VLB ARRAY MEMO No. 124

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To: VLBA Array Design Group

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Subject: A Systematic Search for Ten Station VLB Array Geometries

A systematic search of all possible combinations of several groups of sites were examined to determine the 'best' ten station array using the (u, v) based evaluation described in VLBA Memo No. 84. For each test, five or six sites were fixed and the remaining were chosen from all possible combinations of ten or eleven 'test' sites. Three sets of fixed sites were chosen ('southern', 'continental', and 'dry') for analysis and compared with the array D-2 (NRAO).

Southern Arrays (SQ)

It was already clear from the analysis in Memo No. 84 that the inclusion of at least one South American site dramatically improves overall (u, v) coverage of mostly U. S. based arrays. We chose a single southern site (near Quito, Ecuador) and five U. S. sites (Hawaii, Arecibo, OVRO, Socorro, and Tucson) as 'fixed'. We then examined all 210 combinations of ten other sites for the four remaining elements (see Figure 1). The figure of merit was computed at four standard declinations (44°, 18°, -6°, -30°). The best thirty arrays were then examined at all nine standard declinations (64°, 44°, 30°, 18°, 6°, -6°, -18°, -30°, -44°). In Figure 2 we have plotted at each declination histograms of the number of arrays vs the average figure of merit normalized to the NRAO array D-2 (best thirty arrays only). The histograms clearly illustrate two results: (1) There are only small differences among the top ten or so arrays at all declinations except perhaps at $\delta = -44°$ and (2) only at the very highest declination does array D-2 even marginally outperform the best 'southern' arrays. Since the (u, v) coverage is excellent in both cases at high declinations in any case, this slight improvement is completely outweighed by the dramatic improvement in coverage below $\delta = 18°$.

The ten best 'southern' arrays are given in Table 2. (See Table 1 for station observations.) The top ranked southern array (SQ-1) is mapped in Figure 3. There are several interesting features of the best southern arrays. (1) All of the top ten have a northern midwestern site (Bismark) and a southern Texas site (Brownsville). (2) Eight of the top ten have Bermuda as a site. (3) The two arrays without Bermuda include Haystack (but not NRAO). The best array without Bermuda (SQ-5) is actually the best rated array if $\delta = -44°$ is not included.

Continental Arrays (CA)

We also systematically investigated ten element arrays based entirely on U. S. soil (including Puerto Rico). In order to make the computation feasible, we assumed five fixed sites (Hawaii, OVRO, Socorro, Santa Fe, and Arecibo). The remaining five sites were chosen from all (462) combinations of eleven other sites placed around the continental U. S. (see Figure 4 for map). The analysis was identical to that described for the southern arrays above.

The best ten continental arrays are given in Table 3 along with figures of merit at each declination. The top ranked continental array is shown in the map in Figure 5. Note for the top ten arrays: (1) Haystack is a site for all ten; (2) Brownsville is a site for nine of the top ten; (3) a midwestern U. S. site (either Bismark, ND or NLRO) is a site for all ten; and (4) a northwestern site (either Salem, Oregon or Boise, Idaho) is included for all ten. Note, if $\delta = -44°$ is excluded, that the top ranked array is CA-7.

Dry Arrays (DA)

We next tried to find a continental U. S. ten station array which consisted primarily of dry, western U. S. sites. The fixed sites chosen were Hawaii, OVRO, Socorro, Santa Fe, Arecibo, Haystack, and NLRO. The remaining three sites were chosen from all combinations of twelve western U. S. sites (map, Figure 6). The analysis proceeded as described above. The best ten 'dry' arrays are given in Table 4. The top-ranked array is shown in Figure 7. Note the following characteristics of the best arrays: (1) A south Texas site (Laredo) is in all ten; (2) a north-central site (either Havre, Montana or Bismark, North Dakota) is in all ten; and (3) the existing VLB station at Ft. Davis, Texas shows up only in one (DA-7) array in the top ten. Also note that the second best dry array (DA-2) is the top ranked array if $\delta = -44°$ is not considered.

