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EFFECT OF DOWNLINK PHASED ARRAY PATTERNS ON SYSTEM AVAILABILITY--ETC(U)

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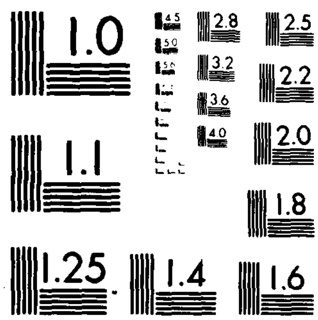

MICROCOPY RESOLUTION TEST CHART

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

(6)

EFFECT OF DOWNLINK PHASED ARRAY PATTERNS ON SYSTEM AVAILABILITY CONTOUR PREDICTIONS

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Abstract

The relative variation in the pattern function for a 32 element, multi-beam EHF satellite phased array has been incorporated into the equation for downlink margin. The corrected margin is used to determine allowable rain attenuation (dB) and predict link availability based on Crane's 8 region world wide rain rate distribution and climate model. Link availability contours are computed for the cases of a 31 beam and 37 beam phased array. Four equi-spaced geostationary satellites are required for either configuration in order to provide 0.99 (or greater) link availability to all points within the 10° elevation angle field of view for the nominal value of downlink margin and a frequency of 20.7 GHz.

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I. INTRODUCTION

A numerical model for computing predicted values of system availability for geostationary satellites operating in EHF or SHF bands has been generated and documented[1]. That model utilizes Crane's 8 region rain rate distribution and climate model[2,3] to determine an allowable value of rain attenuation corresponding to threshold operation from the relation given in Eqn. (1). For any visible point on the Earth's surface, this long term value of allowable attenuation is used to predict percent of time (of year) for which that value of attenuation is exceeded and, hence, availability.

$$L_{rain}(dB) = M(dB) - L_{slant\ range}(dB) - L_{absorption}(dB) \tag{1}$$

where

M = parametric value of system margin (dB)

L_{rain} = allowable rain attenuation (dB)

$L_{slant\ range}$ = differential slant range loss (dB)

$L_{absorption}$ = clear sky attenuation for a moderately humid atmosphere (dB)

The model described in Reference 1 made no provisions for variations in antenna pattern coverage over the Earth field of view, i.e., a uniform (isotropic) gain value was assumed.

The current system design contains a 32 element phased array structure for the downlink antenna. The phase shifters will be programmed to produce a pattern of multiple beams. Current design calls for this pattern to be implemented with 31 beams, the totality of which covers the entire Earth field of view. Prior designs called for the implementation using 37 beams. In either case, the downlink array gain pattern varies less than 5 dB between the maximum value found at the subpoint and the minimum value found at several points on the Earth limb. The system availability contour plots generated in this report incorporate this gain variation for the downlink phased array in determining allowable rain attenuation for threshold operation per Eqn. (2).

$$L_{rain} = M(dB) - L_{slant\ range}(dB) - L_{absorbtion}(dB) + \Delta G_{PA}(dB) \qquad (2)$$

where

ΔG_{PA} = gain degradation variation (dB) of the downlink phased array pattern for any point in the Earth field of view

The computed results given in Section III of this report show moderate reductions in the computed values of system availability in concurrence with the related reduction of allowable rain attenuation per Eqn. (2).

II. BACKGROUND

A. 31 and 37 Beam Downlink Multiple Beam Antenna Configurations

The current system description contains a 32 element downlink phased array structure. Since the selection of the number of beams used to cover the Earth field of view has no direct relationship to the choice of the number of elements in the phased array, it is reasonable to allow and even expect the number of beams to vary during the period of detailed delineation of user requirements. In fact, the most recent description shows the downlink phased array as providing 31 beams vs the previously defined 37 beam distribution covering the Earth field of view.

Fig. 1 shows the distribution of the 31 beam configuration over the Earth view projection plane. The smaller circles represent individual beams and are plotted so that all the interior beams just touch one another. As such, the circles do not represent any specific value of relative gain. The 37 beam configuration of the prior baseline is shown in Fig. 2 again using idealized circular beam cross-sections to depict the individual beams. The current 31 beam configuration is derivable from the prior baseline 37 beam configuration by deleting the six vertex beams, enlarging the area of coverage for each individual beam 3.40^{o} vs 2.98^{o} to beam osculation points, and slightly (0.6^{o}) pulling the centers of the six outermost pairs of beams toward the center of the Earth field of view. The latter modification has the effect of reducing the beam spacing parameter for the outermost 12 beams (3.1732^{o} vs 3.40^{o} for the remainder of the beams). The calculations performed to compute this effective beam spacing parameter for the six pairs of peripheral beams are reproduced in Appendix A. A review of the highlights of the phased array structure is given in Appendix B.

B. System Margin Computation

The system availability contours provided in Reference 1 were computed for 3 parametric values of link margin (6, 12, and 18 dB, respectively). The plots generated for those values were intended for use in scoping system availability as a function of basic system design variables. The current

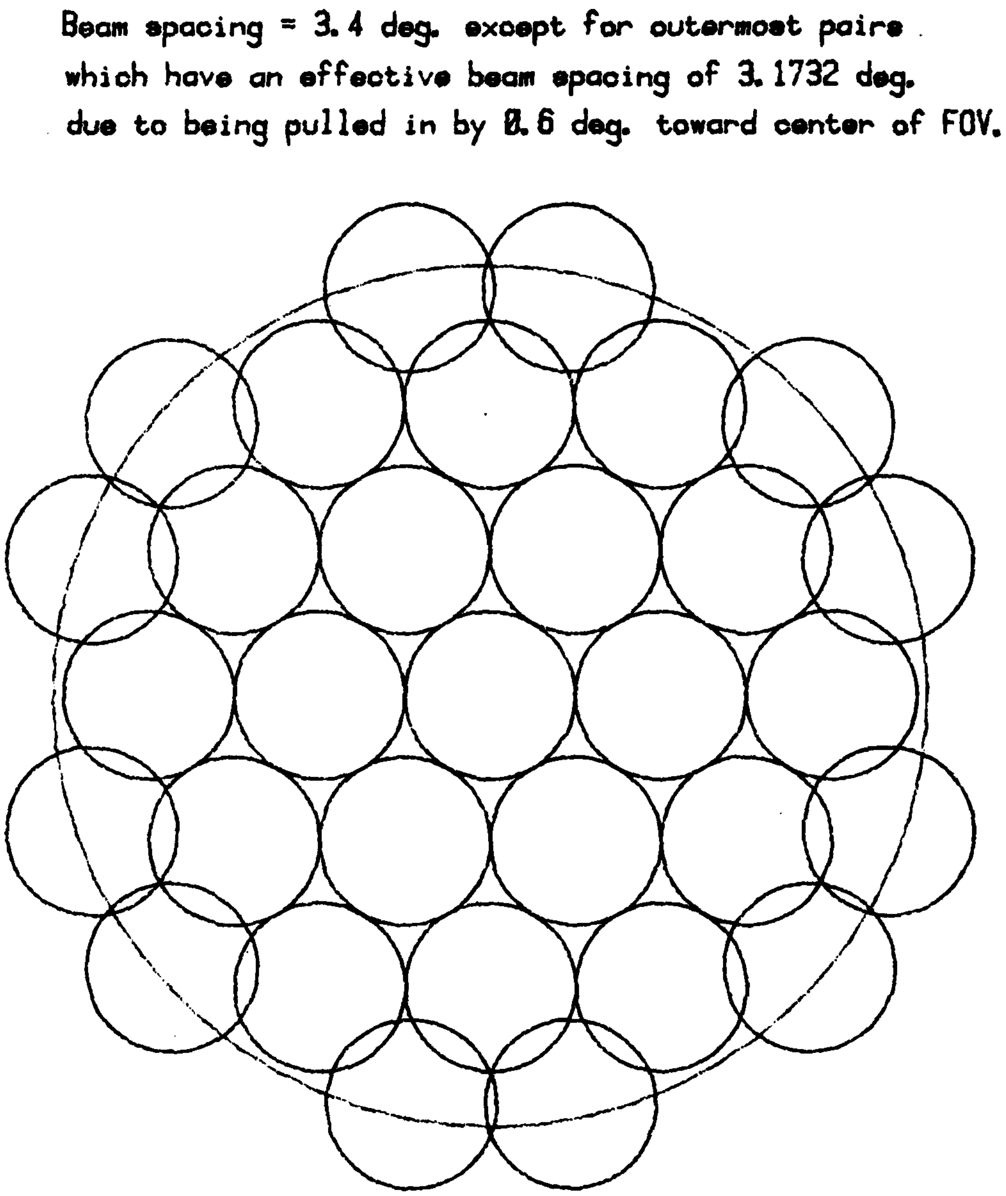

Fig. 1. Current system downlink beam coverage (32 elements; 31 beams)

Beam spacing = 2.98 deg. for all beams.

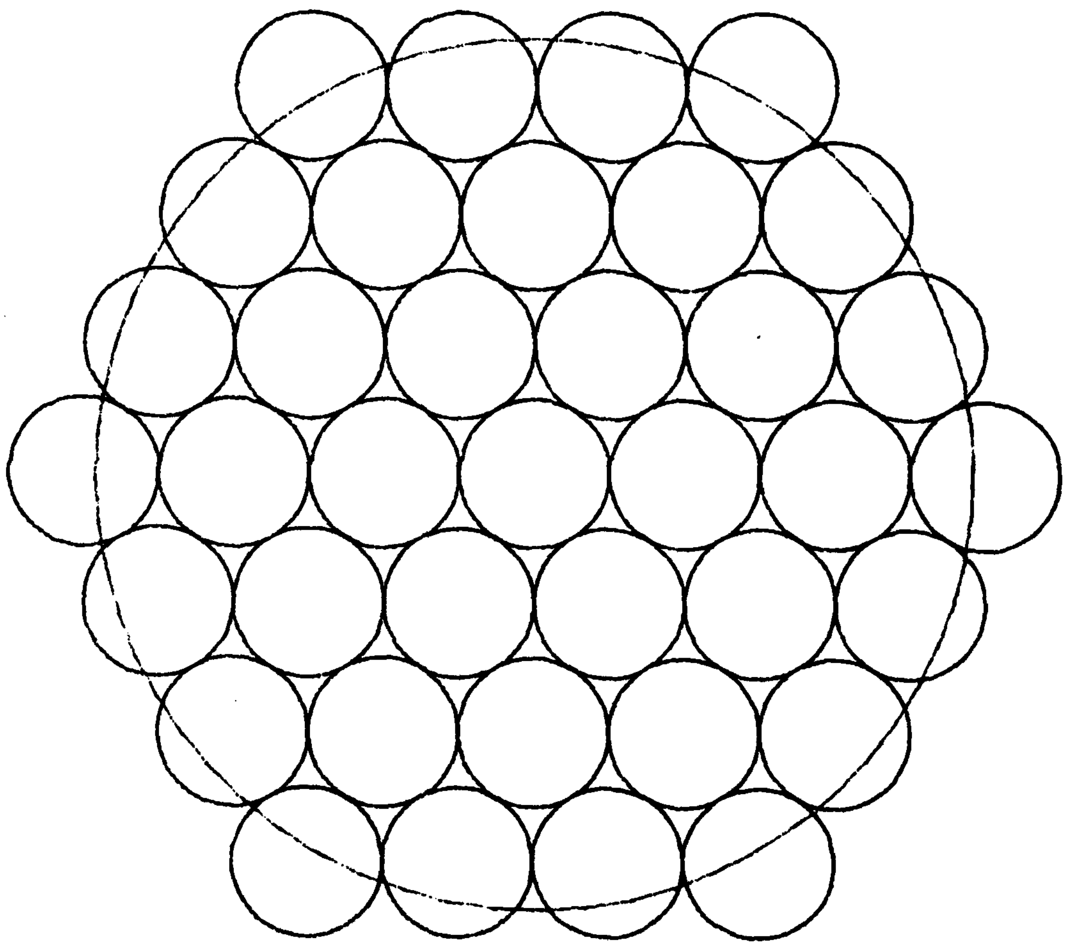

Fig. 2. Prior system downlink beam coverage (32 elements; 37 beams)

system configuration, however, has called out specific values for the downlink parameters (e.g., center frequency of 20.7 GHz and nominal system margin of 13.6 dB for the current baseline and 13.0 dB for the prior baseline (37 beam) array). The derivation of nominal system margin has been reviewed in Table I.

The required value of P_R/N_0 (59.2 dB) represents the nominal data loading case of 52 vocoded voice (VV) users of 2400 bps each with 2 frequency hops per user per data frame (or an equivalent number of moderate bandwidth channels). An increase or reduction by 3 dB from this nominal downlink margin requirement represents an approximate corresponding increase or decrease by a factor of 2 in the user data rates. Current system budgets allow for this (and greater) variation in data rates.

TABLE I

NOMINAL DOWNLINK PHASED ARRAY SYSTEM MARGIN

32 Element PA (Transmit) Gain	+33.0 dBi for 37 beam array +33.6 dBi for 31 beam array
Hardware/Circuit Loss	- 0.4 dB
Phase Shifter Quantization loss	- 0.2 dB
Transmit Power (19.2 W)	+12.8 dBw
Net Satellite EIRP	+45.2 dBw for 37 beam array +45.8 dBw for 31 beam array
Path Loss	-209.8 dB (at subpoint)
Terminal Receive Gain	+39.4 dBi
Receive Feedline Loss	- 1.0 dB
Radome Loss	- 1.0 dB
Pointing Loss	- 0.4 dB
Net Receive Power (P_R)	-127.0 dBw for 31 beam array -127.6 dBw for 37 beam array
Eff. Noise Temp. (N_0) = 800°K	-199.8 dBw
Available P_R/N_0	72.8 dB
Required P_R/N_0	59.2 dB
Downlink Margin	+13.6 dB for 31 beam array +13.0 dB for 37 beam array

III. COMPUTED RESULTS

All availability computations are done for the frequency of 20.7 GHz, the center frequency of the currently defined downlink band. Geostationary orbit and a set of four subpoints (110°W, 20°W, 70°E, 160°E) are assumed. Three margin levels (10.6 dB, 13.6 dB, and 16.6 dB) are used for two of the three downlink array pattern functions (uniform isotropic coverage and 31 beam coverage pattern). The margin levels (10 dB and 16 dB) are used for the 37 beam coverage pattern. Figs. 3-38 provide plots of the system availability contour levels on a Mercator grid of the Earth within the field of view.

The order of the computed availability contour plots is as follows. The 12 cases for the uniform pattern coverage are given in Figs. 3-14, first for the baseline 13.6 dB link margin (Figs. 3-6), then for the 10.6 dB cases (Figs. 7-10), and the 16.6 dB cases (Figs. 11-14). Within each group of four plots, the subpoints are ordered from west to east starting at -110°(W) through +160°(E) in constant 90° increments. Using the same ordering procedure as described above, the 12 cases for the current system baseline 31 beam downlink phased array are given in Figs. 15-26 and those for the prior baseline 37 beam phased array (using the corresponding values of link margin) are given in Figs. 27-38.

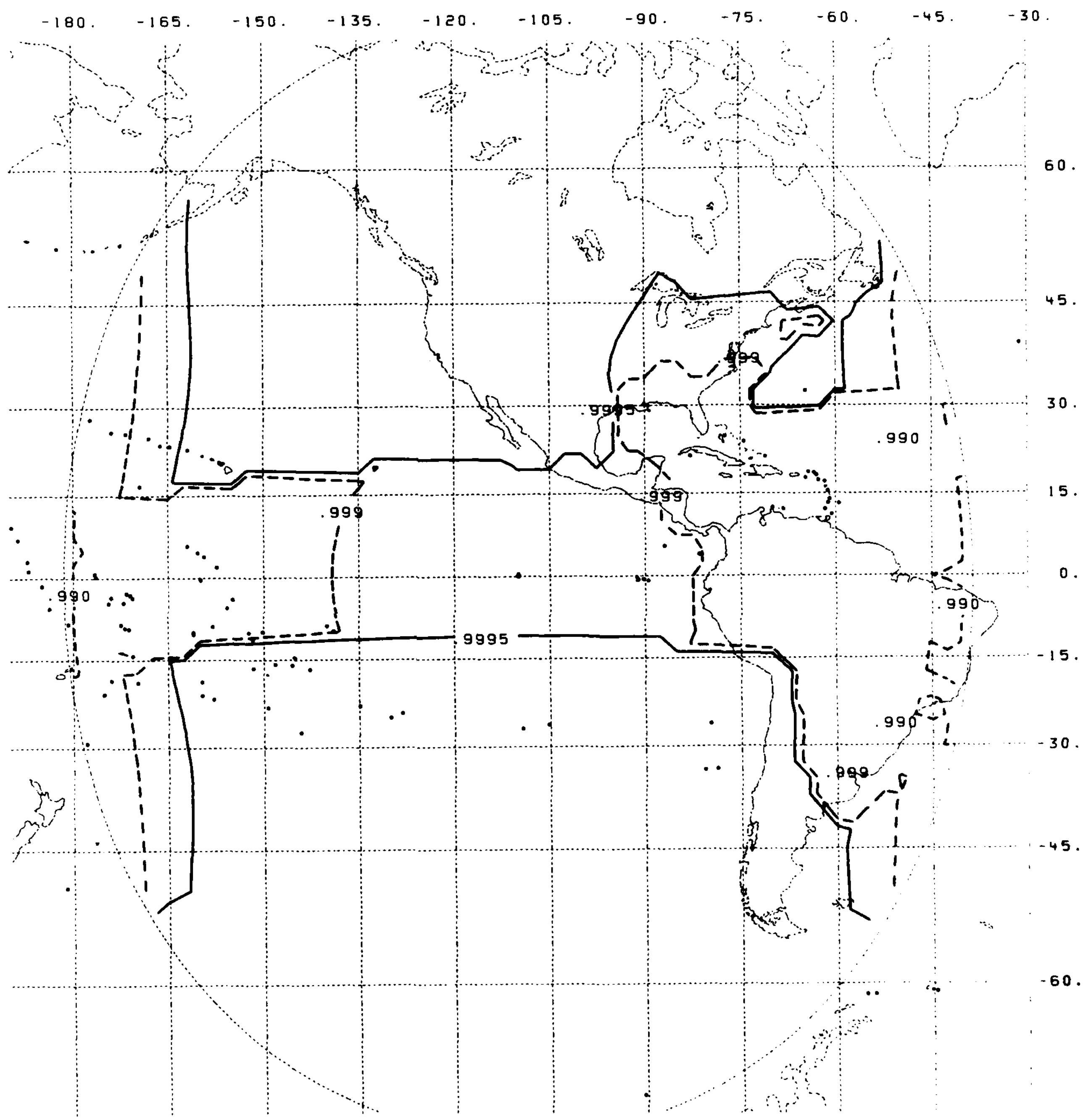

Fig. 3. Availability contours for uniform pattern; 13.6 dB margin; 110°W subpoint

