as a function of the independent elements of the input error vector and the mission parameters:

1. Vehicle velocity, V

2. Distance travelled

3. Relative selenographic region, ϵ^*.

10.2.5.1 Dead Reckoning Component 3σ Postion Error sc 17, sc 18

Figures 10-158 to 10-179 detail the total 3σ vehicle positon error of the dead reckoning subconcepts sc 17 and sc 18. The published performance data provide the baseline accuracy attainment of sc 17 and sc 18 and total vehicle position error due to any combination of numerical input errors may be formed by applying the RSS procedure. If data are not available for a desired sensor error, the given data can be linearized.

10.2.5.2 Dead Reckoning Component 3σ Altitude Error sc 17, sc 18

Figures 10-180 to 10-184 depict the vehicle altitude error component of the vehicle error ellipsoid. Tables 10-48 and 10-49 show the maximum attained vehicle altitude error due to accelerometer errors and heading errors respectively.

In addition, $PE_z \leqq 0.003$ km for all σ_{RE}, σ_t.

10.2.5.3 Dead Reckoning Component 3σ Heading Error

The performance data of the dead reckoning heading subconcepts are shown in Figures 10-185 to 10-188 as a function of the vehicle range. Table 10-50 also lists the path dependent heading errors due to the celestial tracker and vertical sensor errors.

10.2.6 Inertial Subconcepts sc 19, sc 20

Table 5-2, Vol. I defines the inertial subconcepts sc 19, sc 20 configuration, instrumentation, and 3σ input error vector. Tables 10-51 and 10-52 summarize the 3σ error vector elements. Error magnitudes are given in Table 5-3 .

The performance data, the dead reckoning 3σ position error, altitude error, and heading error of the inertial subconcepts, sc 19, sc 20, are presented as a function of independent sensor errors, physical uncertainties, mission duration, and mission length.

The sensitivities of sensor performance which are considered in the ensuing data are mission duration, length, and input error magnitudes. The dependency of position error upon selenographic latitude is not considered since a fundamental selenocentric coordinate shift is all that is needed to eliminate polar singularities.

10.2.6.1 Dead Reckoning Component 3σ Position Error

The 3σ steady-state planar position error of subconcepts sc 19 and sc 20 are plotted in Figures 10-189 to 10-202. The output position error is the transformation of the independent elements of the dead reckoning input error vectors.

10.2.6.2 Dead Reckoning Component 3σ Altitude Error sc 19, sc 20

The input error vectors, applied to the dead reckoning error models, result in the altitude error responses in Figures 10-203 to 10-207.

In the instance when the principal error component was path dependent, the 3σ magnitude of the maximum value was tabulated in Table 10-53.

The heading error contributes errors in vehicle altitude due to the error model cross correlation terms.

10.2.6.3 Dead Reckoning Component 3σ Heading Error sc 19, sc 20

The 3σ heading error of sc 19 and sc 20 is given in the curves of Figures 10-208 to 10-212 as a function of sensor errors, and mission parameters. Also the path dependent error contributions are listed in Table 10-54. The vertical gyro drift terms do not apply to sc 19.

10.3 DEAD RECKONING CONCEPT ERROR ANALYSIS

The dead reckoning subconcept performance data of Section 10.2 show the lunar vehicle navigation errors as a function of a single, independent error source. The data were compiled for those error vectors which had a single component greater than zero, while all remaining vector components were set identically zero. The non-zero error input was, of course, due to the navigational element under study. This approach led to the series of independent error responses, which, with considerable effort, may be combined in an RSS manner to yield an approximation to a total dead reckoning concept steady-state 3σ error response.

The total dead reckoning concept performance data for typical vehicle-lunar-celestial geometry and accuracy design point navigation subconcepts are presented in this section. Total subconcept position errors are exhibited for the dead reckoning subconcepts sc 9, sc 10, . sc 20. The performance data show the concept position error response for the accuracy design points of Table 5-3 and the mission parameters introduced in Section 6, Vol. I.

In addition to geometric variations, the 3σ input error vectors are varied. Operating points are selected for each subconcept error vector, and a single vector component is varied through the selected range of values while the remaining vector components are constant. Thus a spectrum of performance data, about nominal operating points in mission geometry and component errors, is available for the user of the data book.

The lunar mission parameters are selected to provide representative operating points over which total concept performance is evaluated. The mission parameters which simulate the generalized lunar roving vehicle dead reckoning mission are summarized:

1. Relative Selenographic Region, ϵ^*
2. Total Traverse Range and Duration
3. Navigation Requirements
4. Error Budgets
5. Homing Range Constraints.

Concept performance data are given explicitly as a function of selenographic region, total traverse range, and duration. The navigation requirements, error budgeting, and homing range constraints are implicitly considered such that acceptable and realistic sensor performance levels are defined.

The operating point parameters are identified as:

1. Selenographic Region

   Vehicle Latitude x = 10° (nominal)

   Vehicle Longitude y (arbitrary but constrained by ϵ^*, x)

   Observable Altitude ϵ^* = 77° (nominal)

2. Total Range, given by data:

   % Extra Distance Travelled = 15%

   A_{max} = 90°

   h_{max} = 0.450 km

   r_{max} = 13°

   D_j = 2 km

3. Total Duration, given by data for V = 4, 8, 12, 16 km/hr.

The total concept performance data coordinate the total dead reckoning subconcept errors with the independent component errors discussed in Section 10.2. The navigation errors, of that section, can be combined to approximate total concept performance; however, the procedure defines an approximation and requires, at times, considerable effort. The total concept performance data, given in the following figures, reflect the result of ensemble averaging over sets of lunar surface trajectories, and consolidate and display the transformation results of the total input error vector.

The data are organized in the following manner:

1. Dead Reckoning Subconcept, sc i

2. Navigational Element, s i

3. Vehicle Velocity, V

4. Selenographic Region, ϵ^*

5. Accuracy Type System, I, II . . . .

6. Perturbation About Accuracy Type, 1, 2 . . . .

Each plot defines the total concept error response as a function of vehicle range and listed parameters. However the major parameter reflected in the error response is the sensor under study, the odometer, celestial tracker, vertical sensor, etc.

The indexing procedure, which identifies the navigation subconcept error magnitudes, uses the Roman numerals I, II, . . . , and Arabic numerals 1, 2 . . . to correlate errors to technology state of the art.

The Roman numerals identify the accuracy type subconcept. For a given subconcept and given Roman numeral, the 3σ input error vector is fixed at the selected set of values given in Table 5-3. The Arabic numeral identifies the 3σ error input value of the sensor, which is given in the title of the figure. The fixed value is given in Table 5-3.

The 3σ error parameters for the dead reckoning sensors are tabulated in Table 5-3. The error parameters for each sensor are tabulated for seven specific levels of accuracy. The range of the error parameters is from MAXIMUM (MAX) to projected-state-of-the-art (PSOA), with three intermediate values. The seven values I, II, III, ..., VII are the basic accuracy type systems. In the ensuing analysis, the input error vector of a sensor grouping sc i is selected at a specific accuracy level (i.e. II or III...) and the navigational component error is perturbed from MAX to PSOA.

Hence

Roman Numeral $\Rightarrow$ Subconcept Accuracy Type

Arabic Numeral $\Rightarrow$ Sensor Accuracy Type

If the Arabic numeral is replaced by a dash (-), the error response shown suffices for all remaining sensor error perturbations, since the sensor position error is of second order.

Other conditions which are implied by the total performance curves are:

1. Cross axis errors are equated

   $\sigma_r = \sigma_p$ etc.

2. Vertical Anomaly terms are zero

   $\sigma_\gamma = 0.0.$

3. Dead reckoning is relative to the origin

   $(PE)_{PF} = 0.0.$

4. When a sensor position error dominates by a 10:1 ratio, the response is not shown but can be found in the independent component data.

An example will describe the identification procedure. Consider the subconcept sc 12, the odometric-inertial functional component group. The input error vector is, from Table 5-2, Vol. I:

$$3\sigma \text{ Input Error Vector} = \begin{bmatrix} \sigma_{o} \\ \sigma_{GA} \\ \sigma_{gD} \\ \sigma_{p} \\ \sigma_{r} \\ \sigma_{pD} \\ \sigma_{rD} \\ \sigma_{\gamma} \\ (PE)_{PF} \end{bmatrix}$$

When the parametric sensor under study is the directional gyro, and the gyro drift σ_{gD} is being varied, the symbology III-2 defines the magnitude of the error vector components:

$$\begin{matrix} 3\sigma \text{ Input Error Vector} \\ \text{(III-2)} \end{matrix} = \begin{bmatrix} 1.0 \\ 0.1 \\ 0.25 \\ 0.1 \\ 0.1 \\ 0.05 \\ 0.05 \\ 0.0 \\ 0.0 \end{bmatrix}$$

where:

$$\sigma_{\gamma} = (PE)_{PF} = 0.$$

The vertical anomaly term and the position fix error term are initially zero. Thus the curve III-2, on the directional gyro drift plot, shows the position error response for the above input error vector. The remaining data are treated in the same manner.

10.3.1 Dead Reckoning Concept 3σ Position Error

The steady-state 3σ planar position error, as a function of the 3σ input error vectors, is presented for the set of:

1. Odometer Subconcepts

   sc 9, Figures 10-213 to 10-221

   sc 10, Figures 10-222 to 10-233

   sc 11, Figures 10-234 to 10-264

   sc 12, Figures 10-265 to 10-285

2. Velocity Subconcepts

   sc 13, Figures 10-286 to 10-295

   sc 14, Figures 10-296 to 10-307

   sc 15, Figures 10-308 to 10-315

   sc 16, Figures 10-316 to 10-325

3. Acceleration Subconcepts

   sc 19, Figures 10-326 to 10-334

   sc 20, Figures 10-335 to 10-343

10.3.2 Dead Reckoning Component 3σ Altitude Error

The steady-state 3σ altitude error component of the vehicle position error ellipsoid is shown in Figures 10-344 to 10-348 as a function of the parameters - subconcept configuration, vehicle velocity, navigation component, and accuracy type error vector.

10.3.3 Dead Reckoning Concept 3σ Heading Error

The lunar roving vehicle total dead reckoning 3σ heading error is shown in Figures 10-349 to 10-364 for the set of navigational components and navigational subconcepts.

TABLE 10-1

CELESTIAL TRACKING 3σ ERROR TABLE

Input Error							
Source	Element	3σ Error	Units	MAX	NOM	SOA	PSOA
Celestial Tracker	s3, s4, s16, s17, s18, s20, s21	σ_ϵ, σ_α	deg	0.1	0.01	0.001	0.0001
Vertical Sensor	s6, s12, s19	σ_p, σ_r	deg	0.1	0.01	0.001	0.0001
Ephemeris	s23	σ_R, σ_D	deg	0.03	0.01	0.001	0.0001
Timer	s22	σ_t	hr	0.03	0.003	0.0003	0.0
Vertical Anomaly	s24	σ_γ	deg	0.16	0.05	0.005	0.0

TABLE 10-2

CELESTIAL TRACKING, scl 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_e = \sigma_\alpha$	4.3	0.43	0.043	0.0043
$\sigma_r = \sigma_p$	4.3	0.43	0.043	0.0043
$\sigma_R = \sigma_D$	1.3	0.43	0.043	0.0043
σ_t	0.48	0.048	0.0048	0.00048
σ_γ	4.8	1.5	0.15	0.0
PE_{PF}	7.9	1.7	0.17	0.0075
σ_γ = PSOA	6.2	0.75	0.075	0.0075
σ_γ = NOM	6.4	1.7	1.5	1.5
σ_γ = PSOA, σ_R=PSOA	6.1	0.61	0.061	0.0075
σ_γ=PSOA, σ_R=MAX	6.2	1.4	1.3	1.3
σ_γ=SOA, σ_R=NOM	6.1	0.93	0.46	0.45
σ_γ=NOM, σ_R=NOM	6.3	1.7	1.6	1.6

PE_{PF} in km

Case 1: $|\alpha_1^* - \alpha_2^*| = 90^\circ$, $e* = 45^\circ$

TABLE 10-3

CELESTIAL TRACKING, scl 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_e = \sigma_\alpha$	5.0	0.50	0.050	0.0050
$\sigma_r = \sigma_p$	5.0	0.50	0.050	0.0050
$\sigma_R = \sigma_D$	1.4	0.45	0.045	0.0045
σ_t	0.48	0.048	0.0048	0.00048
σ_γ	6.2	2.0	0.20	0.0
PE_{PF}	9.5	2.2	0.22	0.0086
σ_γ = PSOA	7.1	0.86	0.086	0.0086
σ_γ = NOM	7.5	2.2	2.0	2.0
σ_γ=PSOA, σ_R=PSOA	7.1	0.71	0.071	0.0071
σ_γ=PSOA, σ_R=MAX	7.1	1.6	1.4	1.4
σ_γ=SOA, σ_R=NOM	7.1	0.86	0.50	0.49
σ_γ=NOM, σ_R=NOM	7.4	2.2	2.0	2.0

PE_{PF} in km

Case 2: $|\alpha_1^* - \alpha_2^*| = |60^\circ, e^* = 45^\circ$

TABLE 10-4

CELESTIAL TRACKING, scl 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_e = \sigma_\alpha$	6.4	0.64	0.064	0.0064
$\sigma_r = \sigma_p$	6.4	0.64	0.064	0.0064
$\sigma_R = \sigma_D$	1.6	0.53	0.053	0.0053
σ_t	0.48	0.048	0.0048	0.00048
σ_γ	8.0	2.5	0.25	0.0
PE_{PF}	13	2.7	0.27	0.011
σ_γ = PSOA	9:2	1.1	0.11	0.011
σ_γ = NOM	11	2.7	2.5	2.5
σ_γ=PSOA, σ_R=PSOA	9.0	0.900	0.090	0.0090
σ_γ=PSOA, σ_R=MAX	13	1.8	1.6	1.6
σ_γ=SOA, σ_R=NOM	9.0	1.1	0.59	0.58
σ_γ=NOM, σ_R=NOM	9.4	2.7	2.5	2.5

PE_{PF} in km

Case 3: $|\alpha_1^* - \alpha_2^*| = 45^\circ$, $e^* = 45^\circ$

TABLE 10-5
CELESTIAL TRACKING, scl 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_e = \sigma_\alpha$	8.5	0.85	0.085	0.0085
$\sigma_r = \sigma_p$	8.5	0.85	0.085	0.0085
$\sigma_R = \sigma_D$	2.1	0.70	0.070	0.0070
σ_t	0.48	0.048	0.0048	0.00048
σ_γ	12.5	3.9	0.39	0.0
PE_{PF}	18	4.1	0.41	0.014
σ_γ = PSOA	14	1.4	0.14	0.014
σ_γ = NOM	13	4.1	3.9	3.9
σ_γ=PSOA, σ_R=PSOA	12	1.2	0.12	0.012
σ_γ=PSOA, σ_R=MAX	14	2.4	2.1	2.1
σ_γ=SOA, σ_R=NOM	12	2.0	0.81	0.80
σ_γ=NOM, σ_R=NOM	13	4.2	4.0	4.0

PE_{PF} in km

Case 4: $\left| \left| \alpha_1^* - \alpha_2^* \right| \right| = 30$, $e^* = 45^\circ$

TABLE 10-6

CELESTIAL TRACKING 3σ HEADING ERROR TABLE

Error	MAX	NOM	SOA	PSOA
$\sigma_\epsilon = \sigma_\gamma$	0.13	0.013	0.0013	1.3×10^{-4}
$\sigma_r = \sigma_p$	0.13	0.013	0.0013	1.3×10^{-4}
$\sigma_R = \sigma_D$	0.033	0.011	0.0011	1.1×10^{-4}
σ_t	0.018	0.0018	2×10^{-4}	0.0
σ_γ	---	---	---	---
σ_{AO}	0.19	0.021	2.1×10^{-3}	2.1×10^{-4}

σ_{AO} in deg

$\epsilon^* = 45^\circ$

$|\alpha_1^* - \alpha_2^*| = 90^\circ$

Table 10-7 Ranging Navigation Satellite 3 σ Error Table

Input Errors			MAX	NOM	SOA	PSOA
Source	Error	Units				
Satellite Ephemeris	σ_{ρ}	km	3.0	1.0	0.5	0.1
Ranging Measurement	σ_{Rnc}	km	0.1	0.01	0.001	0.0001

TABLE 10-8
RANGING NAVIGATIONAL SATELLITE, sc2 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_\rho = \sigma_u = \sigma_w$	32	10.5	5.3	1.1
R_{nc}	0.70	0.070	0.0070	0.00070
PE_{PF}	32	10.5	5.3	1.1
σ_ω = PSOA	1.3	1.1	1.1	1.1
σ_ω = SOA	5.3	5.3	5.3	5.3
σ_ω = NOM	10.5	10.5	10.5	10.5

PE_{PF} in km

Case 1: | R_c = 2038 km, | e* ≅ 60°

TABLE 10-9
RANGING NAVIGATIONAL SATELLITE, sc2
3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_\rho = \sigma_u = \sigma_w$	18	6.0	3.0	0.60
$\sigma_{R_{nc}}$	0.37	0.037	0.0037	0.00037
PE_{PF}	18	6.0	3.0	0.60
σ_ρ = PSOA	0.70	0.60	0.60	0.60
σ_ρ = SOA	3.0	3.0	3.0	3.0
σ_ρ = NOM	6.0	6.0	6.0	6.0

PE_{PF} in km

Case 2: | R_c = 2038 km | e* ≅ 45°

TABLE 10-10

RANGING NAVIGATIONAL SATELLITE 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_\rho = \sigma_u = \sigma_w$	22	7.2	3.6	0.72
$\sigma_{R_{nc}}$	0.60	0.060	0.0060	0.00060
PE_{PF}	22	7.2	3.6	0.72
σ_ρ = PSOA	0.94	0.72	0.72	0.72
σ_ρ = SOA	3.7	3.6	3.6	3.6
σ_ρ = NOM	7.2	7.2	7.2	7.2

PE_{PF} in km

Case 3: | R_c = 2738 km, | $e^* \cong 60^\circ$

TABLE 10-11

RANGING NAVIGATIONAL SATELLITE 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_\rho = \sigma_u = \sigma_w$	14	4.5	2.2	0.45
$\sigma_{R_{nc}}$	0.36	0.036	0.0036	0.00036
PE_{PF}	14	4.5	2.2	0.45
σ_ρ = PSOA	0.58	0.45	0.45	0.45
σ_ρ = SOA	2.2	2.2	2.2	2.2
σ_ρ = NOM	4.5	4.5	4.5	4.5

PE_{PF} in km

Case 4: | R_c = 2738 km, | $e^* \cong 45^\circ$

TABLE 10-12

ANGLE TRACKING NAVIGATION SATELLITE 3σ ERROR TABLE

Input Errors						
Source	Error	Units	MAX	NOM	SOA	PSOA
Satellite Ephemeris	σ_{hc}	km	3.0	1.0	0.5	0.1
Elevation Pointing Angle	σ_{ϵ}	deg	0.1	0.01	0.001	0.0001
Azimuth Pointing Angle	σ_{σ}	deg	0.1	0.01	0.001	0.0001
Pitch Angle	σ_p	deg	0.1	0.01	0.001	0.0001
Roll Angle	σ_r	deg	0.1	0.01	0.001	0.0001
Vertical Anomaly	σ_{γ}	deg	0.16	0.05	0.005	0.0

TABLE 10-13

ANGLE TRACKING NAVIGATIONAL SATELLITE,
sc3 3σ POSITION FIX ERROR

ERROR	**MAX**	**NOM**	**SOA**	**PSOA**
$\sigma_\rho = \sigma_u = \sigma_w$	33	11	5.5	1.1
$\sigma_e = \sigma_\alpha$	12	1.2	0.12	0.012
$\sigma_r = \sigma_p$	12	1.2	0.12	0.012
σ_γ	16	5.0	0.50	0.0
PE_{PF}	40	12	5.5	1.1
σ_γ = PSOA	37	11	5.5	1.1
σ_γ = NOM	37	12	7.4	5.1
σ_ρ=SOA, σ_γ=PSOA	18	5.8	5.5	5.5
σ_ρ=SOA, σ_γ=NOM	19	7.6	7.4	7.4
σ_ρ= PSOA, σ_γ=PSOA	17	2.1	1.1	1.1
σ_ρ=PSOA, σ_γ=NOM	18	5.4	5.1	5.1

PE_{PF} in km

Case 1: | R_c=2038 km, | $\alpha_1^* - \alpha_2^*$ = | 30°

TABLE 10-14
ANGLE TRACKING NAVIGATIONAL SATELLITE,
sc3 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_\rho = \sigma_u = \sigma_w$	15.9	5.3	2.7	0.53
$\sigma_e = \sigma_\alpha$	7.4	0.74	0.074	0.0074
$\sigma_r = \sigma_p$	7.4	0.74	0.074	0.0074
σ_γ	8.3	0.25	0.025	0.0
PE_{PF}	21	5.4	2.7	0.53
σ_γ = PSOA	19	5.3	2.7	0.53
σ_γ = NOM	19	5.4	2.7	0.59
σ_ρ=SOA, σ_γ=PSOA	11	2.9	2.7	2.7
σ_ρ=SOA, σ_γ=NOM	11	2.9	2.7	2.7
σ_ρ=PSOA, σ_γ=PSOA	7.4	1.9	0.54	0.53
σ_ρ=PSOA, σ_γ=NOM	7.4	2.0	0.59	0.59

PE_{PF} in km

Case 2: R_c = 2038 km, $|\alpha_1^* - \alpha_2^*|$ = 90°

TABLE 10-15

ANGLE TRACKING NAVIGATIONAL SATELLITE,
sc3 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_\rho = \sigma_u = \sigma_w$	9.6	3.2	1.6	0.32
$\sigma_e = \sigma_\alpha$	8.7	0.87	0.087	0.0087
$\sigma_r = \sigma_p$	8.7	0.87	0.087	0.0087
σ_γ	13	3.9	0.39	0.0
PE_{PF}	20	5.2	1.6	0.32
σ_γ = PSOA	16	3.4	1.6	0.32
σ_γ = NOM	16	5.2	4.2	3.9
σ_ρ=SOA, σ_γ=PSOA	12	2.0	1.6	1.6
σ_ρ=SOA, σ_γ=NOM	13	4.2	4.2	4.2
σ_ρ=PSOA, σ_γ=PSOA	12	1.3	0.34	0.32
σ_ρ=PSOA, σ_γ=NOM	13	4.0	3.9	3.9

PE_{PF} in km

Case 3: $\left| R_c = 2738 \text{ km}, \left\| \alpha_1^* - \alpha_2^* \right| = \right| 30^\circ$

TABLE 10-16
ANGLE TRACKING NAVIGATIONAL SATELLITE,
sc3 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_\rho = \sigma_u = \sigma_w$	4.2	1.4	0.70	0.14
$\sigma_e = \sigma_\alpha$	5.0	0.50	0.050	0.0050
$\sigma_r = \sigma_p$	5.0	0.50	0.050	0.0050
σ_γ	5.6	1.8	0.18	0.0
PE_{PF}	10	2.4	0.72	0.14
σ_γ = PSOA	8.2	1.6	0.70	0.14
σ_γ = NOM	8.4	2.4	1.9	1.8
σ_ρ=SOA, σ_γ=PSOA	7.1	1.0	0.70	0.70
σ_ρ=SOA, σ_γ=NOM	7.3	2.0	1.9	1.9
σ_ρ=PSOA, σ_γ=PSOA	7.1	0.71	0.16	0.14
σ_ρ=PSOA, σ_γ=NOM	7.3	1.9	1.8	1.8

PE_{PF} in km

Case 4: $|R_c = 2738$ km, $||\alpha_1^* - \alpha_2^*| = |90^\circ$

TABLE 10-17

ANGLE TRACKING NAVIGATION SATELLITE
3σ HEADING FIX ERROR TABLE

ERROR	MAX	NOM	SOA	PSOA
σ_{hc}	1.2	0.4	0.2	0.1
$\sigma_\epsilon = \sigma$ [illegible]	0.5	0.05	0.005	0.0005
$\sigma_r = \sigma_p$	0.5	0.05	0.005	0.0005
σ_γ	0.8	0.025	0.0025	0.0
$(\sigma_{AO})_T$	1.6	0.41	0.2	0.1
$(\sigma_{AO})_T \big\vert_{\sigma_\gamma = 0}$	1.4	0.41	0.2	0.1

σ_{AO} in deg

$R_c = 2038$ km

$\epsilon^* = 30^\circ$

TABLE 10-18

RANGE RATE NAVIGATIONAL SATELLITE 3σ ERROR TABLE

Error Source						
Definition	Error	Units	MAX	NOM	SOA	PSOA
Satellite Altitude Rate	$\sigma_{\dot{\rho}}$	km/hr	1.0	0.1	10^{-2}	10^{-3}
Satellite Altitude	σ_{ρ}	km	3.0	1.0	0.5	0.1
Satellite Range Rate	$\sigma_{\dot{r}}$	km/hr	200	20	2.0	0.2
Satellite Latitude	σ_u	deg				
Satellite Longitude	σ_w	deg	$\sigma_u \cong \sigma_w = \sigma_{\rho}/Rc$			
Satellite Latitude Rate	$\sigma_{\dot{u}}$	deg/hr				
Satellite Longitude Rate	$\sigma_{\dot{w}}$	deg/hr	$\sigma_{\dot{u}} \cong \sigma_{\dot{w}} = \sigma_{\dot{\rho}}/R_c$			

TABLE 10-19
RANGE RATE NAVIGATIONAL SATELLITE
sc4 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_{\dot{\rho}} = \sigma_{\dot{u}} = \sigma_{\dot{w}}$	0.062	0.0062	0.00062	0.000062
$\sigma_{\rho} = \sigma_{u} = \sigma_{w}$	5.2	1.8	0.90	0.18
$\sigma_{\dot{r}}$	80	8.0	0.8	0.08
PE'_{PF}	80	8.2	1.2	0.20
$\sigma_{\dot{r}}$ = PSOA	5.2	1.8	0.90	0.20
$\sigma_{\dot{r}}$ = SOA	5.3	2.0	1.2	0.82
σ_{ρ} = PSOA	80	8.0	0.82	0.20
σ_{ρ} ≐ SOA	80	8.1	1.2	0.90
σ_{ρ} = NOM	80	8.2	2.0	1.8
$\sigma_{\dot{\rho}}$ = MAX	80	8.2	1.2	0.21

PE_{PF} in km

Case 1: | R_c = 2038km, | $e^* \cong 85^{o}$

TABLE 10-20
RANGE RATE NAVIGATIONAL SATELLITE,
sc4 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_{\dot{\rho}} = \sigma_{\dot{u}} = \sigma_{\dot{w}}$	0.10	0.010	0.0010	0.00010
$\sigma_{\rho} = \sigma_{u} = \sigma_{w}$	4.9	1.7	0.85	0.17
$\sigma_{\dot{r}}$	80	8.0	0.80	0.080
PE_{PF}	80	8.2	1.2	0.19
$\sigma_{\dot{r}}$ = PSOA	4.9	1.7	0.85	0.19
$\sigma_{\dot{r}}$ = SOA	5.0	1.9	1.2	0.82
σ_{ρ} = PSOA	80	8.0	0.82	0.19
σ_{ρ} = SOA	80	8.1	1.2	0.85
σ_{ρ} = NOM	80	8.2	1.9	1.7
$\sigma_{\dot{\rho}}$ = MAX	80	8.2	1.2	0.21

PE_{PF} in km

Case 2: $|R_c = 2038$ km,$|$ $e^* \cong 30^{\circ}$

TABLE 10-21
RANGE RATE NAVIGATIONAL SATELLITE,
sc4 3σ POSITION FIX ERROR

ERROR	**MAX**	**NOM**	**SOA**	**PSOA**
$\sigma_{\dot{\rho}} = \sigma_{\dot{u}} = \sigma_{\dot{w}}$	0.26	0.026	0.0026	0.00026
$\sigma_{\rho} = \sigma_{u} = \sigma_{w}$	4.5	1.5	0.75	0.15
σ_{r}	112	11	1.1	0.11
PE_{PF}	112	11	1.3	0.19
$\sigma_{\dot{r}}$ = PSOA	4.5	1.5	0.76	0.19
$\sigma_{\dot{r}}$ = SOA	4.6	1.9	1.3	1.1
σ_{ρ} = PSOA	112	11	1.1	0.19
σ_{ρ} = SOA	112	11	1.3	0.76
σ_{ρ} = NOM	112	11	1.9	1.5
$\sigma_{\dot{\rho}}$ = MAX	112	11	1.3	0.32

PE_{PF} in km

Case 3: | R_c = 2738 km | $e^* \cong 85^{o}$

TABLE 10-22

RANGE RATE NAVIGATIONAL SATELLITE, sc4 3σ POSITION FIX ERROR

ERROR	MAX	NOM	SOA	PSOA
$\sigma_{\dot{\rho}} = \sigma_{\dot{u}} = \sigma_{\dot{w}}$	0.29	0.029	0.0029	0.00029
$\sigma_{\rho} = \sigma_{u} = \sigma_{w}$	4.2	1.4	0.70	0.14
$\sigma_{\dot{r}}$	118	12	1.2	0.12
PE_{PF}	118	12	1.4	0.18
$\sigma_{\dot{r}}$ = PSOA	4.2	1.4	0.71	0.18
$\sigma_{\dot{r}}$ = SOA	4.4	1.8	1.4	1.2
$\sigma_{\dot{\rho}}$ = PSOA	118	12	1.2	0.18
$\sigma_{\dot{\rho}}$ = SOA	118	12	1.4	0.71
$\sigma_{\dot{\rho}}$ = NOM	118	12	1.8	1.4
$\sigma_{\dot{\rho}}$ = MAX	118	12	1.4	0.34

PE_{PF} in km

Case 4: $R_c = 2738$ km, $e^* \cong 30^\circ$

TABLE 10-23

DSIF TRACKING CAPABILITY VERSUS TRACKING TIME

3σ Semimajor Axis	Ranging (Days)		Doppler (Days)	
	One Station A	Two Stations A and B	One Station A	Two Stations A and B
15	< 1.0	< 1.0	1.9	1.2
6	1.4	< 1.0	3.6	2.6
3	2.1	1.0	6.2	4.6
1	2.6	2.4	10.4	8.2
0.75	3.4	2.9	18.4	15.4
0.30	7.0	5.2	>28.0	>28.0
Station A: Goldstone Station B: Woomera				

TABLE 10-24

3σ POSITION FIX ERROR DSIF sc 5, sc 6

Technique	Data	3σ Accuracy/Parameter Range			
		Max	Nom	SOA	PSOA
	Tracking Time (days)	1.0	2.0	4.0	8.0
DSIF, sc 5	Ranging (km)	8.0	3.0	1.0	0.3
DSIF, sc 6	Range Rate (km)	20.0	8.0	4.0	3.0

TABLE 10-25

TRIANGULATION 3σ ERROR TABLE

Element	Error Inputs			MAX	NOM	SOA	PSOA
	Variable	Error	Units				
$s_1 \cdots s_8$	Initial PF	σ_{xo}, σ_{yo}	km	3.5	1.4	0.7	0.2
$s_1 \cdots s_8$	Initial Altitude	σ_{ho}	km	0.1	0.01	0.001	0.0001
$s_1 \cdots s_8$	Initial Bearing	σ_A	deg	1	0.1	0.01	0.001
s_9, s_{10}, s_{15}	Base Line	σ_{RB}	km	0.005	0.0005	$5\text{x}10^{-4}$	$5\text{x}10^{-5}$
s_9, s_{10}, s_{15}	Sighting Angle	σ_α, σ_e	deg	1.2	0.6	0.06	0.006
s_5, s_{12}, s_{19}	Vertical	σ_r, σ_p	deg	1	0.1	0.01	0.001
		K_r, K_p	--	0.005	0.001	0.0003	10^{-4}
s_{24}	Vertical Anomaly	σ_γ	deg	0.16	0.05	0.005	0.0

TABLE 10-26

TRIANGULATION 3σ $(PE)_T$ TABLE:
$\alpha_2^* = 60^\circ$, $\alpha_1^* = 70^\circ$

Error Input	MAX	NOM	SOA	PSOA
σ_{xo}, σ_{yo}	5	2	1	0.28
σ_A	0.02	0.002	0.0002	0.00002
σ_{RB}	0.0058	0.00058	0.000058	5.8×10^{-6}
σ_α, σ_e	0.05	0.025	0.0025	0.00025
σ_p, σ_r	0.02	0.002	0.0002	0.00002
$(PE)_T^*$	0.057	0.025	0.0025	0.00025
% Accuracy	3.8	1.6	0.16	0.016
Linear Requirement	1:25	1:60	1:600	1:6000

$^* \sigma_{xo} = \sigma_{yo} = 0$

$(PE)_T$ in km

TABLE 10-27

TRILATERATION 3σ ERROR TABLE

Error Inputs							
Element	Variable	Error	Units	MAX	NOM	SOA	PSOA
$s_1 \cdots s_8$	Initial PF	σ_{xo}, σ_{yo}	km	3.5	1.4	0.7	0.2
$s_1 \cdots s_8$	Initial Altitude	σ_{ho}	km	0.1	0.01	0.001	0.0001
$s_1 \cdots s_8$	Initial Bearing	σ_A	deg	1	0.1	0.01	0.001
s_8, s_9, s_{15}	Base Line	σ_{RB}	km	0.005	0.0005	5×10^{-4}	5×10^{-5}
s_8, s_9, s_{15}	Distance	$\sigma_{ROT}, \sigma_{RBT}$	km	0.005	0.0005	5×10^{-4}	5×10^{-5}
s_8, s_9, s_{15}	Elevation	σ_ϵ	deg	1.2	0.6	0.06	0.006
s_5, s_{12}, s_{19}	Vertical	σ_r, σ_p	deg	1	0.1	0.01	0.001
		K_r, K_p	---	0.005	0.001	0.0003	10^{-4}
s_{24}	Vertical Anomaly	σ_α	deg	0.16	0.05	0.005	0.0

TABLE 10-28

TRILATERATION 3σ $(PE)_T$

$\alpha_1{}^* = 60^\circ$ $\alpha_2{}^* = 70^\circ$

Error Input	MAX	NOM	SOA	PSOA
σ_{xo}, σ_{yo}	5	2	1	0.28
σ_A	0.021	0.0021	0.00021	0.000021
σ_{RB}	0.0025	0.00025	2.5×10^{-5}	2.5×10^{-6}
σ_{ROT}, σ_{RBO}	0.008	0.0008	8×10^{-5}	8×10^{-6}
$\sigma_\epsilon{}^*$	-----	-----	-----	-----
$(PE)_T$	0.023	0.0023	2.3×10^{-4}	2.3×10^{-5}
% Accuracy	1.5	0.15	0.015	0.0015
Linear Requirement	1:70	1:700	1:7000	1:70000

$^*\sigma_{xo} = \sigma_{yo} = 0$

$(PE)_T$ in km

TABLE 10-29

3σ ERROR TABLE, DEAD RECKONING SUBCONCEPT sc 9

Input Errors			
Source	Element	3σ Error	Units
Odometer	s_{11}	σ_o	%
		σ_c	--
		K_s	hr/km
		K_{sp}	deg^{-1}
Celestial Tracker	s_3, s_4, s_{19}, s_{20}	σ_a	deg
Pendulous Vertical	s_{12}	$\sigma_p = \sigma_r$	deg
Ephemeris	s_{23}	$\sigma_{RE} = \sigma_{DE}$	deg
Timer	s_{22} s_{22}	σ_t K_t	hr --
Local Vertical	s_{24}	σ_γ	deg

TABLE 10-30

3σ ERROR TABLE, DEAD RECKONING SUBCONCEPT sc 10

Input Errors			
Source	Element	3σ Error	Units
Odometer	s_{11}	σ_o	%
		σ_c	--
		K_s	hr/km
		K_{sp}	deg^{-1}
Celestial Tracker	s_3, s_4, s_{19}, s_{20}	σ_a	deg
Inertial Vertical	s_6	$\sigma_p = \sigma_r$	deg
		$\sigma_{pD} = \sigma_{rD}$	deg/hr
Ephemeris	s_{23}	$\sigma_{RE} = \sigma_{DE}$	deg
Timer	s_{22}	σ_t	hr
	s_{22}	K_t	--
Local Vertical	s_{24}	σ_γ	deg

TABLE 10-31

DEAD RECKONING ALTITUDE ERROR-ODOMETER, sc 9, sc 10

σ_o, %	V, km/hr	4	8	12	16
5		0.140	0.124	0.108	0.094
1		0.019	0.019	0.019	0.020
0.1		0.002	0.002	0.002	0.002
0.01		0.0005	0.0005	0.0005	0.0005

PE_z in km All e *

TABLE 10-32

DEAD RECKONING 3σ HEADING ERROR, sc 9, sc 10

σ_a, deg	e^*, deg 10	30	45	77	85
5	5.10	5.22	5.71	13.4	54.0
1.0	1.01	1.07	1.14	3.10	11.1
0.5	0.51	0.52	0.58	1.76	5.55
0.1	0.102	0.109	0.120	0.343	1.10
0.05	0.051	0.053	0.058	0.176	0.51
0.01	0.0102	0.0109	0.0123	0.0353	0.12
0.002	0.002	0.003	0.004	0.006	0.019
σ_p - deg					
1.0	0.28	0.69	1.10	4.37	11.7
0.1	0.030	0.070	0.116	0.43	1.17
0.01	0.0027	0.0064	0.013	0.044	0.11
0.001	0.0003	0.0007	0.0015	0.0	0.012

All V σ_A in deg

TABLE 10-33

DEAD RECKONING 3σ ERROR TABLE, sc 11

Error Input			
Source	Element	3σ Error	Units
Odometer	s_{11}	σ_o	%
Directional Gyro	s_5	σ_{GA}	deg
		σ_{gD}	deg/hr
Pendulous Inclinometer	s_6	$\sigma_r = \sigma_p$	deg
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-34

DEAD RECKONING 3σ ERROR TABLE, sc 12

Error Input			
Source	Element	3σ Error	Units
Odometer	s_{11}	σ_o	%
Directional Gyro	s_5	σ_{GA}	deg
		σ_{gD}	deg/hr
Vertical Gyro	s_6	$\sigma_p = \sigma_r$	deg
		$\sigma_{pD} = \sigma_{rD}$	deg/hr
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-35

DEAD RECKONING 3σ ALTITUDE ERROR, sc 11, sc 12
ODOMETER COMPONENT

σ_o, %	V, km/hr 4	8	12	16
5	0.139	0.124	0.108	0.094
1	0.019	0.019	0.017	0.020
0.1	0.002	0.002	0.002	0.002
0.01	0.0005	0.0005	0.0005	0.0005

TABLE 10-36

DEAD RECKONING 3σ HEADING ERROR, sc 11, sc 12

σ_p, deg	V, km/hr 4	8	12	16
1.0	0.19	0.19	0.19	0.19
0.1	0.017	0.017	0.017	0.017
0.01	0.002	0.002	0.002	0.002
0.001	0.0005	0.0005	0.0005	0.0005
σ_{pD}, deg/hr				
0.5	2.1	0.96	0.52	0.50
0.05	0.19	0.046	0.063	0.046
0.01	0.029	0.017	0.011	0.011
0.001	0.004	0.002	0.001	0.001

TABLE 10-37

DEAD RECKONING ERROR TABLE sc 13

Error Input			
Source	Element	3σ Error	Units
Doppler Radar	s_2	σ_v	km/hr
Celestial Tracker	s_3, s_4	σ_a	deg
	s_{18}, s_{20}		
Pendulous Inclinometer	s_{12}	$\sigma_r = \sigma_p$	deg
Ephemeris	s_{23}	$\sigma_{RE} = \sigma_{DE}$	deg
Timer	s_{22}	σ_t K_t	hr
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-38

DEAD RECKONING ERROR TABLE sc 14

Error Input			
Source	Element	3 σ Error	Units
Doppler Radar	s_2	σ_v	km/hr
Celestial Tracker	s_3, s_4, s_{18}, s_{20}	σ_a	deg
Vertical Gyro	s_6	$\sigma_r = \sigma_p$	deg
		$\sigma_{rD} = \sigma_{pD}$	deg/hr
Ephemeris	s_{23}	$\sigma_{RE} = \sigma_{DE}$	deg
Timer	s_{22}	σ_t	hr
		K_t	
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-39

DEAD RECKONING 3σ ALTITUDE ERROR - VELOCITY ERROR, sc 13, sc 14

σ_v, km/hr	V, km/hr			
	4	8	12	16
1	0.26	0.087	0.043	0.071
0.5	0.15	0.063	0.025	0.030
0.1	0.035	0.012	0.006	0.008
0.05	0.014	0.006	0.003	0.003
0.01	0.003	0.002	0.001	0.001
0.005	0.001	0.001	0.001	0.001

PE_z in km All ε*

TABLE 10-40

DEAD RECKONING 3σ HEADING ERROR - sc 13, sc 14

σ_a, deg	ε* deg				
	10	30	45	77	85
5	5.1			13.2	46.6
1.0	1.02			2.61	9.68
0.5	0.51			1.35	5.65
0.1	0.102			0.269	0.235
0.05	0.051			0.0596	0.102
0.01	0.0101			0.0128	0.105
0.002	0.002			0.006	0.0206
σ_p, deg					
1.0	0.27			4.35	11.5
0.1	0.033			0.435	1.13
0.01	0.0027			0.0436	0.112
0.001	0.0003			0.0044	0.0113

σ_A in deg All V

TABLE 10-41

DEAD RECKONING 3σ ERROR TABLE sc 15

Input Errors			
Source	Element	3σ Error	Units
Velocity	s_2	σ_v	km/hr
Inertial Heading	s_5	σ_{GA} , σ_{gD}	deg , deg/hr
Pendulous Vertical	s_6	$\sigma_r = \sigma_p$	deg
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-42

DEAD RECKONING 3σ ERROR TABLE sc 16

Input Error			
Source	Element	3σ Error	Units
Velocity	s_2	σ_v	km/hr
Inertial Heading	s_5	σ_{GA}	deg
		σ_{gD}	deg/hr
Inertial Vertical	s_6	$\sigma_r = \sigma_p$	deg
		$\sigma_{rD} = \sigma_{pD}$	deg/hr
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-43

DEAD RECKONING 3σ ALTITUDE ERROR sc 15, sc 16

	V, km/hr			
σ_v, km/hr	4	8	12	16
1.0	0.21	0.14	0.13	0.12
0.5	0.13	0.059	0.046	0.042
0.1	0.030	0.015	0.012	0.011
0.05	0.012	0.005	0.005	0.004
0.01	0.003	0.001	0.001	0.001
0.005	0.001	0.0008	0.0007	0.001

PE_z in km

TABLE 10-44

DEAD RECKONING 3σ HEADING ERROR sc 15, sc 16

σ_p, deg	σ_A, deg
1.0	0.19
0.1	0.017
0.01	0.0015
0.001	0.0002
σ_{GA}, deg	
1.0	1.01
0.5	0.513
0.1	0.101
0.05	0.0506
0.01	0.0102
0.005	0.0051
0.001	0.0010

TABLE 10-45

DEAD RECKONING 3σ HEADING ERROR sc 15, sc 16

	V, km/hr			
σ_{pD}, deg/hr	4	8	12	16
0.5	2.2	0.90	0.70	0.52
0.05	0.17	0.083	0.061	0.046
0.01	0.028	0.014	0.0091	0.0068
0.001	0.005	0.0025	0.00019	0.0012
σ_v, km/hr				
1.0	0.15	0.053	0.035	0.024
0.5	0.076	0.028	0.018	0.018
0.1	0.013	0.0053	0.0034	0.0025
0.05	0.0075	0.0027	0.0017	0.0013
0.01	0.0014	0.0005	0.0003	0.0002
0.005	0.0008	0.0003	0.0002	0.0001

σ_A in deg

TABLE 10-46

DEAD RECKONING ERROR TABLE sc 17

Error Input			
Source	Element	3σ Error	Units
Accelerometer	s_1	$\sigma_{Ax} = \sigma_{Ay} = \sigma_{Az}$	km/hr^2 (10^{-6} earth g = 0.127 km/hr^2)
Celestial Tracker	s_3, s_4 s_{18}, s_{20}	σ_a	deg
Pendulous Inclinometer	s_6	$\sigma_p = \sigma_r$	deg
Ephemeris	s_{23}	$\sigma_{RE} = \sigma_{DE}$	deg
Timer	s_{22}	σ_t K_t	hr --
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-47

DEAD RECKONING ERROR TABLE sc 18

Error Source	Error Input		
	Element	3σ Error	Units
Accelerometers	s_1	$\sigma_{Ax} = \sigma_{Ay} = \sigma_{Az}$	km/hr^2(10^{-6} earth g = 0.127 km/hr^2)
Celestial Tracker	s_3, s_4, s_{18}, s_{20}	σ_a	deg
Vertical Gyro	s_6	$\sigma_r = \sigma_p$	deg
		$\sigma_{rD} = \sigma_{pD}$	deg/hr
Ephemeris	s_{23}	$\sigma_{RE} = \sigma_{DE}$	deg
Timer	s_{22}	σ_t	hr
		K_t	
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-48

DEAD RECKONING 3σ ALTITUDE ERROR sc 17, sc 18; ACCELEROMETER

	V, km/hr			
σ_{Ax}, Earth g	4	8	12	16
10^{-5}	19.0	1.6	1.2	0.36
10^{-6}	0.59	0.22	0.059	0.059
10^{-7}	0.13	0.035	0.011	0.008
10^{-8}	0.007	0.001	0.001	0.001
10^{-9}	0.002	<0.0005	<0.0005	<0.0005

PE_z in km All e^*

TABLE 10-49

DEAD RECKONING 3σ ALTITUDE ERROR sc 17, sc 18; CELESTIAL TRACKER

	V km/hr		
e^*, deg	10	77	85
σ_a, deg			
5	0.058	0.10	0.38
1.0	0.012	0.024	0.10
0.5	0.004	0.013	0.038
0.1	0.001	0.003	0.010
0.05	0.001	0.001	0.004
0.01	0.001	0.001	0.001

PE_z in km

TABLE 10-50

DEAD RECKONING 3σ HEADING ERROR sc 17, sc 18; CELESTIAL TRACKER, VERTICAL SENSOR

	ϵ^*, deg				
σ_a, deg	10	30	45	77	85
5.0	5.10			51.0	
1.0	1.01			10.5	
0.5	5.07			5.4	
0.1	0.102			1.15	
0.05	0.0507			0.518	
0.01	0.0101			0.097	
0.002	0.0020			0.023	
σ_p, deg					
1.0	0.31			4.38	11.3
0.1	0.030			0.44	11.15
0.01	0.0033			0.044	0.12
0.001	0.0003			0.0044	0.012

σ_A in deg

TABLE 10-51

DEAD RECKONING ERROR TABLE sc 19

INPUT ERRORS			
Source	Element	3σ Error	Units
Accelerometers	s_1	$\sigma_{Ax} = \sigma_{Ay} = \sigma_{Az}$	$km/hr^2 (10^{-6}$ earth g = 0. 127 $km/hr^2)$
Directional Gyro	s_5	σ_{GA} , σ_{gD}	deg , deg/hr
Pendulous Inclinometer	s_6	$\sigma_r = \sigma_p$	deg
Vertical Anomaly	s_{24}		deg

TABLE 10-52

DEAD RECKONING ERROR TABLE sc 20

ERROR INPUT			
Source	Element	3σ Error	Units
Accelerometer	s_1	$\sigma_{Ax} = \sigma_{Ay} = \sigma_{Az}$	km/hr^2
Directional Gyro	s_5	σ_{GA}	deg
		σ_{gD}	deg/hr
Vertical Gyro	s_6	$\sigma_p = \sigma_r$	deg
		$\sigma_{pD} = \sigma_{rD}$	deg/hr
Vertical Anomaly	s_{24}	σ_γ	deg

TABLE 10-53

DEAD RECKONING 3σ ALTITUDE ERROR sc 19, sc 20

	V, km/hr			
σ_{Ax}, Earth g	4	8	12	16
10^{-5}	19.0	3.2	1.23	0.77
10^{-6}	0.73	0.13	0.055	0.040
10^{-7}	0.13	0.027	0.011	0.010
10^{-8}	0.007	0.001	0.001	0.001
10^{-9}	0.002	$<$0.001	$<$0.001	$<$0.001
σ_{GA}, deg				
1.0	0.013	0.012	0.012	0.010
0.5	0.006	0.007	0.007	0.009
0.1	0.001	0.001	0.002	0.003
σ_{gD}, deg/hr				
1.0	0.37	0.40	0.049	0.048
0.25	0.032	0.025	0.017	0.013
0.08	0.025	0.007	0.004	0.003
0.01	0.002	0.001	0.001	0.002
0.005	0.002	0.001	$<$0.001	$<$0.001
0.001	$<$0.001	$<$0.001		

PE_z in km

10^{-6} earth g = 0.127 km/hr^2

TABLE 10-54

DEAD RECKONING 3σ HEADING ERROR sc 19, sc 20

	V, Km/hr			
σ_{Ax}, Earth g	4	8	12	16
10^{-5}		0.82	0.28	0.15
10^{-6}		0.086	0.029	0.014
10^{-7}		0.0085	0.0028	0.0015
10^{-8}		0.0008	0.0003	0.0009
10^{-9}		0.0001	$<$0.0001	$<$0.0001
σ_{GA}, deg				
1.0	1.02	For all V		
0.5	0.510			
0.1	0.103			
0.05	0.0510			
0.01	0.0101			
0.005	0.0051			
0.001	0.00101			
σ_{pD}, deg/hr				
0.5	1.7	1.3	0.78	0.60
0.05	0.18	0.10	0.039	0.053
0.01	0.034	0.017	0.0091	0.0051
0.001	0.0027	0.0014	0.0009	0.0010
σ_p, deg				
1.0	0.20	For all V		
0.1	0.019			
0.01	0.0017			
0.001	0.0002			