Comparisons with Array D-2

In order to easily evaluate these arrays in terms of prior VLBA designs, we have normalized the averaged figure of merit by the figure of merit for the NRAO array D-2. Histograms of the thirty best arrays normalized by D-2 are shown in Figures 8 and 9. Note that for the southern arrays the difference is about a factor of two, whereas the best continental and dry arrays provide about 20% better coverage (including $\delta = -44°$). The much improved (u, v) coverage at $\delta = -44°$ is largely a result of substituting Puerto Rico for Anchorage in array D-2. It is surprising that the best 'dry' arrays are nearly as good as the best continental arrays, although there are relatively fewer excellent 'dry' configurations.

Transfer Function Plots

In Figure 10 we have plotted the (u, v) plane coverage at all nine standard declinations for arrays D-2, SQ-1, CA-1, and DA-1. Note especially that reasonable science can be done at $\delta = -44°$ with arrays DA-1 and CA-1 (and, of course, SQ-1), whereas there is essentially no coverage with array D-2.

Conclusions

1. The addition of a single southern hemisphere station improves the total (u, v) coverage by at least 100% compared with all 'northern' arrays. The optimal northern site geometry with a southern site is not substantially different from optimal ten station arrays with a northern site.

2. There are a large number of nearly equivalent 'continental' arrays. For each of the three systematic array configuration studies in this report, the top ten arrays were all within 3% of the 'best' array in each category. This indicates that the final array design can be optimized with regard to weather conditions and logistic support at each site without significantly affecting the overall array performance. For example, the performance of the best 'dry' array (using only relatively dry western sites for variables) was nearly equivalent to the best 'continental' array.

3. The 'optimal' array will very likely require a northeast site, at least one midwest site, a south Texas site, as well as sites near the VLA, Hawaii, and Puerto Rico.

4. For all cases studied, arrays with sites near Haystack Observatory are noticeably better than those with Green Bank, West Virginia.

Location	Abbreviation	Latitude	Longitude
Arecibo, Puerto Rico	ARE	18.3	66.8
Bend, Oregon	BND	44.0	121.2
Bermuda	BER	32.3	64.6
Big Pine, California	OVR	37.0	118.3
Bismarck, North Dakota	BSM	47.0	101.0
Boise, Idaho	BOI	42.7	116.0
Boulder, Colorado	BLD	40.0	105.3
Brownsville, Texas	BRV	26.0	97.4
Ft. Davis, Texas	FDV	30.5	103.9
Green Bank, West Virginia	NRA	38.3	79.8
Havre, Montana	HAV	48.5	109.8
Hawaii	HAW	19.0	155.5
Laredo, Texas	LRD	27.5	99.0
Las Vegas, Nevada	LVG	36.2	115.2
Memphis, Tennessee	MEM	35.1	90.0
Miami, Florida	MIA	26.0	81.0
Moab, Utah	MOB	38.6	109.5
North Liberty, Iowa	IWA	41.6	91.6
Pocatello, Idaho	POC	42.9	112.3
Salem, Oregon	SLM	45.0	123.0
Sante Fe, New Mexico	SAF	35.6	105.9
Socorro, New Mexico	SOC	34.1	106.9
Sterling, Colorado	STL	40.6	103.2
Tucson, Arizona	TUC	32.4	111.0
Wendover, Utah	WEN	40.9	114.0
West Coast, Ecuador	QTW	0.0	80.0
Westford, Massachusetts	HSK	42.4	71.5
Winnemucca, Nevada	WIN	40.8	117.8

Table 1. Station Abbreviations

Stations

HAW, ARE, OVR, SOC, TUC, QTW, +

SQ-1	BER, HSK, BRV, BSM
SQ-2	BER, SLM, BRV, BSM
SQ-3	BER, MIA, BRV, BSM
SQ-4	BER, IWA, BRV, BSM
SQ-5	SLM, HSK, BRV, BSM
SQ-6	BER, BOI, BRV, BSM
SQ-7	MIA, HSK, BRV, BSM
SQ-8	BER, IWA, BRV, SLM
SQ-9	BER, NRA, BRV, BSM
SQ-10	BER, BLD, BRV, BSM