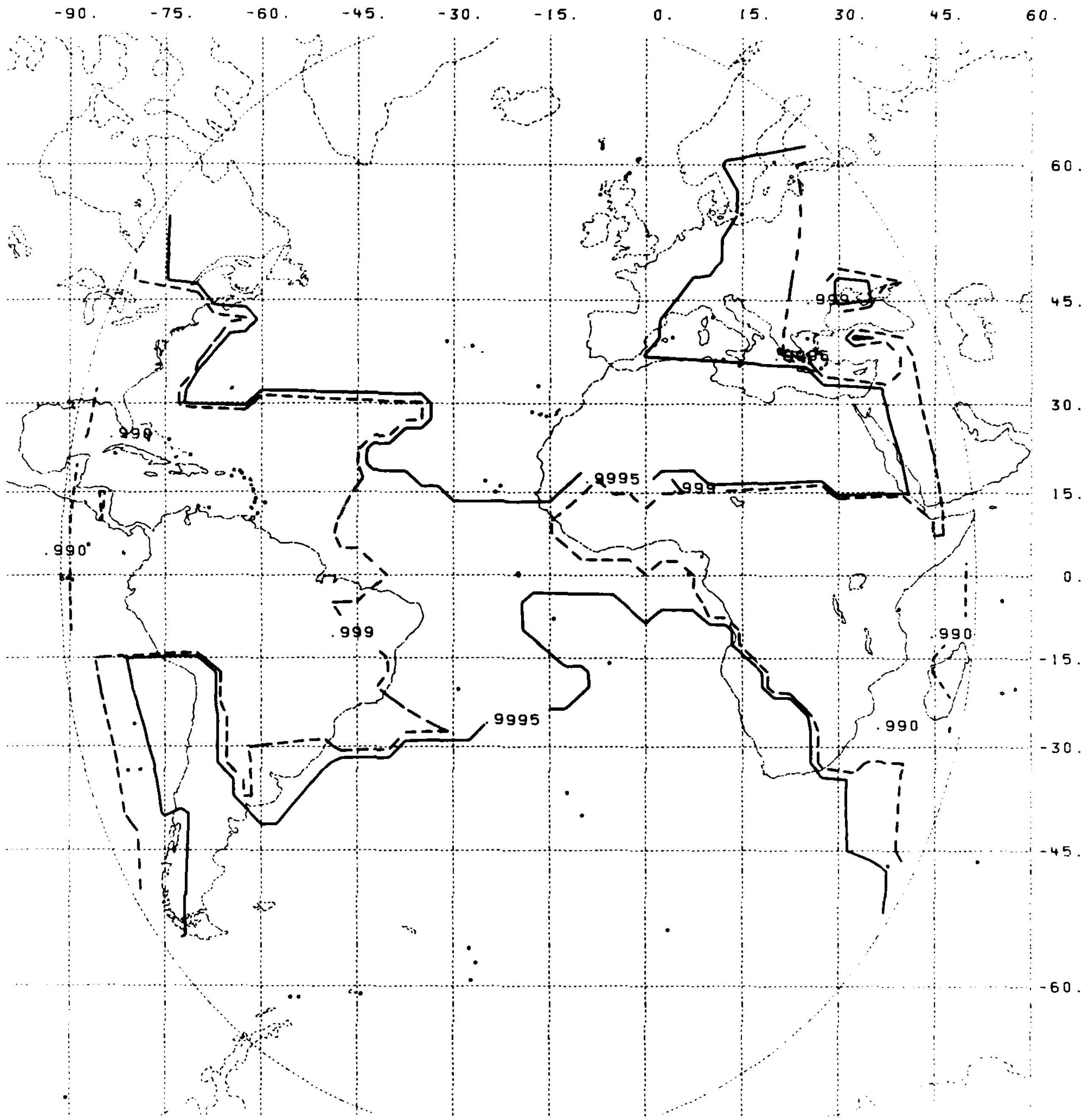

Fig. 4. Availability contours for uniform pattern; 13.6 dB margin; 20°W subpoint

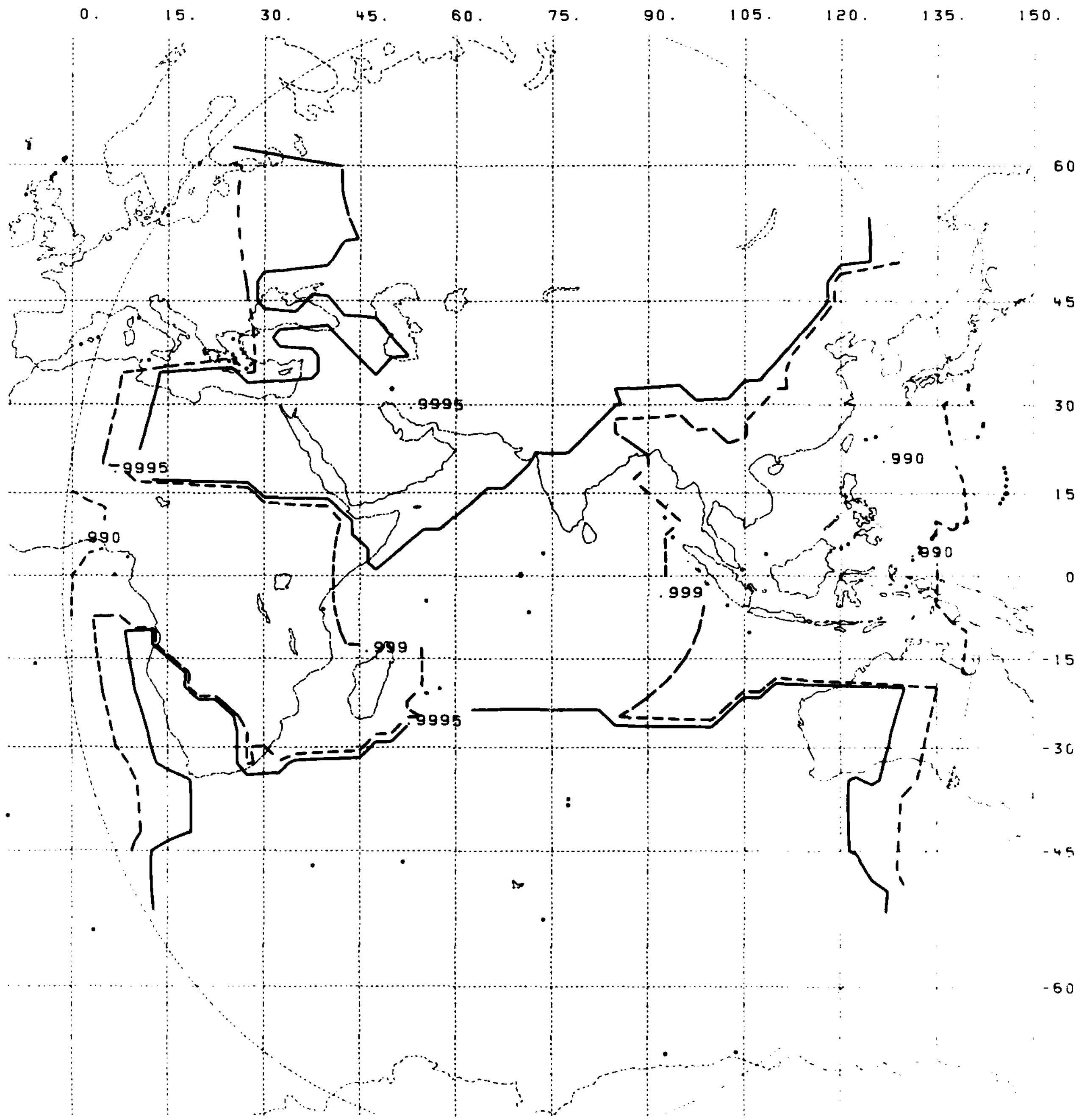

Fig. 5. Availability contours for uniform pattern; 13.6 dB margin; 70°E subpoint

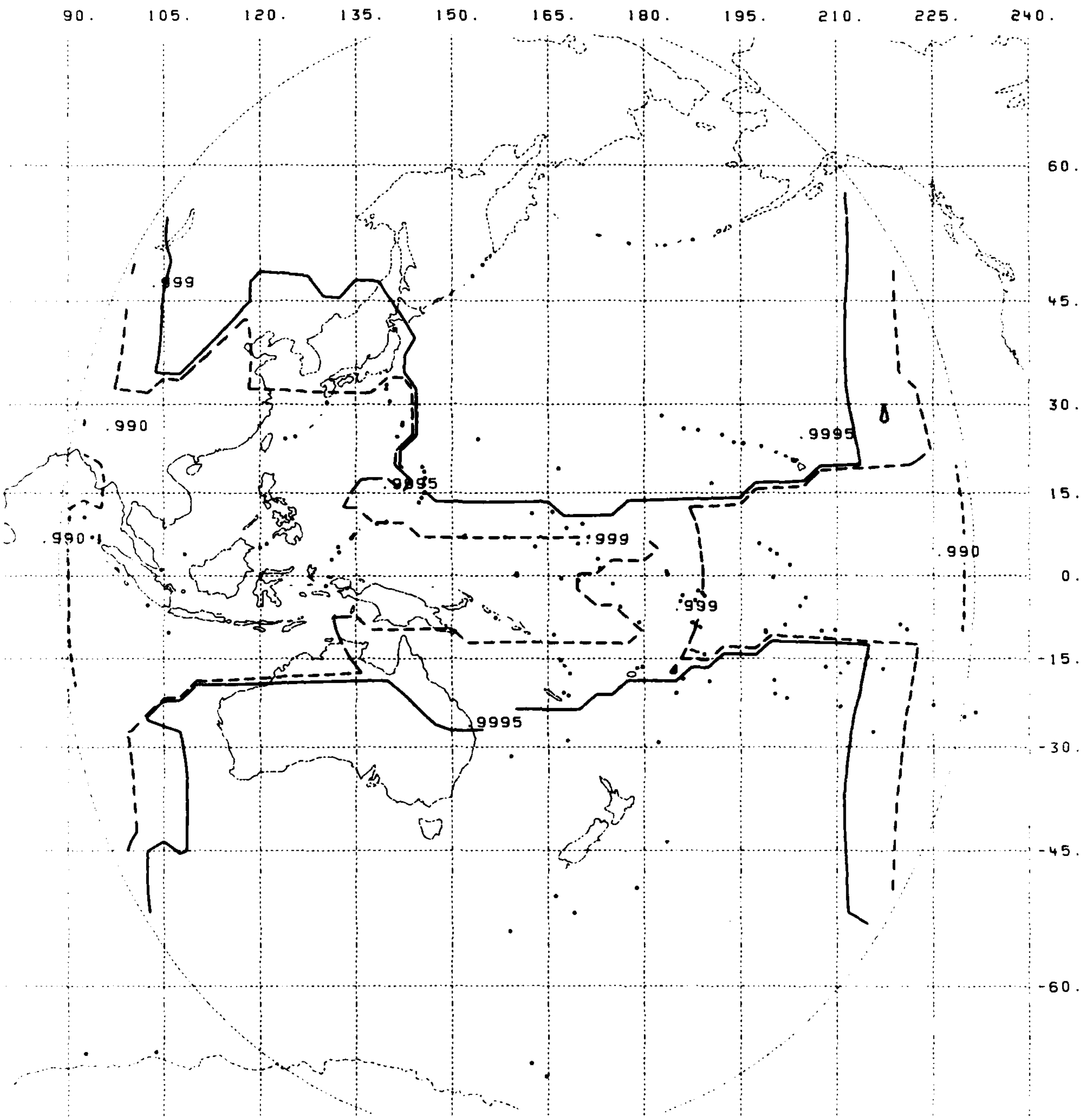

Fig. 6. Availability contours for uniform pattern; 13.6 dB margin; 160°E subpoint

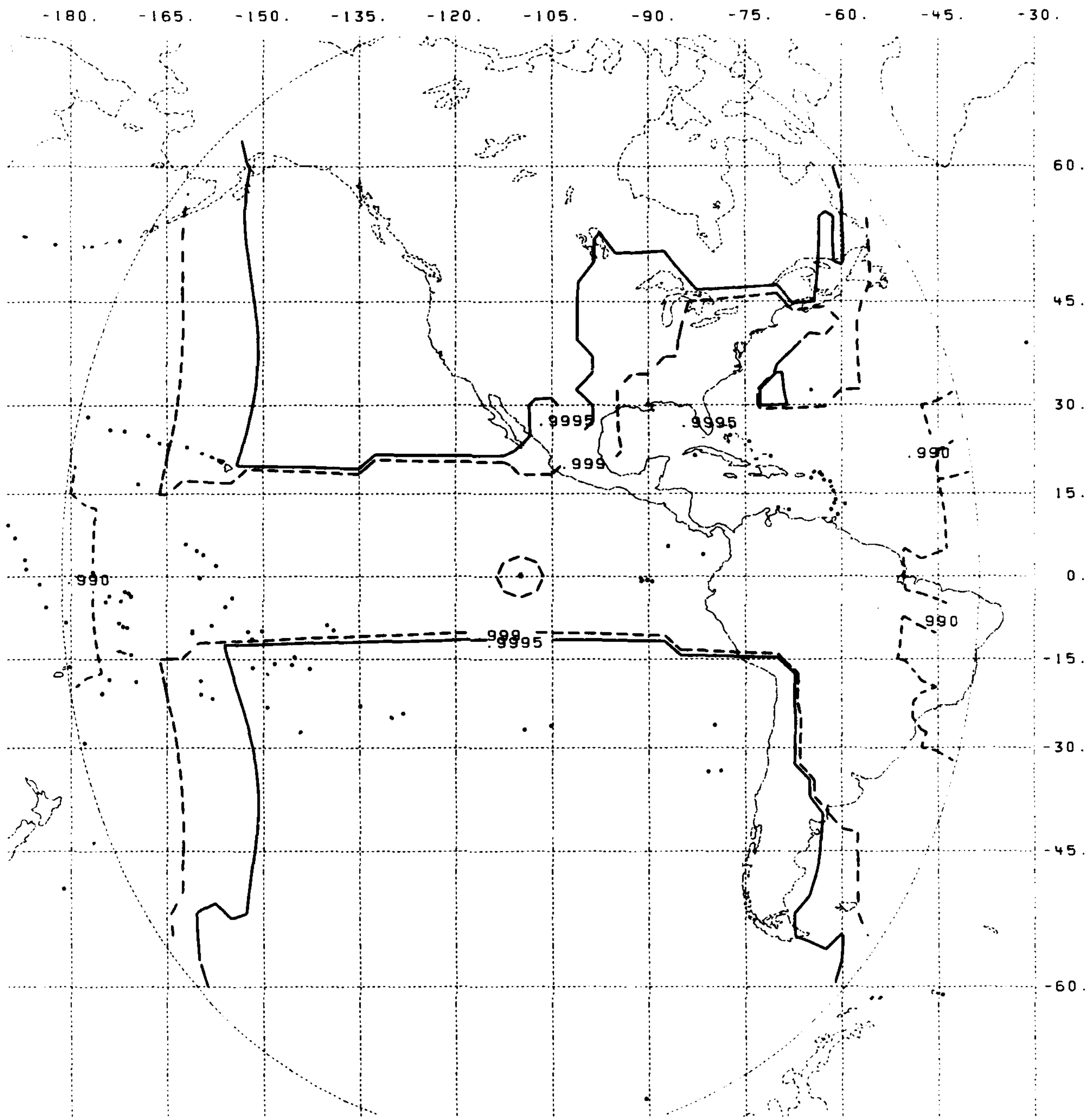

Fig. 7. Availability contours for uniform pattern; 10.6 dB margin; 110°W subpoint