σ_A in deg

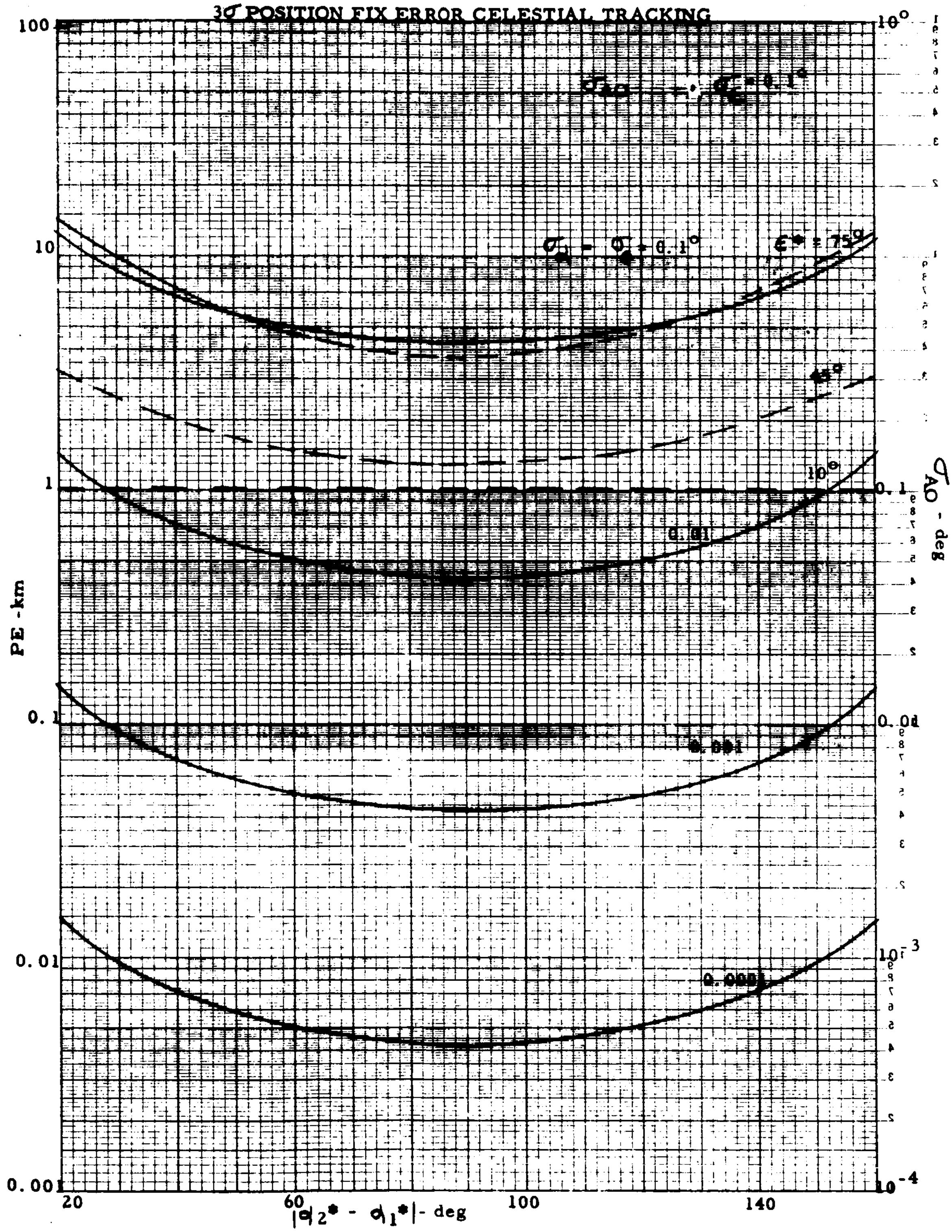


Figure 10-1 3σ Position Fix Error Celestial Tracking

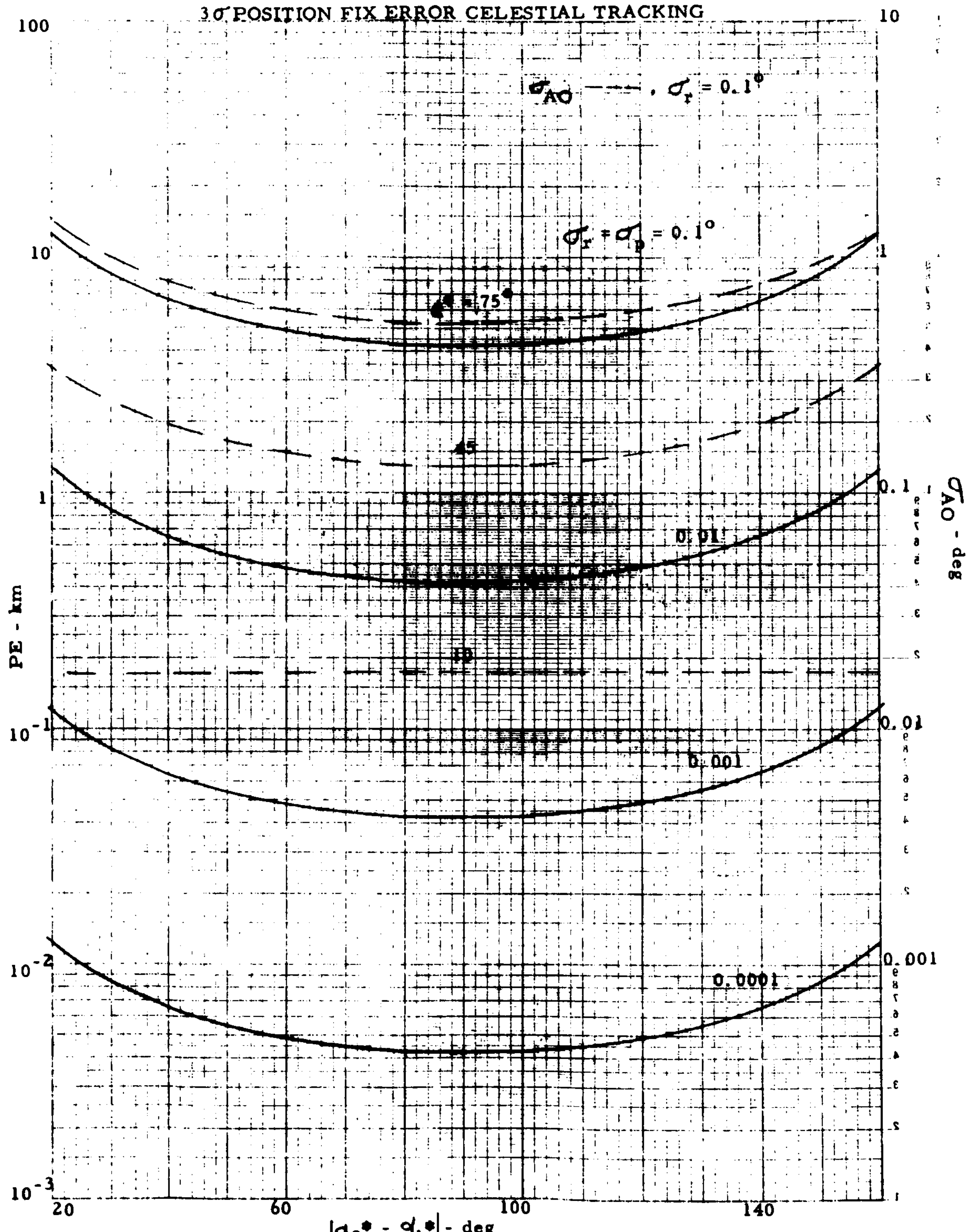


Figure 10-2 3σ Position Fix Error Celestial Tracking

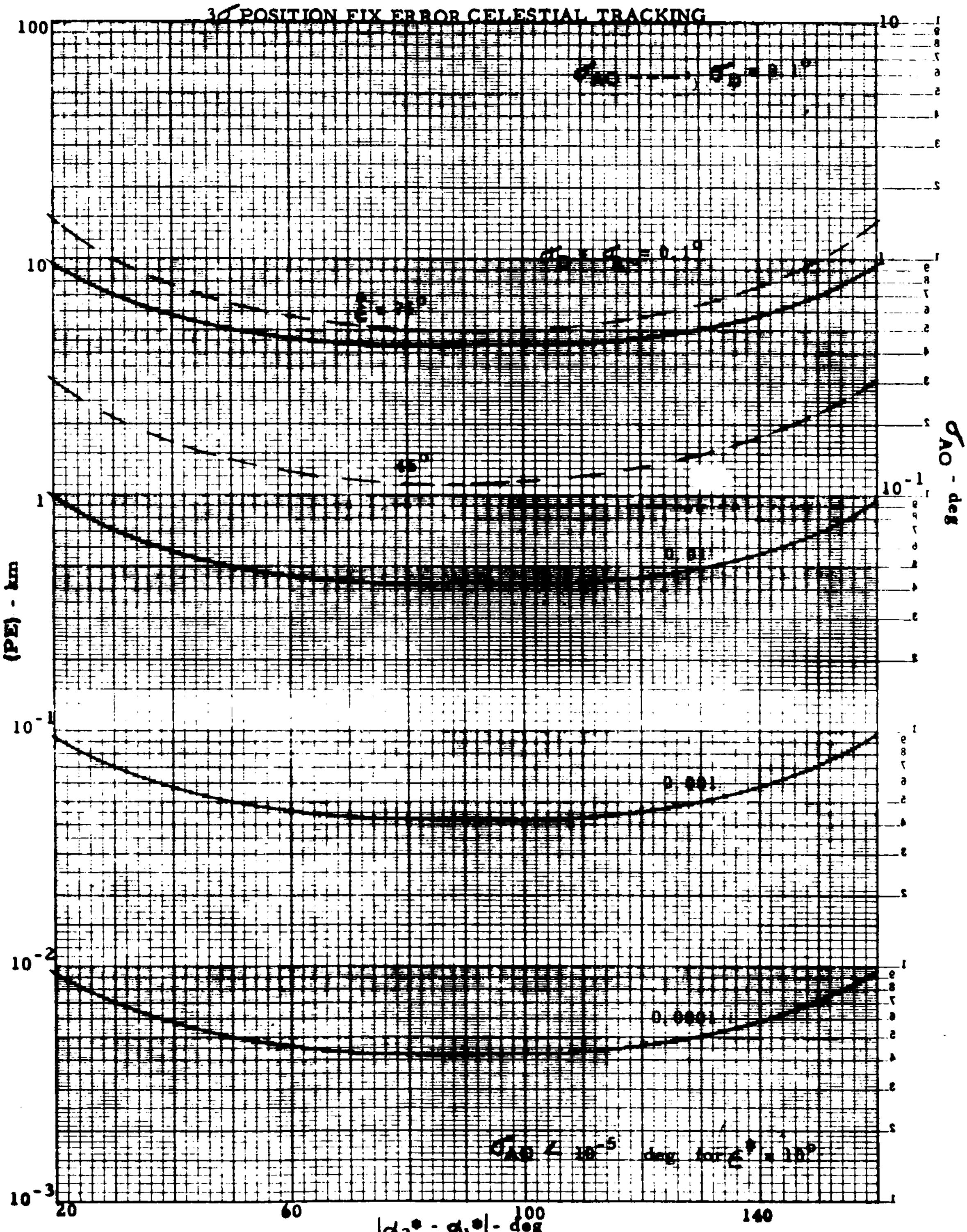


Figure 10-3 3σ Position Fix Error Celestial Tracking

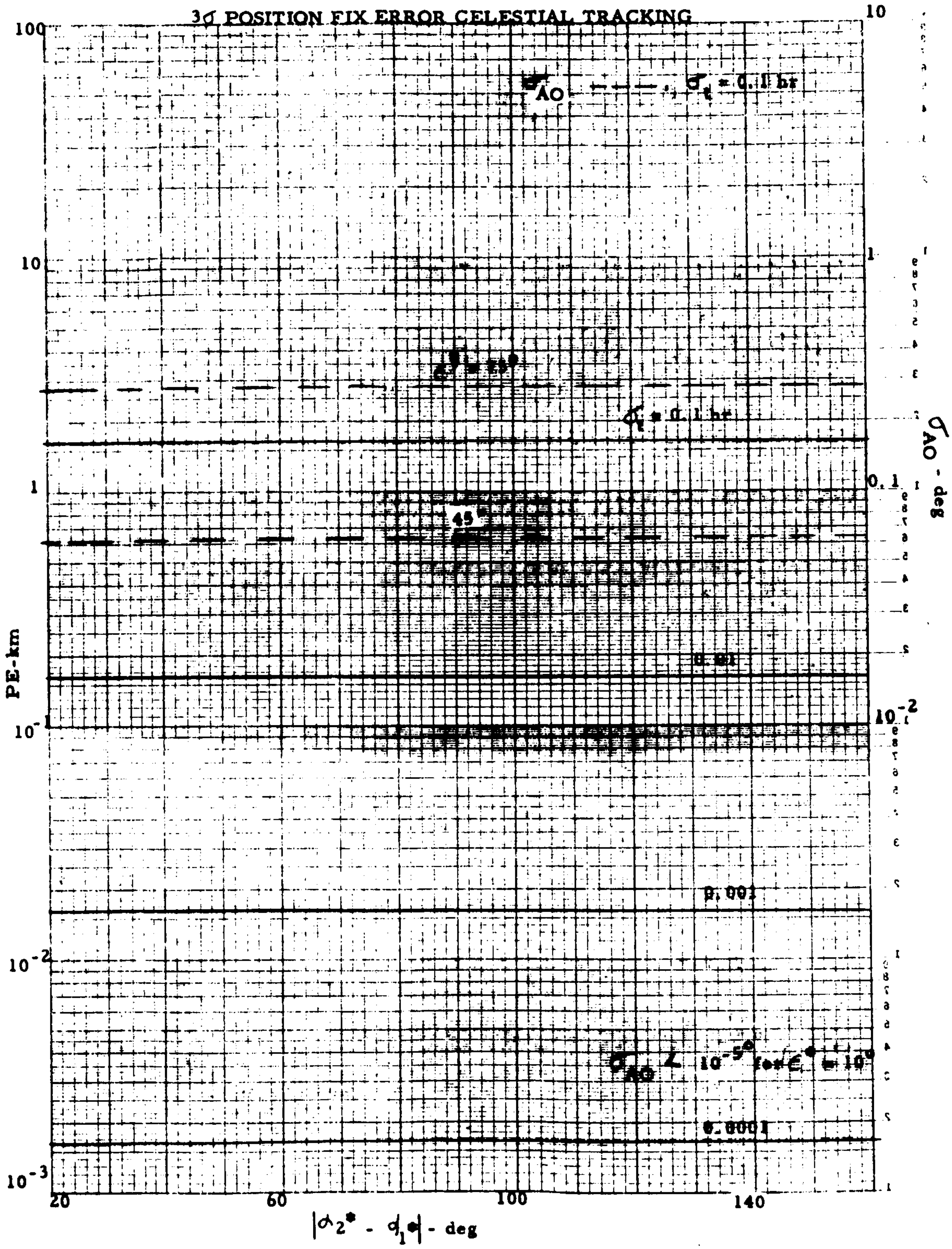


Figure 10-4 3σ Position Fix Error Celestial Tracking

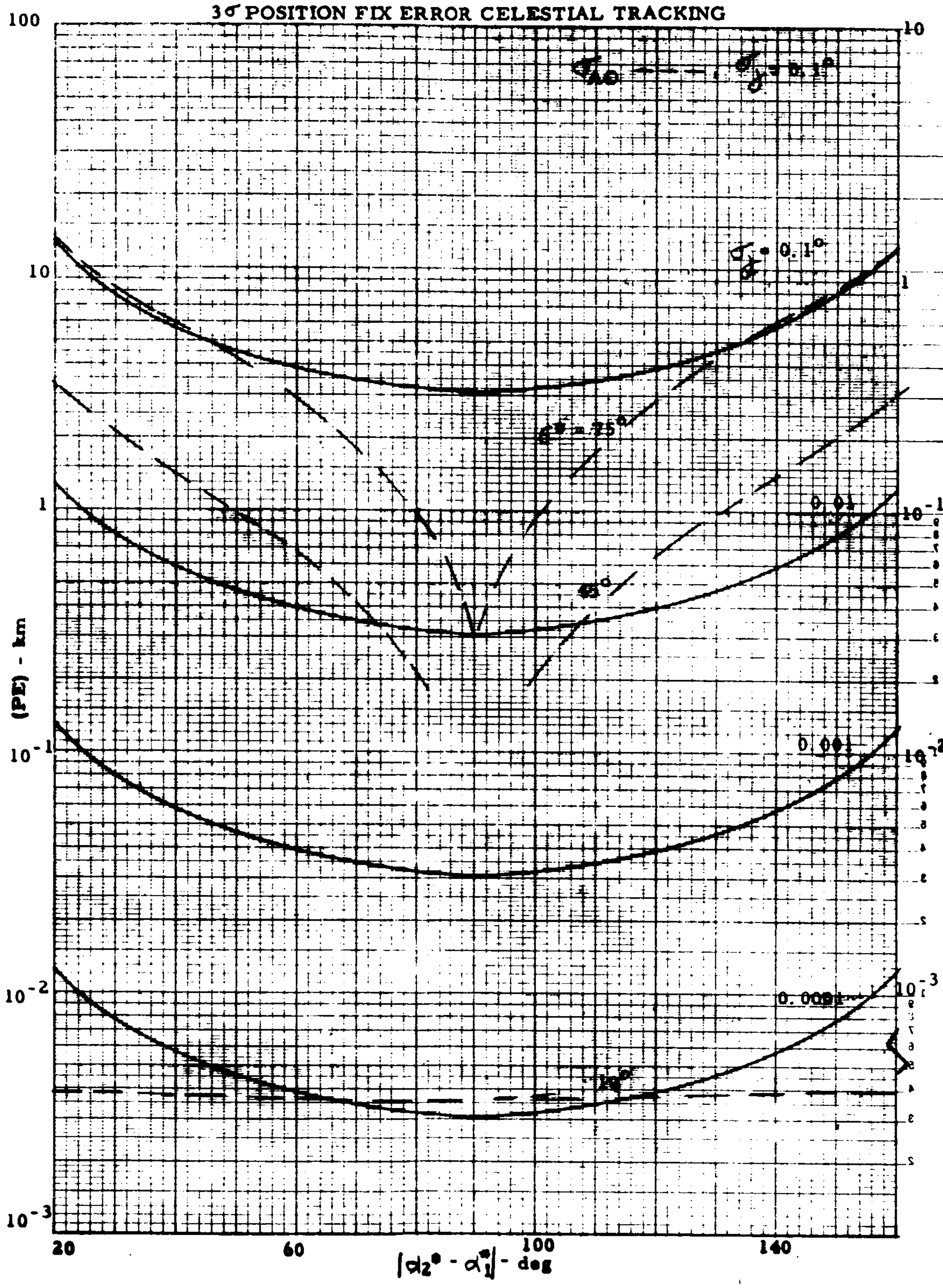


Figure 10-5 3σ Position Fix Error Celestial Tracking

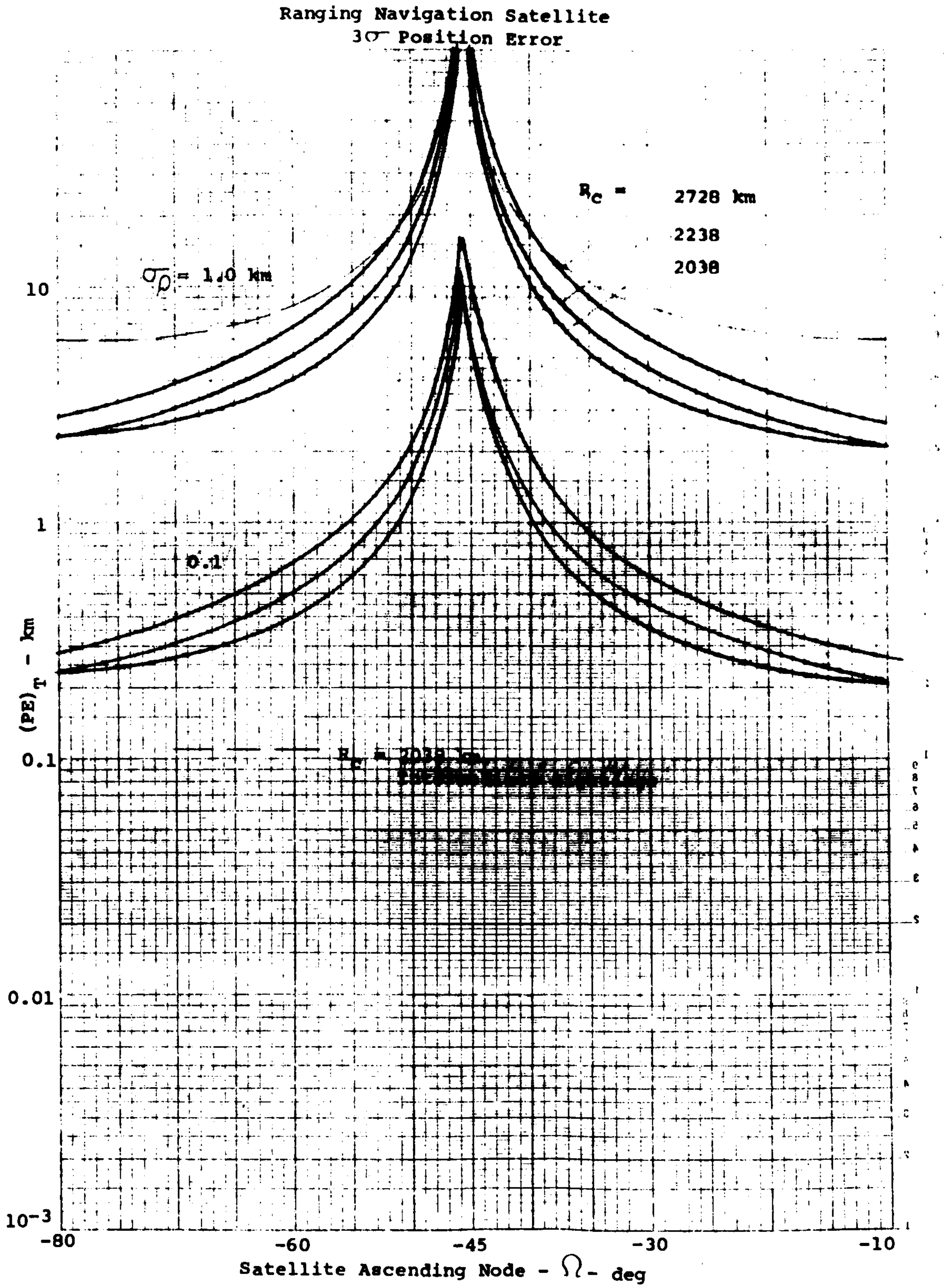


Figure 10-6 Ranging Navigation Satellite 3σ Position Error

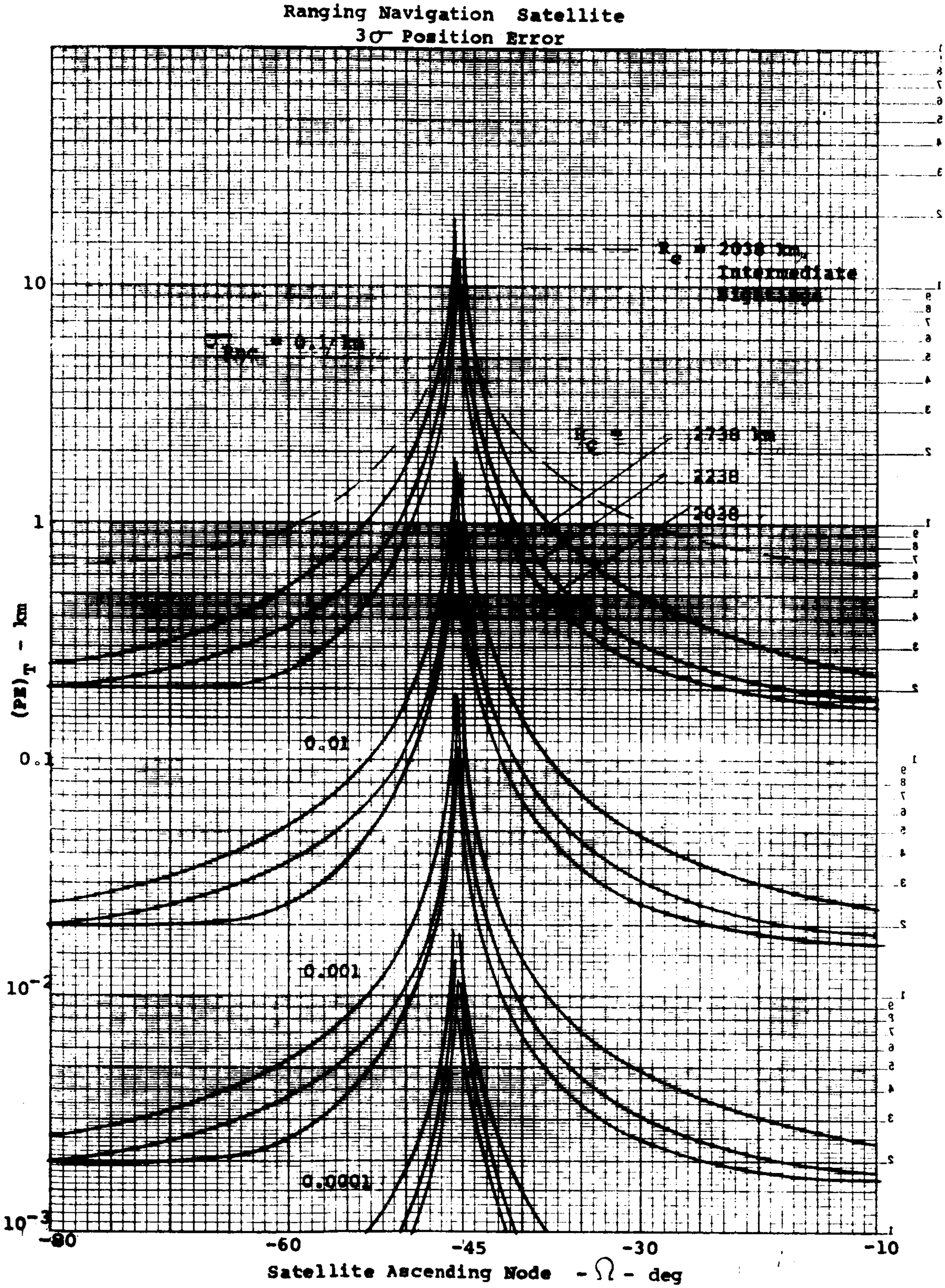


Figure 10-7 Ranging Navigation Satellite 3σ Position Error

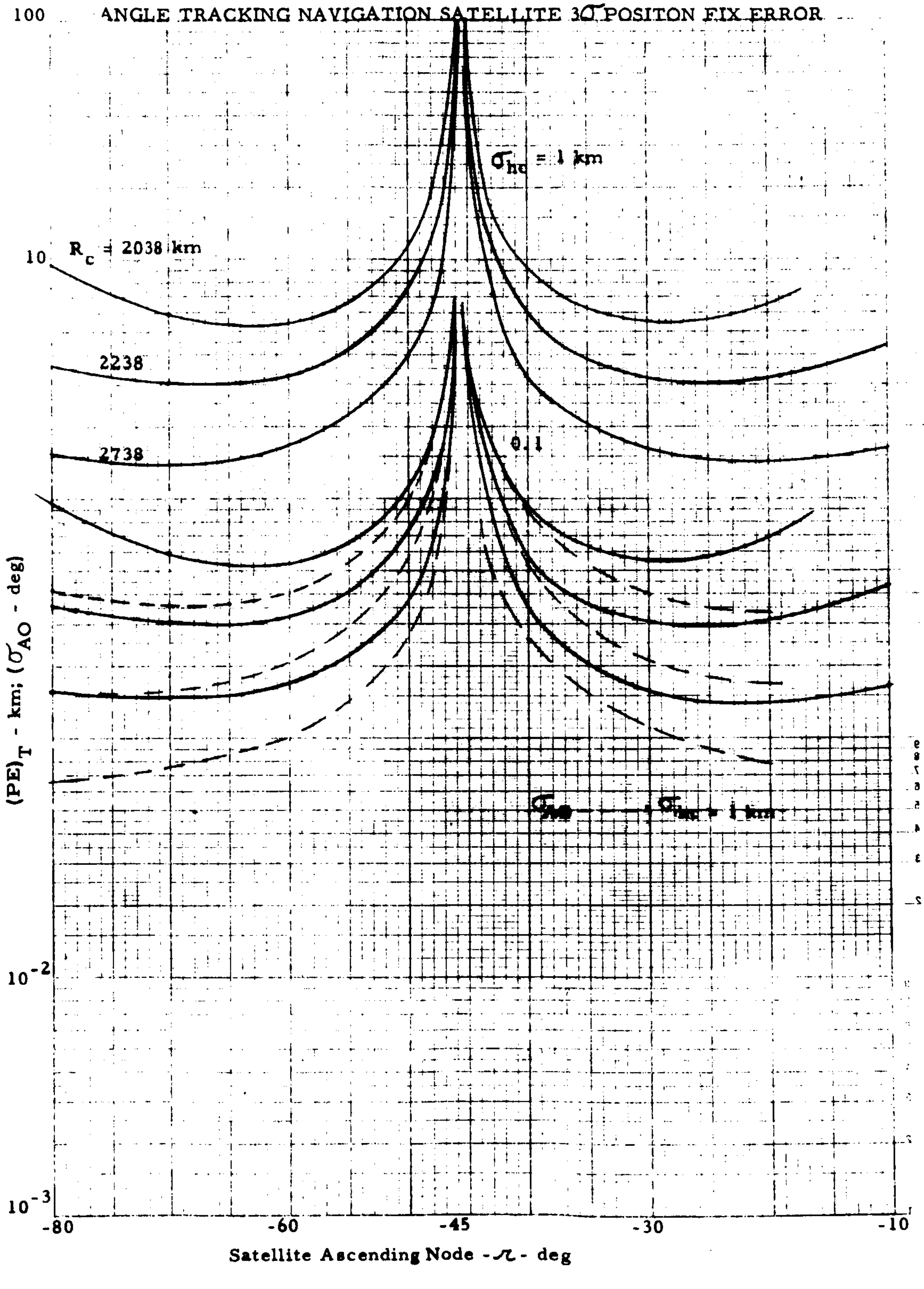


Figure 10-8 Angle Tracking Navigation Satellite 3σ Position Fix Error

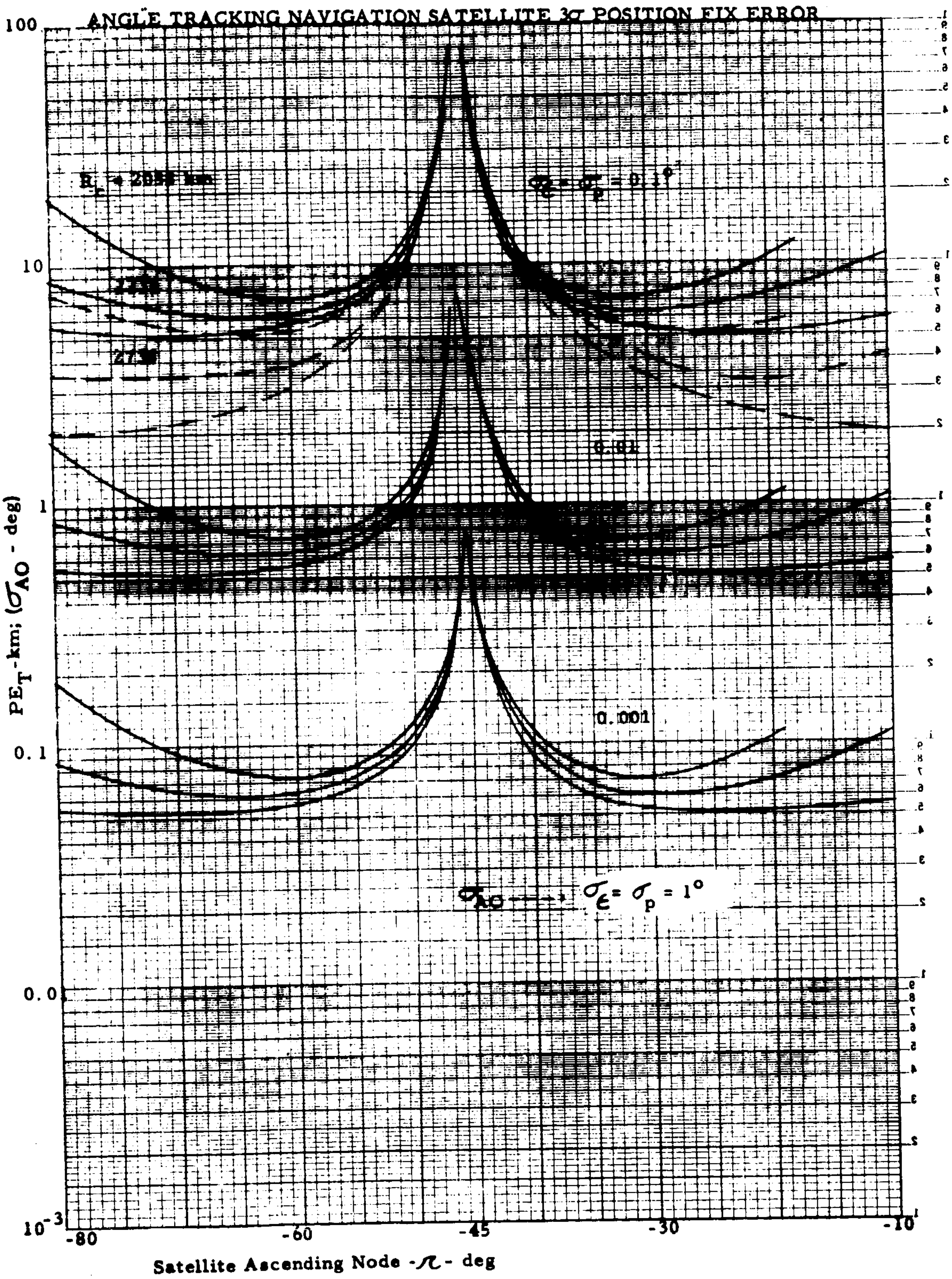


Figure 10-9 Angle Tracking Navigation Satellite 3σ Position Fix Error

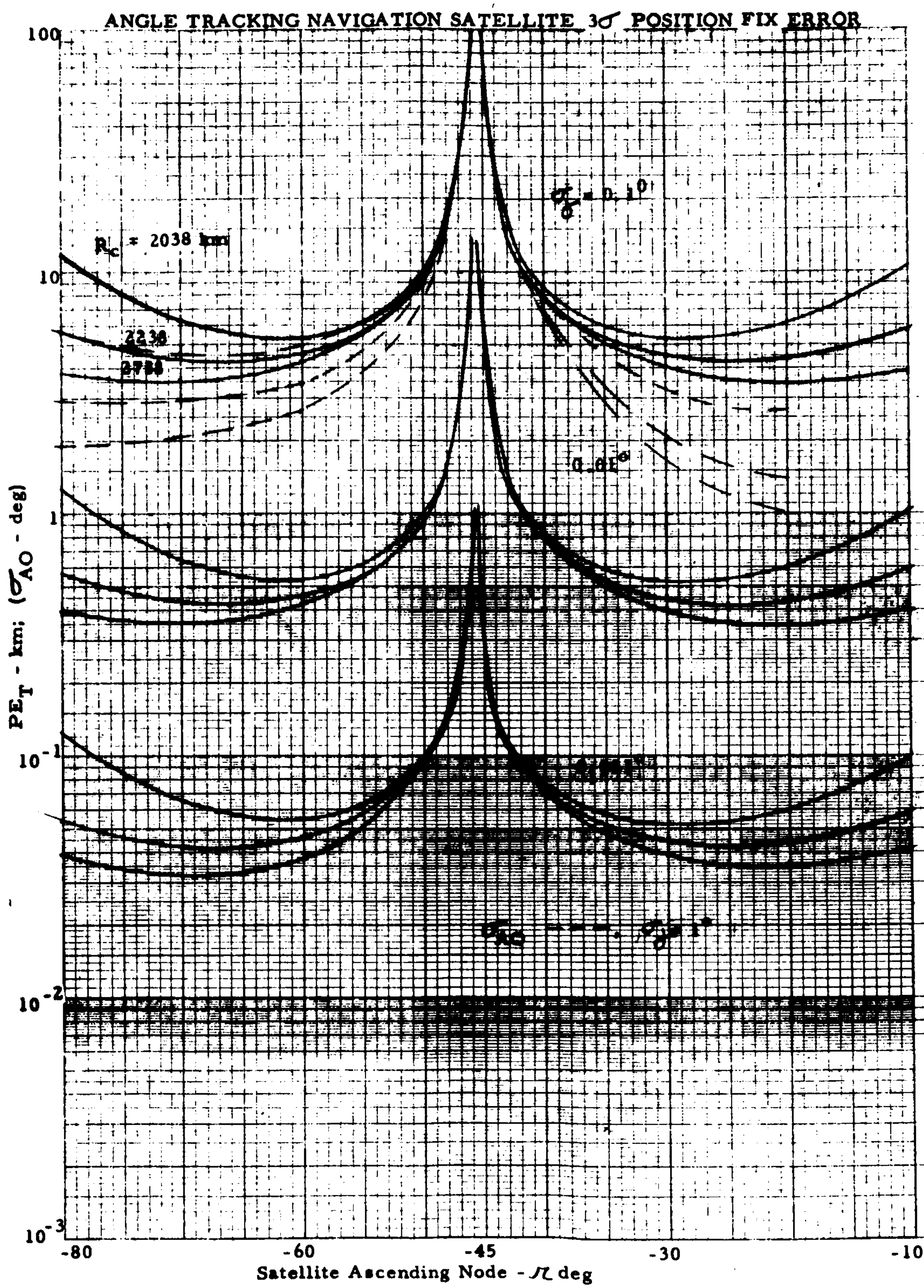


Figure 10-10 Angle Tracking Navigation Satellite 3σ Position Fix Error

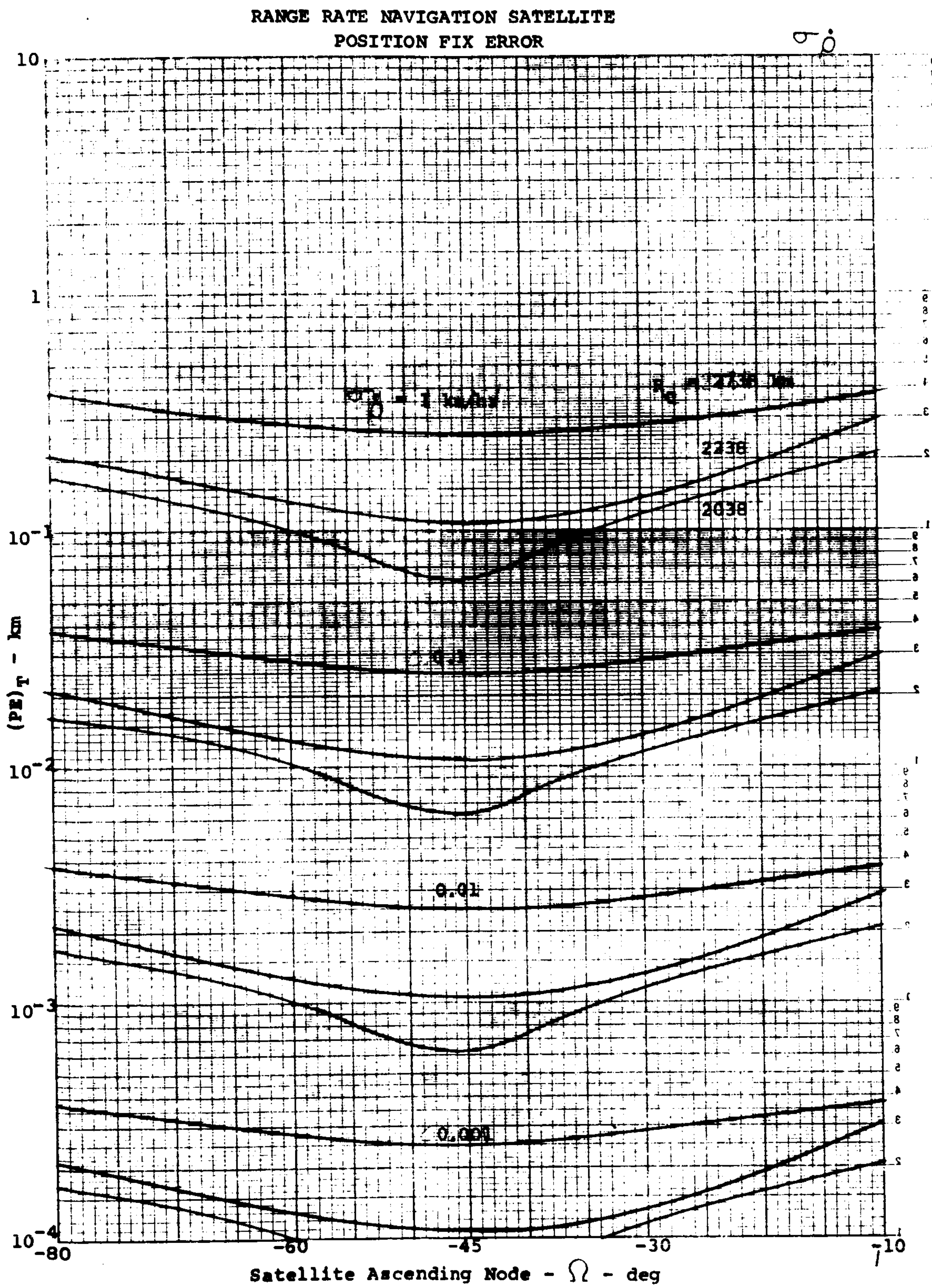


Figure 10-11 Range Rate Navigation Satellite Position Fix Error

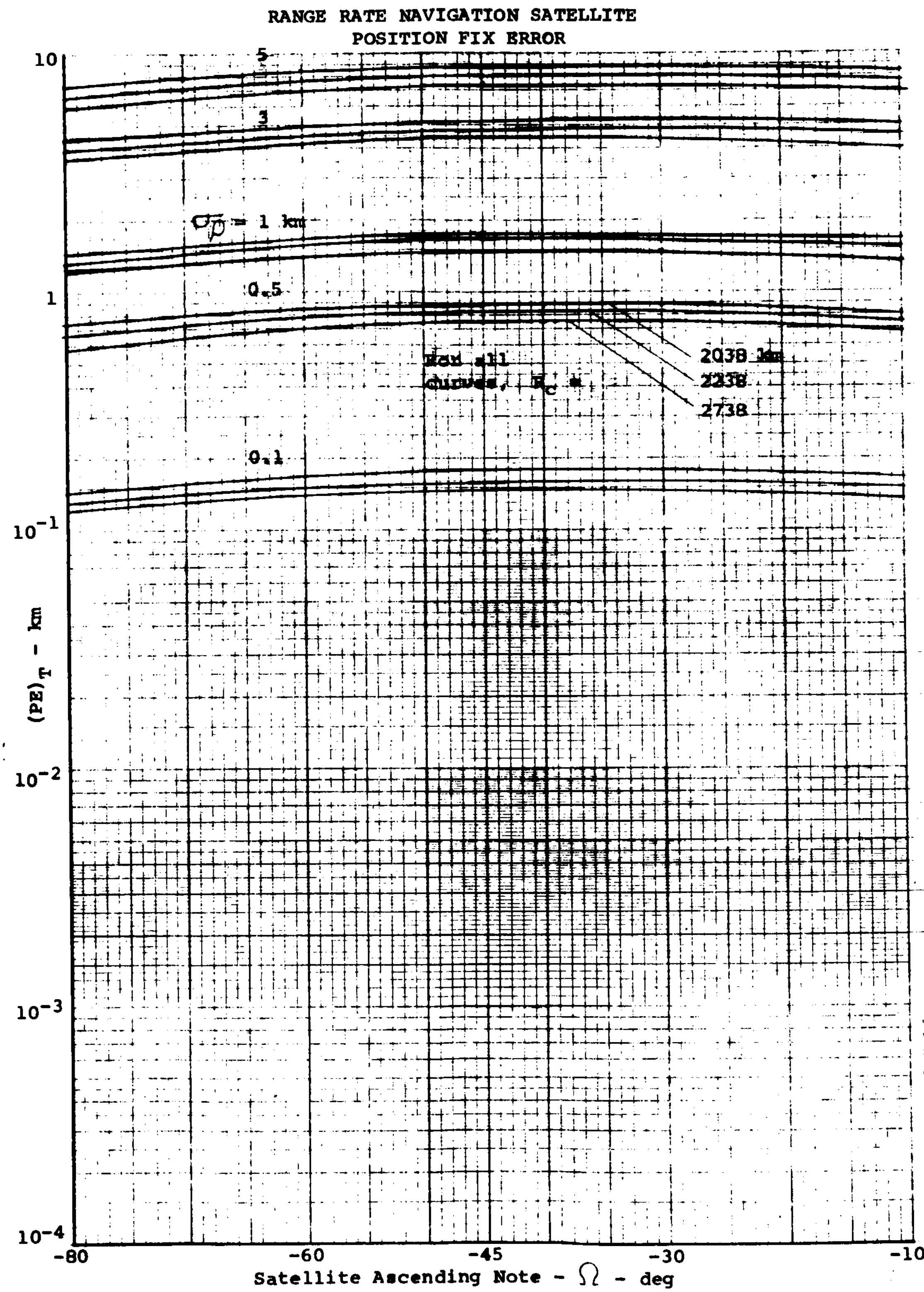


Figure 10-12 Range Rate Navigation Satellite Position Fix Error

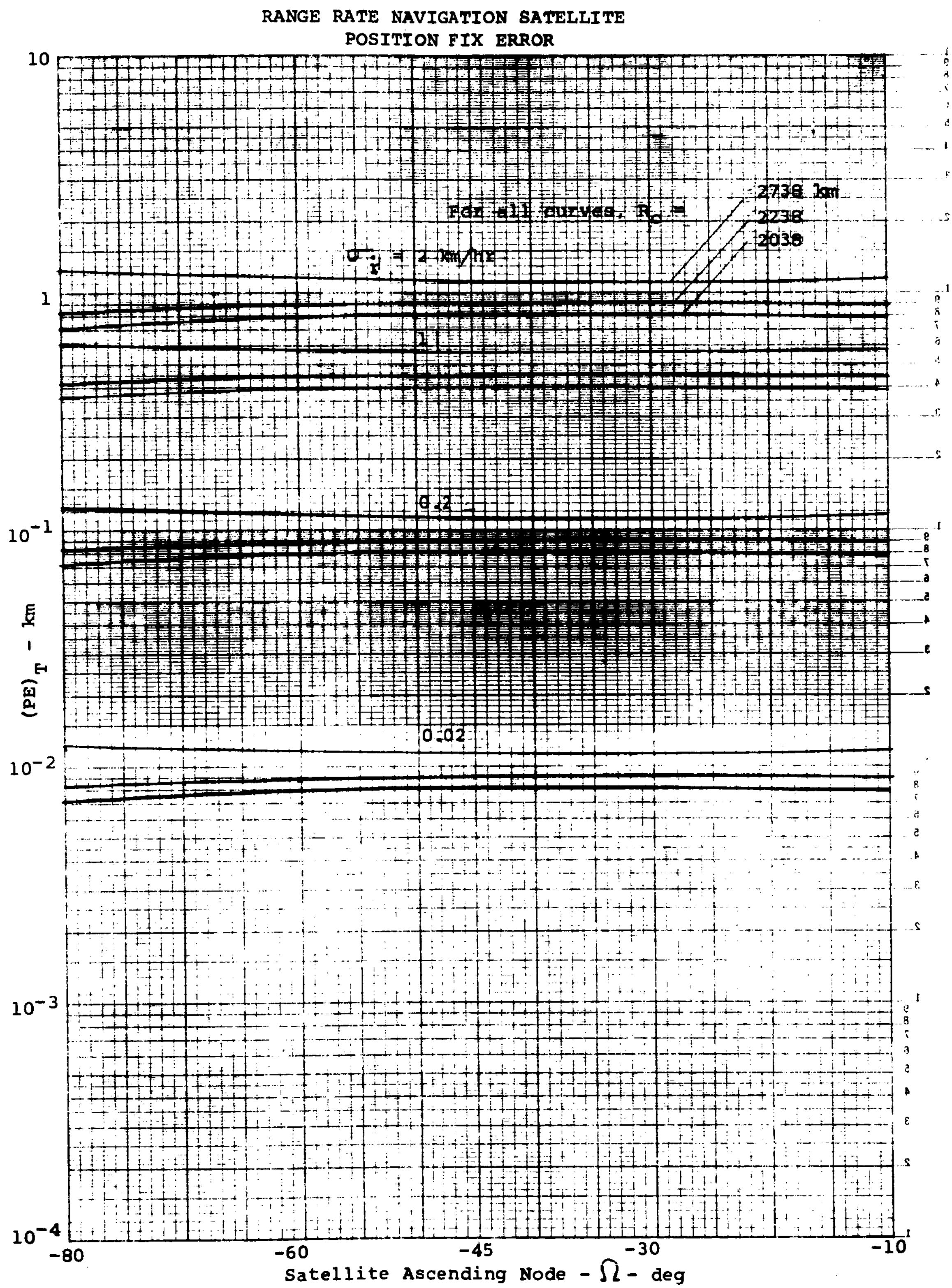


Figure 10-13 Range Rate Navigation Satellite Position Fix Error

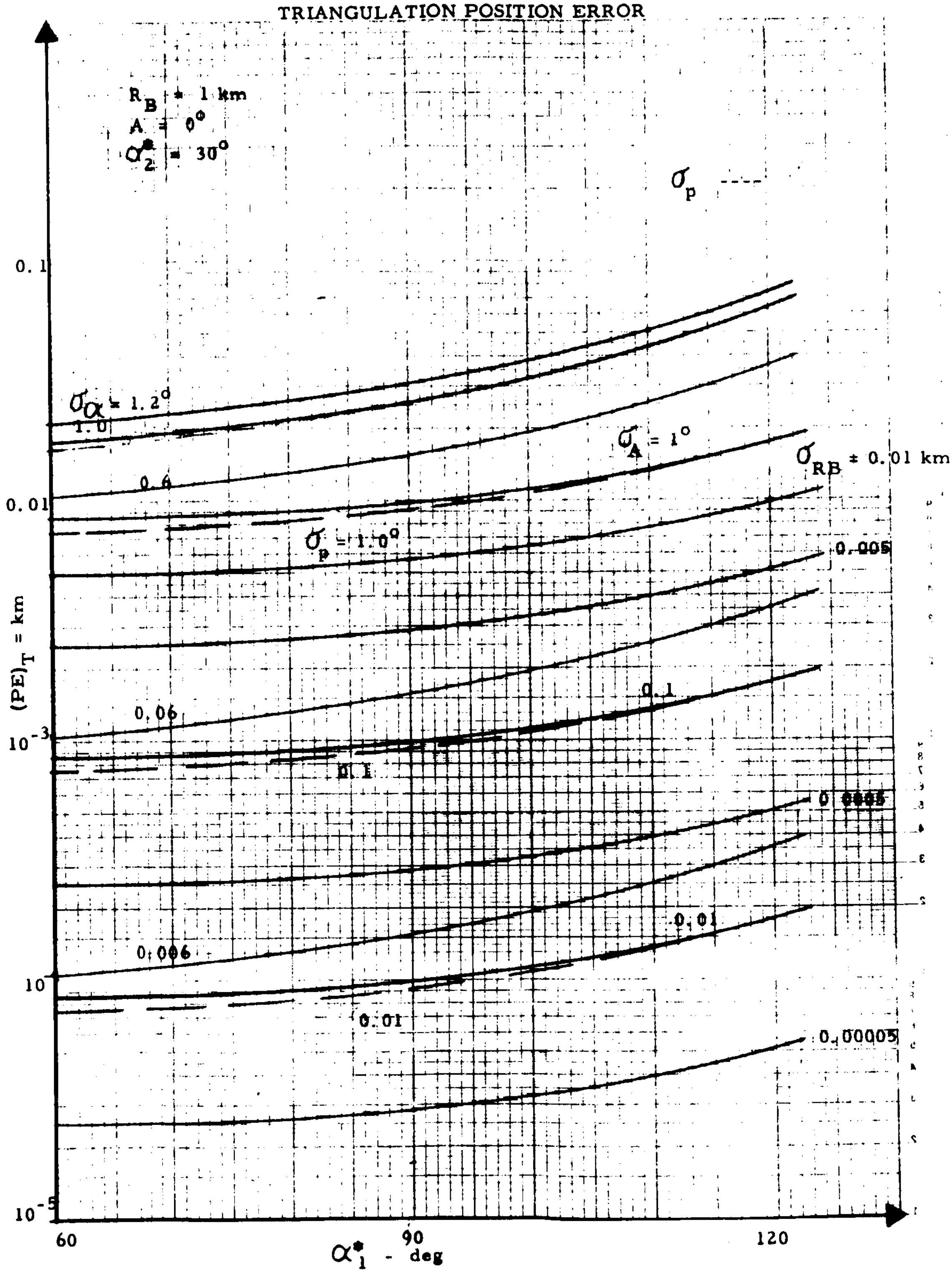


Figure 10-14 Triangulation Position Error

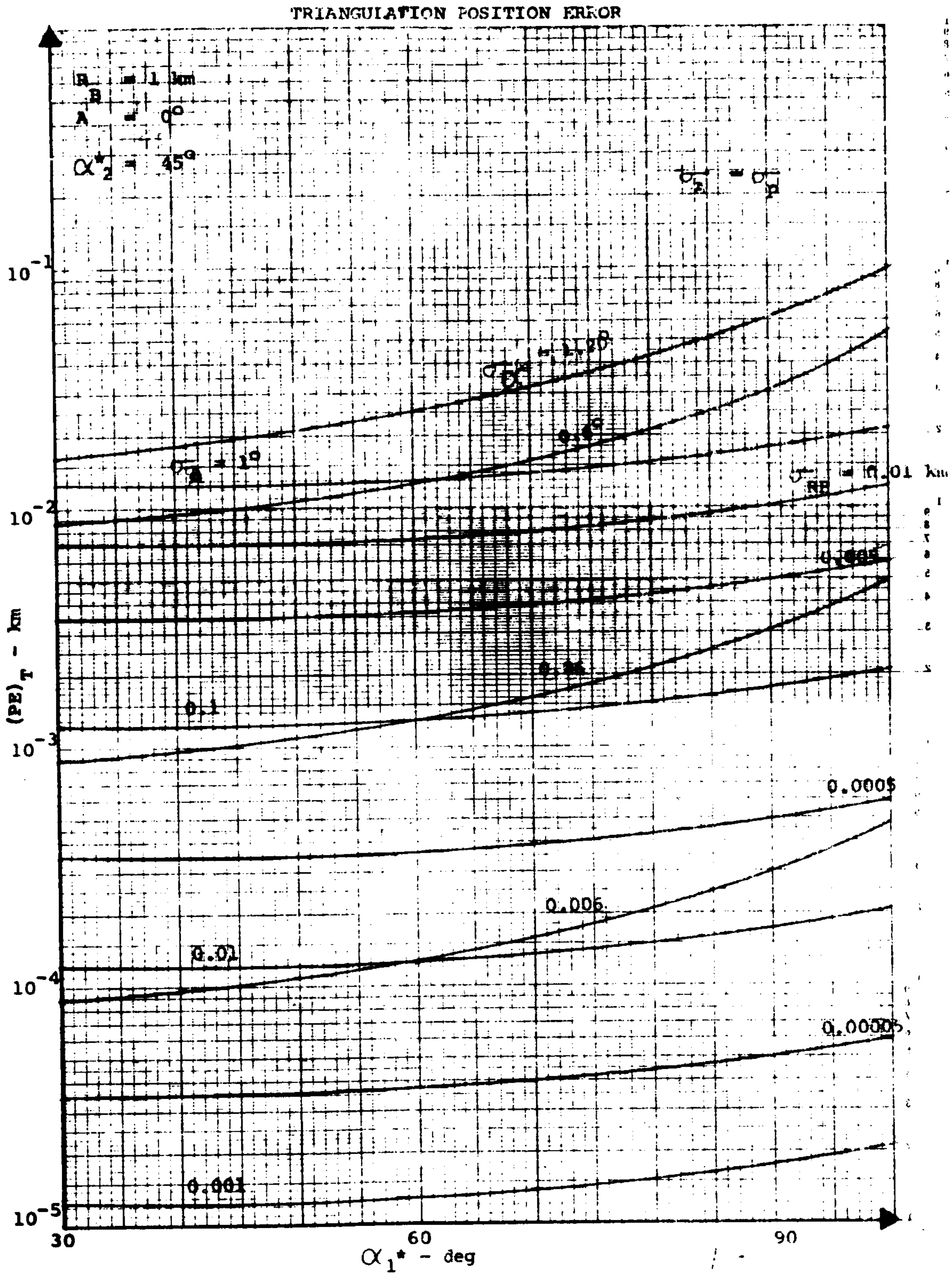


Figure 10-15 Triangulation Position Error

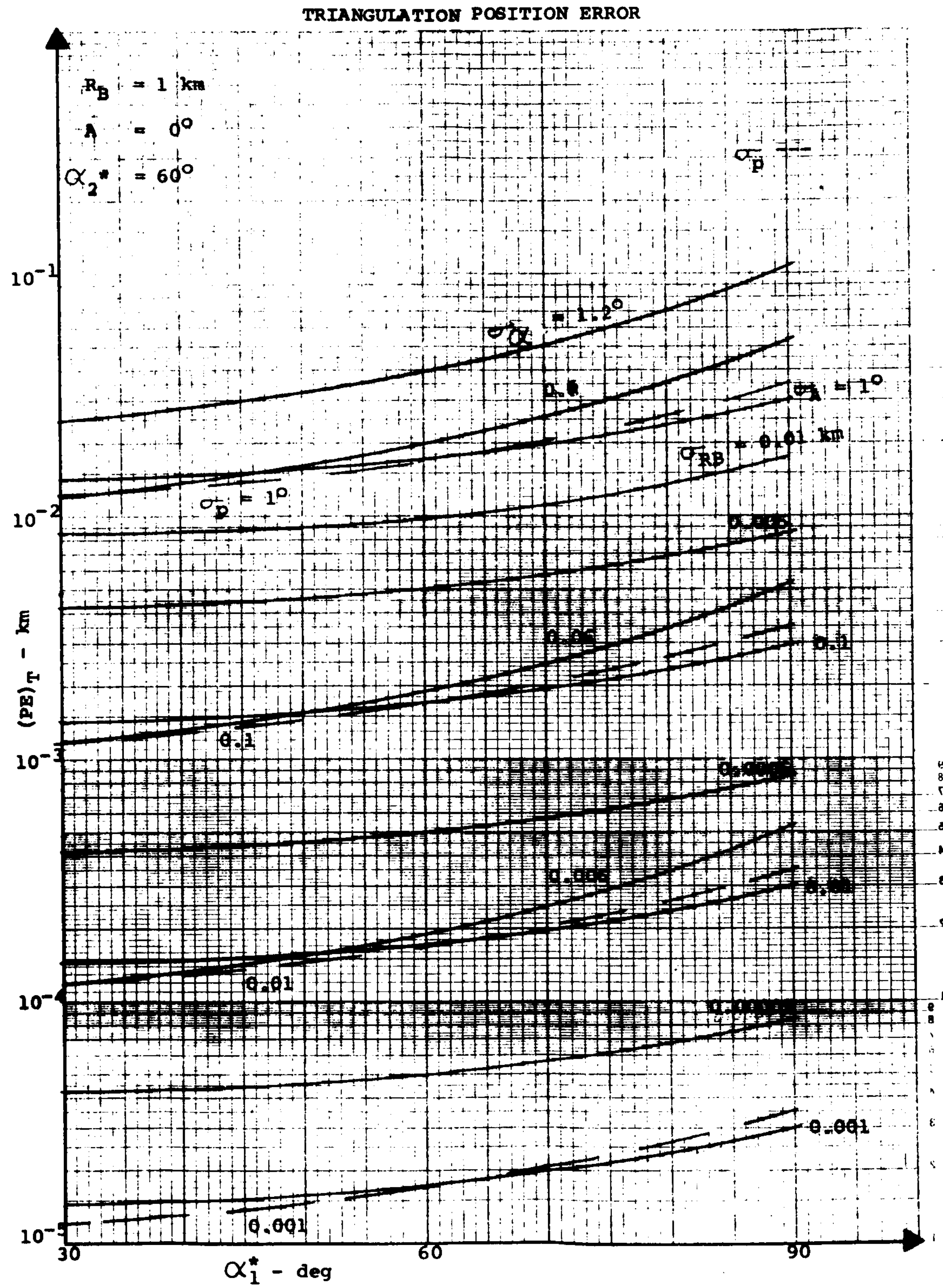


Figure 10-16 Triangulation Position Error

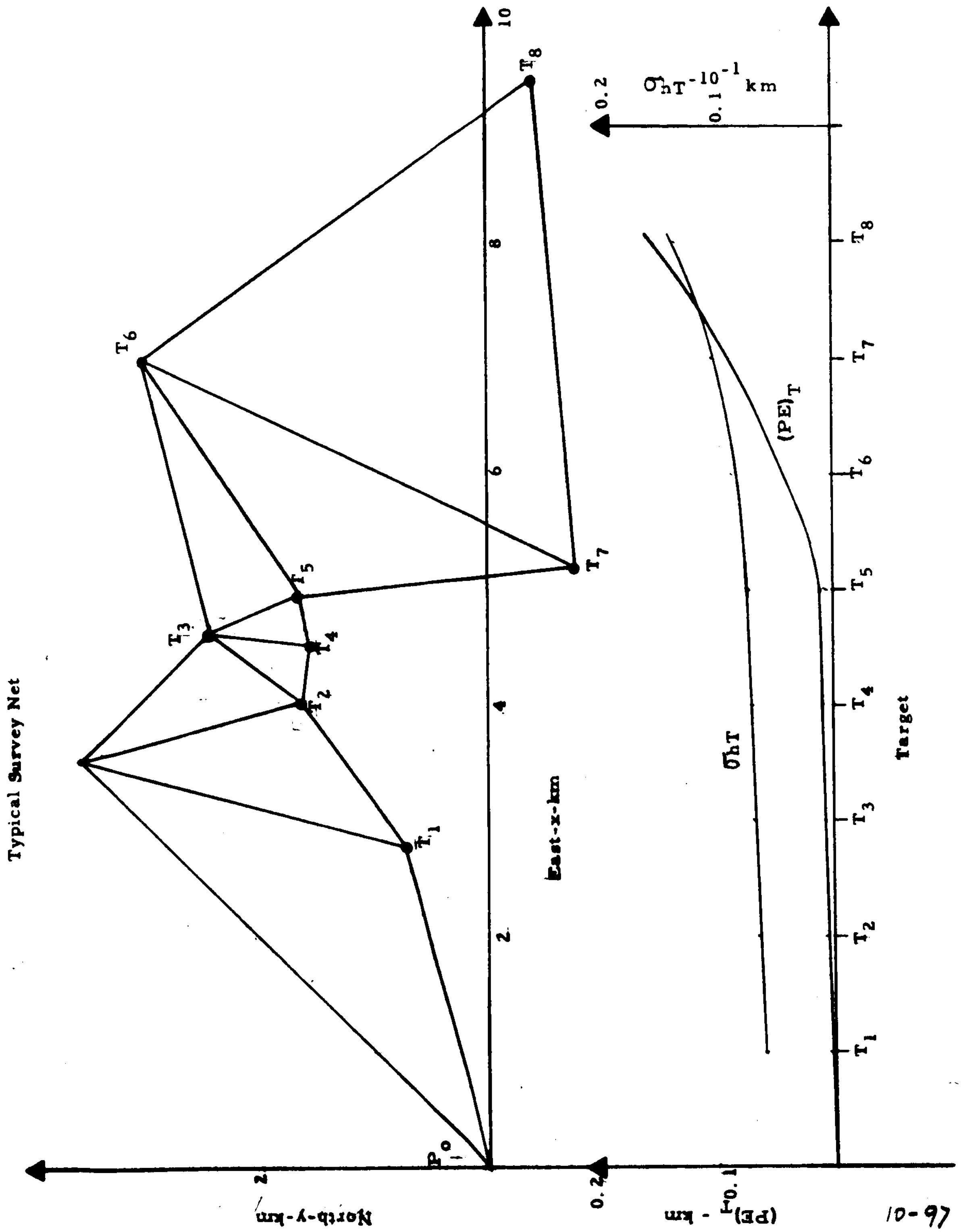


Figure 10-17 Typical Survey Net

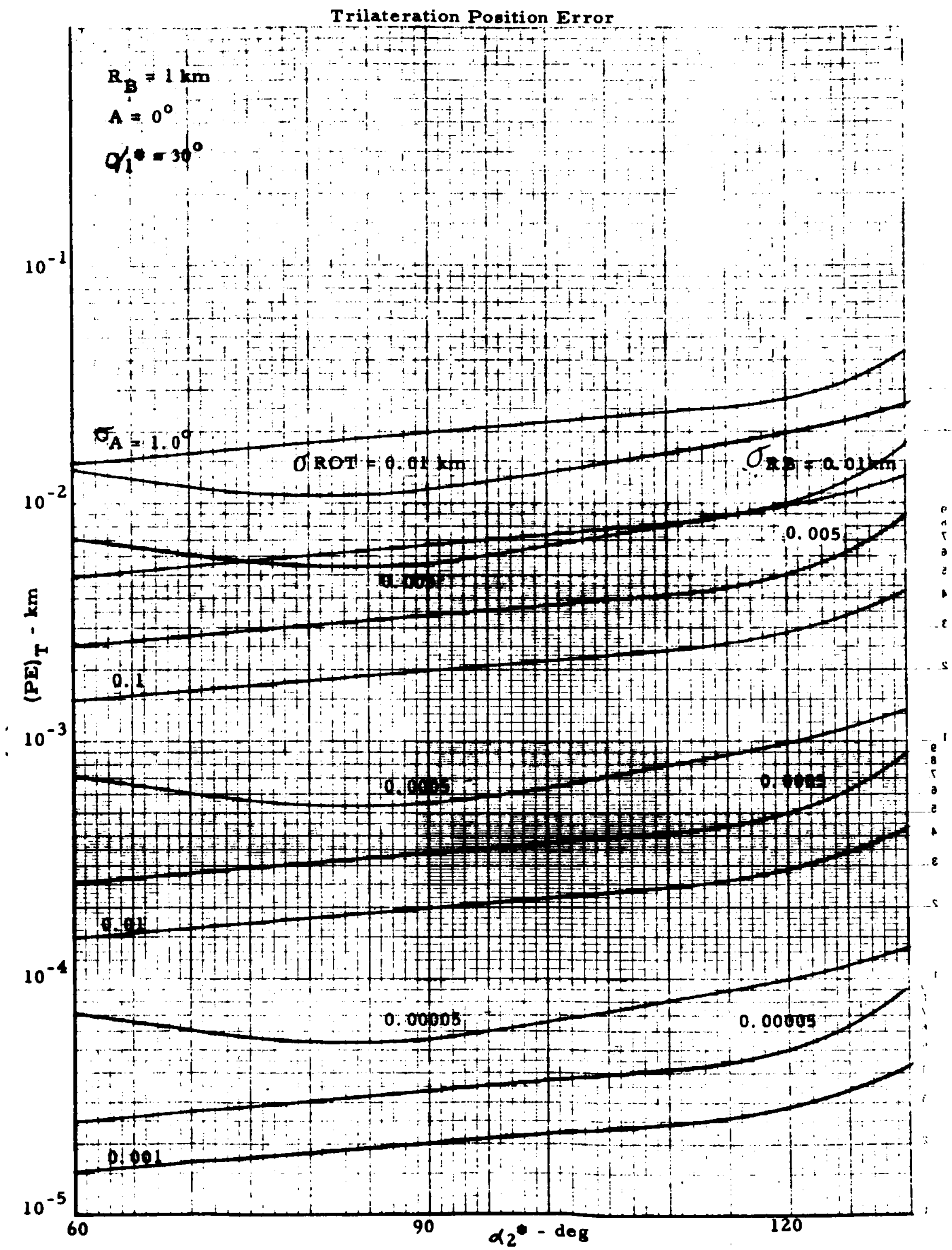


Figure 10-18 Trilateration Position Error

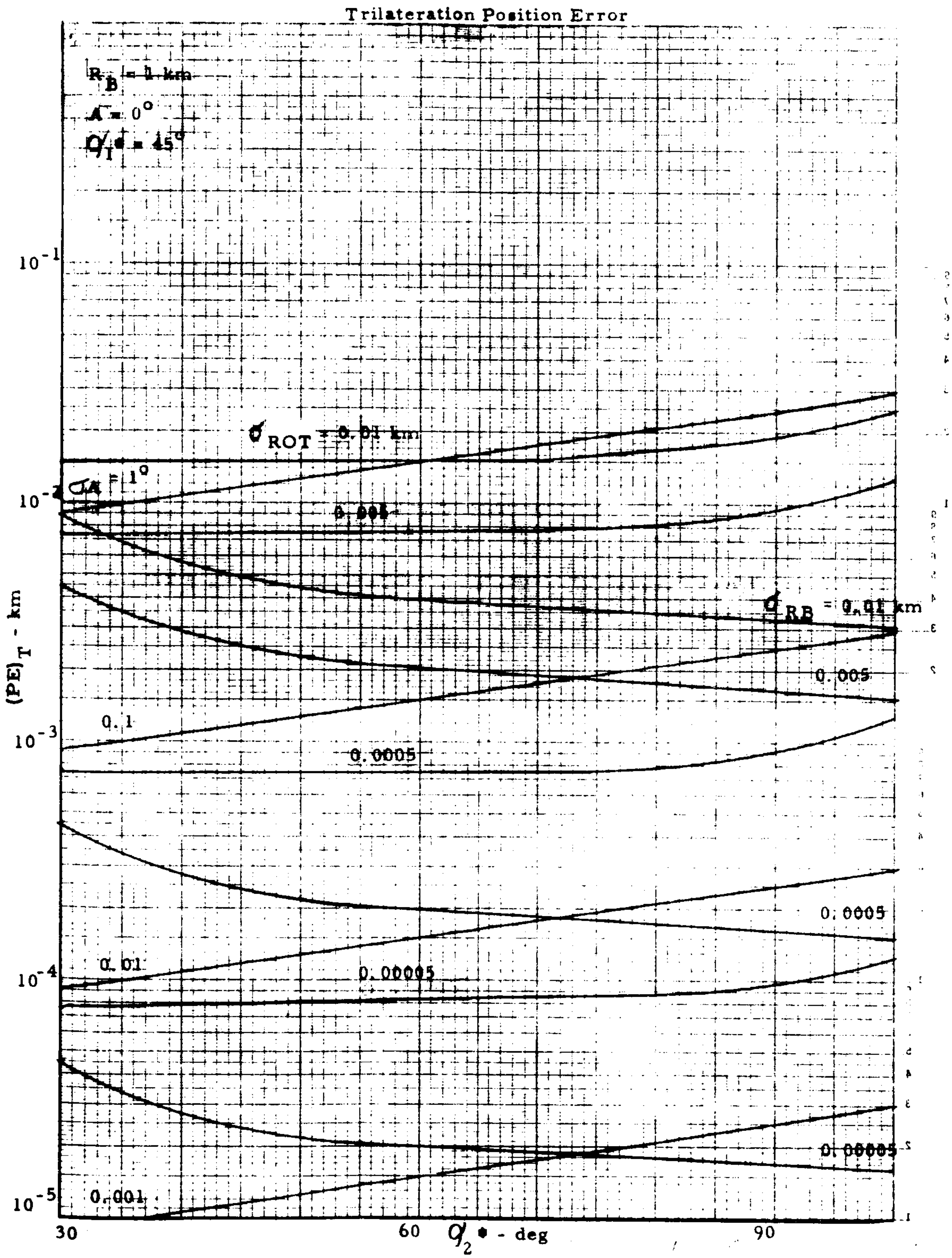


Figure 10-19 Trilateration Position Error

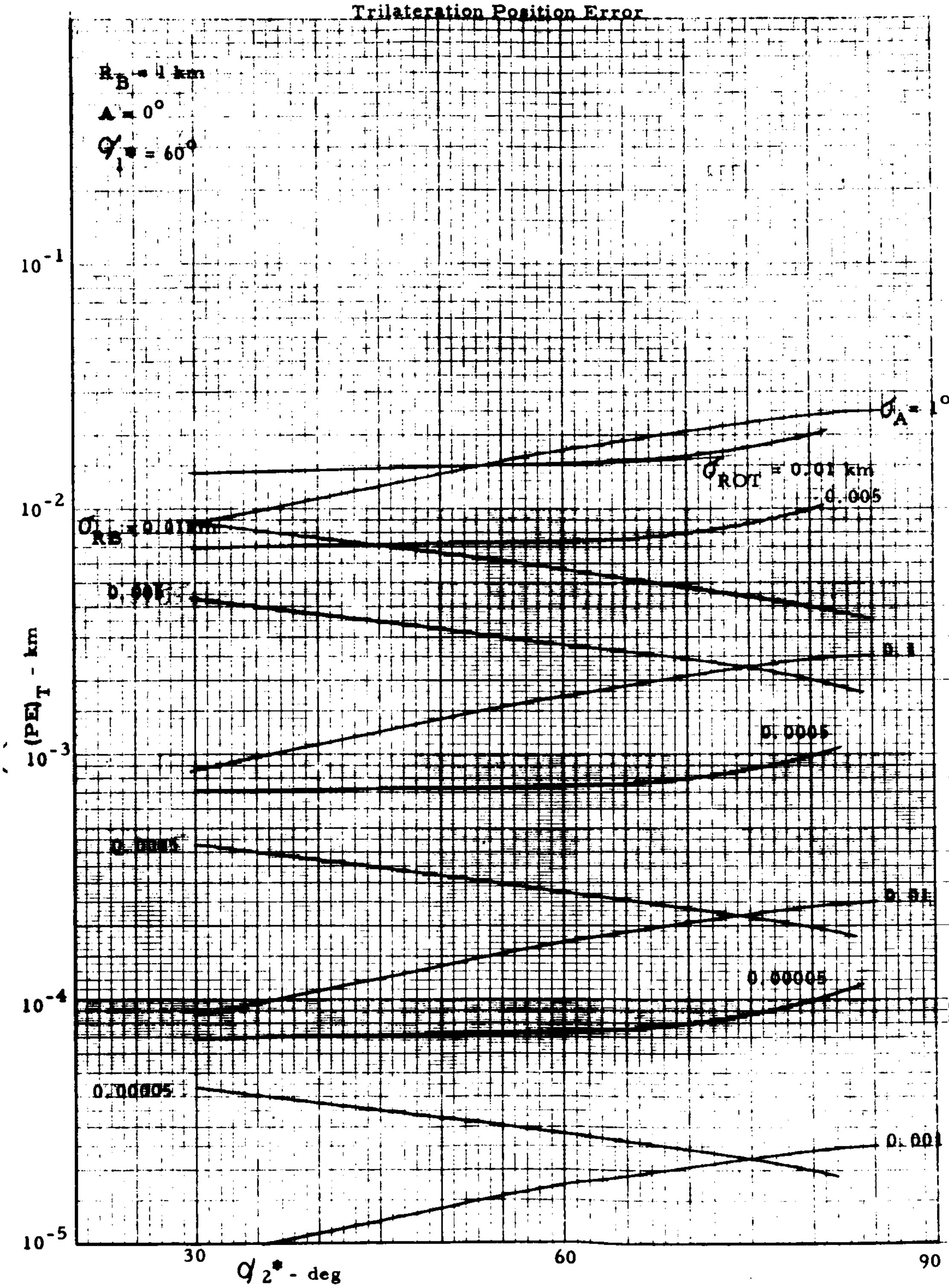


Figure 10-20 Trilateration Position Error

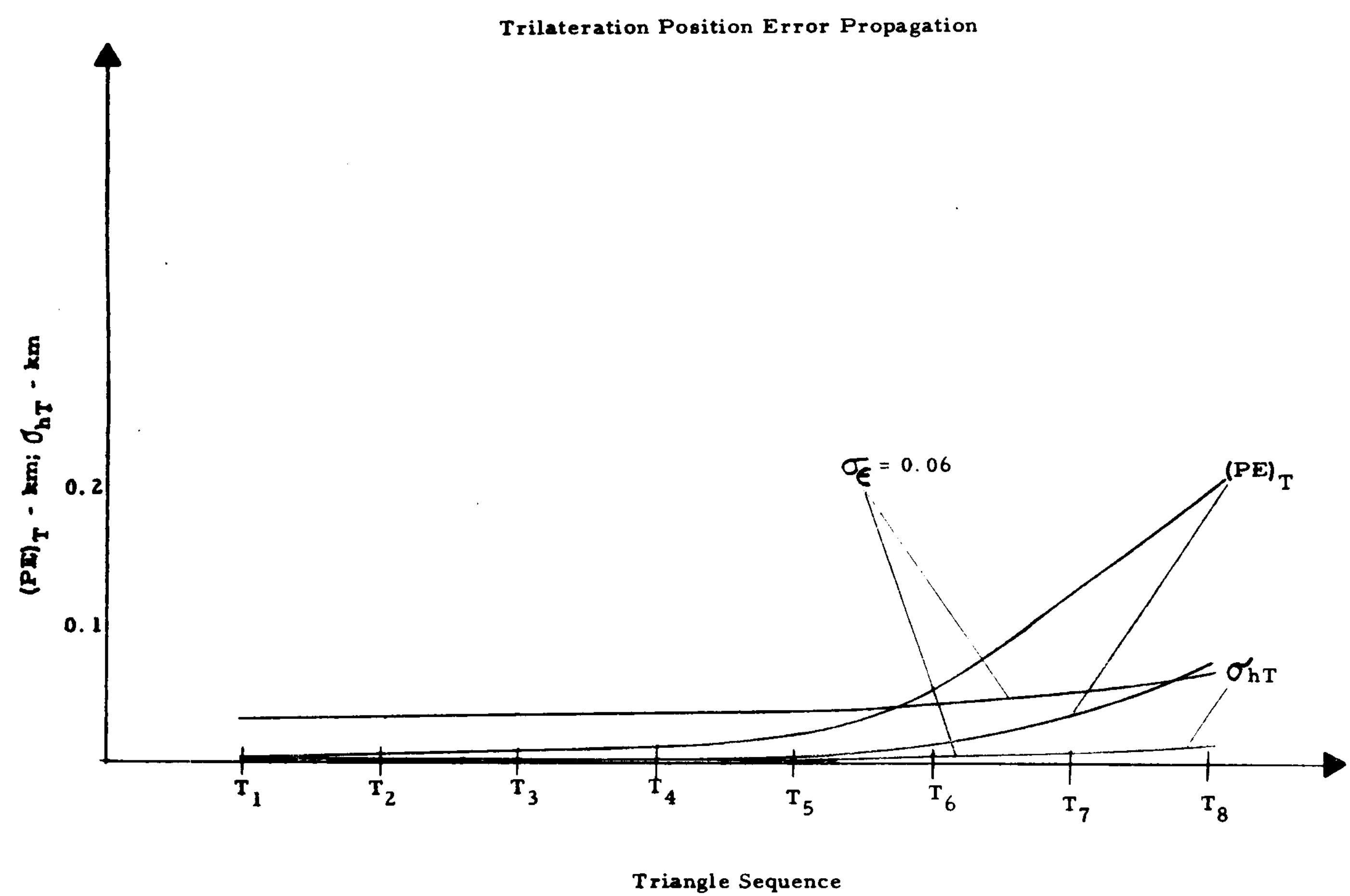


Figure 10-21 Trilateration Position Error Propagation

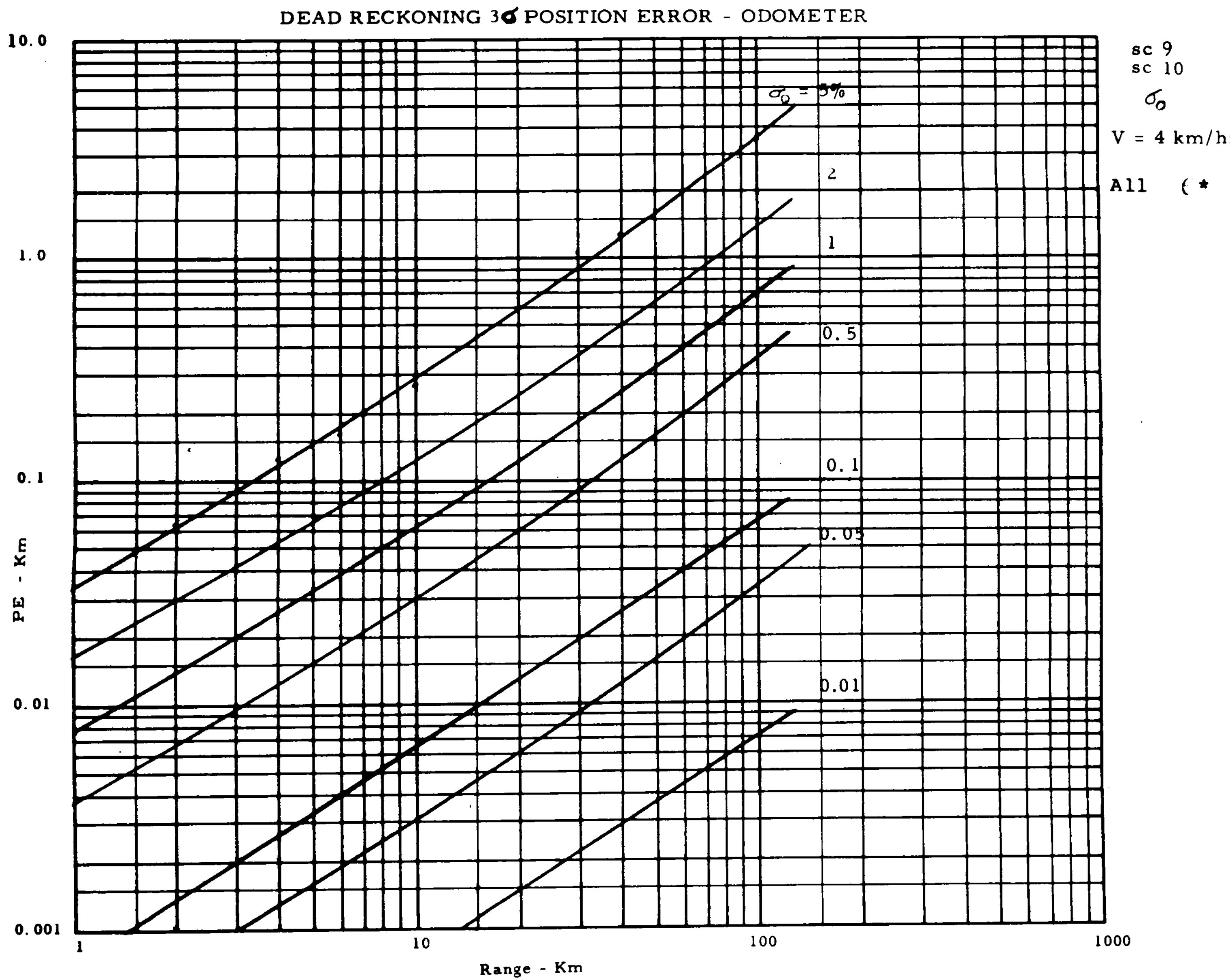


Figure 10-22 Dead Reckoning 3σ Position Error - Odometer

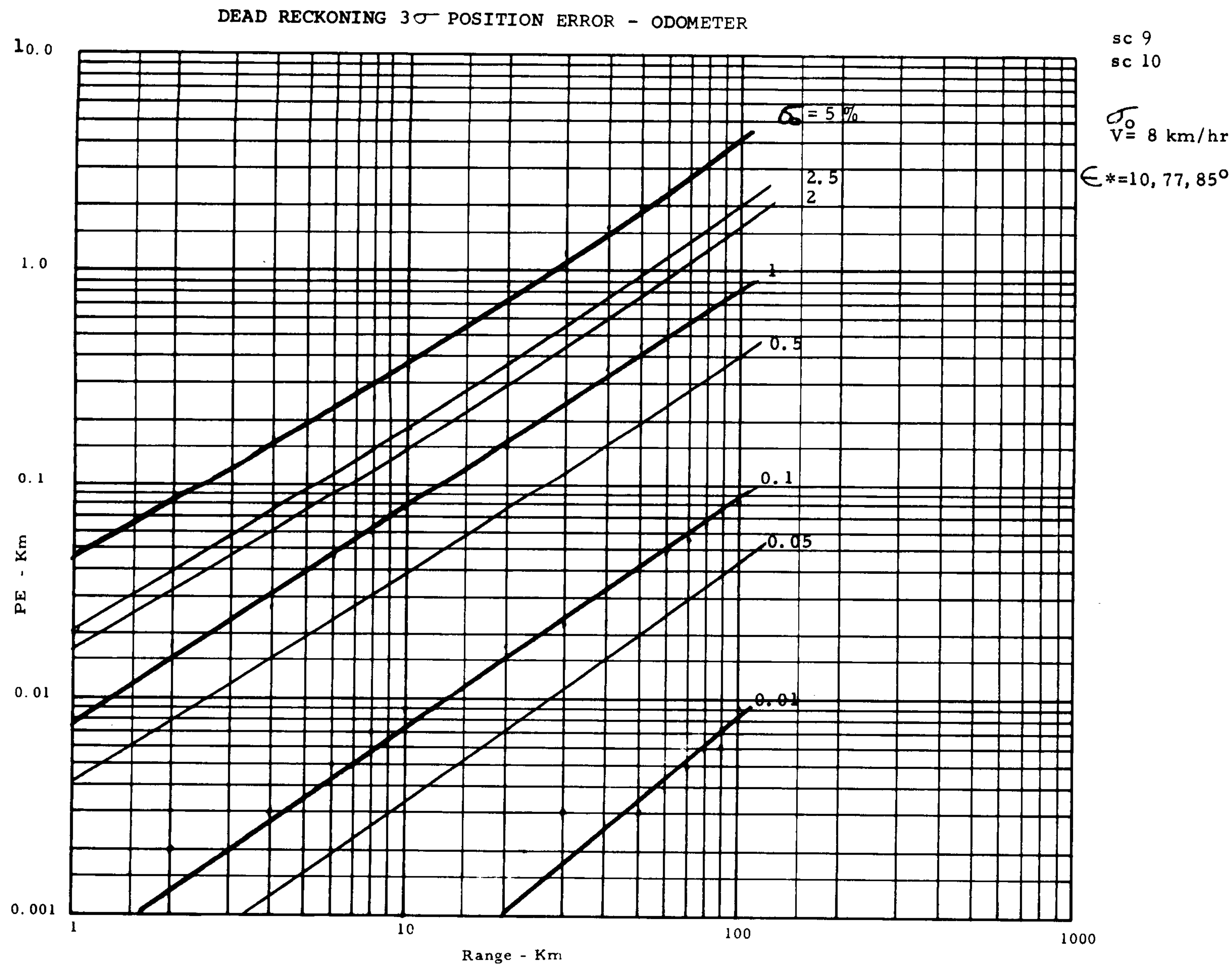


Figure 10-23 Dead Reckoning 3σ Position Error - Odometer

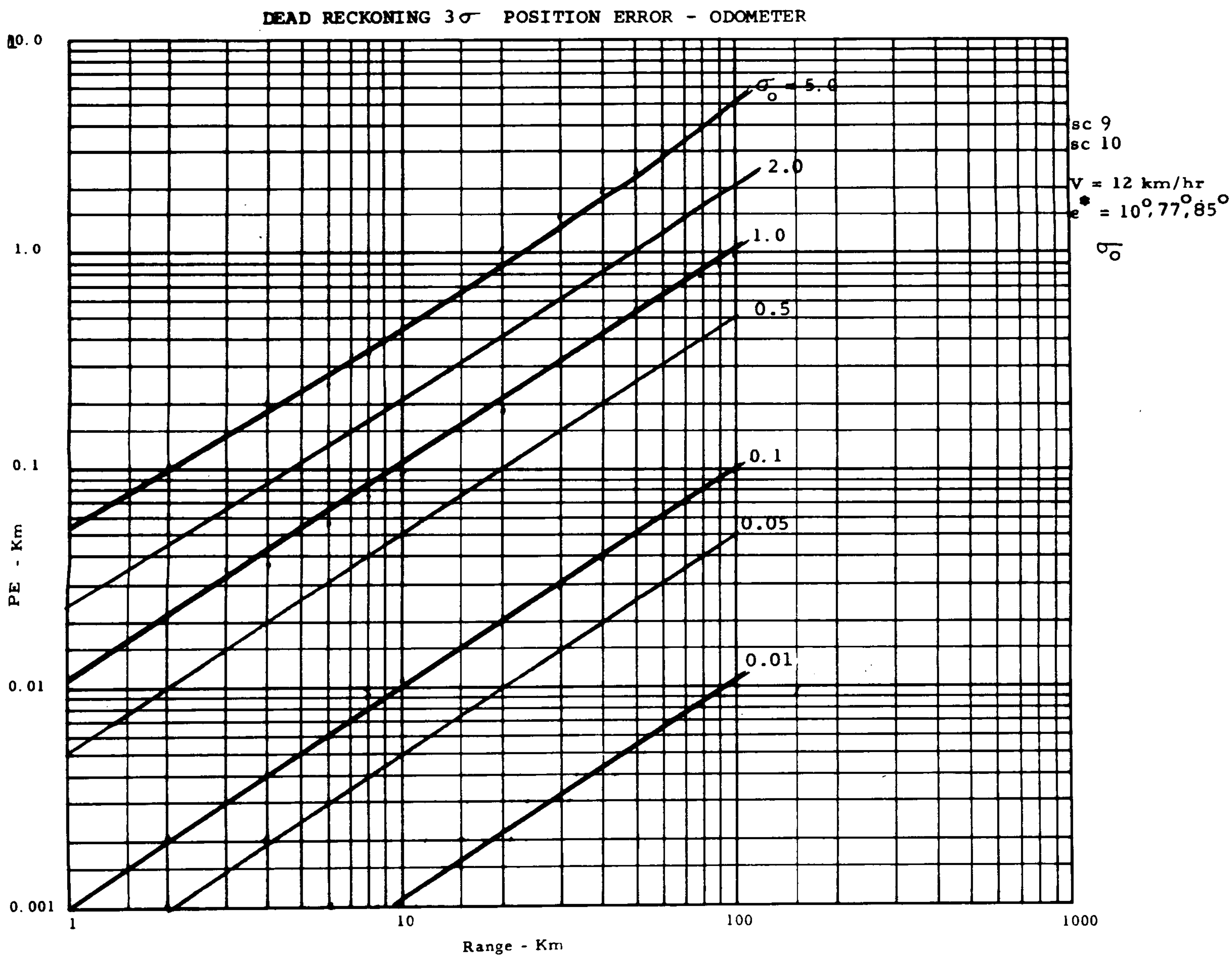


Figure 10-24 Dead Reckoning 3σ Position Error - Odometer

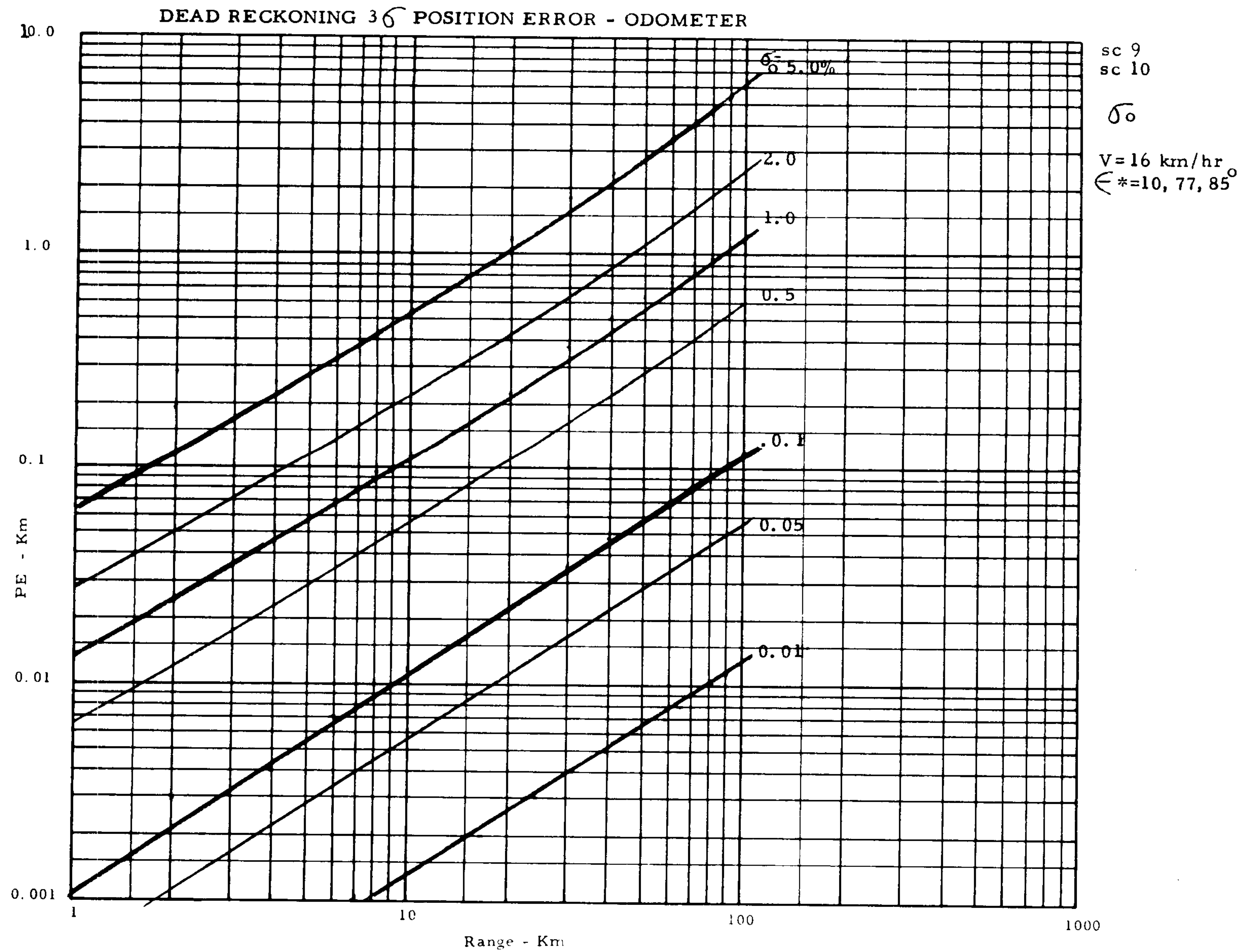


Figure 10-25 Dead Reckoning 3σ Position Error - Odometer

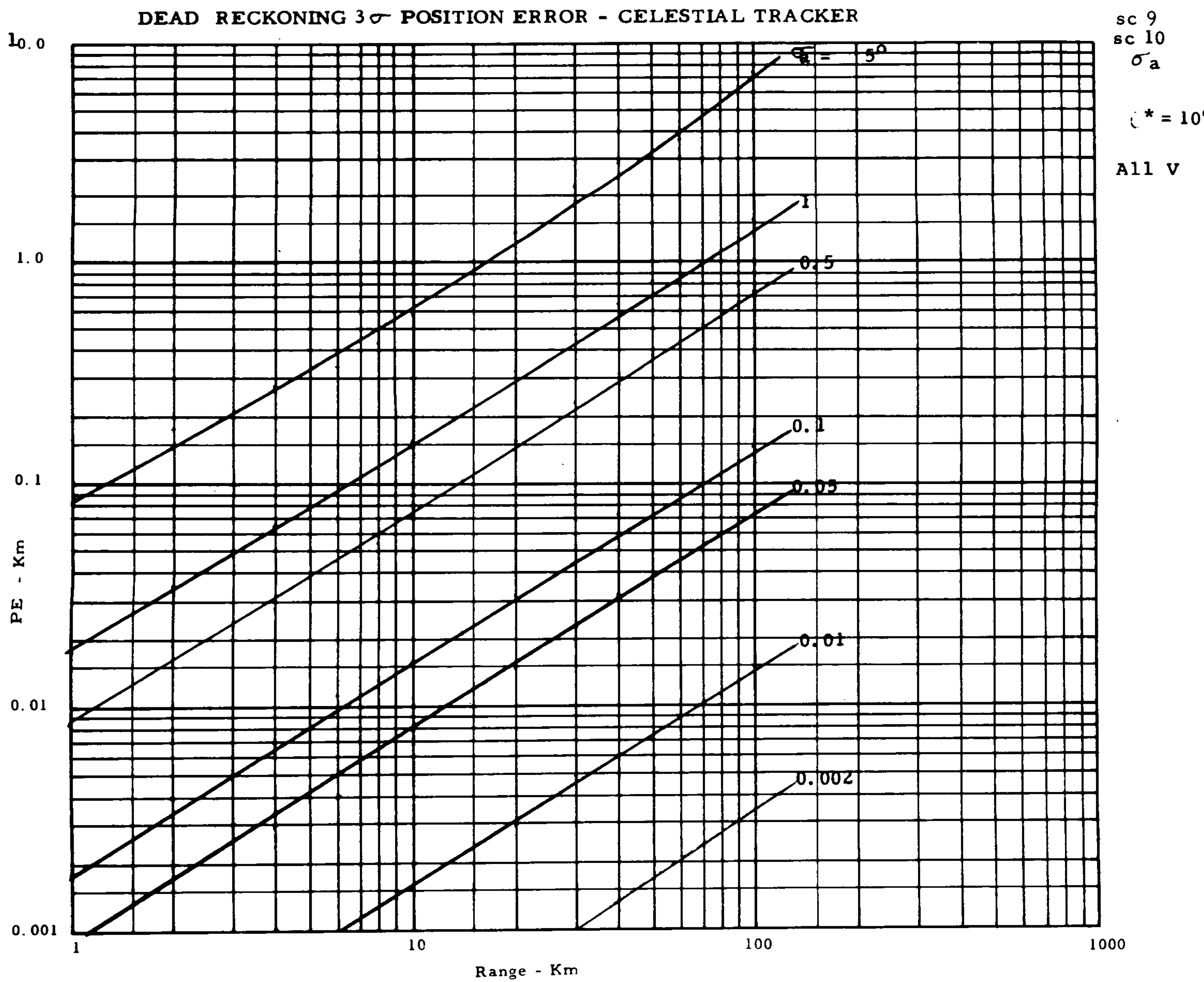


Figure 10-26 Dead Reckoning 3σ Position Error - Celestial Tracker

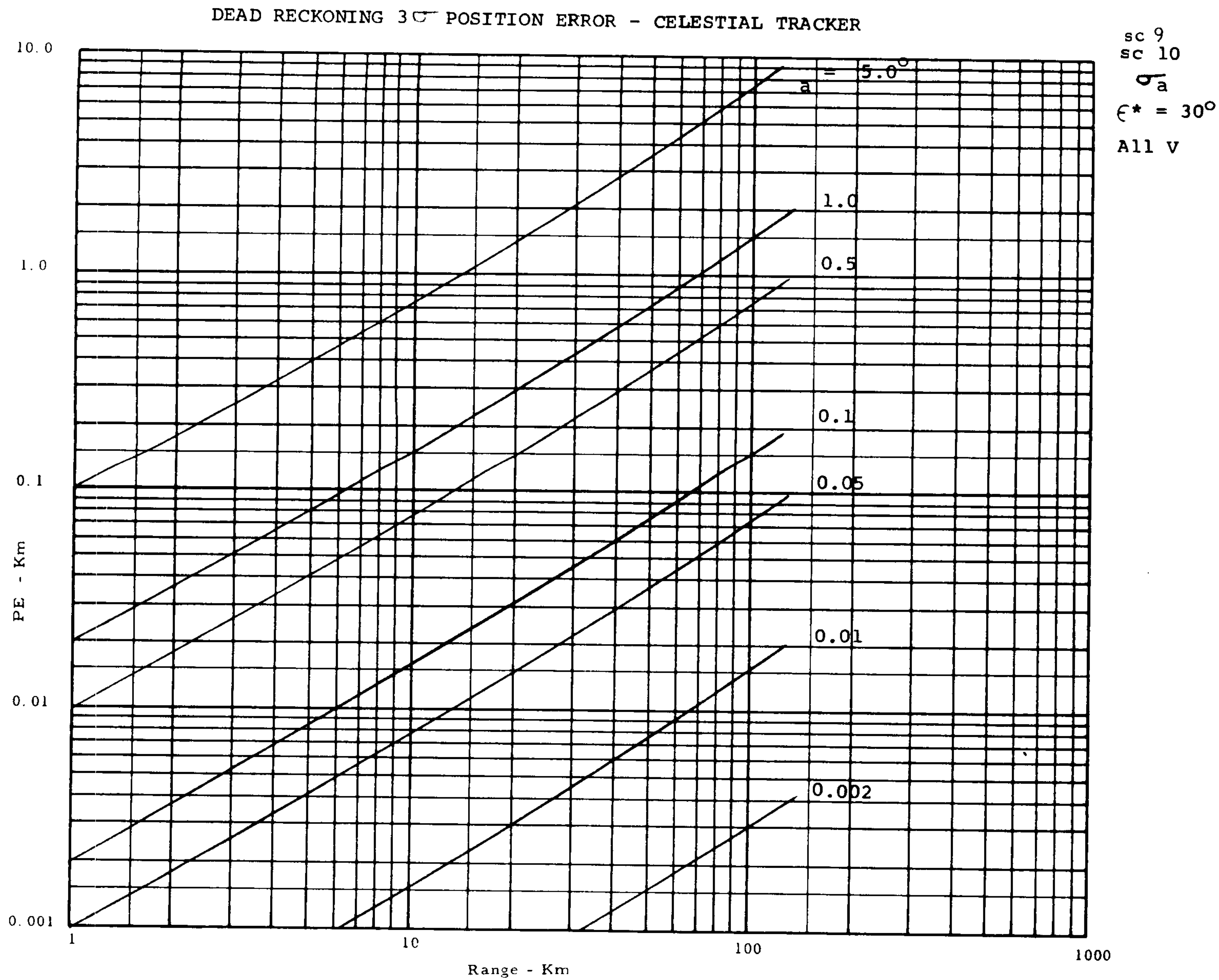


Figure 10-27 Dead Reckoning 3σ Position Error - Celestial Tracker

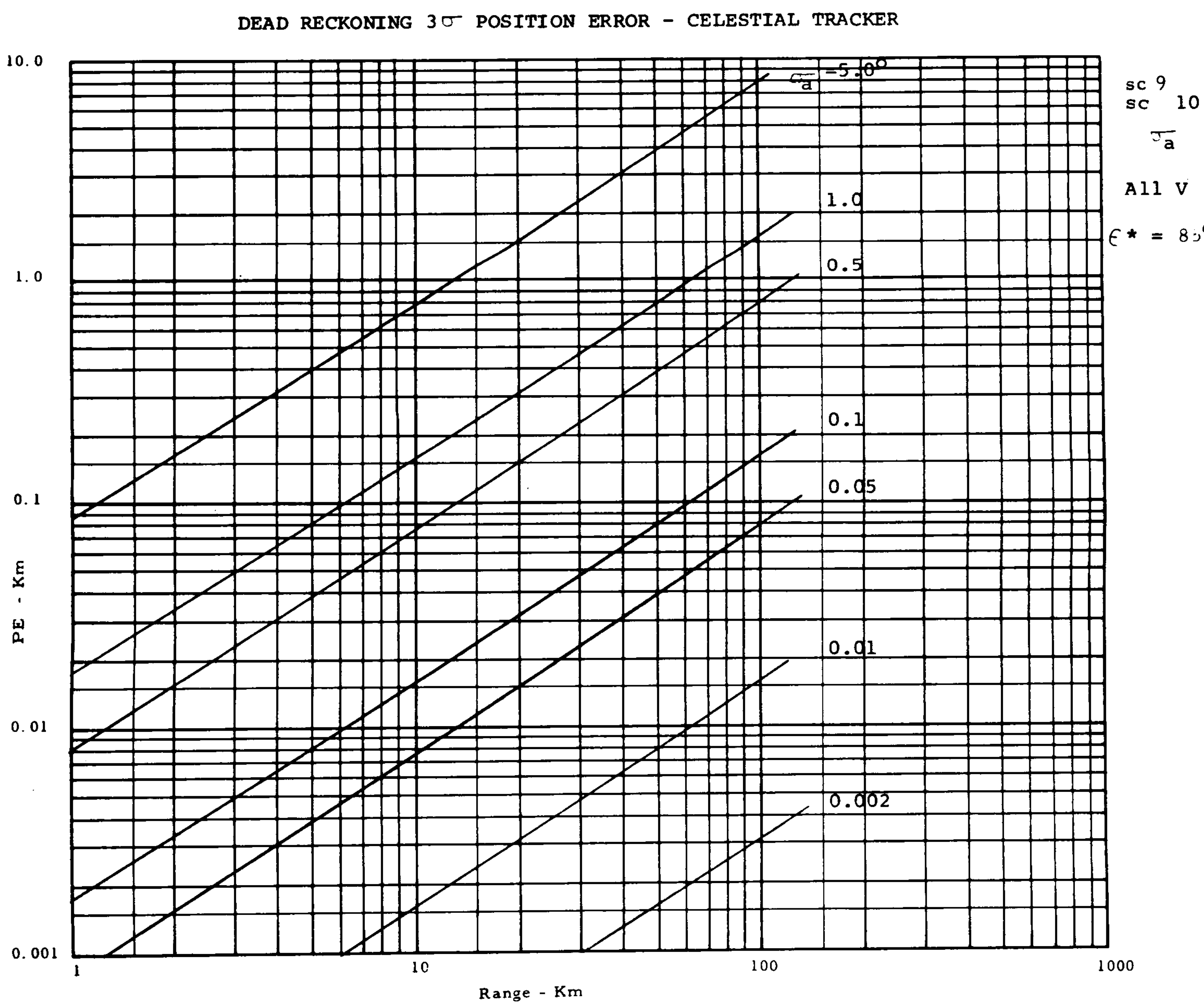


Figure 10-28 Dead Reckoning 3σ Position Error - Celestial Tracker

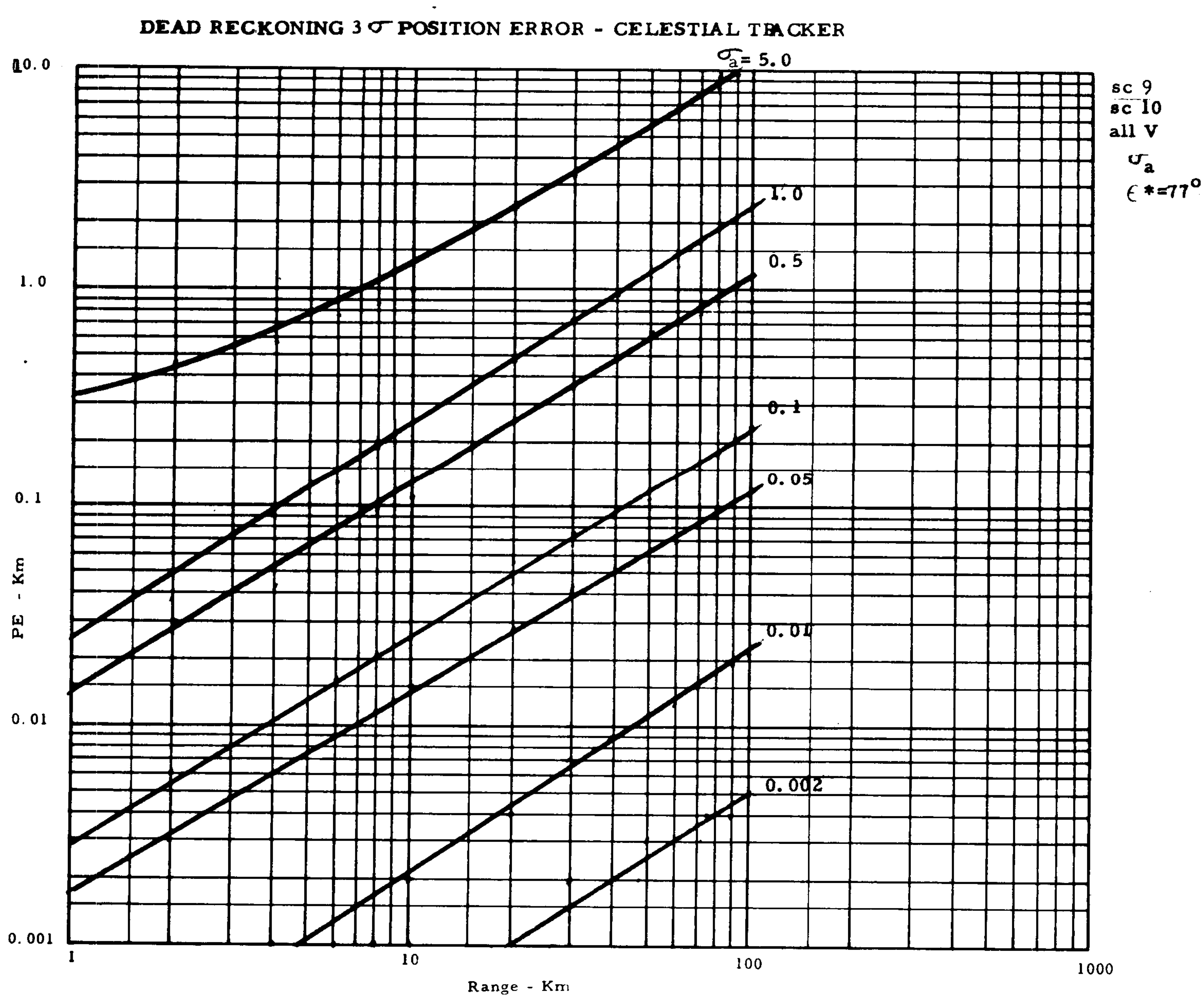


Figure 10-29 Dead Reckoning 3σ Position Error - Celestail Tracker

DEAD RECKONING 3σ POSITION ERROR - CELESTIAL TRACKER

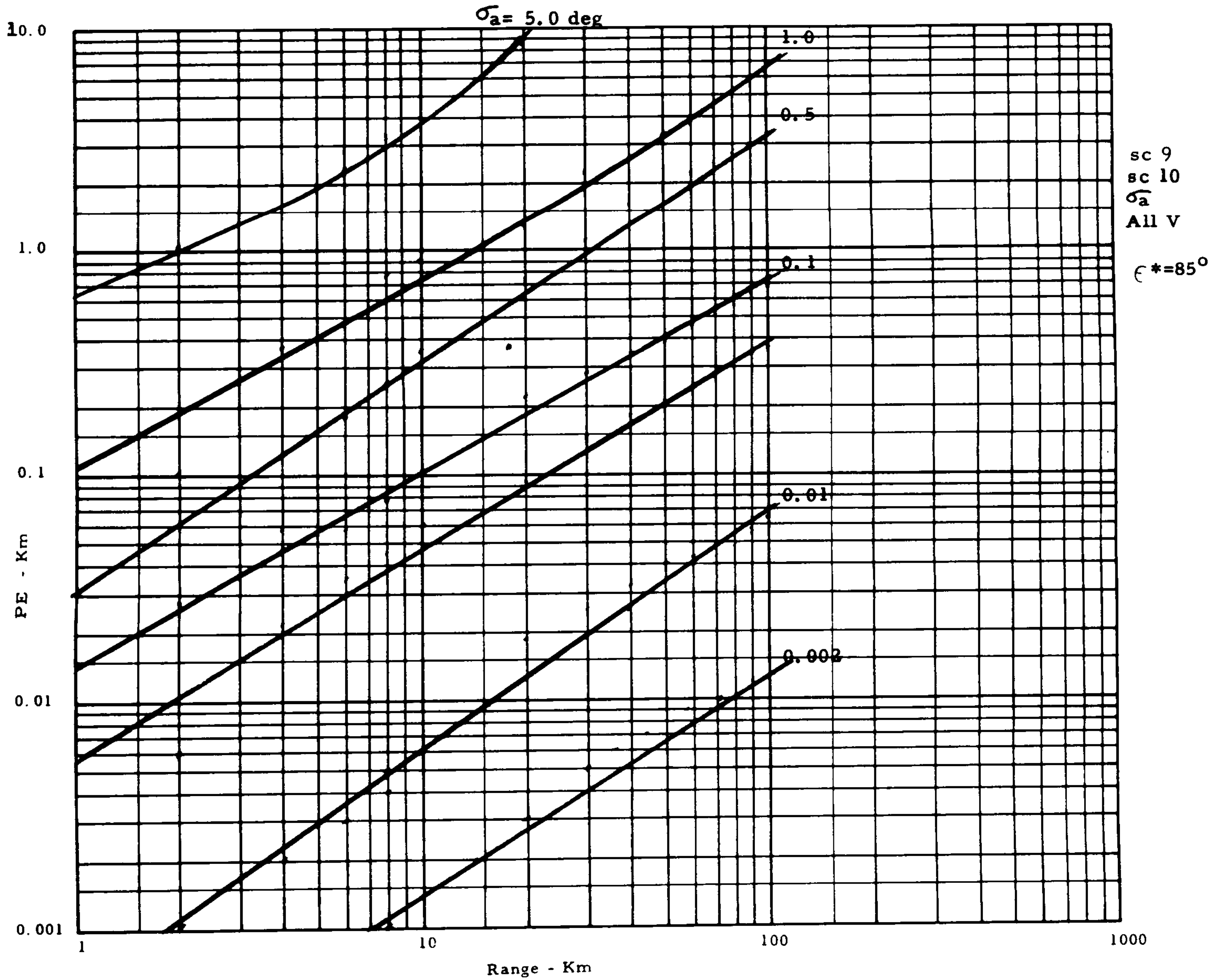


Figure 10-30 Dead Reckoning 3σ Position Error - Celestial Tracker

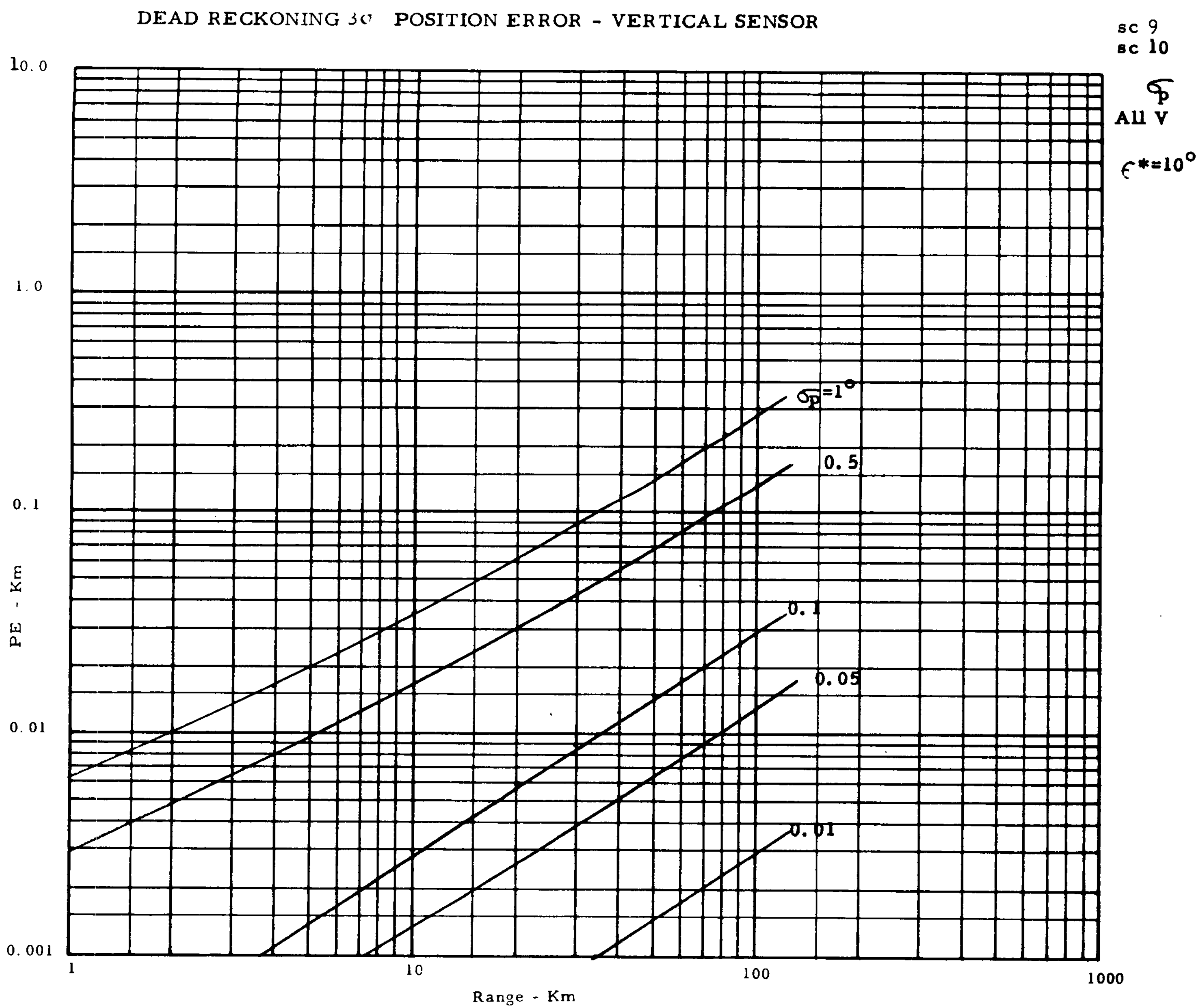


Figure 10-31 Dead Reckoning 3σ Position Error - Vertical Sensor

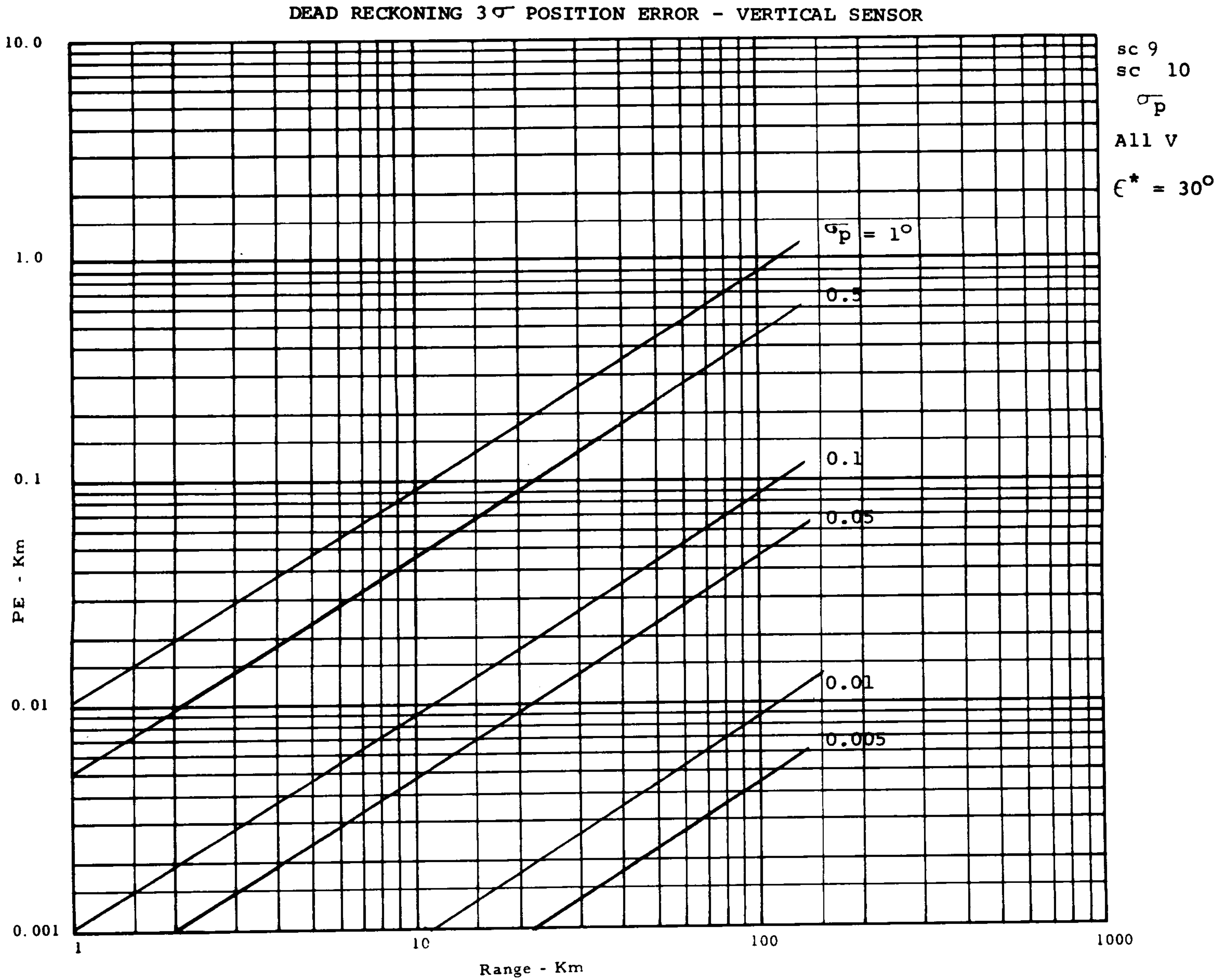


Figure 10-32 Dead Reckoning 3σ Position Error—Vertical Sensor

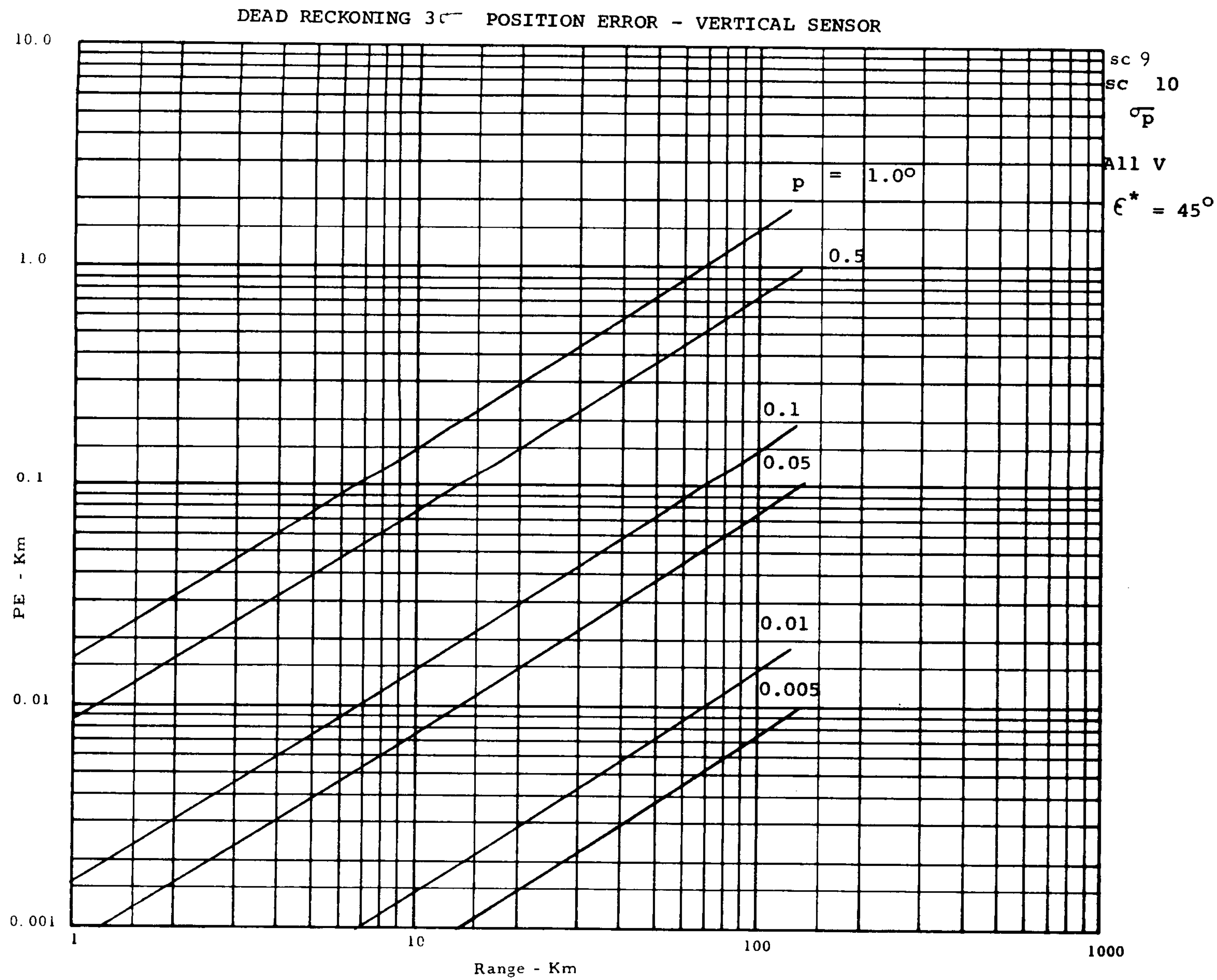


Figure 10-33 Dead Reckoning 3σ Position Error—Vertical Sensor

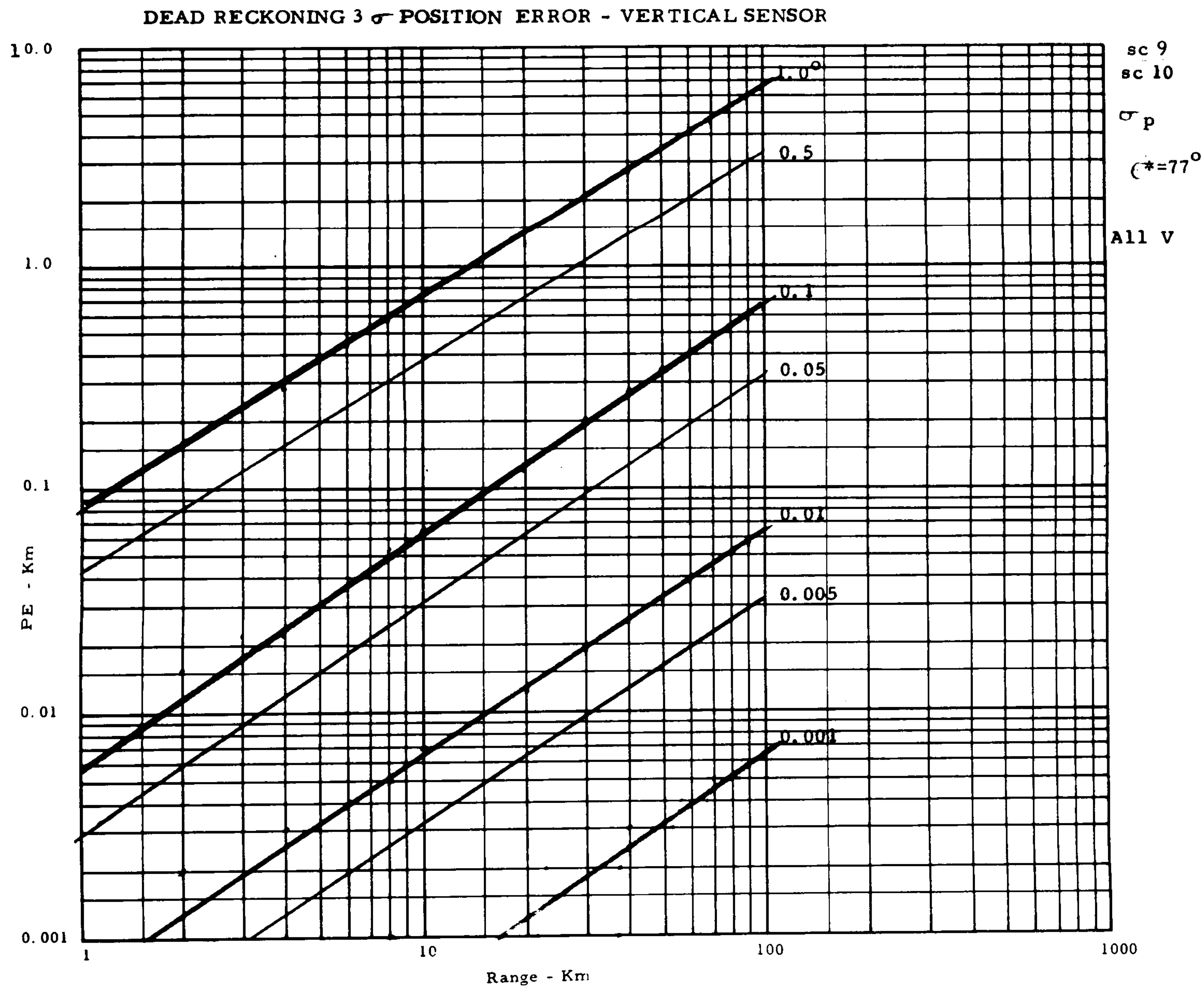


Figure 10-34 Dead Reckoning 3σ Position Error—Vertical Sensor

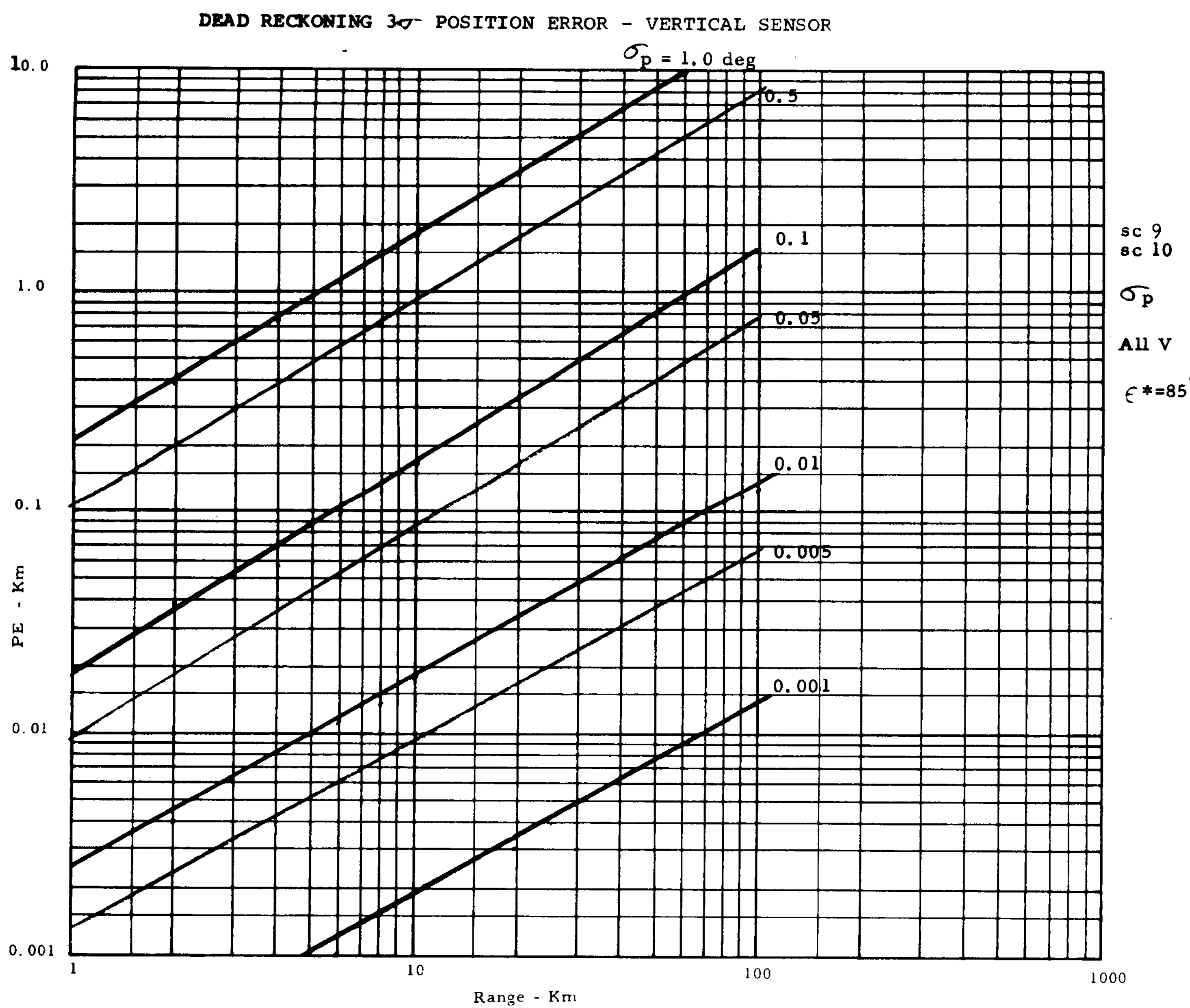


Figure 10-35 Dead Reckoning 3σ Position Error—Vertical Sensor

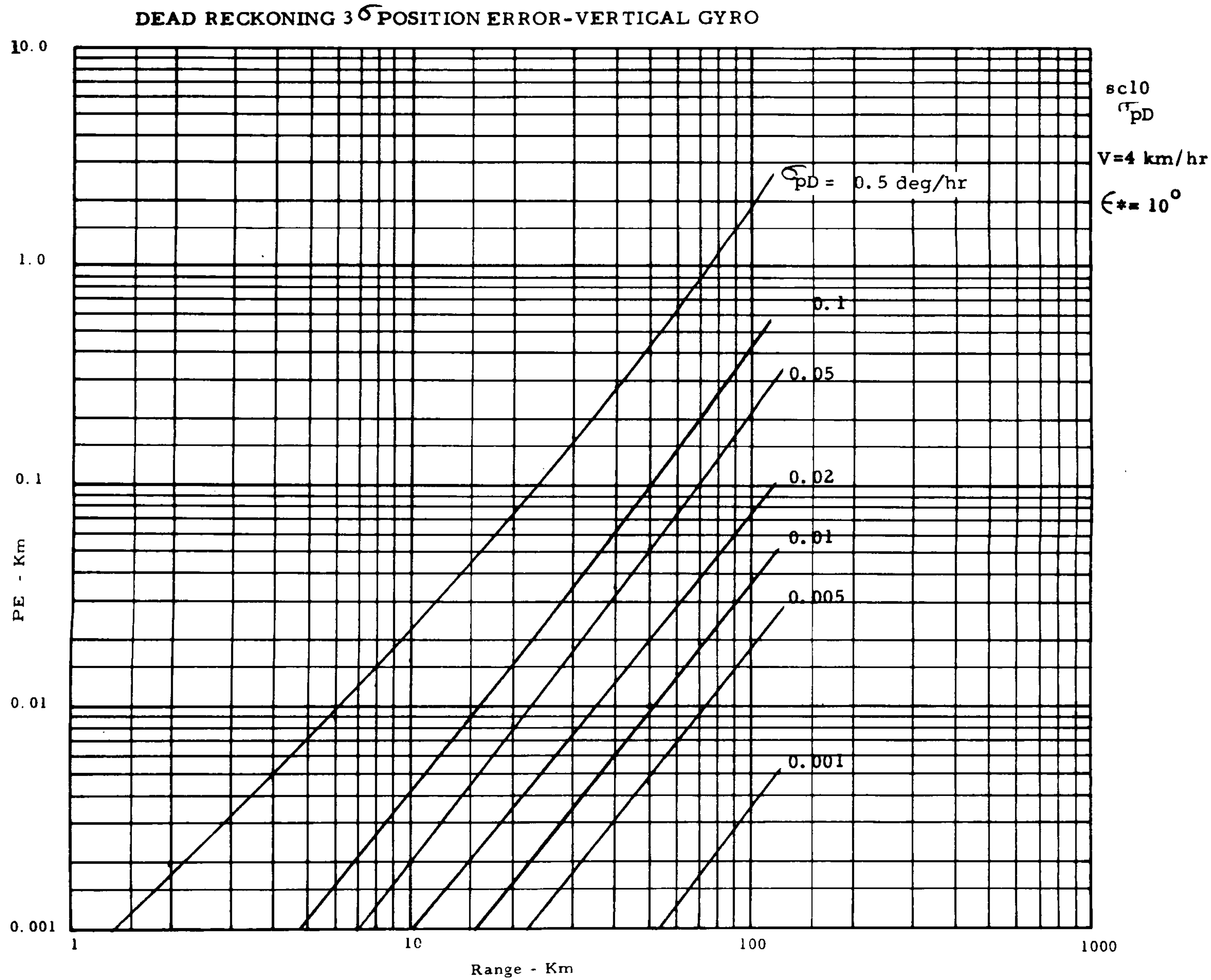


Figure 10-36 Dead Reckoning 3σ Position Error—Vertical Gyro

DEAD RECKONING 3σ POSITION ERROR - VERTICAL GYRO

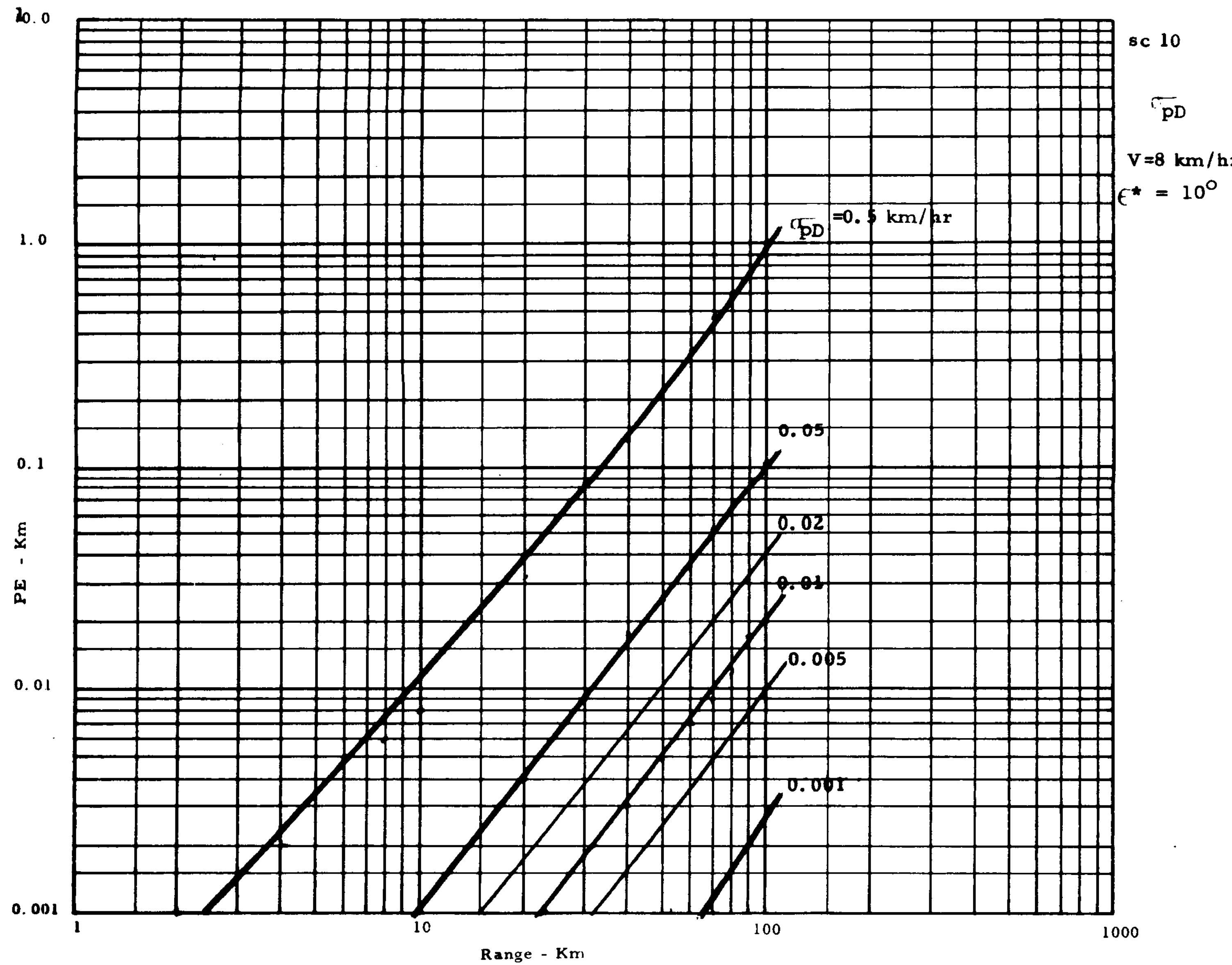


Figure 10-37 Dead Reckoning 3σ Position Error—Vertical Gyro

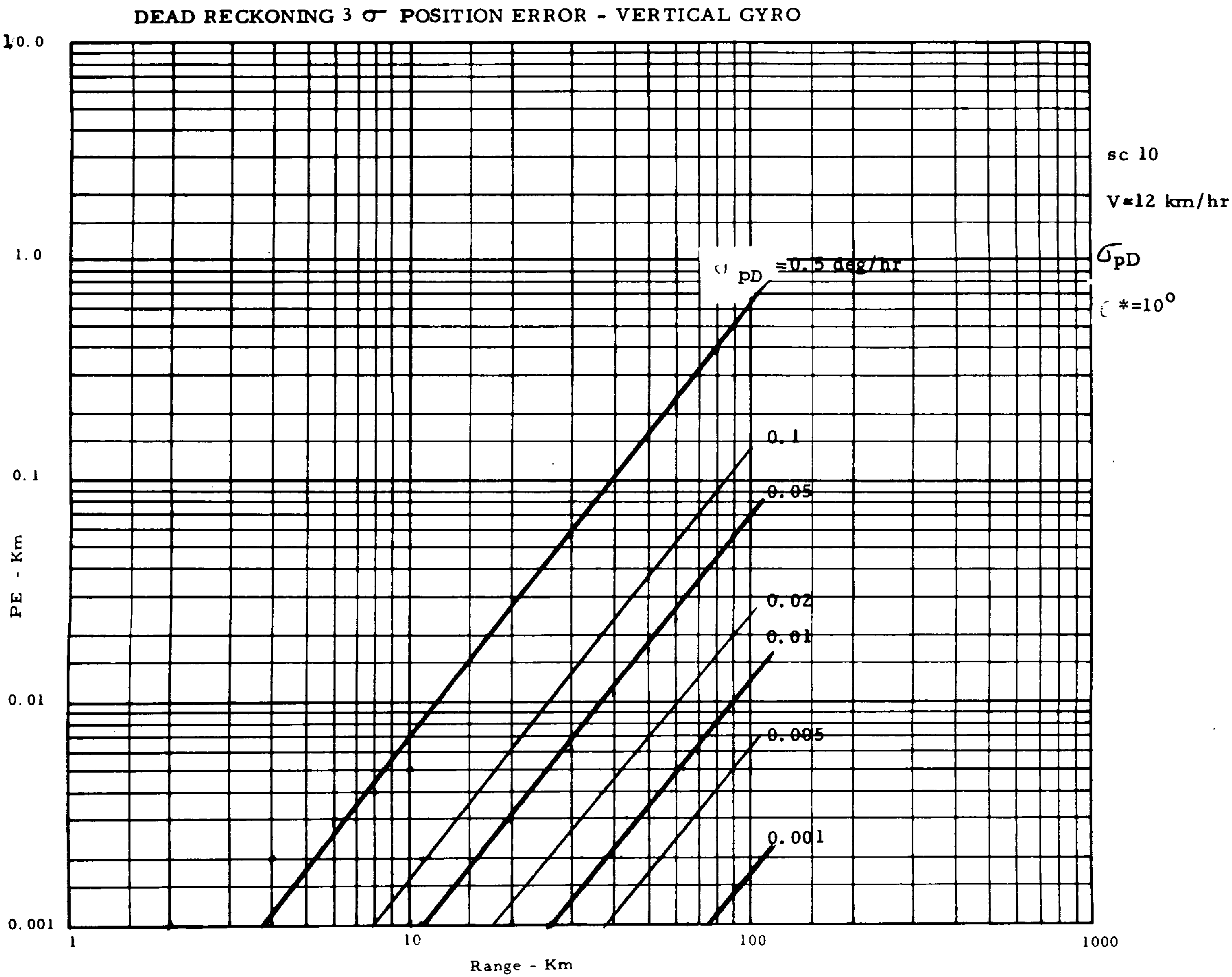


Figure 10-38 Dead Reckoning 3σ Position Error—Vertical Gyro

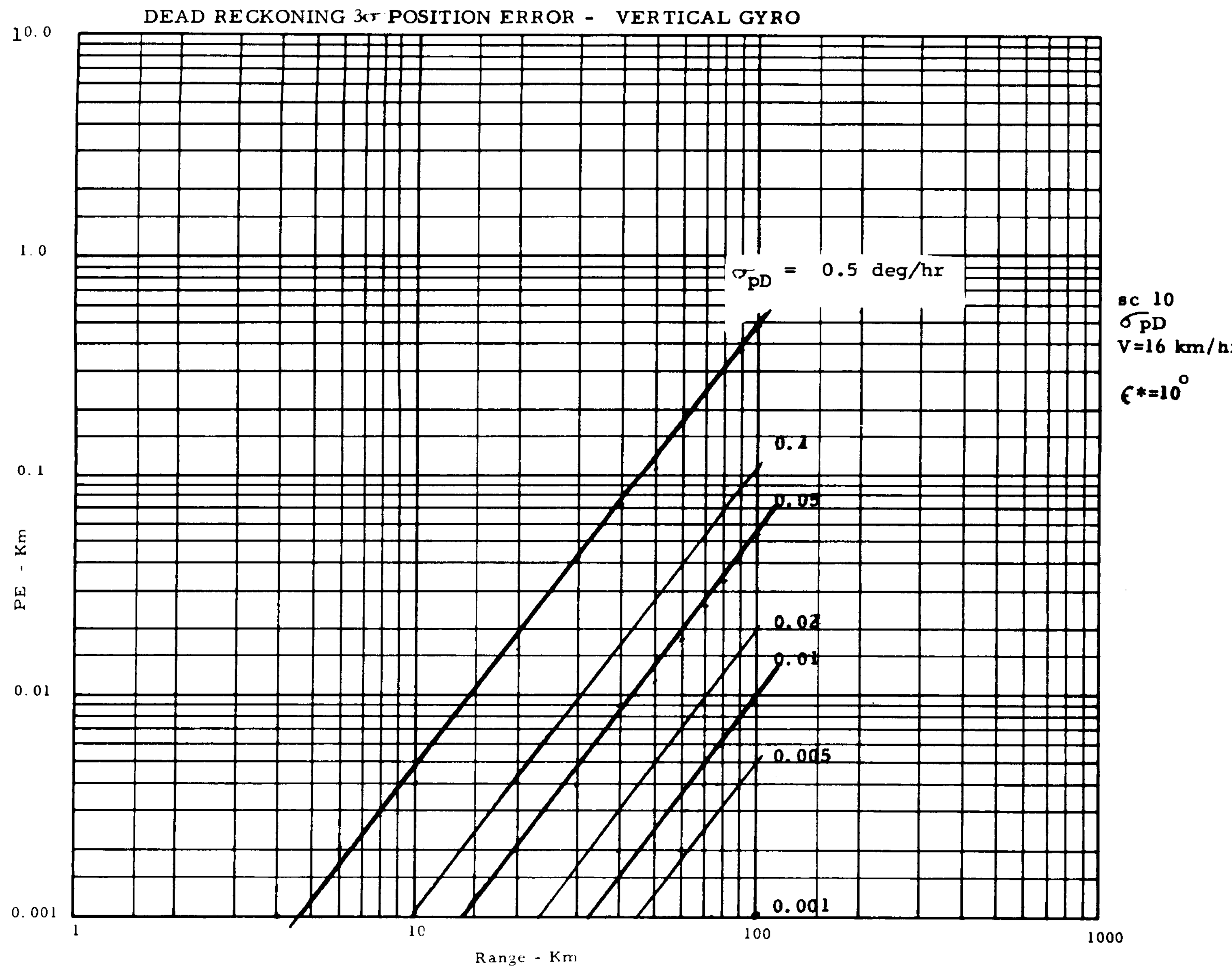


Figure 10-39 Dead Reckoning 3σ Position Error—Vertical Gyro

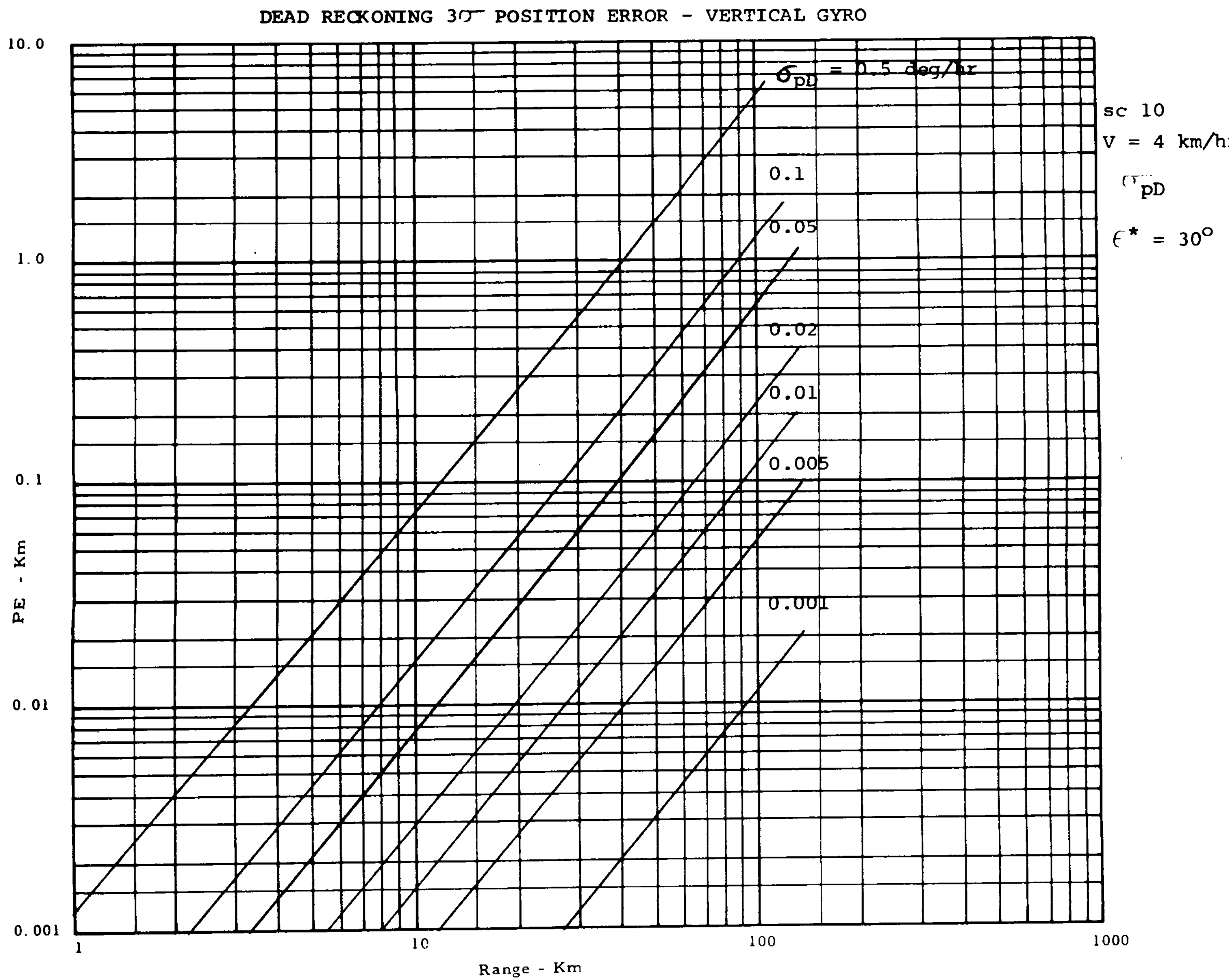


Figure 10-40 Dead Reckoning 3σ Position Error—Vertical Gyro

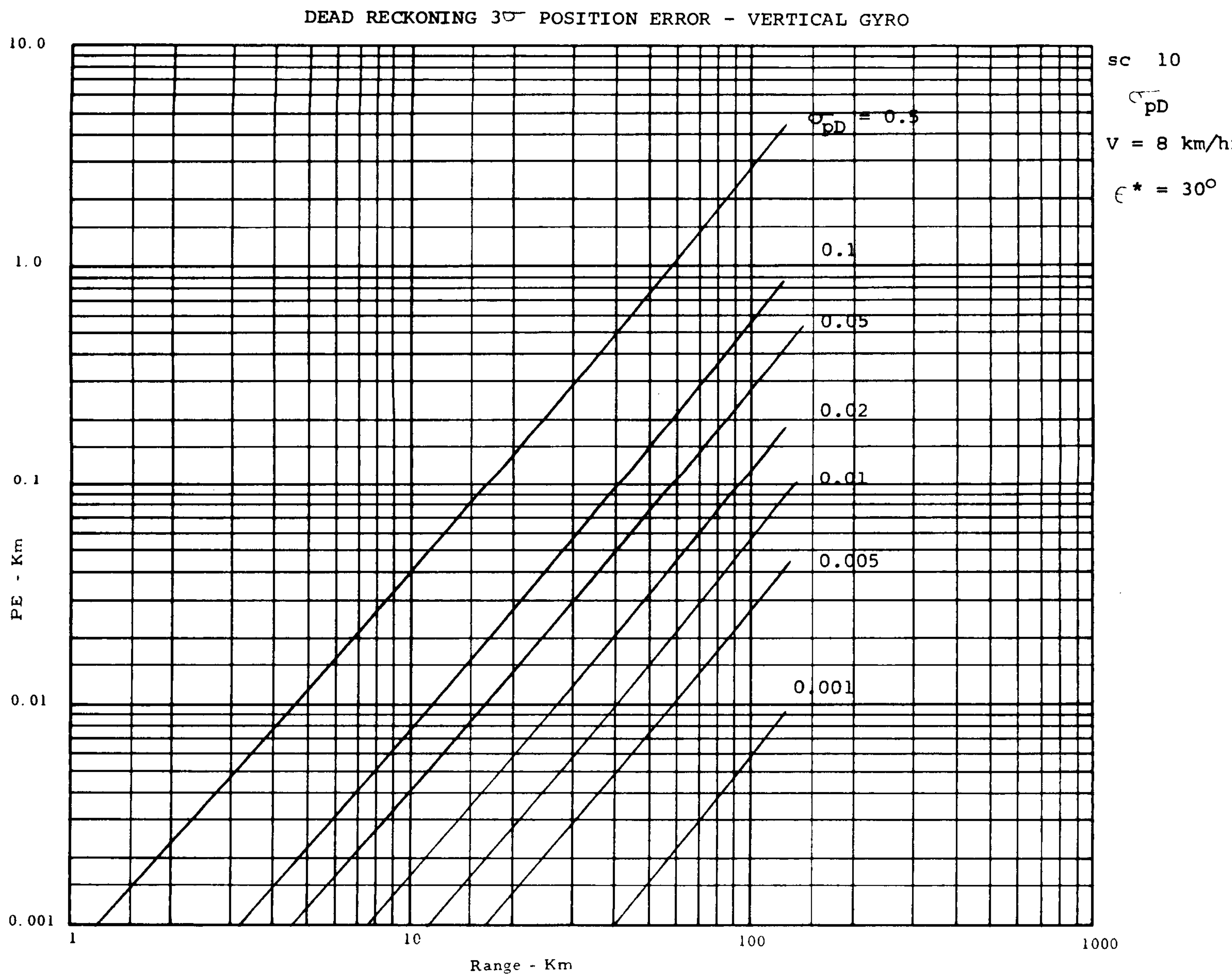


Figure 10-41 Dead Reckoning 3σ Position Error—Vertical Gyro

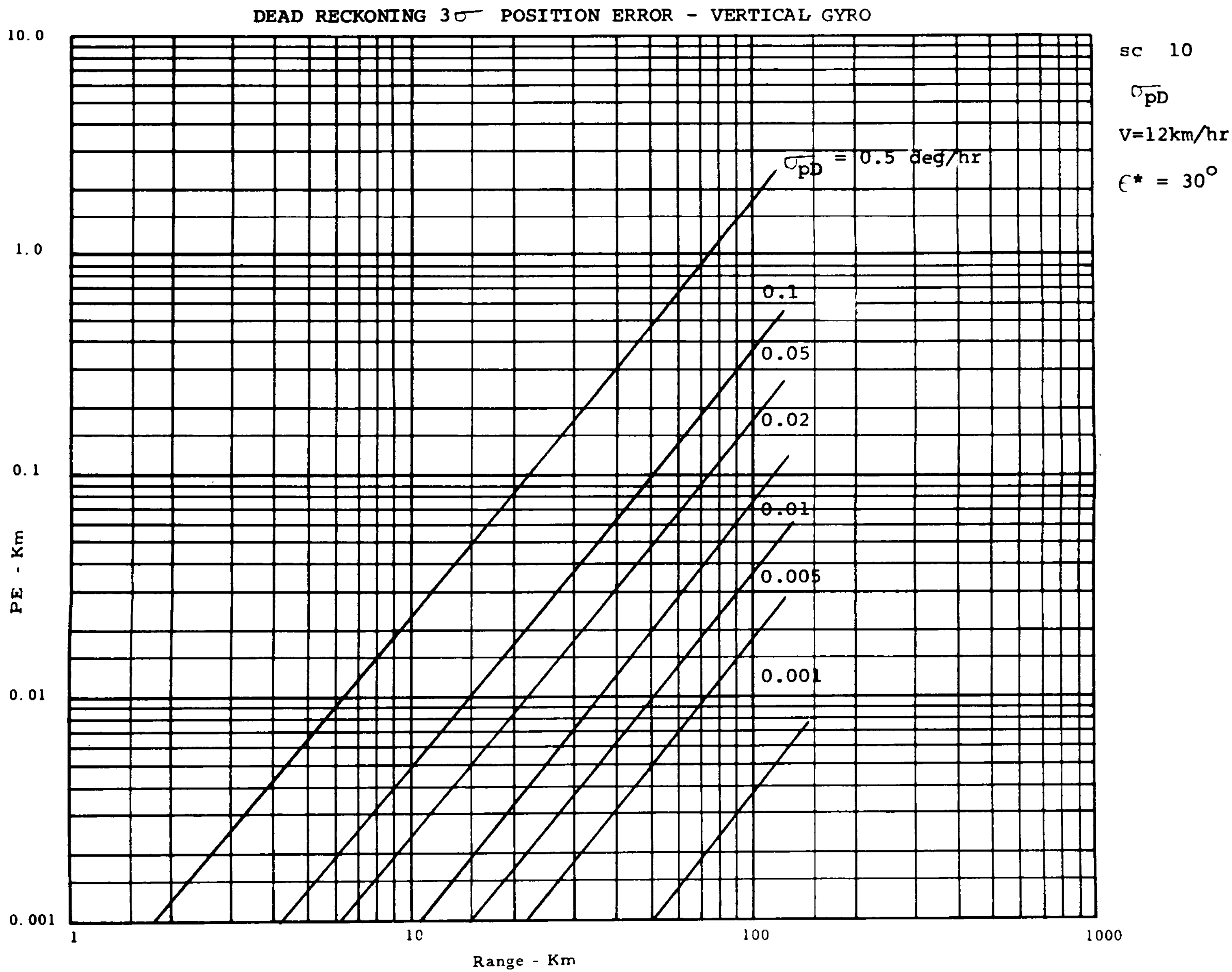


Figure 10-42 Dead Reckoning 3σ Position Error—Vertical Gyro

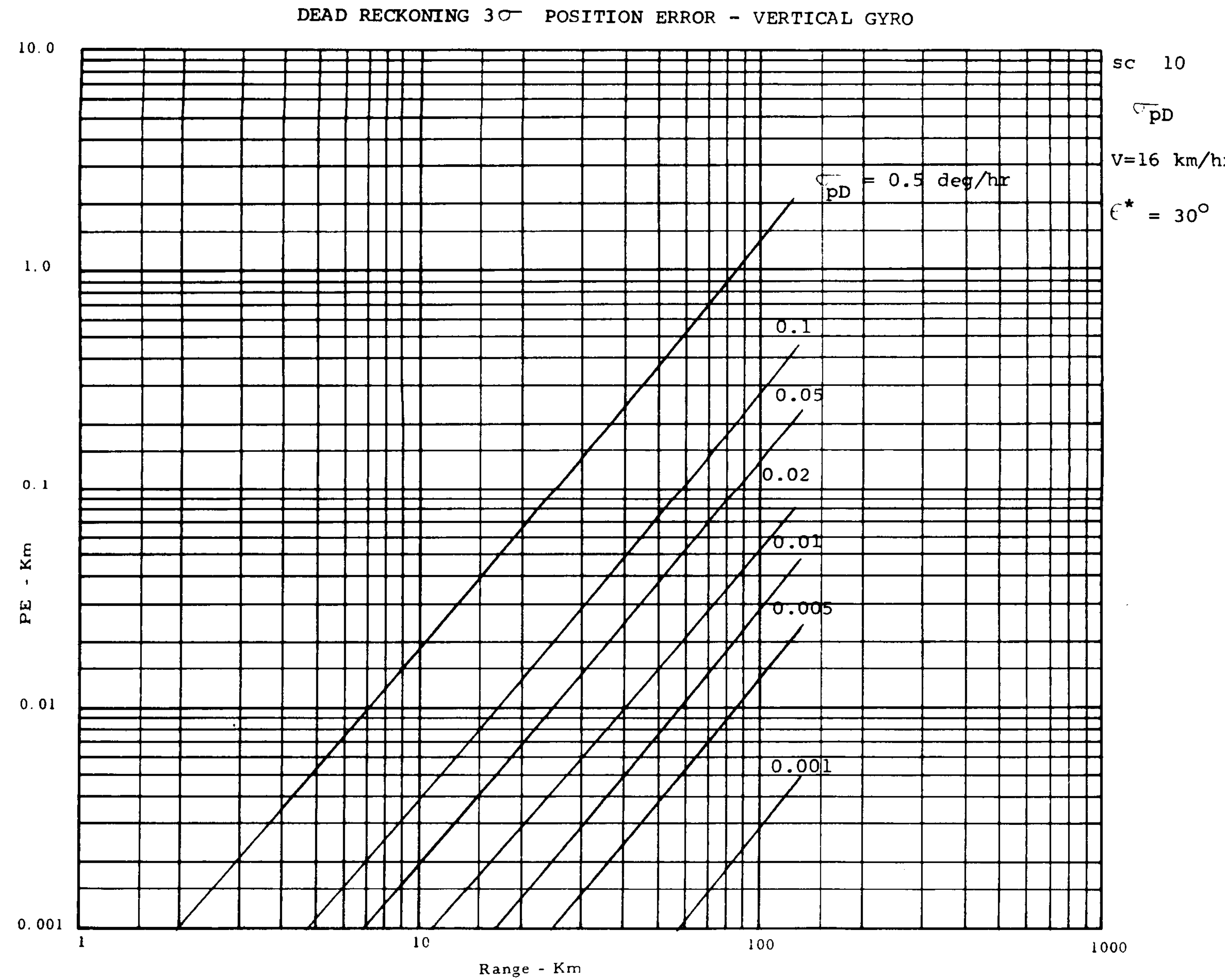


Figure 10-43 Dead Reckoning 3σ Position Error—Vertical Gyro

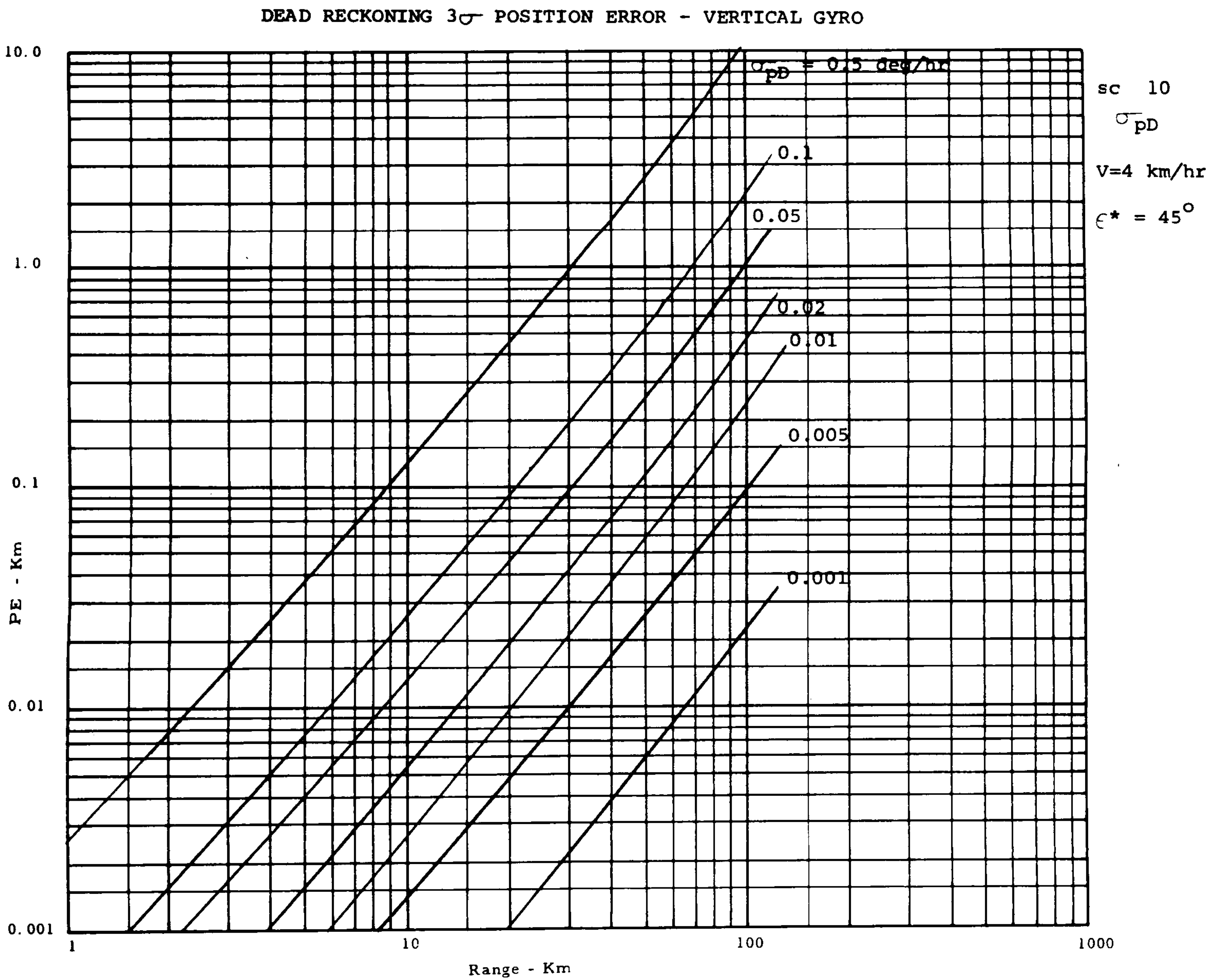


Figure 10-44 Dead Reckoning 3σ Position Error—Vertical Gyro

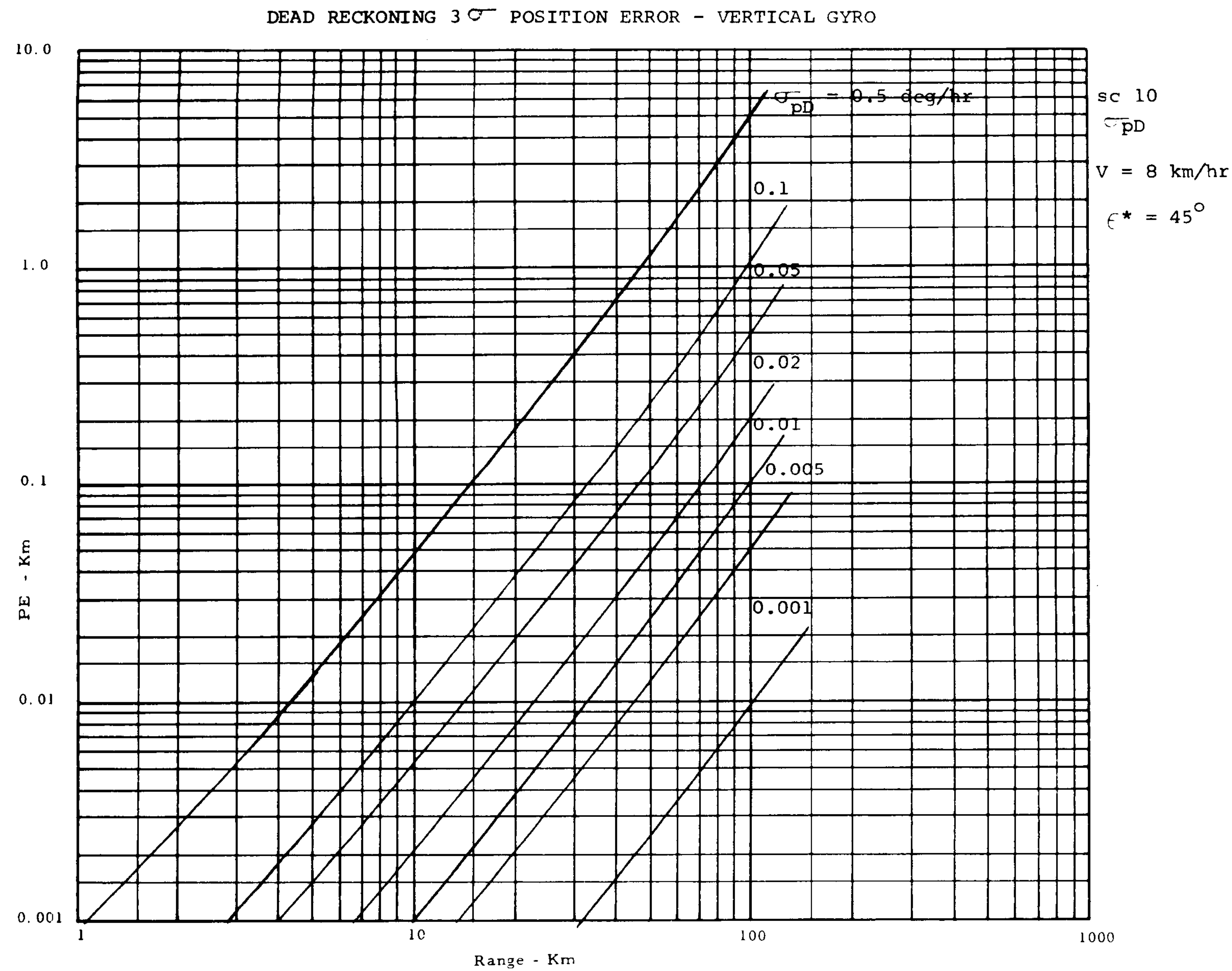


Figure 10-45 Dead Reckoning 3σ Position Error—Vertical Gyro

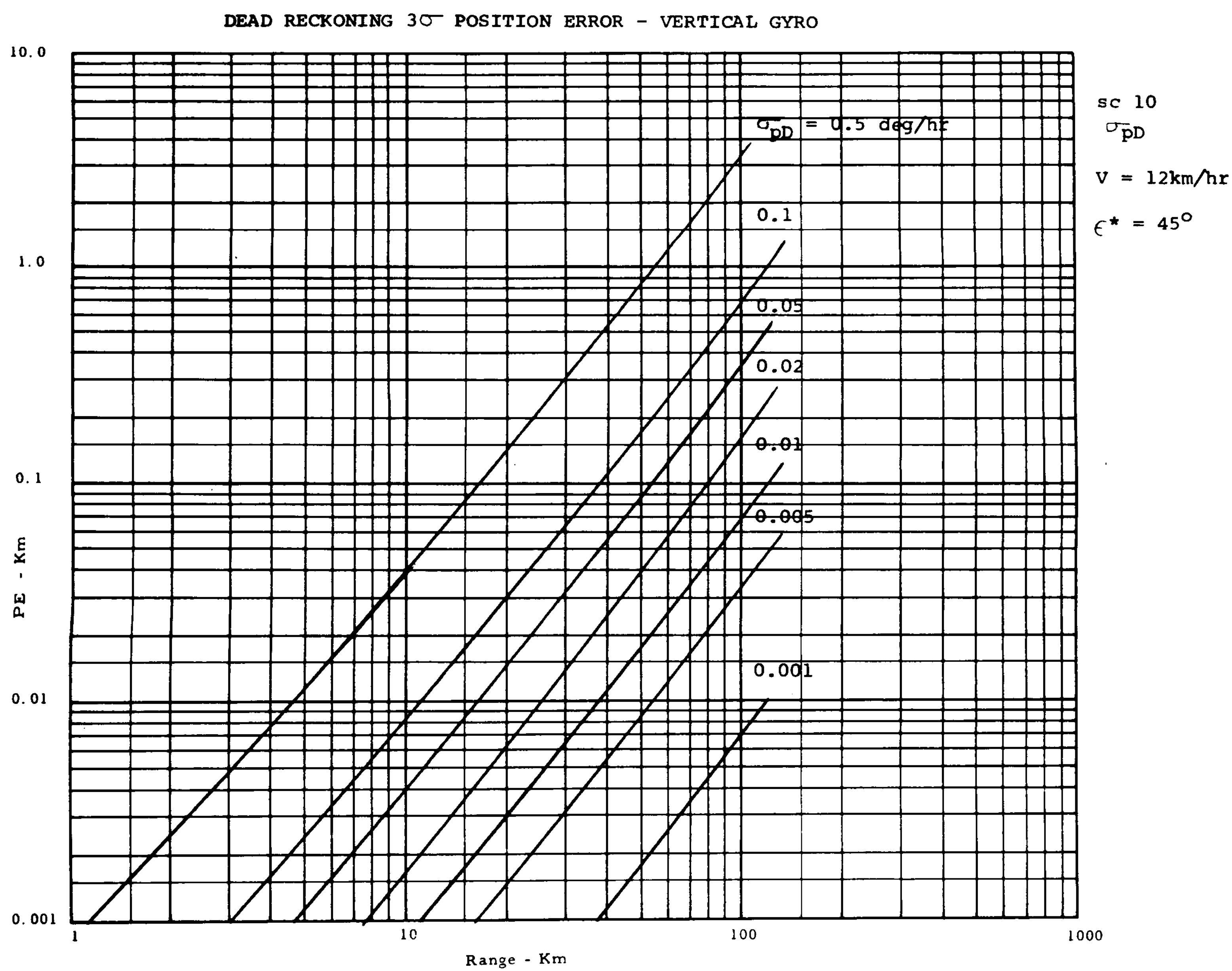


Figure 10-46 Dead Reckoning 3σ Position Error—Vertical Gyro

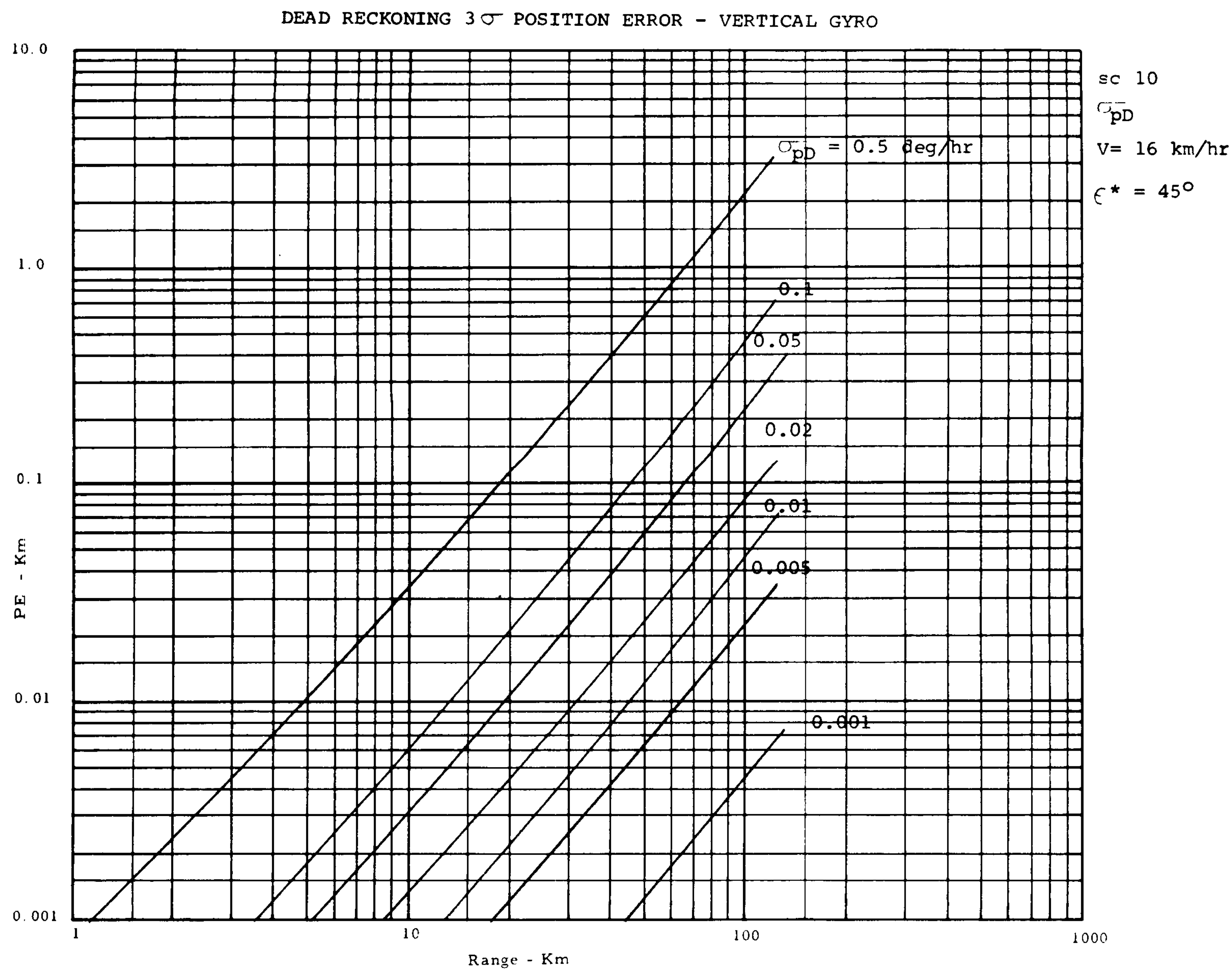


Figure 10-47 Dead Reckoning 3σ Position Error—Vertical Gyro

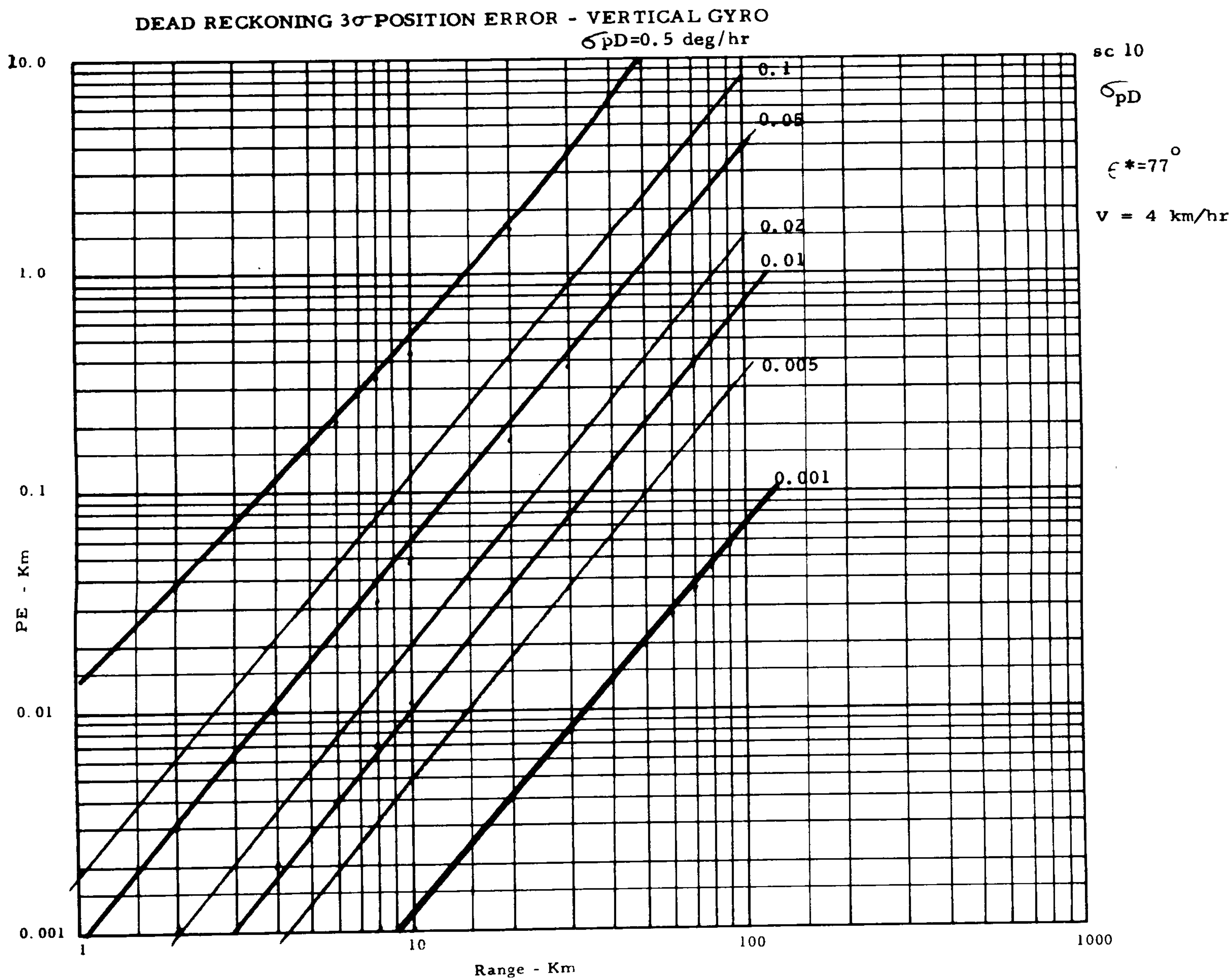


Figure 10-48 Dead Reckoning 3σ Position Error—Vertical Gyro

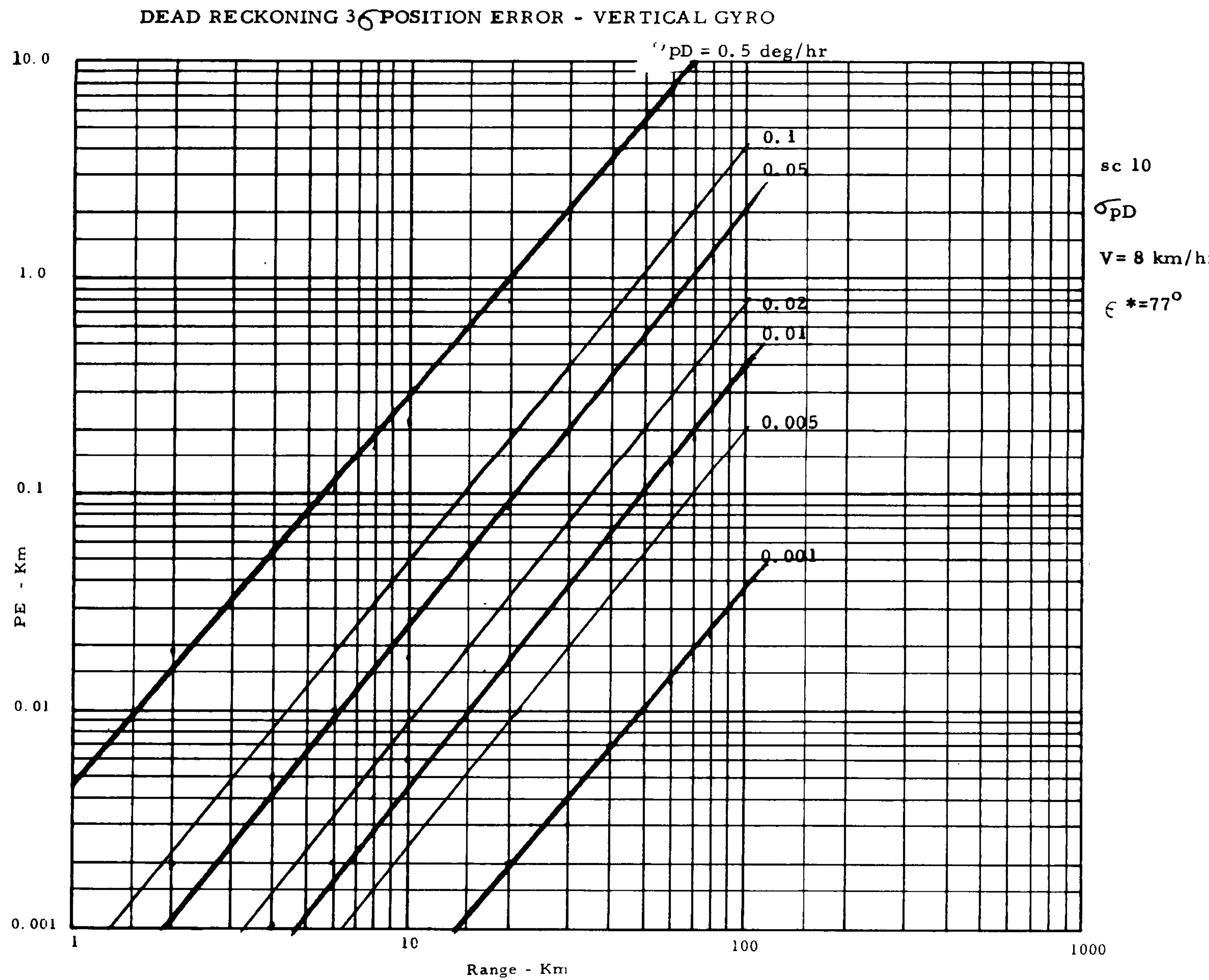


Figure 10-49 Dead Reckoning 3σ Position Error - Vertical Gyro

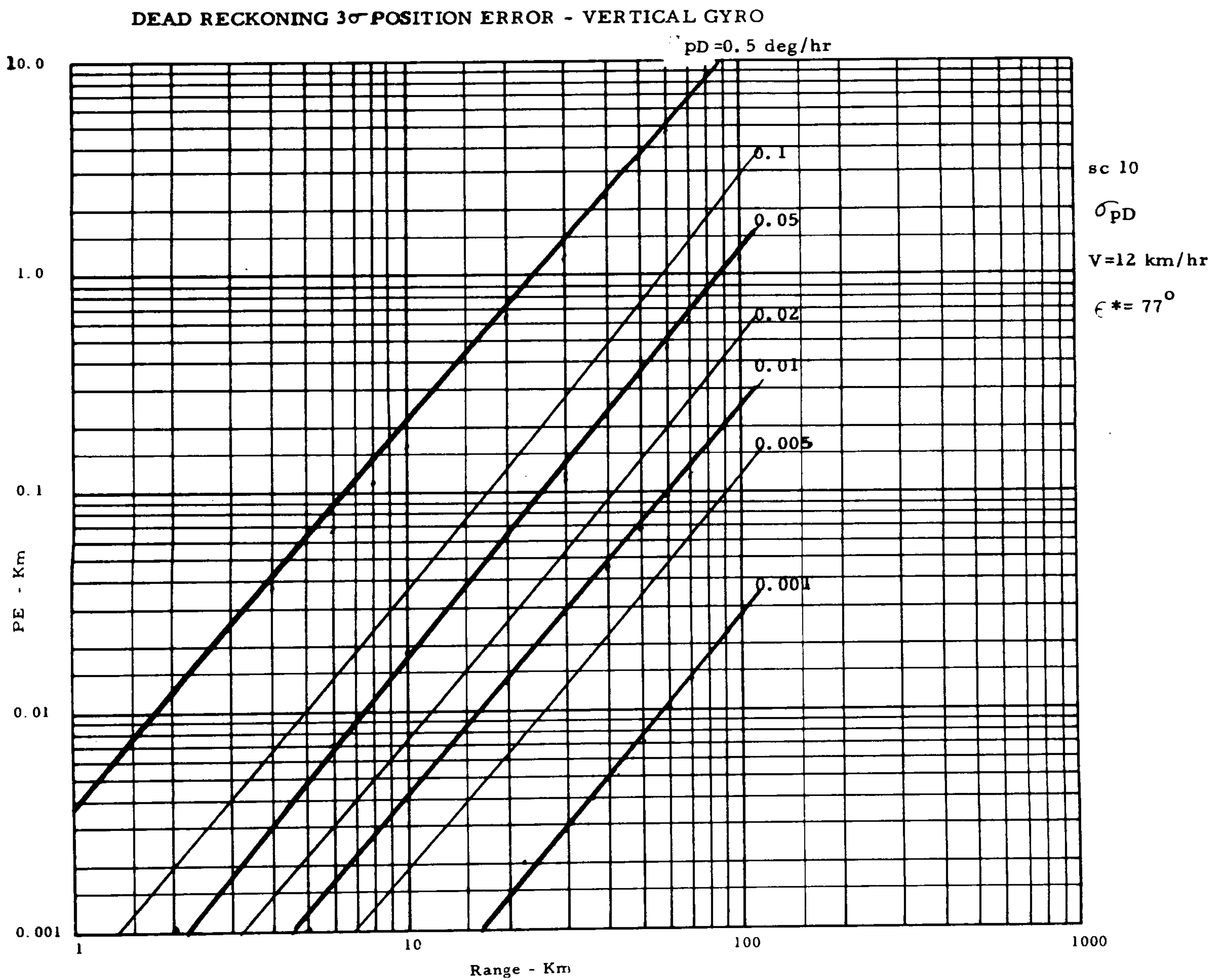


Figure 10-50 Dead Reckoning 3σ Position Error - Vertical Gyro

DEAD RECKONING 3σ POSITION ERROR - VERTICAL GYRO

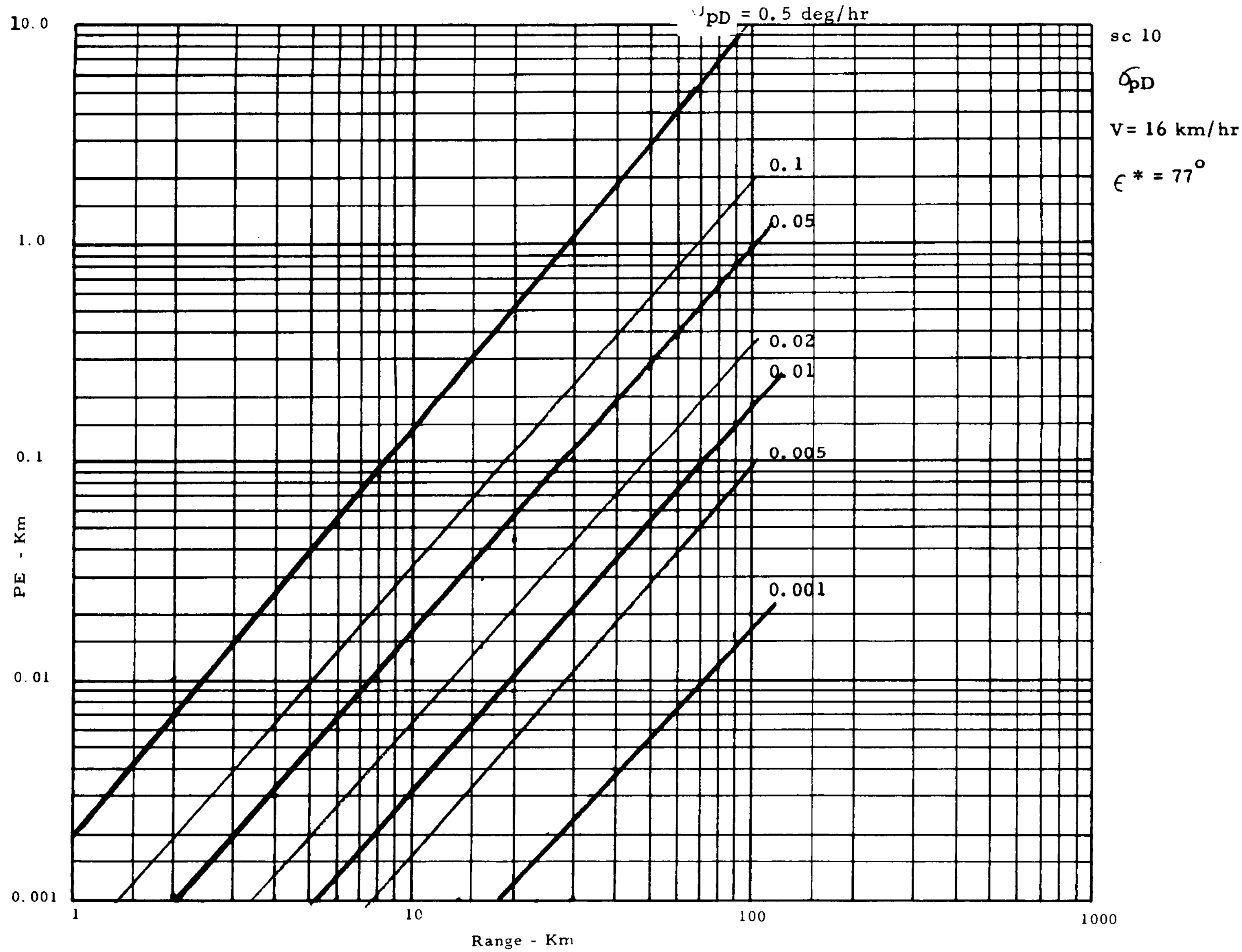


Figure 10-51 Dead Reckoning 3σ Position Error - Vertical Gyro

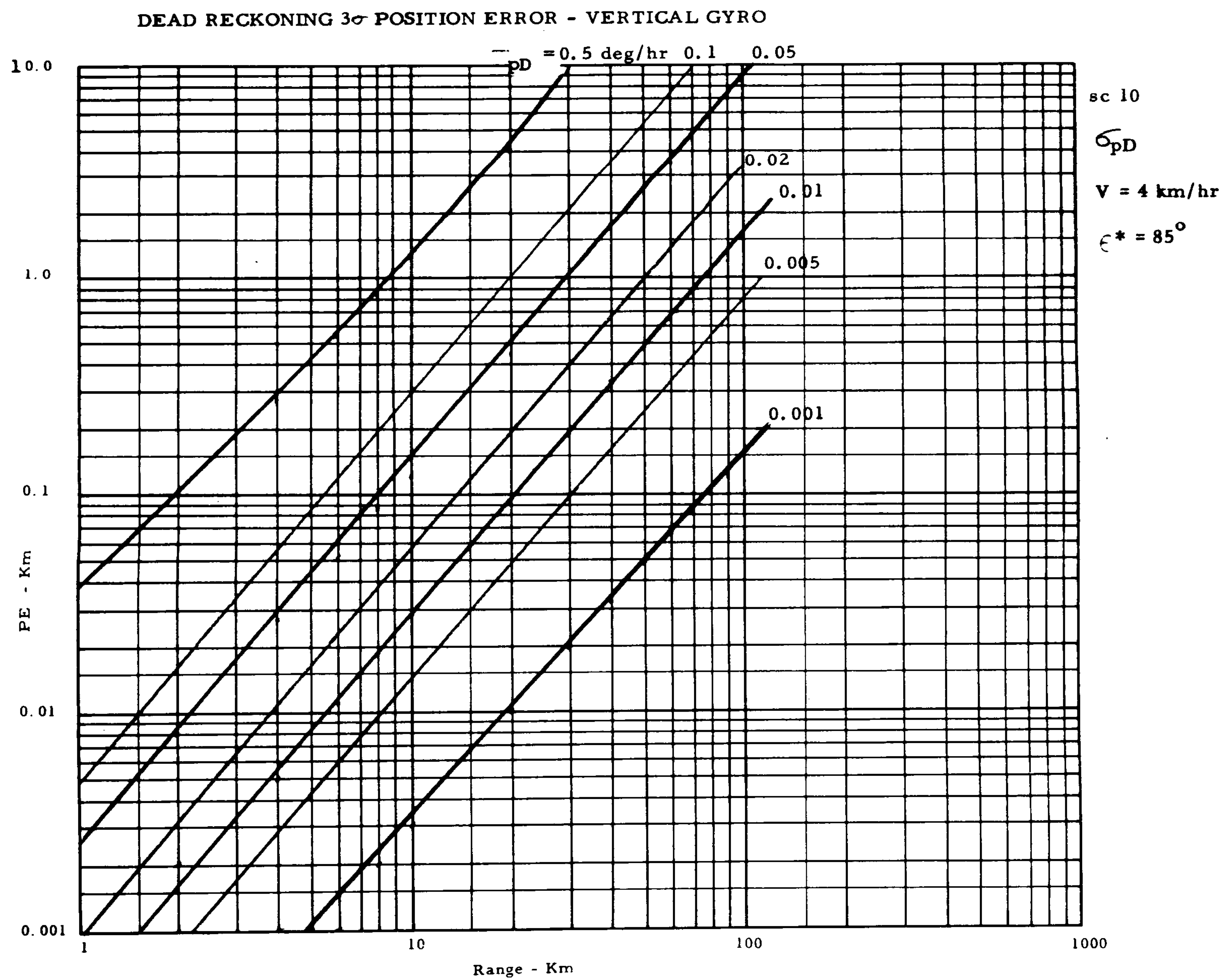


Figure 10-52 Dead Reckoning 3σ Position Error - Vertical Gyro

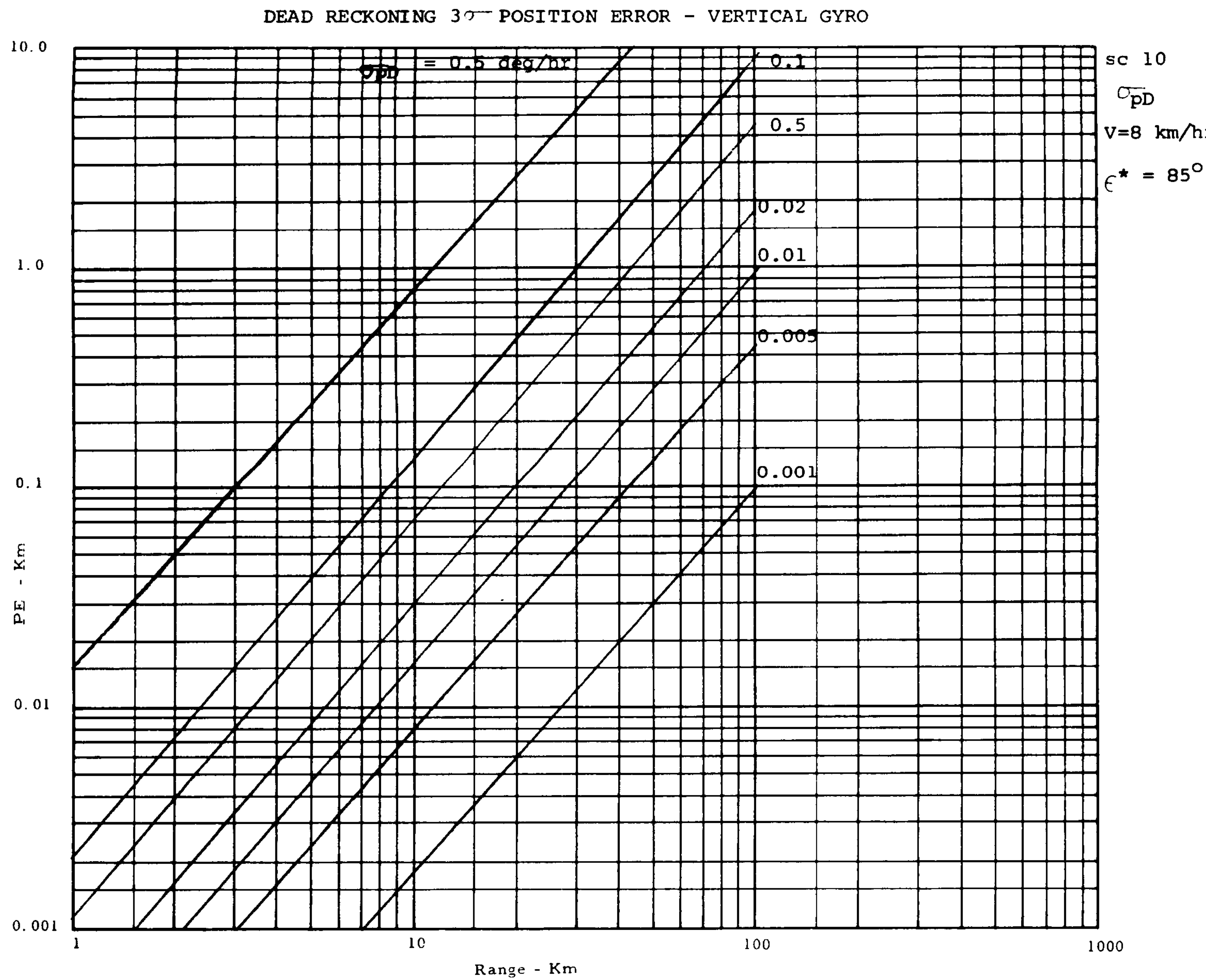


Figure 10-53 Dead Reckoning 3σ Position Error - Vertical Gyro

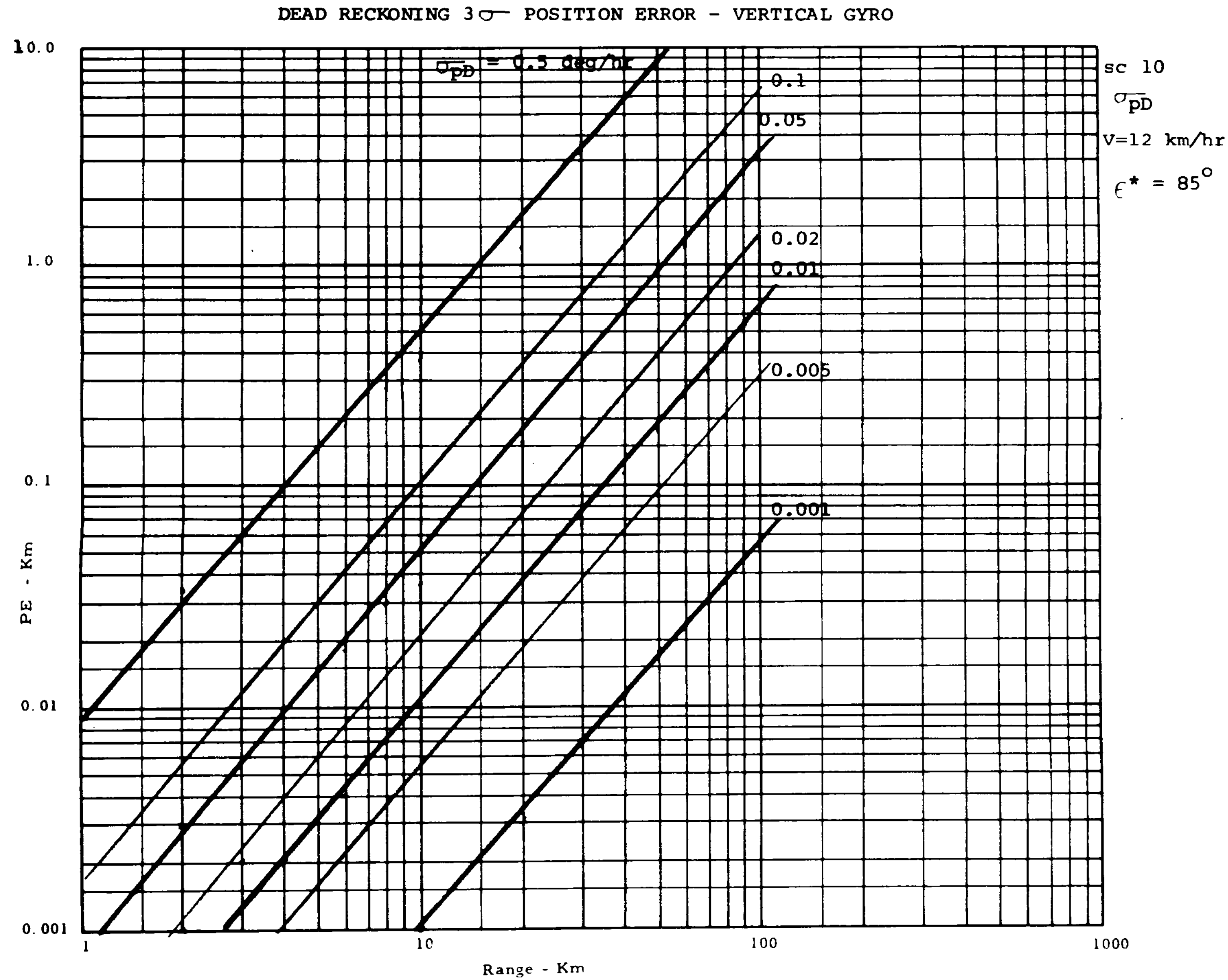


Figure 10-54 Dead Reckoning 3σ Position Error - Vertical Gyro

DEAD RECKONING 3σ POSITION ERROR - VERTICAL GYRO