Merit

	-44°	-30°	-18°	-6°	6°	18°	30°	44°	64°	Avg w/o -44°	Avg
SQ-1	571	284	214	195	152	101	79	54	38	139.8	187.7
SQ-2	571	303	232	195	151	97	74	50	36	142.2	189.9
SQ-3	526	298	242	207	158	107	79	53	42	148.2	190.2
SQ-4	571	288	232	205	154	105	79	51	39	144.2	191.6
SQ-5	633	292	217	198	149	90	73	52	32	137.8	192.8
SQ-6	571	305	237	201	154	101	76	52	45	146.4	193.6
SQ-7	584	285	220	216	165	101	79	53	40	144.9	193.7
SQ-8	571	293	238	214	159	105	79	50	34	146.5	193.7
SQ-9	571	286	236	210	158	111	78	55	39	146.7	193.9
SQ-10	571	306	239	208	157	103	76	56	43	148.6	195.6

Table 2. Best Ten SQ Arrays

Stations

HAW, ARE, OVR, SOC, SAF, +

CA-1	HSK, MIA, BRV, BSM, SLM
CA-2	HSK, TUC, BRV, BSM, SLM
CA-3	HSK, MEM, BRV, BSM, SLM
CA-4	HSK, MIA, BRV, BSM, BOI
CA-5	HSK, MIA, BRV, BSM, TUC
CA-6	HSK, TUC, BRV, IWA, SLM
CA-7	HSK, IWA, BRV, BSM, SLM
CA-8	HSK, MIA, BRV, IWA, SLM
CA-9	HSK, MIA, TUC, BSM, SLM
CA-10	HSK, TUC, BRV, BSM, BOI

Merit

	-44°	-30°	-18°	-6°	6°	18°	30°	44°	64°	Avg w/o -44°	Avg
CA-1	977	590	470	444	315	159	96	61	39	271.6	350.1
CA-2	1010	590	470	438	311	160	91	56	30	268.3	350.7
CA-3	1023	581	470	438	315	159	97	63	38	270.1	353.8
CA-4	977	590	483	455	323	180	102	61	36	278.7	356.3
CA-5	930	594	492	474	332	196	110	59	36	286.6	358.1
CA-6	1010	569	483	468	346	175	89	53	31	276.8	358.2
CA-7	1113	569	462	438	311	157	89	54	38	264.7	359.0
CA-8	977	577	487	474	356	173	94	61	42	283.0	360.2
CA-9	1023	612	487	444	311	166	97	66	40	277.8	360.7
CA-10	1010	594	487	455	319	184	107	65	32	280.5	361.5

Table 3. Best Ten CA Arrays

BEST 10 DA ARRAYS

Stations

HAW, ARE, OVR, SOC, SAF, HSK, IWA, +

DA-1	HAV, LRD, TUC
DA-2	HAV, LRD, BND
DA-3	BSM, LRD, BND
DA-4	BSM, LRD, TUC
DA-5	HAV, LRD, BSM
DA-6	TUC, LRD, BND
DA-7	HAV, LRD, FDV
DA-8	HAV, LRD, WIN
DA-9	HAV, LRD, WEN
DA-10	HAV, LRD, STL

Merit

	-44°	-30°	-18°	-6°	6°	18°	30°	44°	64°	Avg w/o -44°	Avg
DA-1	1030	577	483	449	300	175	103	64	45	274.6	358.5
DA-2	1138	569	470	438	289	169	95	57	39	265.8	362.7
DA-3	1138	569	470	444	315	168	94	56	39	269.3	365.8
DA-4	1030	577	492	474	332	196	109	58	35	284.0	366.9
DA-5	1138	577	479	444	300	168	100	58	43	270.8	367.1
DA-6	1030	569	492	474	367	186	96	57	34	284.3	367.2
DA-7	1105	581	483	449	303	173	106	69	47	276.5	368.5
DA-8	1138	581	479	449	300	171	107	63	49	274.9	370.8
DA-9	1138	581	483	449	300	171	106	66	46	275.3	371.1
DA-10	1138	577	483	449	303	171	105	69	48	275.6	371.4