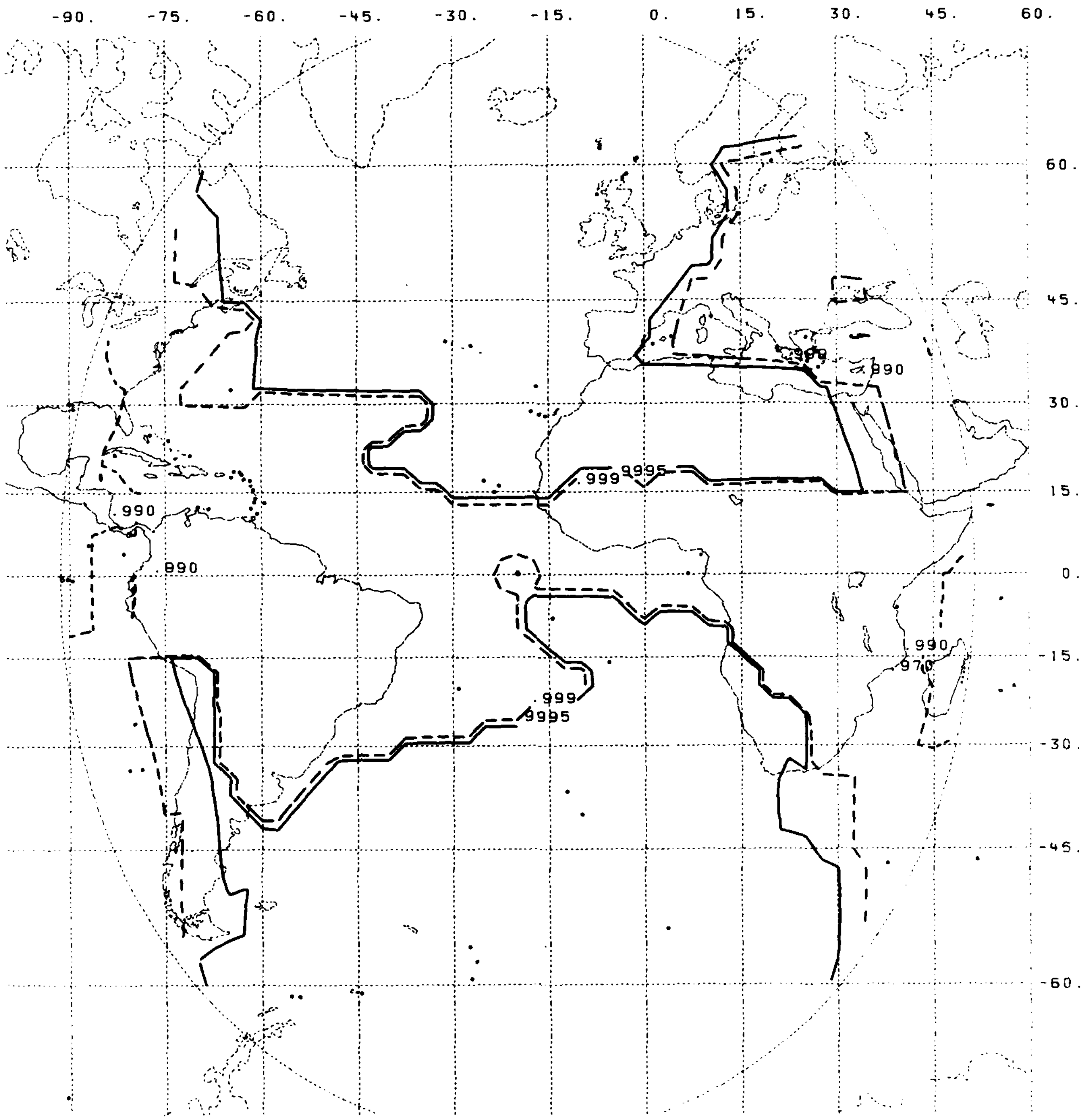

Fig. 8. Availability contours for uniform pattern; 10.6 dB margin; 20°W subpoint

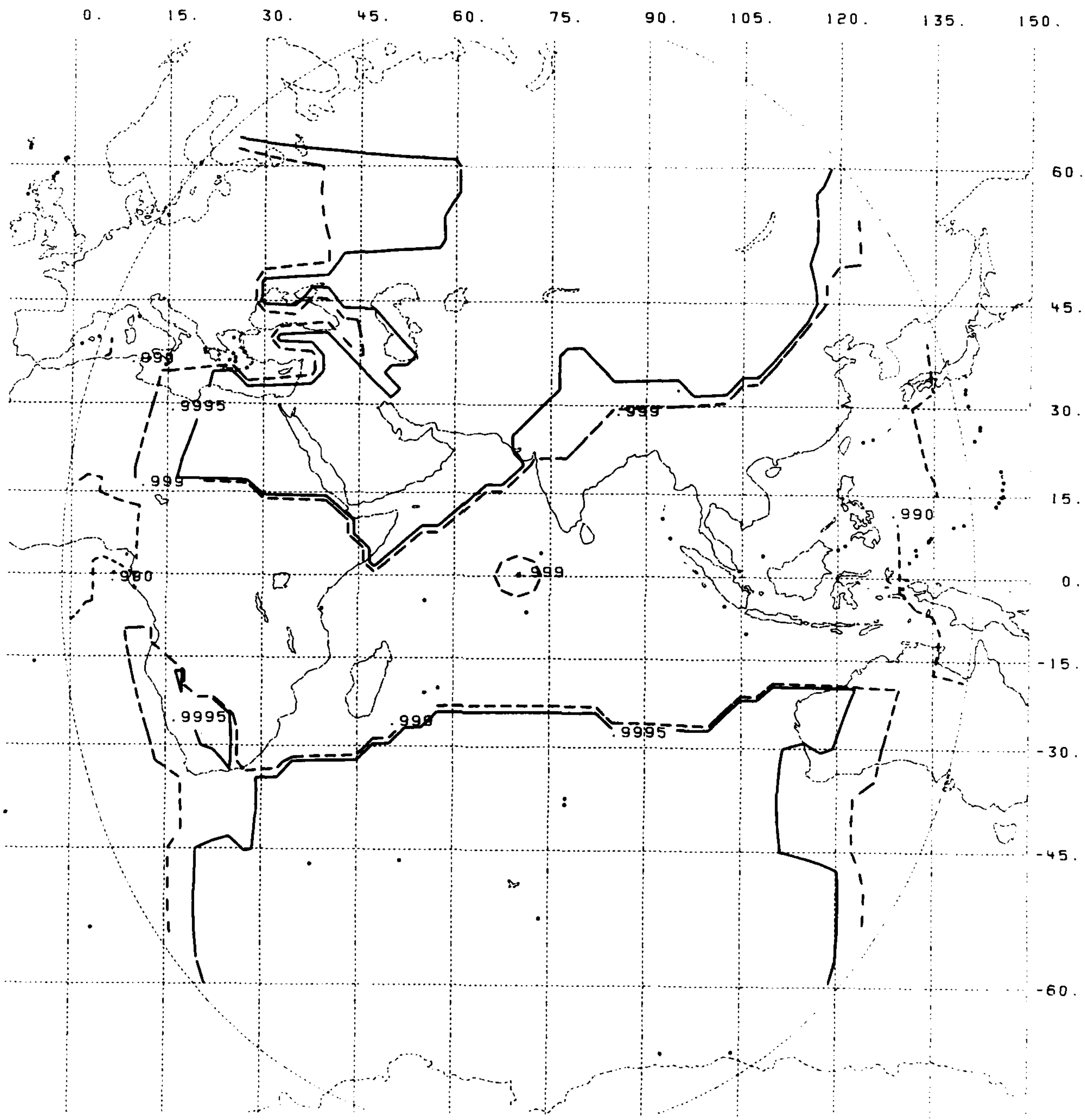

Fig. 9. Availability contours for uniform pattern; 10.6 dB margin; 70°E subpoint

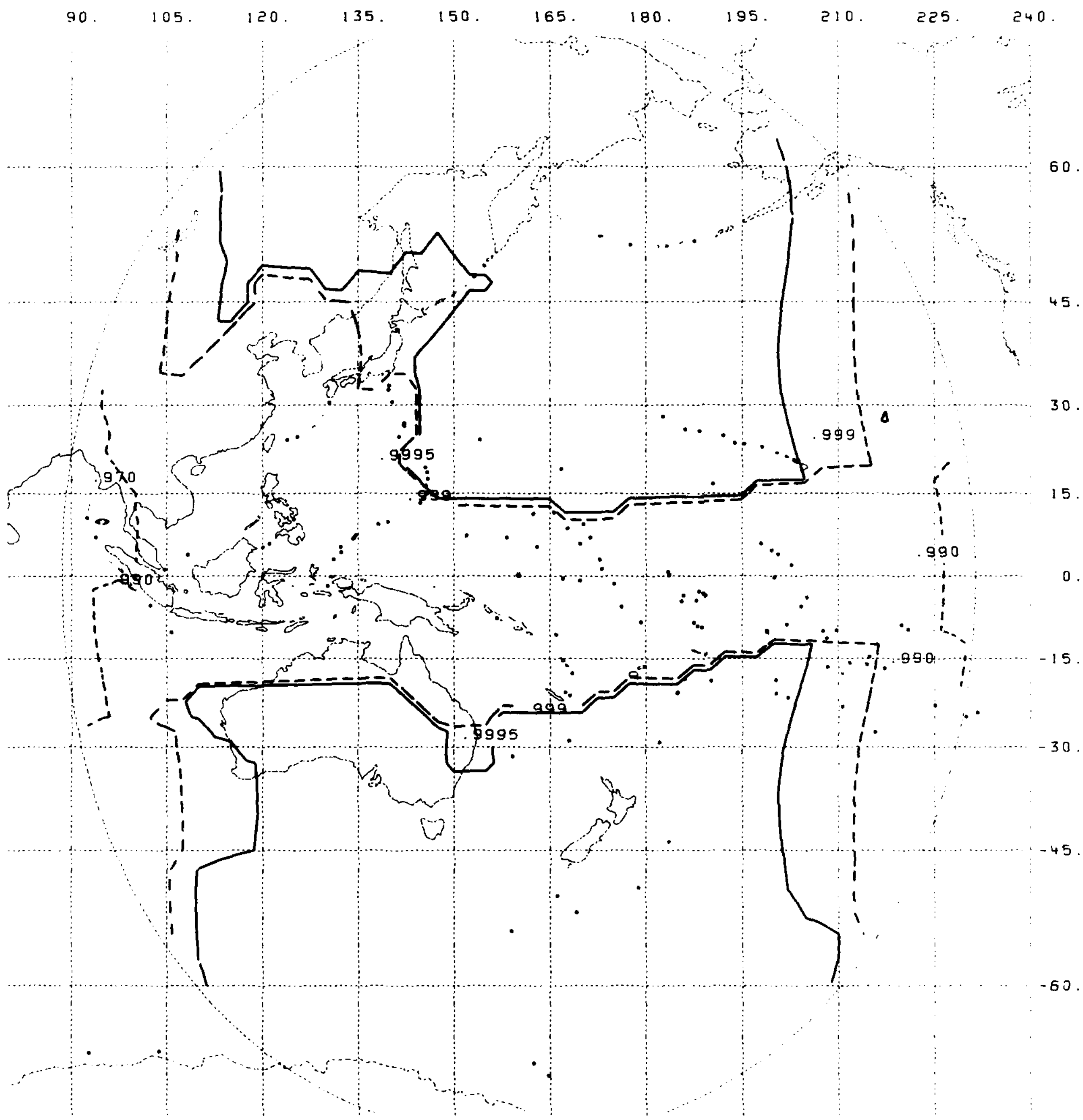

Fig. 10. Availability contours for uniform pattern; 10.6 dB margin; 160°E subpoint

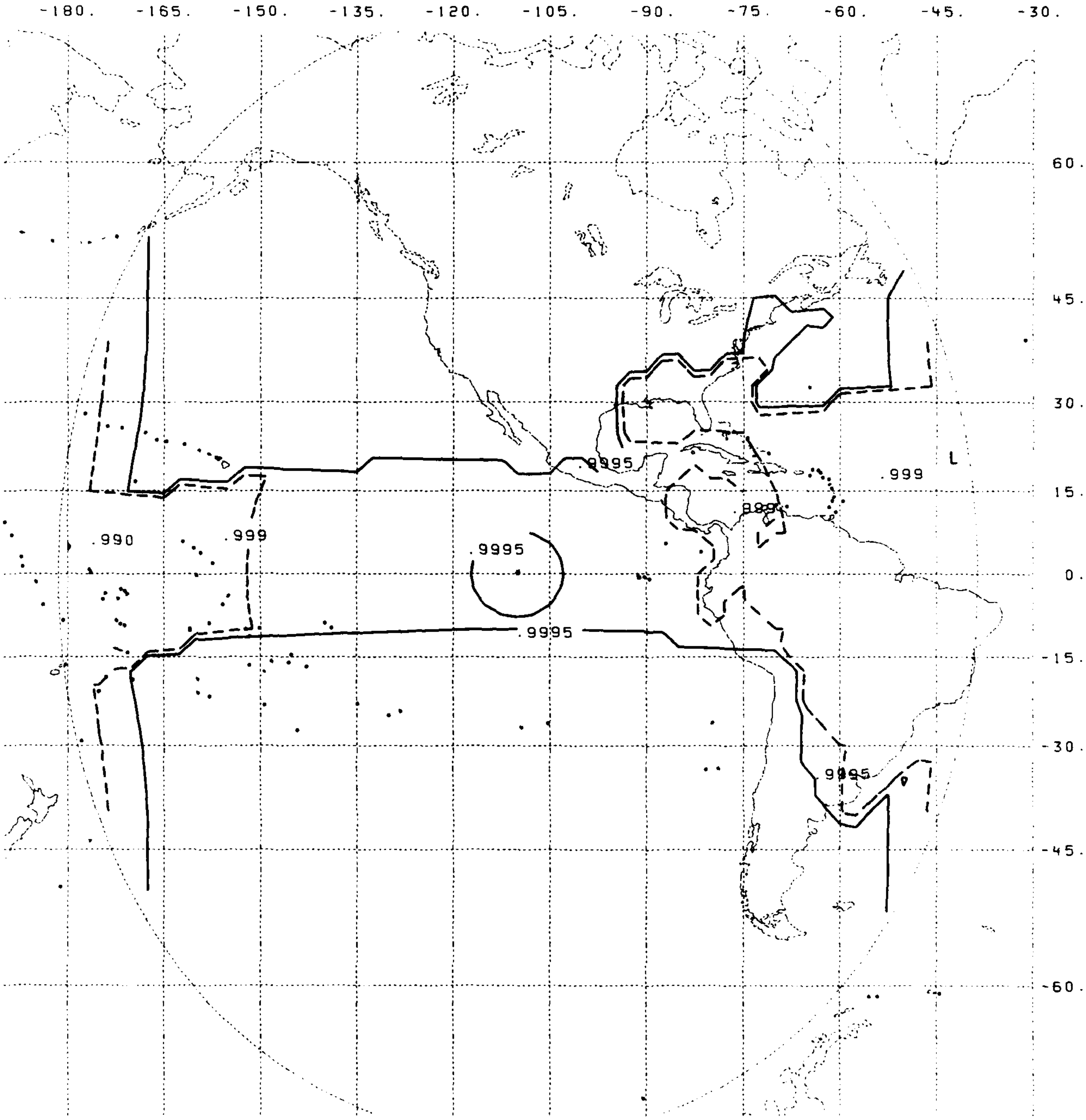

Fig. 11. Availability contours for uniform pattern; 16.6 dB margin; 110°W subpoint

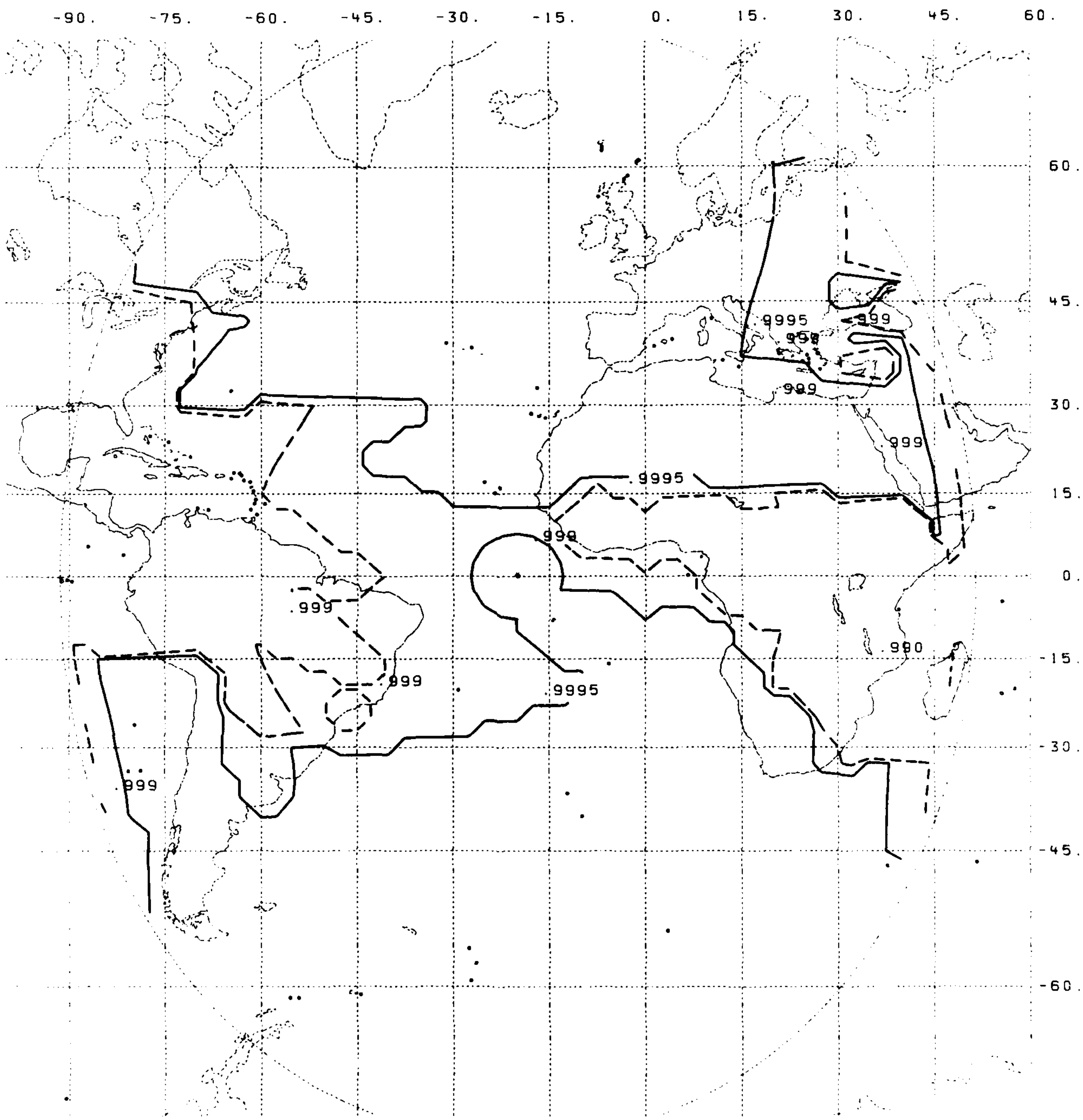

Fig. 12. Availability contours for uniform pattern; 16.6 dB margin; 20°W subpoint

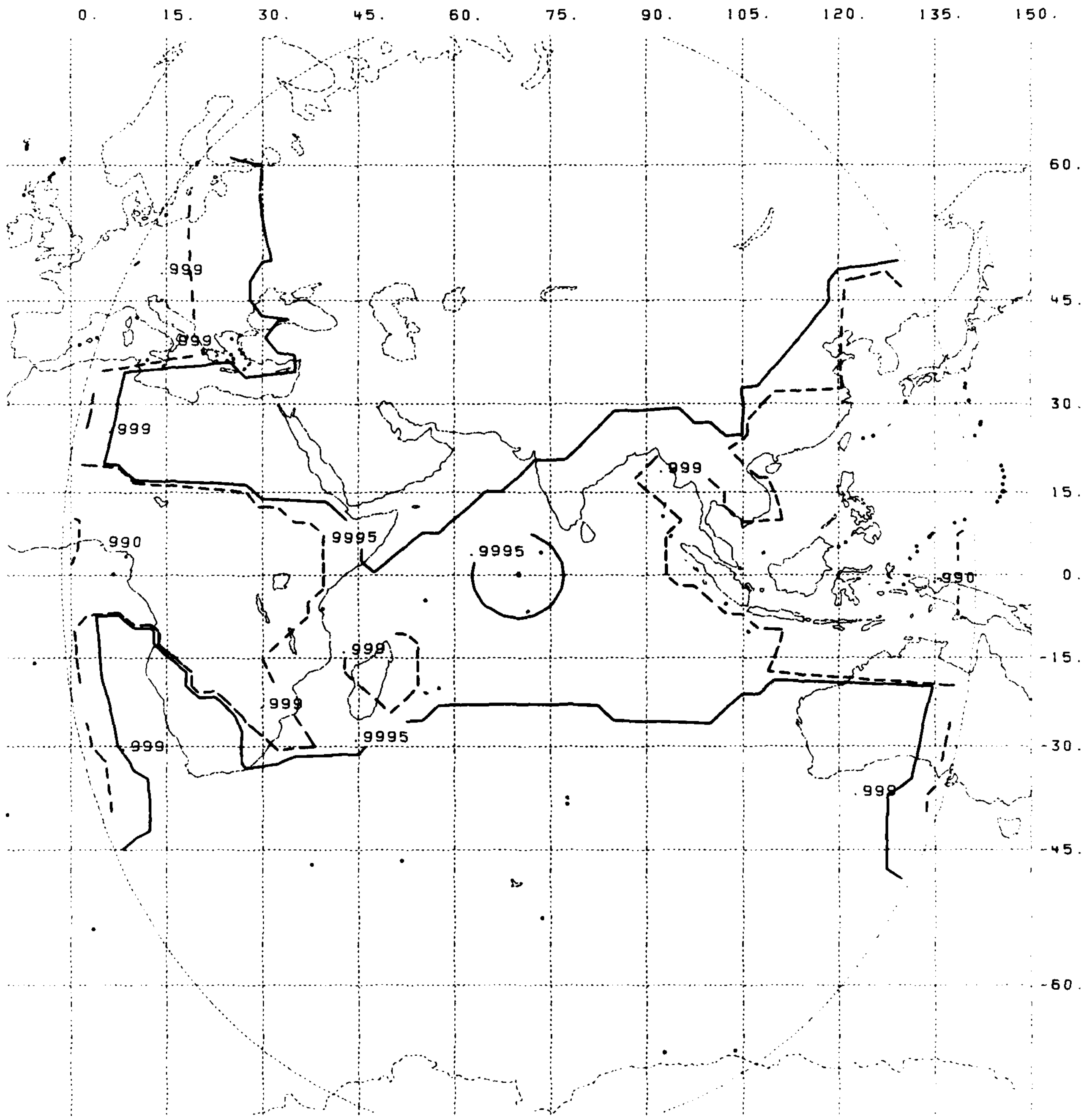

Fig. 13. Availability contours for uniform pattern; 16.6 dB margin; 70°E subpoint

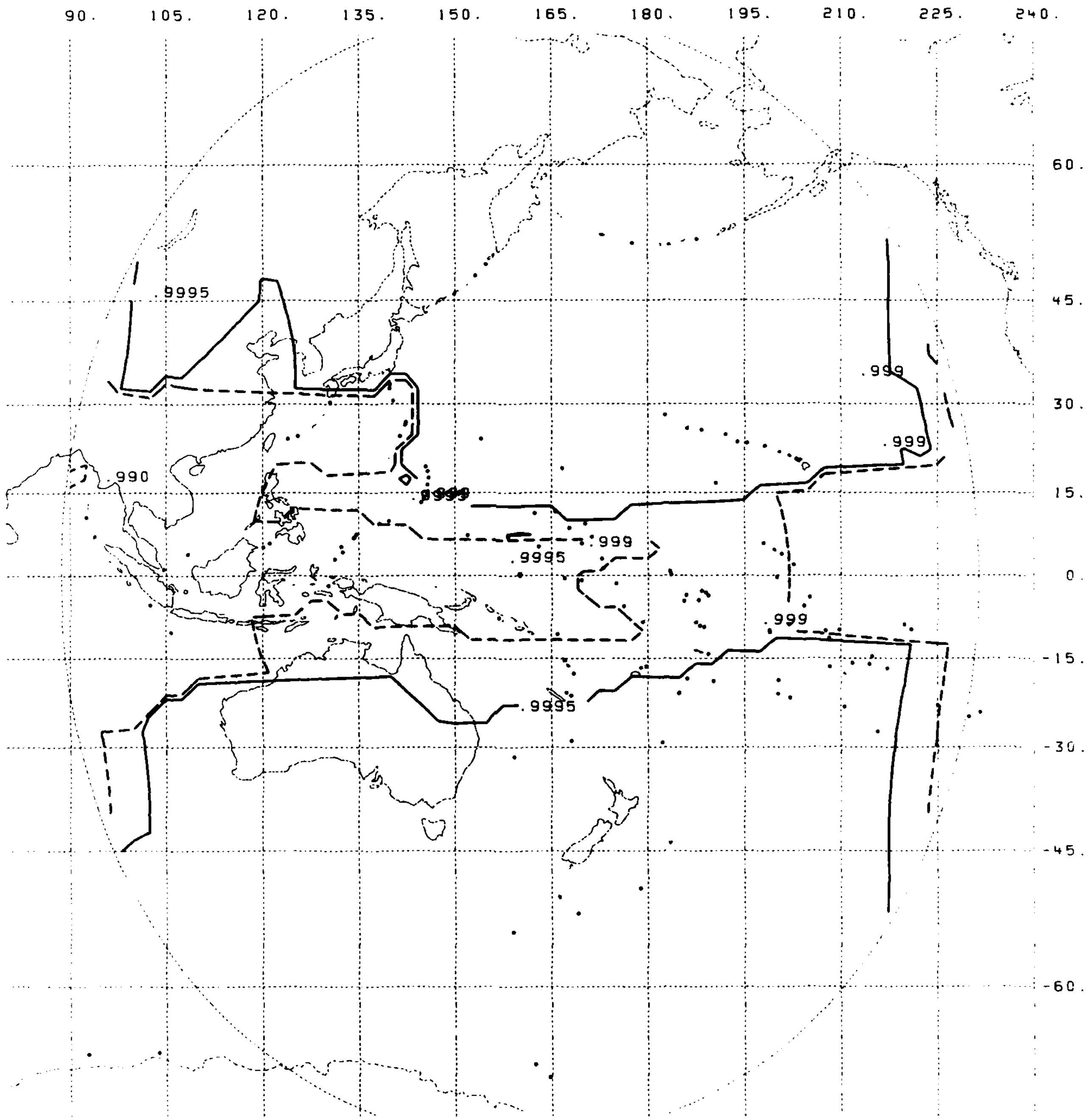

Fig. 14. Availability contours for uniform pattern; 16.6 dB margin; 160°E subpoint