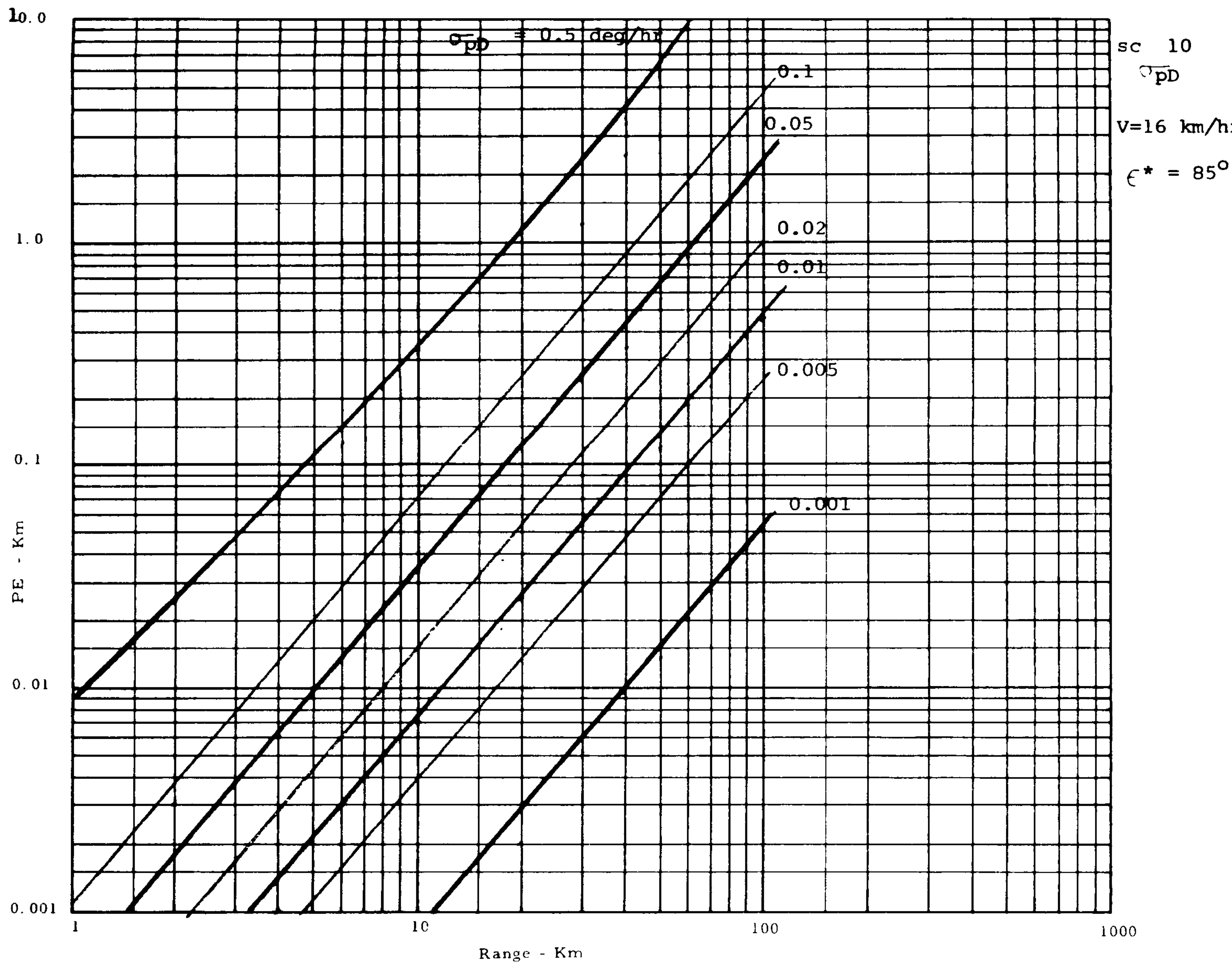


Figure 10-55 Dead Reckoning 3σ Position Error - Vertical Gyro

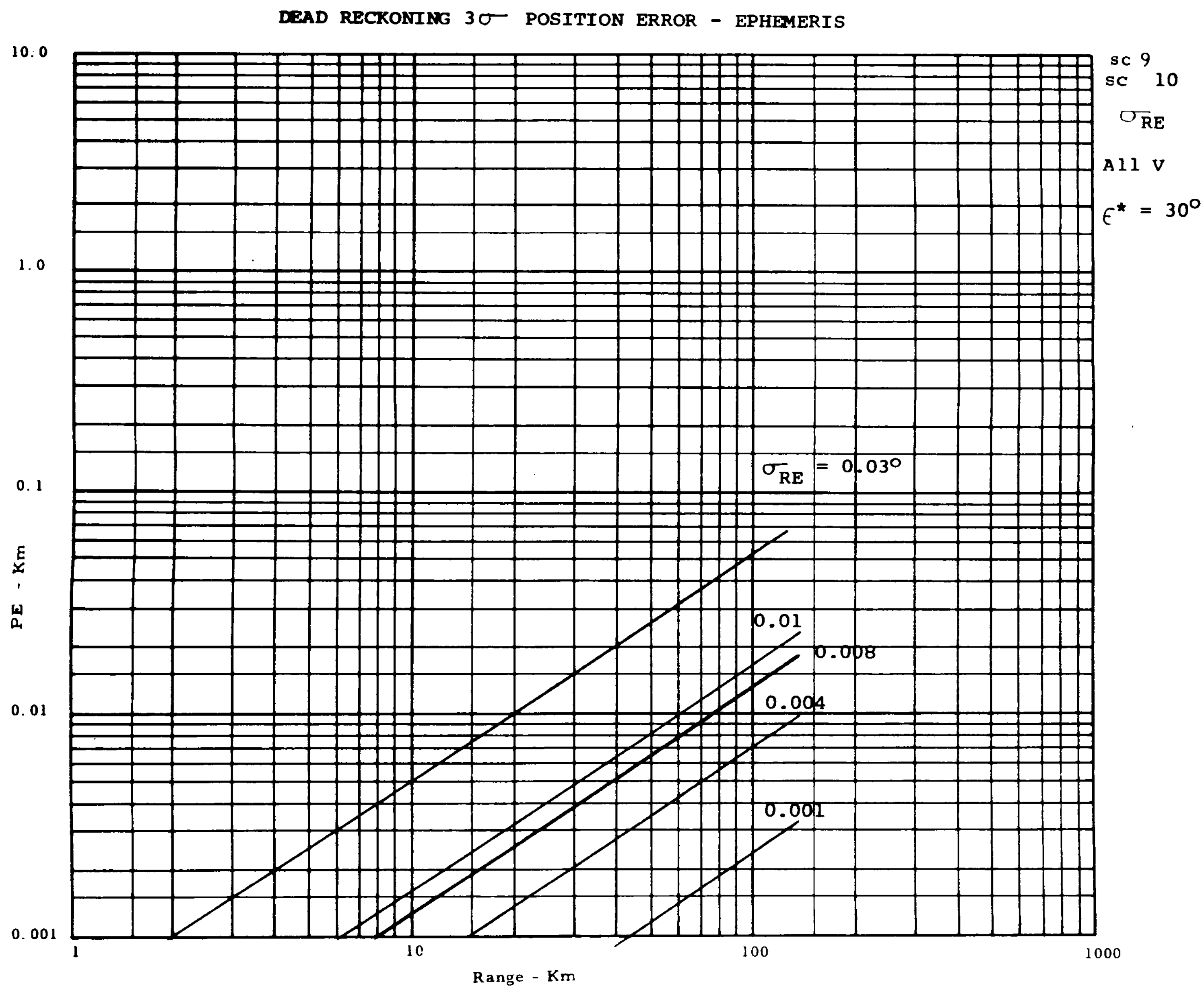


Figure 10-56 Dead Reckoning 3σ Position Error - Ephemeris

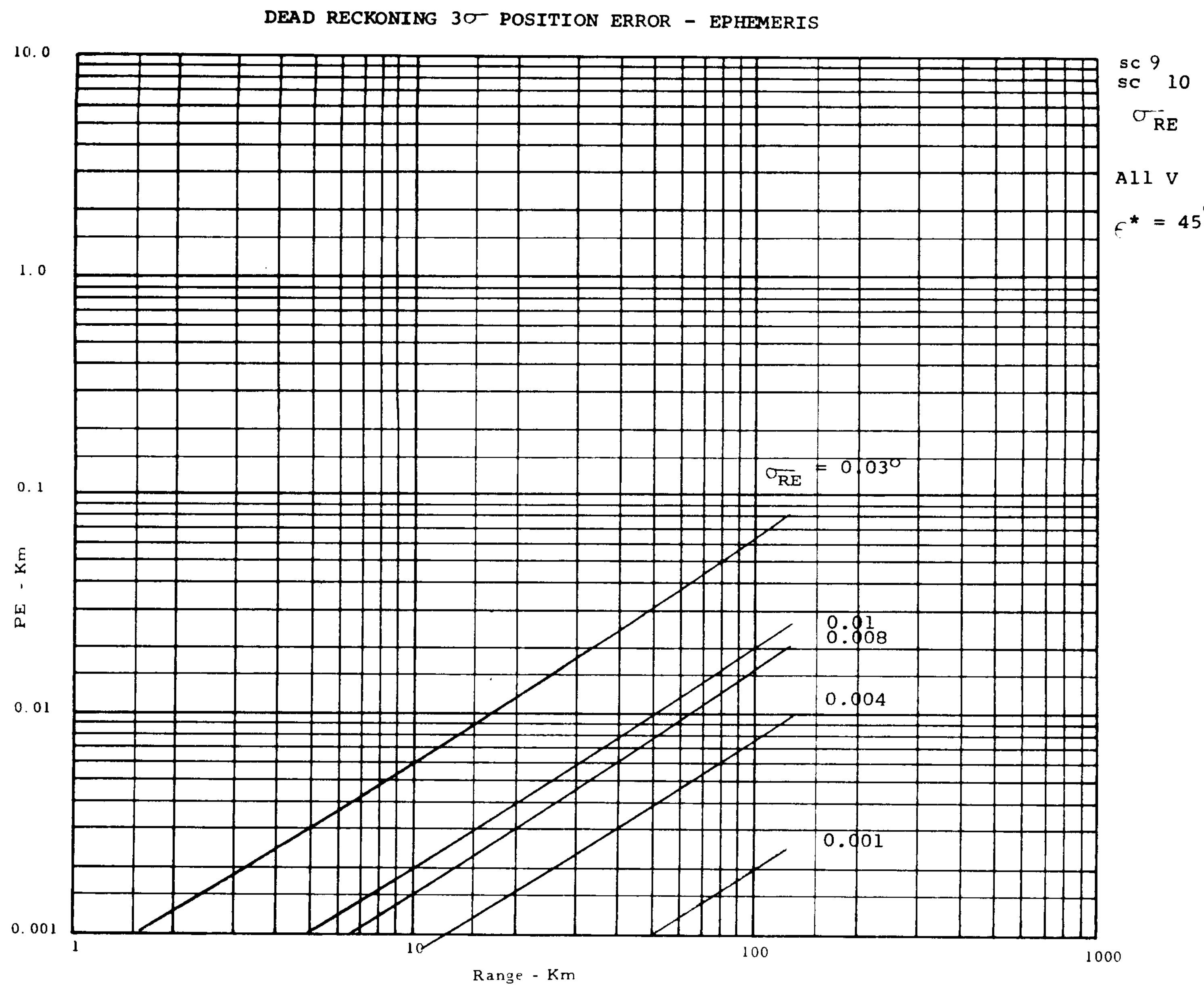


Figure 10-57 Dead Reckoning 3σ Position Error - Ephemeris

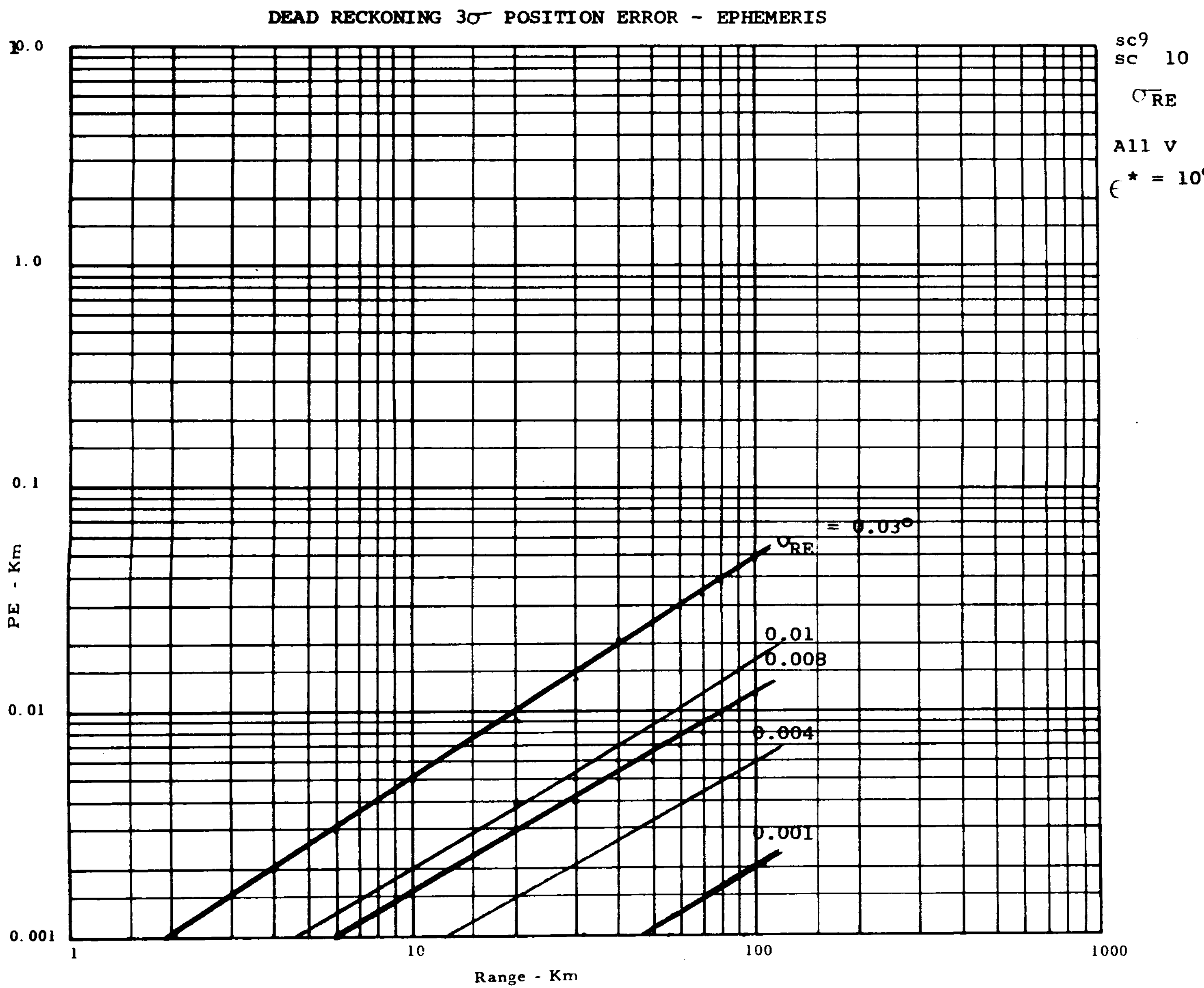


Figure 10-58 Dead Reckoning 3σ Position Error - Ephemeris

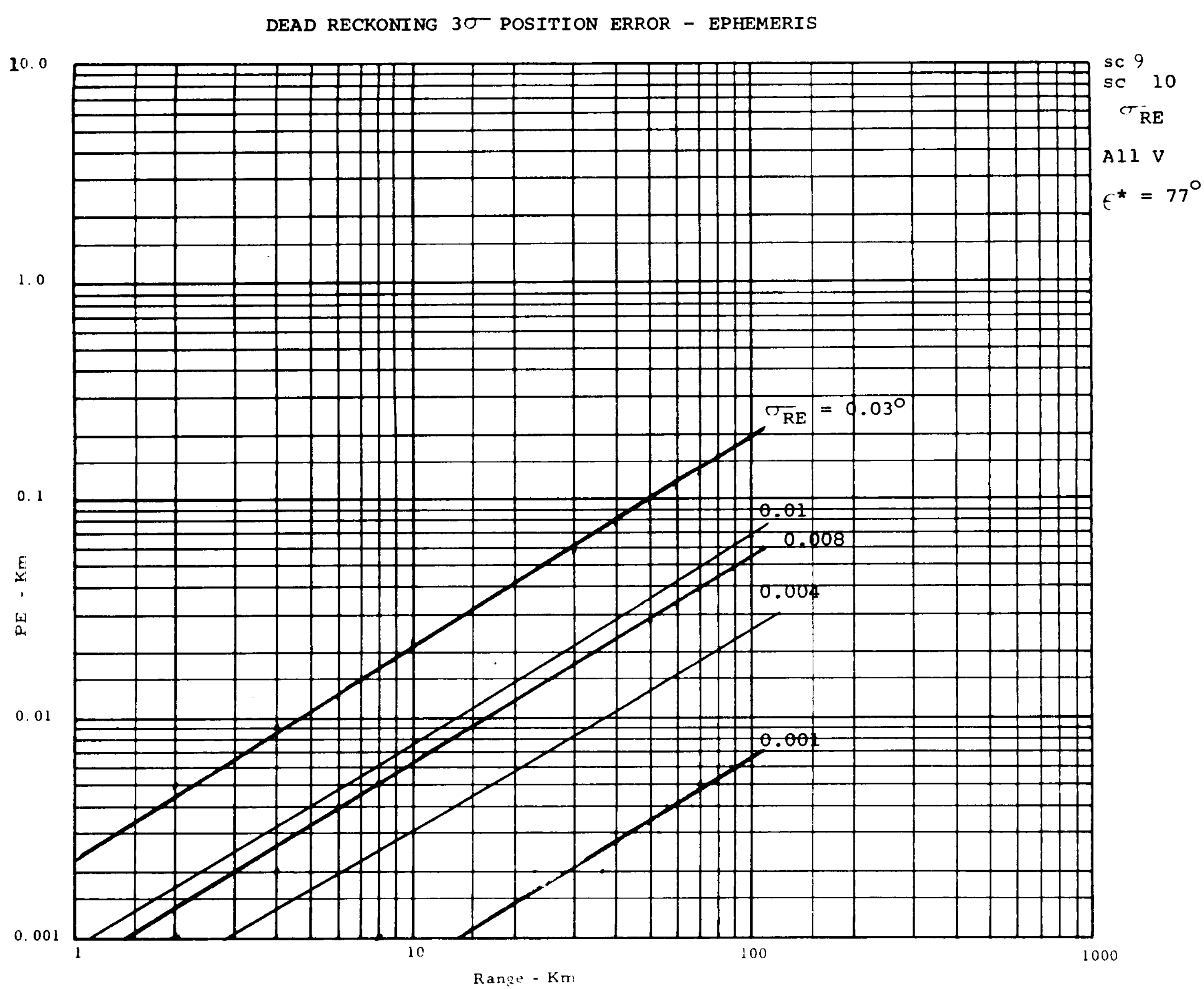


Figure 10-59 Dead Reckoning 3σ Position Error - Ephemeris

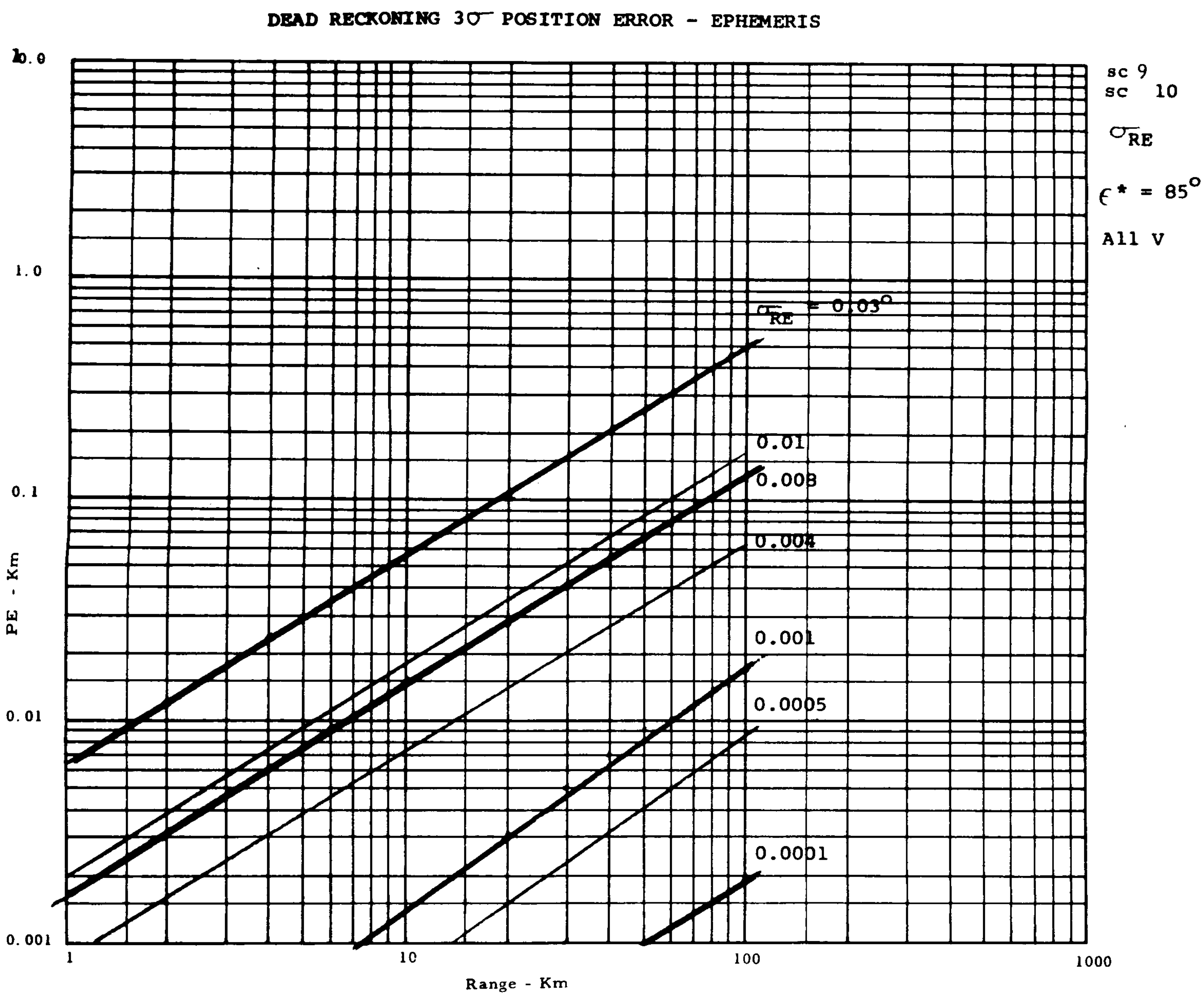


Figure 10-60 Dead Reckoning 3σ Position Error - Ephemeris

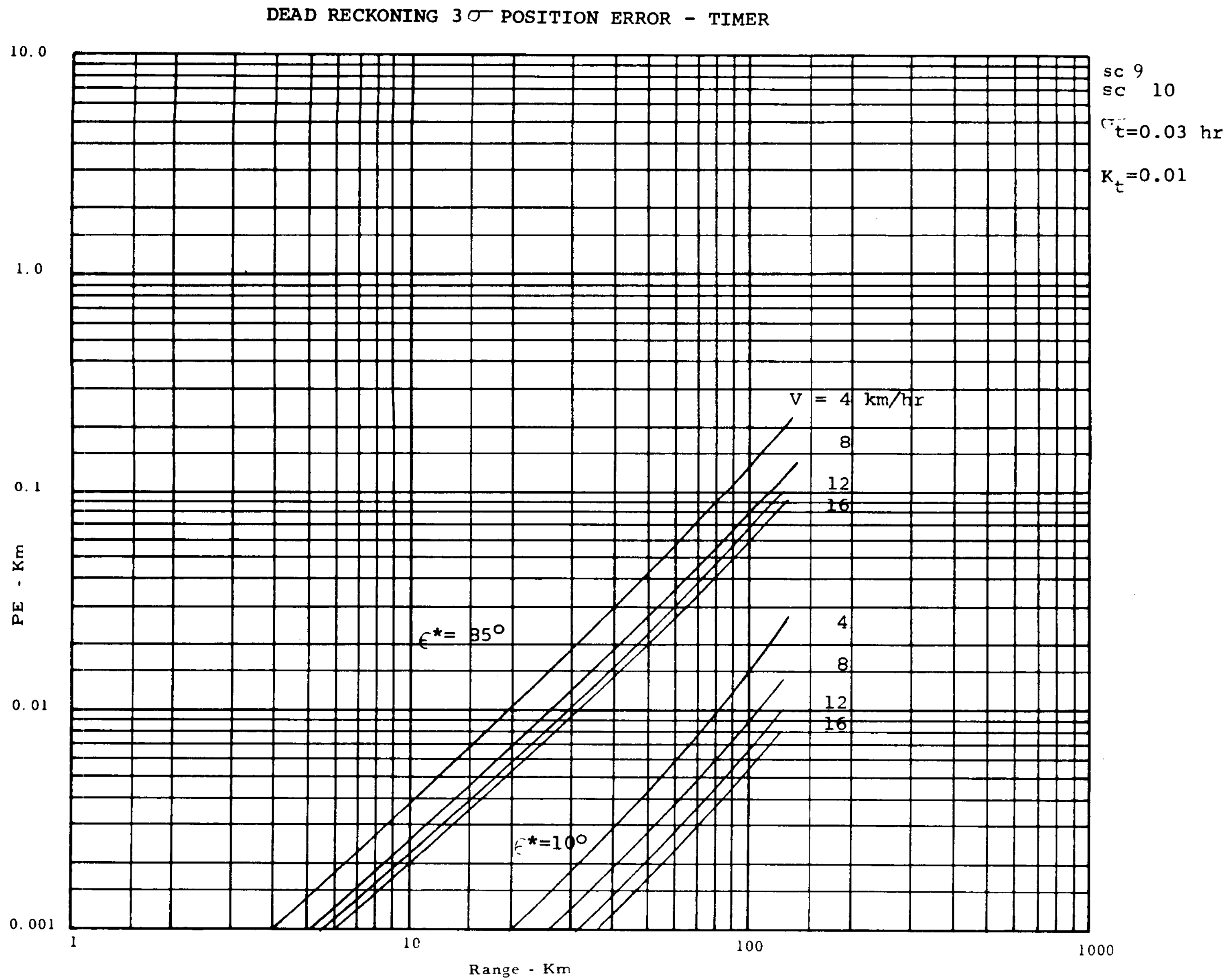


Figure 10-61 Dead Reckoning 3σ Position Error—Timer

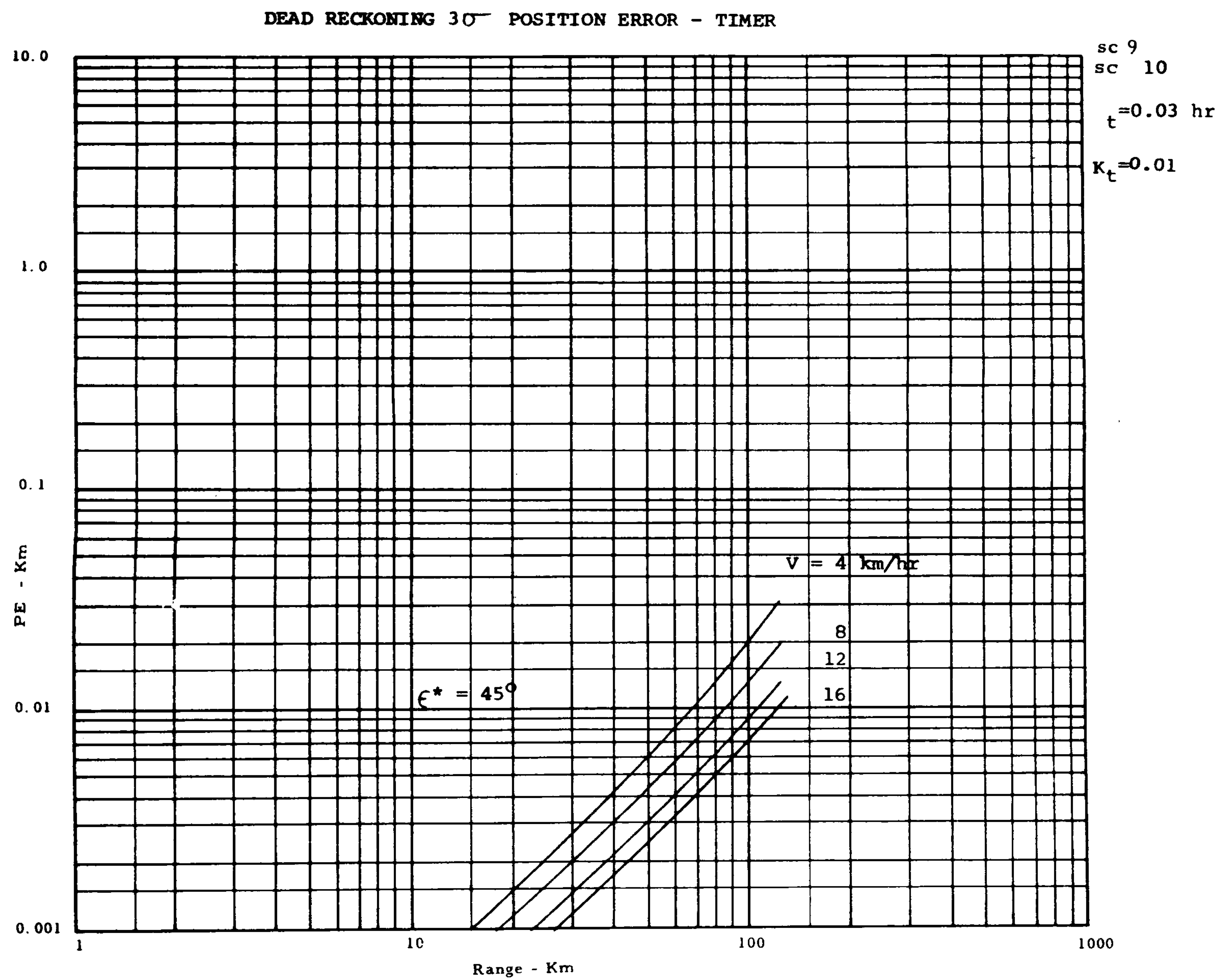


Figure 10-62 Dead Reckoning 3σ Position Error—Timer

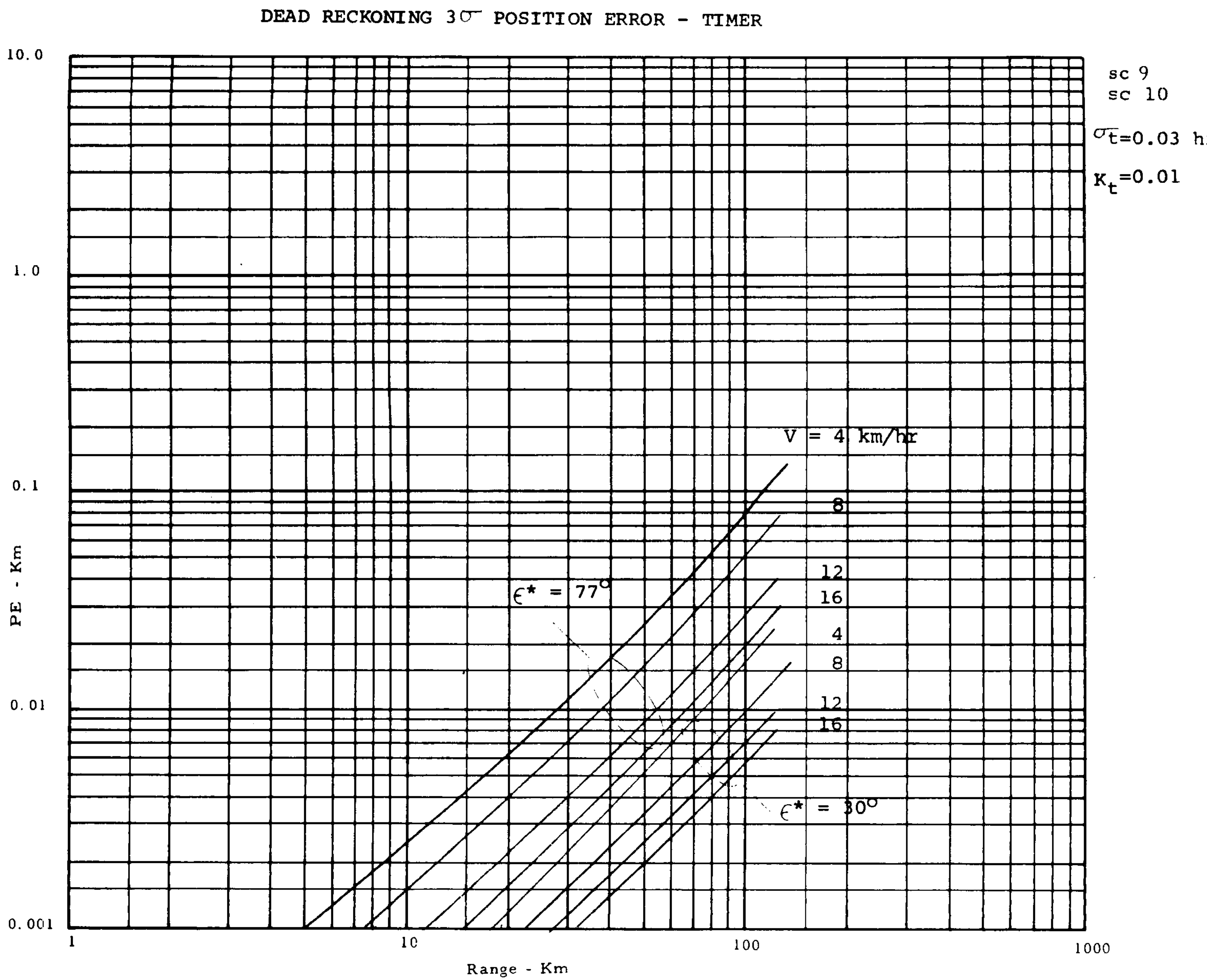


Figure 10-63 Dead Reckoning 3σ Position Error—Timer

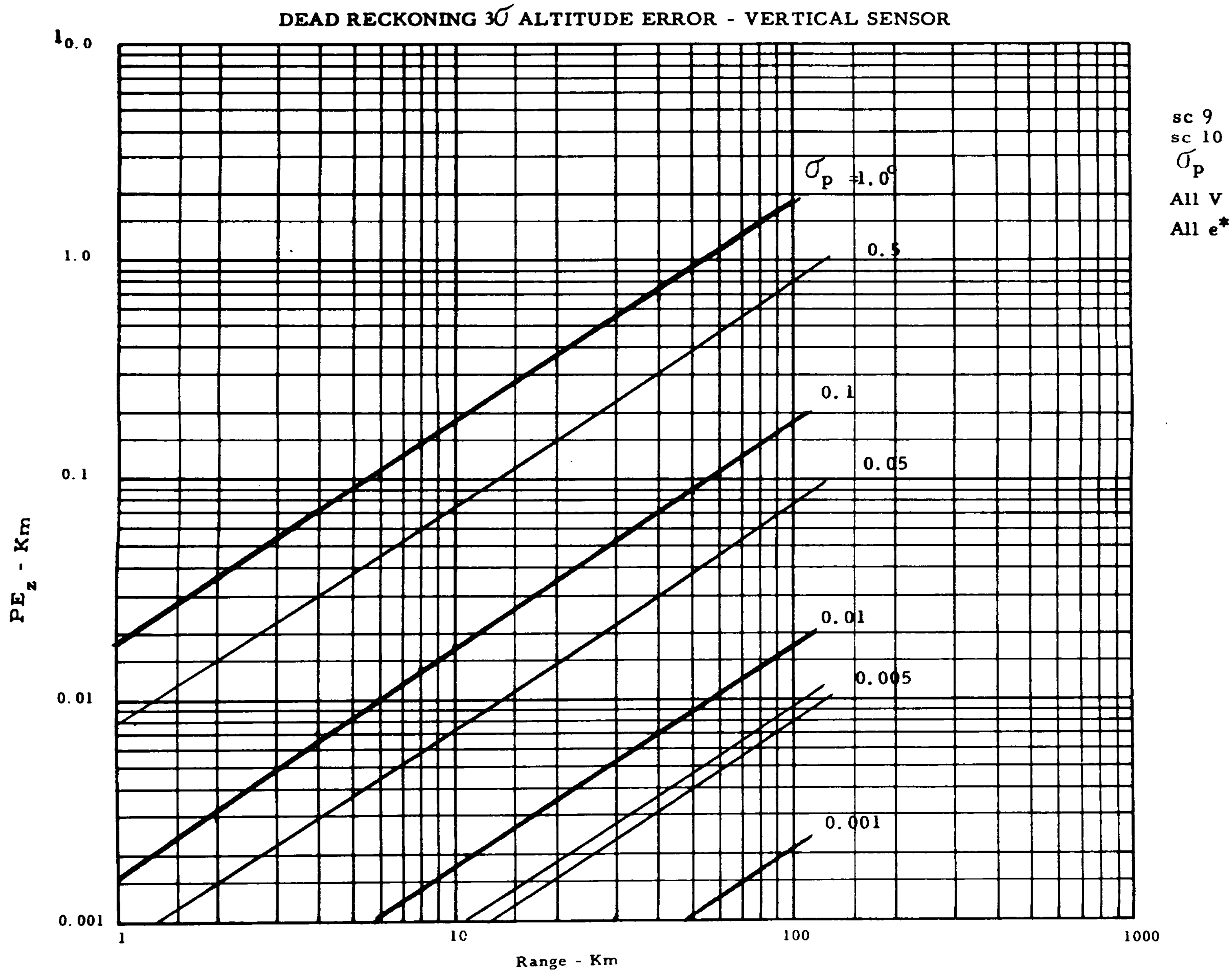


Figure 10-64 Dead Reckoning 3σ Position Error—Vertical Sensor

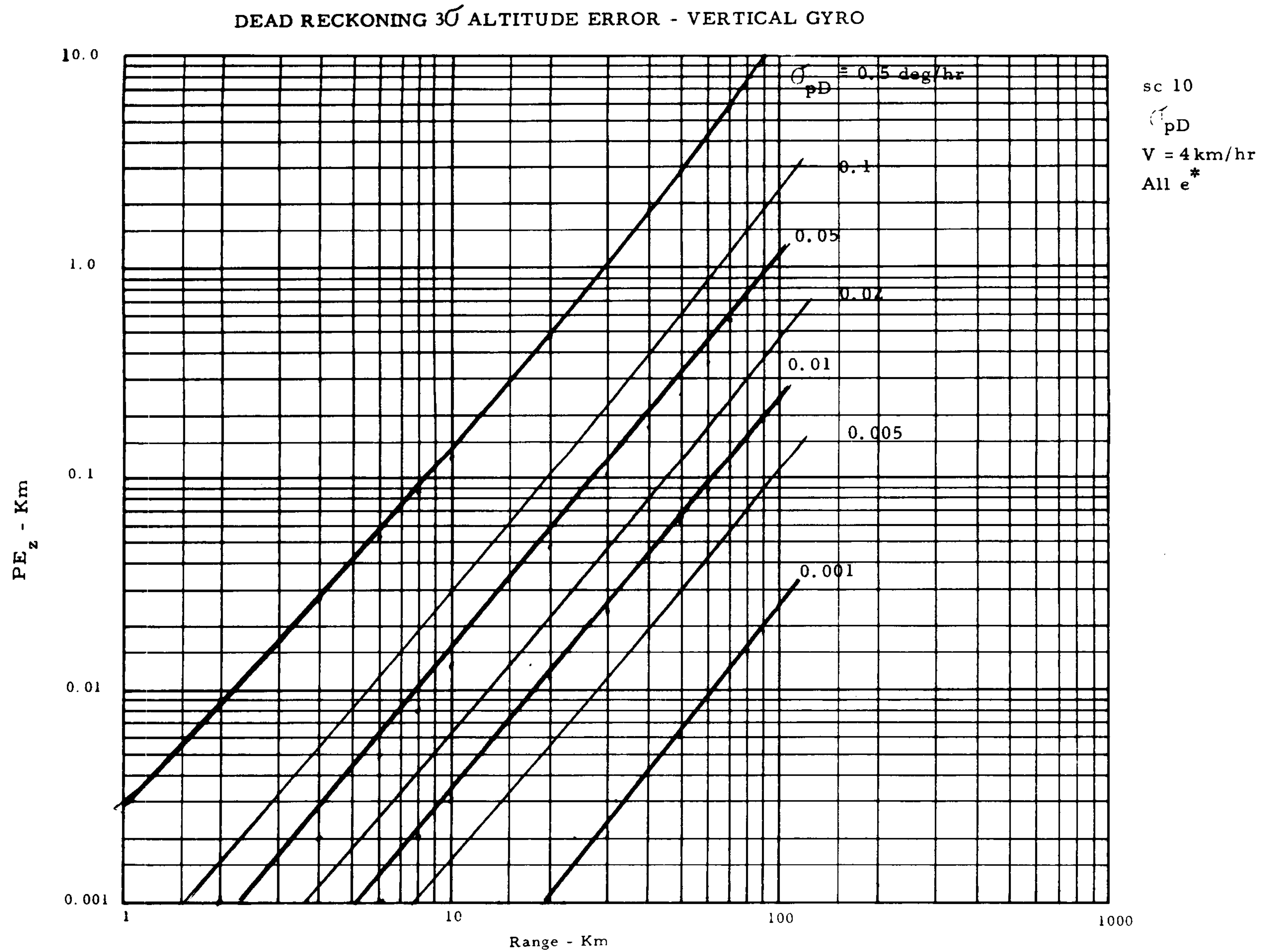


Figure 10-65 Dead Reckoning 3σ Altitude Error—Vertical Gyro

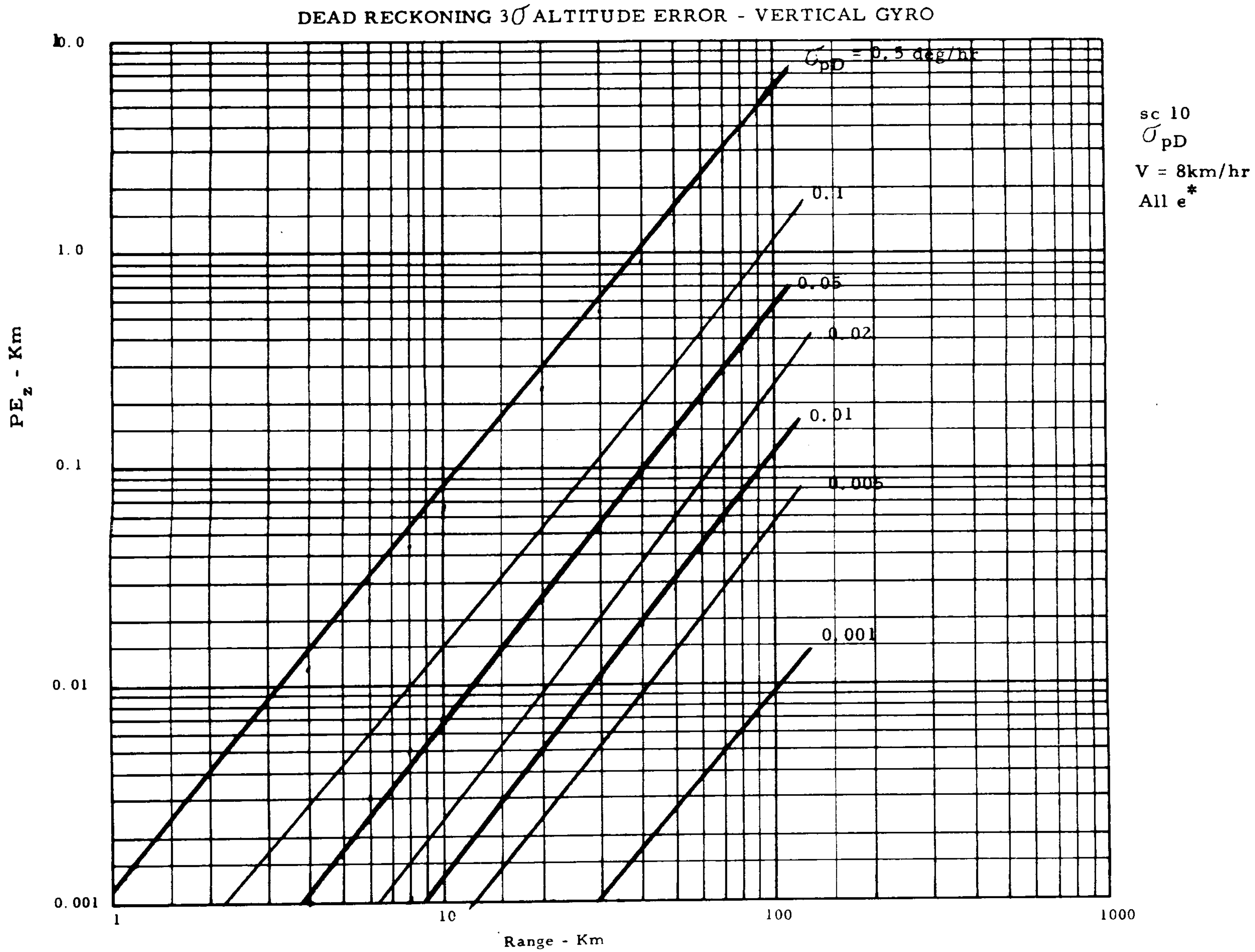


Figure 10-66 Dead Reckoning 3σ Altitude Error—Vertical Gyro

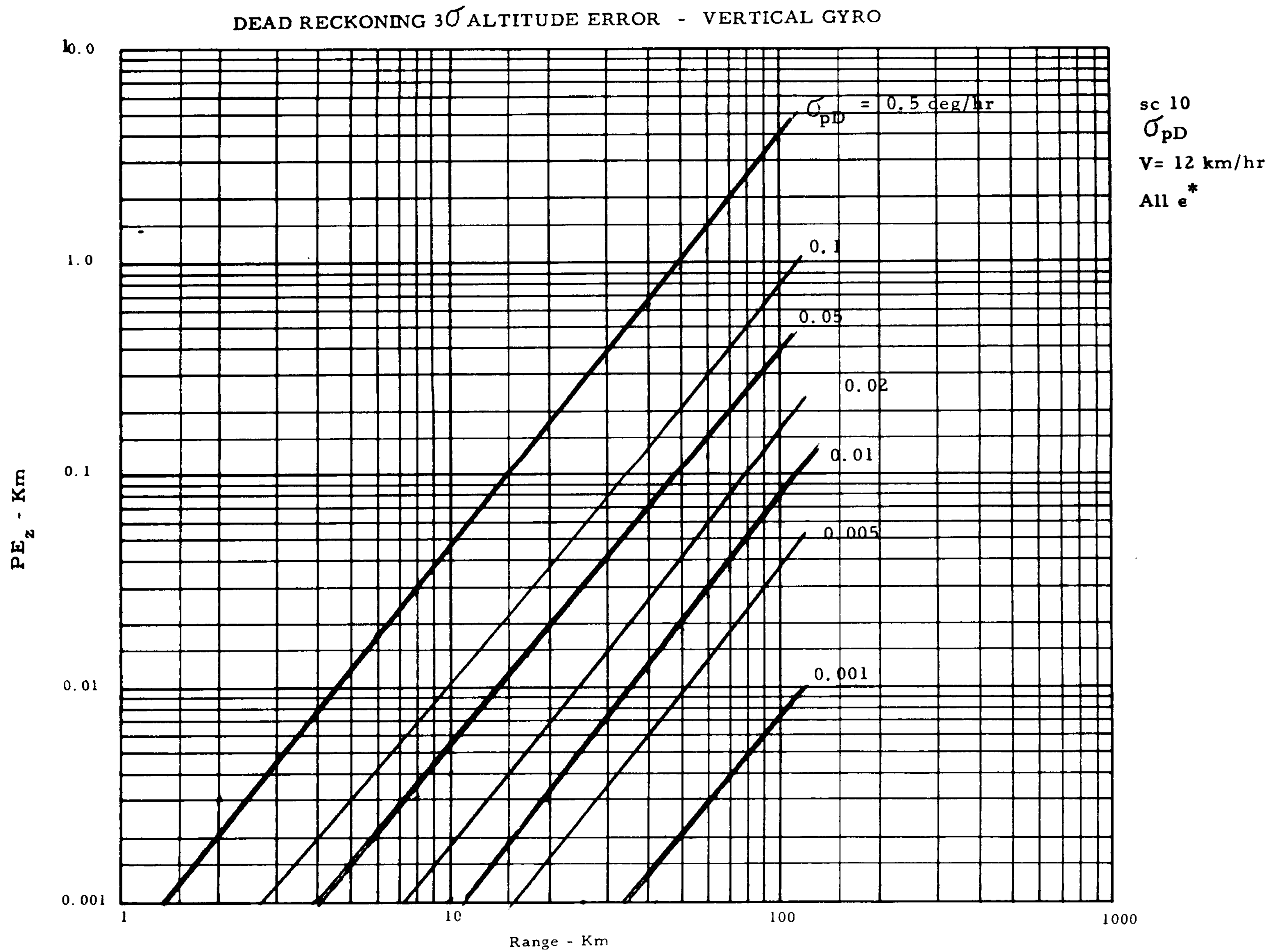


Figure 10-67 Dead Reckoning 3σ Altitude Error—Vertical Gyro

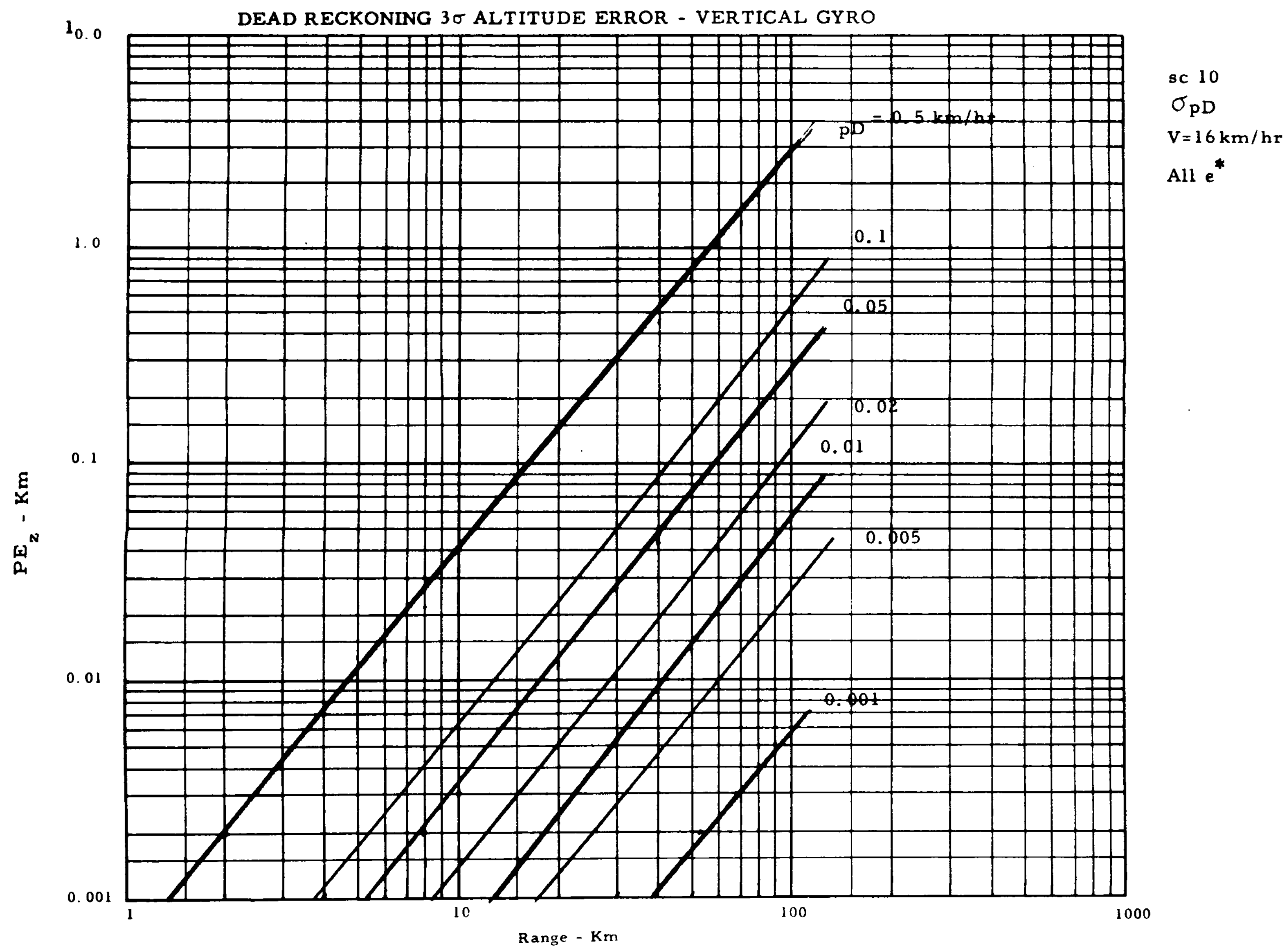


Figure 10-68 Dead Reckoning 3σ Altitude Error—Vertical Gyro

DEAD RECKONING 3σ HEADING ERROR - ODOMETER

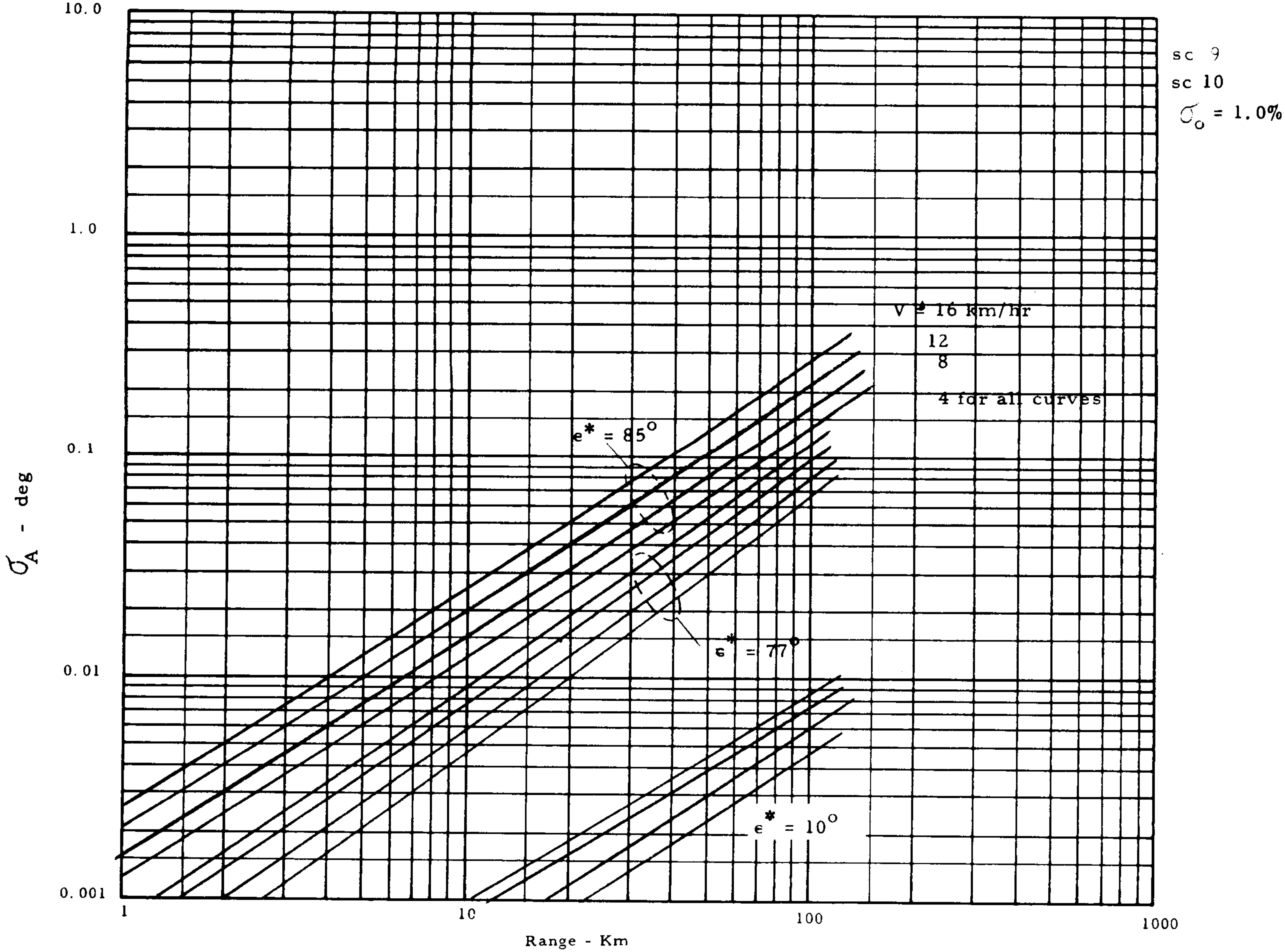


Figure 10-69 Dead Reckoning 3σ Heading Error—Odometer

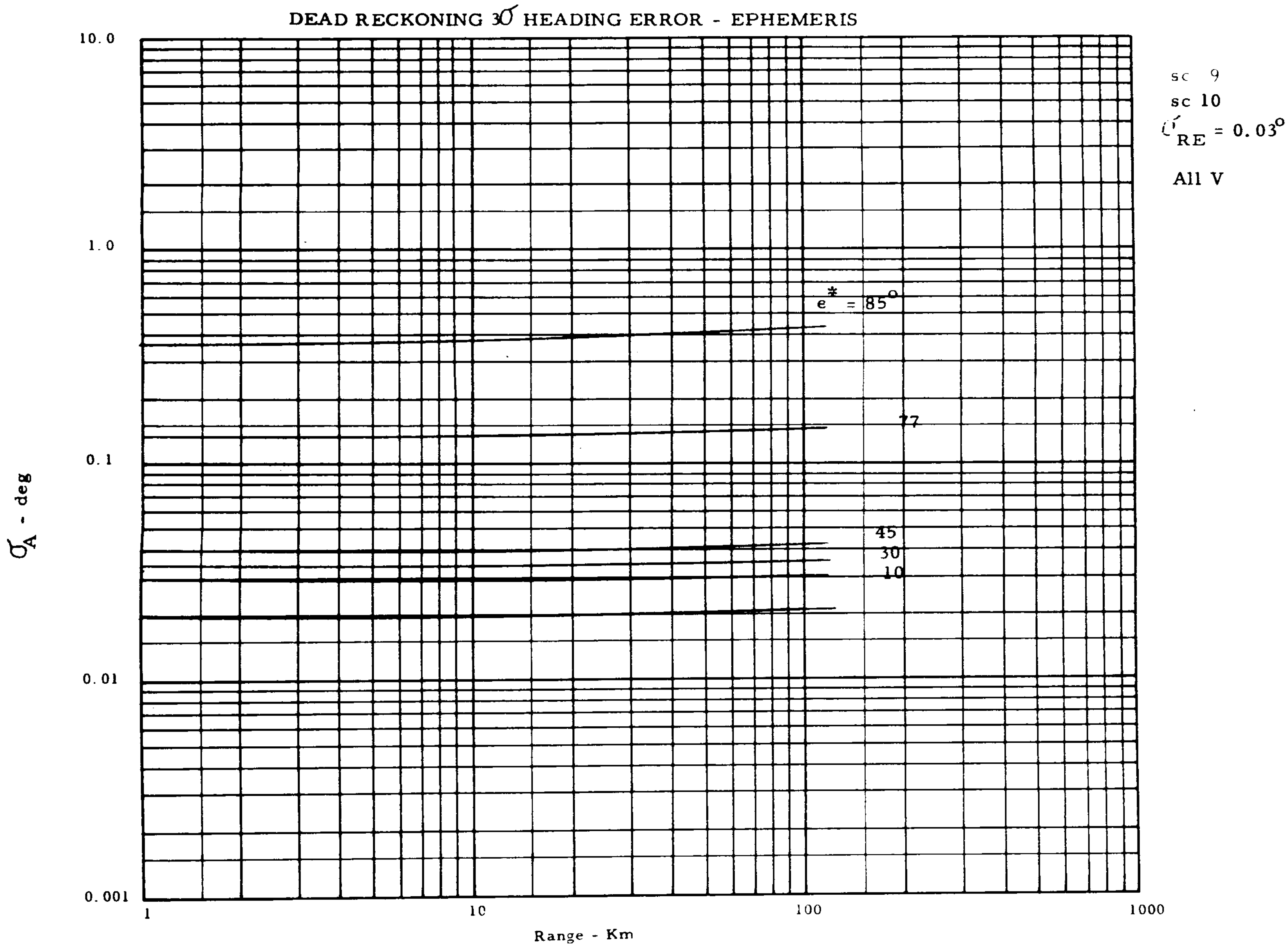


Figure 10-70 Dead Reckoning 3σ Heading Error—Ephemeris

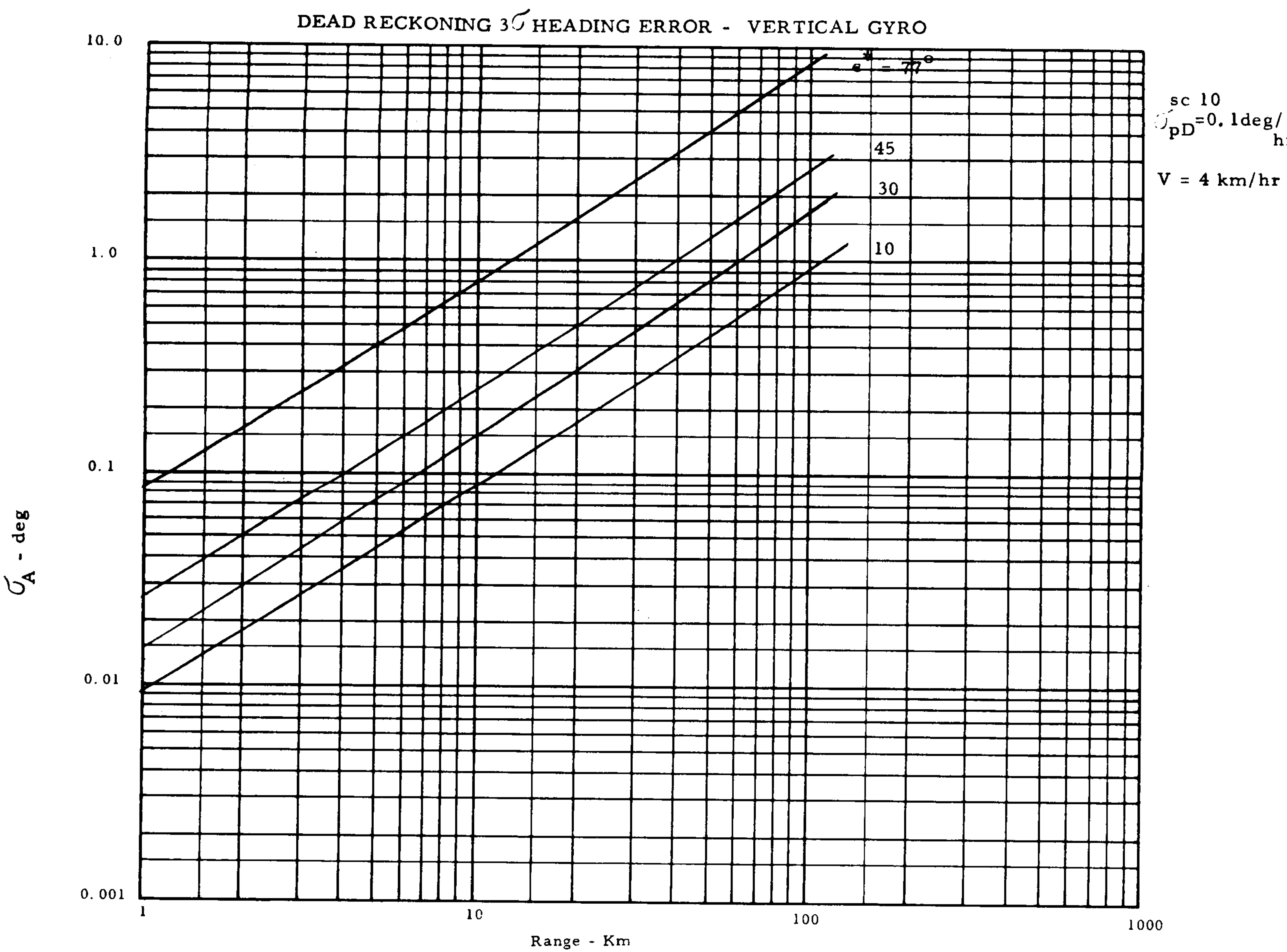


Figure 10-71 Dead Reckoning 3σ Heading Error—Vertical Gyro

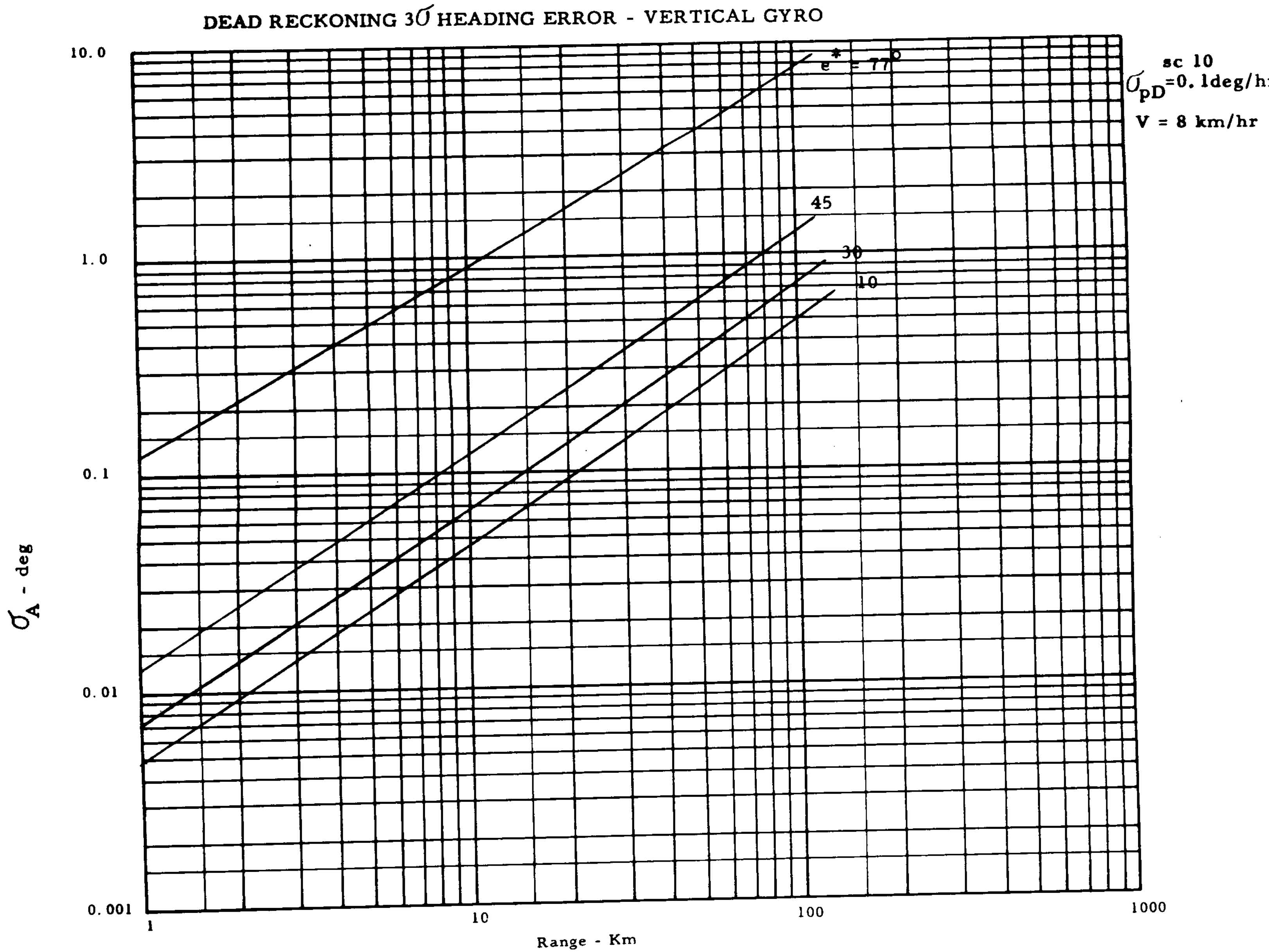


Figure 10-72 Dead Reckoning 3σ Heading Error—Vertical Gyro

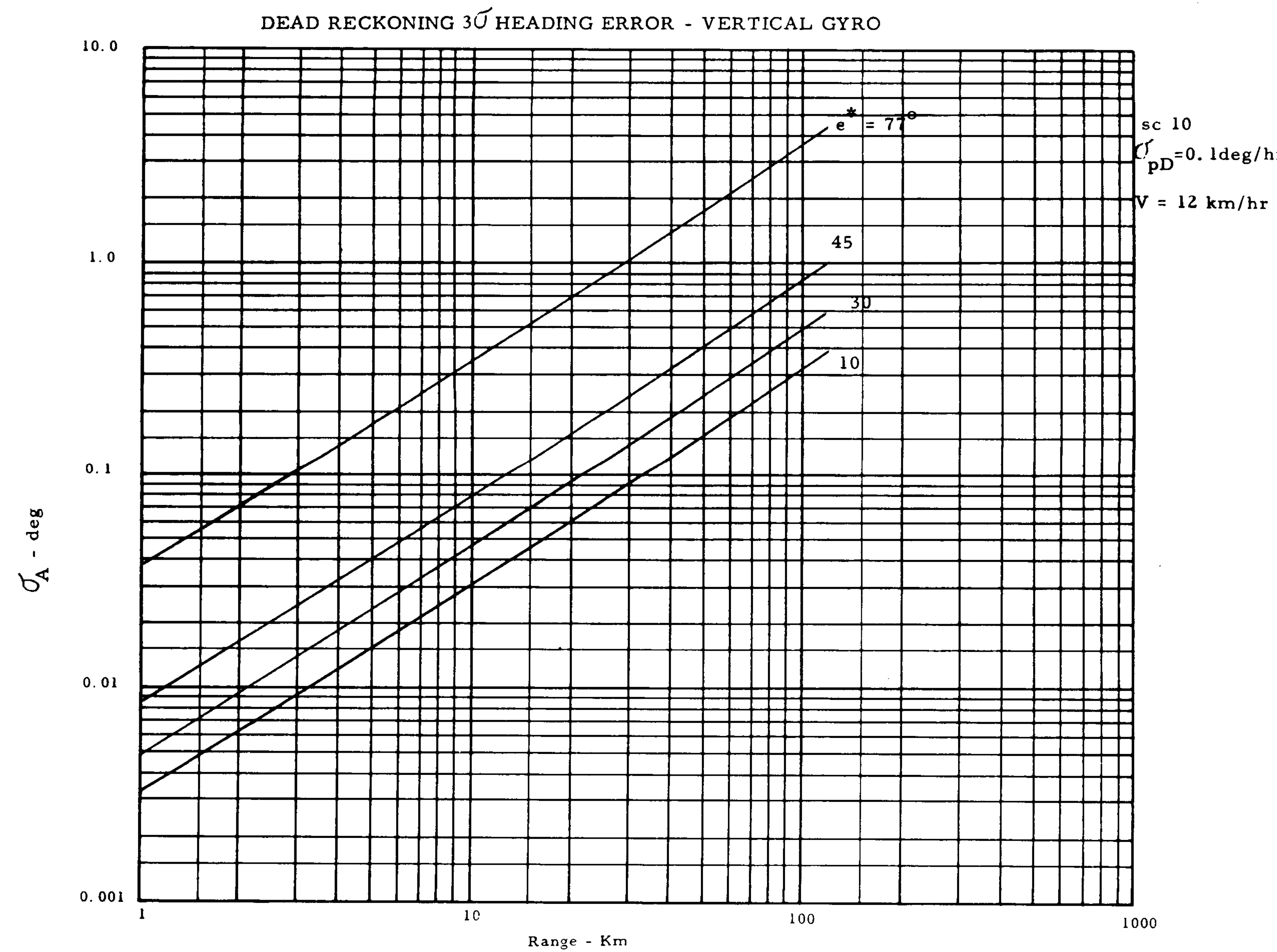


Figure 10-73 Dead Reckoning 3σ Heading Error—Vertical Gyro

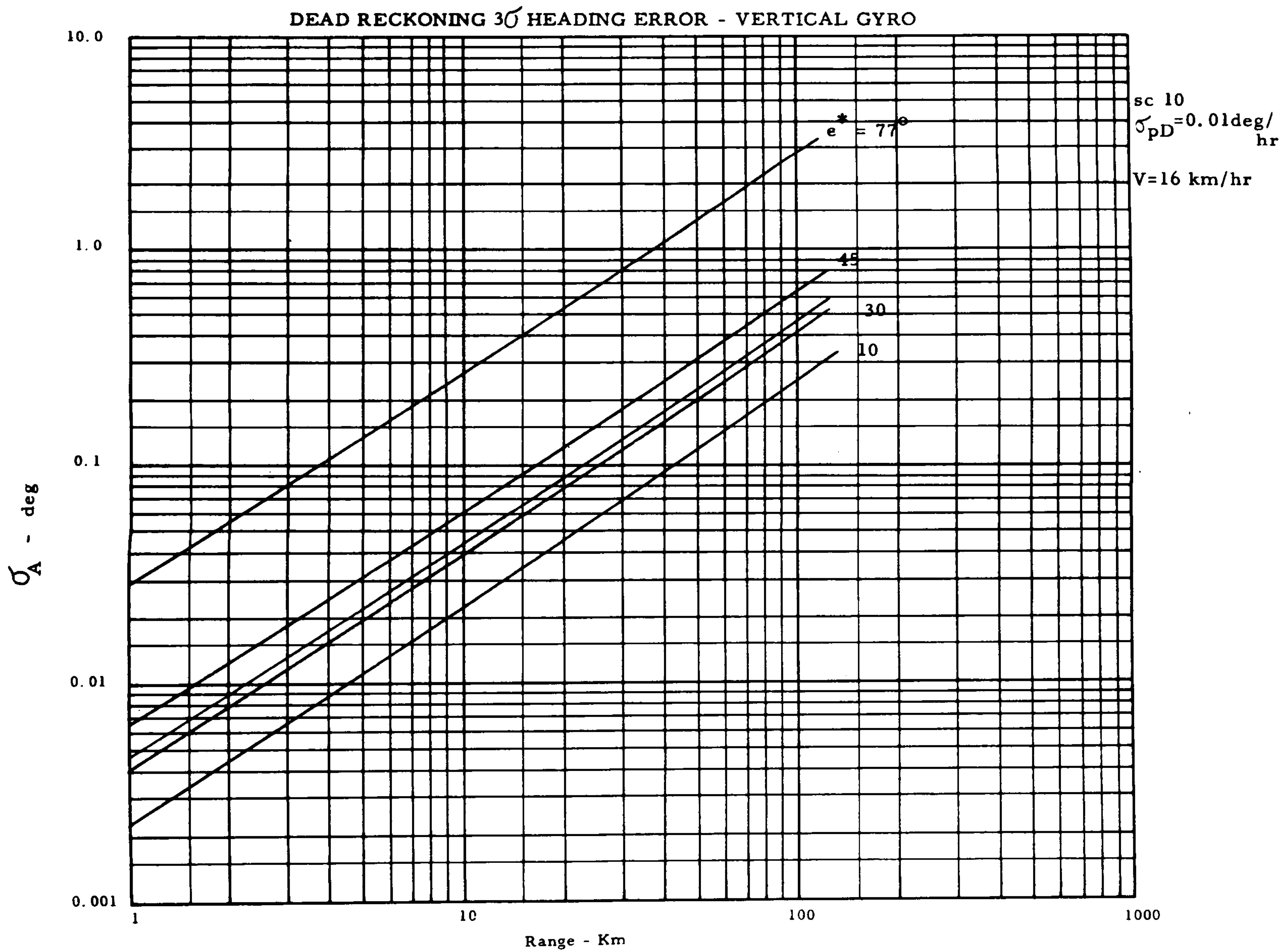


Figure 10-74 Dead Reckoning 3σ Heading Error—Vertical Gyro

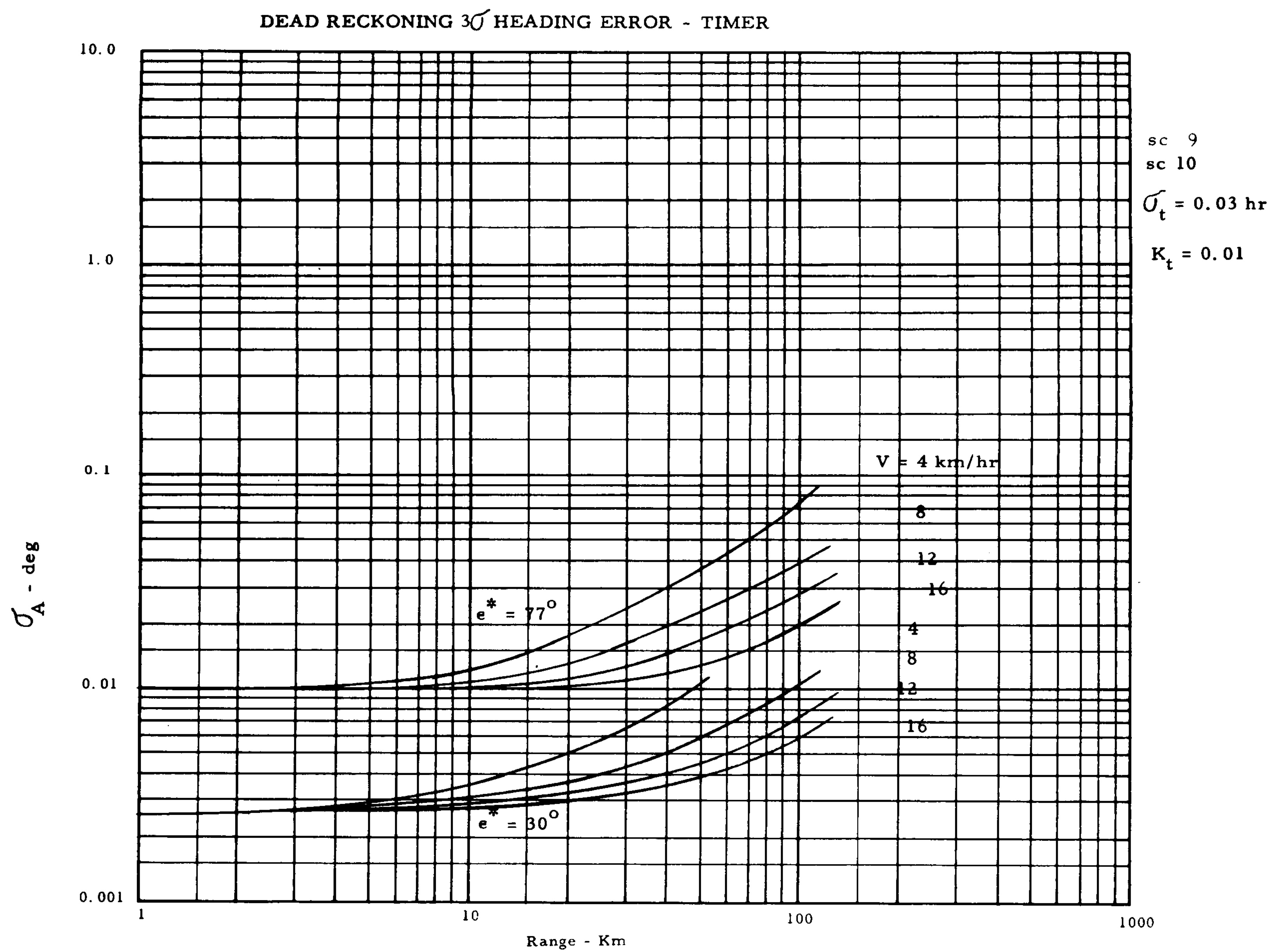


Figure 10-75 Dead Reckoning 3σ Heading Error—Timer

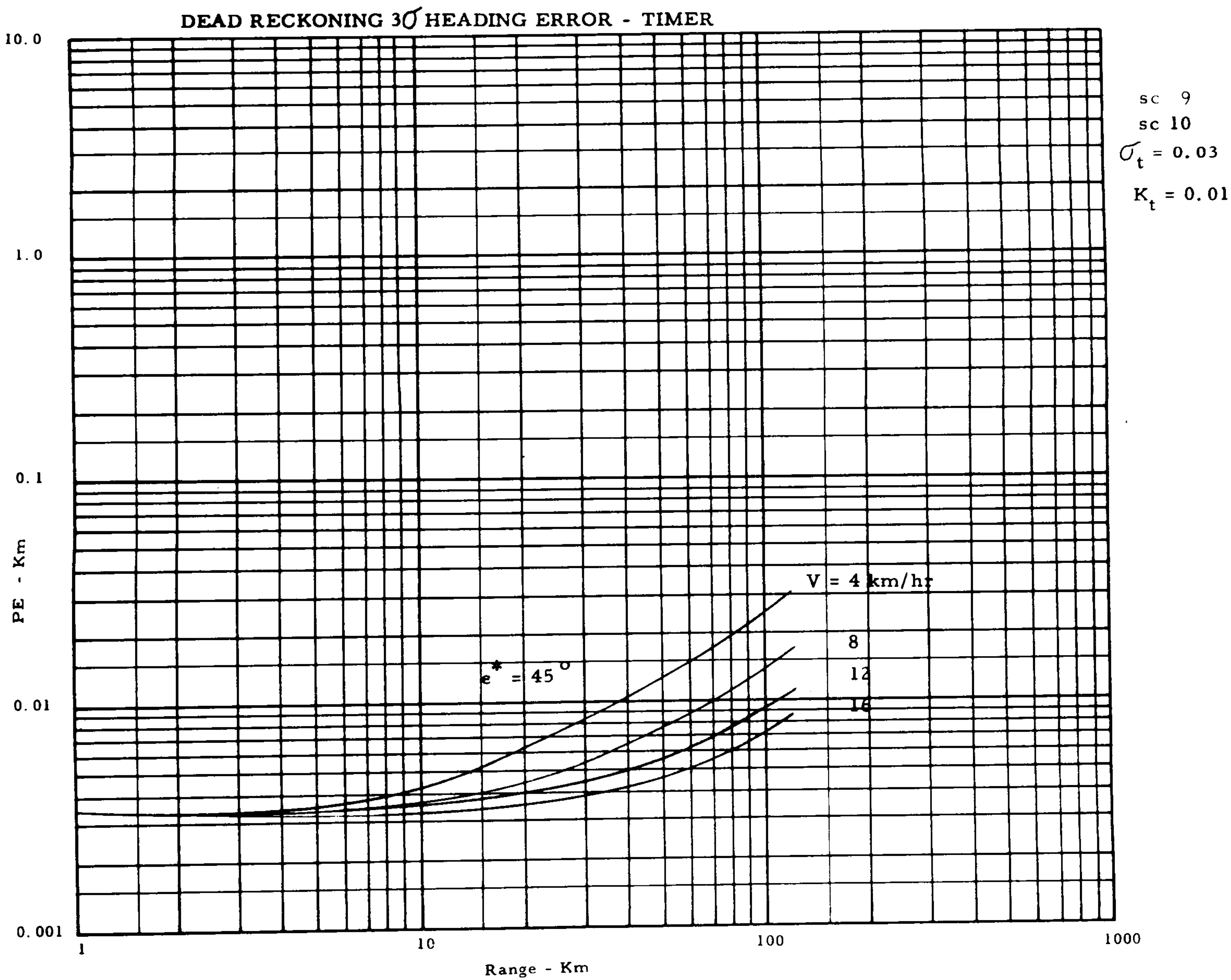


Figure 10-76 Dead Reckoning 3σ Heading Error—Timer

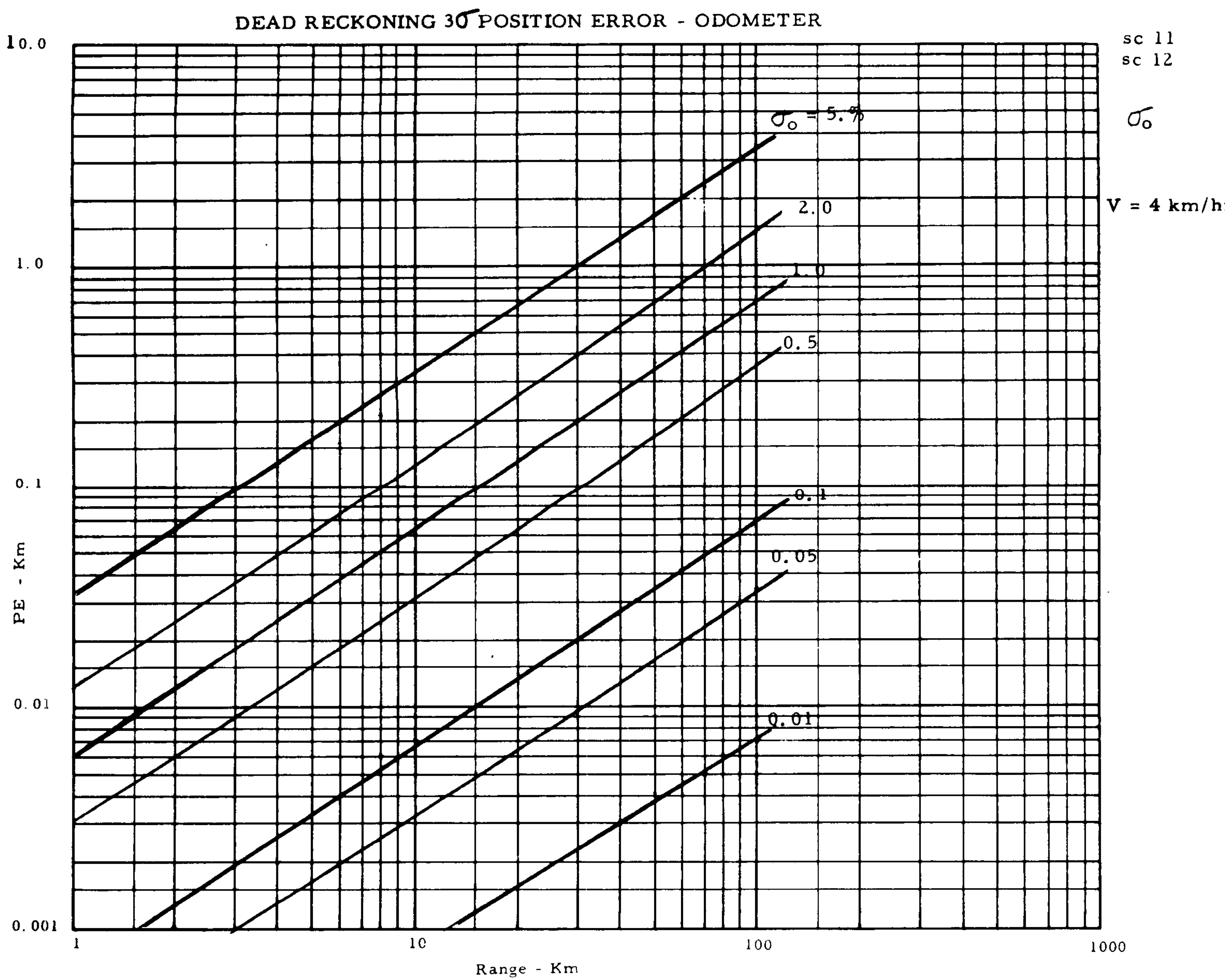


Figure 10-77 Dead Reckoning 3σ Position Error—Odometer

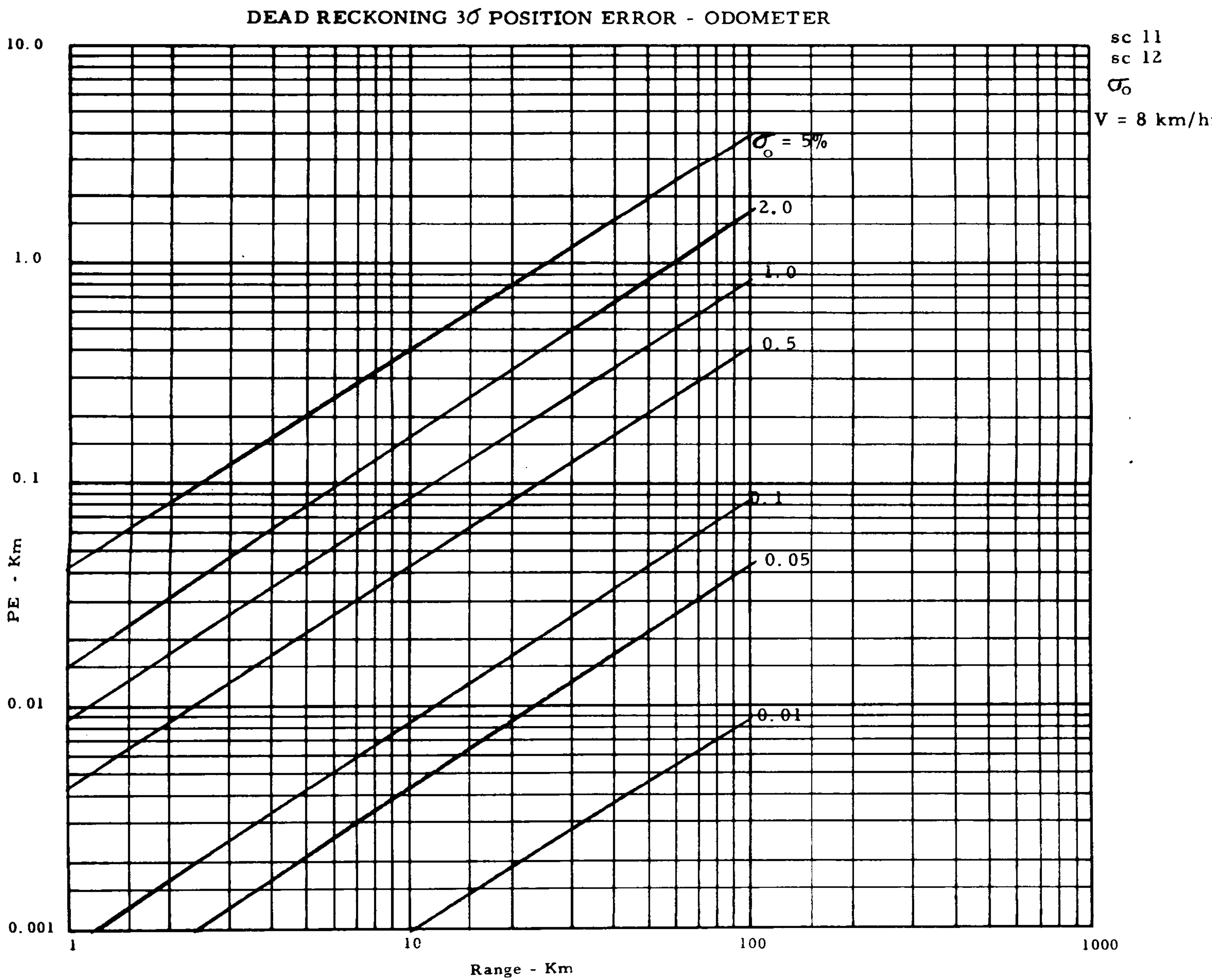


Figure 10-78 Dead Reckoning 3σ Position Error—Odometer

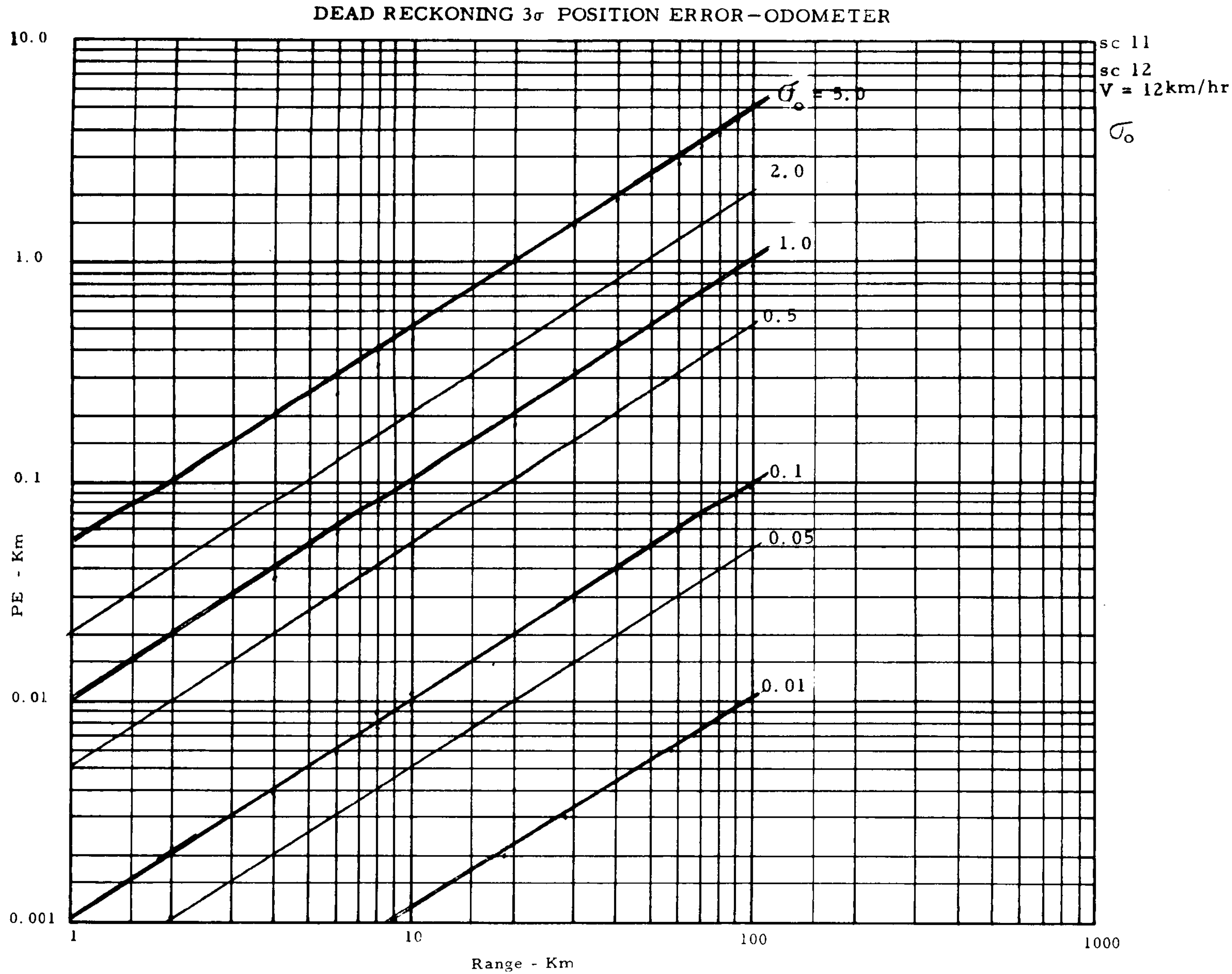


Figure 10-79 Dead Reckoning 3σ Position Error—Odometer

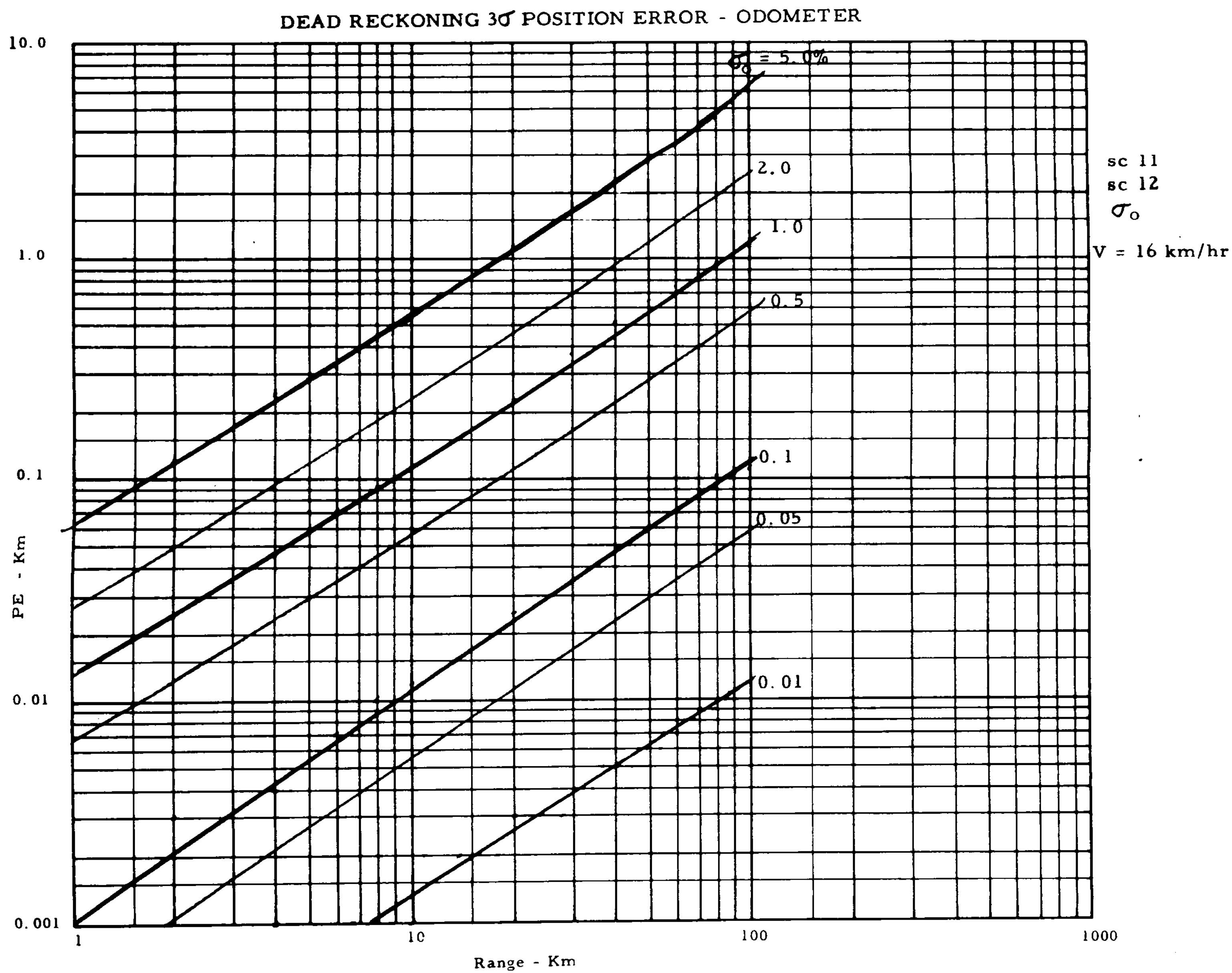


Figure 10-80 Dead Reckoning 3σ Position Error—Odometer

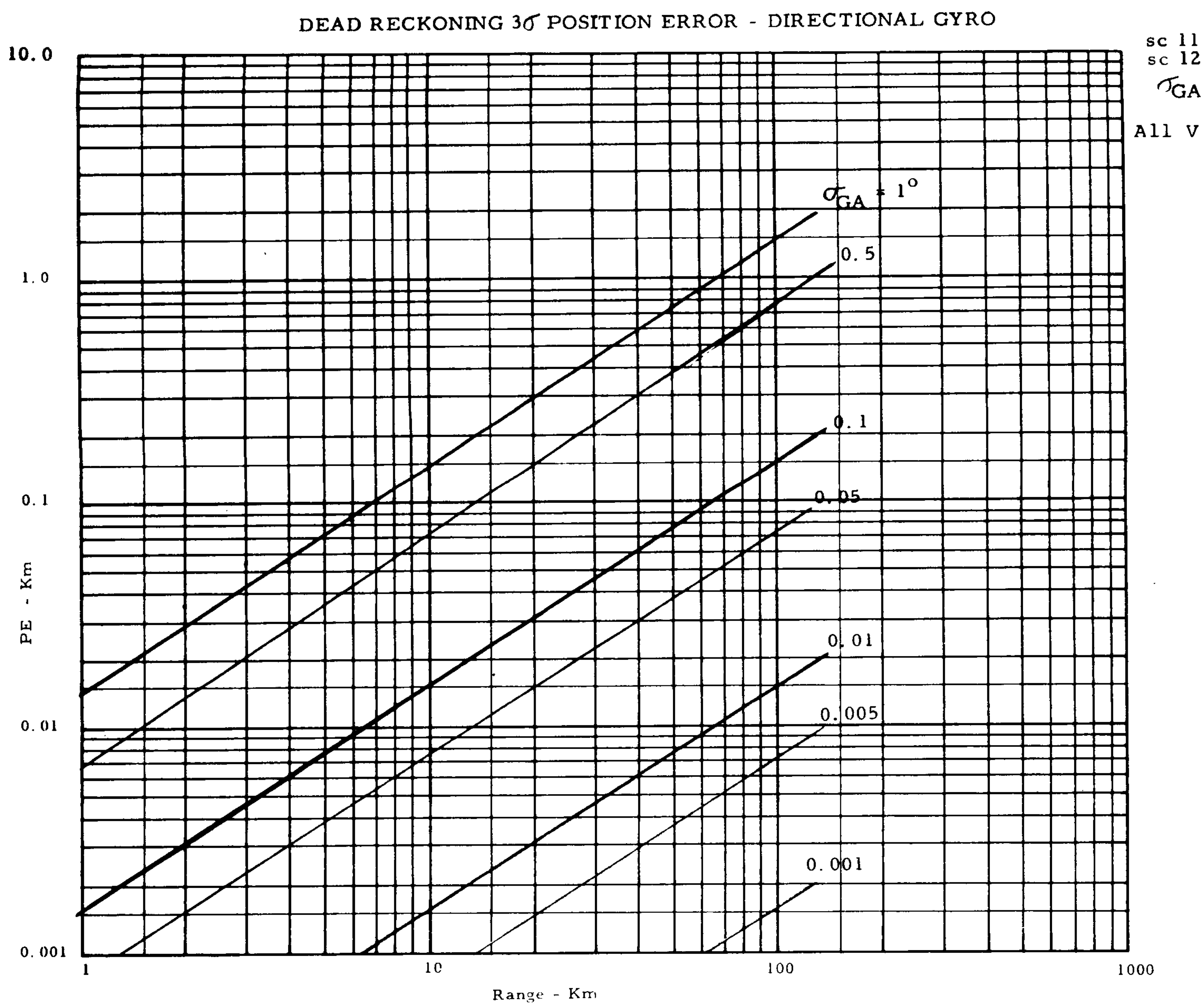


Figure 10-81 Dead Reckoning 3σ Position Error—Directional Gyro

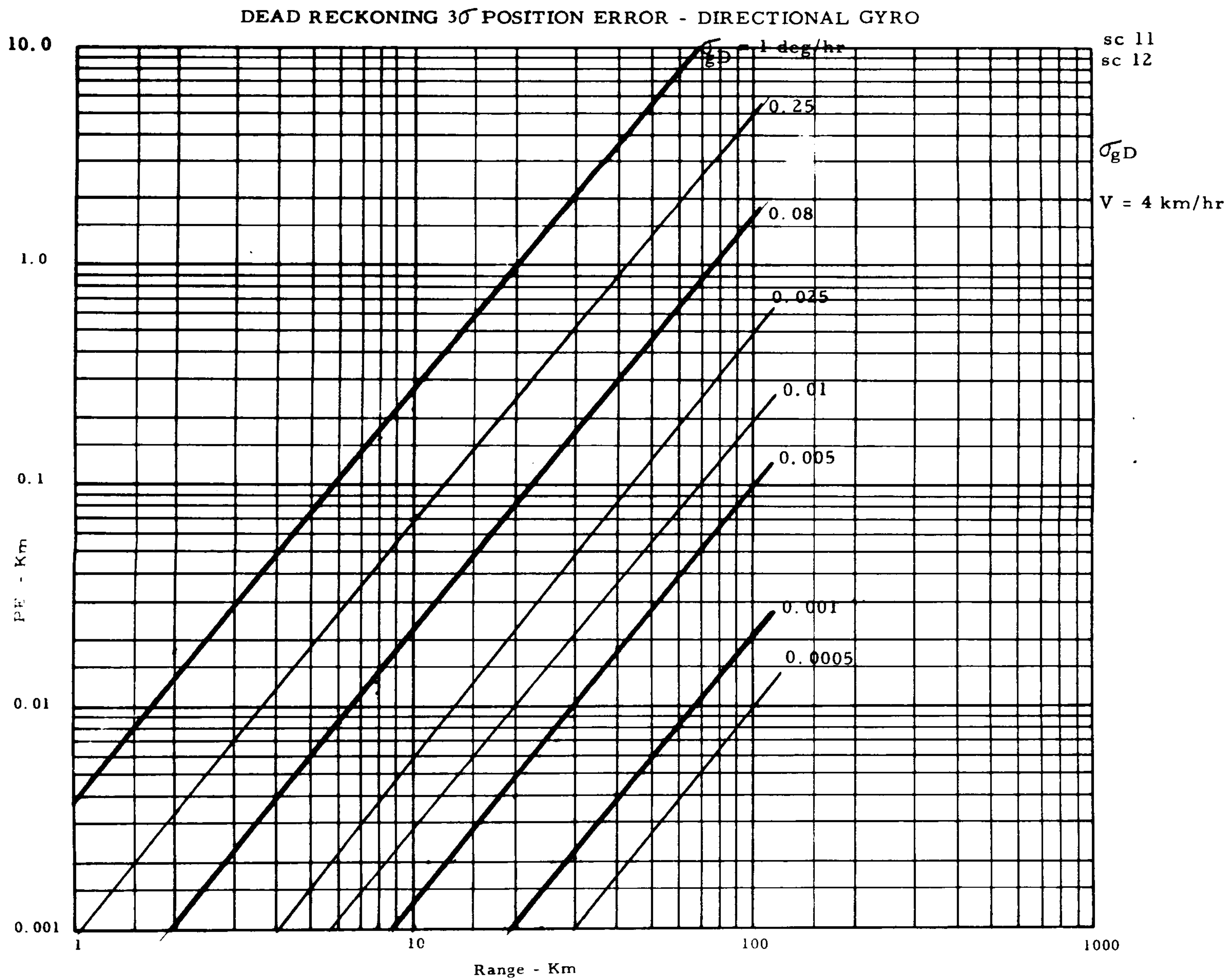


Figure 10-82 Dead Reckoning 3σ Position Error—Directional Gyro

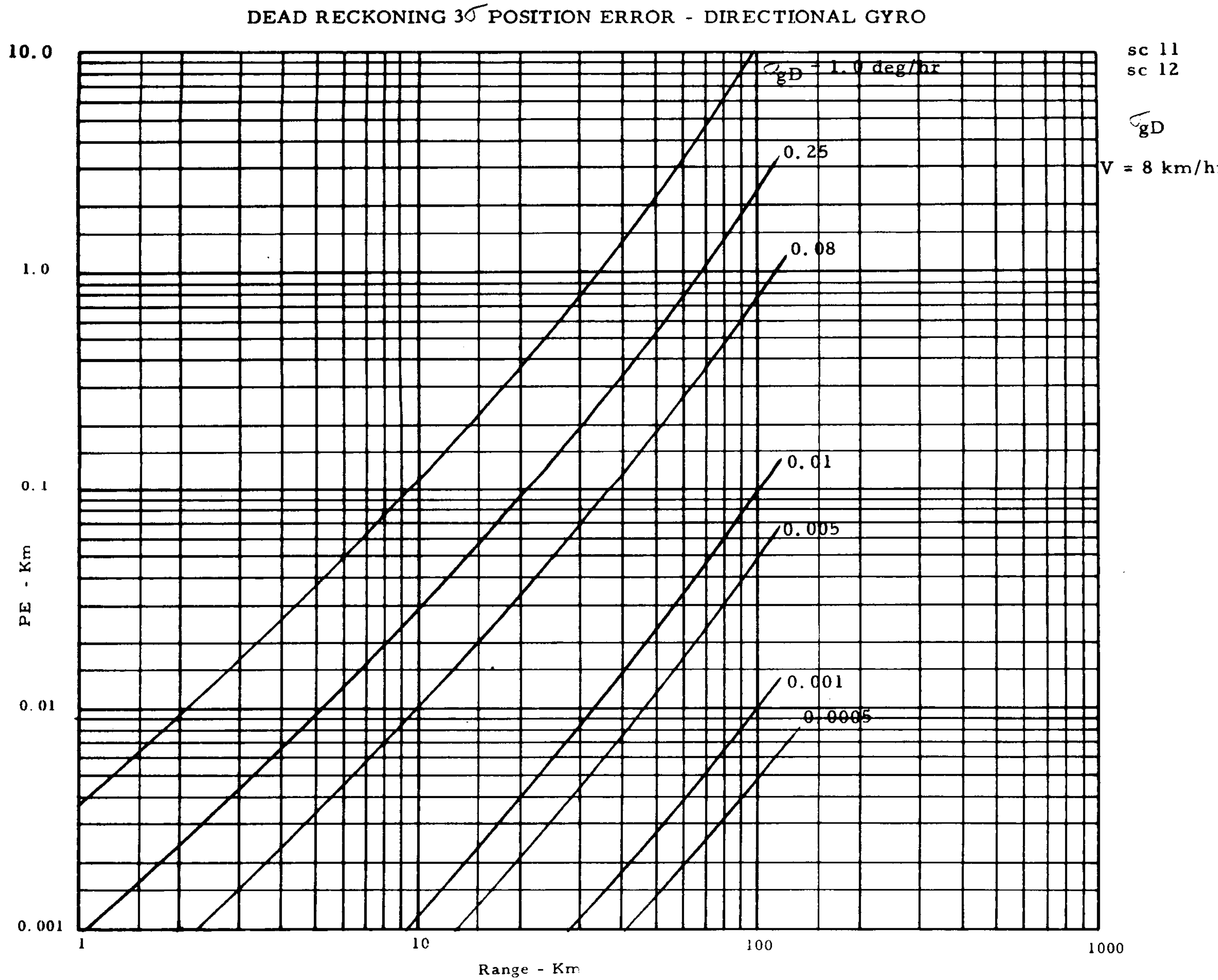


Figure 10-83 Dead Reckoning 3σ Position Error—Directional Gyro

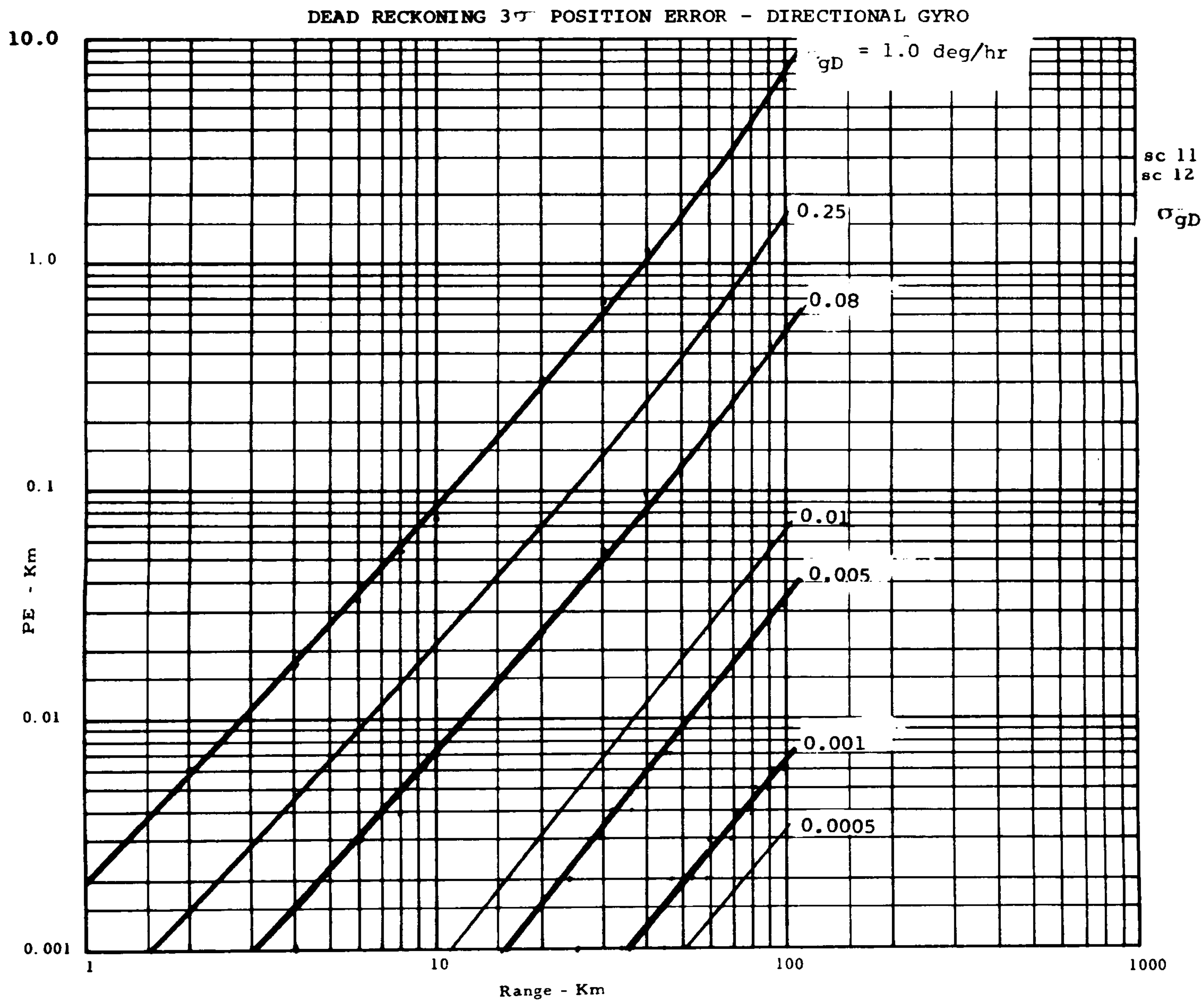


Figure 10-84 Dead Reckoning 3σ Position Error—Directional Gyro

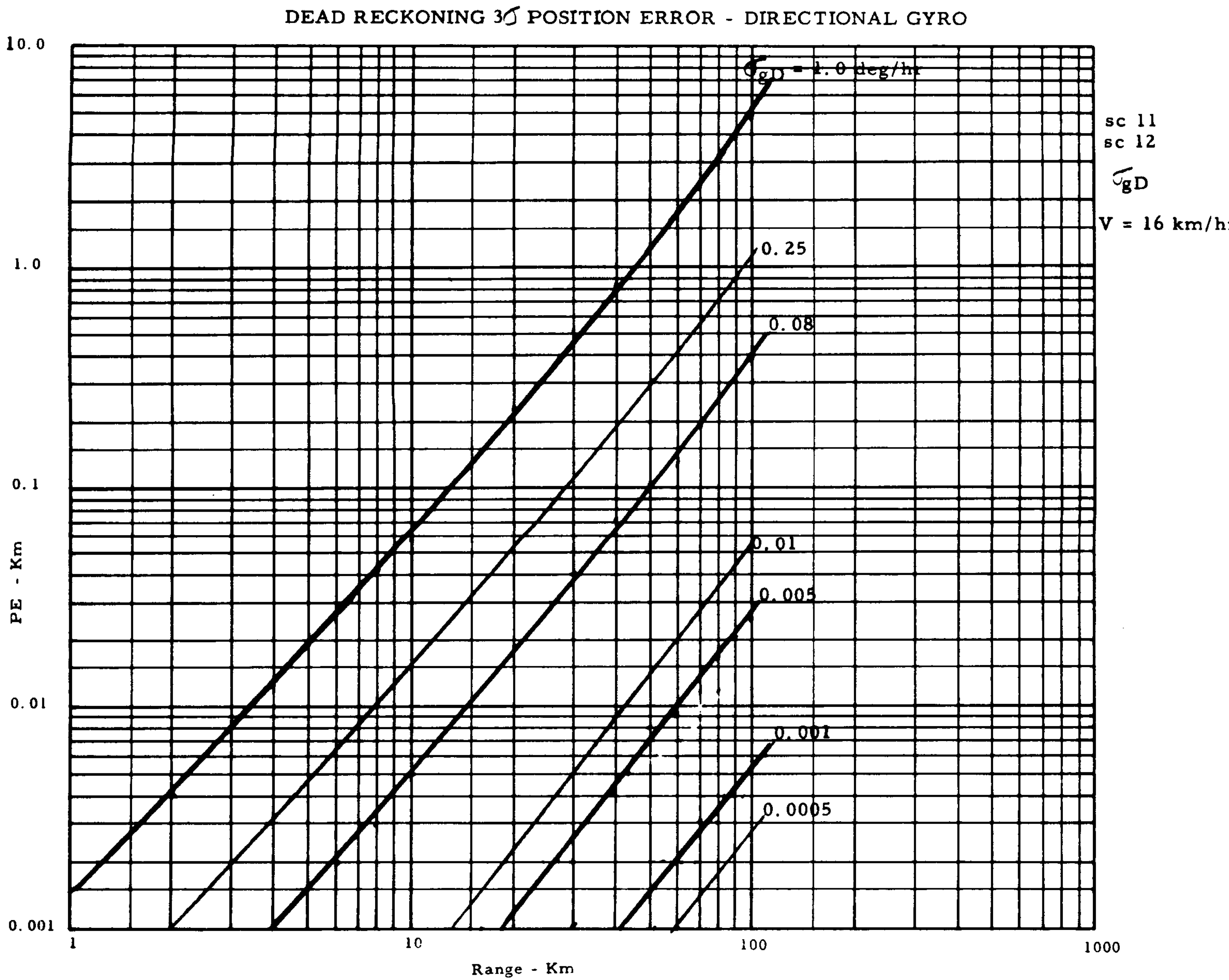


Figure 10-85 Dead Reckoning 3σ Position Error—Odometer

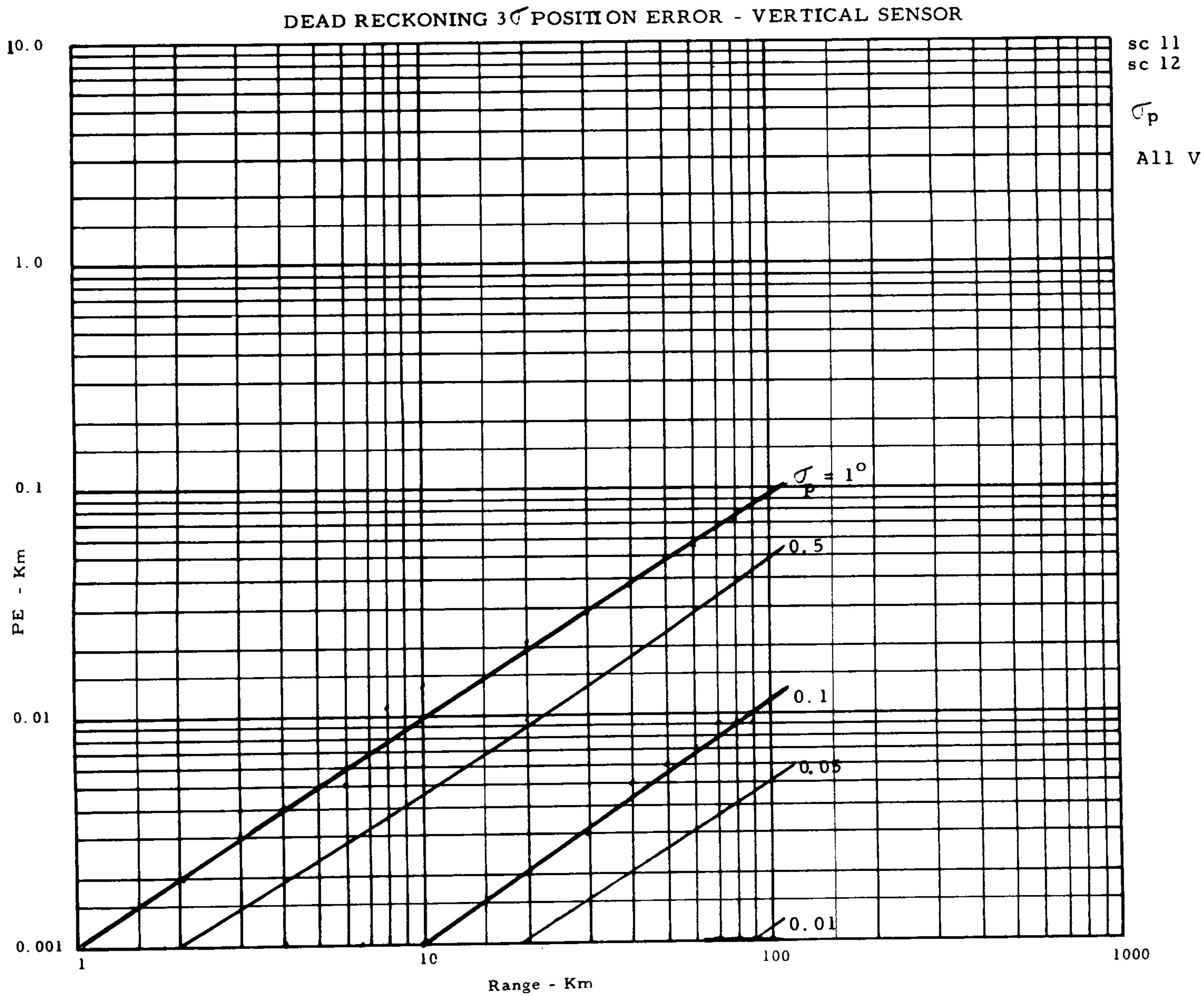


Figure 10-86 Dead Reckoning 3σ Position Error—Vertical Sensor

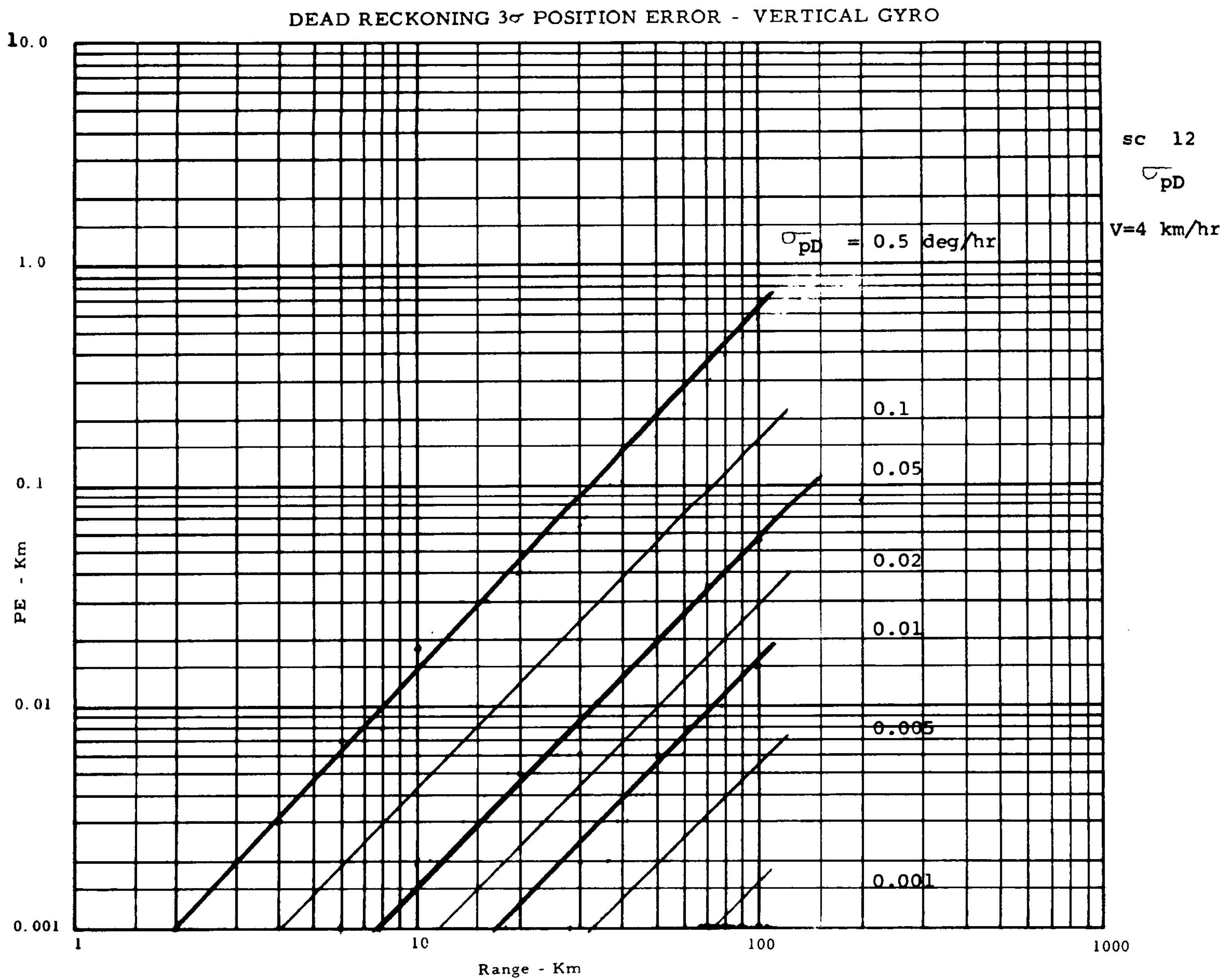


Figure 10-87 Dead Reckoning 3σ Position Error—Vertical Gyro

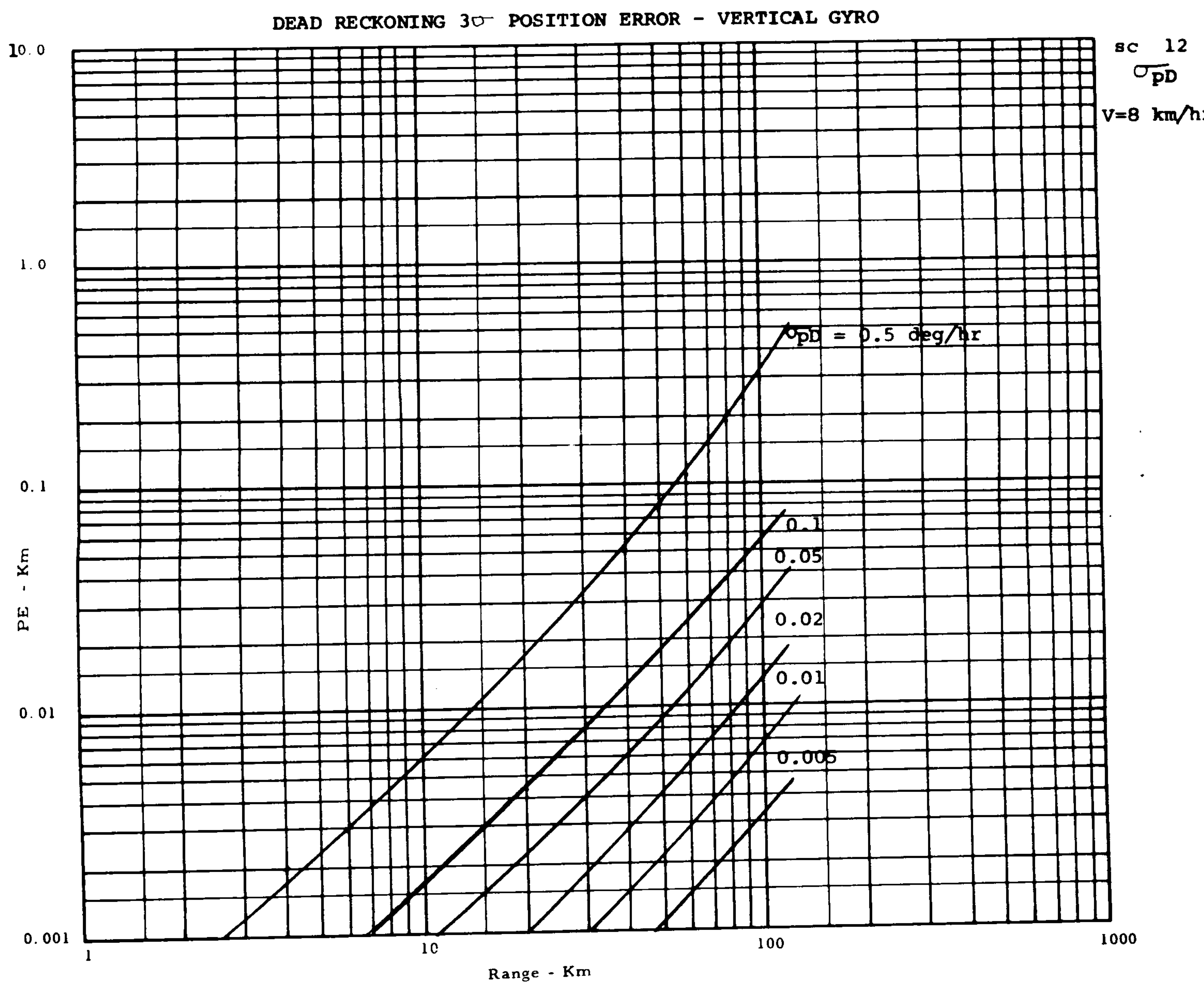


Figure 10-88 Dead Reckoning 3σ Position Error—Vertical Gyro

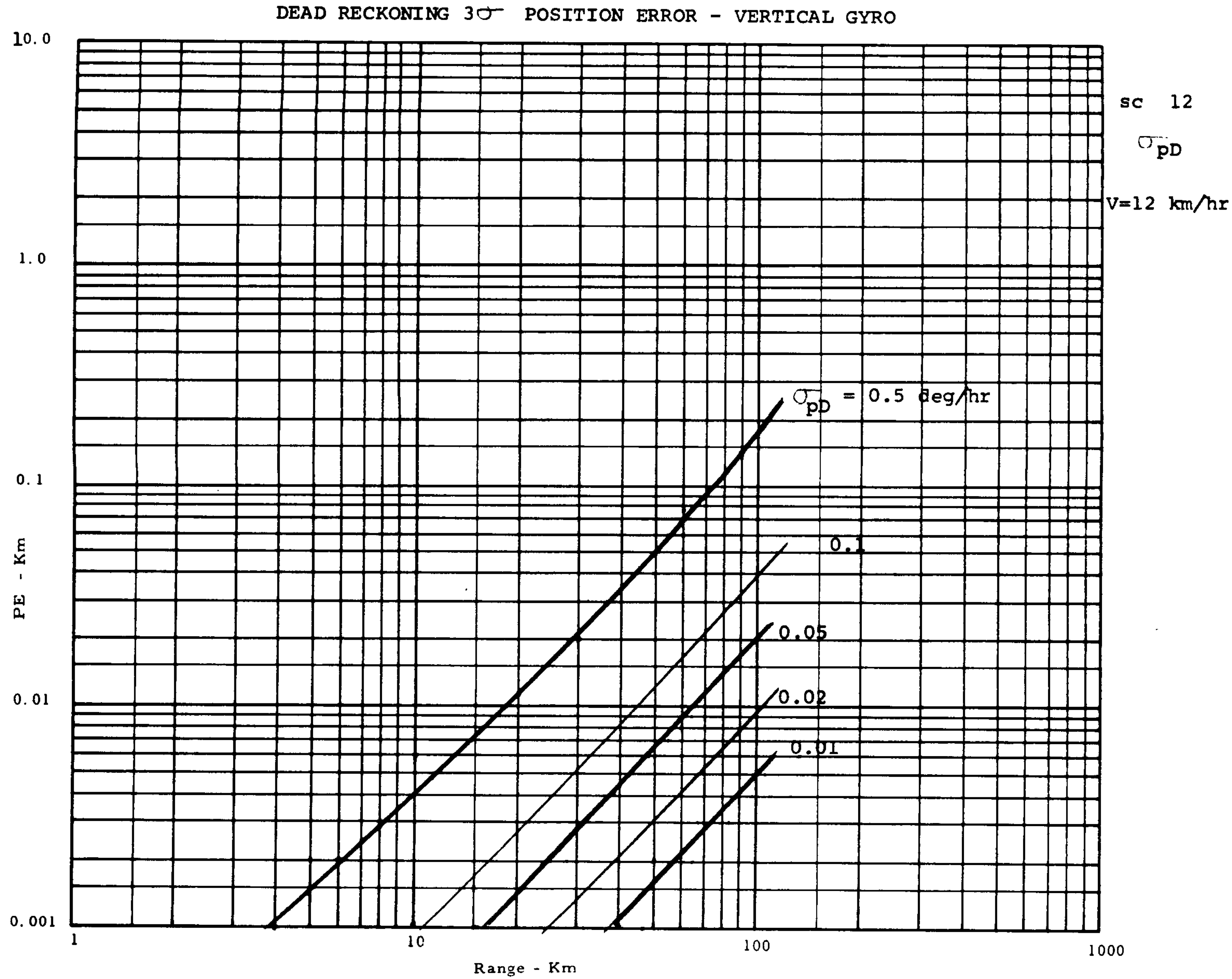


Figure 10-89 Dead Reckoning 3σ Position Error—Vertical Gyro

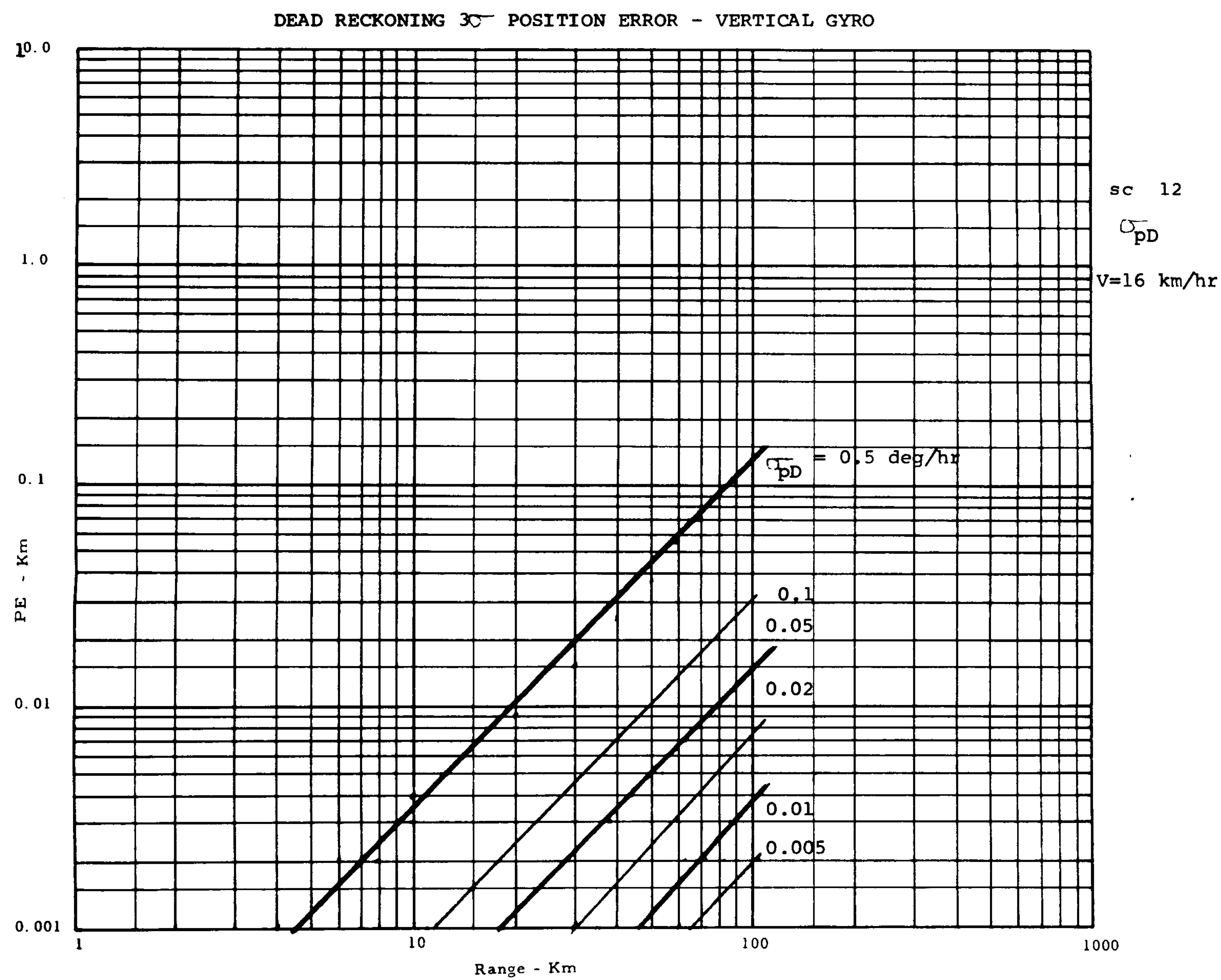


Figure 10-90 Dead Reckoning 3σ Position Error—Vertical Gyro

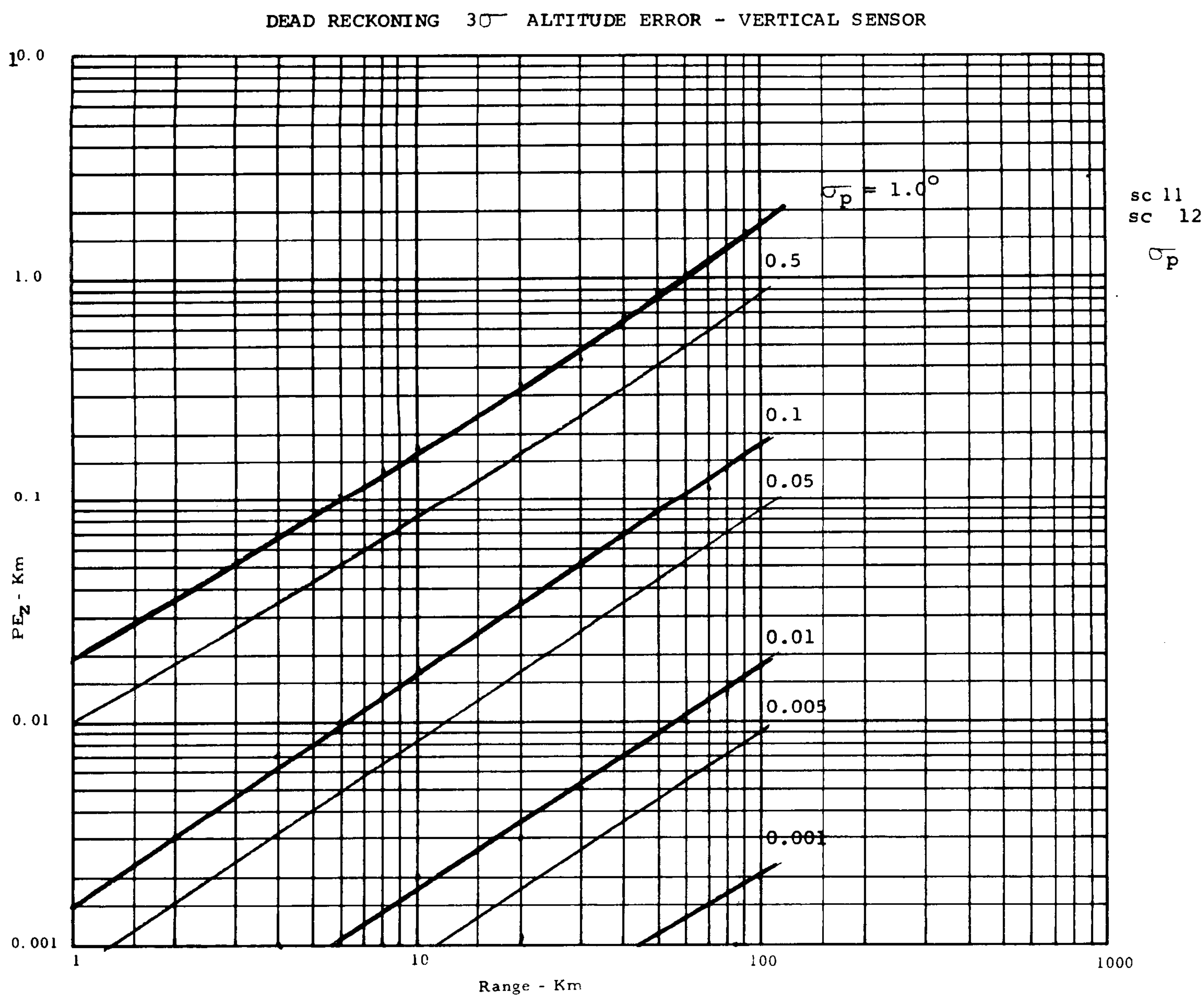


Figure 10-91 Dead Reckoning 3σ Altitude Error—Vertical Sensor

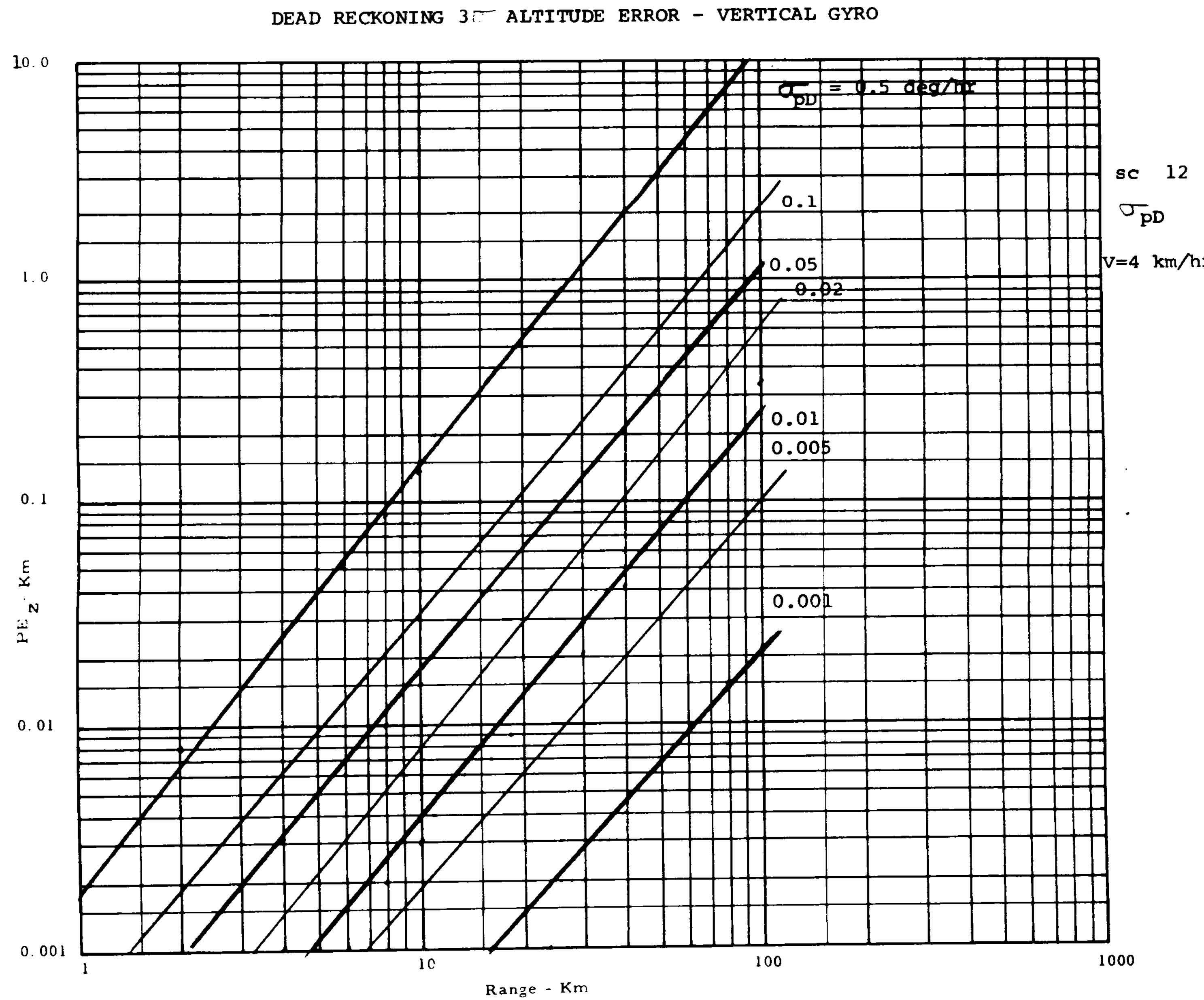


Figure 10-92 Dead Reckoning 3σ Altitude Error—Vertical Gyro

DEAD RECKONING 3σ ALTITUDE ERROR - VERTICAL GYRO

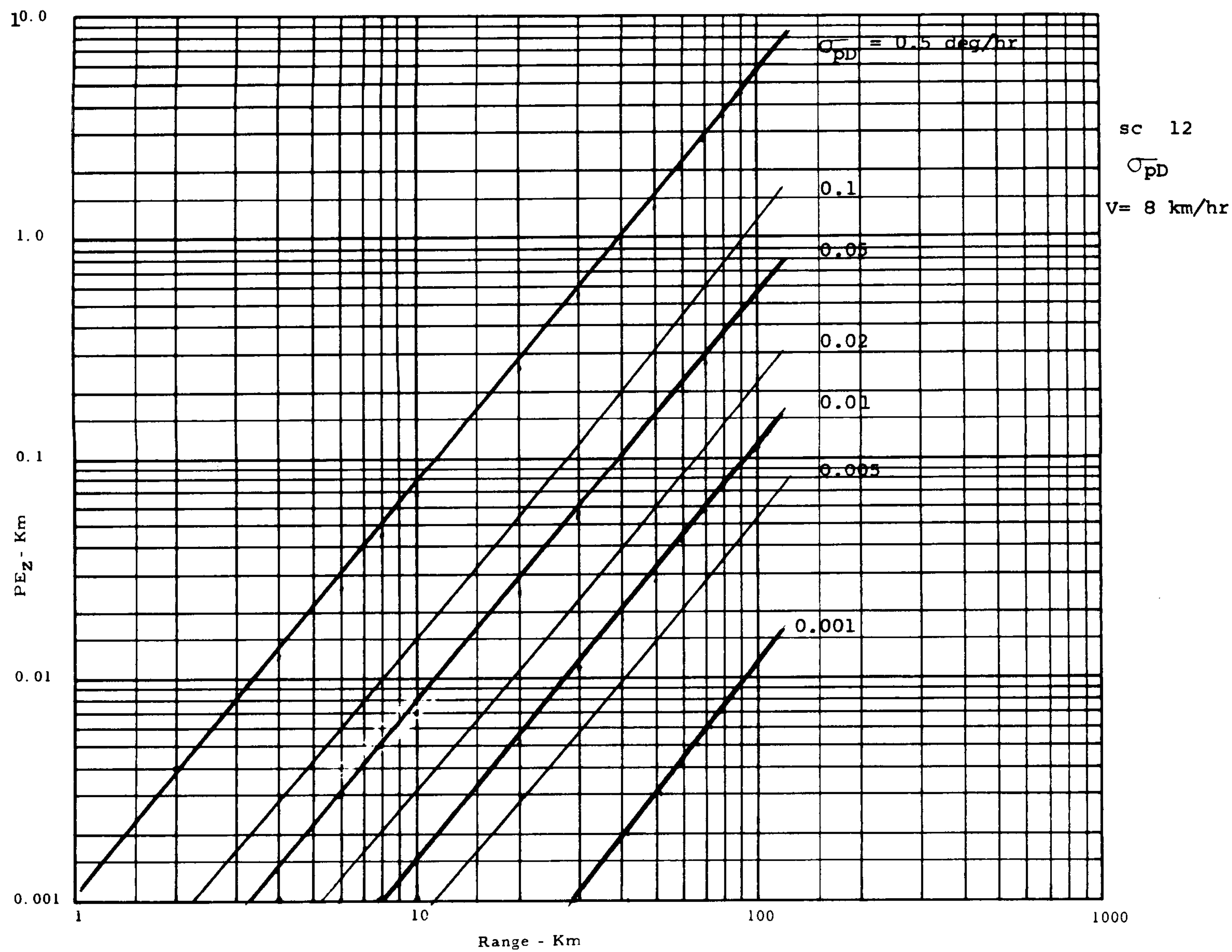


Figure 10-93 Dead Reckoning 3σ Altitude Error—Vertical Gyro

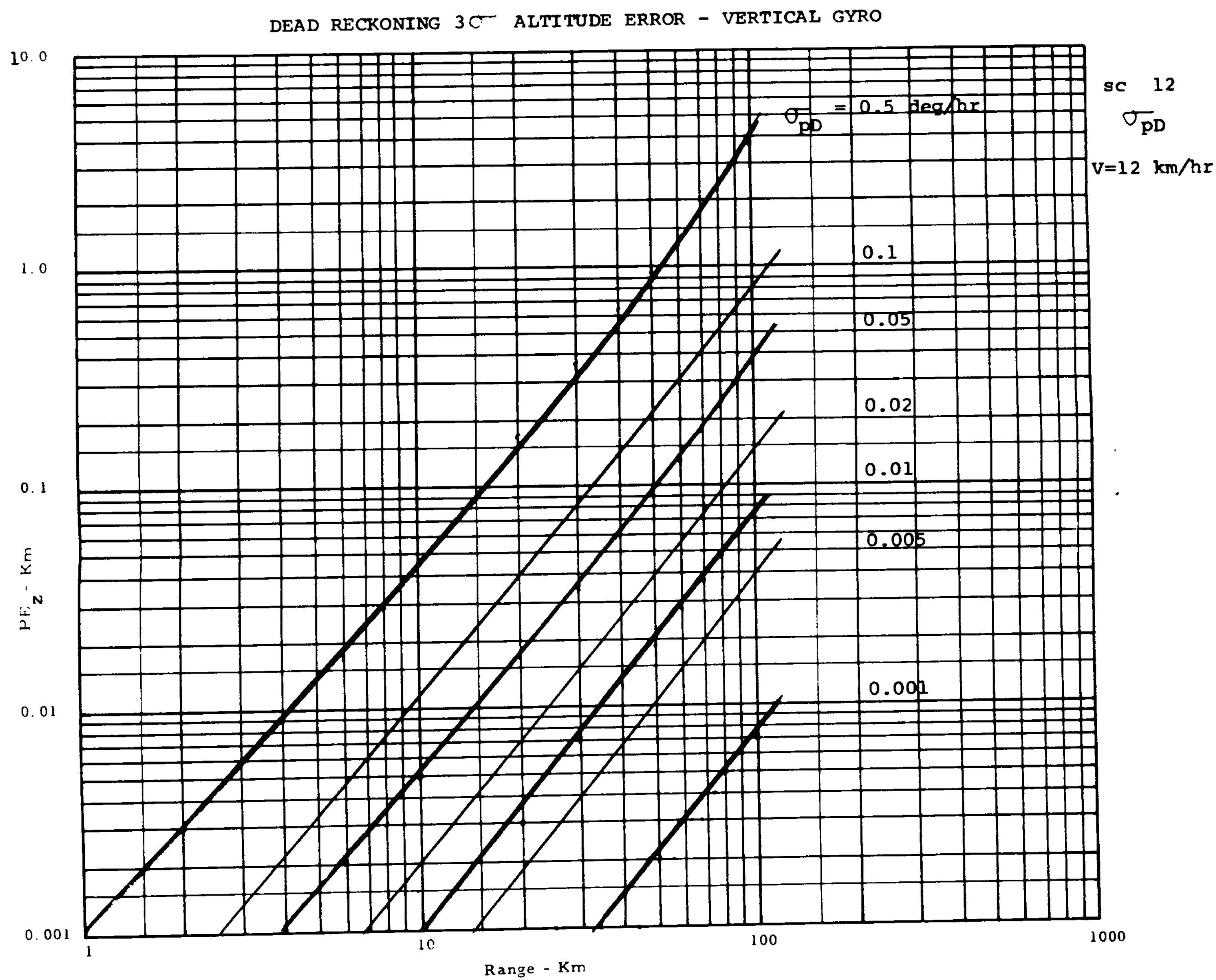


Figure 10-94 Dead Reckoning 3σ Altitude Error—Vertical Gyro

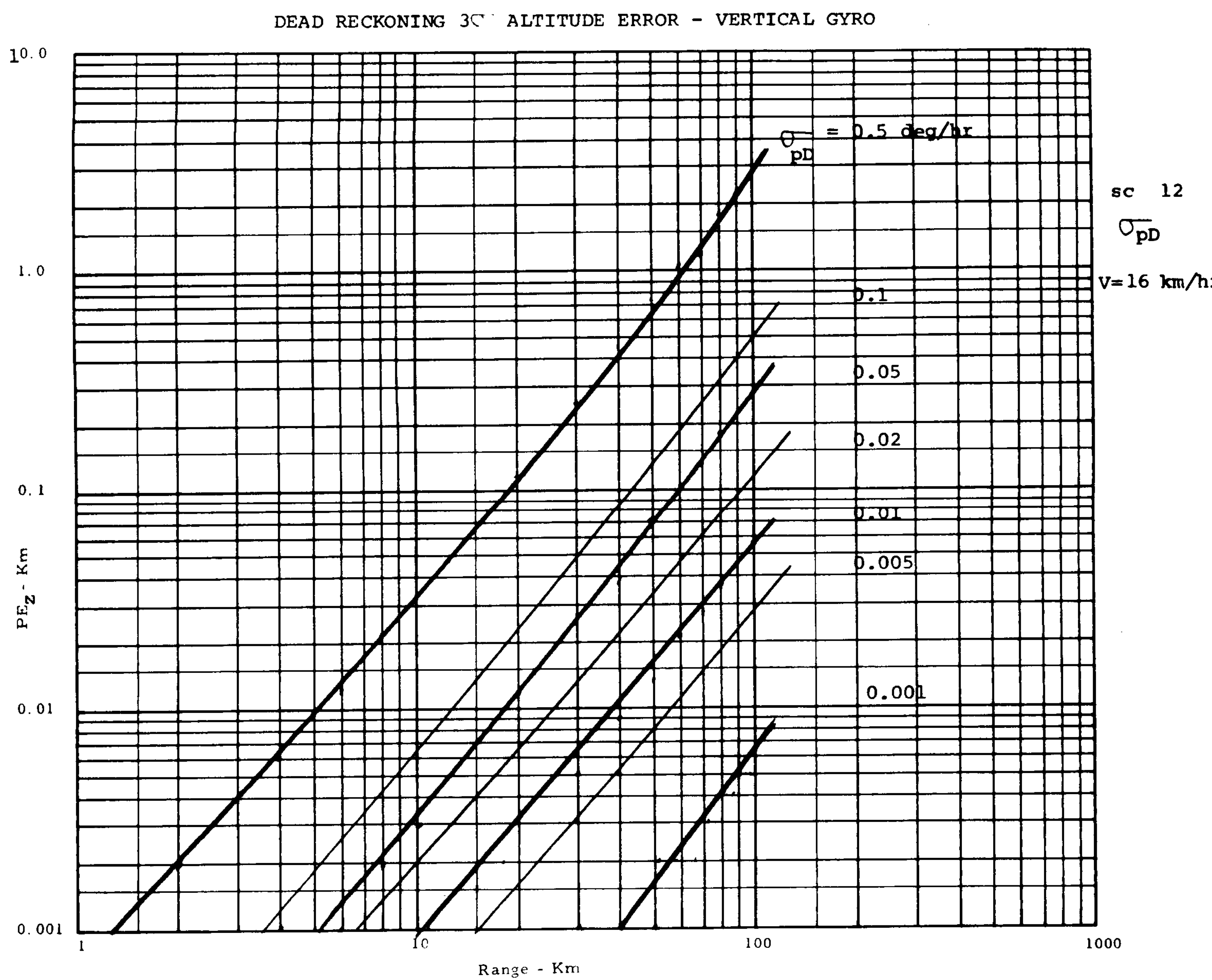


Figure 10-95 Dead Reckoning 3σ Altitude Error—Vertical Gyro

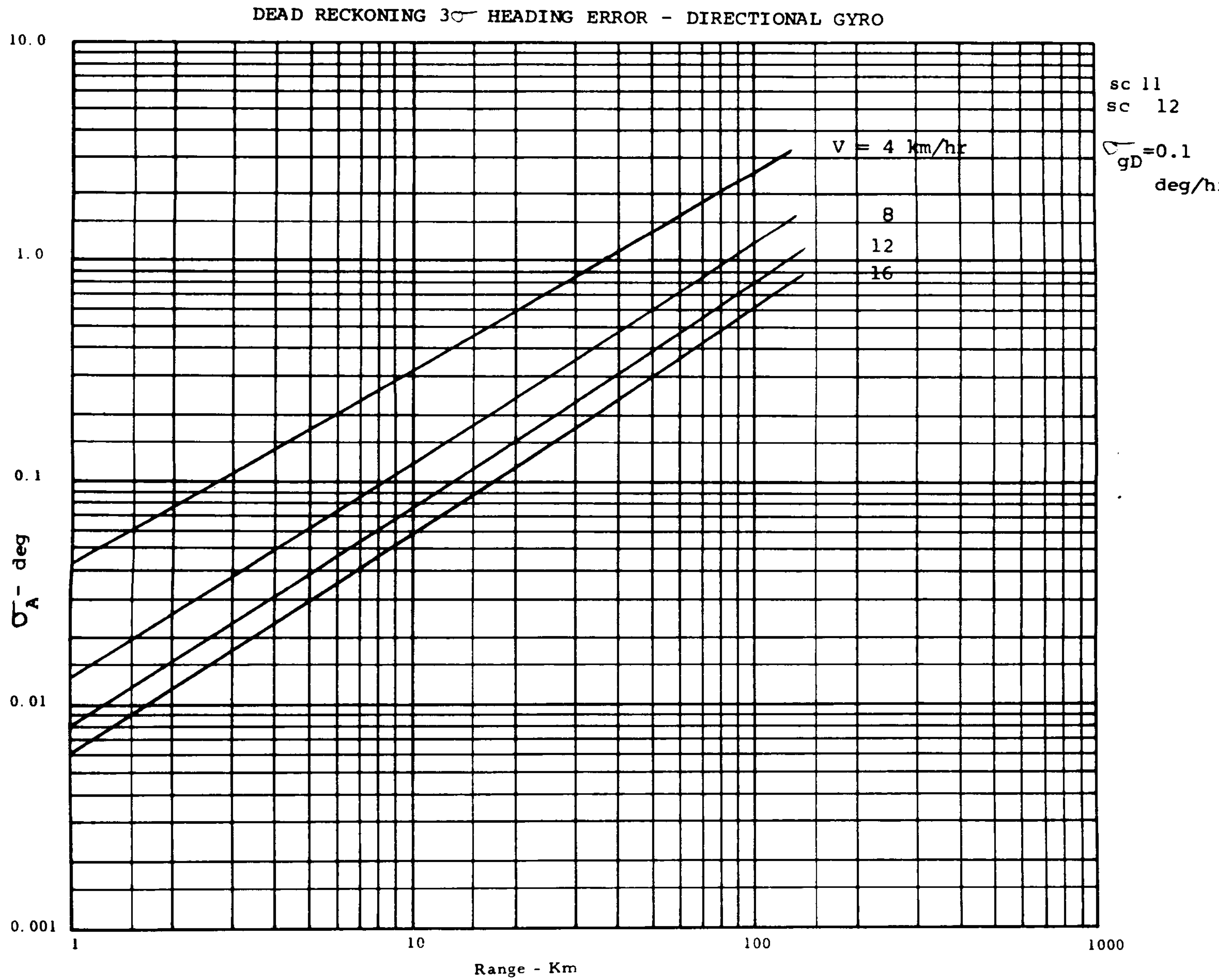


Figure 10-96 Dead Reckoning 3σ Heading Error—Directional Gyro

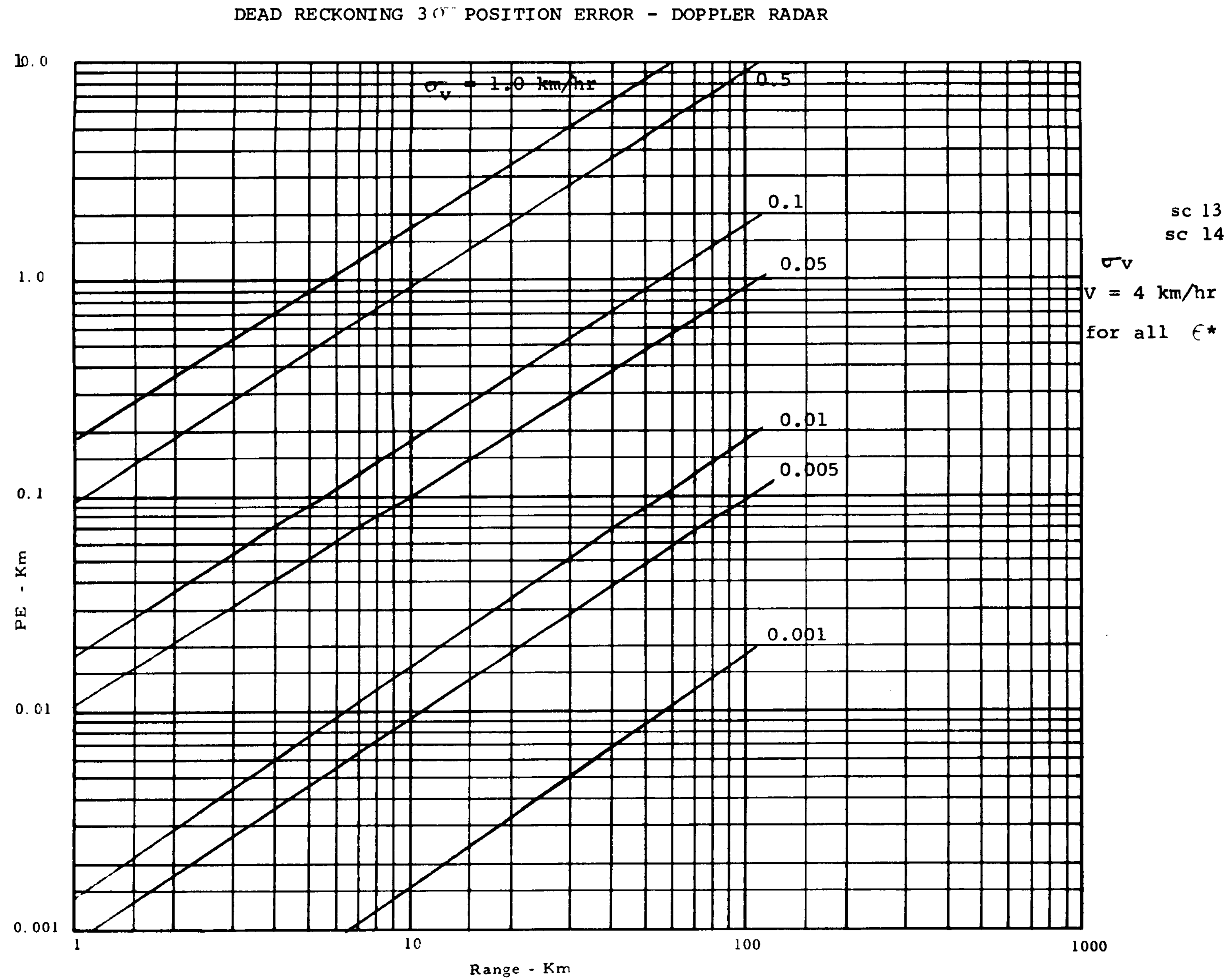


Figure 10-97 Dead Reckoning 3σ Position Error—Doppler Radar

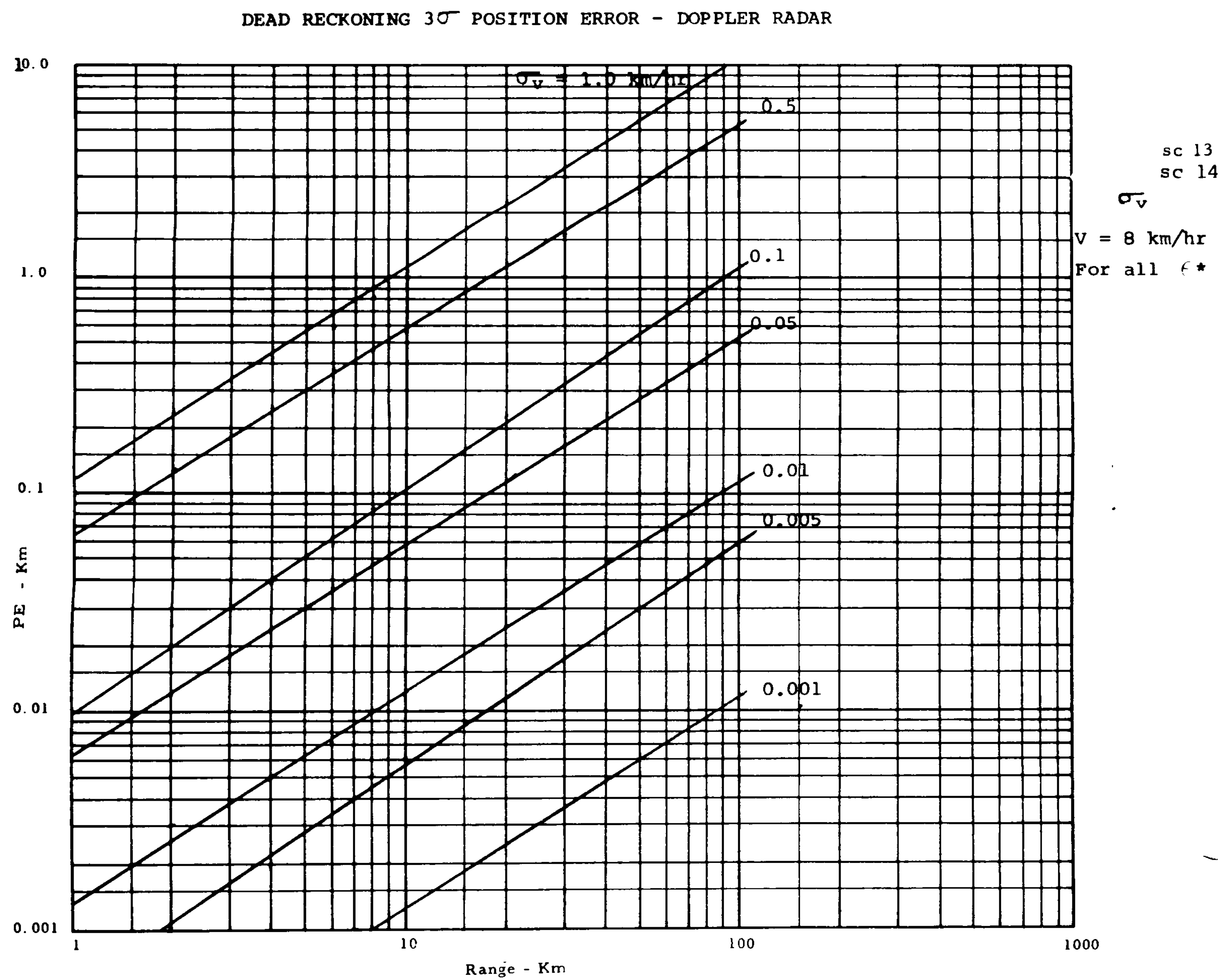


Figure 10-98 Dead Reckoning 3σ Position Error—Doppler Radar

DEAD RECKONING 3σ POSITION ERROR - DOPPLER RADAR

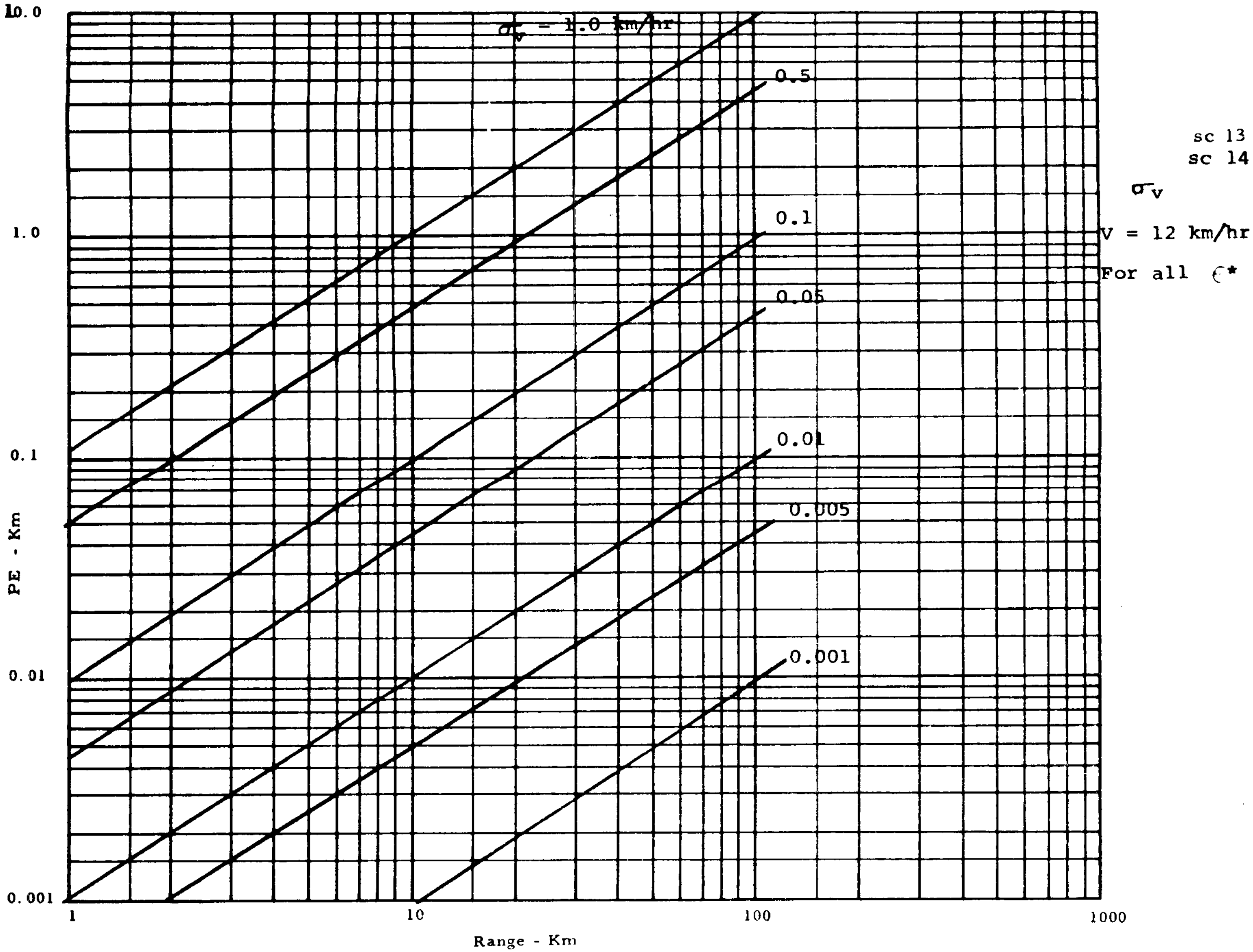


Figure 10-99 Dead Reckoning 3σ Position Error—Doppler Radar

DEAD RECKONING 3σ POSITION ERROR - DOPPLER RADAR

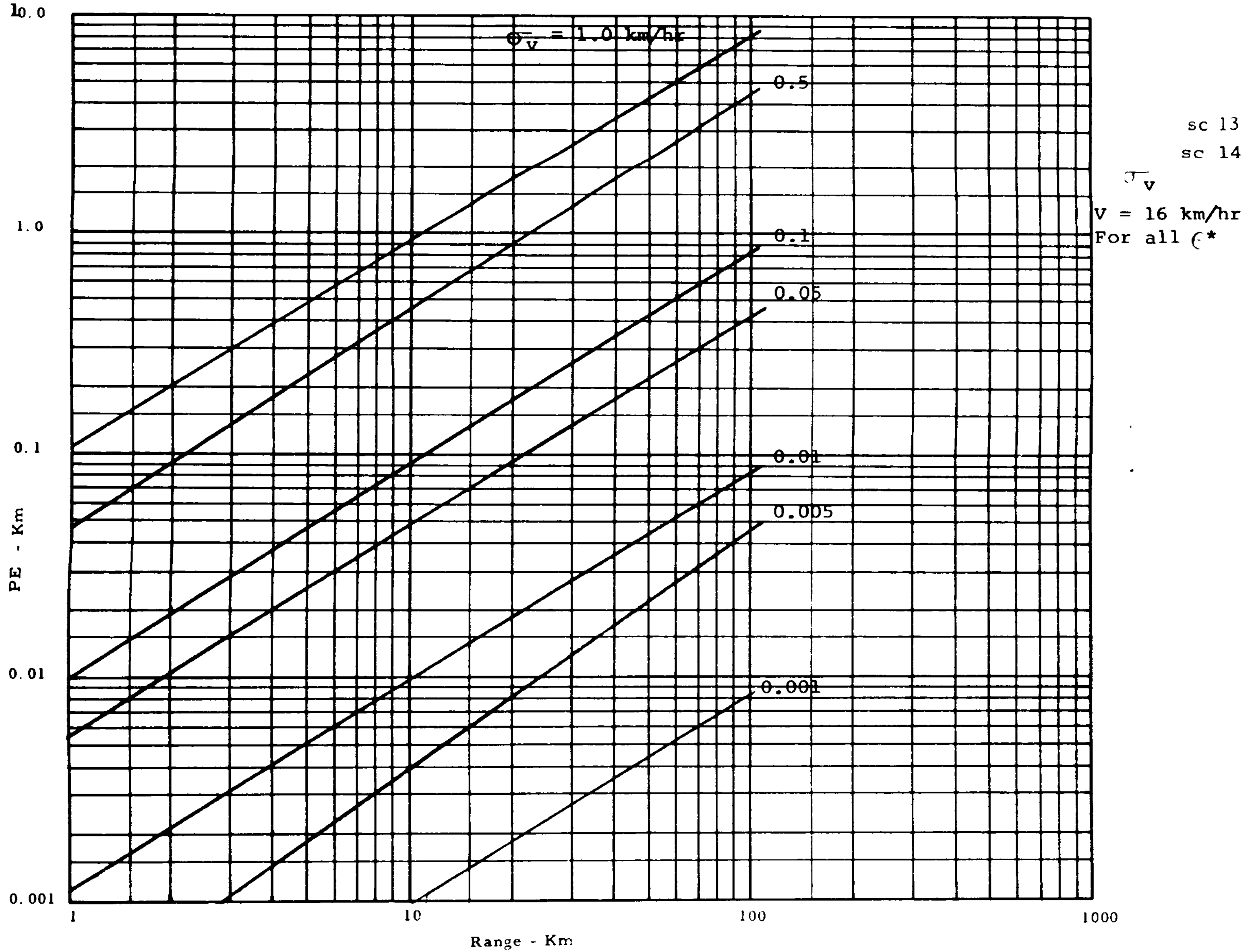


Figure 10-100 Dead Reckoning 3σ Position Error—Doppler Radar

DEAD RECKONING 3σ POSITION ERROR - CELESTIAL TRACKER

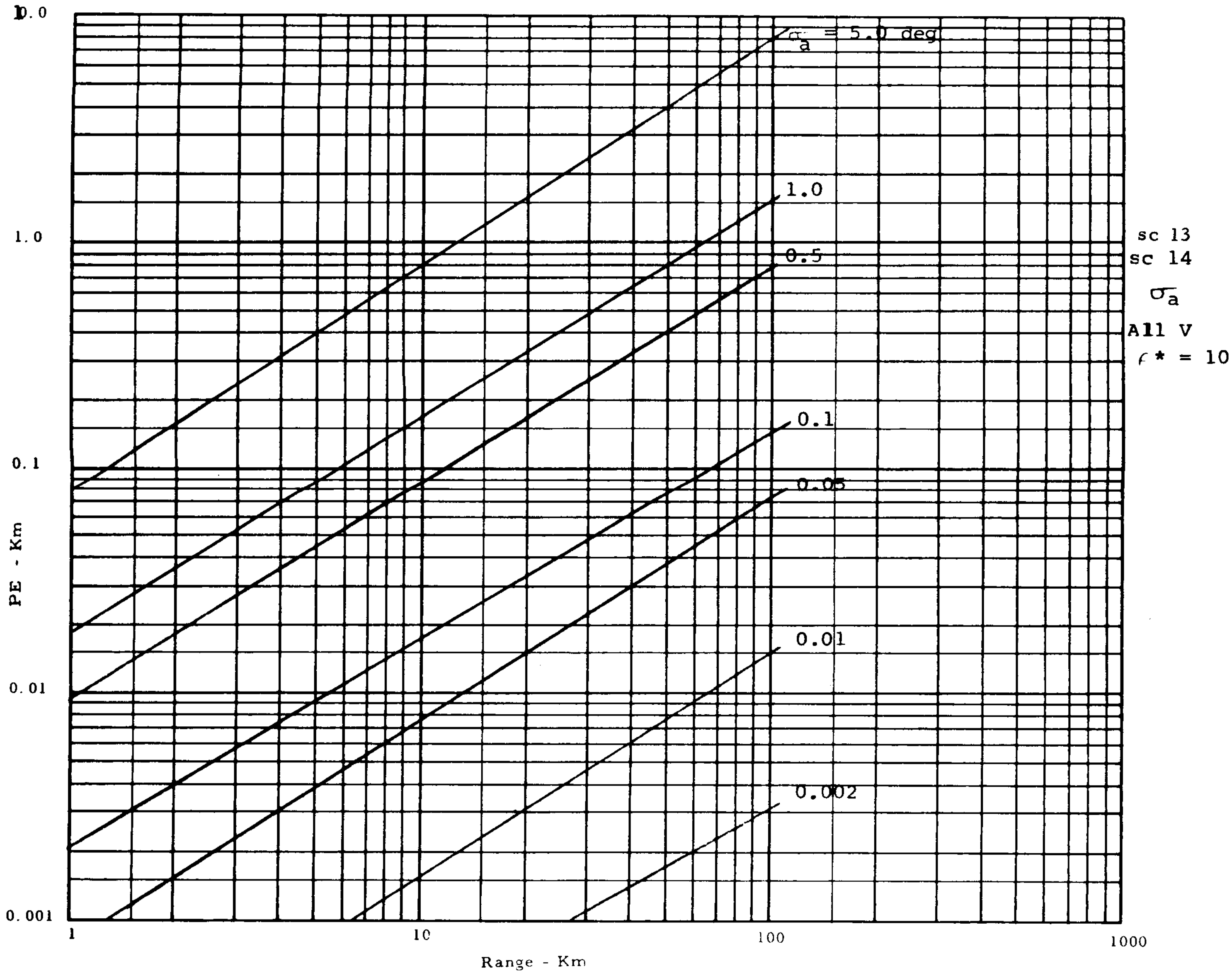


Figure 10-101 Dead Reckoning 3σ Position Error—Celestial Tracker

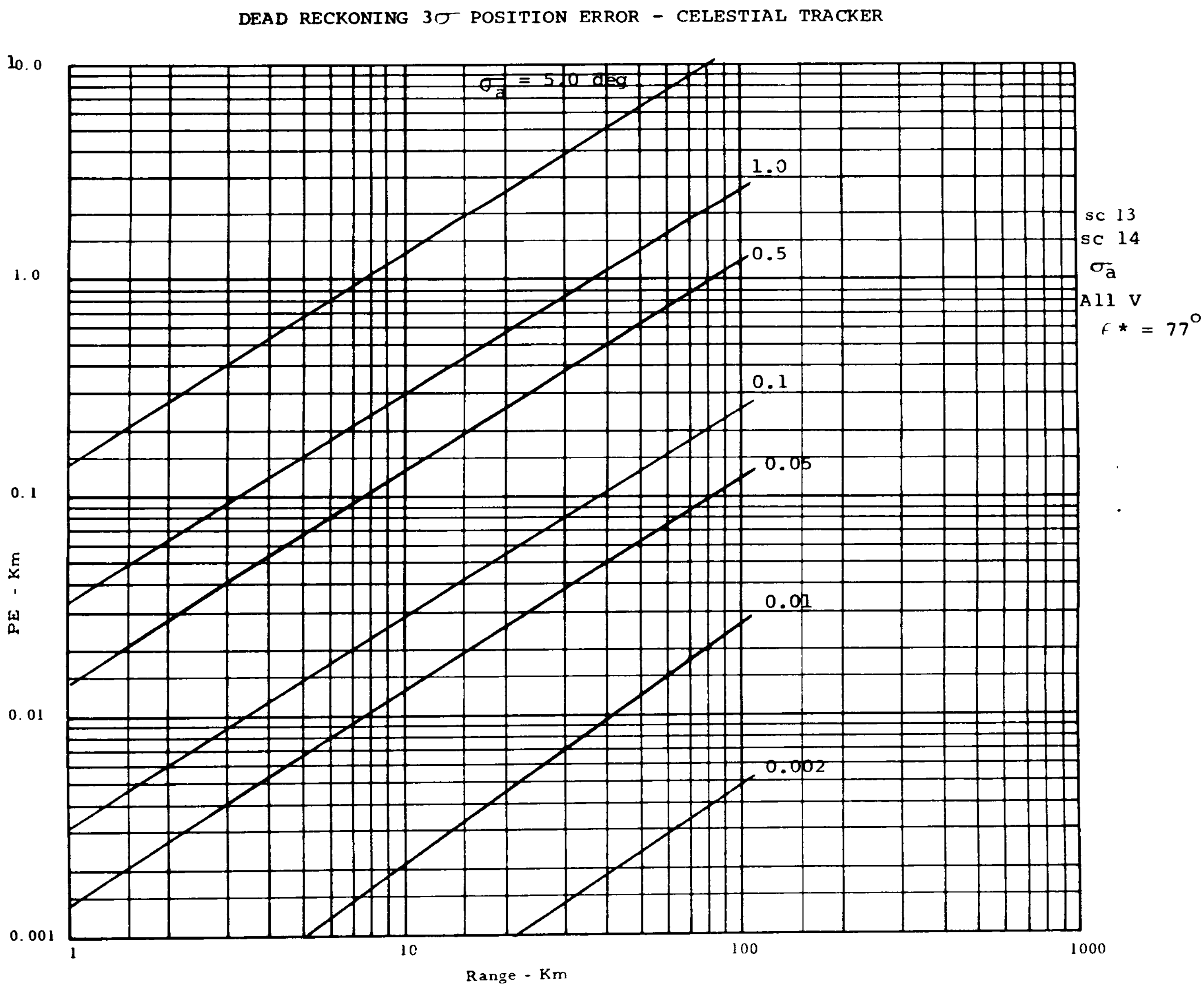


Figure 10-102 Dead Reckoning 3σ Position Error—Celestial Tracker

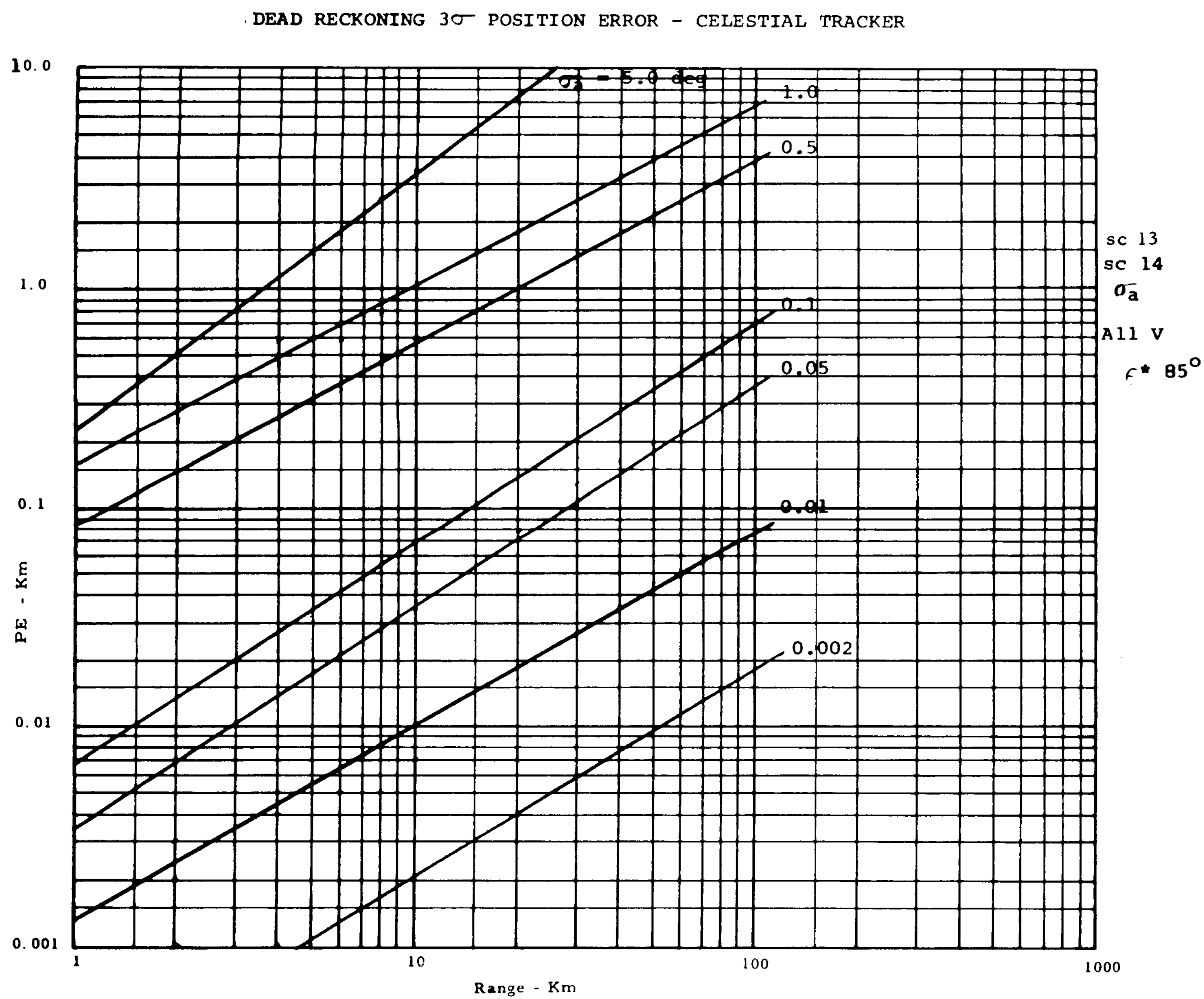


Figure 10-103 Dead Reckoning 3σ Position Error—Celestial Tracker

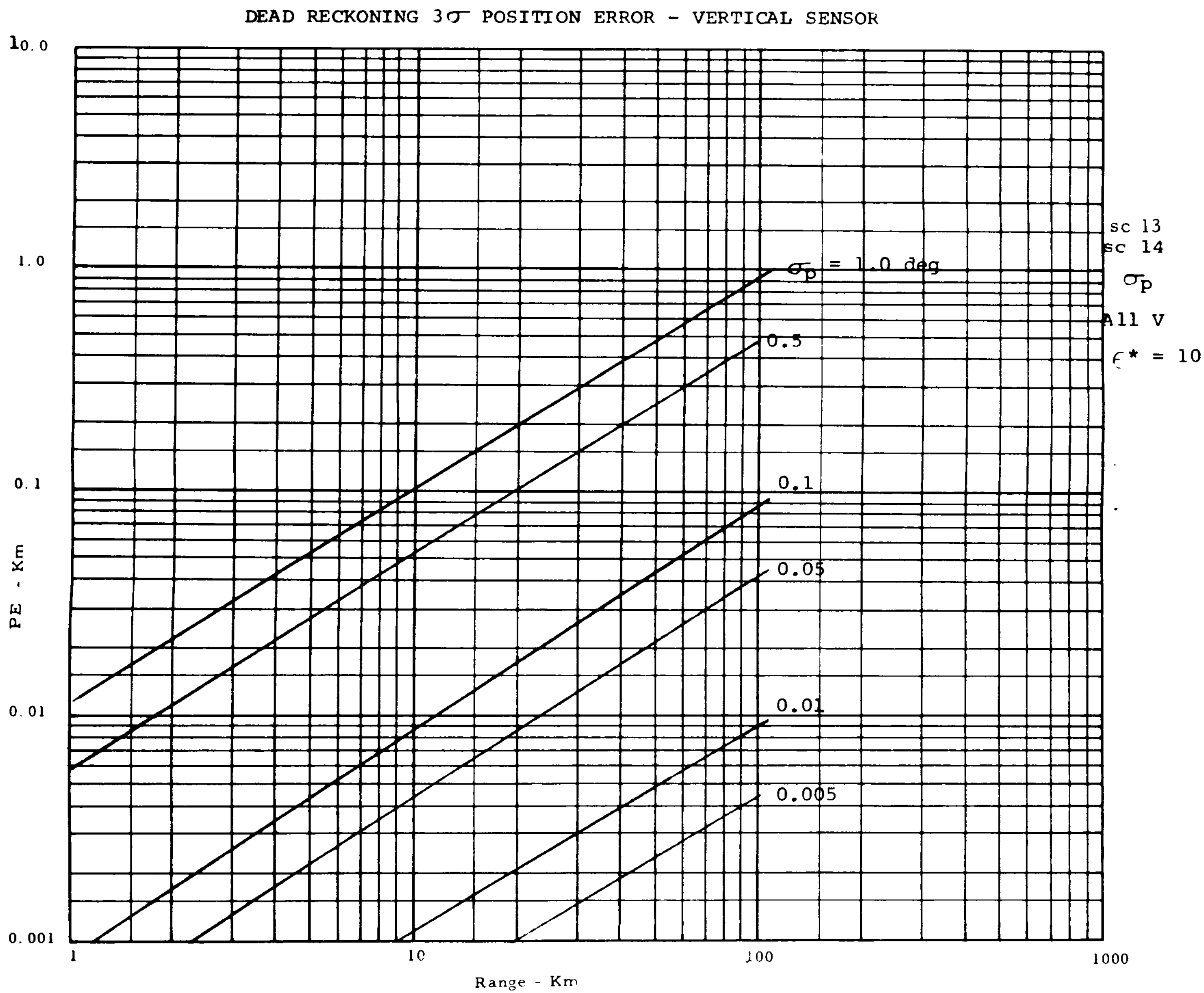


Figure 10-104 Dead Reckoning 3σ Position Error—Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - VERTICAL SENSOR

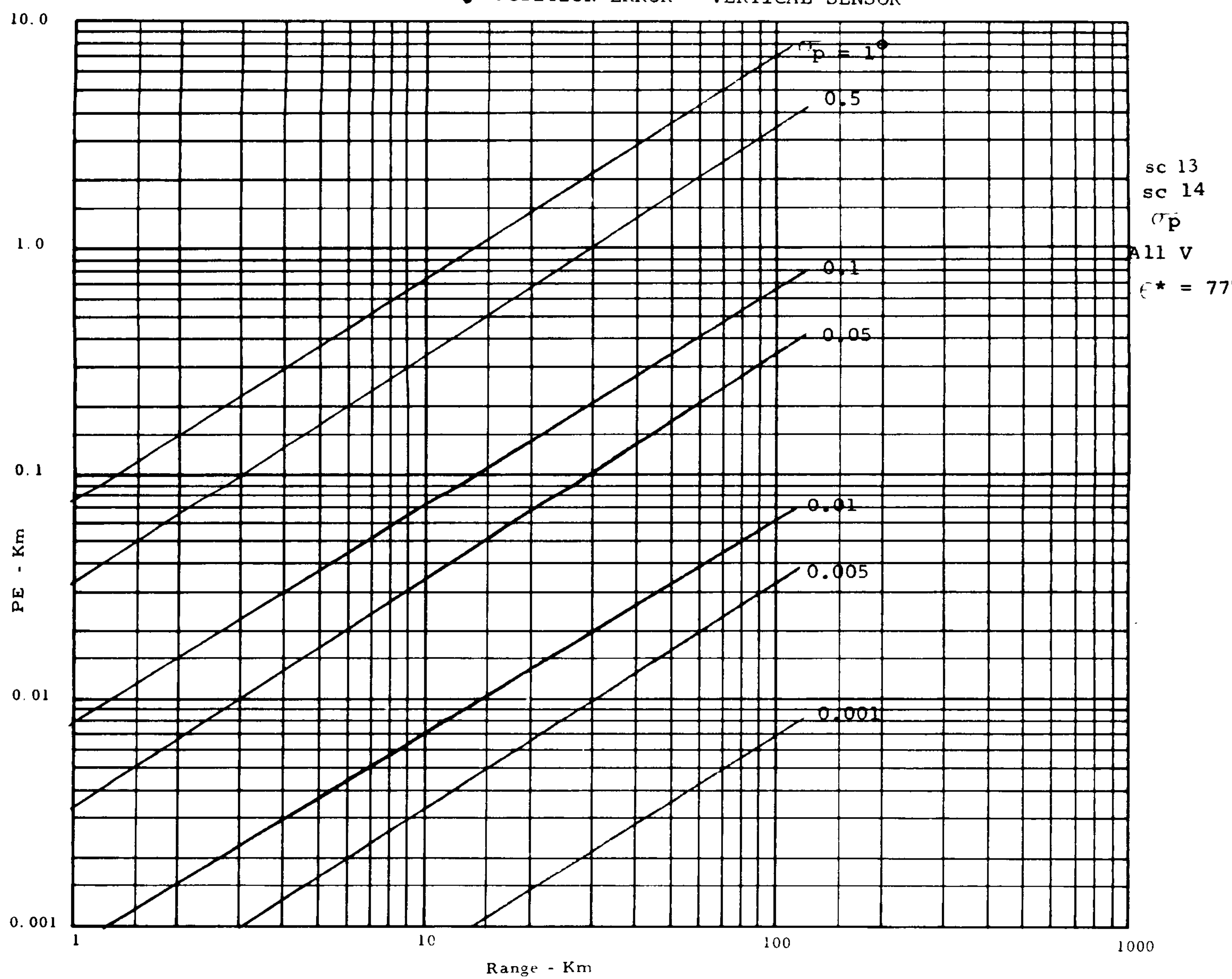


Figure 10-105 Dead Reckoning 3σ Position Error—Vertical Sensor

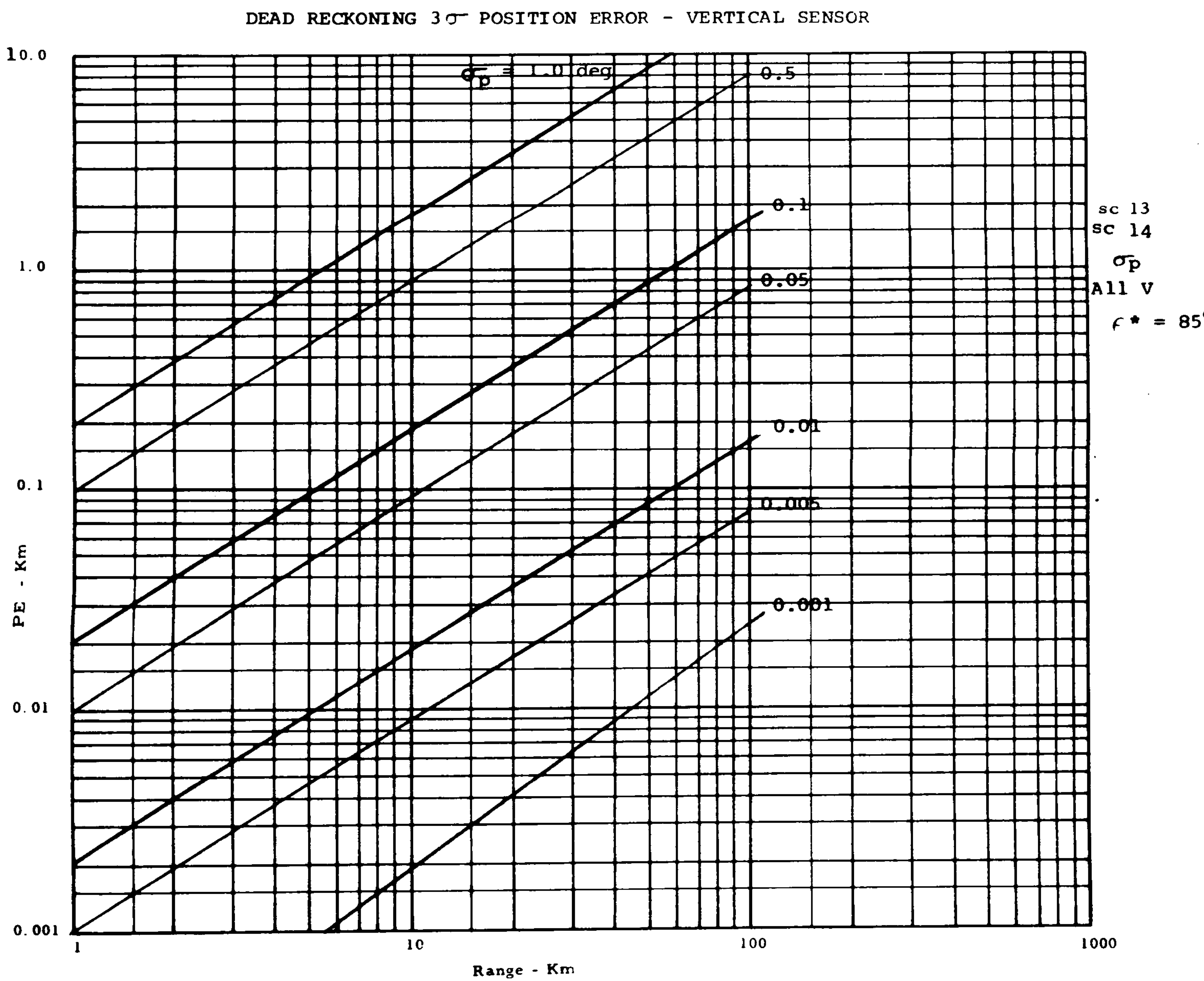


Figure 10-106 Dead Reckoning 3σ Position Error—Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - VERTICAL GYRO