Table 4. Best Ten DA Arrays

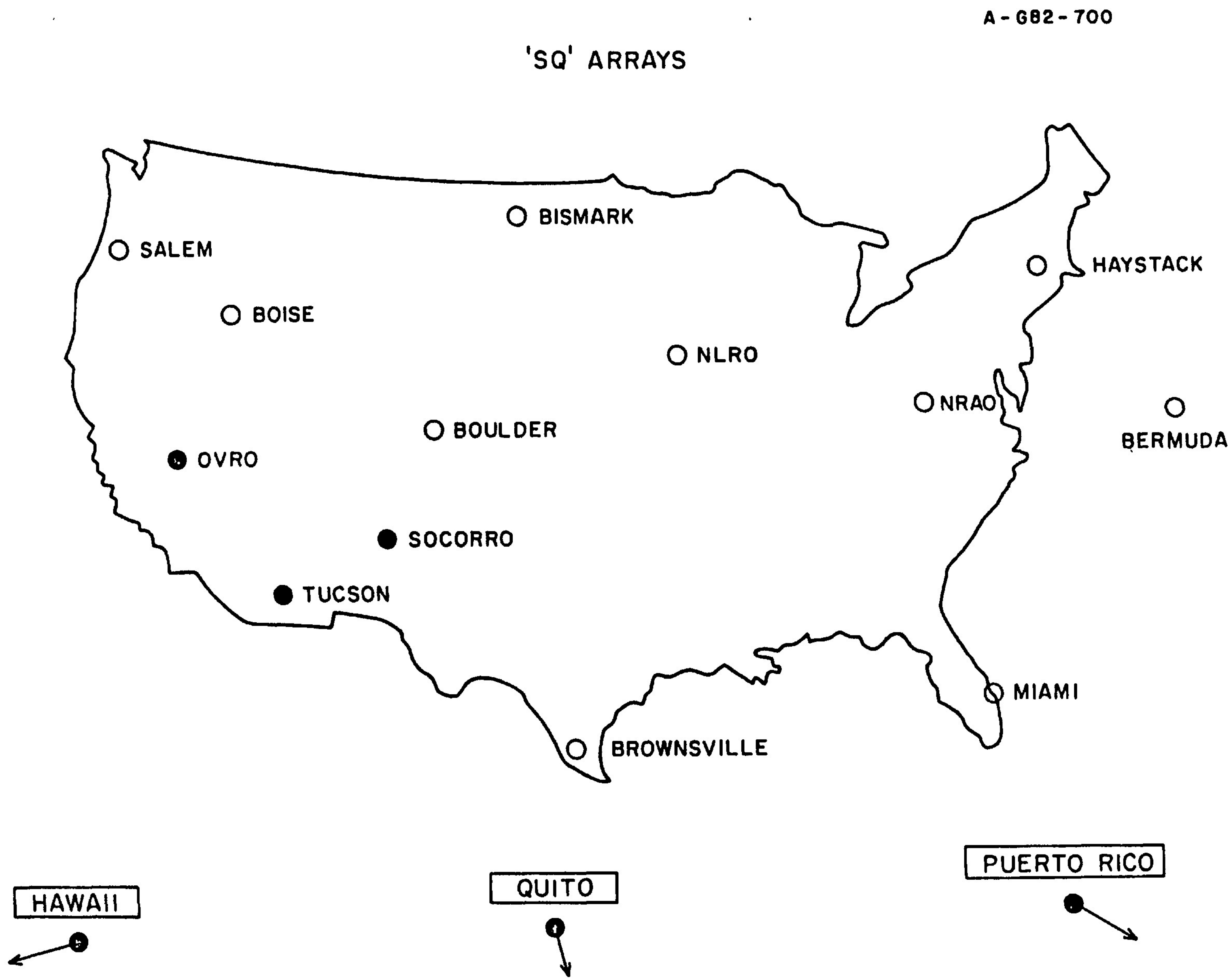

Figure 1. Southern arrays. Black dots are fixed sites; open dots are sites used in test arrays.