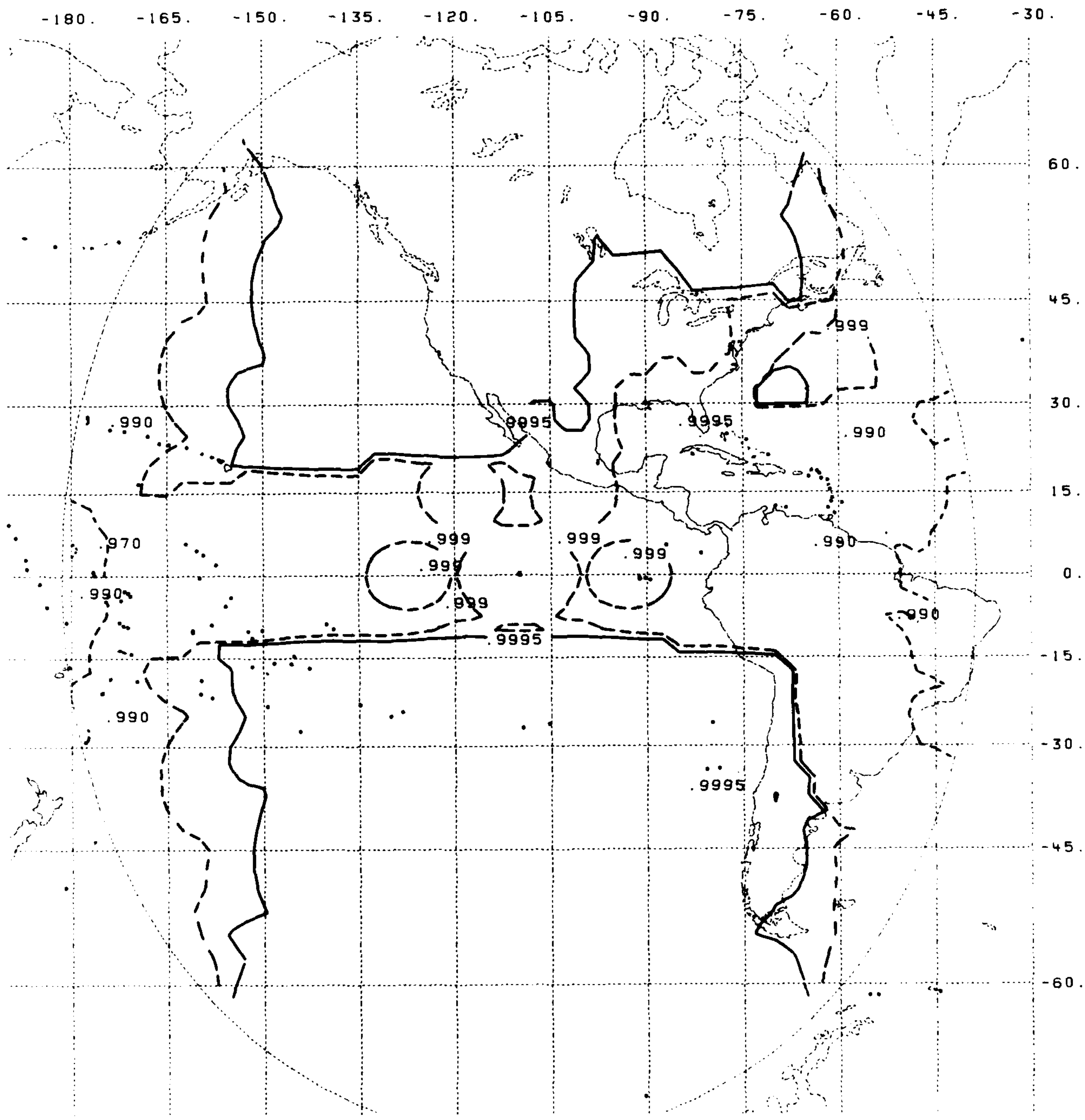

Fig. 15. Availability contours for 31 beam PA pattern; 13.6 dB margin; 110°W subpoint

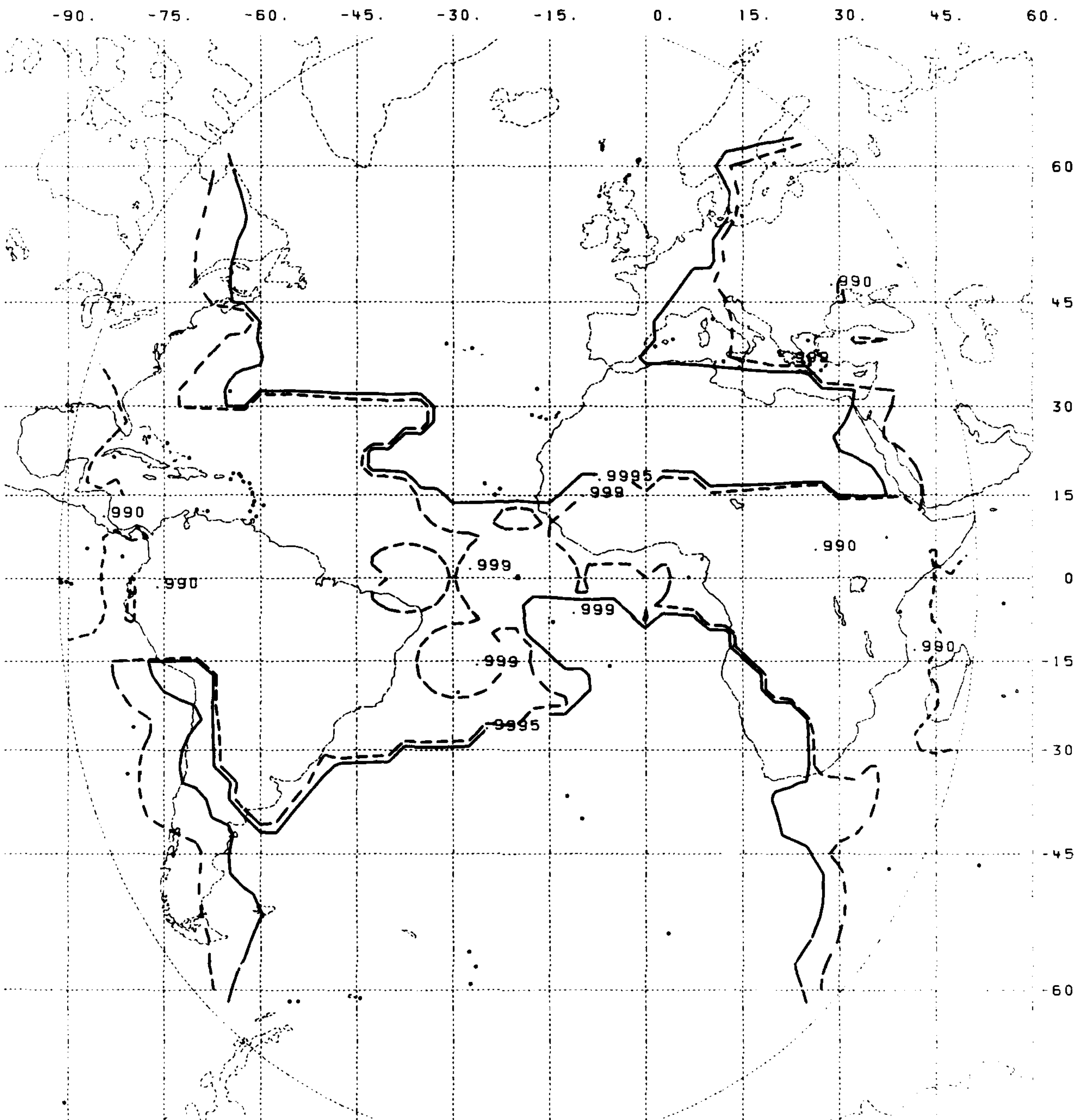

Fig. 16. Availability contours for 31 beam PA pattern; 13.6 dB margin; 20°W subpoint

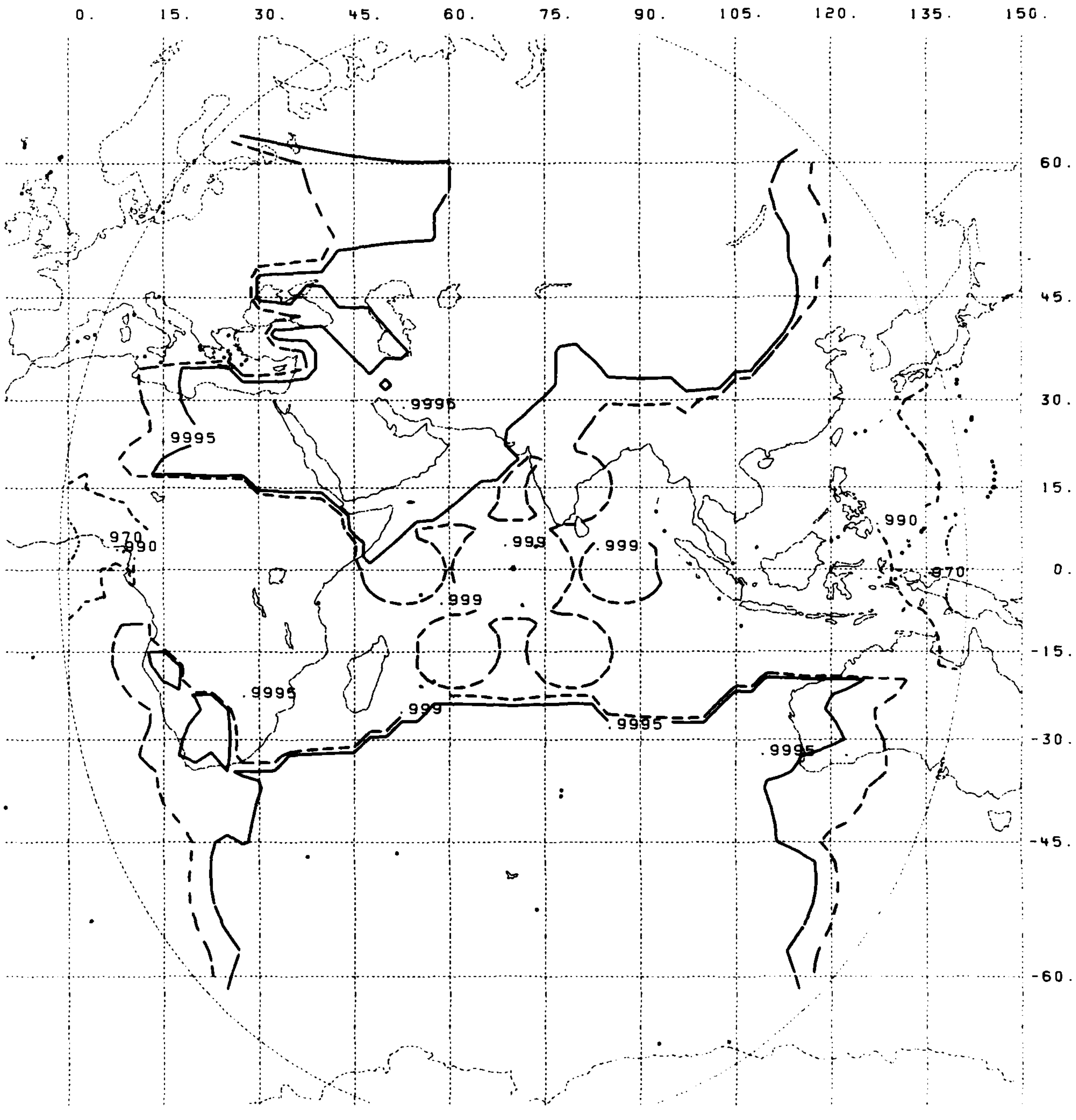

Fig. 17. Availability contours for 31 beam PA pattern; 13.6 dB margin; 70°E subpoint

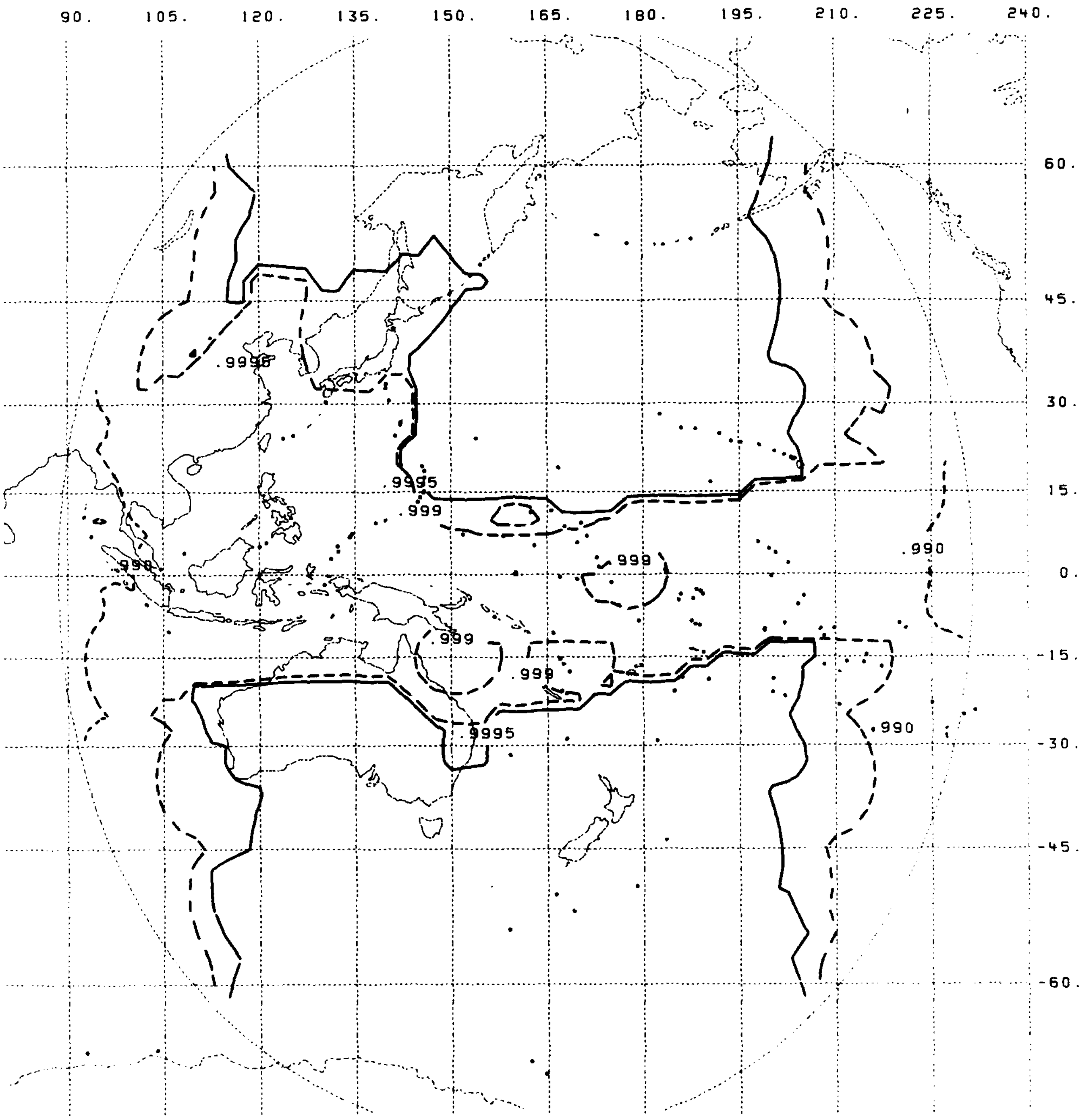

Fig. 18. Availability contours for 31 beam PA pattern; 13.6 dB margin; 160°E subpoint

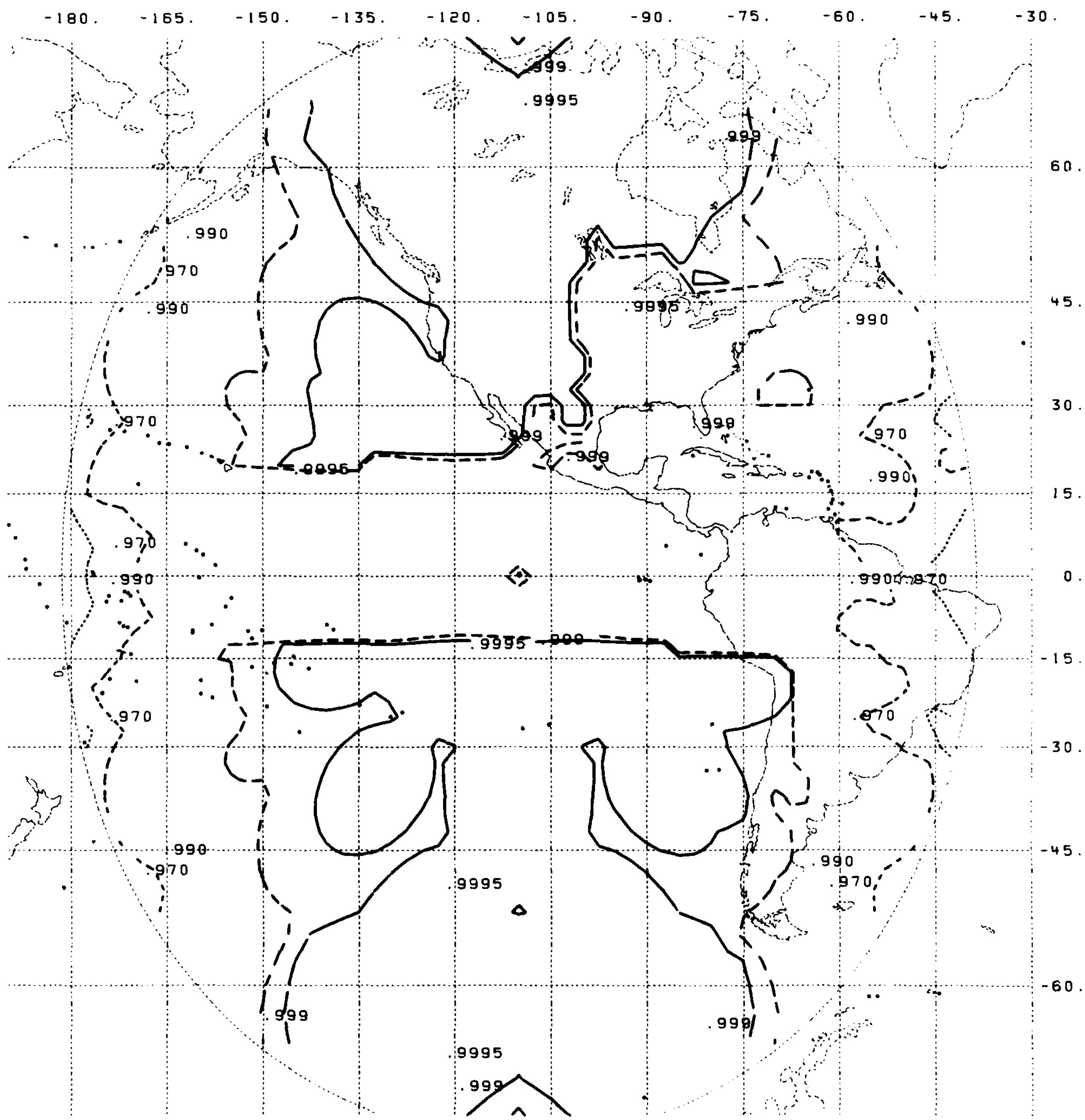

Fig. 19. Availability contours for 31 beam PA pattern; 10.6 dB margin; 110°W subpoint