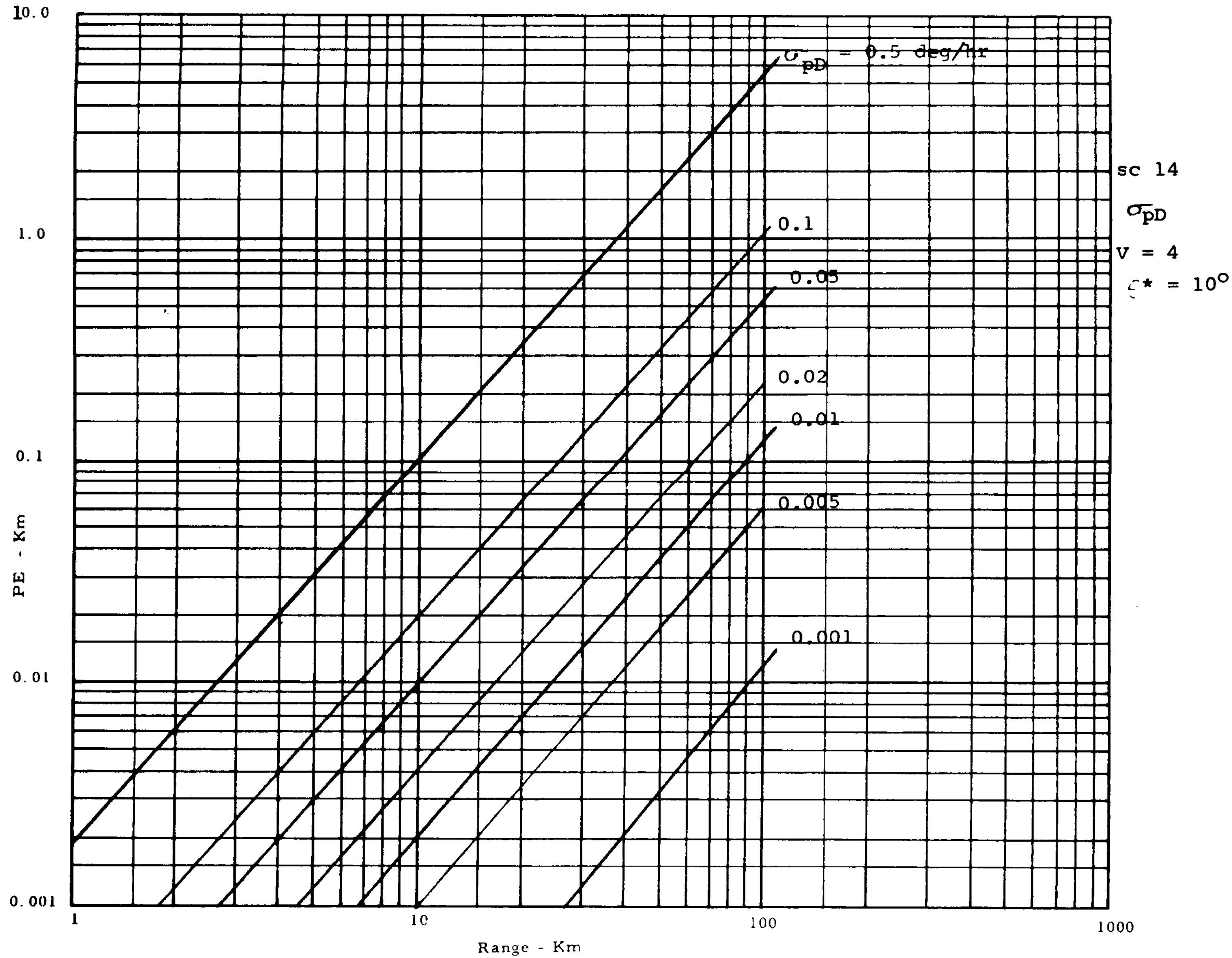


Figure 10-107 Dead Reckoning 3σ Position Error—Vertical Gyro

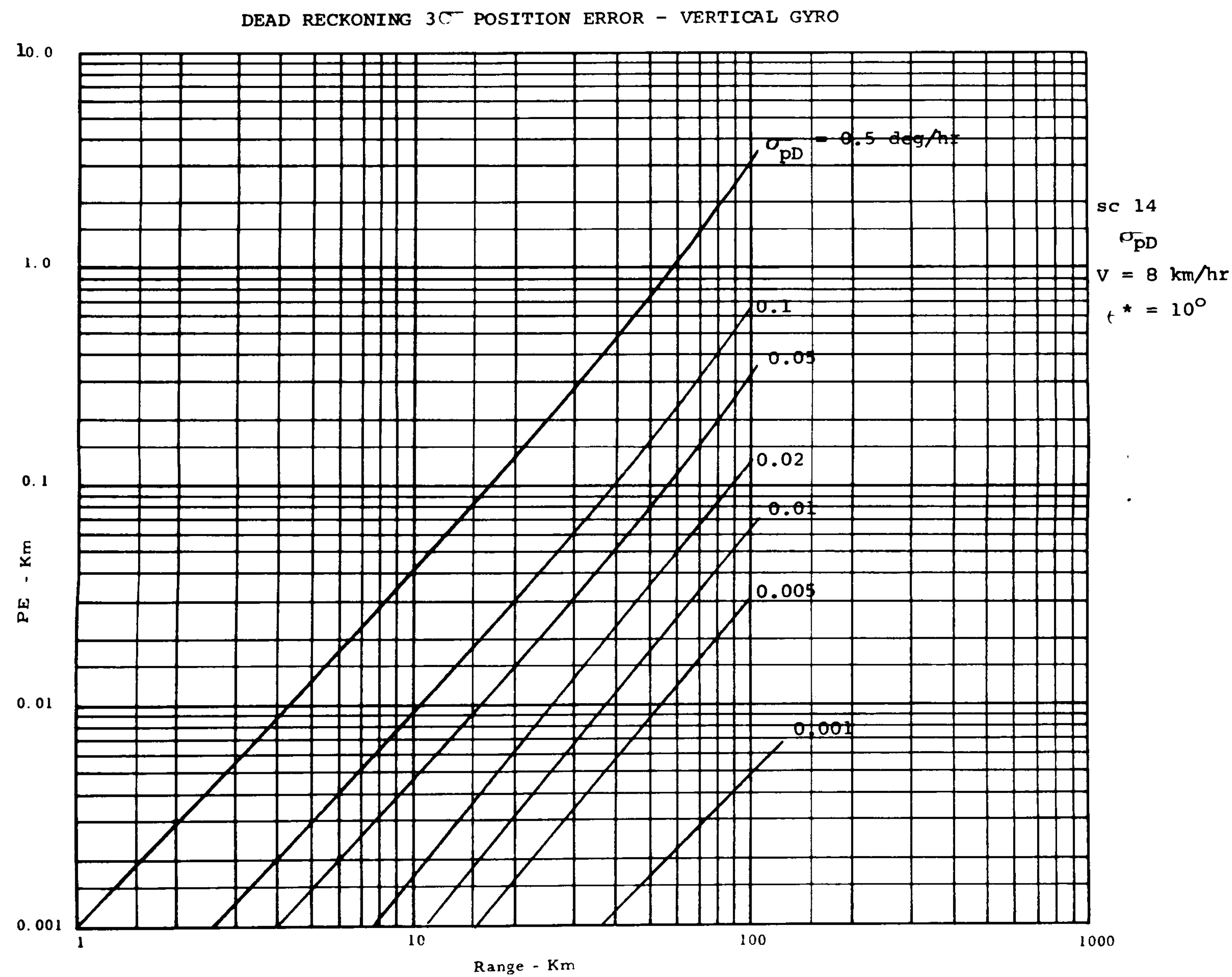


Figure 10-108 Dead Reckoning 3σ Position Error—Vertical Gyro

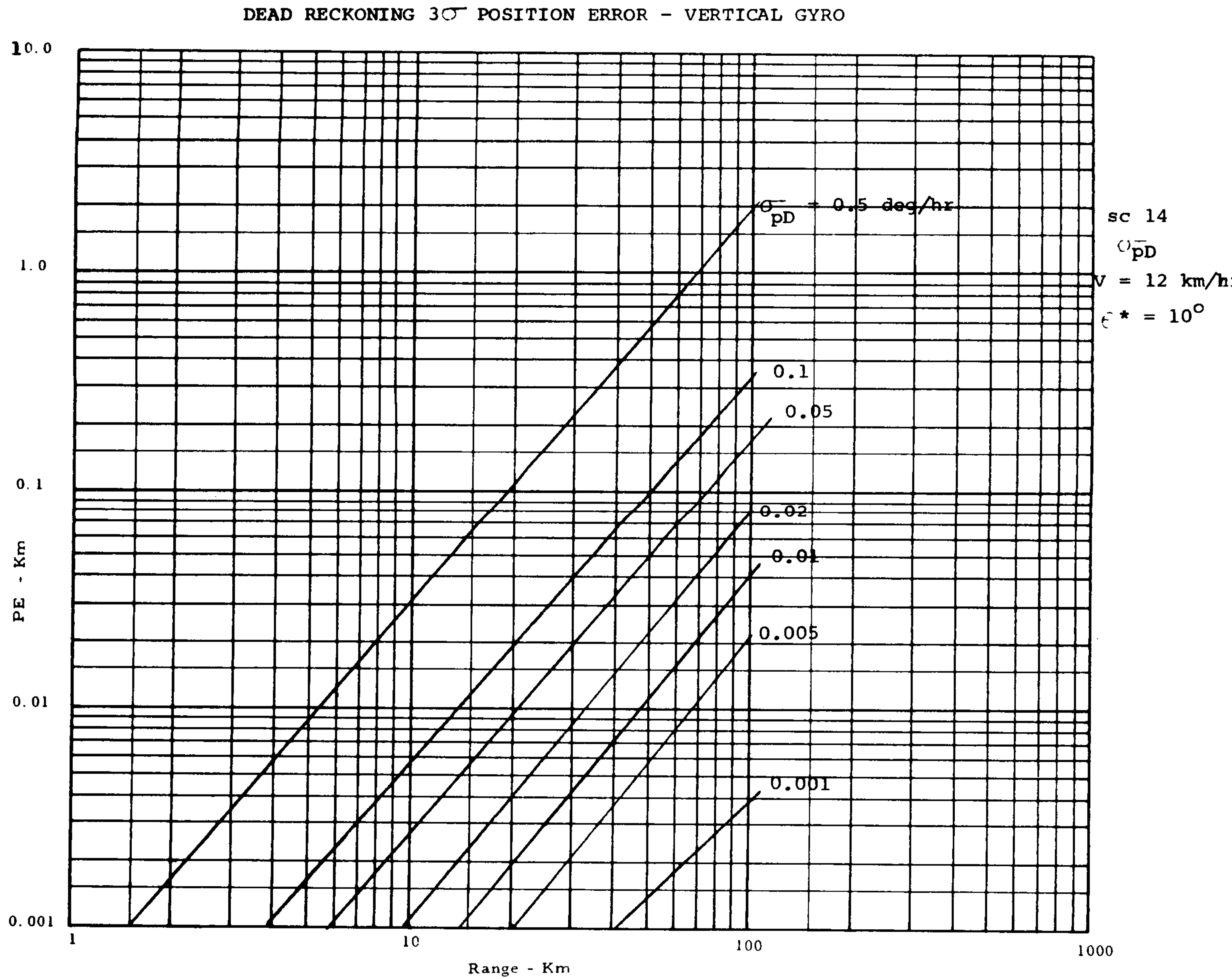


Figure 10-109 Dead Reckoning 3σ Position Error—Vertical Gyro

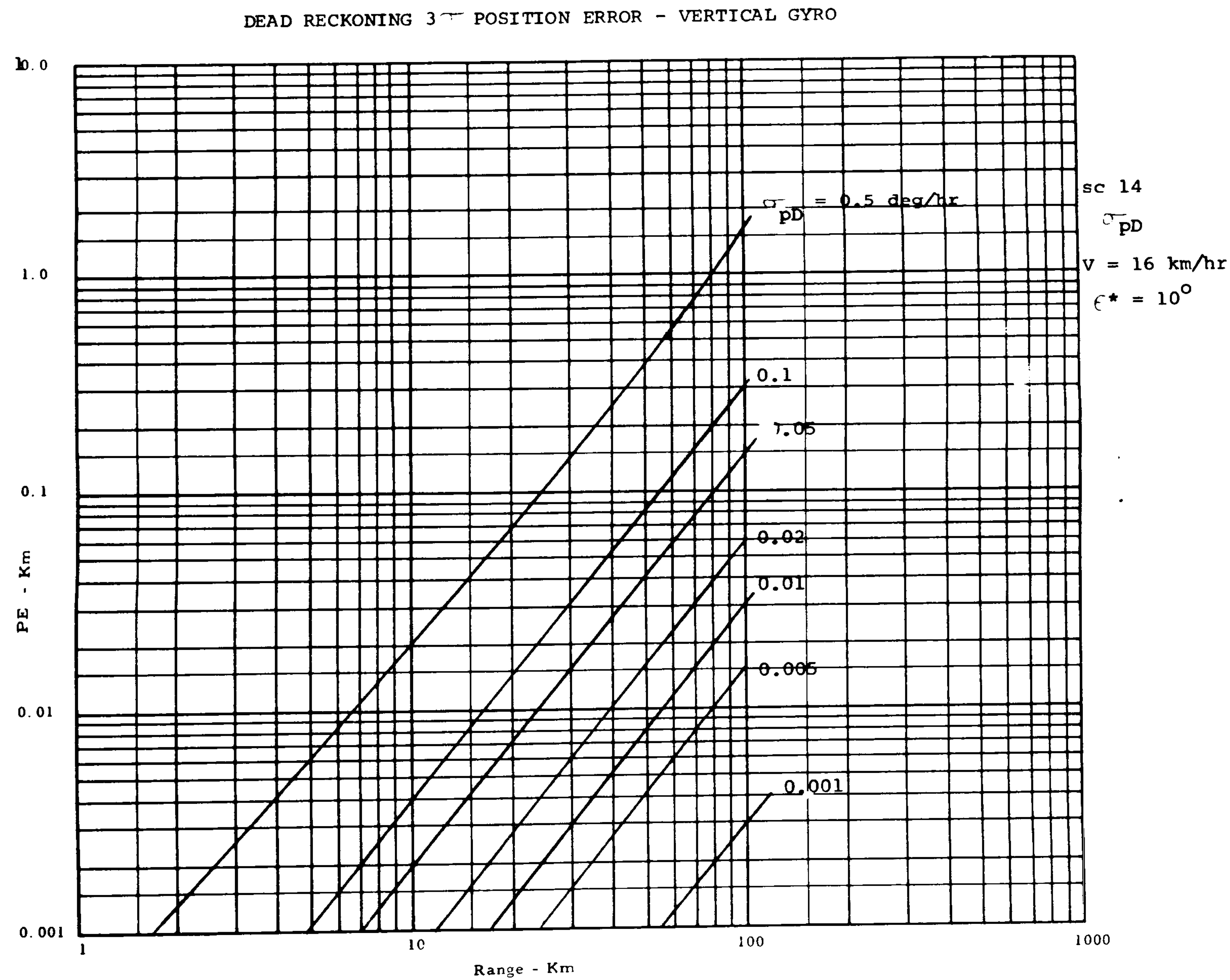


Figure 10-110 Dead Reckoning 3σ Position Error—Vertical Gyro

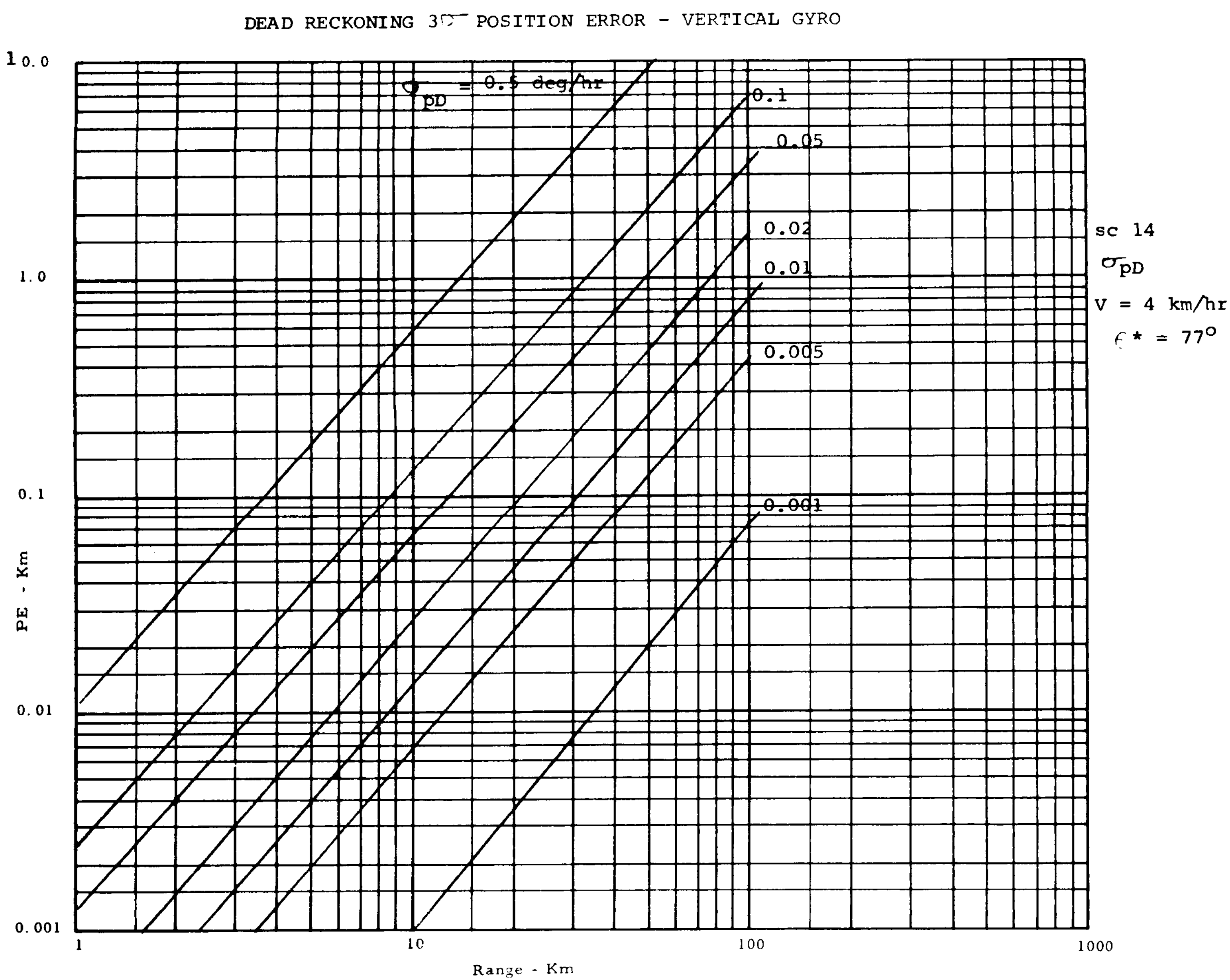


Figure 10-111 Deac Reckoning 3σ Position Error—Vertical Gyro

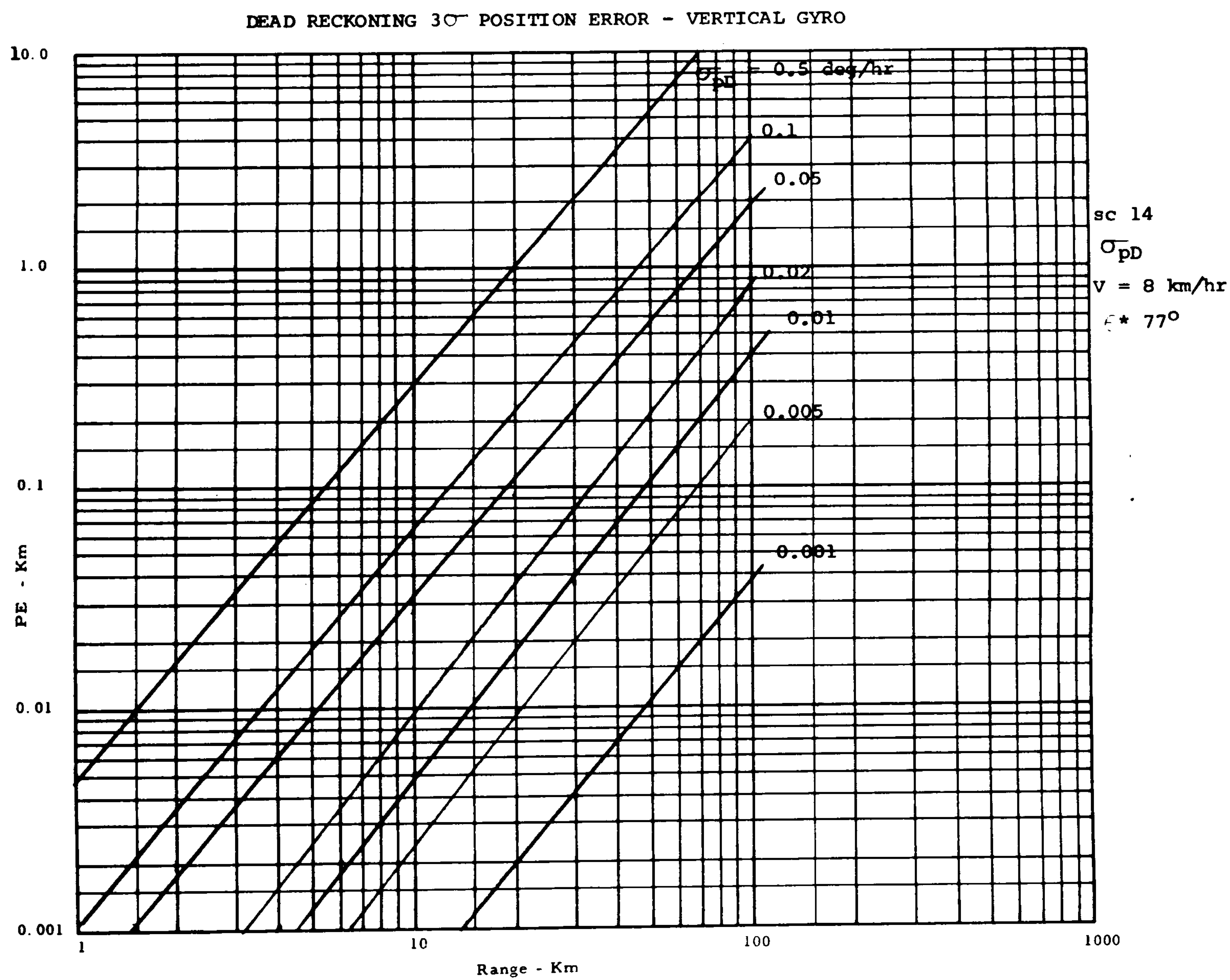


Figure 10-112 Dead Reckoning 3σ Position Error—Vertical Gyro

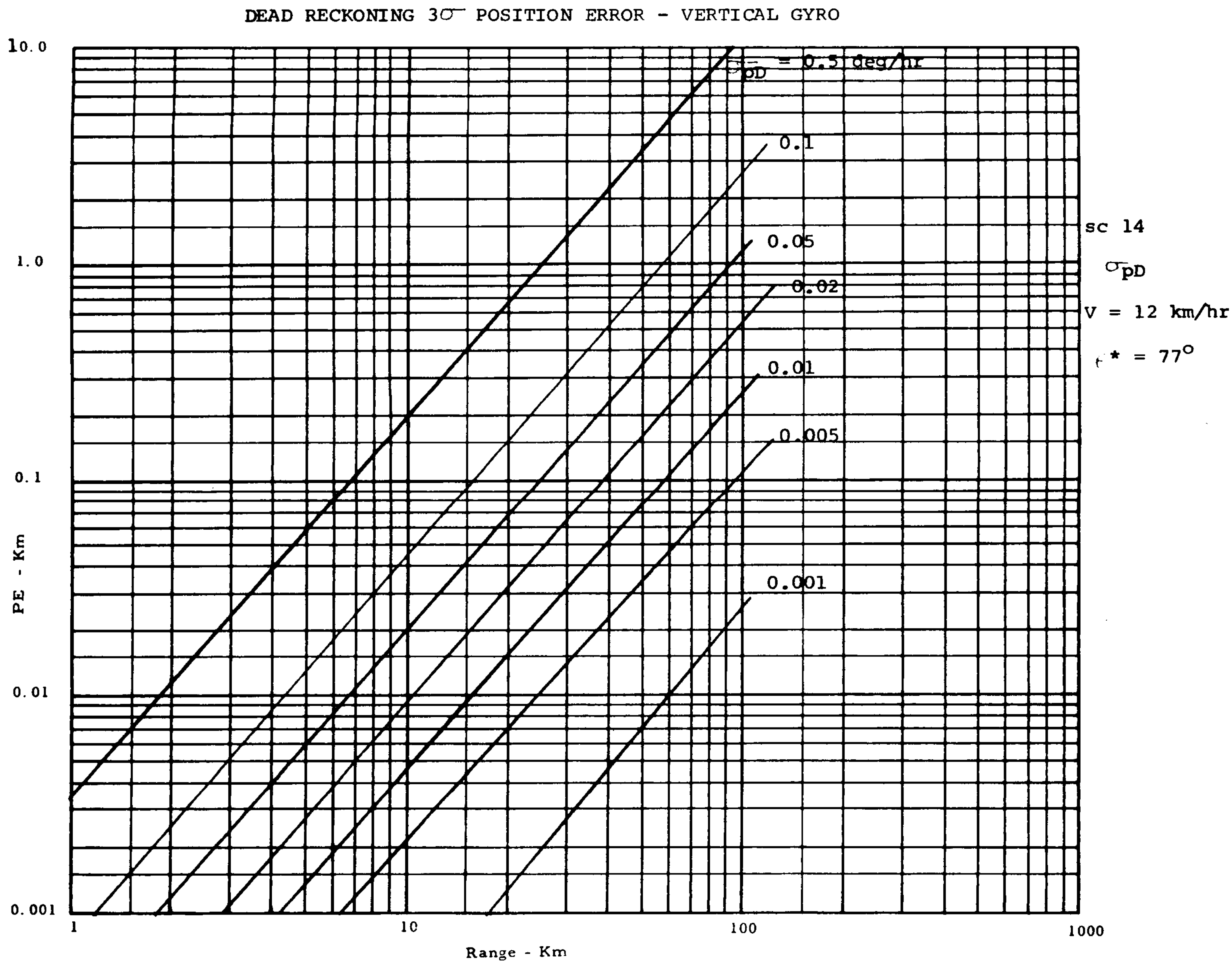


Figure 10-113 Dead Reckoning 3σ Position Error—Vertical Gyro

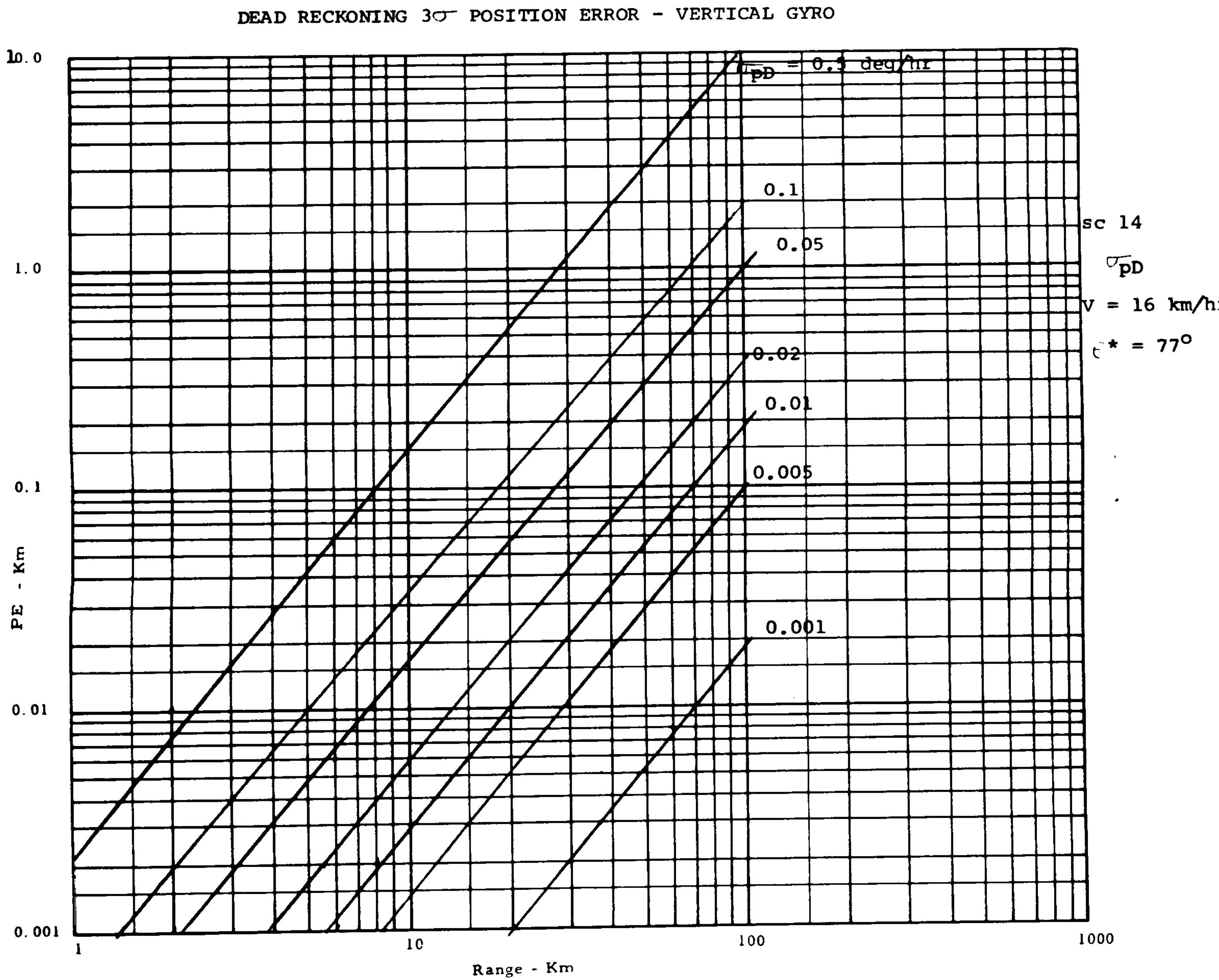


Figure 10-114 Dead Reckoning 3σ Position Error—Vertical Gyro

DEAD RECKONING 3σ POSITION ERROR - VERTICAL GYRO

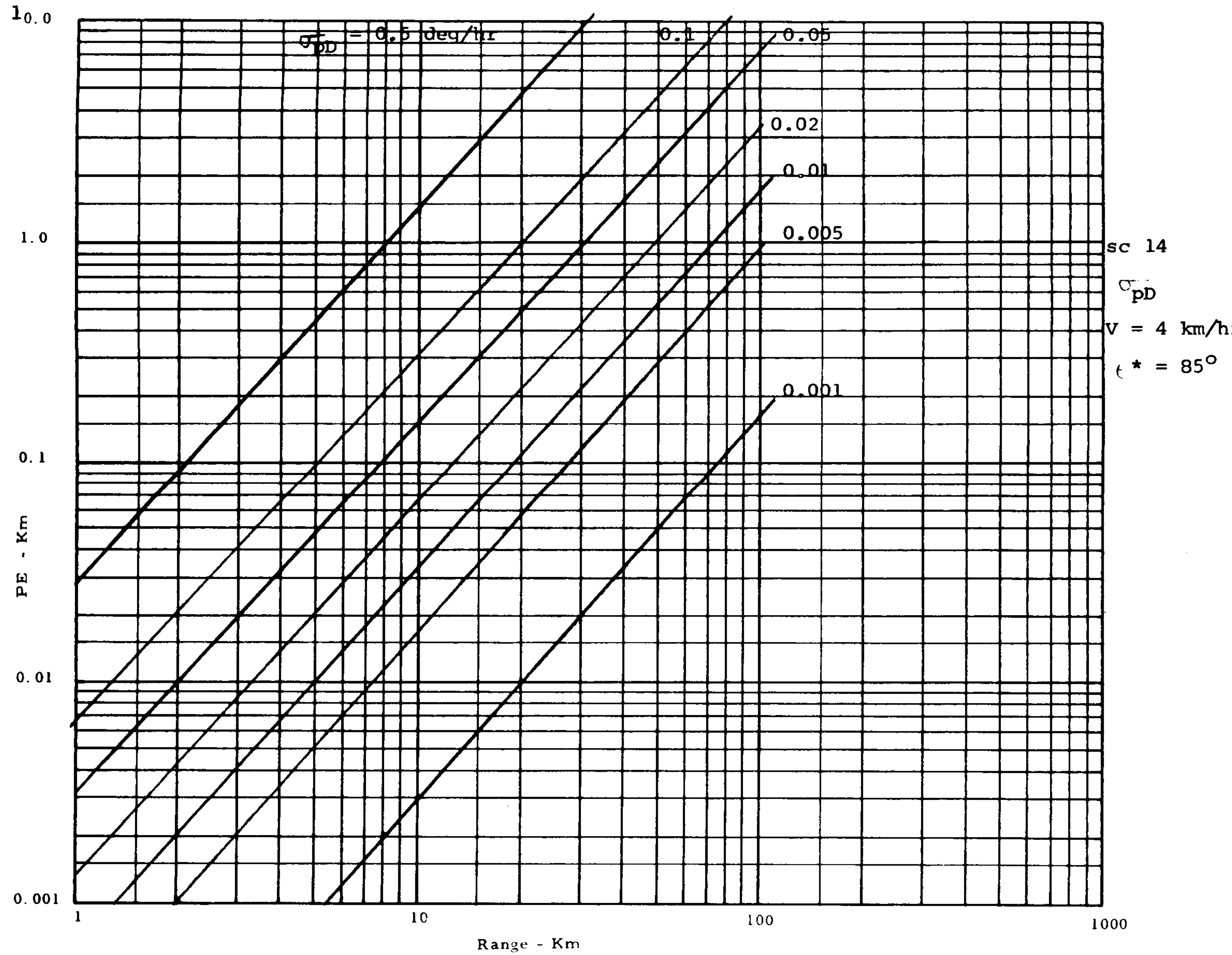


Figure 10-115 Dead Reckoning 3σ Position Error—Vertical Gyro

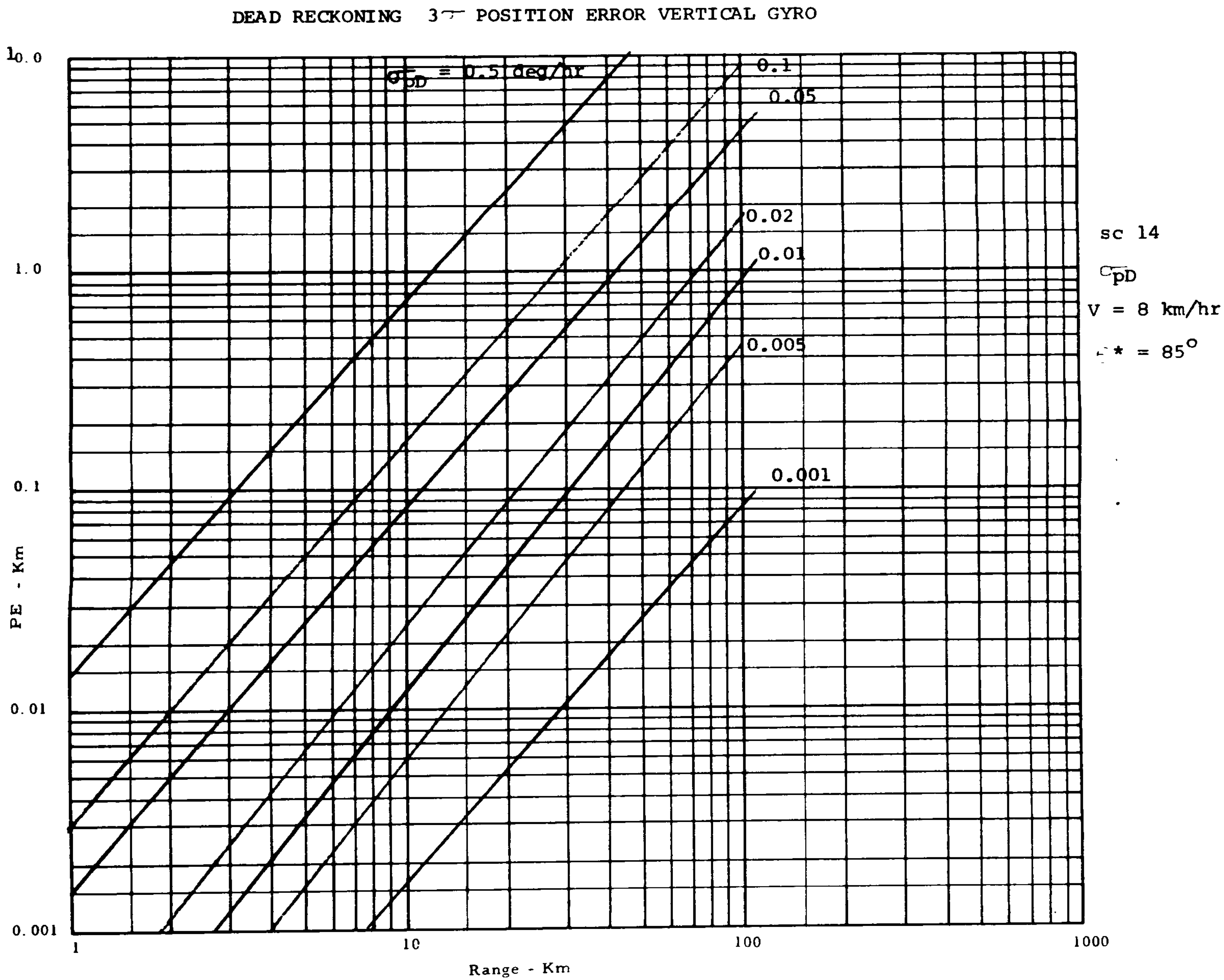


Figure 10-116 Dead Reckoning 3σ Position Error—Vertical Gyro

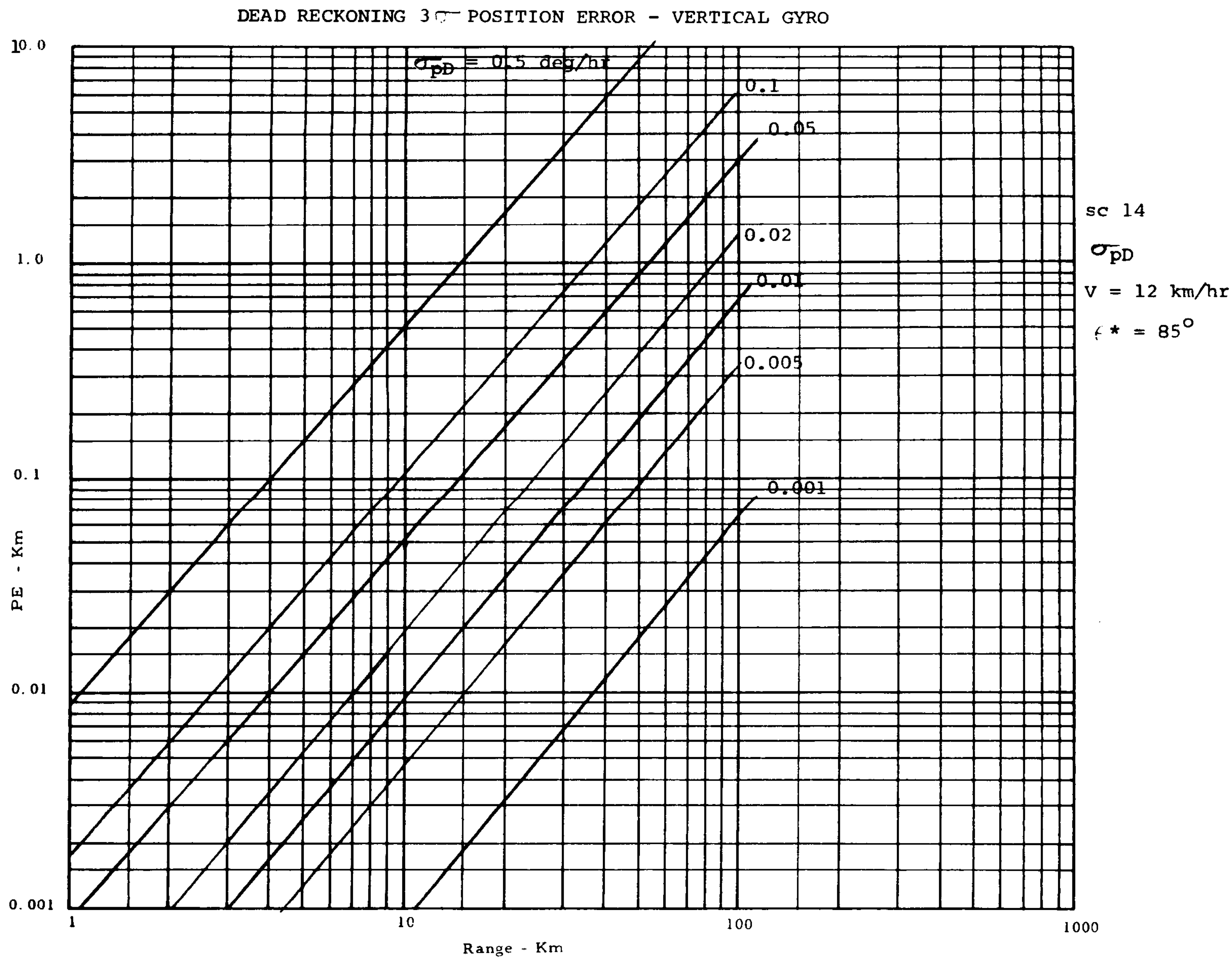


Figure 10-117 Dead Reckoning 3σ Position Error—Vertical Gyro

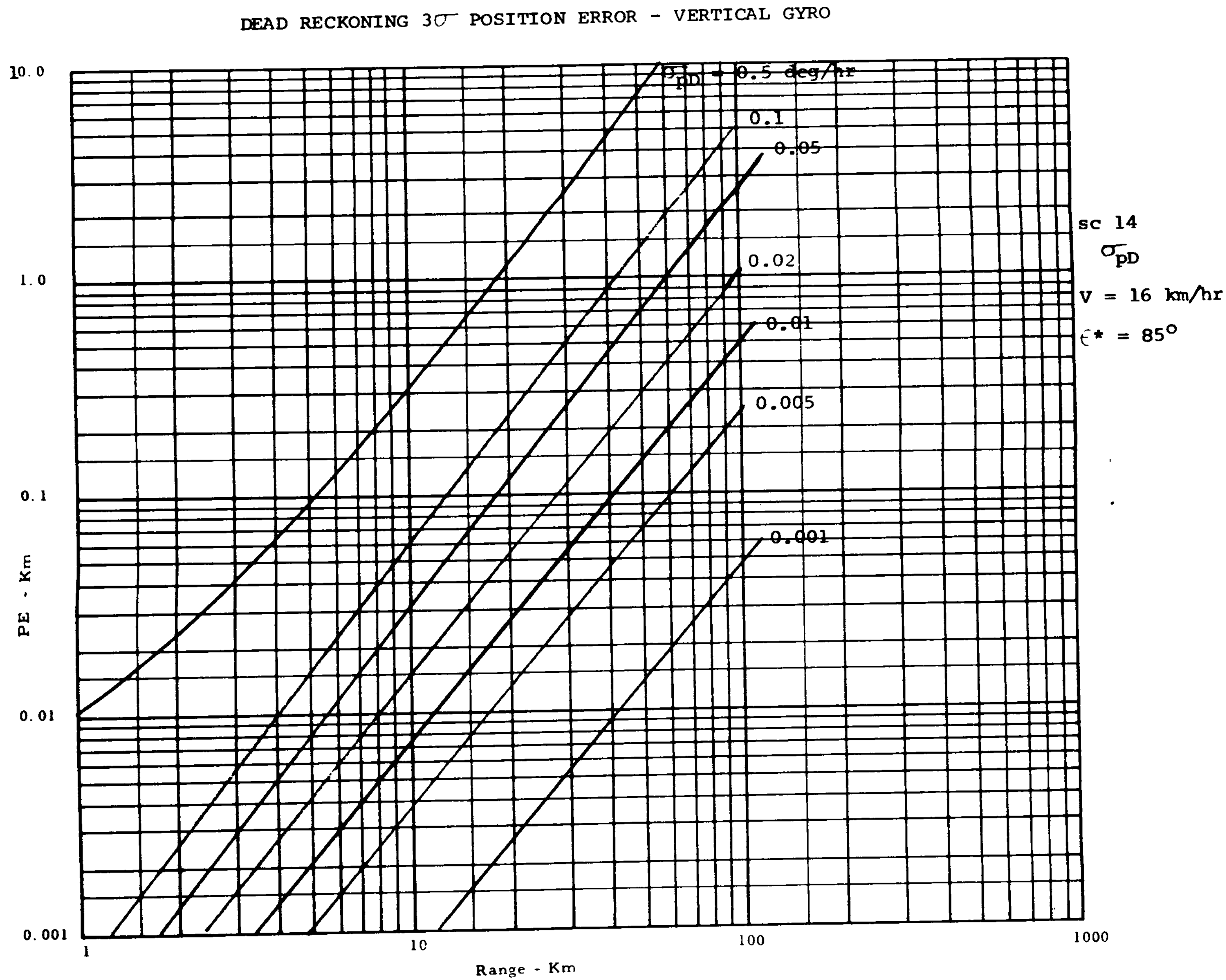


Figure 10-118 Dead Reckoning 3σ Position Error—Vertical Gyro

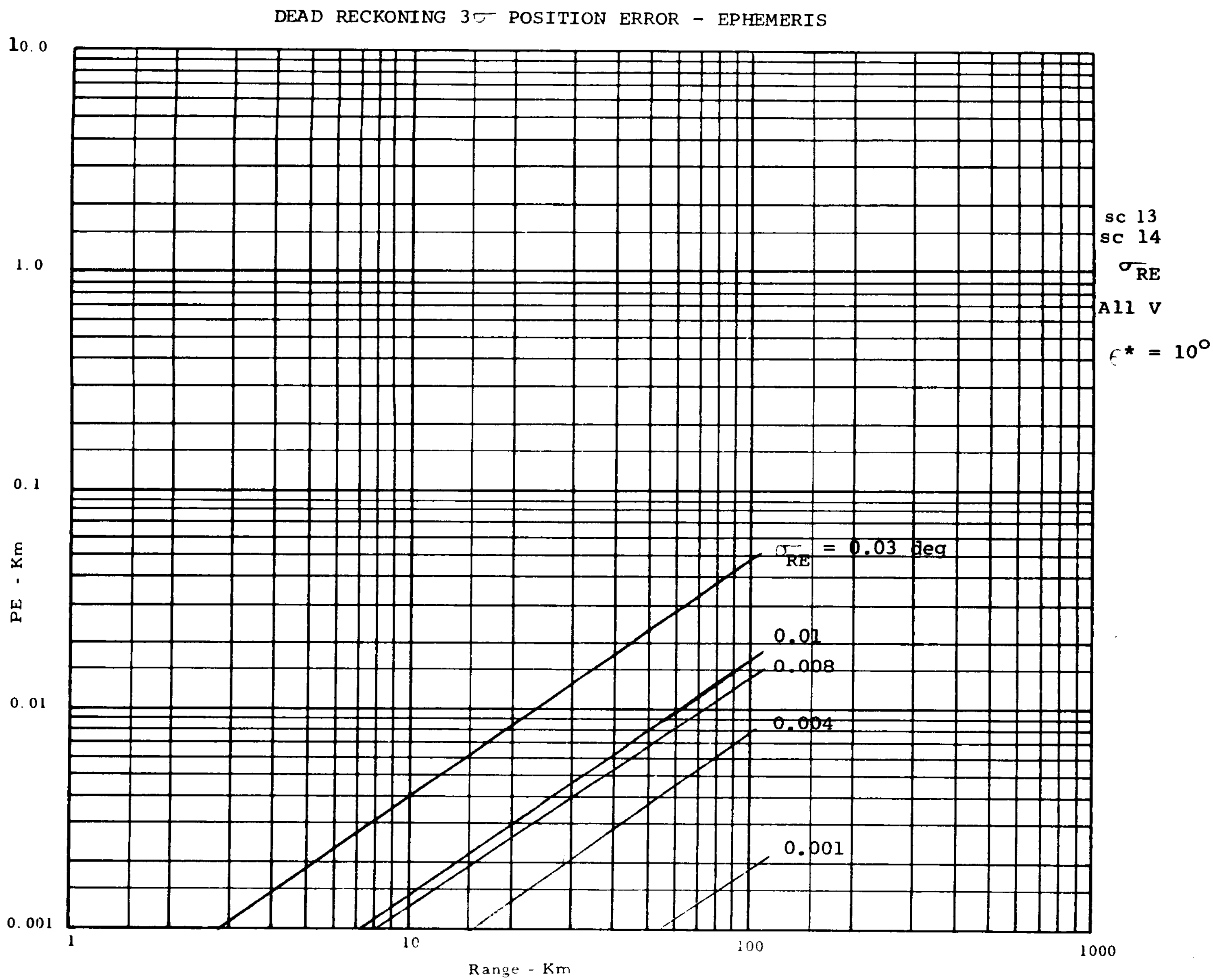


Figure 10-119 Dead Reckoning 3σ Position Error—Ephemeris

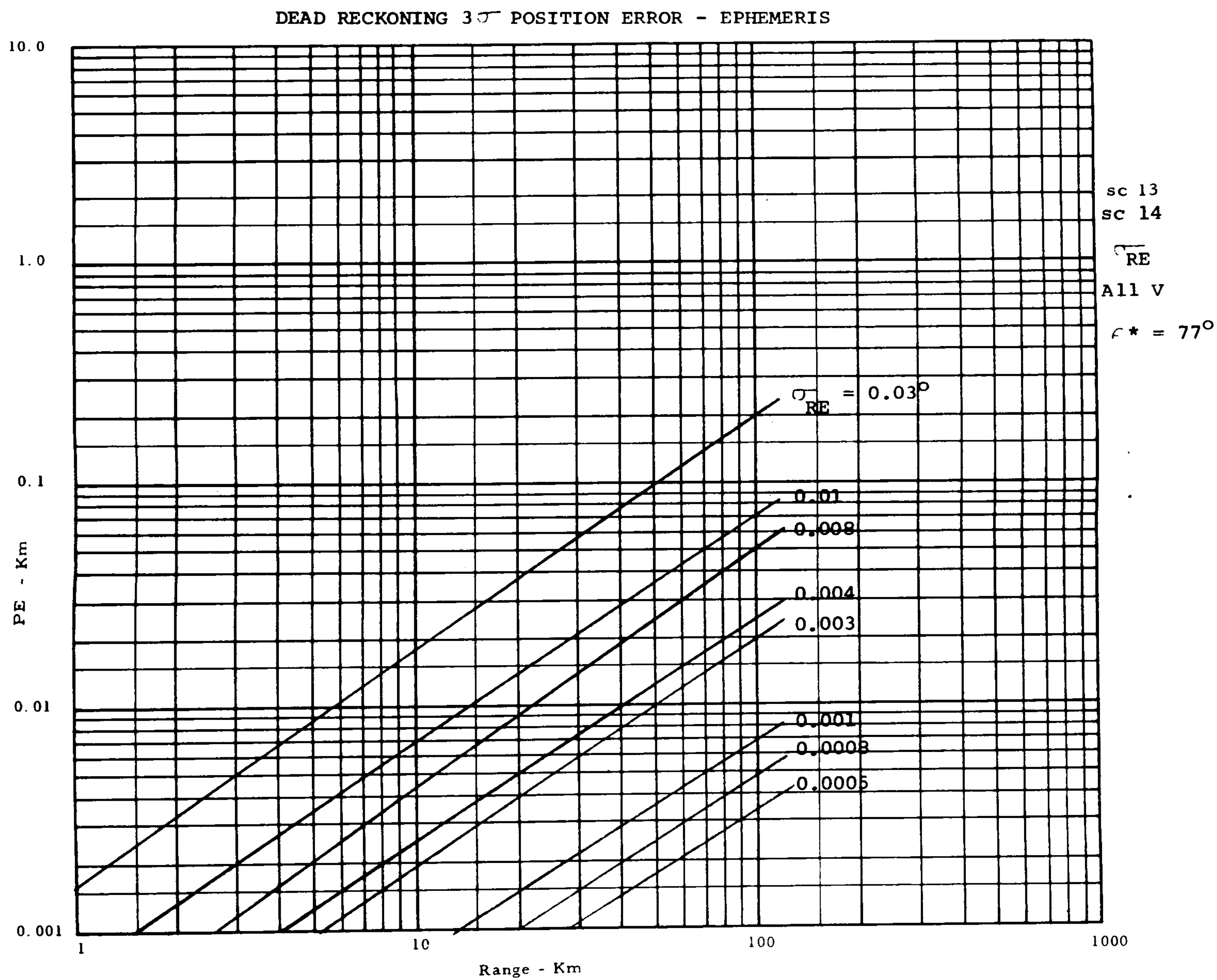


Figure 10-120 Dead Reckoning 3σ Position Error—Ephemeris

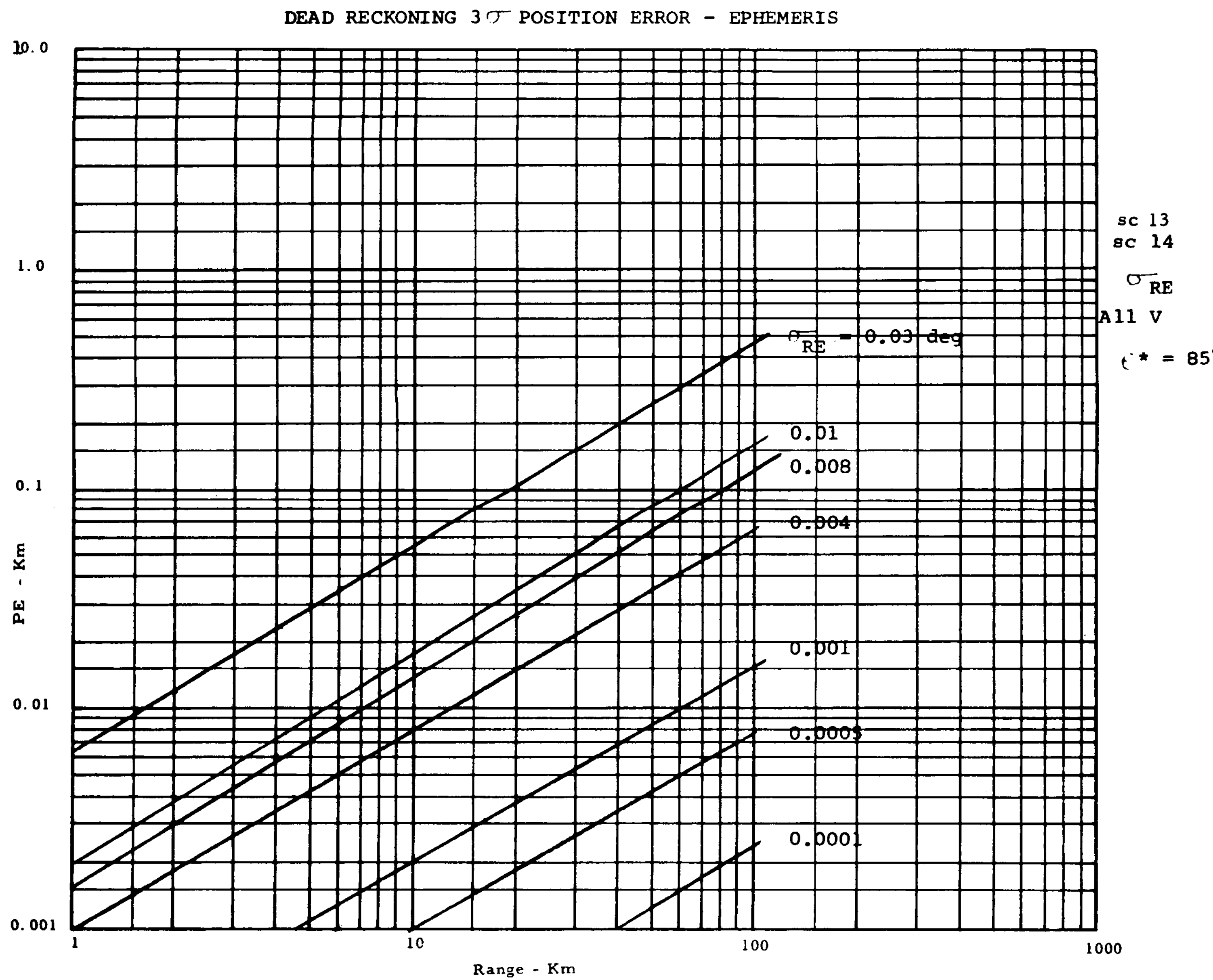


Figure 10-121 Dead Reckoning 3σ Position Error—Ephemeris

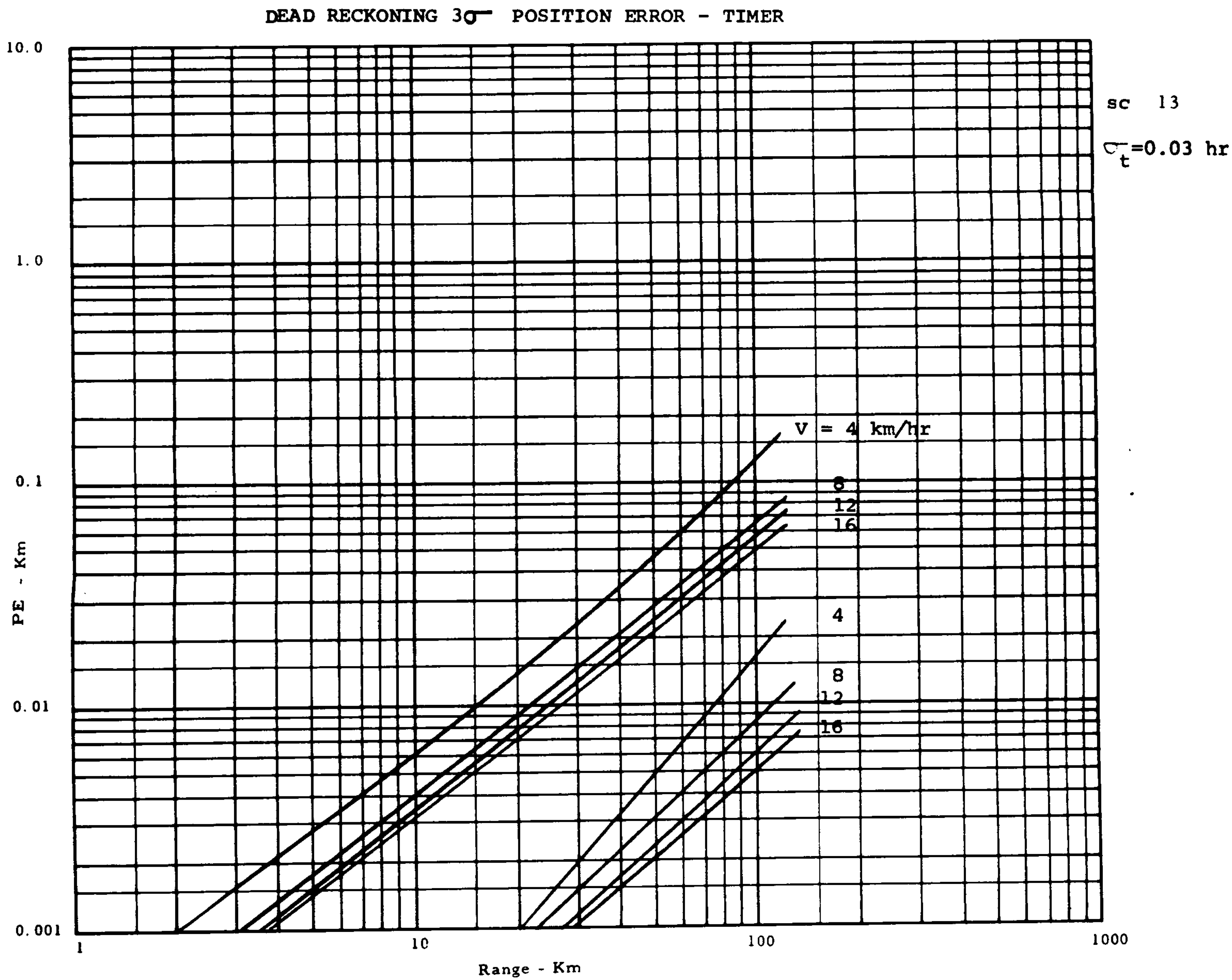


Figure 10-122 Dead Reckoning 3σ Position Error—Timer

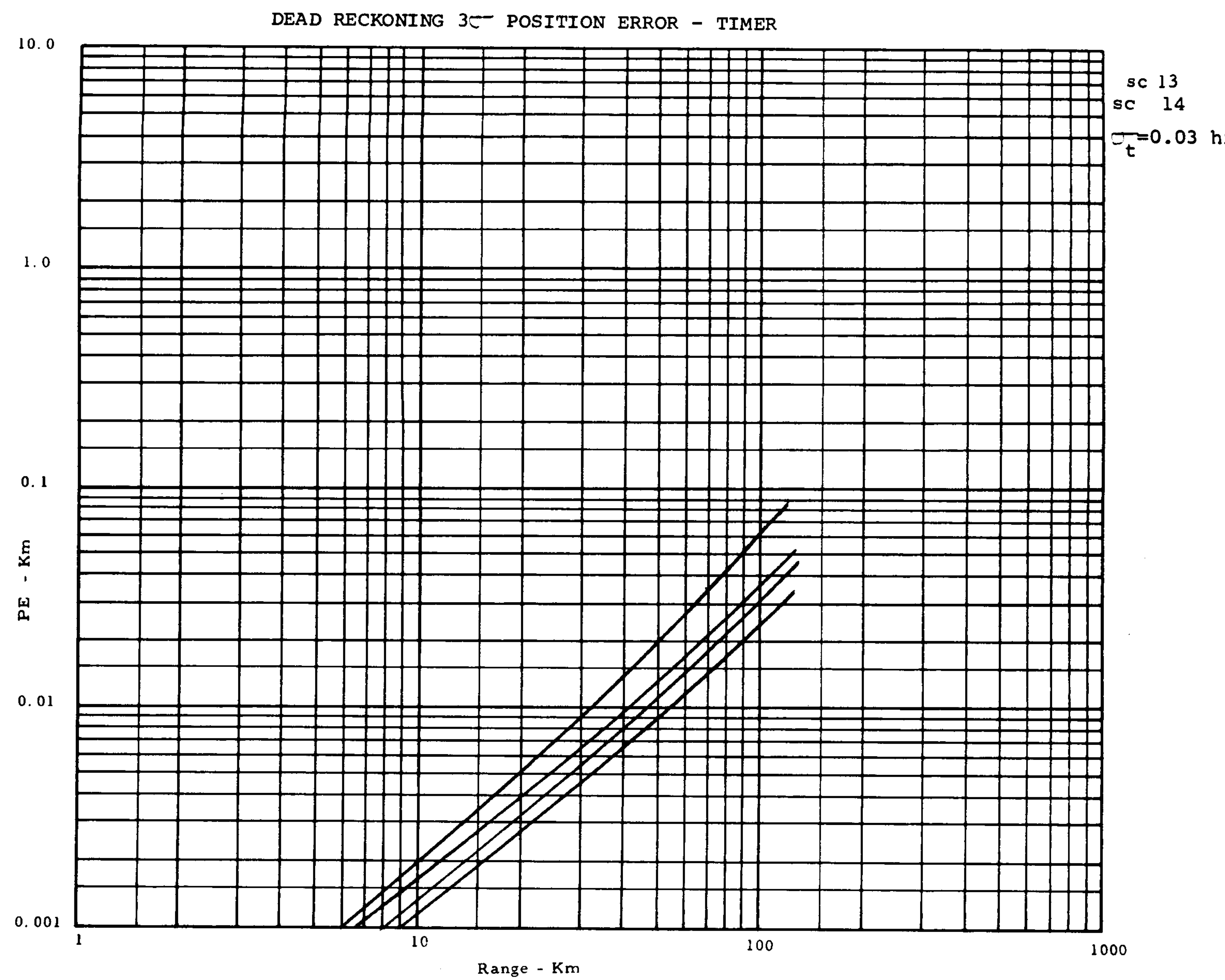


Figure 10-123 Dead Reckoning 3σ Position Error—Timer

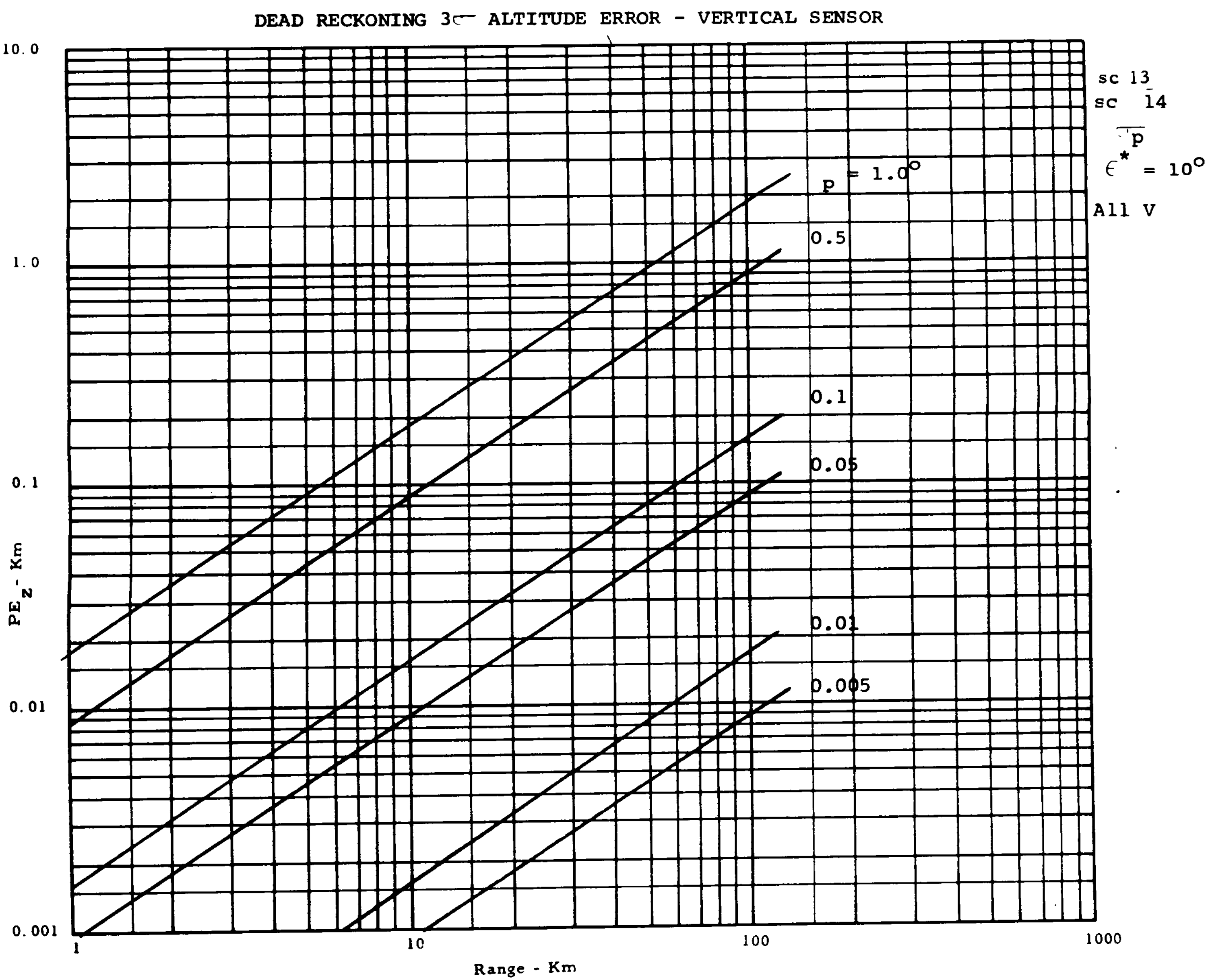


Figure 10-124 Dead Reckoning 3σ Position Error—Vertical Sensor

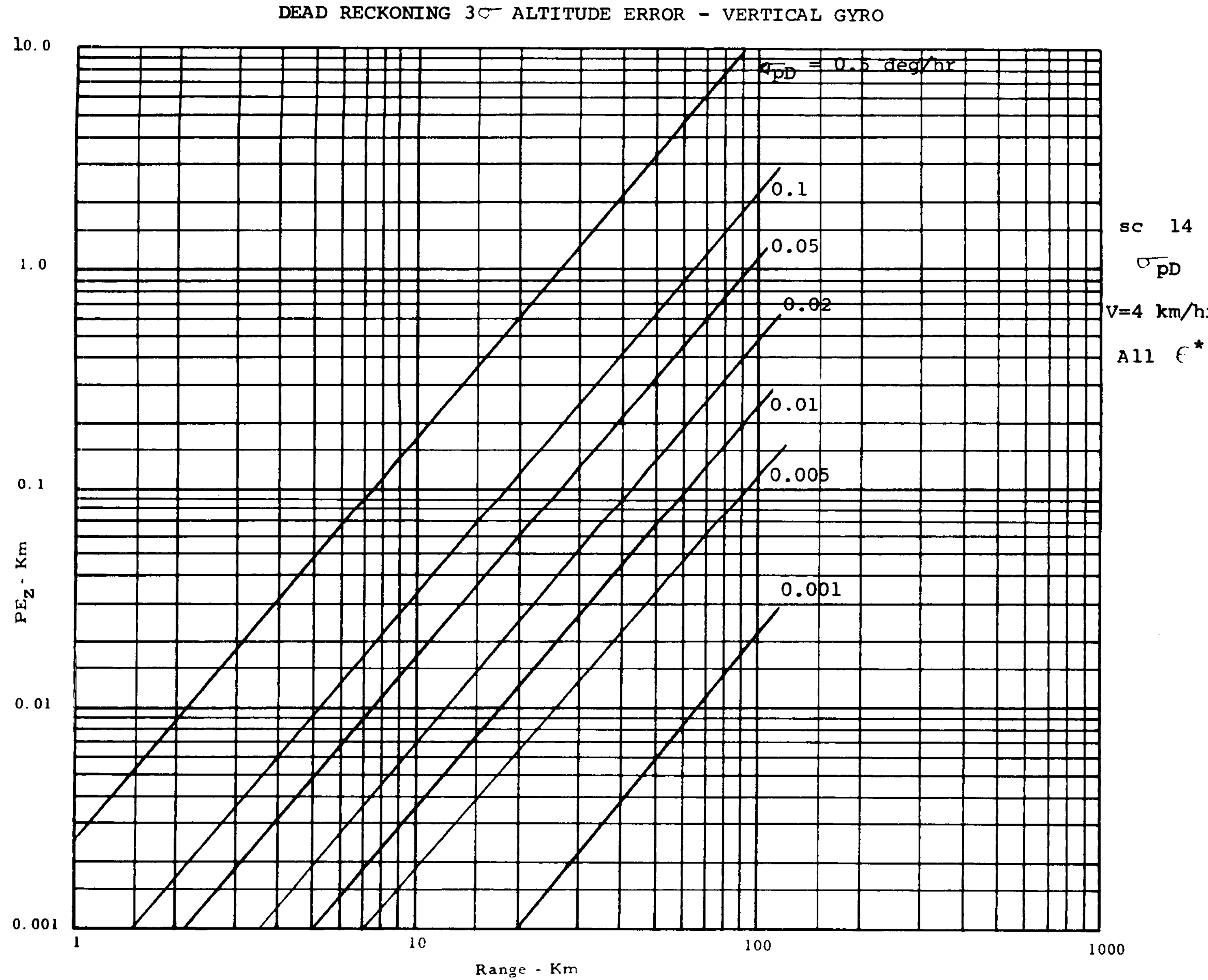


Figure 10-125 Dead Reckoning 3σ Altitude Error—Vertical Gyro

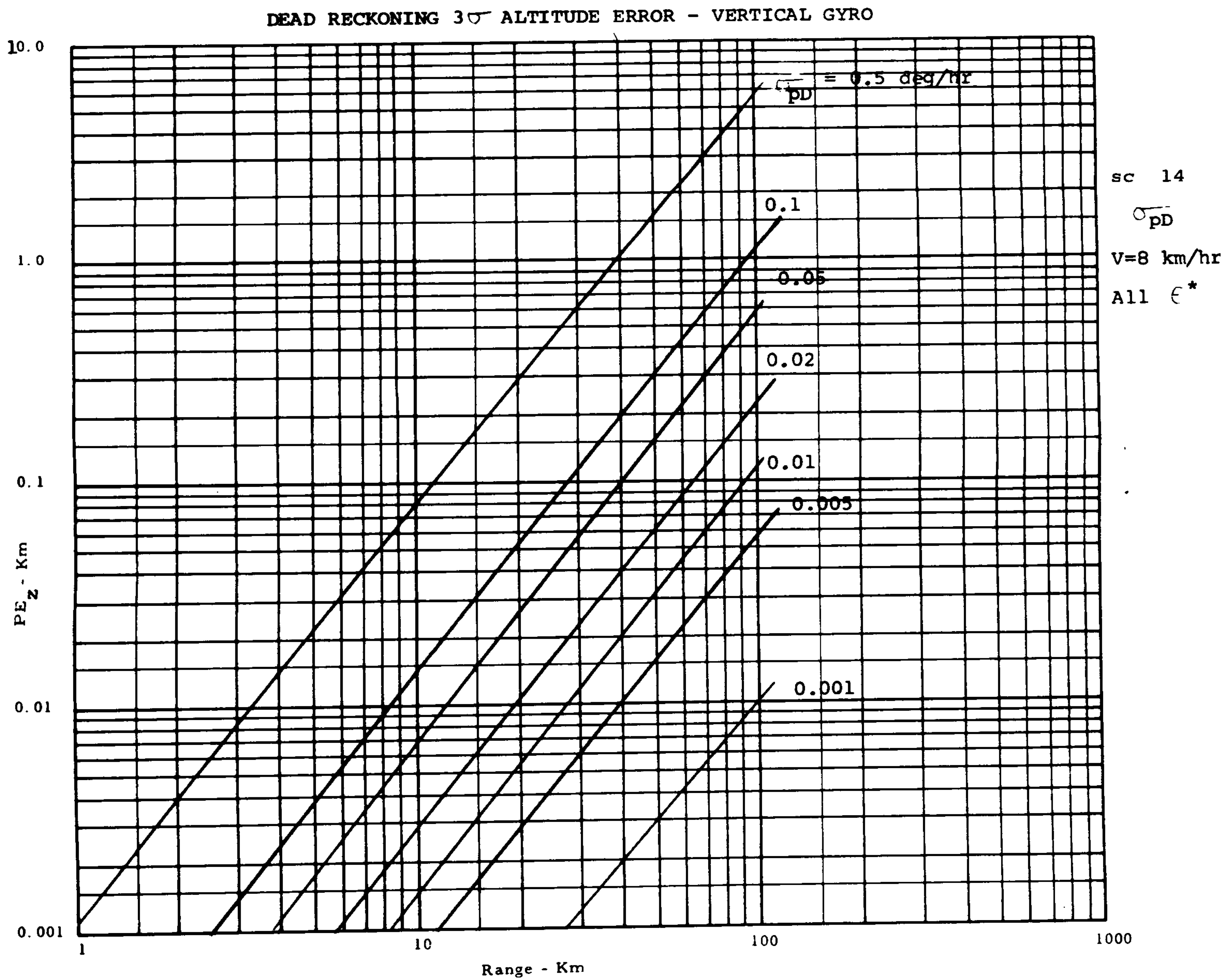


Figure 10-126 Dead Reckoning 3σ Altitude Error—Vertical Gyro

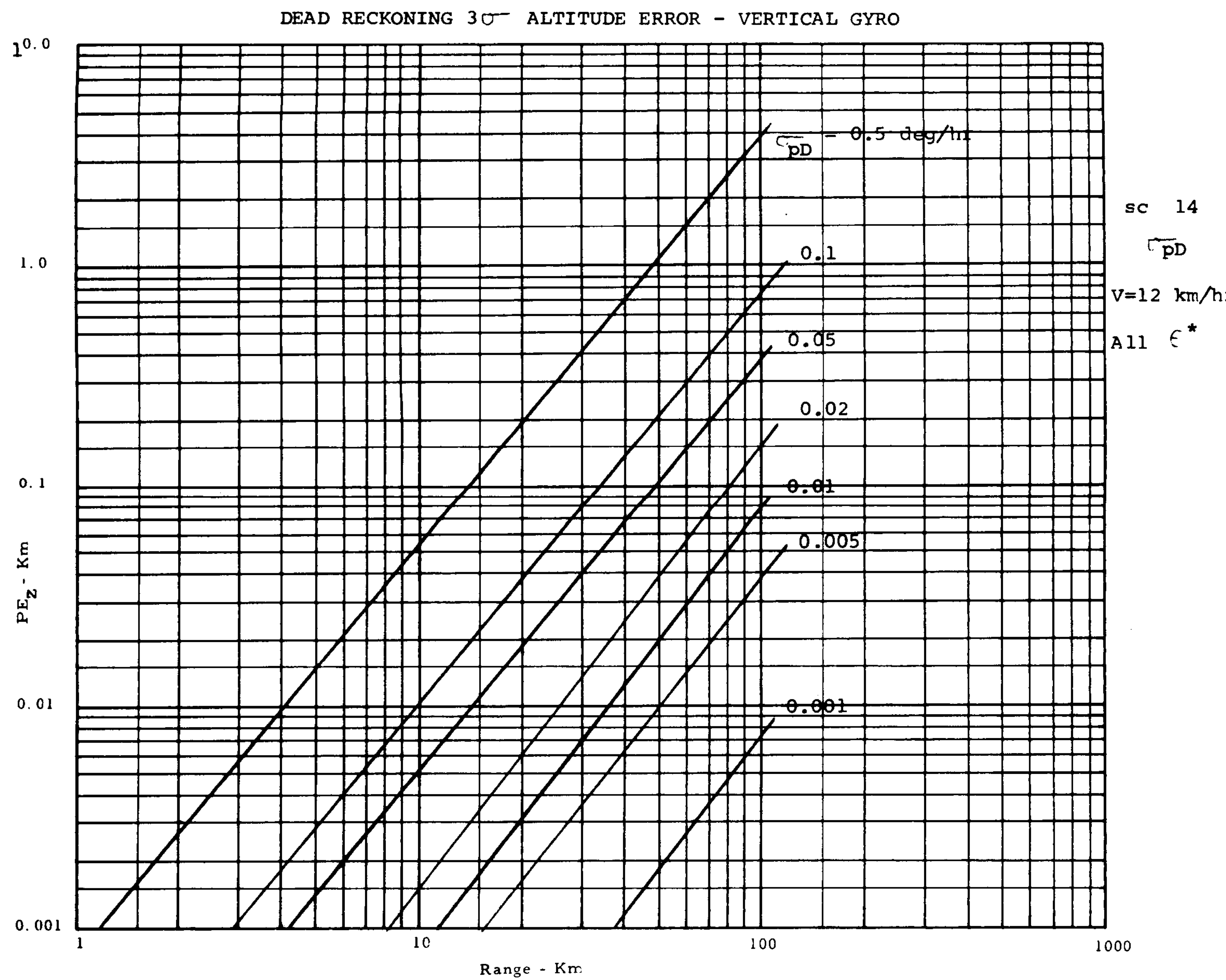


Figure 10-127 Dead Reckoning 3σ Altitude Error—Vertical Gyro

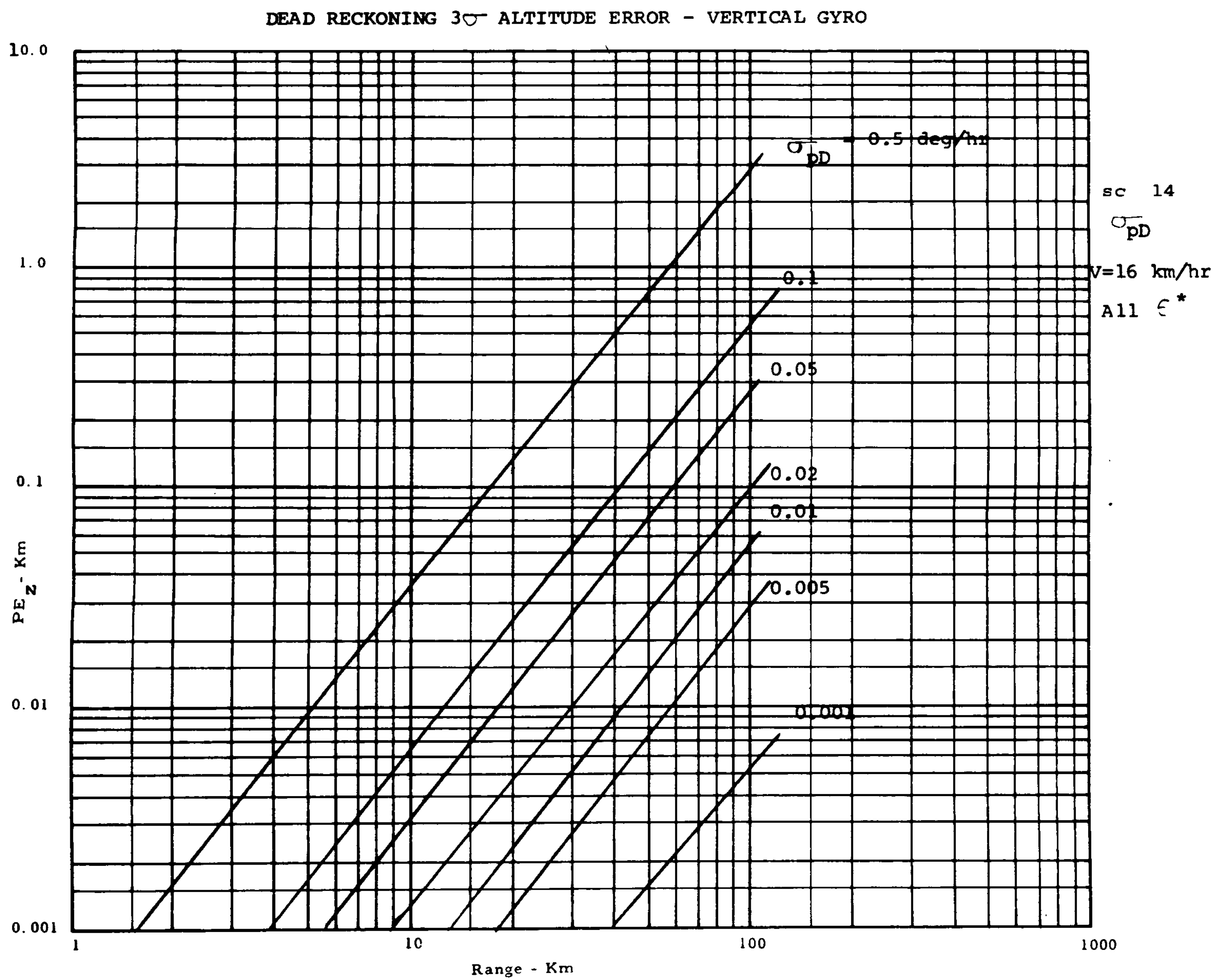


Figure 10-128 Dead Reckoning 3σ Altitude Error—Vertical Gyro

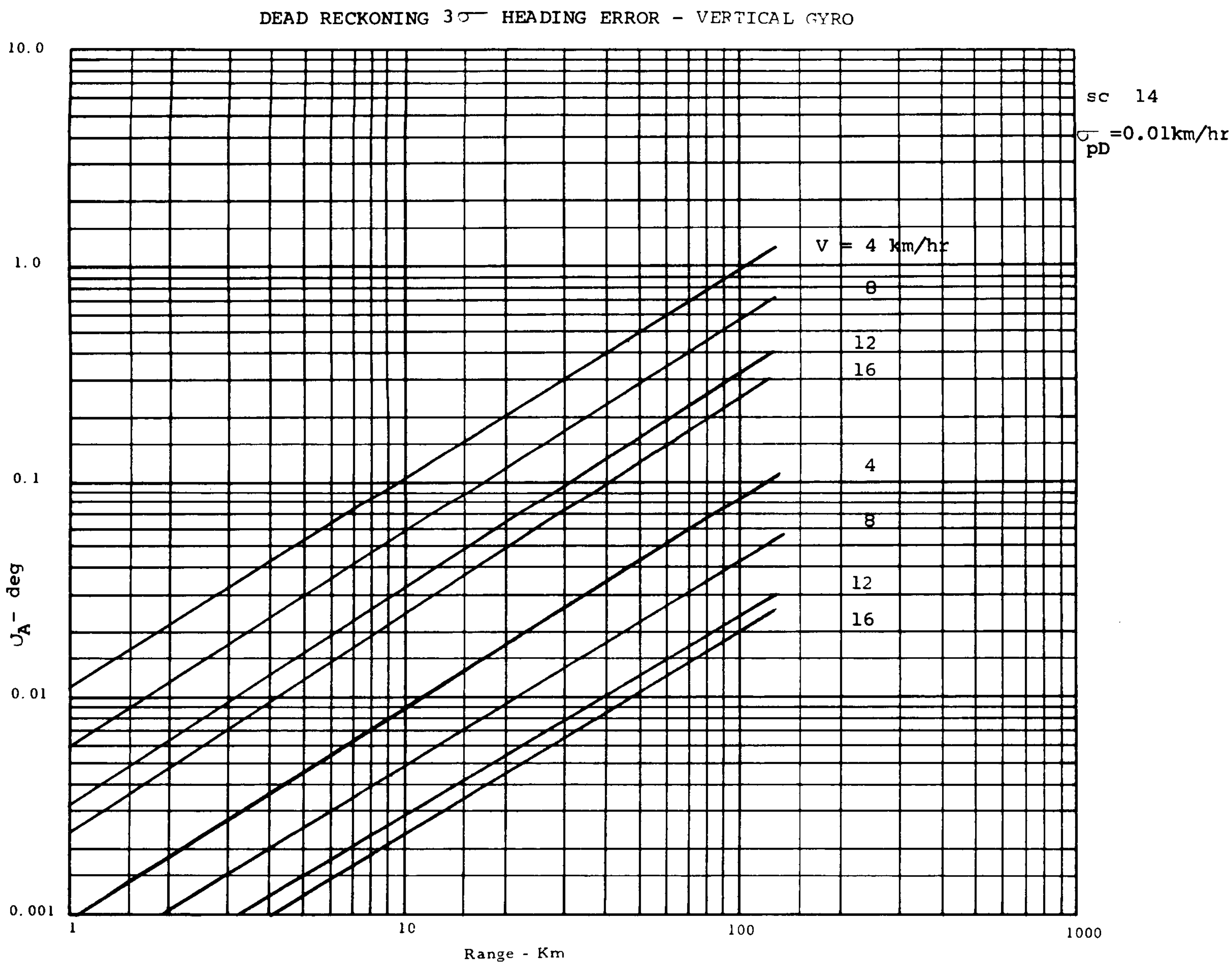


Figure 10-129 Dead Reckoning 3σ Altitude Error—Vertical Gyro

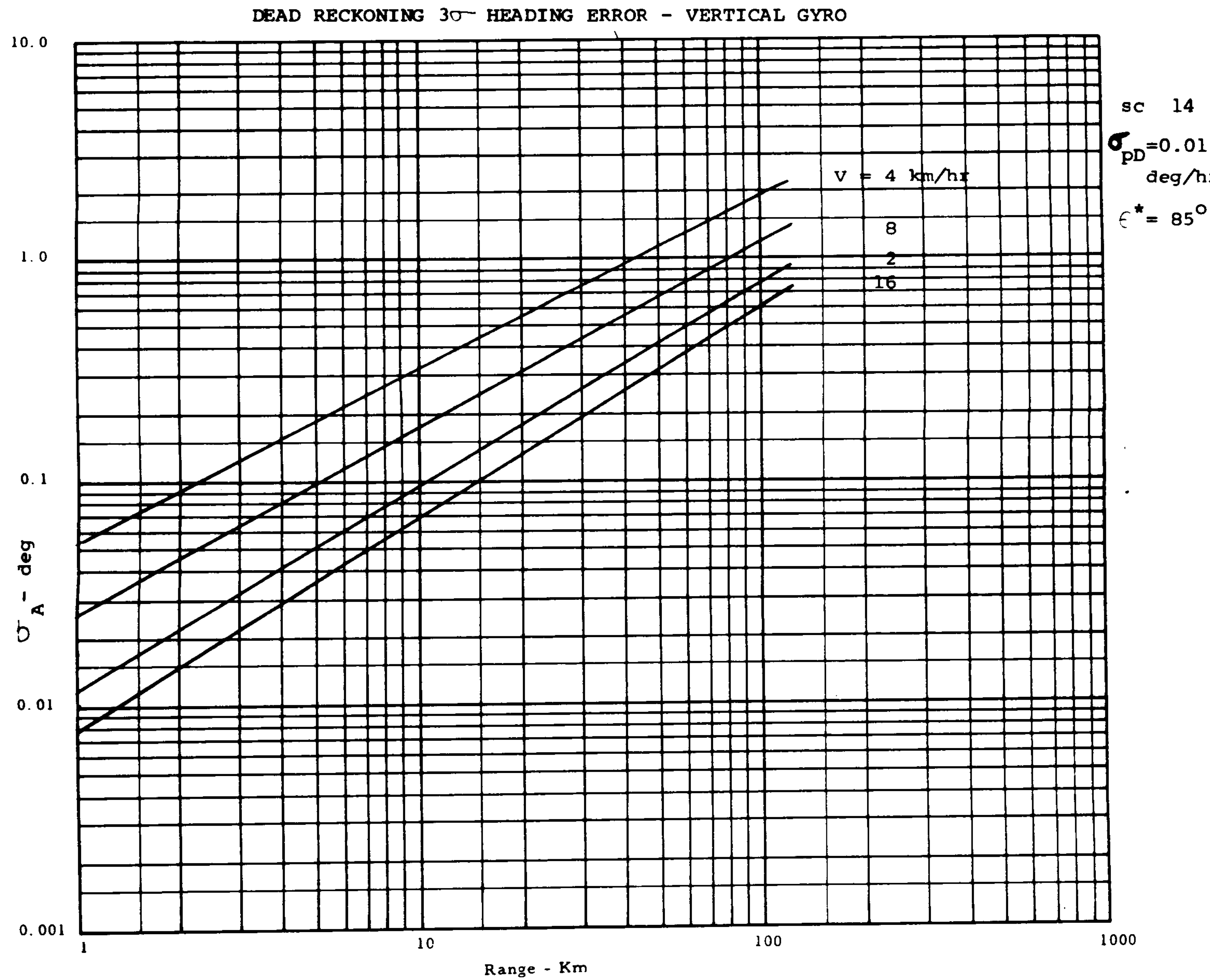


Figure 10-130 Dead Reckoning 3σ Altitude Error—Vertical Gyro

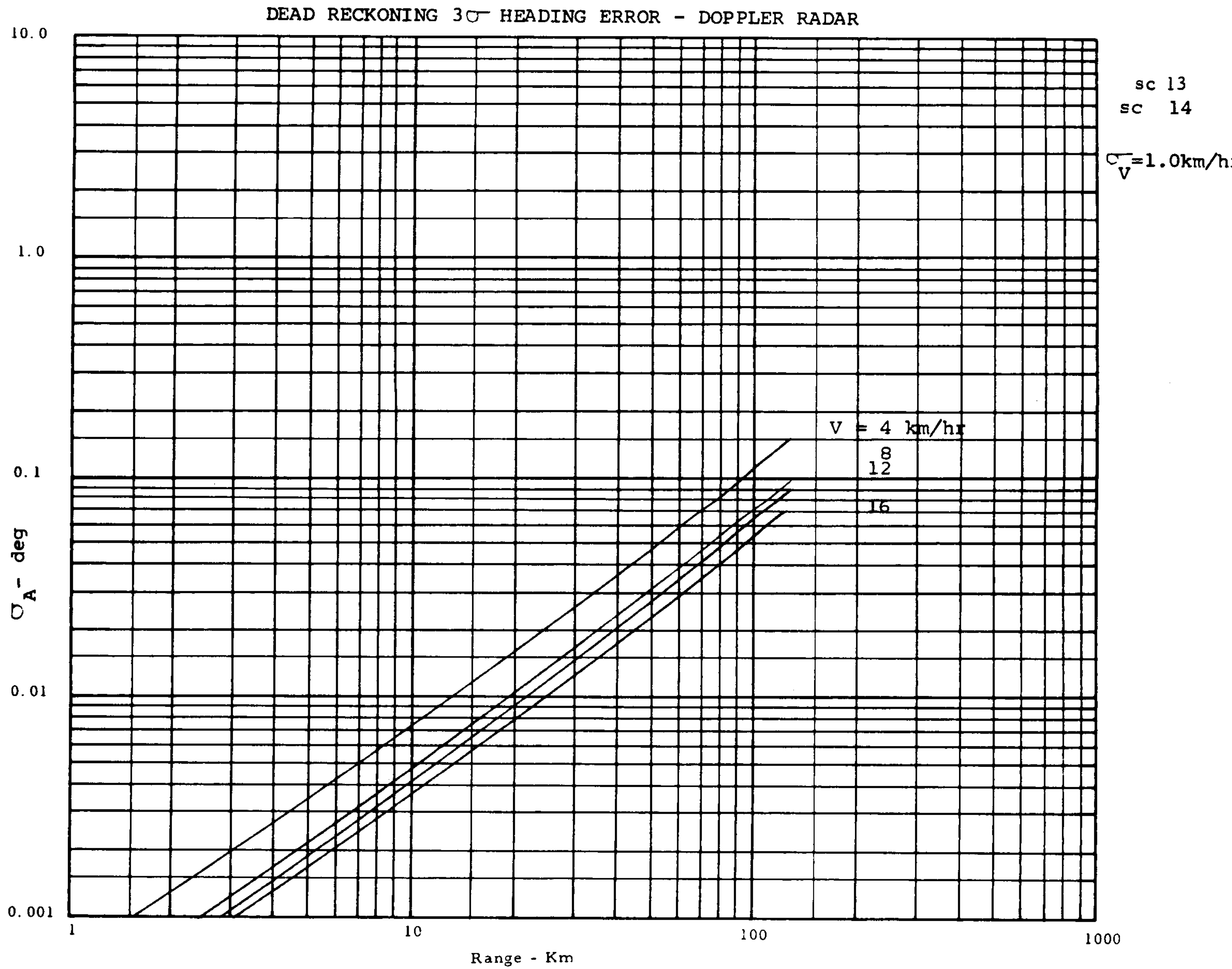


Figure 10-131 Dead Reckoning 3σ Heading Error—Doppler Radar

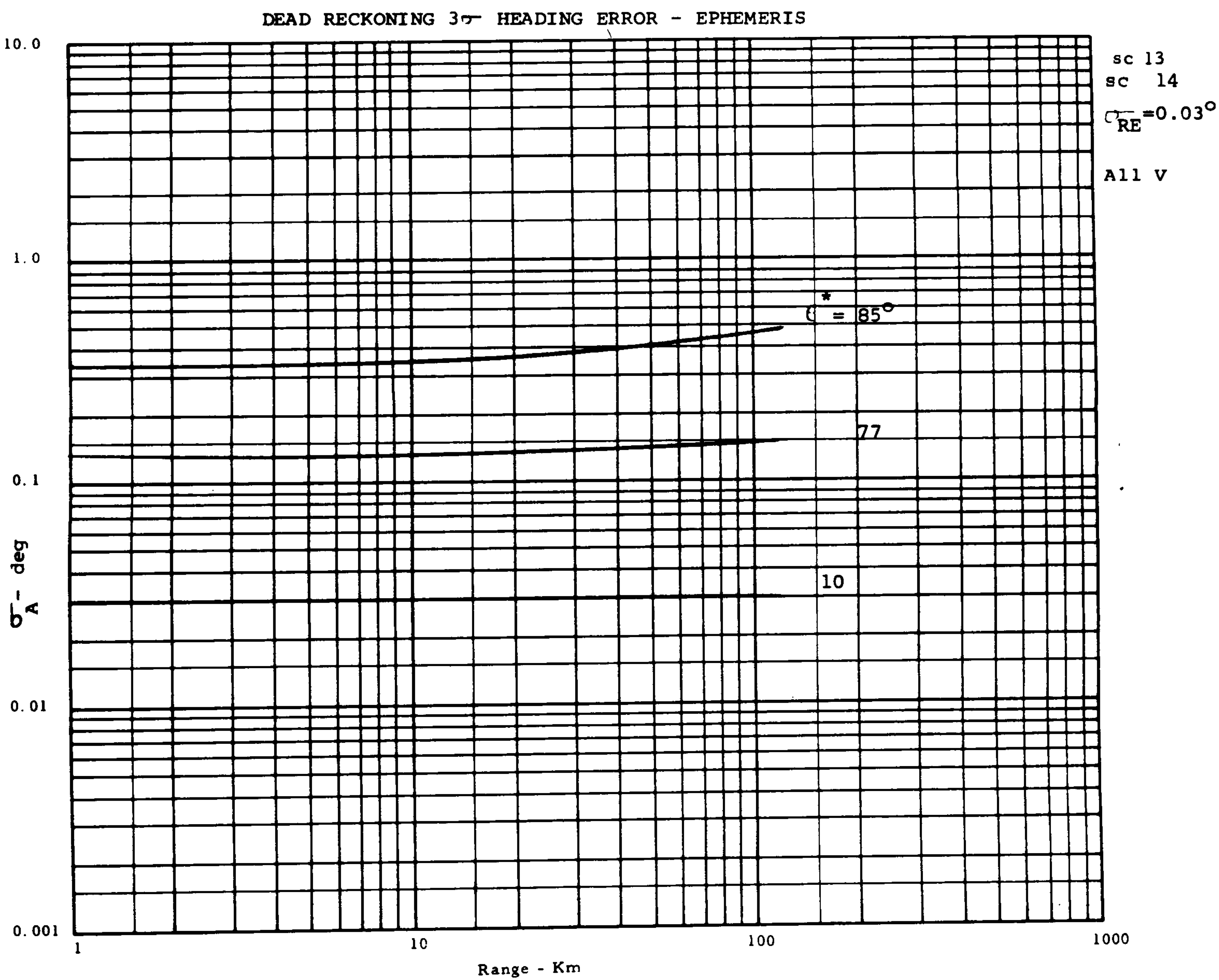


Figure 10-132 Dead Reckoning 3σ Heading Error—Ephemeris

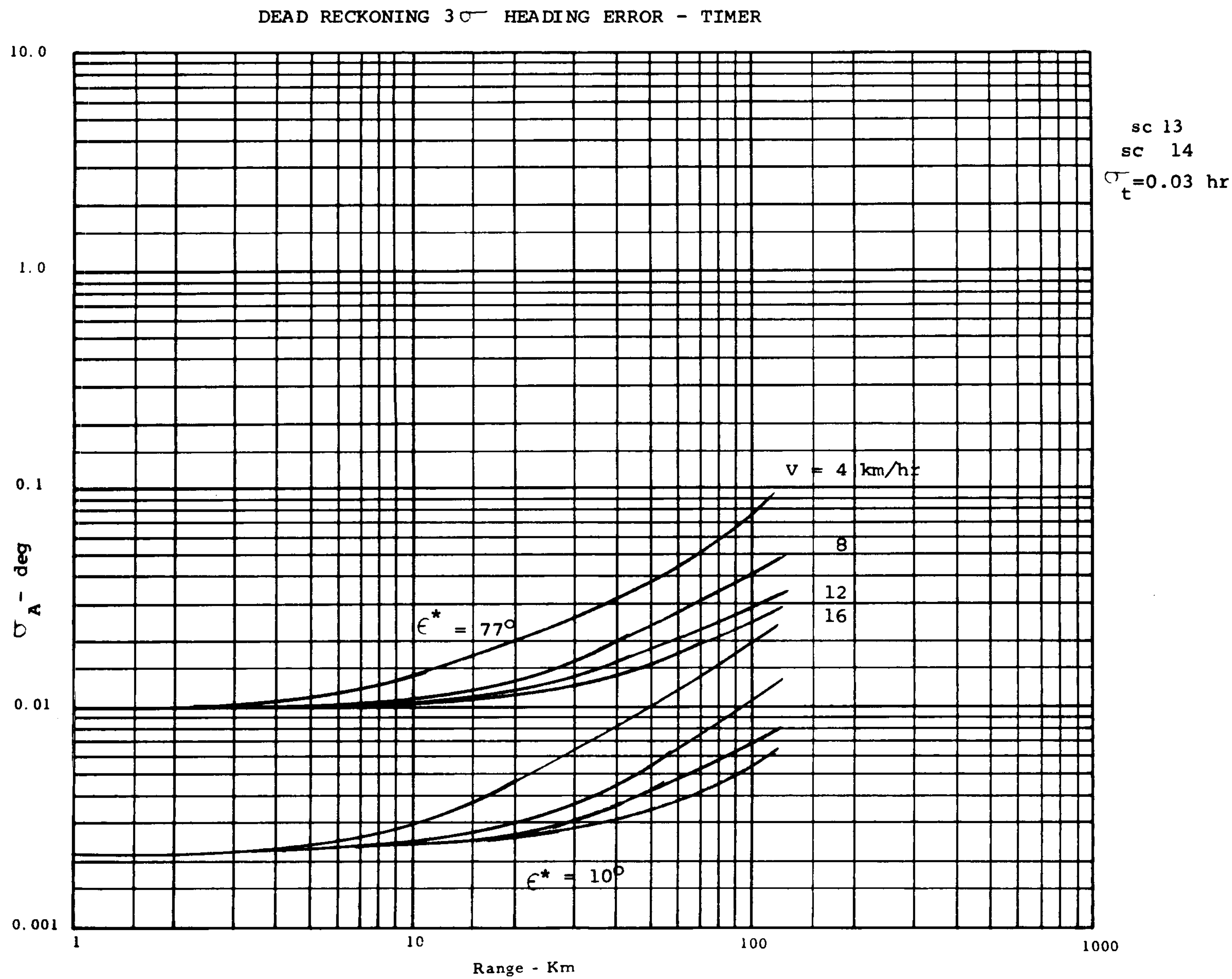


Figure 10-133 Dead Reckoning 3σ Heading Error—Timer

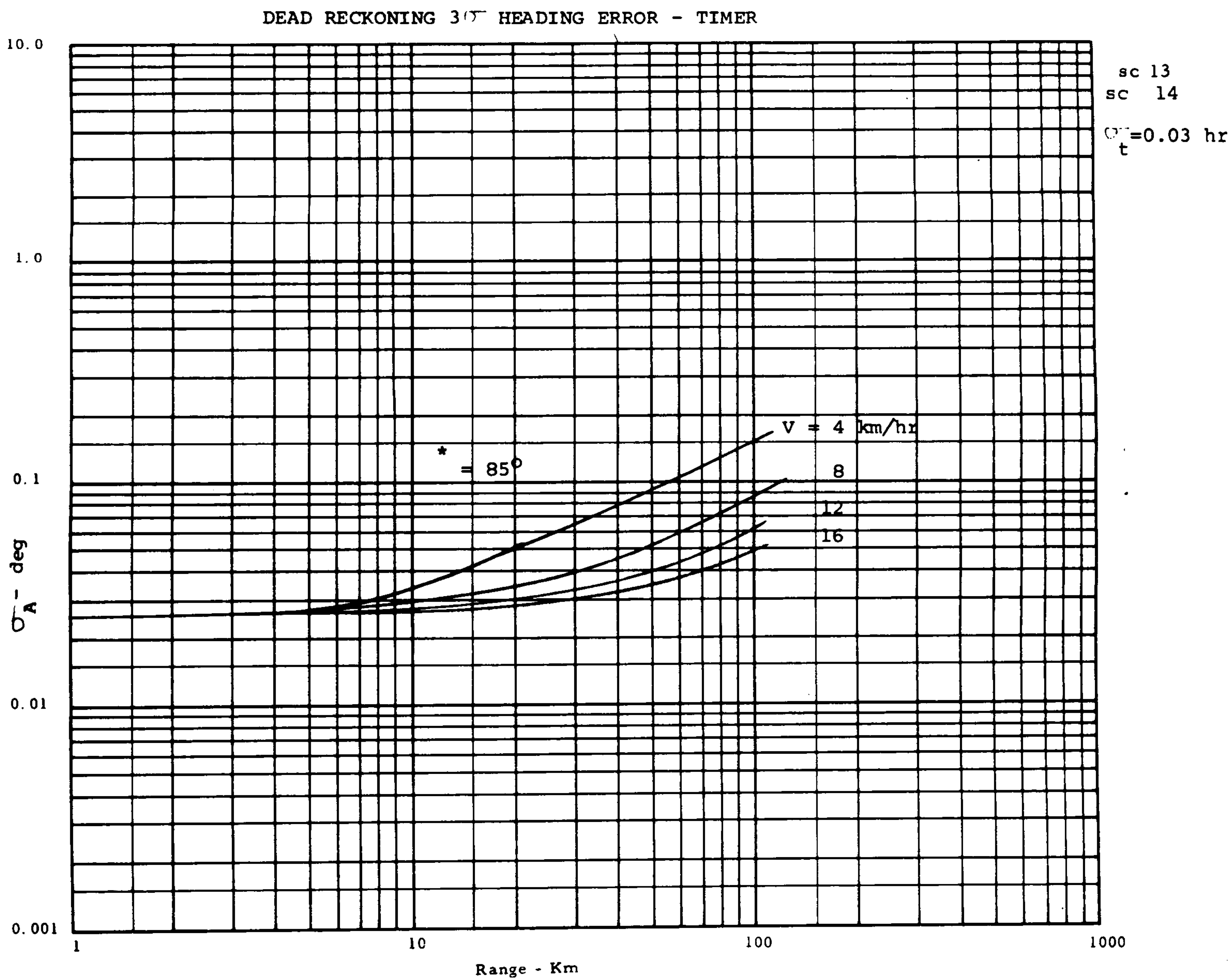


Figure 10-134 Dead Reckoning 3σ Heading Error—Timer

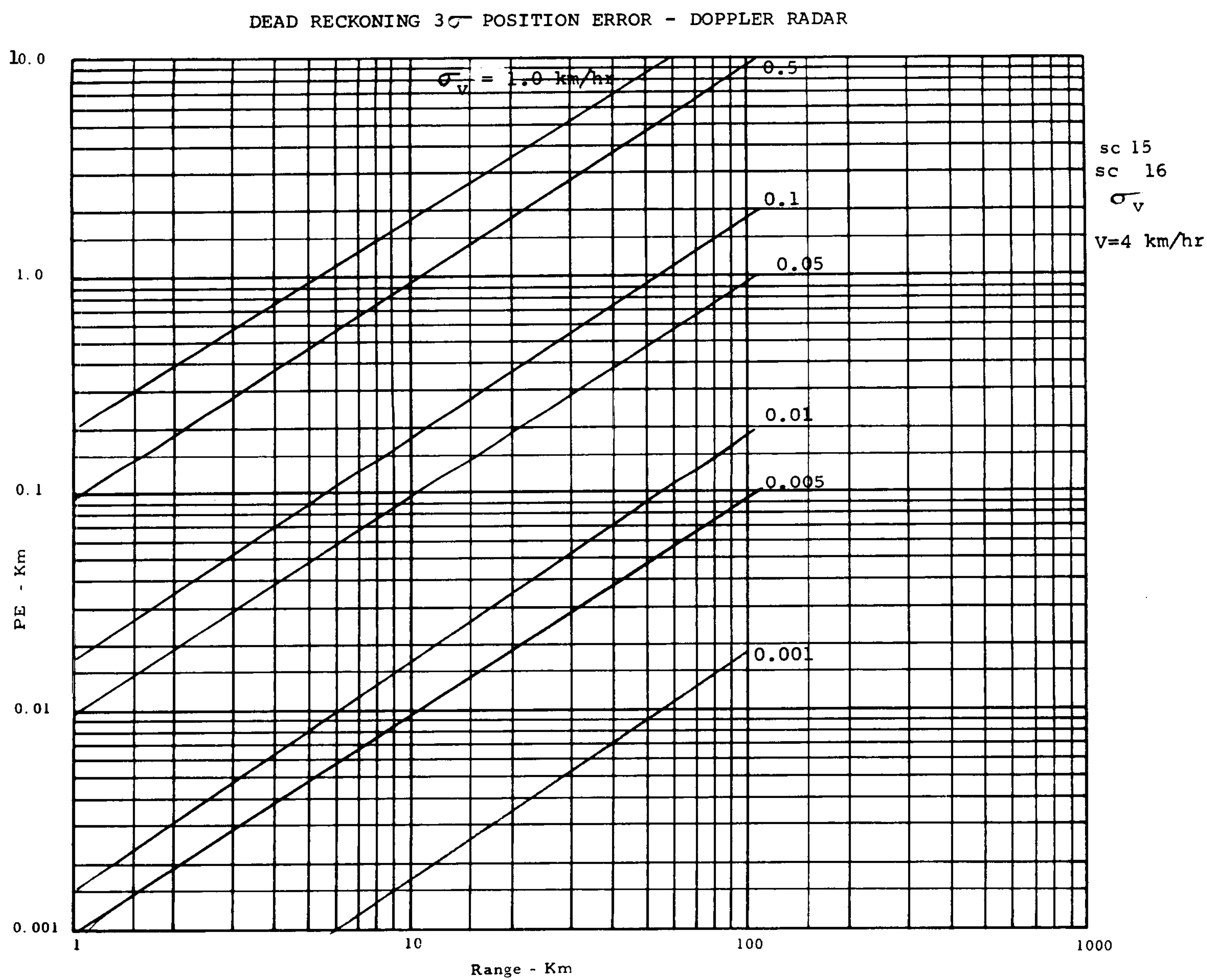


Figure 10-135 Dead Reckoning 3σ Position Error—Doppler Radar

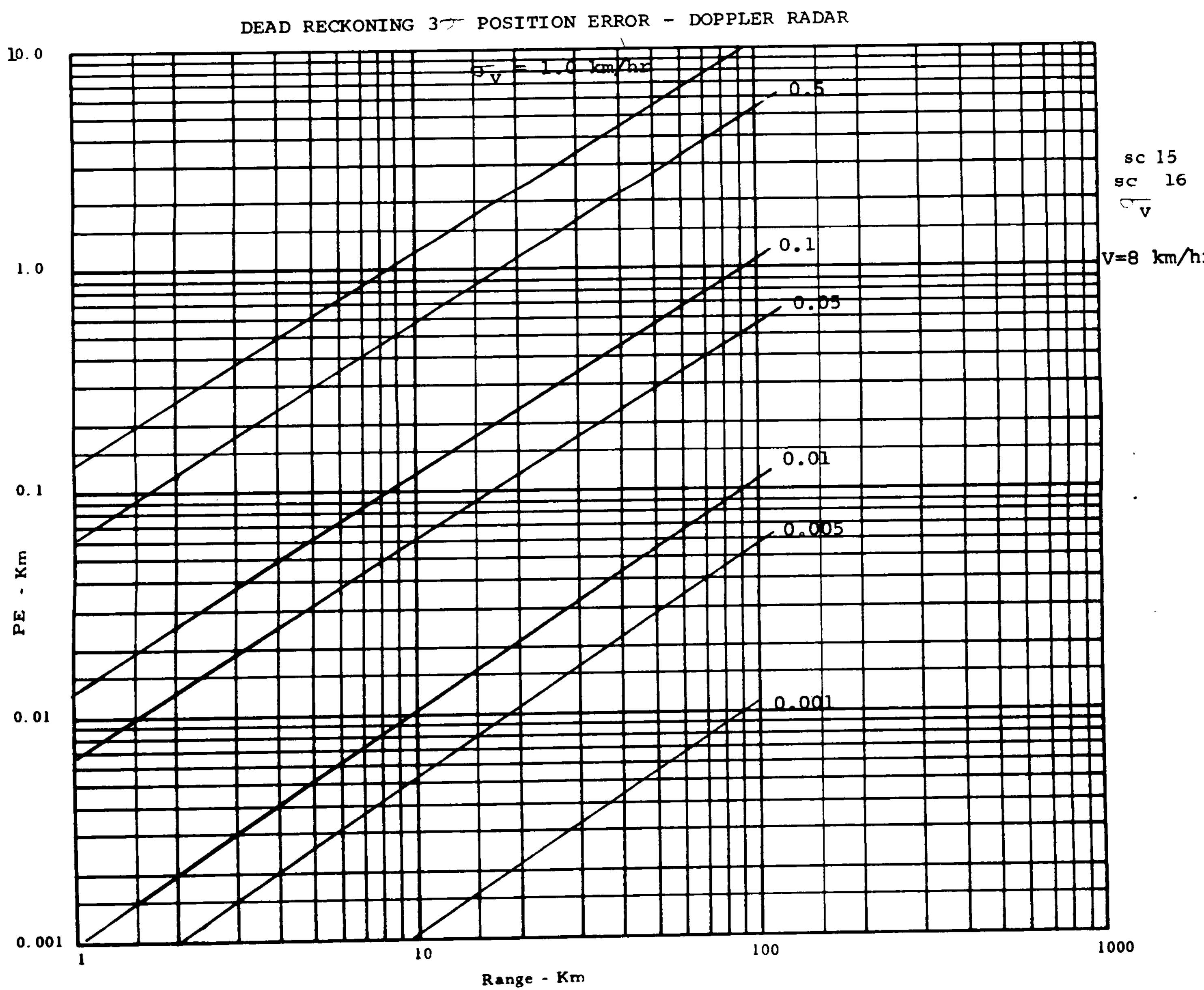


Figure 10-136 Dead Reckoning 3σ Position Error—Doppler Radar

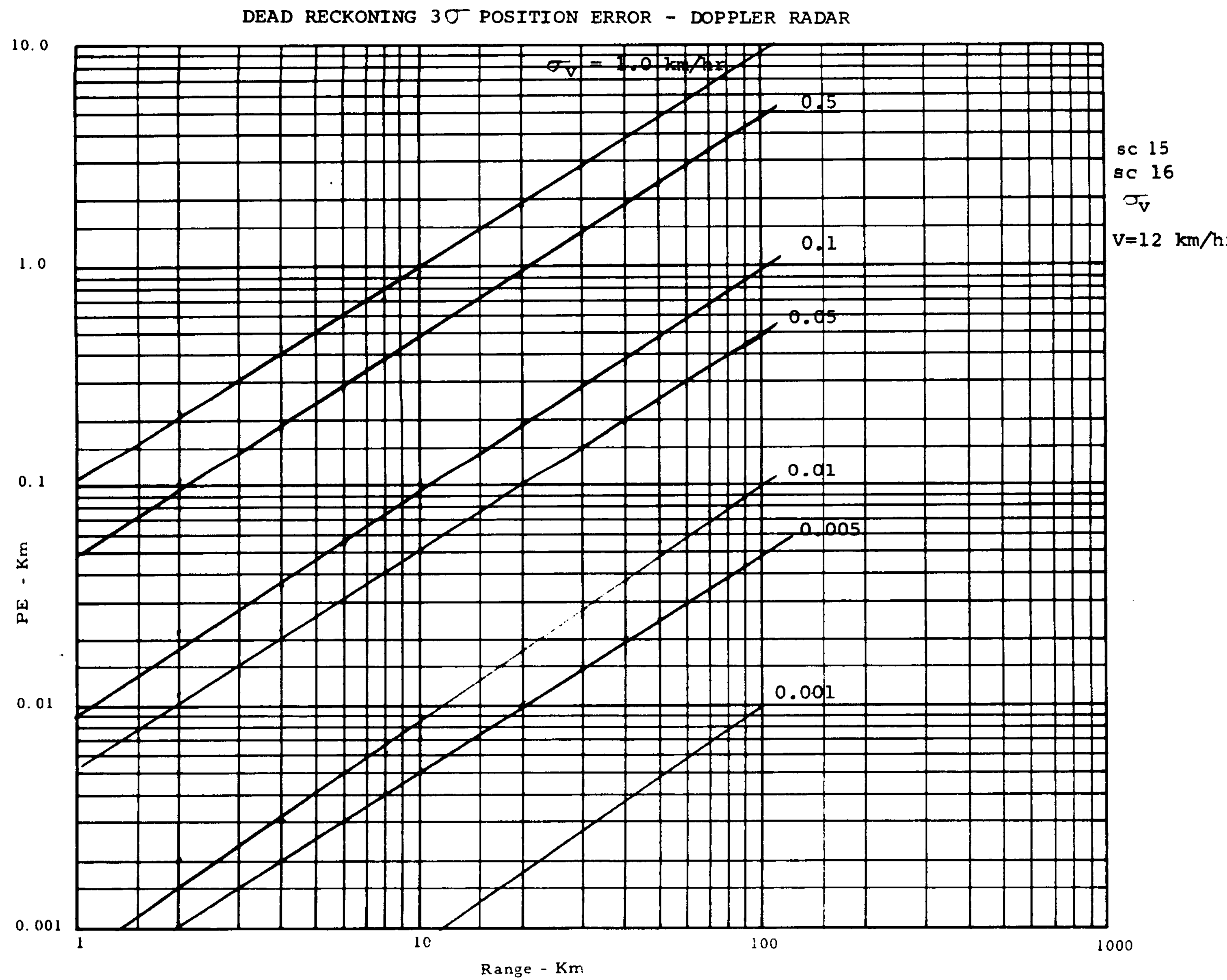


Figure 10-137 Dead Reckoning 3σ Position Error—Doppler Radar

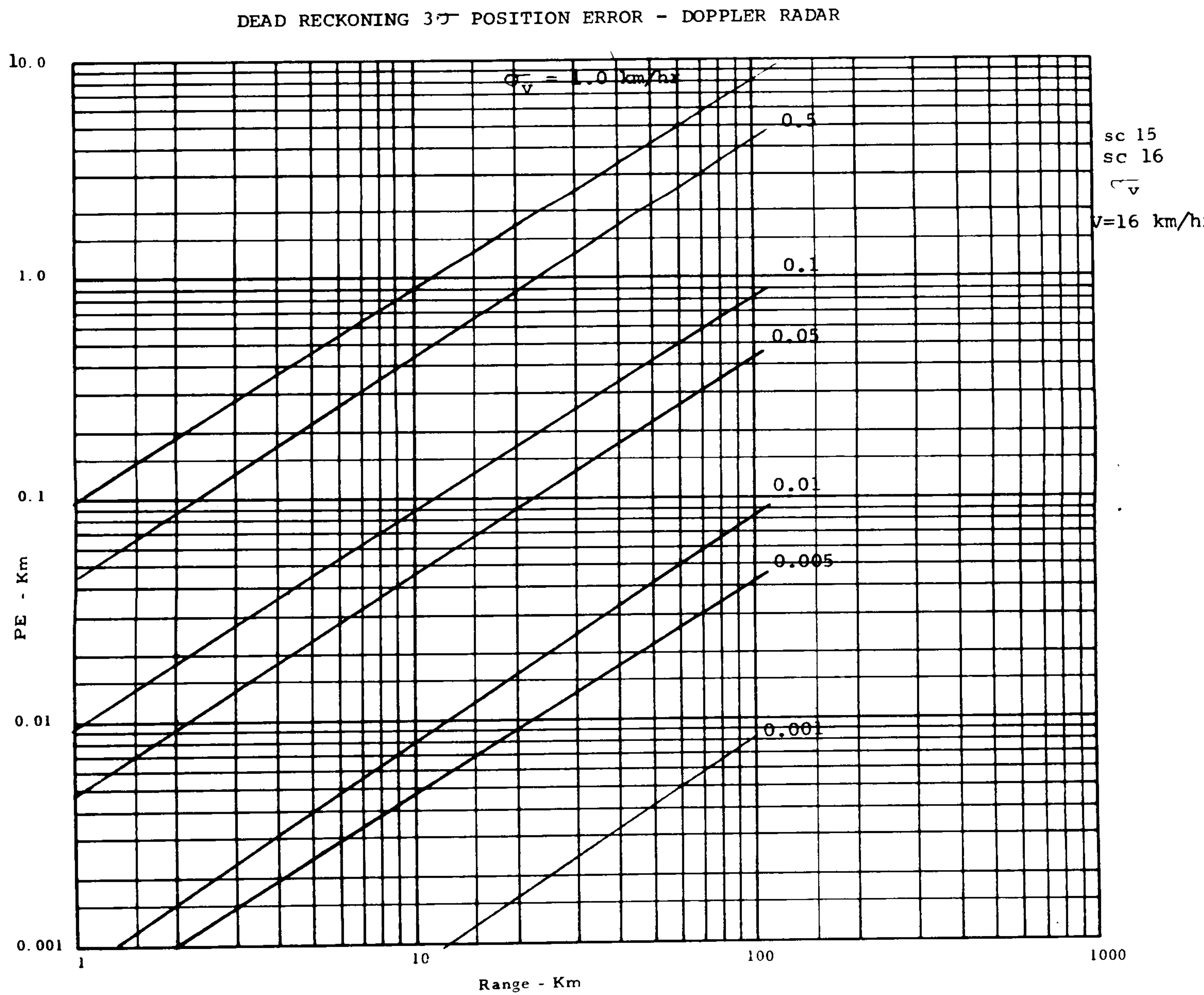


Figure 10-138 Dead Reckoning 3σ Position Error—Doppler Radar

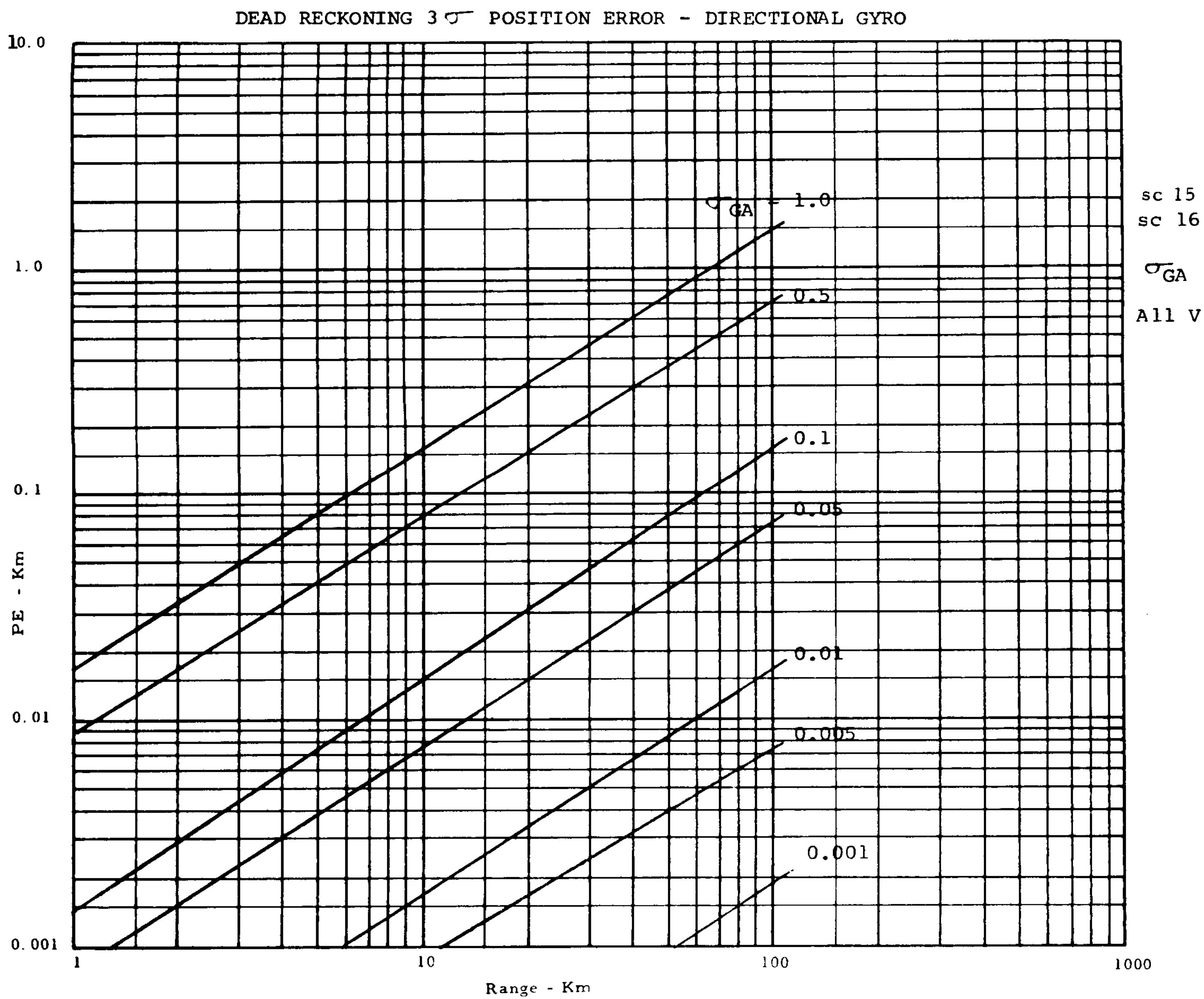


Figure 10-139 Dead Reckoning 3σ Position Error—Doppler Radar

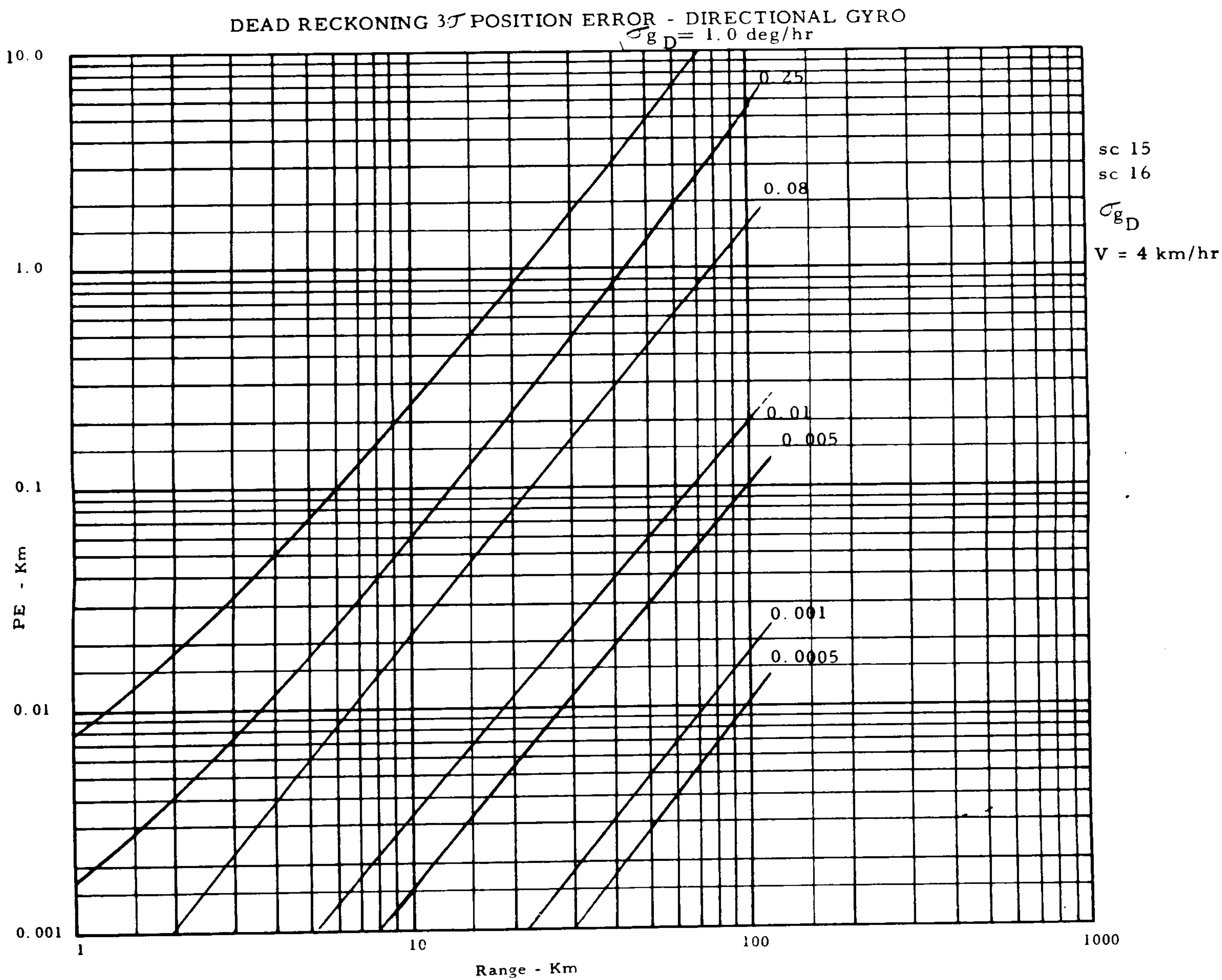


Figure 10-140 Dead Reckoning 3σ Position Error—Directional Gyro

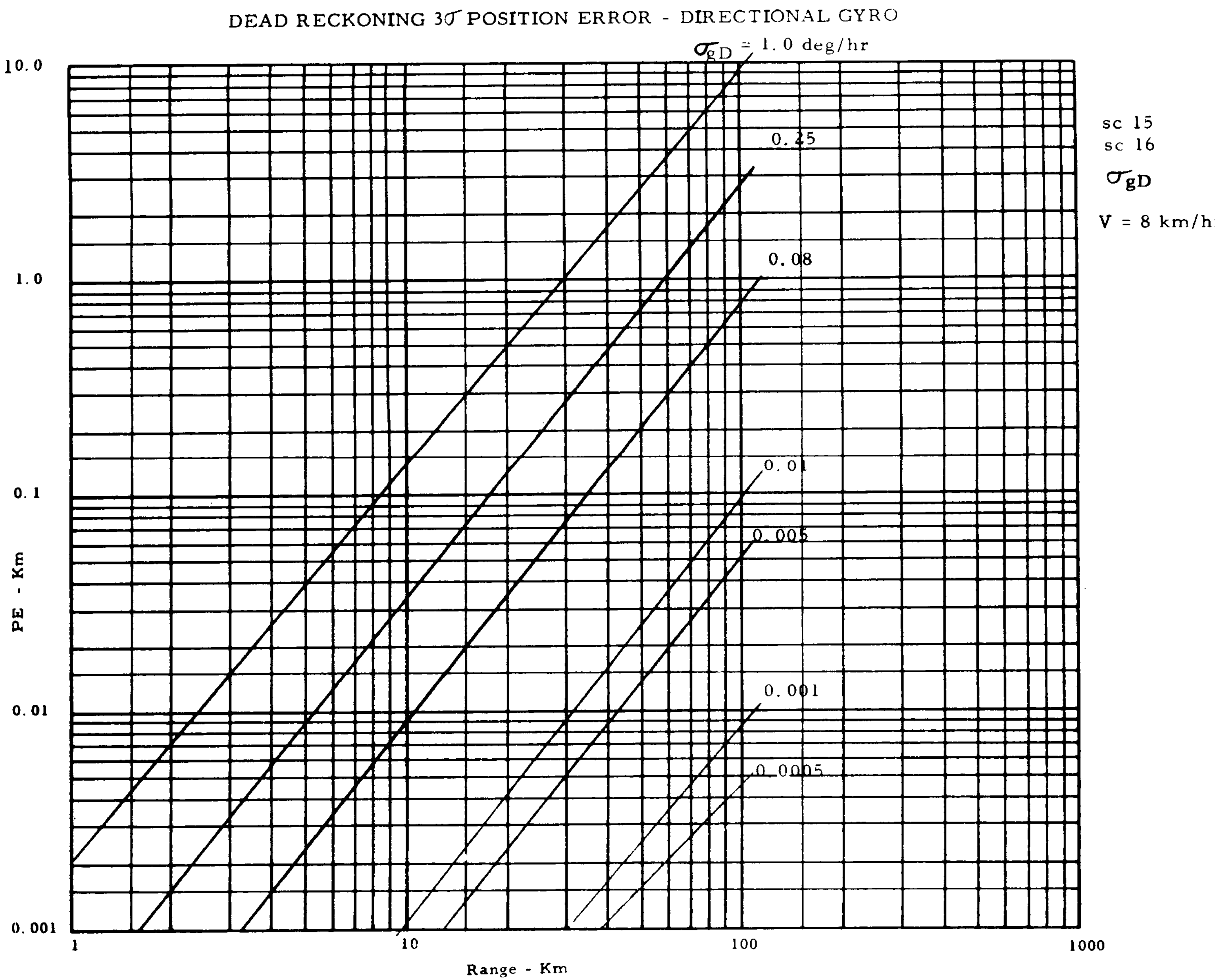


Figure 10-141 Dead Reckoning 3σ Position Error—Directional Gyro

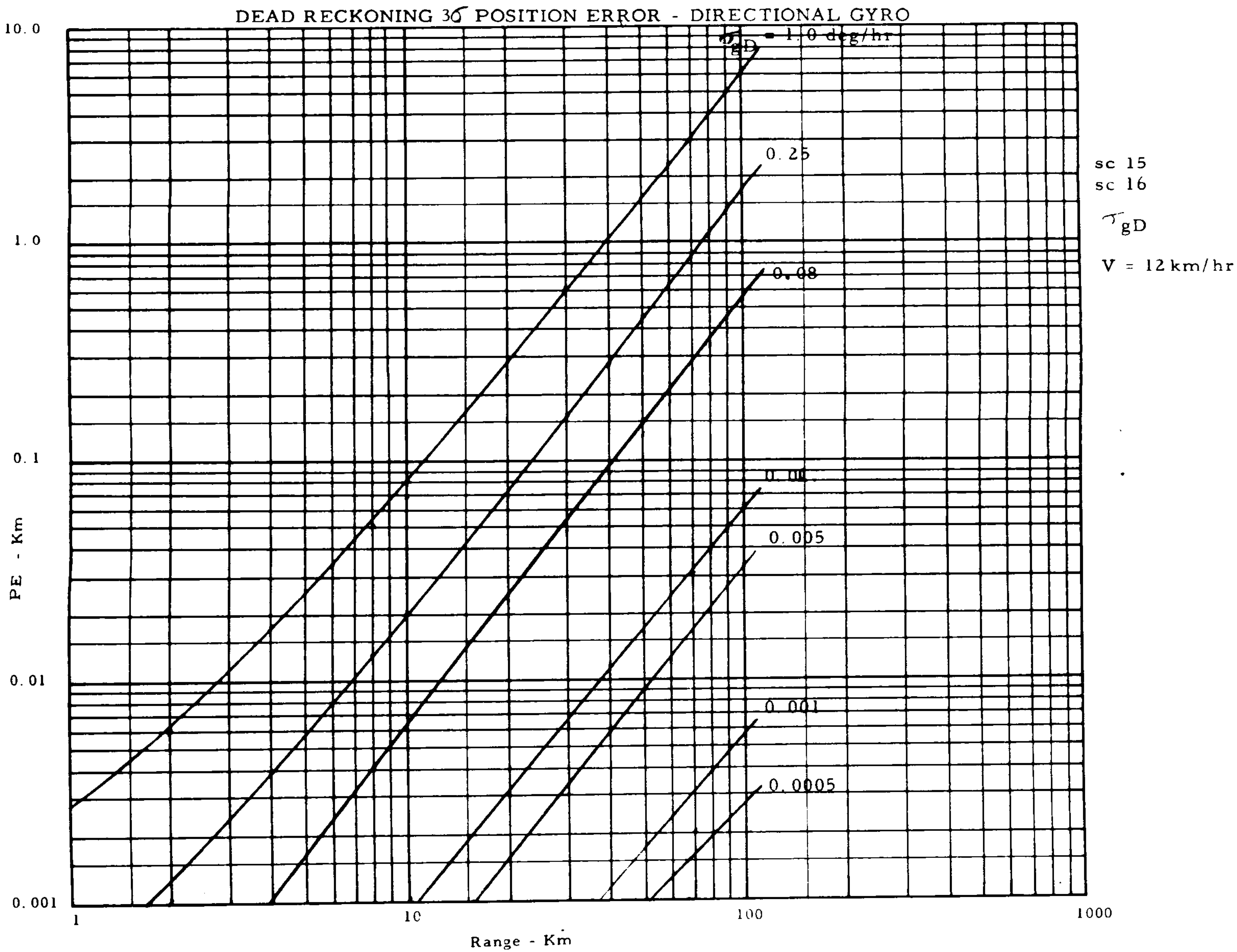


Figure 10-142 Dead Reckoning 3σ Position Error—Directional Gyro

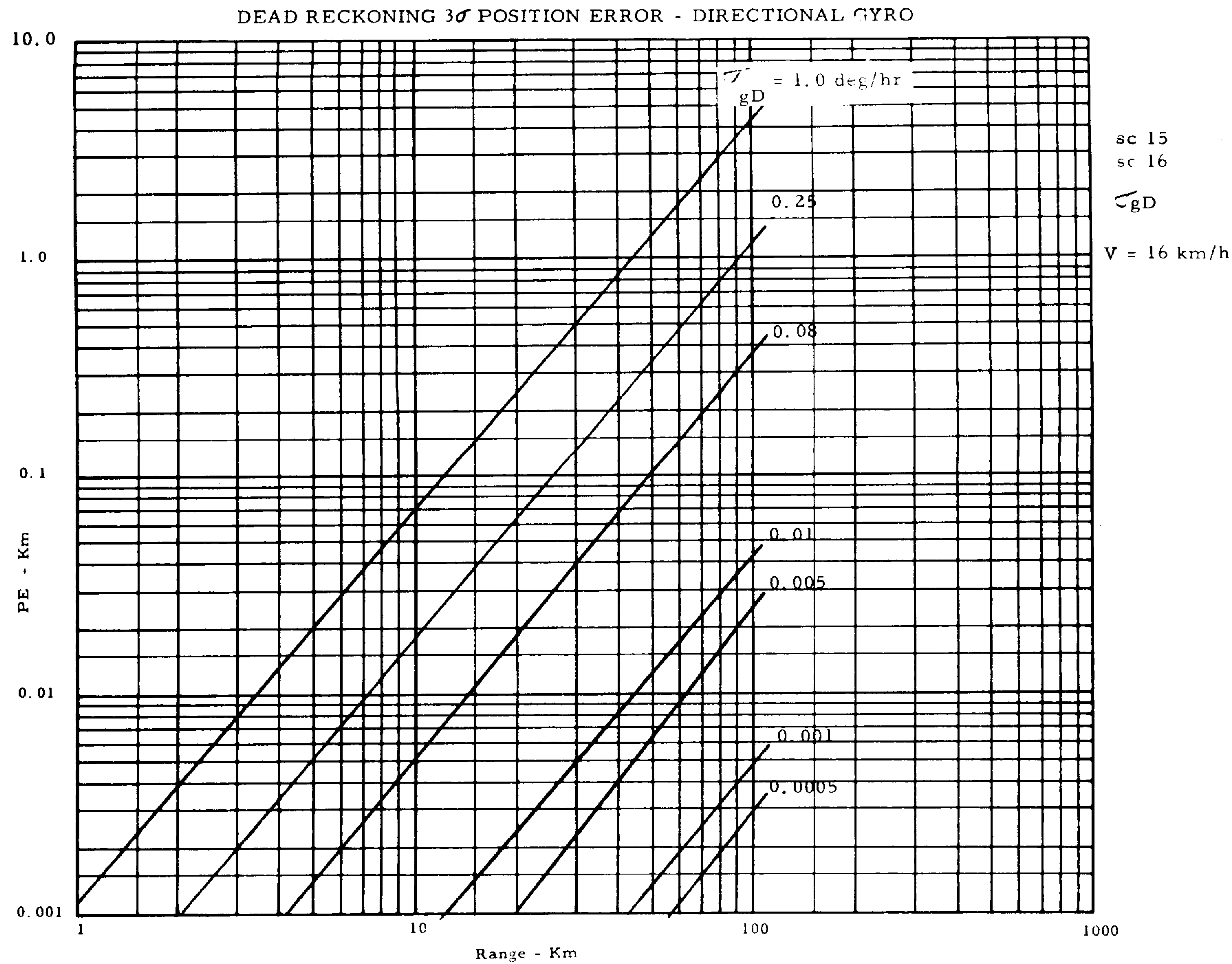


Figure 10-143 Dead Reckoning 3σ Position Error—Directional Gyro

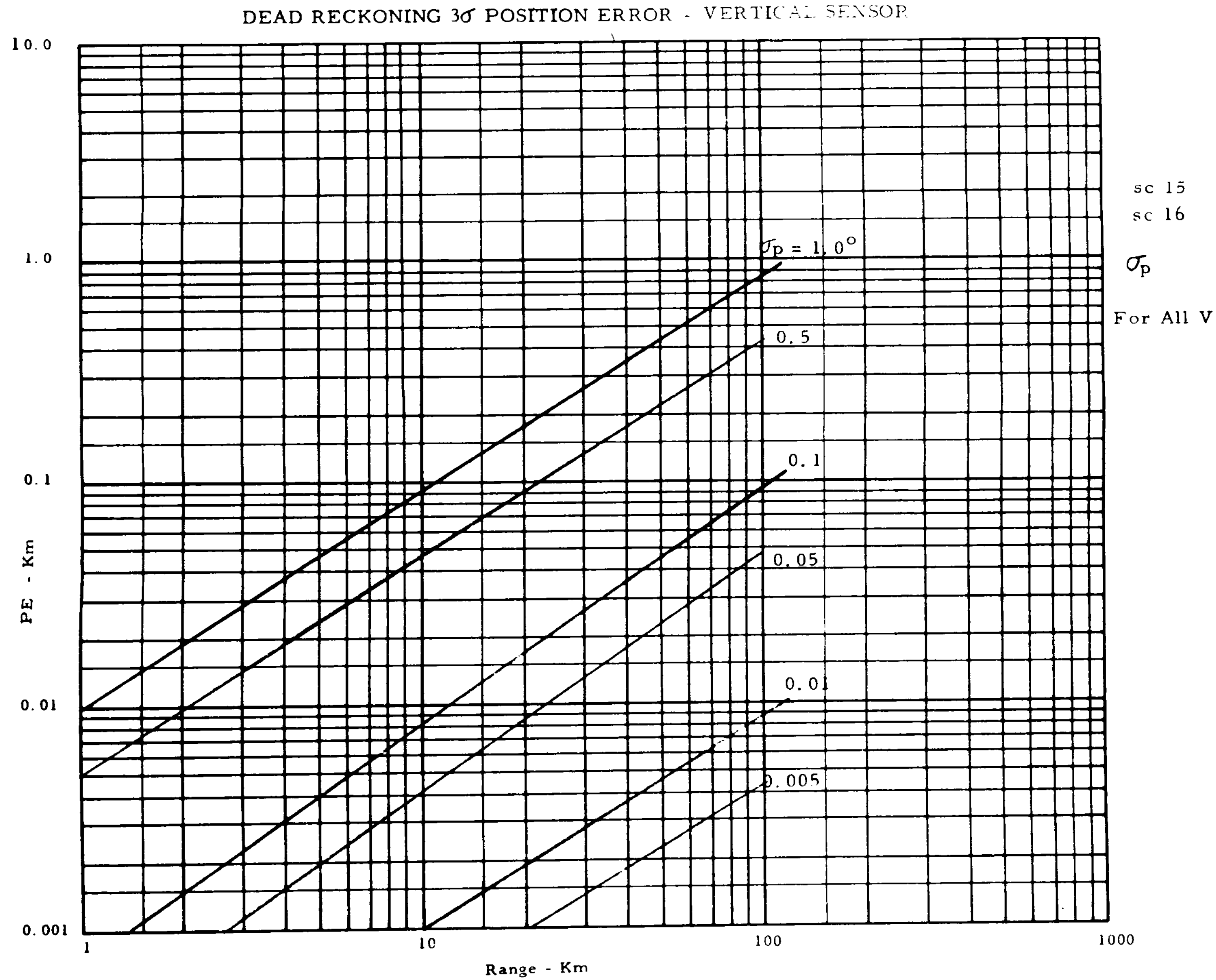


Figure 10-144 Dead Reckoning 3σ Position Error—Vertical Sensor

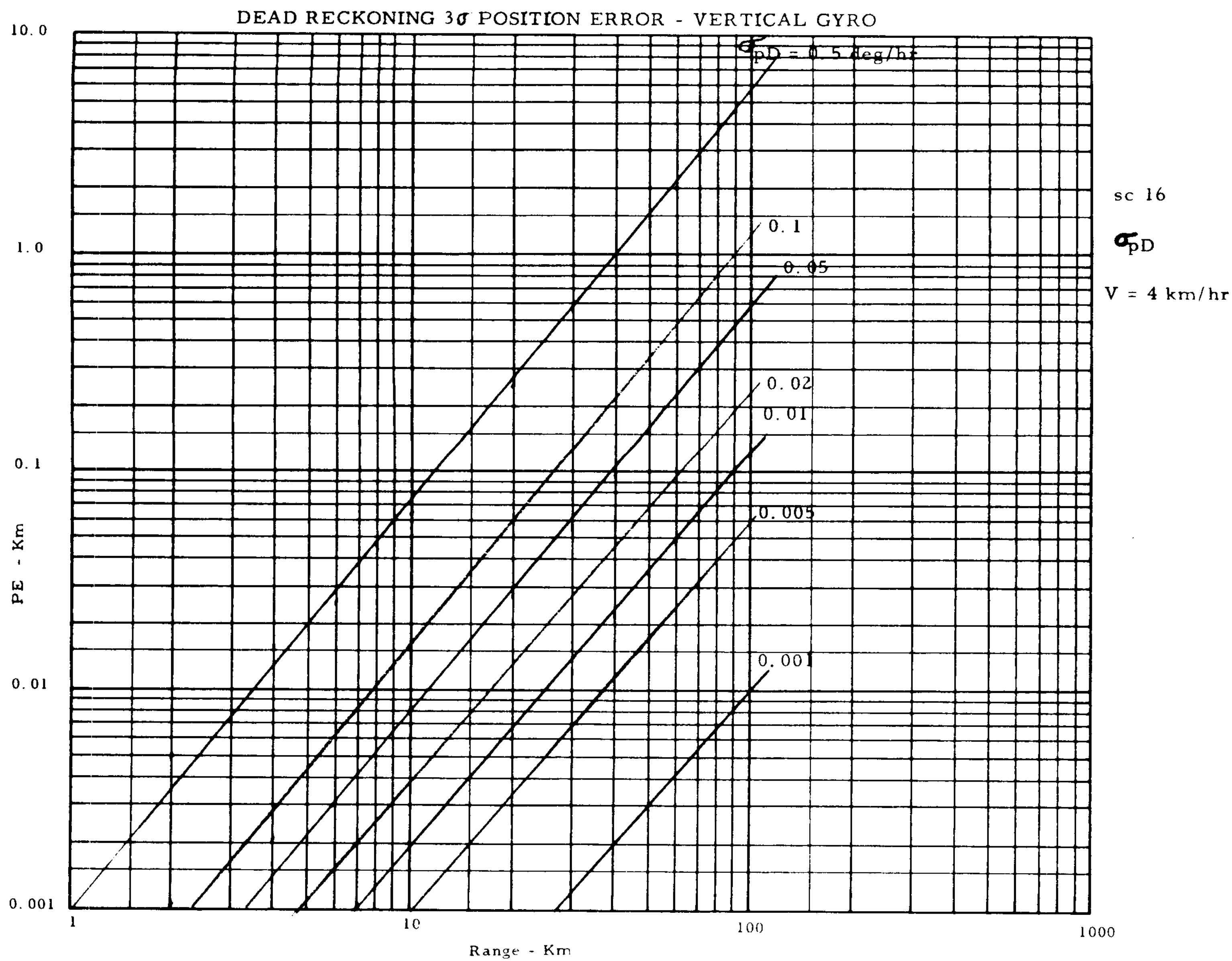


Figure 10-145 Dead Reckoning 3σ Position Error — Vertical Gyro

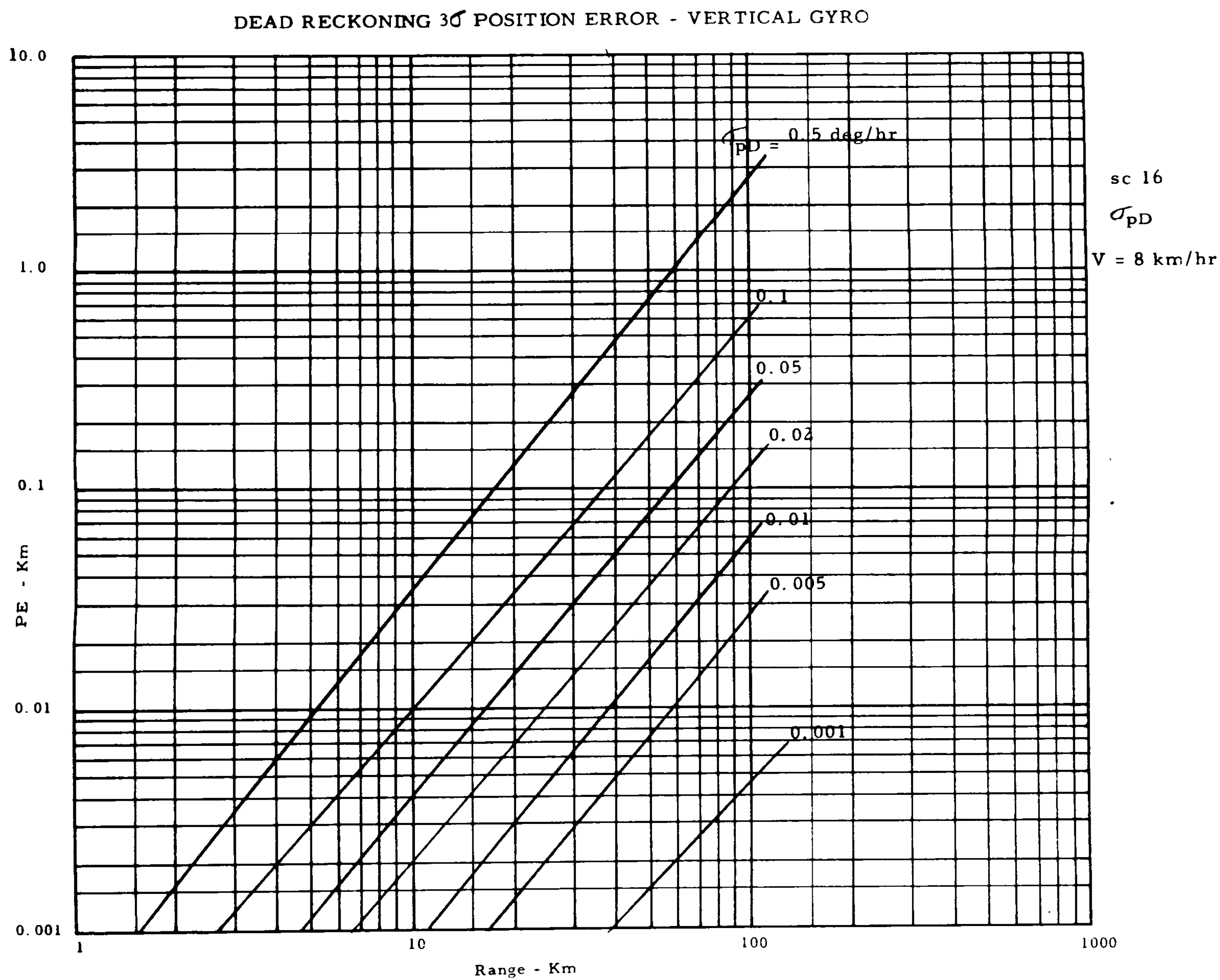


Figure 10-146 Dead Reckoning 3σ Position Error — Vertical Gyro

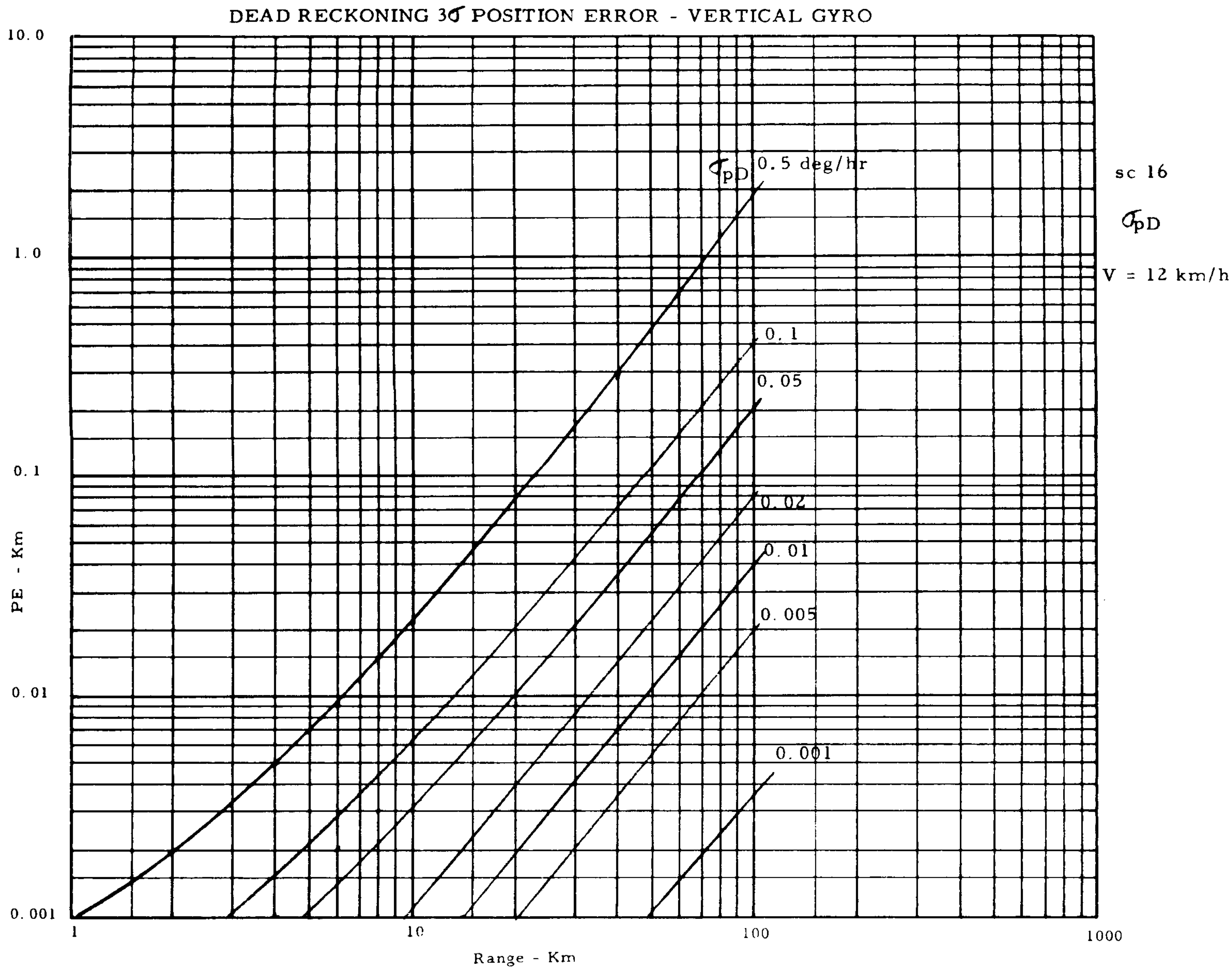


Figure 10-147 Dead Reckoning 3σ Position Error — Vertical Gyro

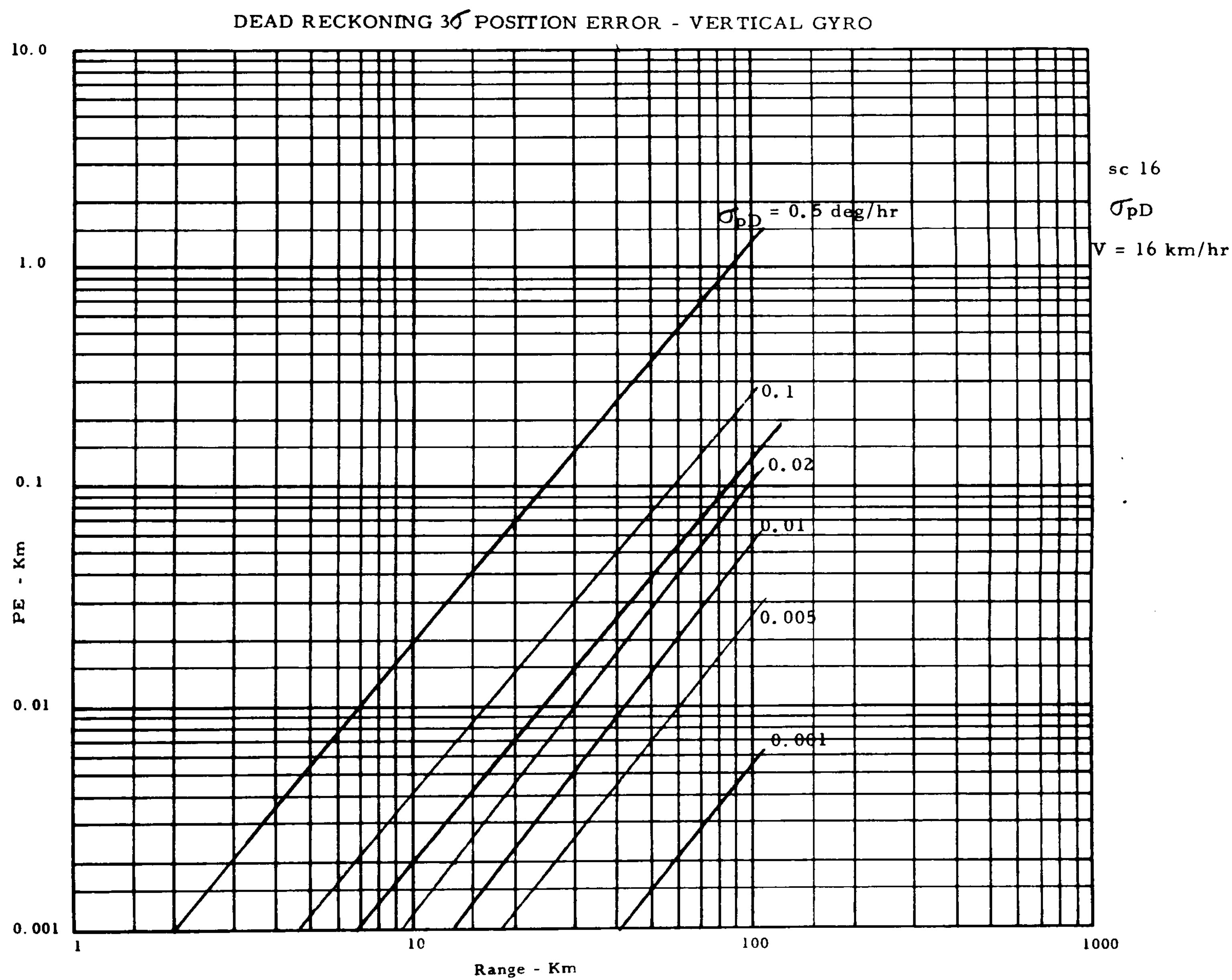


Figure 10-148 Dead Reckoning 3σ Position Error — Vertical Gyro

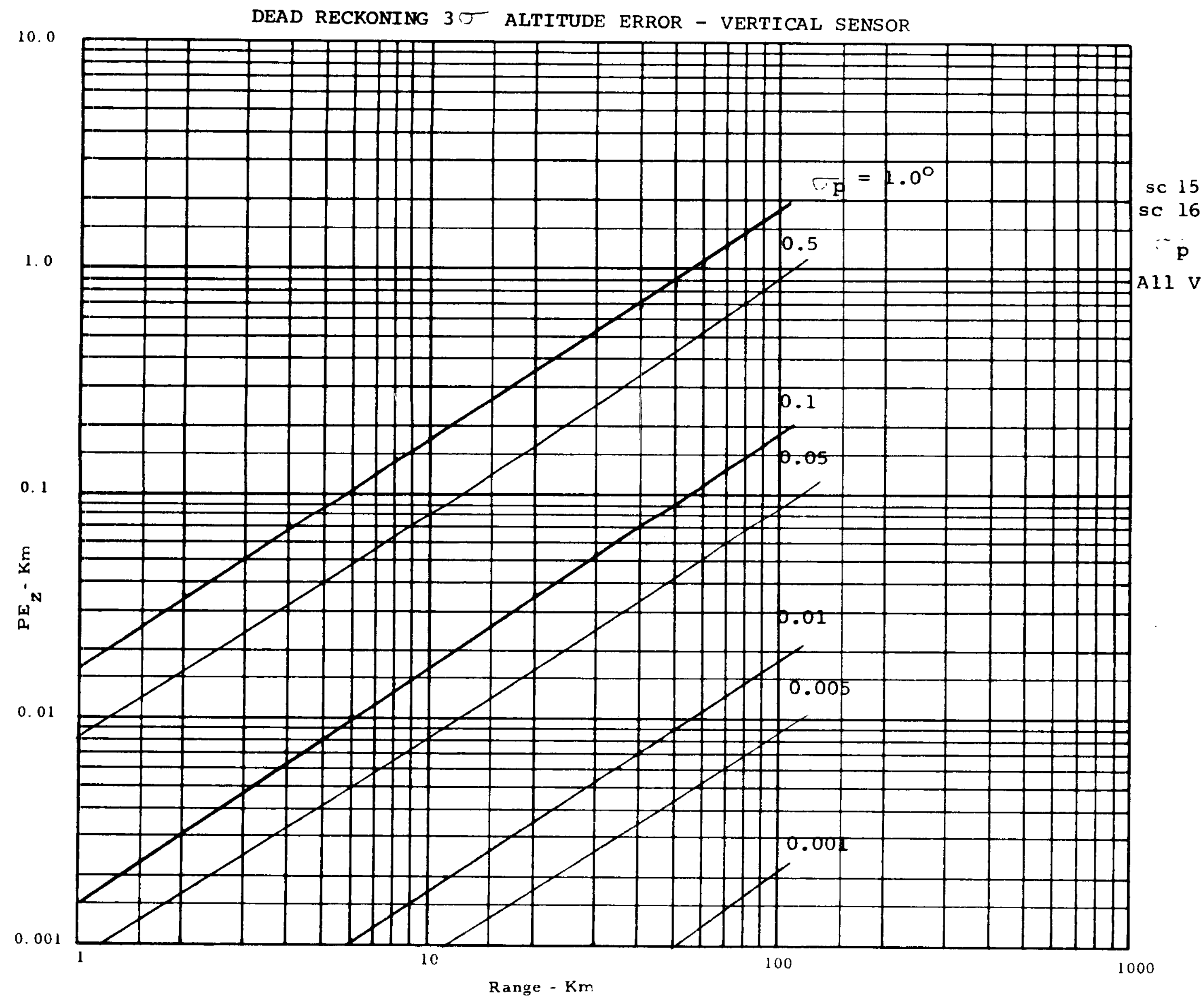


Figure 10-149 Dead Reckoning 3σ Altitude Error — Vertical Sensor

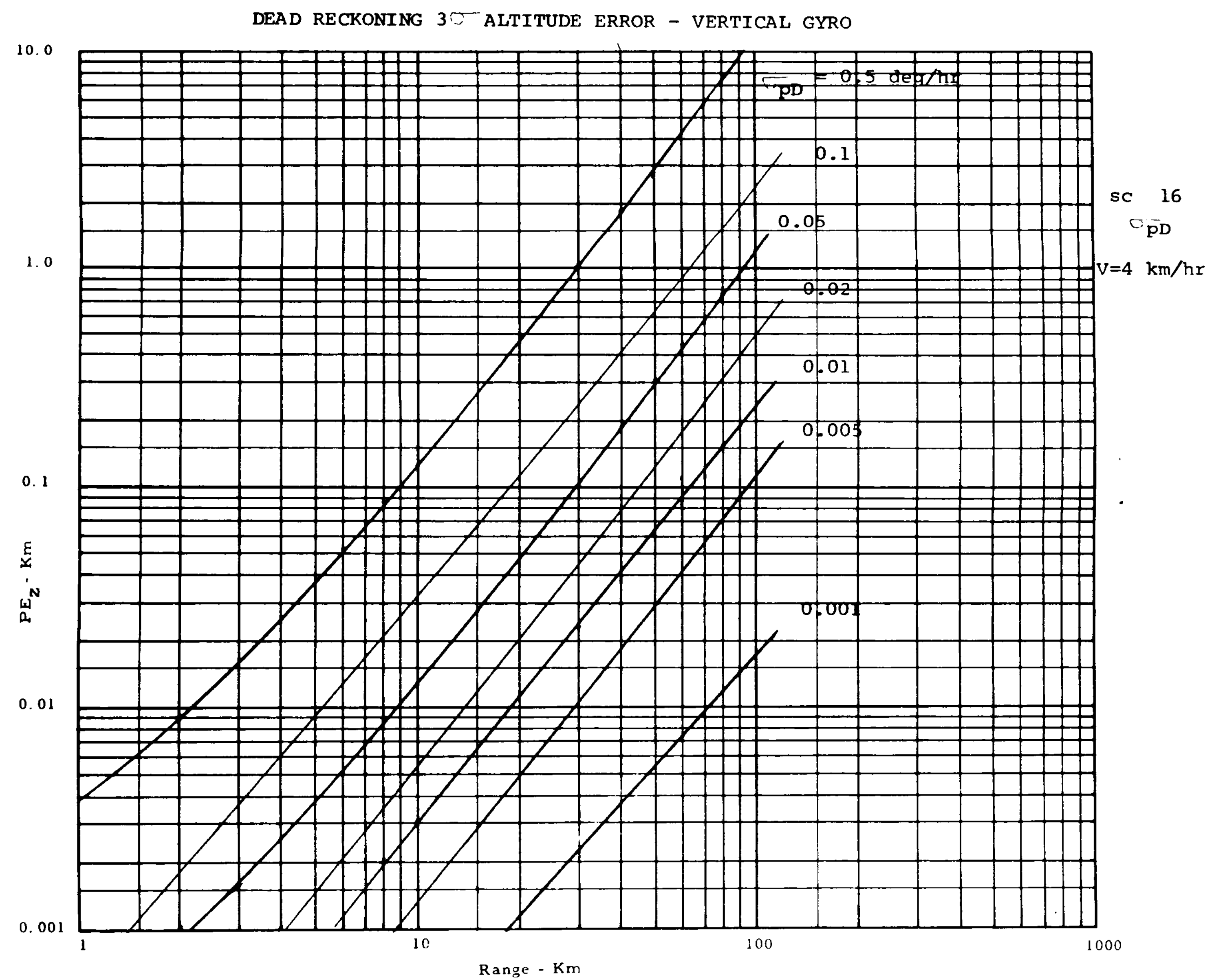


Figure 10-150 Dead Reckoning 3σ Altitude Error — Vertical Gyro

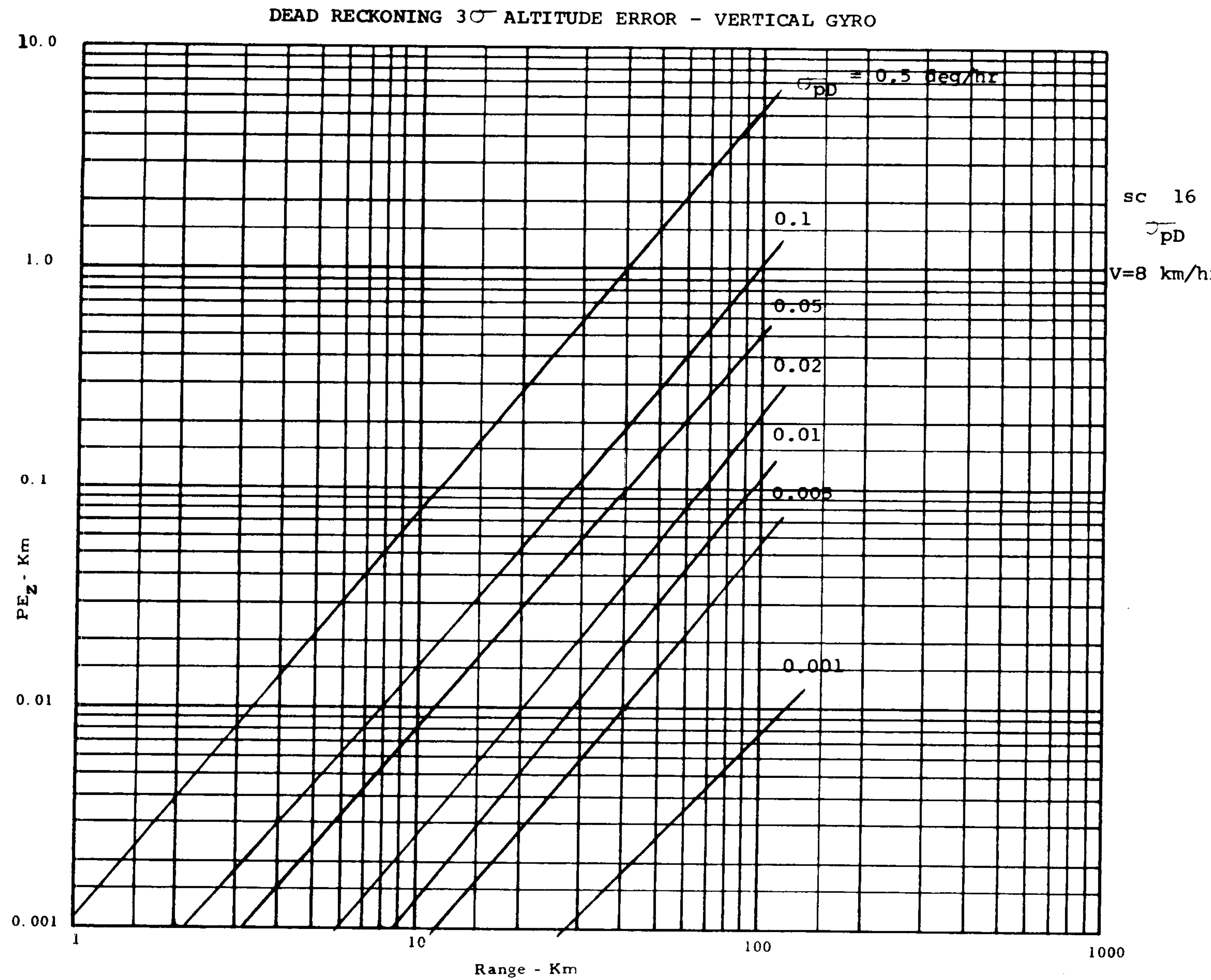


Figure 10-151 Dead Reckoning 3σ Altitude Error — Vertical Gyro

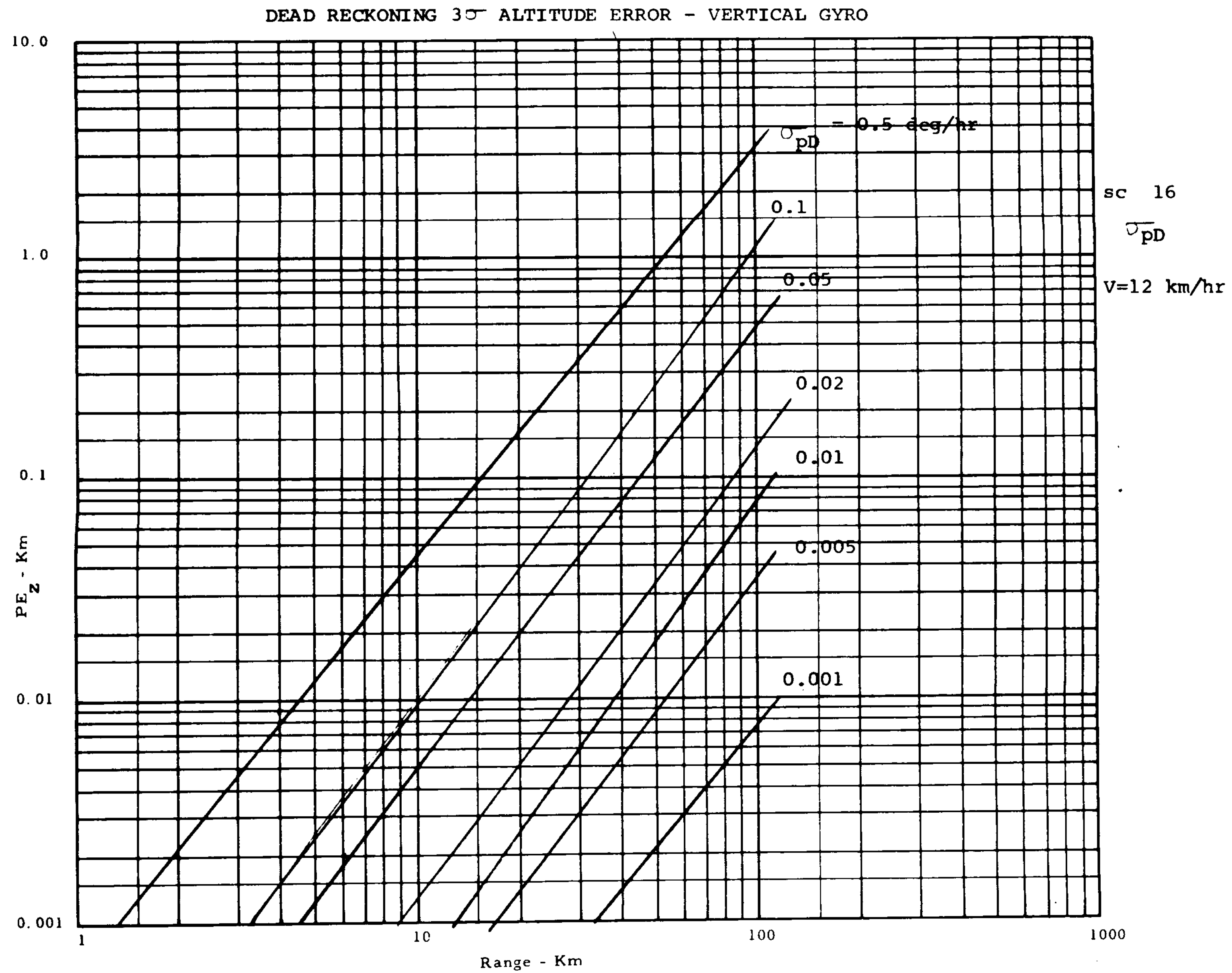


Figure 10-152 Dead Reckoning 3σ Altitude Error — Vertical Gyro

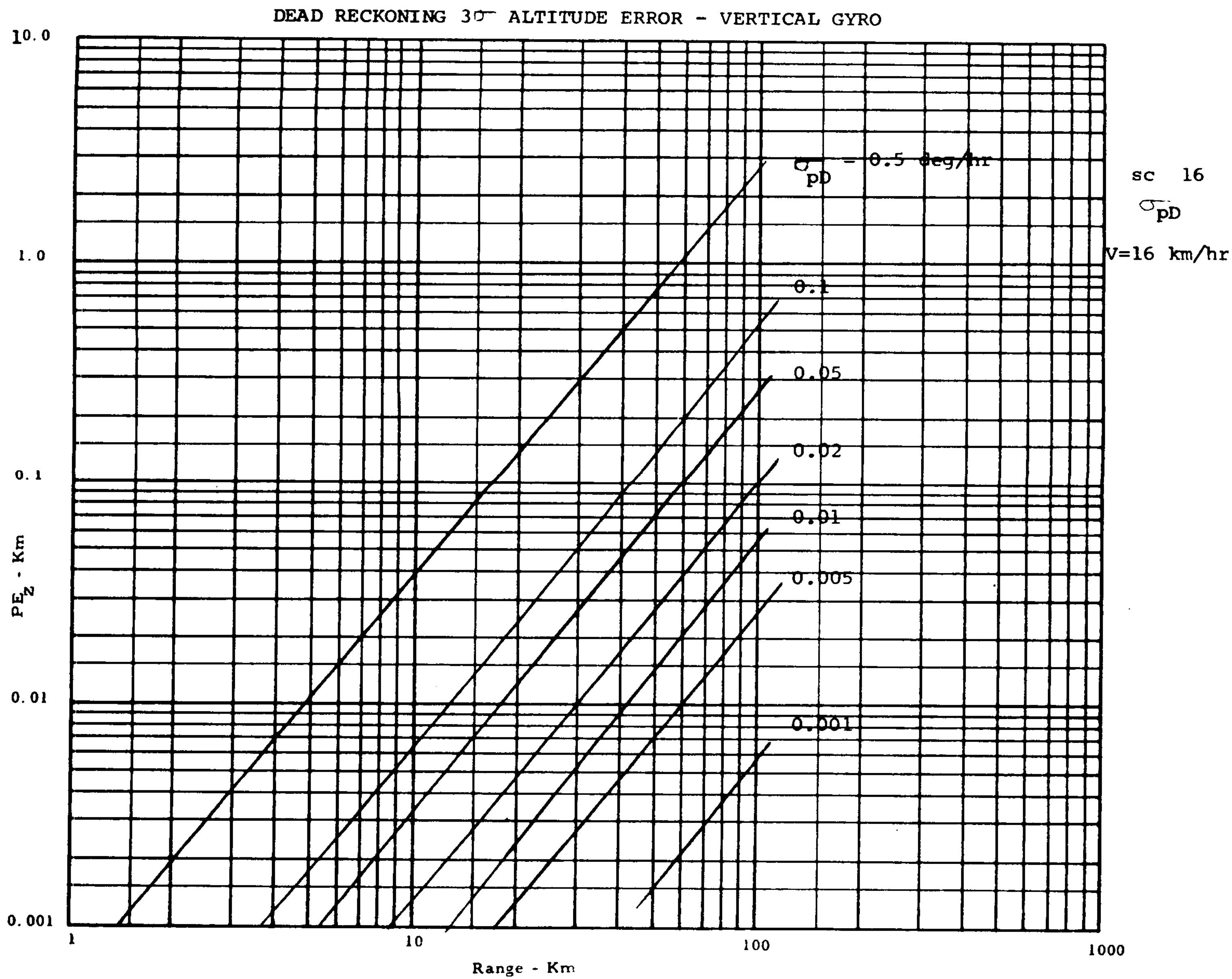


Figure 10-153 Dead Reckoning 3σ Altitude Error — Vertical Gyro

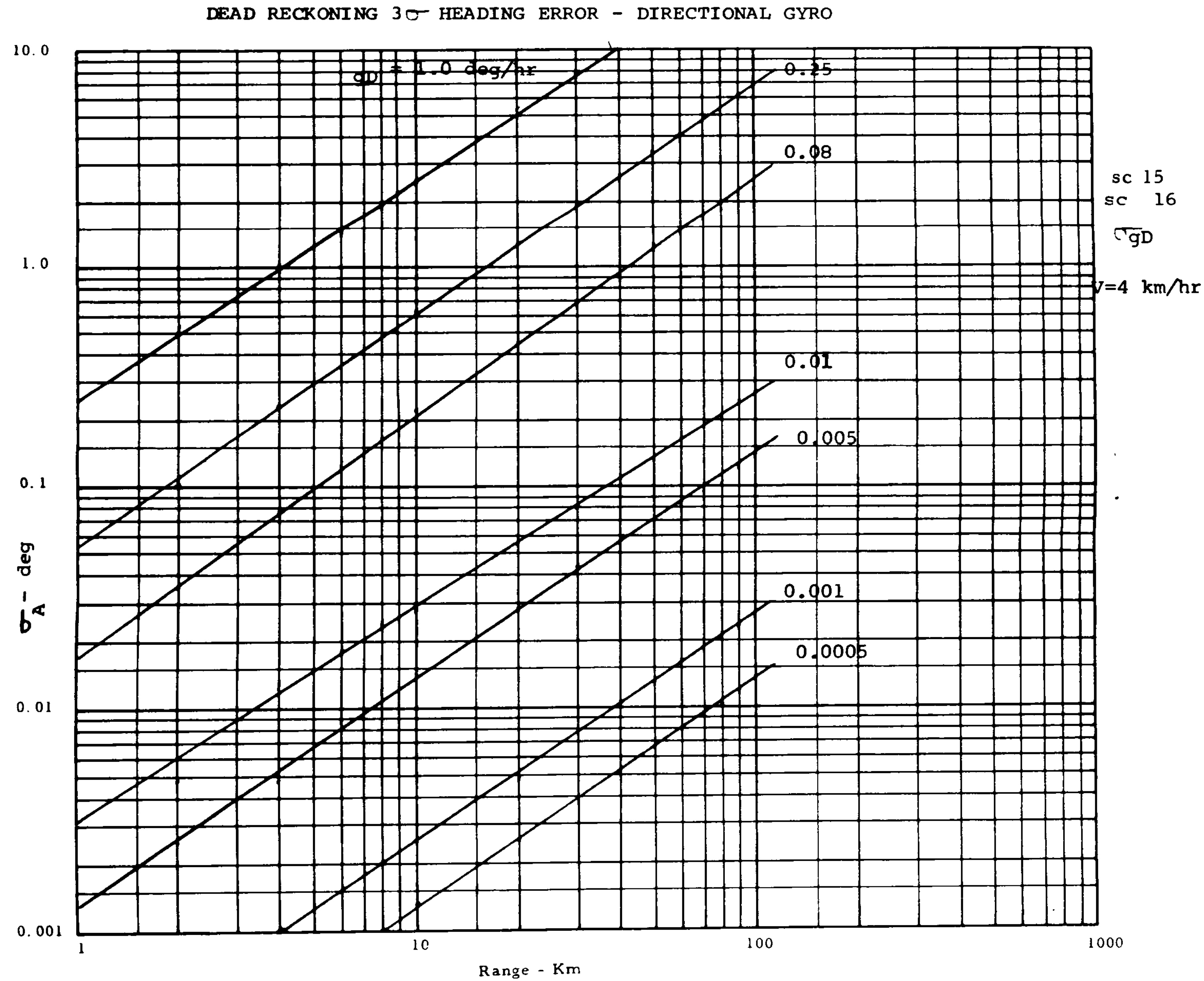


Figure 10-154 Dead Reckoning 3σ Heading Error — Directional Gyro

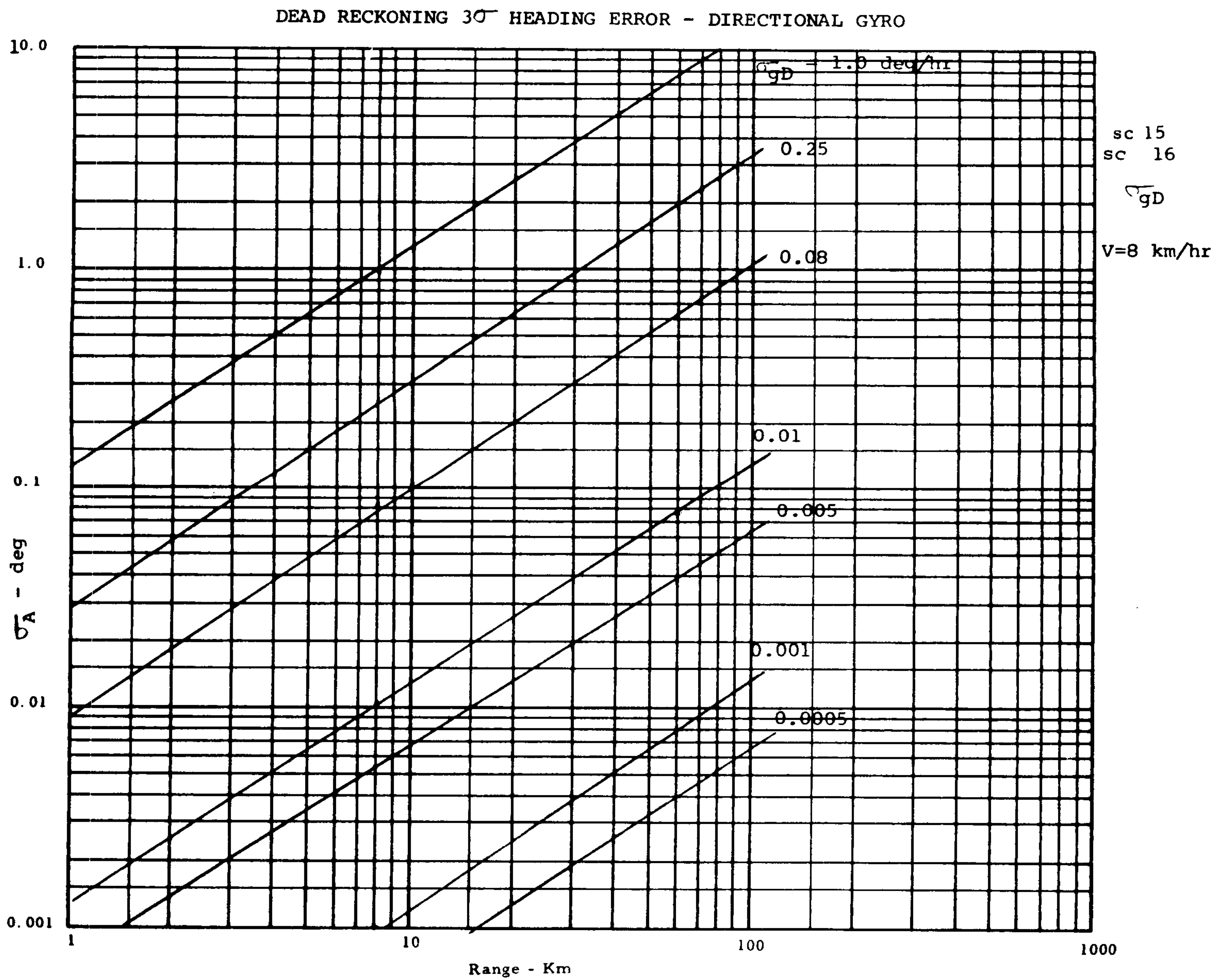


Figure 10-155 Dead Reckoning 3σ Heading Error — Directional Gyro

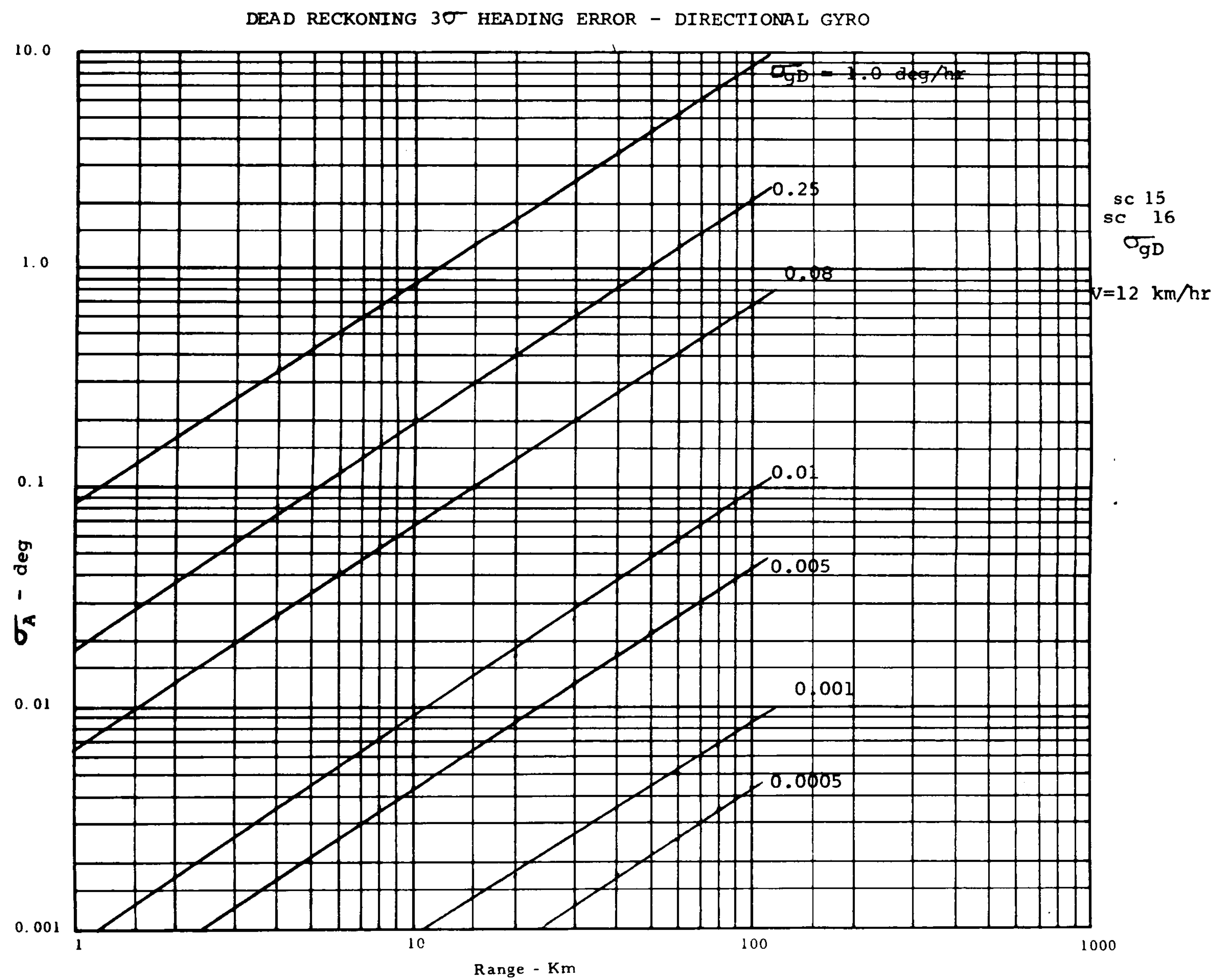


Figure 10-156 Dead Reckoning 3σ Heading Error — Directional Gyro

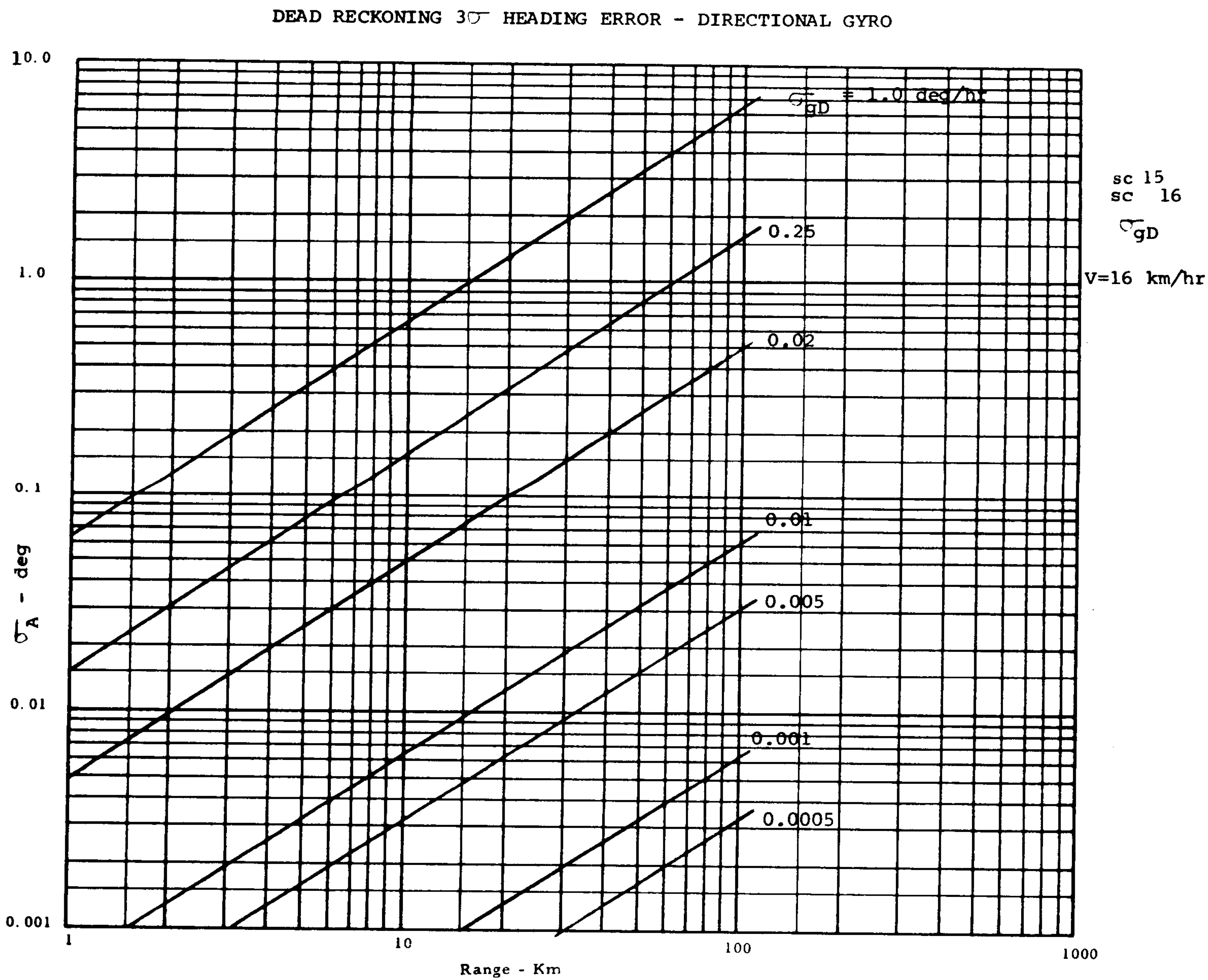


Figure 10-157 Dead Reckoning 3σ Heading Error — Directional Gyro

DEAD RECKONING 3σ POSITION ERROR - ACCELEROMETER

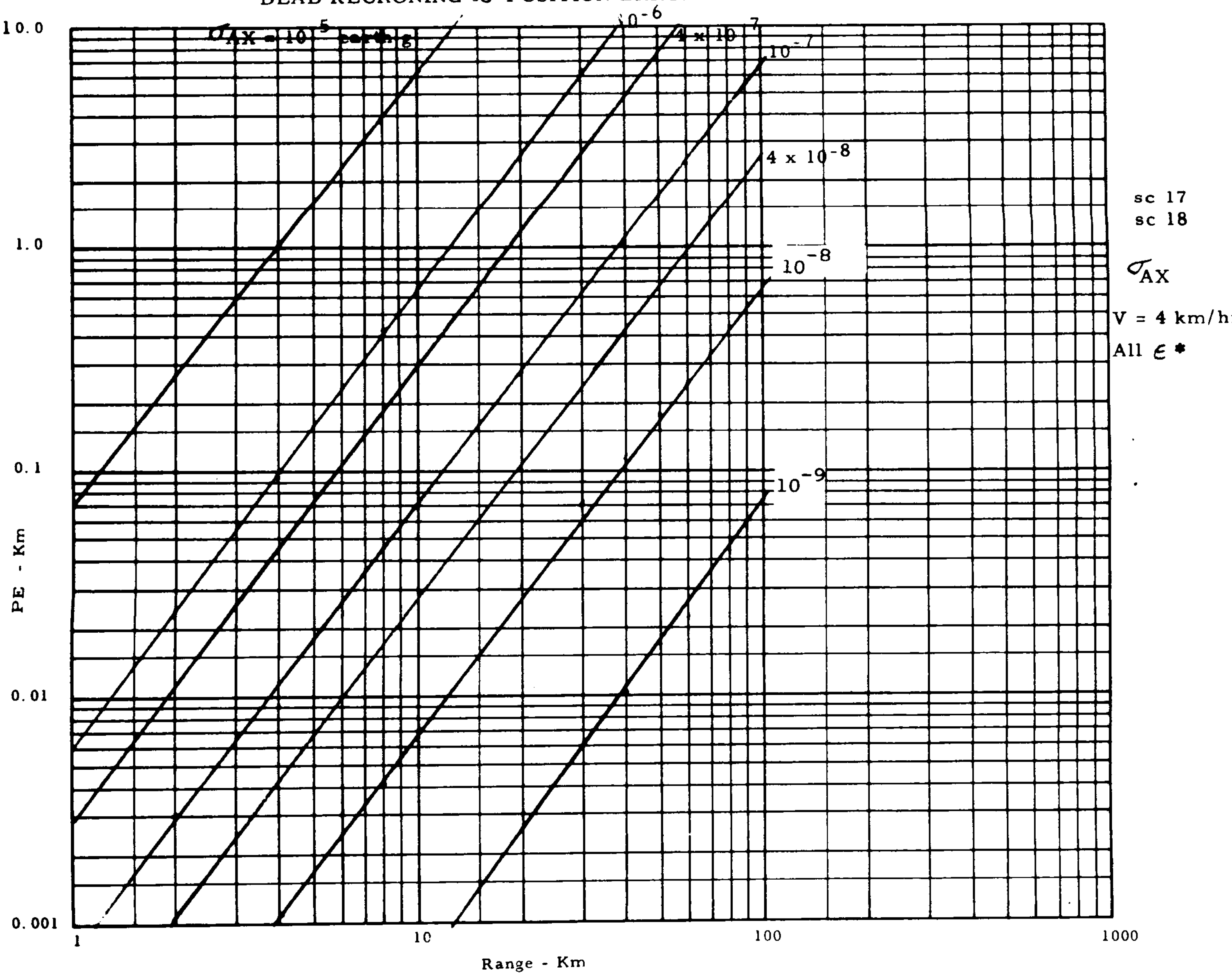


Figure 10-158 Dead Reckoning 3σ Position Error — Accelerometer

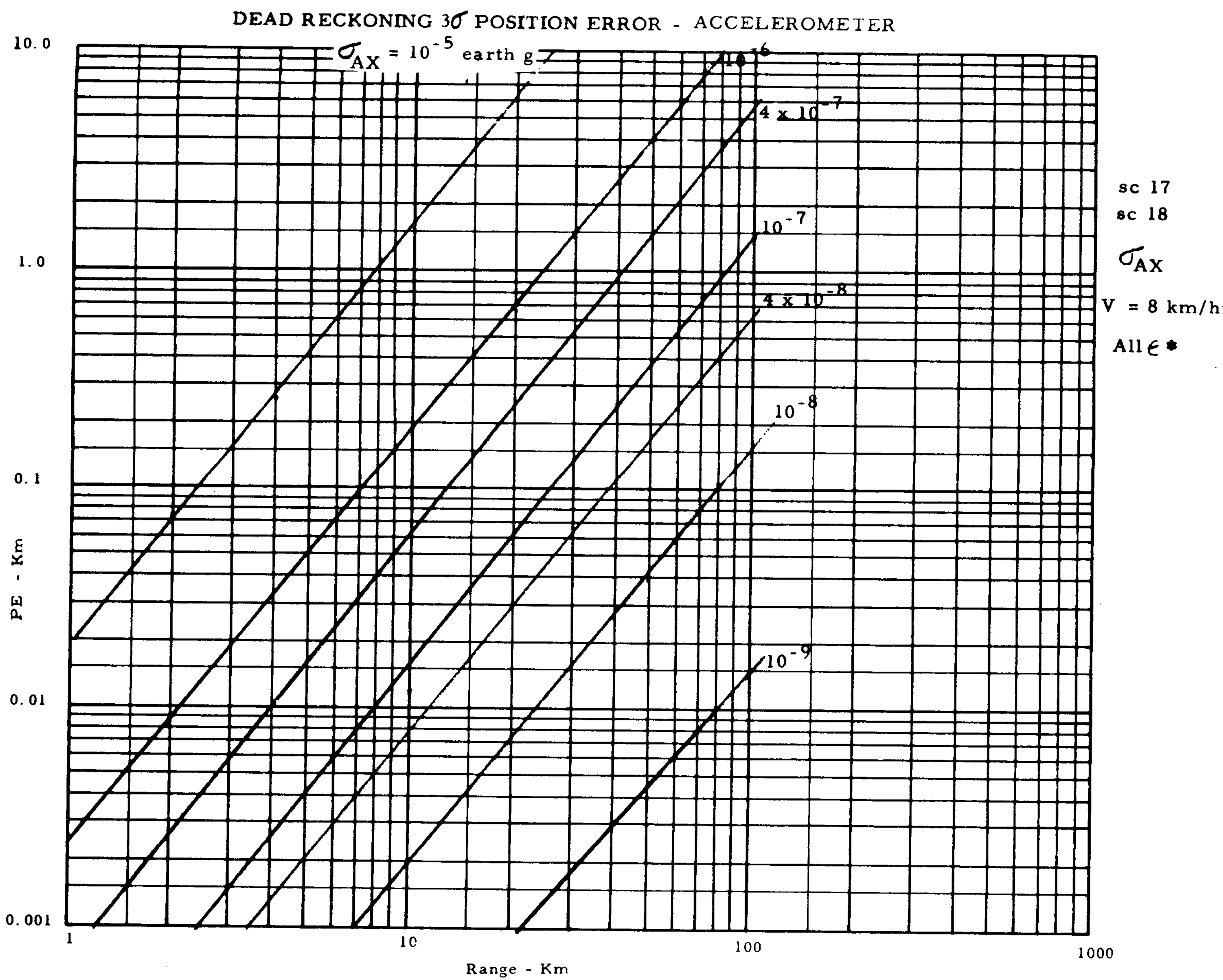


Figure 10-159 Dead Reckoning 3σ Position Error — Accelerometer

DEAD RECKONING 3σ POSITION ERROR - ACCELEROMETER

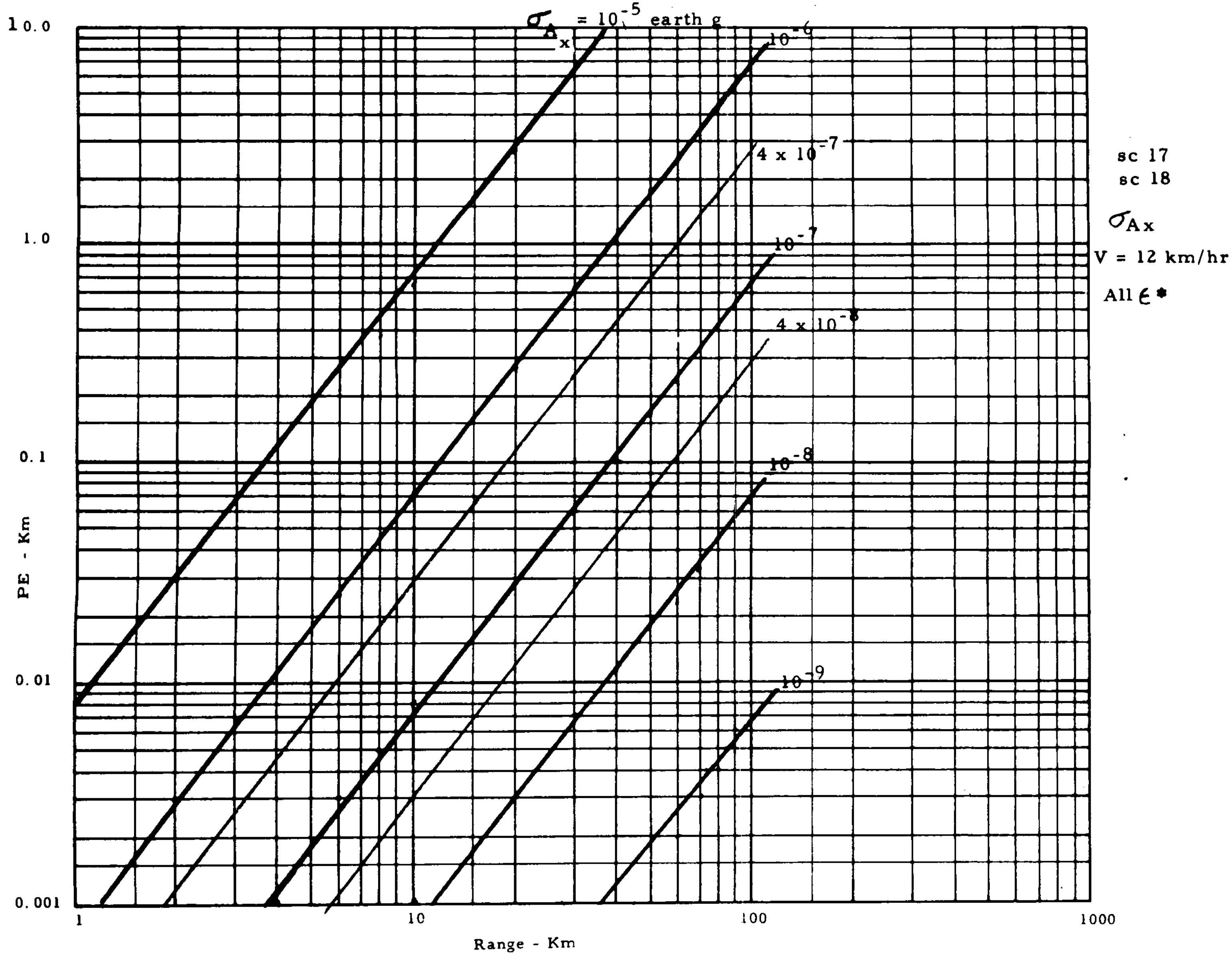


Figure 10-160 Dead Reckoning 3σ Position Error — Accelerometer

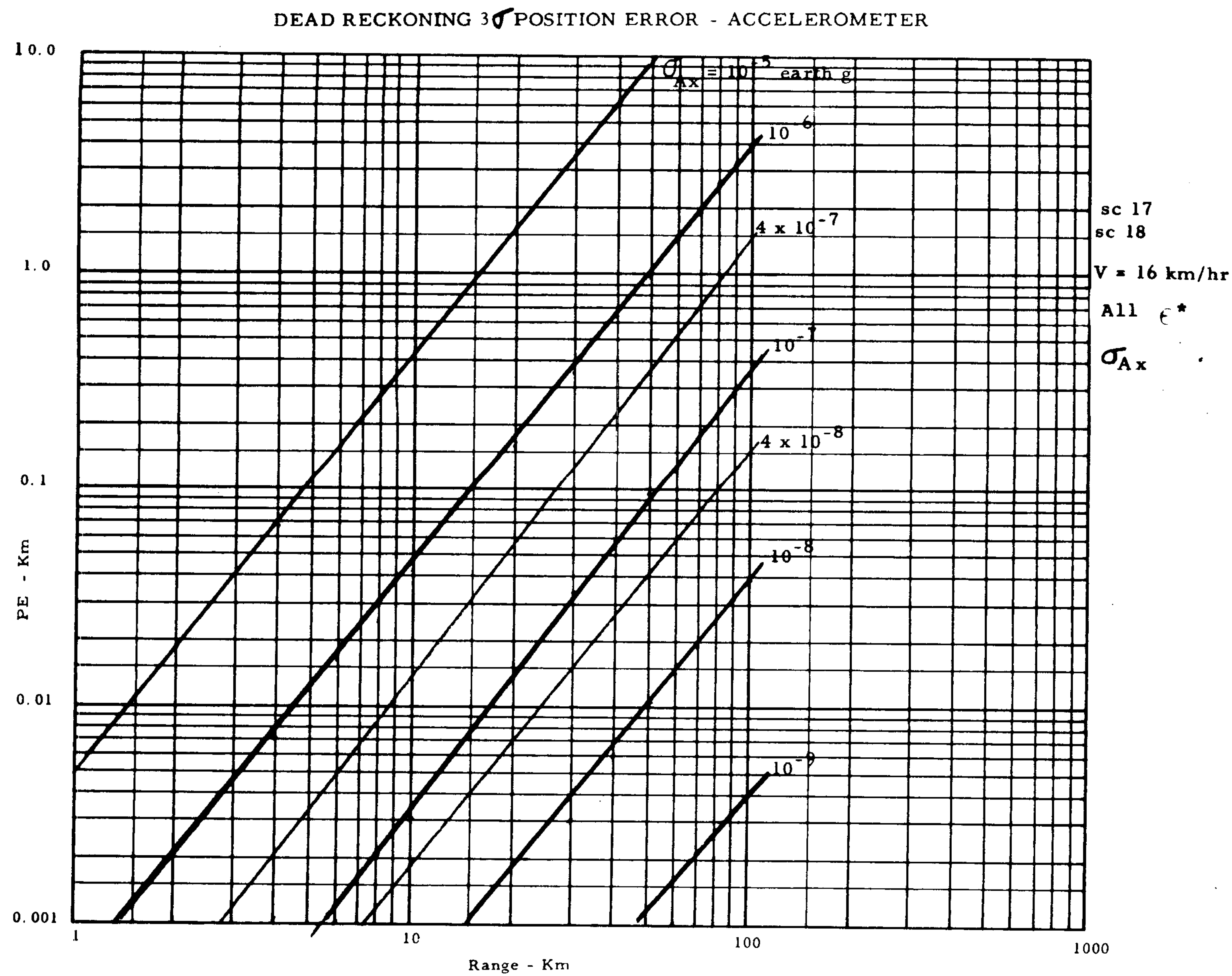


Figure 10-161 Dead Reckoning 3σ Position Error — Accelerometer

DEAD RECKONING 3σ POSITION ERROR - CELESTIAL TRACKER

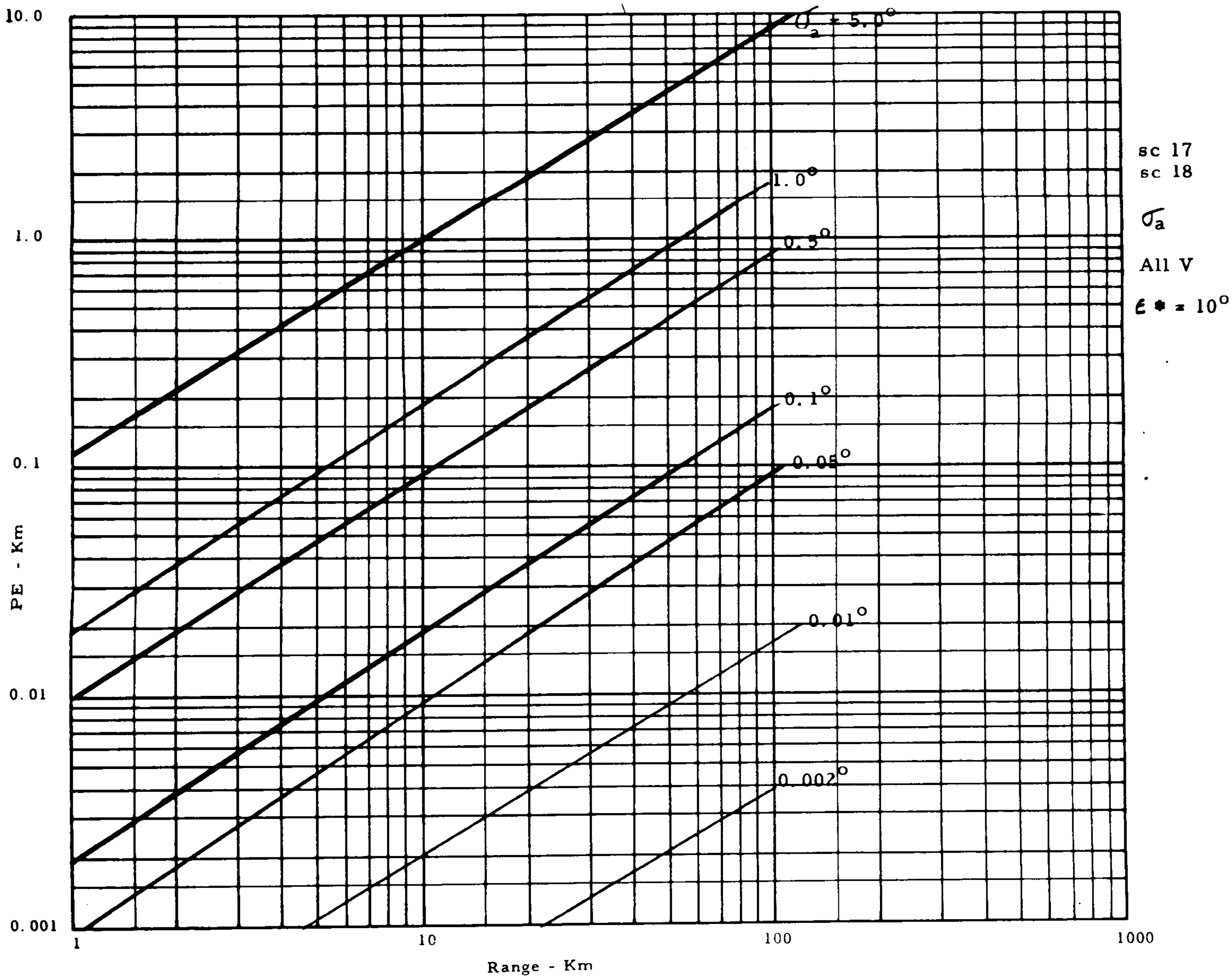


Figure 10-162 Dead Reckoning 3σ Position Error — Celestial Tracker

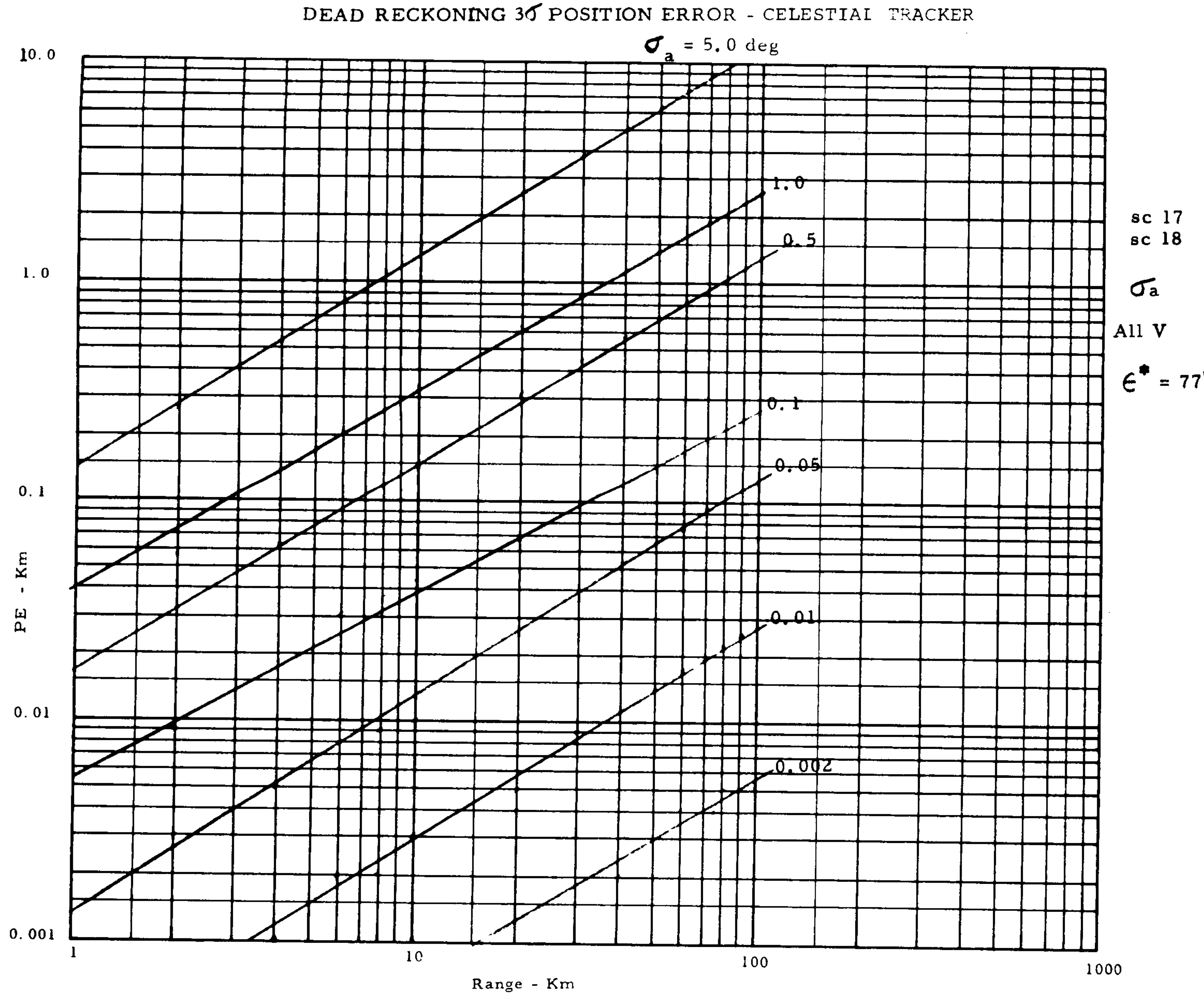


Figure 10-163 Dead Reckoning 3σ Position Error — Celestial Tracker

DEAD RECKONING 3σ POSITION ERROR - CELESTIAL TRACKER

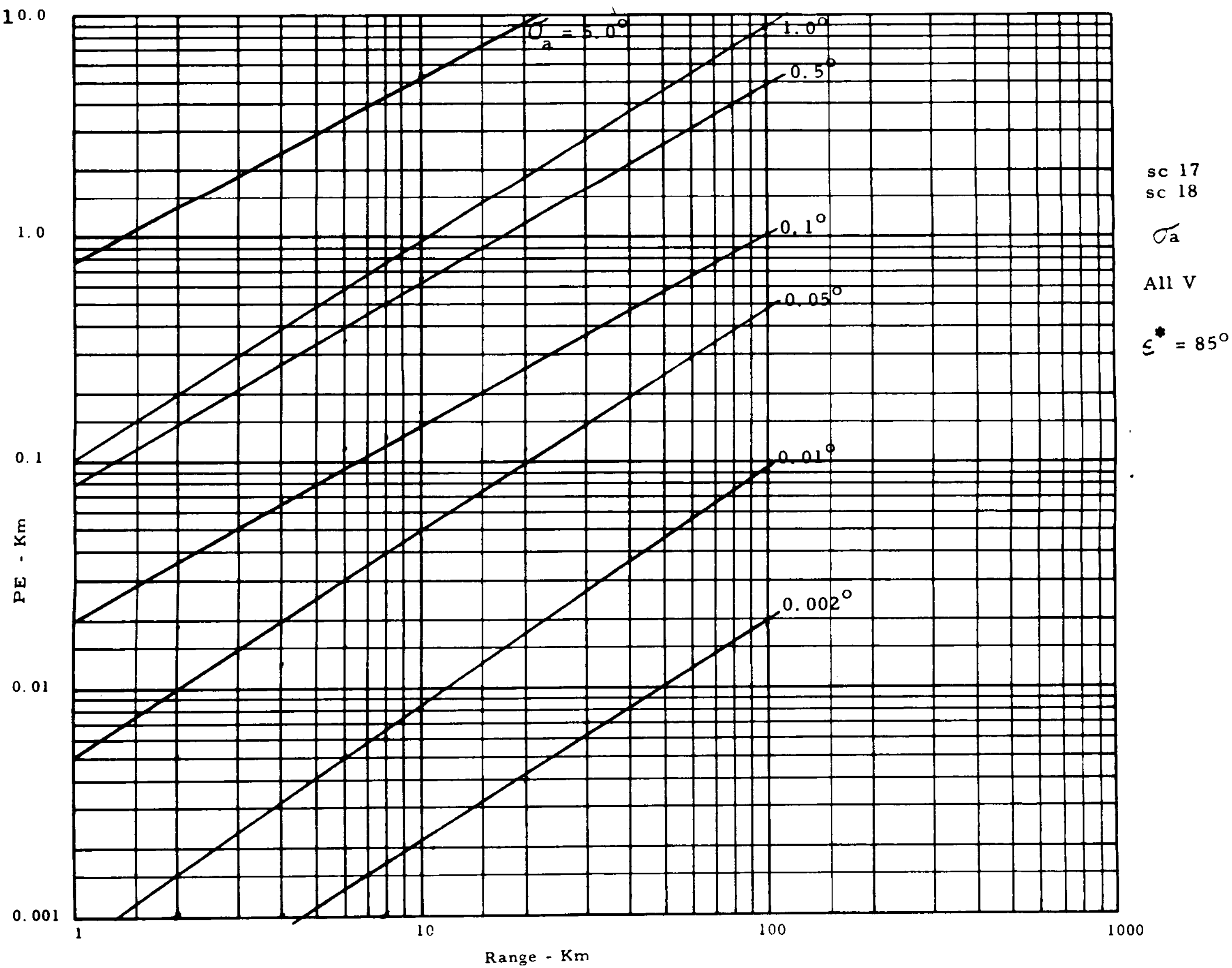


Figure 10-164 Dead Reckoning 3σ Position Error — Celestial Tracker

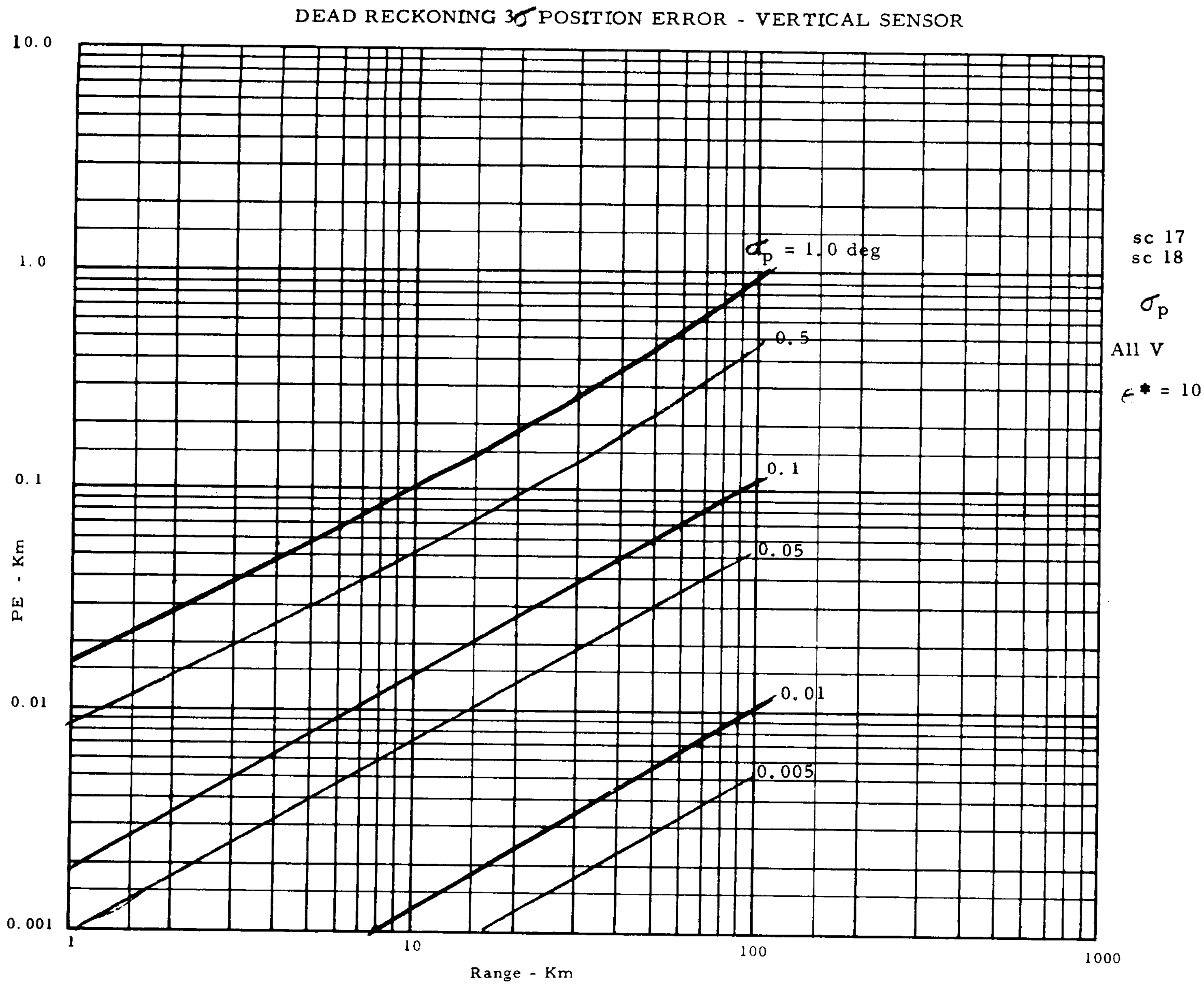


Figure 10-165 Dead Reckoning 3σ Position Error — Vertical Sensor

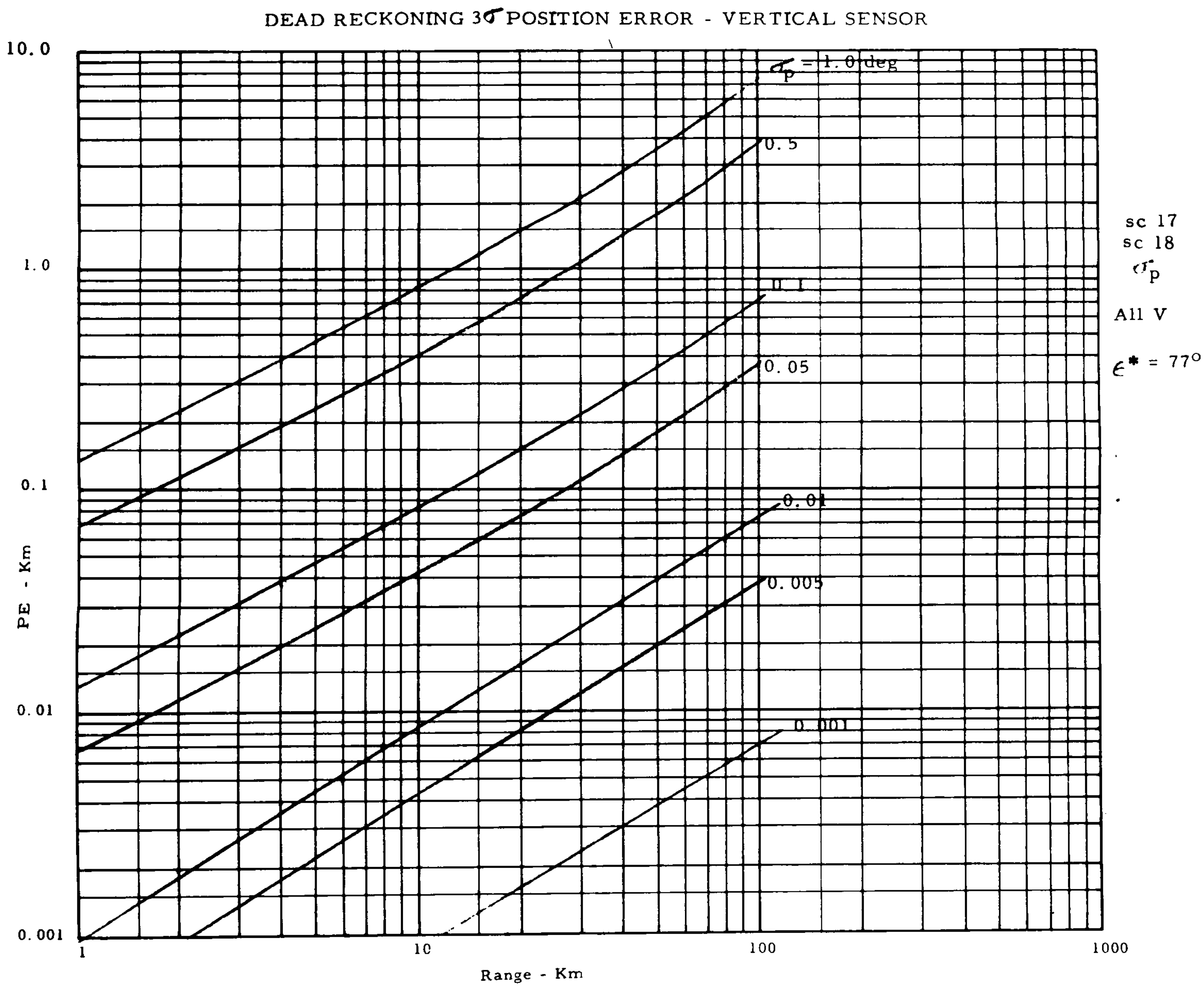


Figure 10-166 Dead Reckoning 3σ Position Error — Vertical Sensor

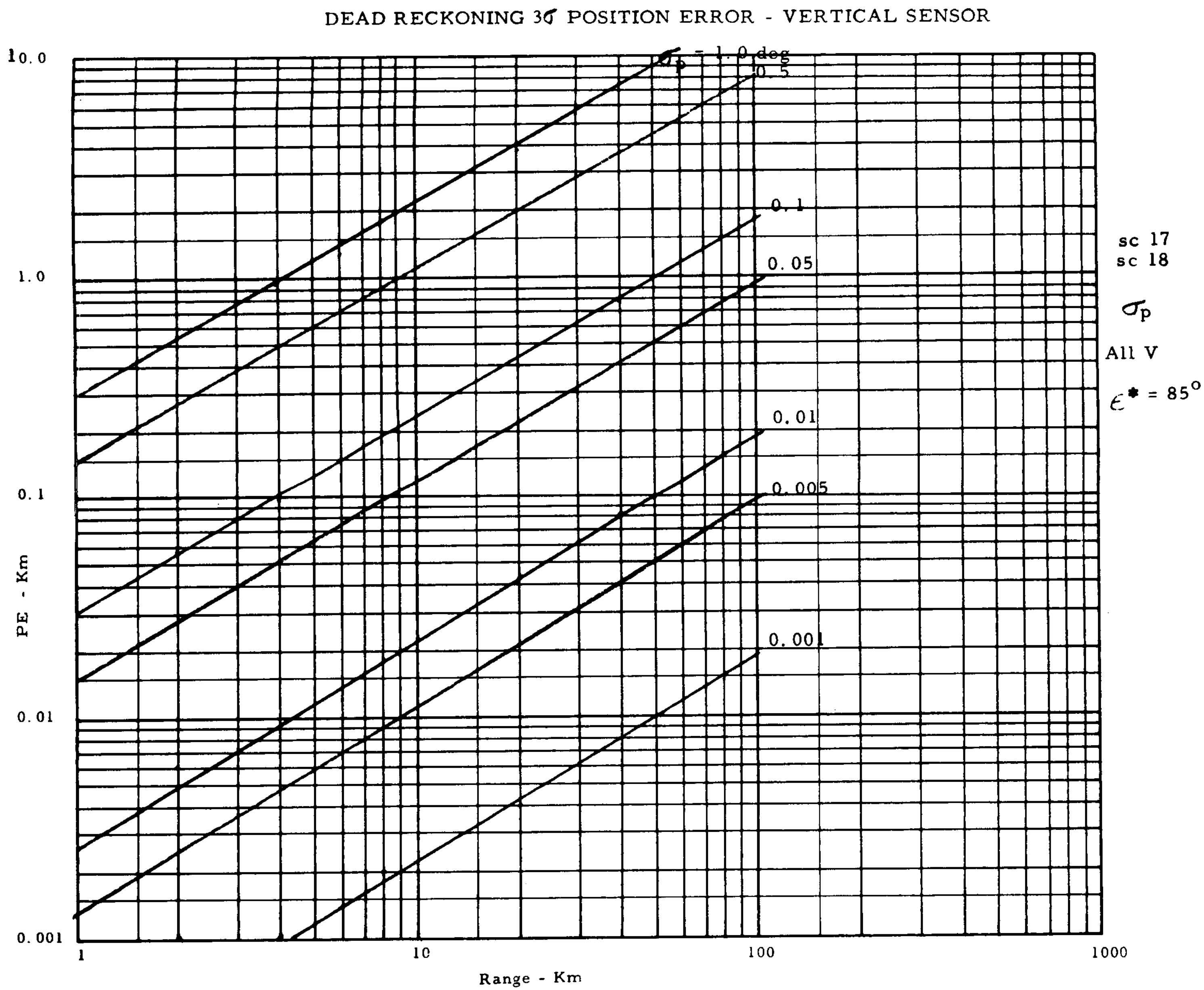


Figure 10-167 Dead Reckoning 3σ Position Error — Vertical Sensor

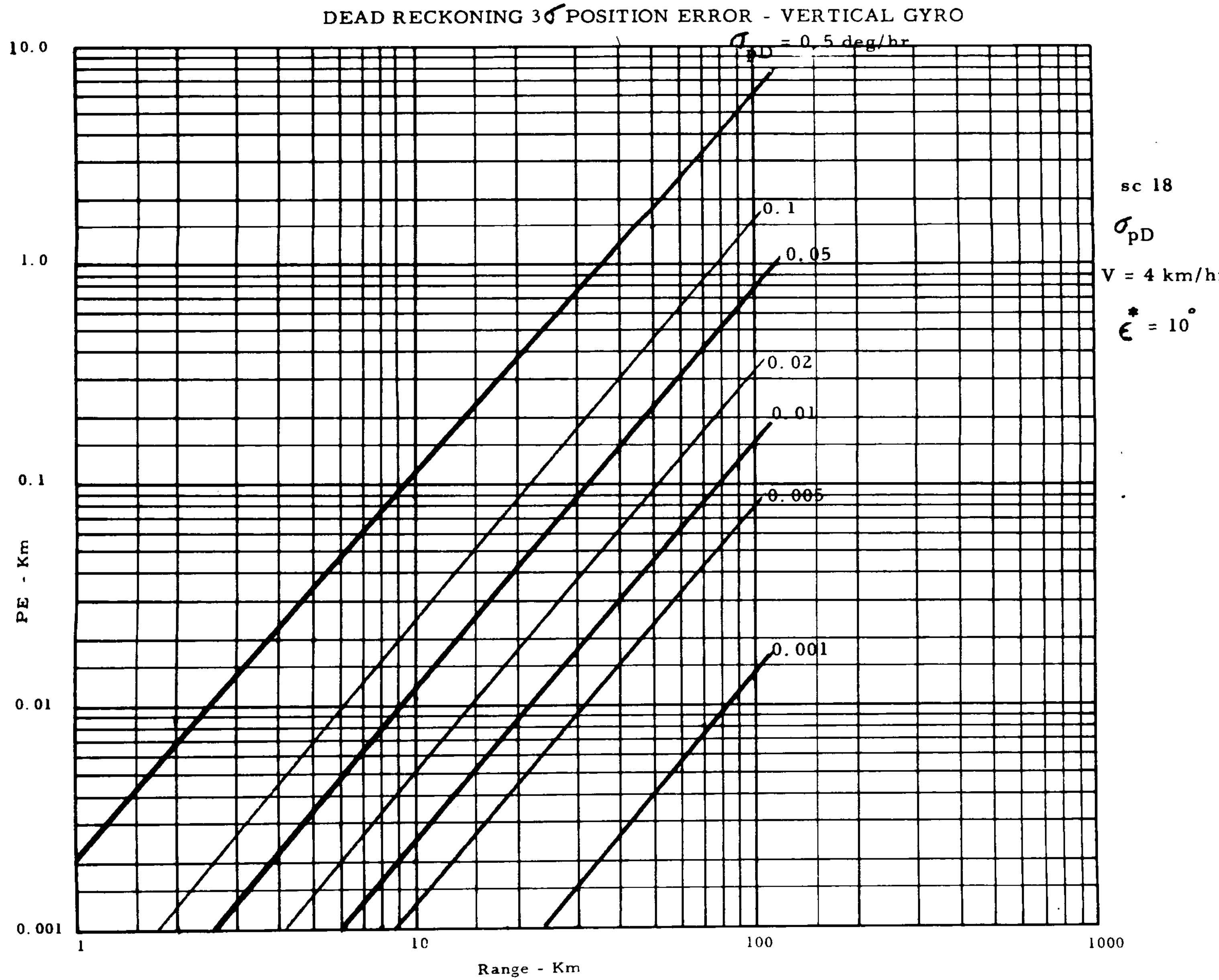


Figure 10-168 Dead Reckoning 3σ Position Error — Vertical Gyro

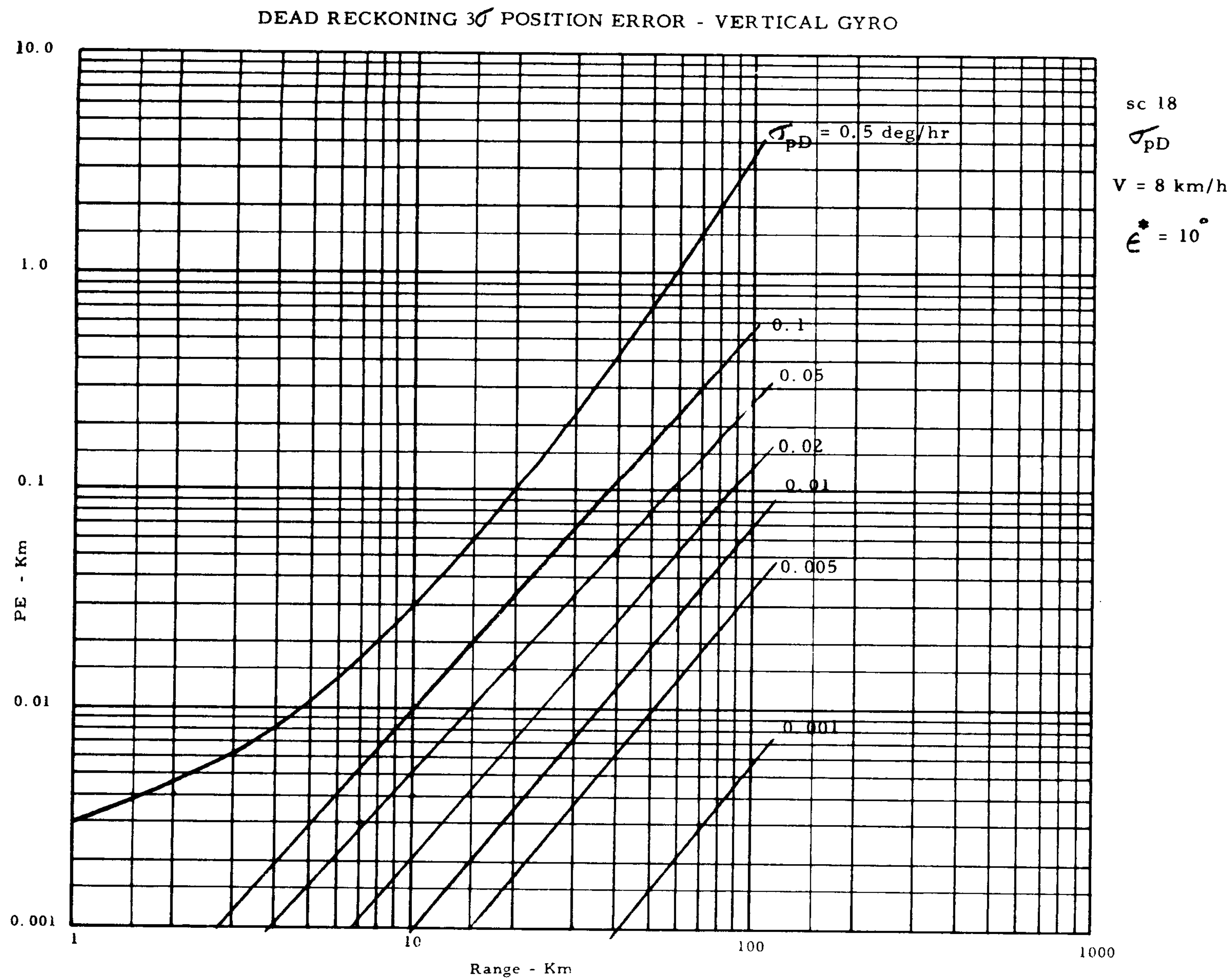


Figure 10-169 Dead Reckoning 3σ Position Error — Vertical Gyro

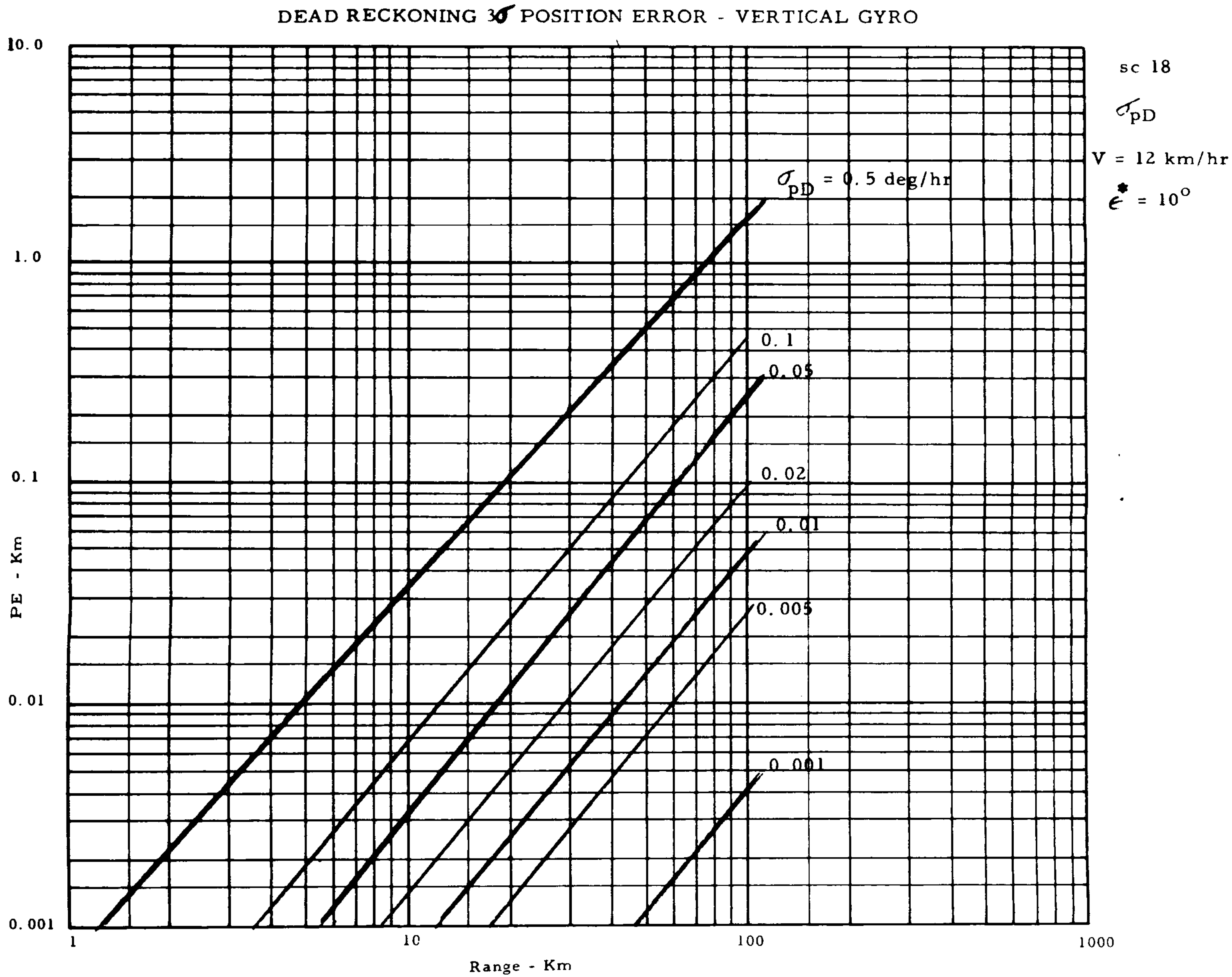


Figure 10-170 Dead Reckoning 3σ Position Error — Vertical Gyro

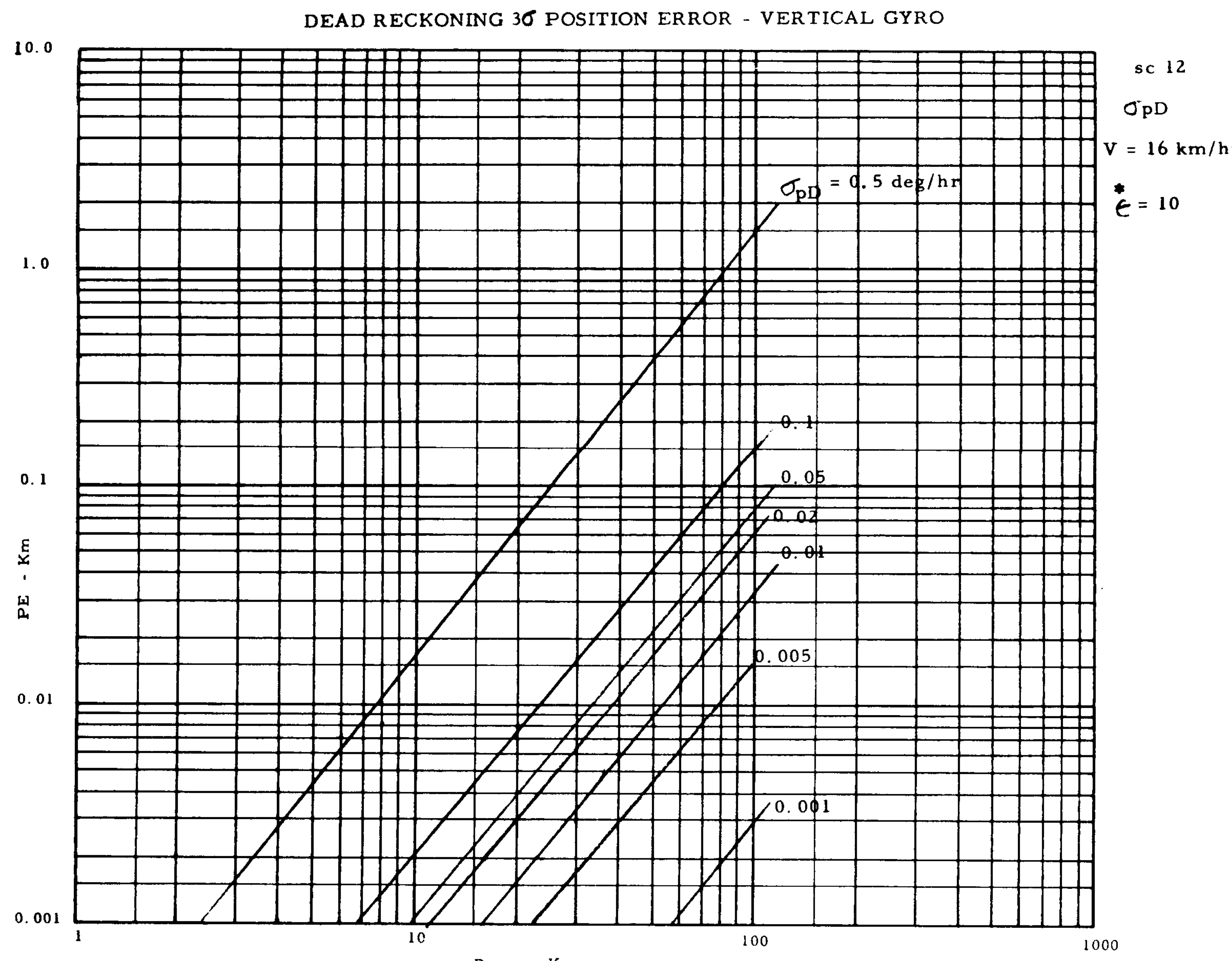


Figure 10-171 Dead Reckoning 3σ Position Error — Vertical Gyro

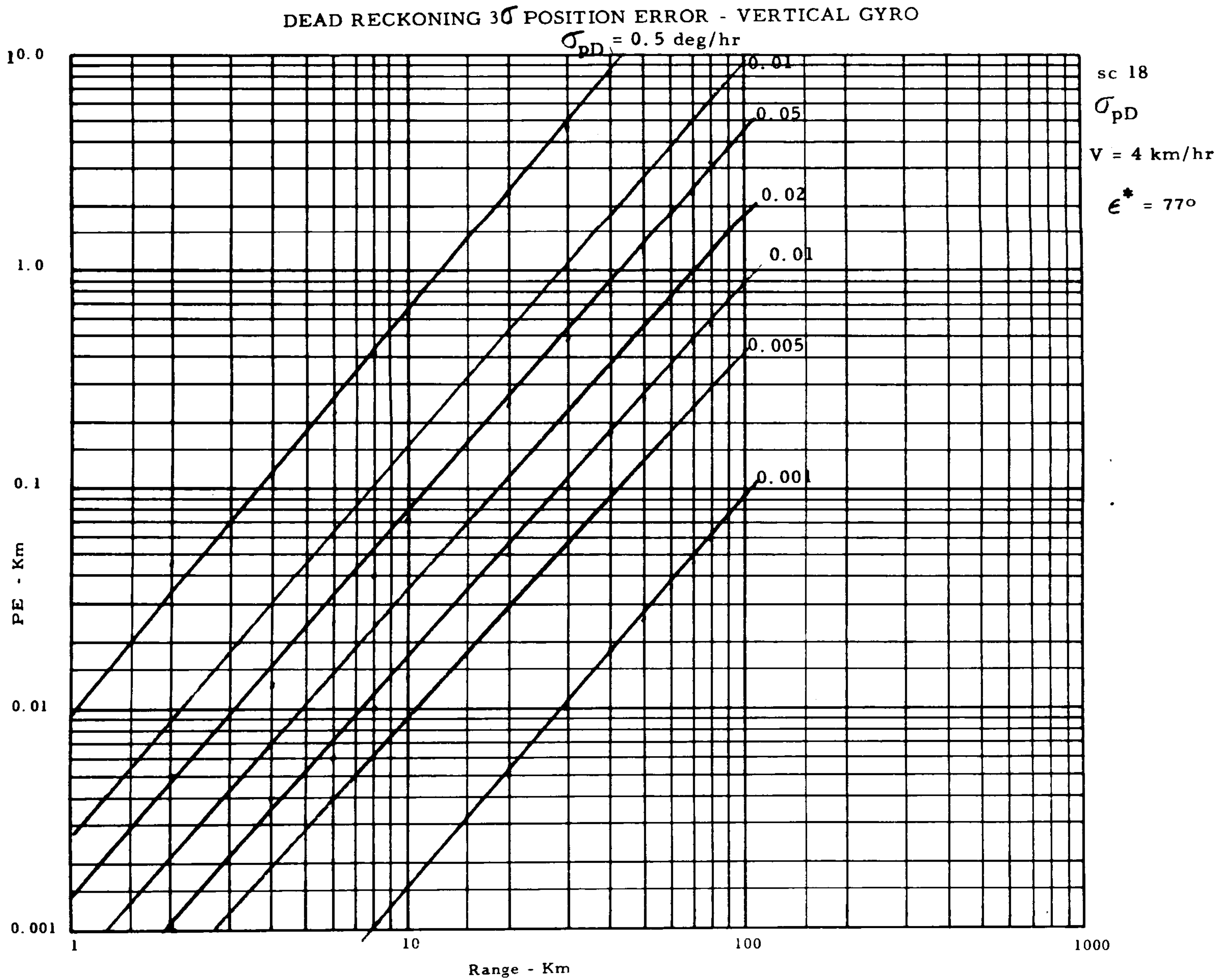


Figure 10-172 Dead Reckoning 3σ Position Error — Vertical Gyro

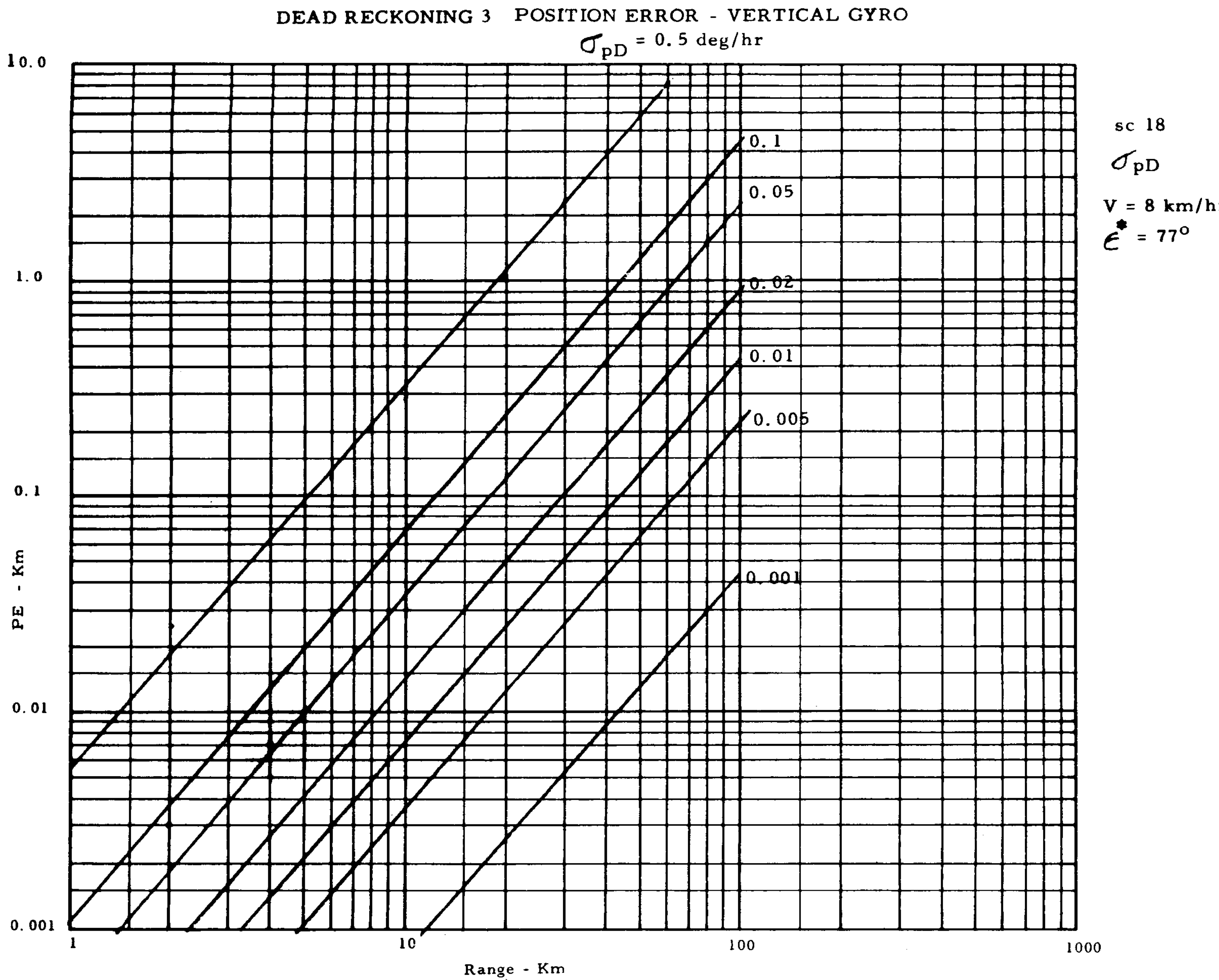


Figure 10-173 Dead Reckoning 3σ Position Error — Vertical Gyro

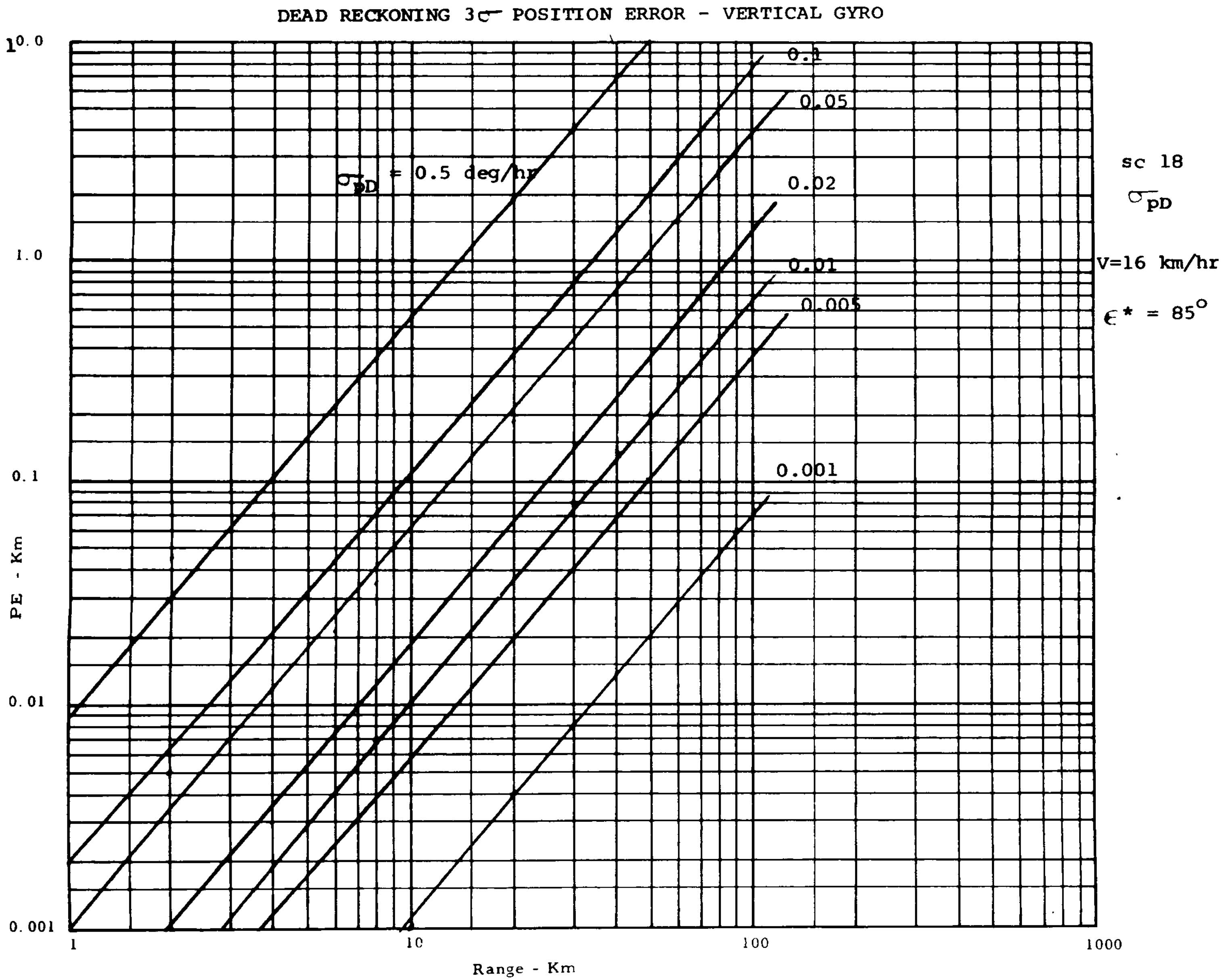