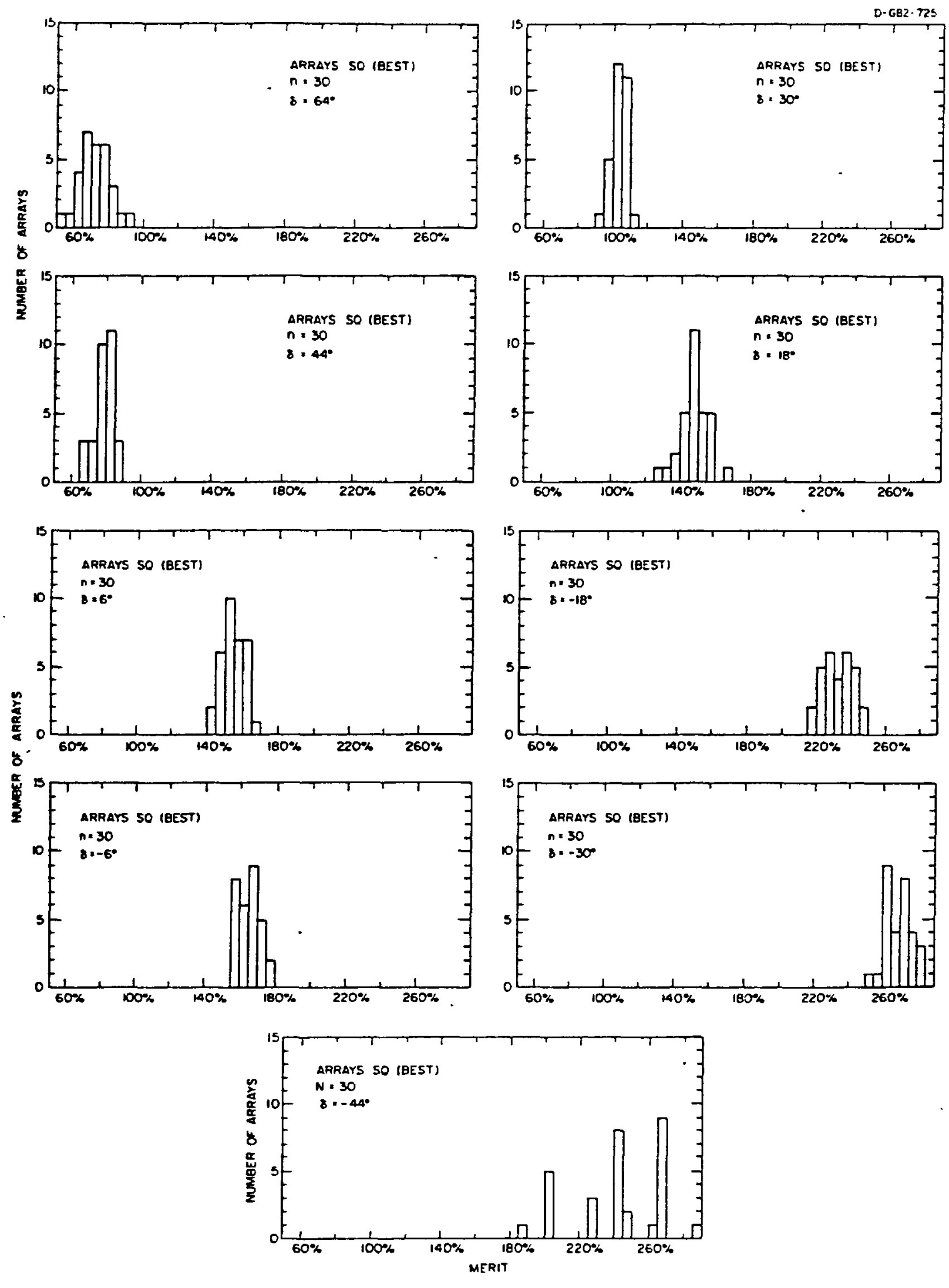

Figure 2. Histogram of the distribution of the thirty best southern arrays as a function of figure of merit, normalized to NRAO array D-2.