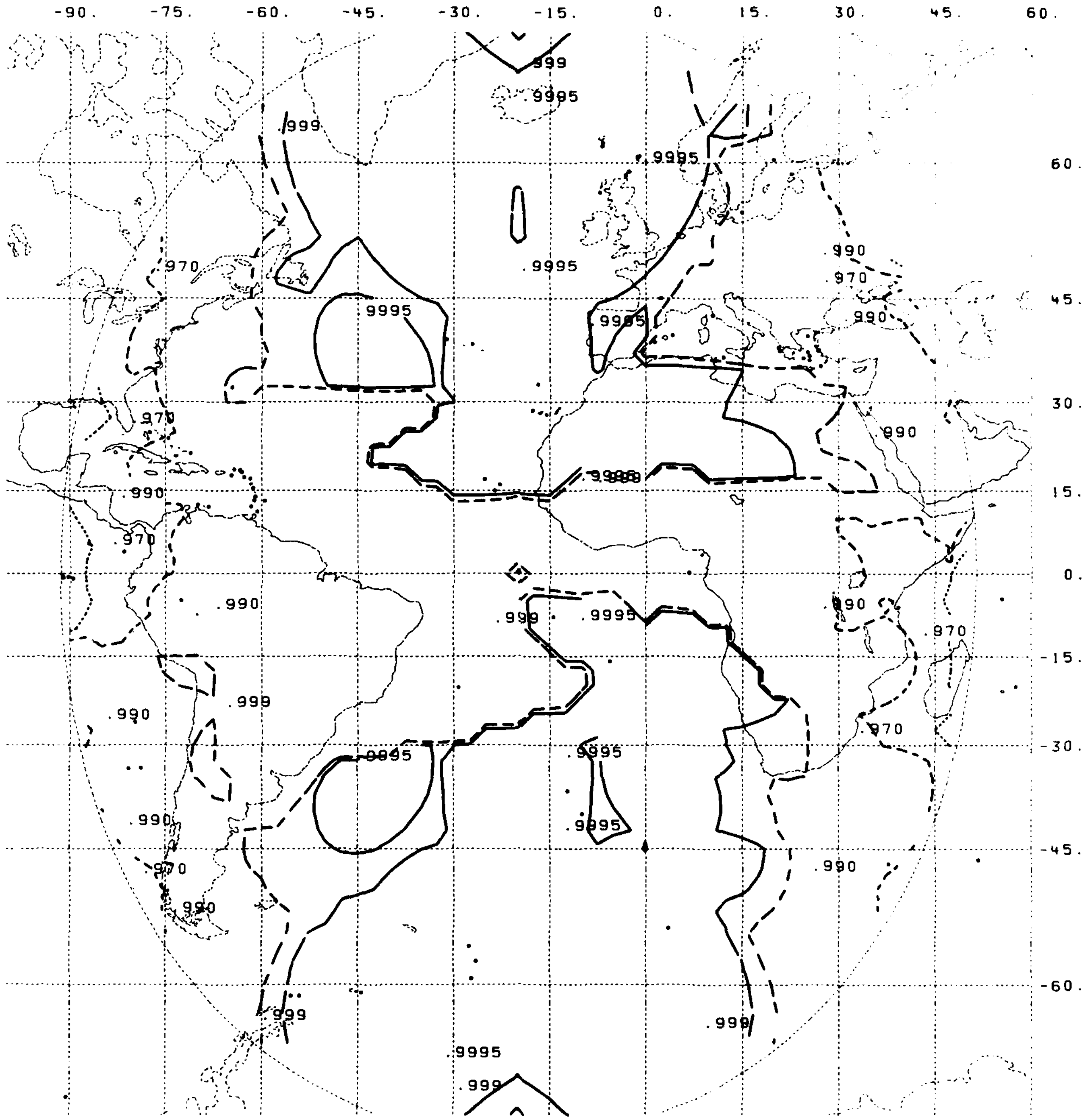

Fig. 20. Availability contours for 31 beam PA pattern; 10.6 dB margin; 20°W subpoint

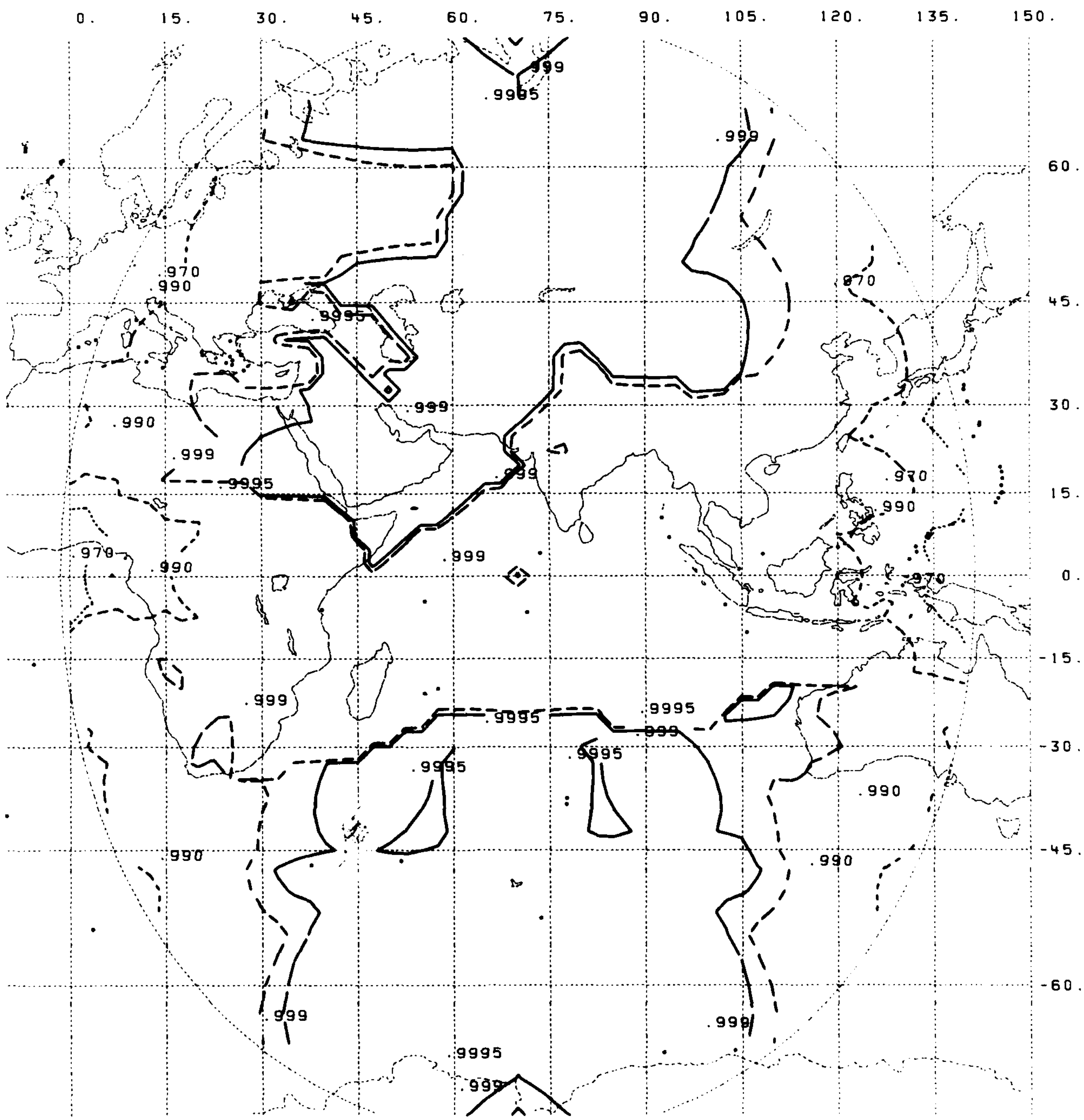

Fig. 21. Availability contours for 31 beam PA pattern; 10.6 dB margin; 70°E subpoint

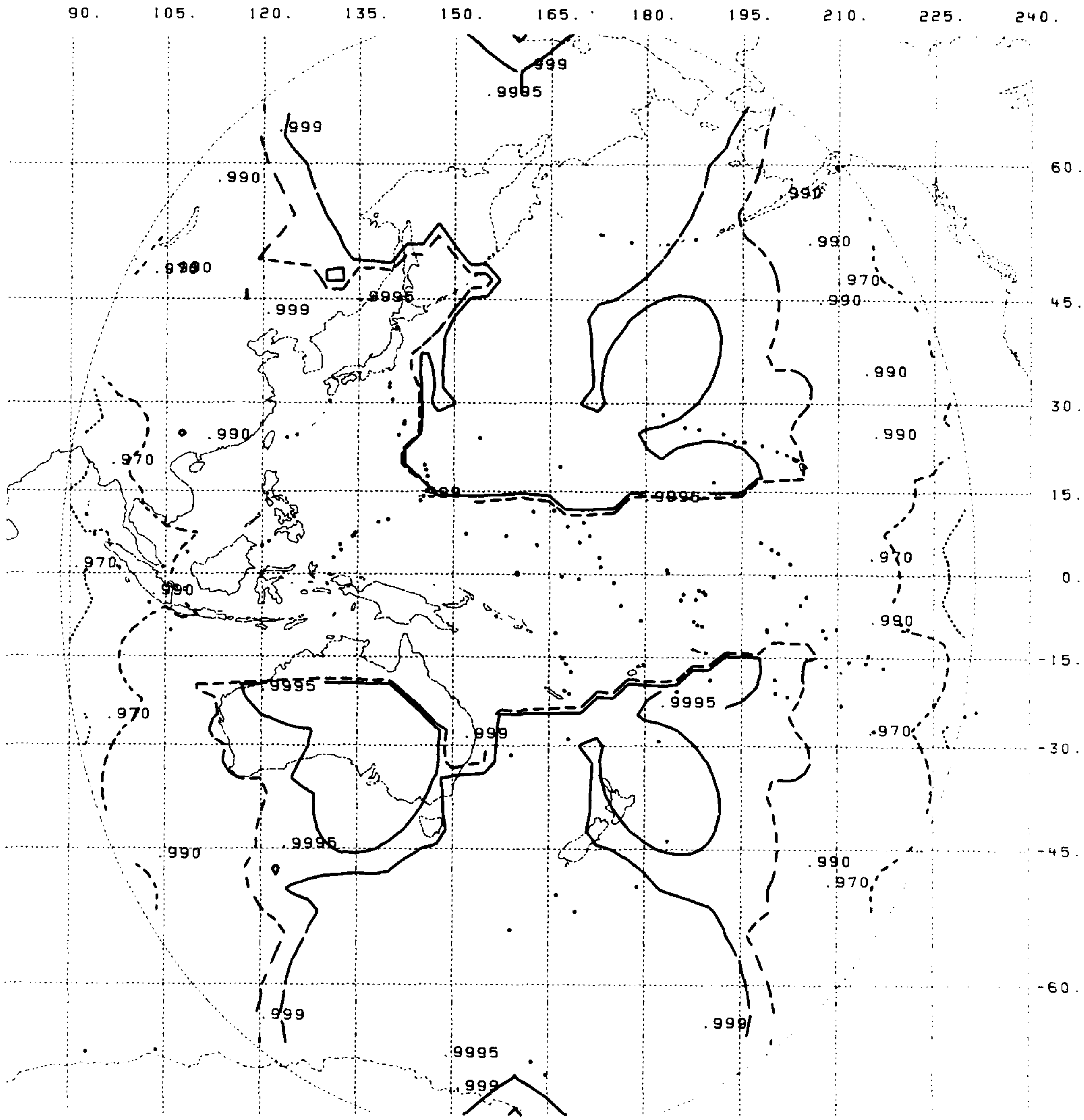

Fig. 22. Availability contours for 31 beam PA pattern; 10.6 dB margin; 160°E subpoint

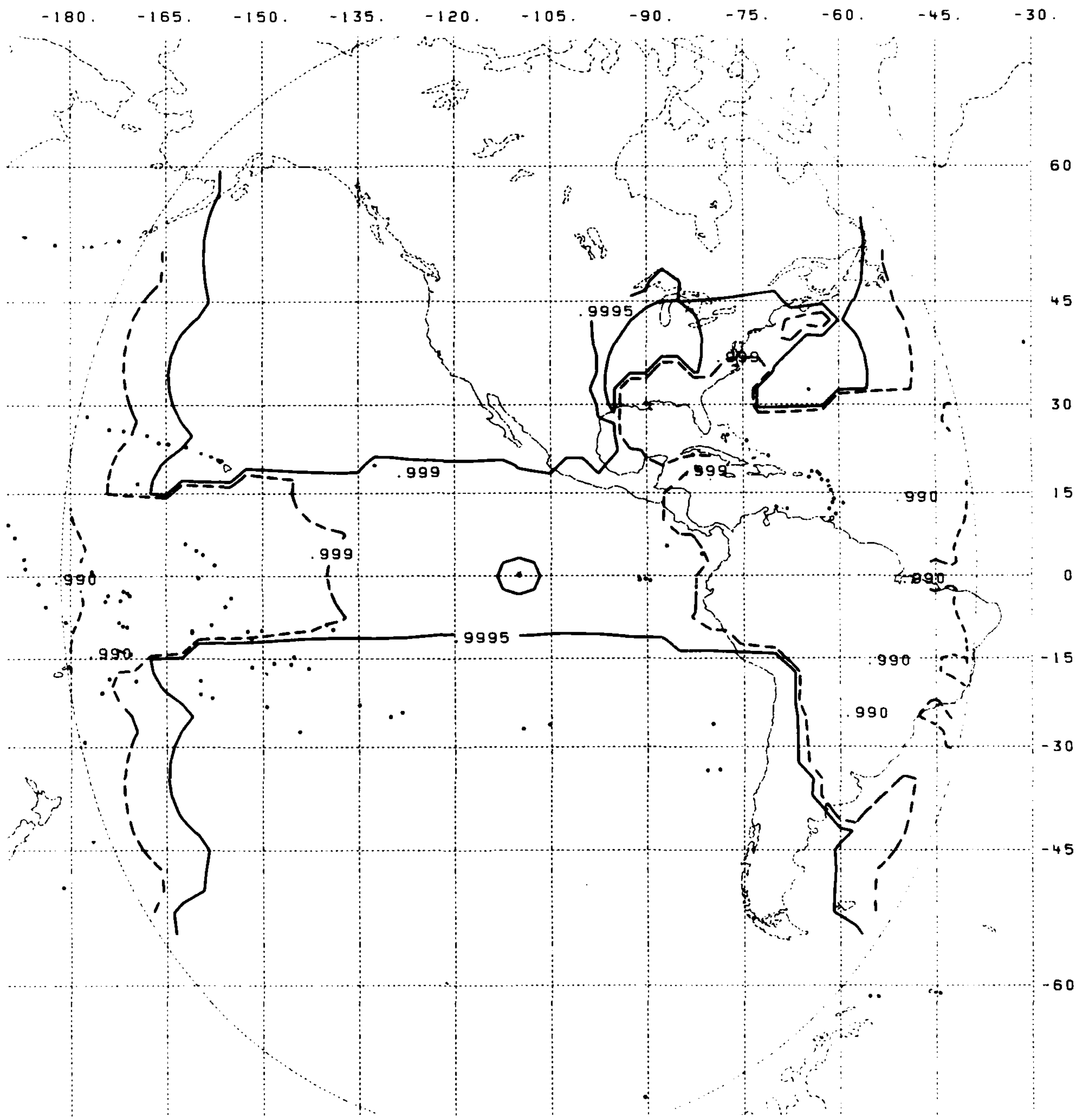

Fig. 23. Availability contours for 31 beam PA pattern; 16.6 dB margin; 110°W subpoint

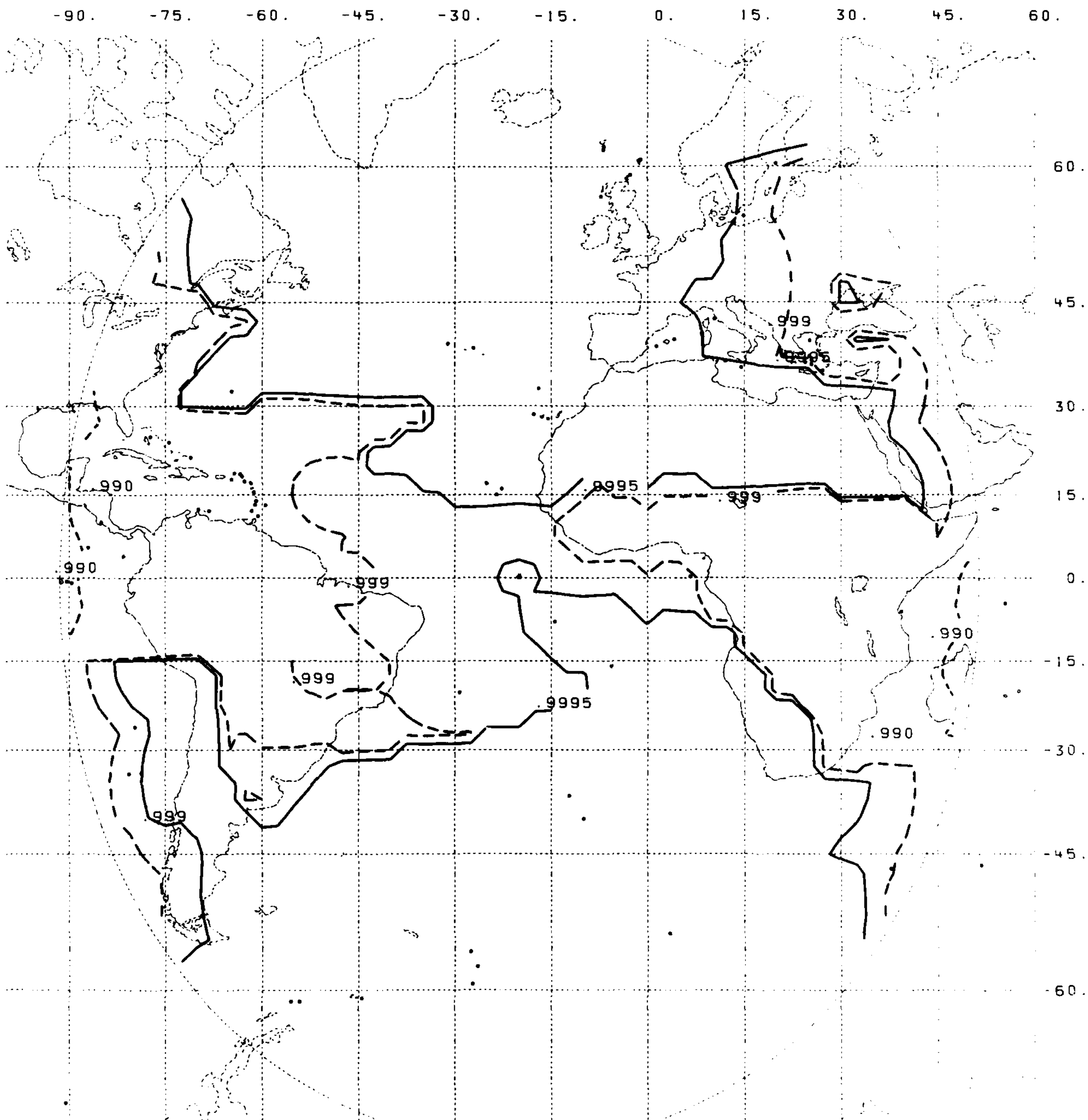

Fig. 24. Availability contours for 31 beam PA pattern; 16.6 dB margin; 20°W subpoint