Figure 10-174 Dead Reckoning 3σ Position Error — Vertical Gyro

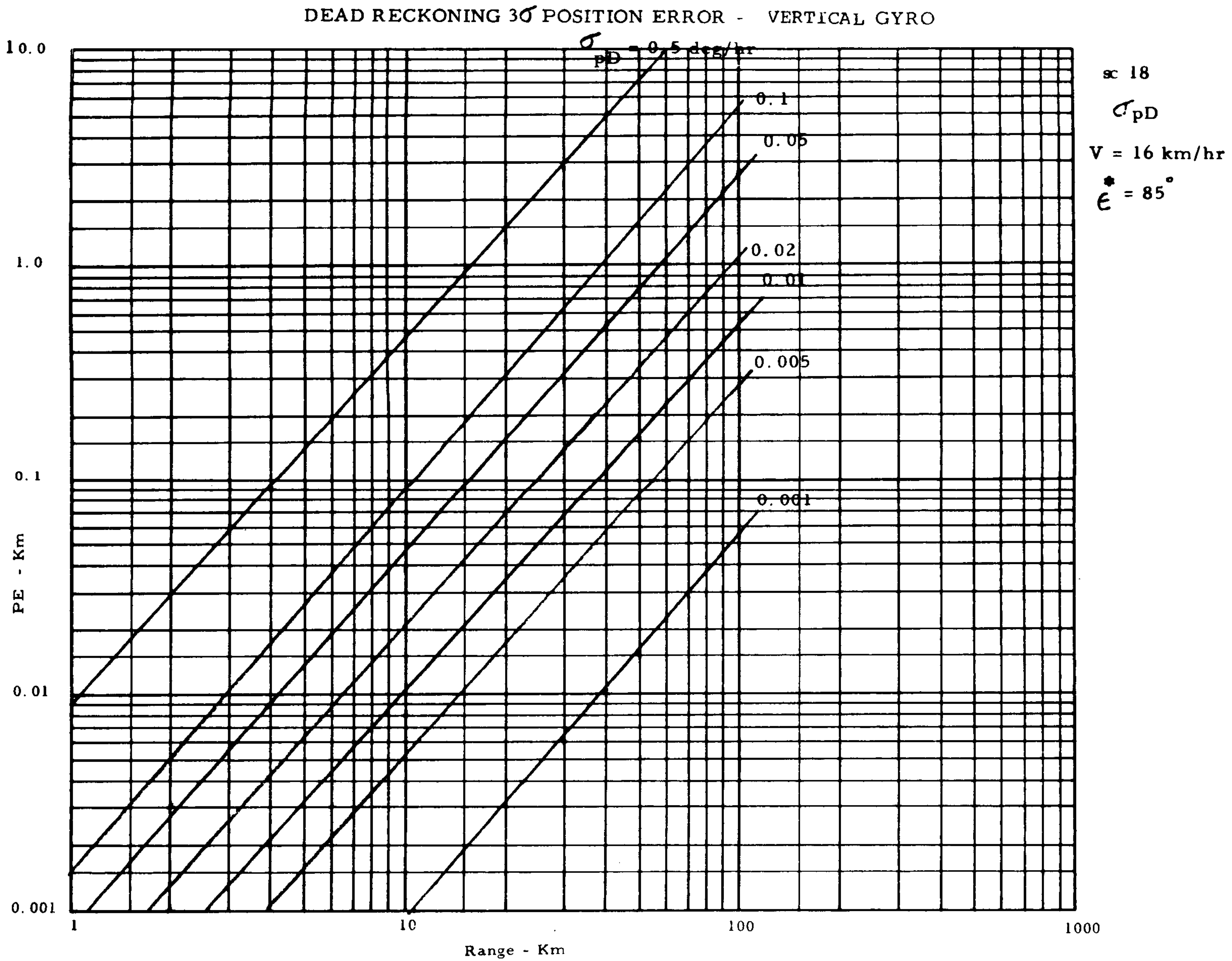


Figure 10-175 Dead Reckoning 3σ Position Error — Vertical Gyro

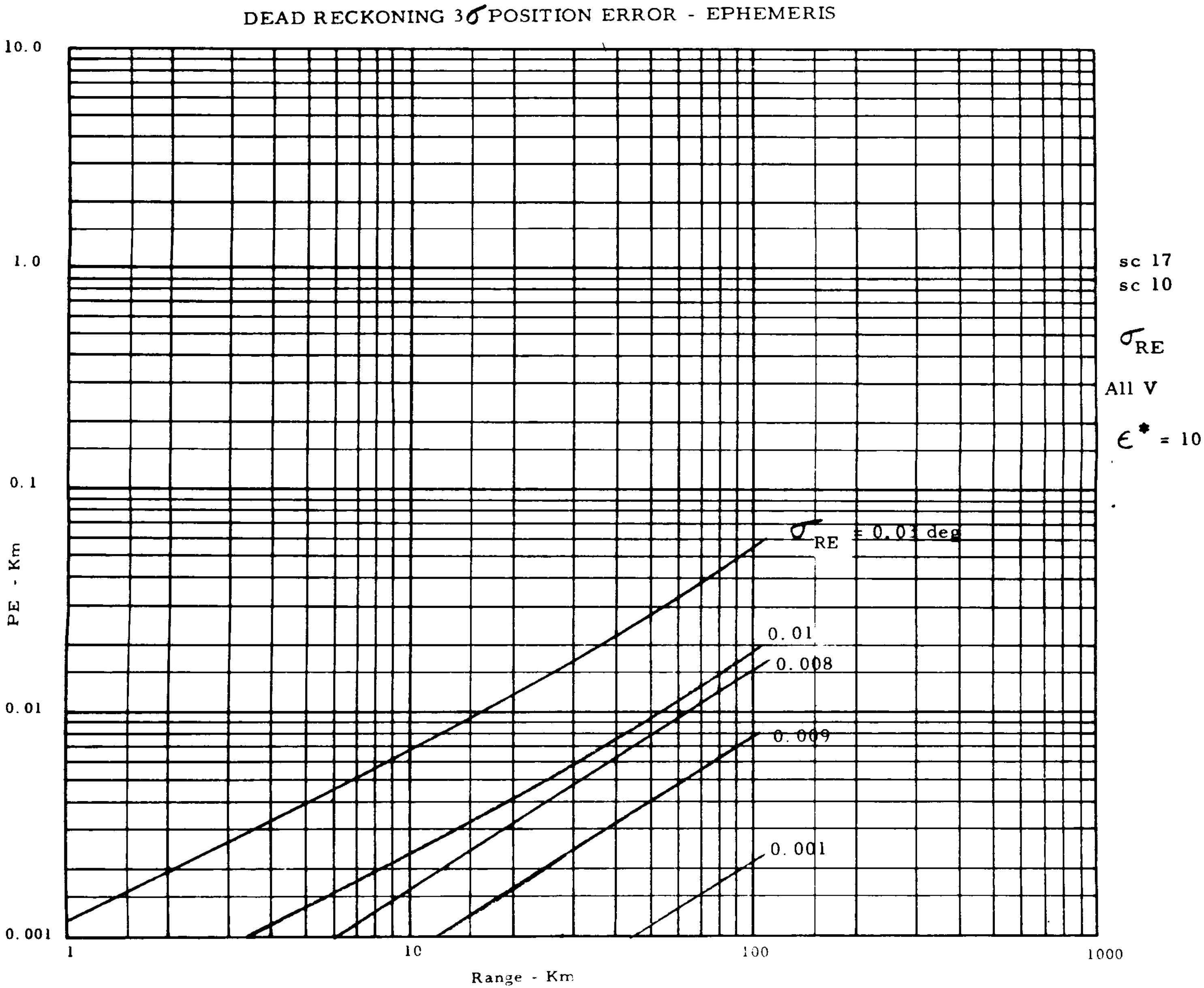


Figure 10-176 Dead Reckoning 3σ Position Error — Ephemeris

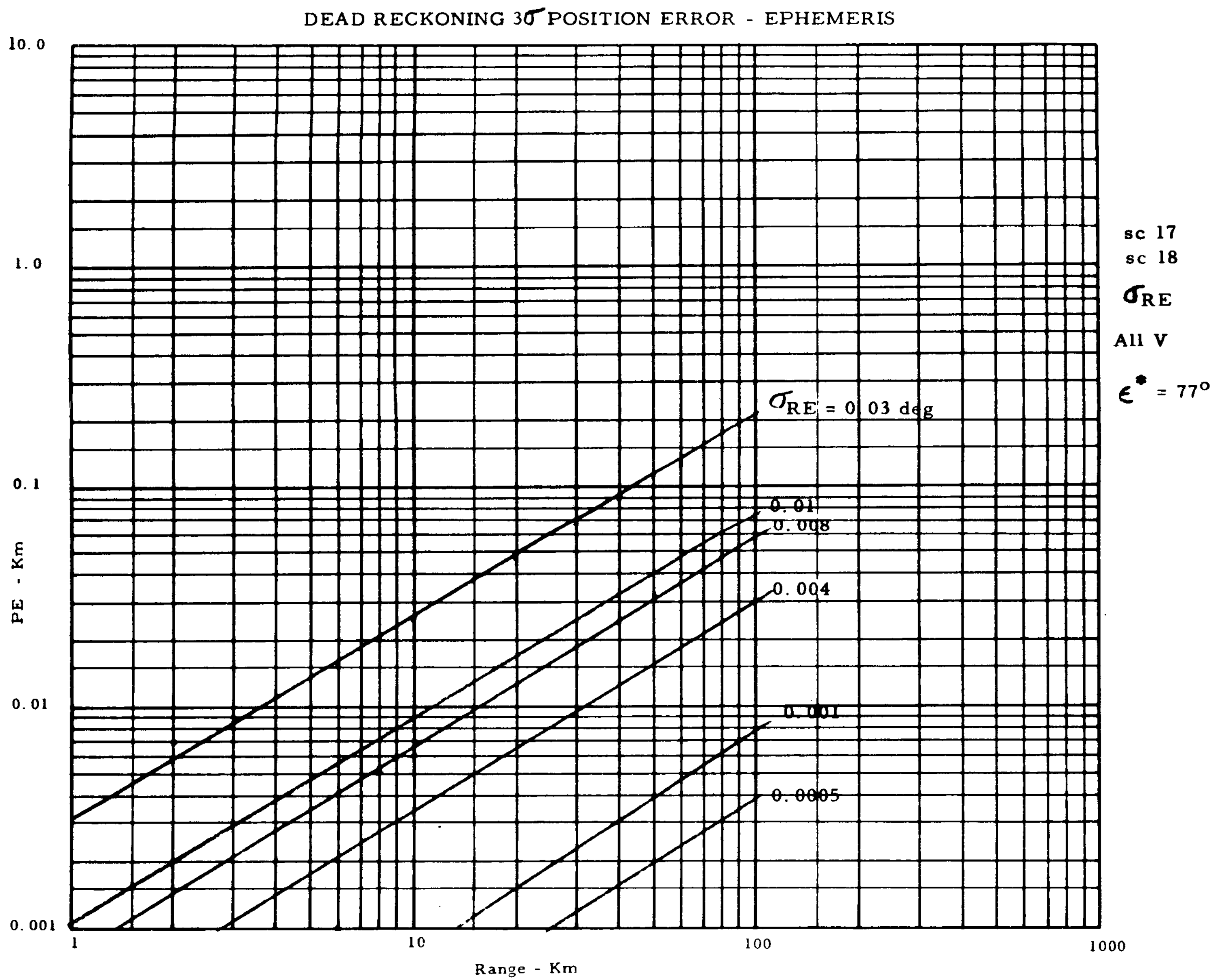


Figure 10-177 Dead Reckoning 3σ Position Error — Ephemeris

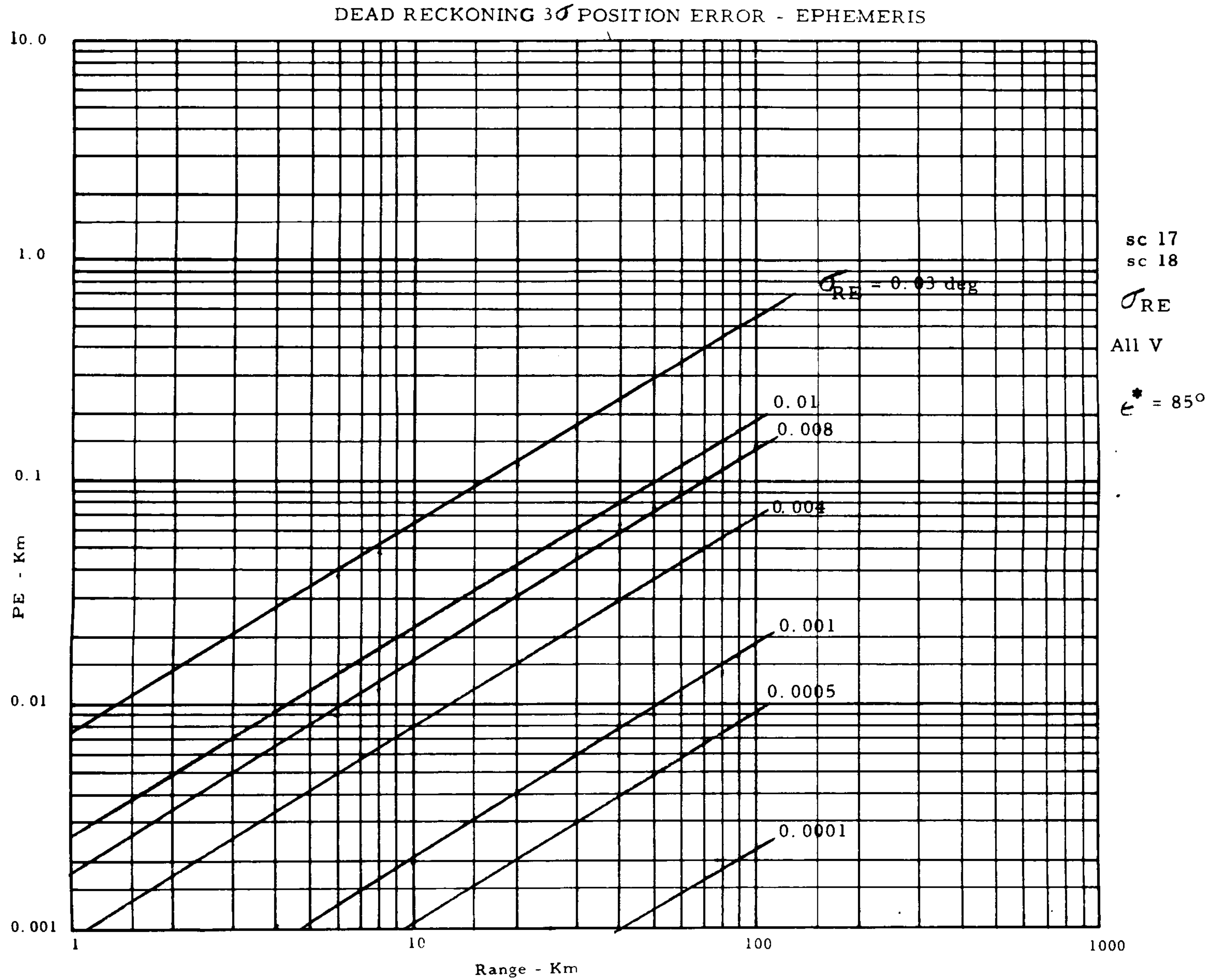


Figure 10-178 Dead Reckoning 3σ Position Error — Ephemeris

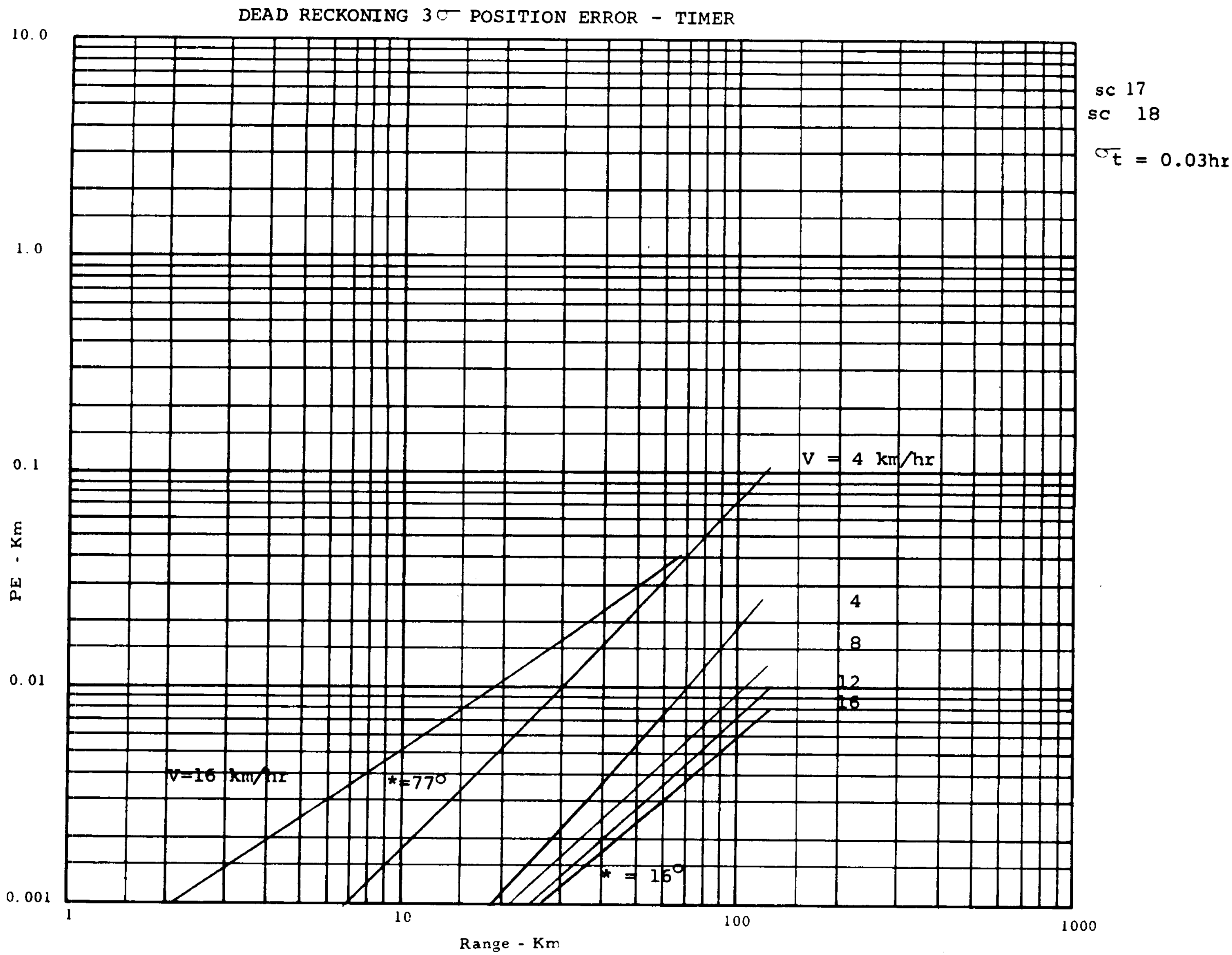


Figure 10-179 Dead Reckoning 3σ Position Error — Timer

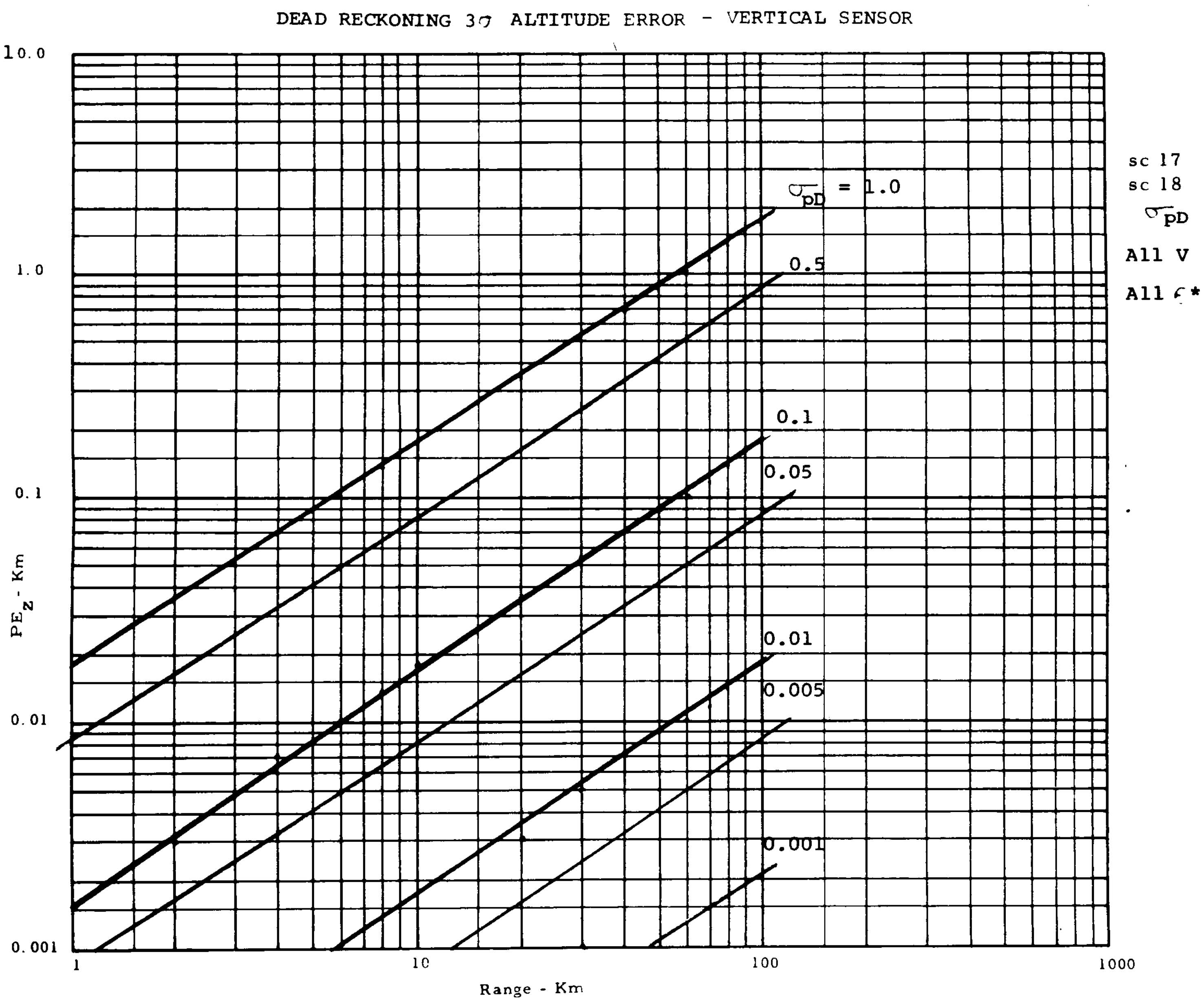


Figure 10-180 Dead Reckoning 3σ Position Error — Vertical Sensor

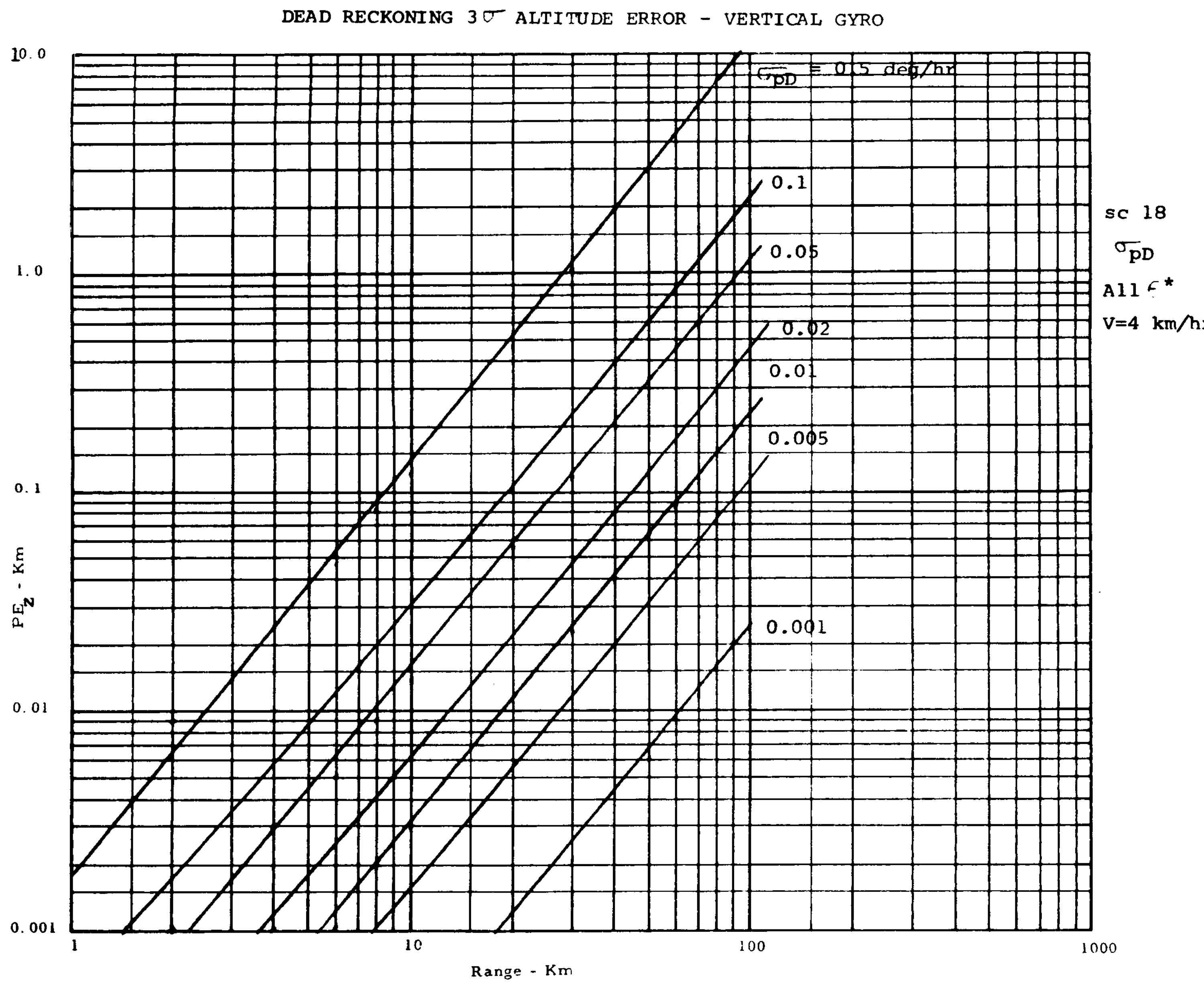


Figure 10-181 Dead Reckoning 3σ Altitude Error — Vertical Gyro

DEAD RECKONING 3σ ALTITUDE ERROR - VERTICAL GYRO

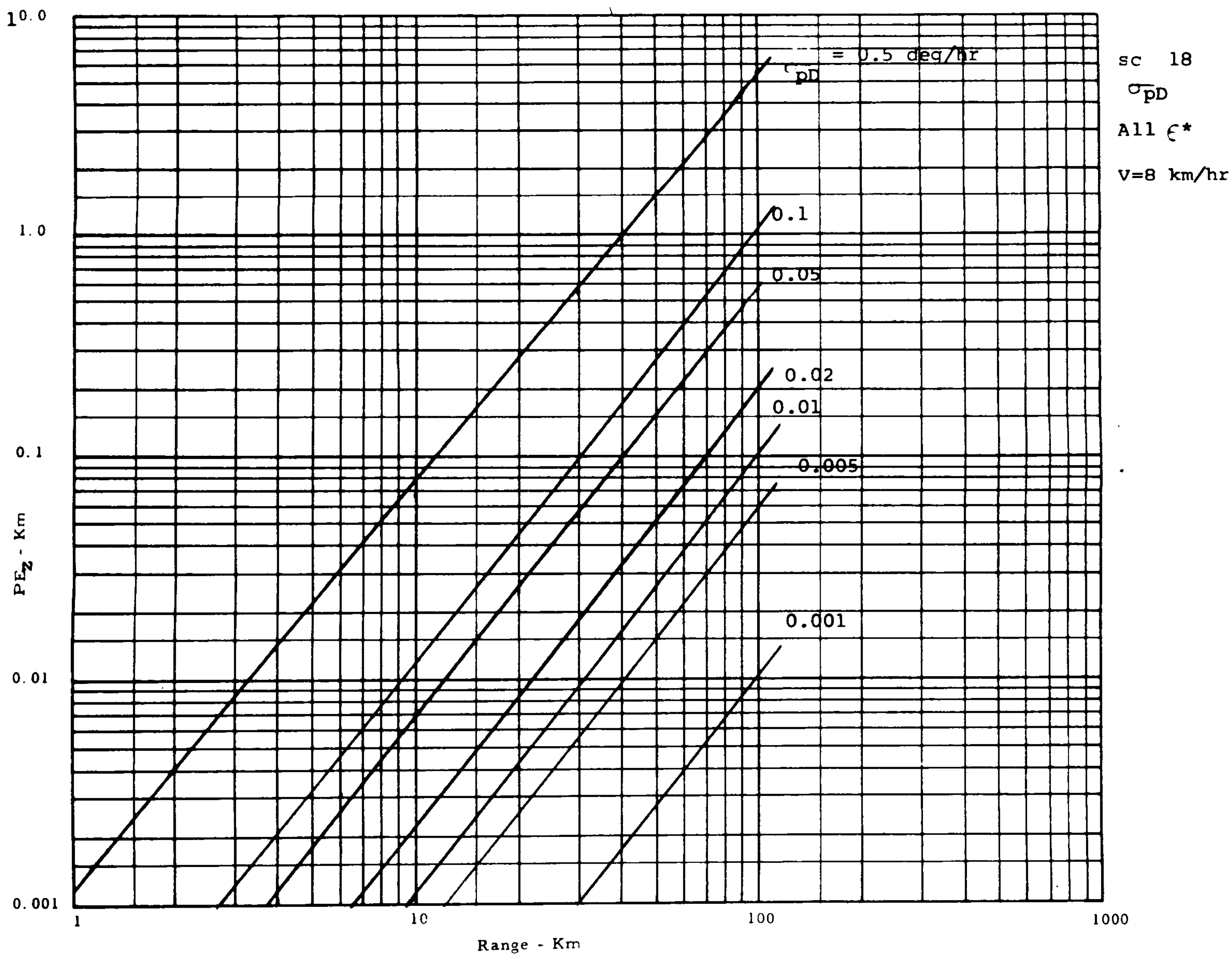


Figure 10-182 Dead Reckoning 3σ Altitude Error — Vertical Gyro

DEAD RECKONING 3σ ALTITUDE ERROR - VERTICAL GYRO

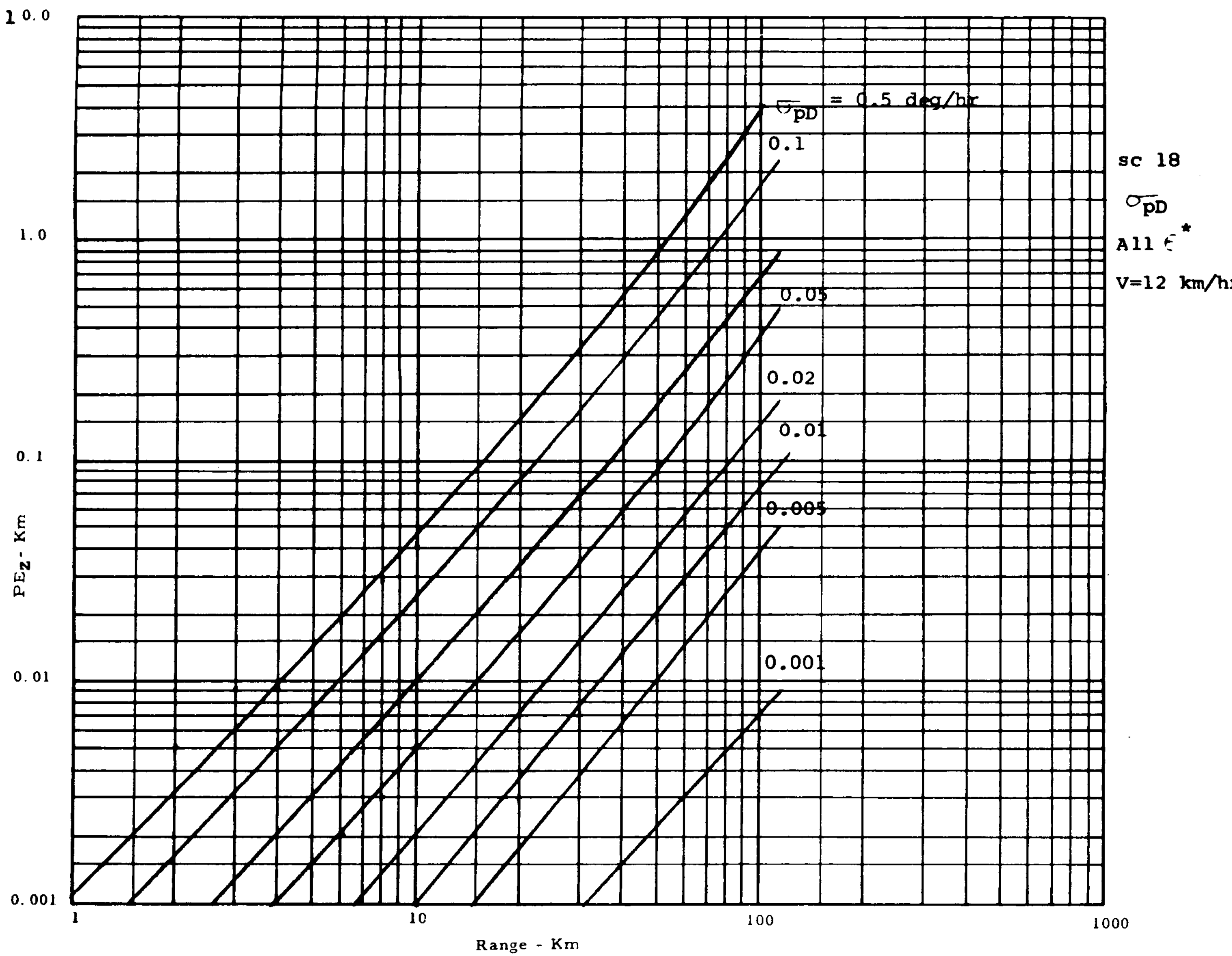


Figure 10-183 Dead Reckoning 3σ Altitude Error — Vertical Gyro

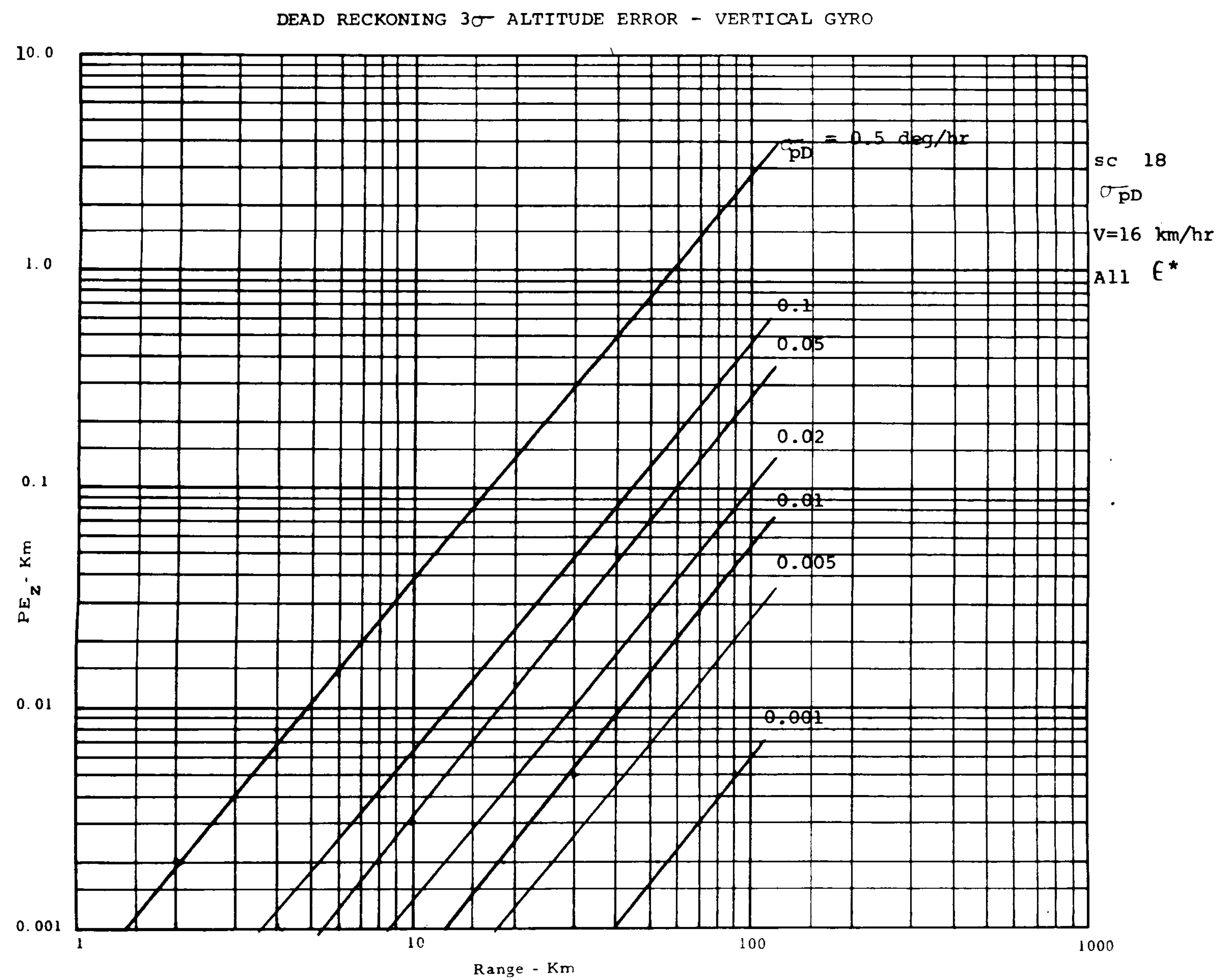


Figure 10-184 Dead Reckoning 3σ Altitude Error — Vertical Gyro

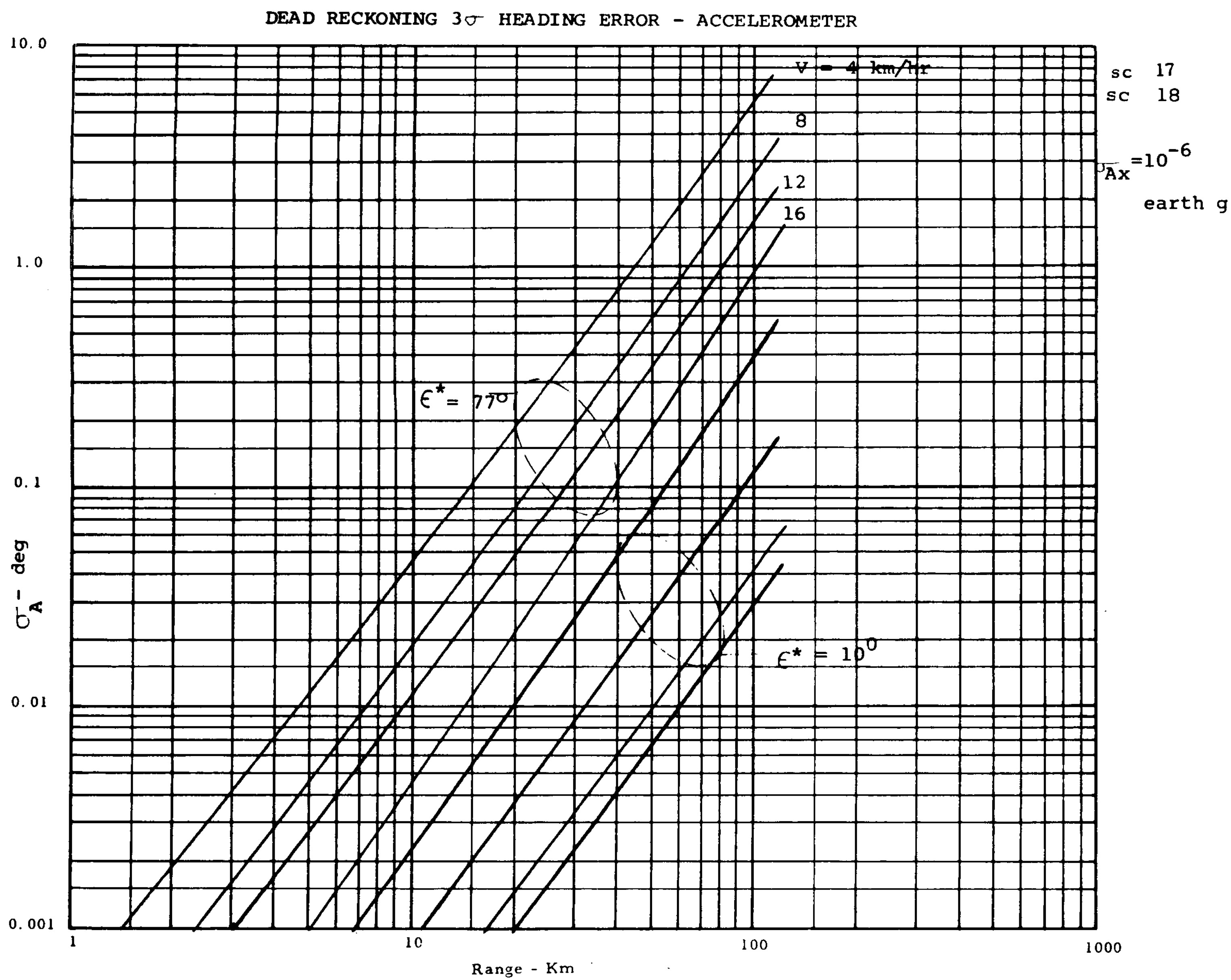


Figure 10-185 Dead Reckoning 3σ Heading Error — Accelerometer

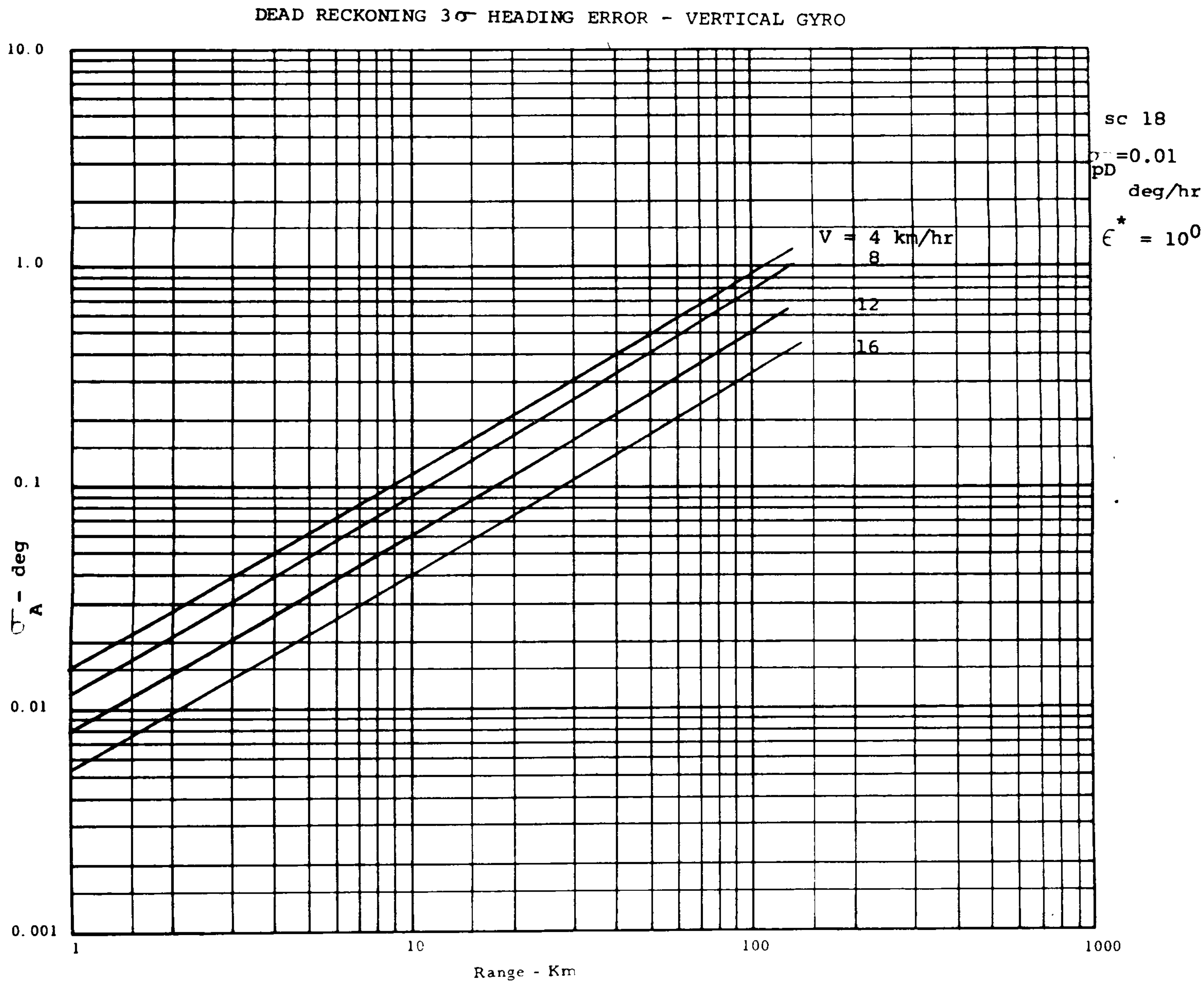


Figure 10-186 Dead Reckoning 3σ Heading Error — Vertical Gyro

DEAD RECKONING 3σ HEADING ERROR - EPHEMERIS

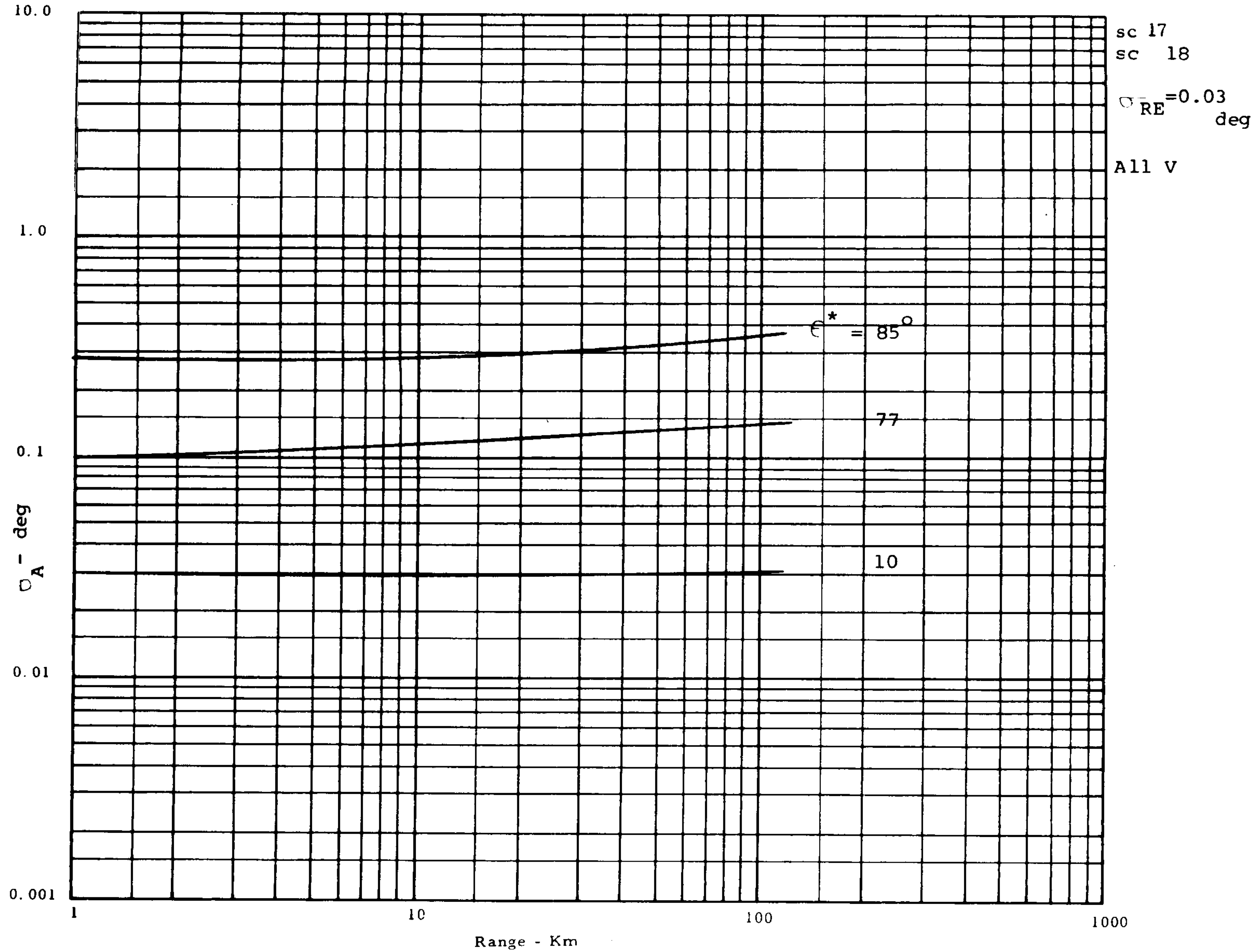


Figure 10-187 Dead Reckoning 3σ Heading Error — Ephemeris

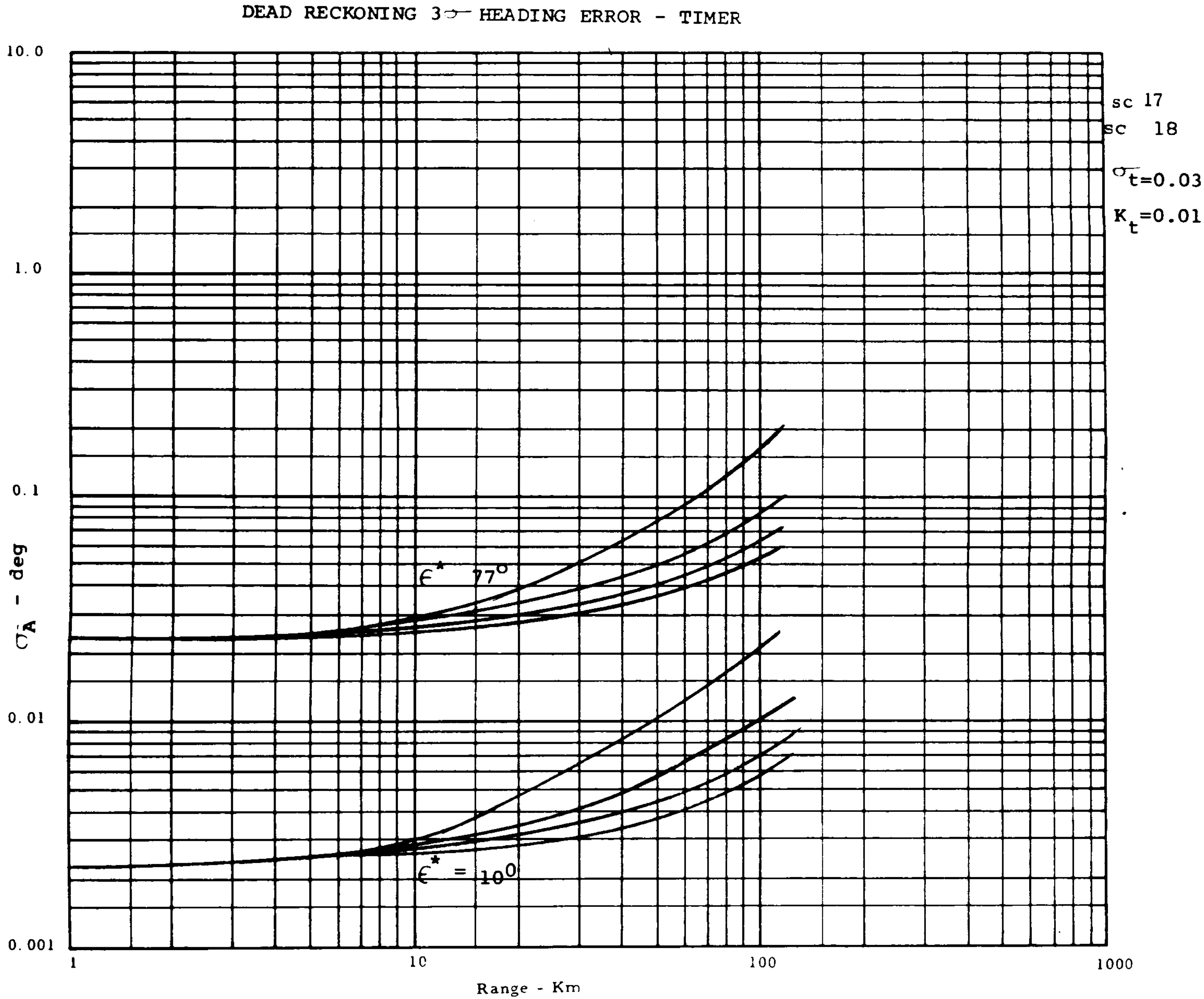


Figure 10-188 Dead Reckoning 3σ Heading Error — Timer

DEAD RECKONING 3σ POSITION ERROR - ACCELEROMETER

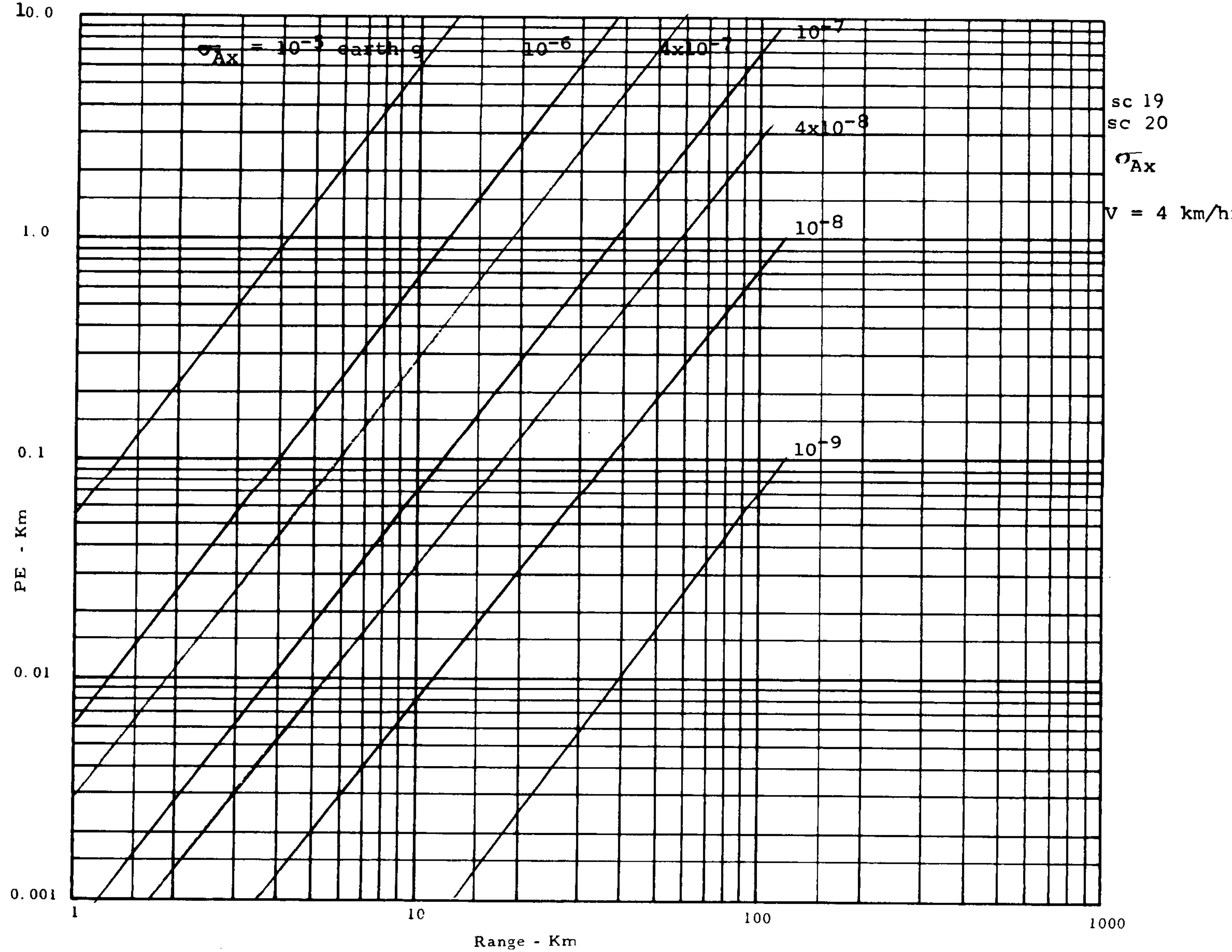


Figure 10-189 Dead Reckoning 3σ Position Error — Accelerometer

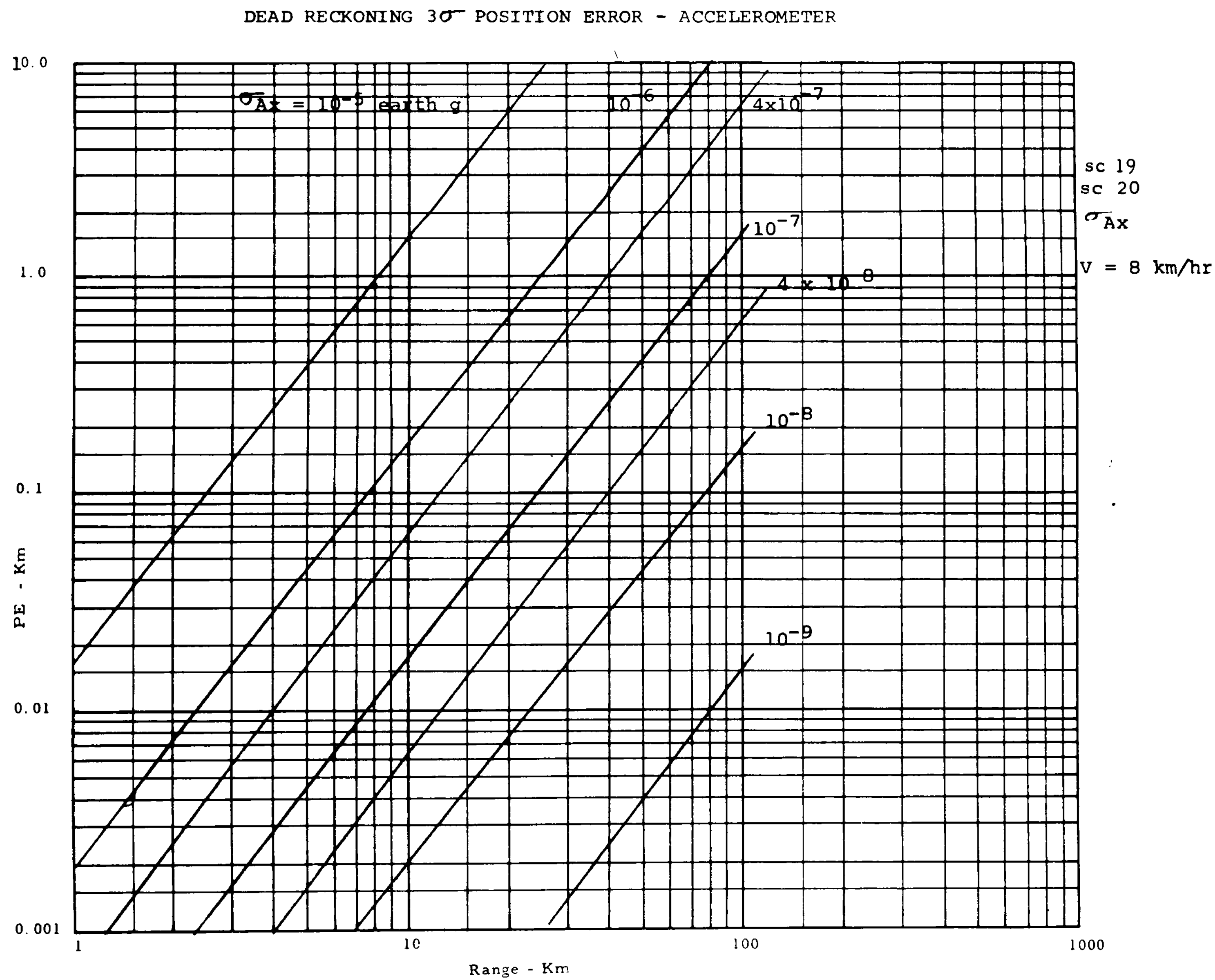


Figure 10-190 Dead Reckoning 3σ Position Error — Accelerometer

DEAD RECKONING 3σ POSITION ERROR - ACCELEROMETER

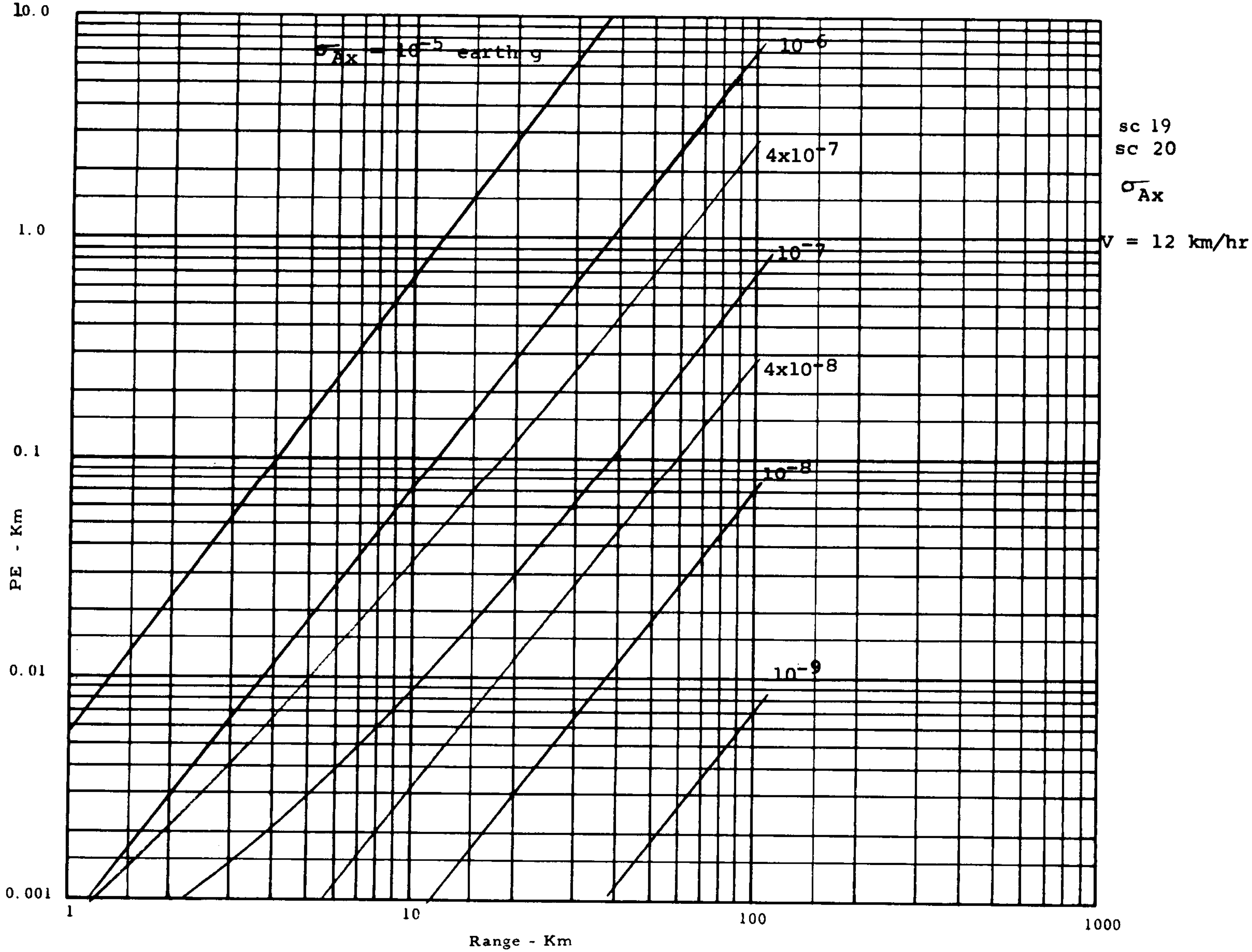


Figure 10-191 Dead Reckoning 3σ Position Error — Accelerometer

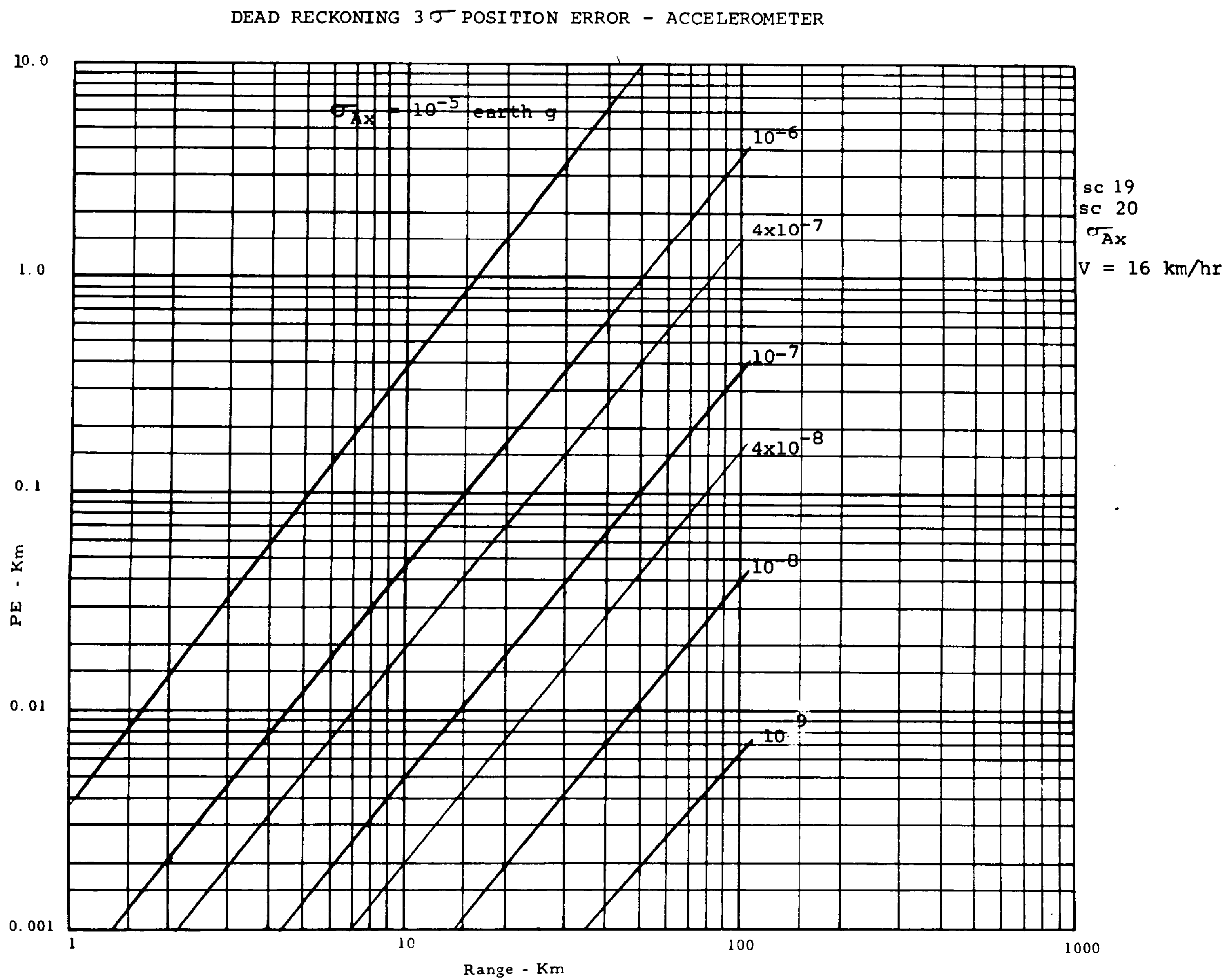


Figure 10-192 Dead Reckoning 3σ Position Error — Accelerometer

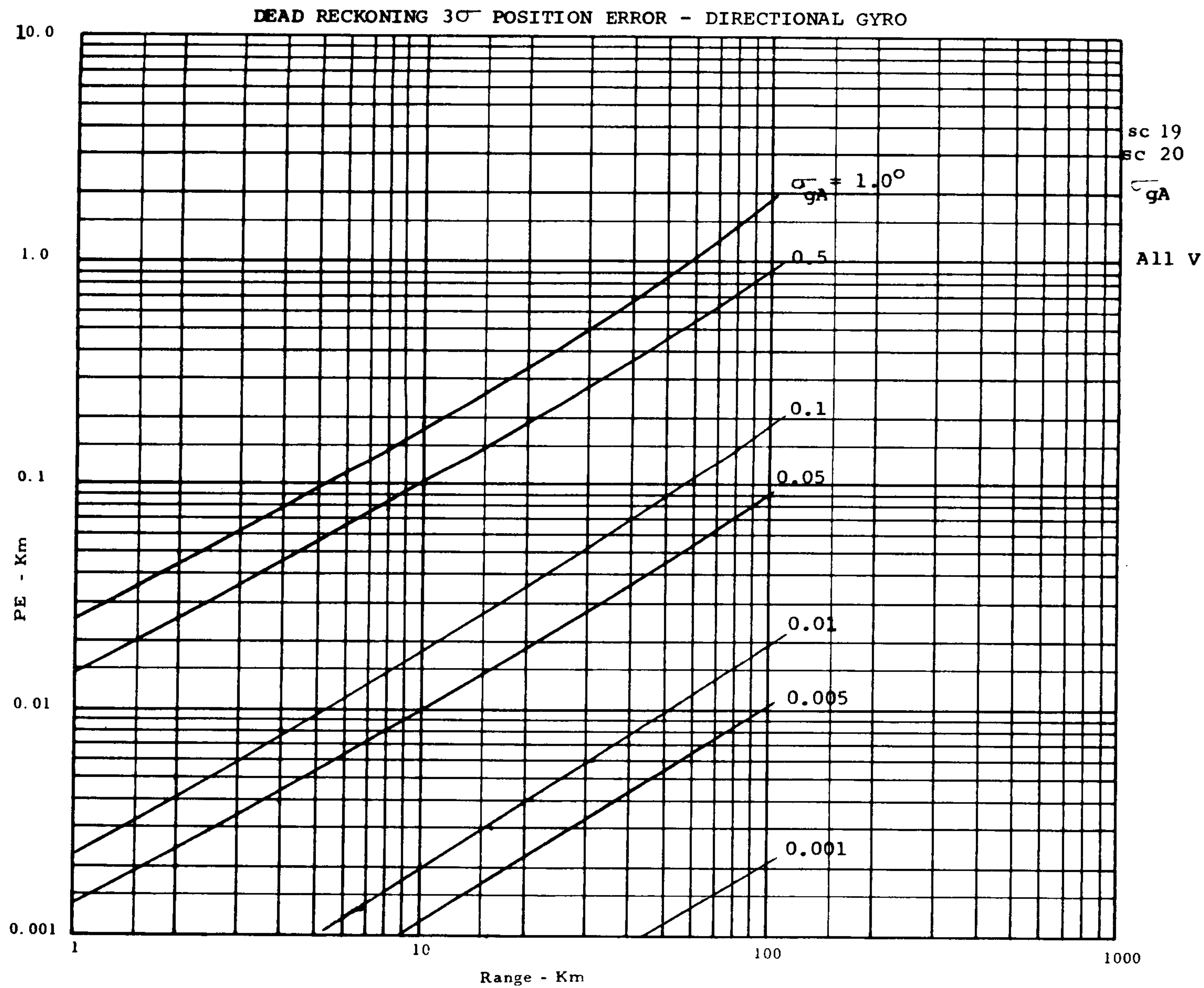


Figure 10-193 Dead Reckoning 3σ Position Error - Directional Gyro

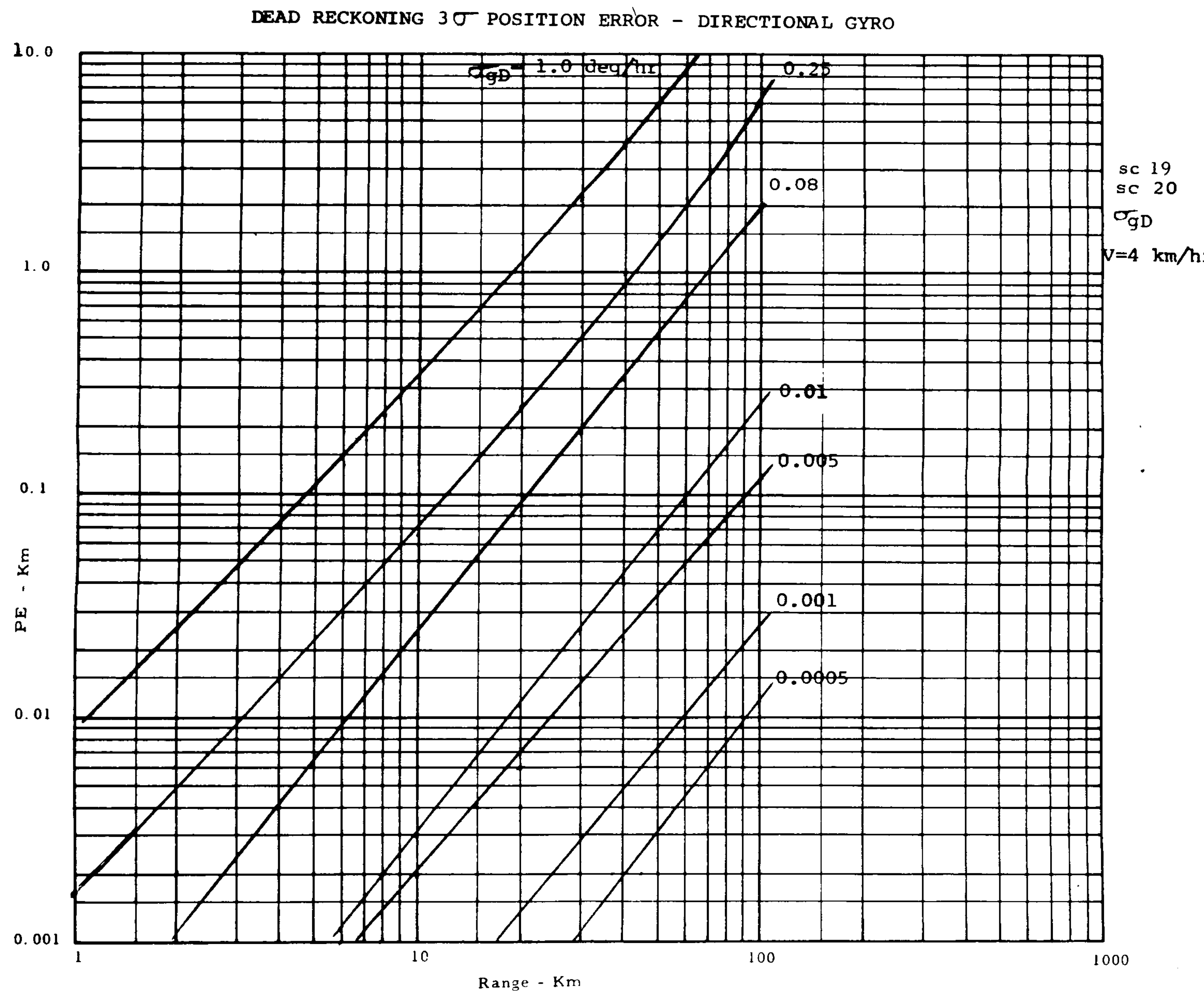


Figure 10-194 Dead Reckoning 3σ Position Error - Directional Gyro

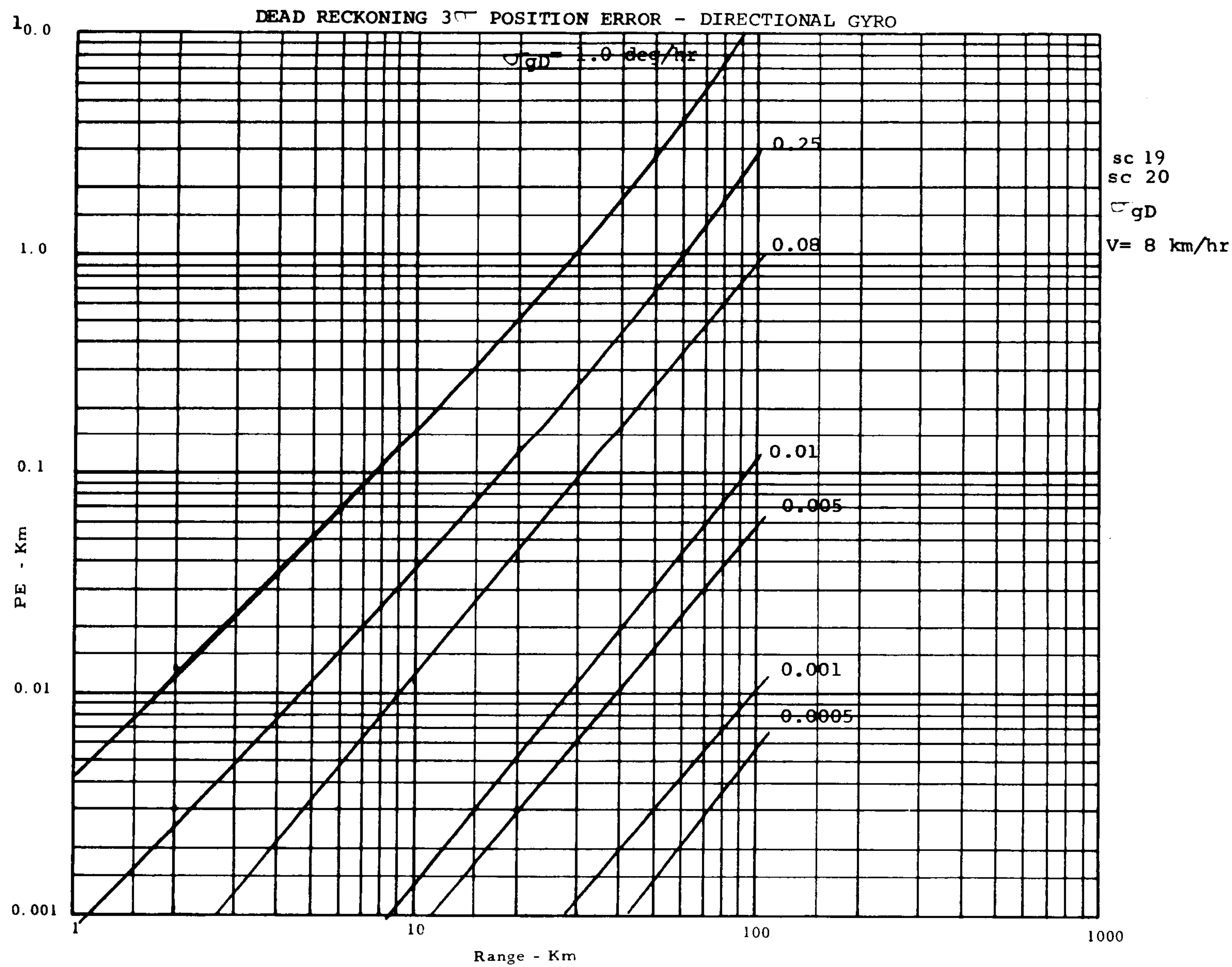


Figure 10-195 Dead Reckoning 3σ Position Error - Directional Gyro

DEAD RECKONING 3 σ POSITION ERROR - DIRECTIONAL GYRO

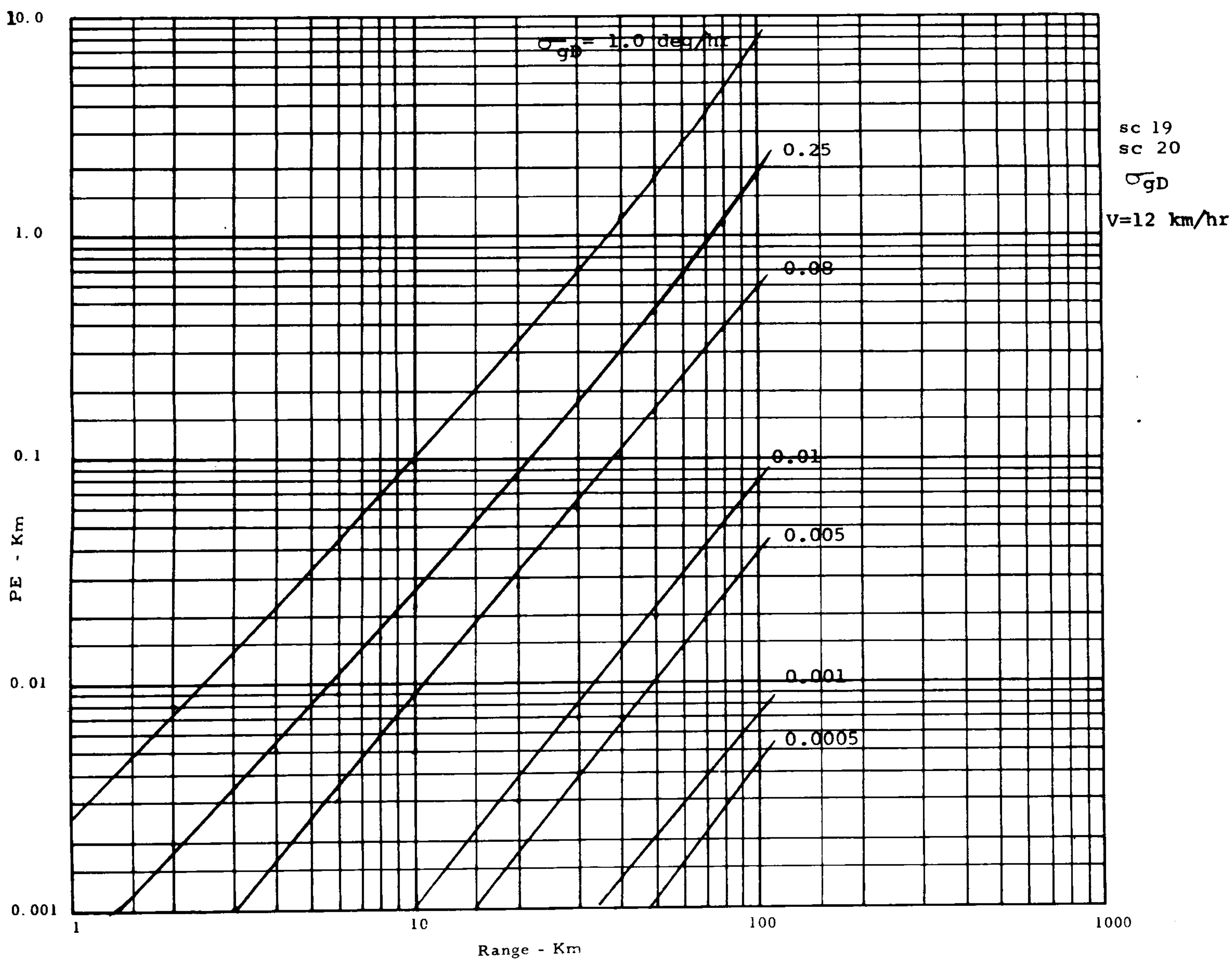


Figure 10-196 Dead Reckoning 3σ Position Error - Directional Gyro

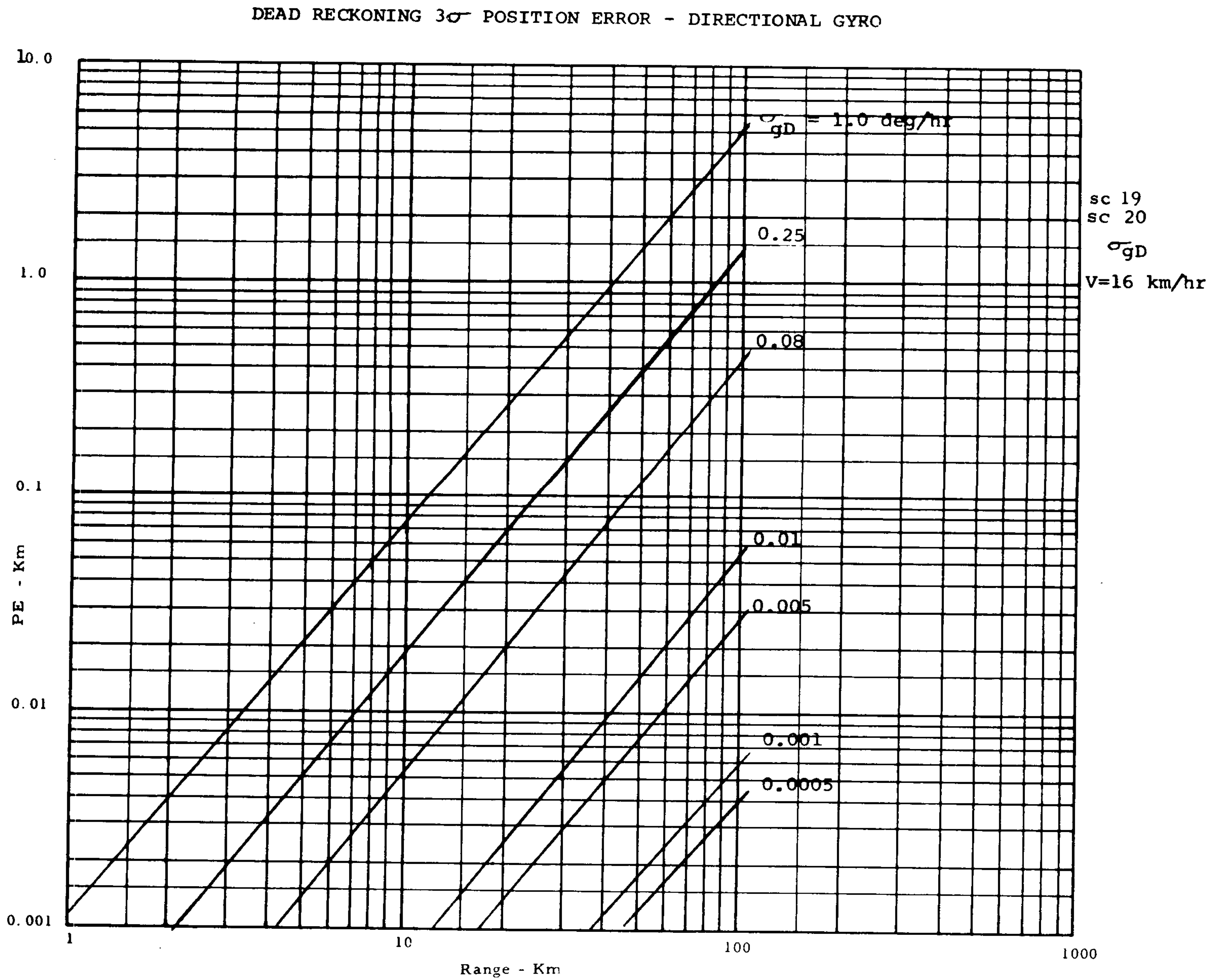


Figure 10-197 Dead Reckoning 3σ Position Error - Directional Gyro

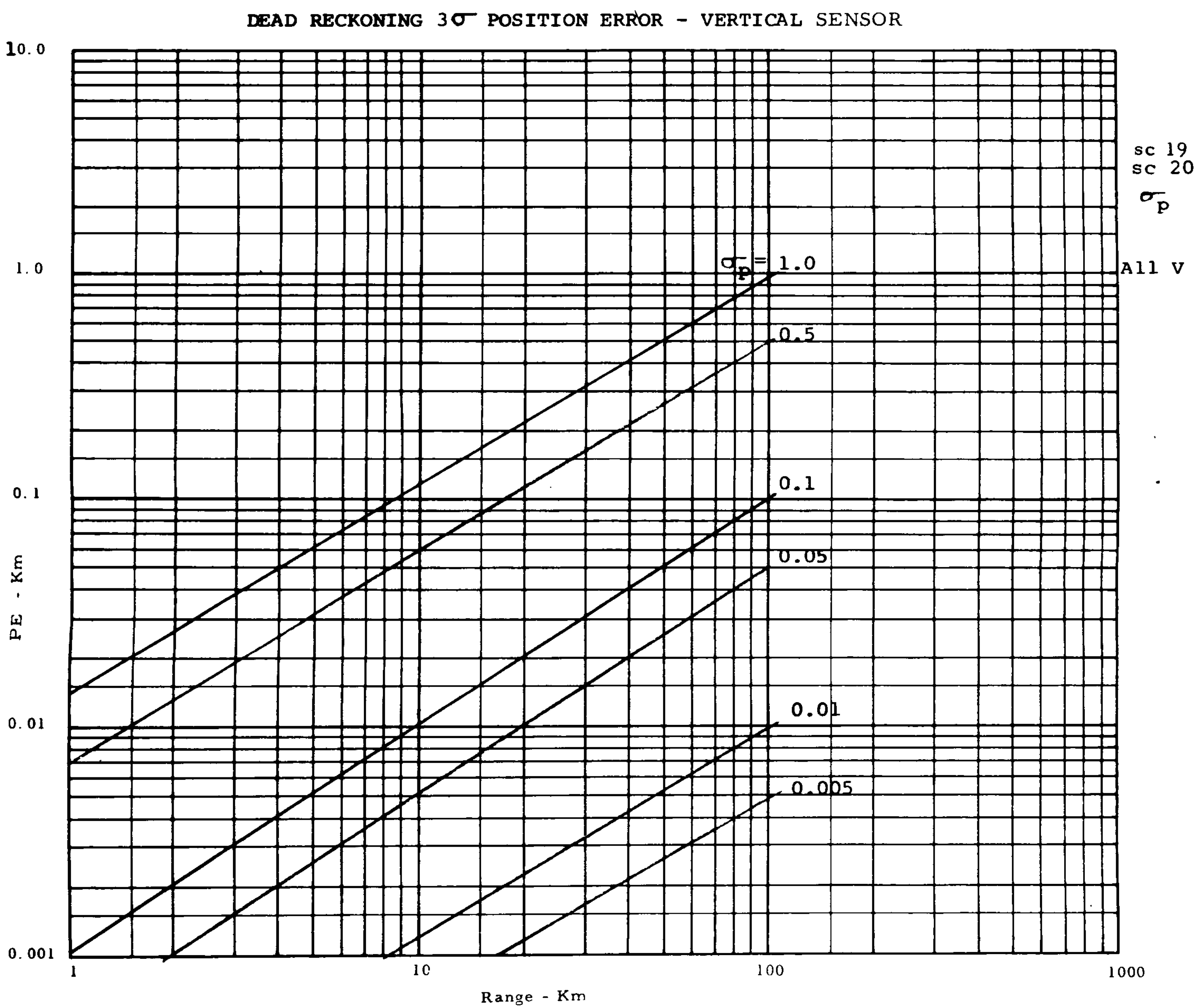


Figure 10-198 Dead Reckoning 3σ Position Error — Vertical Sensor

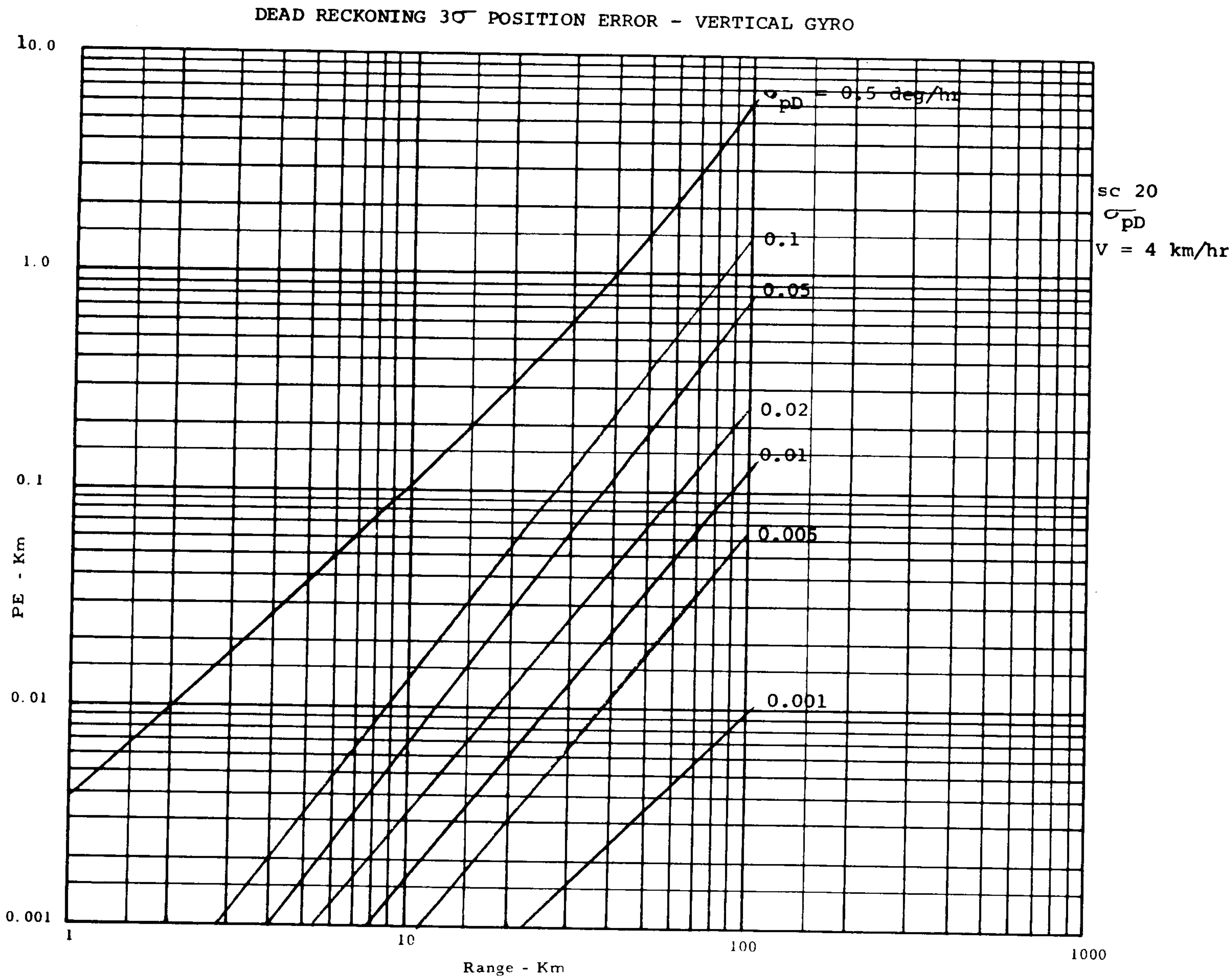


Figure 10-199 Dead Reckoning 3σ Position Error — Vertical Gyro

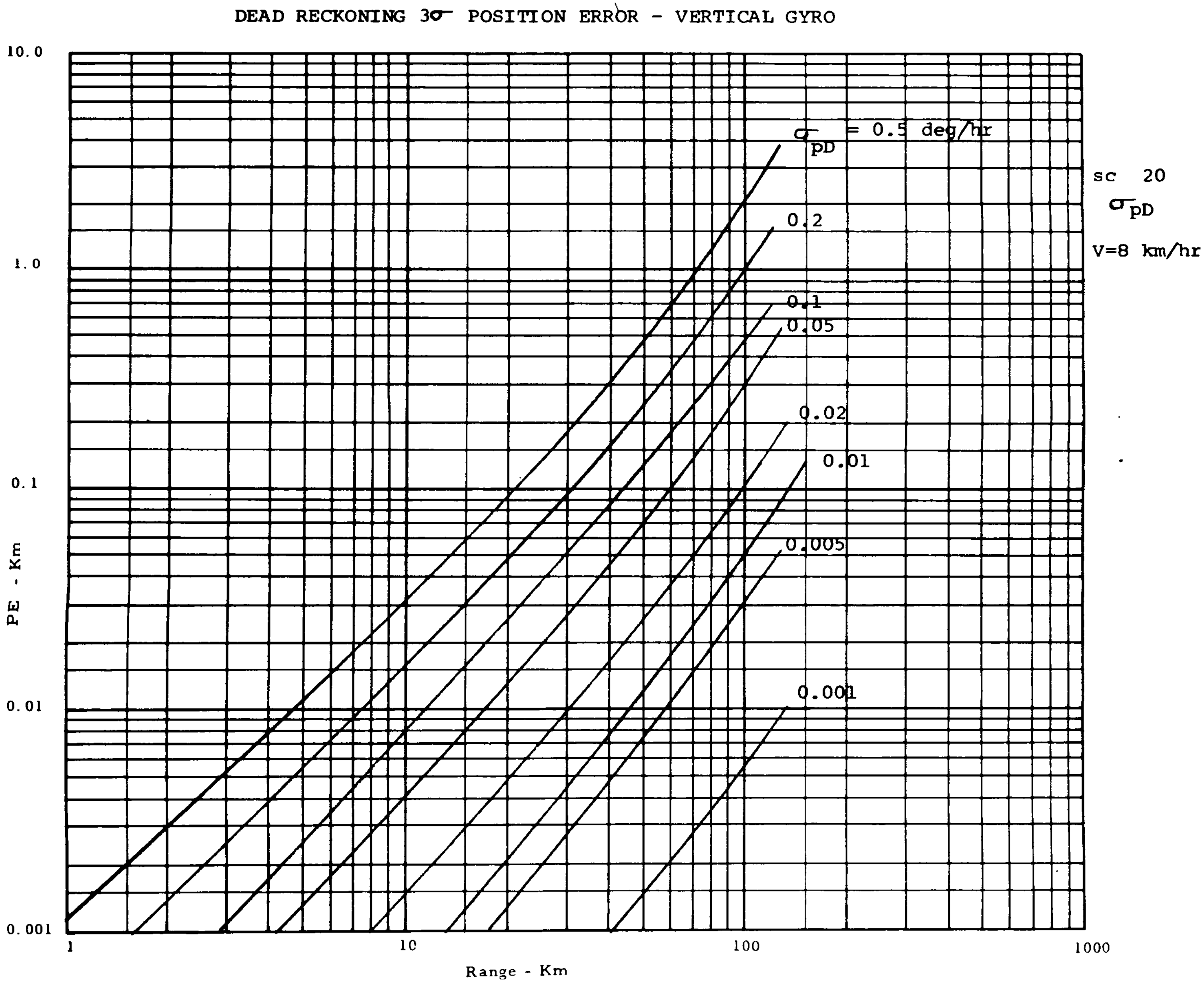


Figure 10-200 Dead Reckoning 3σ Position Error — Vertical Gyro

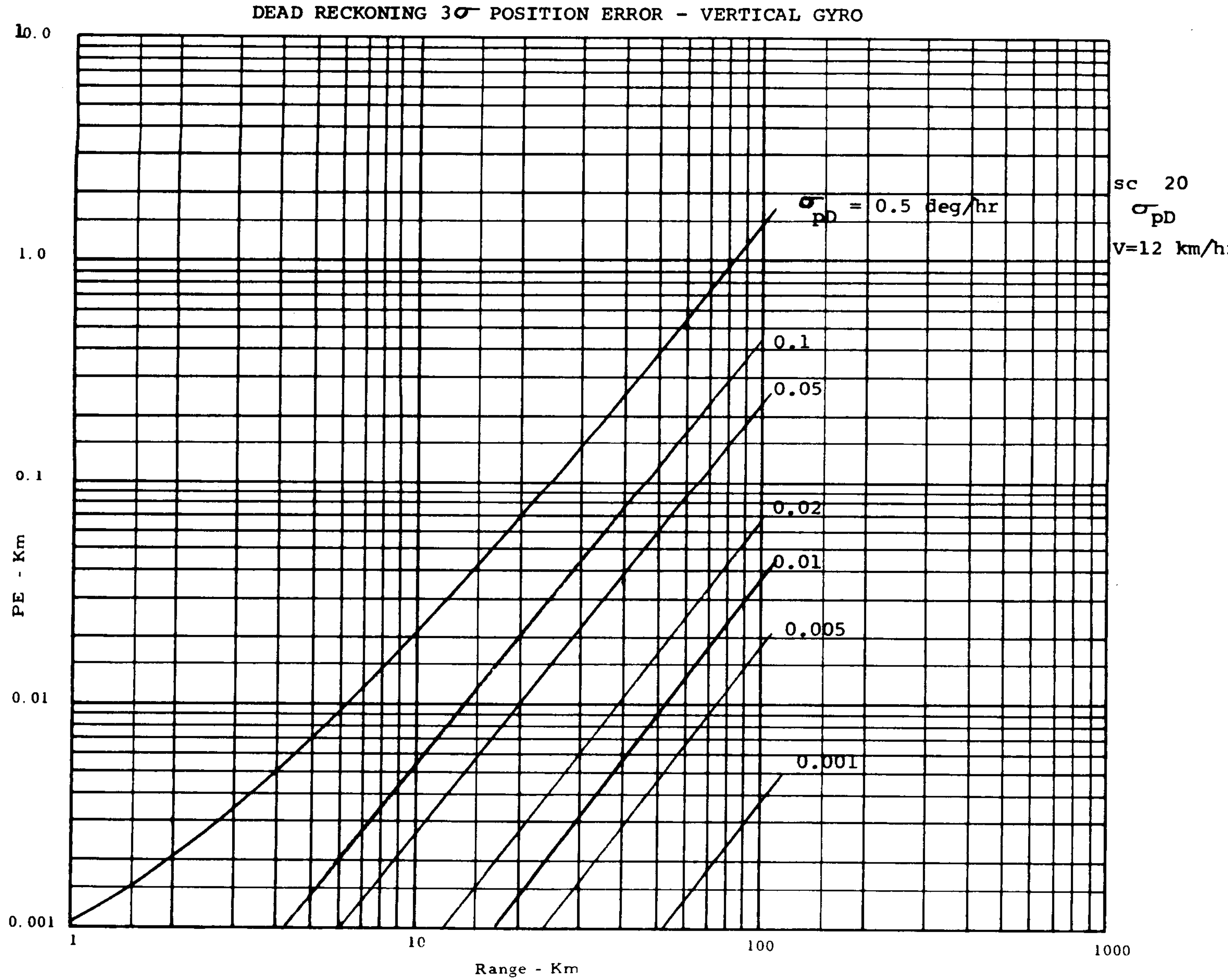


Figure 10-201 Dead Reckoning 3σ Position Error — Vertical Gyro

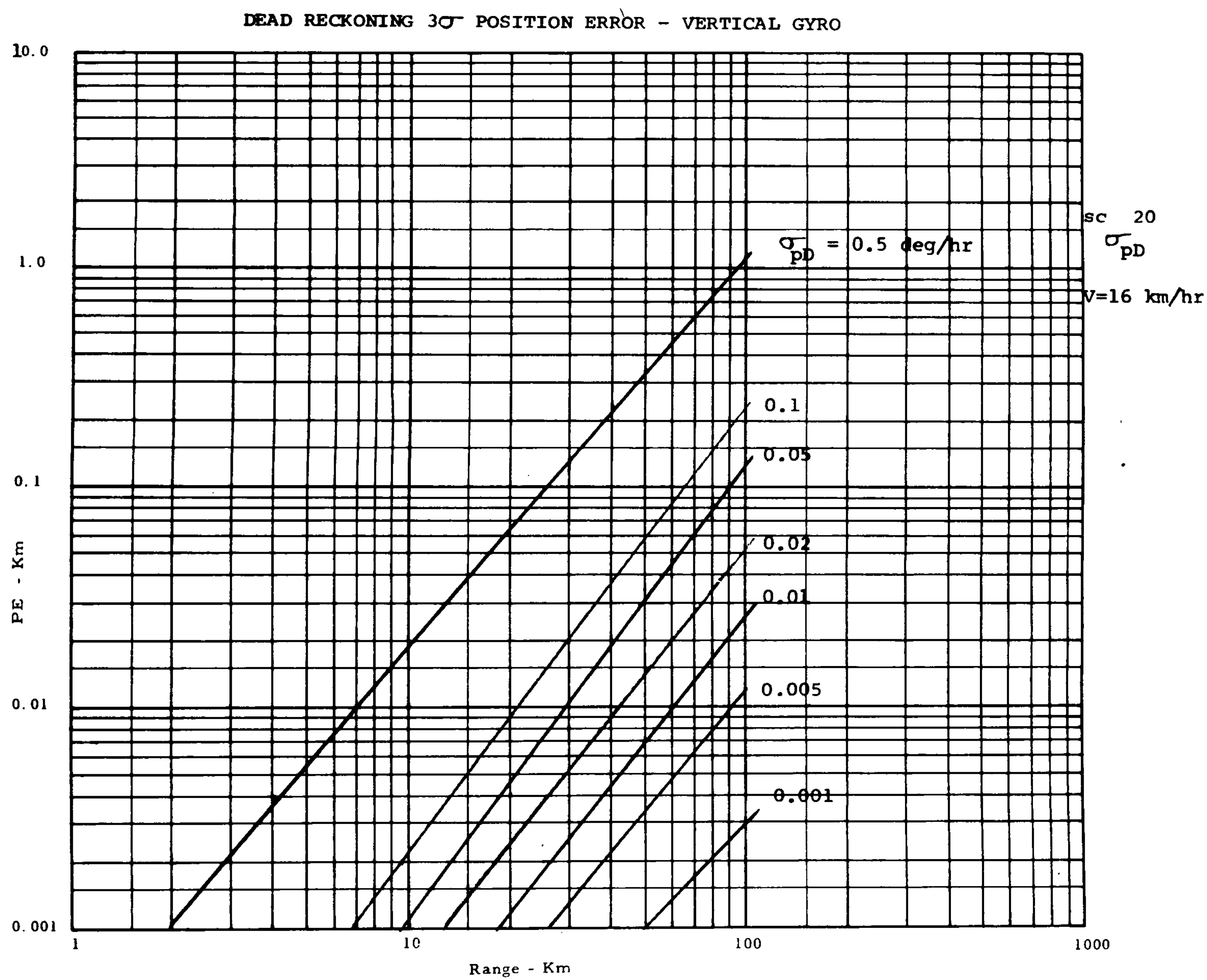


Figure 10-202 Dead Reckoning 3σ Position Error — Vertical Gyro

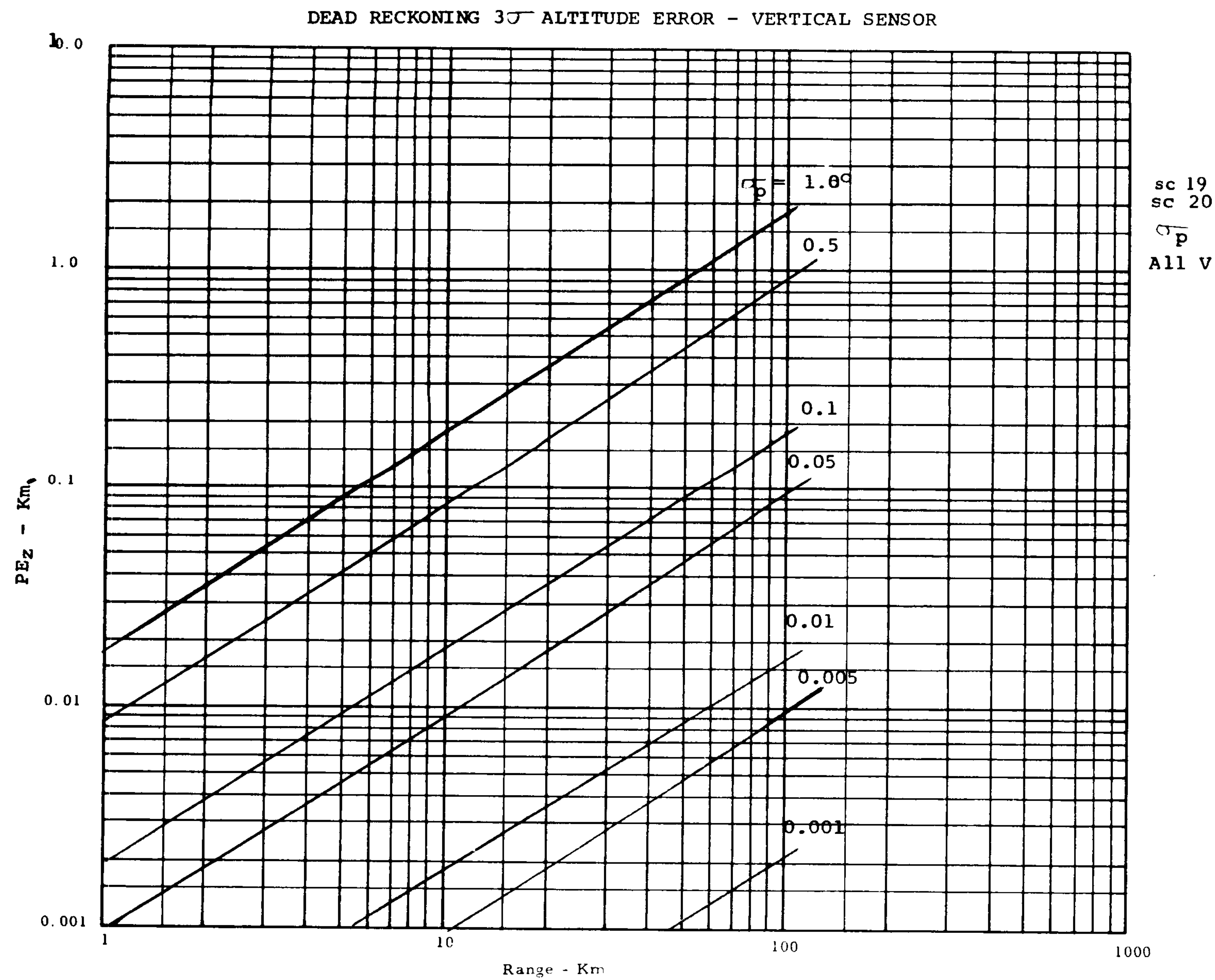


Figure 10-203 Dead Reckoning 3σ Altitude Error - Vertical Sensor

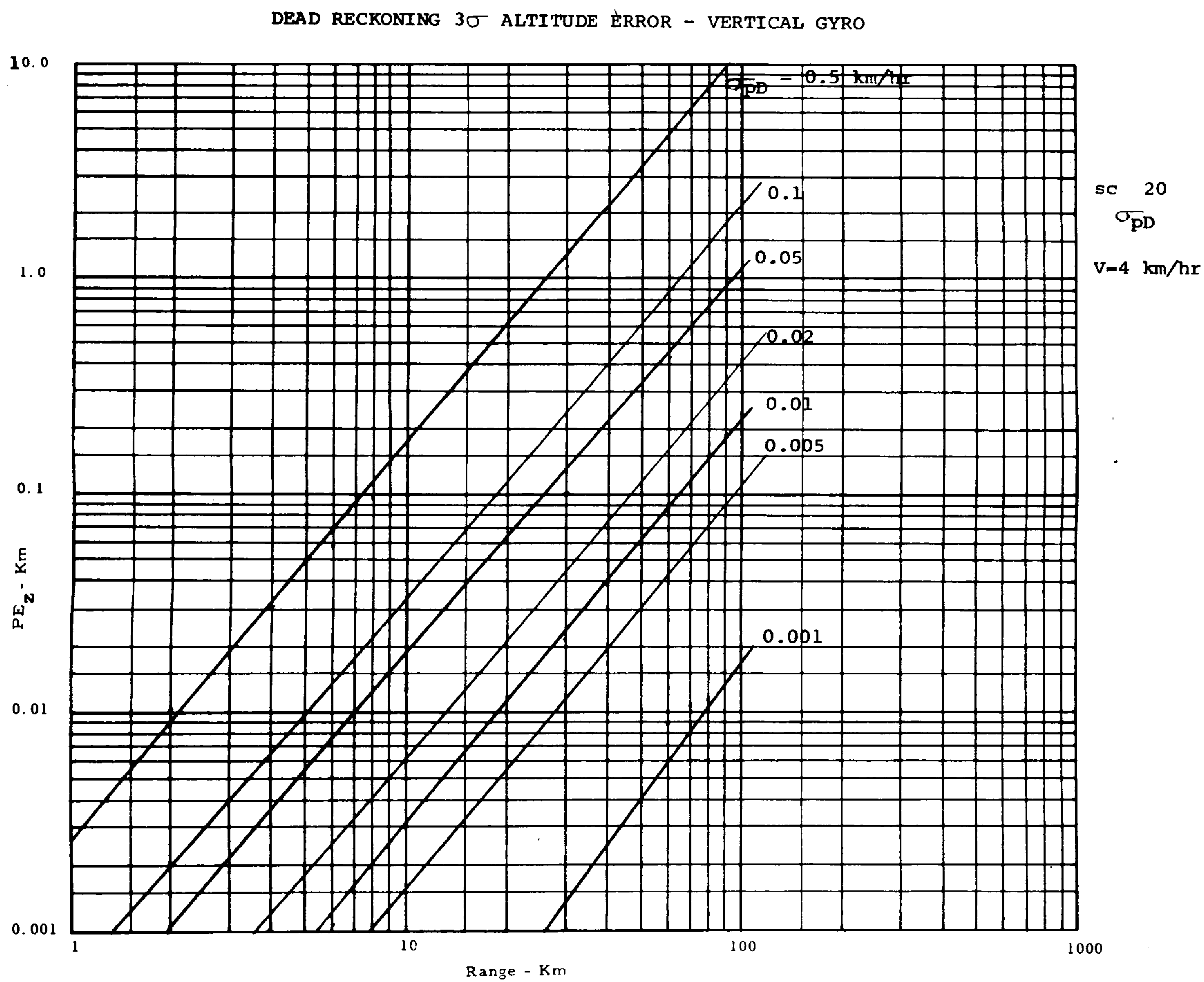


Figure 10-204 Dead Reckoning 3σ Altitude Error - Vertical Gyro

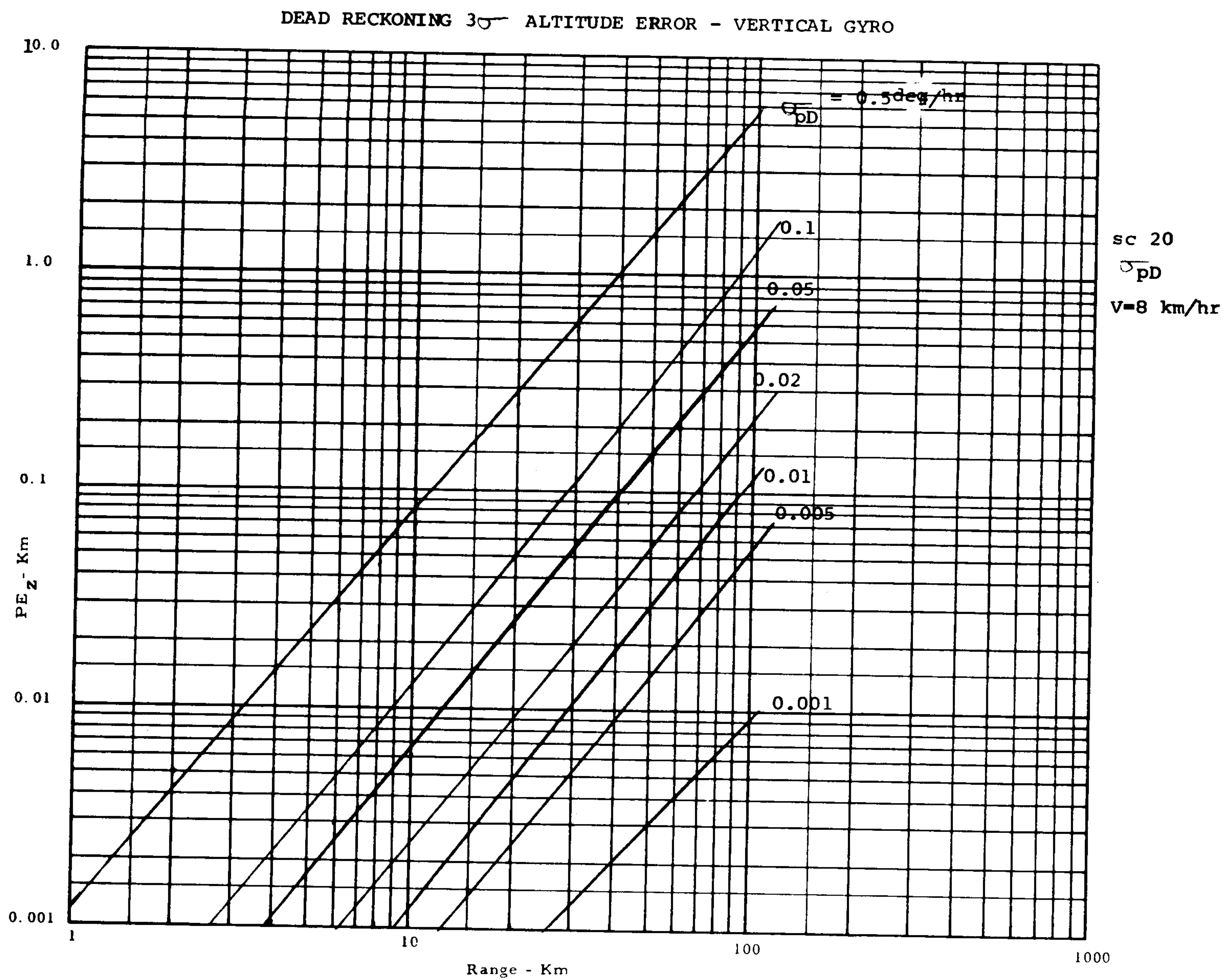


Figure 10-205 Dead Reckoning 3σ Altitude Error - Vertical Gyro

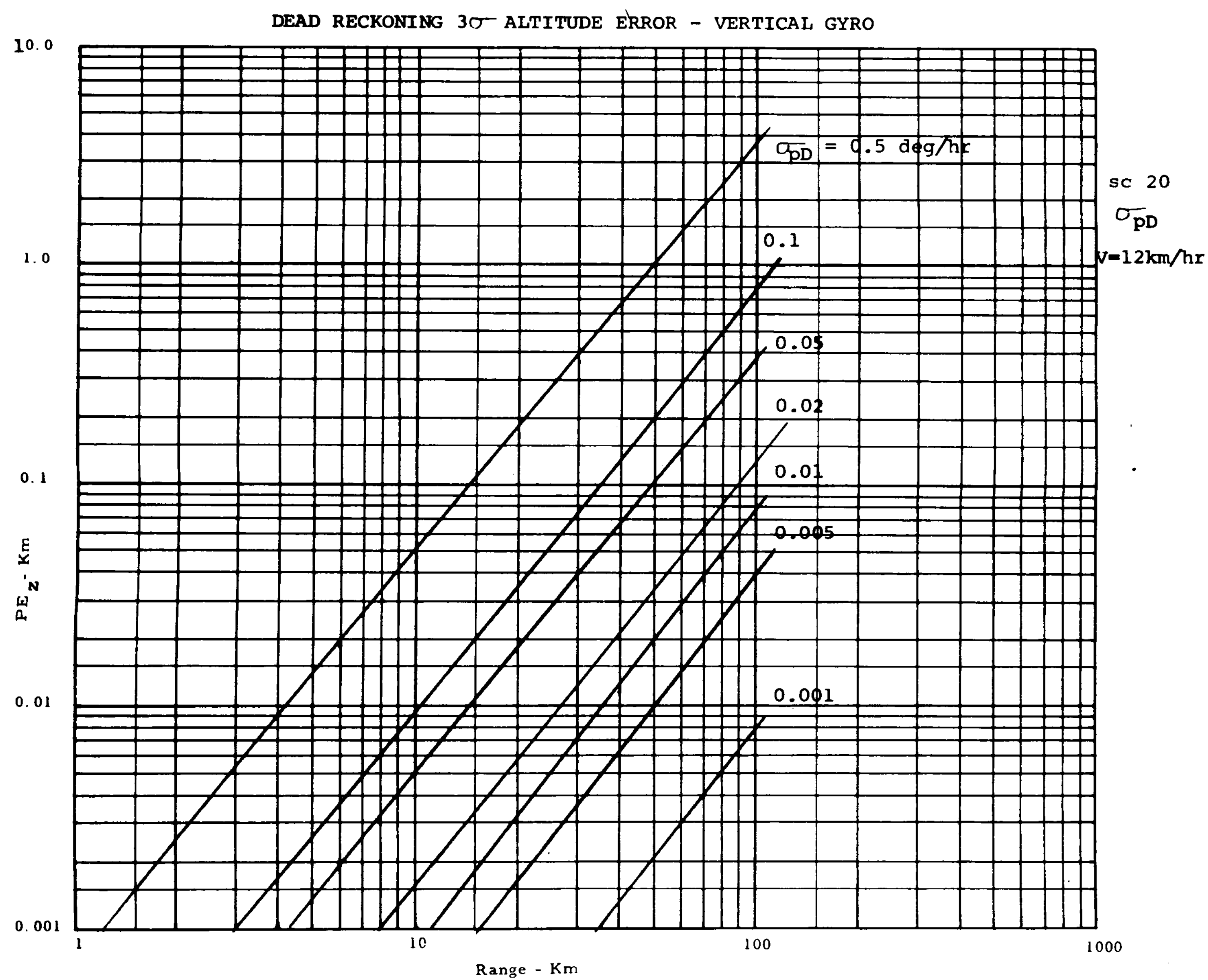


Figure 10-206 Dead Reckoning 3σ Altitude Error - Vertical Gyro

DEAD RECKONING 3σ ALTITUDE ERROR - VERTICAL GYRO

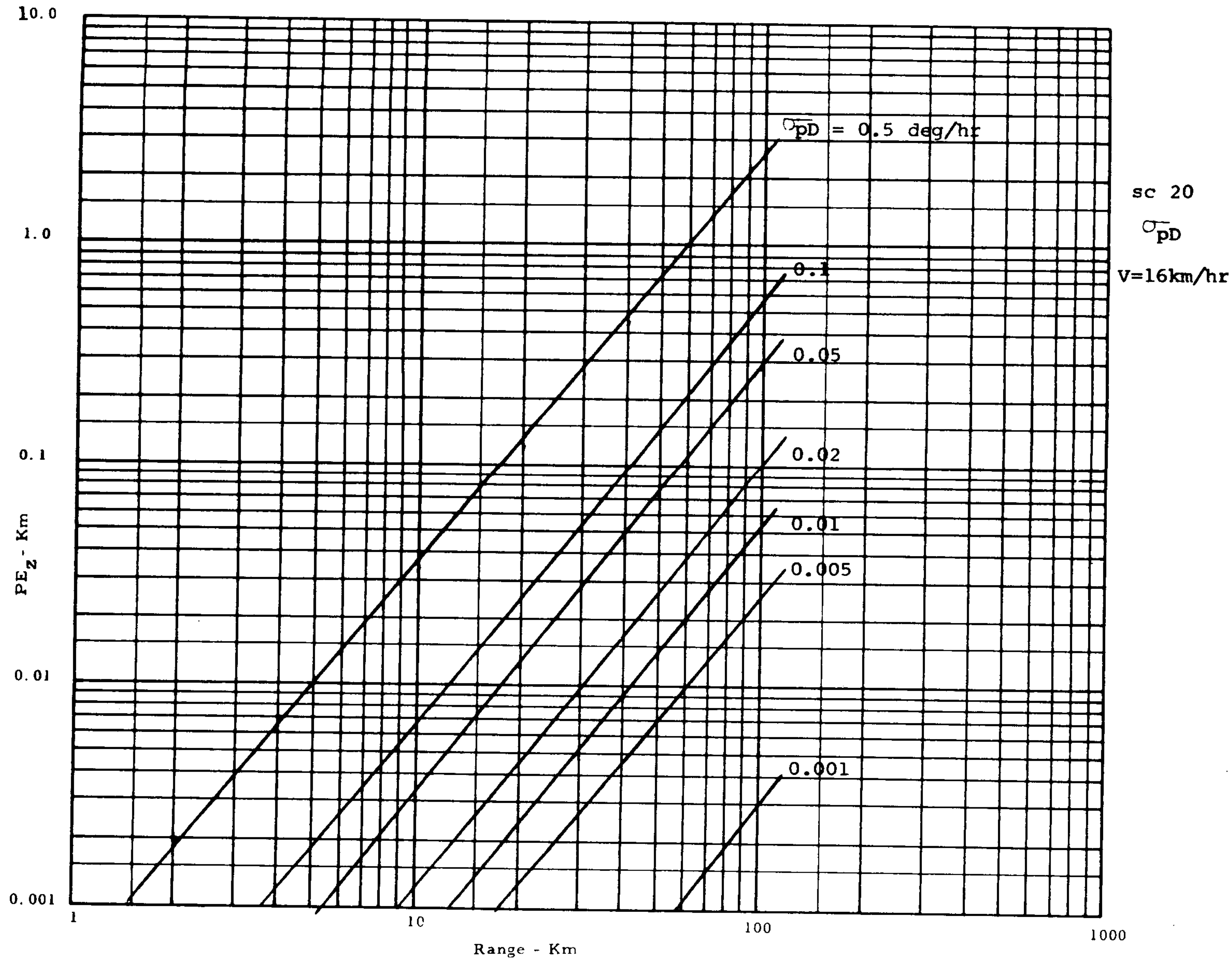


Figure 10-207 Dead Reckoning 3σ Altitude Error - Vertical Gyro

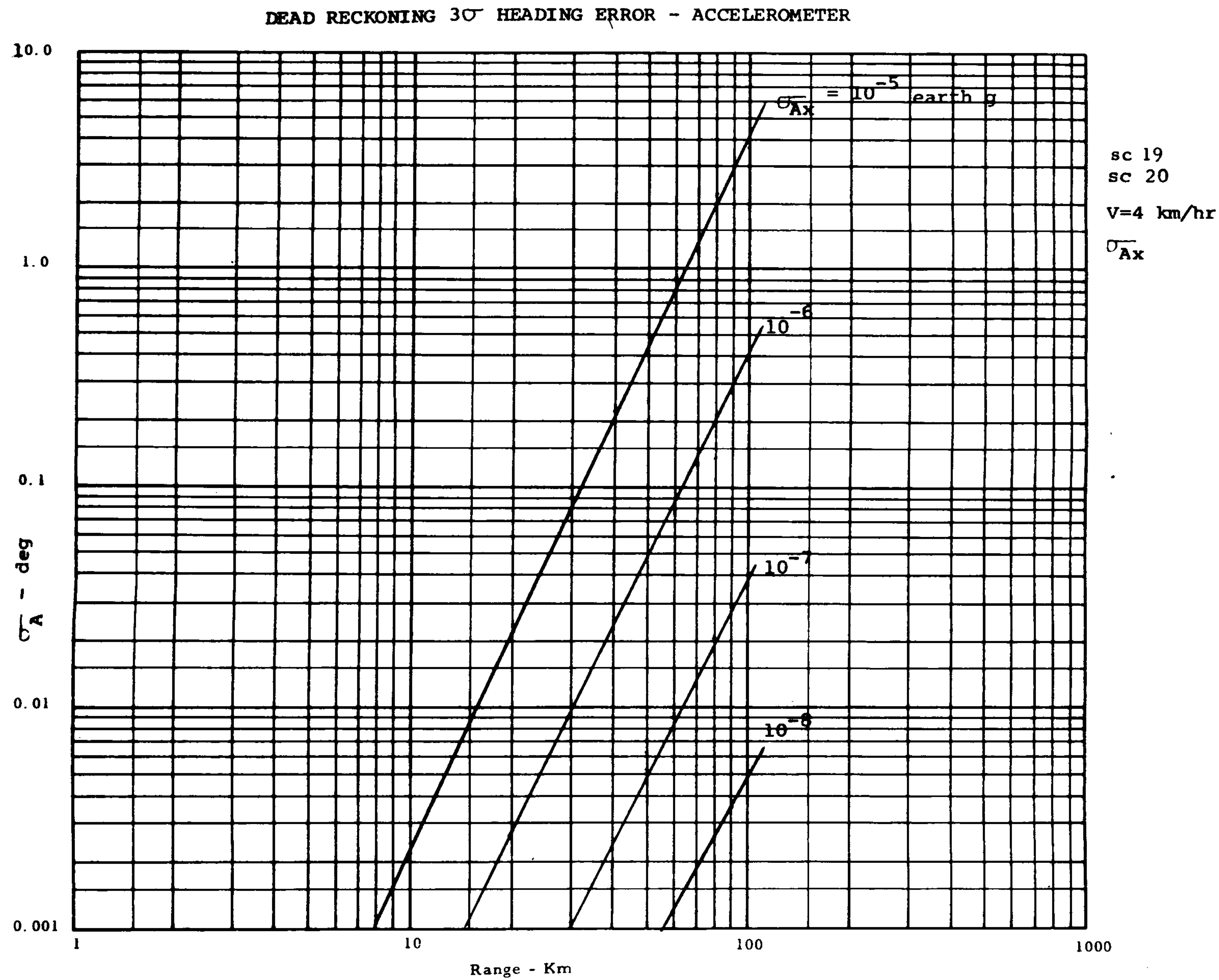


Figure 10-208 Dead Reckoning 3σ Heading Error - Accelerometer

DEAD RECKONING 3σ HEADING ERROR - DIRECTIONAL GYRO

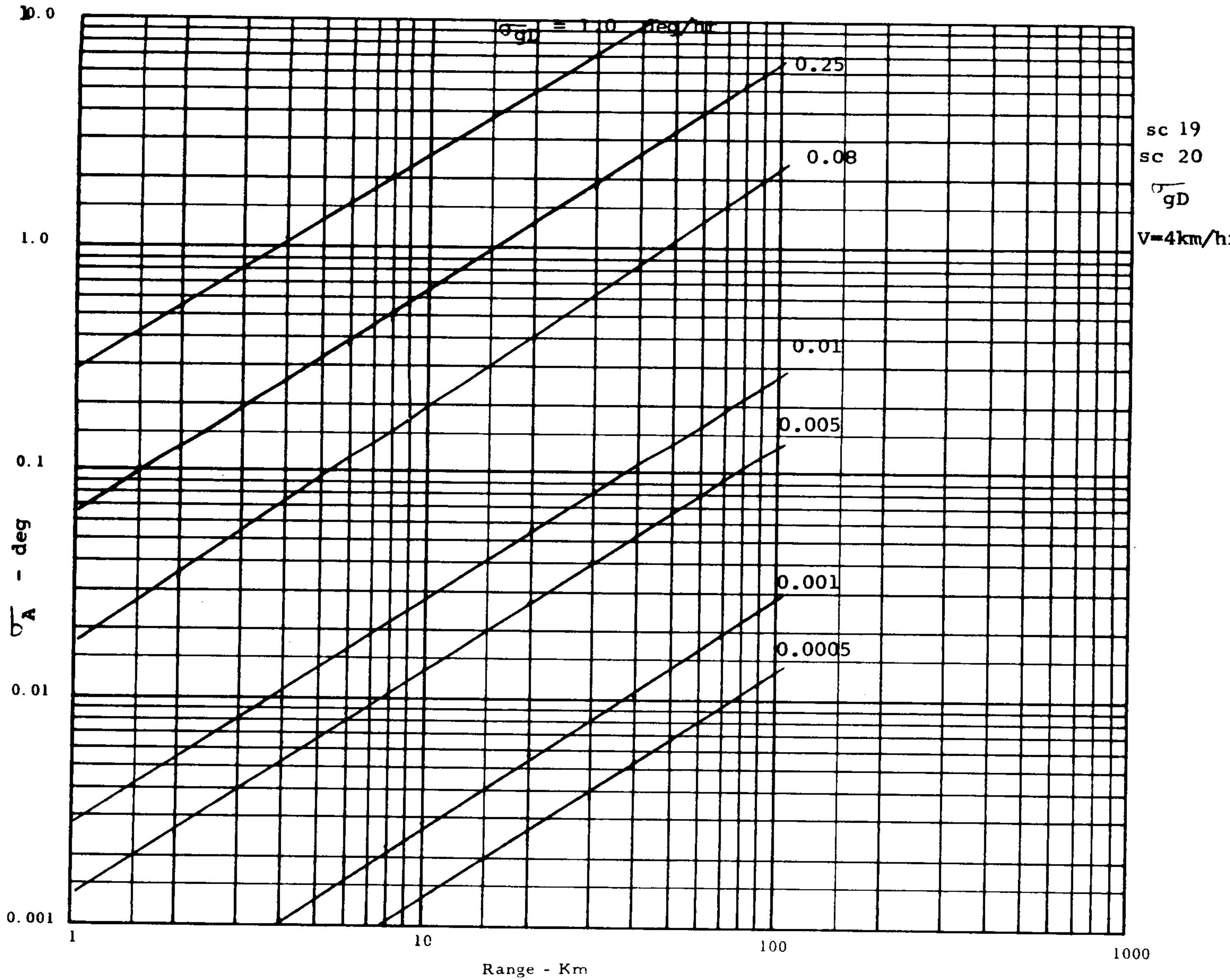


Figure 10-209 Dead Reckoning 3σ Heading Error - Directional Gyro

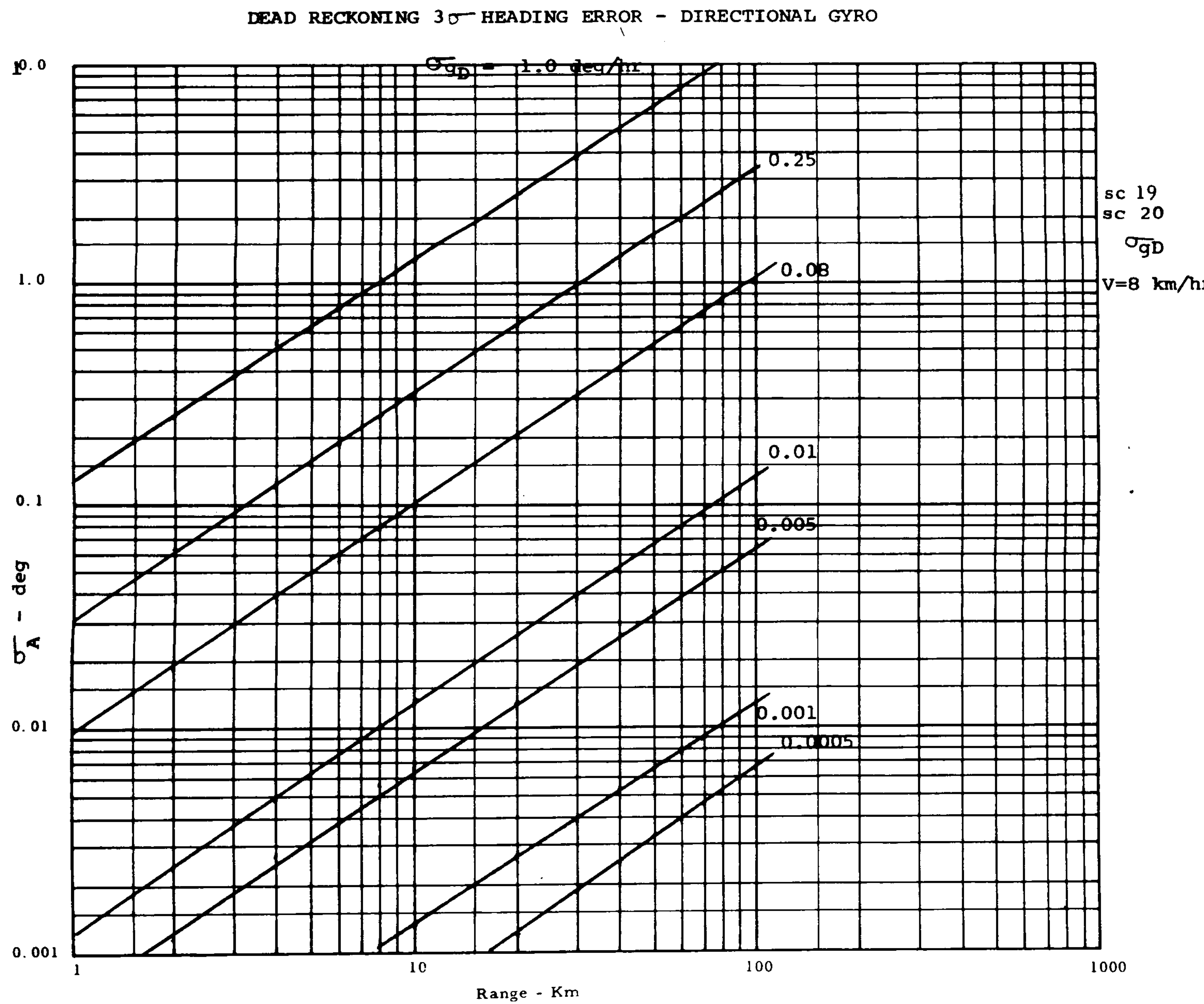


Figure 10-210 Dead Reckoning 3σ Heading Error - Directional Gyro

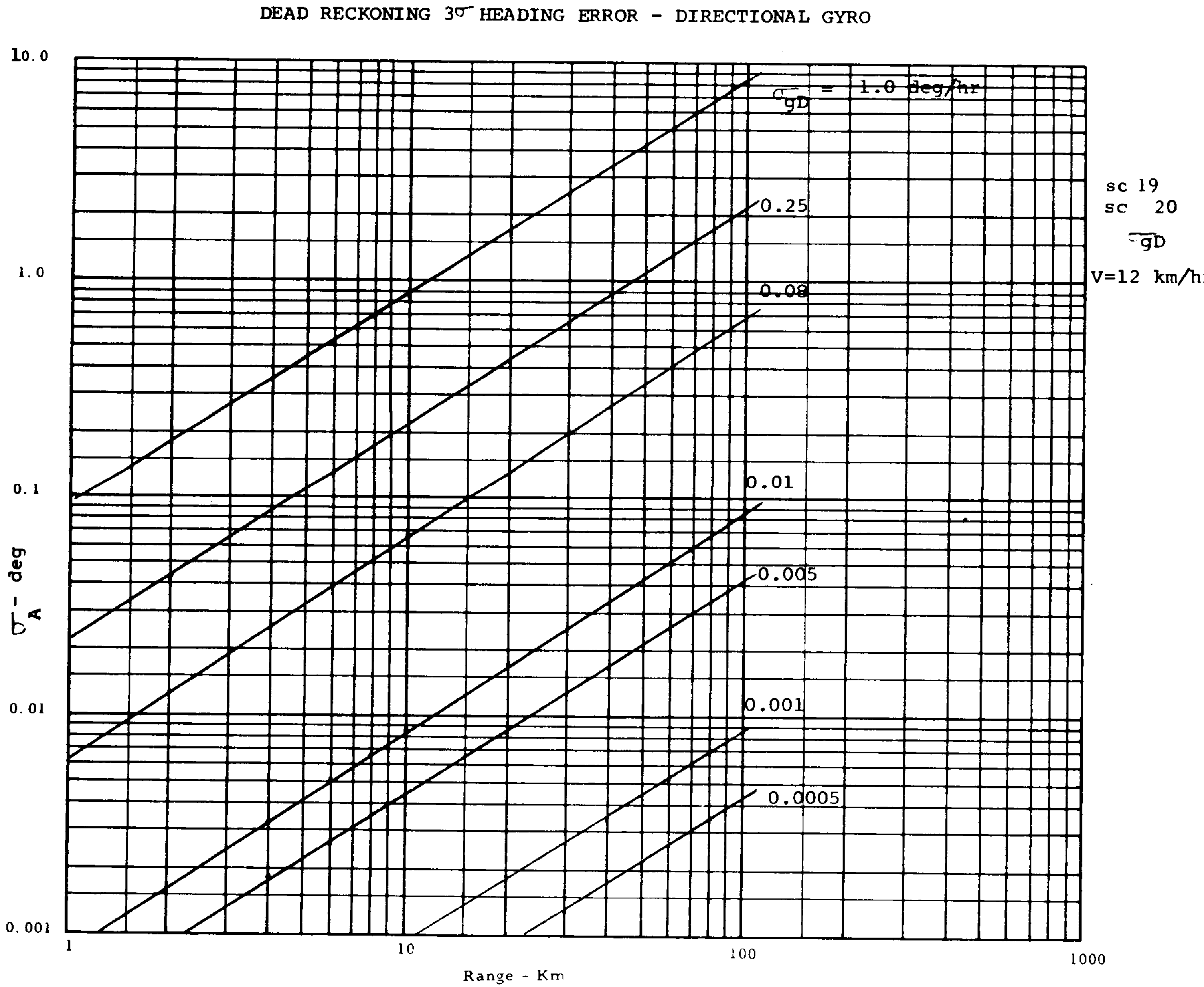


Figure 10-211 Dead Reckoning 3σ Heading Error - Directional Gyro

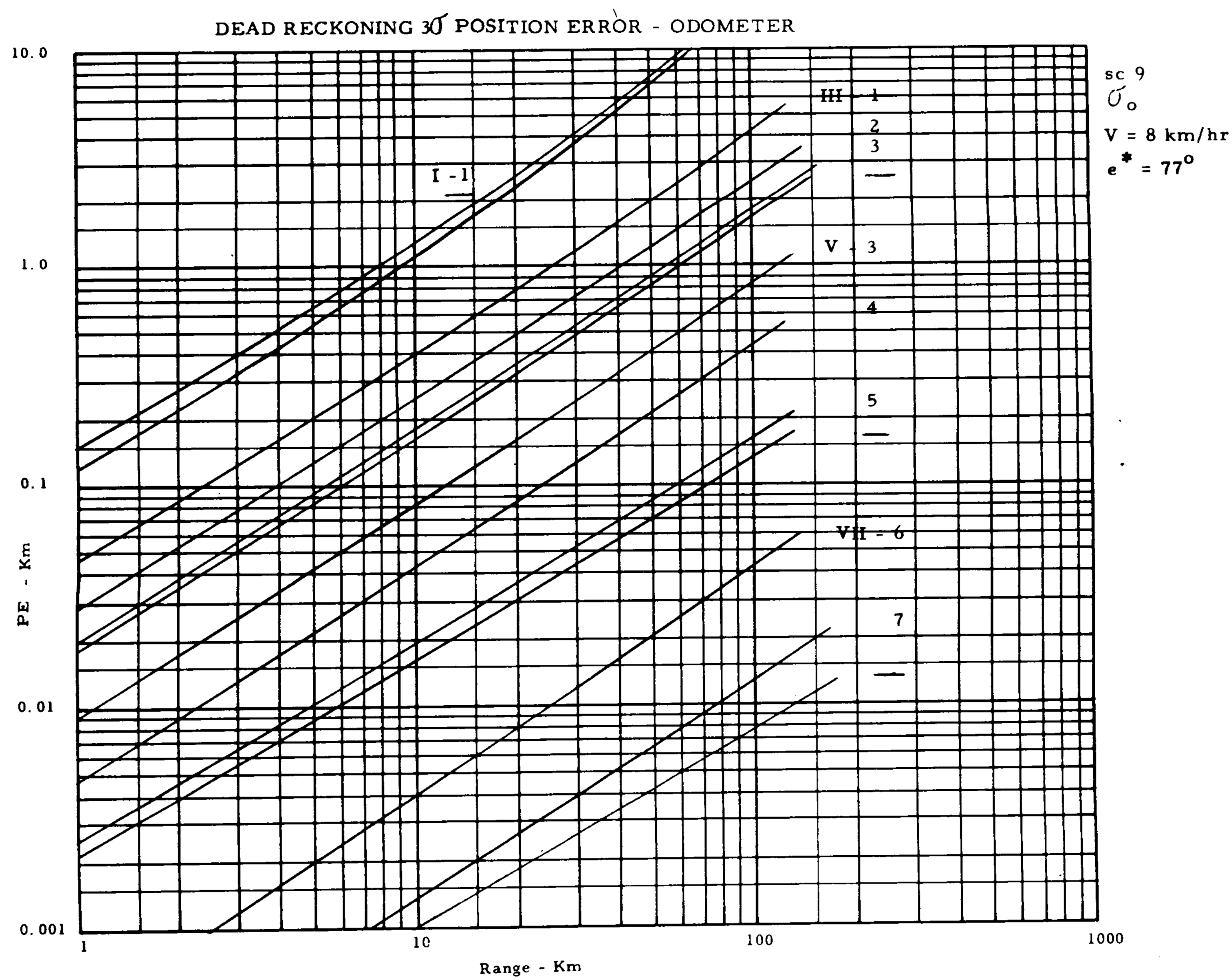


Figure 10-212 Dead Reckoning 3σ Position Error - Odometer

DEAD RECKONING 3σ POSITION ERROR - ODOMETER

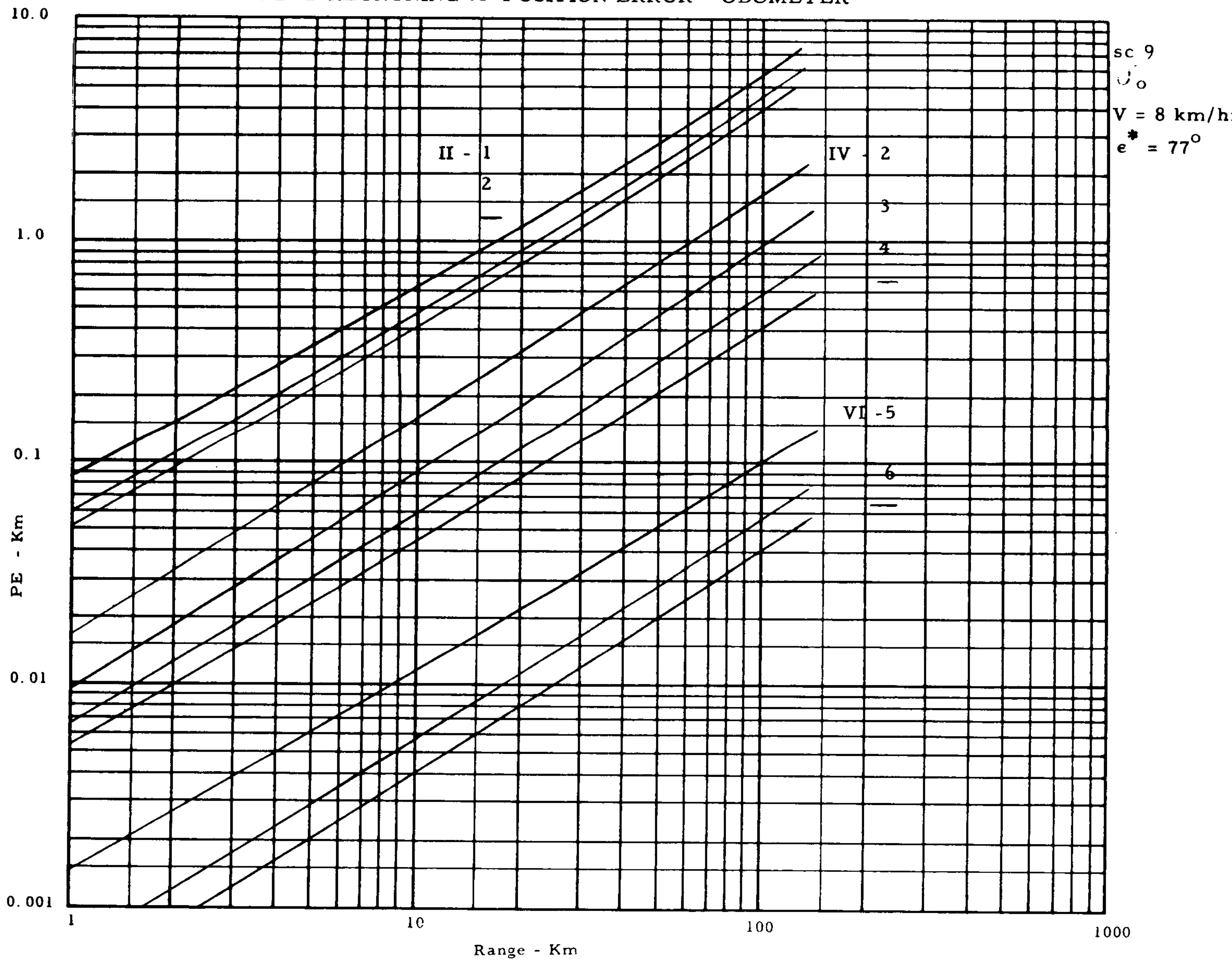


Figure 10-213 Dead Reckoning 3σ Position Error - Odometer

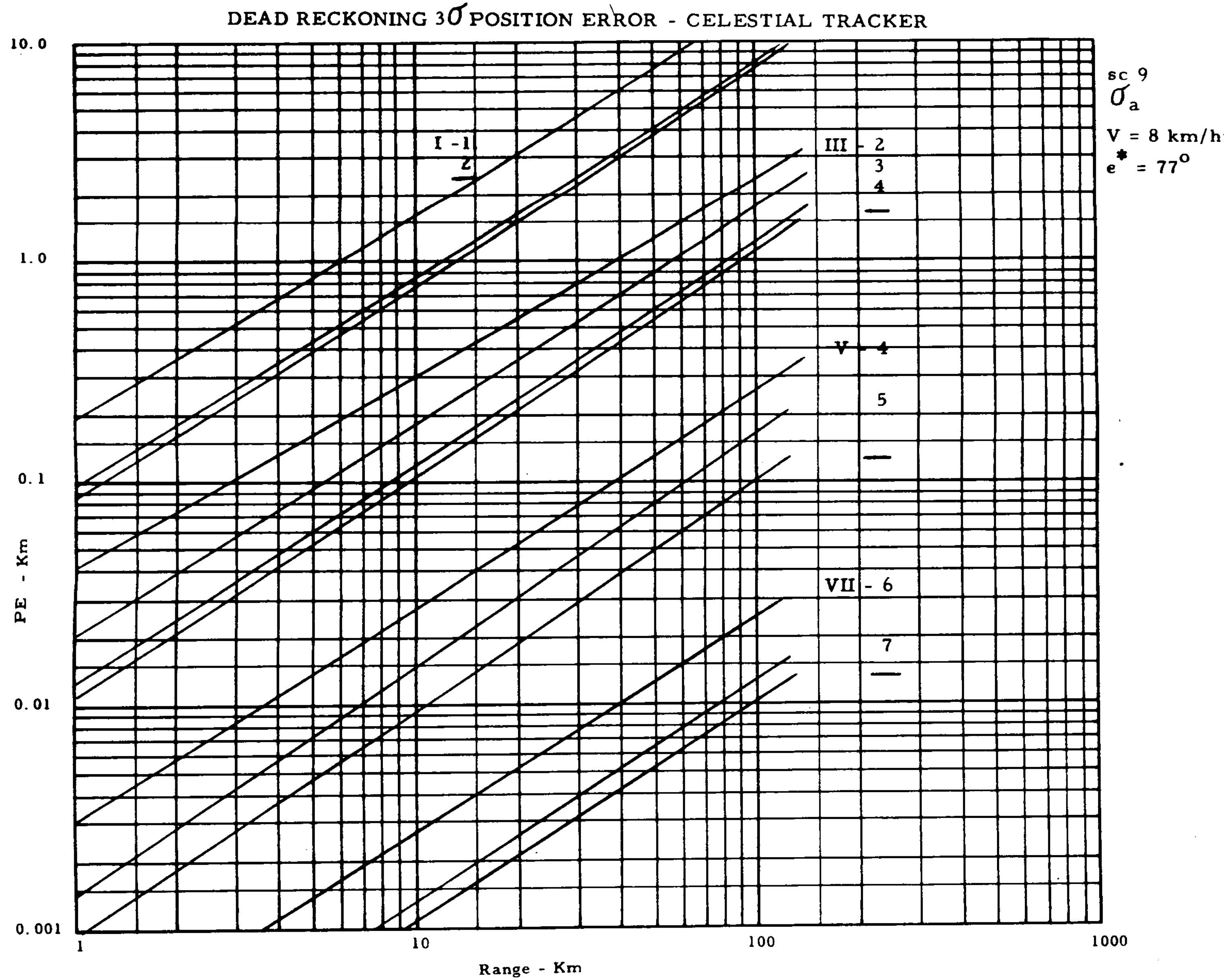


Figure 10-214 Dead Reckoning 3σ Position Error - Celestial Tracker

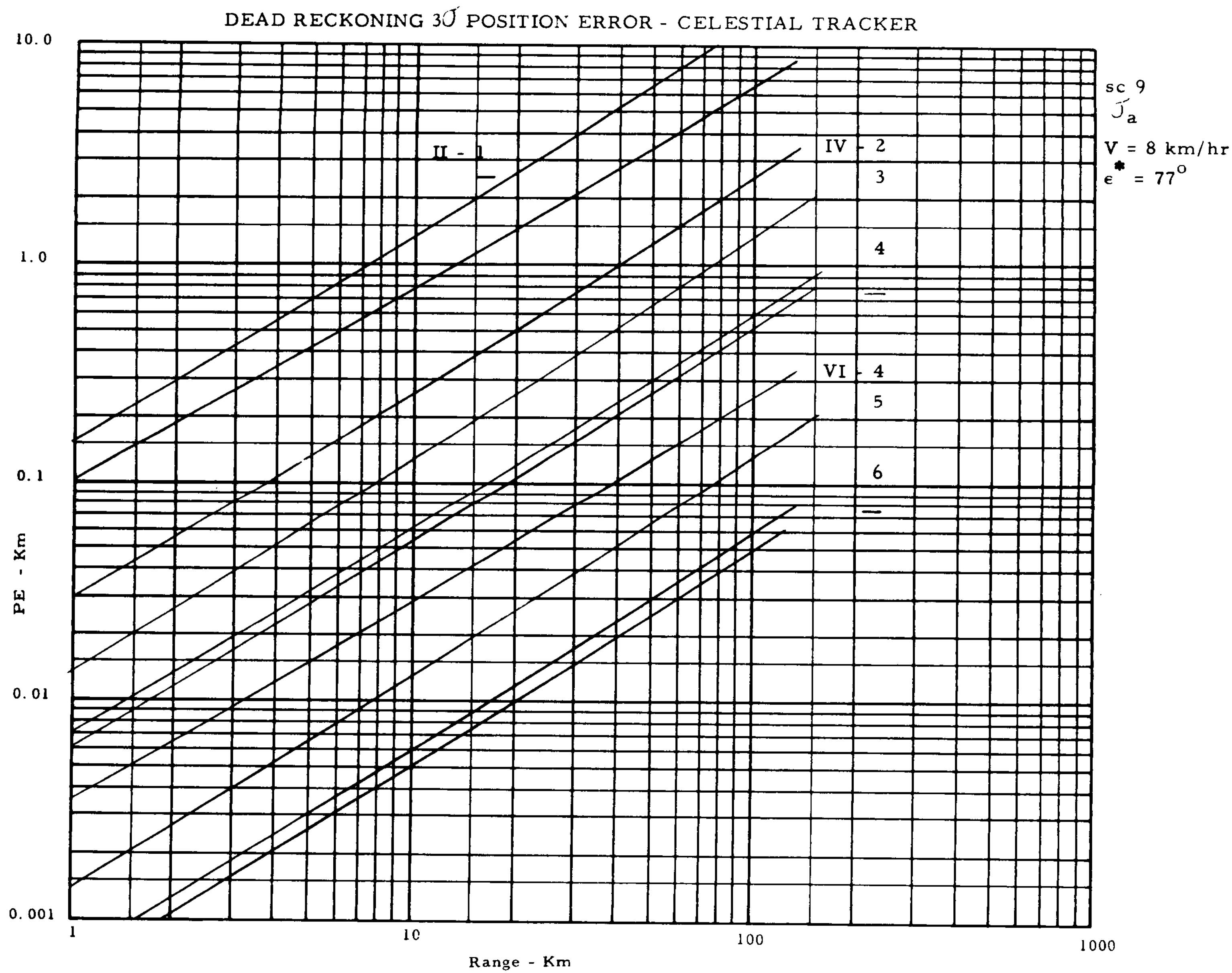


Figure 10-215 Dead Reckoning 3σ Position Error — Celestial Tracker

DEAD RECKONING 3σ POSITION ERROR - VERTICAL SENSOR

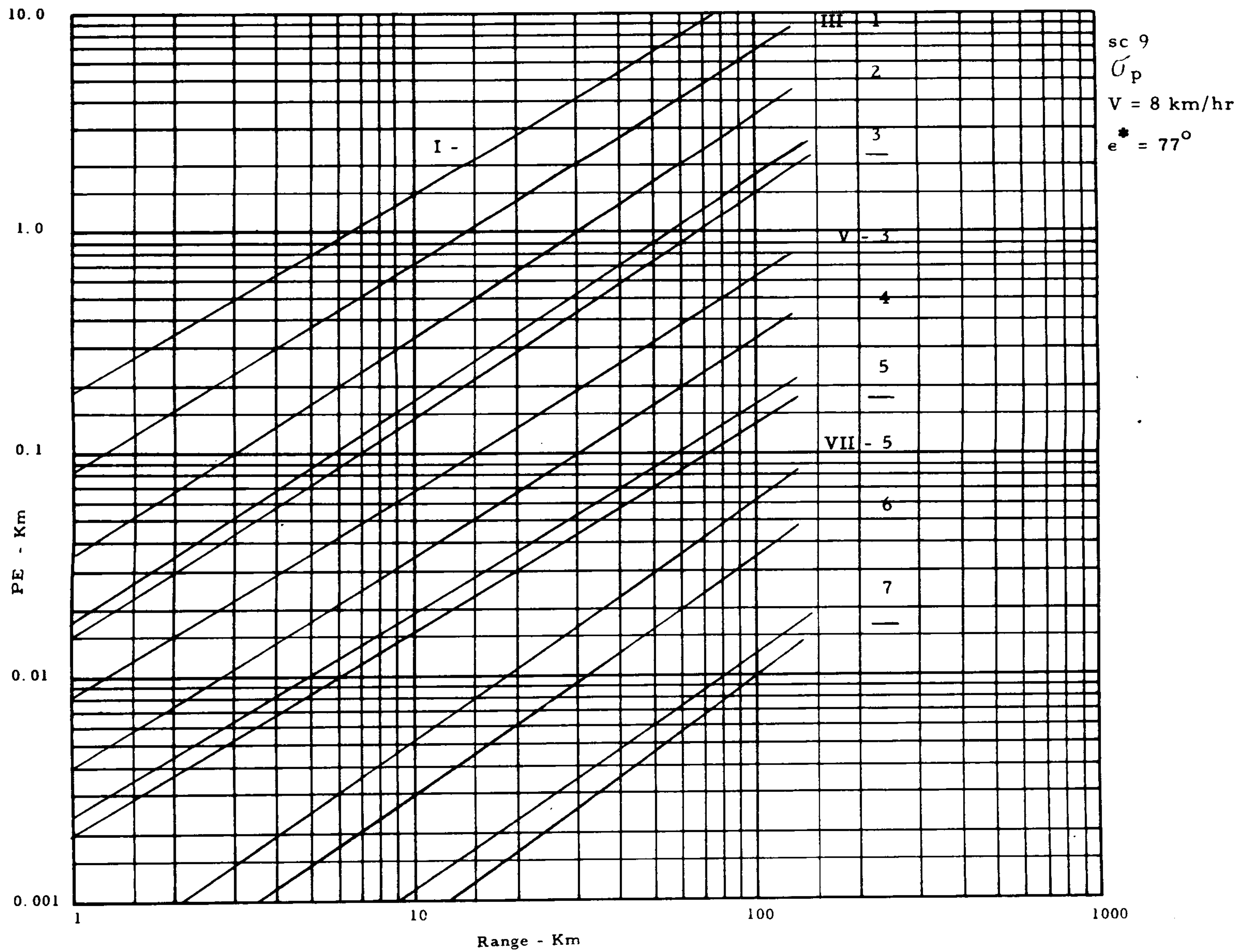


Figure 10-216 Dead Reckoning 3σ Position Error - Vertical Sensor

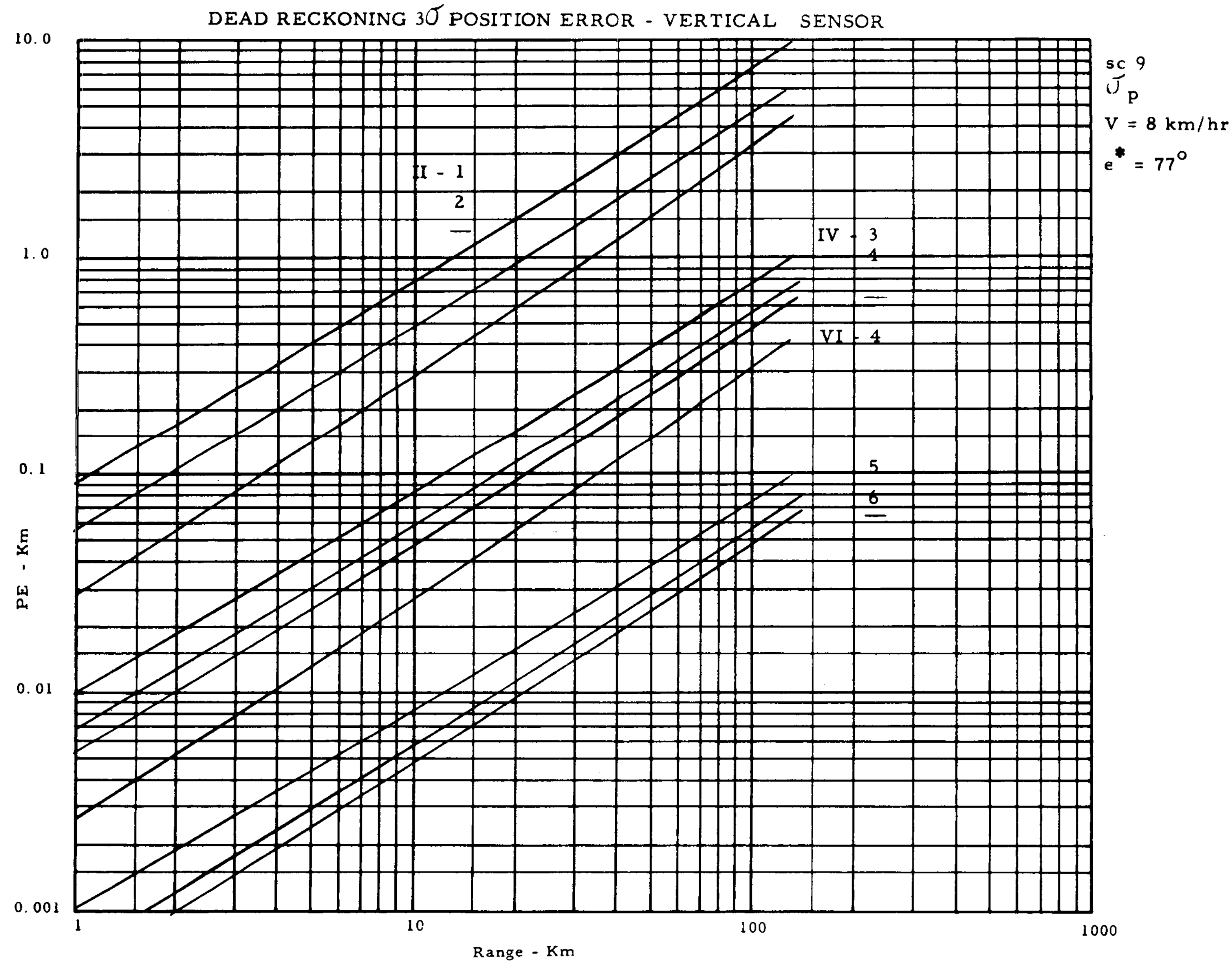


Figure 10-217 Dead Reckoning 3σ Position Error - Vertical Sensor

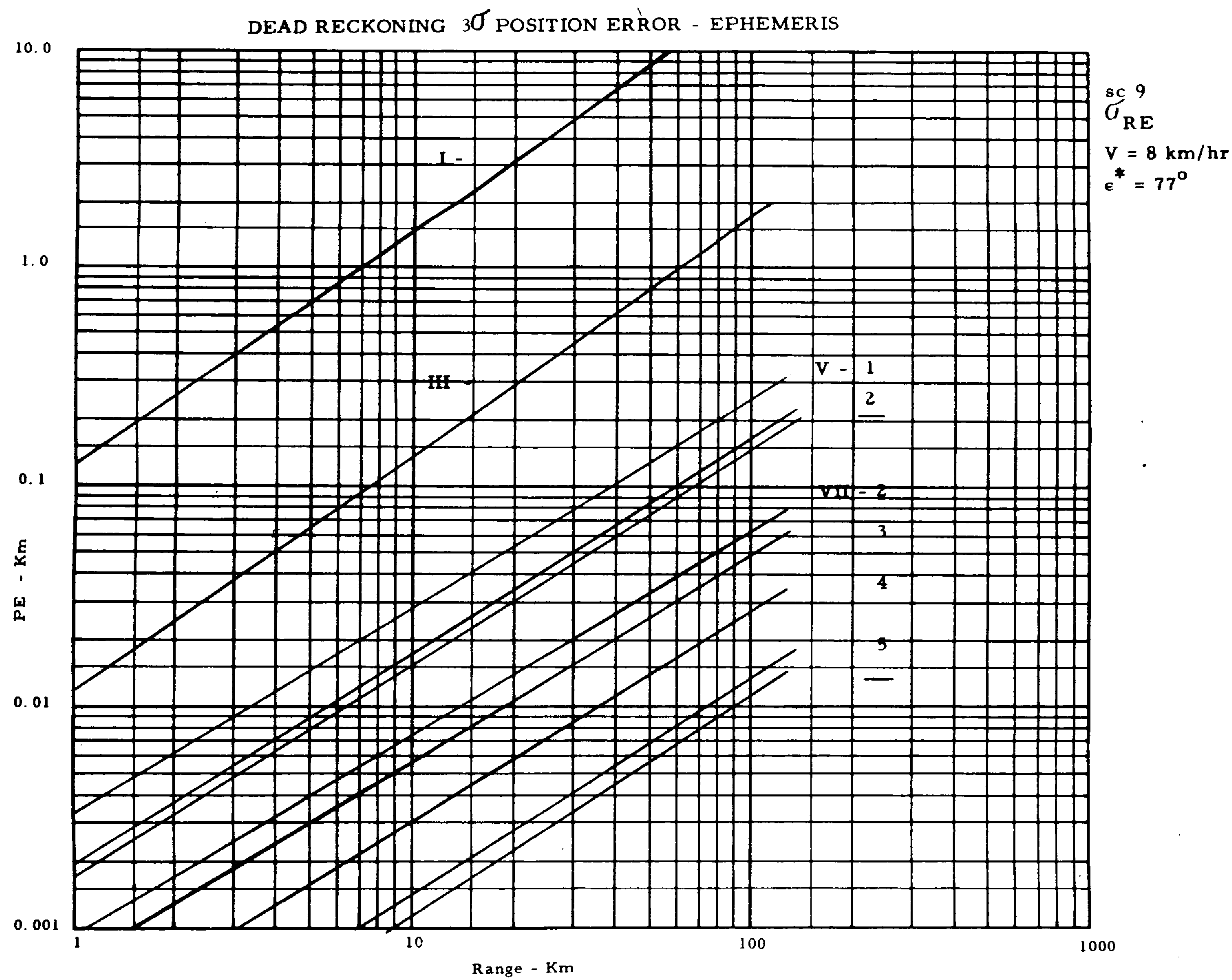


Figure 10-218 Dead Reckoning 3σ Position Error - Ephemeris

DEAD RECKONING 3σ POSITION ERROR - EPHEMERIS

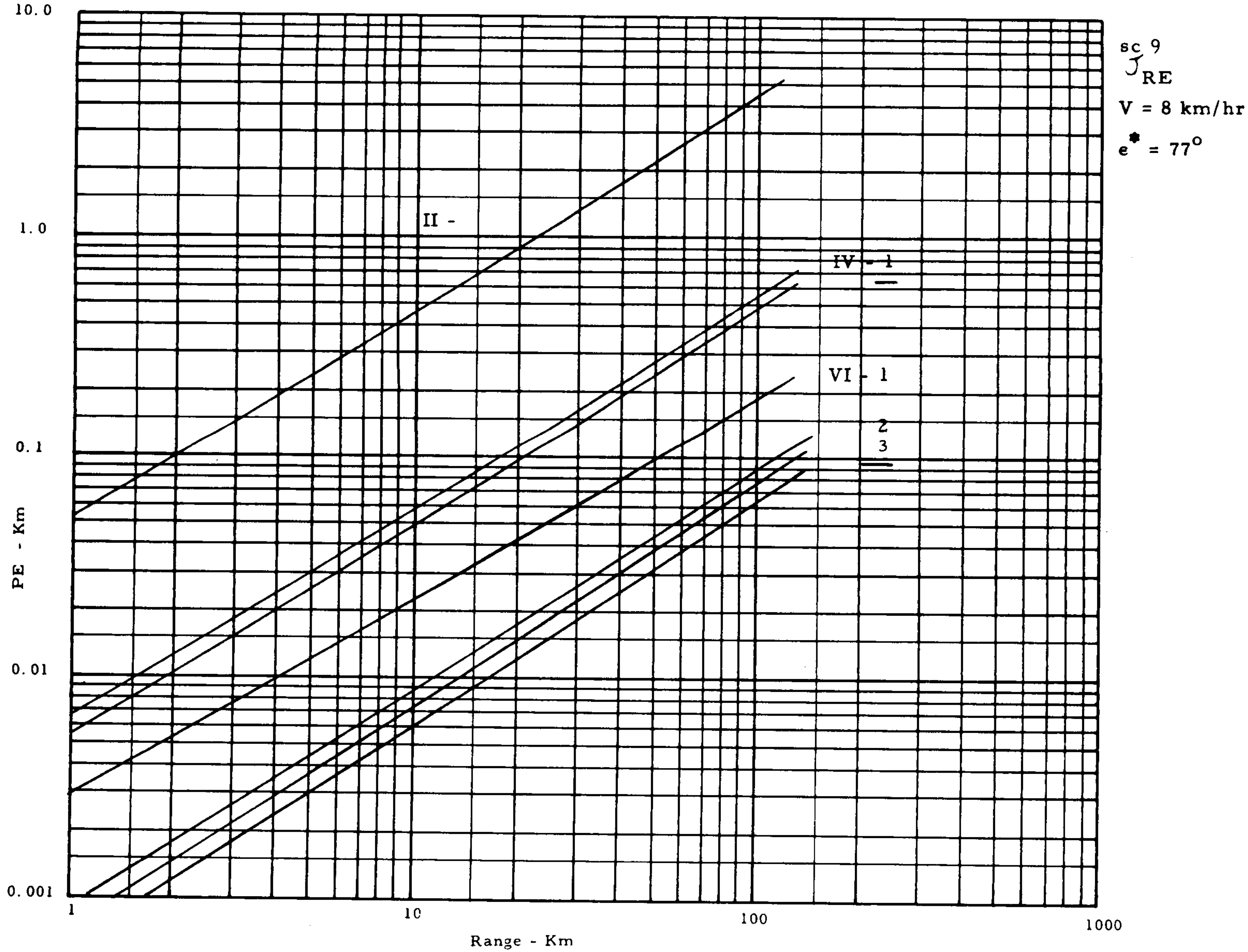


Figure 10-219 Dead Reckoning 3σ Position Error - Ephemeris

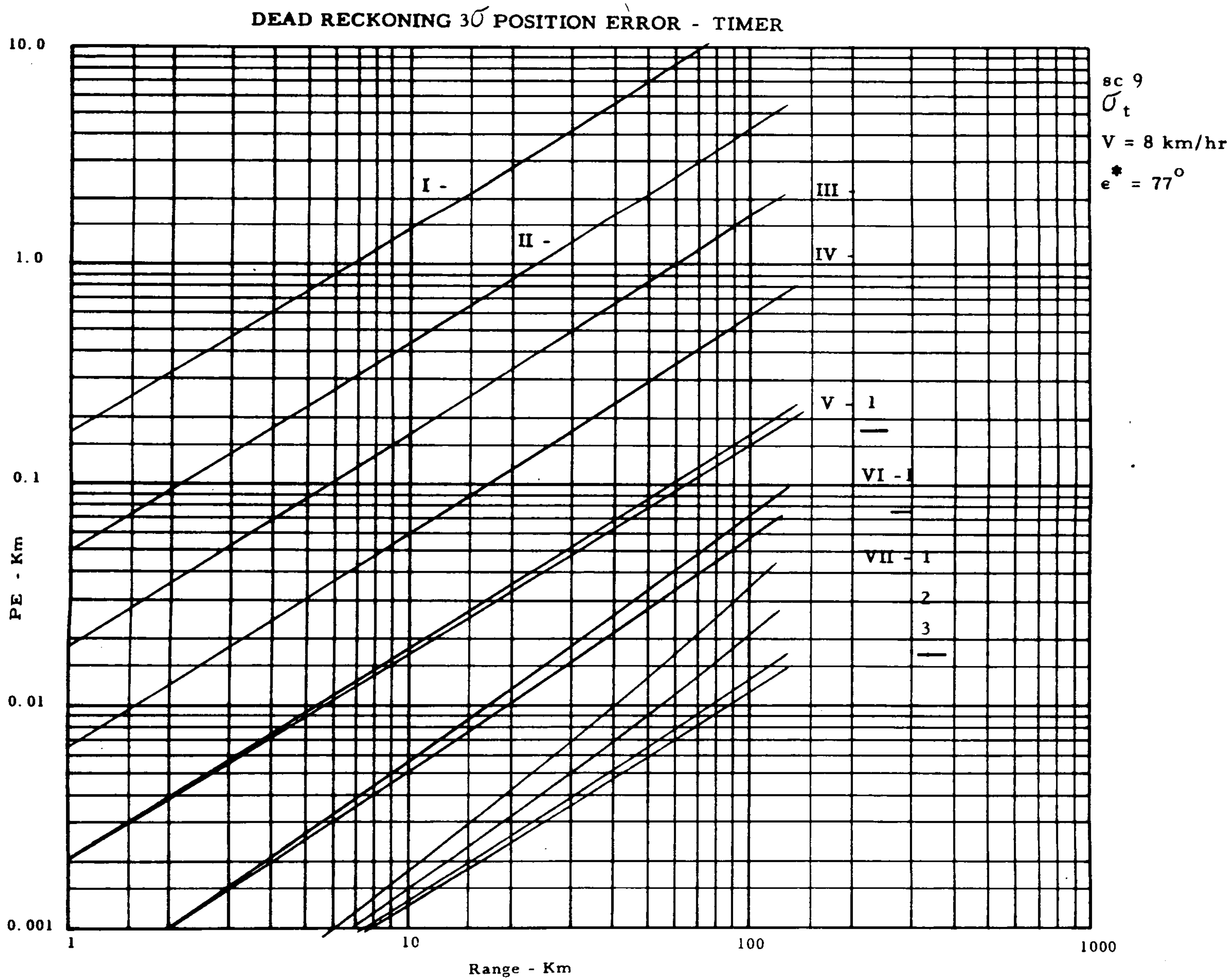


Figure 10-220 Dead Reckoning 3σ Position Error - Timer

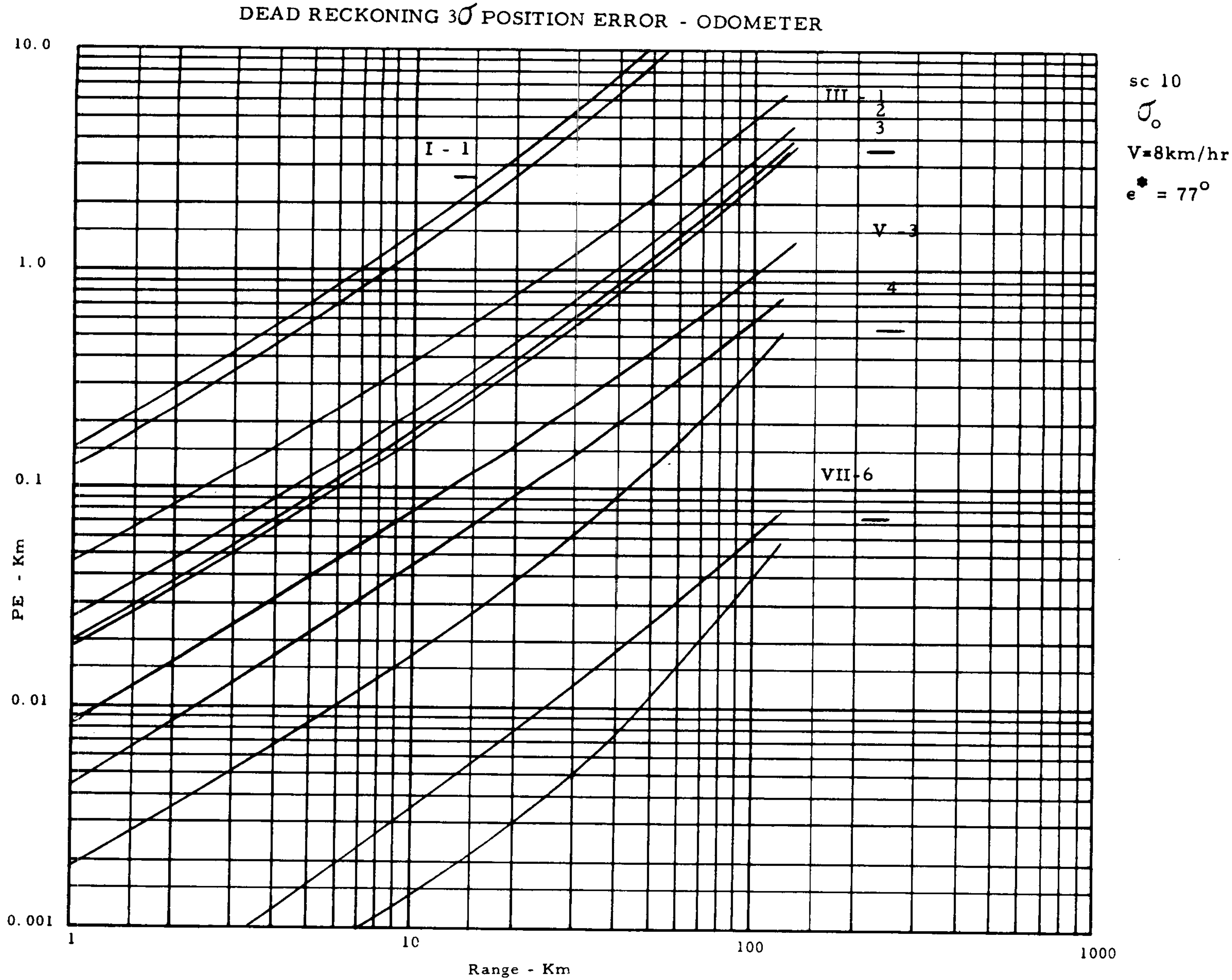


Figure 10-221 Dead Reckoning 3σ Position Error - Odometer

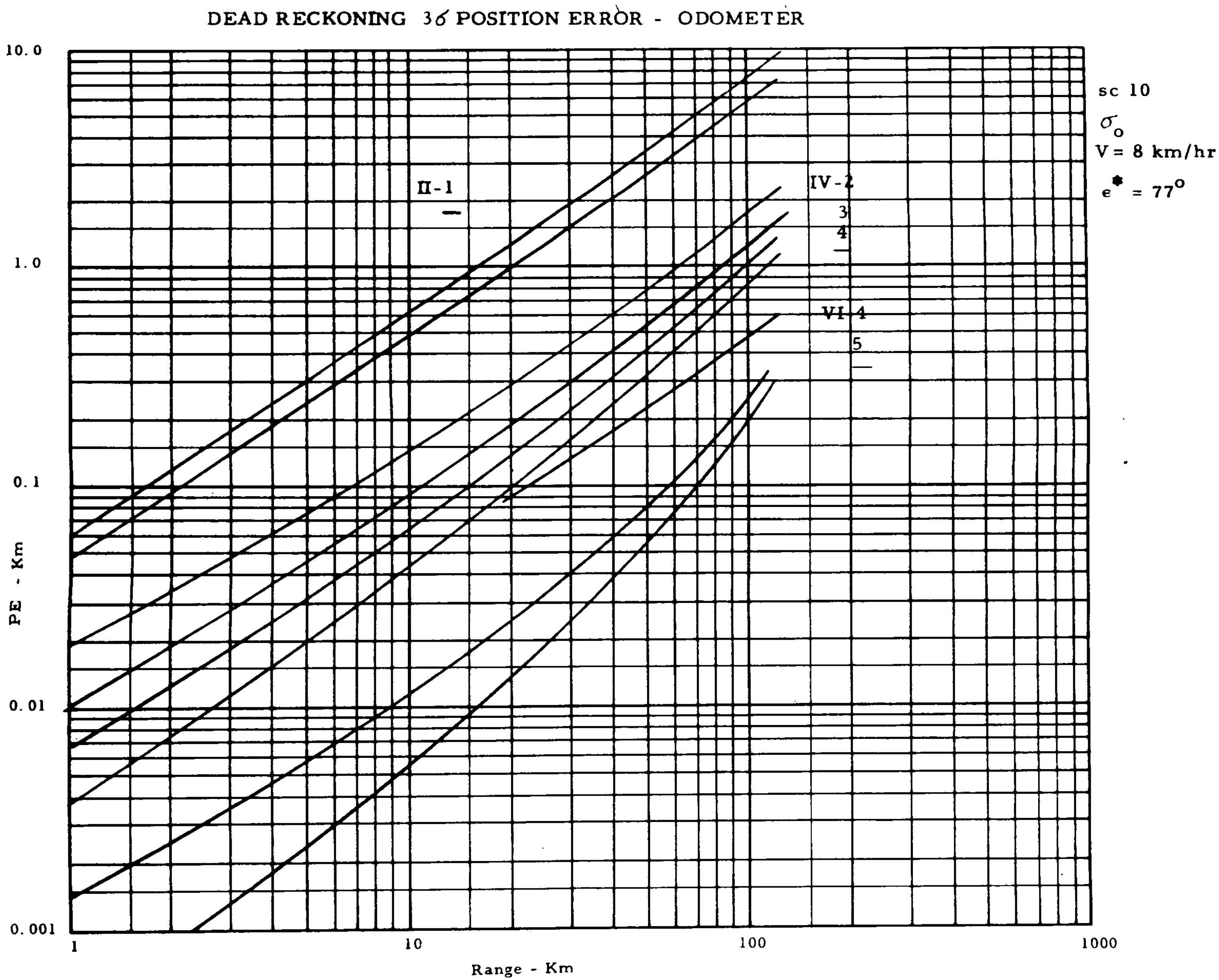


Figure 10-222 Dead Reckoning 3σ Position Error - Odometer

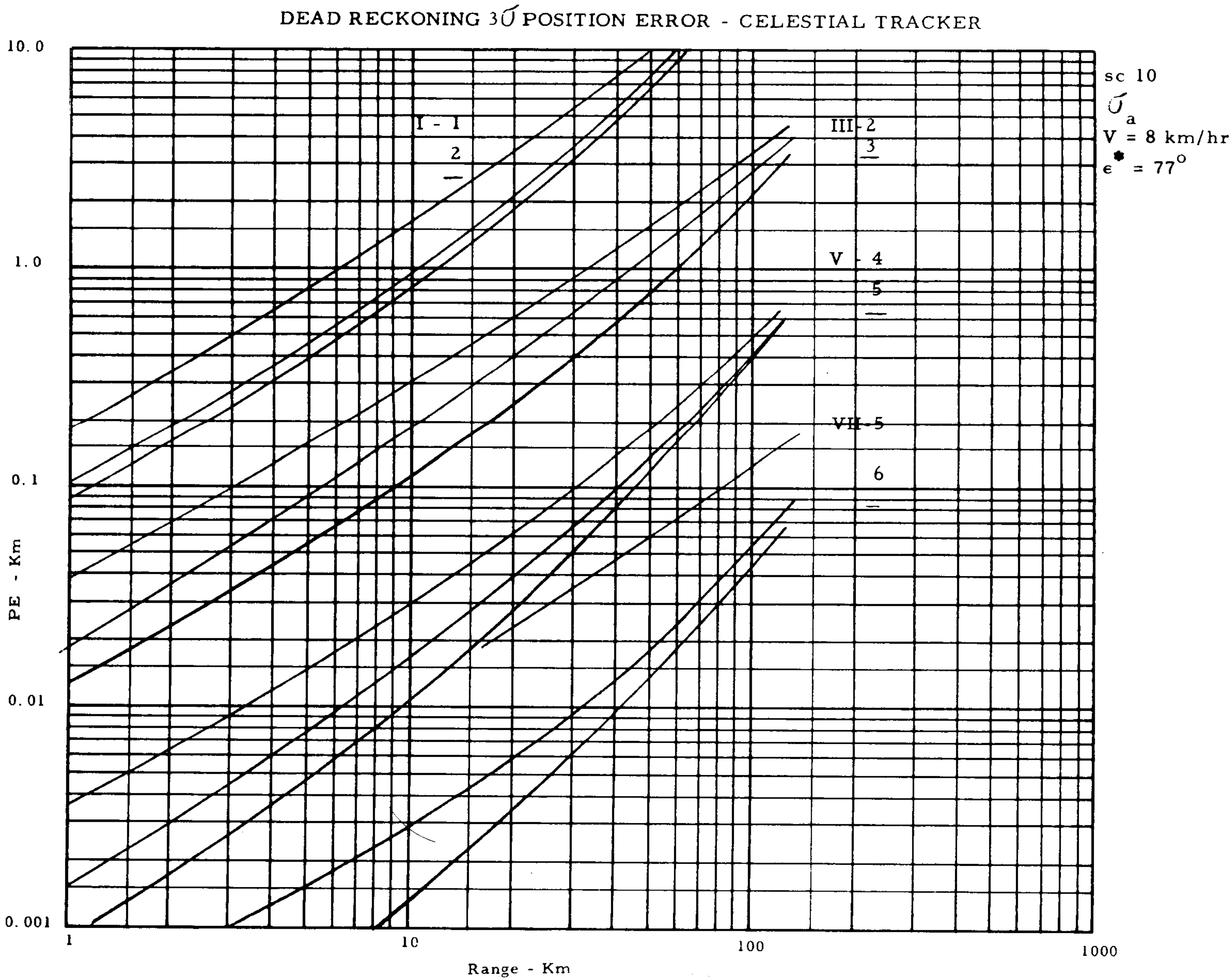


Figure 10-223 Dead Reckoning 3σ Position Error - Celestial Tracker

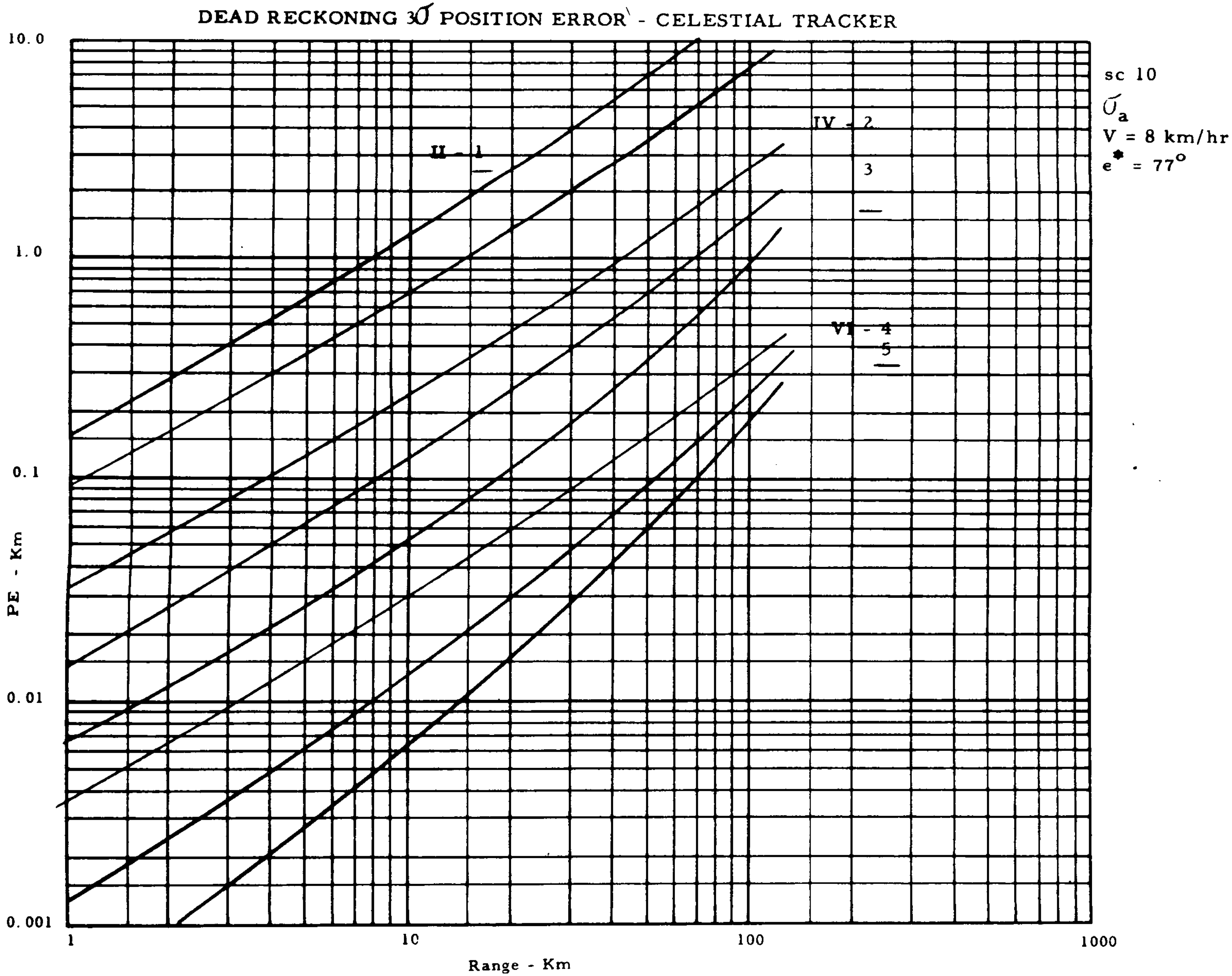


Figure 10-224 Dead Reckoning 3σ Position Error - Celestial Tracker

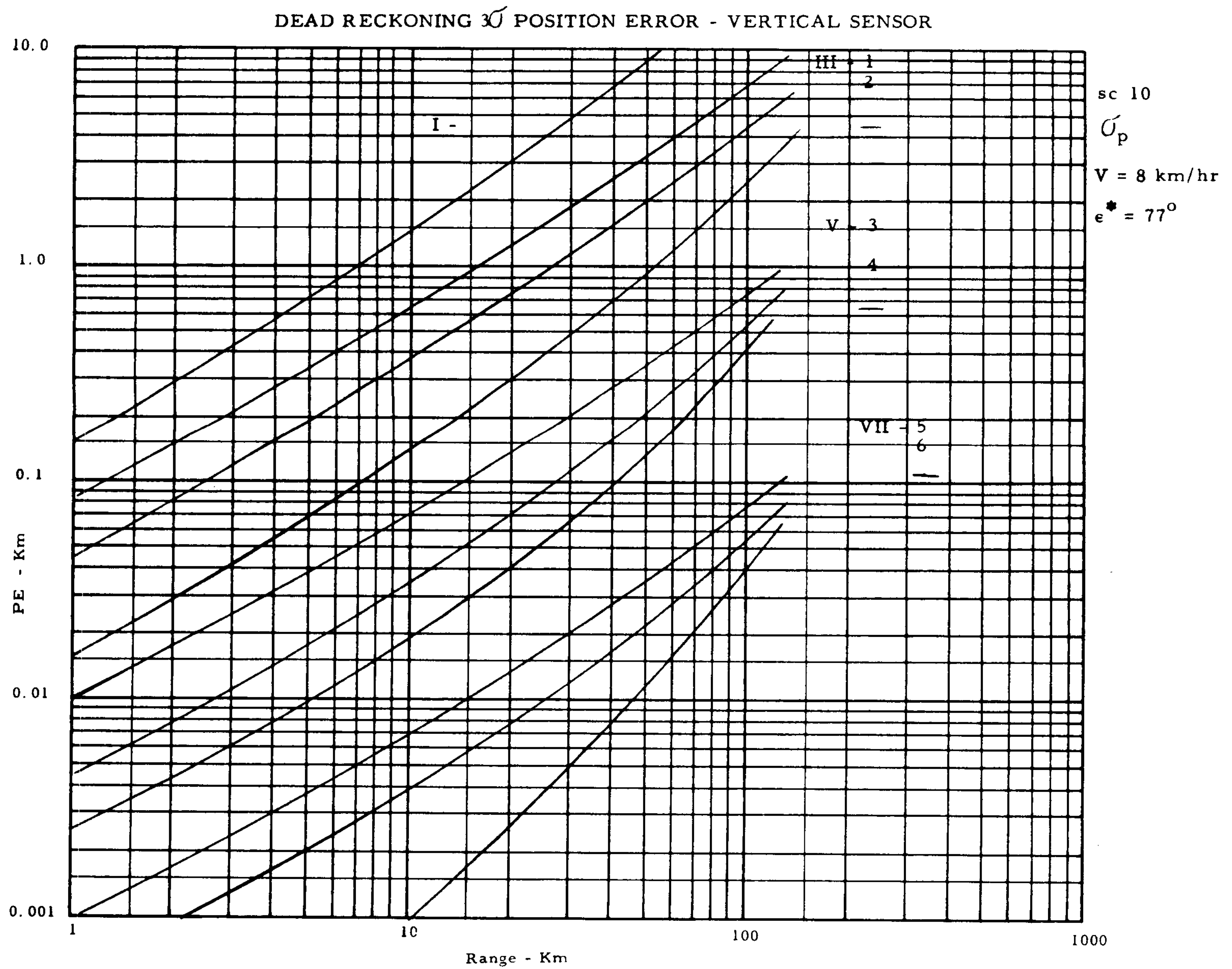


Figure 10-225 Dead Reckoning 3σ Position Error - Vertical Sensor

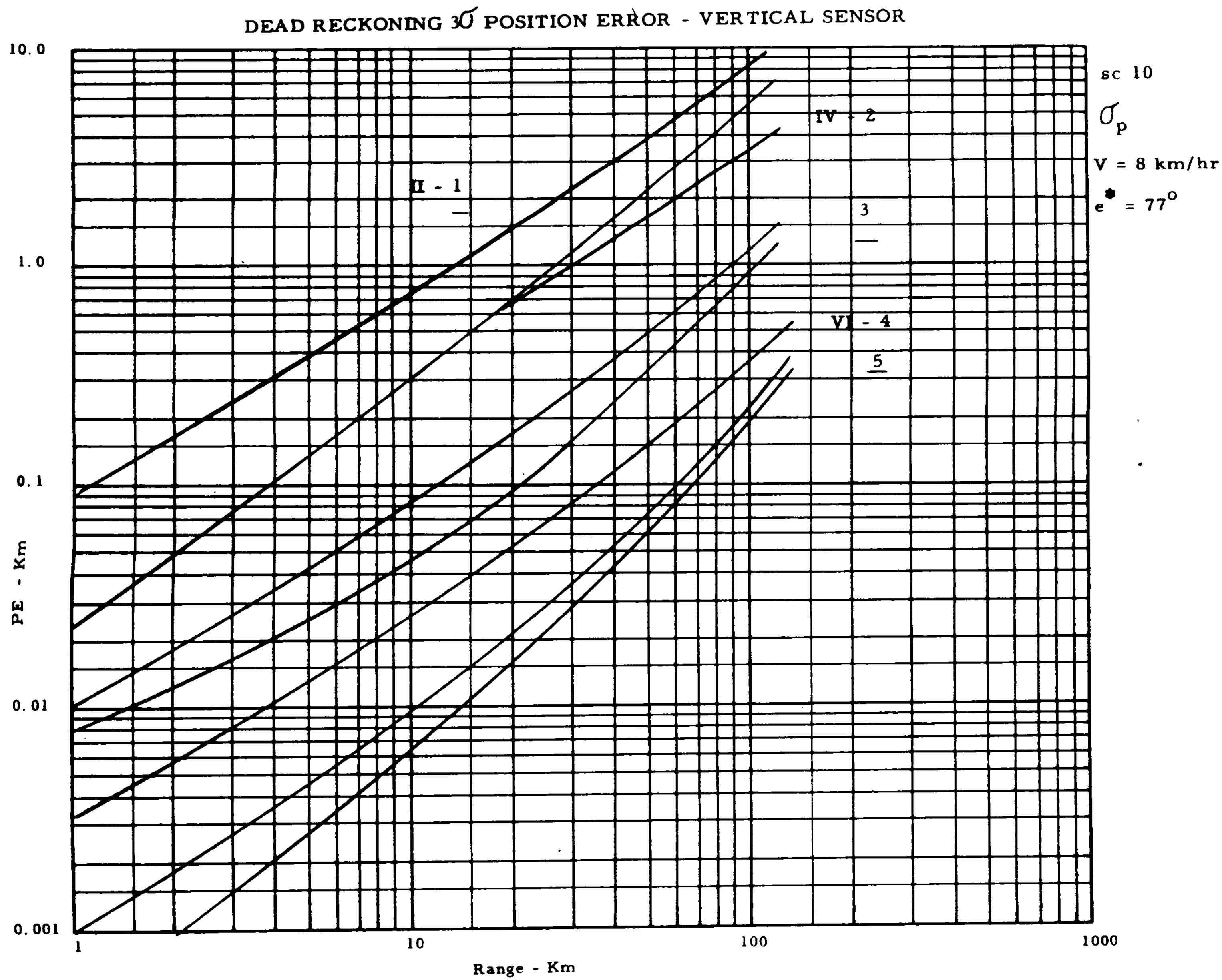


Figure 10-226 Dead Reckoning 3σ Position Error - Vertical Sensor

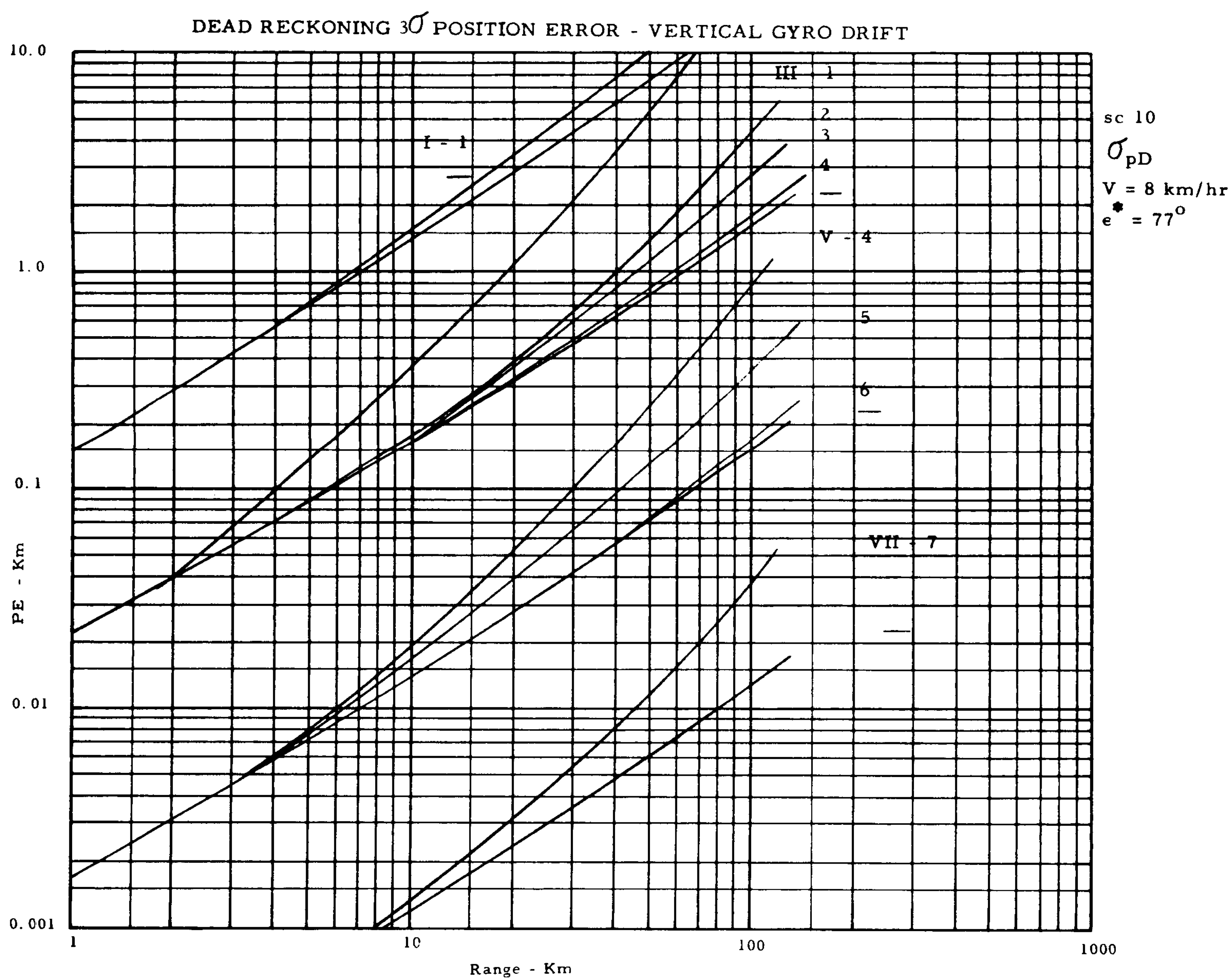


Figure 10-227 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

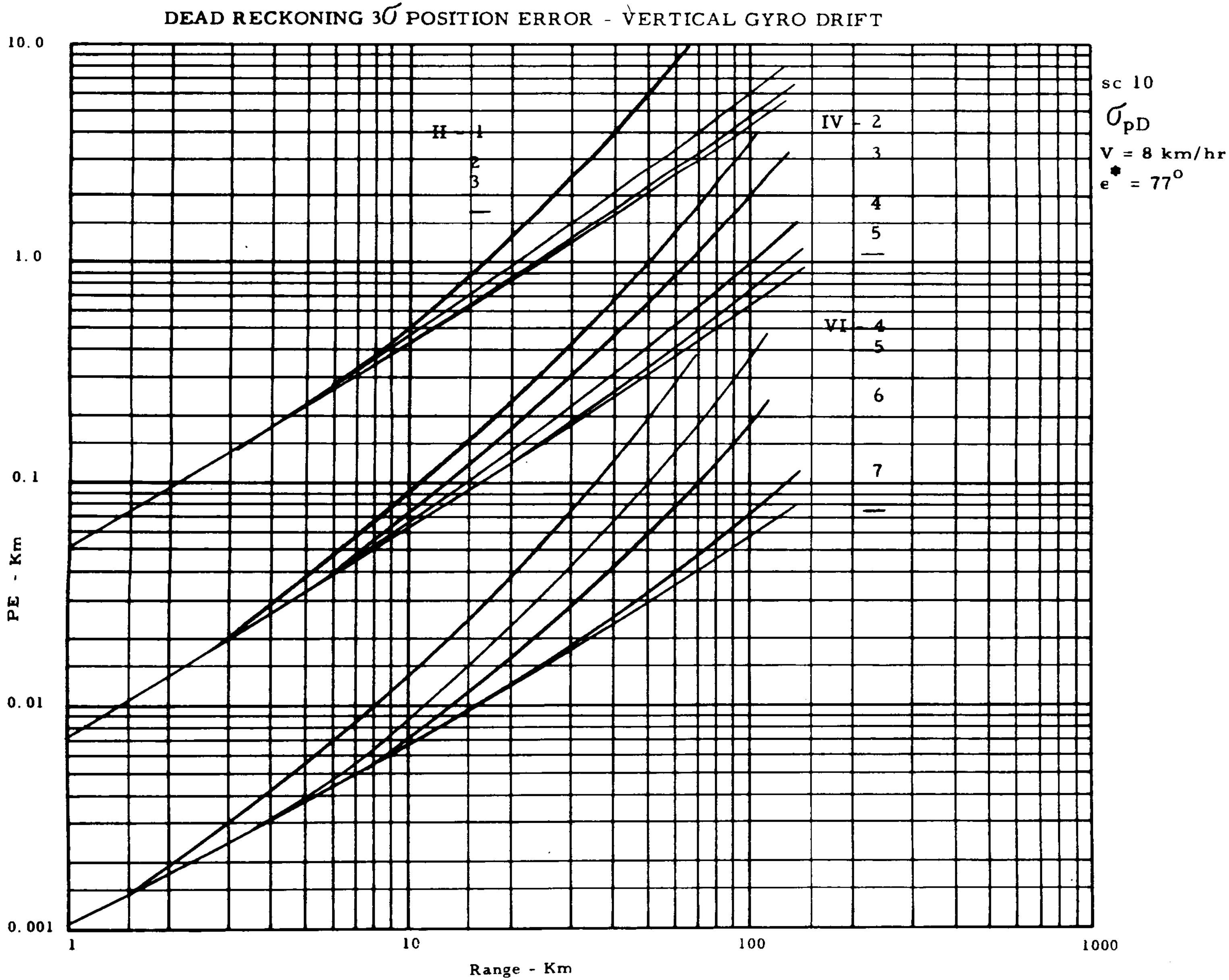


Figure 10-228 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

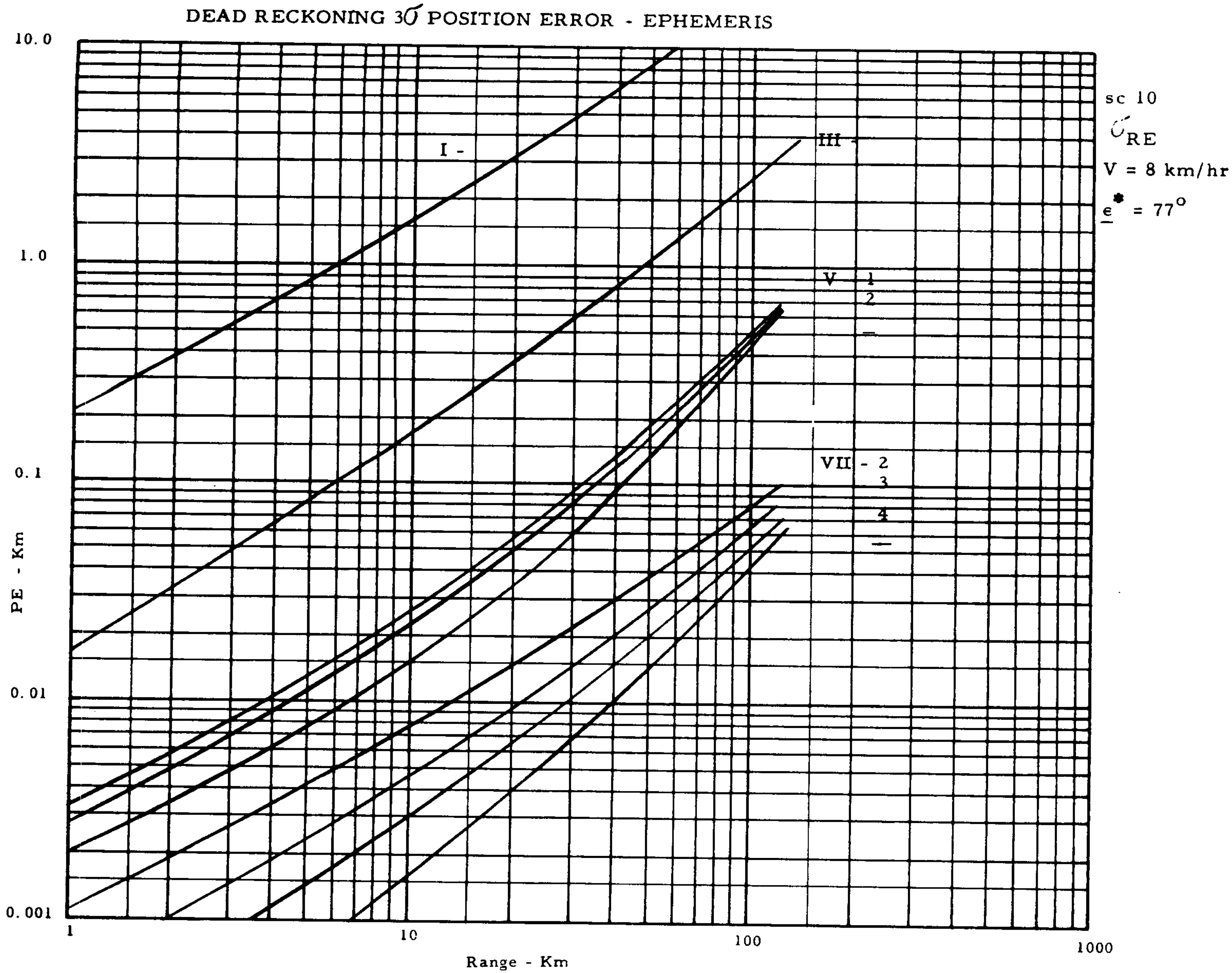


Figure 10-229 Dead Reckoning 3σ Position Error - Ephemeris

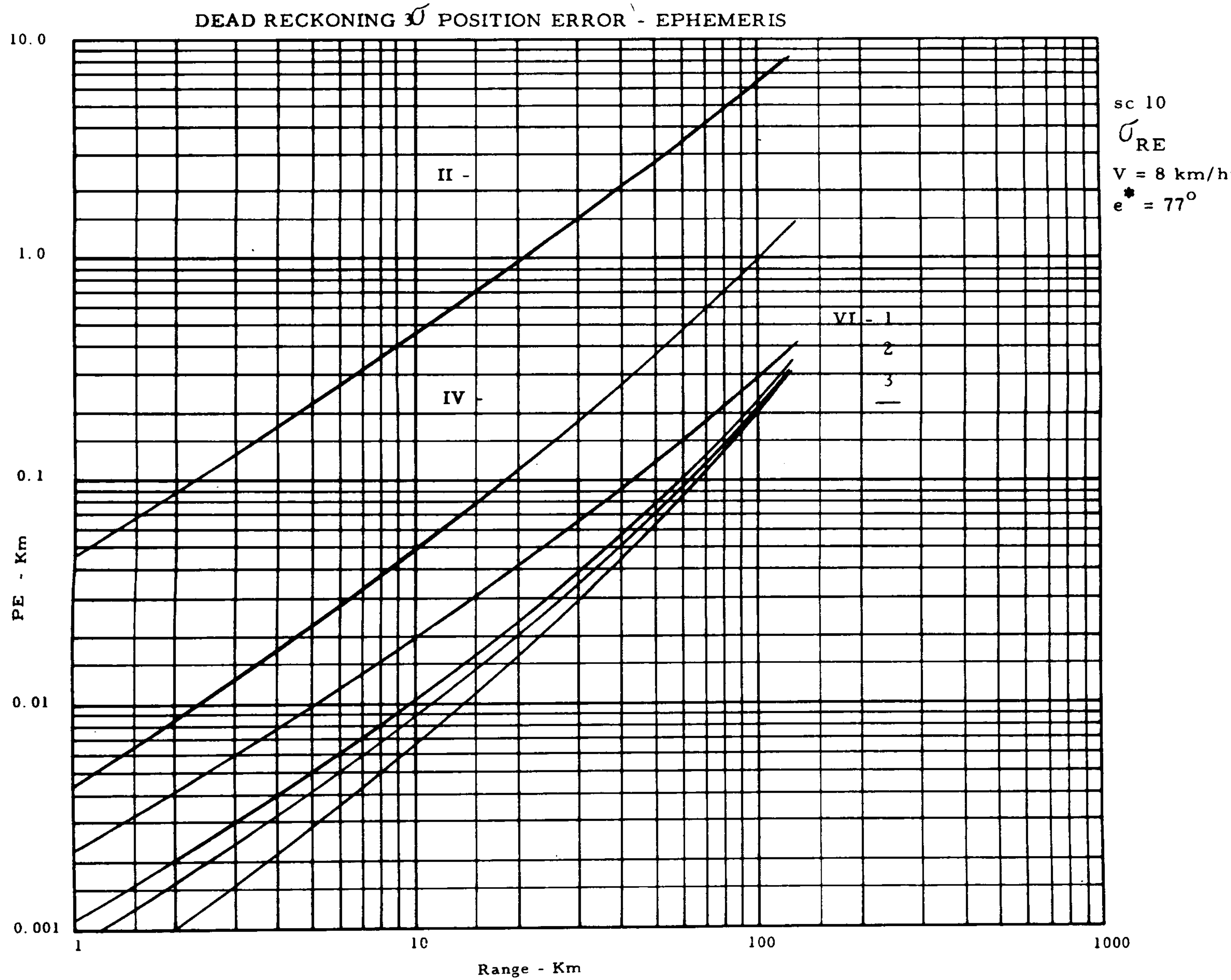


Figure 10-230 Dead Reckoning 3σ Position Error - Ephemeris

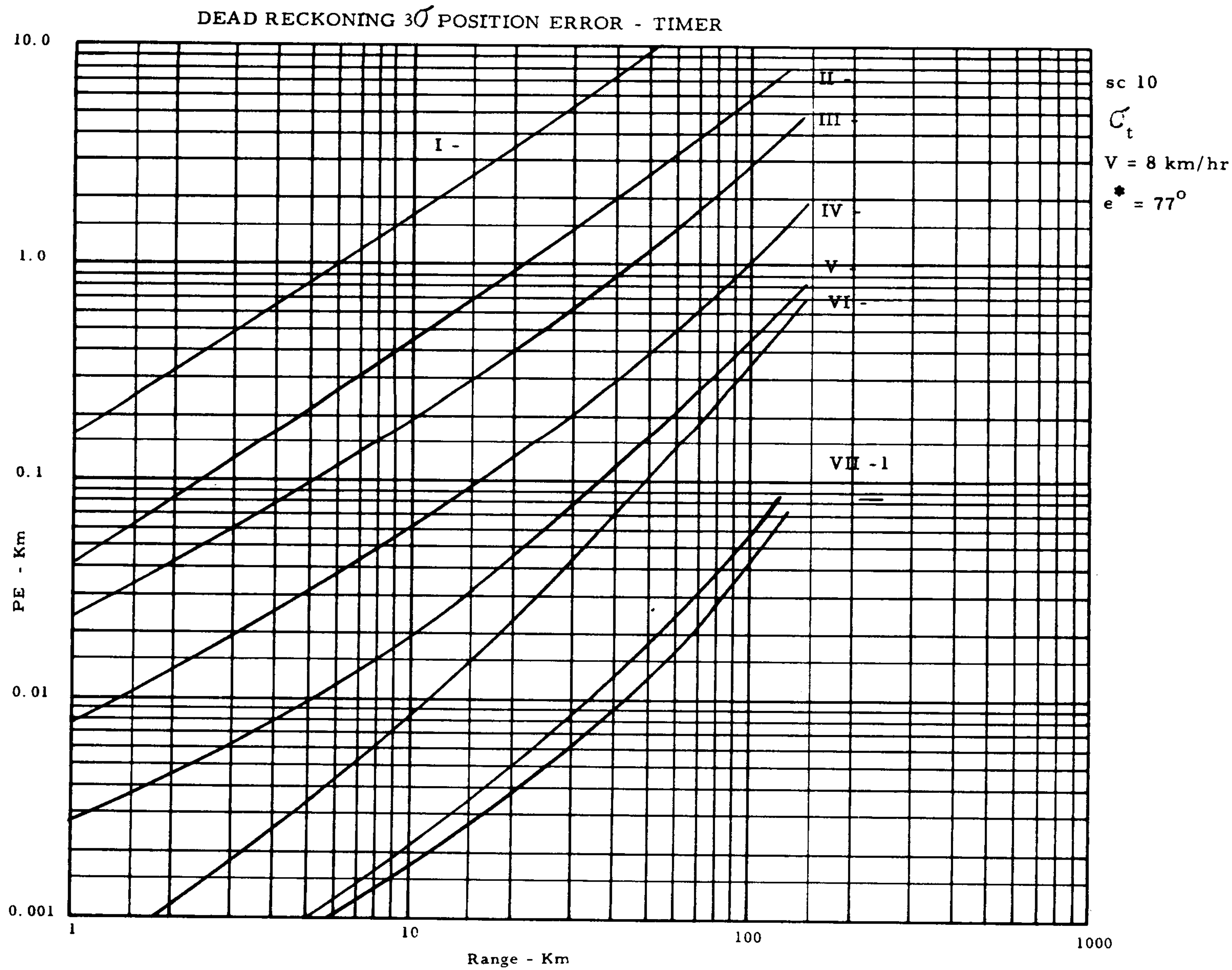


Figure 10-231 Dead Reckoning 3σ Position Error - Timer

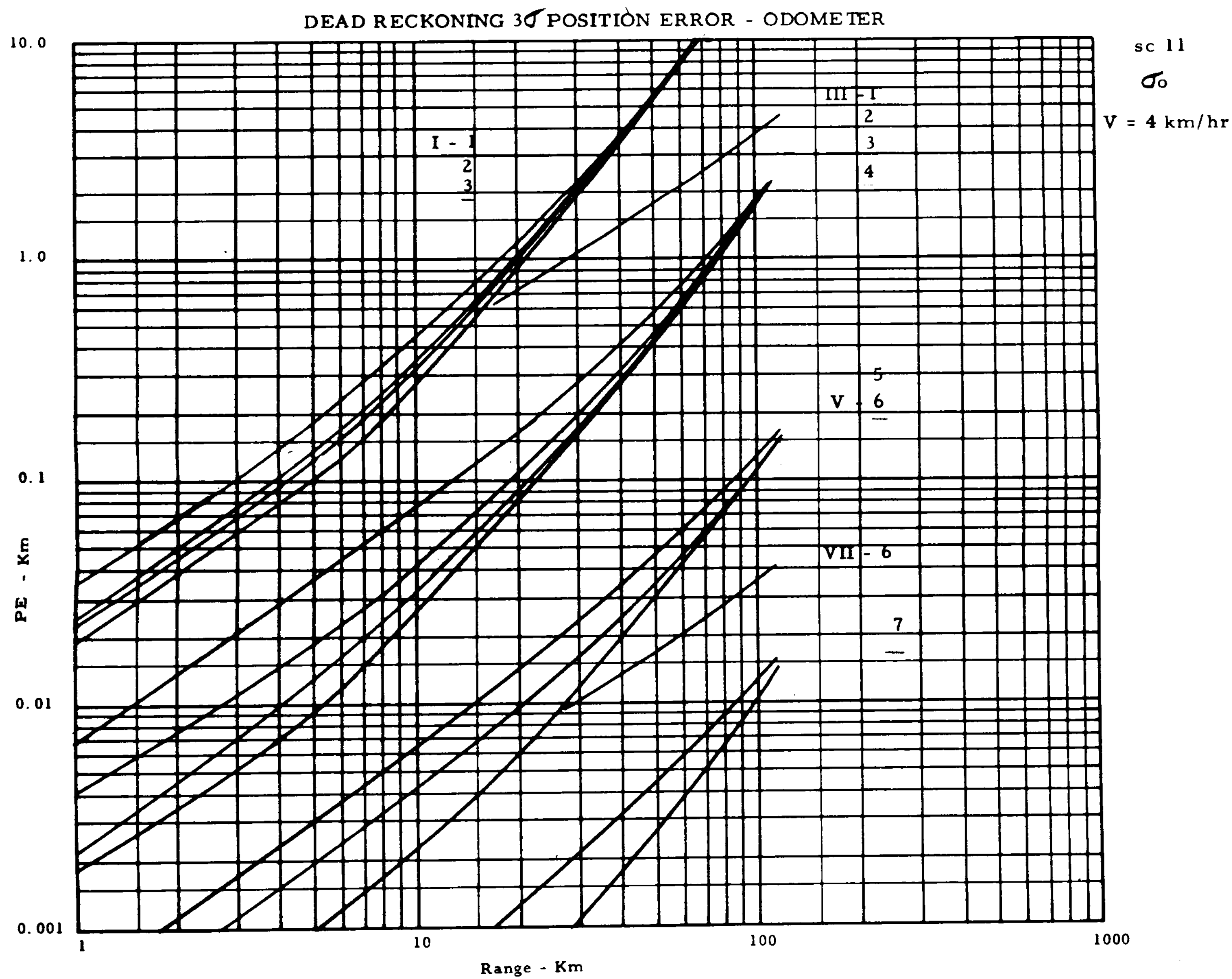


Figure 10-232 Dead Reckoning 3σ Position Error - Odometer

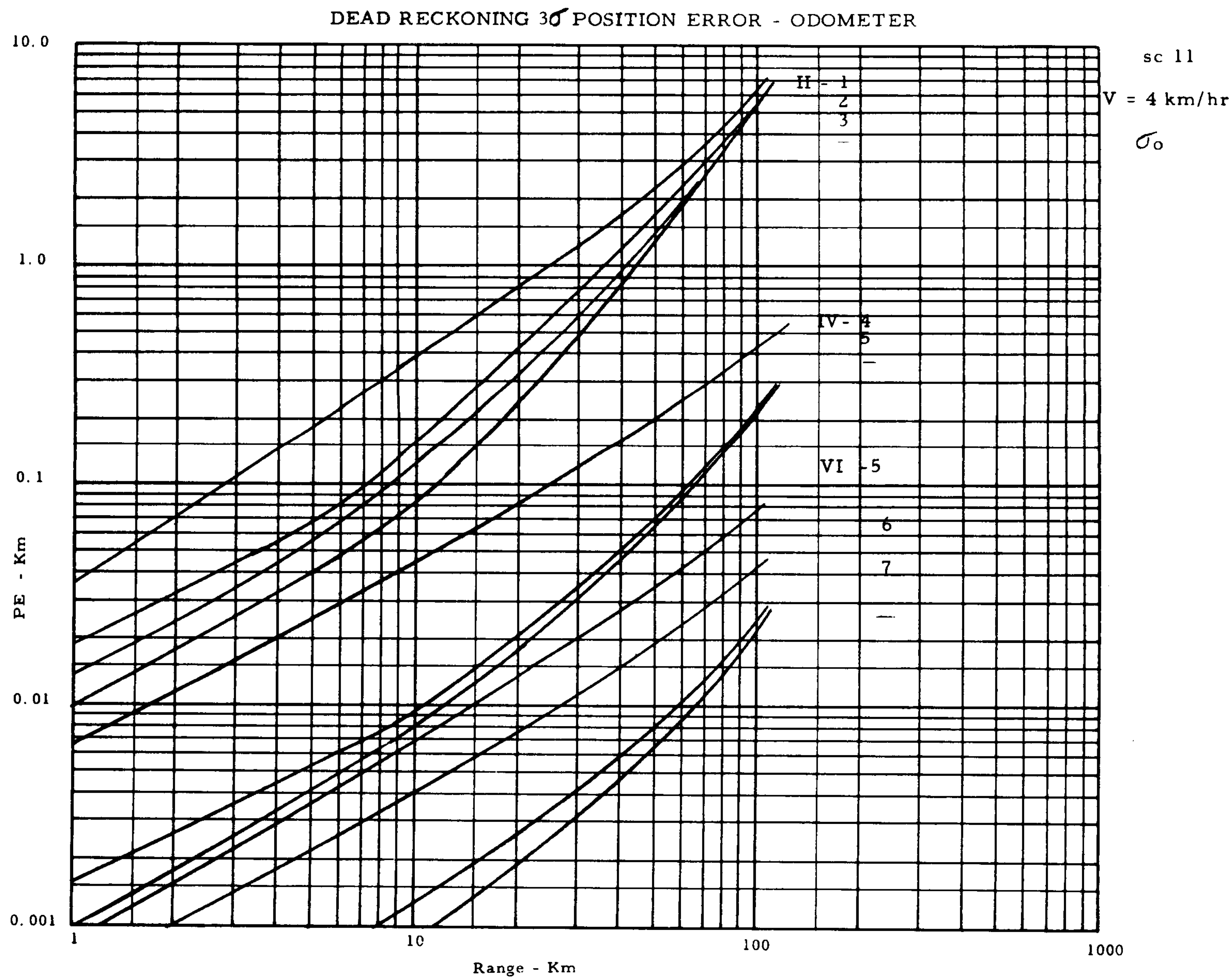


Figure 10-233 Dead Reckoning 3σ Position Error - Odometer

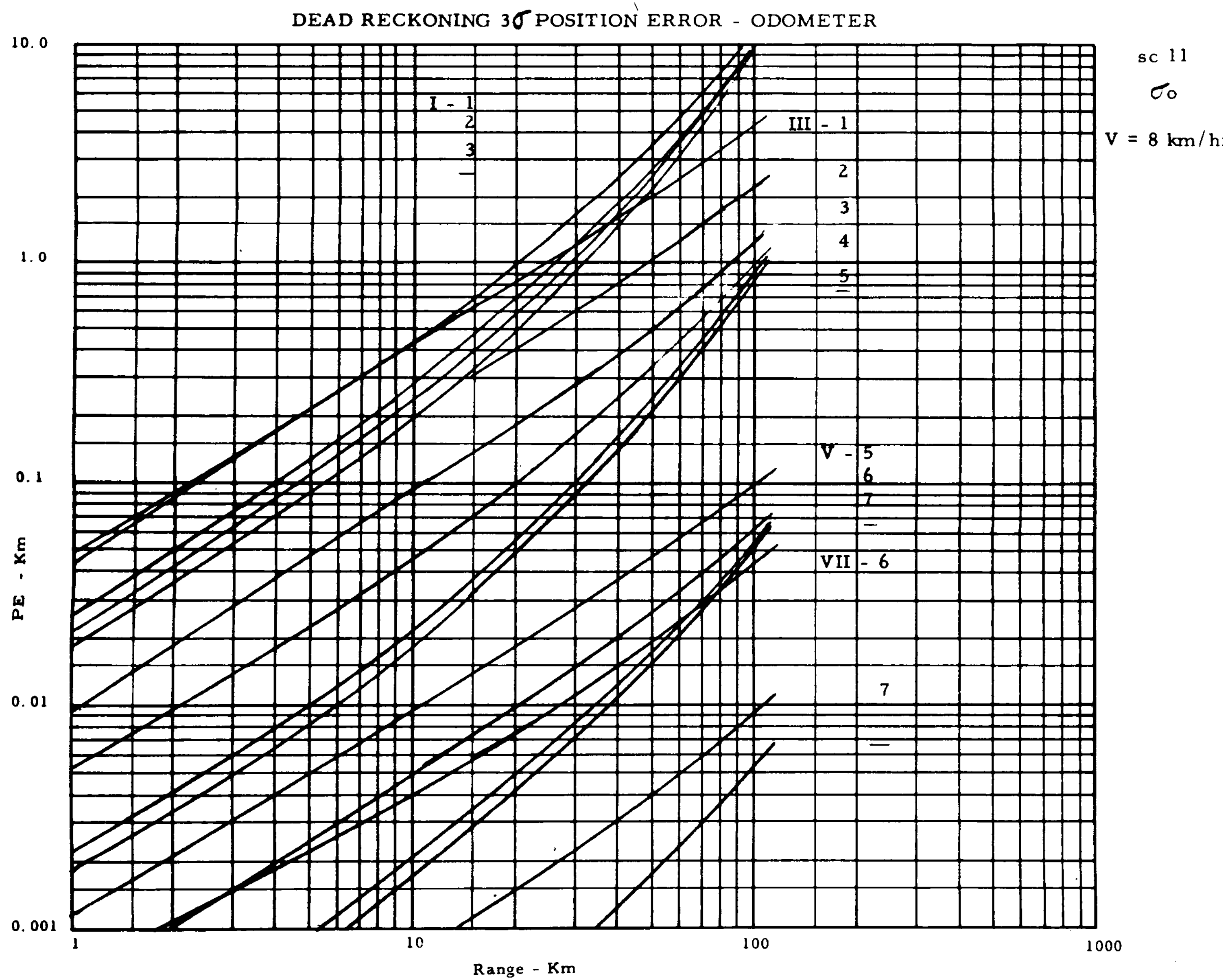


Figure 10-234 Dead Reckoning 3σ Position Error - Odometer

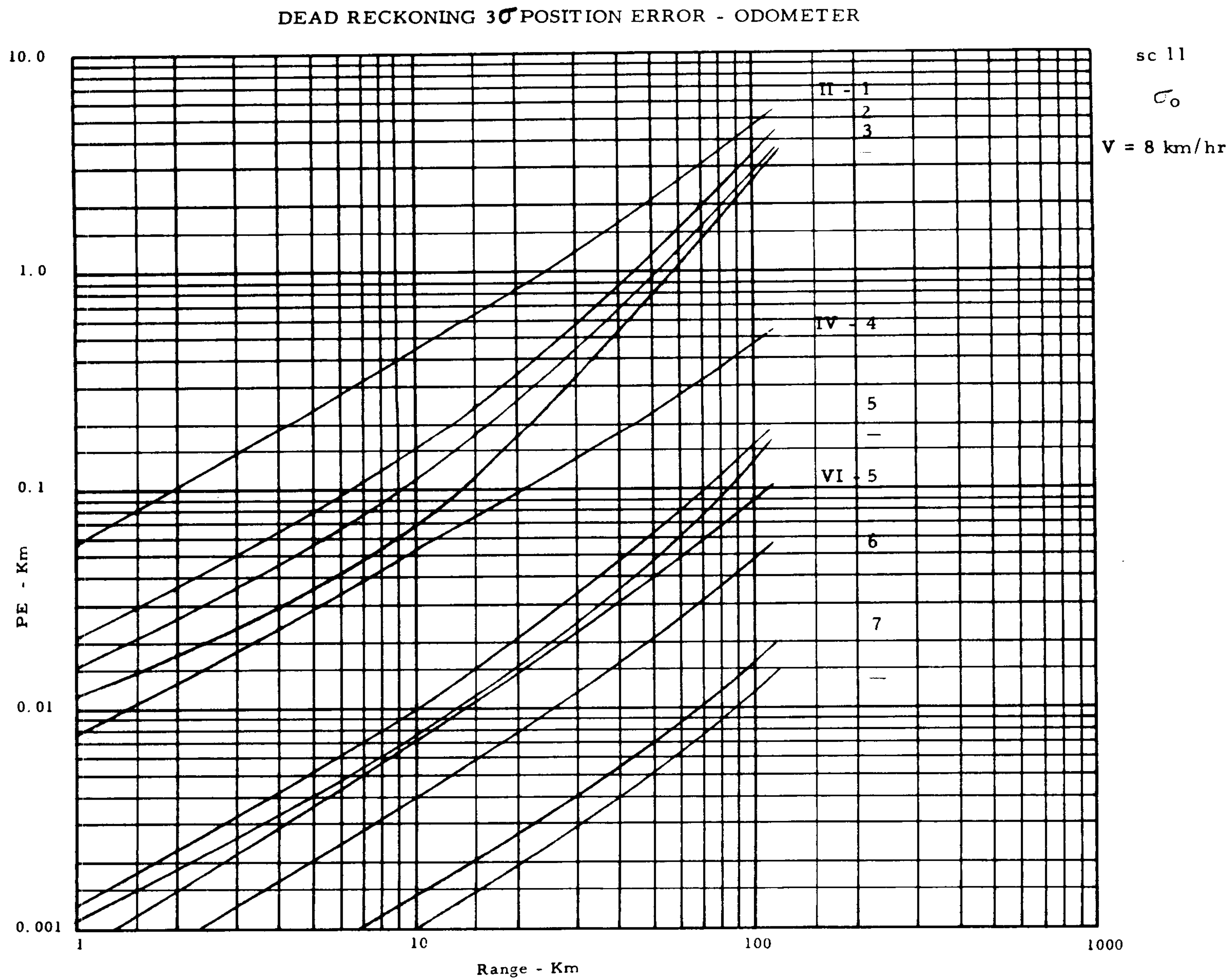


Figure 10-235 Dead Reckoning 3σ Position Error - Odometer

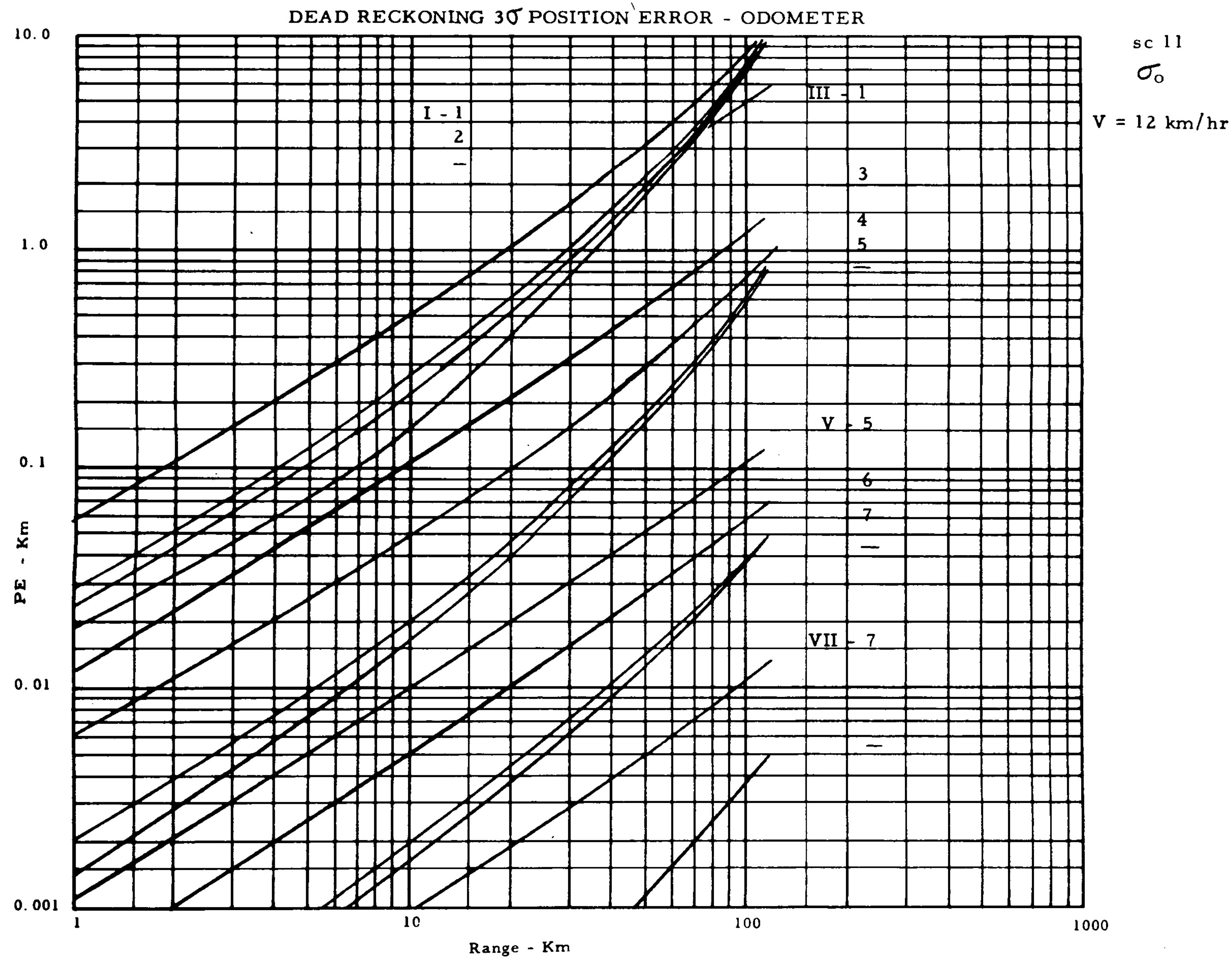


Figure 10-236 Dead Reckoning 3σ Position Error - Odometer

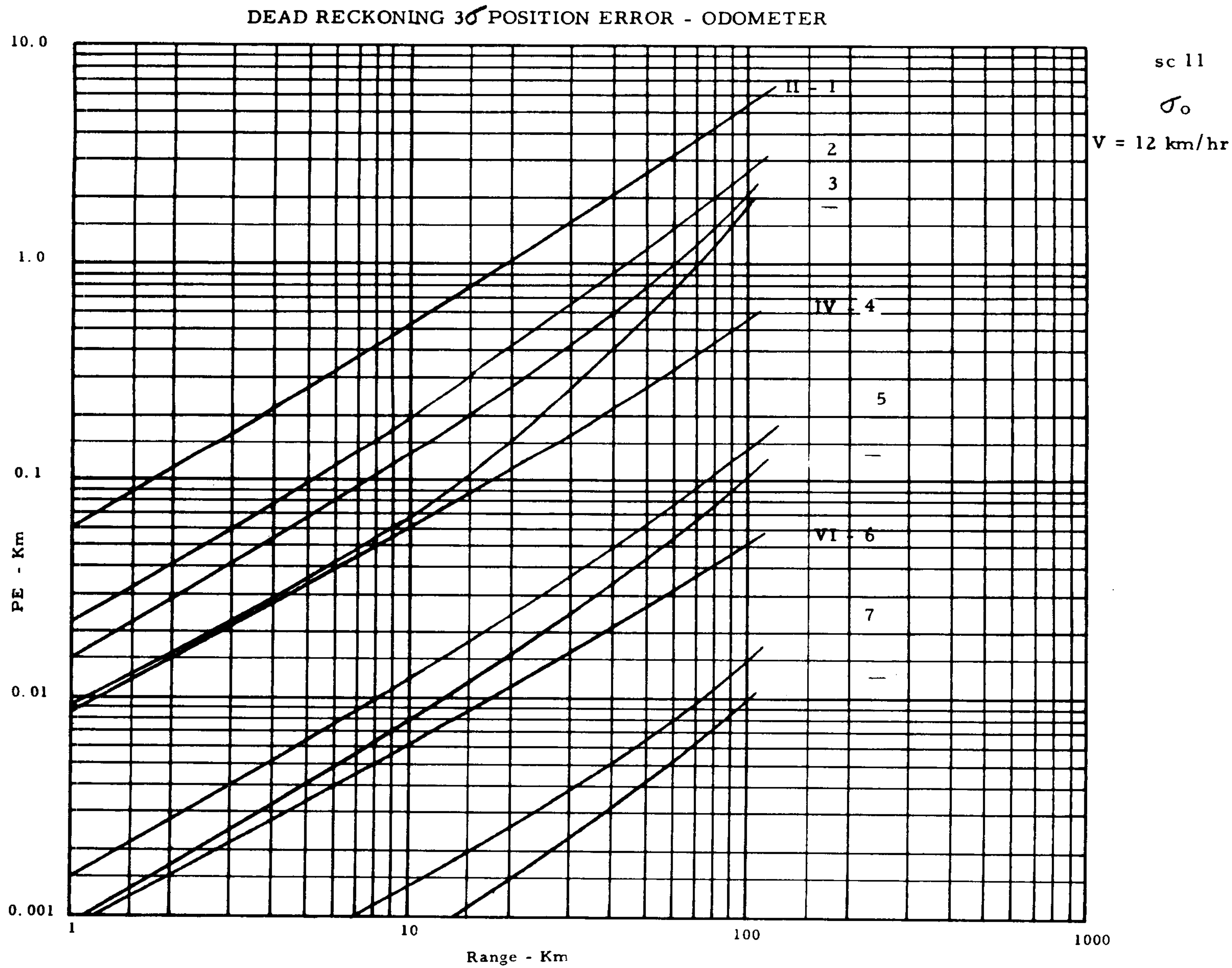


Figure 10-237 Dead Reckoning 3σ Position Error - Odometer

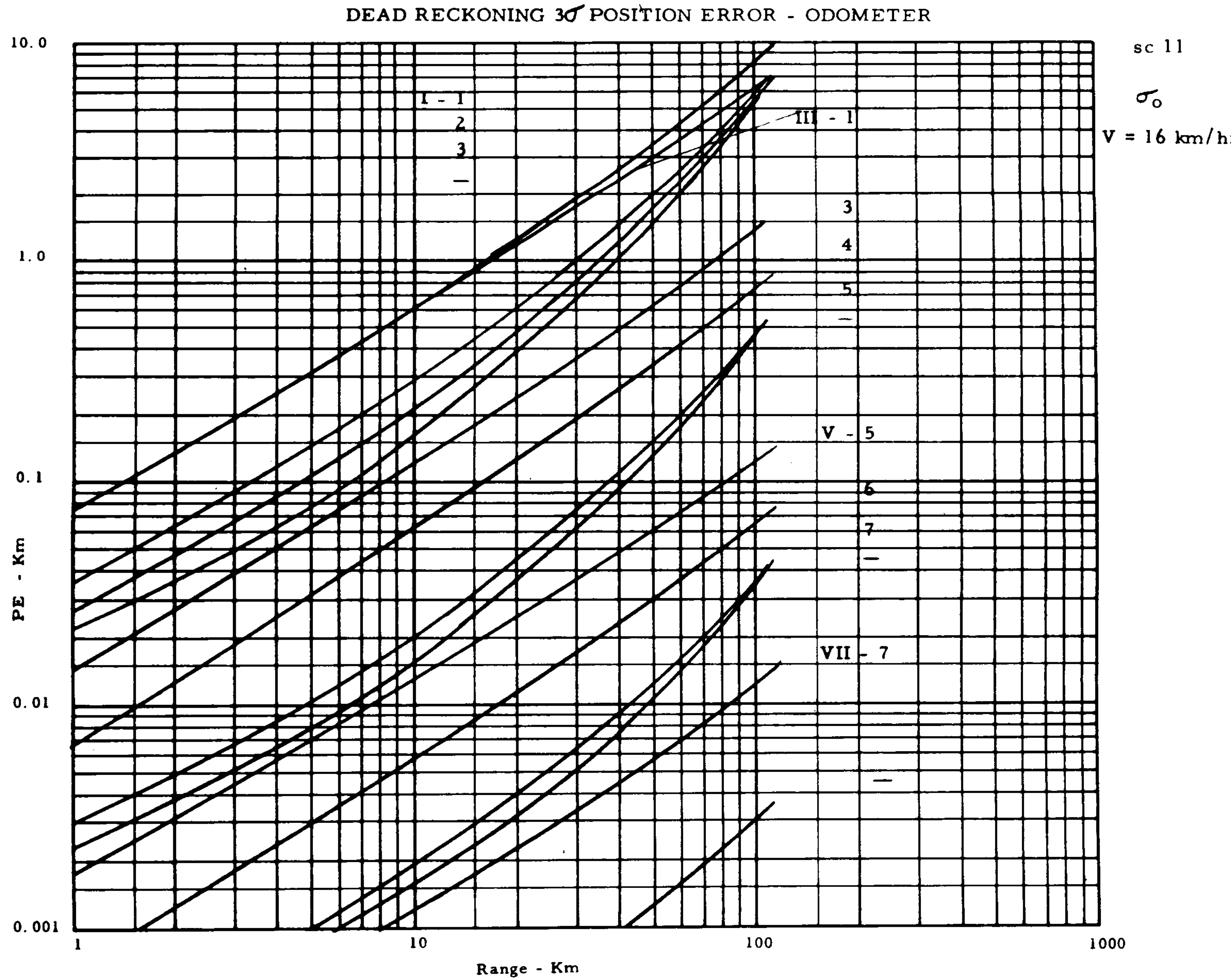


Figure 10-238 Dead Reckoning 3σ Position Error - Odometer