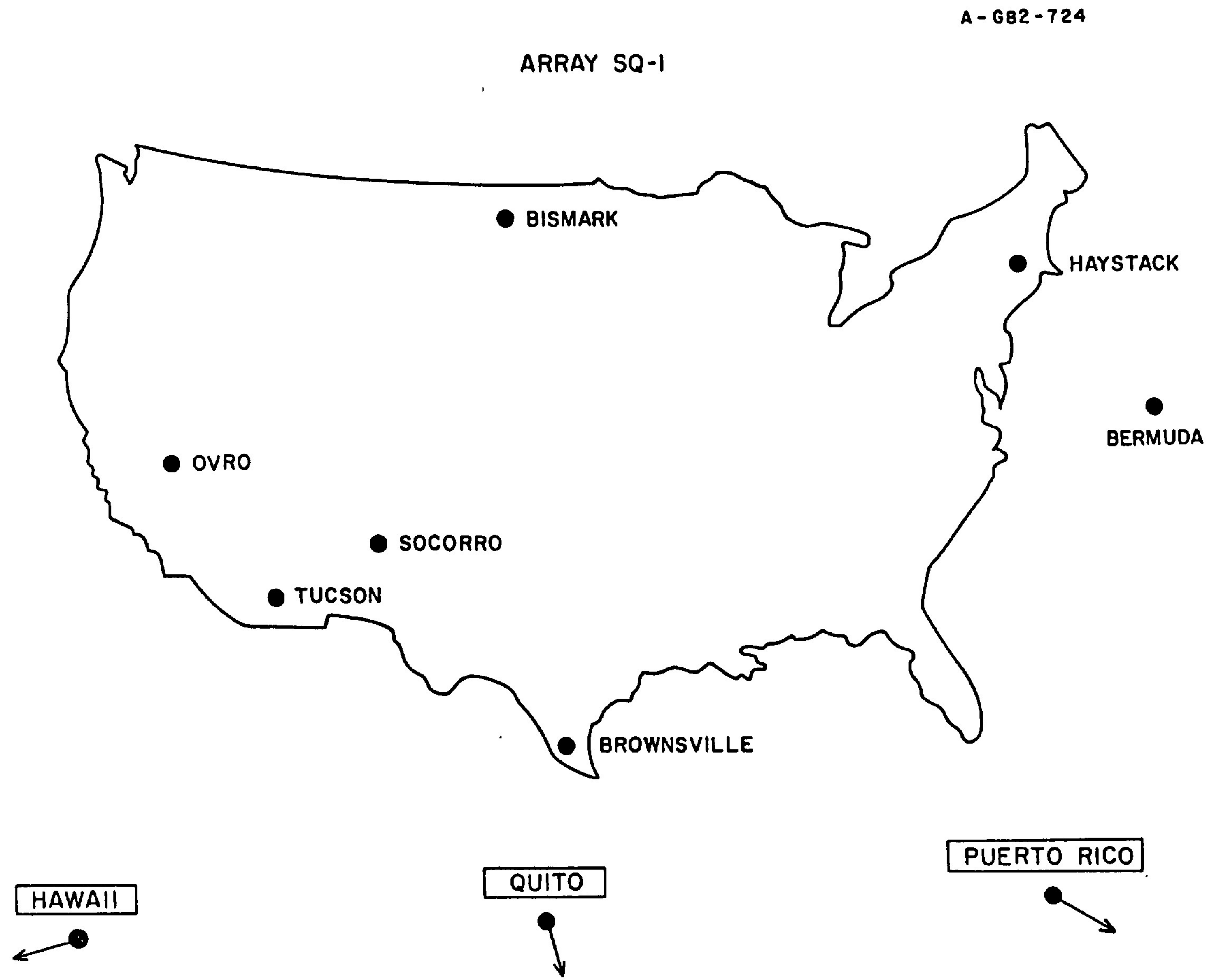

Figure 3. Top-ranked 'southern' array configuration.