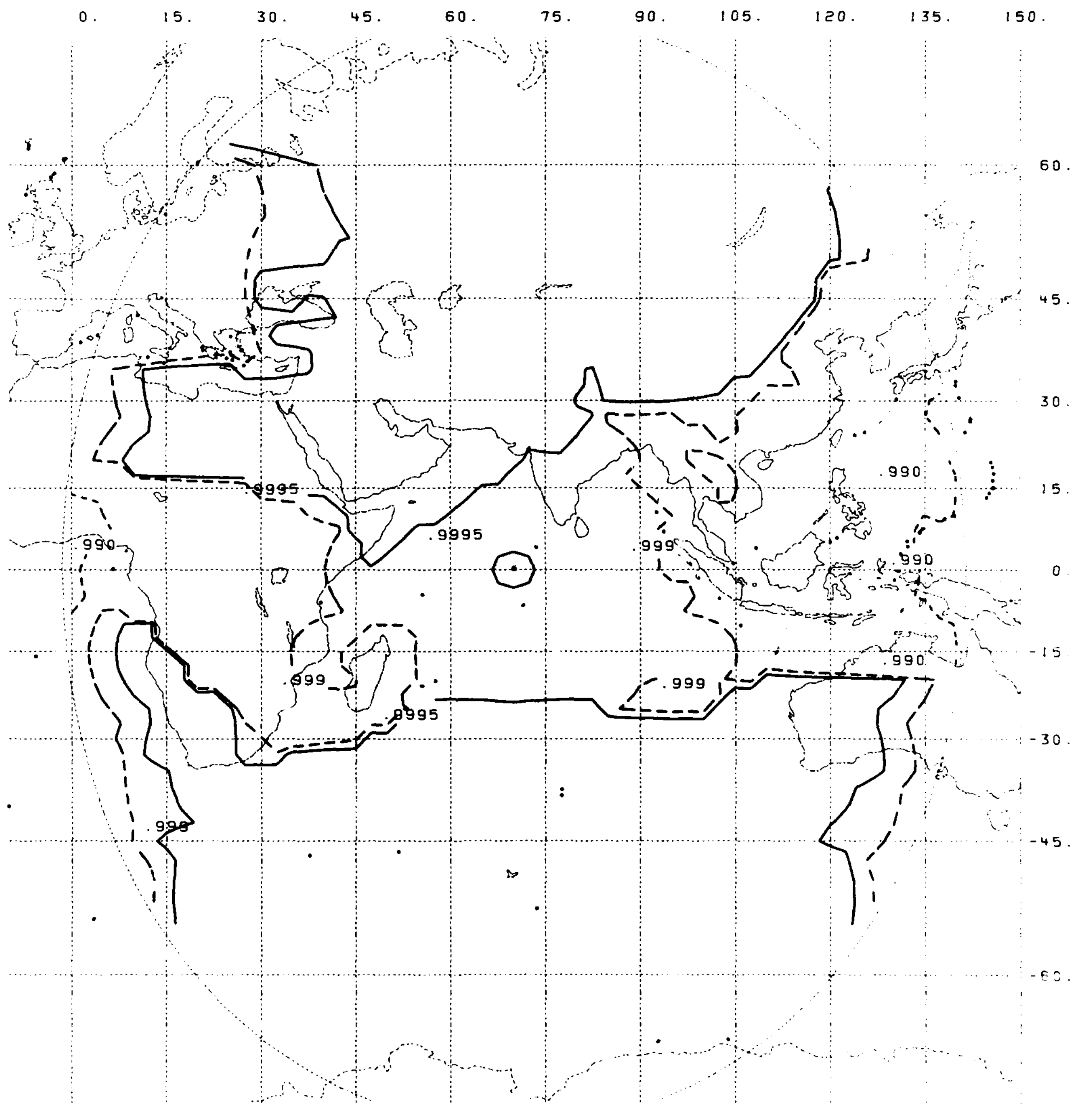

Fig. 25. Availability contours for 31 beam PA pattern; 16.6 dB margin; 70°E subpoint

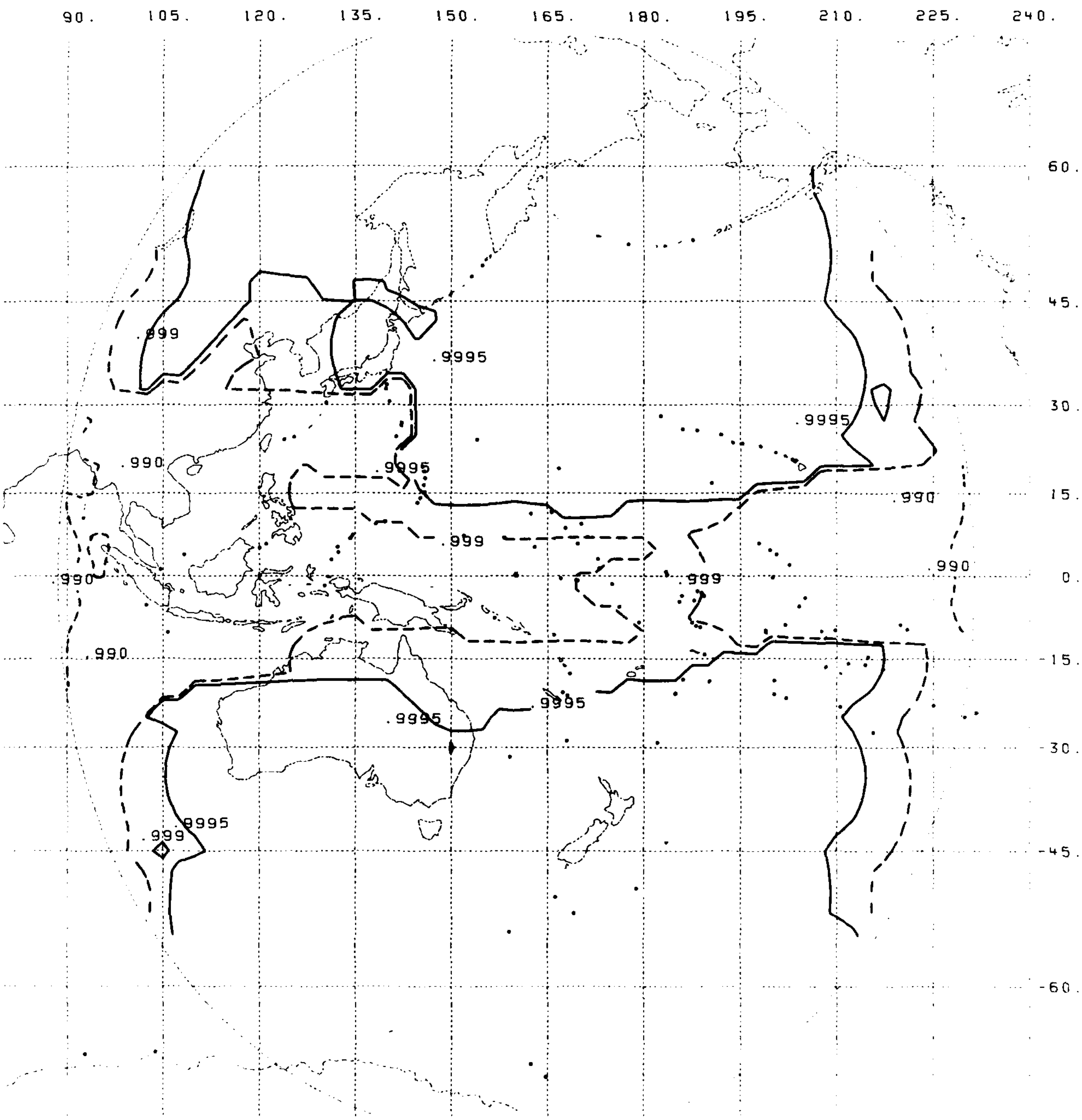

Fig. 26. Availability contours for 31 beam PA pattern; 16.6 dB margin; 160°E subpoint

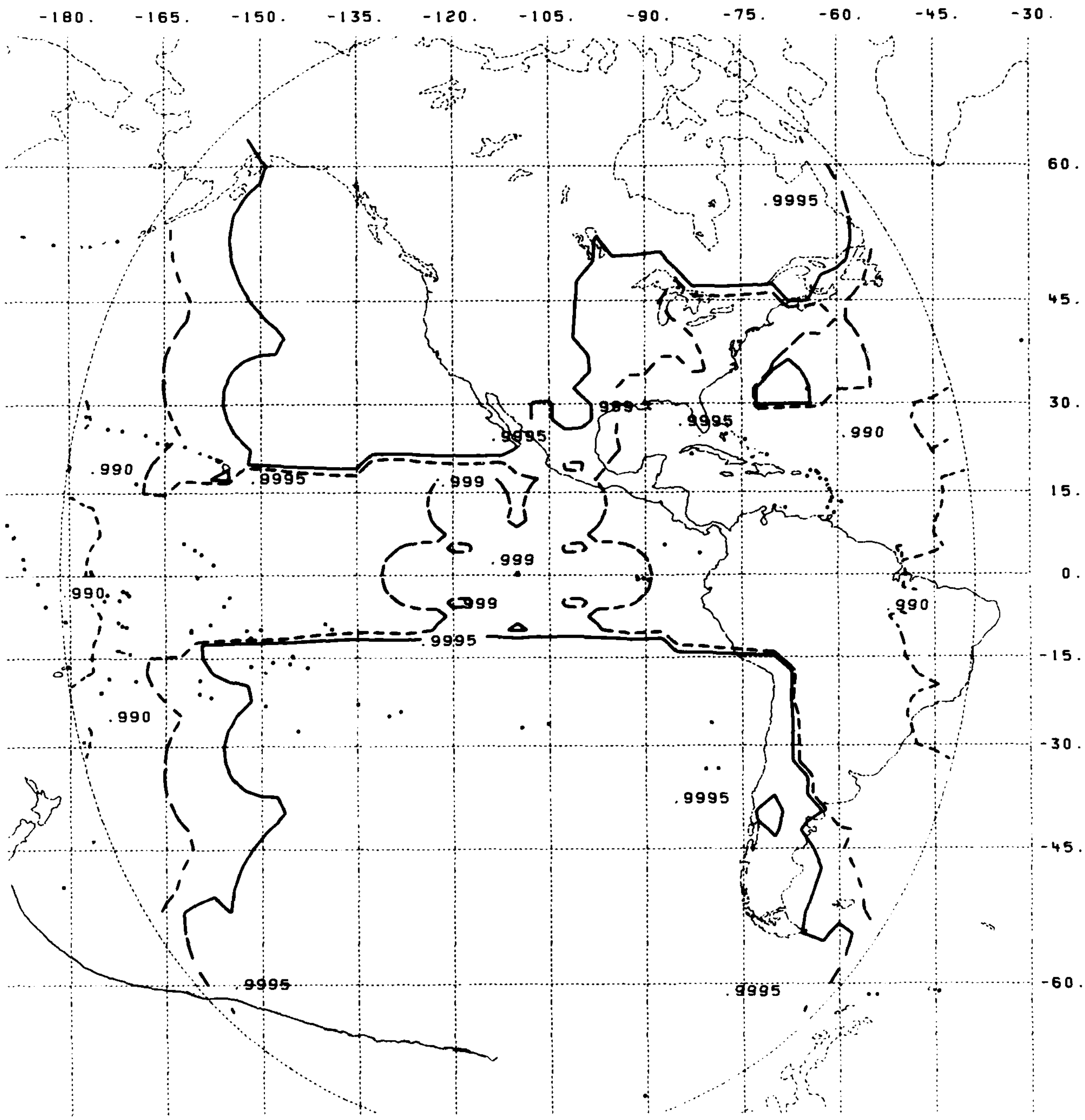

Fig. 27. Availability contours for 37 beam PA pattern; 13.0 dB margin; 110°W subpoint

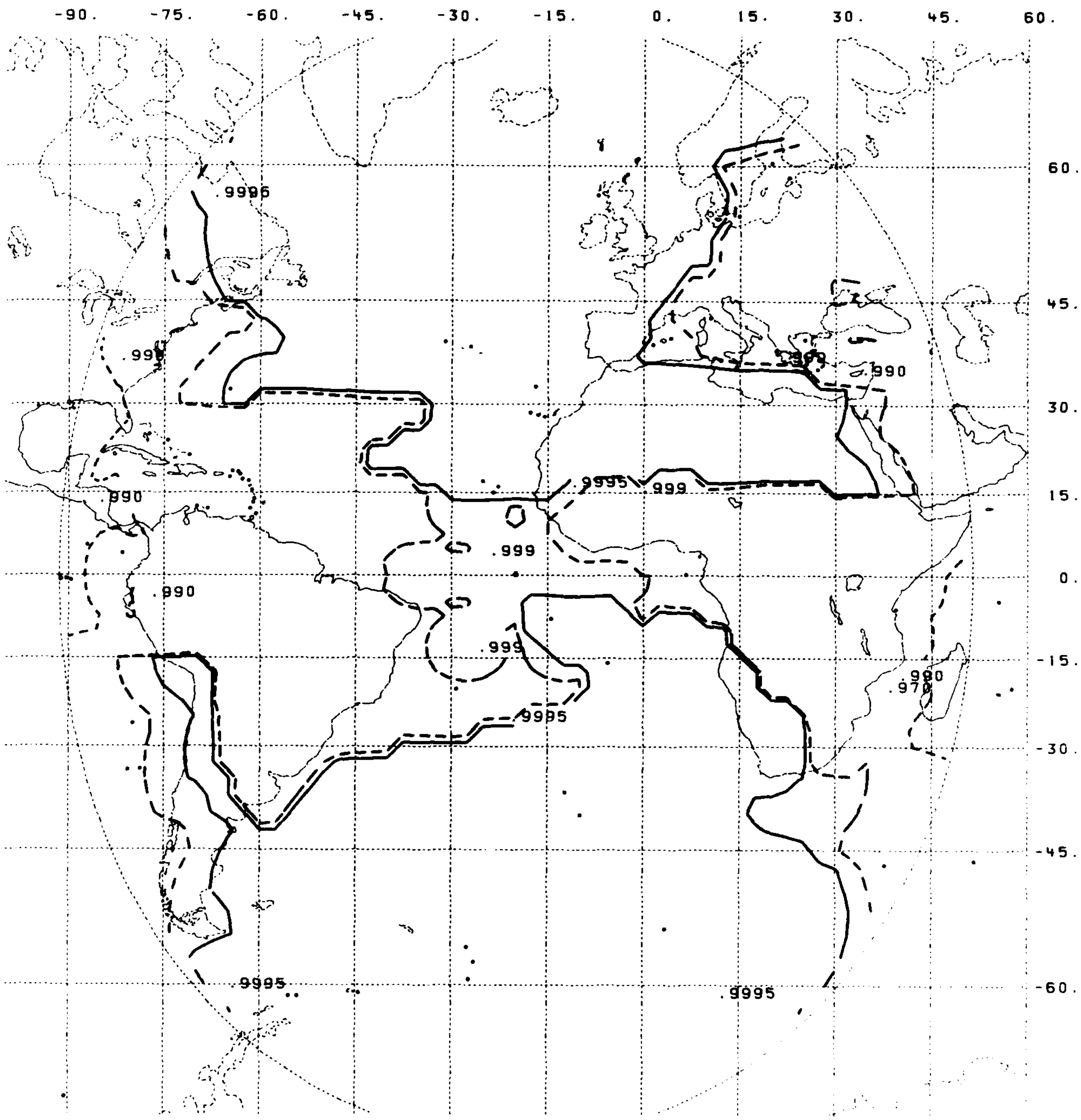

Fig. 28. Availability contours for 37 beam PA pattern; 13.0 dB margin; 20°W subpoint

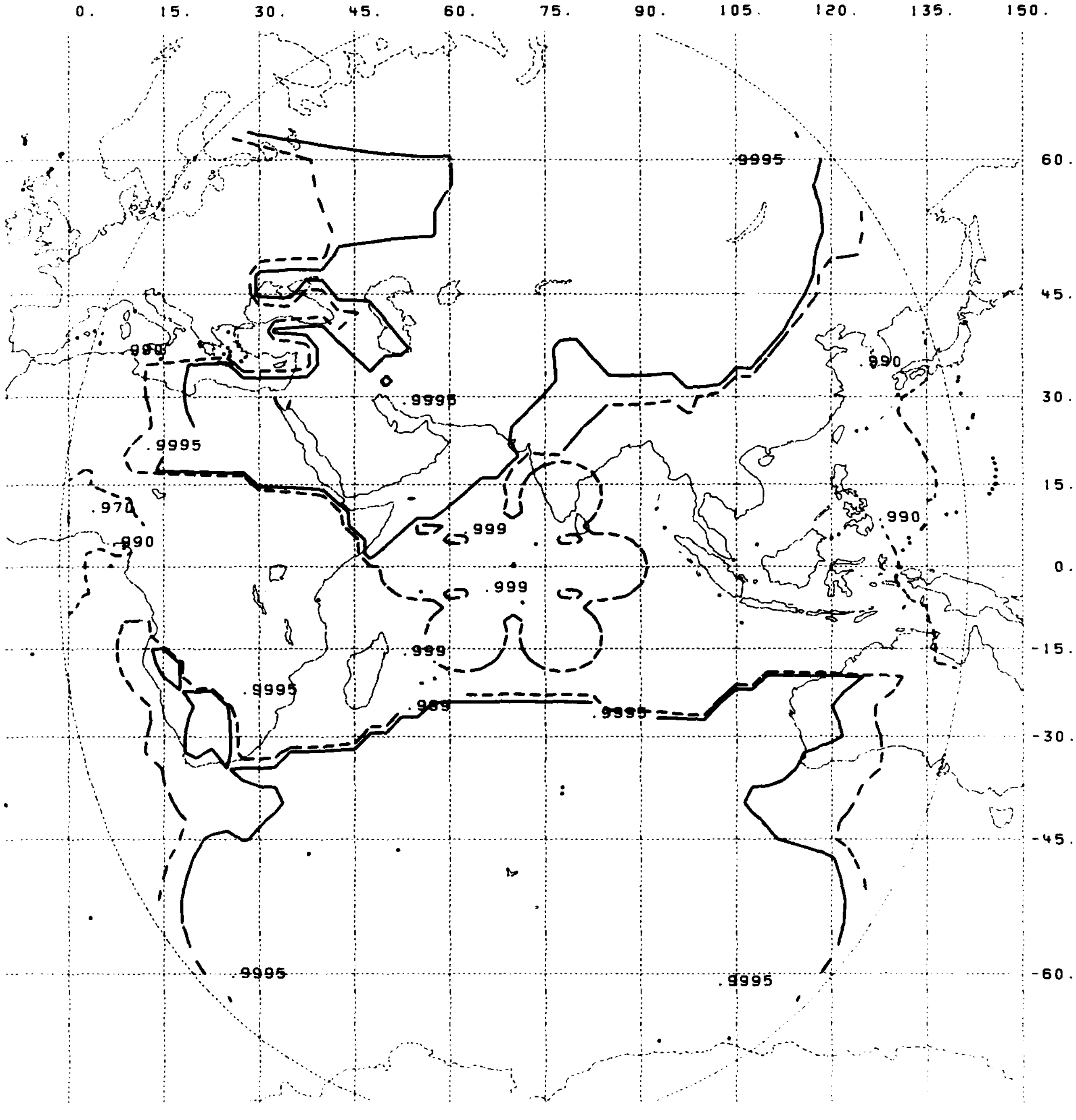

Fig. 29. Availability contours for 37 beam PA pattern; 13.0 dB margin; 70°E subpoint