DEAD RECKONING 3σ POSITION ERROR - ODOMETER

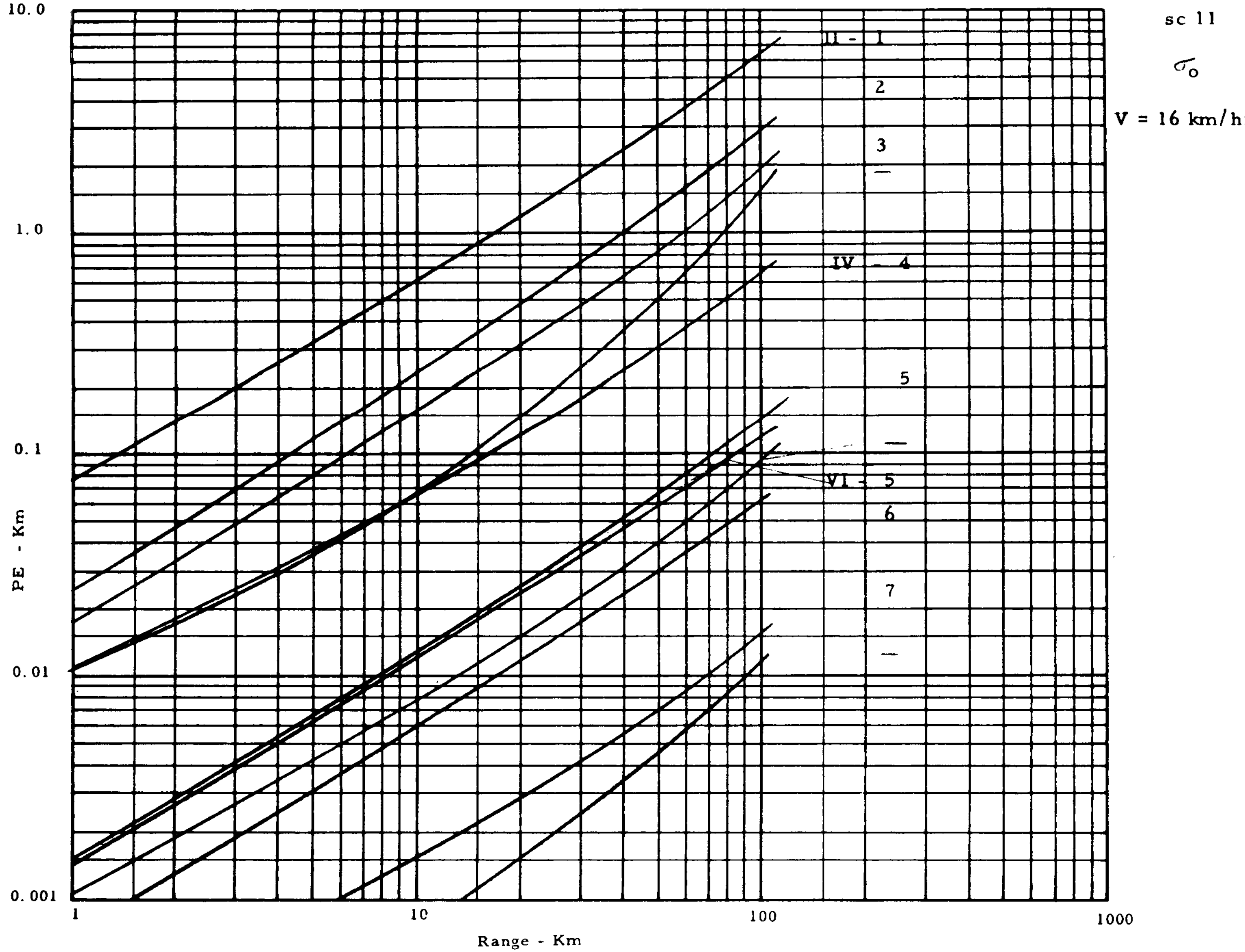


Figure 10-239 Dead Reckoning 3σ Position Error - Odometer

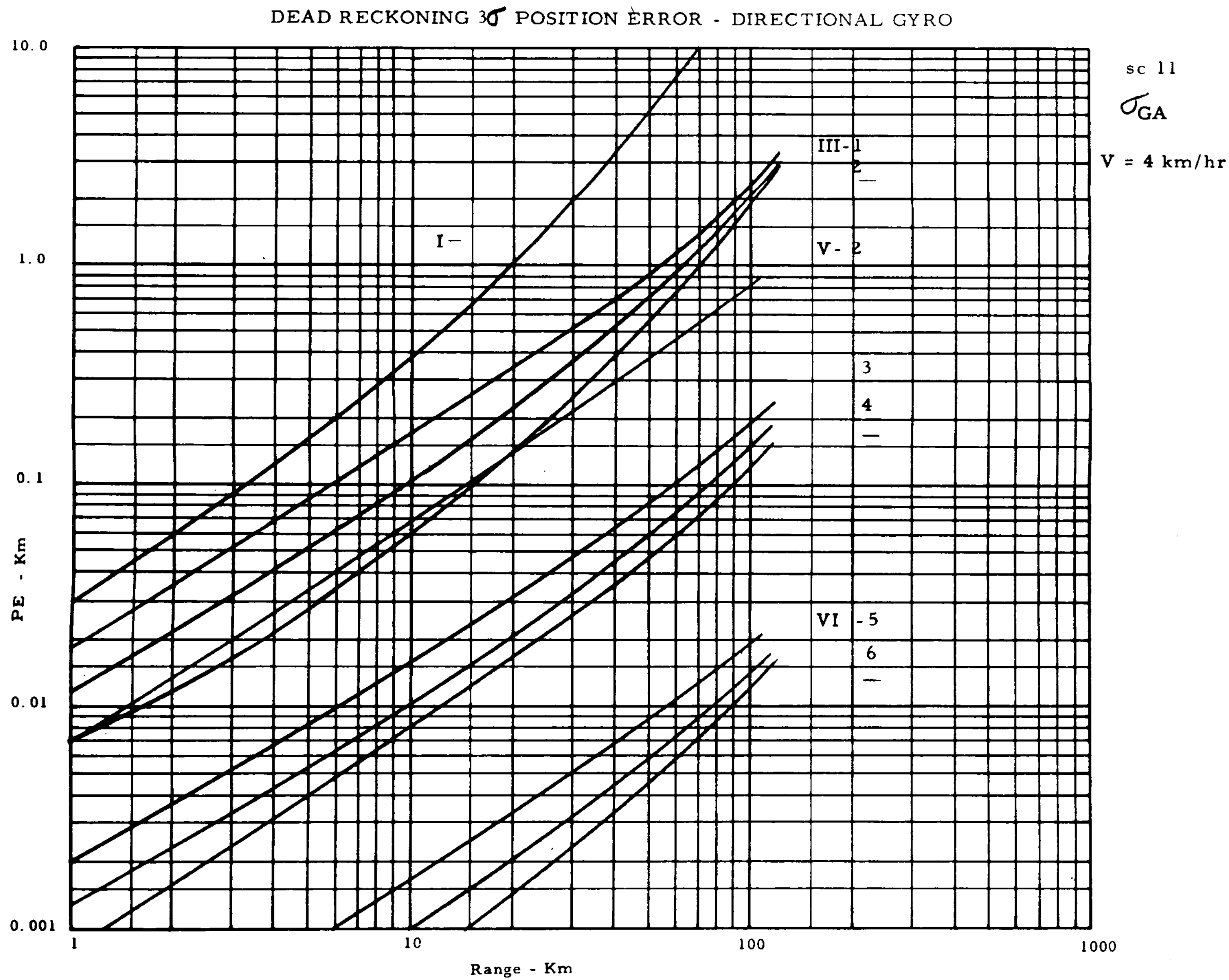


Figure 10-240 Dead Reckoning 3σ Position Error - Directional Gyro

DEAD RECKONING 3σ POSITION ERROR - DIRECTIONAL GYRO

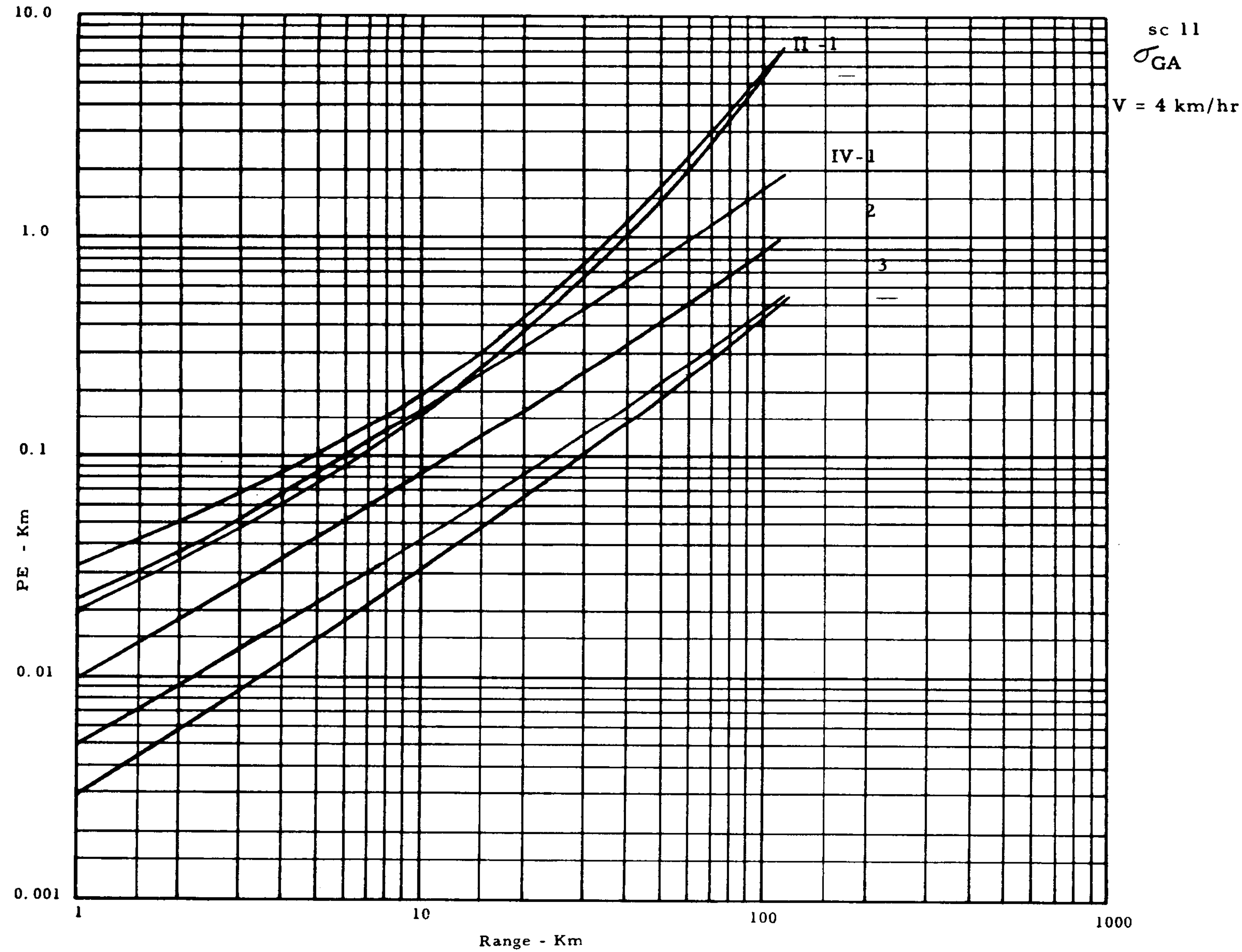


Figure 10-241 Dead Reckoning 3σ Position Error - Directional Gyro

DEAD RECKONING 3σ POSITION ERROR - DIRECTIONAL GYRO

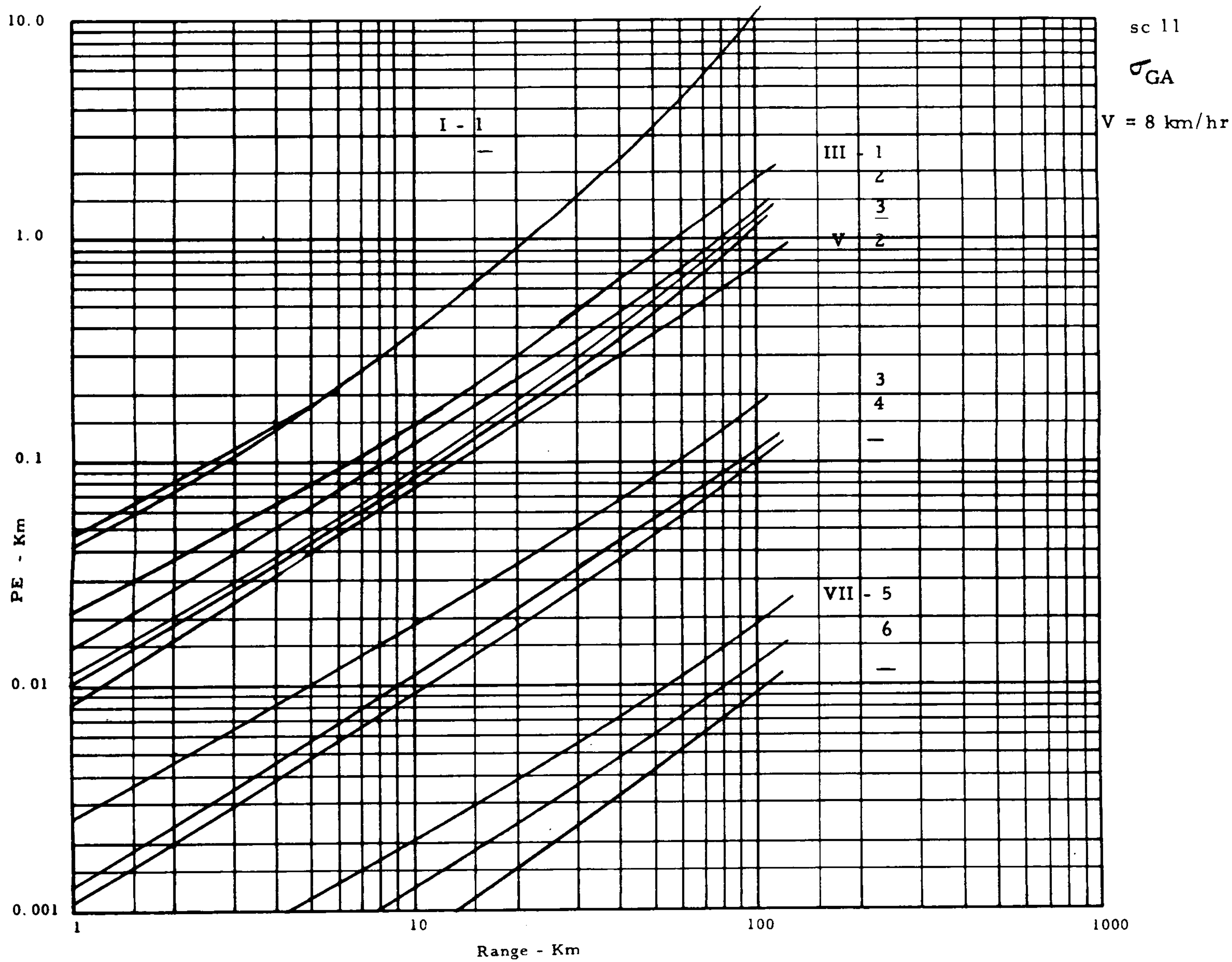


Figure 10-242 Dead Reckoning 3σ Position Error - Directional Gyro

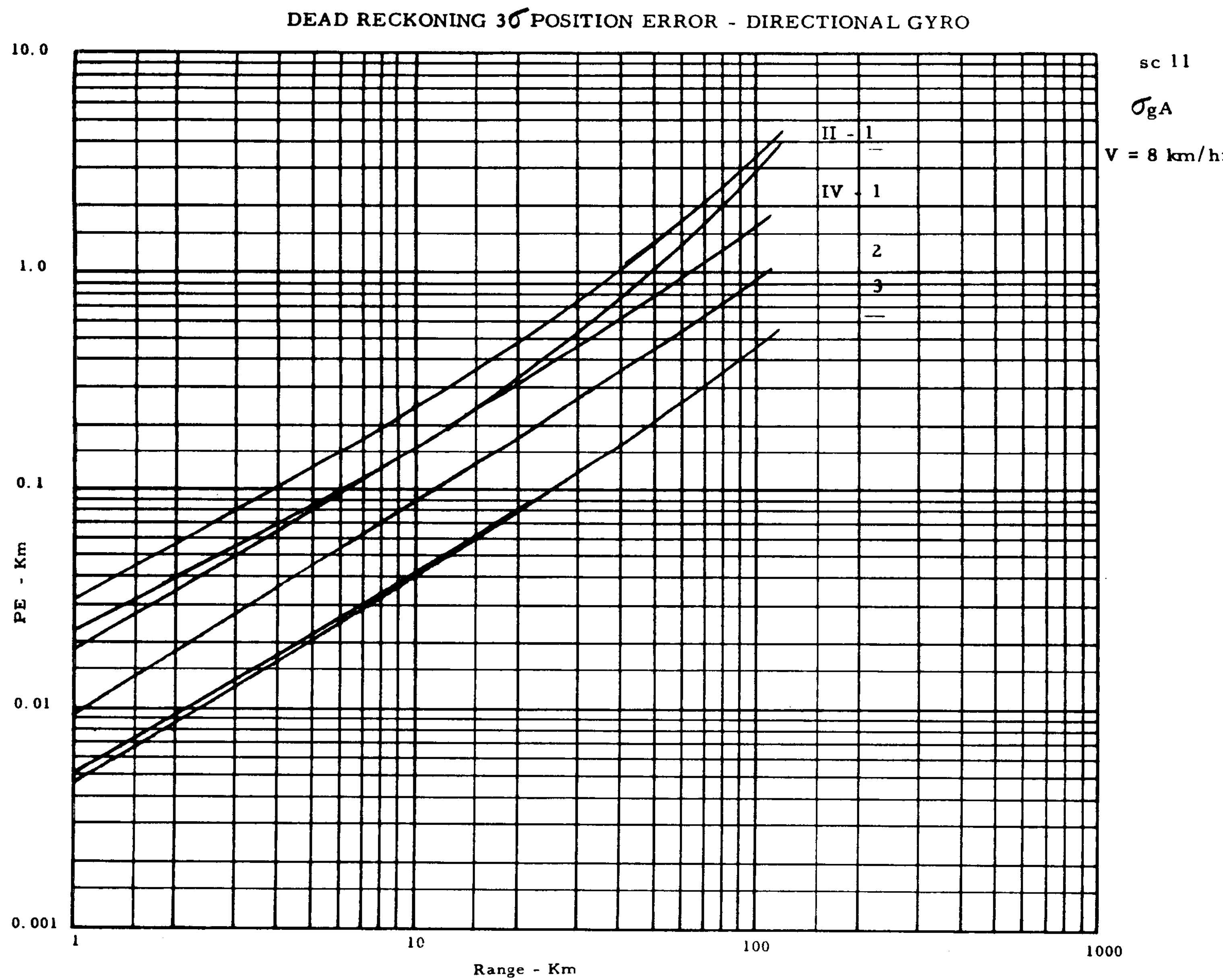


Figure 10-243 Dead Reckoning 3σ Position Error - Directional Gyro

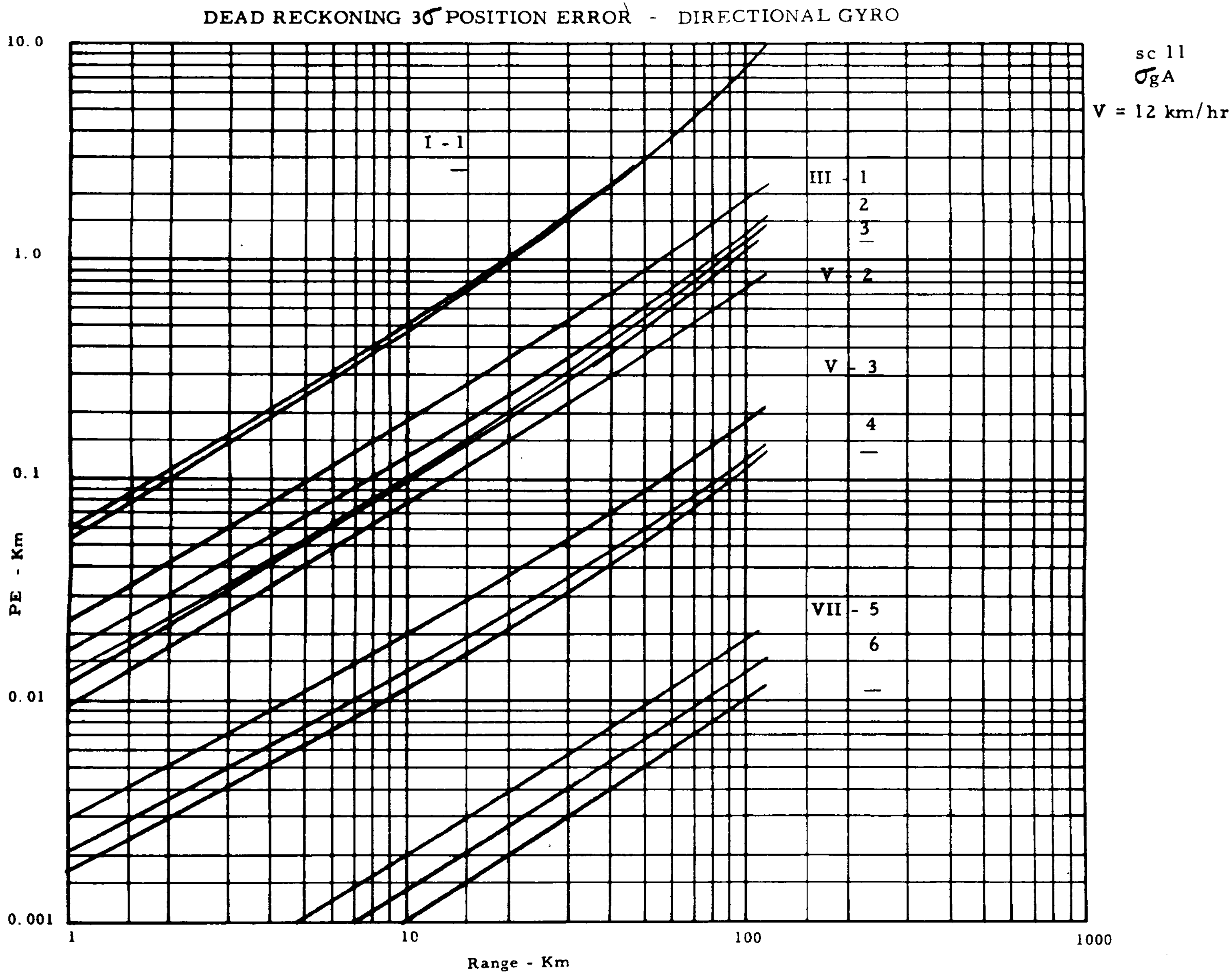


Figure 10-244 Dead Reckoning 3σ Position Error - Directional Gyro

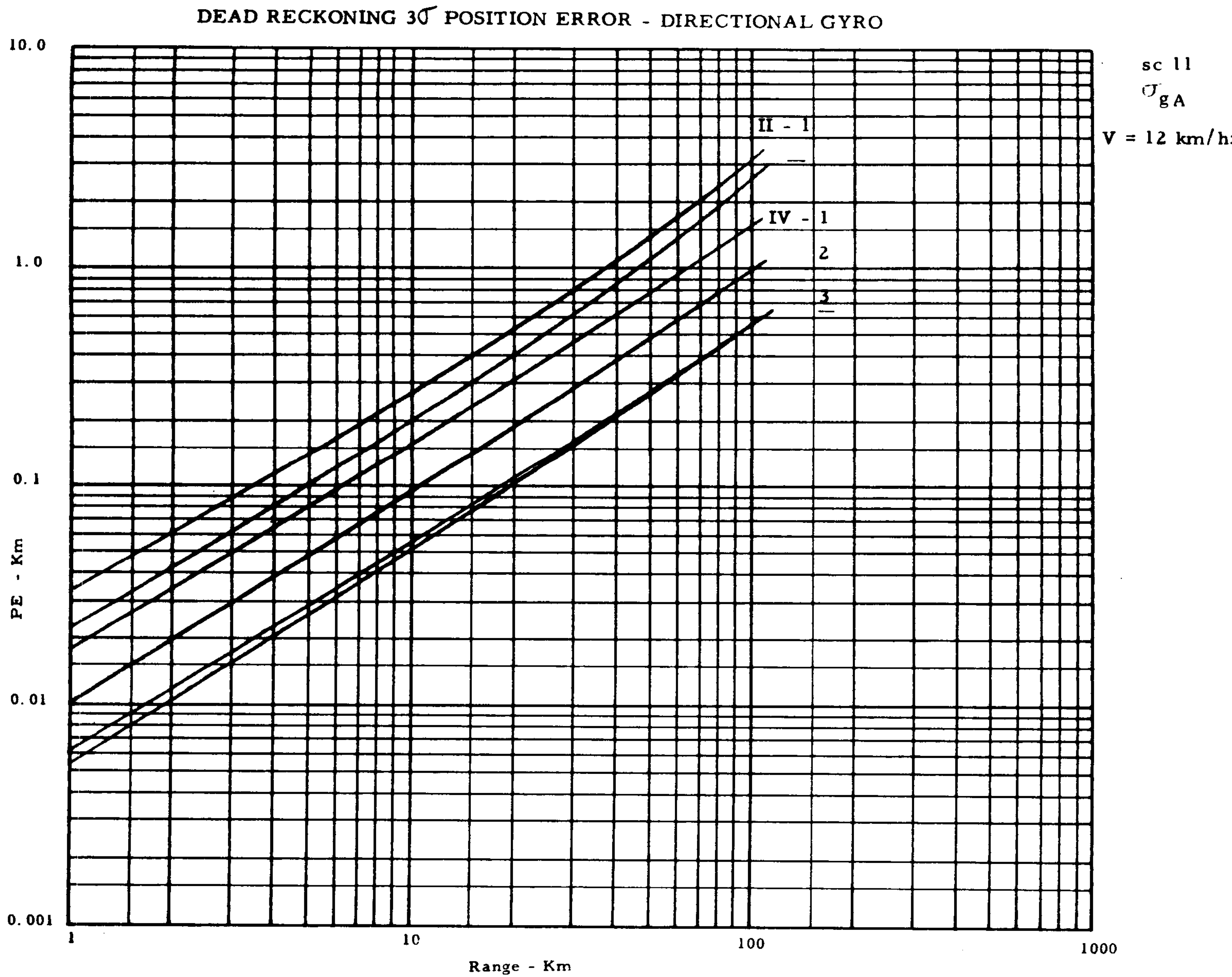


Figure 10-245 Dead Reckoning 3σ Position Error - Directional Gyro

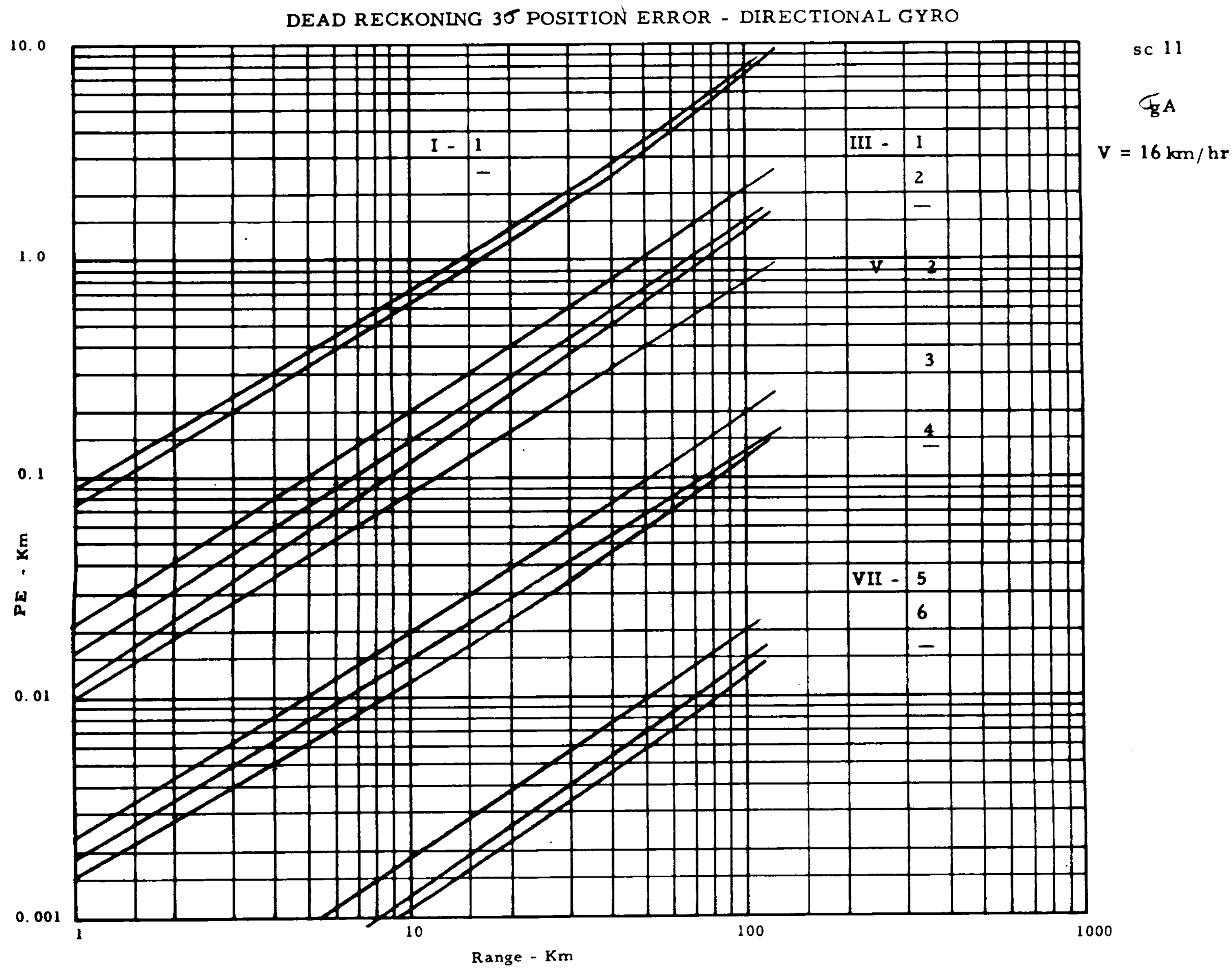


Figure 10-246 Dead Reckoning 3σ Position Error - Directional Gyro

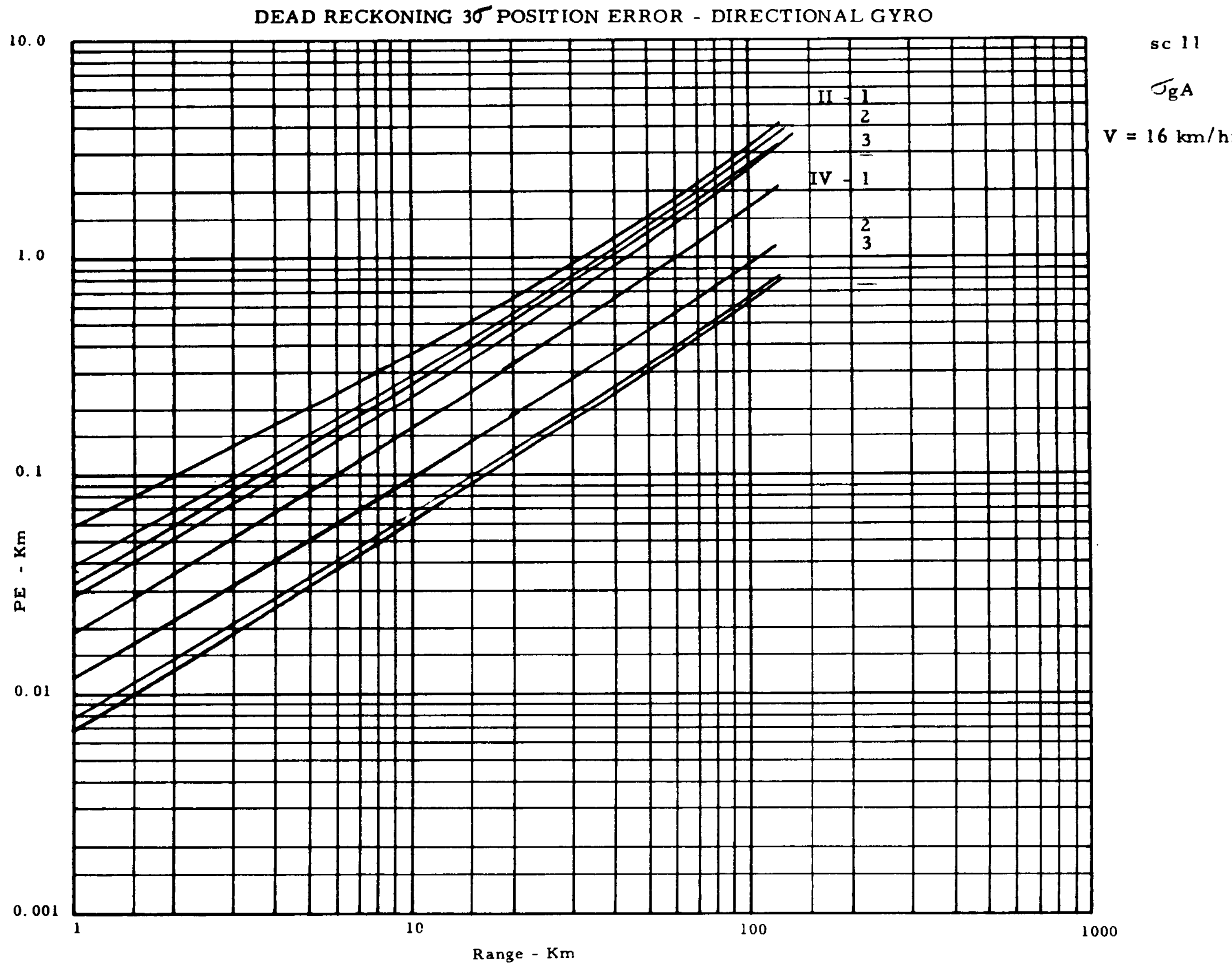


Figure 10-247 Dead Reckoning 3σ Position Error - Directional Gyro

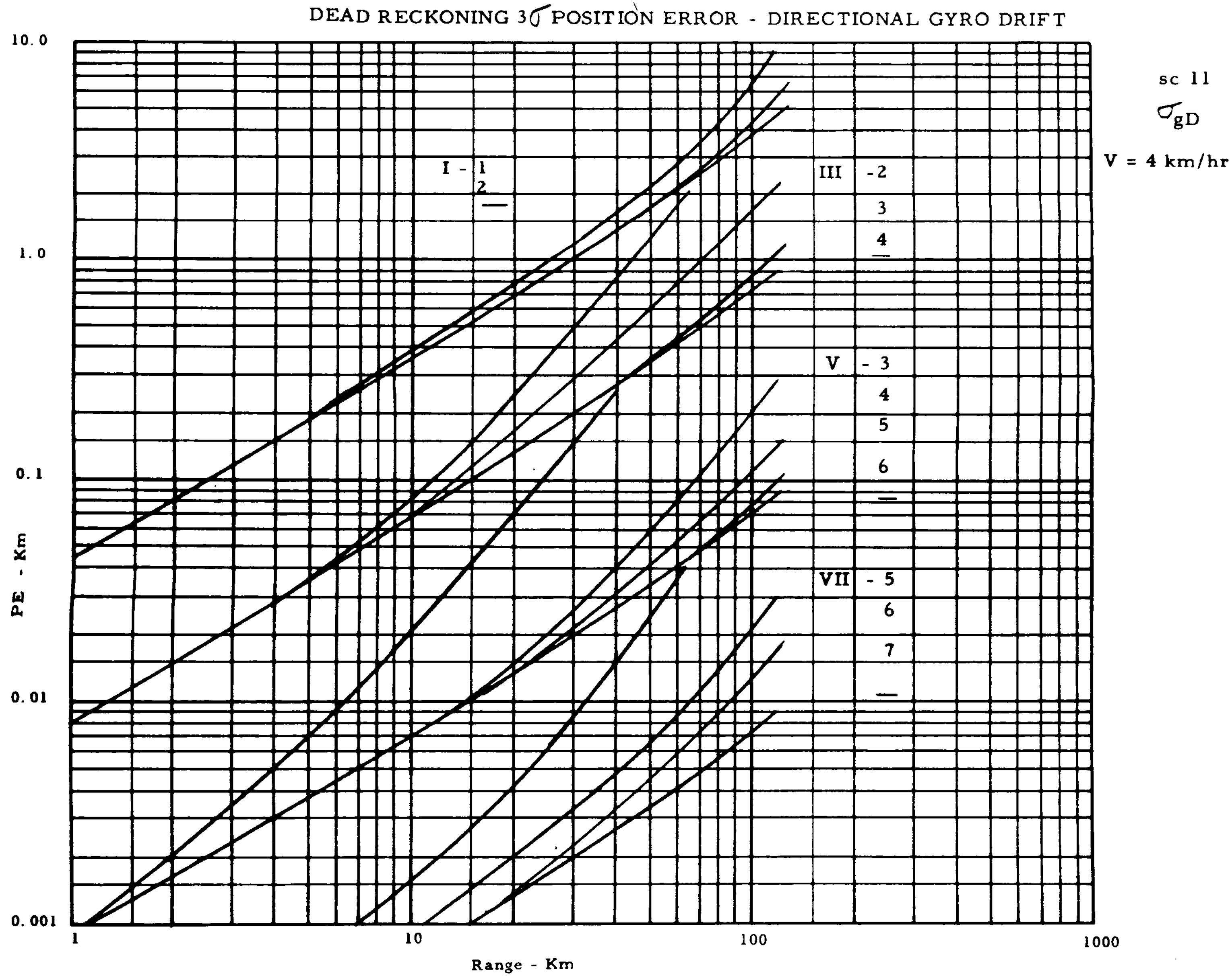


Figure 10-248 Dead Reckoning 3σ Position Error - Directional Gyro Drift

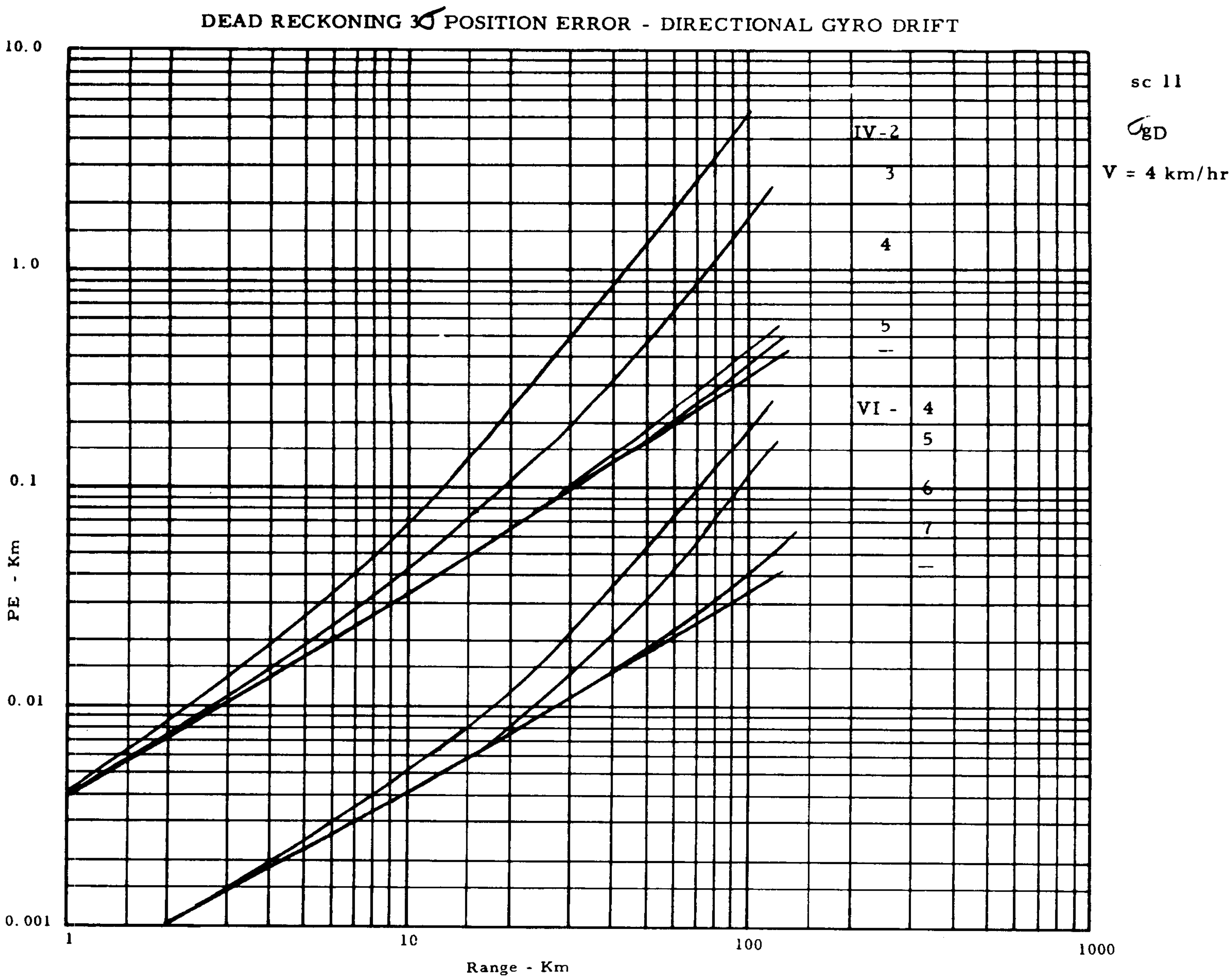


Figure 10-249 Dead Reckoning 3σ Position Error - Directional Gyro Drift

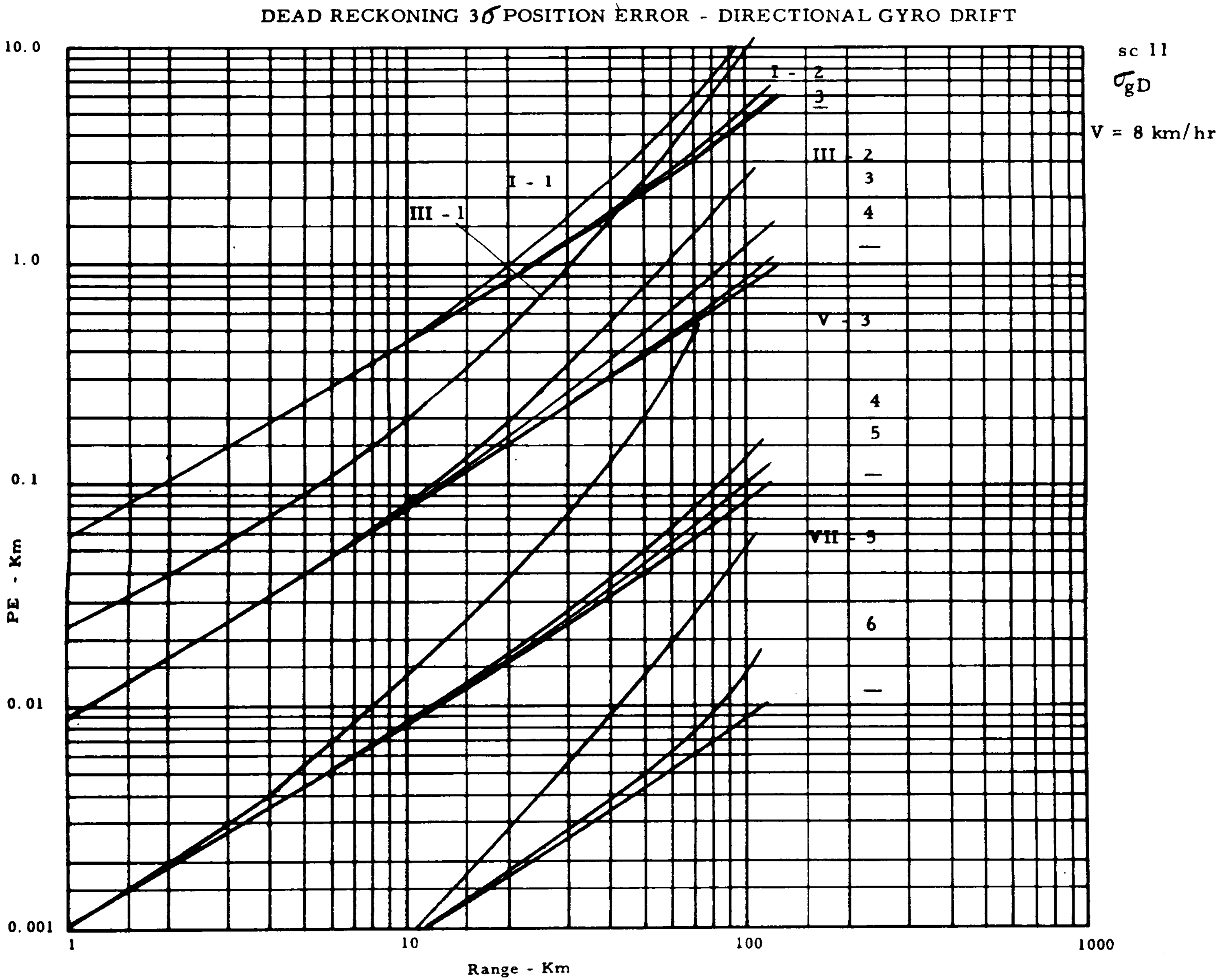


Figure 10-250 Dead Reckoning 3σ Position Error - Directional Gyro Drift

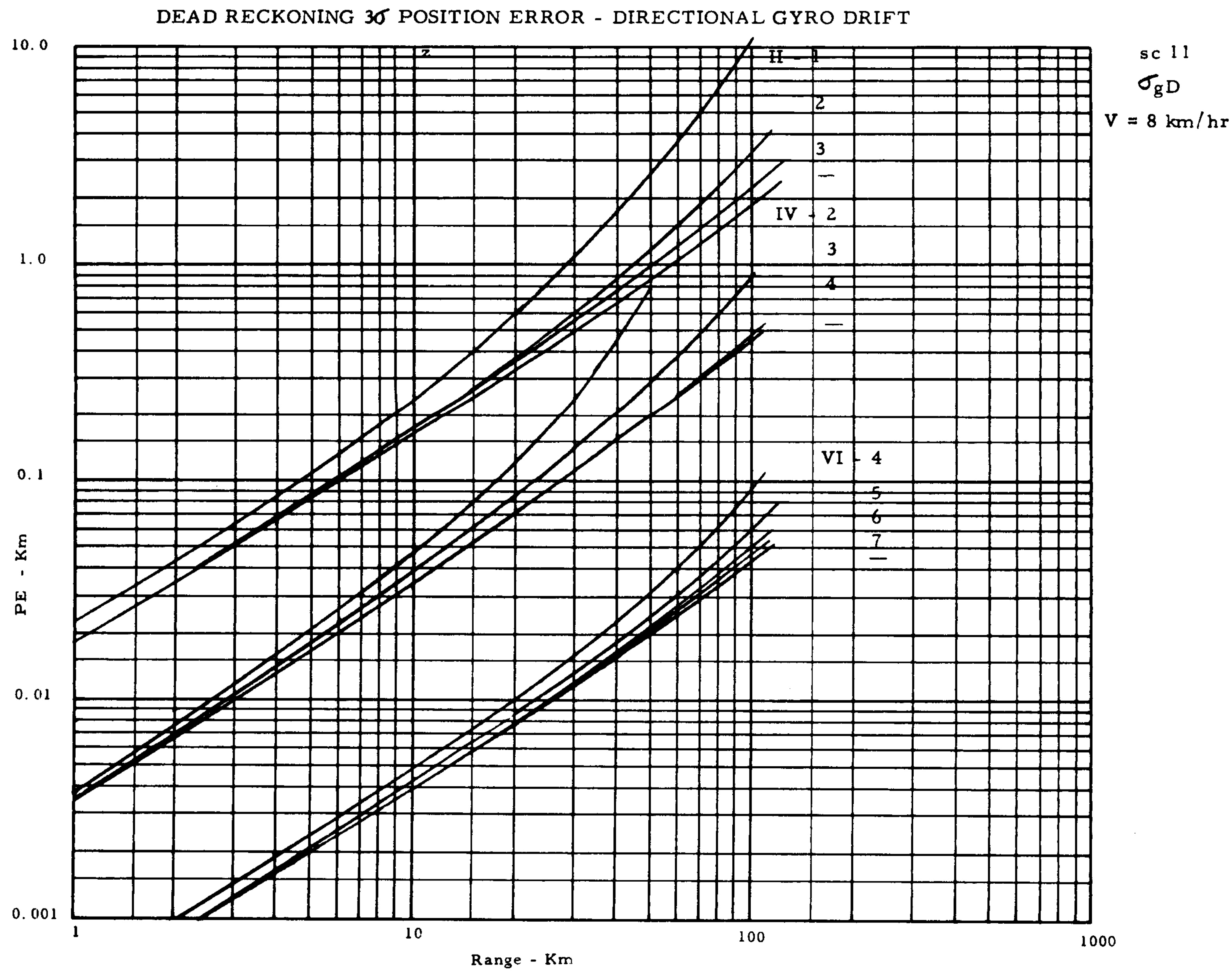


Figure 10-251 Dead Reckoning 3σ Position Error - Directional Gyro Drift

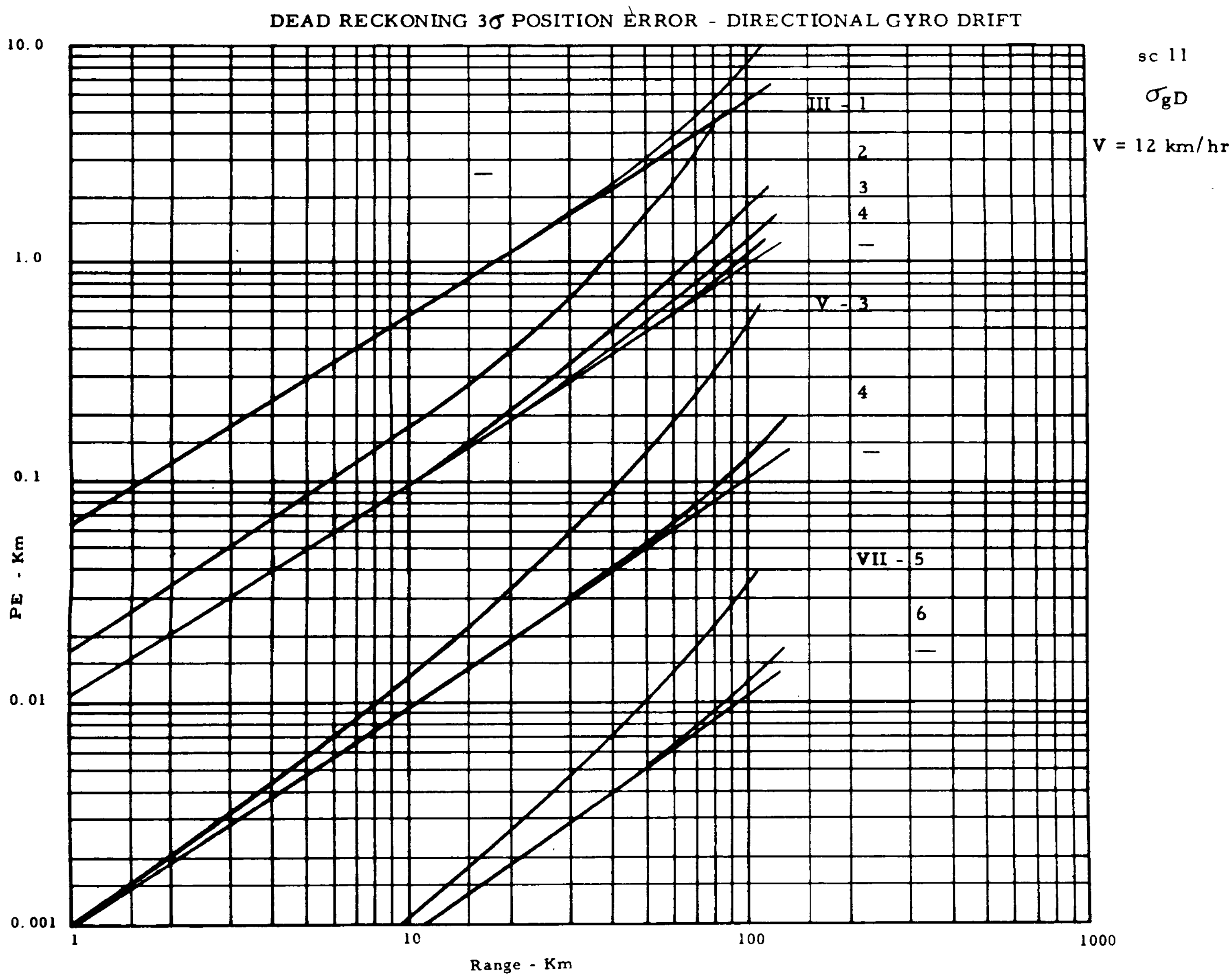


Figure 10-252 Dead Reckoning 3σ Position Error - Directional Gyro Drift

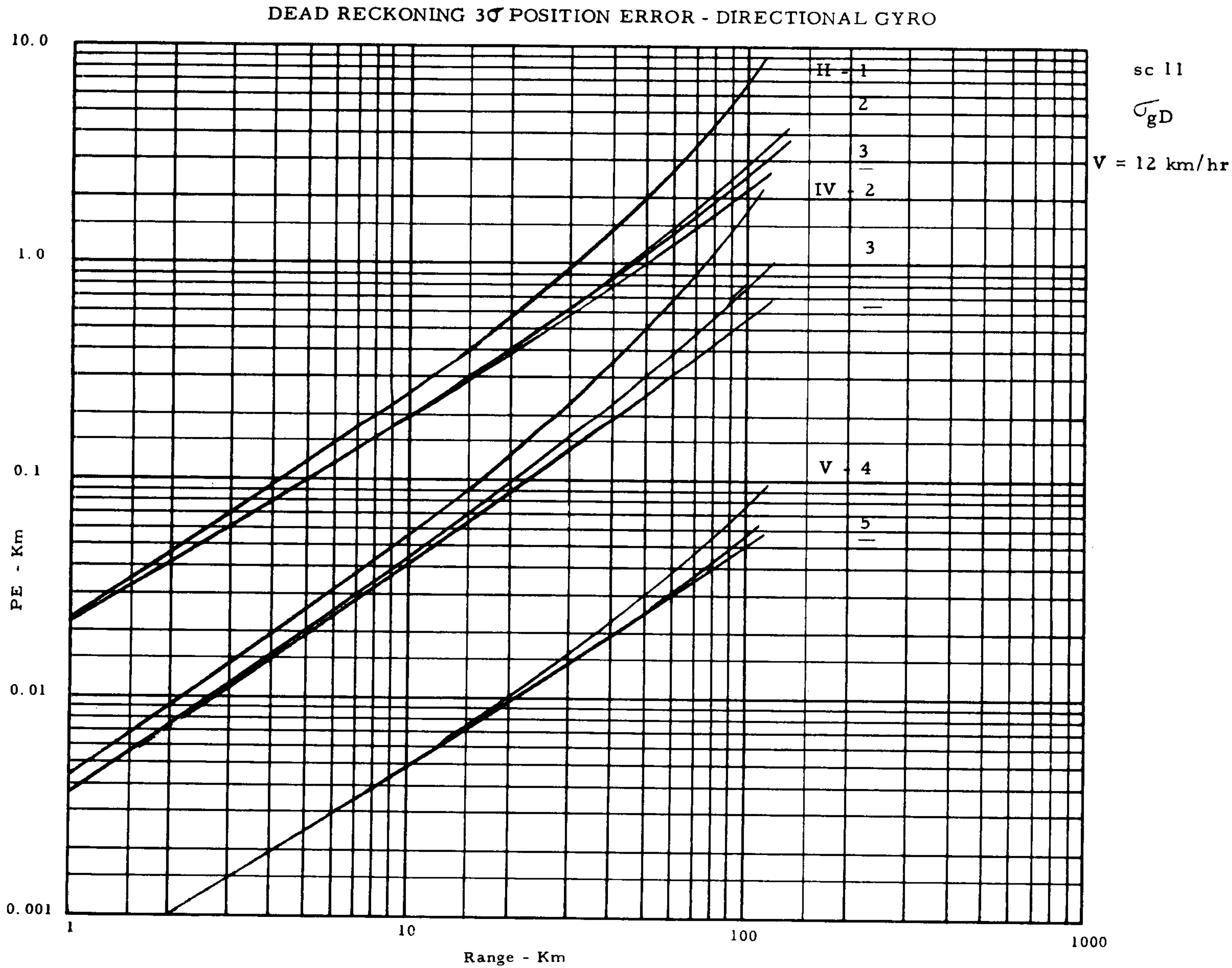


Figure 10-253 Dead Reckoning 3σ Position Error - Directional Gyro Drift

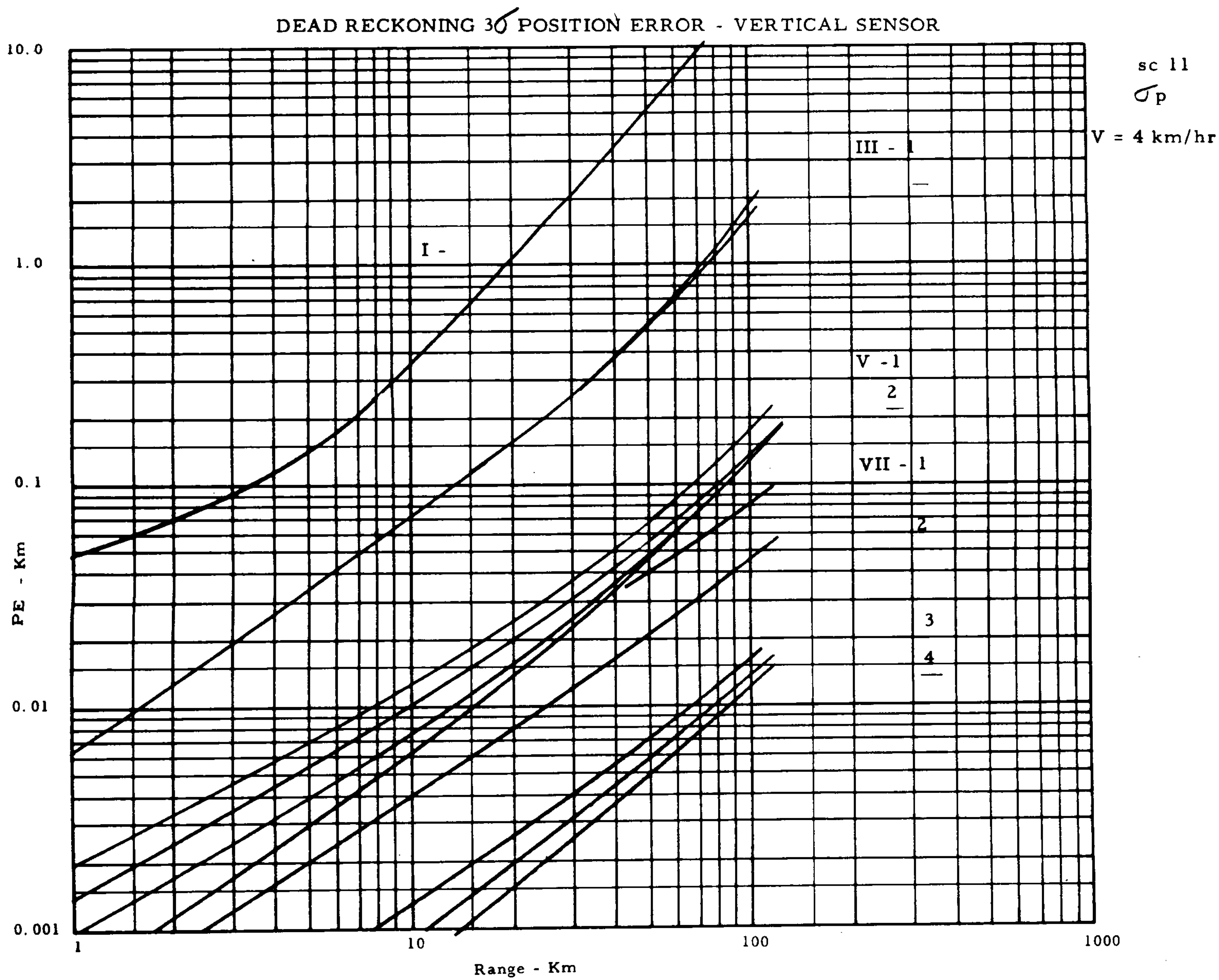


Figure 10-254 Dead Reckoning 3σ Position Error - Vertical Sensor

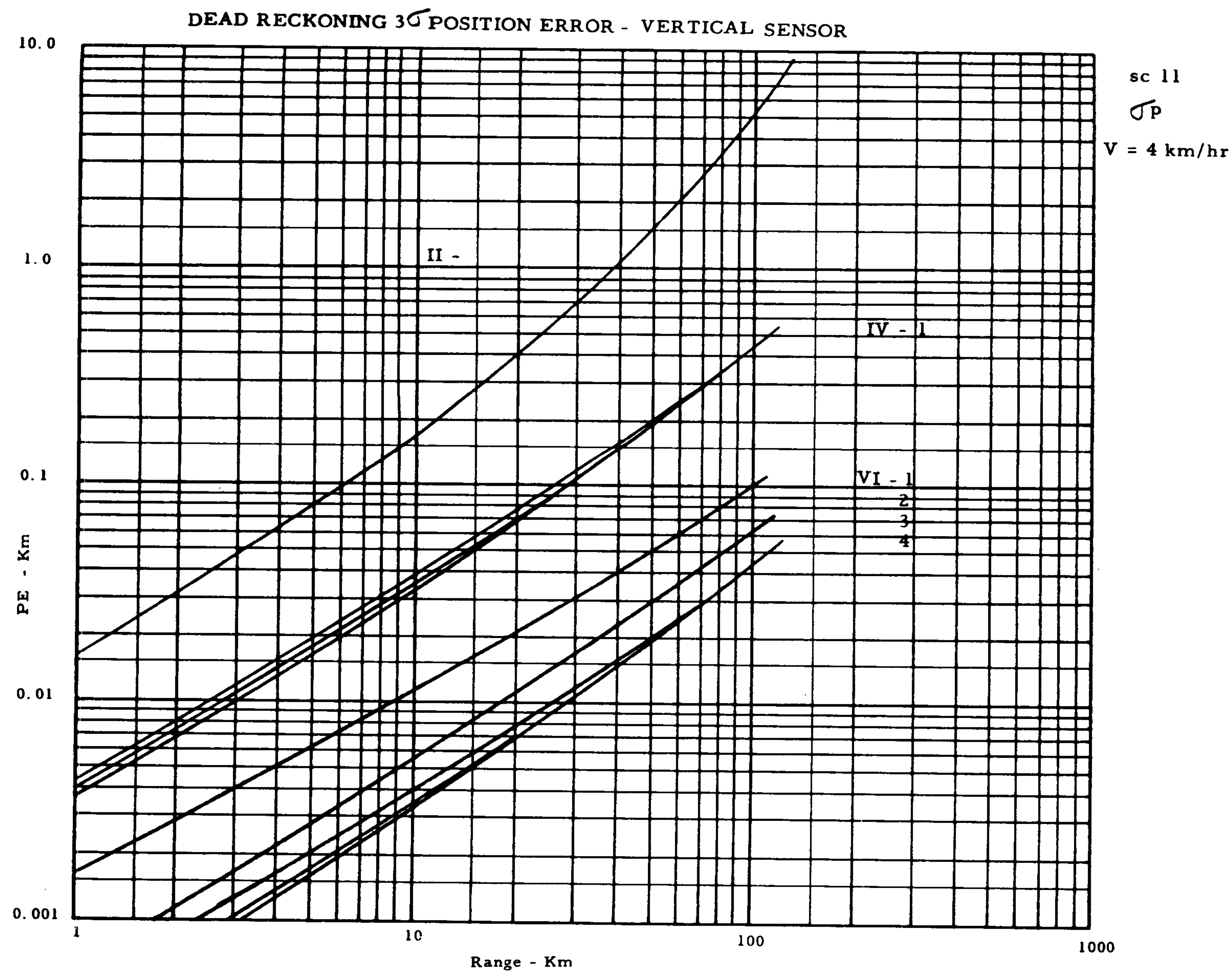


Figure 10-255 Dead Reckoning 3σ Position Error - Vertical Sensor

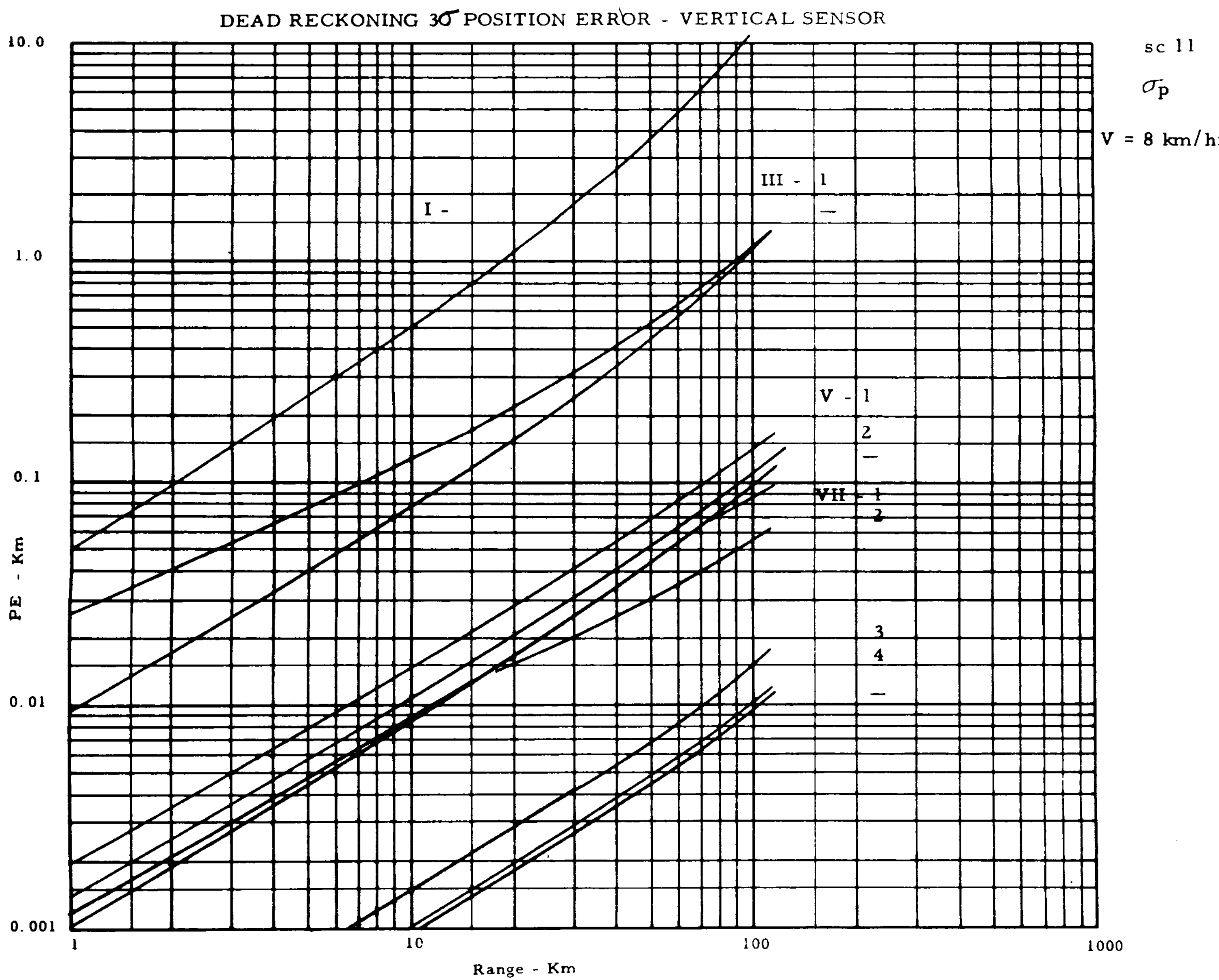


Figure 10-256 Dead Reckoning 3σ Position Error - Vertical Sensor

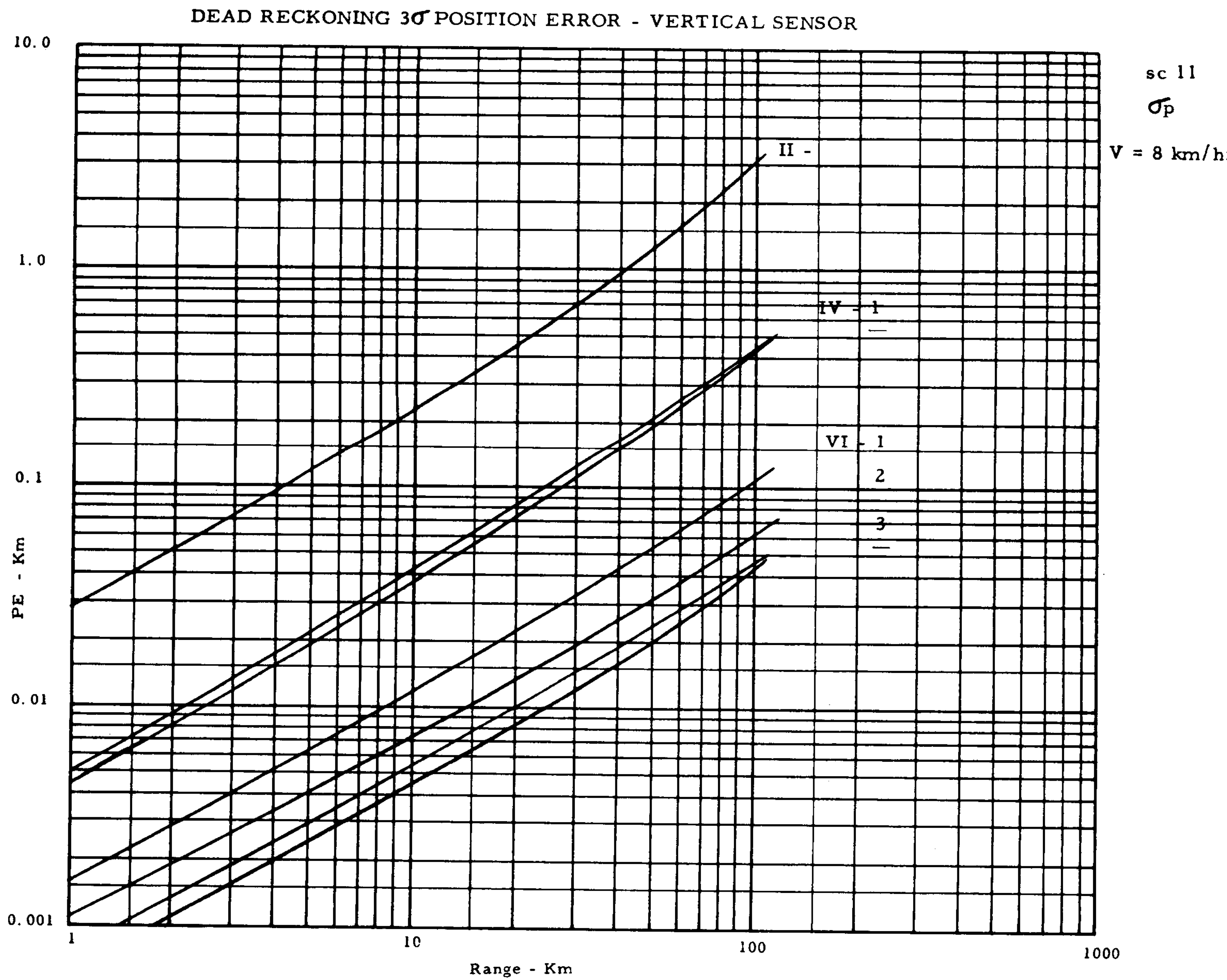


Figure 10-257 Dead Reckoning 3σ Position Error - Vertical Sensor

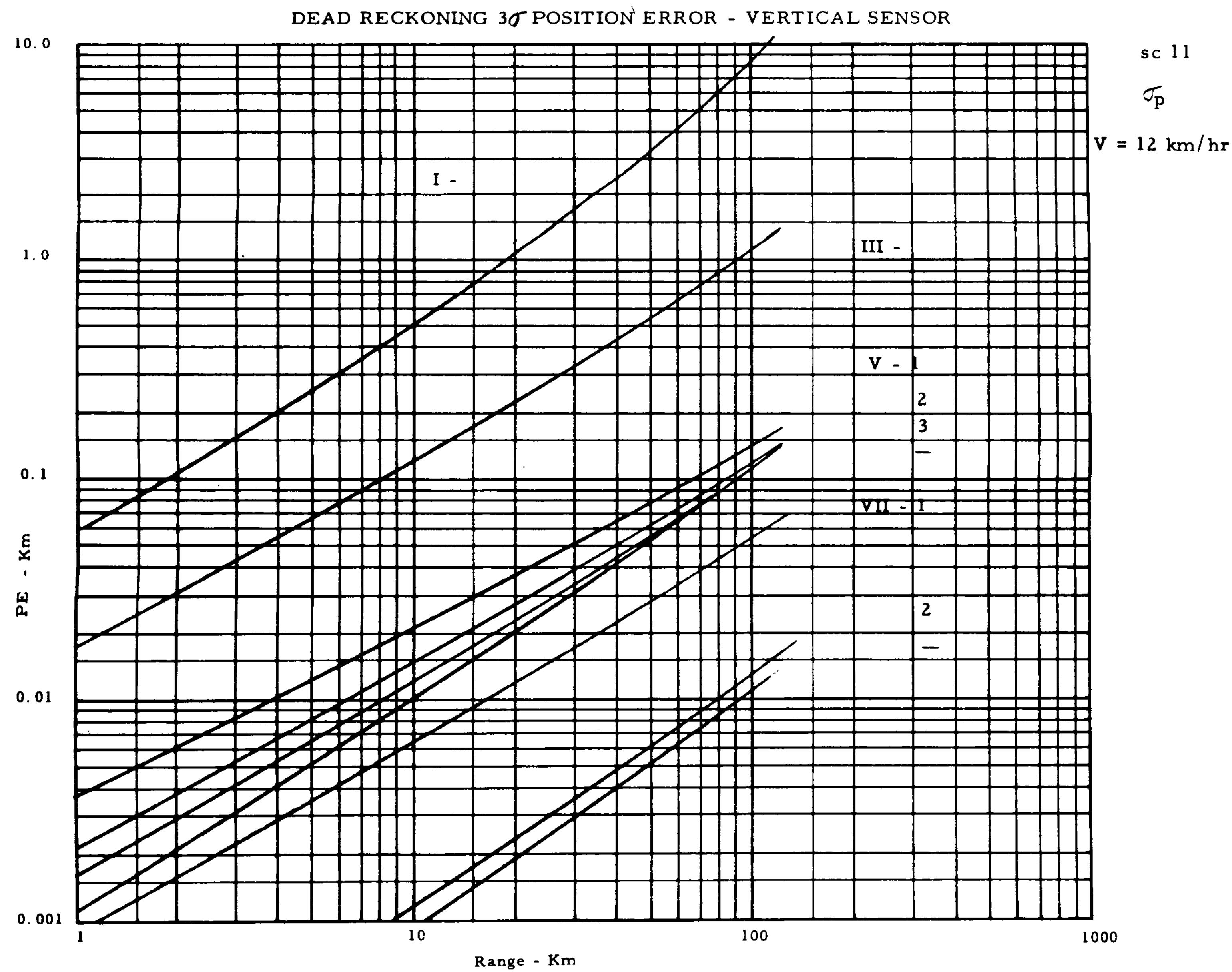


Figure 10-258 Dead Reckoning 3σ Position Error - Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - VERTICAL SENSOR

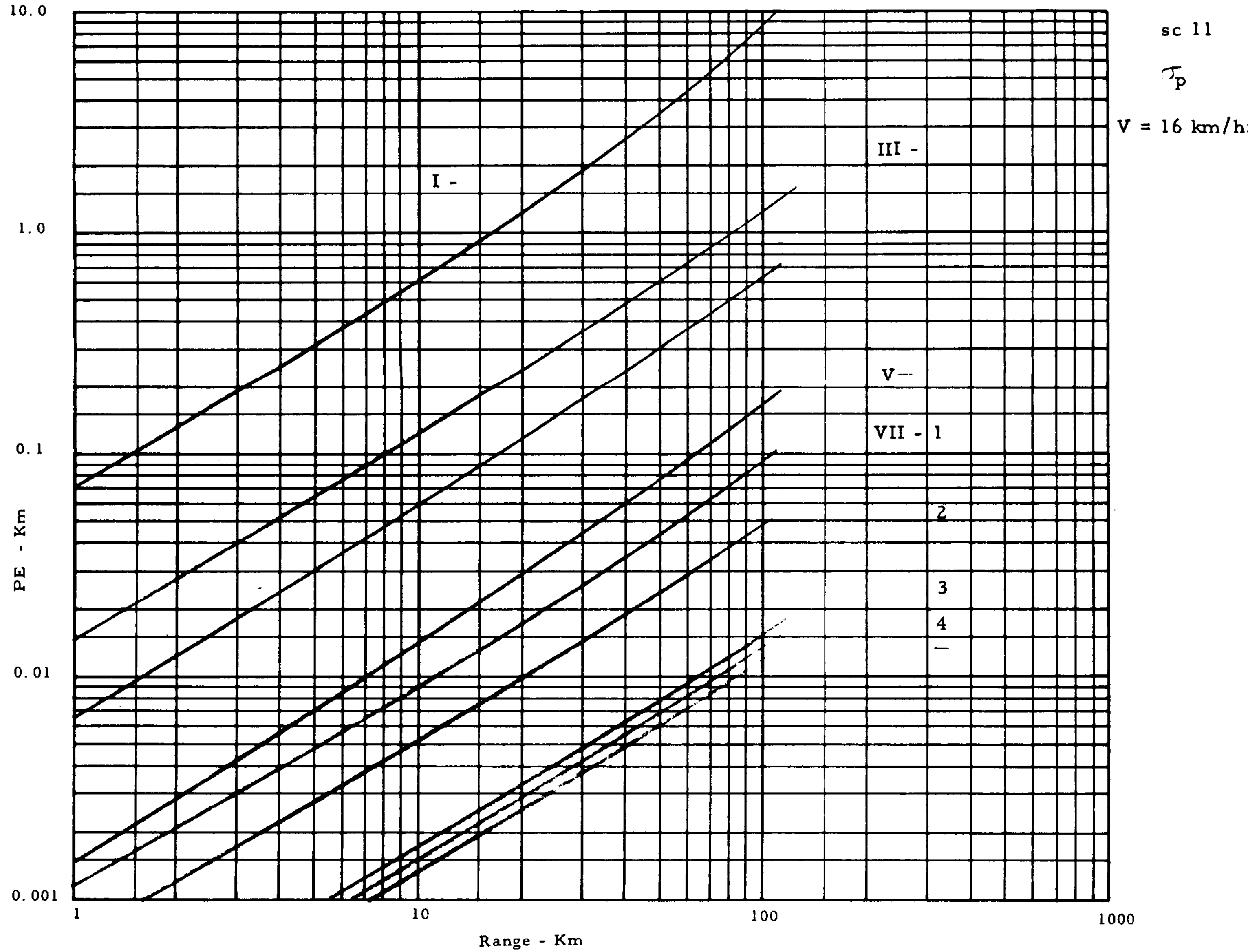


Figure 10-259 Dead Reckoning 3σ Position Error - Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - VERTICAL SENSOR

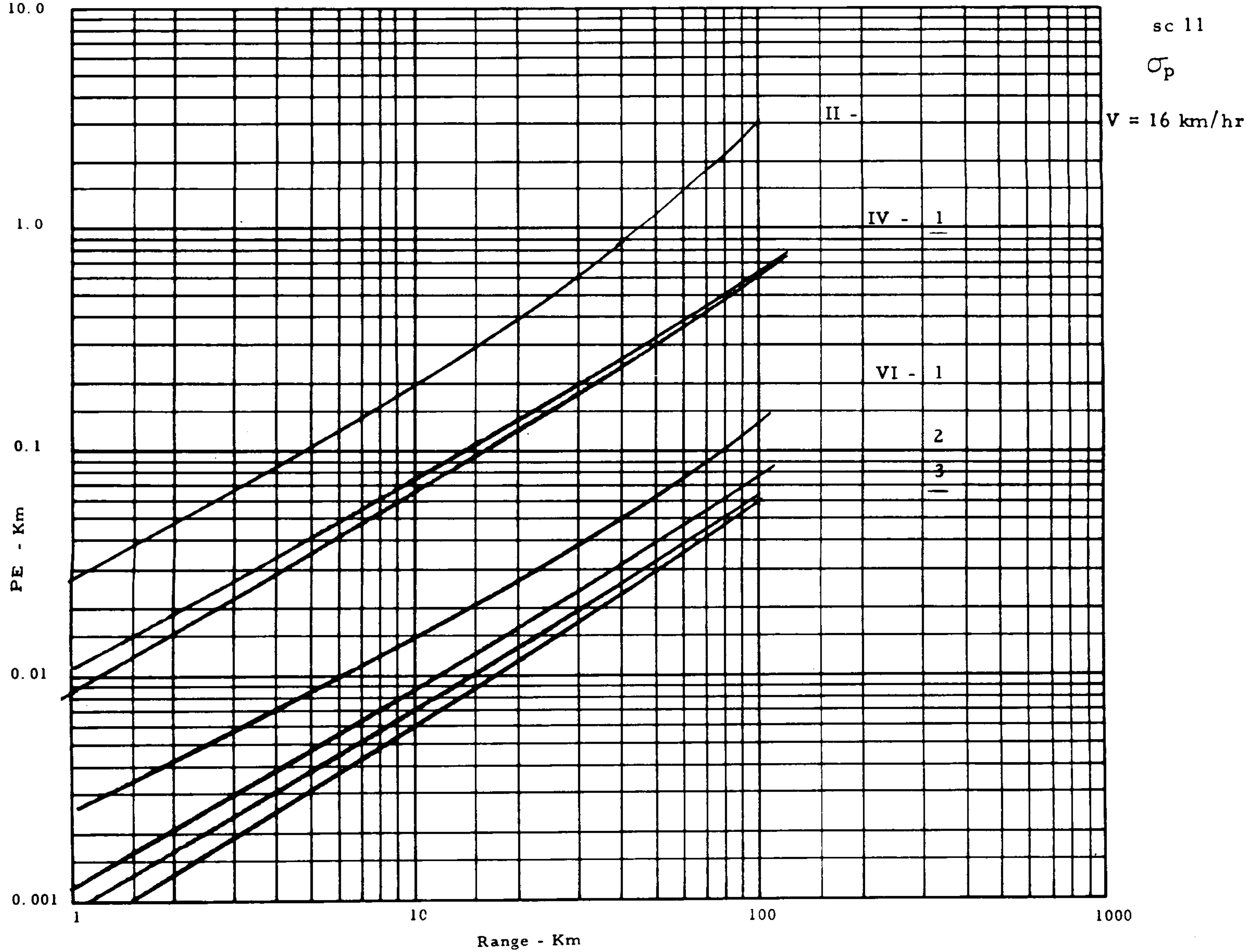


Figure 10-260 Dead Reckoning 3σ Position Error - Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - DIRECTIONAL GYRO DRIFT

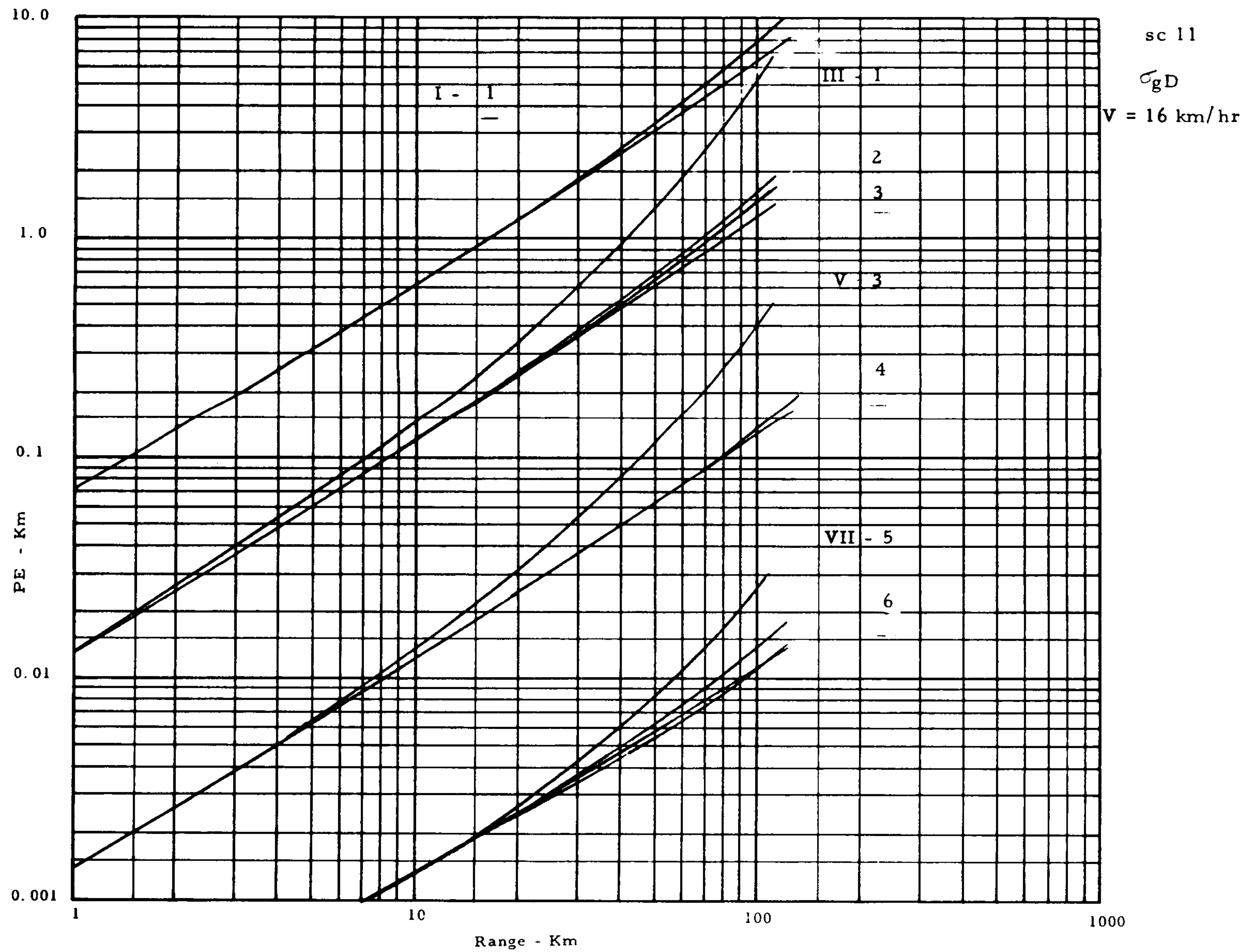


Figure 10-261 Dead Reckoning 3σ Position Error - Directional Gyro Drift

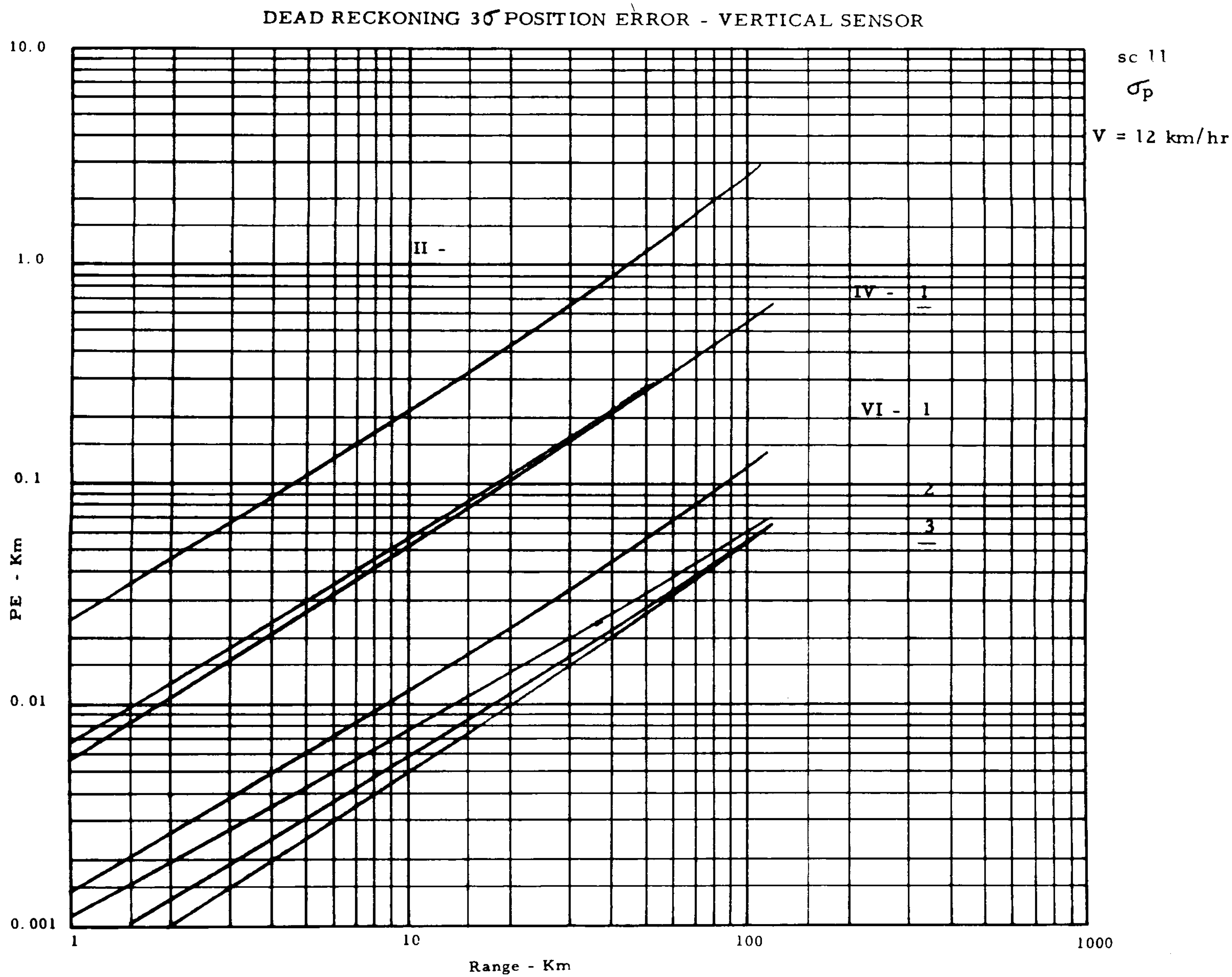


Figure 10-262 Dead Reckoning 3σ Position Error - Vertical Sensor

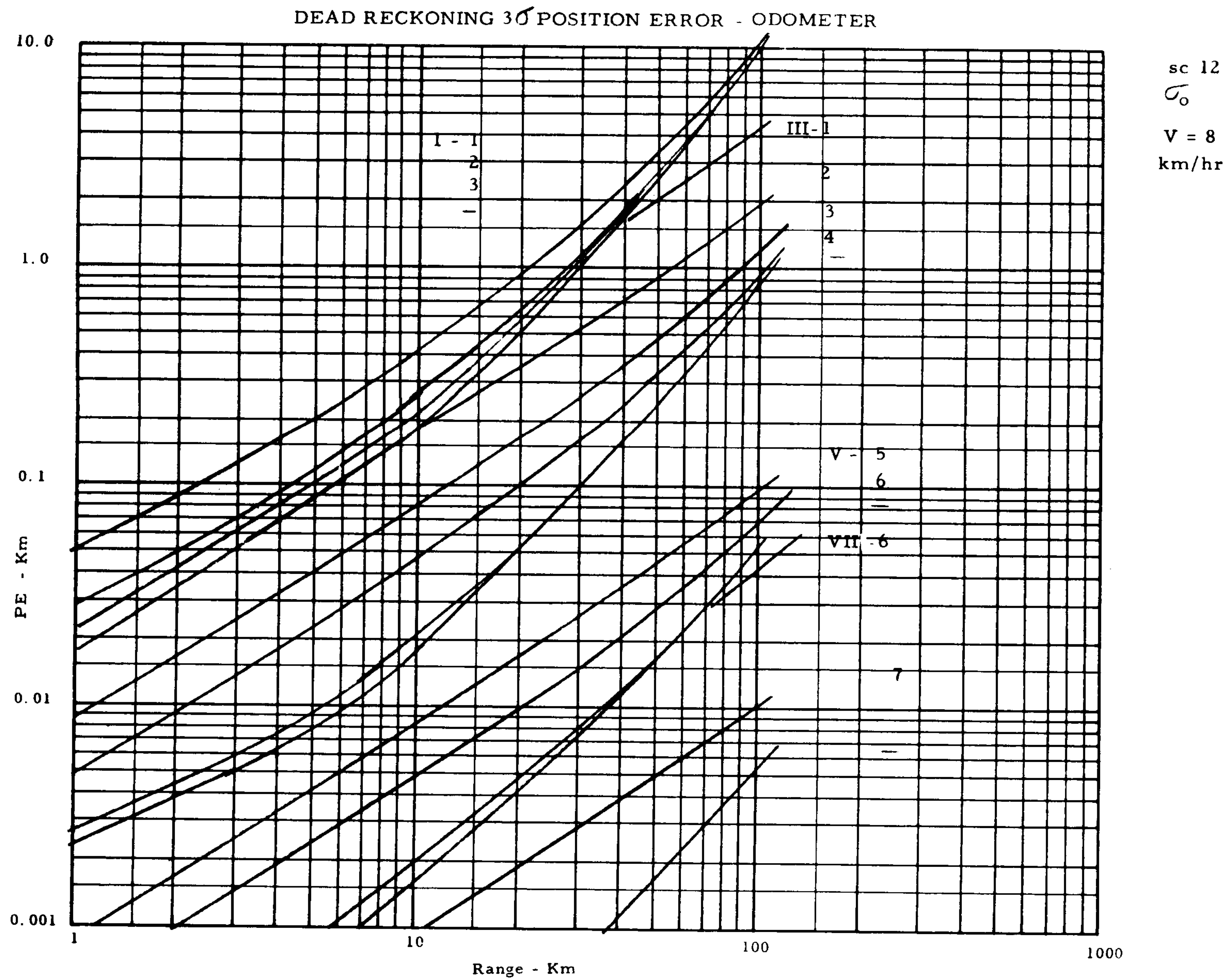


Figure 10-263 Dead Reckoning 3σ Position Error - Odometer

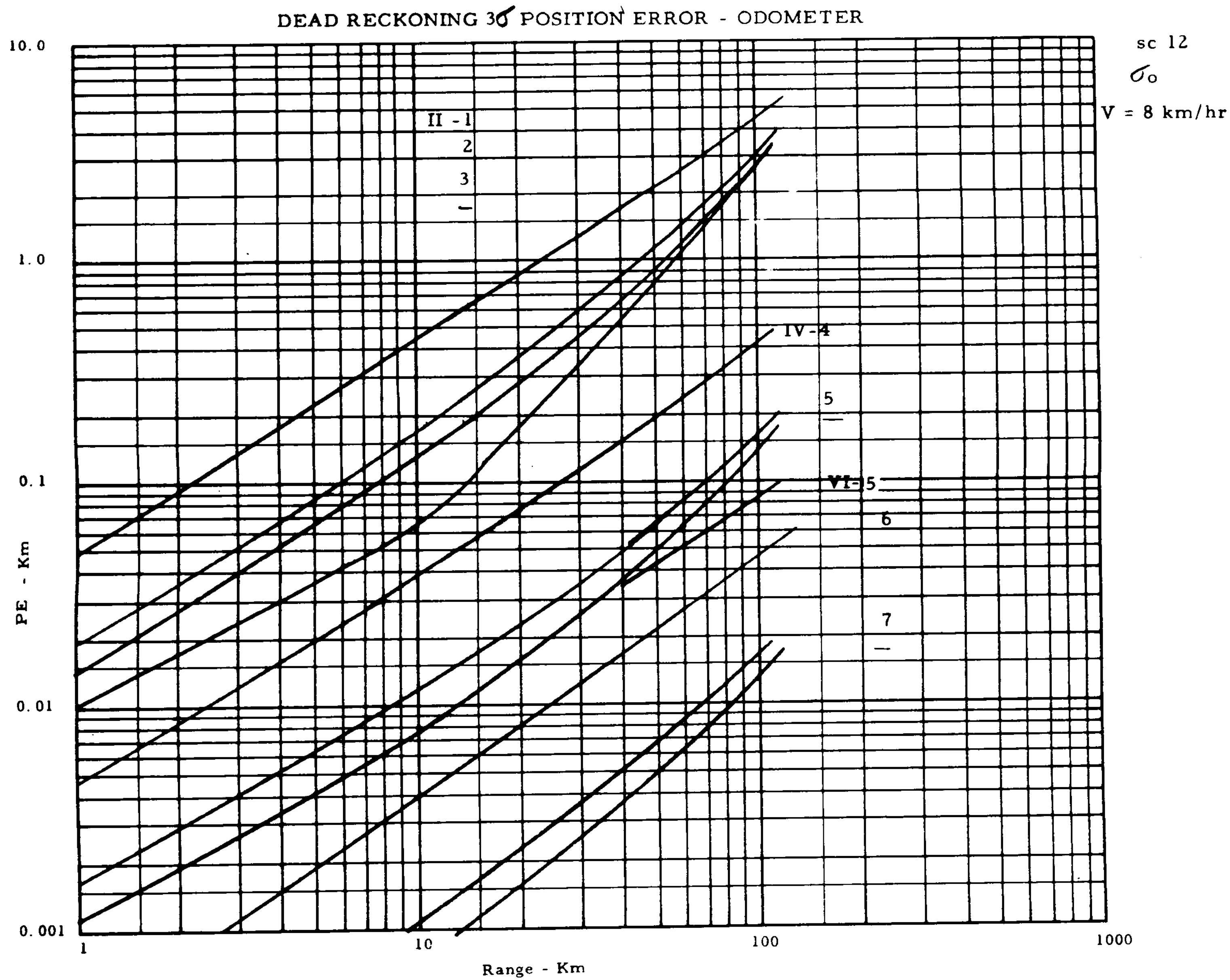


Figure 10-264 Dead Reckoning 3σ Position Error - Odometer

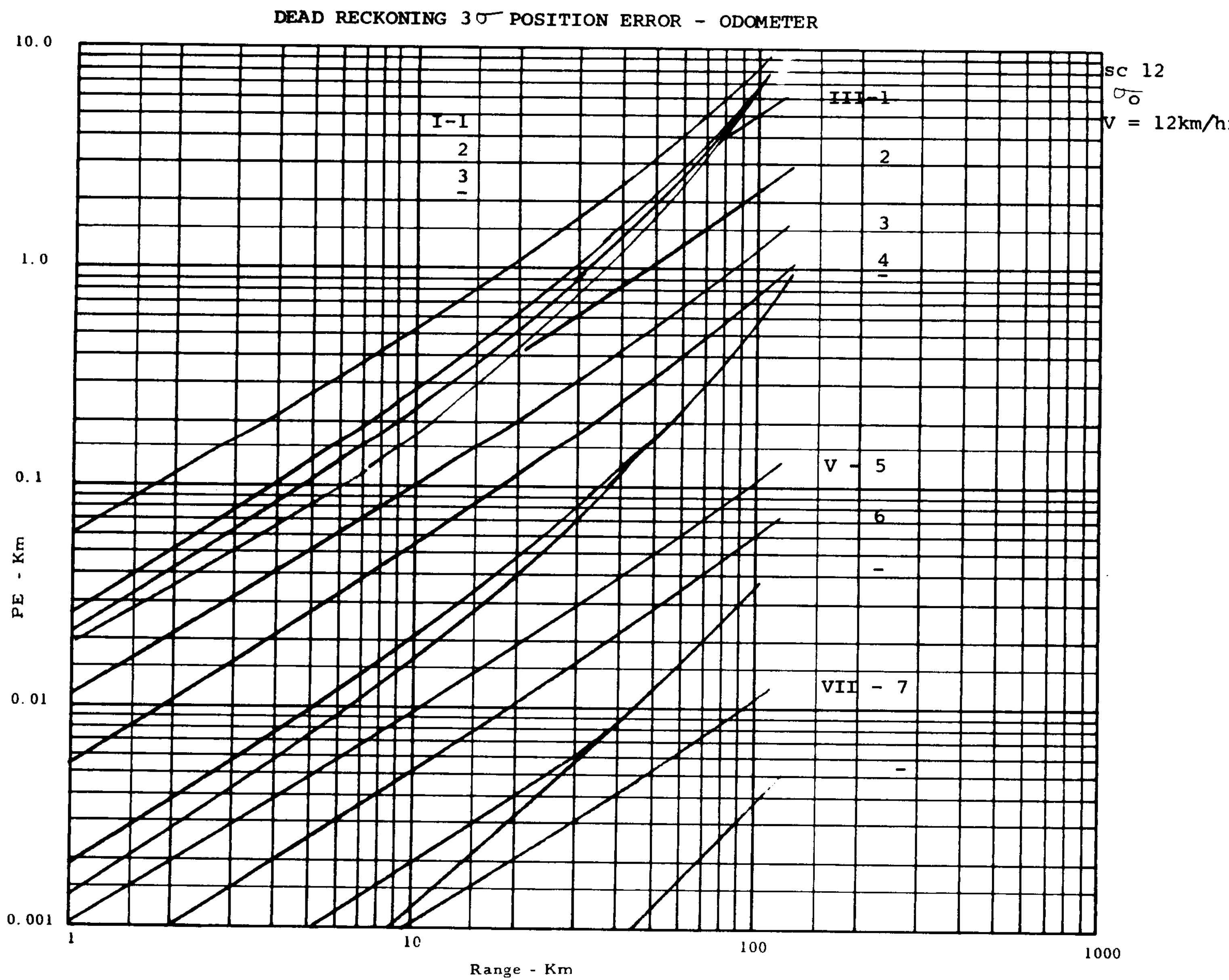


Figure 10-265 Dead Reckoning 3σ Position Error - Odometer

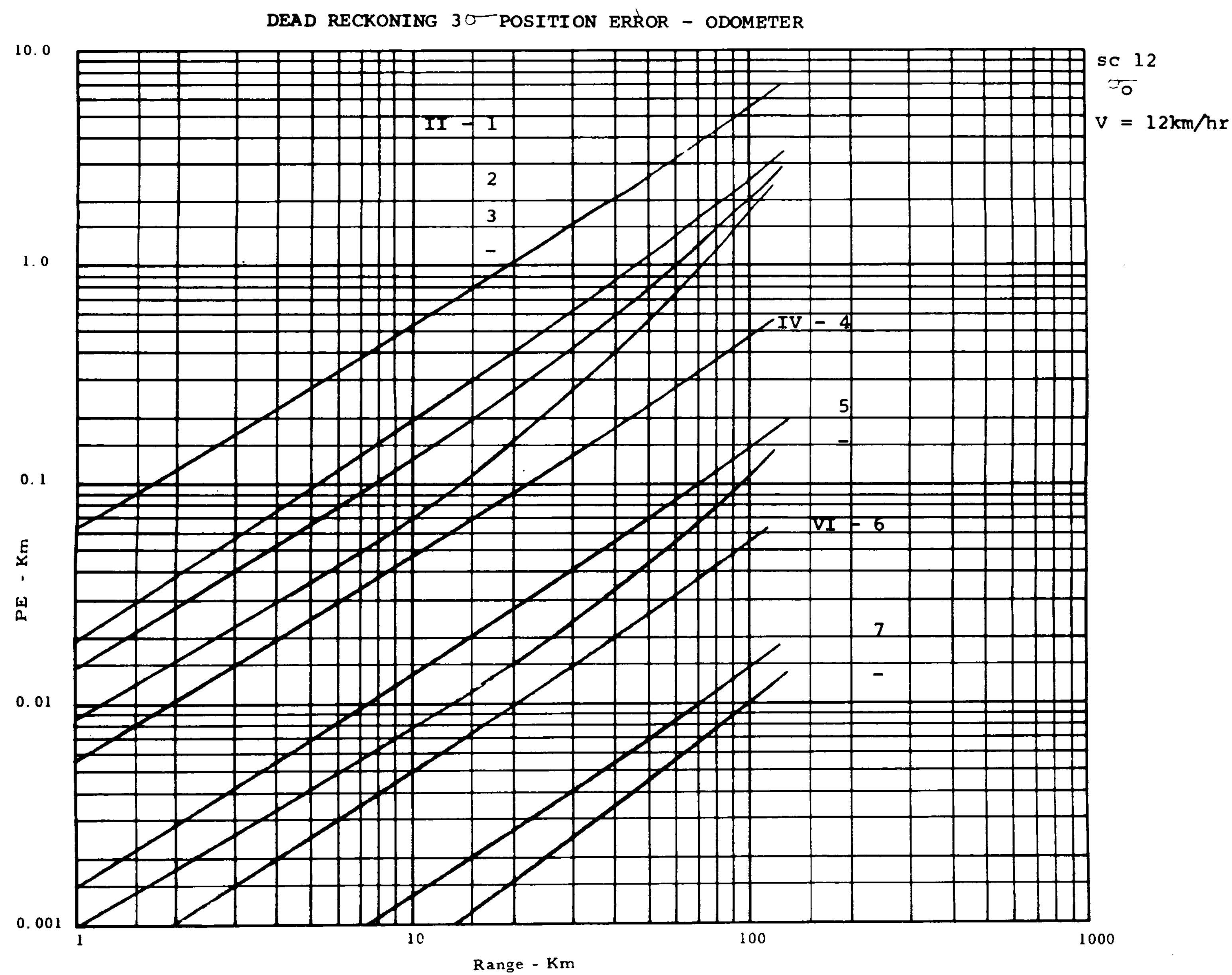


Figure 10-266 Dead Reckoning 3σ Position Error - Odometer

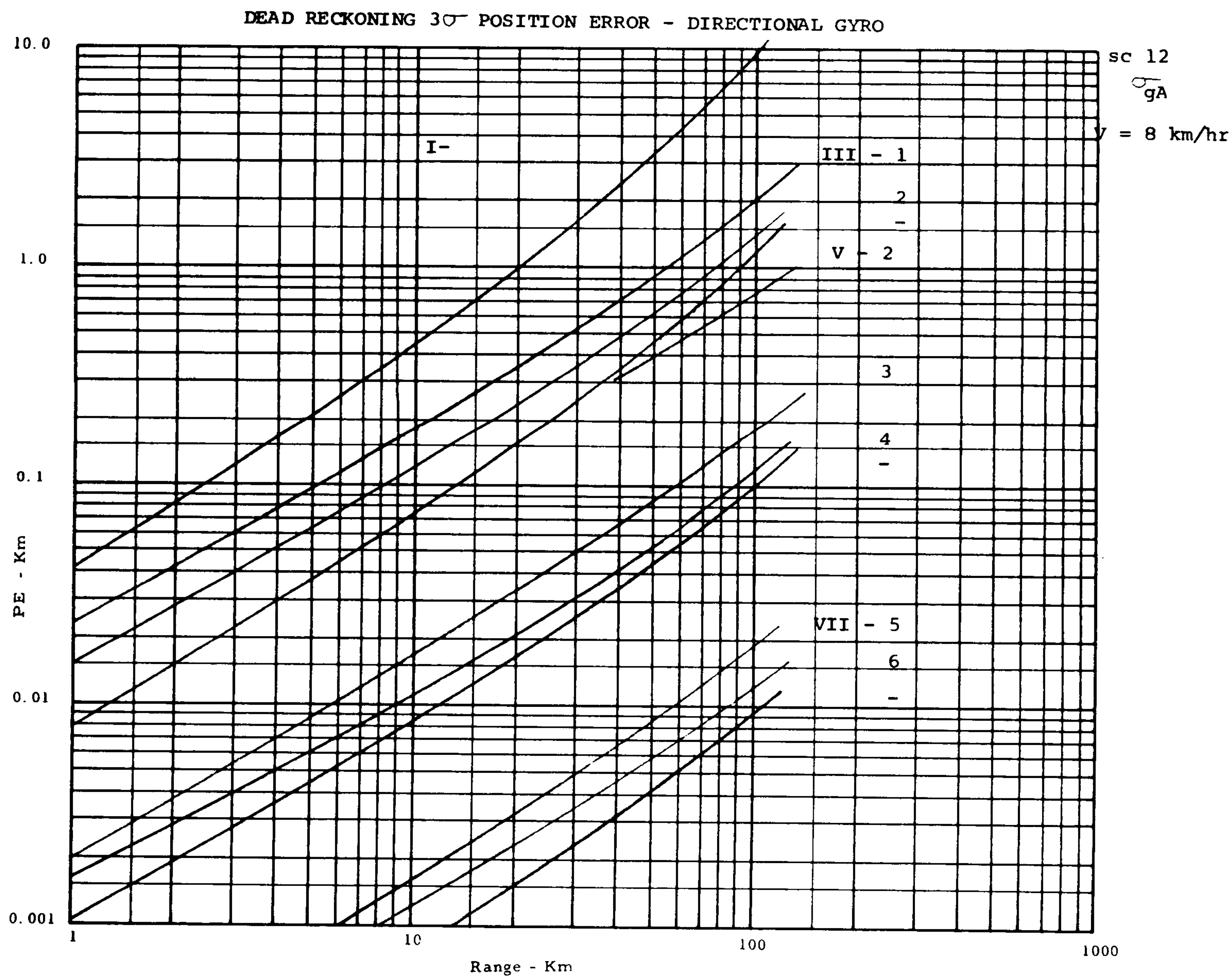


Figure 10-267 Dead Reckoning 3σ Position Error - Directional Gyro

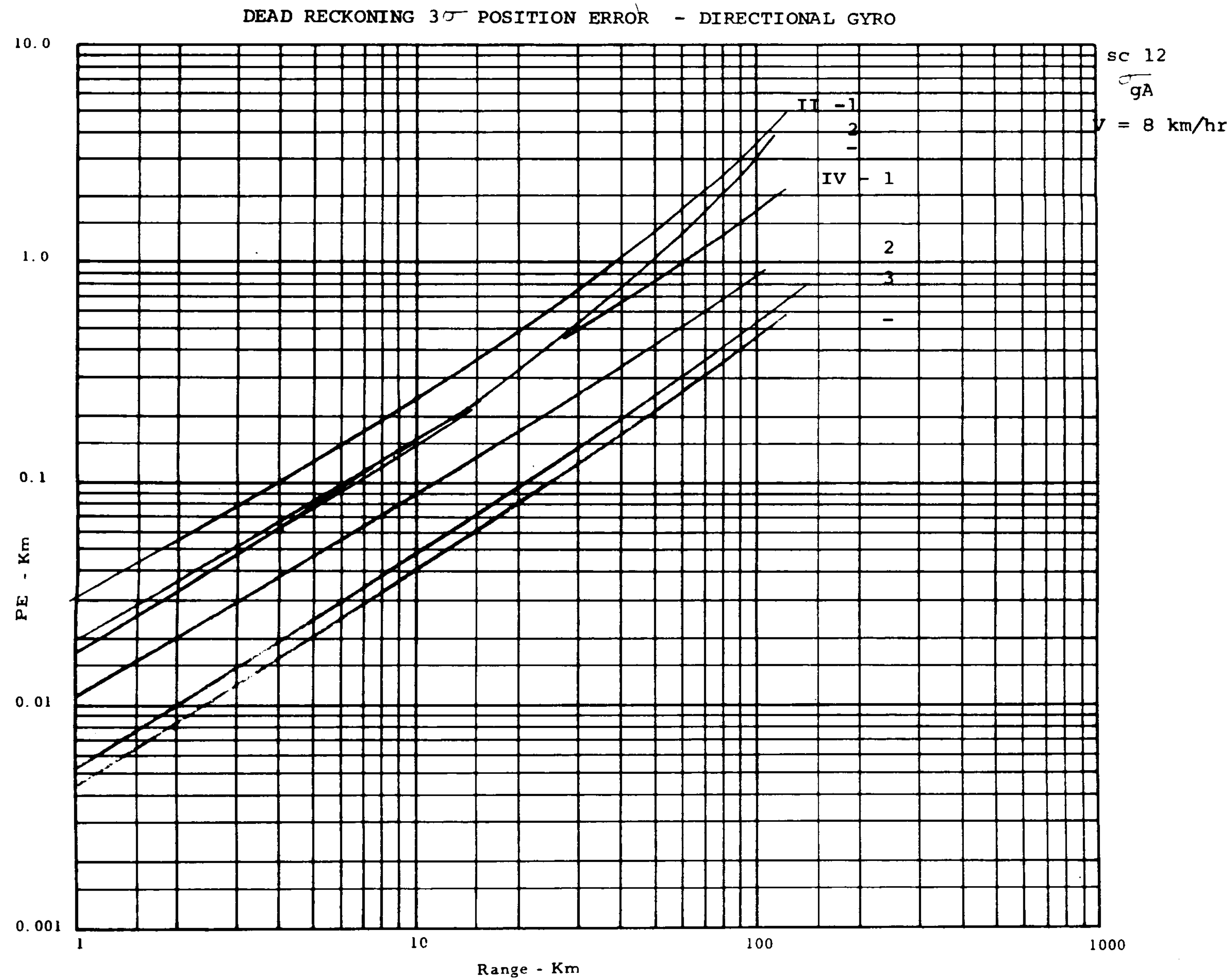


Figure 10-268 Dead Reckoning 3σ Position Error - Directional Gyro

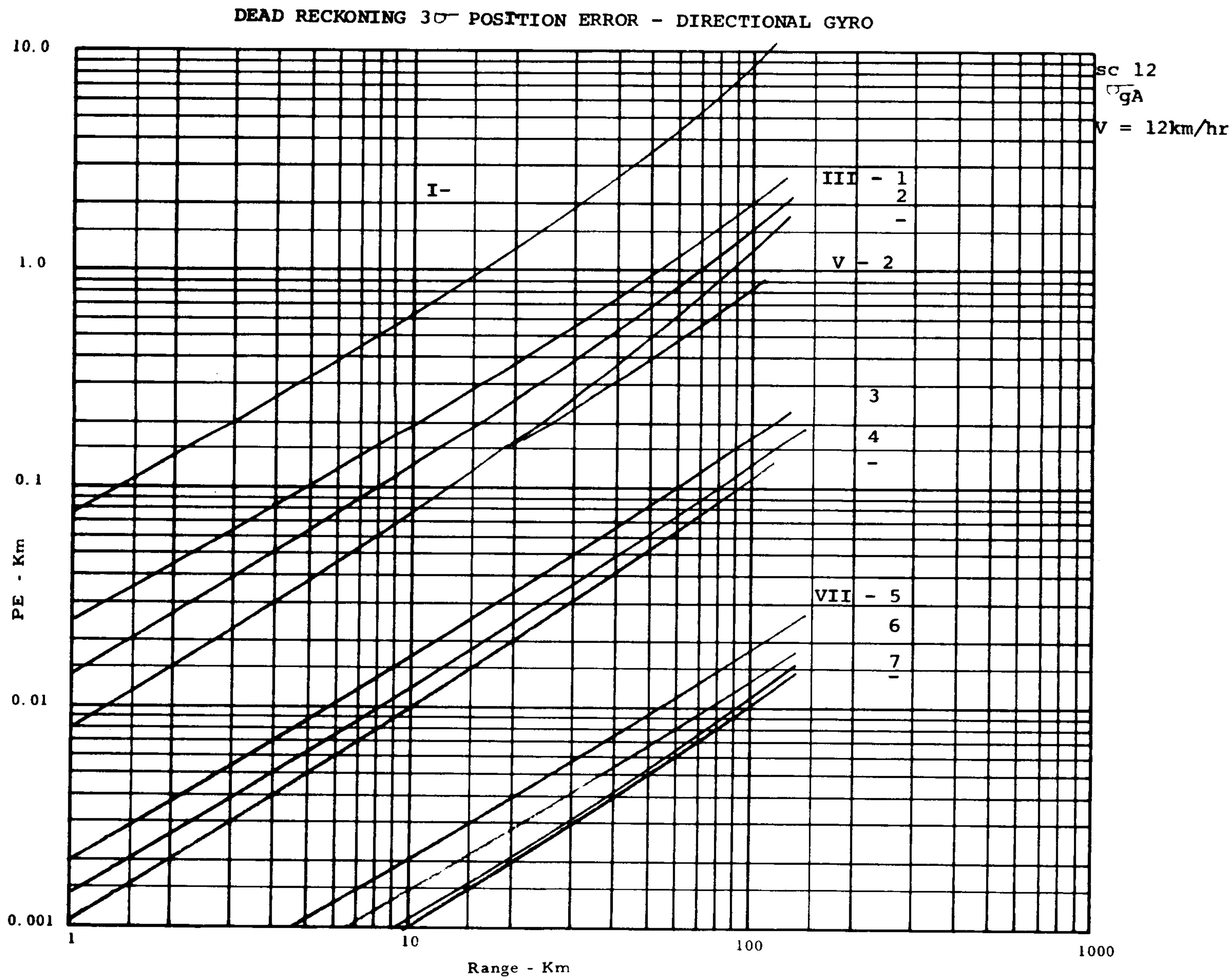


Figure 10-269 Dead Reckoning 3σ Position Error - Directional Gyro

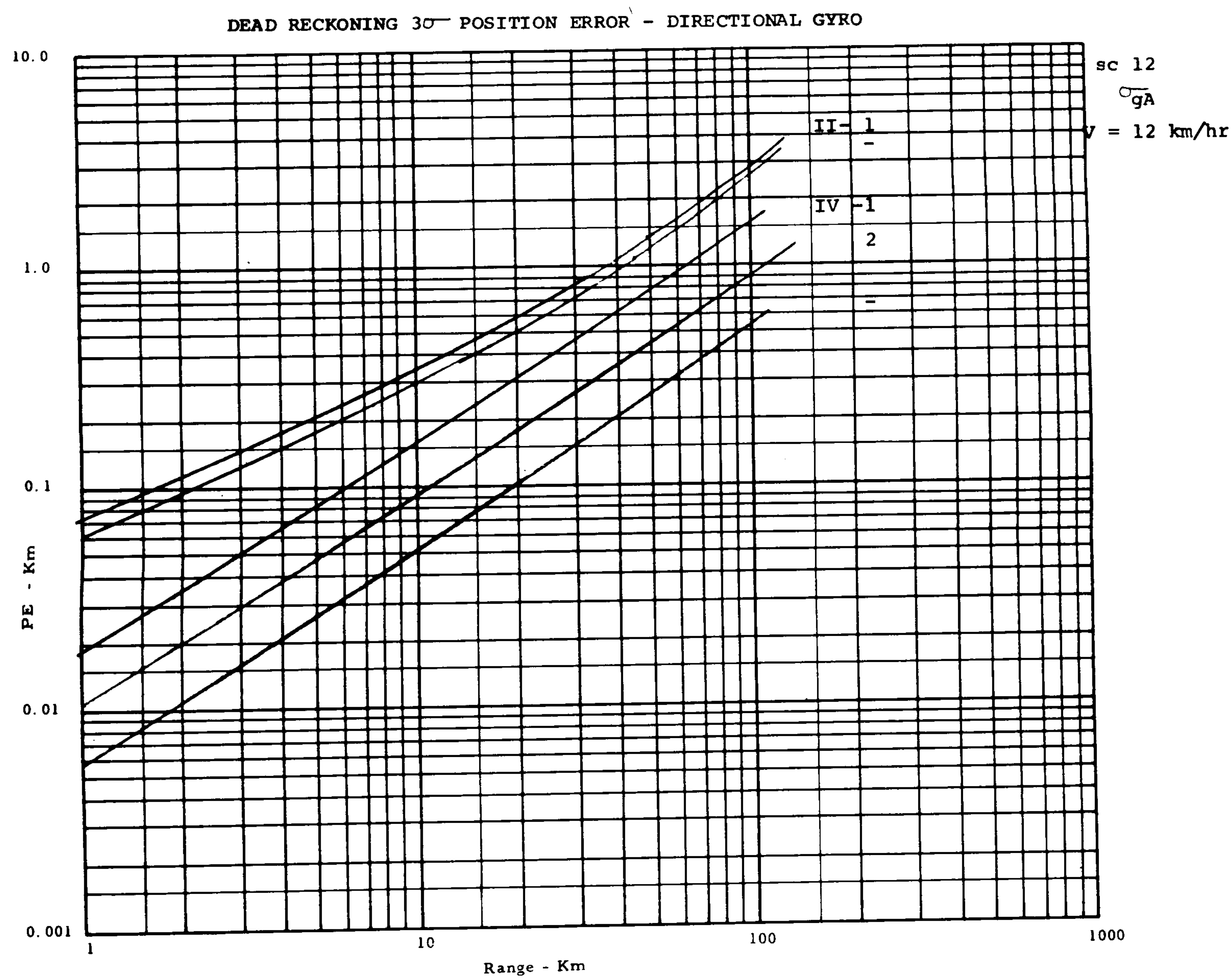


Figure 10-270 Dead Reckoning 3σ Position Error - Directional Gyro

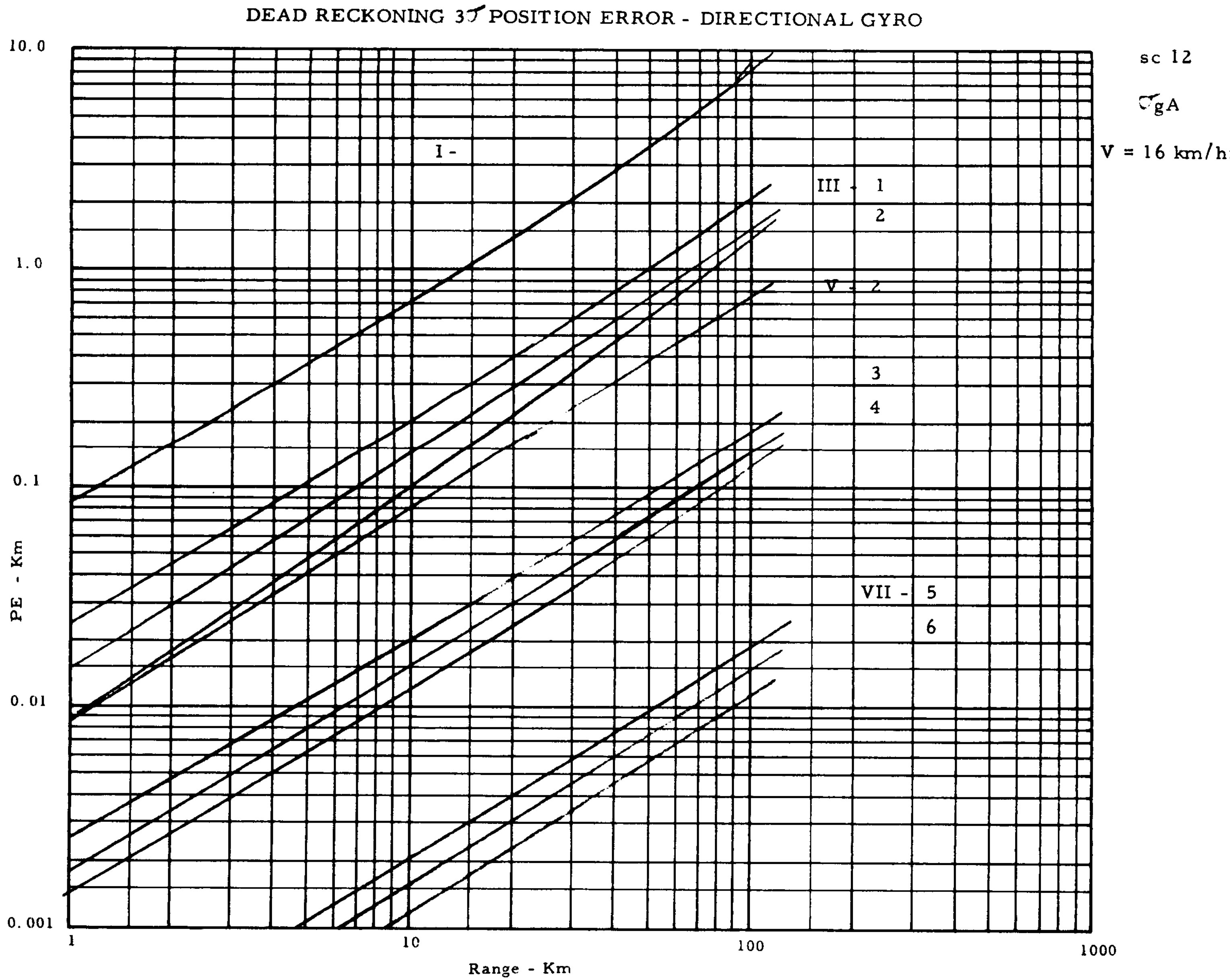


Figure 10-271 Dead Reckoning 3σ Position Error - Directional Gyro

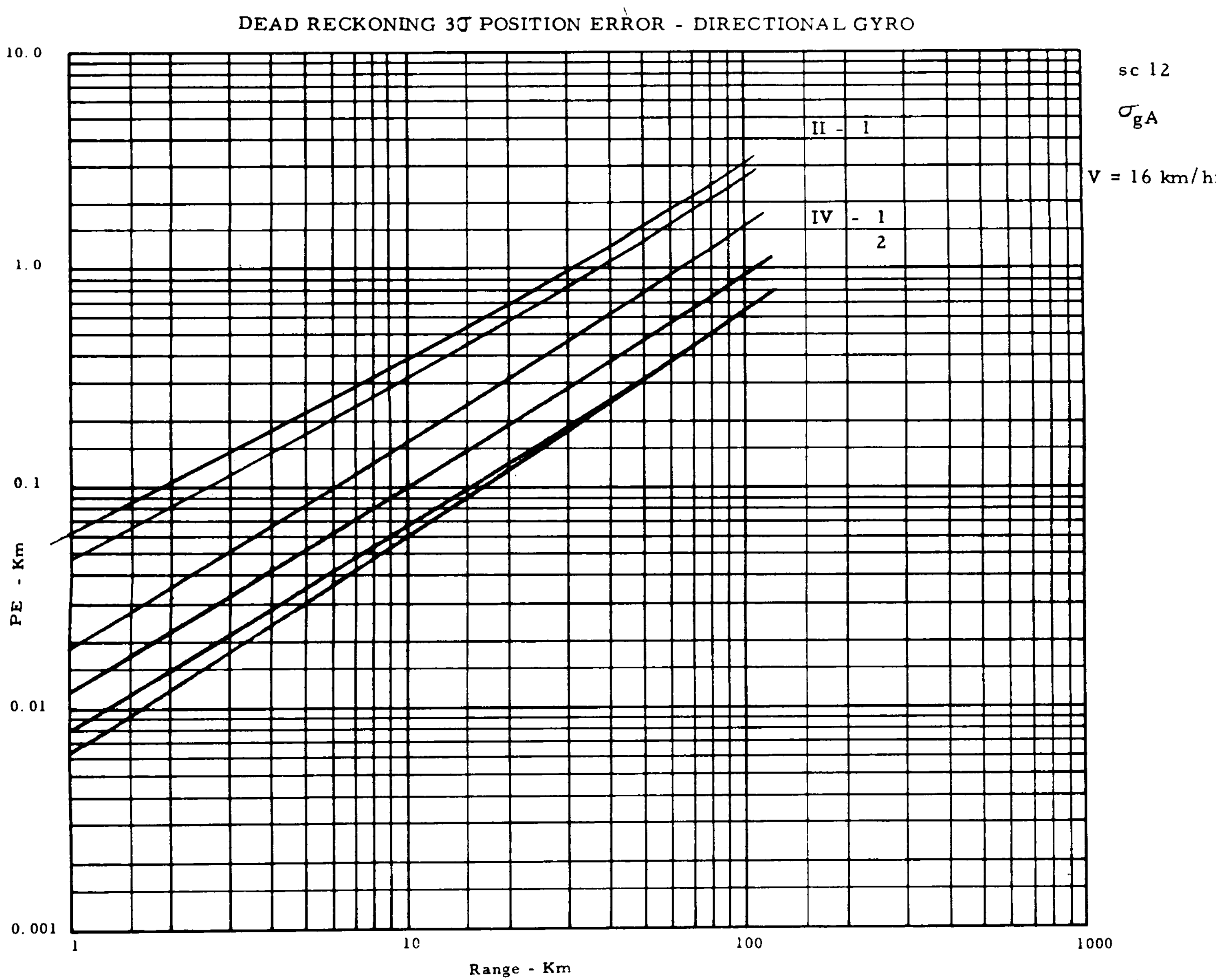


Figure 10-272 Dead Reckoning 3σ Position Error - Directional Gyro

DEAD RECKONING POSITION ERROR - GYRO DRIFT

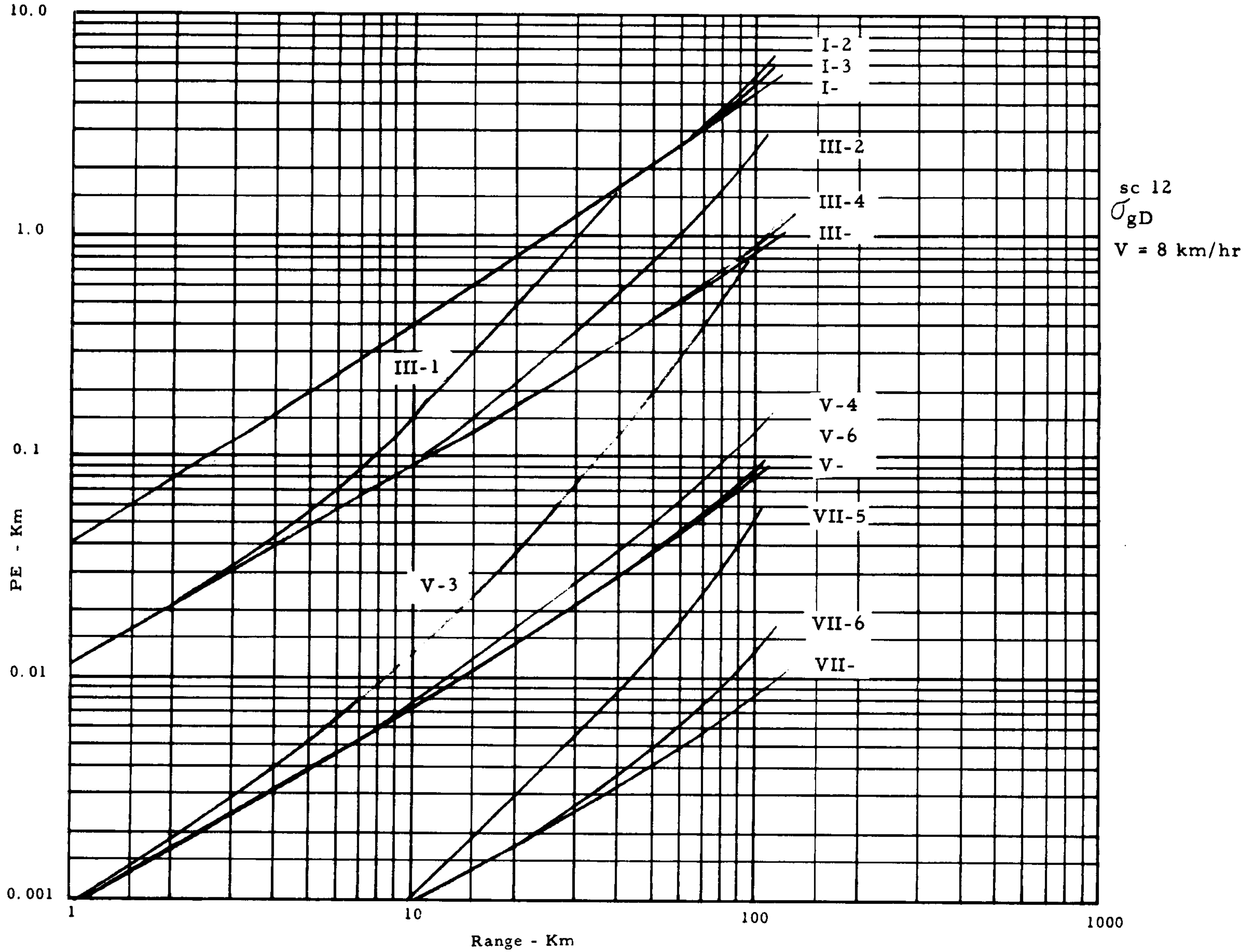


Figure 10-273 Dead Reckoning Position Error - Gyro Drift

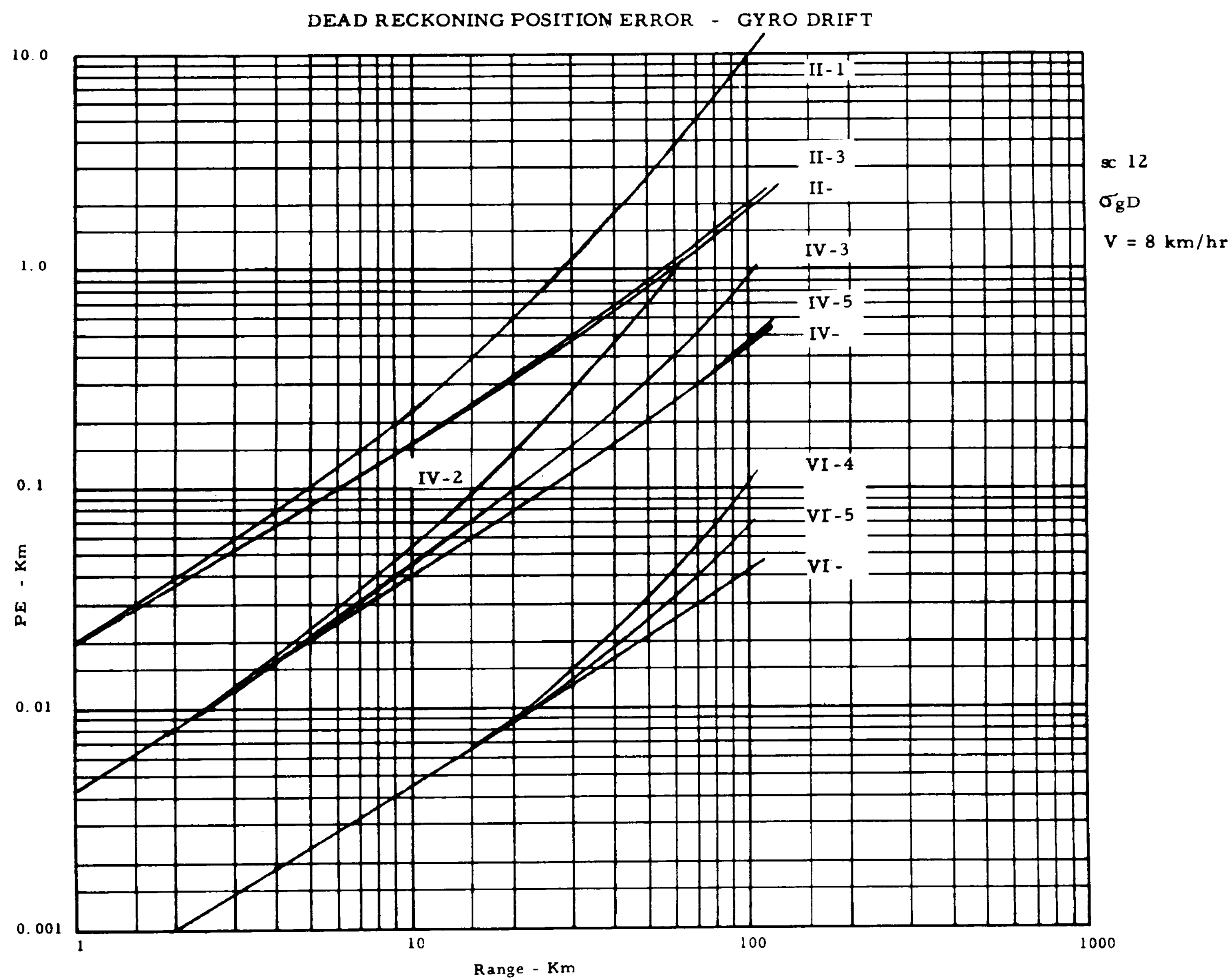


Figure 10-274 Dead Reckoning Position Error - Gyro Drift

DEAD RECKONING 3σ POSITION ERROR - DIRECTIONAL GYRO DRIFT

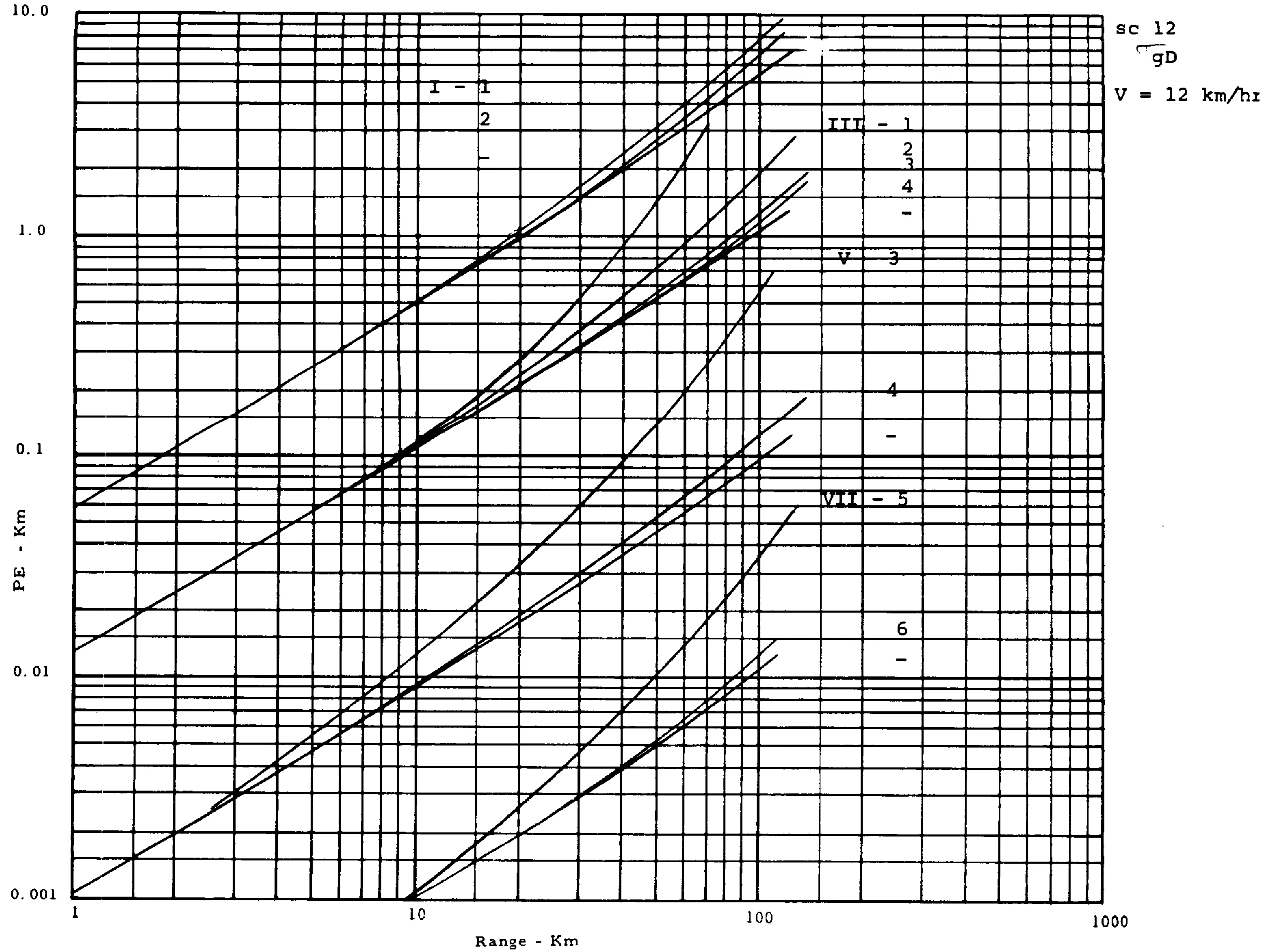


Figure 10-275 Dead Reckoning 3σ Position Error - Directional Gyro Drift

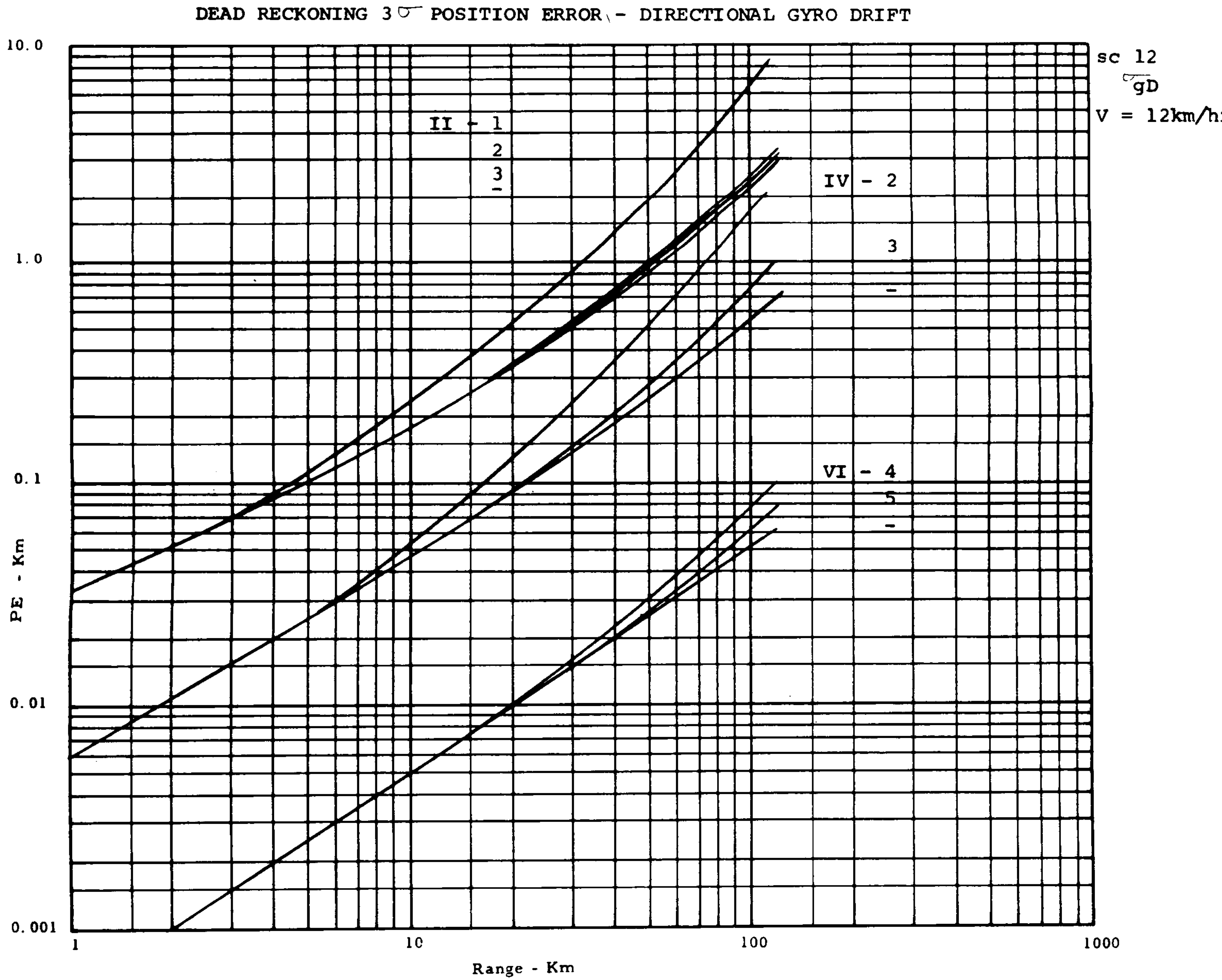


Figure 10-276 Dead Reckoning 3σ Position Error - Directional Gyro Drift

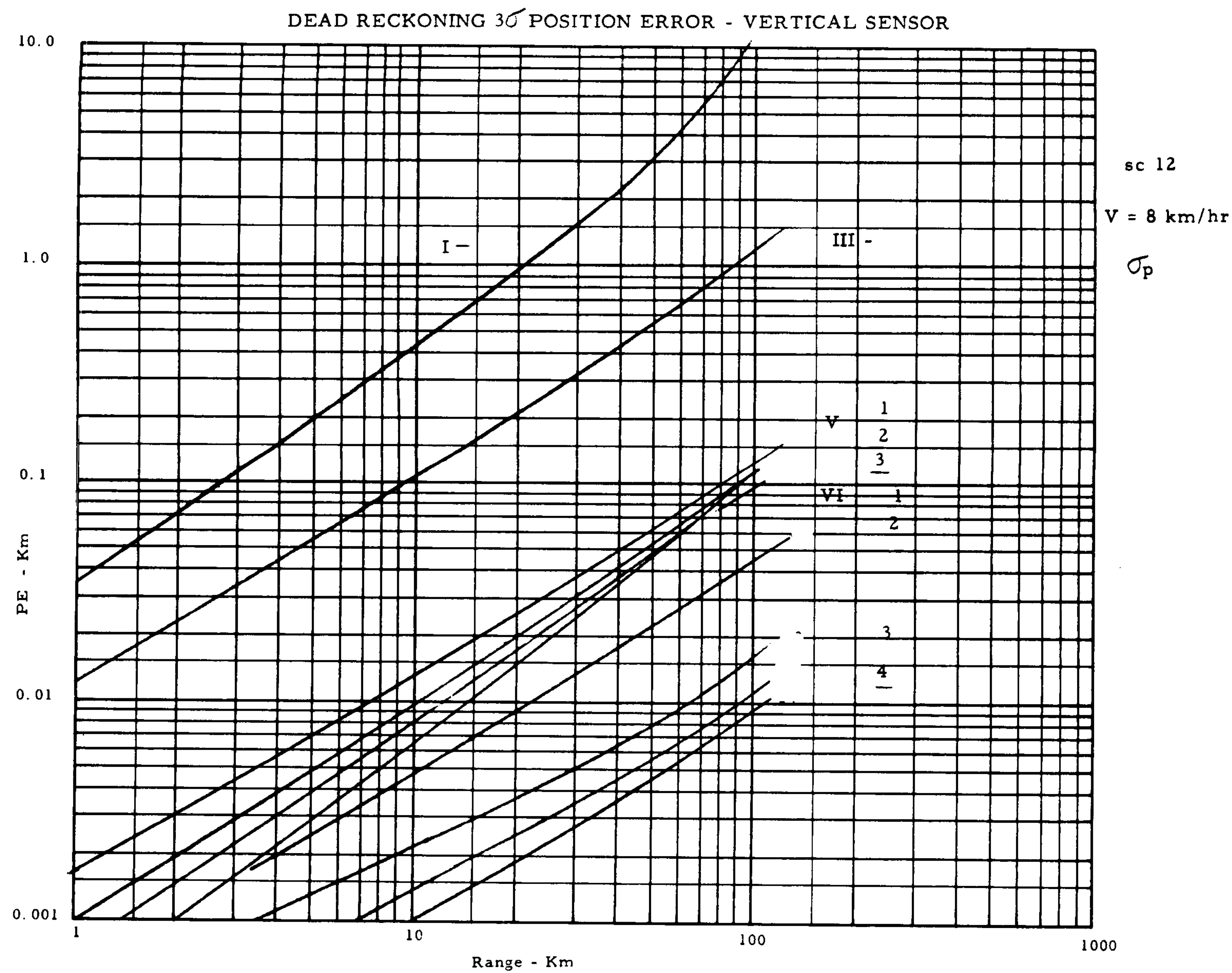


Figure 10-277 Dead Reckoning 3σ Position Error - Vertical Sensor

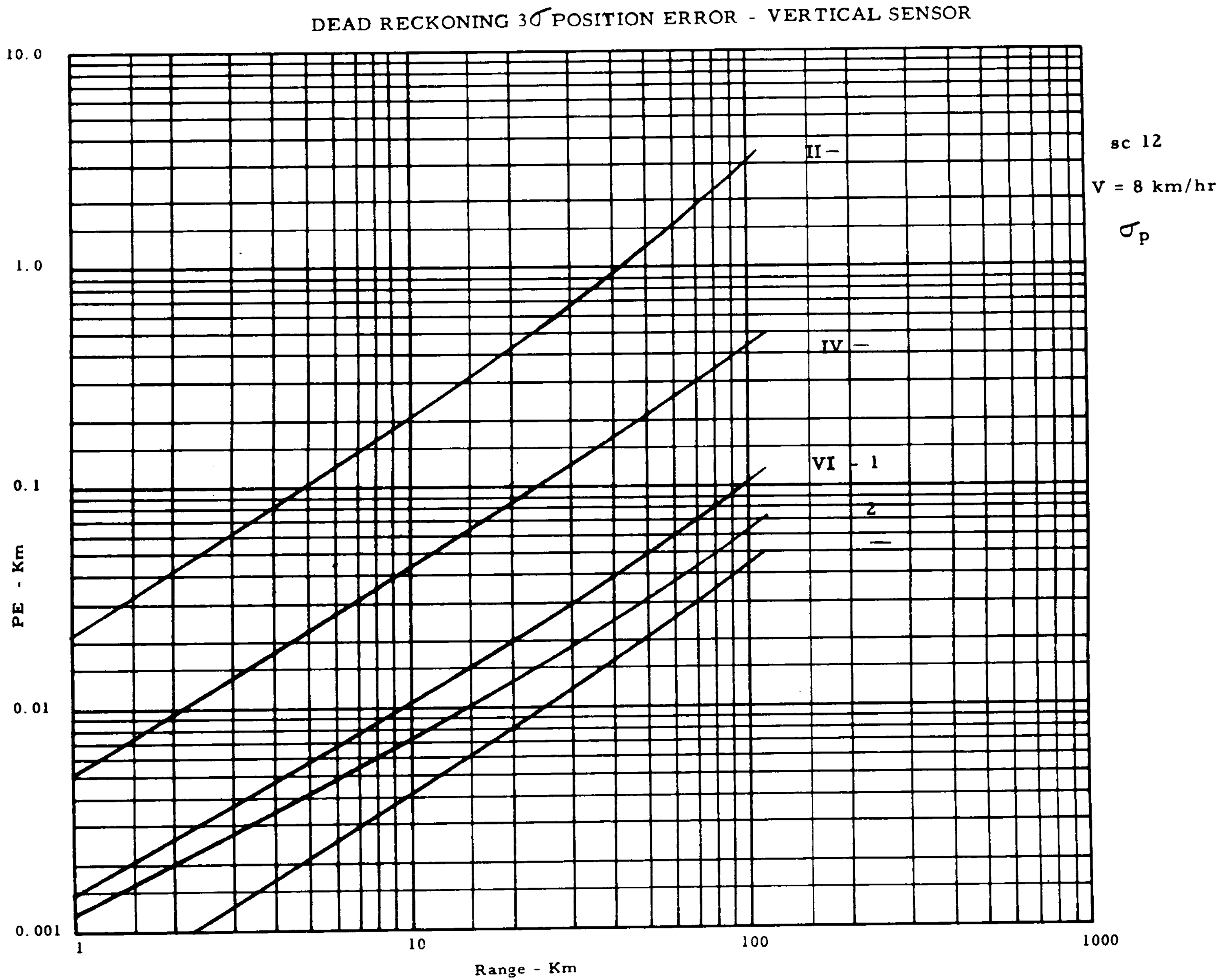


Figure 10-278 Dead Reckoning 3σ Position Error - Vertical Sensor

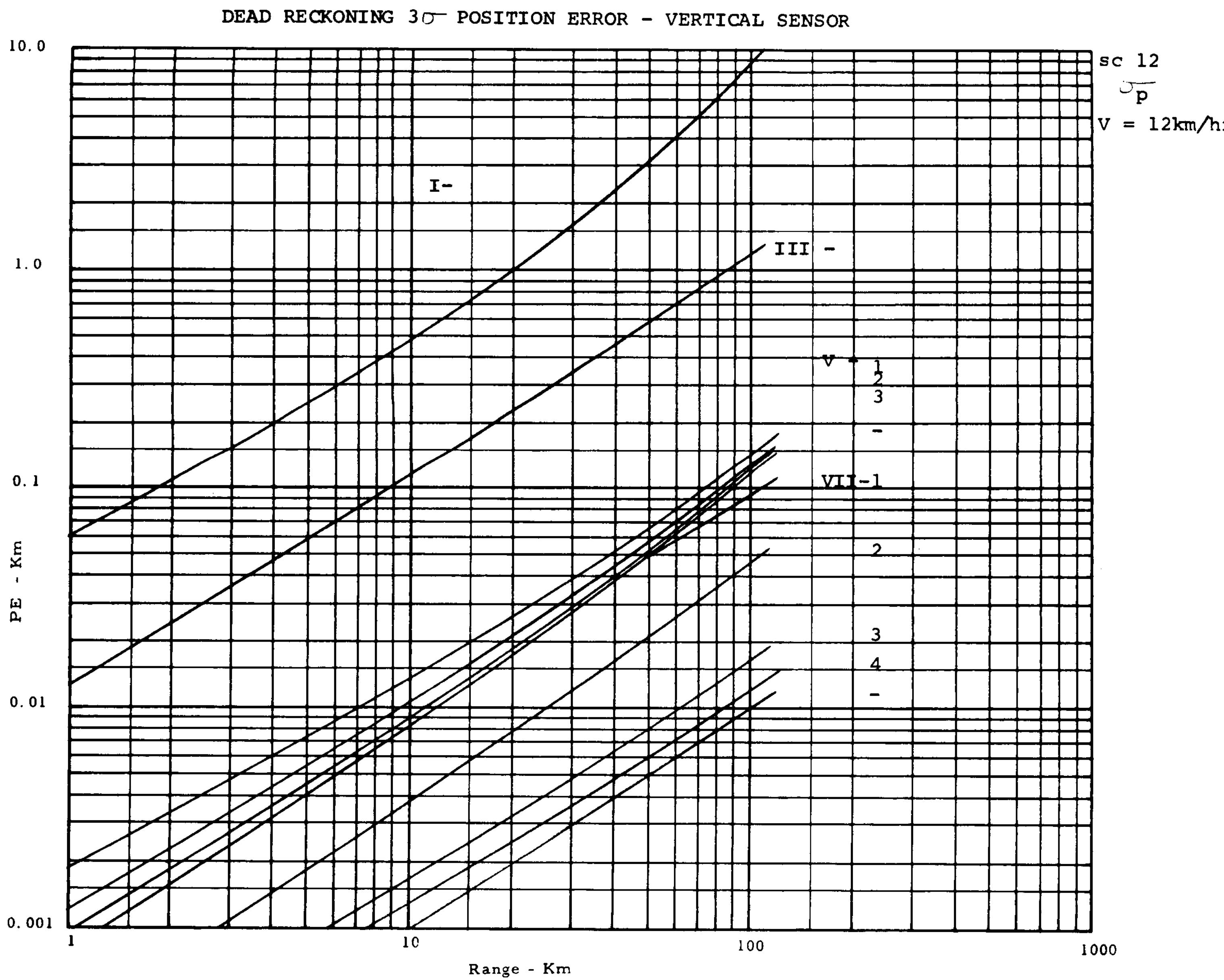


Figure 10-279 Dead Reckoning 3σ Position Error - Vertical Sensor

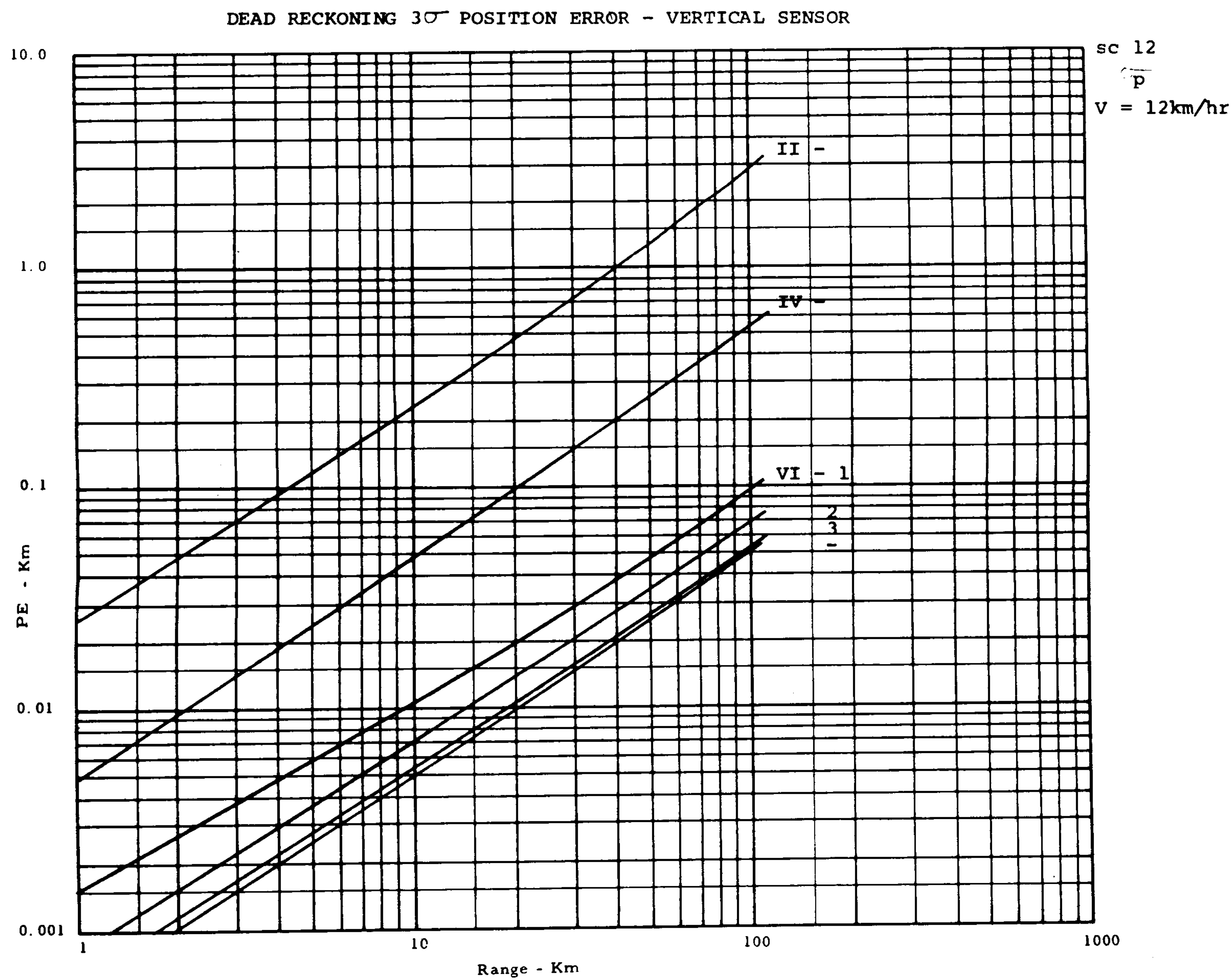


Figure 10-280 Dead Reckoning 3σ Position Error - Vertical Sensor

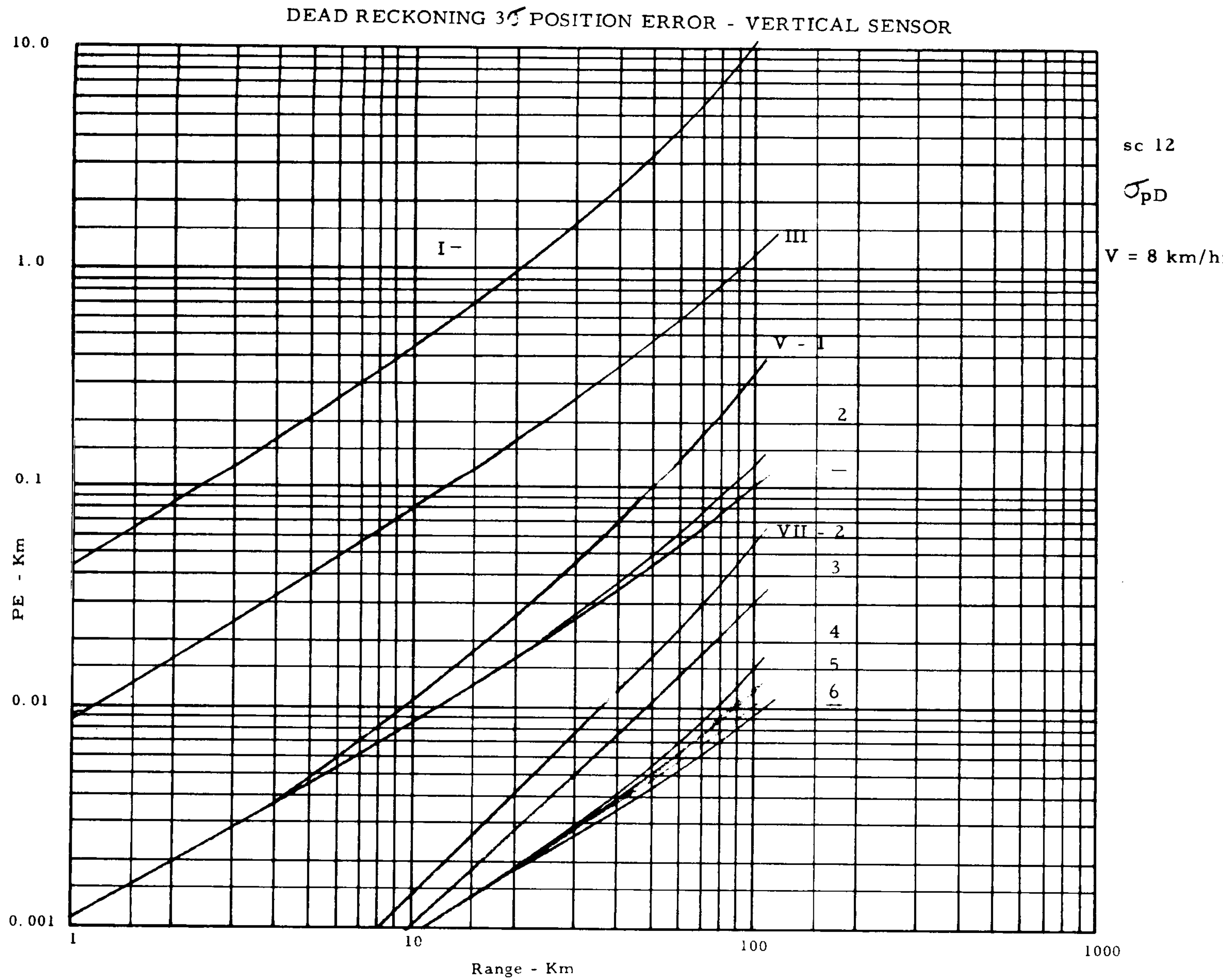


Figure 10-281 Dead Reckoning 3σ Position Error - Vertical Sensor

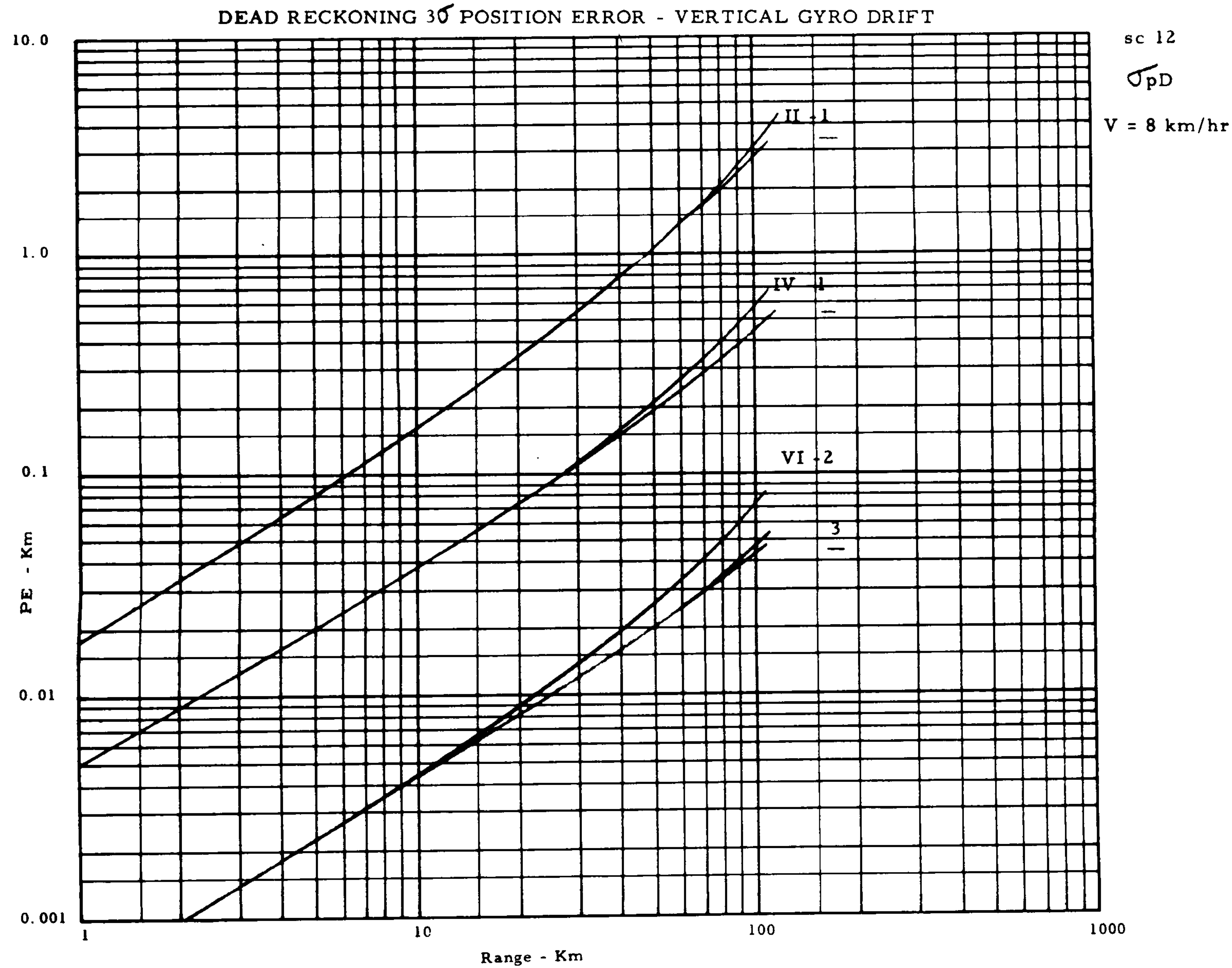


Figure 10-282 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

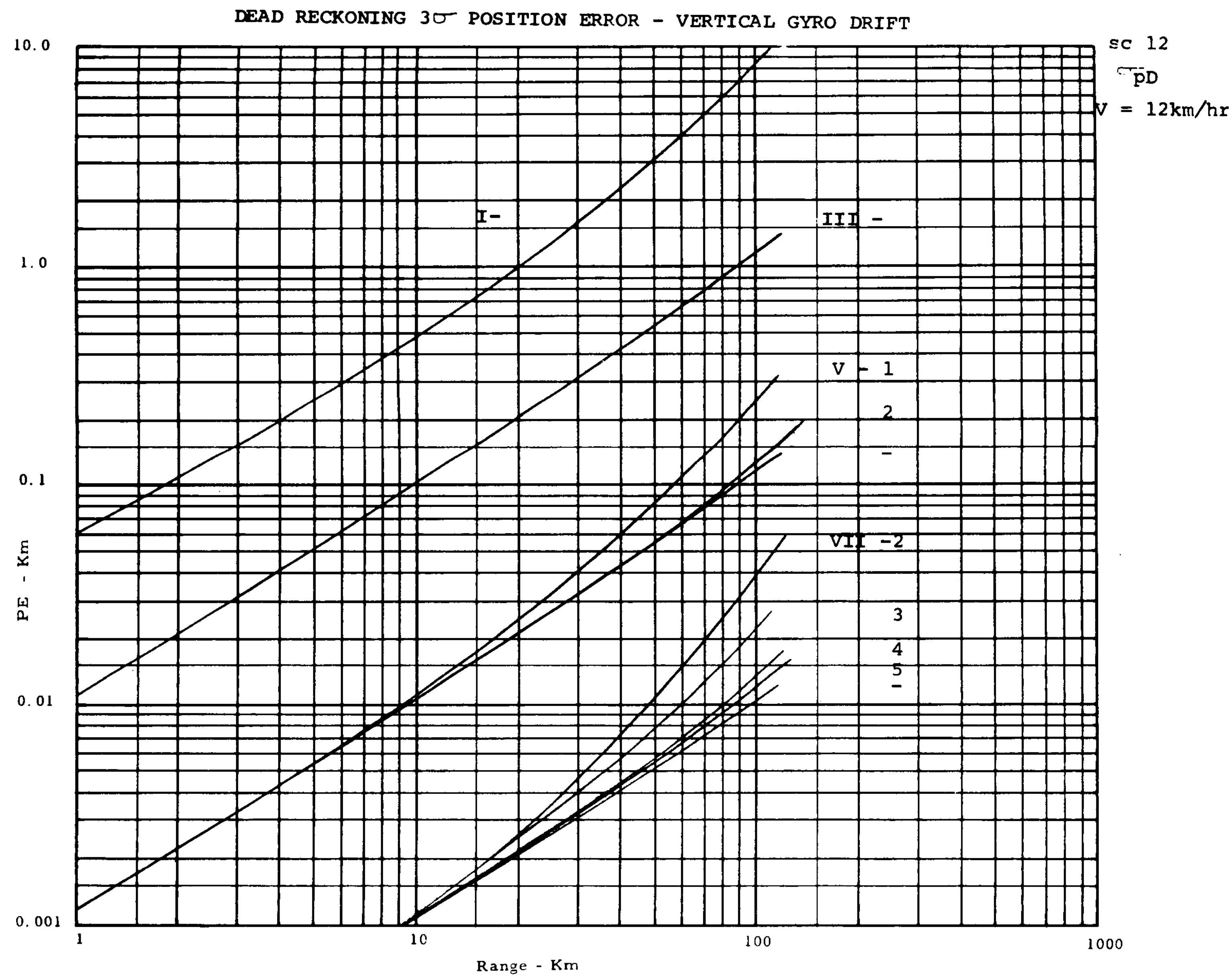


Figure 10-283 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

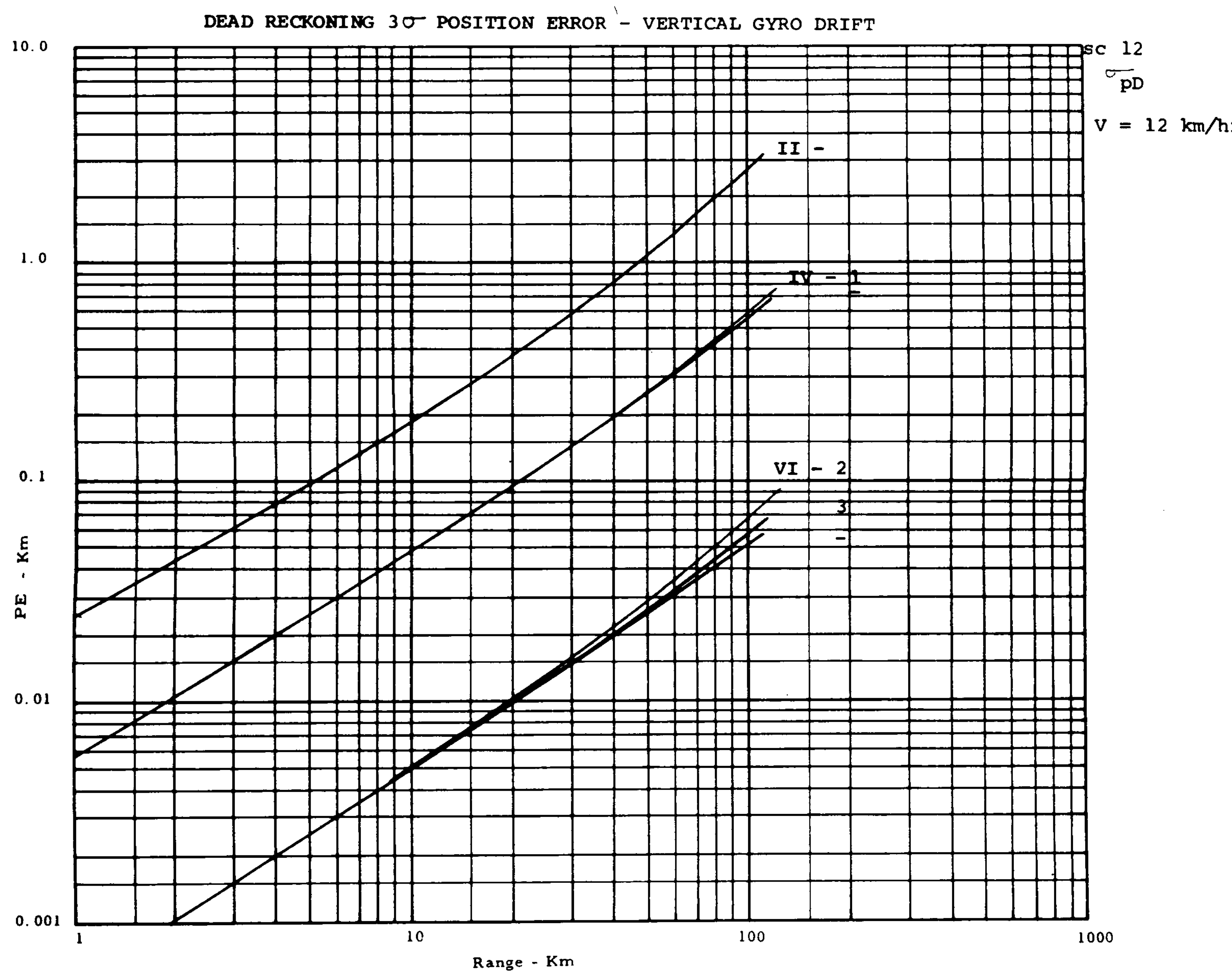


Figure 10-284 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

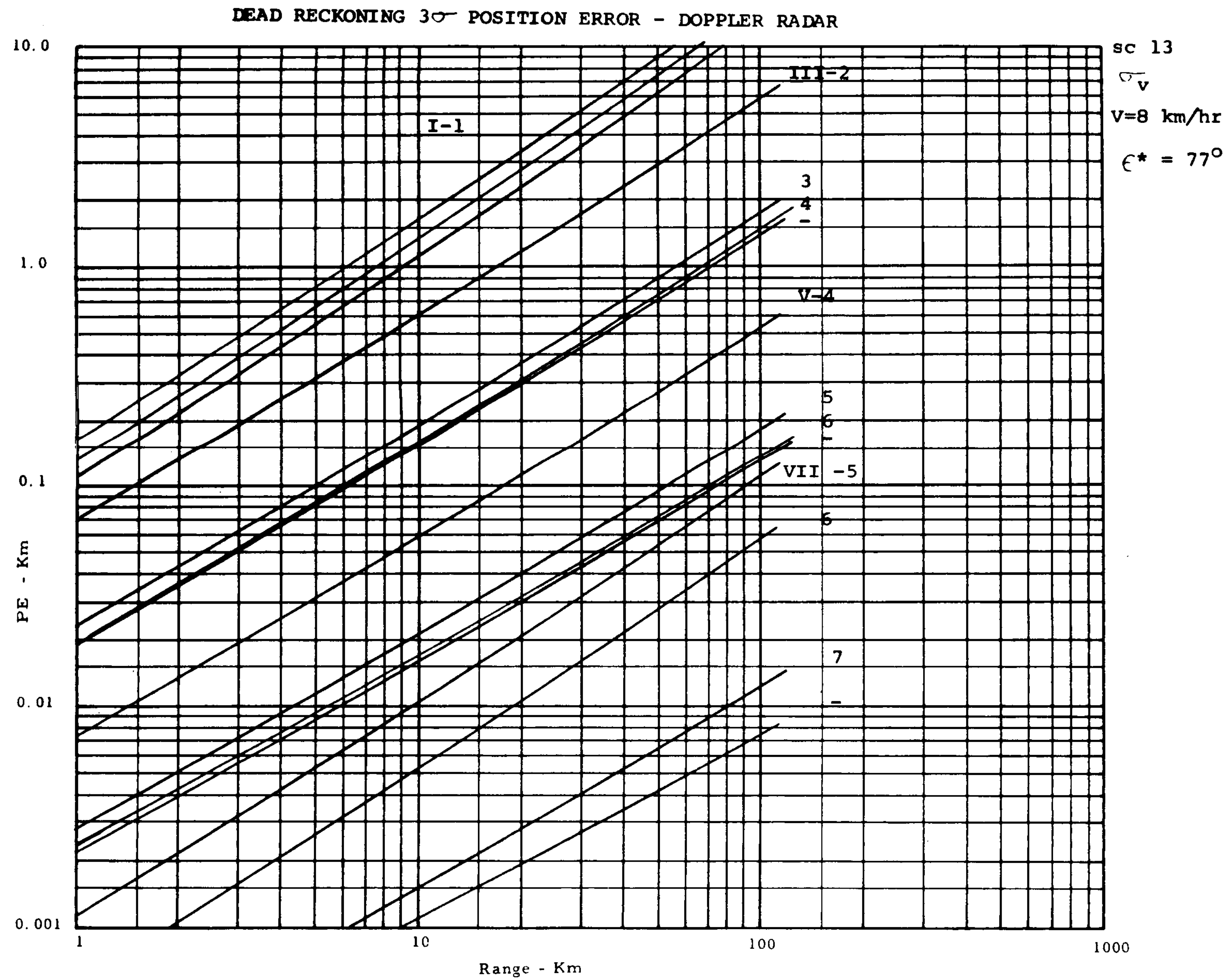


Figure 10-285 Dead Reckoning 3σ Position Error - Doppler Radar

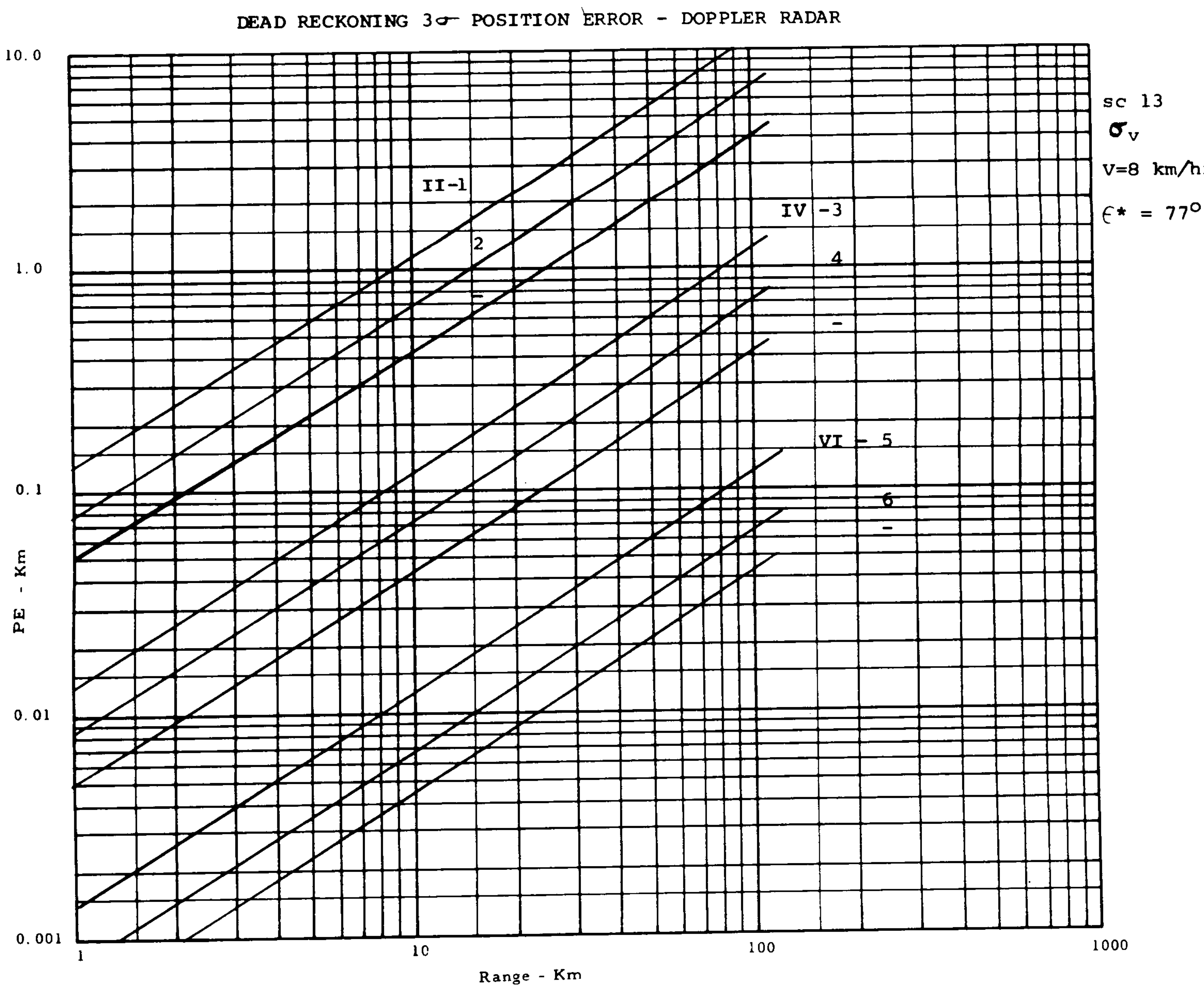


Figure 10-286 Dead Reckoning 3σ Position Error - Doppler Radar

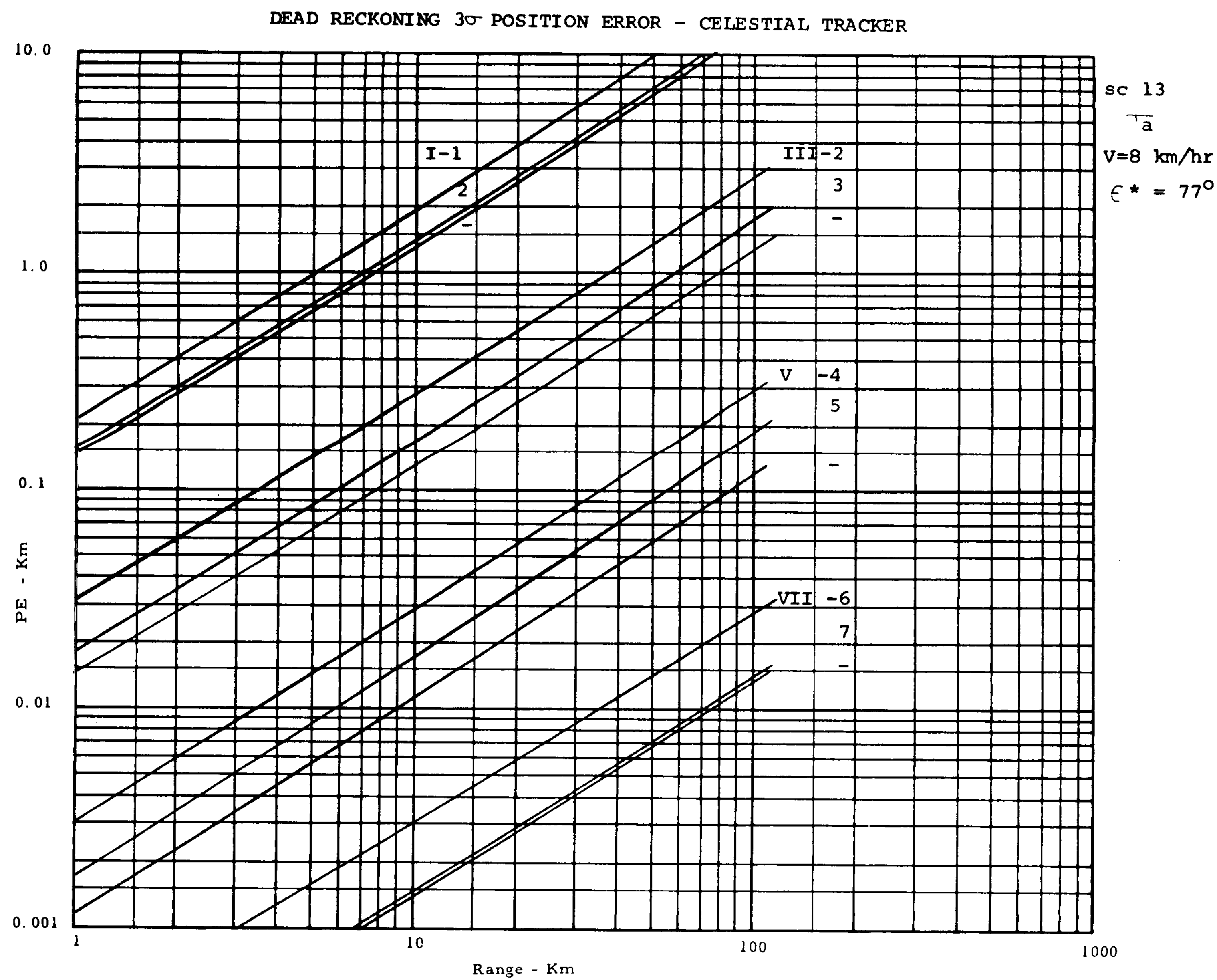


Figure 10-287 Dead Reckoning 3σ Position Error - Celestial Tracker

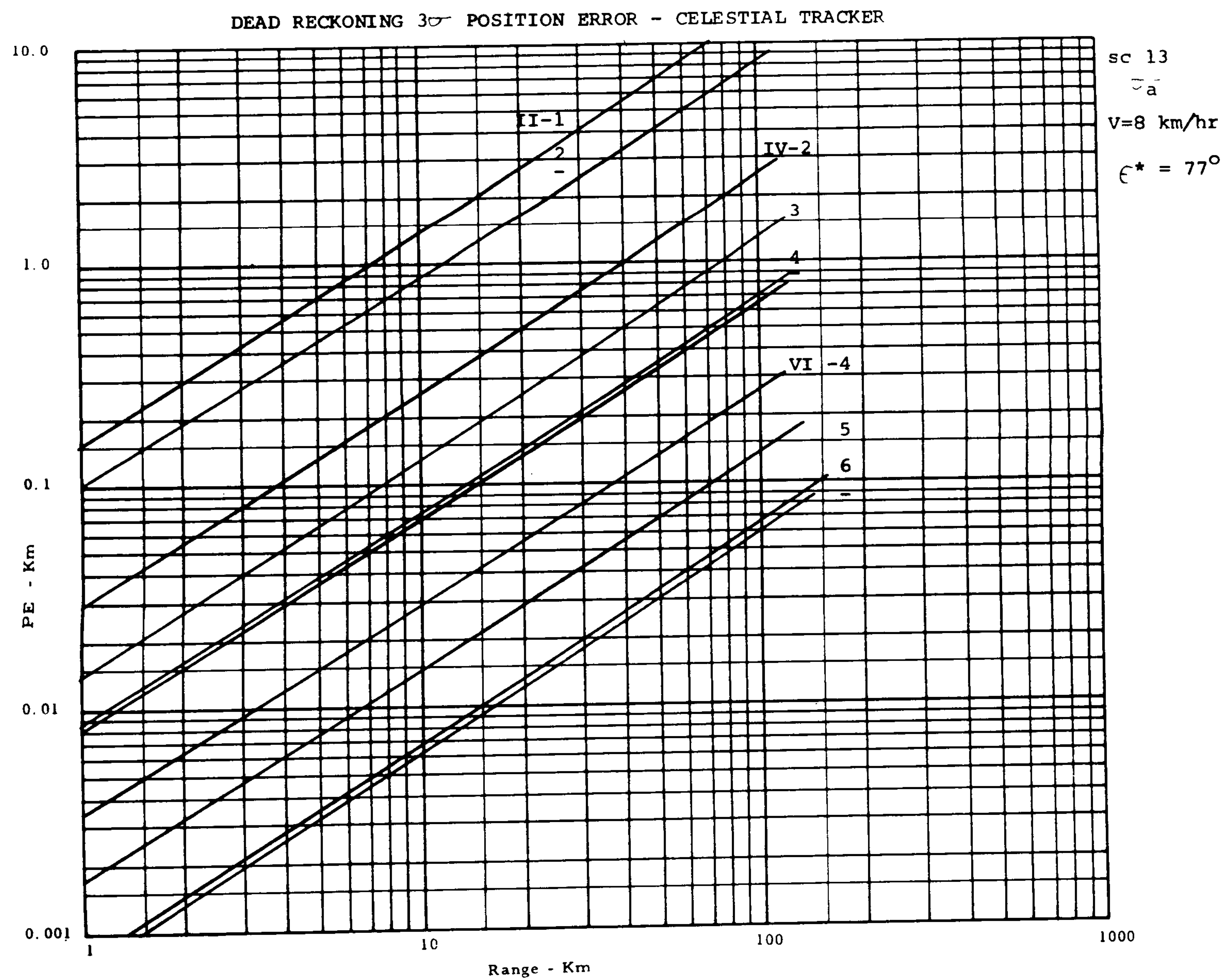


Figure 10-288 Dead Reckoning 3σ Position Error - Celestial Tracker

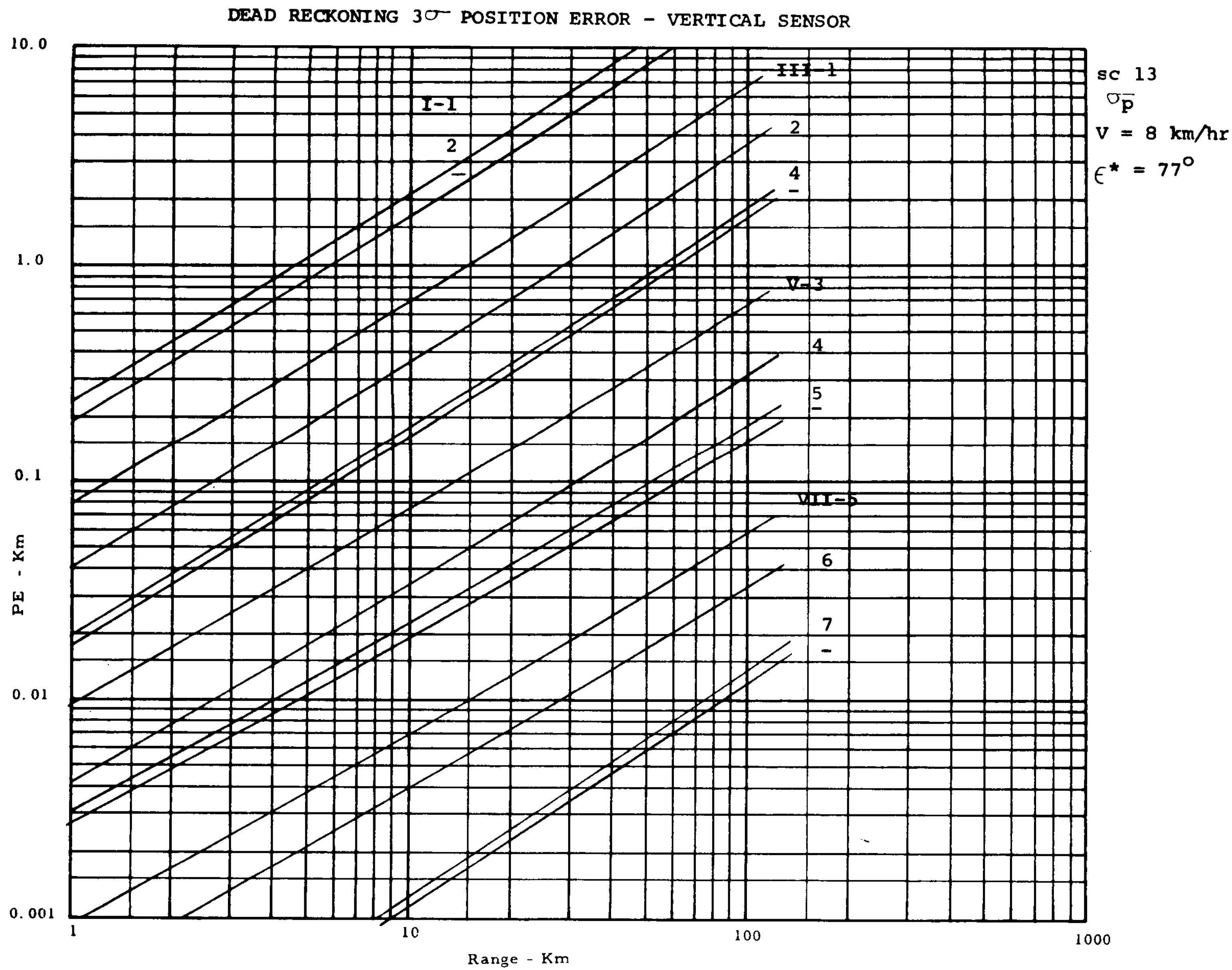


Figure 10-289 Dead Reckoning 3σ Position Error - Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - VERTICAL SENSOR

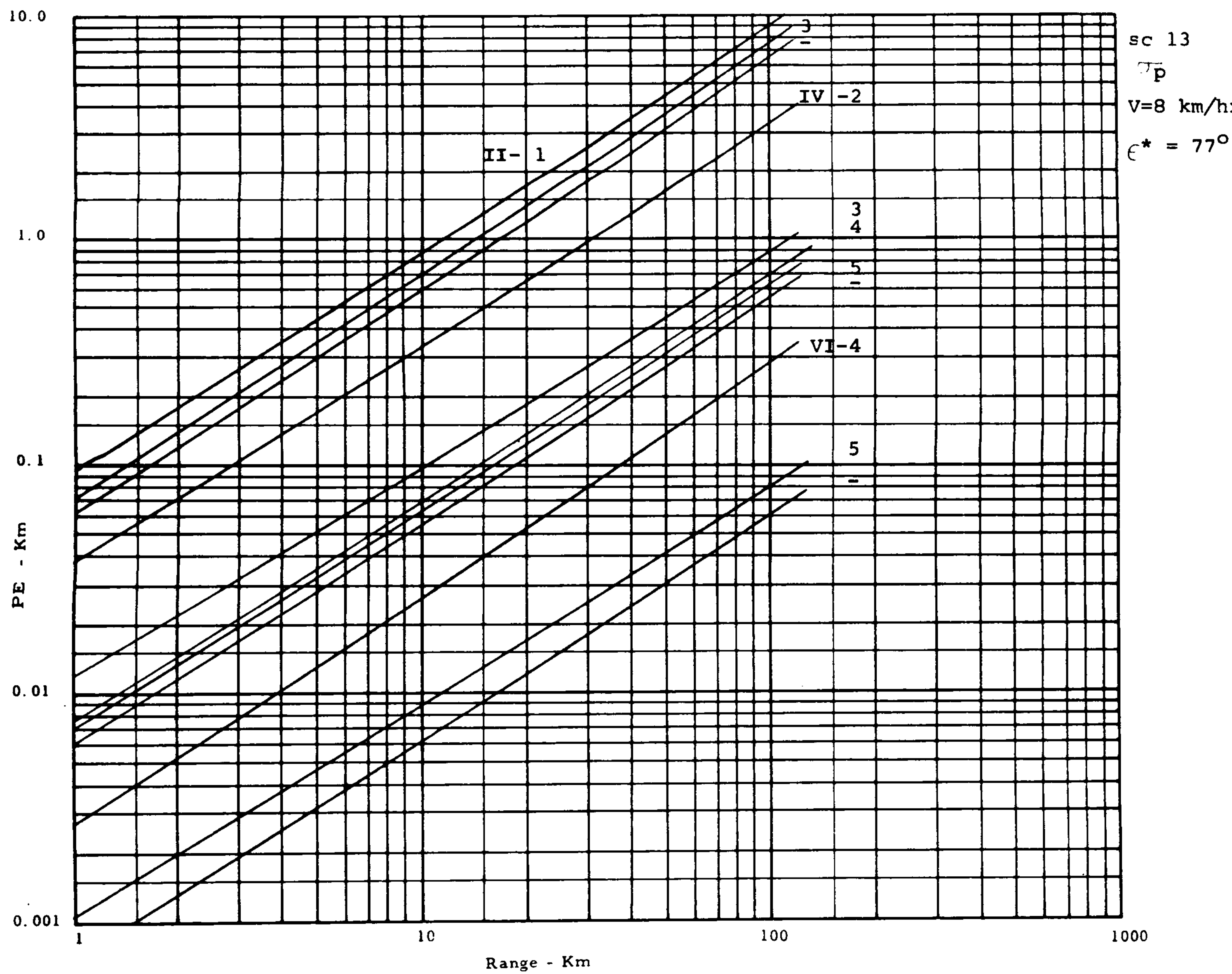


Figure 10-290 Dead Reckoning 3σ Position Error - Vertical Sensor

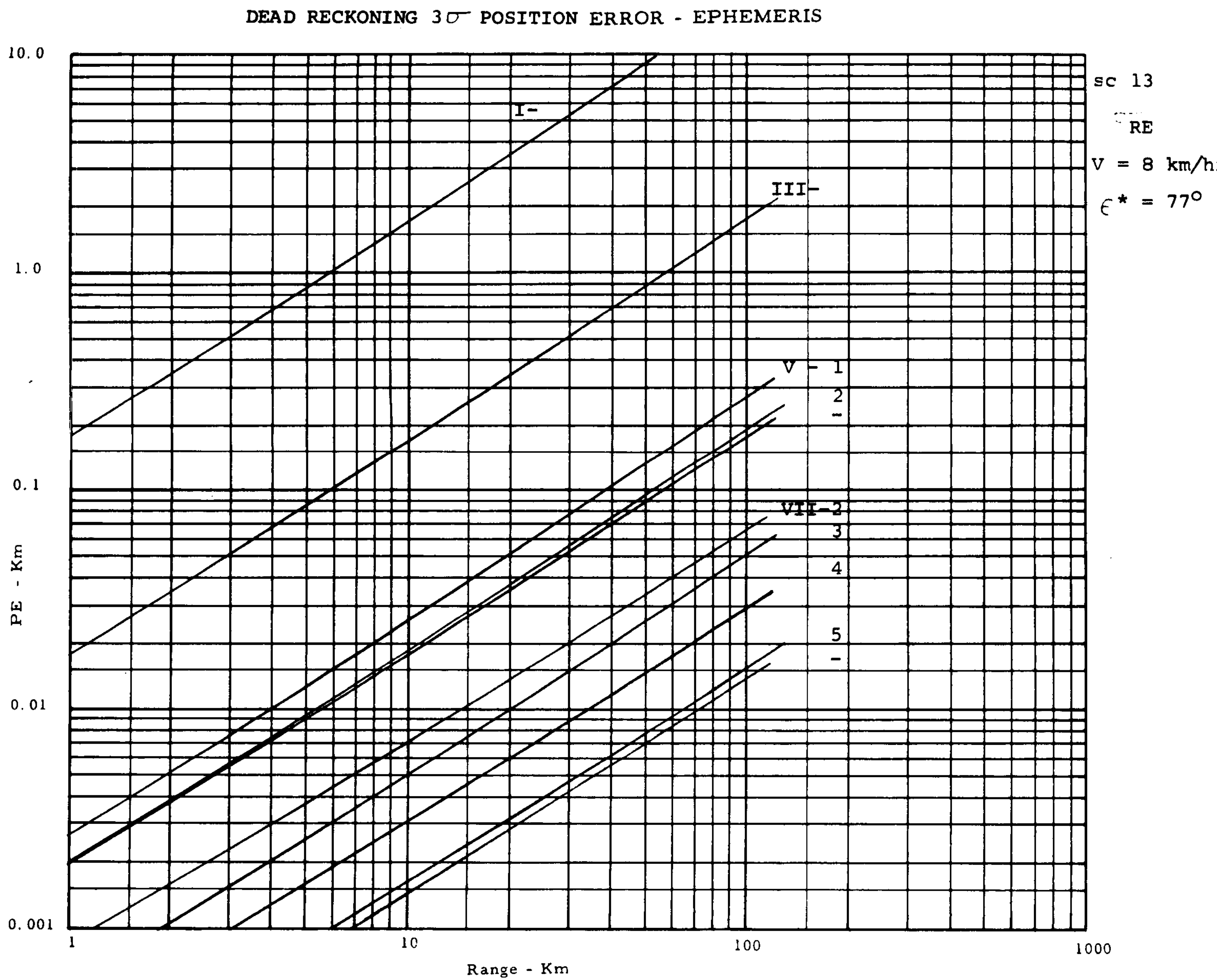


Figure 10-291 Dead Reckoning 3σ Position Error - Ephemeris

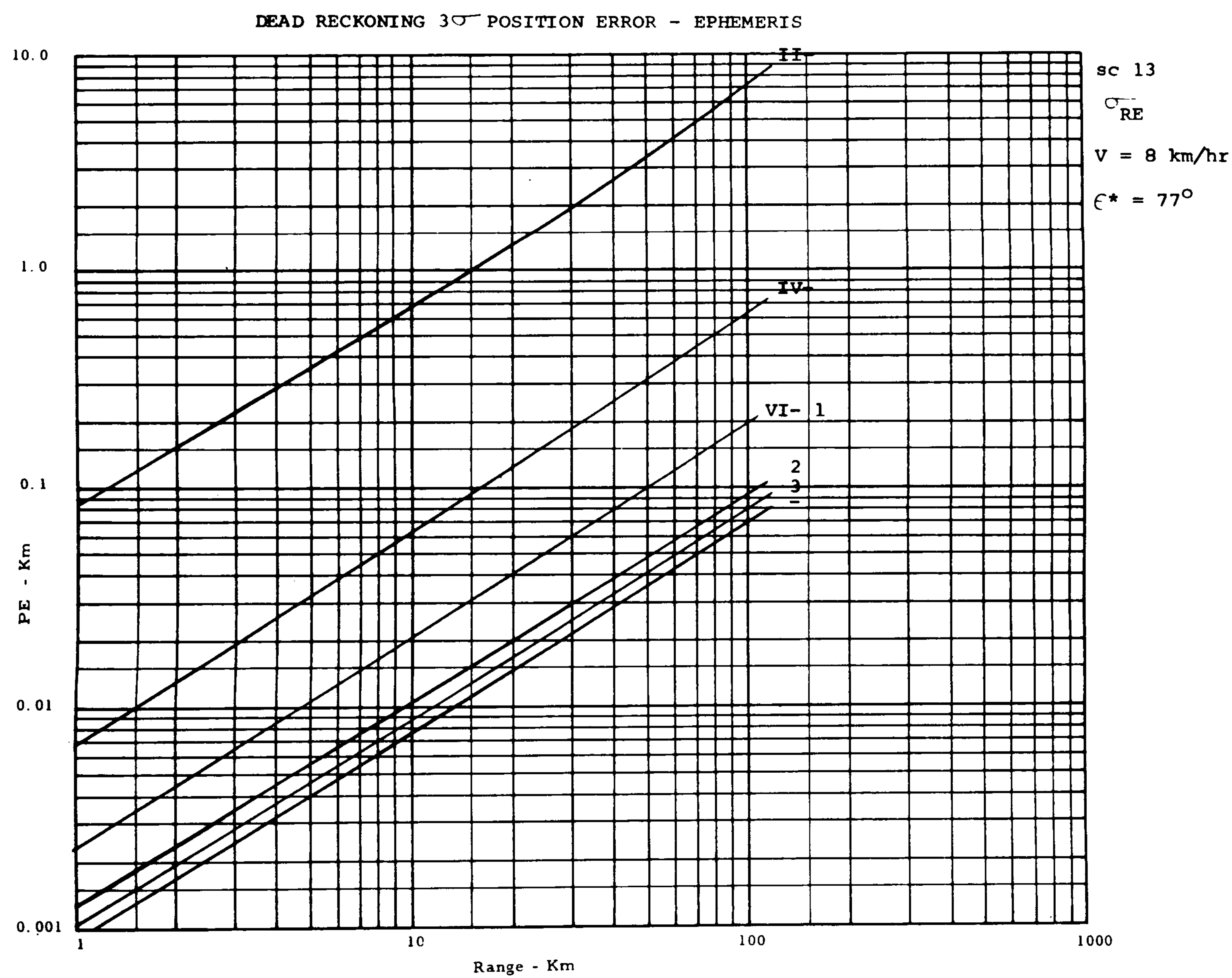


Figure 10-292 Dead Reckoning 3σ Position Error - Ephemeris

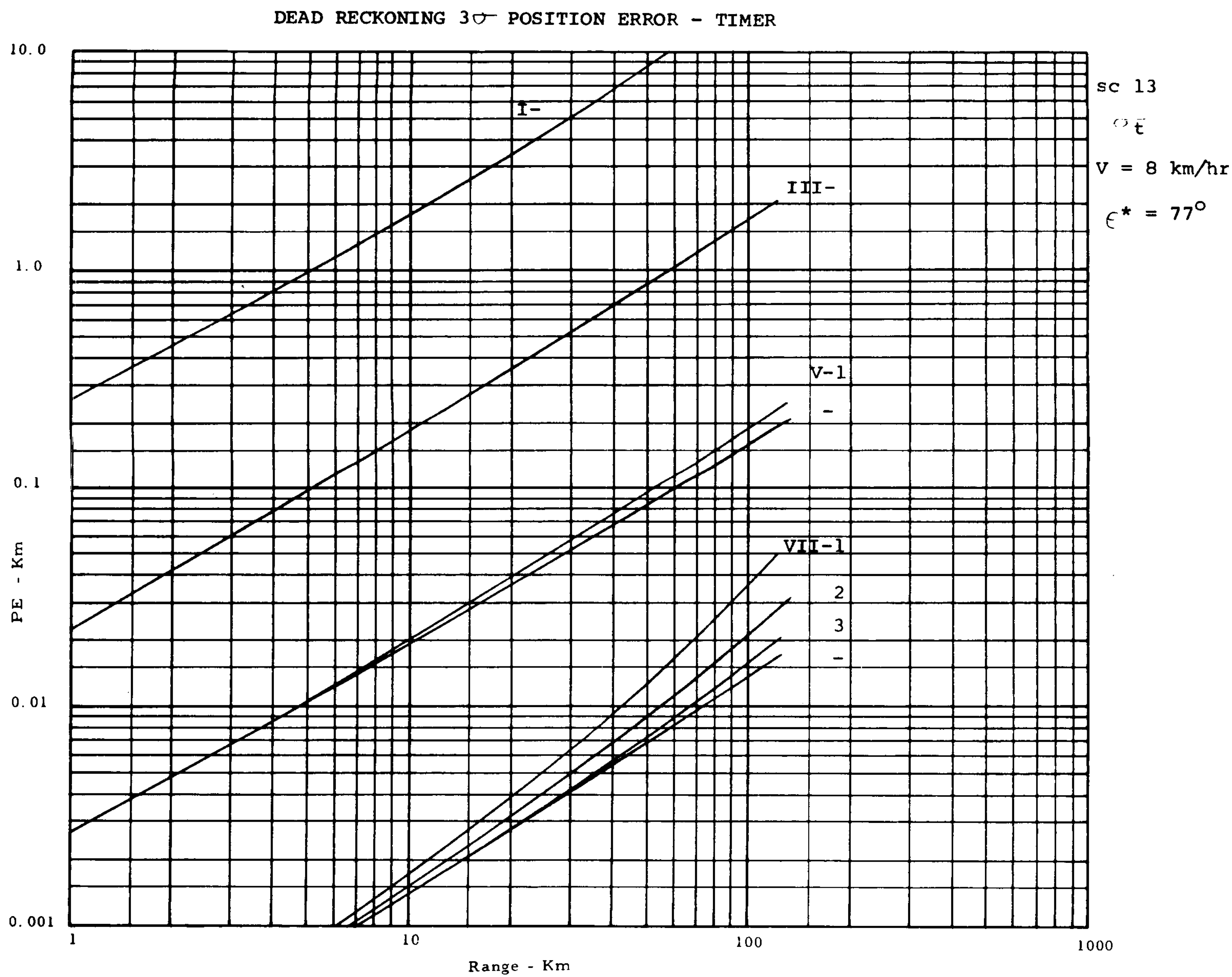


Figure 10-293 Dead Reckoning 3σ Position Error - Timer

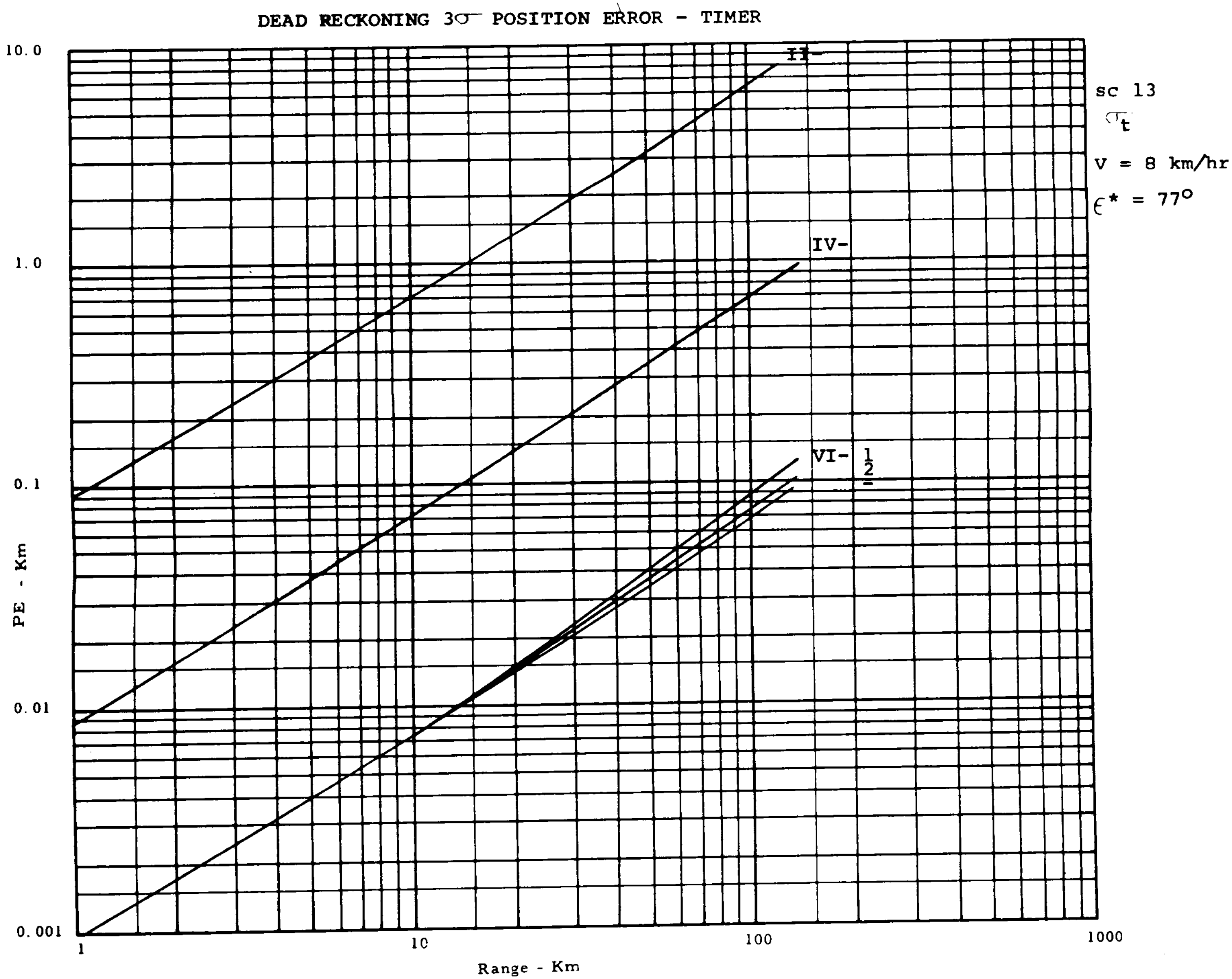


Figure 10-294 Dead Reckoning 3σ Position Error - Timer

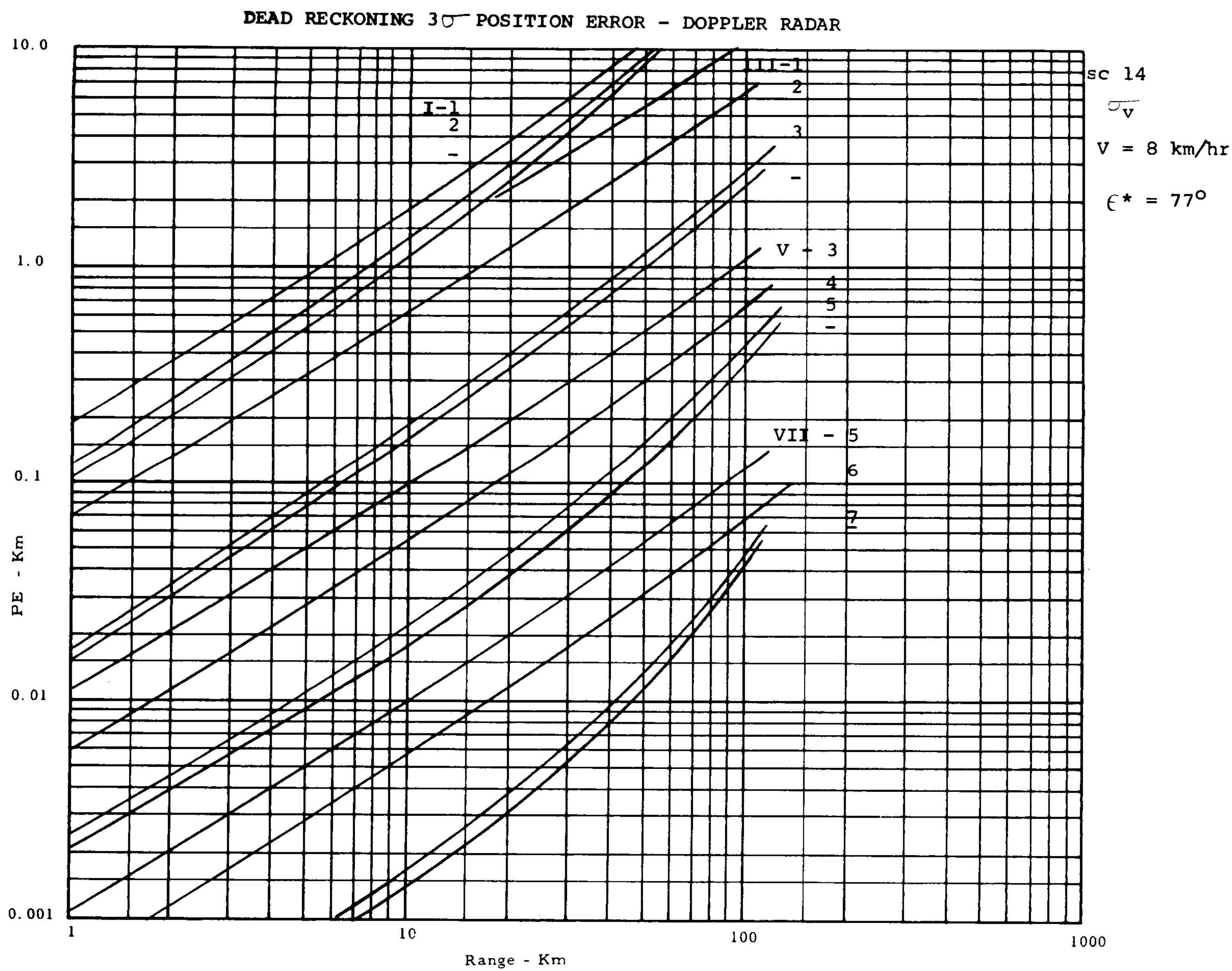


Figure 10-295 Dead Reckoning 3σ Position Error - Doppler Radar

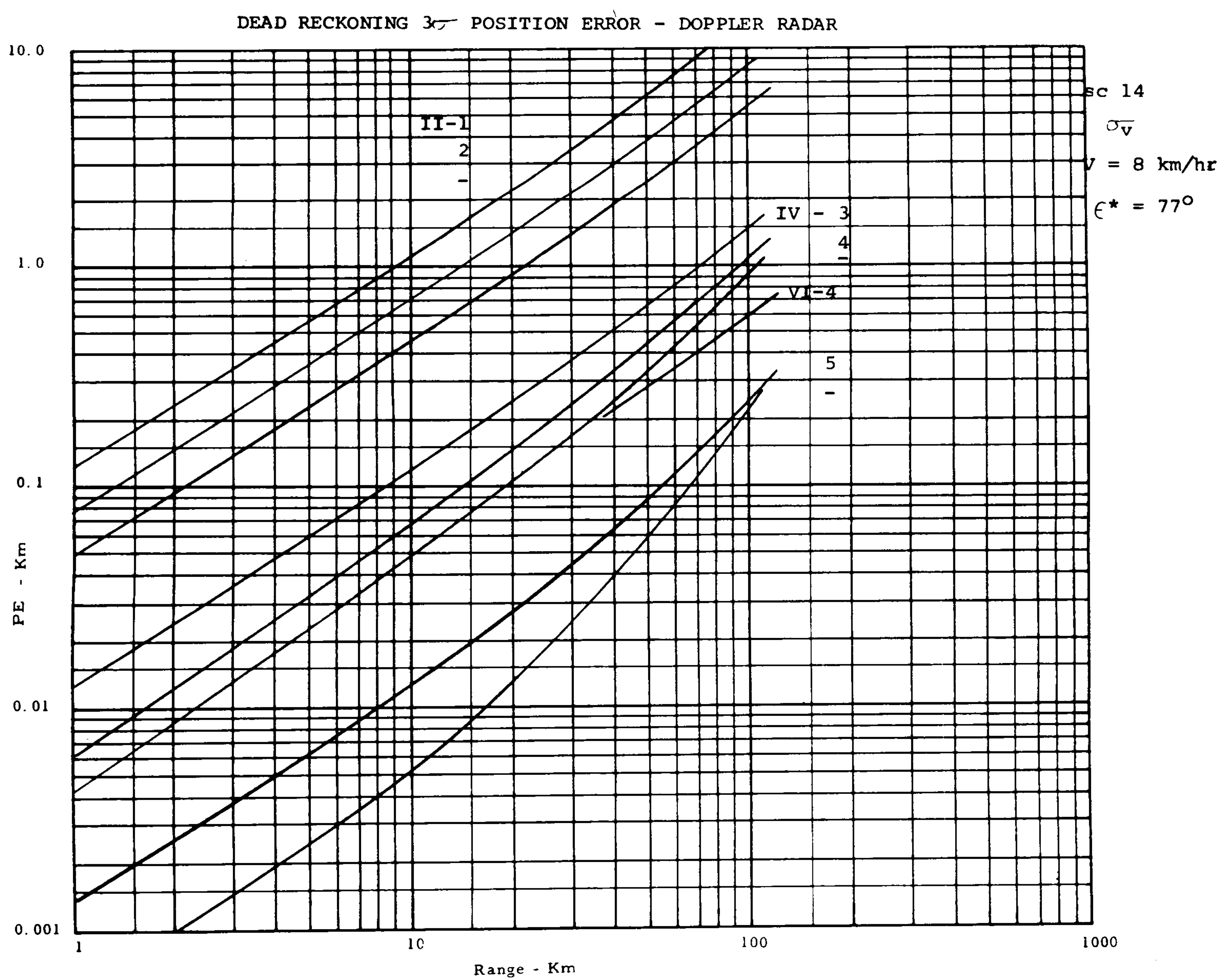


Figure 10-296 Dead Reckoning 3σ Position Error - Doppler Radar

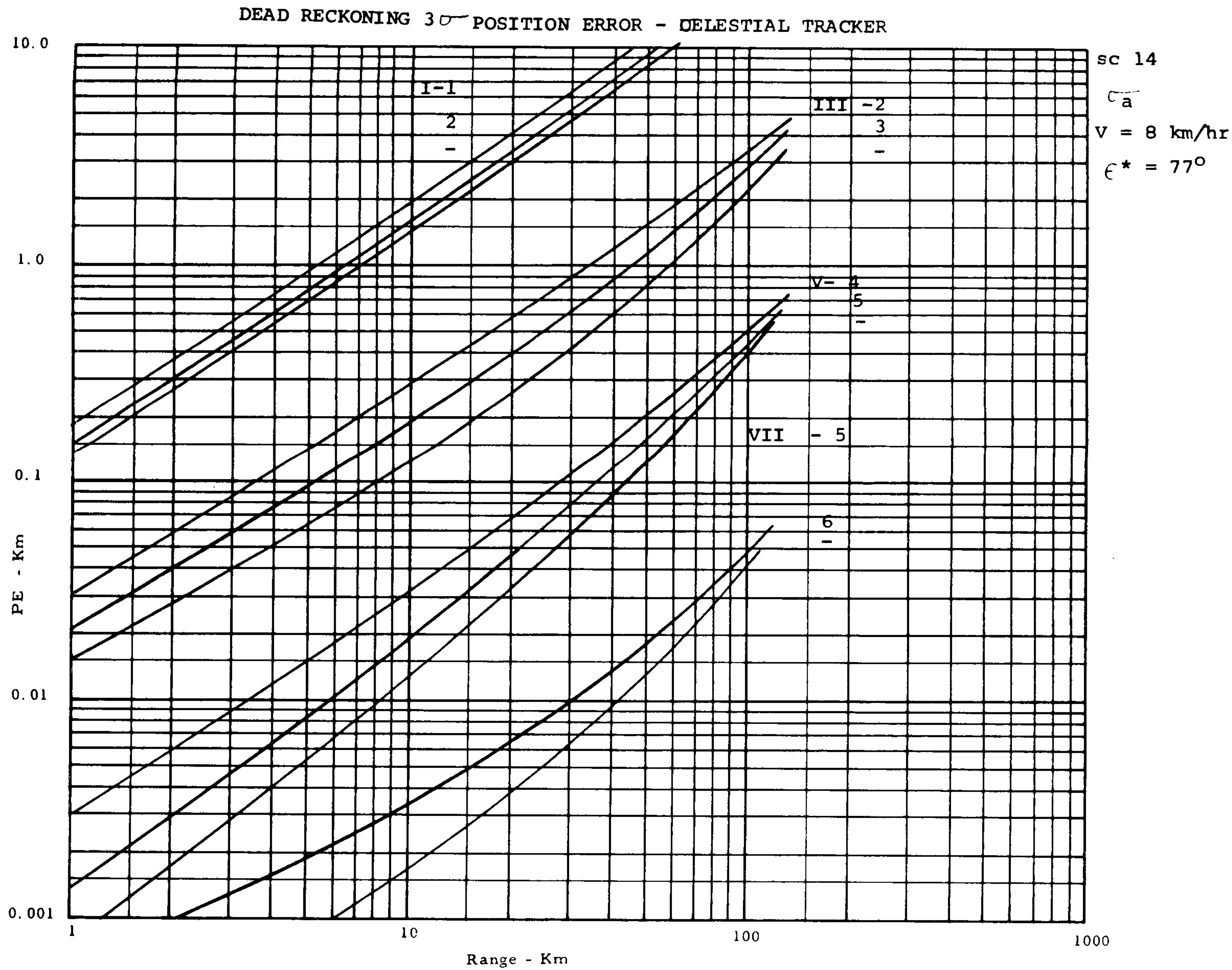


Figure 10-297 Dead Reckoning 3σ Position Error - Celestial Tracker

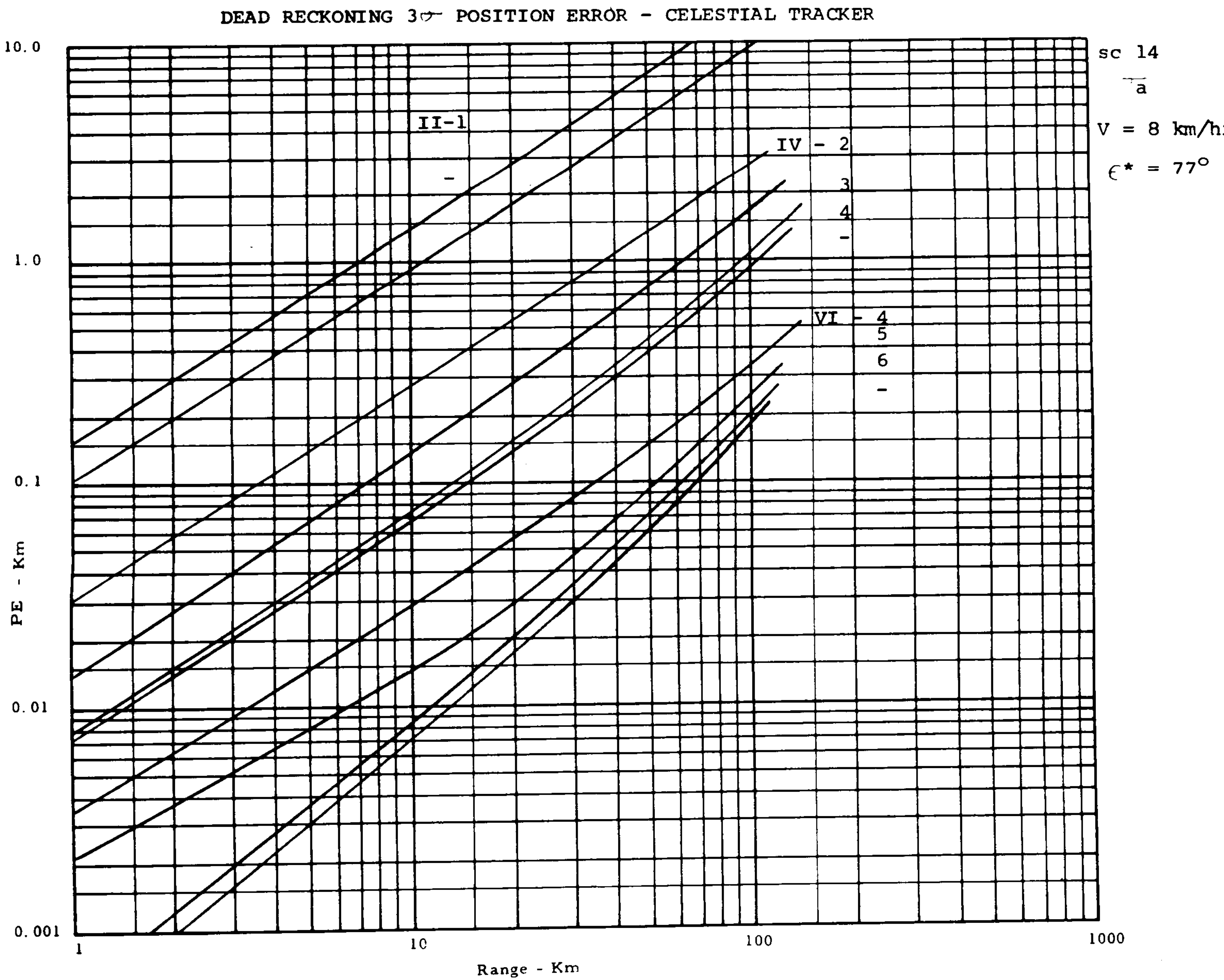


Figure 10-298 Dead Reckoning 3σ Position Error - Celestial Tracker

DEAD RECKONING 3σ POSITION ERROR - VERTICAL SENSOR

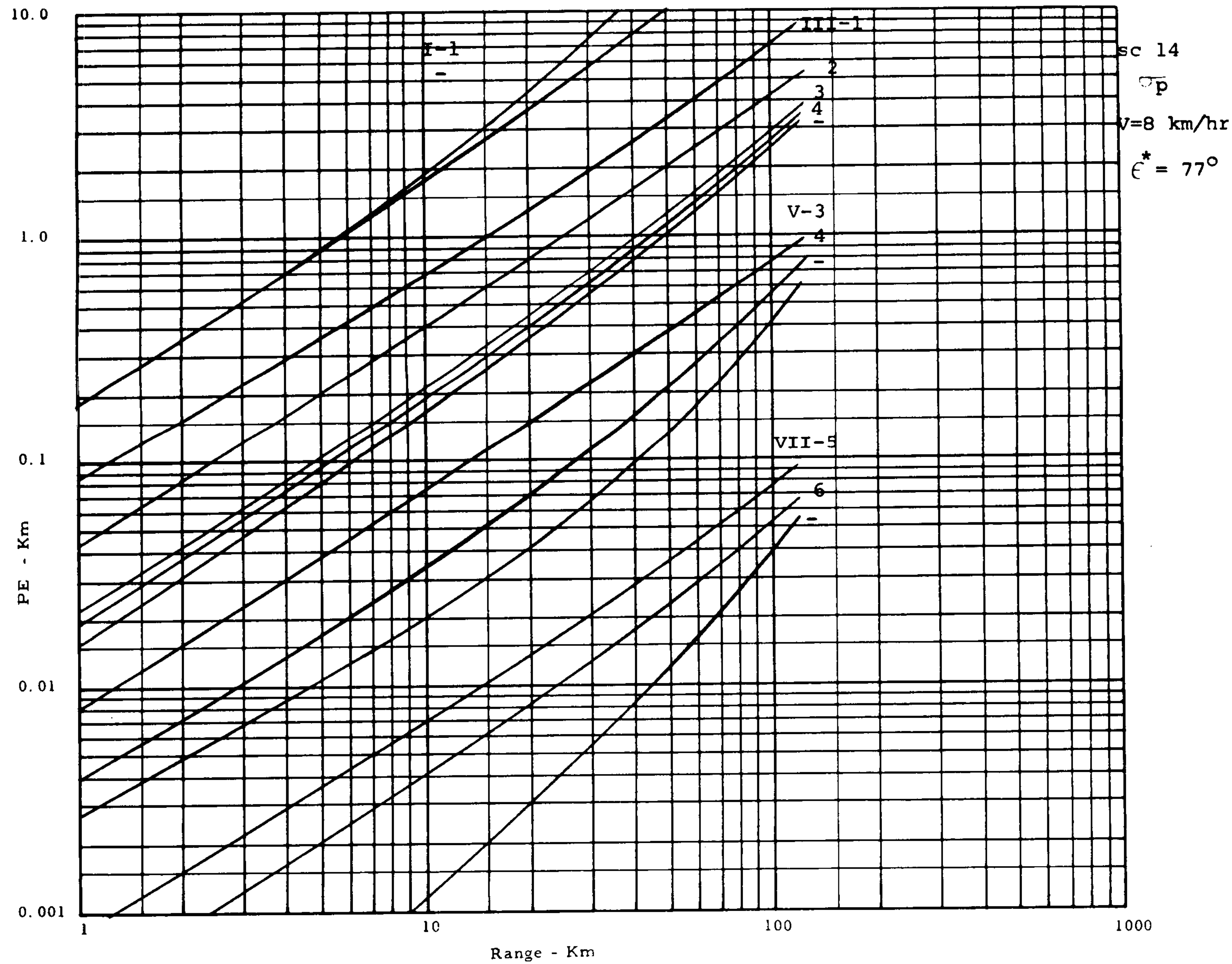


Figure 10-299 Dead Reckoning 3σ Position Error - Vertical Sensor

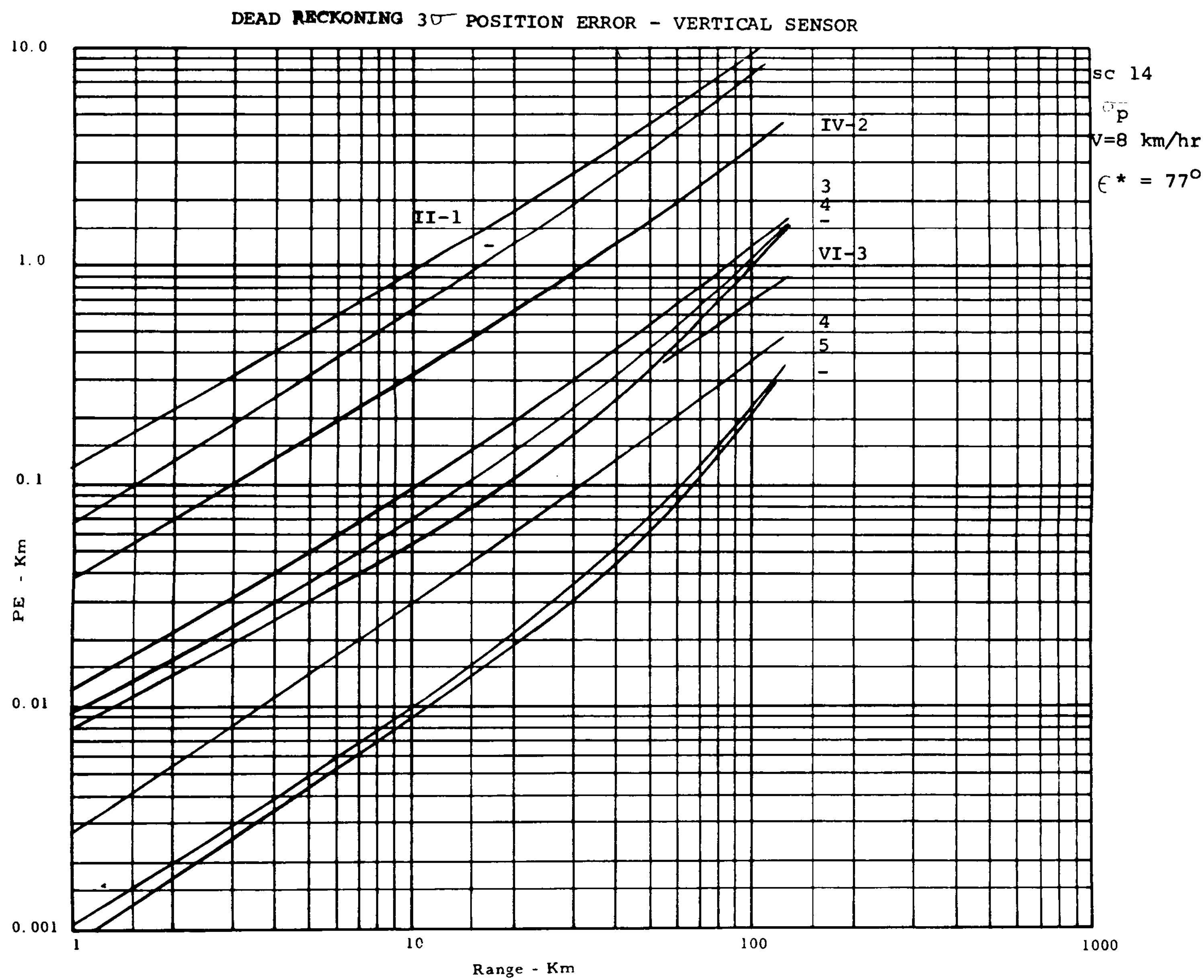


Figure 10-300 Dead Reckoning 3σ Position Error - Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - VERTICAL GYRO DRIFT