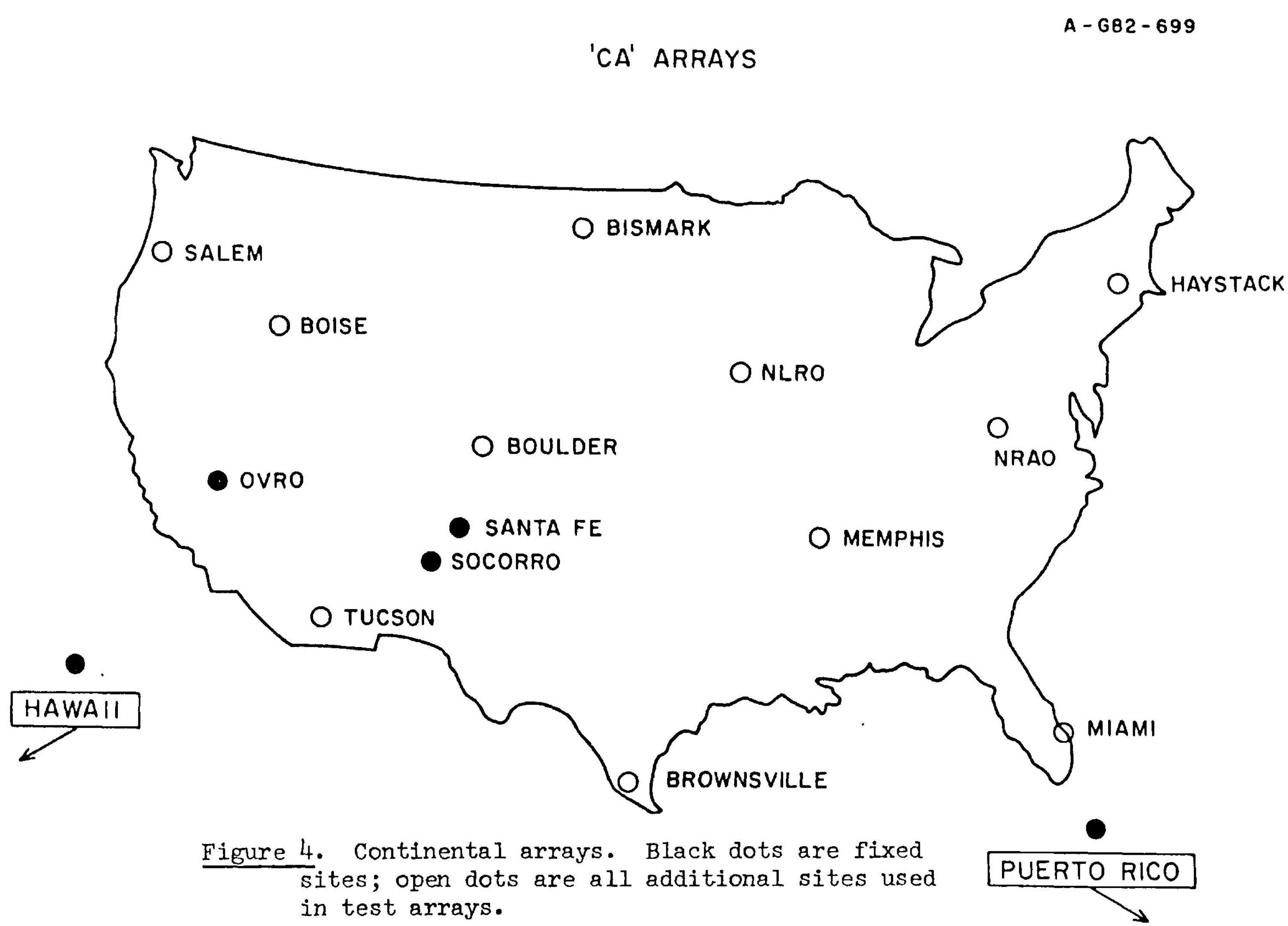

Figure 4. Continental arrays. Black dots are fixed sites; open dots are all additional sites used in test arrays.