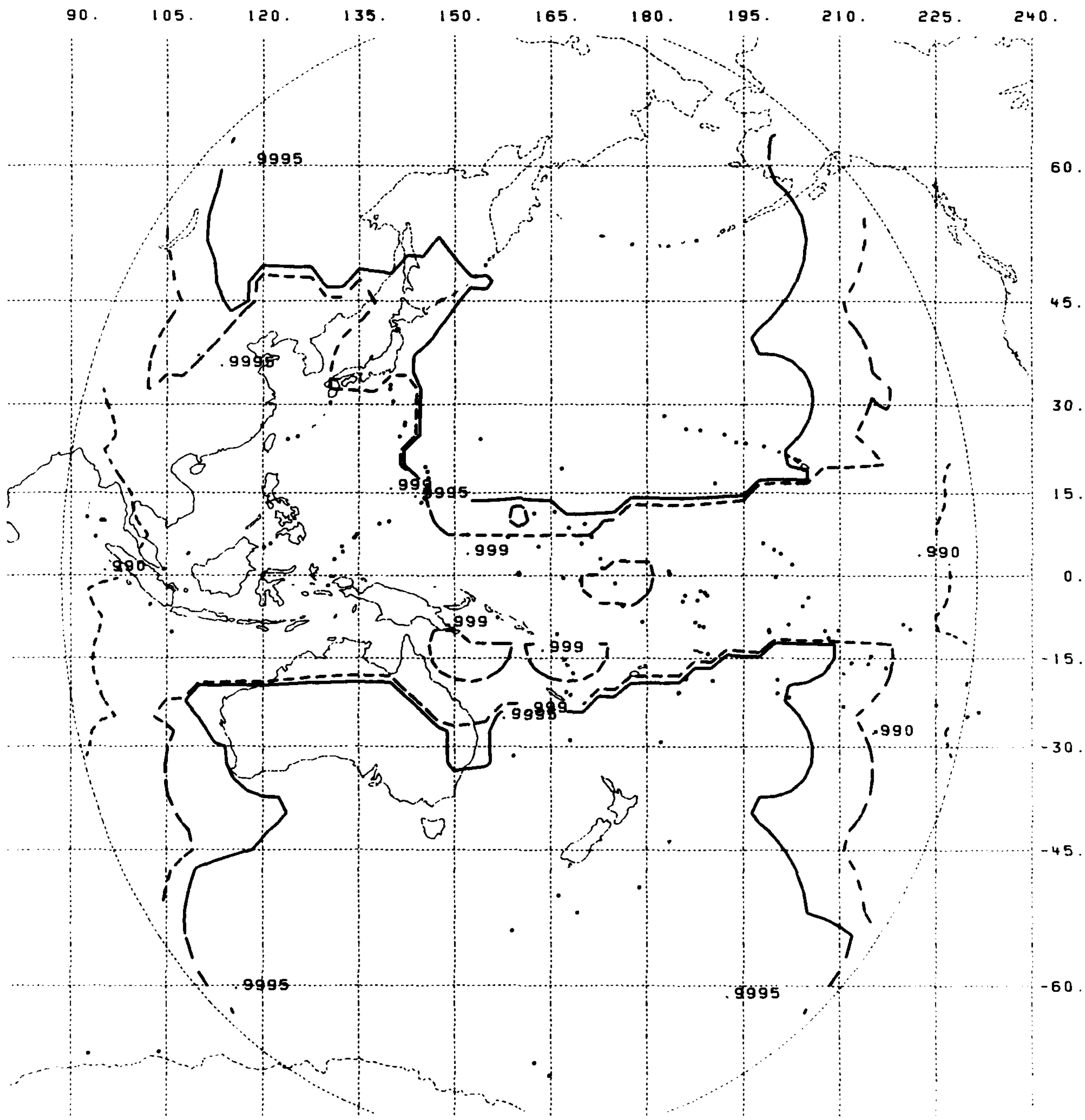

Fig. 30. Availability contours for 37 beam PA pattern; 13.0 dB margin; 160°E subpoint

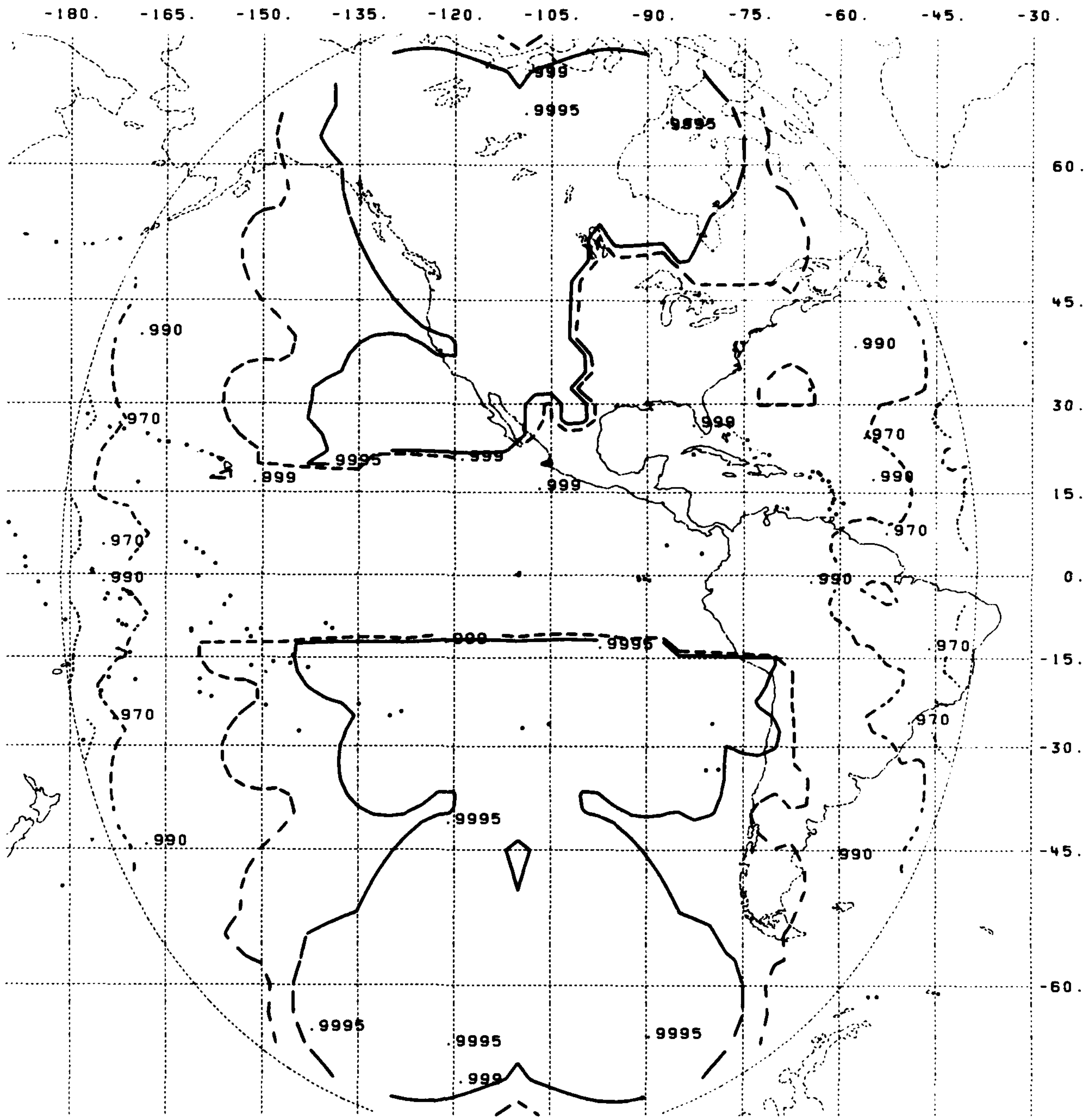

Fig. 31. Availability contours for 37 beam PA pattern; 10.0 dB margin; 110°W subpoint

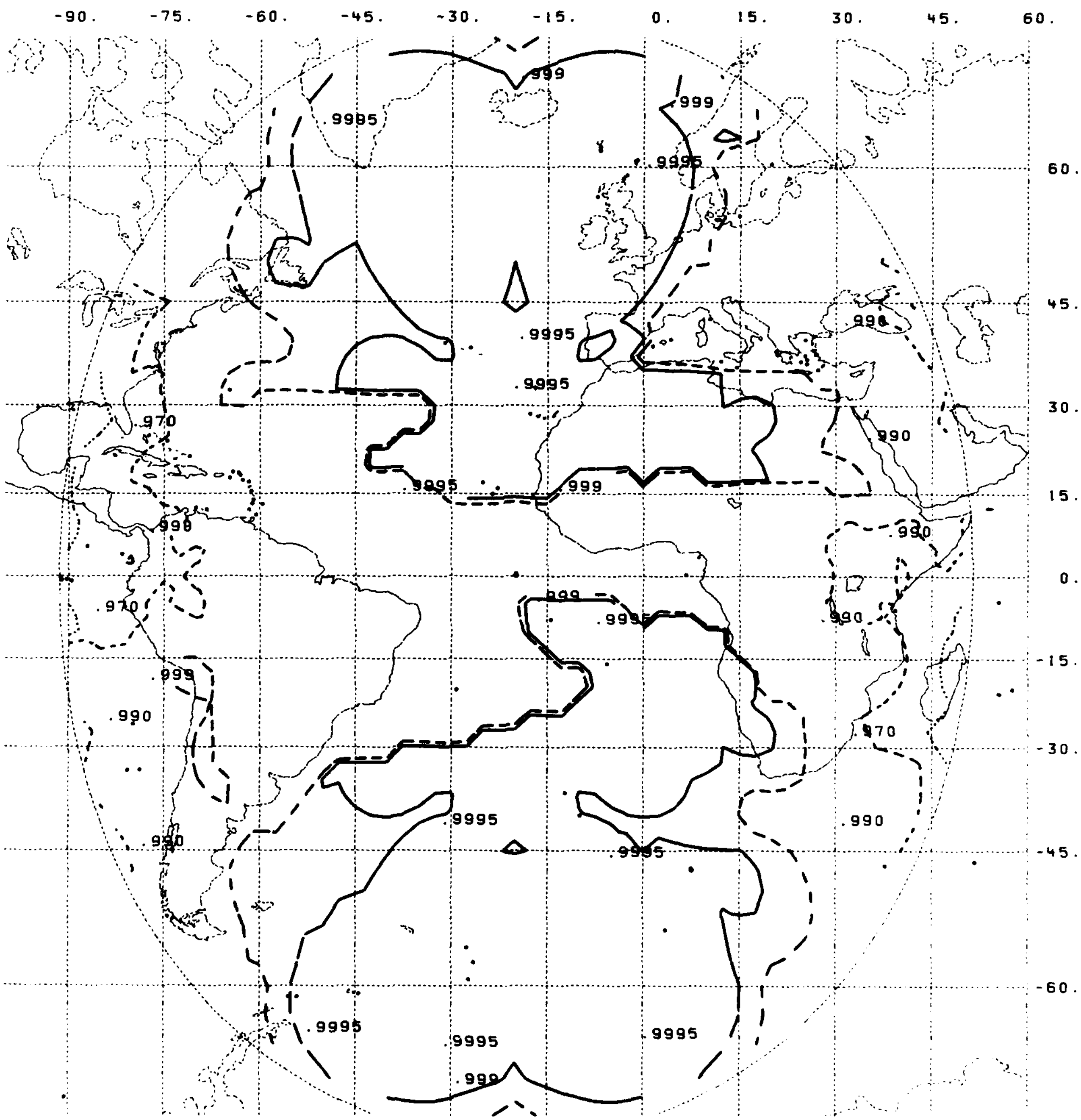

Fig. 32. Availability contours for 37 beam PA pattern; 10.0 dB margin; 20°W subpoint

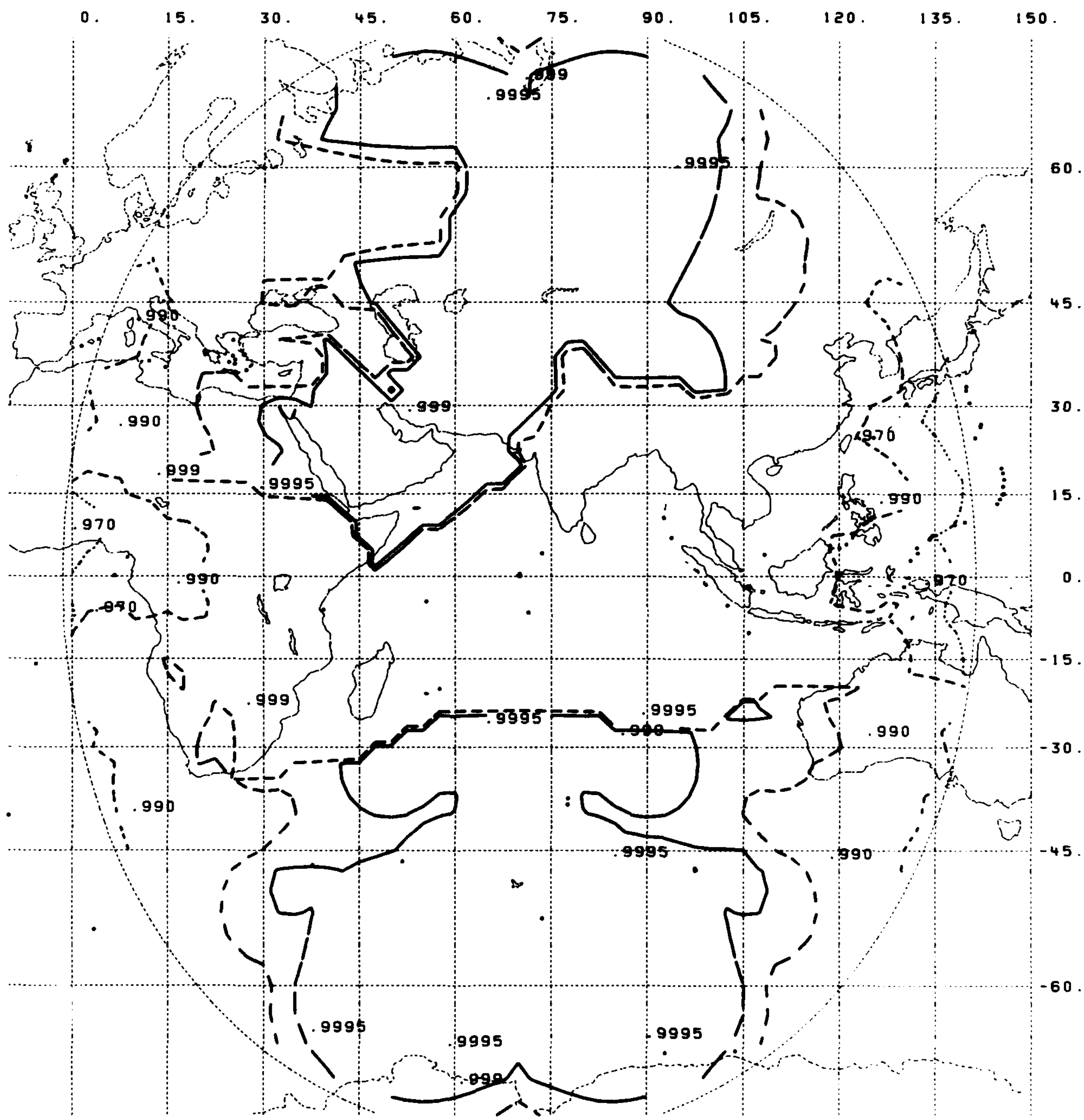

Fig. 33. Availability contours for 37 beam PA pattern; 10.0 dB margin; 70°E subpoint

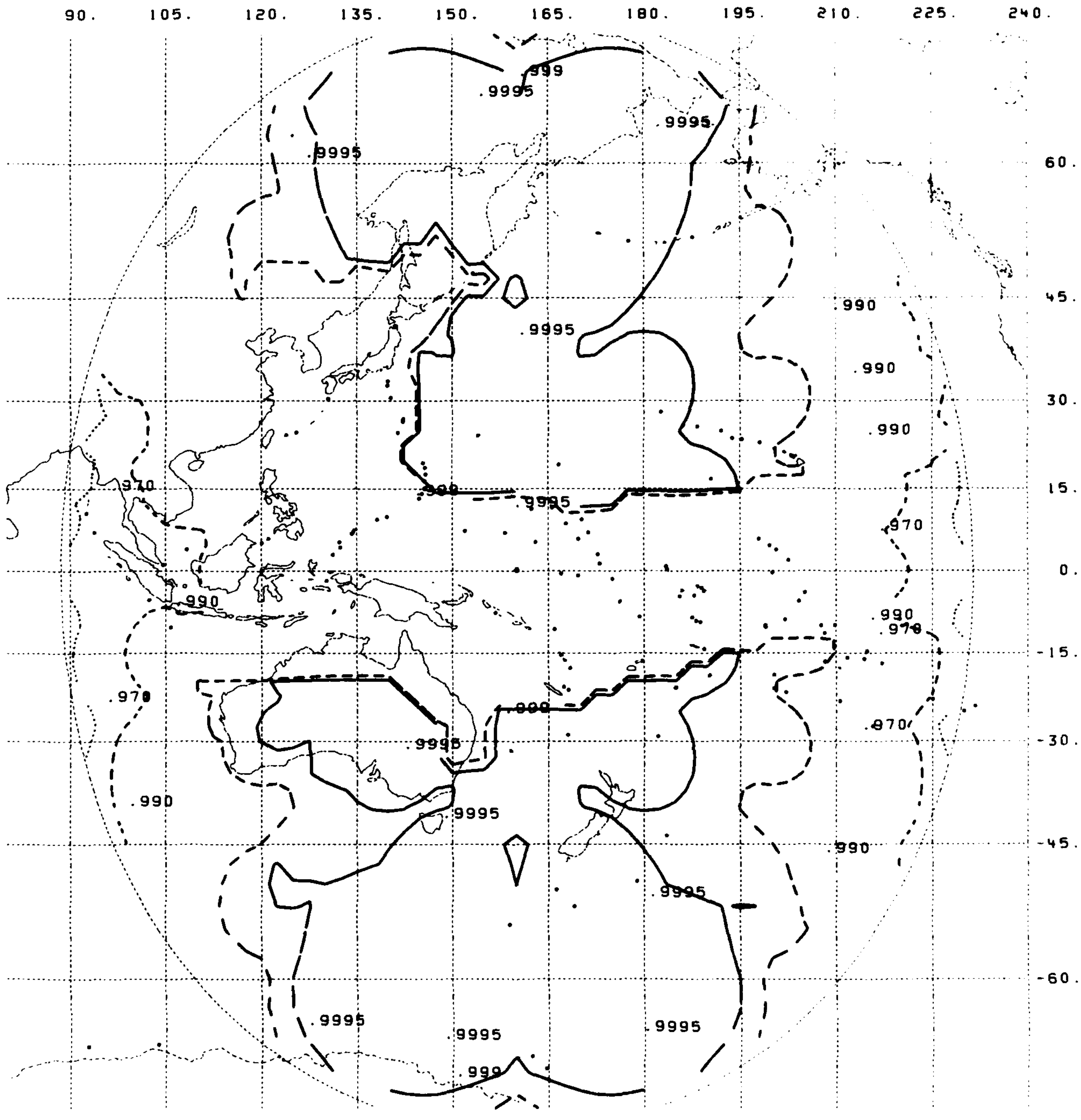

Fig. 34. Availability contours for 37 beam PA pattern; 10.0 dB margin; 160°E subpoint

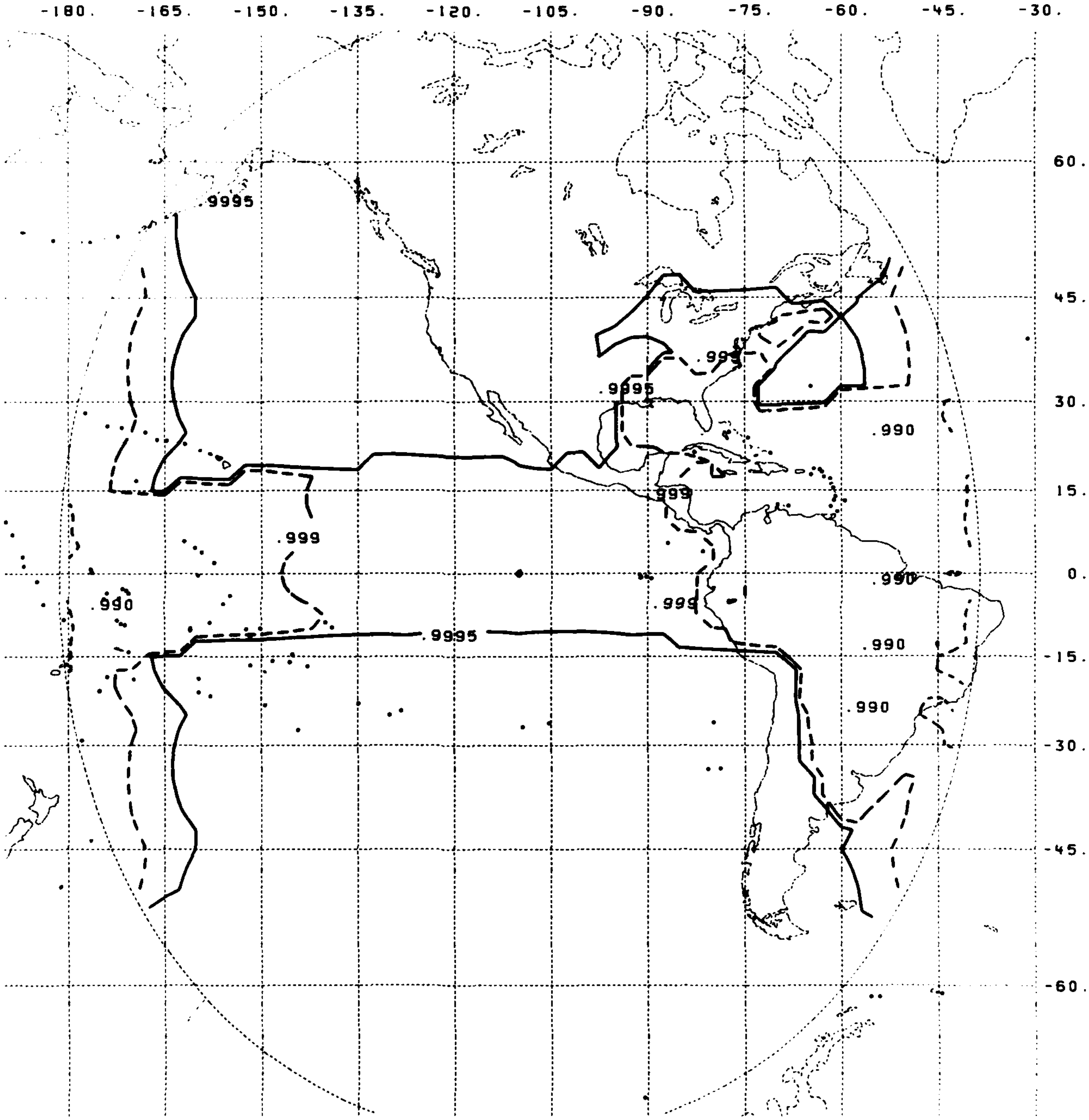

Fig. 35. Availability contours for 37 beam PA pattern; 16.0 dB margin; 110°W subpoint