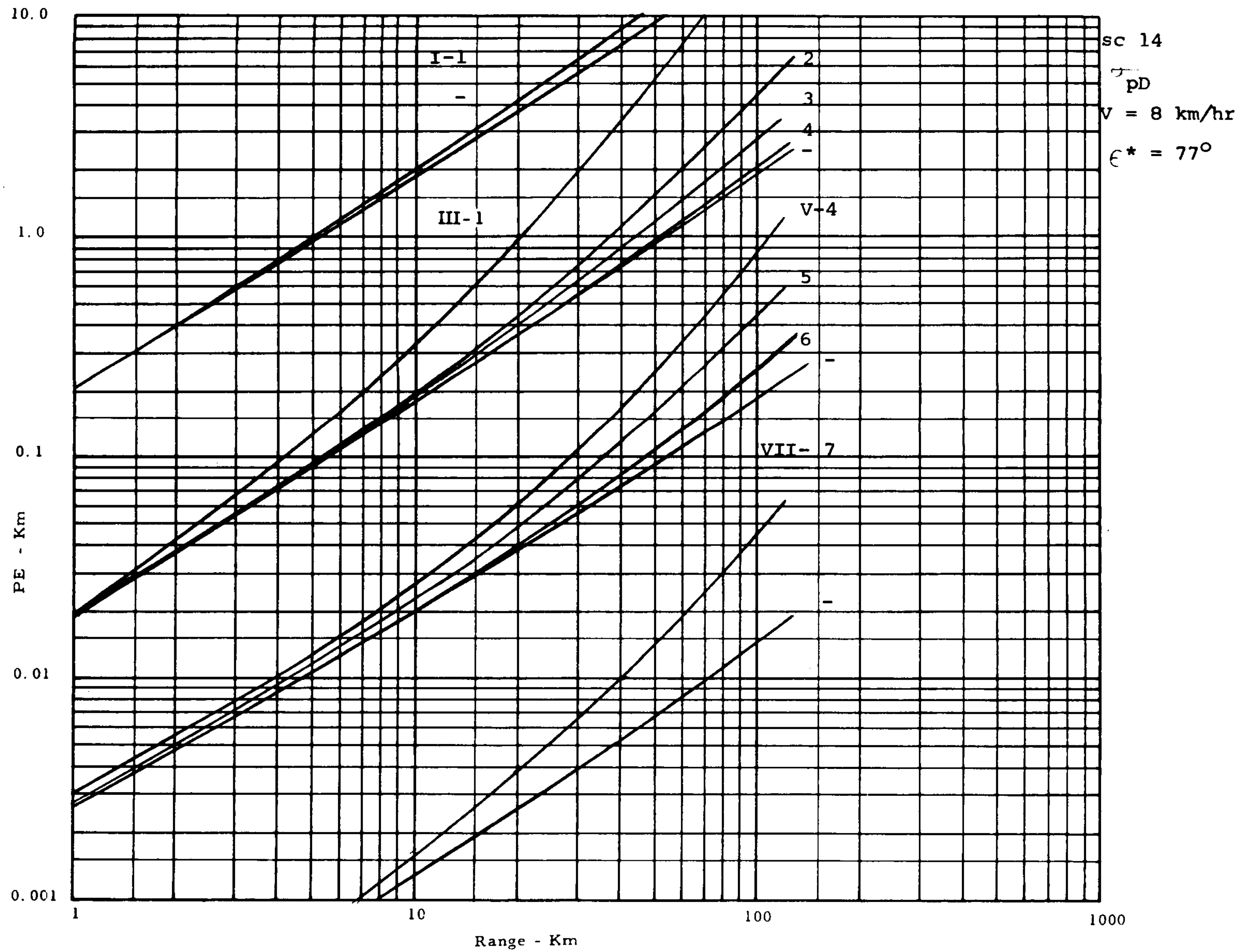


Figure 10-301 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

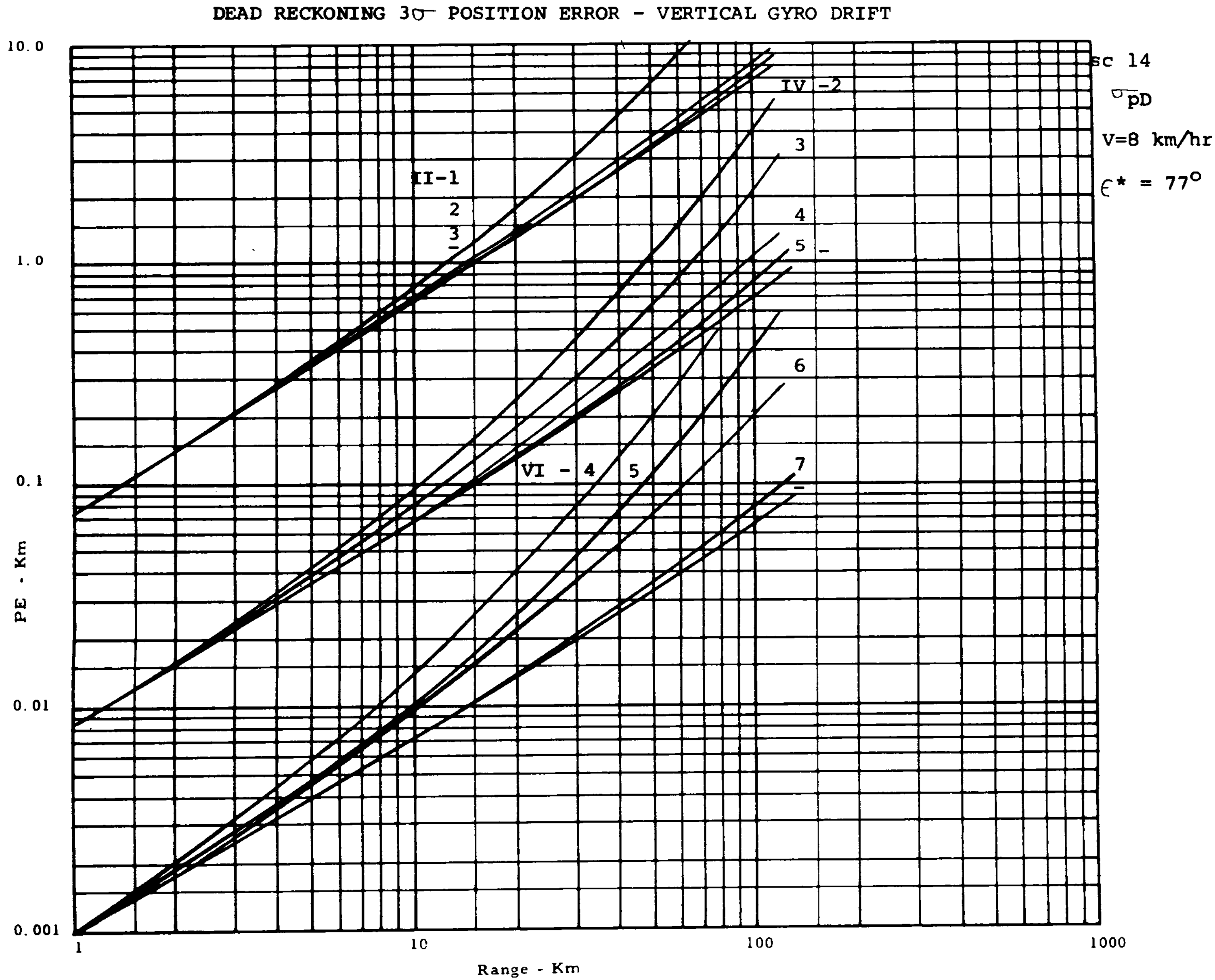


Figure 10-302 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

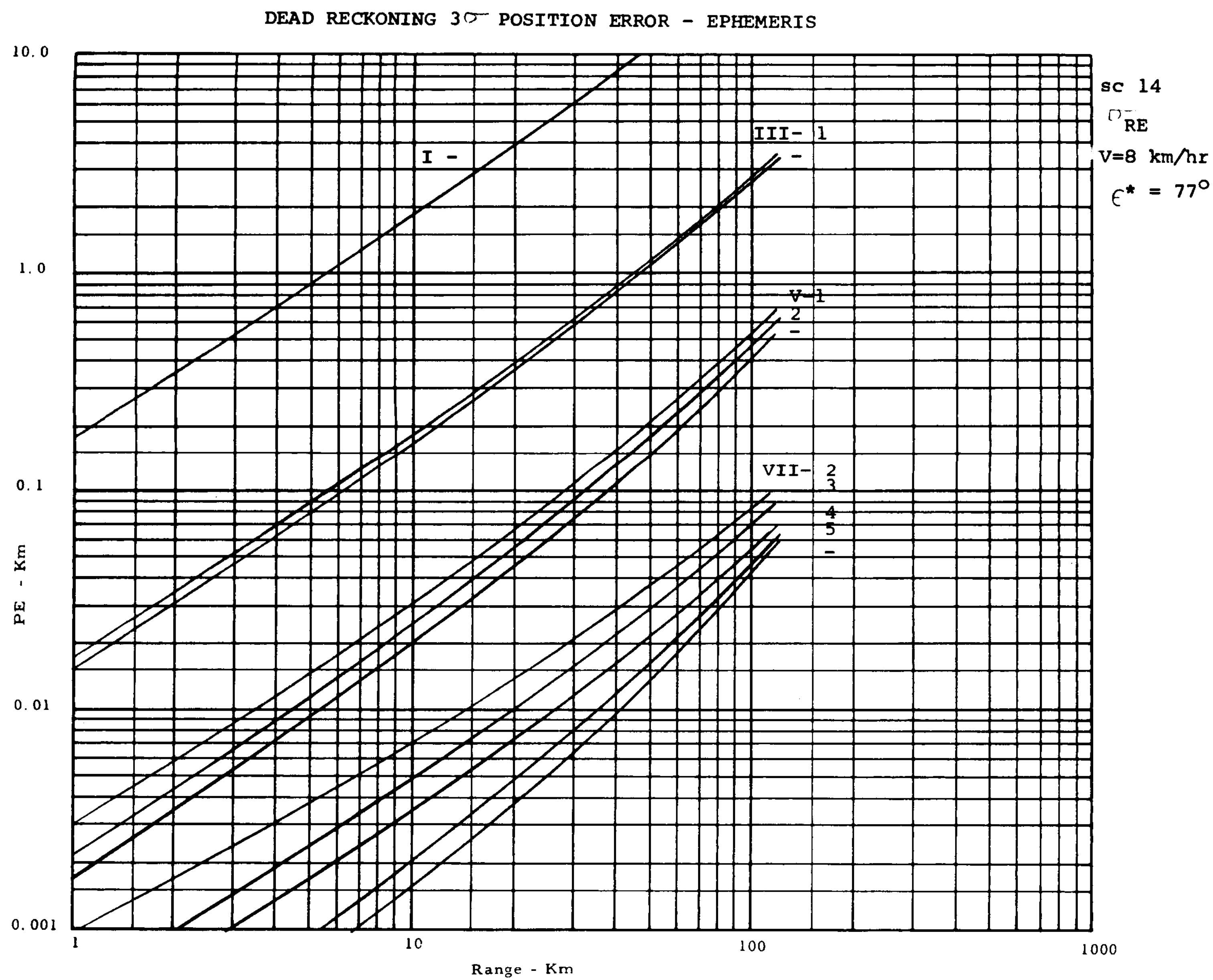


Figure 10-303 Dead Reckoning 3σ Position Error - Ephemeris

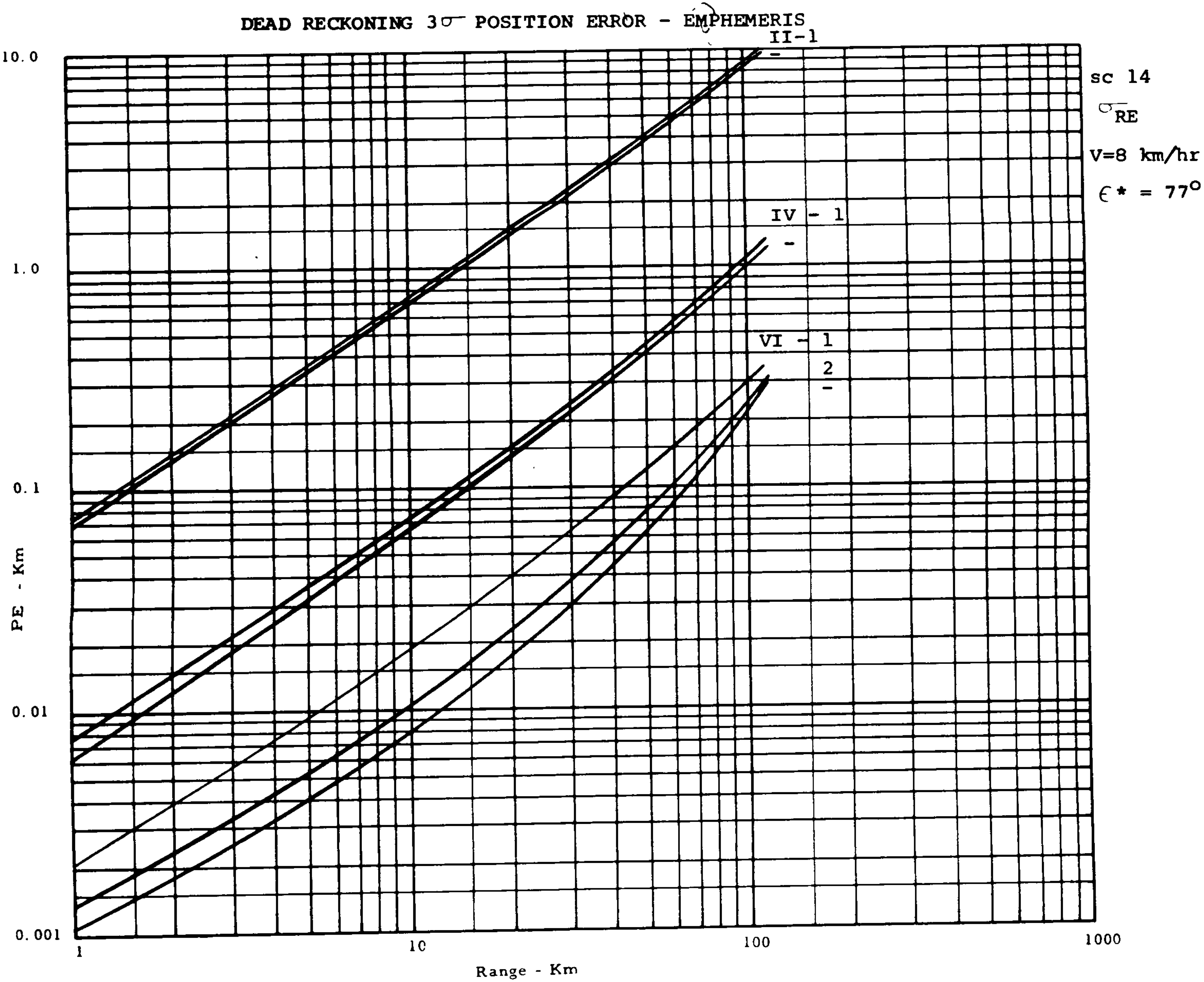


Figure 10-304 Dead Reckoning 3σ Position Error - Ephemeris

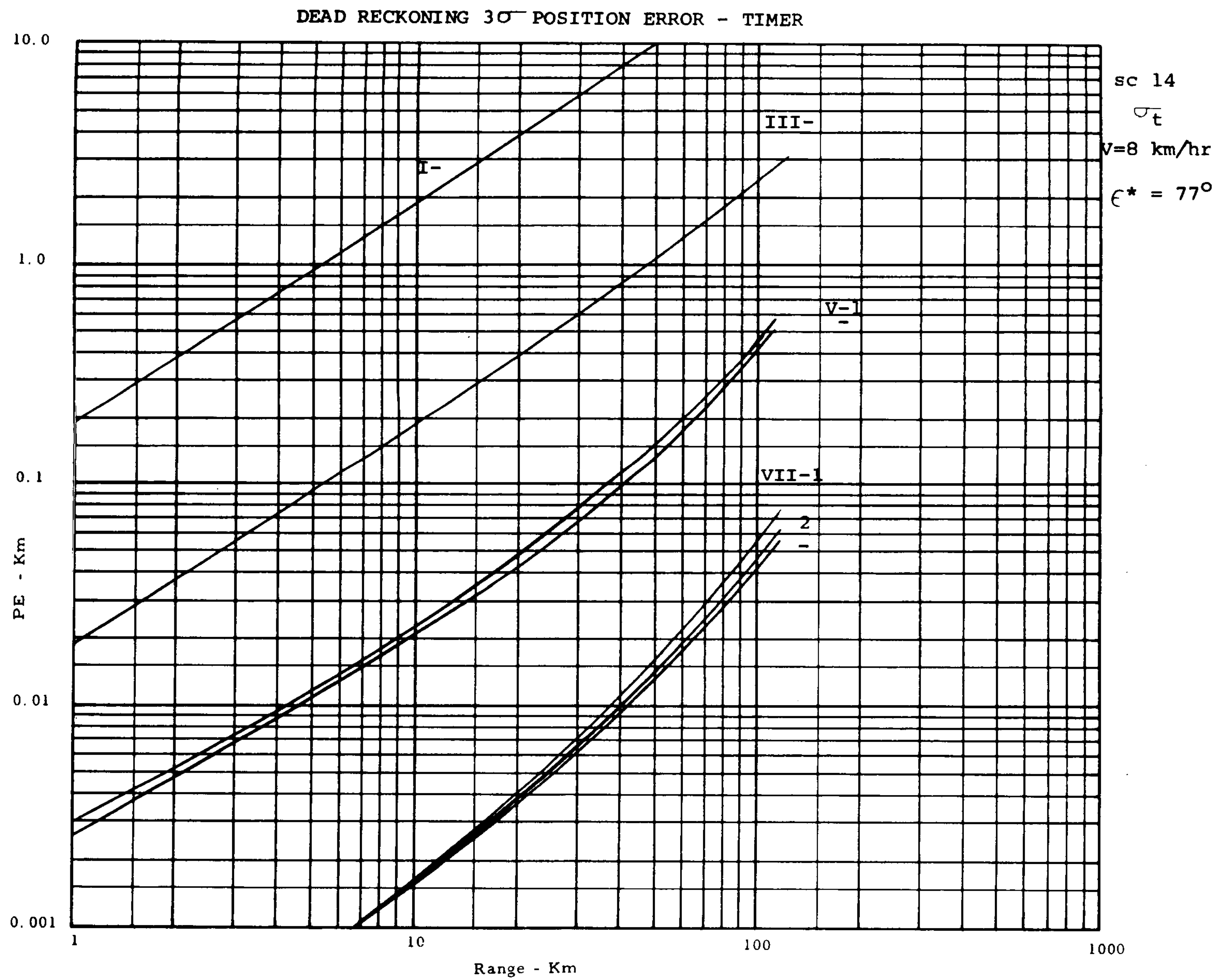


Figure 10-305 Dead Reckoning 3σ Position Error - Timer

DEAD RECKONING 3σ POSITION ERROR - TIMER

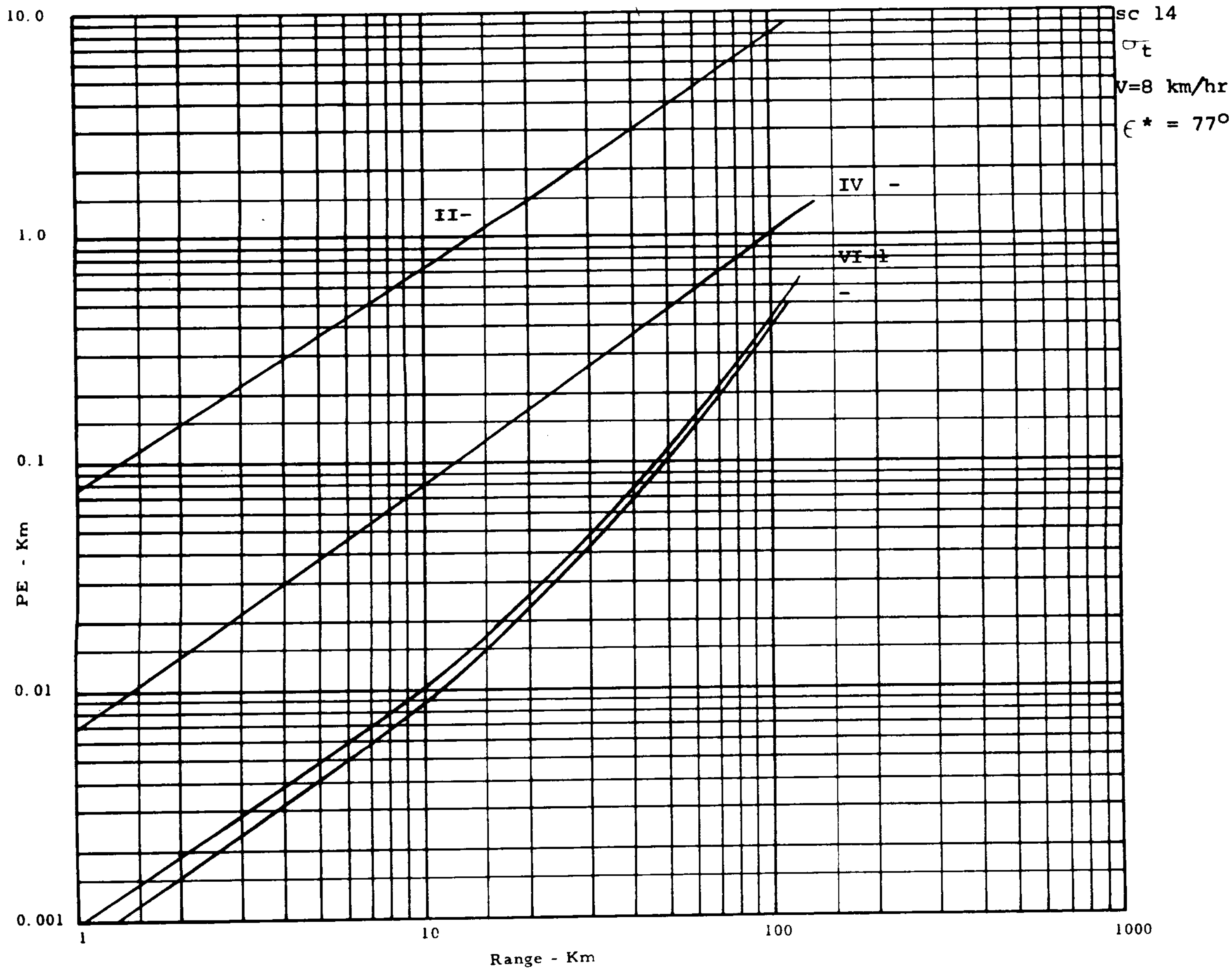


Figure 10-306 Dead Reckoning 3σ Position Error - Timer

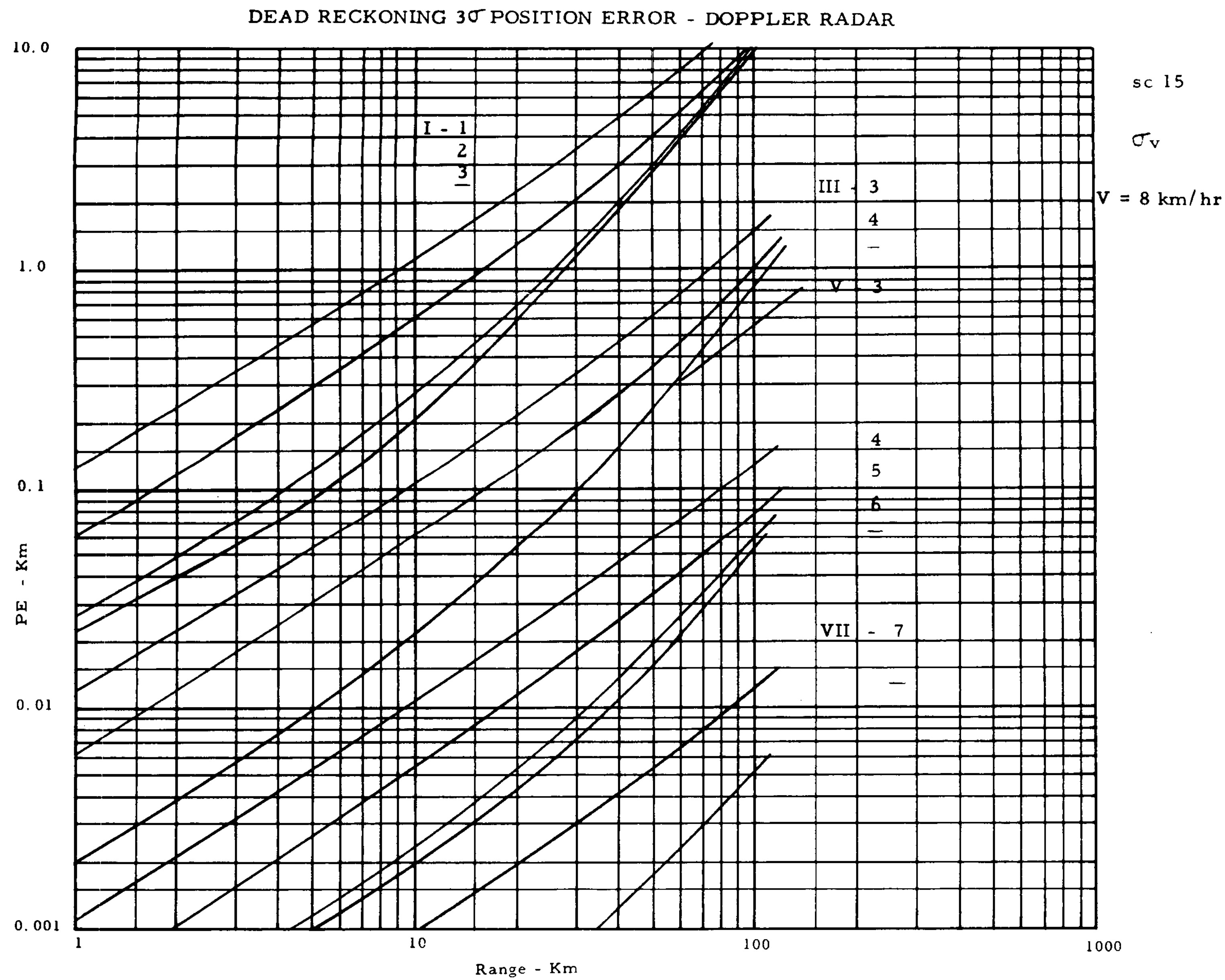


Figure 10-307 Dead Reckoning 3σ Position Error - Doppler Radar

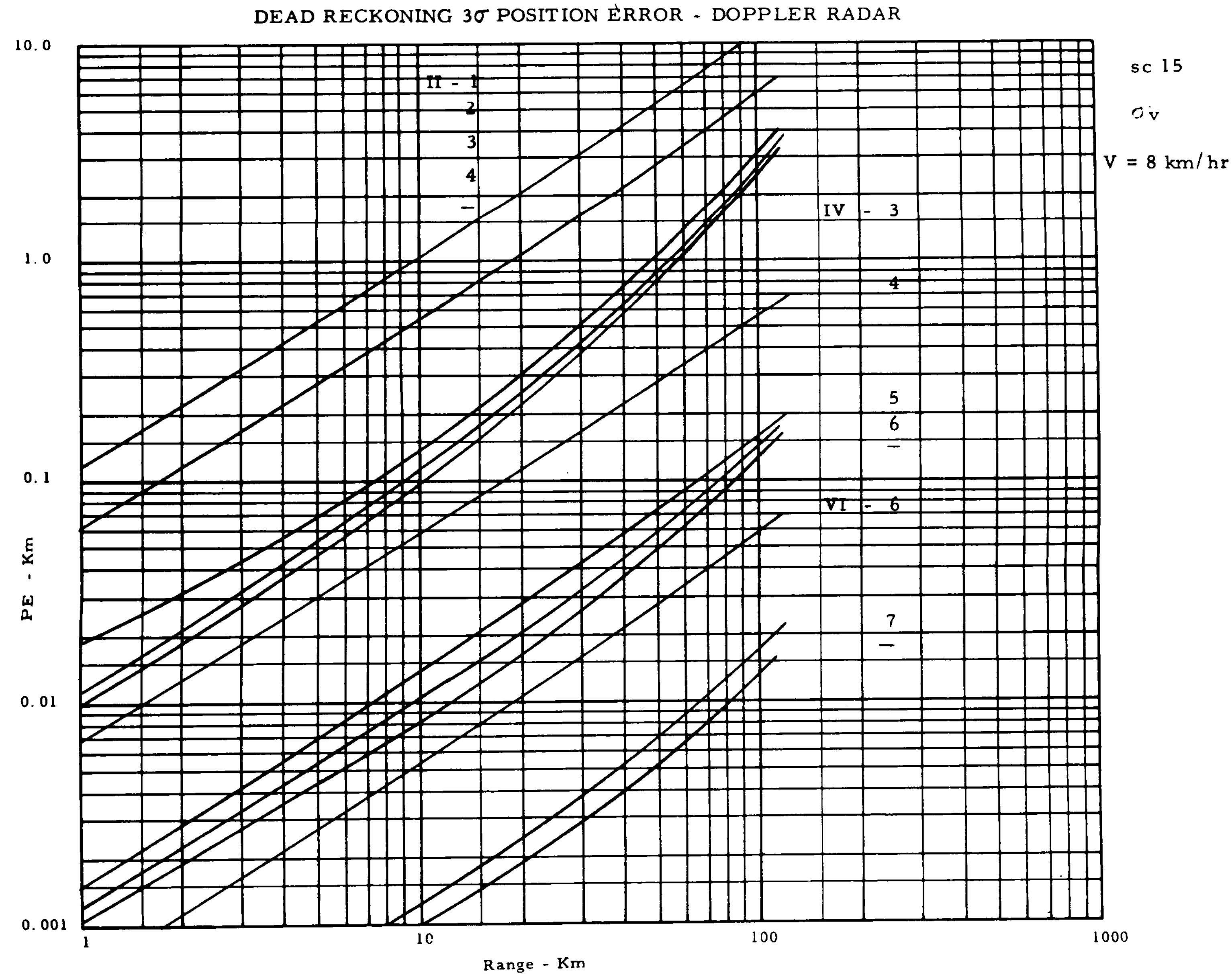


Figure 10-308 Dead Reckoning 3σ Position Error - Doppler Radar

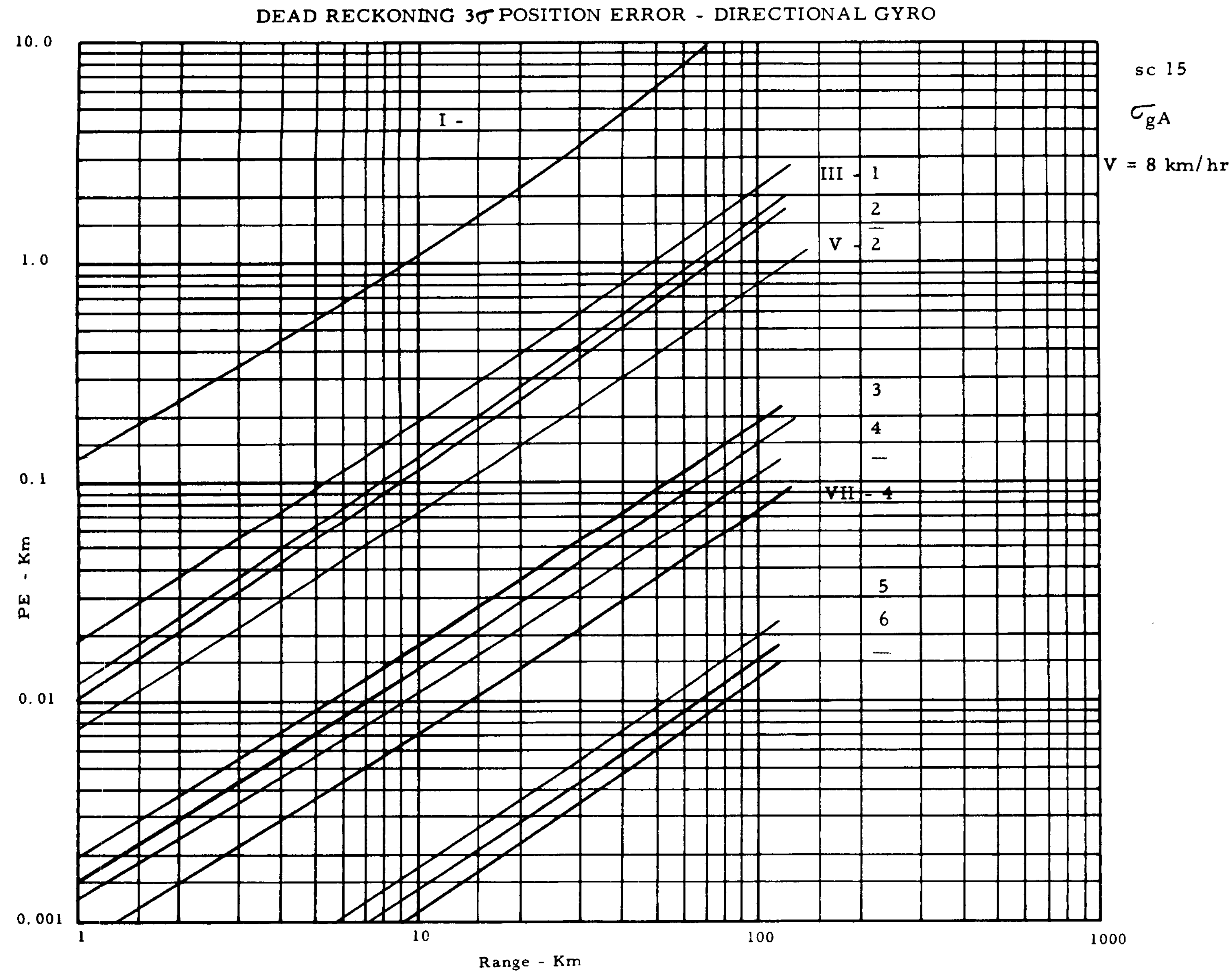


Figure 10-309 Dead Reckoning 3σ Position Error - Directional Gyro

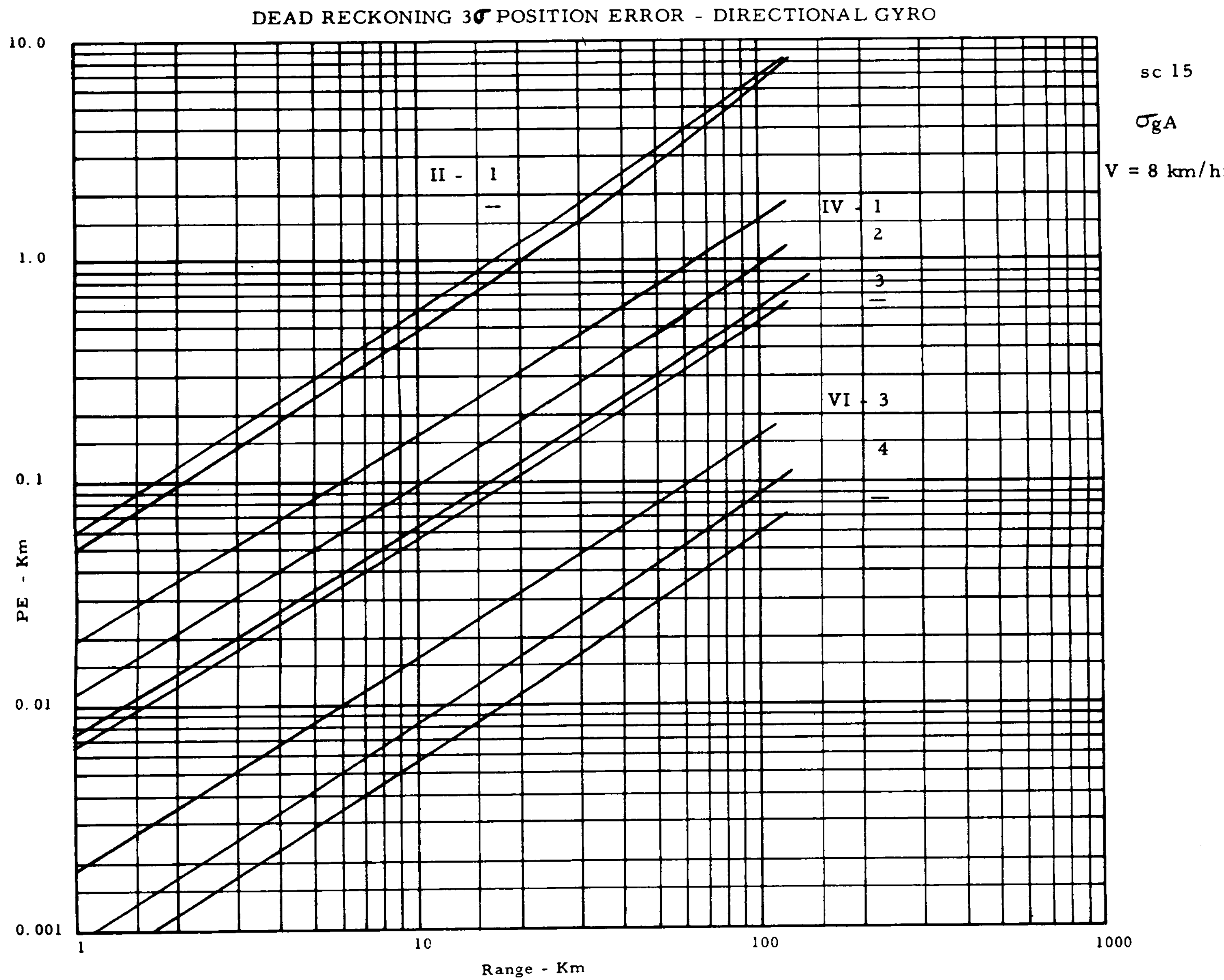


Figure 10-310 Dead Reckoning 3σ Position Error - Directional Gyro

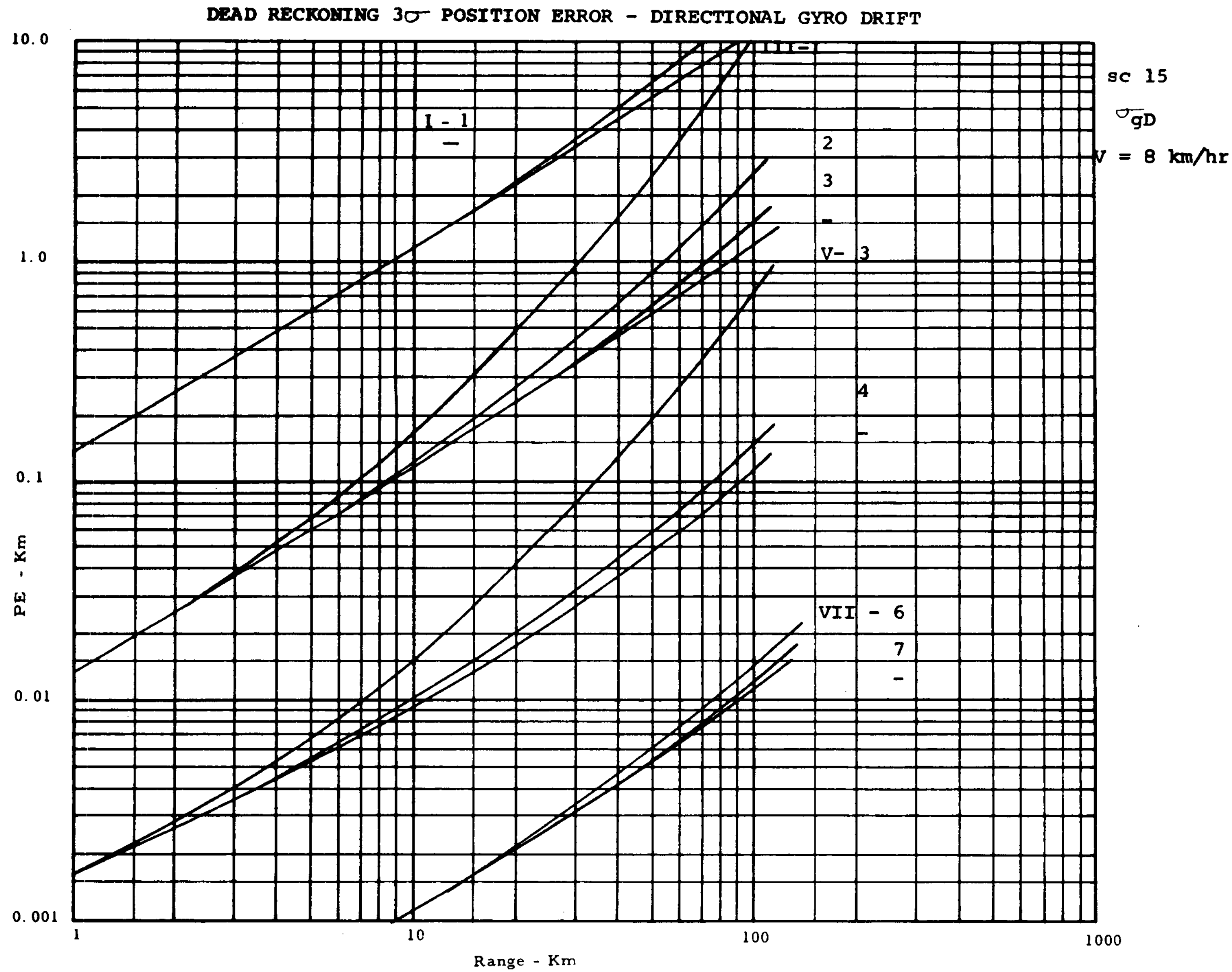


Figure 10-311 Dead Reckoning 3σ Position Error - Directional Gyro Drift

DEAD RECKONING 3σ POSITION ERROR - DIRECTIONAL GYRO DRIFT

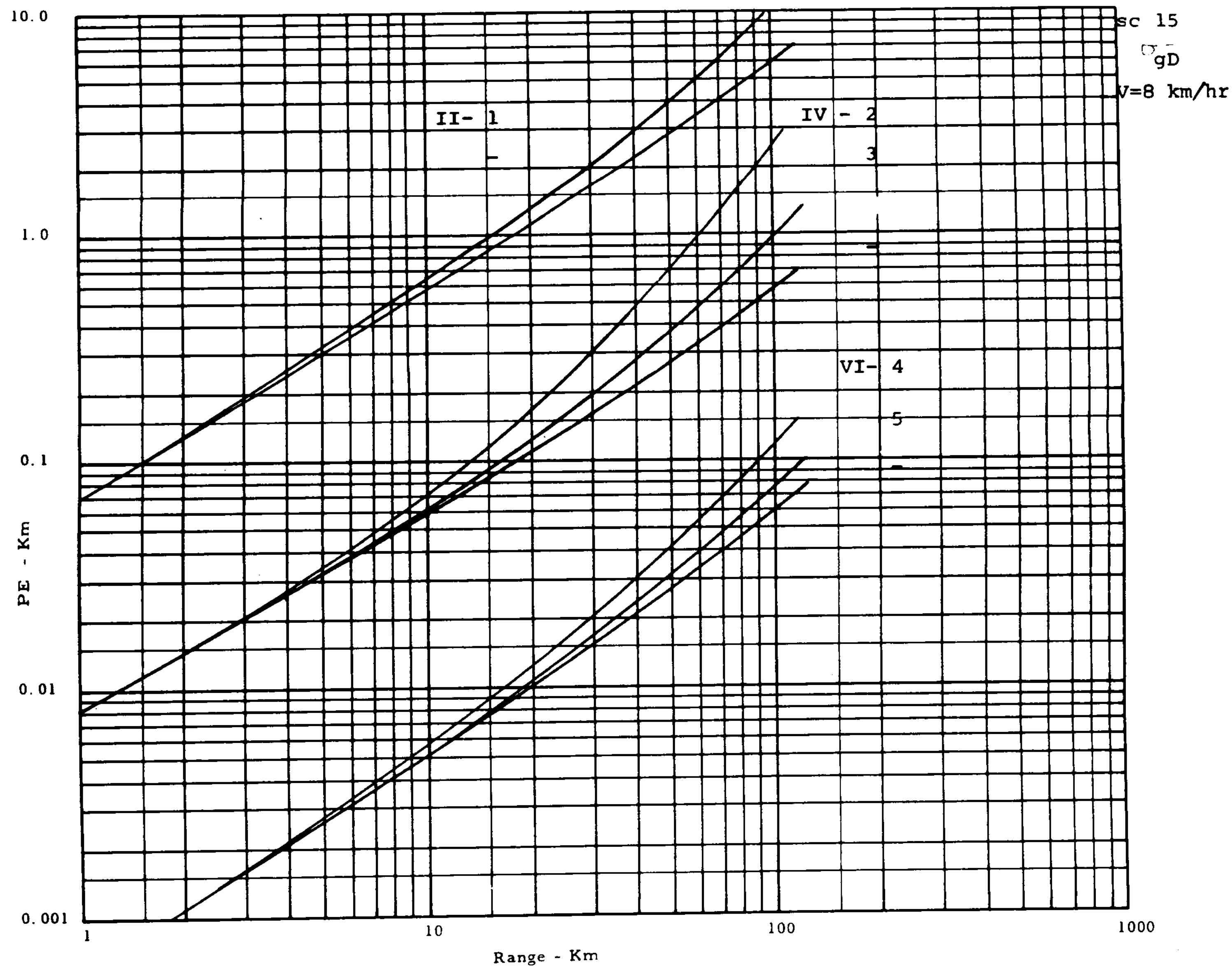


Figure 10-312 Dead Reckoning 3σ Position Error - Directional Gyro Drift

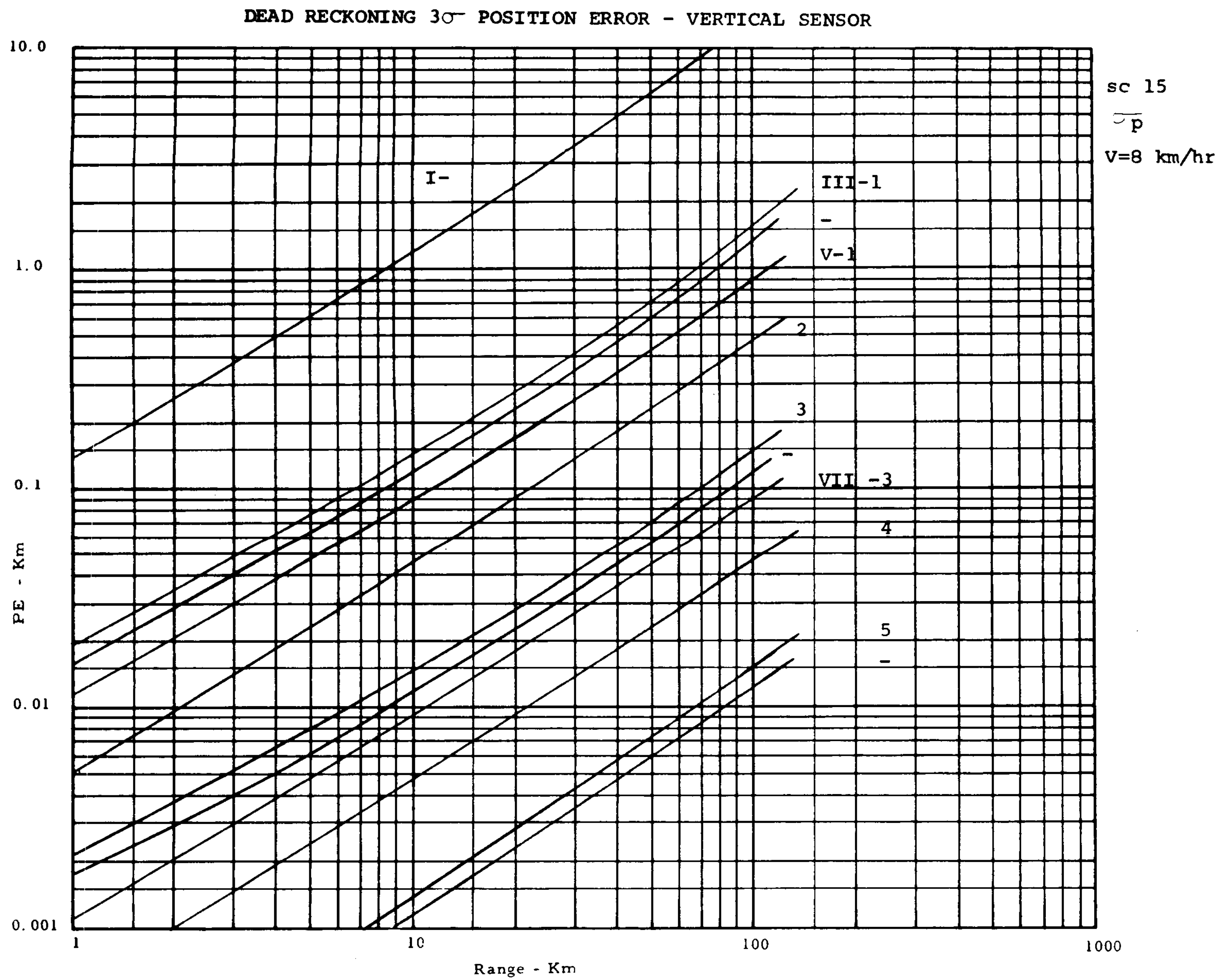


Figure 10-313 Dead Reckoning 3σ Position Error - Vertical Sensor

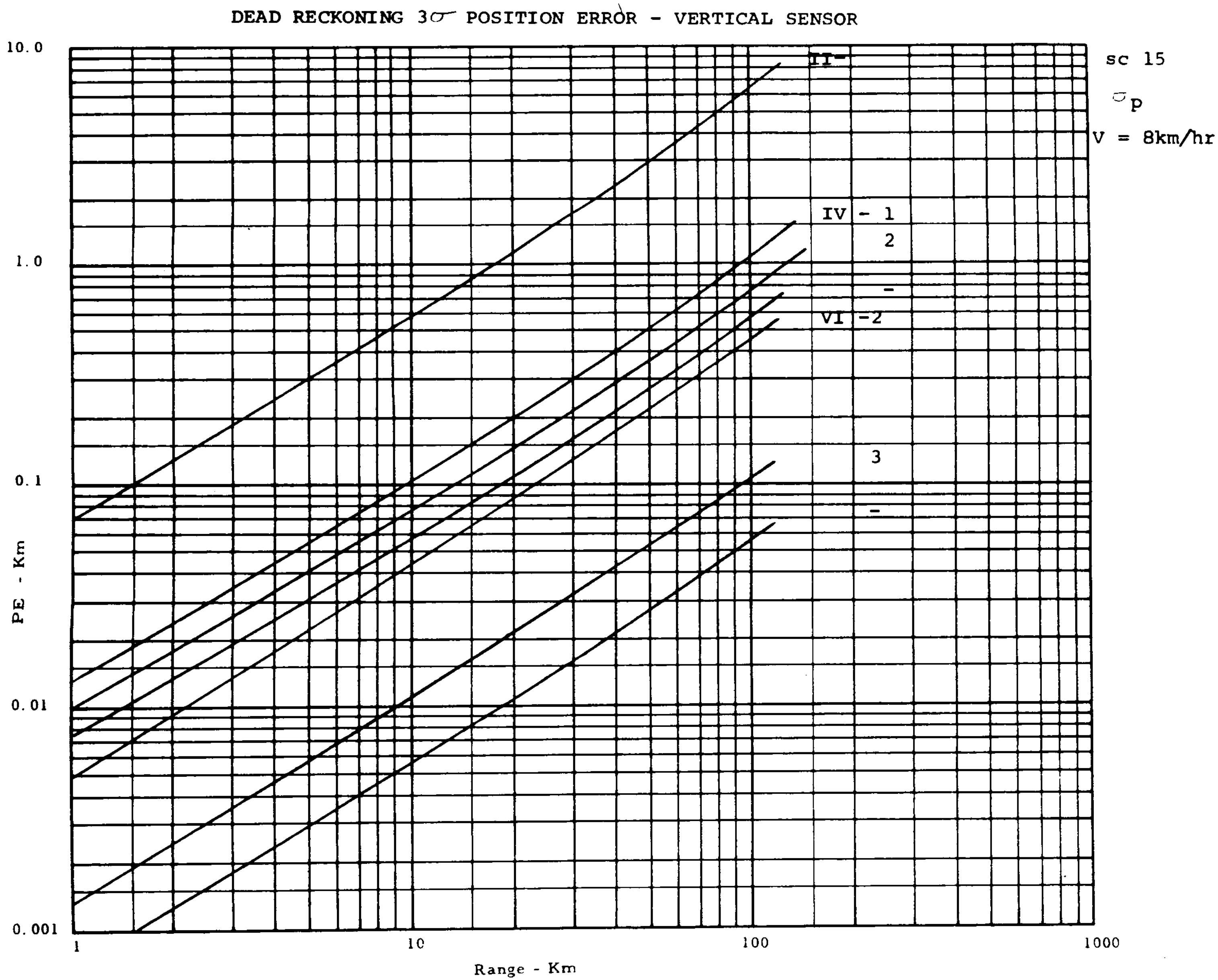


Figure 10-314 Dead Reckoning 3σ Position Error - Vertical Sensor

DEAD RECKONING 3σ POSITION ERROR - DOPPLER RADAR

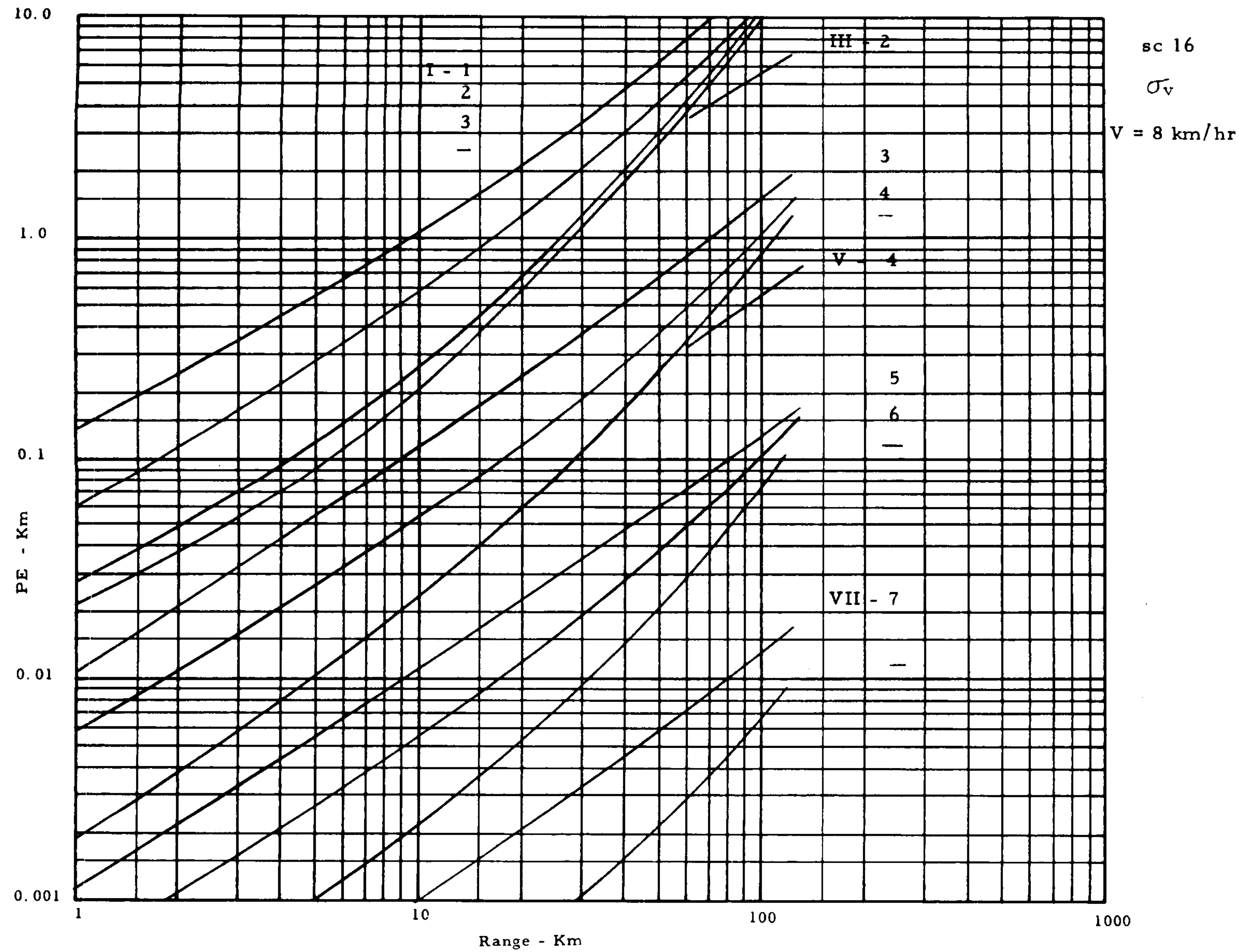


Figure 10-315 Dead Reckoning 3σ Position Error - Doppler Error

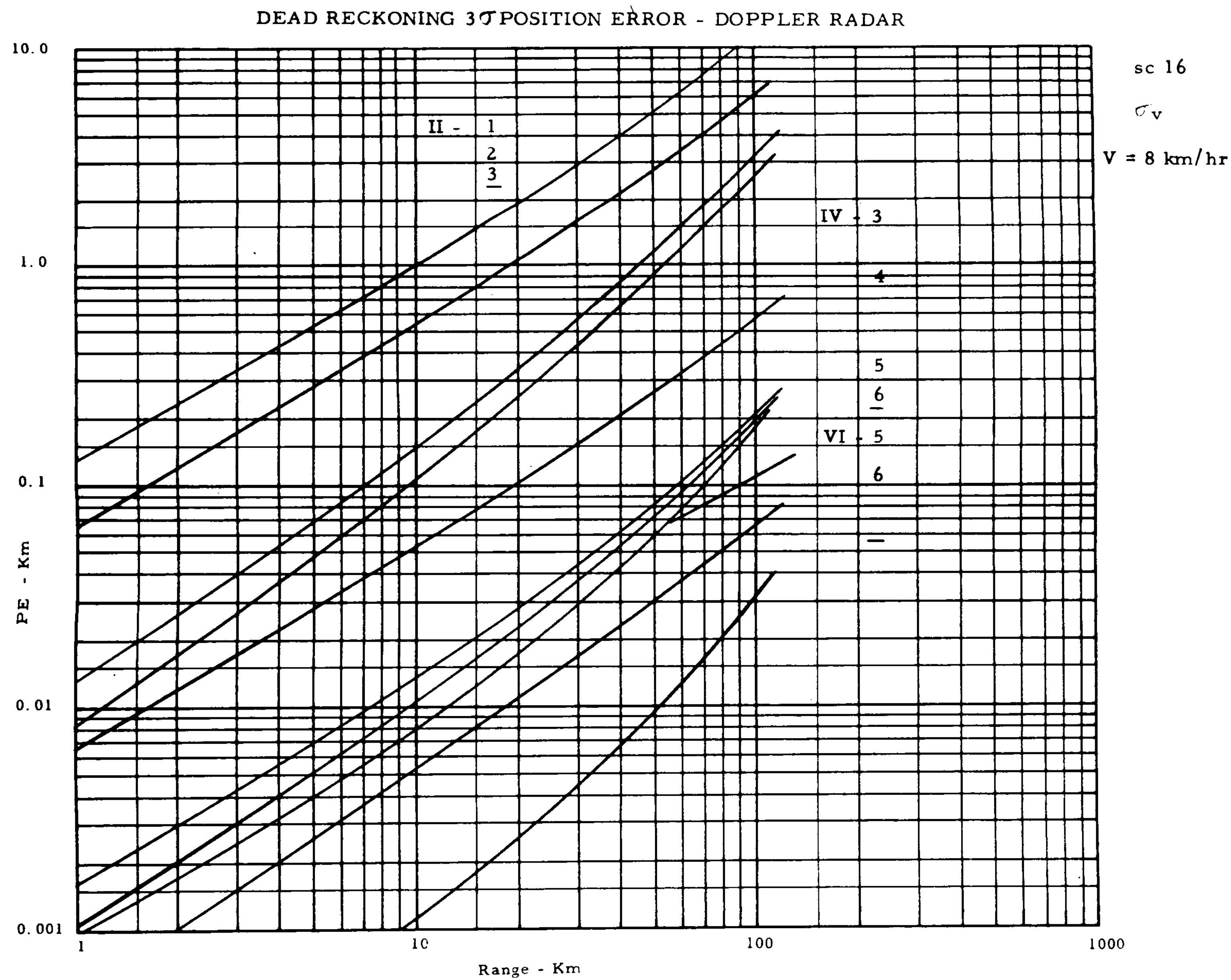


Figure 10-316 Dead Reckoning 3σ Position Error - Doppler Error

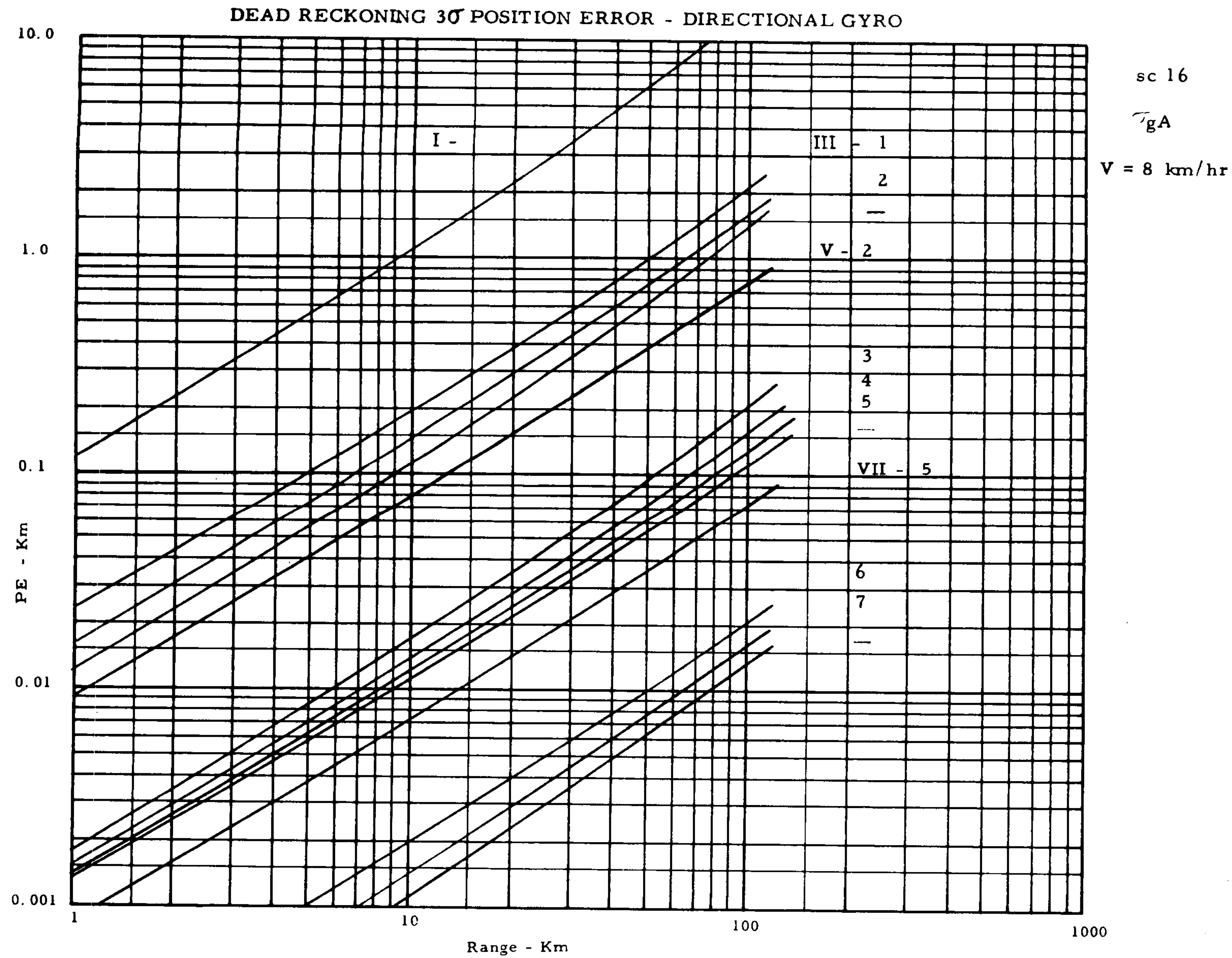


Figure 10-317 Dead Reckoning 3σ Position Error - Directional Gyro

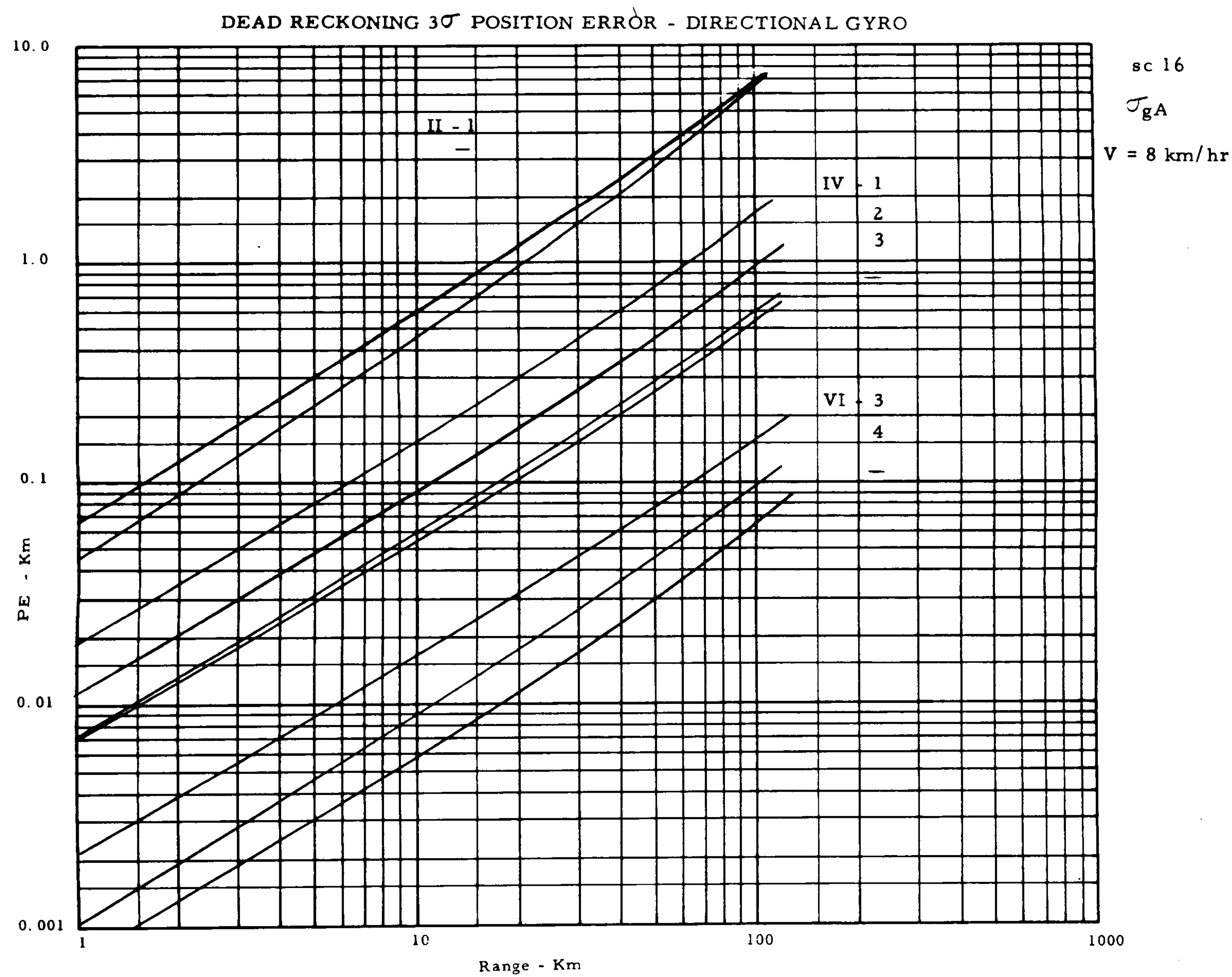


Figure 10-318 Dead Reckoning 3σ Position Error - Directional Gyro

DEAD RECKONING 3σ POSITION ERROR - DIRECTIONAL GYRO DRIFT

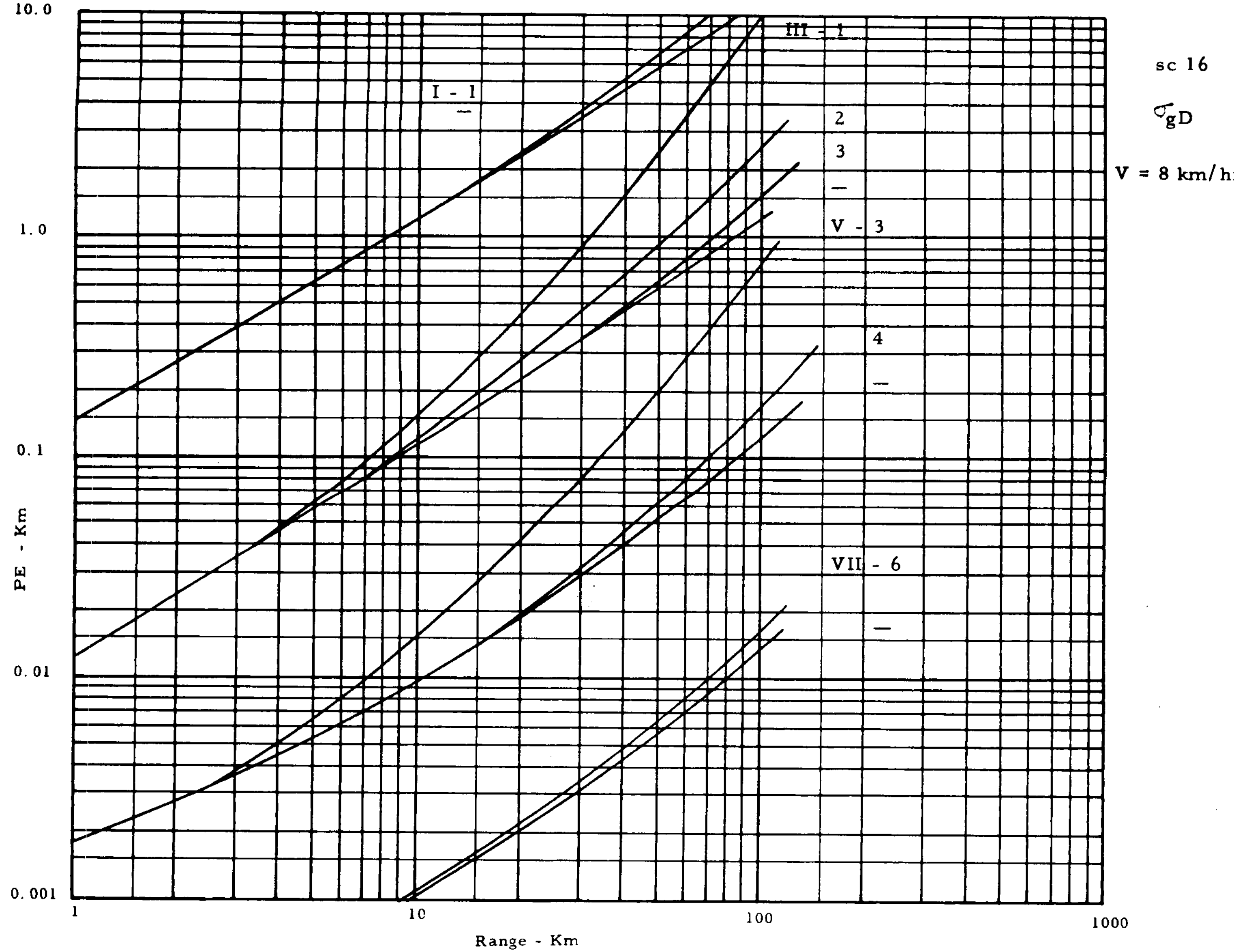


Figure 10-319 Dead Reckoning 3σ Position Error - Directional Gyro Drift

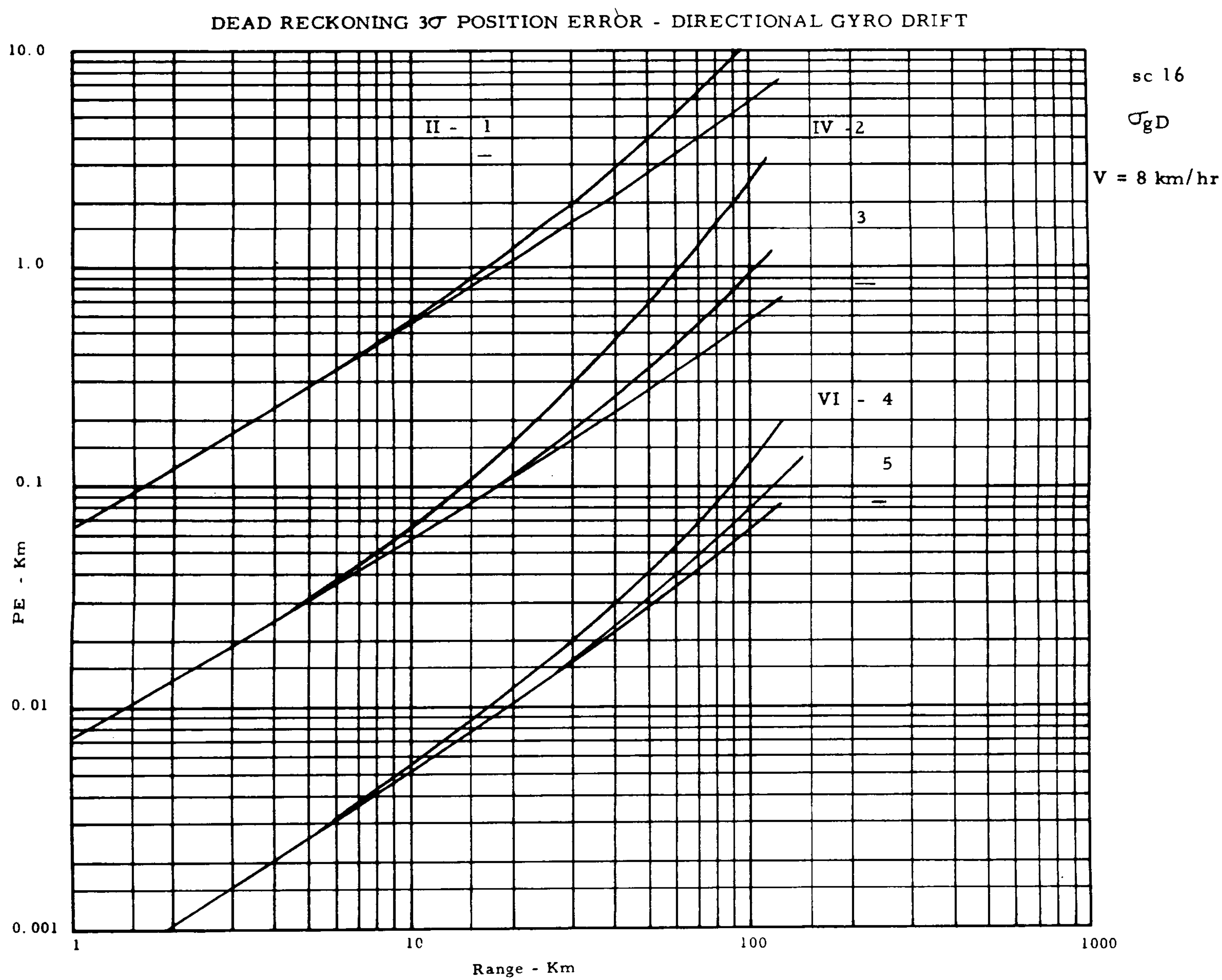


Figure 10-320 Dead Reckoning 3σ Position Error - Directional Gyro Drift

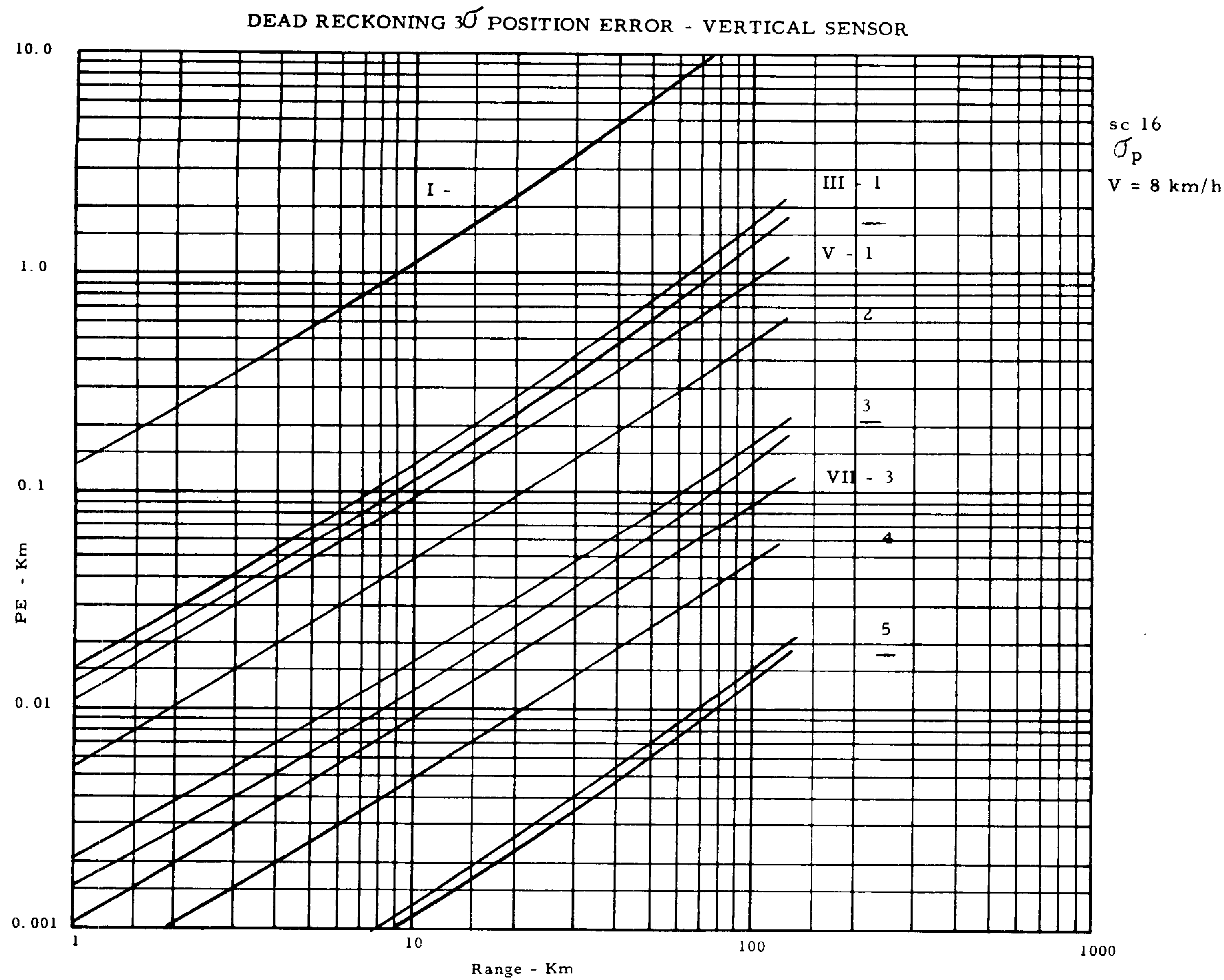


Figure 10-321 Dead Reckoning 3σ Position Error - Vertical Sensor

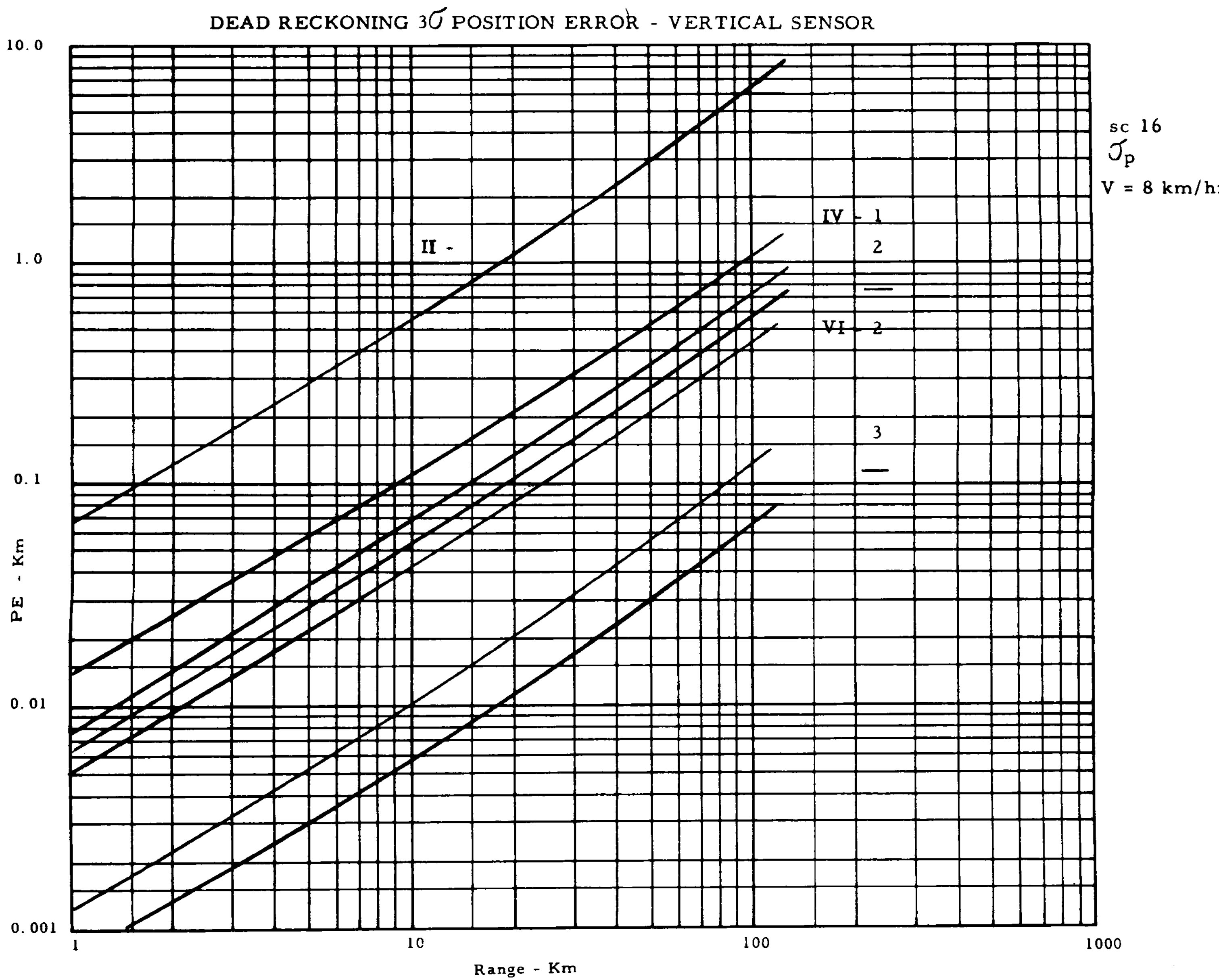


Figure 10-322 Dead Reckoning 3σ Position Error - Vertical Sensor

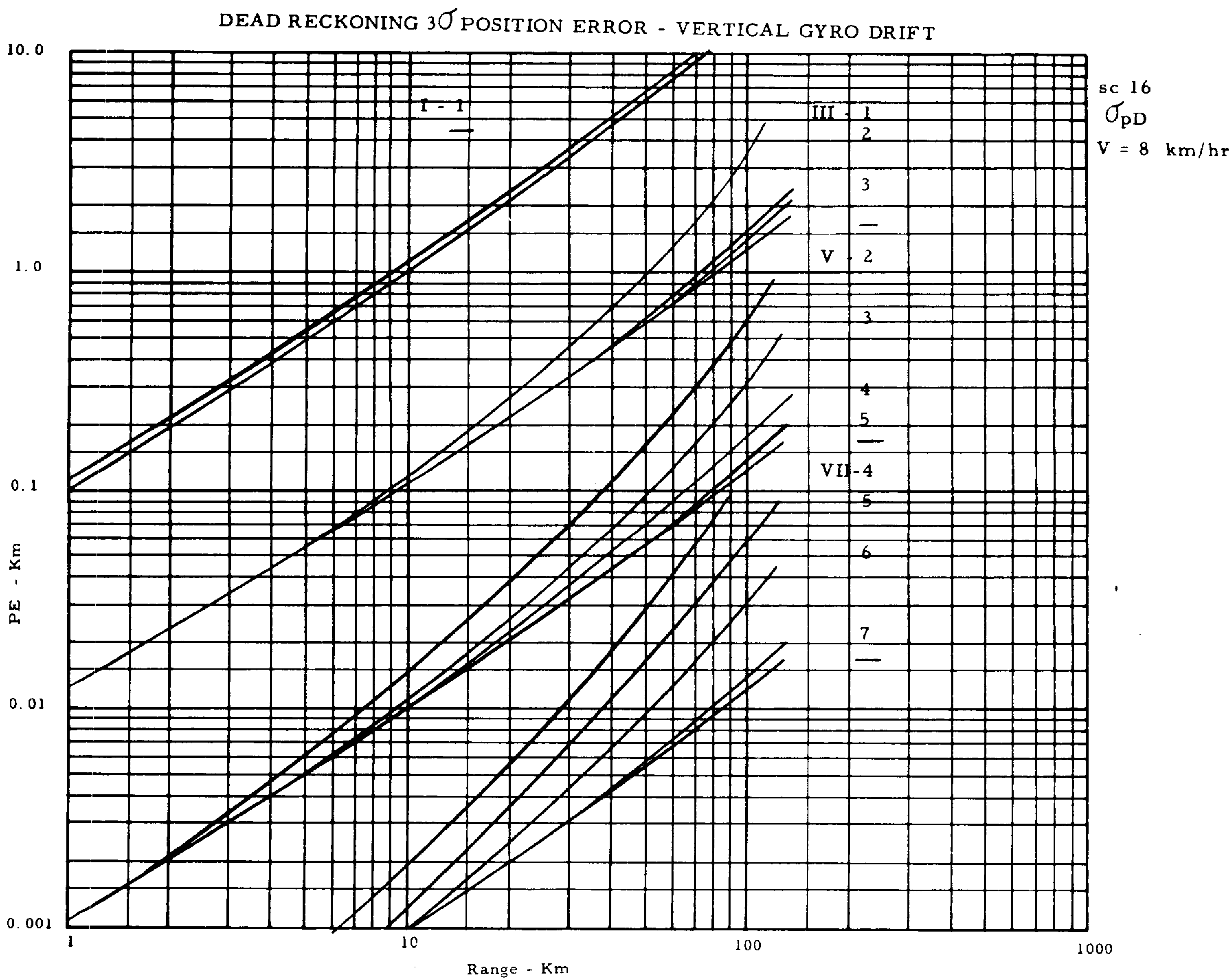


Figure 10-323 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

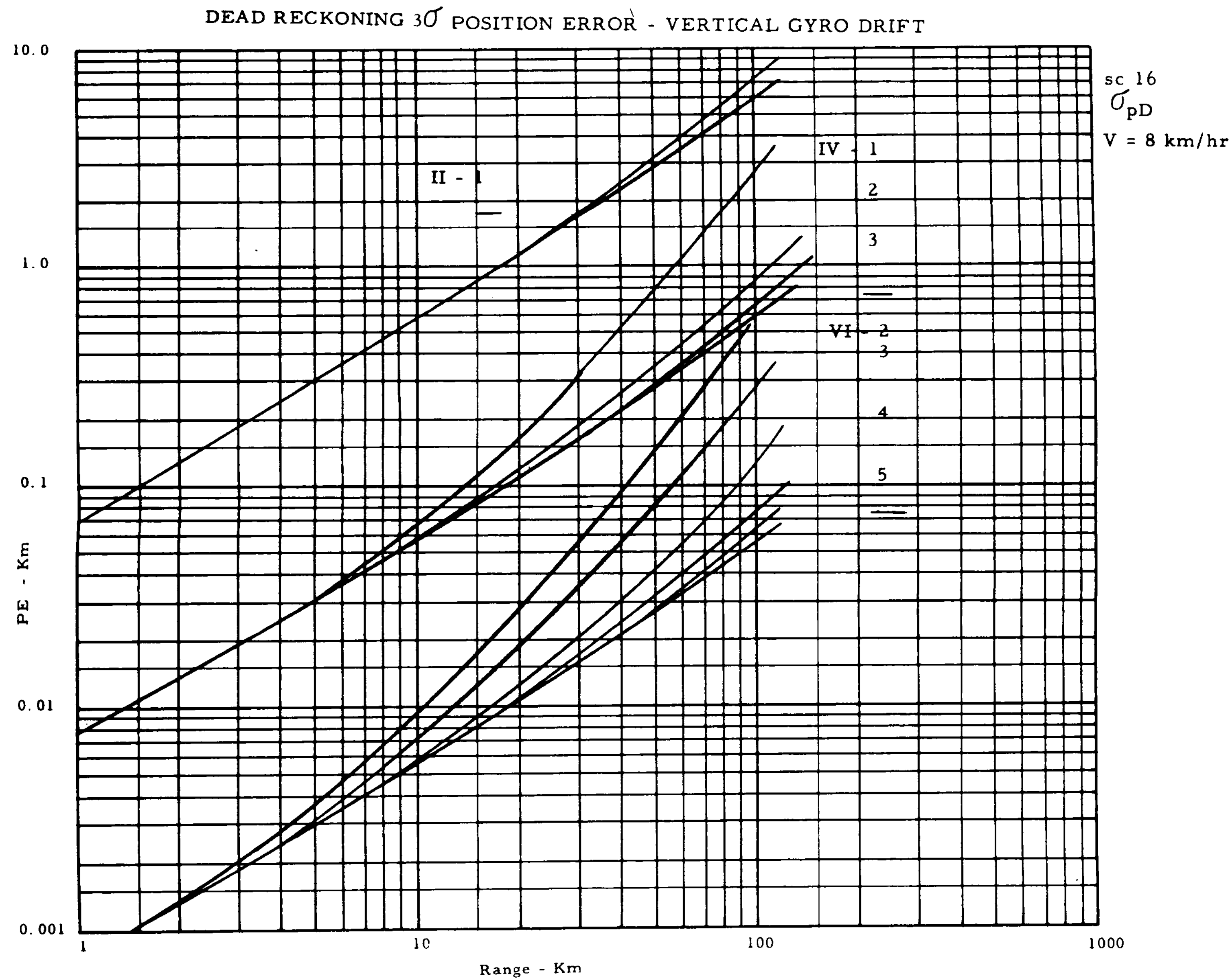


Figure 10-324 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

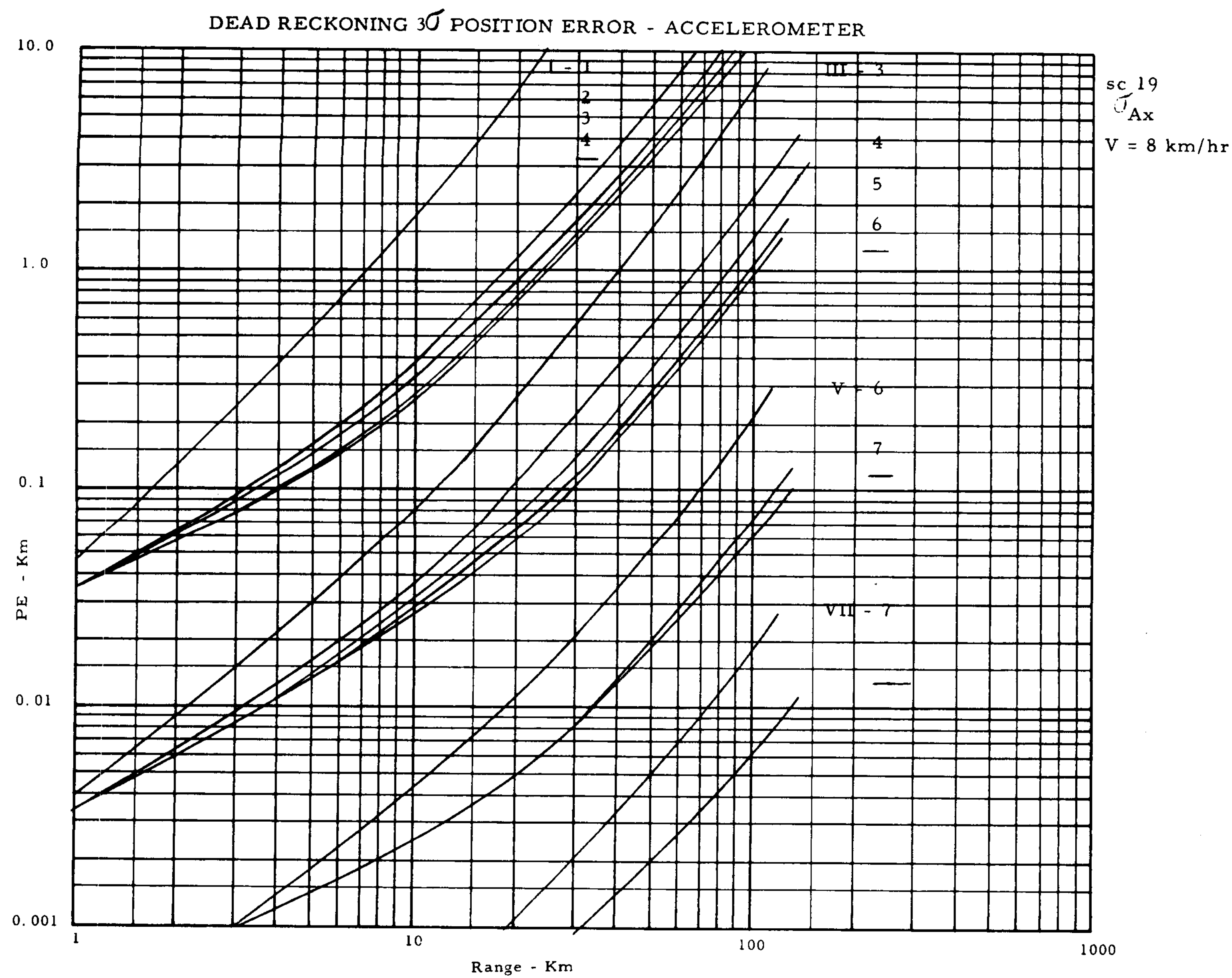


Figure 10-325 Dead Reckoning 3σ Position Error - Accelerometer

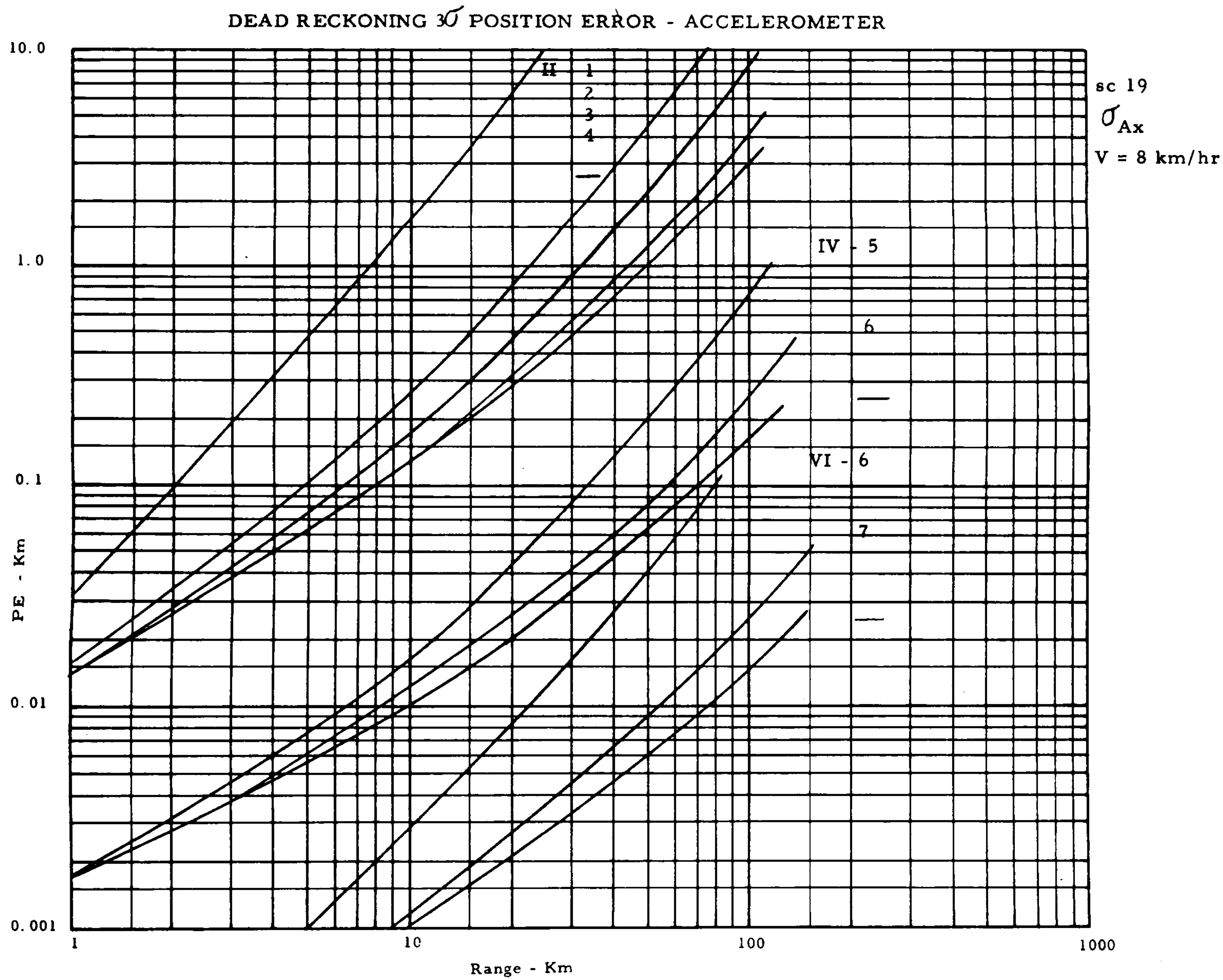


Figure 10-326 Dead Reckoning 3σ Position Error - Accelerometer

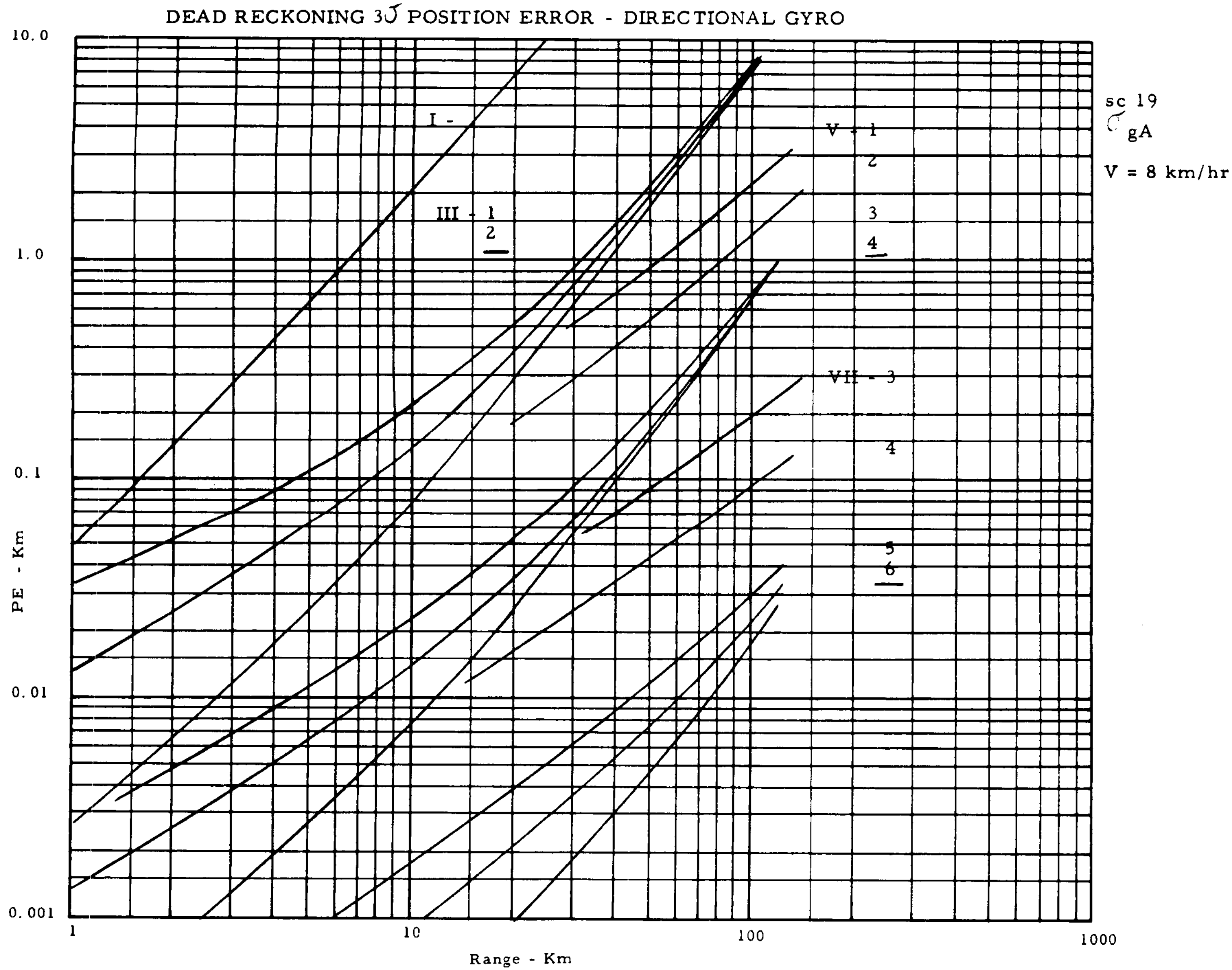


Figure 10-327 Dead Reckoning 3σ Position Error - Directional Gyro

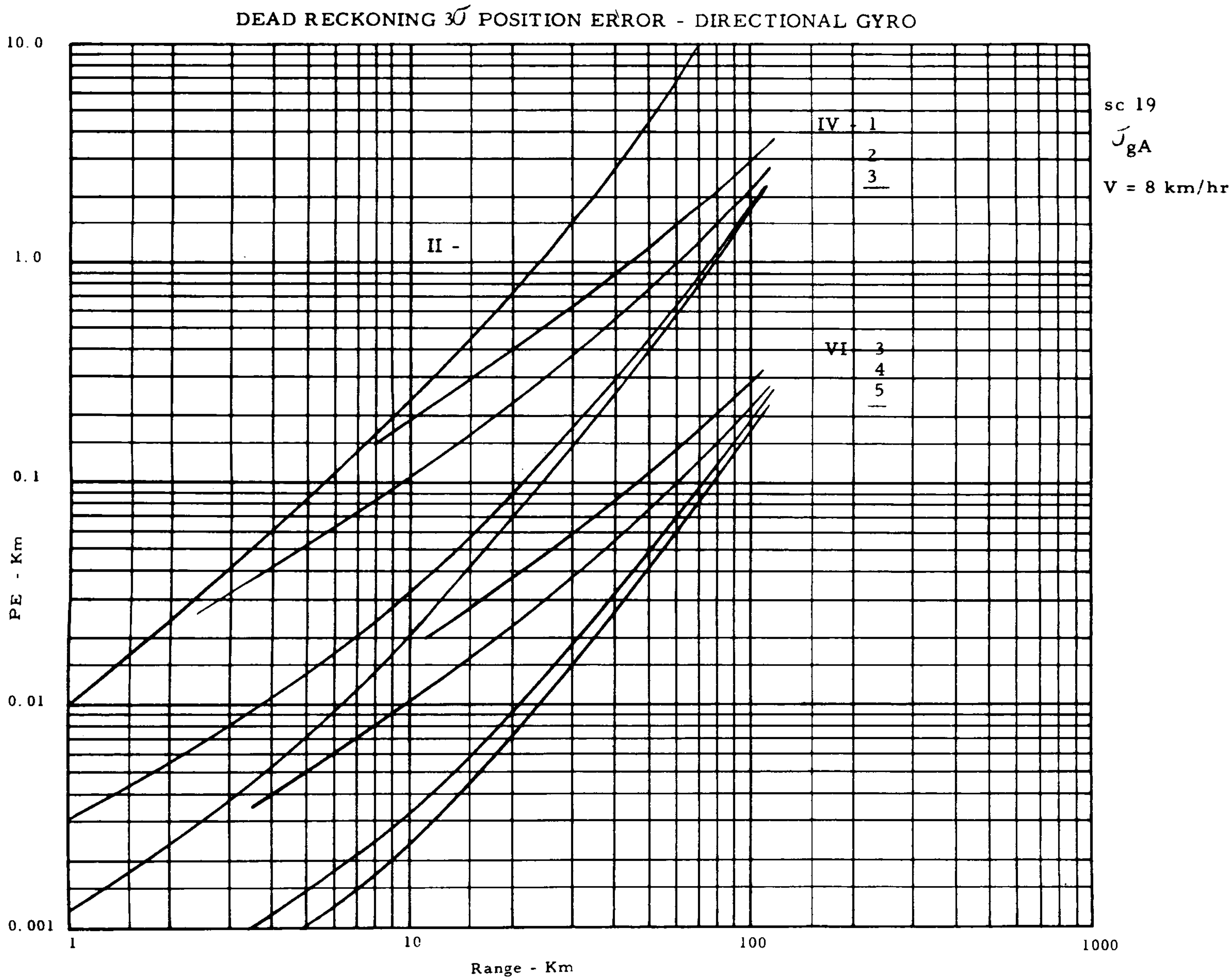


Figure 10-328 Dead Reckoning 3σ Position Error - Directional Gyro

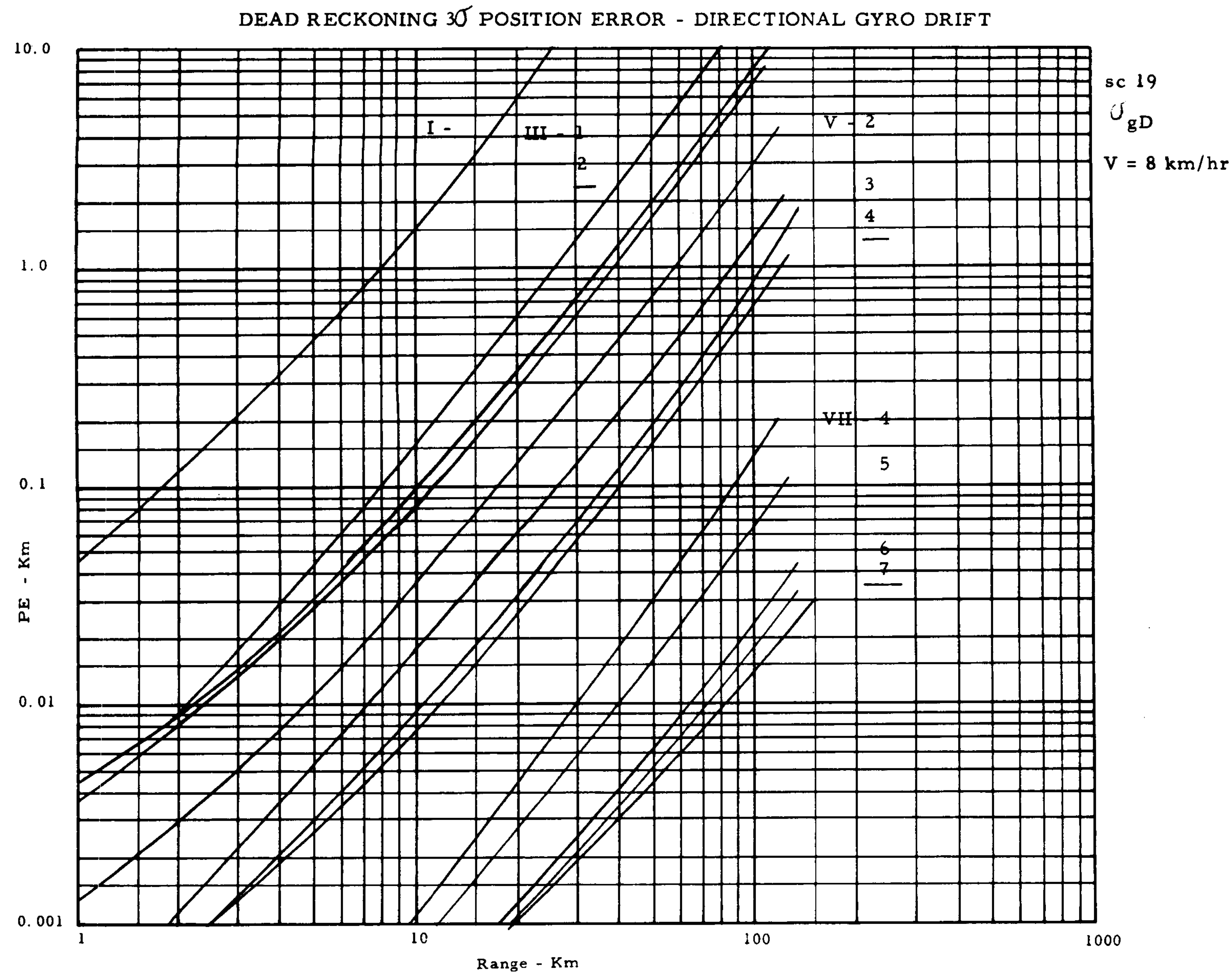


Figure 10-329 Dead Reckoning 3σ Position Error - Directional Gyro Drift

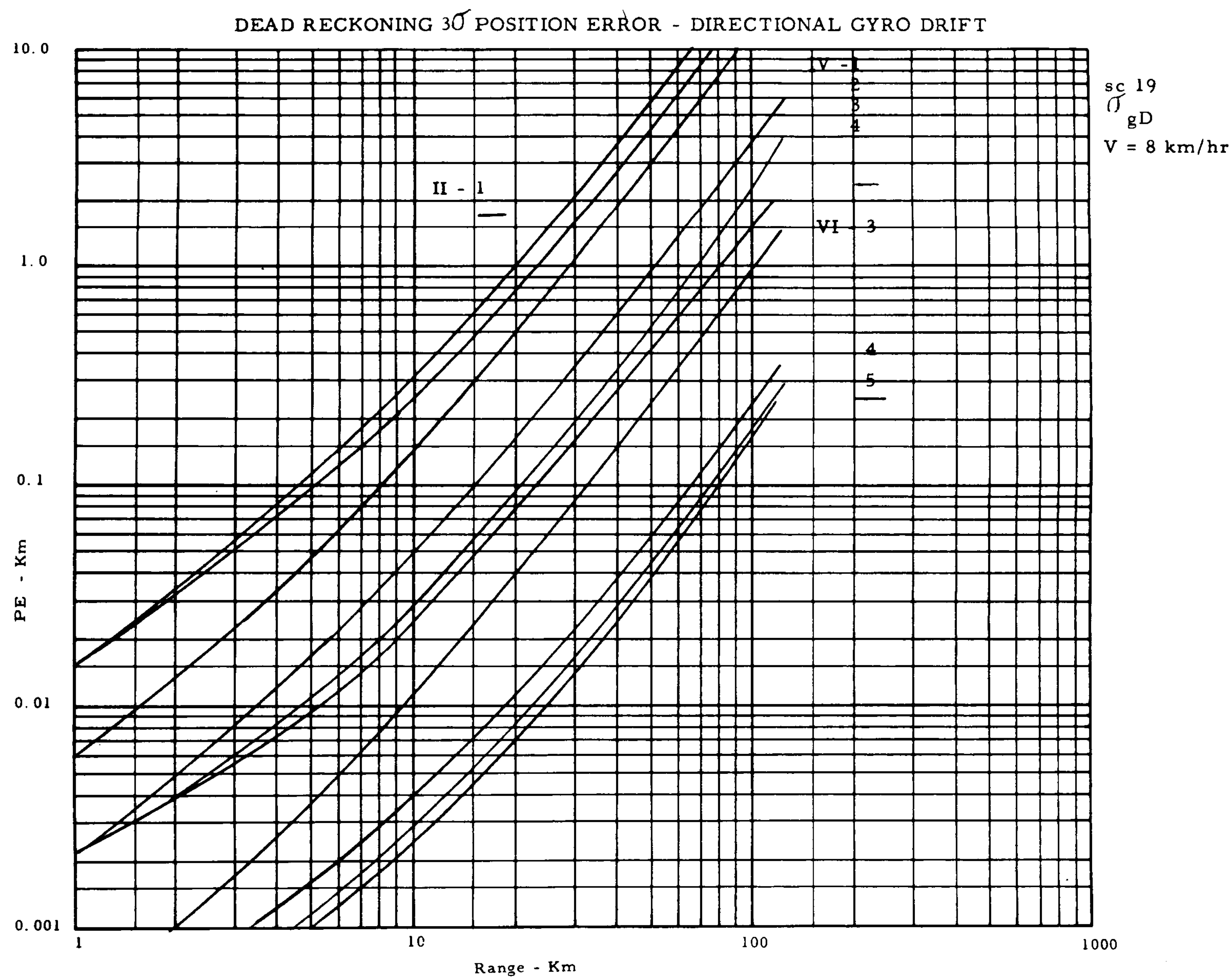


Figure 10-330 Dead Reckoning 3σ Position Error - Directional Gyro Drift

DEAD RECKONING 3σ POSITION ERROR - VERTICAL SENSOR

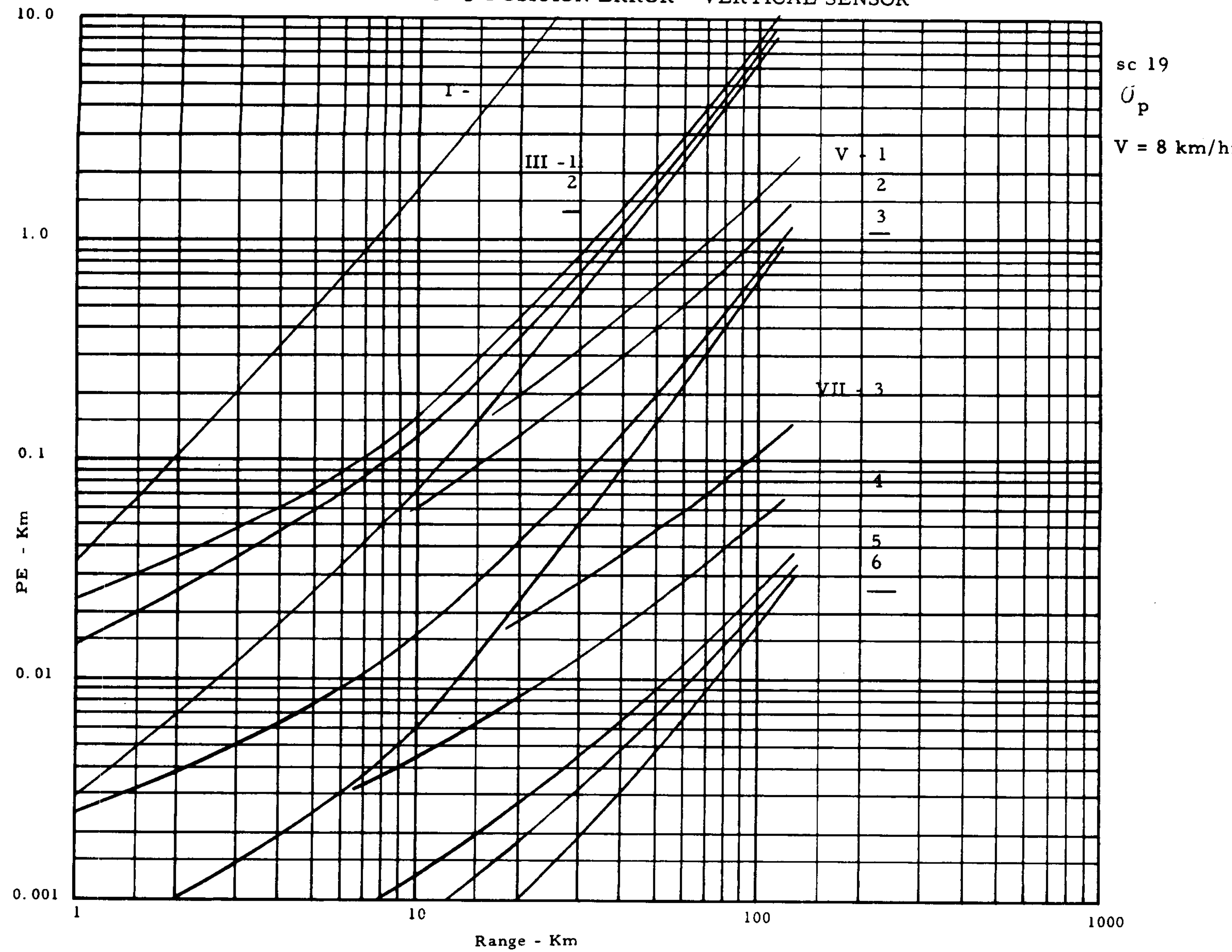


Figure 10-331 Dead Reckoning 3σ Position Error - Vertical Sensor

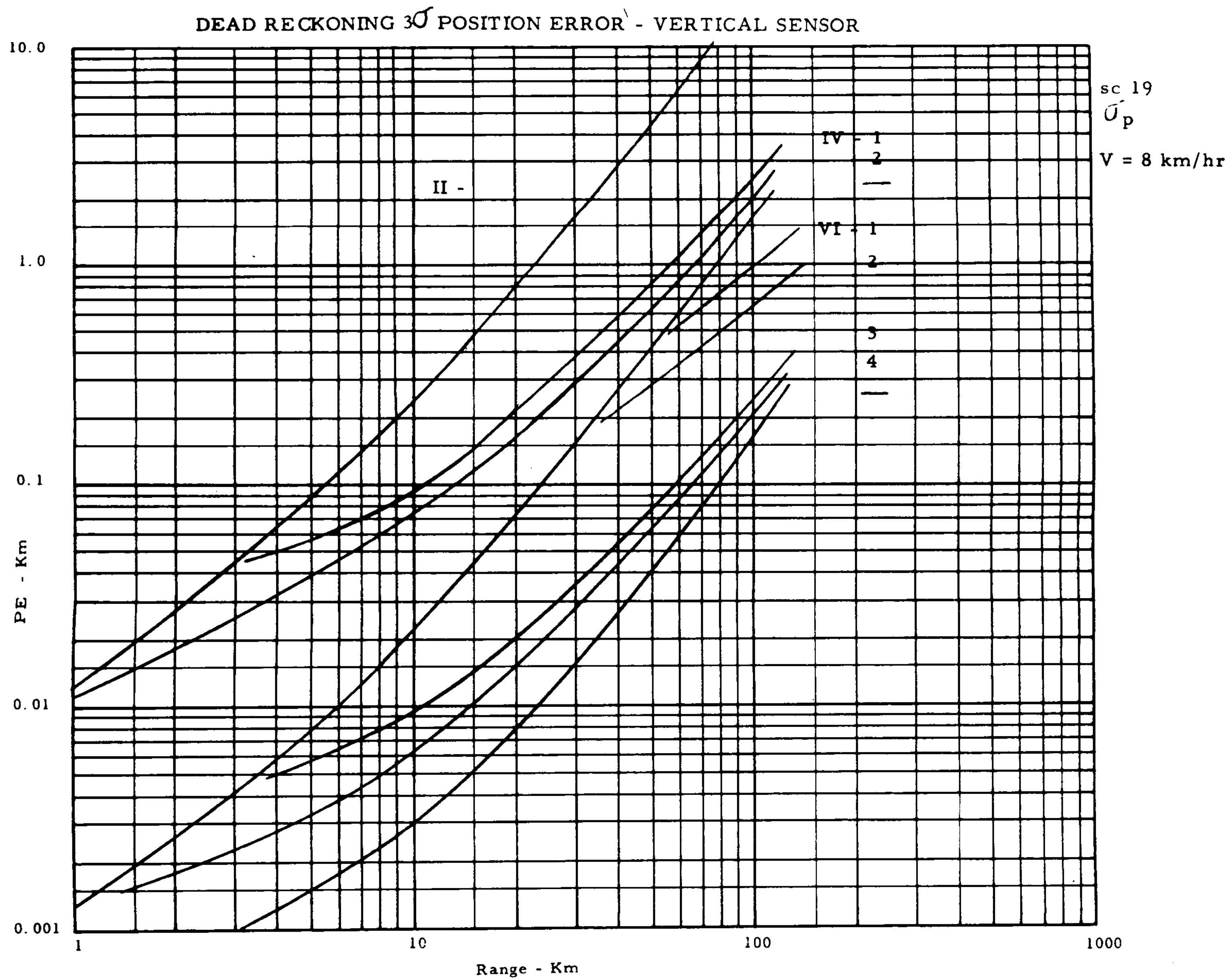


Figure 10-332 Dead Reckoning 3σ Position Error - Vertical Sensor

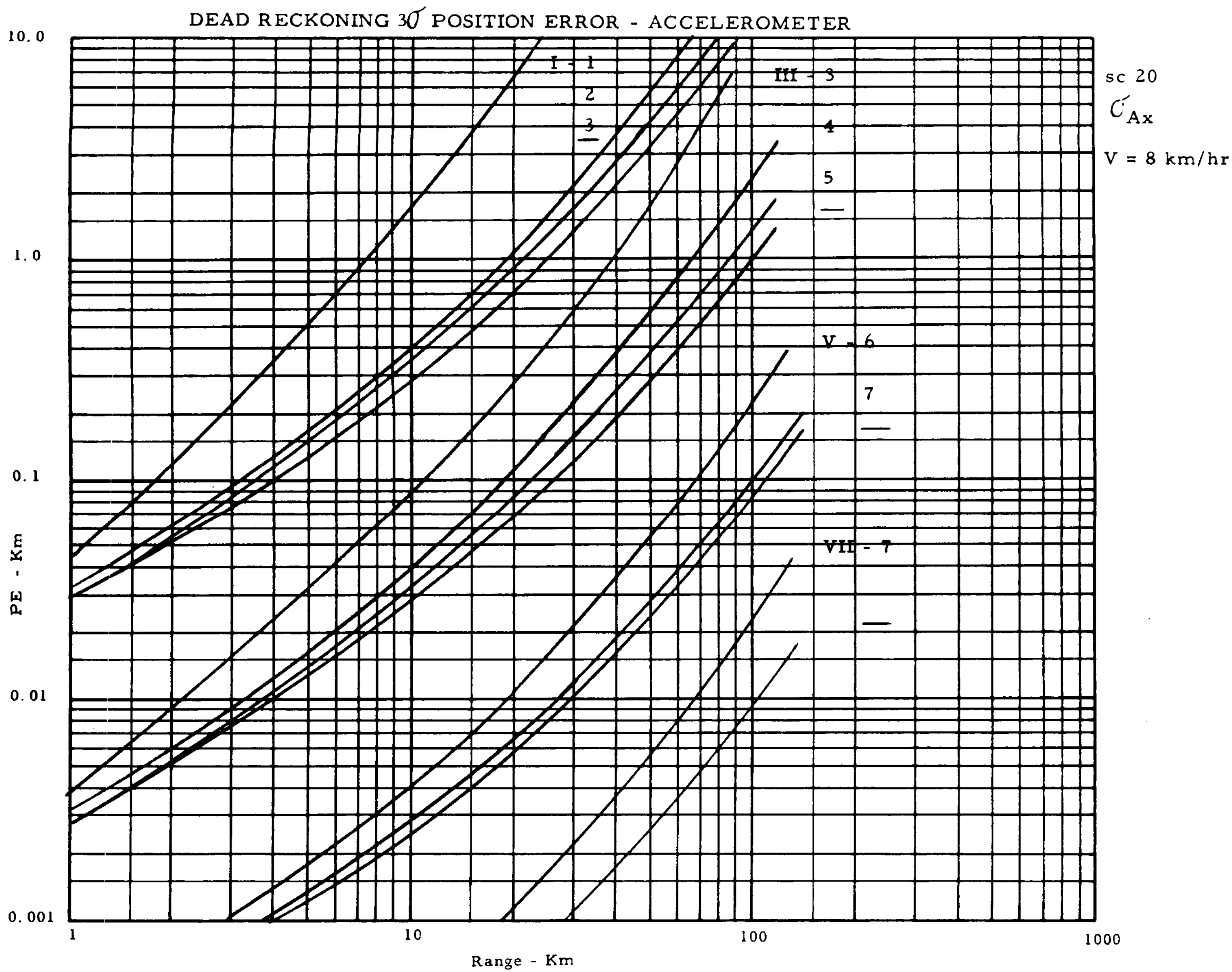


Figure 10-333 Dead Reckoning 3σ Position Error - Accelerometer

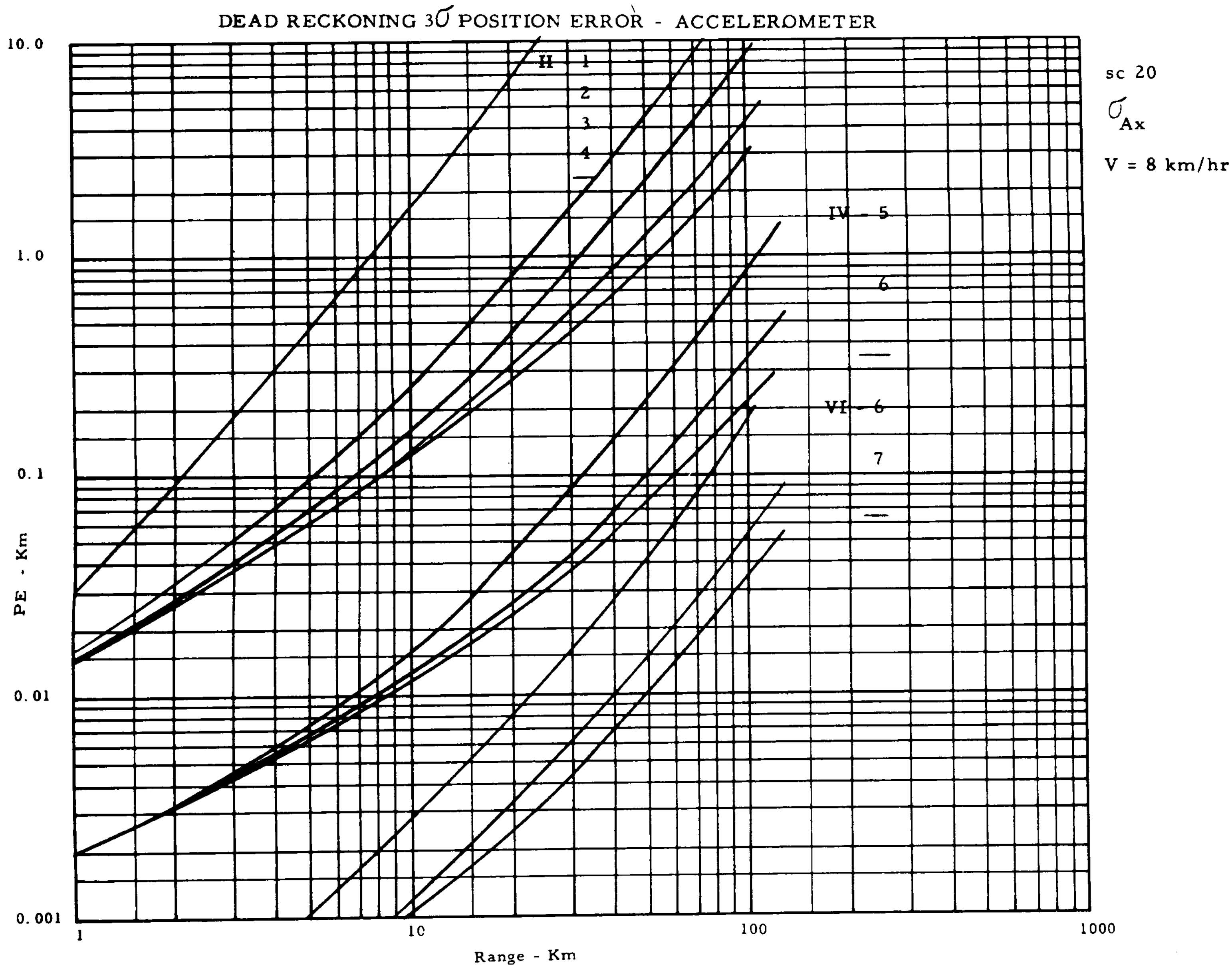


Figure 10-334 Dead Reckoning 3σ Position Error - Accelerometer

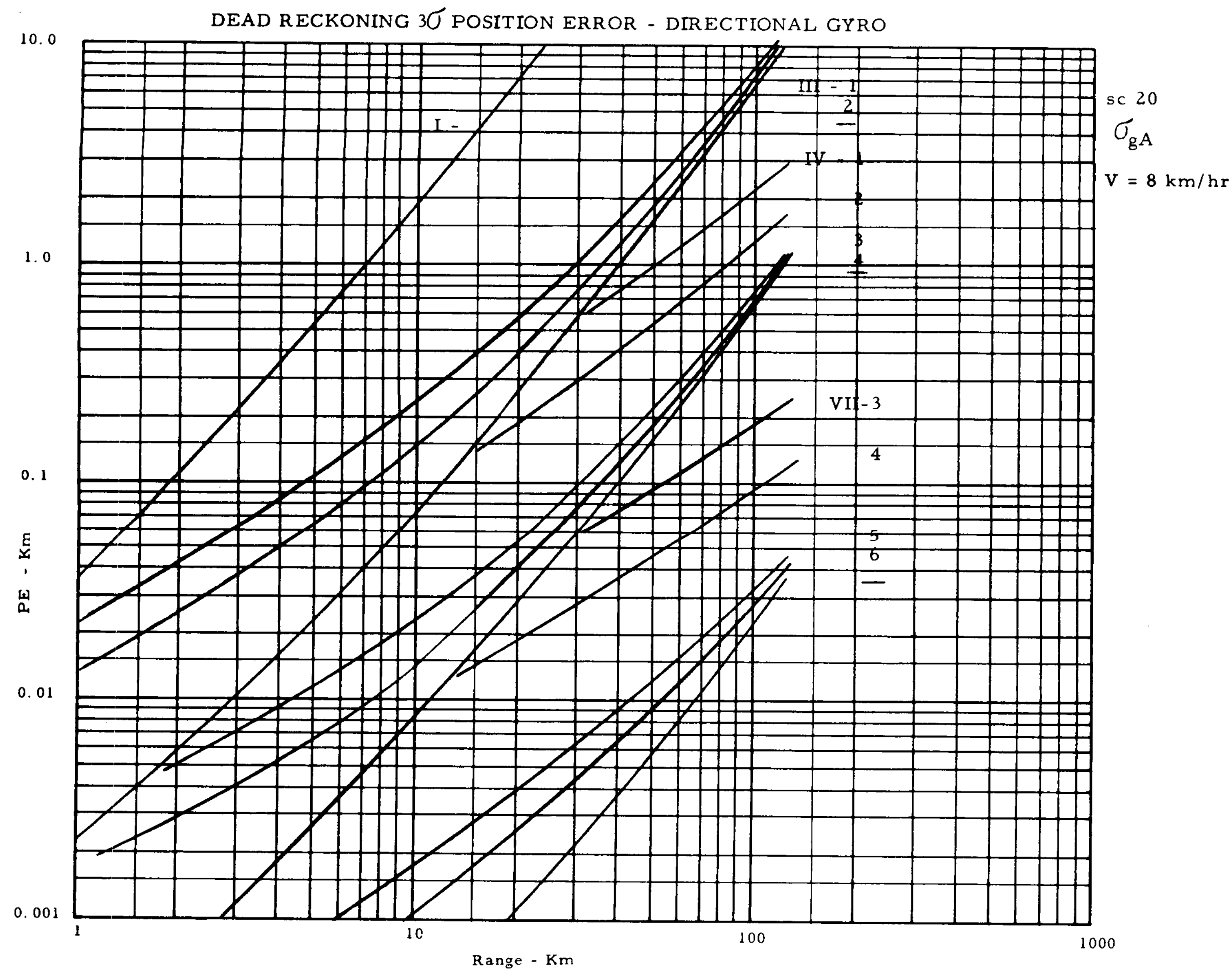


Figure 10-335 Dead Reckoning 3σ Position Error - Directional Gyro

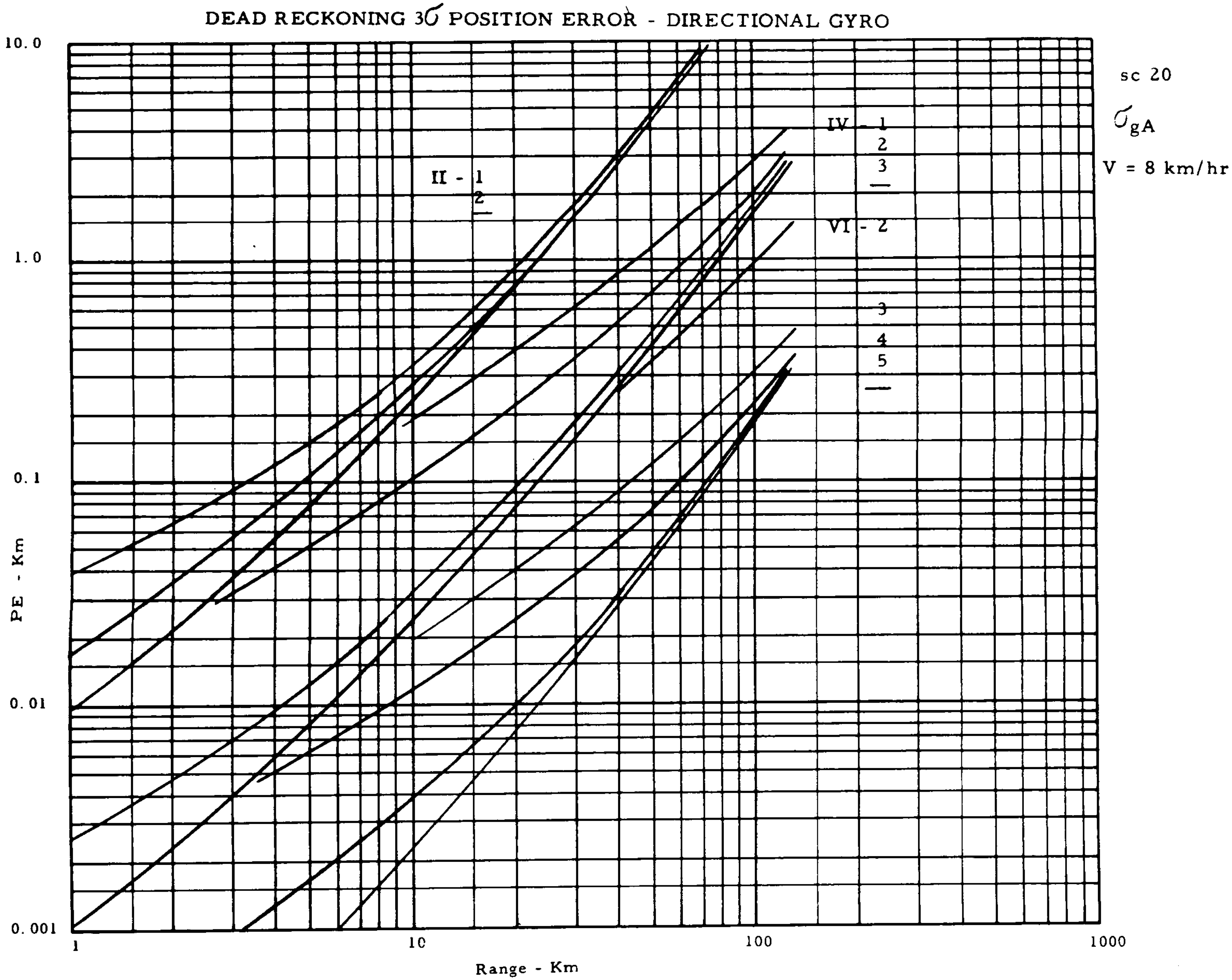


Figure 10-336 Dead Reckoning 3σ Position Error - Directional Gyro

DEAD RECKONING 3σ POSITION ERROR - DIRECTIONAL GYRO DRIFT

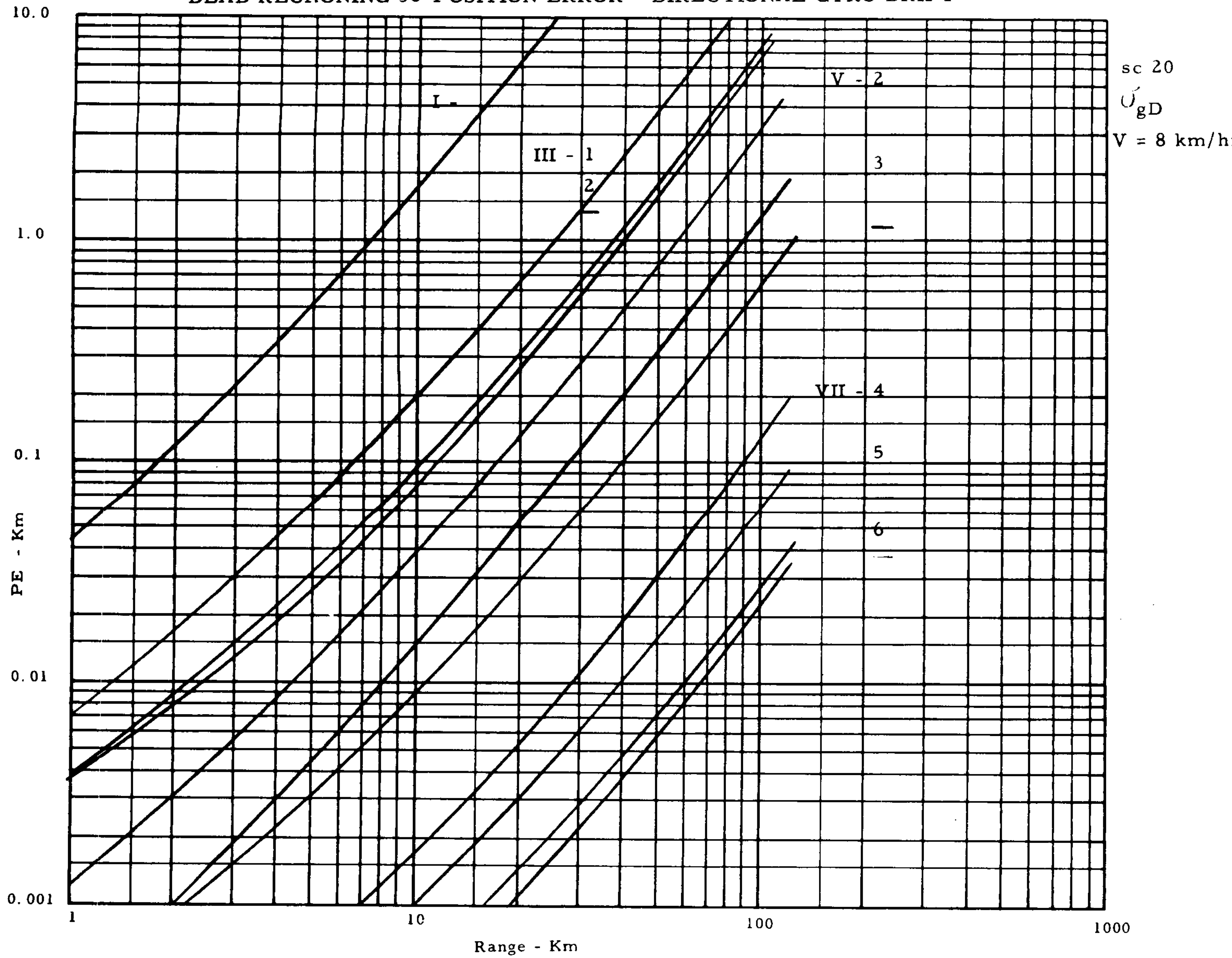


Figure 10-337 Dead Reckoning 3σ Position Error - Directional Gyro Drift

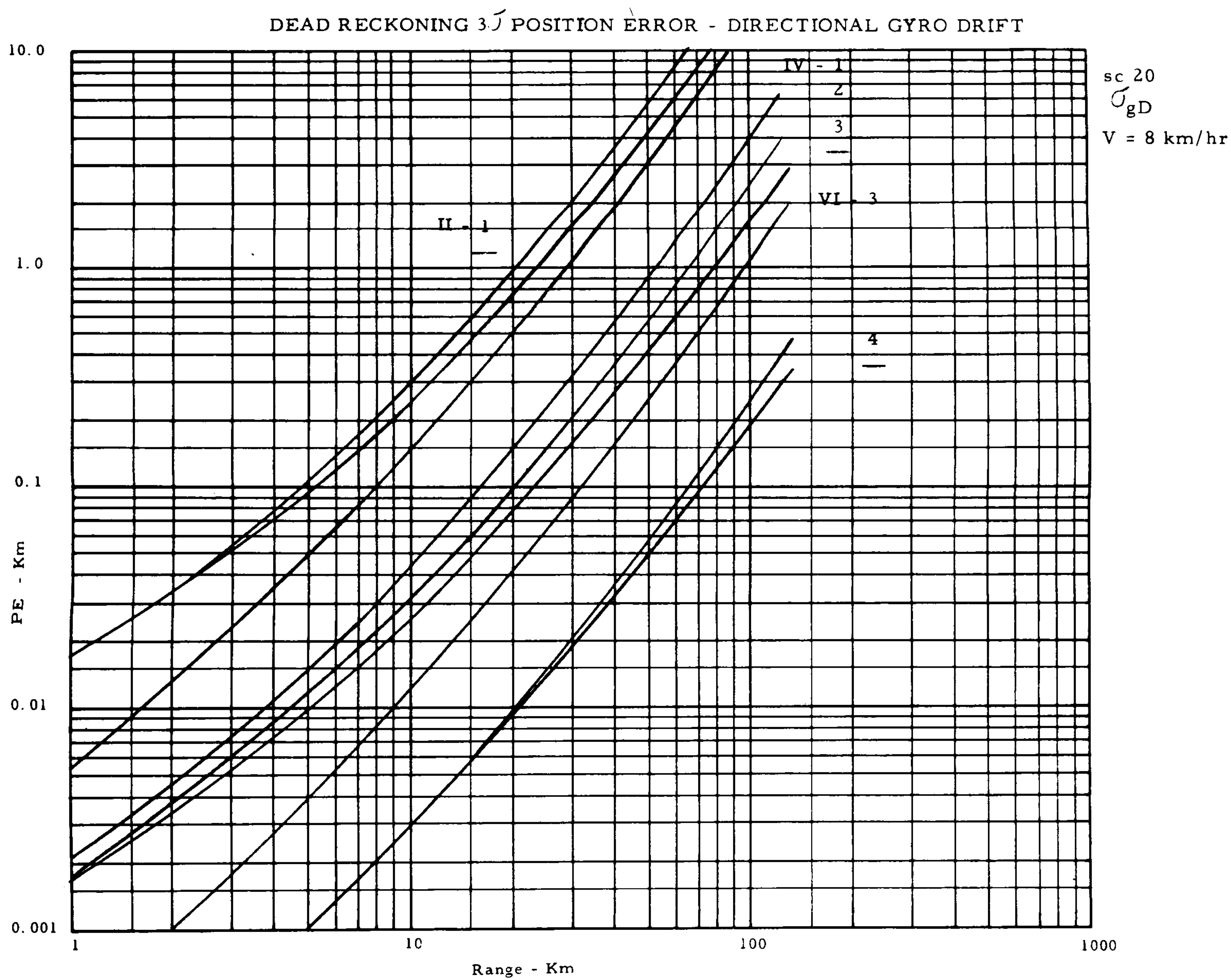


Figure 10-338 Dead Reckoning 3σ Position Error - Directional Gyro Drift

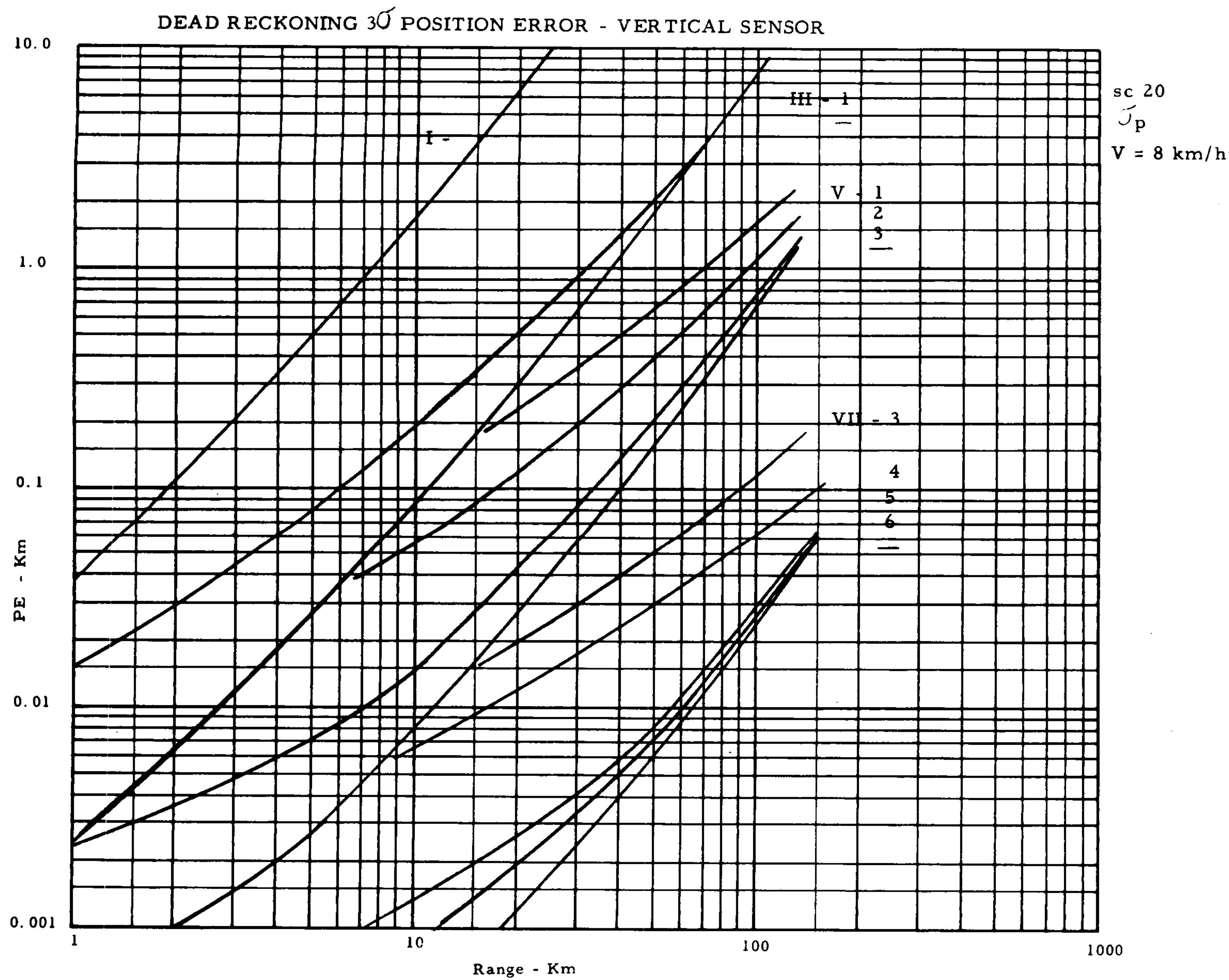


Figure 10-339 Dead Reckoning 3σ Position Error - Vertical Sensor

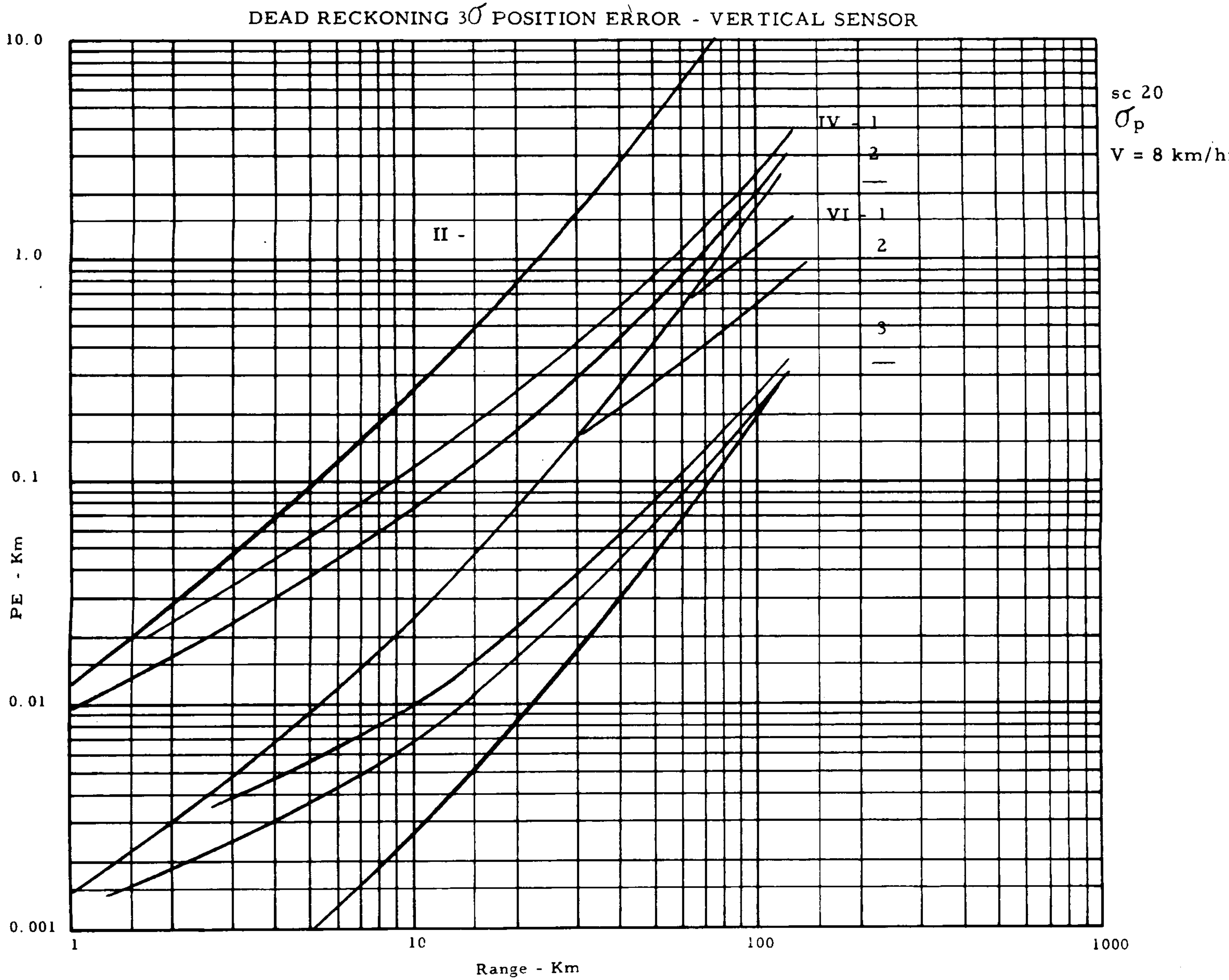


Figure 10-340 Dead Reckoning 3σ Position Error - Vertical Sensor

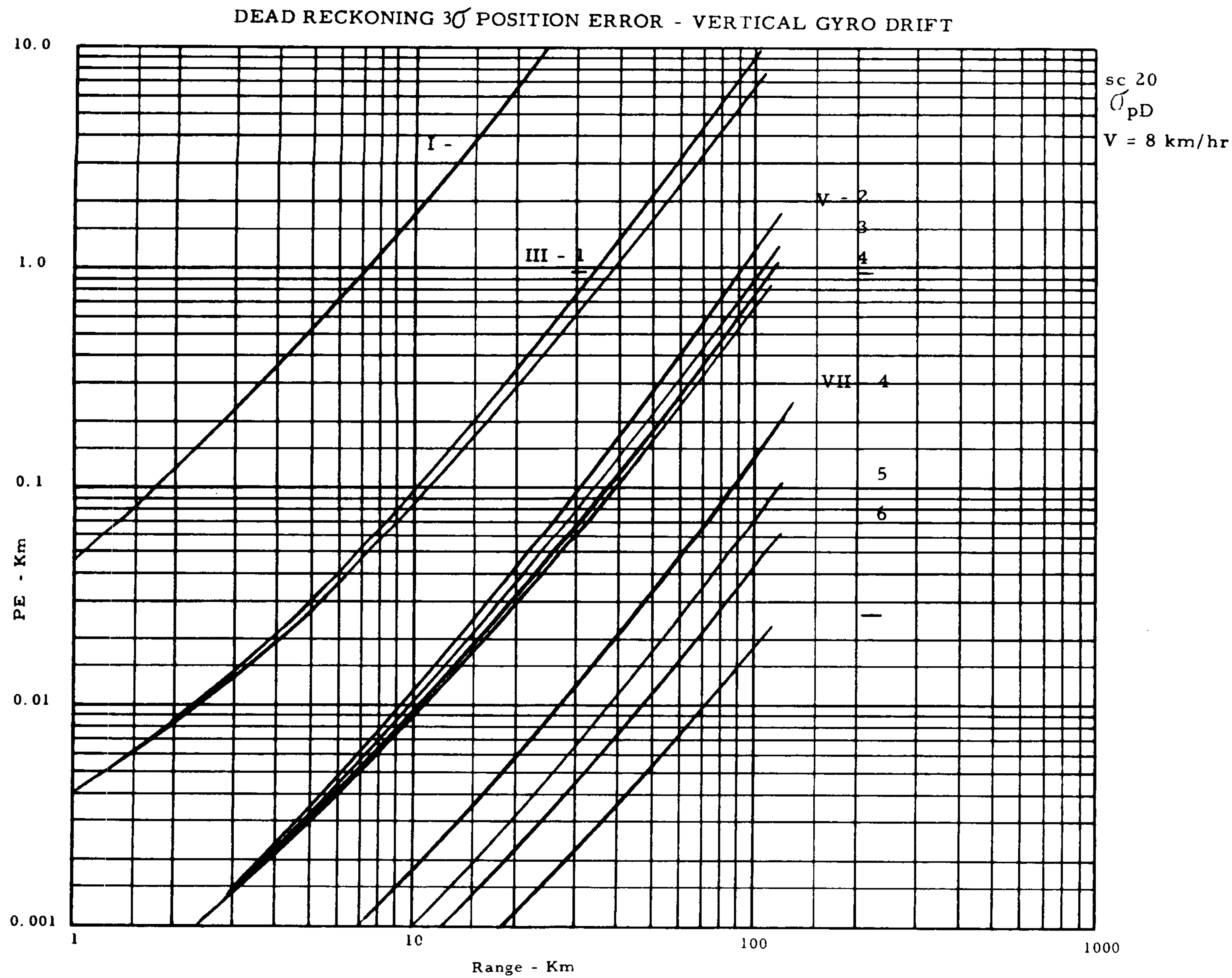


Figure 10-341 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

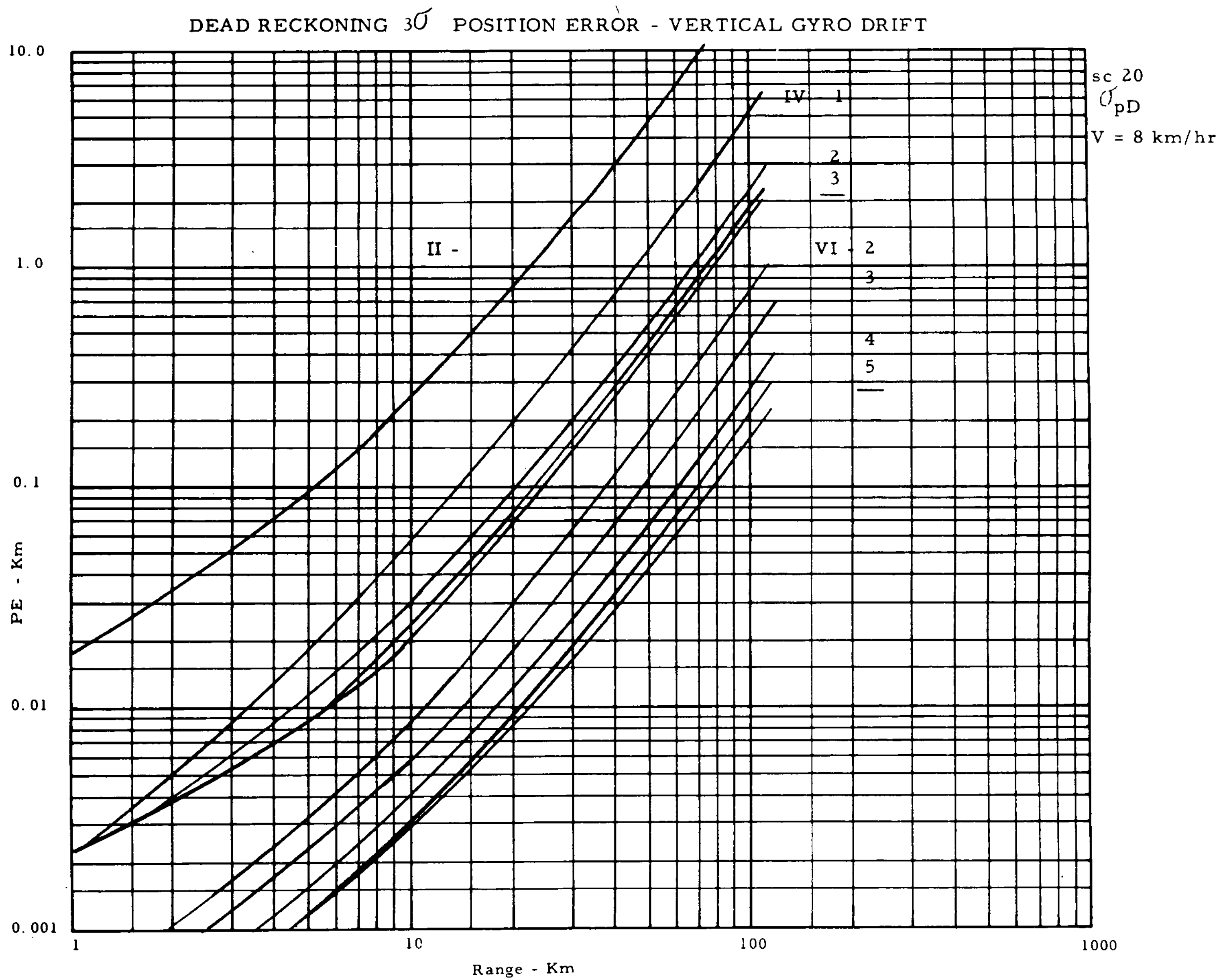


Figure 10-342 Dead Reckoning 3σ Position Error - Vertical Gyro Drift

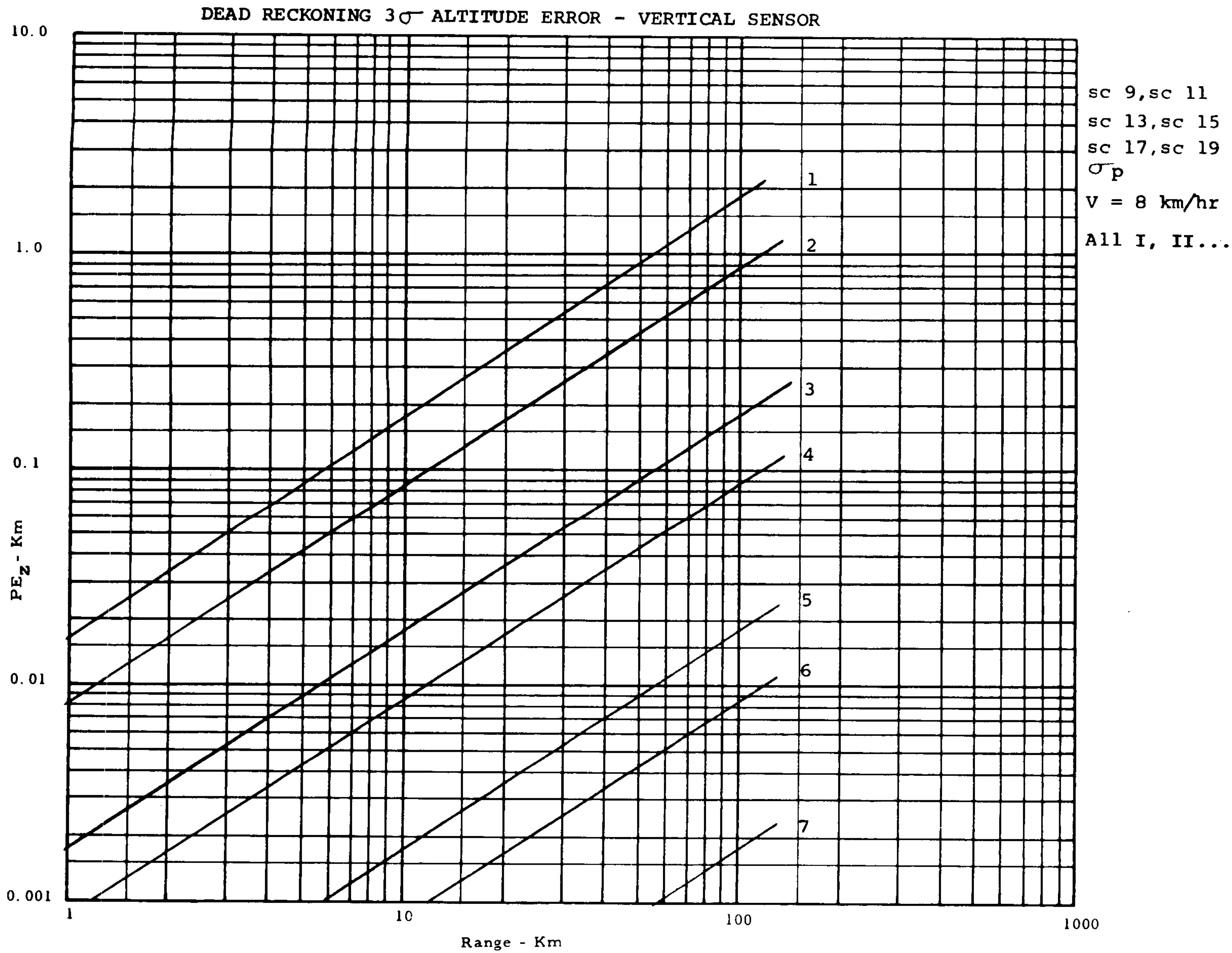


Figure 10-343 Dead Reckoning 3σ Altitude Error - Vertical Sensor

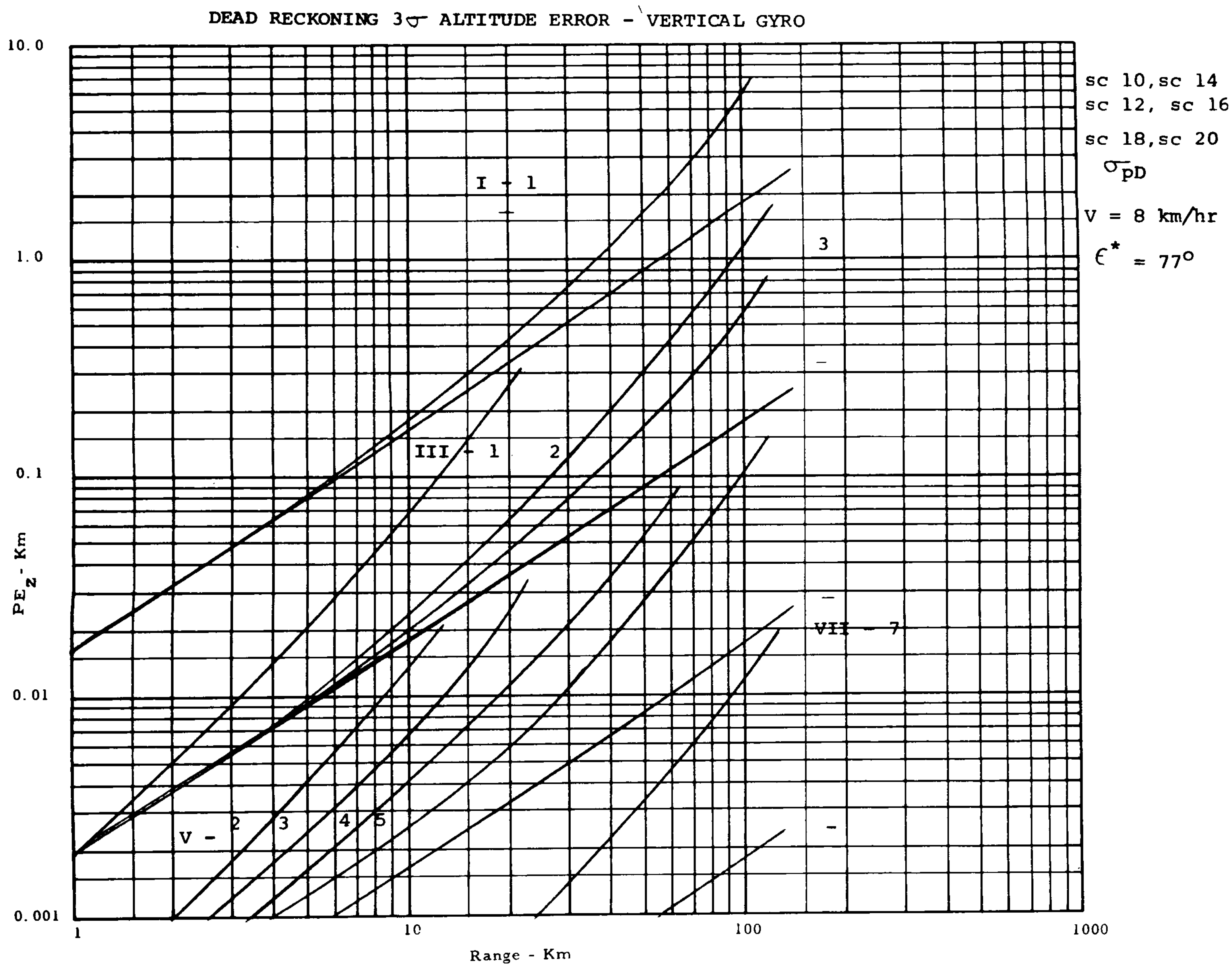


Figure 10-344 Dead Reckoning 3σ Altitude Error - Vertical Gyro

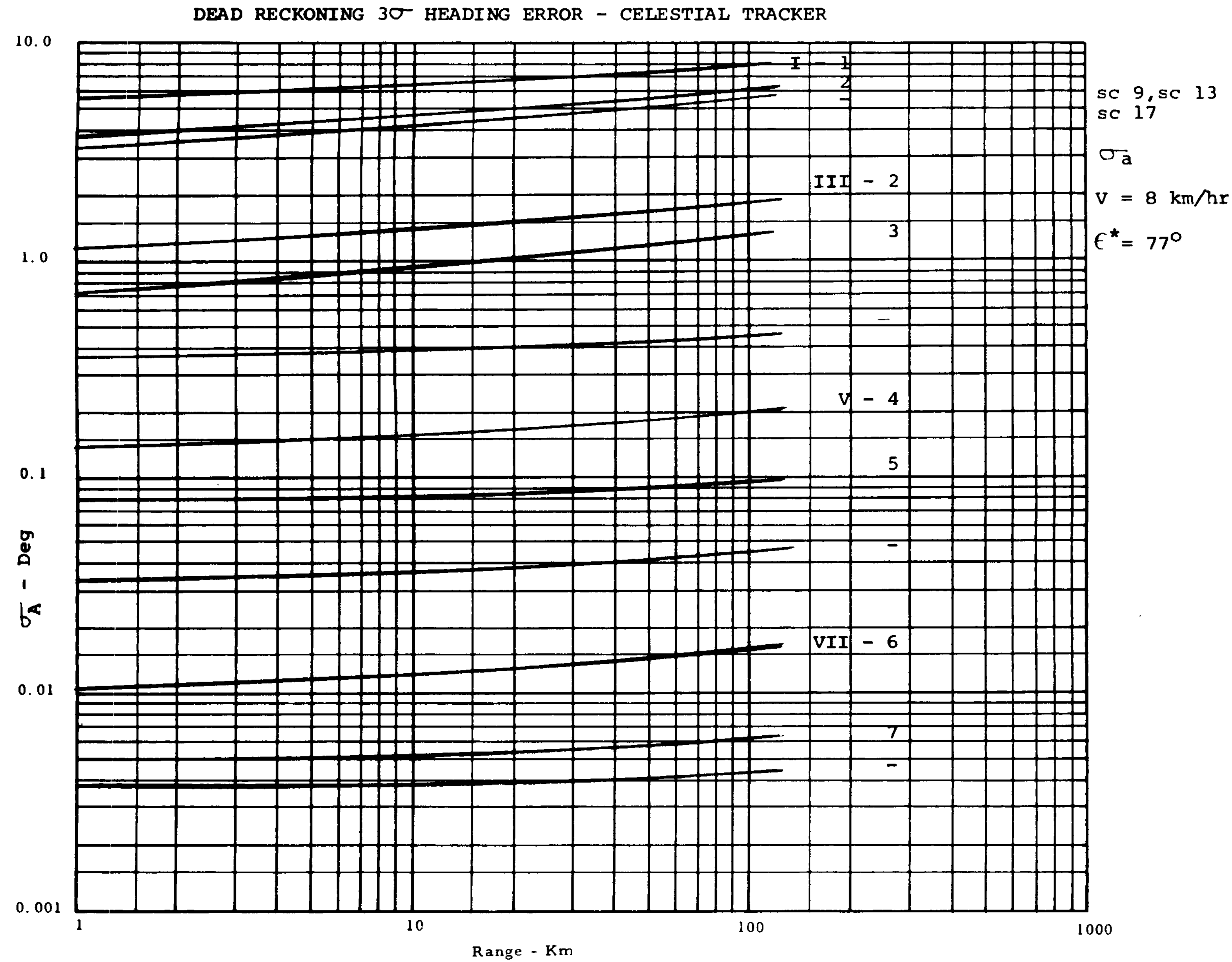


Figure 10-345 Dead Reckoning 3σ Heading Error - Celestial Tracker

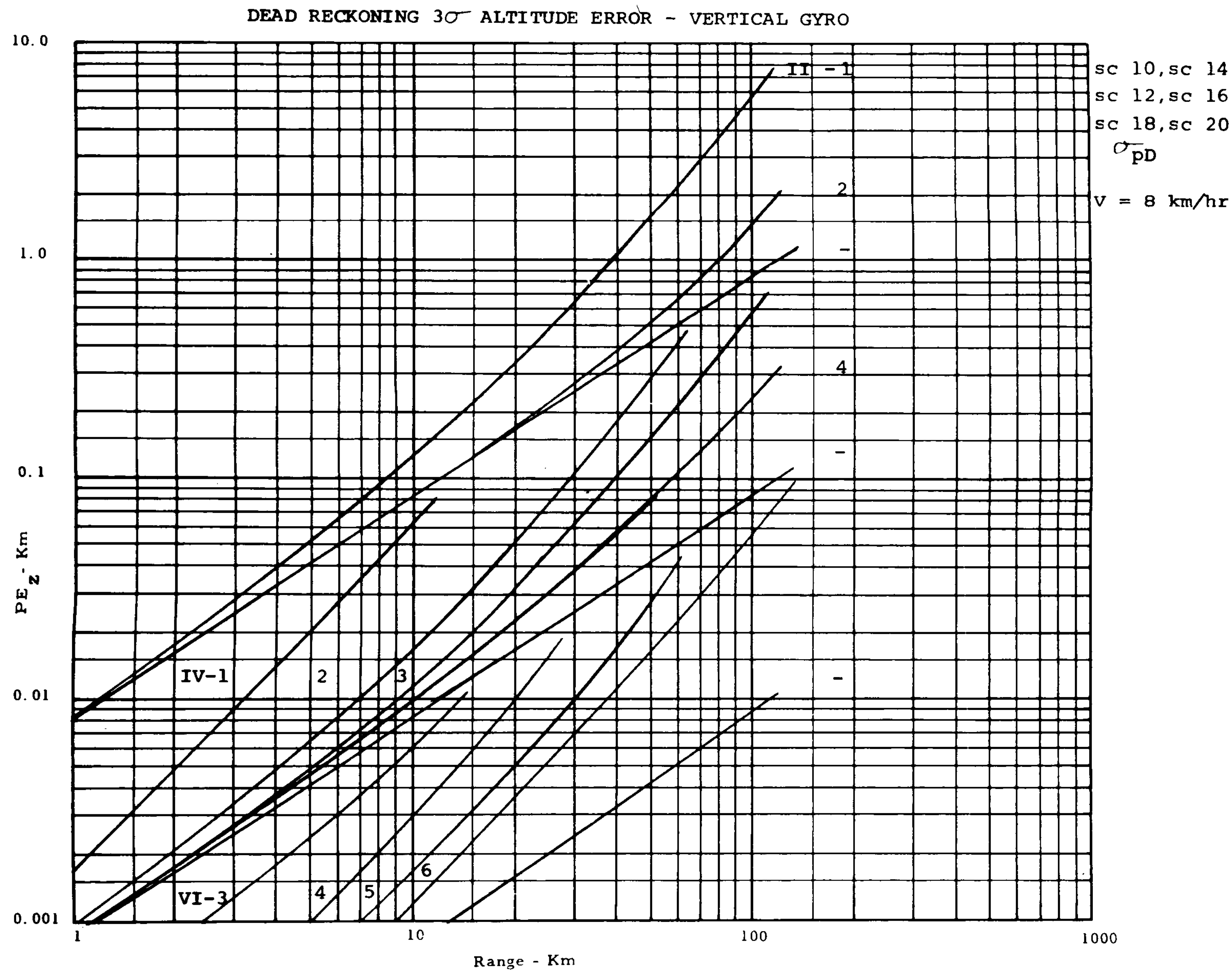


Figure 10-346 Dead Reckoning 3σ Altitude Error - Vertical Gyro

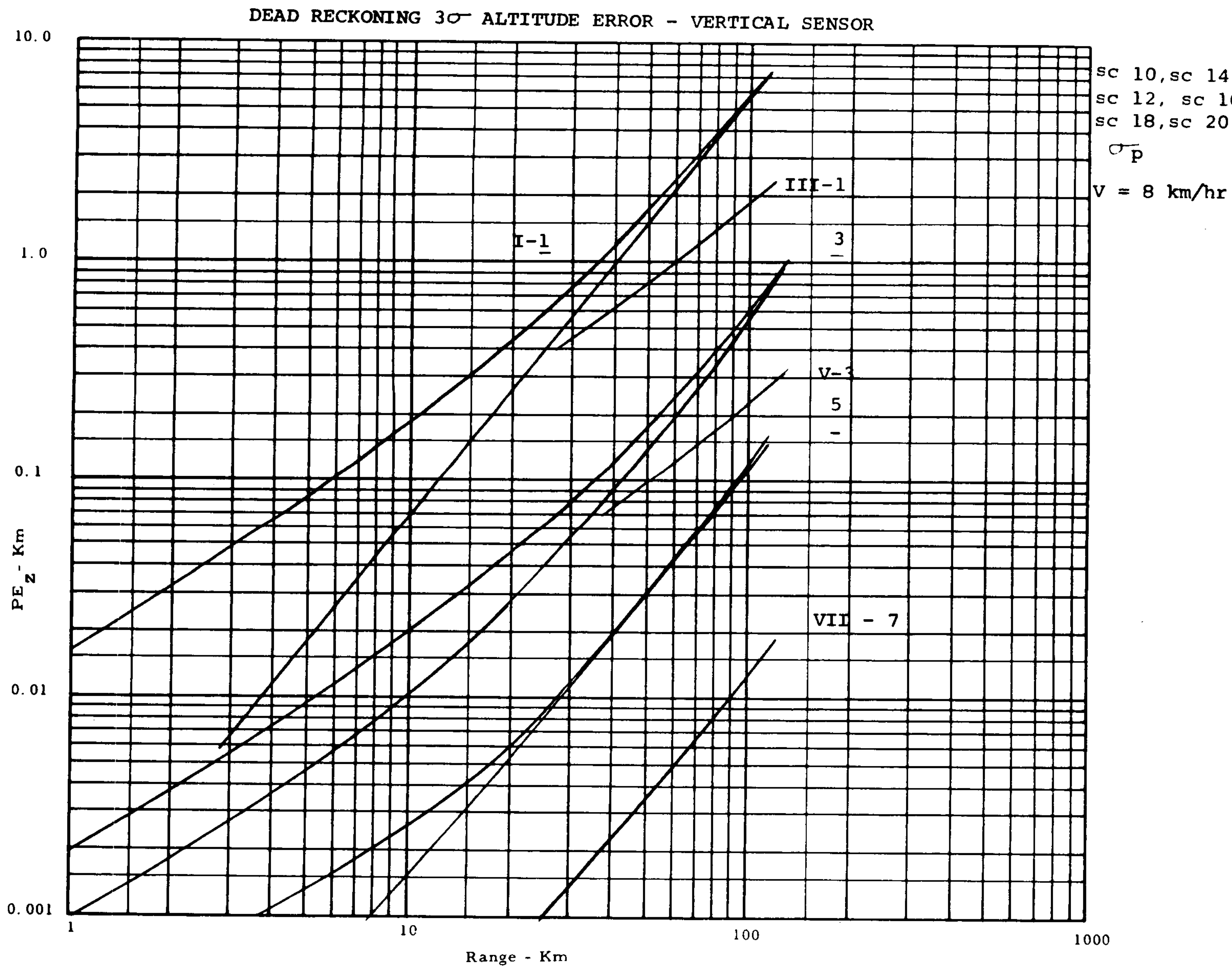


Figure 10-347 Dead Reckoning 3σ Altitude Error - Vertical Sensor

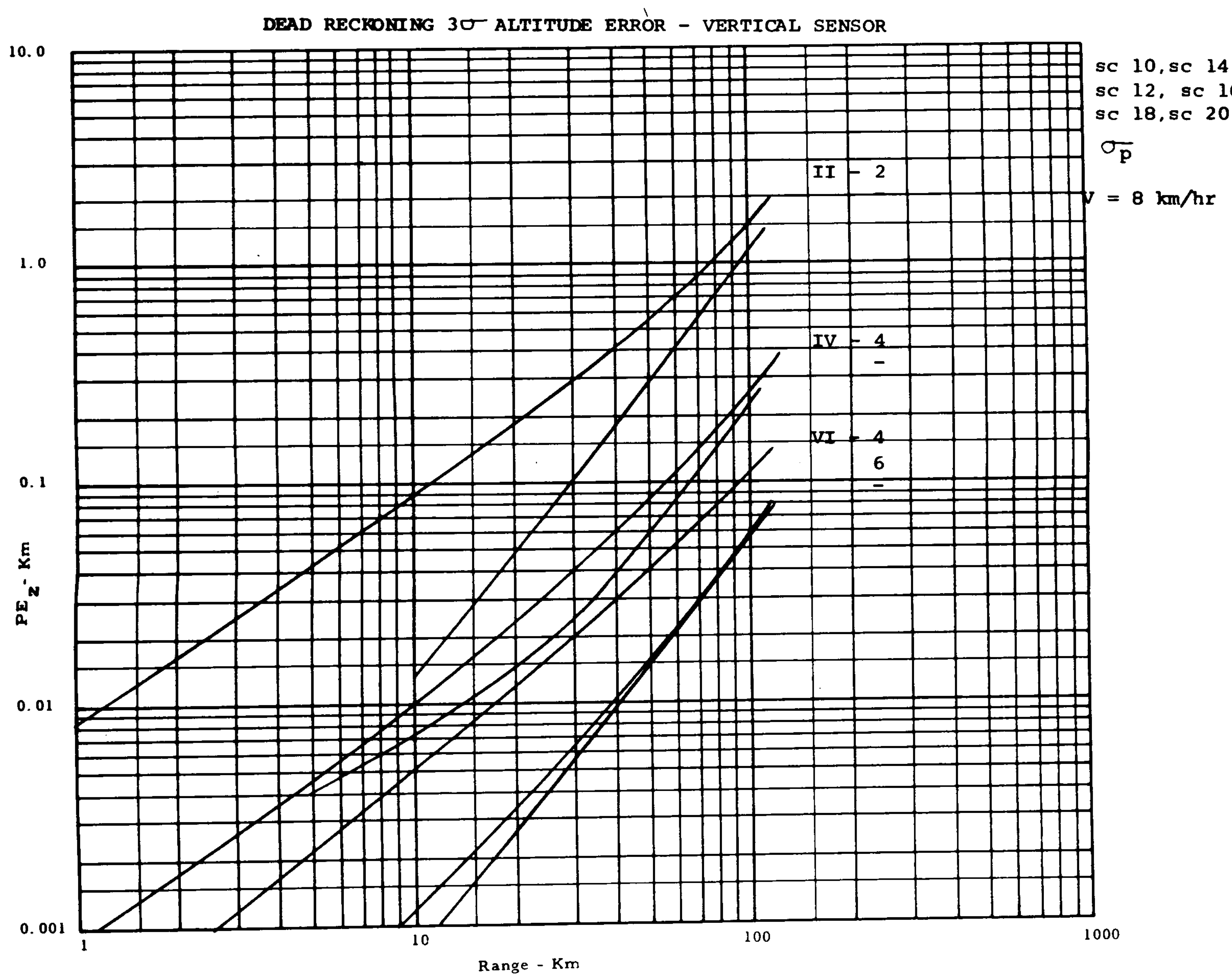


Figure 10-348 Dead Reckoning 3σ Altitude Error - Vertical Sensor

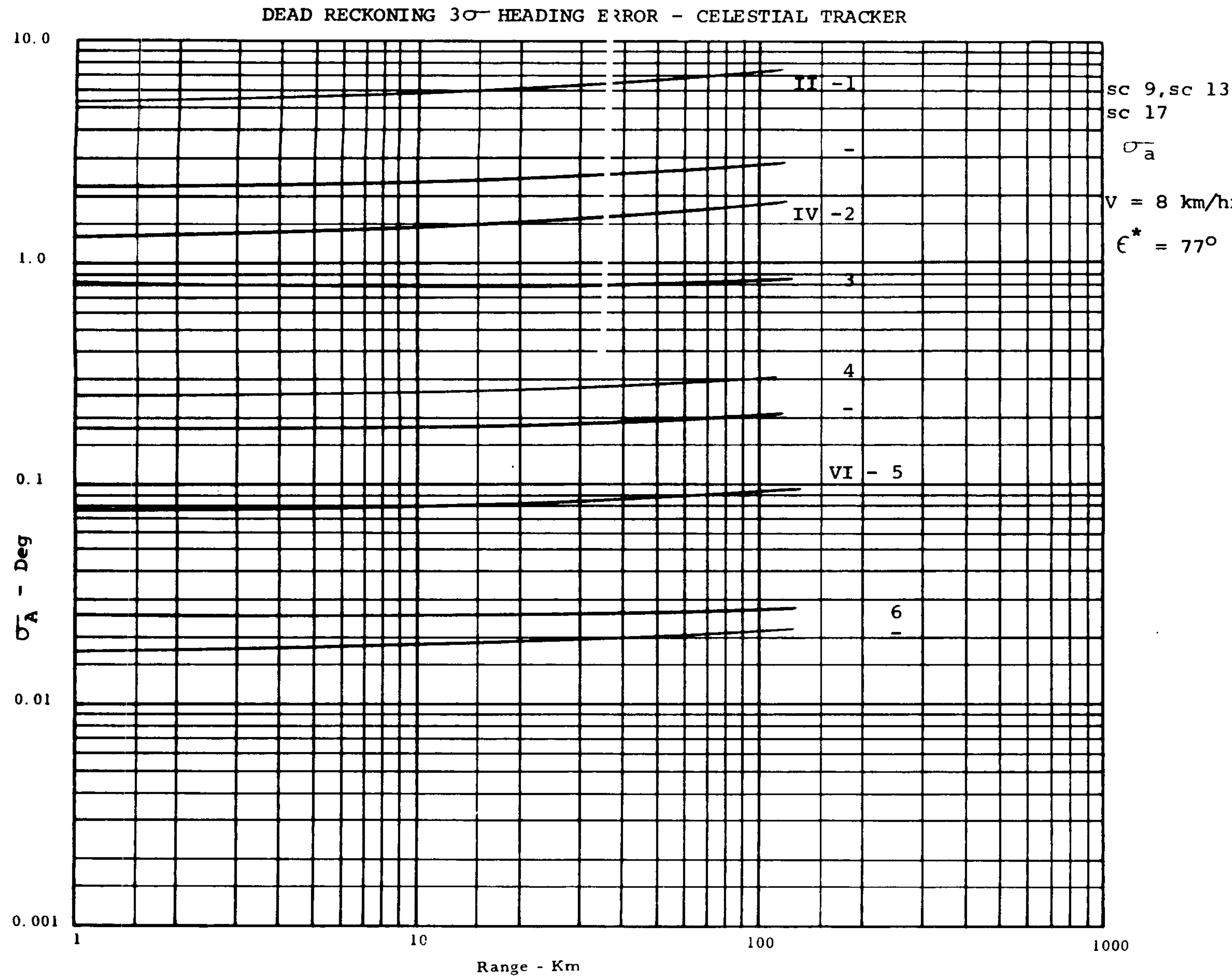


Figure 10-349 Dead Reckoning 3σ Heading Error - Celestial Tracker

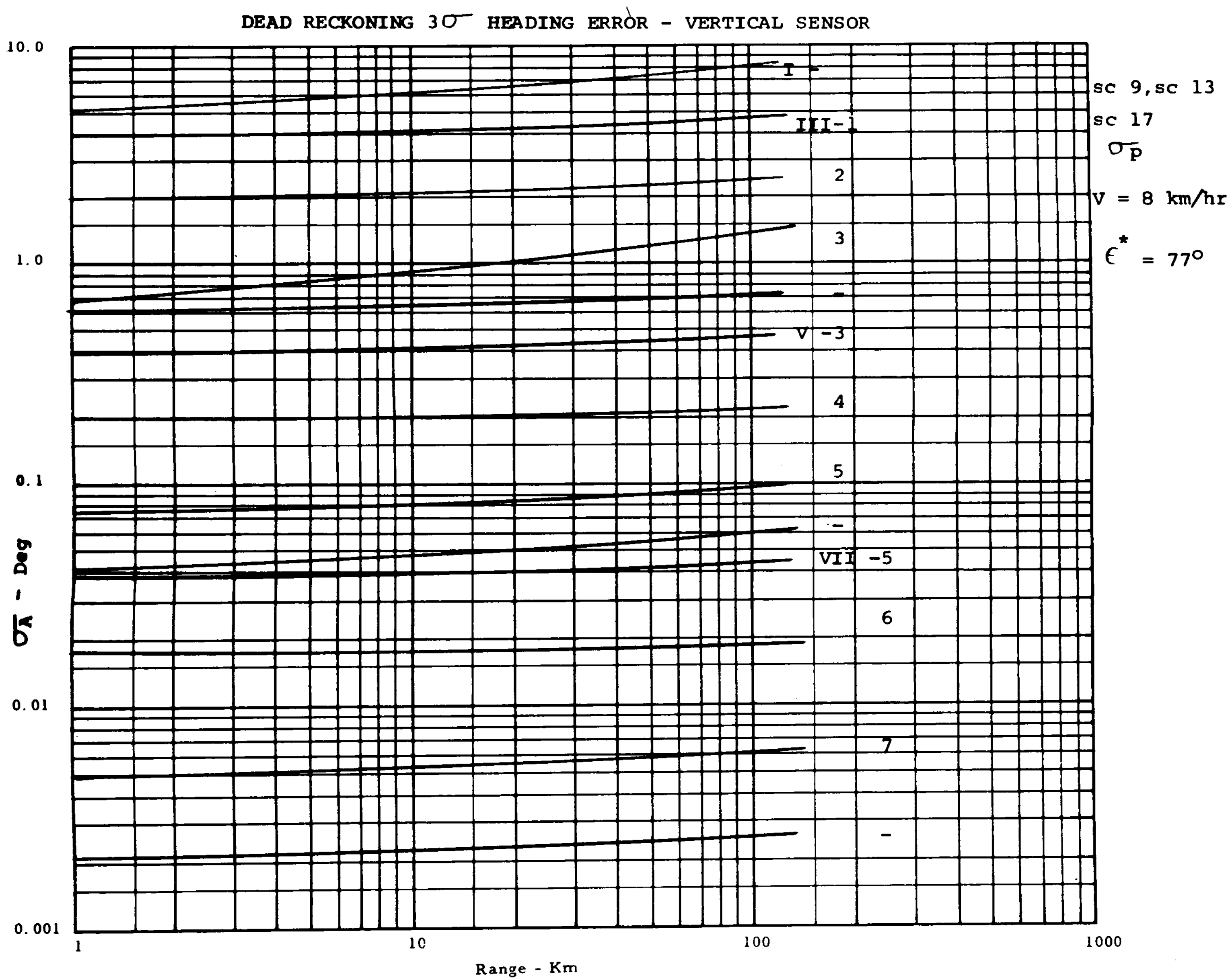


Figure 10-350 Dead Reckoning 3σ Heading Error—Vertical Sensor

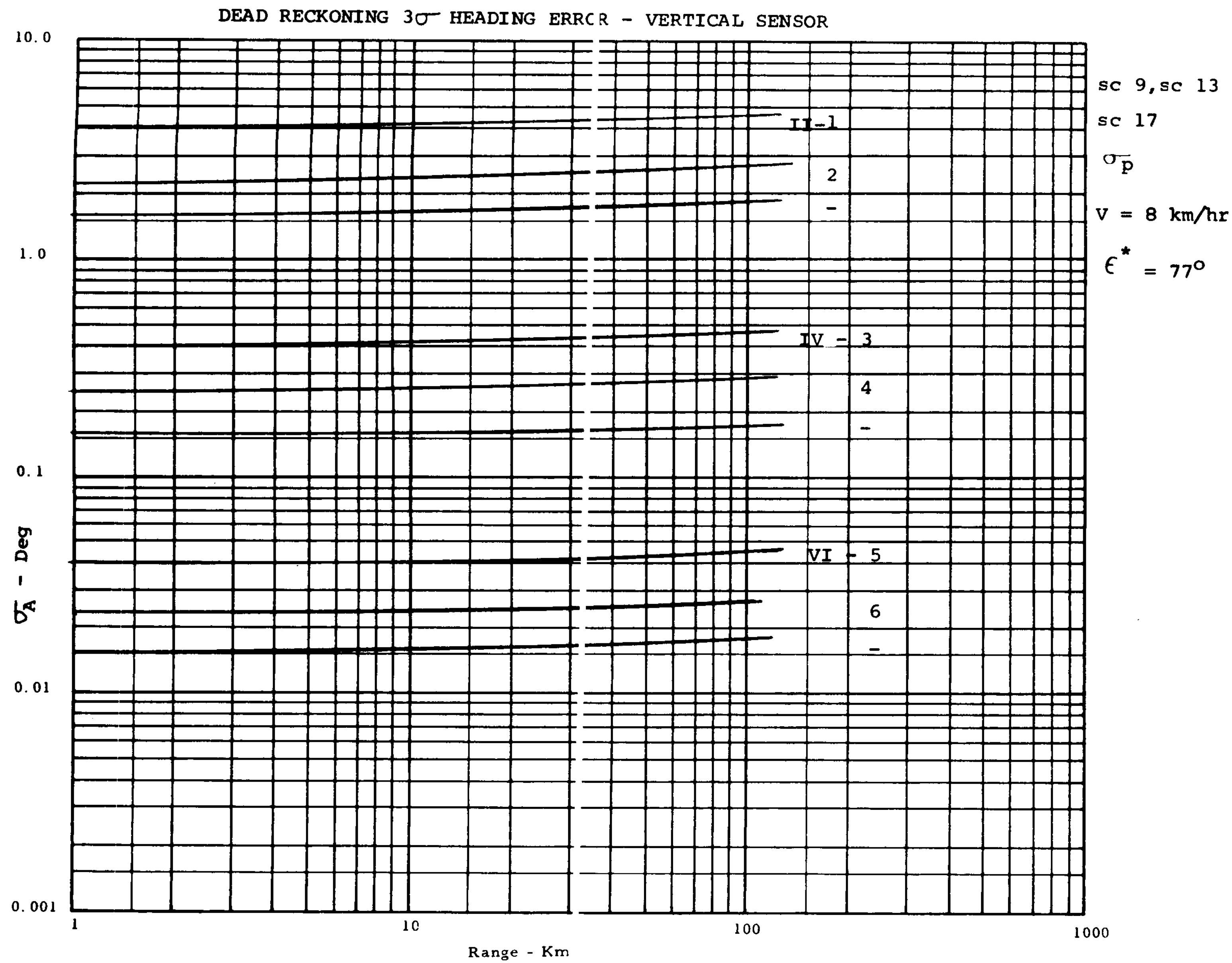


Figure 10-351 Dead Reckoning 3σ Heading Error—Vertical Sensor

DEAD RECKONING 3σ HEADING ERROR + EPHEMERIS, TIMER

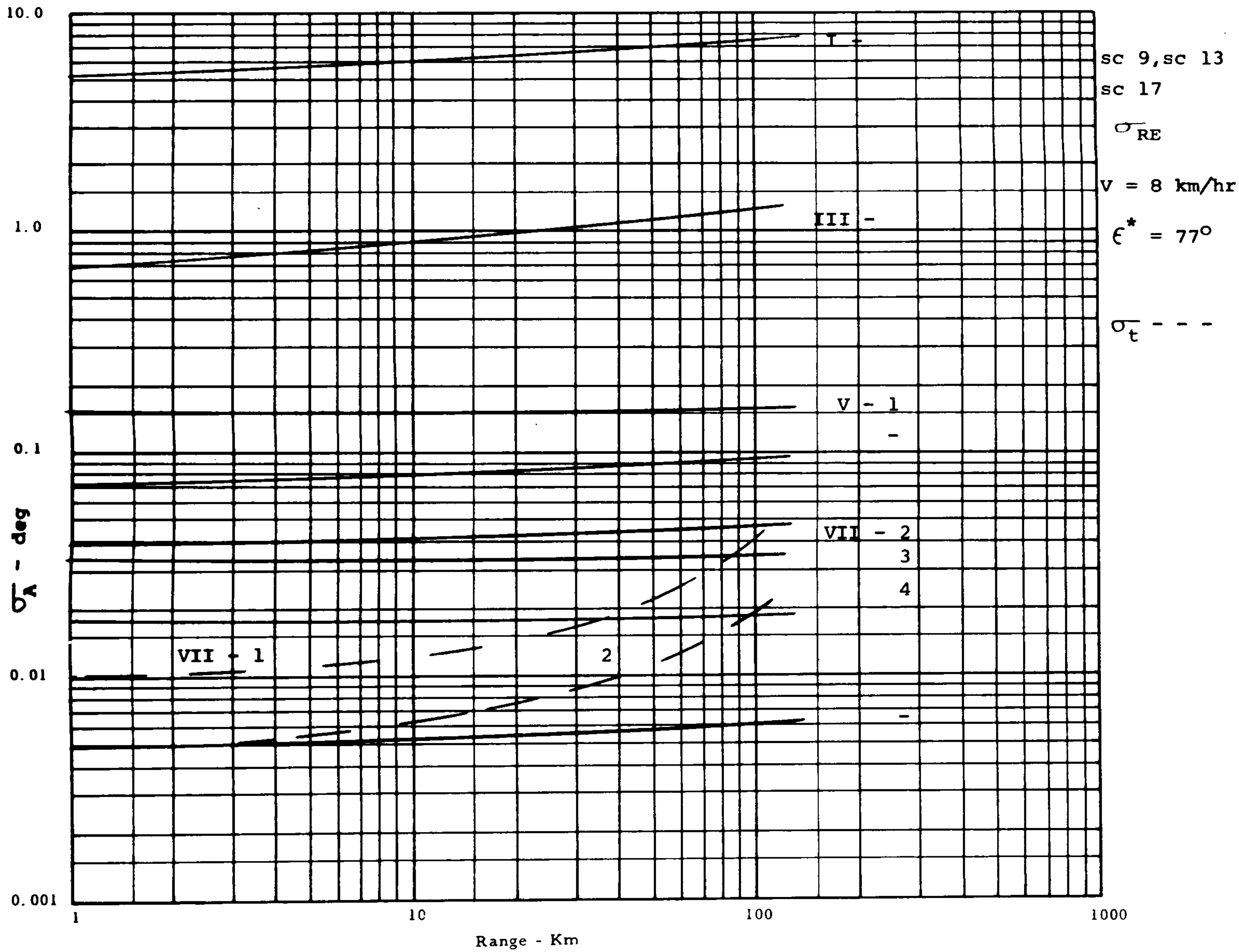


Figure 10-352 Dead Reckoning 3σ Heading Error—Ephemeris, Timer

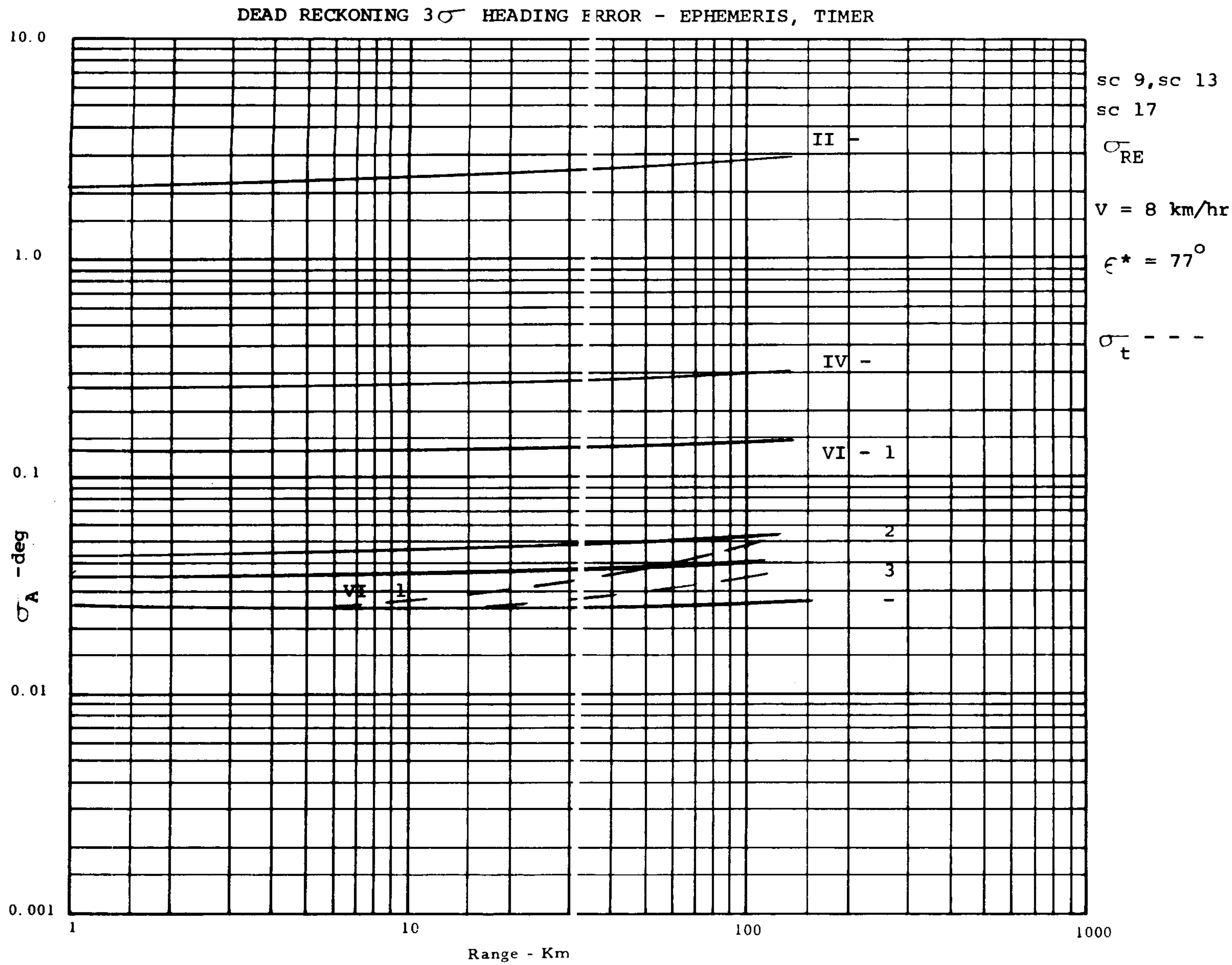


Figure 10-353 Dead Reckoning 3σ Heading Error—Ephemeris, Timer

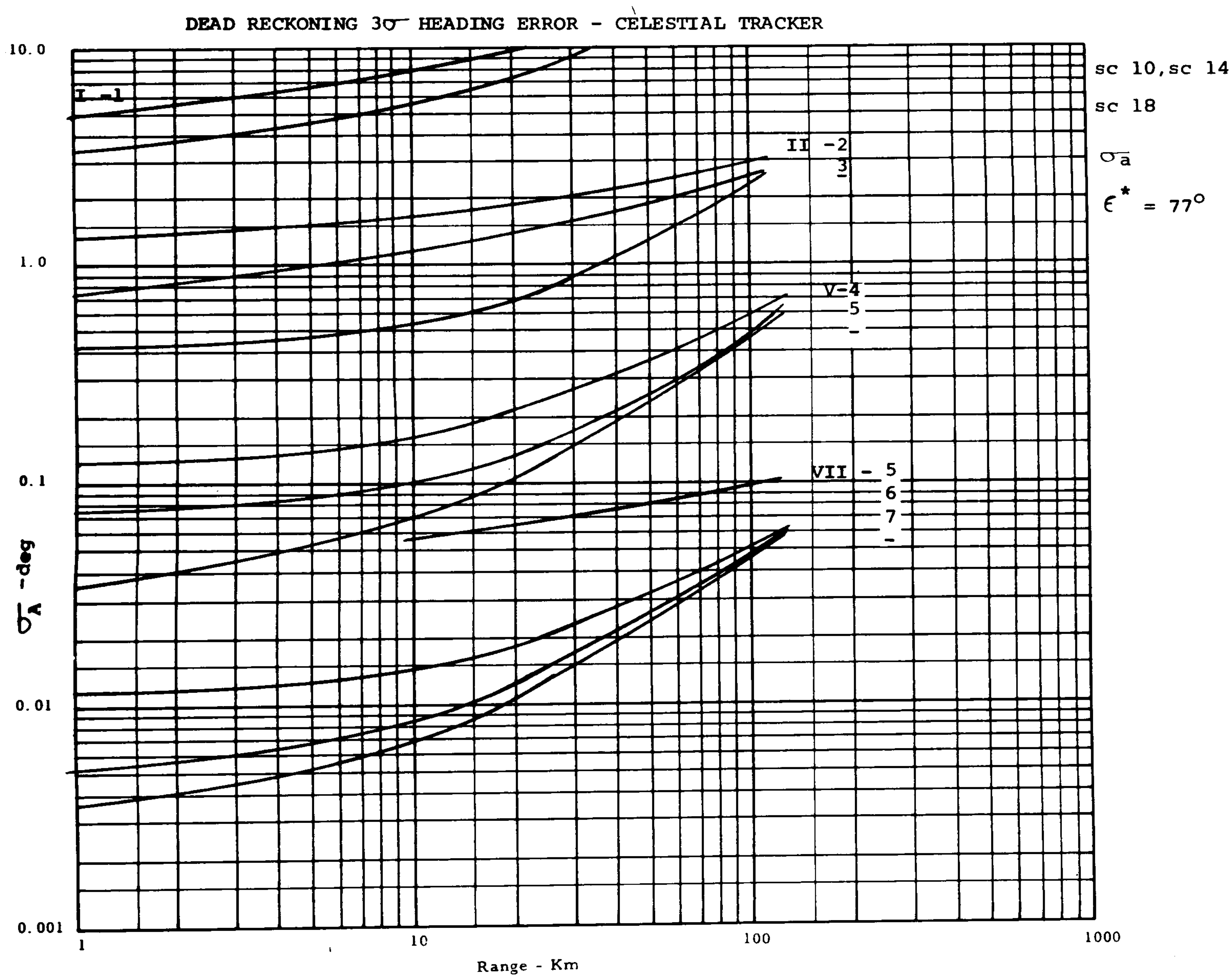


Figure 10-354 Dead Reckoning 3σ Heading Error—Celestial Tracker

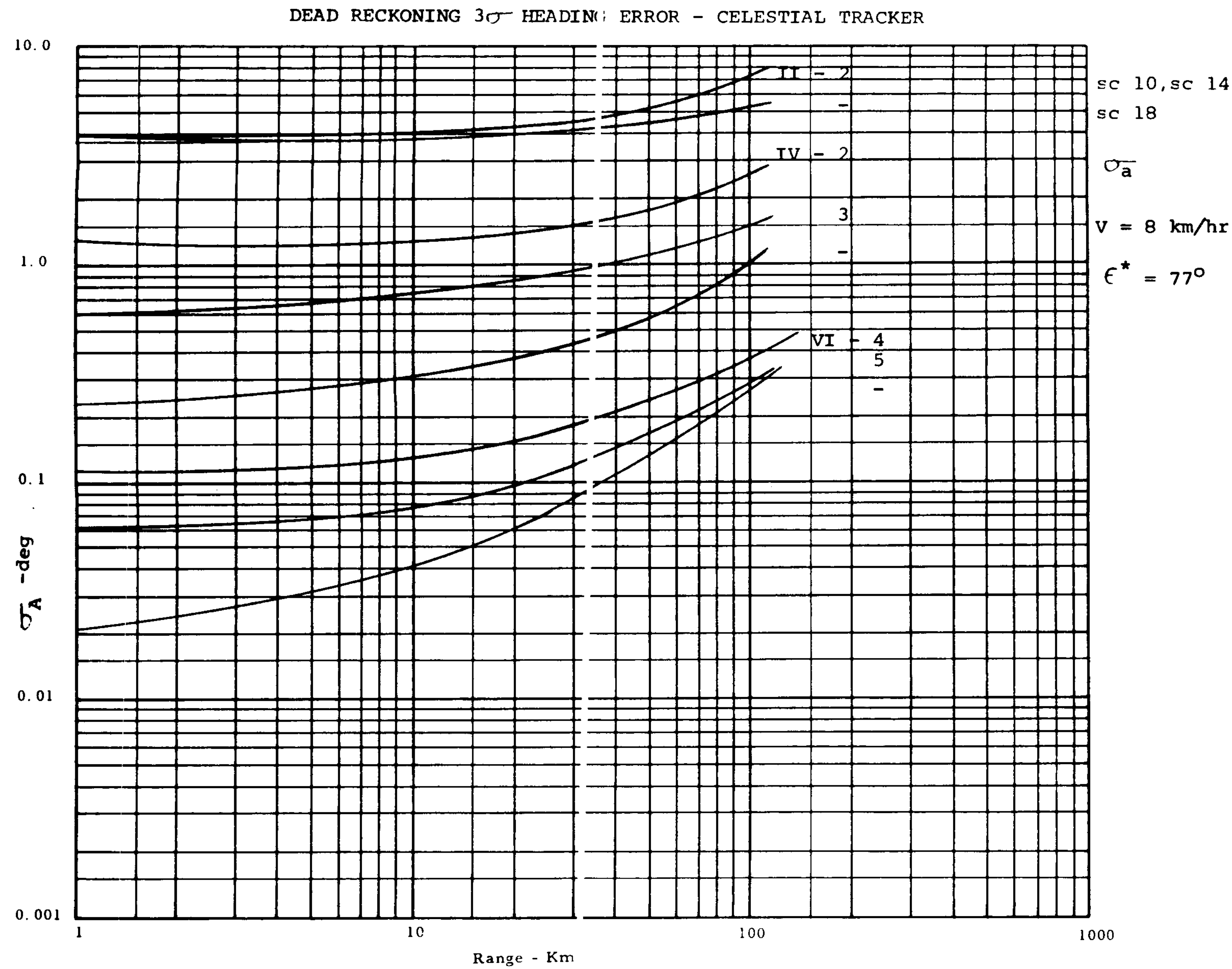


Figure 10-355 Dead Reckoning 3σ Heading Error—Celestial Tracker

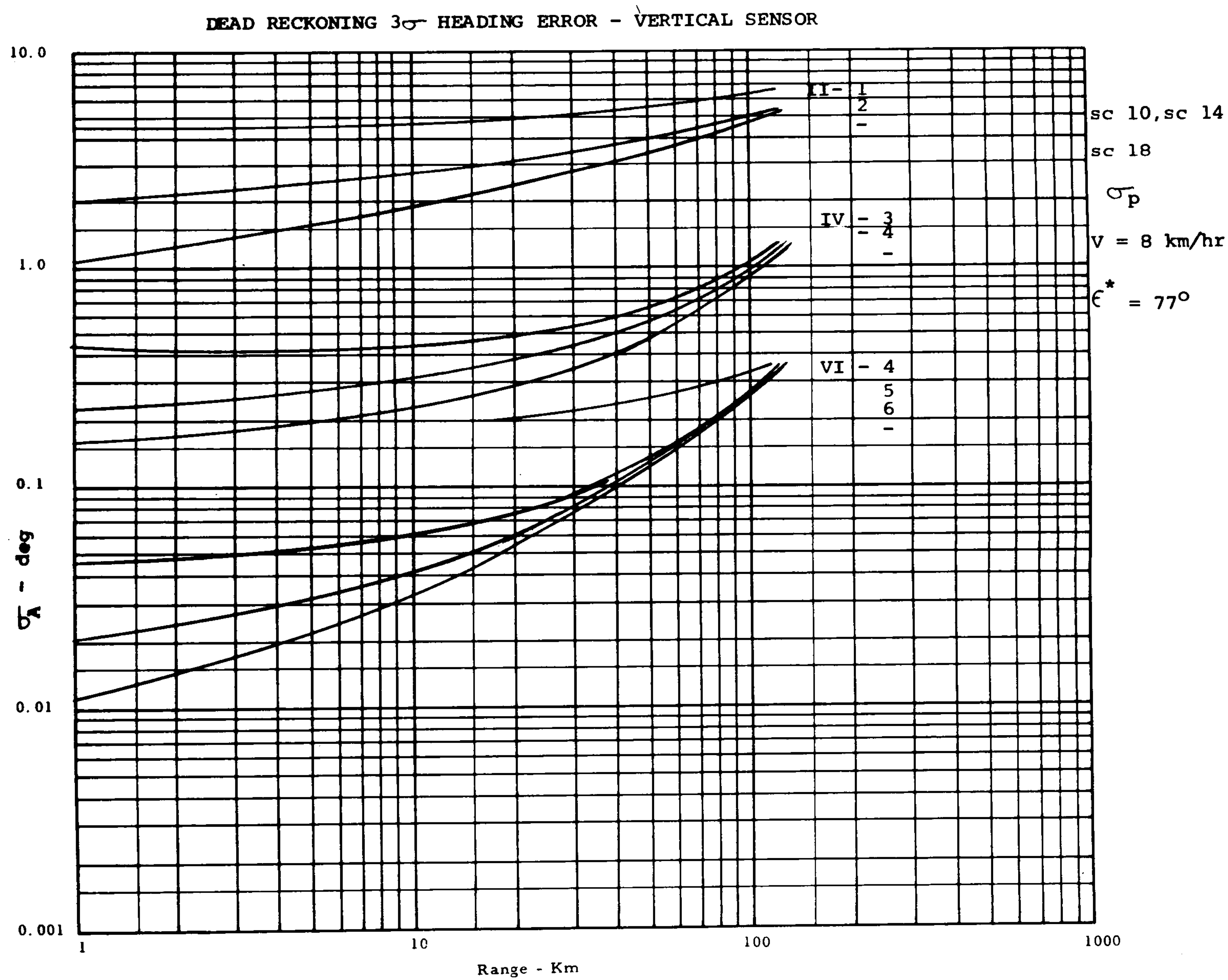


Figure 10-356 Dead Reckoning 3σ Heading Error—Vertical Sensor

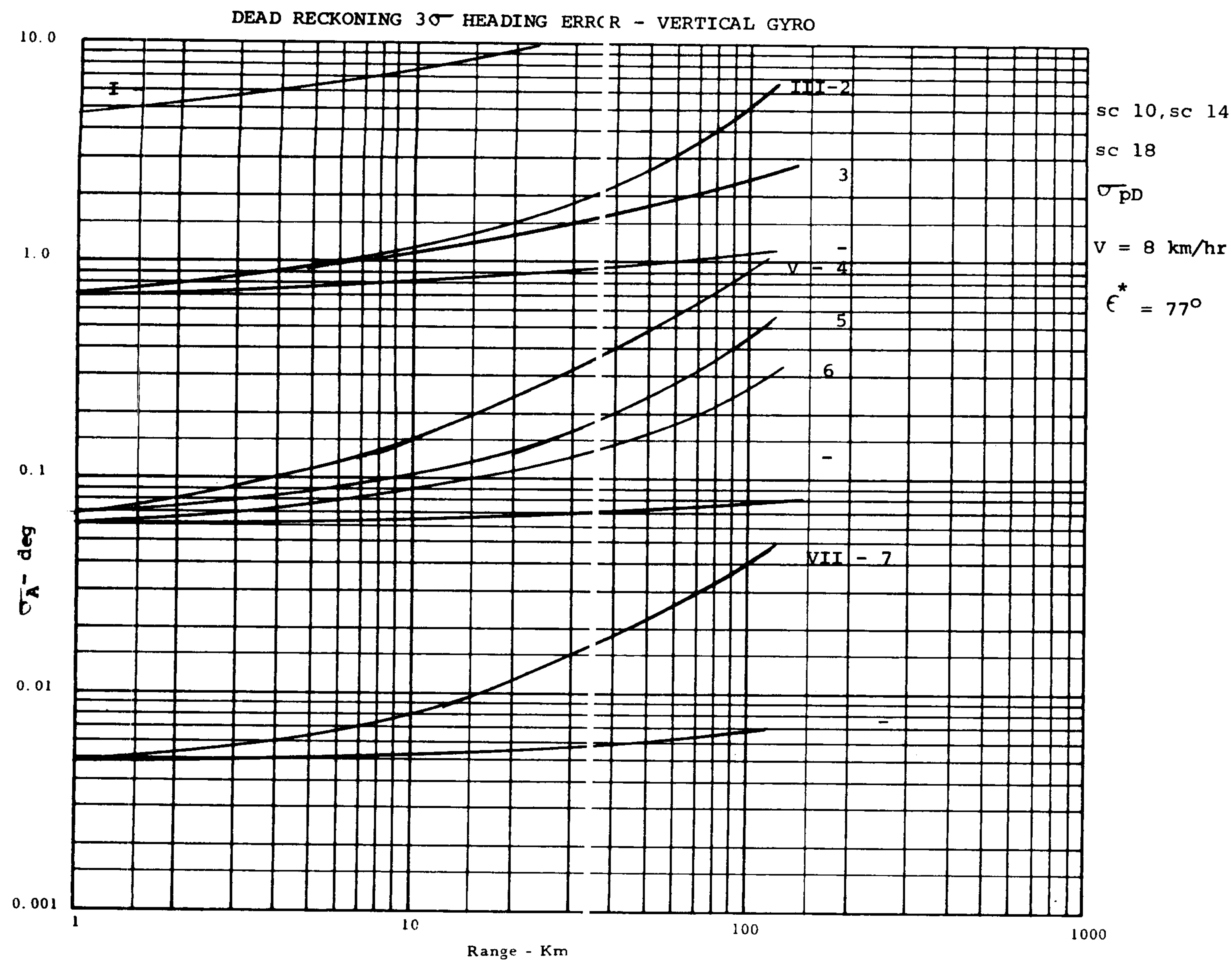


Figure 10-357 Dead Reckonin; 3σ Heading Error—Vertical Gyro

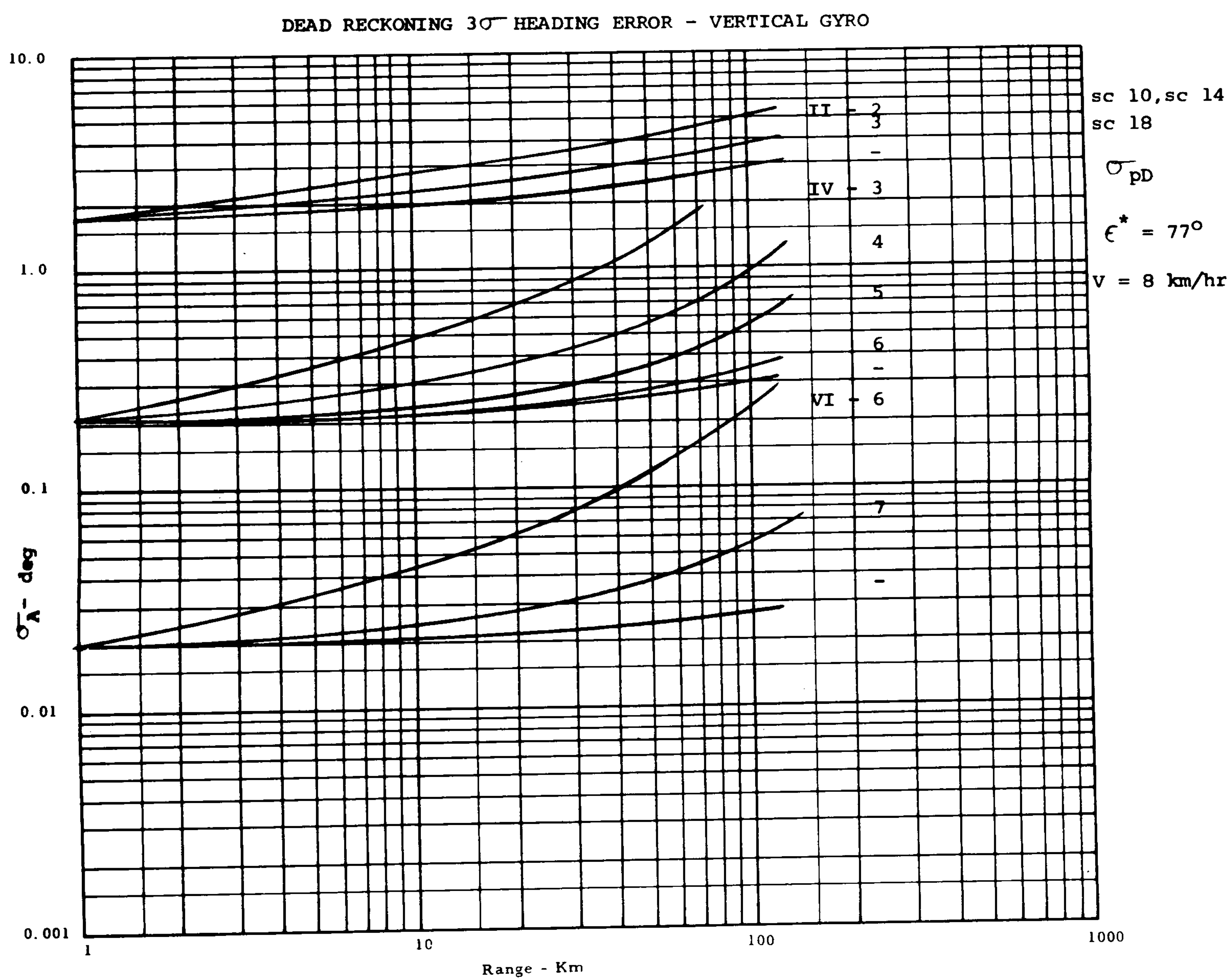


Figure 10-358 Dead Reckoning 3σ Heading Error—Vertical Gyro

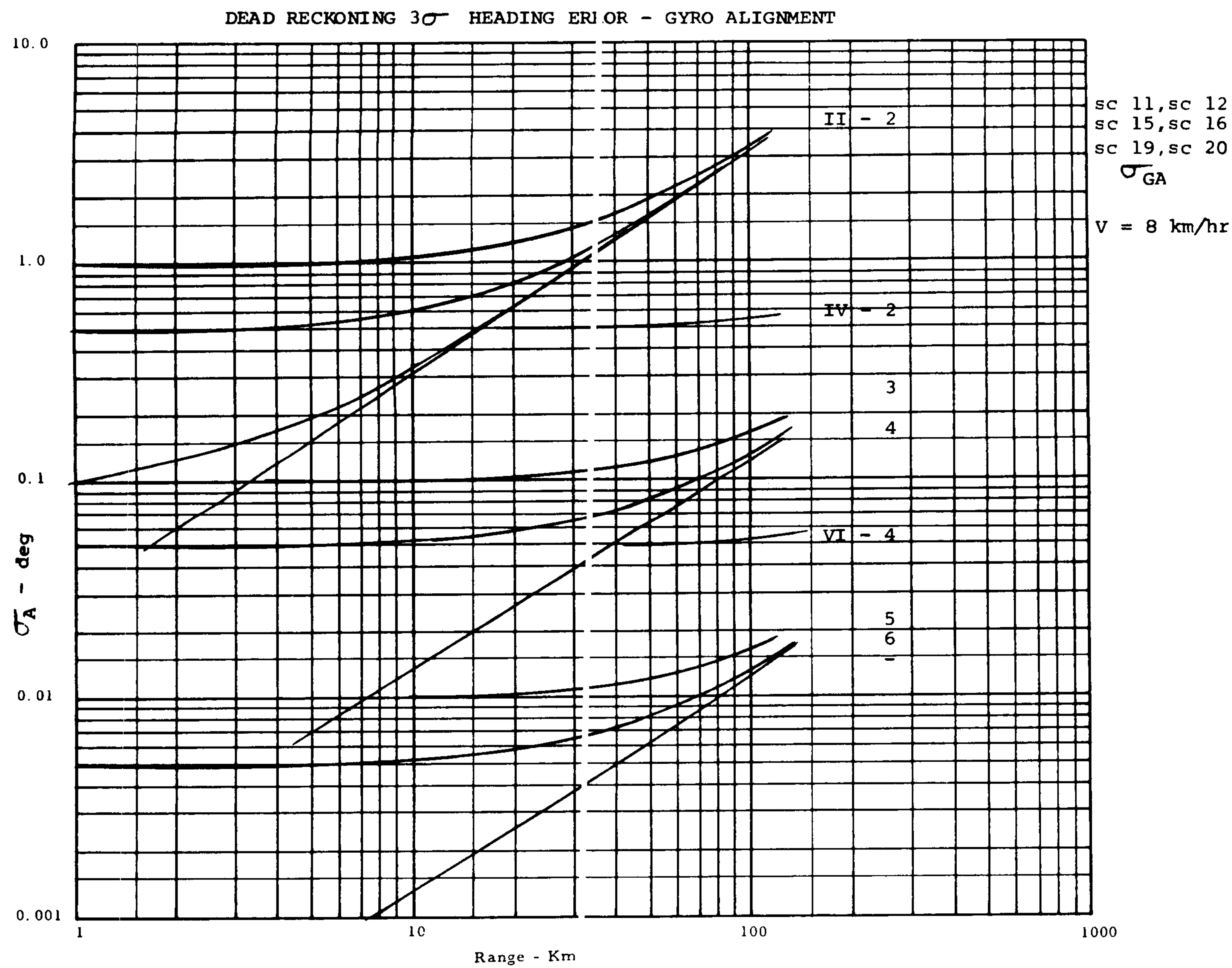


Figure 10-359 Dead Reckoning 3σ Heading Error—Gyro Alignment

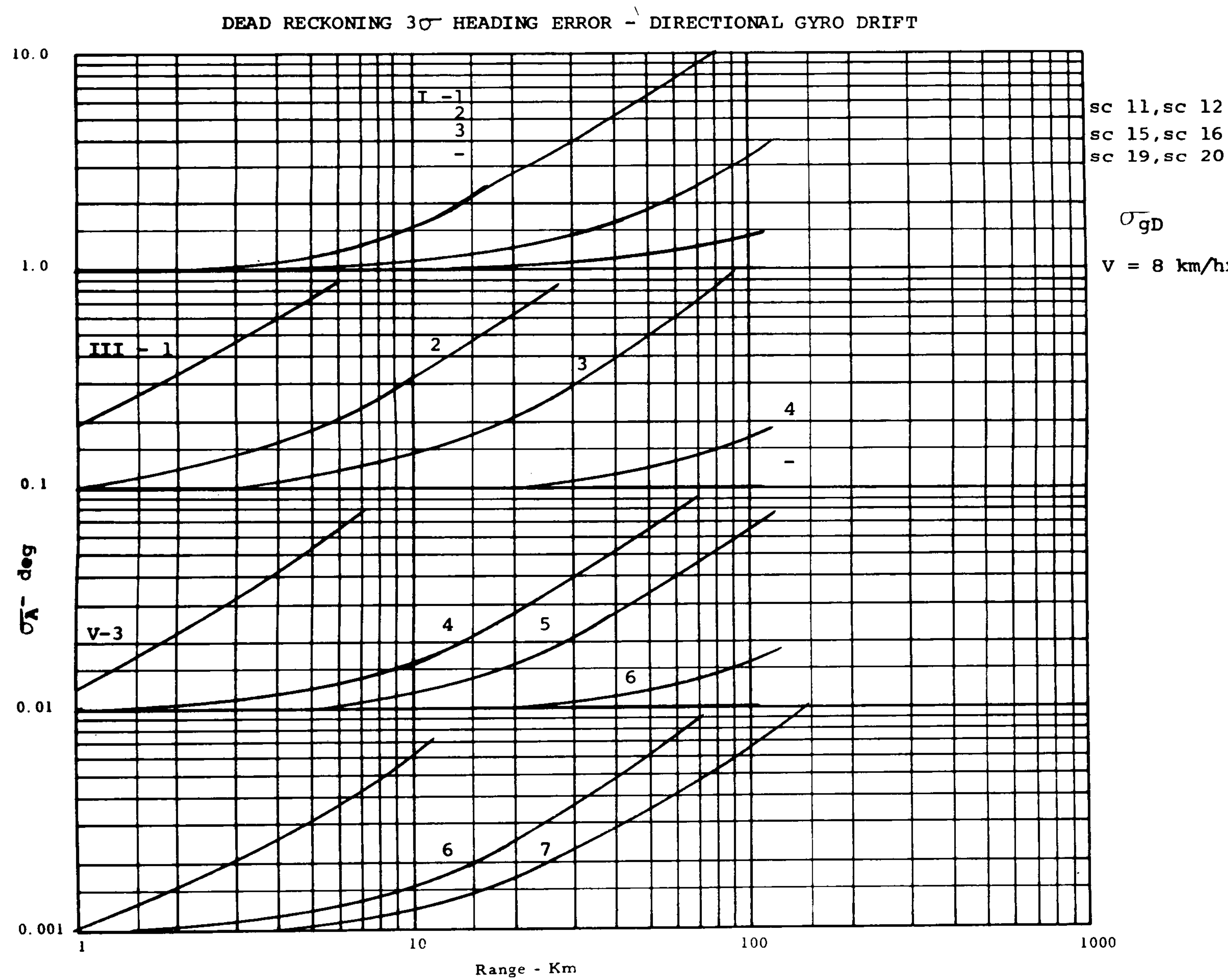


Figure 10-360 Dead Reckoning 3σ Heading Error—Directional Gyro Drift

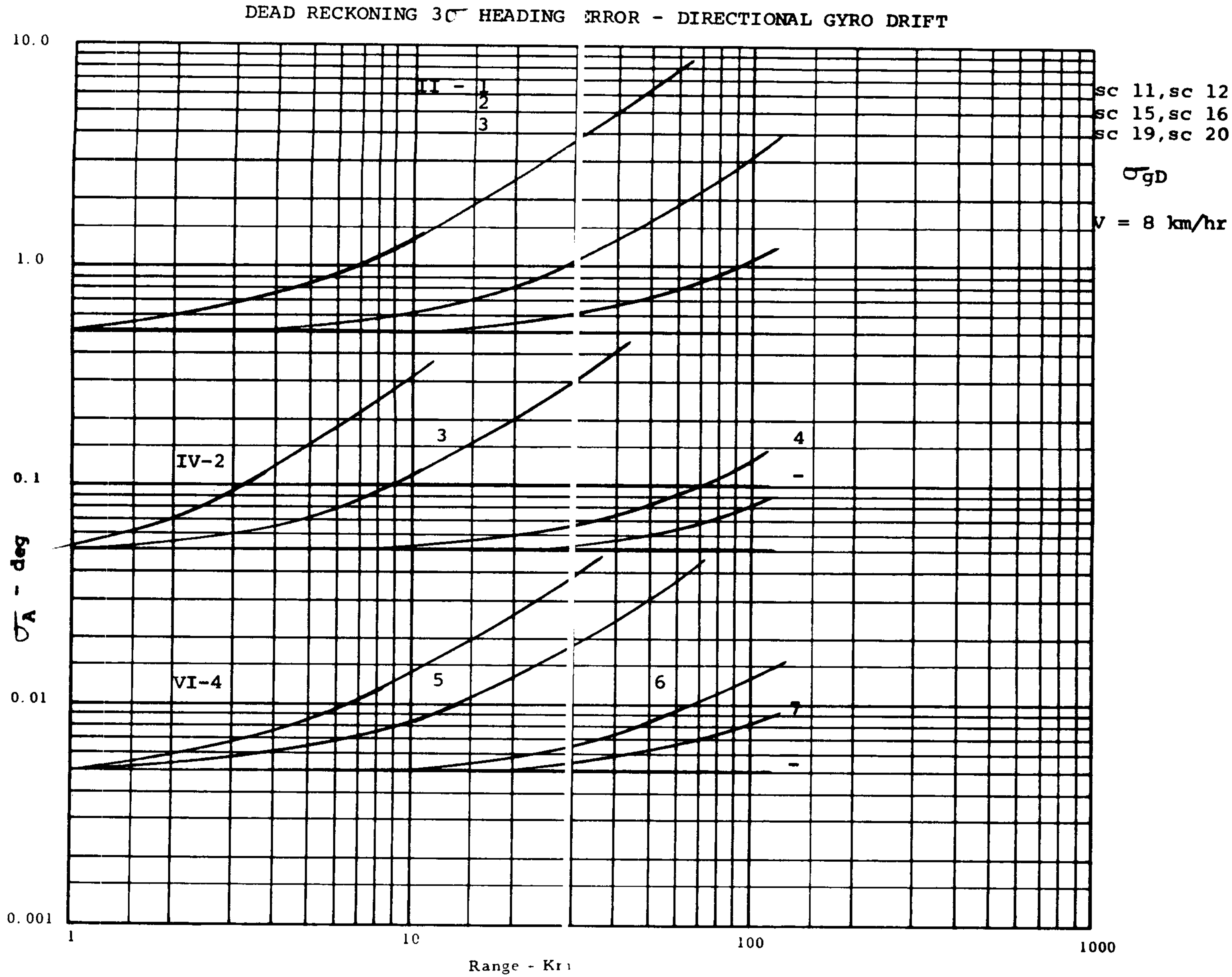


Figure 10-361 Dead Reckoning 3σ Head Error—Directional Gyro Drift

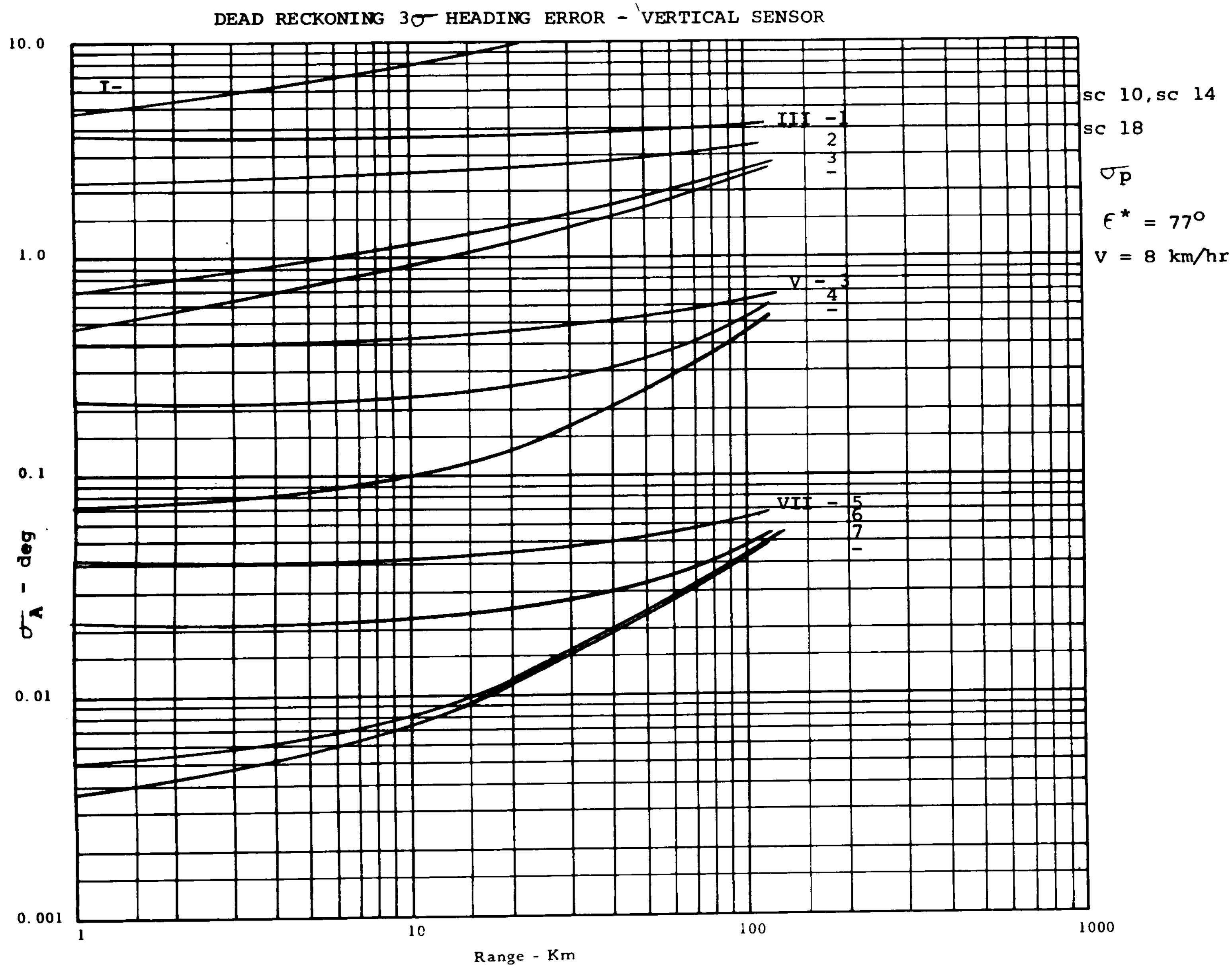


Figure 10-362 Dead Reckoning 3σ Heading Error—Vertical Sensor

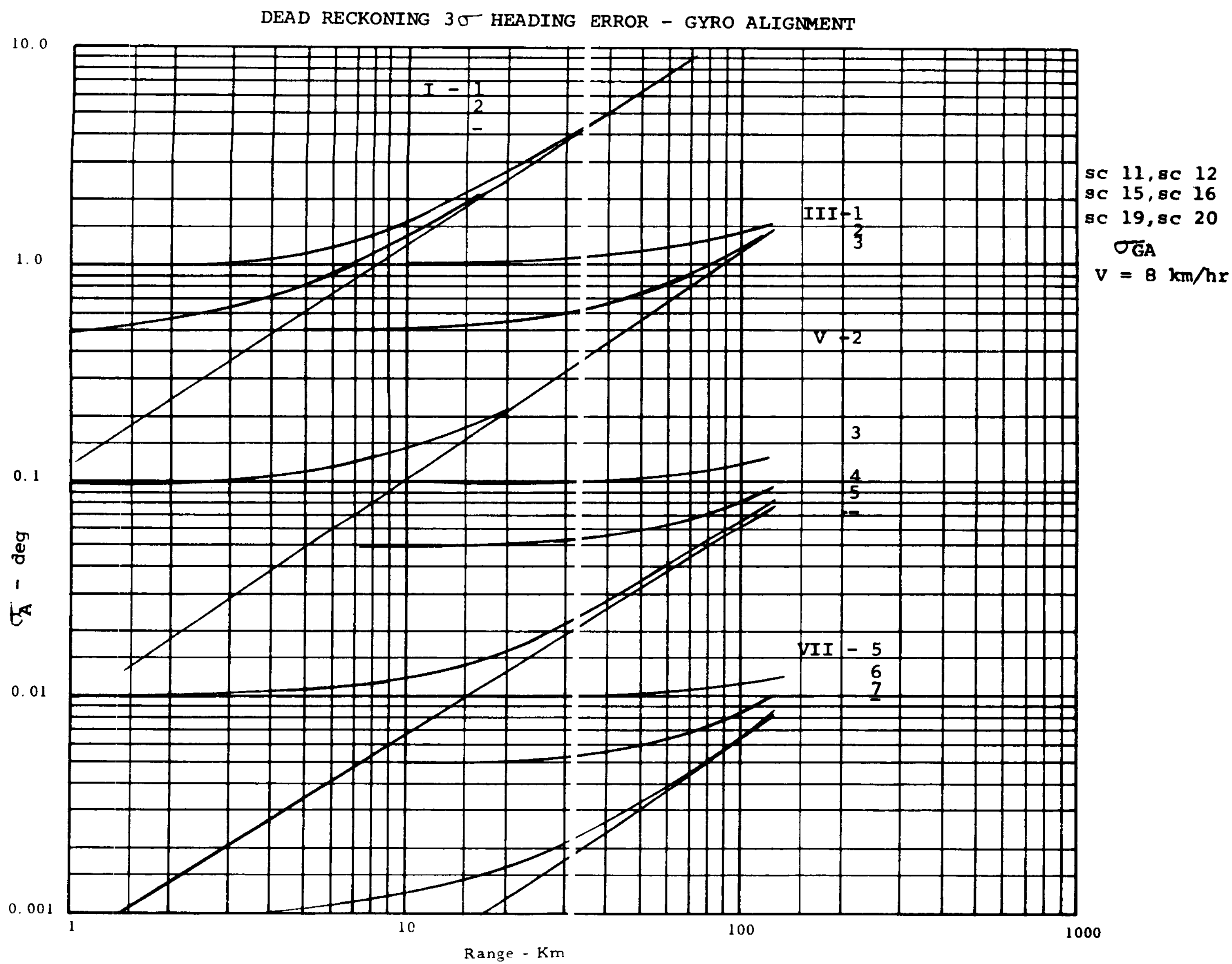


Figure 10-363 Dead Reckoning 3σ Heading Error—Gyro Alignment

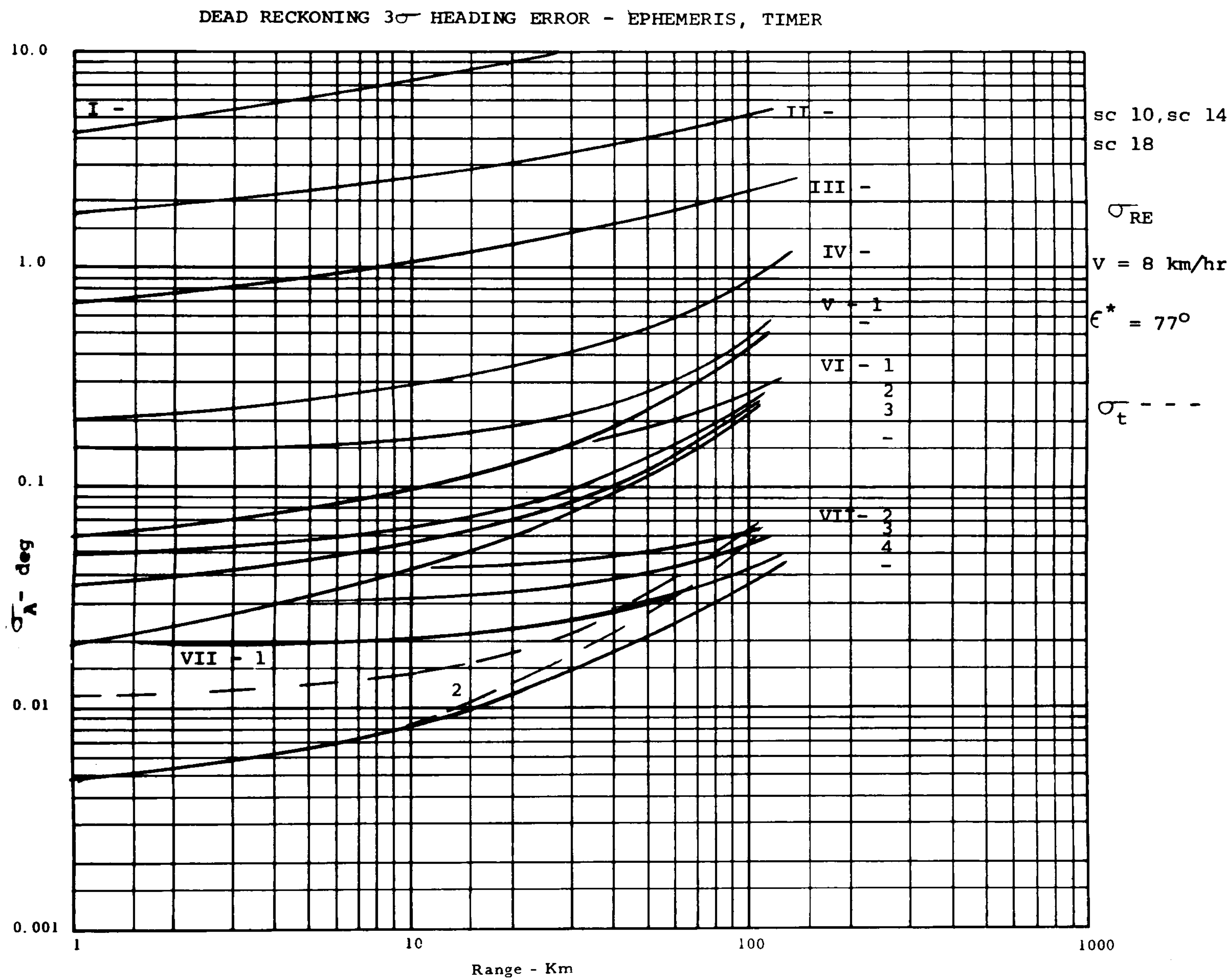


Figure 10-364 Dead Reckoning 3σ Heading Error—Ephemeris, Timer

SECTION 11

DEAD RECKONING SENSITIVITY PERFORMANCE DATA

The performance of a navigation sensor or element can be a function of the complete navigation system and the parameters which simulate the lunar roving vehicle mission. The performance of a navigation sensor is defined by the 3σ vehicle position error, altitude error, or heading error, that is coupled into the system by the sensor inaccuracies; and the position and heading errors form the performance index with which to evaluate sensor performance.

This sensitivity study shows the degradation of component performance due to variations in the postulated mission parameters, mission durations and instrumentation conditions. Section 4, Vol I introduced the operational dependence and this Section presents the numerical data. The results of the study also supplement the dead reckoning performance data so that a wider range of parametric lunar vehicle missions can be analyzed by a user applying the data.

The critical variables which affect the dead reckoning performance data of the lunar navigation sensors and which form the basis of the sensitivity study include the mission parameters selenographic region, vehicle velocity, terrain characterization factors, time delays, and instrumented dead reckoning concepts without vertical sensors, or without ephemeris calculations. Sensor performance is assessed as a function of the above operational dependencies.

11.1 OPERATIONAL DEPENDENCE SENSITIVITY ANALYSIS

11.1.1 Mission Duration

The major factor which affects the performance of the time dependent navigational sensors is the elapsed time of mission duration. Mission duration must be defined within the context of the study parameters and particularly with respect to the utilization of the dead reckoning performance data. The mission duration is the elapsed time since a position fix, heading fix, or dead reckoning system alignment was performed and during which the dead reckoning system operates continuously. Therefore, the expression for mission duration, a random variable, is given by

$$t = \frac{\text{Total Distance Traveled}}{\text{Average Vehicle Velocity}} \qquad (11\text{-}1)$$

where

$$\text{Total Distance Traveled} = \text{Range} = \sum_{n=0}^{N} D_{n,\ n+1} \qquad (11\text{-}2)$$

$$\text{Average Vehicle Velocity} = V \triangleq$$ The nominal vehicle speed on flat terrain or with vehicle pitch angle p = 0.

Often, a more desirable expression is given by relating elapsed time to slant range of the lunar vehicle; in this case time, a random variable, is also a function of the terrain characterization factors, A_{max}, h_{max}, r_{max}.

$$t = \frac{\text{Slant Range}\left(1 + \frac{\%EDT}{100}\right)}{V} \qquad (11\text{-}3)$$

where

Slant Range = D_{on}, distance from origin o, to n the vehicle position

Percent Extra Distance Traveled = % EDT

$$\% \text{ EDT} = \frac{\left[\sum_{n=0}^{N} D_{n,\ n+1}\right] - D_{on}}{D_{on}} \times 100, \text{ or} \qquad (11\text{-}4)$$

the % distance traveled exceeding the slant range. % EDT is a random variable, a function of the terrain characterization factors. See Section 6 for the standarized lunar surface trajectory data.

From Equations 11-1 and 11-3 it is apparent that given an average vehicle velocity the position error as a function of slant range, and the lunar surface terrain characterization factors, the position error as a function of mission duration can be computed. Shown in Figures 11-1 to 11-5 are the 3σ planar position errors, and altitude errors of the velocity dependent sensors, the accelerometers, odometer, doppler radar, vertical gyro and directional gyro. The dependency of vehicle position errors upon timer errors and variations in vehicle velocity are given in Section 10.2

The data have been plotted as a function of vehicle range where the terrain characterization factors are

$$A_{max} = 90^{\circ}$$

$$h_{max} = 0.45 \text{ km}$$

$$r_{max} = 13^{\circ}$$

$$D_j = 2.0 \text{ km}$$

Refer to Figure 6-14, Section 6, to determine the percent extra distance traveled.

$$\% \text{ EDT} = 15\%.$$

Therefore, the following performance data can be replotted as a function of vehicle slant range or mission duration depending on the aims of the analyst.

Typical design point error parameters are selected for each sensor or navigational aid, and are identified by the key for each figure.

If the sensor position error is dependent upon the total dead reckoning subconcept, then the subconcept parametric variations are included. For example, the performance data, as a function of vehicle velocity, are given for the vertical gyro drift error in subconcepts sc 10 and sc 12.

Although the selected design point error parameters limit the completeness of the data display, an excellent approximation to the sensor position error for other 3σ errors and varied operational dependencies is given by assuming linearity or constructing auxiliary data plots and interpolating between given data points. Thus, the performance data given below summarize, supplement, and complete the previous data.

If the performance data of a navigational sensor are not included in the following figures, then the navigational aid is independent of mission duration.

11.1.2 Selenographic Region

Two operational dependencies are associated with the selenographic region. The first is the type of surface terrain, the severity and density of the surface obstacles, which transform into lunar roving vehicle maneuvers during the dead reckoning traverse. The second factor is the vehicle selenographic region of operation relative to a celestial observable. The parameters which simulate these operational dependencies over the ensemble of trajectories are %EDT and observable true elevation angle ϵ^*.

The correlation between mean %EDT and the terrain factor A_{max} is summarized from Section 6.

%EDT	A_{max}
50	150°
30	120°
15	90°
6.0	60°
0.0	0.0°

To relate the true elevation angle ϵ^* to the range between vehicle position and observable subpoint, refer to Section 6, Vol I. The true elevation angle $\epsilon^* = 45^o$ or 30^o or 10^o etc., does not imply that the true elevation angle is fixed at the specified value for the entire dead reckoning traverse. On the contrary, the angle stated is the initial nominal elevation angle, and varies during the vehicle trajectory. The angle variation depends on the position of the vehicle and the apparent motion of the celestial body (earth, sun, or star).

The following design point data of Figures 11-6 to 11-13 supplement the standard dead reckoning performance data and by selectively applying linearity, choosing identical parametric conditions, and consulting the standardized trajectory data, an entire family of design point concepts can be analyzed.

The sensors or navigational elements which are independent of the selenographic region of operation are omitted in the following data, or considered as a single error response. (See the accelerometer, doppler radar, and odometer 3σ position errors.) Although many sensors appear to be independent of %EDT when the position error is plotted versus slant range, the position error will show variations when plotted as a function of range owing to %EDT.

11.1.3 Time Delays

The conventional dead reckoning traverse is initiated at a set of initial coordinates, and proceeds to a given mission objective or destination. The significance of the destination, the homing range about the destination, and the mission objectives are beyond the scope of the study and can only be simulated as selected ranges of parameters. The parameter ranges are subject to the interpretation of the analyst using the data handbook and a wide range of lunar surface exploration and scientific missions can be analyzed.

As stated however, the dead reckoning mission is simulated by traversing from an initial point to the destination point over an ensemble of possible surface trajectories and average velocites. To supplement this presentation and to simulate the effect of performing auxiliary scientific, exploratory, maintenance, and surveillance functions from aboard a non-moving vehicle at arbitrary points of the dead reckoning traverse, time delays are considered.

At the end of each incremental leg of the dead reckoning traverse, a sample time delay was "drawn" from the computer random number generator. The density function of the time delay is gaussian with 3σ limits set and truncated by $\pm\ \Delta t_{max}$.

The sensor performance data as a function of slant range and the time delay parameter are shown in Figures 11-14 and 11-15. The sensors affected by the time delay are the doppler radar, accelerometers and the computer integrators, the directional and vertical gyro. Ephemeris and timer variations are not shown.

11.1.4 Position Fix Error

The dead reckoning subconcepts are in general influenced by the initial position fix error. The celestial tracking-heading reference techniques, when used in an absolute coordinate system, require the vehicle coordinates to compute the vehicle heading from the established analytic heading reference. Similarly DG and VG torquing commands are functions of the vehicle selenocentric position. Therefore, an error in position is transformed to true heading and vehicle position errors.

The sensitivity of the dead reckoning position error to initial position fix errors is shown in Figure 11-16. The effect is of second order and the initial position fix error dominates the total vehicle position error. The heading error response is also shown in Figure 11-17 for the celestial tracking techniques.

Since the position fix term completely dominates the components of the position error ellipsoid for the inertial subconcepts, it is sufficient to use the position fix error for the entire traverse.

11.1.5 Subconcept Implementation

Several dead reckoning subconcepts, depending upon the accuracy constraint of the lunar navigation mission, can be implemented without a vertical reference, or without ephemeris calculations. The output of such a system configuration is simply a set of latitude, longitude or north, east coordinates since there will be no altitude channel. Since position is basically computed from a set of body fixed coordinates, a position error component is introduced. The sensitivity of subconcept performance is shown in the Figures 11-18 and 11-19 for subconcepts sc 10, sc 12, and sc 19, instrumented without vertical sensors.

The output error response shown is the result of an ensemble of typical lunar surface trajectories; the terrain characterization factors were

$$D_j = 2 \text{ km}$$

$$A_{max} = 90^o$$

$$h_{max} = 0.45\text{km}$$

$$r_{max} = 13^o$$

The response of the celestial subconcept sc 10 is shown as a function of selenographic region, designated by ϵ_i^*. Also the sensitivity of the celestial tracking subconcepts to no ephemeris calculations is shown in Figure 11-20.

The following error outputs are the position errors solely attributable to the missing navigational elements. All remaining system errors are zero.

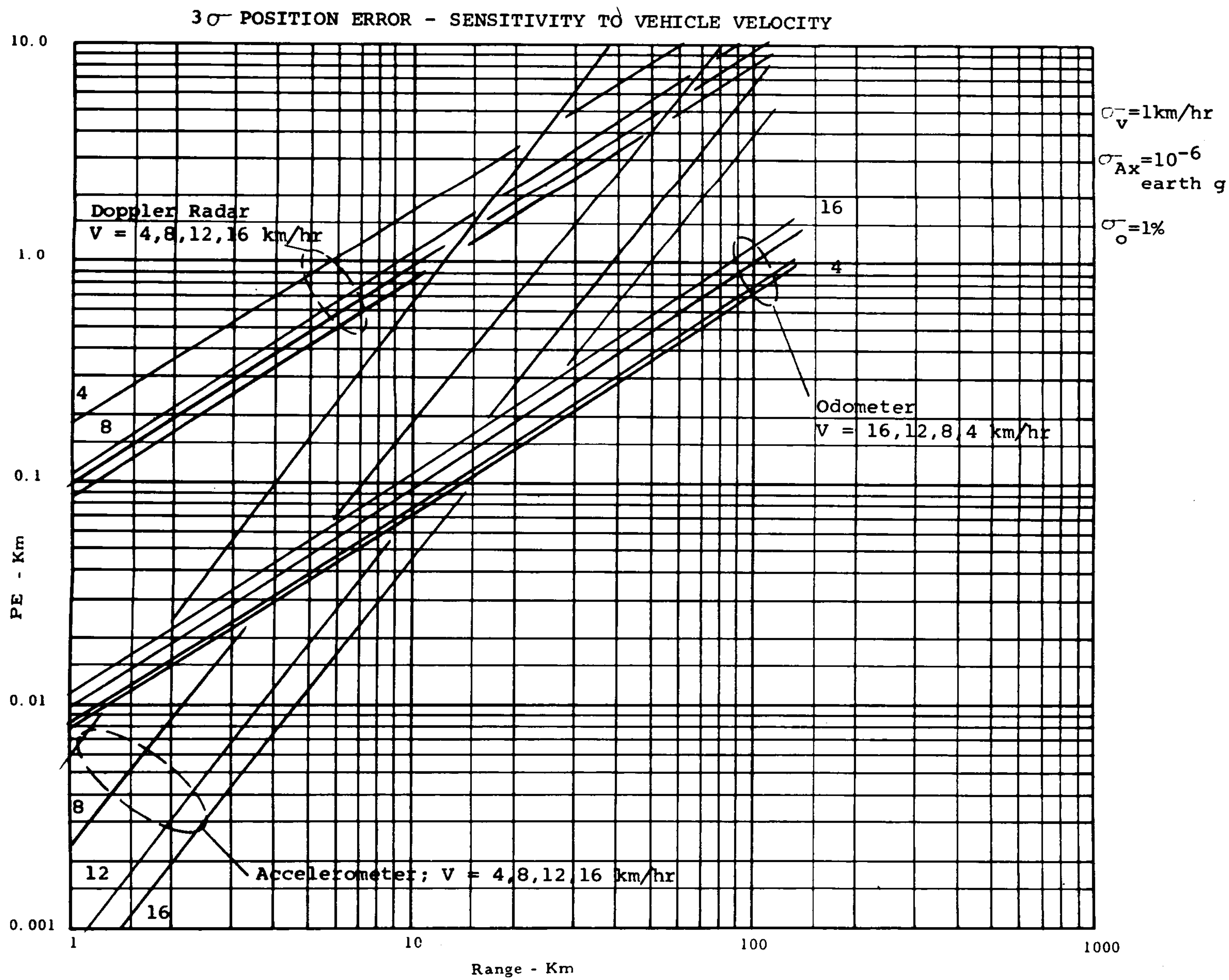


Figure 11-1 3σ Position Error—Sensitivity to Vehicle Velocity

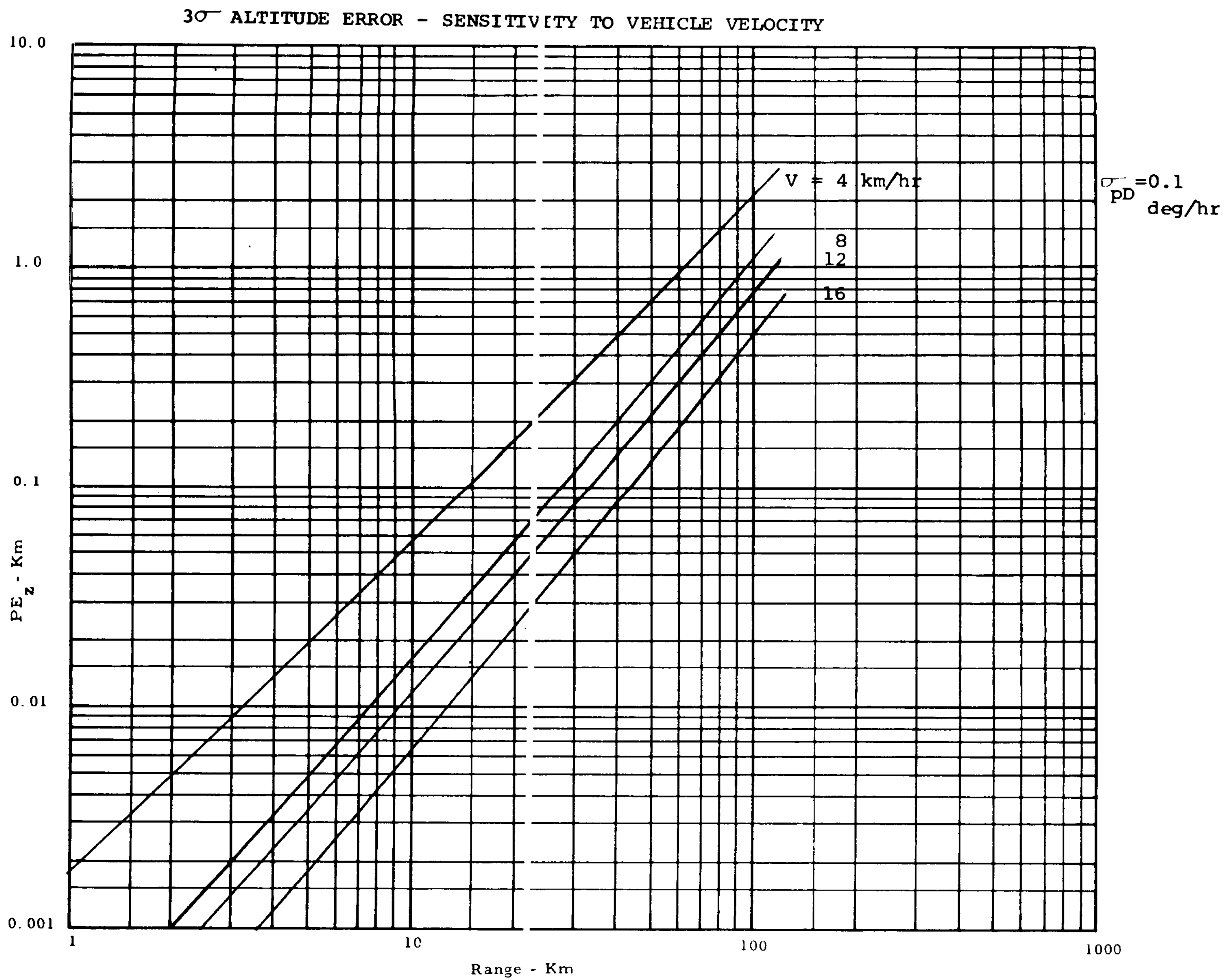


Figure 11-2 3σ Altitude Error—Sensitivity to Vehicle Velocity

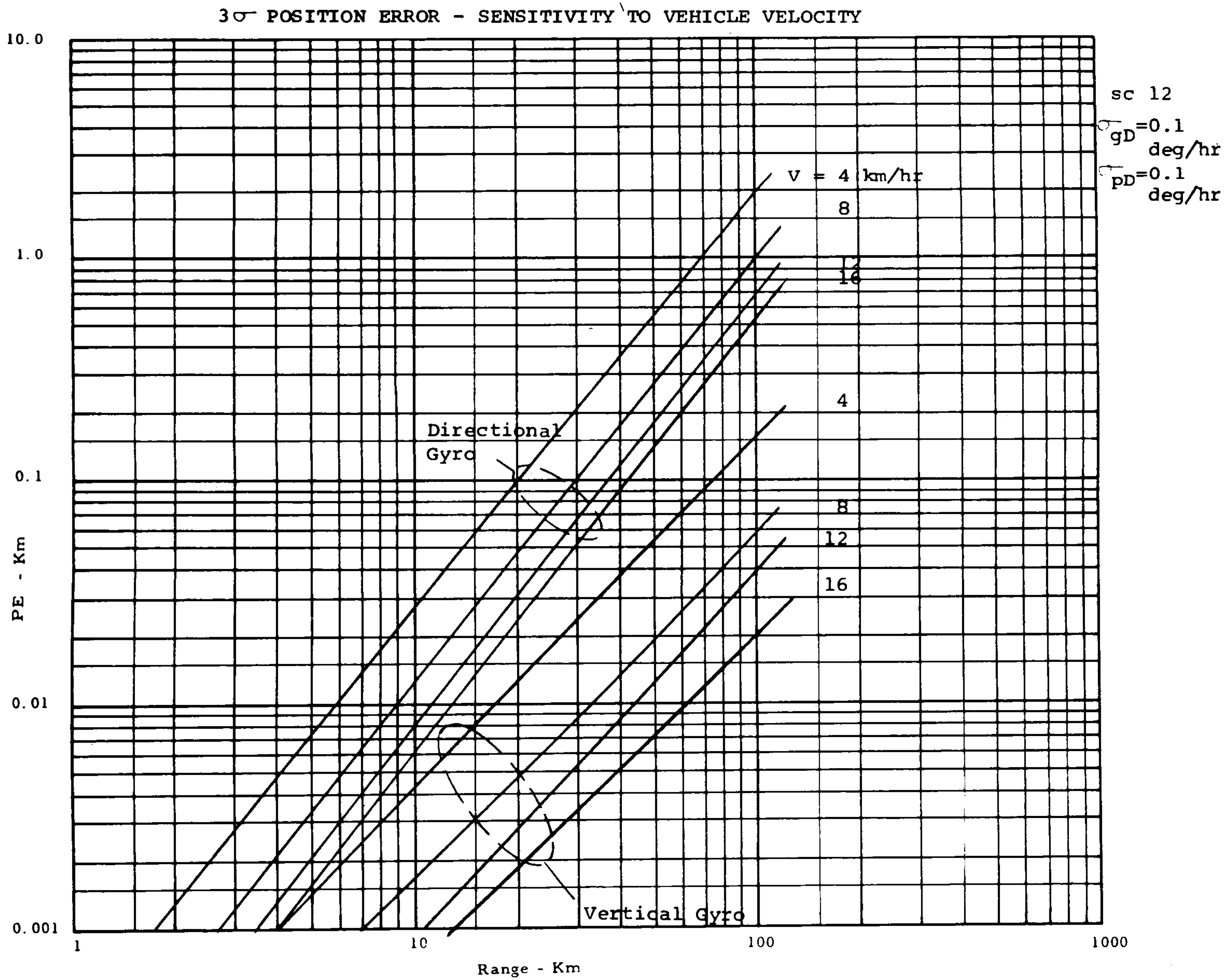


Figure 11-3 3σ Position Error—Sensitivity to Vehicle Velocity

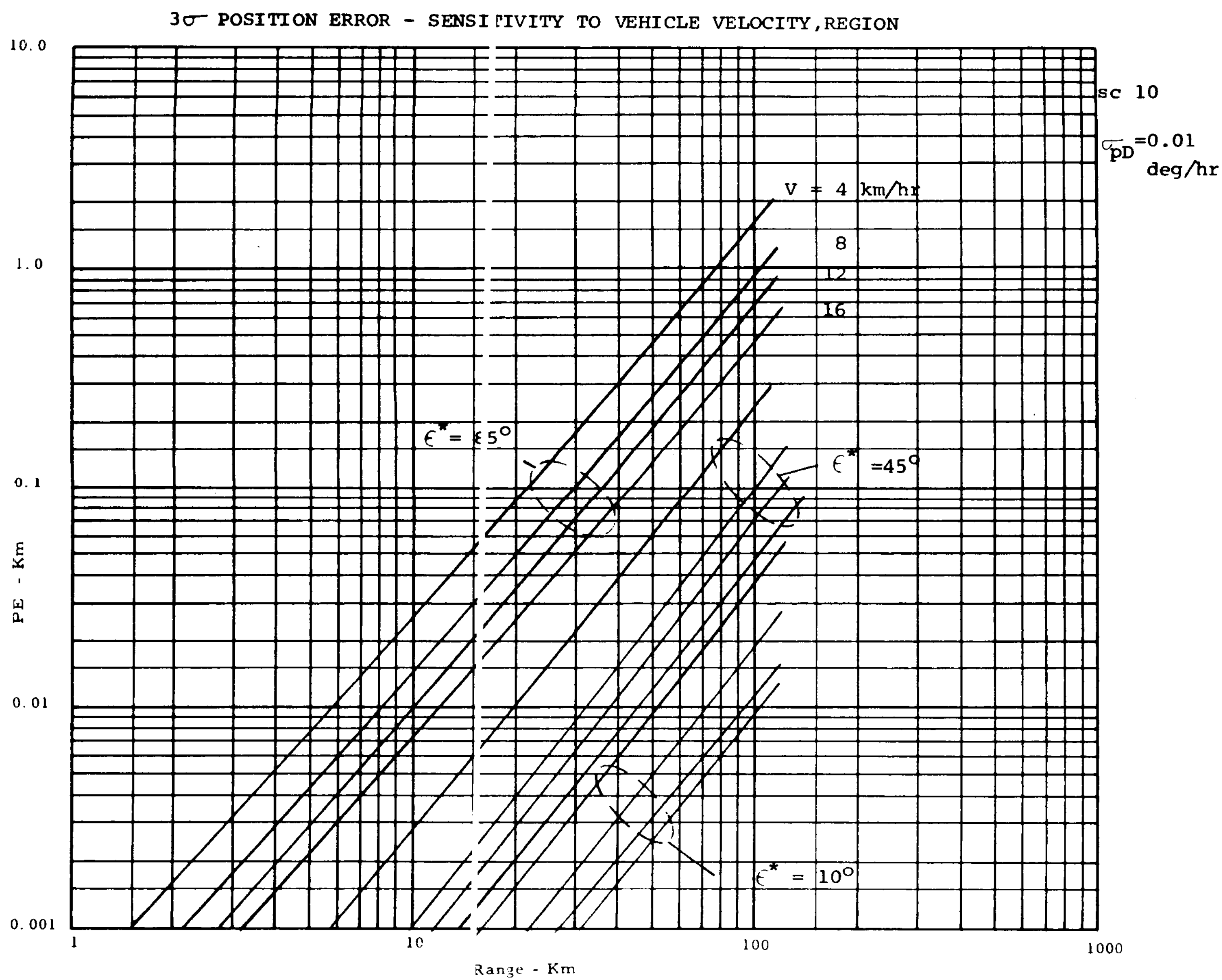


Figure 11-4 3σ Position Error—Sensitivity to Vehicle Velocity, Region

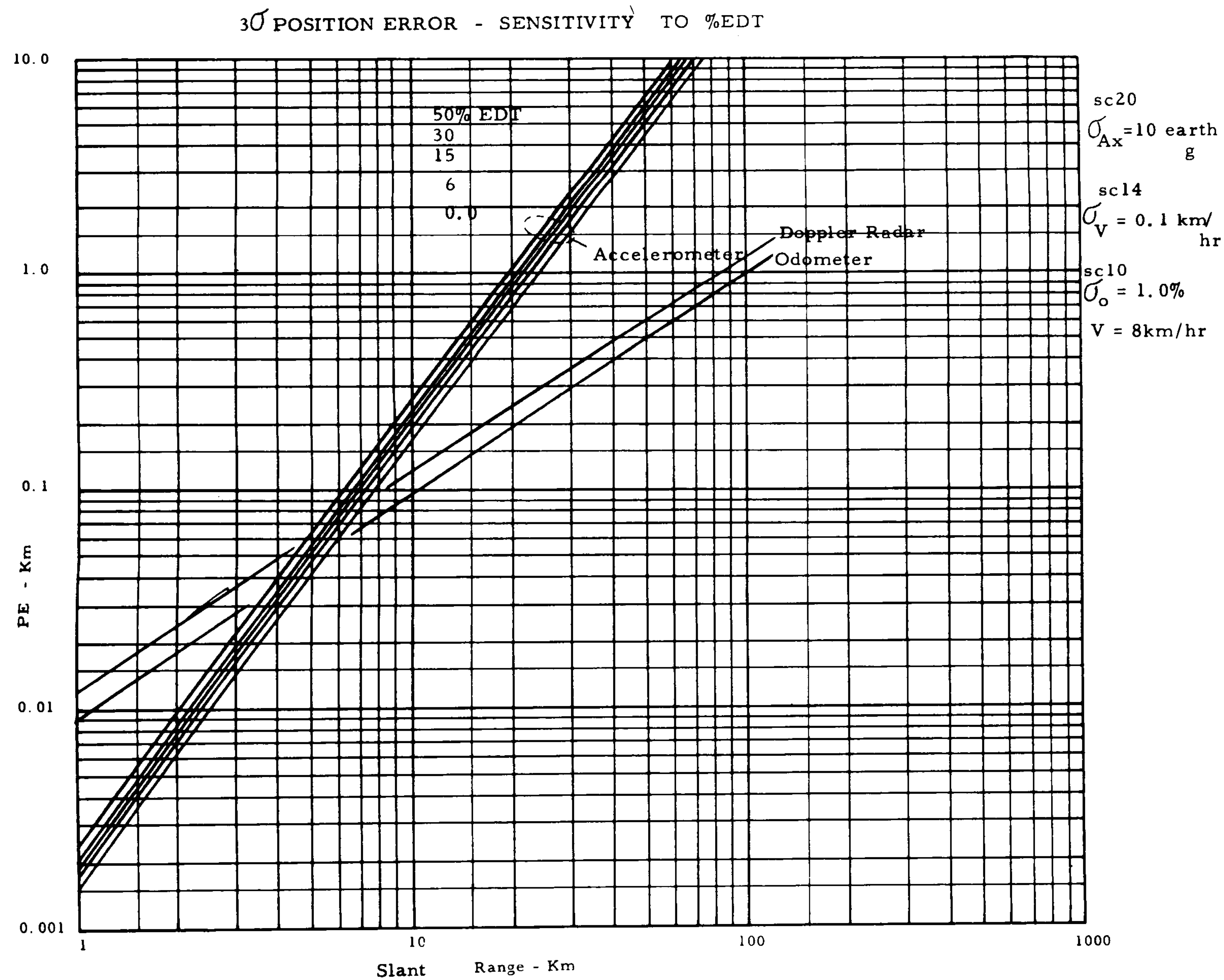


Figure 11-5 3σ Position Error—Sensitivity to %EDT

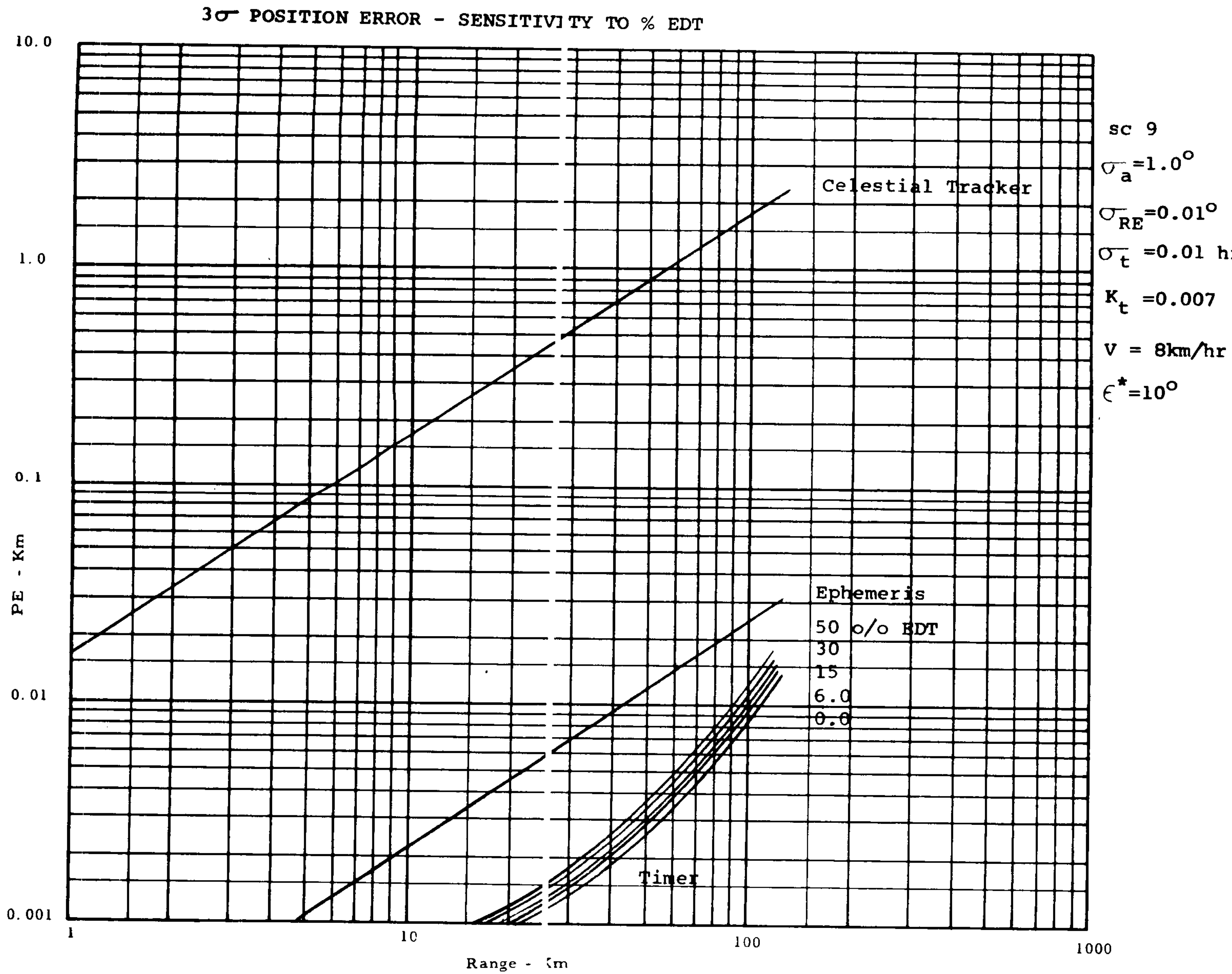


Figure 11-6 3σ Position Error—Sensitivity to % EDT

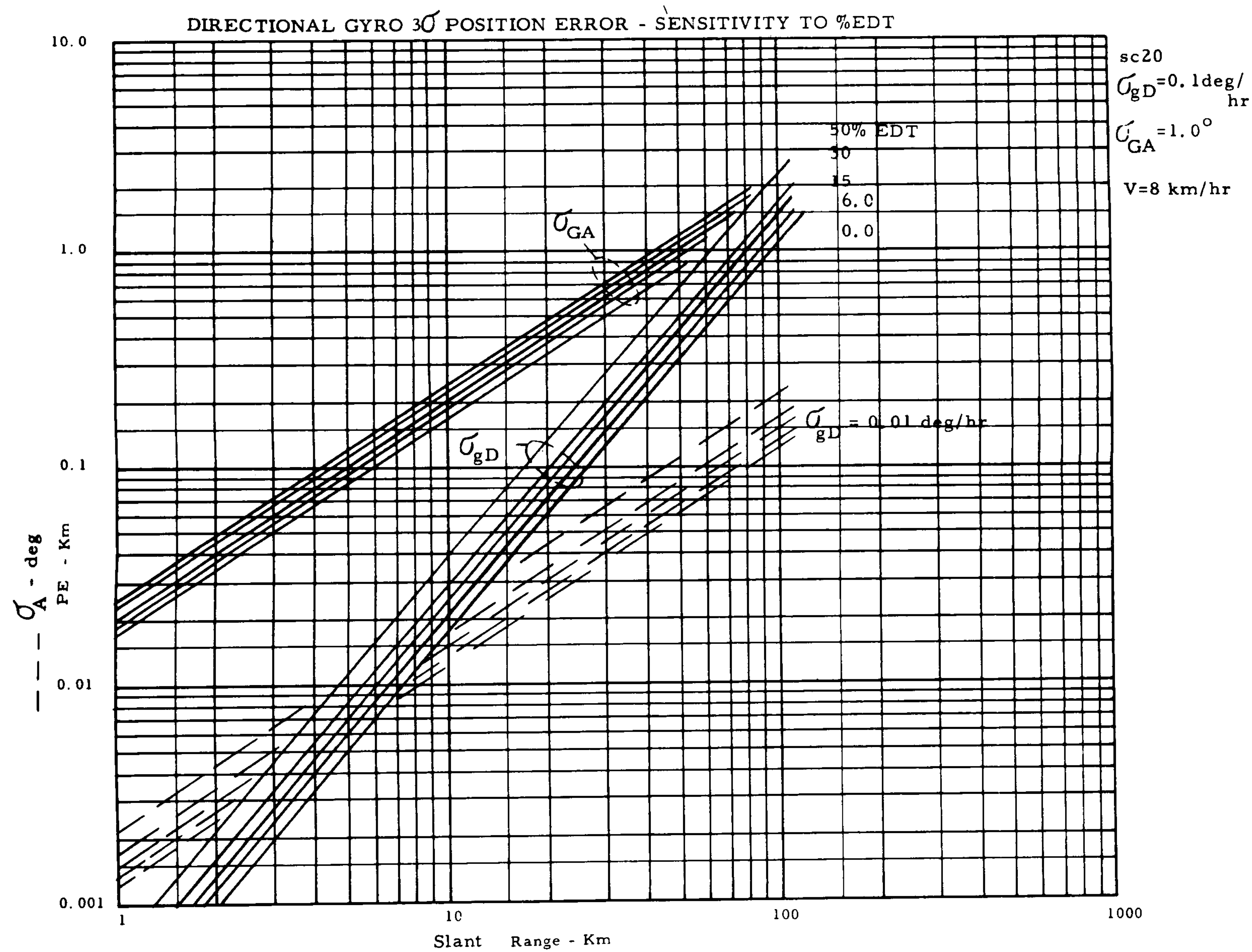


Figure 11-7 Directional Gyro 3σ Position Error—Sensitivity to % EDT

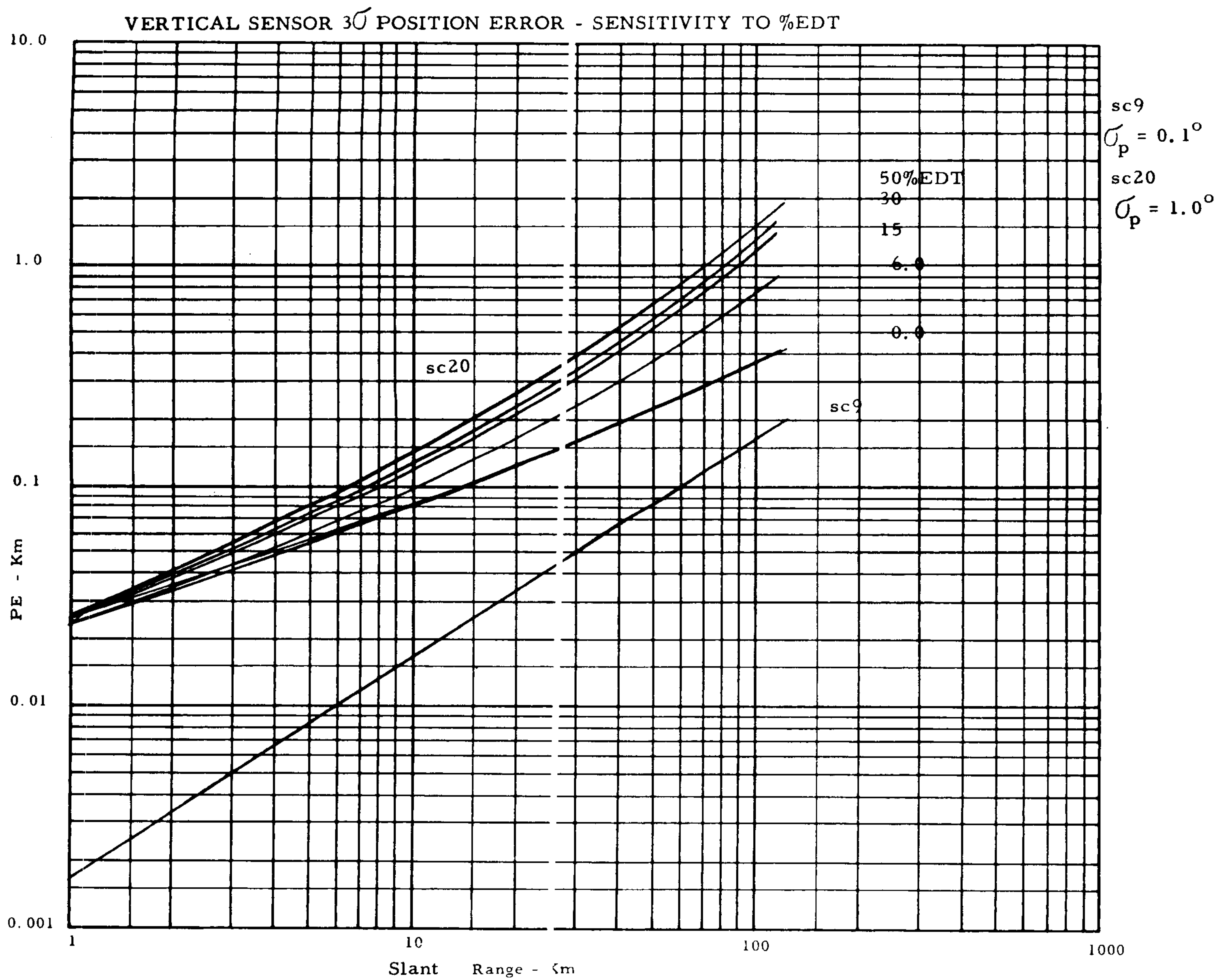


Figure 11-8 Vertical Sensor 3σ Position Error—Sensitivity to % EDT

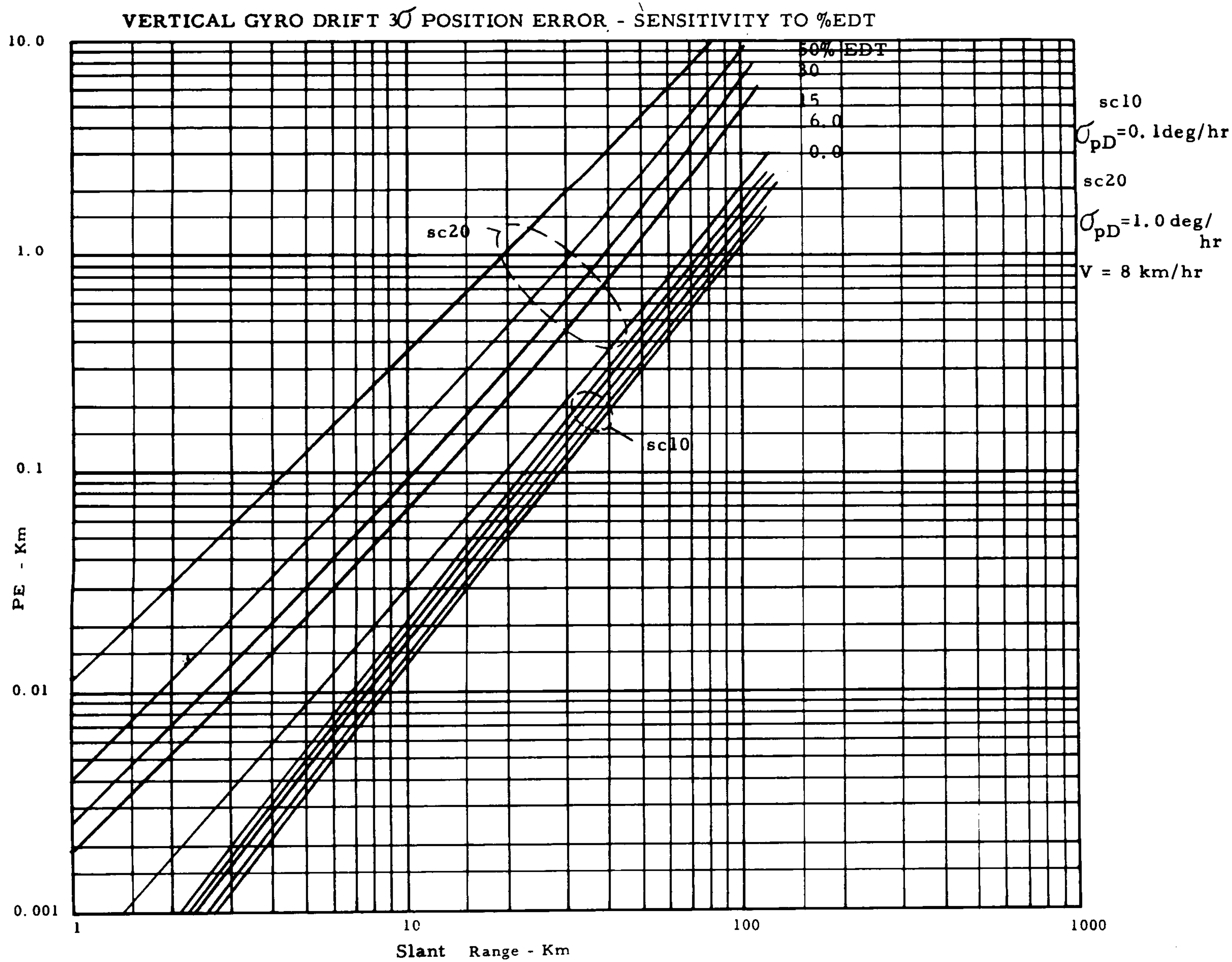


Figure 11-9 Vertical Gyro Drift 3σ Position Error—Sensitivity to % EDT

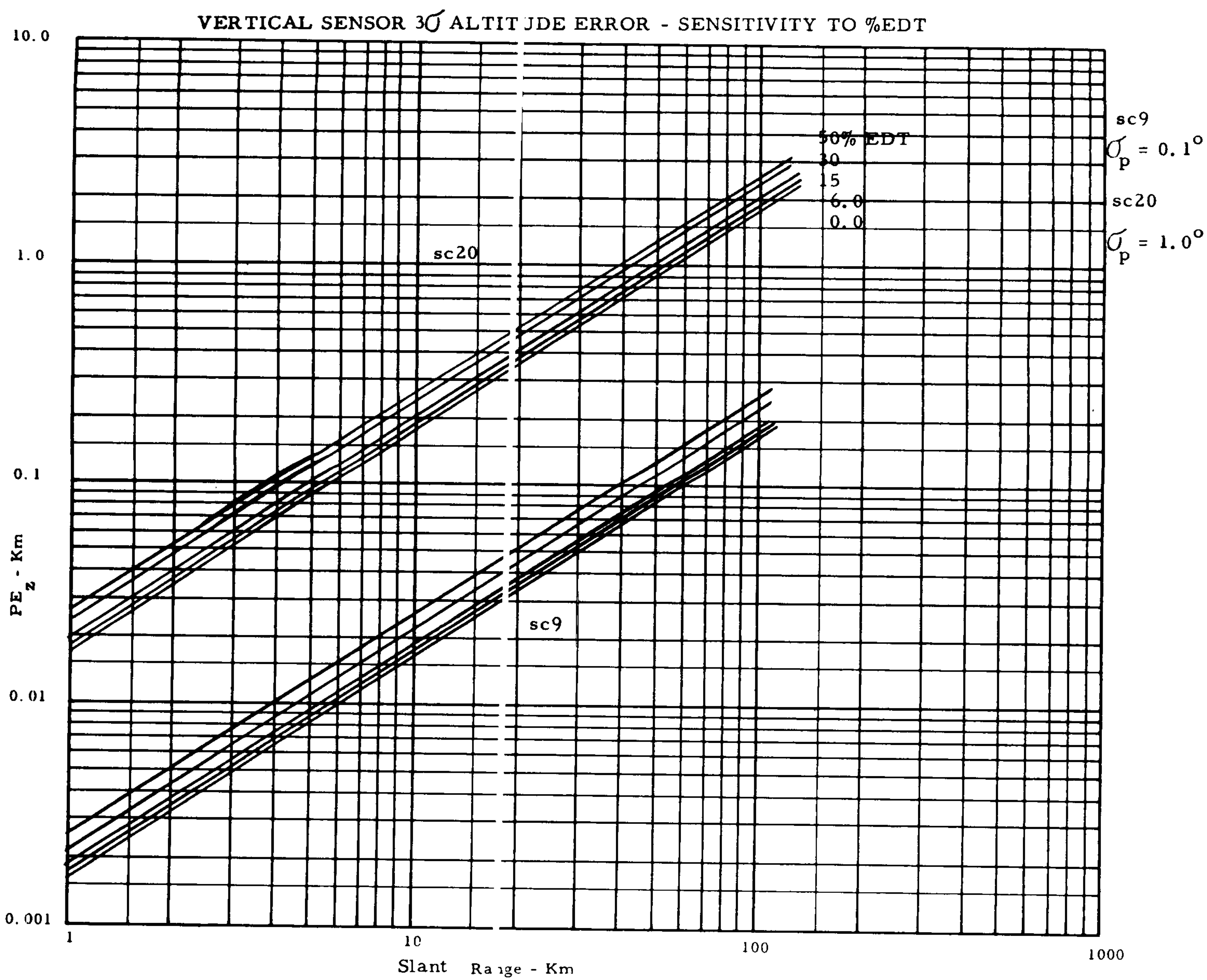


Figure 11-10 Vertical Sensor 3σ Altitude Error—Sensitivity to % EDT

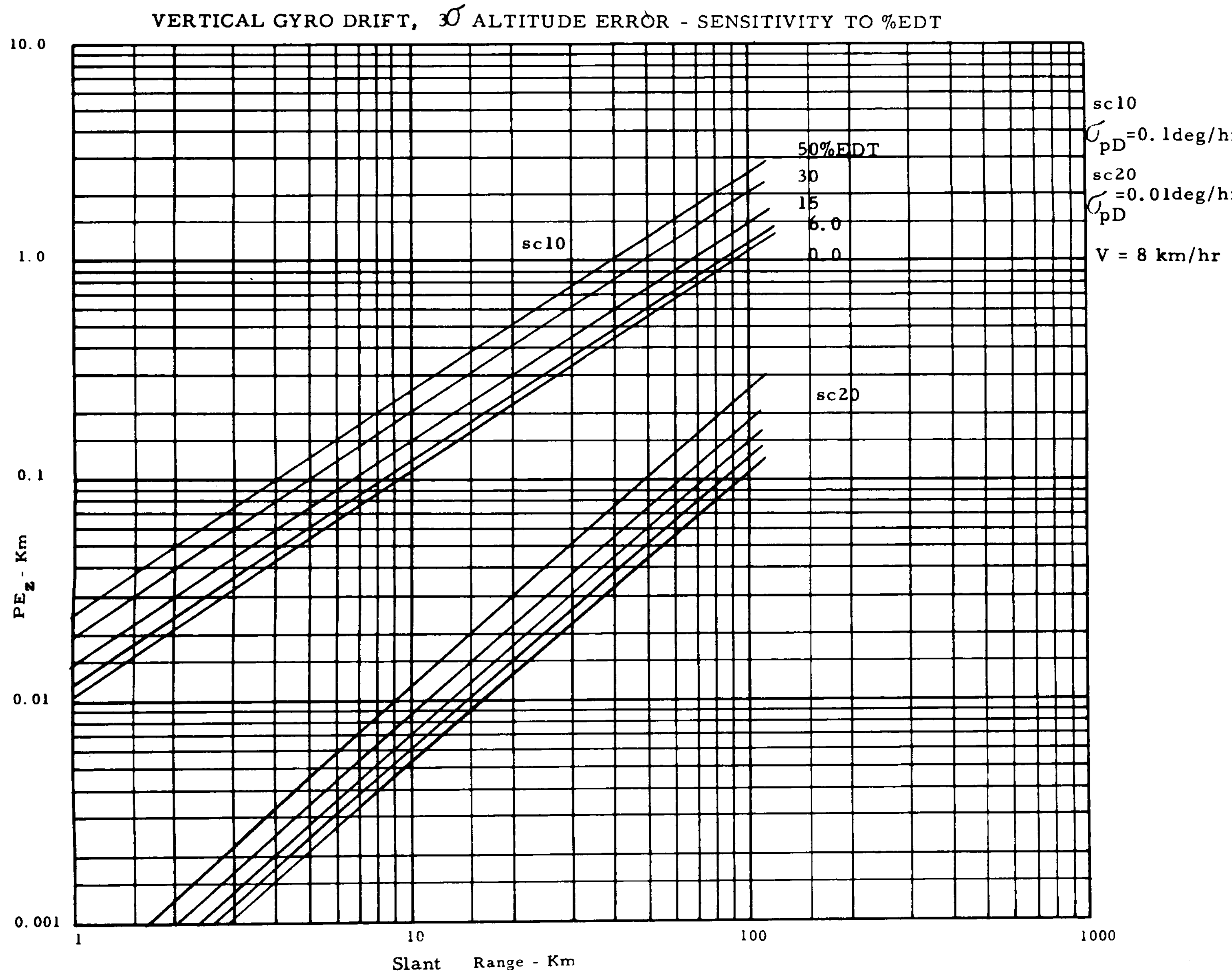


Figure 11-11 Vertical Gyro Drift, 3σ Altitude Error—Sensitivity to % EDT

3σ POSITION ERROR - SENSITIVITY TO SELENOGRAPHIC REGION

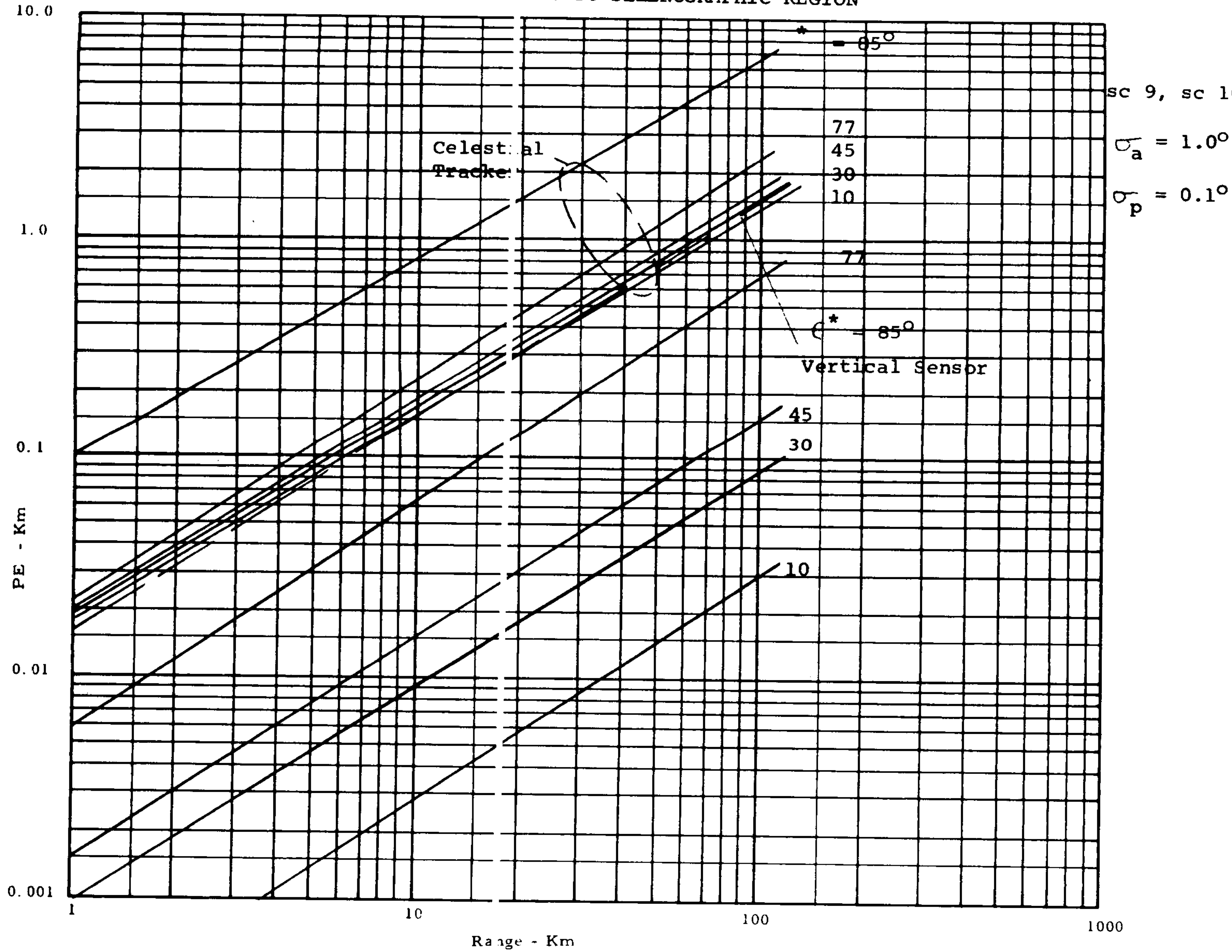


Figure 11-12 3σ Position Error—Sensitivity to Selenographic Region

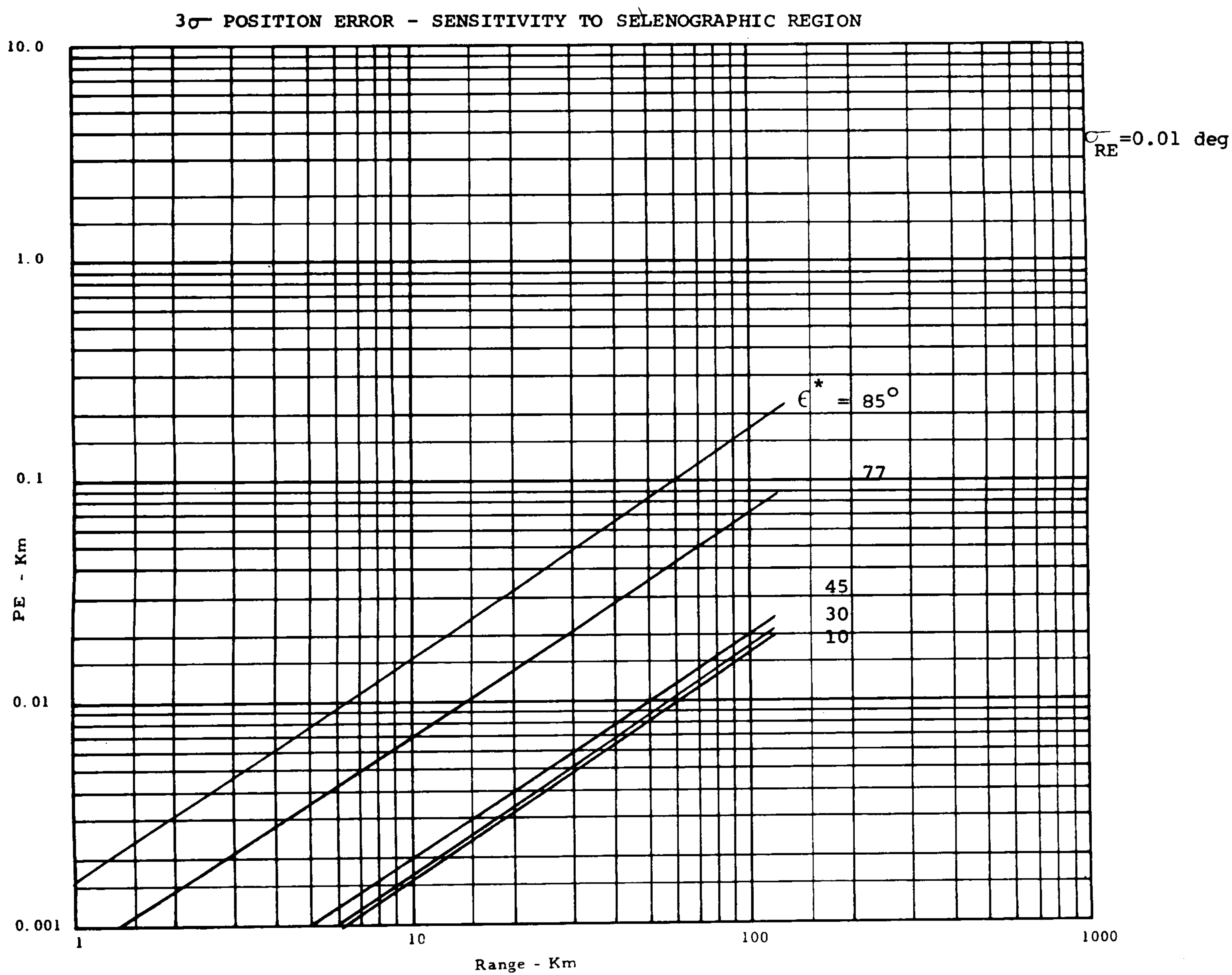


Figure 11-13 3σ Position Error—Sensitivity to Selenographic Region

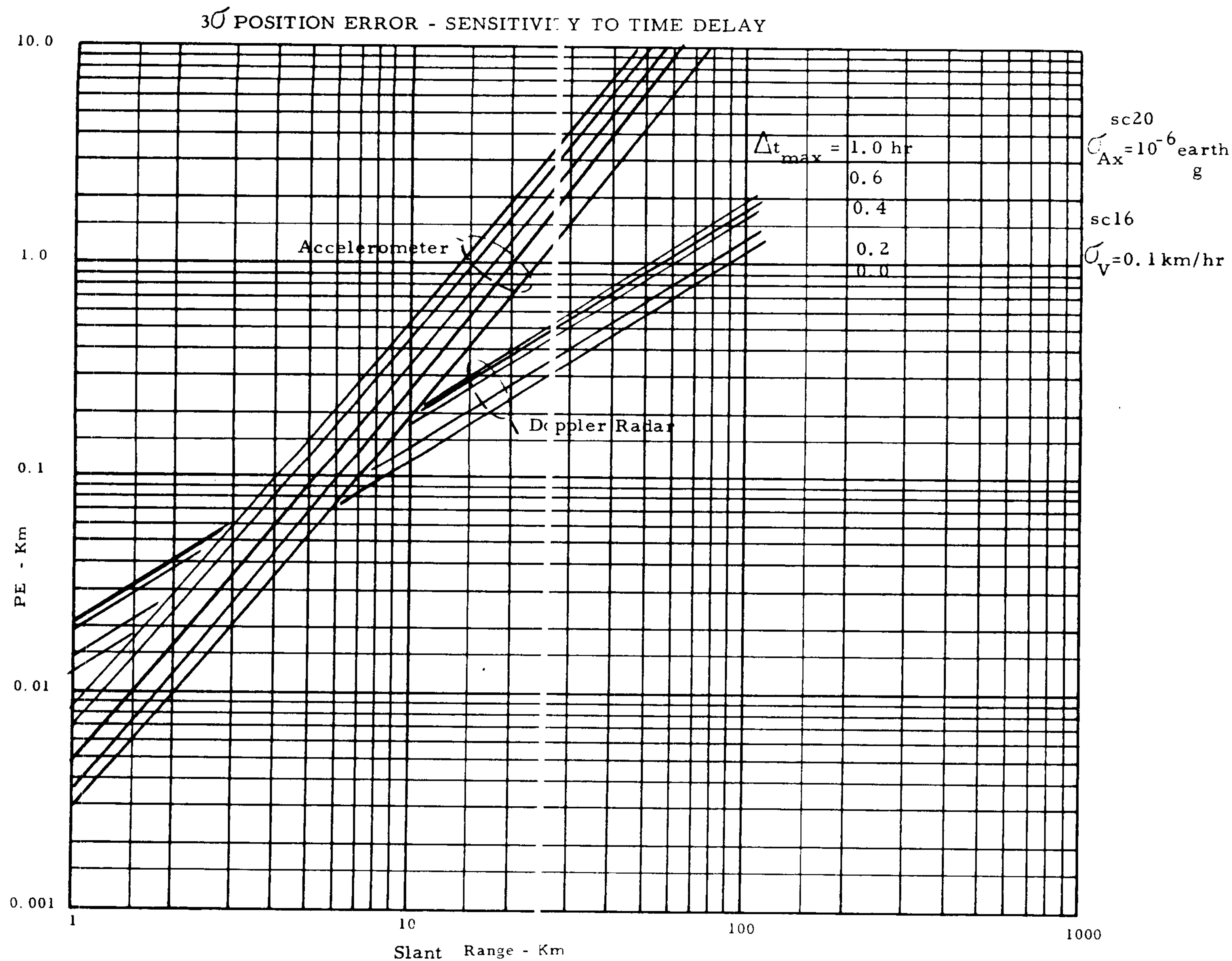


Figure 11-14 3σ Position Error—Sensitivity to Time Delay

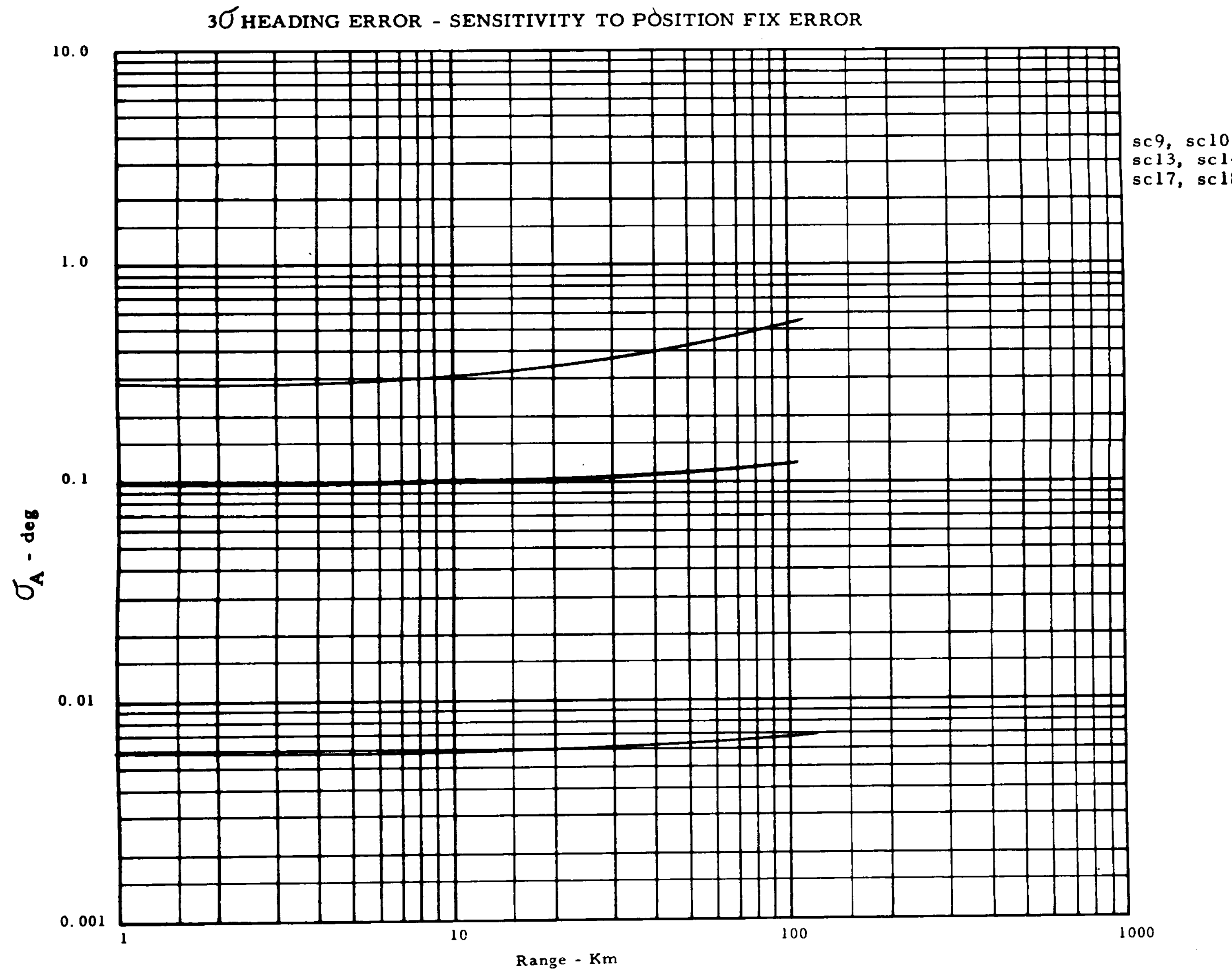


Figure 11-15 3σ Heading Error—Sensitivity to Position Fix Error

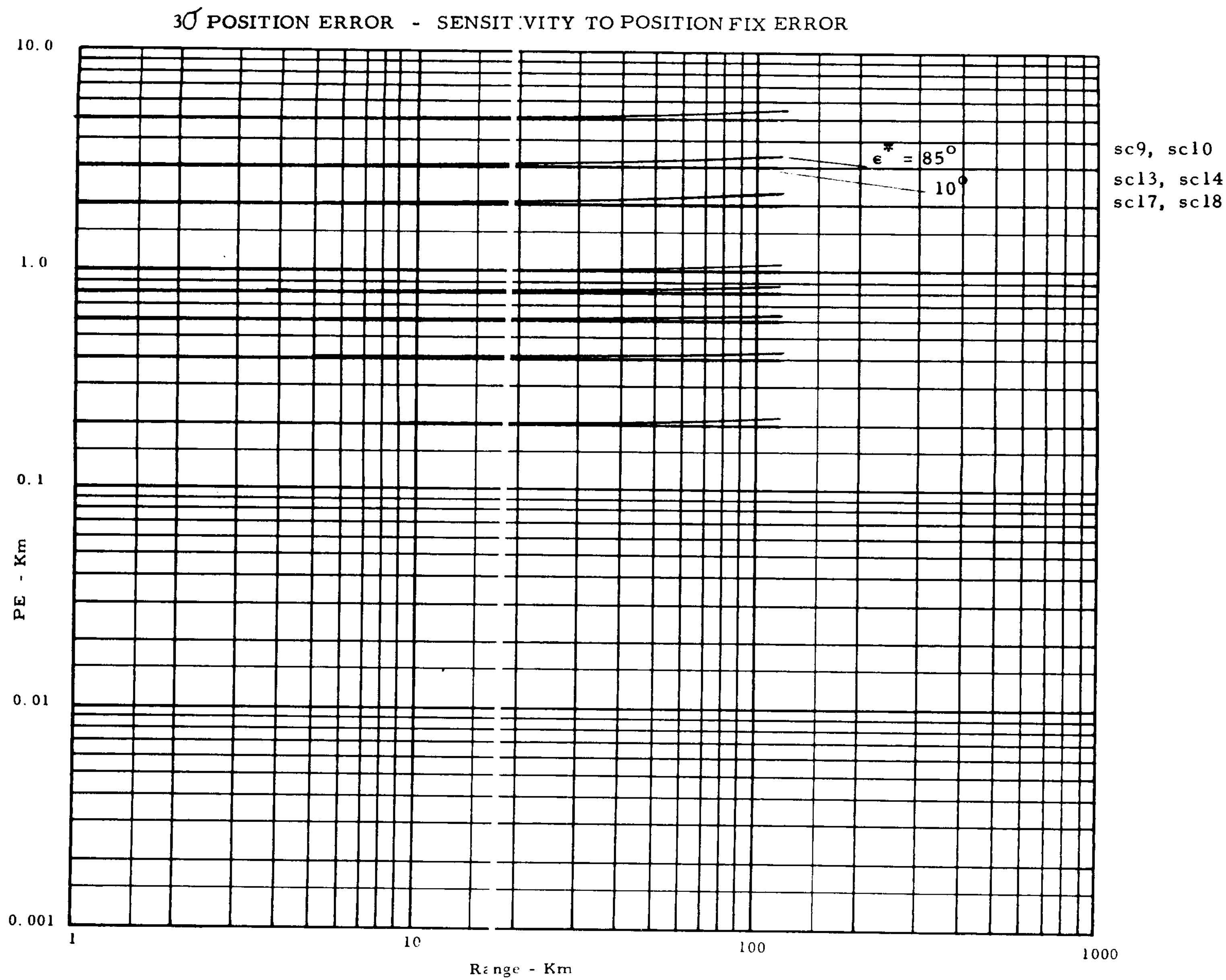


Figure 11-16 3σ Position Error—Sensitivity to Position Fix Error

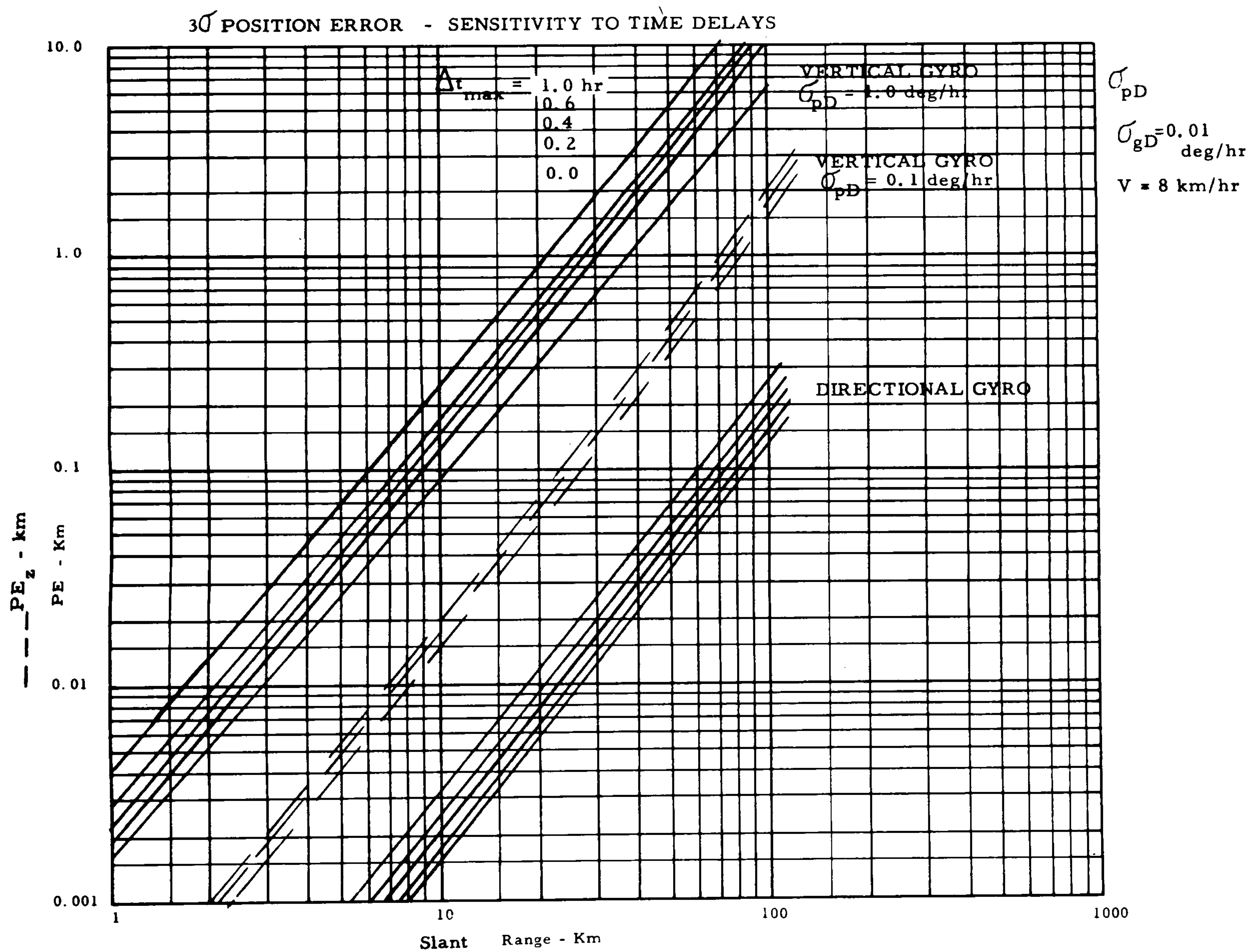


Figure 11-17 3σ Position Error—Sensitivity to Time Delays

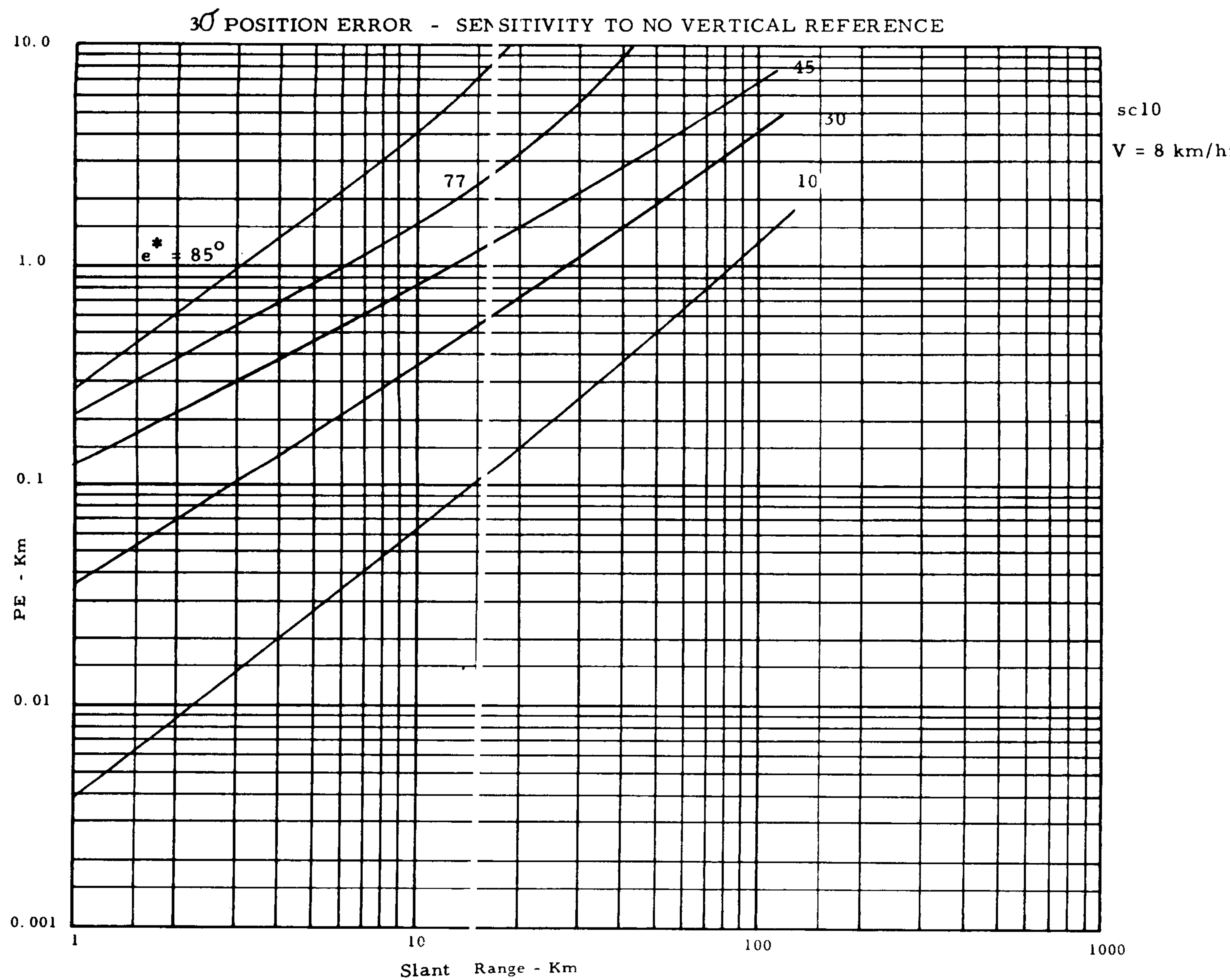


Figure 11-18 3σ Position Error—Sensitivity to No Vertical Reference

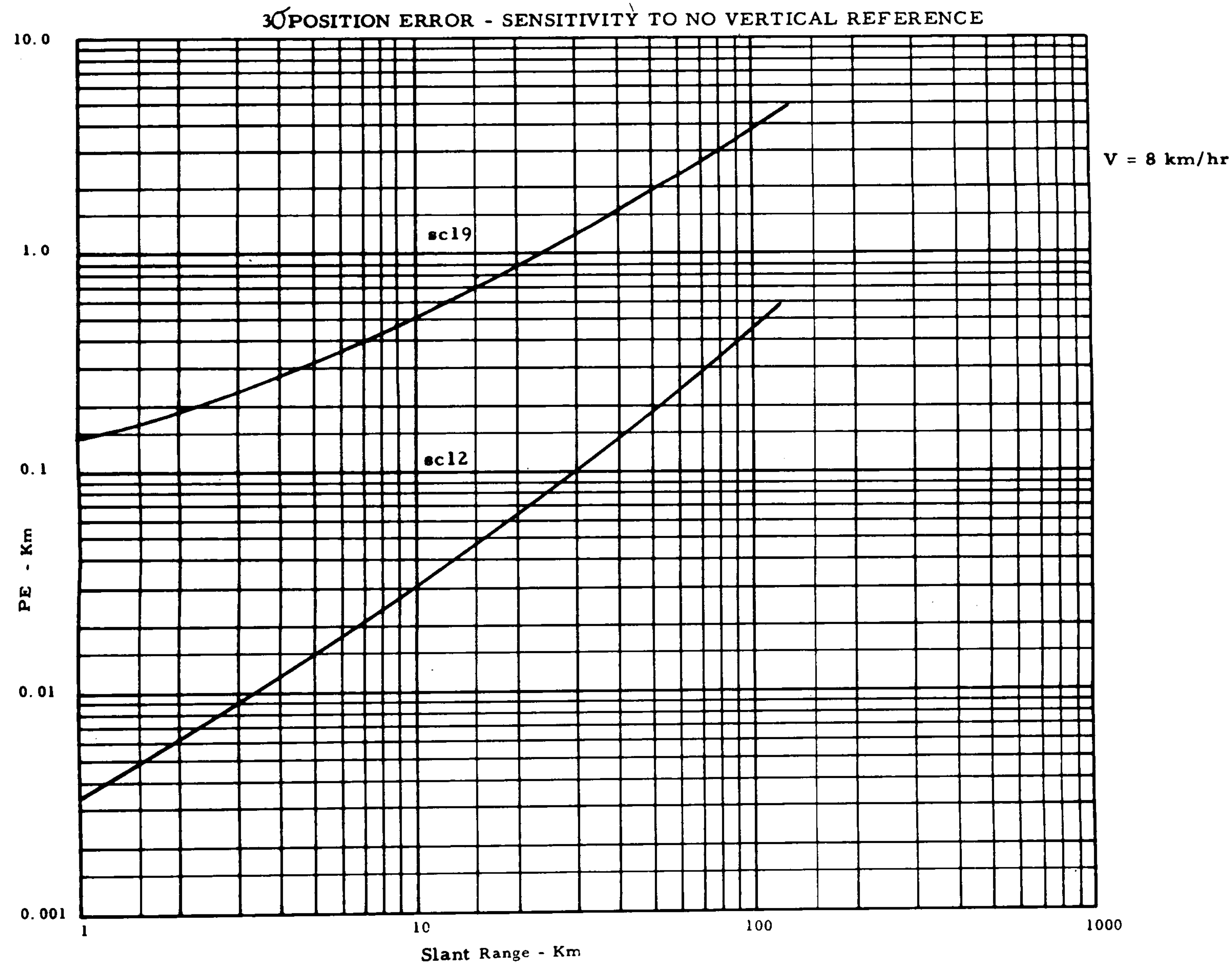


Figure 11-19 3σ Position Error—Sensitivity to No Vertical Reference

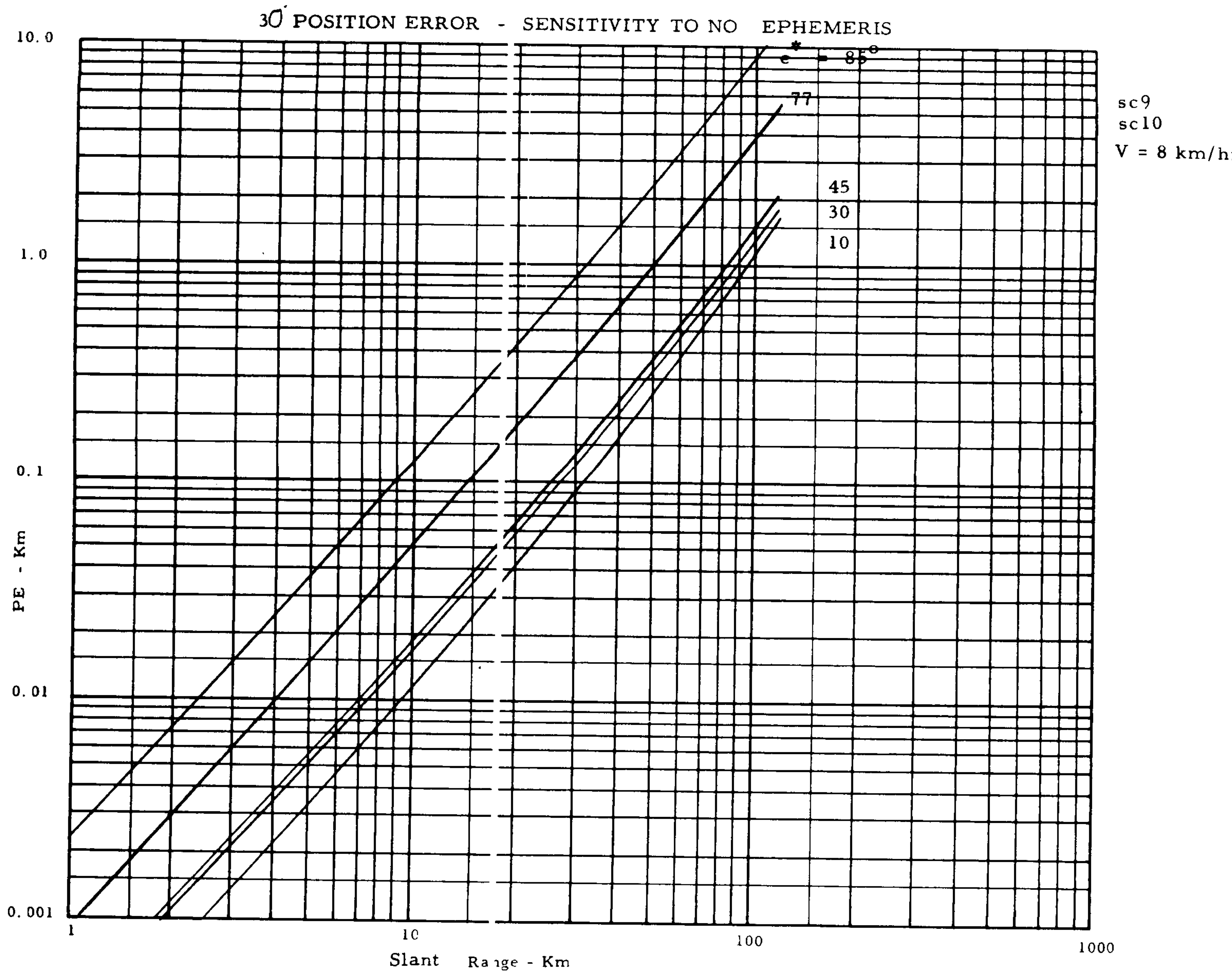


Figure 11-20 3σ Position Error—Sensitivity to No Ephemeris

SECTION 12

FUNCTIONAL COMPONENT GROUPS

Previous sections documented the performance data of the lunar surface navigation systems. The documentation is sufficiently general to permit a navigation system analyst or a lunar mission analyst to evaluate the performance of a variety of navigation concepts for a wide choice of lunar missions. Both mission parameters and navigation concept parameters can be varied to achieve a navigation concept and a mission plan acceptable to overall mission objectives.

The systematic process which is used to reach an accuracy design point in the lunar surface navigation concept is outlined in Section 9. However, because of the many parameters, and the high number of permutations, the process can be lengthy. To circumvent the possibility of an extensive effort and to supplement the standardized performance data, this section lists typical functional component groups each of which is capable of meeting a representative accuracy requirement. Tables are given for each navigation sensor or navigational aid which list navigation requirements and in turn designate the design point navigation concept which meets the requirement. Nominal mission operating points have been selected for the data presentation. The operating conditions, although arbitrary, represent typical mission factors which combine to give moderate environmental sensitivity to concept performance and appear to represent future nominal lunar missions.

Thus, comparison of requirements and performance yields the accuracy type and design point of each navigation sensor which meets a representative navigation requirement not only as a function of mission parameters, but also as a function of the subconcept implementation, navigational sensors, and aids.

12.1 POSITION FIX FUNCTIONAL COMPONENT GROUPS

12.1.1 Celestial Tracking Subconcept sc 1

Table 12-1 shows the functional component groups of the celestial tracking subconcepts, each of which is capable of meeting representative position fix requirements. The position fix requirement μ, extends from the relaxed 10 km to a stringent 0.100 km. The entries of the table are the 3σ error parameters of the defined sensor error which when combined with the other sensor errors meets the total subconcept requirement μ for the specified mission conditions Case 1, Case 2, Case 3, and Case 4. Each case is defined in Section 10.1.1.

The technique which was applied to solve for the component requirements was simply a linear iteration process where the cost function was defined as those sets of error conditions which required the minimum component development. Having solved for the component errors, then the vertical anomaly position error term was equated to one-tenth the maximum component position error term. The value of the vertical anomaly was taken from the position fix performance data. Thus, the vertical anomaly which is given in the table is the maximum allowable 3σ anomaly that does not affect the component requirements.

Several conclusions can be drawn from Table 12-1:

1. If the observable separation angle is restricted from 60° to 90°, and the vertical anomaly term is negligible, the absolute position fix requirement of $\mu = 0.100$ km 3σ can be satisfied by a state-of-the-art accuracy design point.

2. If it is desired to achieve a position fix error of 1.0 km 3σ, then the worst case dictates a celestial tracker with a pointing resolution 0.006°, 3σ, a vertical sensor error of 0.006°, 3σ, a lunar based ephemeris with 3σ error equal to 0.01° and a timer error of 0.0030 hr. The allowable vertical anomaly is less than 0.00065 degree. All the quoted values of equipment errors exceed the state of the art, while the timer and ephemeris errors equal the nominal value.

3. The optimal case, Case 1, requires nominal design point components and an allowable vertical anomaly of 0.0018°.

4. Case 4 component errors will satisfy the Case 1, 2, and 3 error requirements, and thus these functional component groups satisfy the entire array of position fix requirements.

12. 1. 2 Ranging Navigational Satellite sc 2

The functional component groups which meet the representative position fix requirements are given in Table 12-2. The component error magnitudes which are required to meet the standard position fix requirements μ are given by Table 12-2. Where no table entry is made, the subconcept sc 2 does not meet the requirement even though component errors are reduced to the projected state of the art. The mission conditions, Case 1, . . . Case 4, are defined in Section 10. 1. 2. In general, the following conclusions can be made:

1. The functional component groups of Case 1 meet the position fix requirements of other cases; μ = 10, 5, 2.

2. The ranging error σ_{Rnc} = 0. 100 km (MAX) does not need reduction for values of ephemeris error within the state of the art.

3. The satellite ephemeris error must exceed the state-of-the-art value (σ_{ρ} = 0. 500) to satisfy the 2 km requirement.

12. 1. 3 Angle Tracking Navigational Satellite sc 3

The angle tracking navigational satellite functional component groups which meet the representative position fix requirements are tabulated in Table 12-3. The accuracy design points of the sensor errors which satisfy the position fix requirement are shown for the subconcept error sources, the satellite ephemeris, satellite tracker, vertical sensor, and the allowable vertical anomaly. The position fix requirement μ, ranging from 10 km to 0. 100 km, is satisfied by the combination of sensor errors, and in the instance where no entry is given, no combination of sensor errors within the projected state of the art can meet the requirement. Depending on the mission geometry, the uncompromising requirement varies from 1 km to 0. 100 km. The mission conditions, Case 1, . . . Case 4, are identified in Section 10. 1. 3.