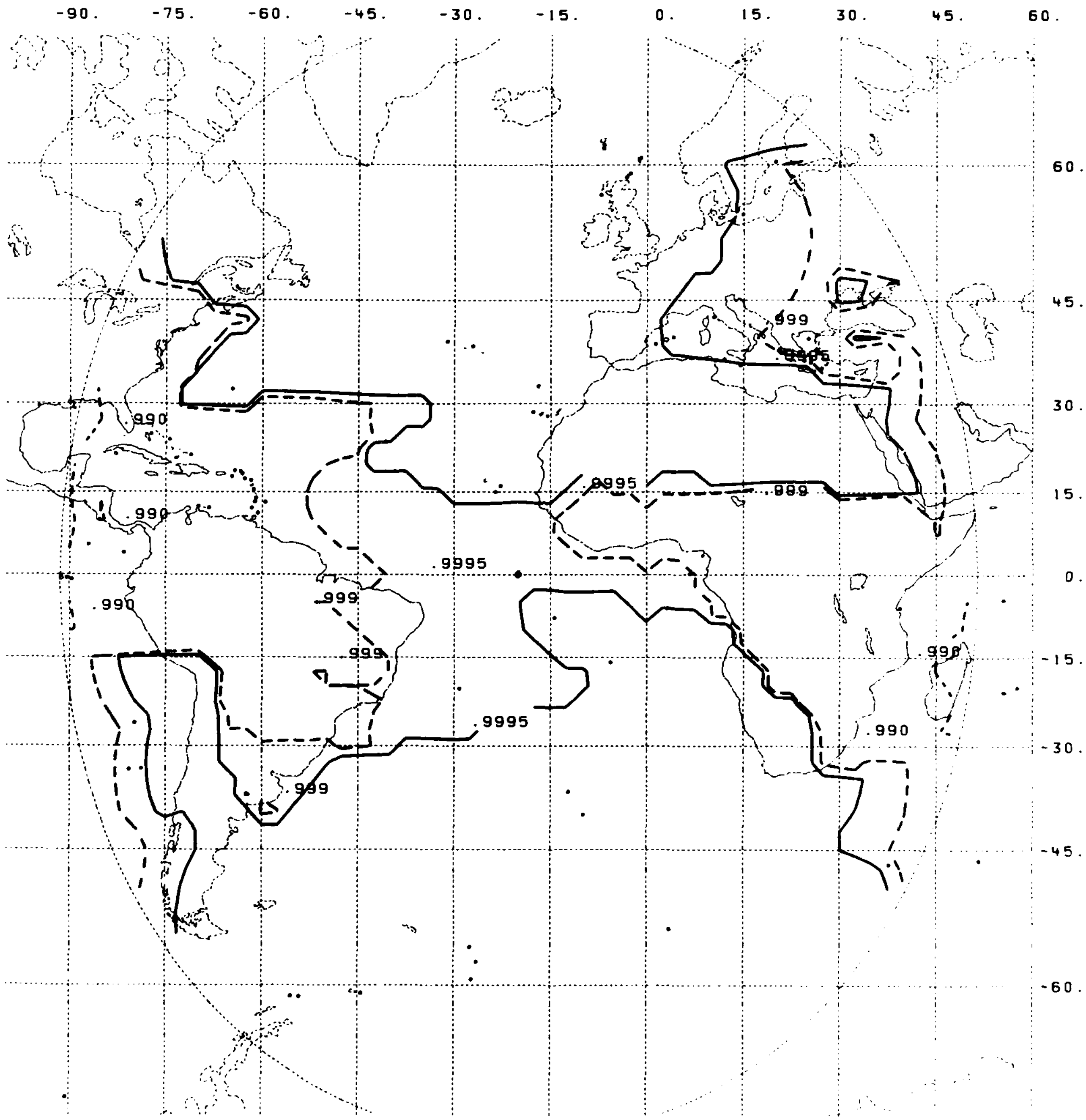

Fig. 36. Availability contours for 37 beam PA pattern; 16.0 dB margin; 20°W subpoint

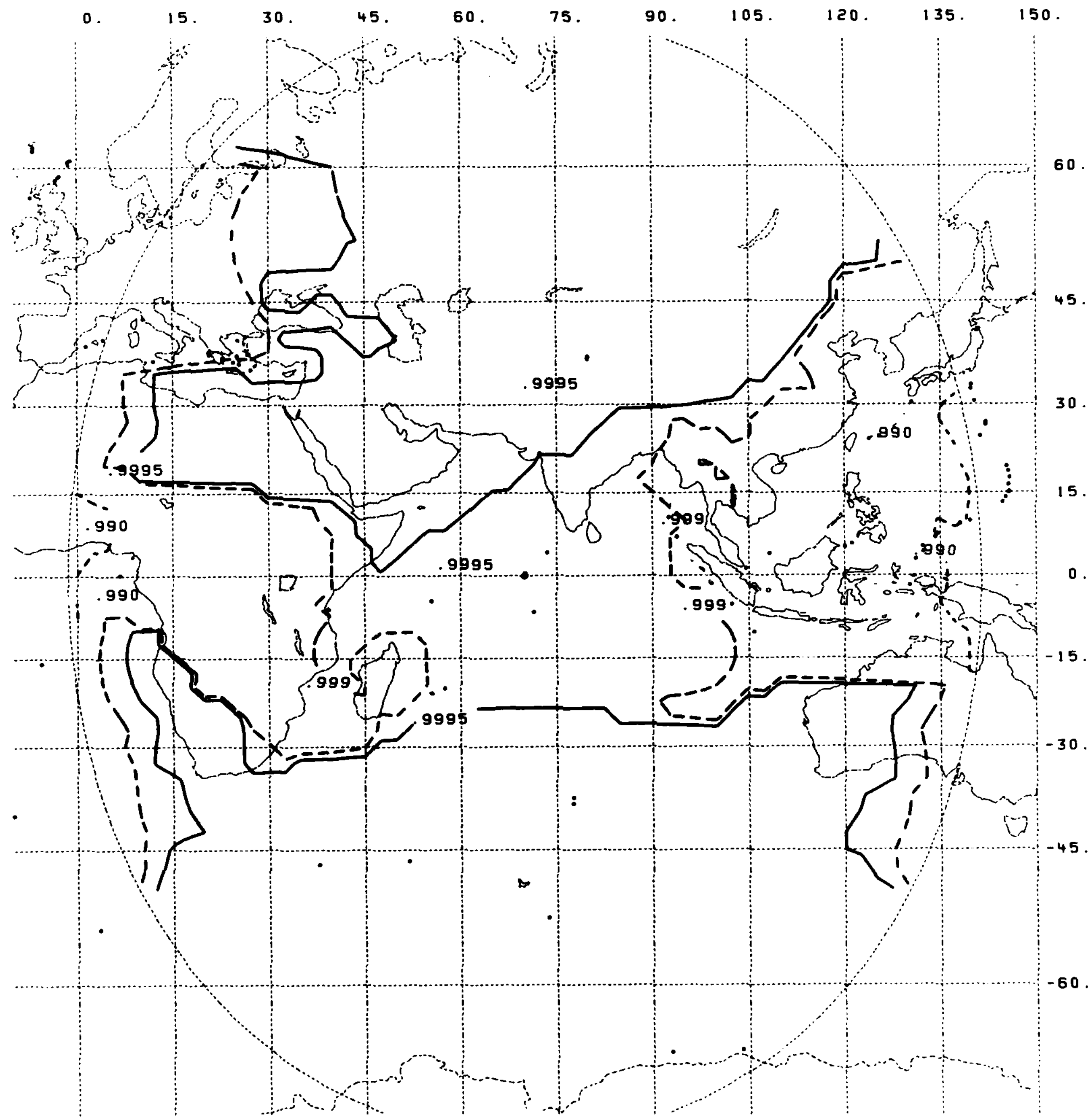

Fig. 37. Availability contours for 37 beam PA pattern; 16.0 dB margin; 70°E subpoint

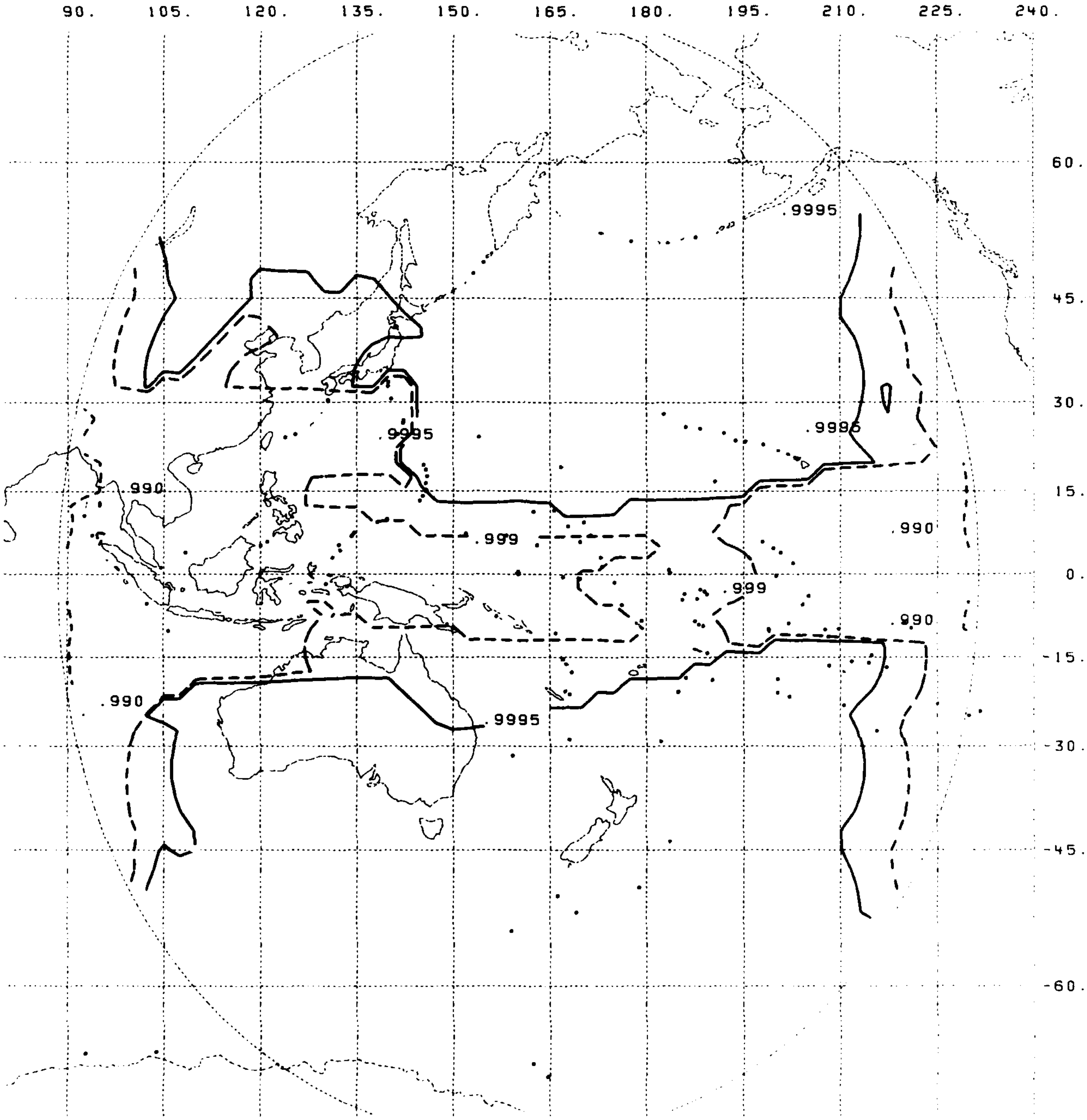

Fig. 38. Availability contours for 37 beam PA pattern; 16.0 dB margin; 160°E subpoint

IV. CONCLUSIONS

Introducing the downlink phased array pattern factor into the link margin equation for computing system availability results in moderate reductions in availability referred to the idealized uniform gain case. Not surprisingly, the contours for the 31 beam phased array are not significantly different from the contours for the 37 beam structure which uses smaller beam spacing and has a better pattern at the Earth limb (-4.5 dB vs -4.9 dB at worst case points)*.

Ultimately, the architecture of any advanced satellite communications system must address the number of satellites needed to provide maximum Earth coverage. For the geostationary orbit cases studied in this report, this number can be extracted from the availability contour plots given in Figs. 3-38 by determining the maximum longitudinal width coverage for a given availability at each subpoint. Table II summarizes that minimum number of satellites required as a function of the value of long-term system availability for each of the 3 values of system margin assumed. Note that since all satellite subpoints are for geostationary orbits, the "maximum Earth coverage" for which Table II is derived does not include either polar area. Non-geostationary orbits are always required to achieve polar coverage. Full equatorial coverage with a long-term system availability of 0.99 or greater at a baseline link margin of 13.6 dB cannot be achieved with 3 satellites using either a 31 beam downlink phased array or a 37 beam phased array. However, 3 dB of added margin allows 3 satellites to provide full longitudinal coverage with either phased array configuration.

A trend of latitudinally oriented clusters of availability contours (i.e., rapid variation in availability with change in latitude) can be seen for most of the subpoints used and for all three pattern functions used. In general,

*Note that the difference in horn spacing for the arrays almost exactly compensates for this difference in the relative patterns with the result that the gains at Earth limb are almost the same, whereas the subpoint gains differ by 0.6 dB per Table I.

TABLE II

NUMBER OF SATELLITES REQUIRED FOR MAXIMUM EARTH COVERAGE FROM GEOSTATIONARY ORBIT*

LONG TERM SYSTEM AVAILABILITY	31 BEAM	37 BEAM
.9995	Not Achievable	Not Achievable
.999	Not Achievable	Not Achievable
.990	4/4/3	4/4/3
.970	3/3/3	3/3/3

*Entries XX/XX/XX correspond to 10.6, 13.6, and 16.6 dB for system margin for the 31 beam configuration and 10.0, 13.0, and 16.0 dB margin for the 37 beam configuration.

this trend appears to correspond with Crane's climate region borders which tend to also be latitudinally oriented.

For the cases using the 31 and 37 beam phased array pattern functions, there are several instances where the availability contours located near the subpoint tend to follow (circular) beam contour levels. This was found to occur only for higher levels of availability and only in the subpoint region. There would not appear to be any deleterious effects from this phenomenon.

ACKNOWLEDGMENT

The authors would like to thank Dr. Andre R. Dion for supplying the subroutine BIMHOP used to compute the phased array pattern.

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APPENDIX A

COMPUTATION OF EFFECTIVE BEAM SPACING PARAMETER FOR PERIPHERAL BEAMS OF THE 31 BEAM CURRENT SYSTEM CONFIGURATION

The center of the (M,N) beam of the original 37 beam phased array pattern is given by

ELCNTR = (-M+MBIM/2+0.5)*BIMSPA*.866

AZCNTR = -(-N+NEND/2+0.5)*BIMSPA

where

MBIM = number of rows of beams (=7)
NEND = NBIM (M)
NBIM = 4,5,6,7,6,5,4 for M=1,2,...,7, respectively
BIMSPA = beam spacing parameter (=2.98°)

For example, the (1,2) beam has center coordinates given by

ELCNTR = 7.742°

AZCNTR = -1.49°

The current 31 beam phased array configuration has a larger beam spacing parameter (BIMSPA=3.40°) due to the smaller number of beams covering the same Earth field of view. Using this new value of BIMSPA to compute the new center coordinates of the (1,2) beam (before moving the outermost elements inward by 0.6°)

ELCNTR' = 8.8332°

$$AZCNTR' = -1.70^o$$

These Cartesian coordinates are transformed to the equivalent cylindrical coordinate frame

$$ELCNTR' = \alpha' \sin\beta' = 8.8332^o$$

$$AZCNTR' = \alpha' \cos\beta' = -1.70^o$$

which yields

$$\alpha' = 8.9953^o$$

$$\beta' = 100.894^o$$

Pulling the center of the (1,2) beam in toward the center of the field of view is accomplished by

$$\alpha = (\alpha' - 0.6^o) = 8.3953^o$$

which yields the corrected beam center coordinates of

$$ELCNTR(1,2) = \alpha \sin\beta' = 8.2440^o$$

$$AZCNTR(1,2) = \alpha \cos\beta' = -1.5866^o$$

Finally, the effective value of the beam spacing parameter for the (1,2) beam (and the other 11 outermost beams) is given by

$$BIMSPA_{edge} = \frac{8.2440^o}{(3)(.866)} = 3.1732^o$$

This result can be verified on a different edge beam, e.g., the (3,6) beam

$$ELCNTR(3,6) = (1)(BIMSPA_{edge})(.866) = 2.748^{o}$$

$$AZCNTR(3,6) = (2.5)(BIMSPA_{edge}) = 7.933^{o}$$

yielding

$$\alpha = (ELCNTR^{2}+AZCNTR^{2})^{1/2} = 8.3953^{o}$$

$$\beta = \tan^{-1}\left(\frac{ELCNTR}{AZCNTR}\right) = 19.1061^{o}$$

which agrees with the scaled drawing given in Fig. 1.

APPENDIX B

32 ELEMENT PHASED ARRAY STRUCTURE

The downlink phased array is designed to be fabricated from 32 identical square aperture horns symmetrically positioned in six rows and containing (4,6,6,6,6,4) elements per row, respectively. For the current 31 beam baseline, the horn spacing is 1.5 inches vs 1.4 inches for the prior 37 beam configuration. The efficiency of a square waveguide horn operating in the TE_{10} mode is approximately 81%. The element pattern and array factors are respectively given by

$$G_e(\theta) \simeq [2J_1(v_1)/v_1]^2$$

and

$$G_a(\psi) \simeq [2J_1(v_2)/v_2]^2$$

where

θ = angle measured from the array axis

ψ = angle measured from the beam axis

v_1 = $2\pi d \sin\theta/\lambda$

d = aperture width (inches) = element spacing

λ = operating wavelength (inches)

v_2 = $\pi\sqrt{N}\, d\, \sin\psi/\lambda$

N = number of elements (=32)

Greater detail on the directive gain analysis of this type of square horn element phased array can be found in Reference 4.

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The relative variation in the pattern function for a 32 element, multibeam EHF satellite phased array has been incorporated into the equation for downlink margin. The corrected margin is used to determine allowable rain attenuation (dB) and predict link availability based on Crane's 8 region world wide rain rate distribution and climate model. Link availability contours are computed for the cases of a 31 beam and 37 beam phased array. Four equispaced geostationary satellites are required for either configuration in order to provide 0.99 (or greater) link availability to all points within the 10° elevation angle field of view for the nominal value of downlink margin and a frequency of 20.7 GHz.

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