Although the data are tabulated for reference information, several conclusions can be made:

1. The functional component group which can meet the limiting requirement of each case (2 km, Case 1; 0.5 km, Case 3) requires a projected state-of-the-art ephemeris $\sigma_\rho = 0.1$ km, state-of-the-art trackers and vertical sensors $\sigma_r = \sigma_\epsilon = 0.002^\circ$ and a negligible vertical anomaly, $\sigma_\gamma = 0.0004^\circ$.

2. In no case does the requirement of the celestial tracker and vertical sensor exceed the state-of-the-art error magnitude $\sigma_r = \sigma_\epsilon = 0.001^\circ$; however, such precise laboratory type equipment will have operational restrictions.

3. For the functional component groups shown, the allowable vertical anomaly ranges from 0.16° to 0.0004°, and does not represent a major error input.

4. If the ephemeris error were limited to the state-of-the-art magnitude $\sigma_\rho = 0.5$ km 3σ, then the tabulated functional component groups satisfy requirements ranging from 10 km of Case 1 to 1 km of Case 4; thus it is apparent that the ephemeris error is the principal input error requiring improvement.

12.1.4 Range Rate Navigational Satellite sc 4

The range rate navigational satellite accuracy design points which meet representative position fix requirements are tabulated in Table 12-4. The accuracy design point required of each error source is shown. The position fix errors arising from the error inputs combine to equal the tabulated position fix requirement, μ. Case 1, Case 2, . . , Case 4, the mission conditions are defined in Section 10.1.4. Several conclusions follow:

1. The design point concept which meets the array of position fix requirements (none can equal 0.1 km) would consist of ephemeris errors and range rate errors equal to the projected state of the art $\sigma_\rho = 0.10$ km. $\sigma_{\dot{r}} = 9.20$ km/hr, and ephemeris rate errors of 0.10 km/hr.

2. The 5-km position fix requirement is satisfied with MAX ephemeris errors, 3.0 km, 3σ, but with range rate errors typical of state of the art to nominal values 2 km/hr to 20 km/hr.

3. The 2-km position fix requirement is equaled with nominal ephemeris data, and slightly greater than state-of-the-art range rate errors.

4. To position fix to an accuracy of 1.0 km 3σ requires either the range rate or ephemeris data to exceed the state-of-the-art parameter range.

5. Sophisticated position fix requirements can be equaled only by developing sufficient range rate or ephemeris technology, typical of the projected stated of the art.

12.1.5 Earth-Based RF Tracking sc 5, sc 6

The capability to define lunar roving vehicle position by earth-based tracking of a vehicle mounted S-band transponder is tabulated in Section 10.1.5 as a function of tracking duration.

12.2 DEAD RECKONING FUNCTIONAL COMPONENT GROUPS

The total concept performance data of Section 10.3 displayed dead reckoning 3σ position error as a function of distance travelled for the design point dead reckoning subconcepts sc 9 to sc 20. To generate the performance data, the input error components of each navigation system were fixed at the magnitude of errors corresponding to technology state of the art. To develop the tables listing functional component groups, the standardized dead reckoning requirements listed in Table 12-5 are compared to the total concept performance data and the appropriate design point subconcept which can meet the requirement is chosen. Tables 12-6 through 12-16 define the dead reckoning subconcepts which meet the representative requirements.

Table 12-5 shows the standard dead reckoning requirement

$$1/\eta = \frac{1}{20}, \frac{1}{50} \text{ etc.},$$

the range of the lunar surface traverse

10, 20, 30 km etc.,

and the 3σ position error in km which is allowed at the traverse termination or trajectory end point.

The mission parameters which simulate the nominal navigation system environment are:

$$A_{max} = 90^{o}; \ \% \ EDT = 15\%$$

$$h_{max} = 0.45 \ km$$

$$r_{max} = 13^{o}$$

$$V = 8 \ km/hr$$

$$\epsilon^{*} = 77^{o}.$$

These mission parameters combine a satisfactory cross-section of possible mission factors and represent neither an absurd worst case or optimal case for defining system and component performance.

Tables 12-6 to 12-16 can be quickly applied by a mission analyst to define the design point dead reckoning navigation concept which will meet the mission objectives. The entries of the tables are the dead reckoning subconcept which satisfy the terminal requirements of Table 12-5, and are the functional component groups which meet the representative requirements.

The organization of the tables is as follows:

1. Navigation Sensor or Aid odometer, doppler radar, . . .

2. Subconcept sc 9, sc 10, . . .

3. System Accuracy Design Points I, II, III, . . .

4. Sensor Accuracy Design Point 1, 2, 3, . . .

5. The navigation sensor is given by the title to the table. The subconcepts which contain the sensor are listed in the key of each table, and the accuracy design point for the system and sensor is given by the table entry.

6. The accuracy design point specifies the system error components (I, II, ...) and the sensor error component (1, 2, ...). The correlation between the system subconcept and the accuracy design point is noted by the physical placement of the key and the table entry. For instance, if a sensor can be used in six subconcepts, then the key will have six entries, and each table entry will correspond to the elements of the key.

An example clarifies the organization

Consider Table 12-6

Navigation Sensor - Odometer

Subconcepts (key) -sc 9, sc 11, sc 10, sc 12

System Accuracy Design Points - I, II, ...

Sensor Accuracy Design Point - 1, 2, ...

Consider a postulated mission requirement. It is desired to dead reckon for 30 km to an accuracy of 1/200. From Table 12-5, the terminal requirement is

0.15 km.

The navigation concepts which can meet the requirement are given in Tables 12-6 through 12-16 for the appropriate linear requirement and range.

Consider Table 12-6. The entries which meet the requirement are given by:

IV-5	IV-4
V-4	III-5

And to what subconcepts do these accuracy design points refer? Consider the physical placement of the key:

sc 9	sc 11
sc 10	sc 12

Thus simply pairing off the subconcept with the accuracy design point gives the functional component group which meets the terminal constraint.

Subconcept	Accuracy Design Point	
	Other Sensor Errors	Odometer Error
sc 9	IV	5
sc 10	V	4
sc 11	IV	4
sc 12	III	5

The correlation between the accuracy identification, the numerical values, and navigational sensor state of the art is given by Table 5-3 In summary,

I, 1 ⇒ Maximum (MAX)

III, 3 ⇒ Nominal (NOM)

V, 5 ⇒ State of the art (SOA)

VII, 7 ⇒ Projected state of the art (PSOA)

The remaining numerals are intermediate error magnitudes. Thus referring to the example, an accuracy design point which meets the requirement with the minimum strain on the sensor technology is subconcept sc 11 at IV-4. The error vector for this system is

$$\begin{bmatrix} \sigma_o \\ \sigma_{GA} \\ \sigma_{gD} \\ \sigma_p \\ \sigma_r \end{bmatrix} = \begin{bmatrix} 0.5\% \\ 0.05^\circ \\ 0.01^\circ/hr \\ 0.05^\circ \\ 0.05^\circ \end{bmatrix}$$

where all magnitudes exceed the state-of-the-art (SOA) magnitude.

The remaining tables, Tables 12-7 through 12-16, can be referred to and other alternate subconcepts can be selected to meet the requirement. At this point, it is extremely important to note that table entries specify dead reckoning subconcepts which meet planar navigation position error requirements. The vehicle heading error and altitude error for the selected subconcept, and for the designated mission conditions, are obtained from the total concept figures of Sections 10.3.2 and 10.3.3. As an example it is found for the selected subconcept sc11, IV-4 of the above problem, that

$$\sigma_A = 0.068^\circ \qquad \text{(Figure 10-358)}$$

$$PE_z = 0.027 \text{ km} \qquad \text{(Figure 10-341)}$$

If these 3σ values are too large, and do not meet the total navigation requirements, then the curves and tables should be reiterated until a solution is found. An aid in the process of reiteration would be to consult the independent performance data of Section 10.2. Then by satisfying each of the requirements, planar, altitude, and directional, the functional dead reckoning concept can be selected.

Thus the following dead reckoning requirement tables in conjunction with the heading error and altitude error curves can be used by the mission analyst to determine the feasibility of performing a given mission objective where a supporing task is necessary of the navigation subsystem.

The dead reckoning error tables presented in this section tabulate the functional component groups which meet typical lunar navigation requirements, and afford a mission analyst or exploration system designer an immediate answer to the dead reckoning navigation subsystem design feasibility. The designer can trade off, with the aid of the standardized performance data, vehicle position, altitude, and heading requirements with candidate subconcept and sensor implementation schemes. The data presented in the tables culminate, through a systematic procedure, the technology data of navigation and guidance and lunar exploration missions, and permit maximum flexibility for the user of the data.

TABLE 12-1

CELESITAL TRACKING sc 1 3σ POSITION FIX REQUIREMENTS

CASE	ERROR	POSITION FIX REQUIREMENT, u, in km 10	5	2	1	0.5	0.2	0.1
1	σ_e	0.10	0.079	0.024	0.012	0.0067	0.0031	0.0015
	σ_p	0.10	0.079	0.024	0.012	0.0067	0.0031	0.0015
	σ_R	0.030	0.030	0.030	0.010	0.0067	0.0010	0.0010
	σ_t	0.030	0.030	0.030	0.030	0.0030	0.0030	0.00030
	σ_γ	0.26	0.011	0.0043	0.0018	0.00096	0.00043	0.0
2	σ_e	0.10	0.068	0.019	0.011	0.0058	0.0027	0.0013
	σ_p	0.10	0.068	0.019	0.011	0.0058	0.0027	0.0013
	σ_R	0.030	0.030	0.030	0.010	0.0058	0.0010	0.0010
	σ_t	0.030	0.030	0.030	0.030	0.0030	0.0030	0.00030
	σ_γ	0.18	0.0087	0.0024	0.0014	0.00073	0.00034	0.0
3	σ_e	0.10	0.052	0.012	0.010	0.0045	0.0021	0.0010
	σ_p	0.10	0.052	0.012	0.010	0.0045	0.0021	0.0010
	σ_R	0.030	0.030	0.030	0.0066	0.0045	0.0010	0.00066
	σ_t	0.030	0.030	0.030	0.0030	0.0030	0.0030	0.00030
	σ_γ	0.073	0.0066	0.0016	0.0013	0.00058	0.00027	0.00
4	σ_ϵ	0.08	0.041	0.010	0.0060	0.0034	0.0015	0.00060
	σ_p	0.08	0.041	0.010	0.0060	0.0034	0.0015	0.00060
	σ_R	0.030	0.030	0.018	0.010	0.0034	0.0010	0.0010
	σ_t	0.030	0.030	0.03	0.0030	0.0030	0.0030	0.00030
	σ_γ	0.0087	0.0044	0.0011	0.00065	0.00037	0.00017	0.0

TABLE 12-2

RANGING NAVIGATIONAL SATELLITE
sc 2 3σ POSITION FIX REQUIREMENTS

		POSITION FIX REQUIREMENT, u, km							
CASE	**ERROR**	**10**	**5**	**2**	**1**	**0.5**	**0.2**	**0.1**	
1	σ_ρ	0.95	0.47	0.18					
	$\sigma_{R_{nc}}$	0.10	0.10	0.10					
2	σ_ρ	1.7	0.83	0.33	0.15				
	$\sigma_{R_{nc}}$	0.10	0.10	0.10	0.10				
3	σ_ρ	1.4	0.69	0.26	0.11				
	$\sigma_{R_{nc}}$	0.10	0.10	0.10	0.10				
4	σ_ρ	2.2	1.1	0.44	0.21	0.10			
	$\sigma_{R_{nc}}$	0.10	0.10	0.10	0.10	0.060			

TABLE 12-3

ANGLE TRACKING NAVIGATION SATELLITE sc 3 POSITION FIX REQUIREMENTS

CASE	ERROR	POSITION FIX REQUIREMENT, u, in km						
		10	5	2	1	0.5	0.2	0.1
1	σ_ρ	0.93	0.45	0.10				
	σ_e	0.010	0.010	0.0098				
	σ_r	0.010	0.010	0.0098				
	σ_γ	0.010	0.0047	0.0012				
2	σ_ρ	1.0	0.91	0.28	0.10			
	σ_e	0.081	0.010	0.010	0.0081			
	σ_r	0.081	0.010	0.010	0.0081			
	σ_γ	0.012	0.0098	0.0030	0.0012			
3	σ_ρ	3.0	1.0	0.49	0.10	0.10		
	σ_e	0.023	0.031	0.010	0.0081	0.0031		
	σ_r	0.023	0.031	0.010	0.0081	0.0031		
	σ_γ	0.012	0.0041	0.0021	0.00063	0.00041		
4	σ_ρ	3.0	3.0	1.0	0.50	0.10	0.10	
	σ_e	0.10	0.038	0.020	0.010	0.0068	0.0020	
	σ_r	0.10	0.038	0.020	0.010	0.0068	0.0020	
	σ_γ	0.16	0.012	0.0029	0.0020	0.00097	0.00040	

TABLE 12-4

RANGE RATE NAVIGATIONAL SATELLITE
sc 4 POSITION FIX REQUIREMENTS

CASE	ERROR	POSITION FIX REQUIREMENT, u, km 10	5	2	1	0.5	0.2	0.1	
1	$\sigma_{\dot{\rho}}$	1.0	1.0	1.0	1.0	1.0	0.56		
	σ_{ρ}	3.0	3.0	1.0	0.35	0.28	0.10		
	$\sigma_{\dot{r}}$	21	12	2.2	2.0	0.20	0.20		
2	$\sigma_{\dot{\rho}}$	1.0	1.0	1.0	1.0	1.0	0.10		
	σ_{ρ}	3.0	3.0	1.0	0.37	0.30	0.10		
	$\sigma_{\dot{r}}$	22	2.5	2.8	2.0	0.20	0.25		
3	$\sigma_{\dot{\rho}}$	1.0	1.0	1.0	1.0	1.0	0.28		
	σ_{ρ}	3.0	3.0	1.0	0.50	0.1	0.10		
	$\sigma_{\dot{r}}$	17	3.9	2.3	1.1	0.71	0.20		
4	$\sigma_{\dot{\rho}}$	1.0	1.0	1.0	1.0	1.0	0.27		
	σ_{ρ}	3.0	3.0	1.0	0.50	0.28	0.10		
	$\sigma_{\dot{r}}$	15	4.5	2.3	1.1	0.20	0.20		

TABLE 12-5

DEAD RECKONING REQUIREMENTS

T_R in km

Range, km / $1/\eta$ Requirement	10	20	30	50	75	100
1/20	0.5	1.0	1.5	2.5	3.75	5.0
1/50	0.2	0.4	0.6	1.0	1.5	2.0
1/100	0.1	0.2	0.3	0.5	0.75	1.0
1/200	0.05	0.1	0.15	0.25	0.375	0.5
1/500	0.02	0.04	0.06	0.1	0.15	0.2
1/1000	0.01	0.02	0.030	0.05	0.075	0.1
1/10,000	0.001	0.002	0.0030	0.005	0.0075	0.01

TABLE 12-6

DEAD RECKONING REQUIREMENT TABLE-ODOMETER σ_o

Key: sc9 sc11
sc10 sc12
V = 8km/hr
$\epsilon^* = 77^o$

Range, km / $1/\eta$ Requirement	10		20		30		50		75		100	
1/20	II-2	I-1	II-2	I-1	II-2	I-2	II-2	I-3	II-2	II-1	II-2	II-1
	II-2	I-1	II-2	I-1	III-1	I-2	III-1	II-1	III-1	II-1	III-1	II-1
1/50	III-3	II-1	III-3	II-1	III-3	II-1	III-3	II-2	III-3	III-3	III-3	III-3
	III-3	II-2	III-3	II-2	III-3	II-2	III-4	II-3	IV-2	III-2	IV-2	III-2
1/100	IV-3	III-3	IV-3	III-3	IV-3	III-3	IV-3	III-3	IV-3	III-4	IV-3	III-4
	IV-3	III-3	IV-3	III-3	IV-3	III-3	IV-4	III-3	IV-4	III-4	IV-5	III-4
1/200	IV-5	III-4	IV-5	III-4	IV-5	IV-4	IV-5	IV-4	IV-5	IV-4	IV-5	IV-4
	IV-5	III-4	IV-5	III-5	V-4	III-5	V-4	III-5	V-5	IV-4	V-5	IV-4
1/500	V-5	IV-5	V-5	IV-5	V-5	IV-5	V-5	IV-5	V-5	IV-5	V-5	IV-5
	V-5	IV-5	V-5	IV-5	V-5	IV-5	VI-4	IV-5	VI-4	IV-5	VI-4	IV-5
1/1000	VI-6	IV-5	VI-6	IV-5	VI-6	V-5	VI-6	V-5	VI-6	V-6	VI-5	V-5
	VI-6	V-5	VI-6	V-5	VI-6	V-5	VII-6	V-5	VII-6	V-5	VII-6	V-5
1/10,000	-	VII-7	-	VII-7	-	VII-7	-	VII-7	-	VII-7	-	VII-7
	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 12-7

DEAD RECKONING REQUIREMENT TABLE—DOPPLER RADAR σ_v

Key: sc13 sc15
sc14 sc16

V = 8 km/hr

$\epsilon^* = 17^o$

Range, km / 1/η Requirement	10		20		30		50		75		100	
1/20	II-3	I-3	II-3	I-3	II-3	I-3	II-3	II-3	II-3	II-3	II-3	II-3
	II-3	I-3	II-3	I-3	II-3	I-3	II-3	II-3	III-3	II-3	III-3	II-3
1/50	II-3	III-3	III-3	III-3	III-3	III-3	III-3	III-3	III-3	III-3	III-3	III-3
	IV-3	III-3	IV-3	III-3	IV-4	III-3	IV-3	III-3	IV-3	III-3	IV-3	III-3
1/100	IV-4	III-4	IV-4	III-4	IV-4	III-4	IV-4	III-4	IV-4	III-4	IV-4	III-4
	IV-4	III-4	IV-4	III-4	IV-4	III-4	IV-4	III-4	V-4	III-4	V-4	IV-4
1/200	IV-5	III-5	IV-5	III-5	IV-5	III-5	IV-5	III-5	IV-5	IV-5	IV-5	IV-5
	IV-5	IV-4	V-5	IV-4	V-5	IV-4	V-5	IV-4	V-5	IV-5	V-5	IV-5
1/500	V-5	IV-5	V-5	IV-5	V-5	IV-5	V-5	IV-5	V-5	IV-5	V-5	IV-5
	V-6	IV-5	V-6	IV-5	V-6	IV-5	VI-5	IV-5	VI-6	IV-5	VII-6	IV-5
1/1000	VI-6	V-5	VI-6	V-5	VI-6	V-5	VI-6	V-5	VI-6	V-5	VI-6	V-5
	VI-6	IV-6	VI-6	IV-6	VI-6	IV-6	VII-6	V-6	VII-6	V-6	VII-6	V-6
1/10,000	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 12-8

DEAD RECKONING REQUIREMENT TABLE—ACCELEROMETERS, σ_{Ax}

Key: sc19
sc20
V = 8 km/hr

$1/\eta$ Requirement \ Range, km	10	20	30	50	75	100
1/20	I-2 I-2	II-2 II-3	V-3 II-3	II-3 II-3	II-4 II-4	II-4 II-4
1/50	II-3 II-3	III-3 III-3	III-3 III-3	III-4 III-4	III-4 III-4	III-5 III-5
1/100	III-3 III-3	III-4 III-4	III-4 III-4	III-5 III-5	IV-5 IV-5	IV-5 IV-5
1/200	III-4 III-4	III-5 III-5	III-5 IV-5	IV-5 IV-5	IV-6 IV-6	IV-6 IV-6
1/500	IV-5 IV-5	IV-6 IV-6	IV-6 IV-6	IV-6 V-6	V-6 V-6	IV-7 V-7
1/1000	V-6 V-6	V-6 V-6	V-6 V-6	VI-6 V-7	V-7 V-7	V-7 V-7
1/10,000	VII-7 VII-7	VII-7 VII-7	VII-7 VII-7	VII-7 -	- -	- -

TABLE 12-9

DEAD RECKONING REQUIREMENT TABLE—
DIRECTIONAL GYRO ALIGNMENT, σ_{GA}

Key: sc11 sc12
sc15 sc16
sc19 sc20
V = 8 km/hr

Range, km / $1/\eta$ Requirement	10		20		30		50		75		100	
1/20	I-1	I-1	I-1	I-1	II-1	II-1	II-1	II-1	II-1	II-1	II-1	II-1
	II-2	II-2	II-2	II-2	III-2	III-1	III-1	III-1	III-1	III-1	III-1	III-1
	II-1	II-1	II-1	II-1	III-1	III-1	IV-1	III-1	IV-1	III-3	IV-1	III-1
1/50	II-2	II-2	II-2	II-2	II-2	II-2	III-1	III-1	III-1	III-1	III-1	III-1
	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-2	III-2	III-2	III-2
	III-2	III-2	III-2	III-3	IV-2	III-3	IV-2	IV-2	IV-2	IV-2	IV-3	IV-3
1/100	III-3	III-3	III-3	III-3	III-3	III-3	III-4	IV-2	IV-2	IV-2	IV-2	IV-2
	IV-2	IV-2	IV-2	IV-2	IV-2	IV-2	IV-2	IV-2	IV-2	IV-2	IV-2	IV-2
	IV-3	IV-3	IV-3	IV-3	IV-3	IV-3	IV-3	IV-3	V-3	V-3	V-3	V-3
1/200	IV-3	IV-3	IV-3	IV-3	IV-3	IV-3	IV-3	IV-3	IV-3	V-3	IV-3	V-3
	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3
	IV-3	IV-3	IV-3	IV-3	IV-4	V-3	V-3	V-3	V-4	V-5	VI-3	VI-3
1/500	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3
	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-4
	IV-4	V-4	VI-3	V-5	VI-3	V-5	VI-4	VI-4	VI-4	VI-4	VI-5	VI-5
1/1000	V-5	V-5	V-5	V-5	V-5	V-5	V-5	V-5	V-5	V-5	V-5	V-5
	VI-4	VI-4	VI-4	VI-4	VI-4	VI-4	VI-4	VI-4	VI-4	VI-4	VI-4	VI-4
	VI-5	VI-5	VI-5	VI-5	VI-5	VI-5	VI-5	VI-5	VII-4	VII-4	VII-4	VII-4
1/10,000	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-
	VII-6	VII-7	VII-7	VII-7	VII-7	VII-7	VII-7	-	-	-	-	-

TABLE 12-10

DEAD RECKONING REQUIREMENT TABLE—
DIRECTIONAL GYRO DRIFT, σ_{gD}
Key: sc11 sc12
sc15 sc16
sc19 sc20
V = 8 km/hr

Range, km / $1/\eta$ Requirement	10		20		30		50		75		100	
1/20	I-1	I-1	I-1	I-1	I-2	I-2	I-2	I-2	I-2	I-2	II-2	II-2
	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-2	III-2	III-2	III-2
	II-1	II-1	II-2	II-2	II-3	II-3	III-2	III-2	IV-1	IV-1	IV-1	IV-1
1/50	II-2	II-2	II-2	II-2	II-2	II-2	II-3	II-3	III-3	III-3	III-3	III-3
	III-1	III-1	III-2	III-2	III-2	III-2	III-2	III-2	III-3	III-3	III-3	III-3
	III-1	III-2	III-2	III-2	III-3	III-3	IV-2	IV-2	IV-3	IV-3	IV-4	IV-4
1/100	III-2	III-2	III-2	III-3	III-3	III-3	III-3	IV-3	III-4	IV-4	III-4	III-4
	IV-2	IV-2	IV-2	IV-2	IV-2	IV-3	IV-2	IV-3	IV-2	IV-3	IV-2	IV-3
	III-2	III-2	IV-2	IV-2	IV-3	IV-3	IV-4	IV-4	V-3	V-3	V-4	V-4
1/200	IV-2	IV-3	IV-3	IV-3	IV-3	IV-4	IV-4	IV-4	IV-4	IV-5	IV-4	IV-5
	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-3	V-4	V-4	V-4	V-4
	IV-2	IV-2	IV-3	IV-3	V-3	V-3	V-4	V-4	VI-4	VI-4	VI-4	VI-4
1/500	V-3	V-3	V-3	V-3	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4
	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4
	V-3	V-3	V-4	V-4	V-5	VI-4	VI-4	VI-4	VI-4	VI-4	VI-5	VI-5
1/1000	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-5	V-5	V-5	V-5
	V-5	VI-4	V-5	VI-4	V-5	VI-4	V-5	VI-4	VI-4	VI-5	VI-4	VI-5
	V-3	V-4	VI-4	VI-4	VI-4	VI-4	VI-5	VI-5	VII-4	VII-4	VII-5	VII-5
1/10,000	VII-5	VII-6	VII-6	VII-6	VII-6	VII-6	VII-6	VII-6	VII-7	VII-7	VII-7	VII-7
	-	-	-	-	-	-	-	-	-	-	-	-
	VII-5	VII-6	VII-6	VII-6	VII-6	VII-6	-	-	-	-	-	-

TABLE 12-11

DEAD RECKONING REQUIREMENT TABLE—
PENDULOUS INCLINOMETER σ_p

Key: sc9sc11
sc13 sc15
sc19
V = 8 km/hr
$\epsilon^* = 77^o$

Range, km / 1/η Requirement	10	20	30	50	75	100
1/20	II-2 II-1 III-2 III-1 II-1	II-2 II-1 III-2 III-1 II-1	II-2 II-1 III-2 III-1 III-1	II-2 II-1 III-2 III-1 III-1	II-2 II-1 III-2 III-1 III-3	II-2 II-1 III-2 III-1 IV-1
1/50	III-3 III-1 III-3 III-1 III-1	III-3 III-1 III-3 III-1 III-2	III-3 III-1 III-3 III-1 III-3	III-3 III-1 III-3 III-1 IV-1	III-3 III-1 III-3 III-1 IV-2	III-3 III-1 III-3 III-1 IV-2
1/100	IV-3 III-2 IV-3 IV-2 III-3	IV-3 III-2 IV-3 IV-2 IV-2	IV-3 III-2 IV-3 IV-2 IV-2	IV-3 III-2 IV-3 IV-2 IV-3	IV-3 IV-1 IV-3 IV-2 V-1	IV-3 IV-1 IV-3 IV-2 V-2
1/200	IV-5 IV-1 V-4 V-2 V-3	IV-5 IV-1 V-4 V-2 V-4	IV-5 IV-1 V-4 V-2 V-4	IV-5 IV-1 V-4 V-2 VI-3	IV-5 IV-1 V-4 V-2 VI-3	IV-5 IV-1 V-4 V-2 VI-5
1/500	V-5 V-1 V-5 V-3 V-3	V-5 V-1 V-5 V-3 V-4	V-5 V-1 V-5 VI-4 V-4	V-5 V-1 VI-5 VI-4 VI-3	V-5 V-1 VI-5 VI-4 VI-3	V-5 V-1 V-5 V-3 VI-5
1/1000	VI-5 V-3 VI-5 VI-4 V-4	VI-5 V-3 VI-5 VI-4 VI-4	VI-5 V-3 VI-5 VI-4 VI-4	VI-5 V-3 VI-5 VI-4 VI-5	VI-5 V-3 VI-5 VI-4 VII-4	VI-5 V-3 VI-5 VI-4 VII-4
1/10,000	- VII-5 - - VII-6	- VII-5 - - VII-6	- VII-5 - - VII-7	- VII-5 - - VII-7	- VII-5 - - - -	- VII-5 - - - -

TABLE 12-12

DEAD RECKONING REQUIREMENT TABLE—
VERTICAL GYRO, σ_p

Key: sc10 sc12
sc14 sc16
sc20

$1/\eta$ Requirement \ Range, km	10	20	30	50	75	100
1/20	II-2 I-1 III-2 III-1 II-1	II-2 I-1 III-2 III-1 II-1	II-2 II-1 III-2 III-1 III-1	II-2 II-1 III-2 III-1 III-1	III-2 II-1 III-2 III-1 IV-2	III-2 II-1 III-2 III-1 IV-2
1/50	III-3 III-1 III-4 III-1 III-2	III-3 III-1 III-4 III-1 III-2	III-3 III-1 III-5 III-1 IV-1	III-3 III-1 IV-3 III-1 IV-1	IV-3 III-1 IV-3 III-1 IV-2	IV-3 III-1 IV-3 III-1 IV-2
1/100	IV-3 IV-1 IV-3 IV-2 IV-2	IV-3 IV-1 IV-3 IV-2 IV-2	IV-3 IV-1 IV-3 IV-2 IV-2	IV-3 IV-1 IV-4 IV-2 IV-3	IV-4 IV-1 IV-5 IV-2 V-2	IV-4 IV-1 IV-5 IV-2 V-3
i/200	V-4 IV-1 V-4 V-2 IV-3	V-4 IV-1 V-4 V-2 IV-3	V-4 IV-1 V-4 V-2 V-3	V-4 IV-1 V-4 V-2 V-3	V-5 IV-1 V-4 V-2 VI-3	V-5 IV-1 V-5 V-2 VI-3
1/500	VI-5 V-1 VI-5 V-3 V-3	VI-5 V-1 VI-5 V-3 V-4	VI-5 V-1 VI-5 V-3 VI-4	VI-5 V-1 VI-5 V-3 VI-4	VI-6 V-1 VI-5 V-3 VI-4	VI-6 V-1 VII-5 V-3 VI-5
1/1000	VI-5 V-3 VII-5 VI-4 VI-4	VI-5 V-3 VII-5 VI-4 VI-4	VI-5 V-3 VII-5 VI-4 VI-4	VII-4 V-3 VII-5 VI-4 VI-5	VII-4 VI-1 VII-5 VI-4 VII-4	VII-4 VI-1 VII-5 VI-4 VII-4
1/10,000	- VII-5 - - VII-6	- VII-5 - - VII-6	- VII-5 - - VII-7	- VII-5 - - -	- VII-5 - - -	- VII-5 - - -

TABLE 12-13

DEAD RECKONING REQUIREMENT TABLE—VERTICAL GYRO DRIFT, σ_{pD}

Key: sc10 sc12

sc14 sc16

sc20

$V = 8$ km/hr

$\epsilon^* = 77°$

Requirement $1/\eta$ \ Range, km	10		20		30		50		75		100	
1/20	II-1	I-1	II-2	I-1	II-2	II-1	II-3	II-1	II-3	II-1	II-3	II-1
	III-1	III-1	III-1	III-1	III-2	III-1	III-2	III-1	III-2	III-1	III-2	III-1
	II-1		II-1		III-1		III-1		III-2		IV-2	
1/50	III-1	II-1	III-1	II-1	III-2	II-1	III-3	III-1	III-3	III-1	III-3	III-1
	III-2	III-1	III-3	III-1	III-4	III-1	III-4	III-1	III-5	III-2	III-5	III-2
	III-1		III-1		IV-1		IV-2		IV-3		IV-3	
1/100	IV-2	III-1	IV-3	III-1	IV-3	III-1	IV-4	III-1	IV-4	IV-1	IV-4	IV-1
	IV-2	IV-1	IV-3	IV-4	IV-4	IV-2	IV-4	IV-2	IV-4	IV-1	IV-5	IV-2
	IV-1		IV-1		V-2		IV-4		V-2		V-3	
1/200	V-4	IV-1	V-4	IV-1	V-4	IV-1	V-4	IV-1	V-4	IV-1	V-5	IV-2
	V-4	V-2	V-4	V-2	V-4	V-2	V-4	V-2	V-5	V-2	V-5	V-3
	IV-2		IV-2		IV-4		V-3		VI-3		VI-3	
1/500	V-4	V-1	V-5	V-1	V-6	V-1	V-6	V-1	V-6	V-2	V-6	V-2
	V-6	V-2	V-6	V-2	VI-5	V-3	VI-6	V-3	VI-6	V-4	VI-7	V-4
	VI-2		VI-2		VI-3		VI-4		VI-5		VI-6	
1/1000	VI-5	V-2	VI-6	V-2	VI-6	V-2	VI-7	V-2	VI-7	V-3	VI-7	V-3
	VI-6	VI-2	VI-7	VI-3	VI-7	VI-4	VI-7	VI-4	VI-7	VI-5	VI-7	VI-5
	VI-2		VI-3		VI-4		VI-6		VII-5		VII-5	
1/10,000	-	VII-4	-	VII-4	-	VII-4	-	VII-6	-	VII-6	-	VII-6
	-	-	-	-	-	-	-	-	-	-	-	-
	VII-6		VII-7		VII-7		-		-		-	

TABLE 12-14

DEAD RECKONING REQUIREMENT TABLE—CELESTIAL TRACKER, σ_a

Key: sc9 sc10

sc13 sc14

V = 8 km/hr

$\epsilon^* = 77^o$

Range, km / $1/\eta$ Requirement	10		20		30		50		75		100	
1/20	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2
	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2	III-2
1/50	III-3	III-3	III-3	III-3	III-3	III-4	III-3	III-4	III-3	III-4	III-3	IV-3
	III-3	III-4	III-3	III-4	III-3	III-4	III-3	III-4	III-3	III-4	III-3	IV-3
1/100	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4
	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-4	IV-5
1/200	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4
	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4	V-4
1/500	V-5	V-5	V-5	V-5	V-5	V-6	V-5	VI-6	V-5	VI-6	V-5	VI-6
	V-5	V-5	V-5	V-6	V-5	V-6	V-5	VI-5	V-5	VI-6	V-5	VI-6
1/1000	V-6	VI-6	V-6	VI-6	V-6	VI-6	VI-6	VII-6	VI-6	VII-6	VI-6	VII-6
	VI-6	VI-6	VI-6	VI-7	VI-6	VI-7	VI-6	VII-6	VI-6	VII-6	VI-6	VII-6
1/10,000	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 12-15

DEAD RECKONING REQUIREMENT TABLE—EPHEMERIS, σ_{RE}

Key: sc9 sc10

sc1[illegible] sc14

V = 8 km/hr

$\epsilon^* = 77^\circ$

$1/\eta$ Requirement \ Range, km	10		20		30		50		75		100	
1/20	II-1	II-1	II-1	II-1	II-	II-1	II-1	III-1	II-1	III-1	II-1	III-1
	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1
1/50	III-1	III-1	III-1	III-1	III-1	III-1	III-1	IV-1	III-1	IV-1	III-1	IV-1
	III-1	III-1	III-1	III-1	III-1	III-2	III-1	IV-1	III-1	IV-1	III-1	IV-1
1/100	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1
	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-2
1/200	IV-2	V-1	IV-2	V-1	IV-2	V-1	IV-2	V-1	IV-2	V-1	IV-2	V-2
	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-2
1/500	V-2	V-3	V-2	V-3	V-2	V-3	V-2	VI-1	V-2	VI-1	V-2	VI-1
	V-2	VI-1	V-2	VI-1	V-2	VI-2	V-2	VI-2	V-2	VI-2	V-2	VII-2
1/1000	VI-2	VI-3	VI-2	VI-4	VI-2	VI-4	VI-2	VII-2	VI-2	VII-2	VI-2	VII-2
	VI-2	VI-3	VI-2	VI-3	VI-2	VI-3	VI-2	VII-2	VI-2	VII-2	VI-2	VII-2
1/10,000	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-

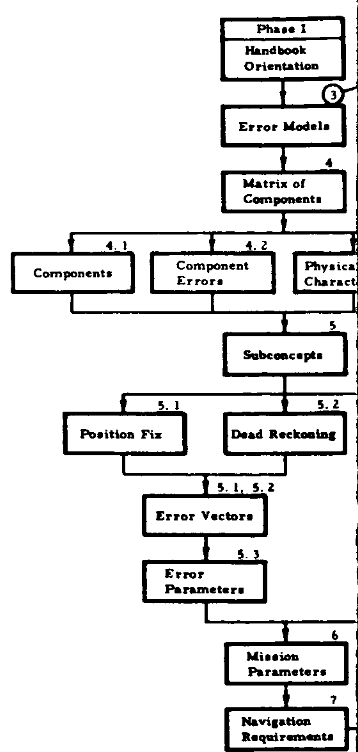
TABLE 12-16

DEAD RECKONING REQUIREMENT TABLE—TIMER, σ_t, K_t

Key: sc9 sc10
sc13 sc14
V = 8 km/hr
$\epsilon^* = 77^o$

$1/\eta$ Requirement \ Range, km	10		20		30		50		75		100	
1/20	II-1	II-1	II-1	II-1	II-1	II-1	II-1	III-1	II-1	III-1	II-1	III-1
	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1	III-1
1/50	III-1	IV-1	III-1	IV-1	III-1	IV-1	III-1	IV-1	III-1	IV-1	III-1	IV-1
	III-1	III-1	III-1	III-1	III-1	III-1	III-1	IV-1	III-1	IV-1	III-1	IV-1
1/100	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1
	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1	IV-1
1/200	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1
	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1	V-1
1/500	V-1	V-1	V-1	VI-1	V-1	VI-1	V-1	VI-1	V-1	VII-1	V-1	VII-1
	V-1	VI-1	V-1	VI-1	V-1	VI-1	V-1	VII-1	V-1	VII-1	V-1	VII-1
1/1000	V-1	VI-1	VI-1	VII-1	VI-1	VII-1	VI-1	VII-1	VI-1	VII-1	VI-1	VII-1
	VI-1	VI-2	VI-1	VII-1	VI-1	VII-1	VI-1	VII-1	VI-1	VII-1	VI-1	VII-1
1/10,000	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-

Key:
sc9 sc10
sc13 sc14
V=8km/hr
$e^* = 77^o$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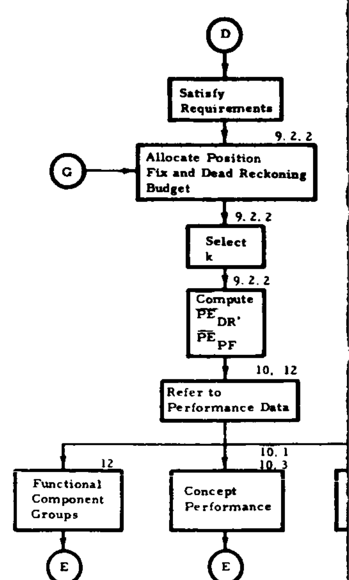
Handbook Orientation
3
Error Models
4
Matrix of Components
4.1
Components
4.2
Component Errors
5
Subconcepts
5.1
Position Fix
5.2
Dead Reckoning
5.1, 5.2
Error Vectors
5.3
Error Parameters
6
Mission Parameters
7
Navigation Requirements


D
Satisfy Requirements
9.2.2
Allocate Position Fix and Dead Reckoning Budget
G
9.2.2
Select k
9.2.2
Compute $\overline{PE}_{DR}$, $\overline{PE}_{PF}$
10, 12
Refer to Performance Data
12
Functional Component Groups
10.1
10.3
Concept Performance
E
E

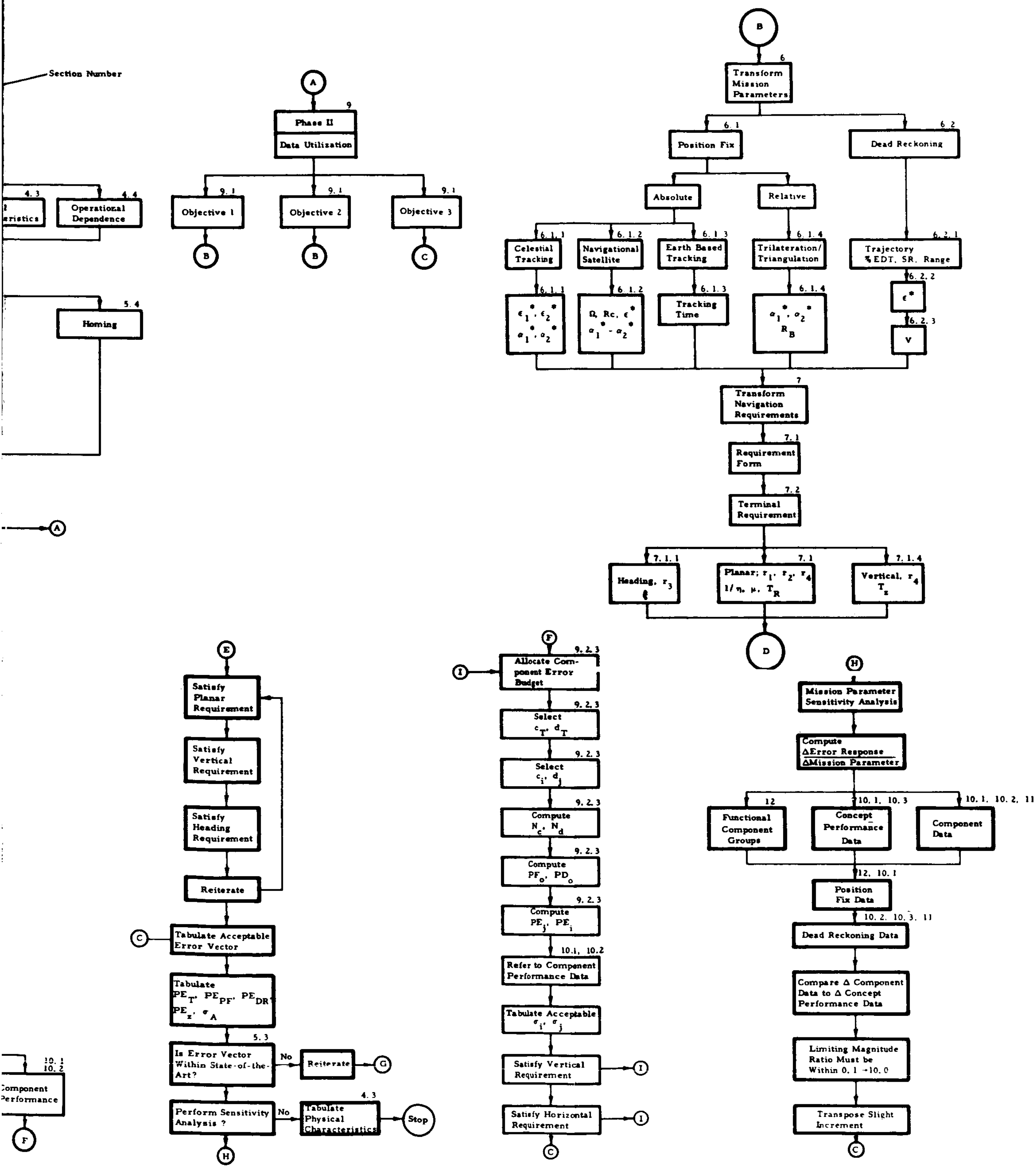


Figure 9-2A Data Utilization

Fig 9-2B

FOR REFERENCE, SEE PAGE 12-27/12-28