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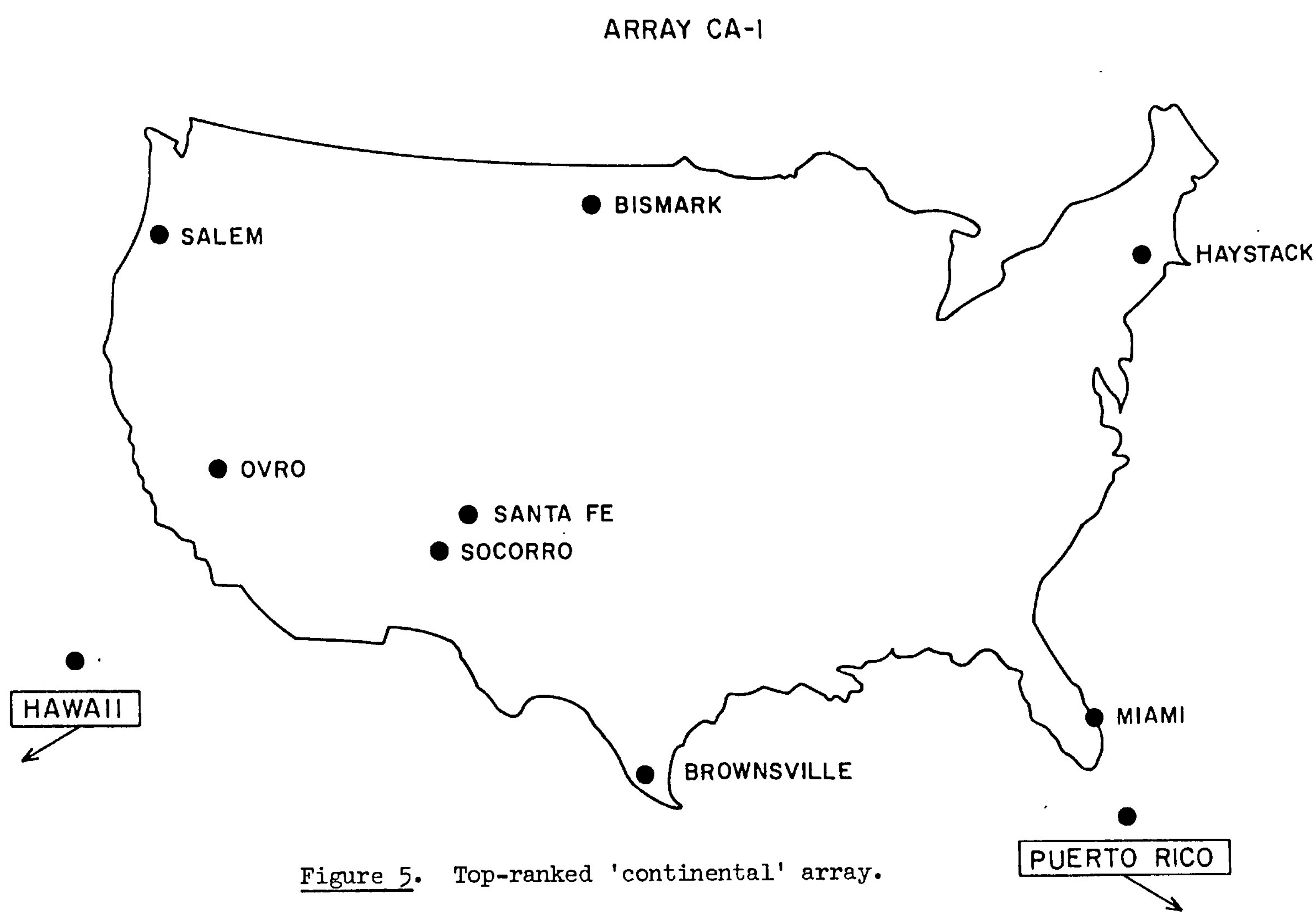

Figure 5. Top-ranked 'continental' array.

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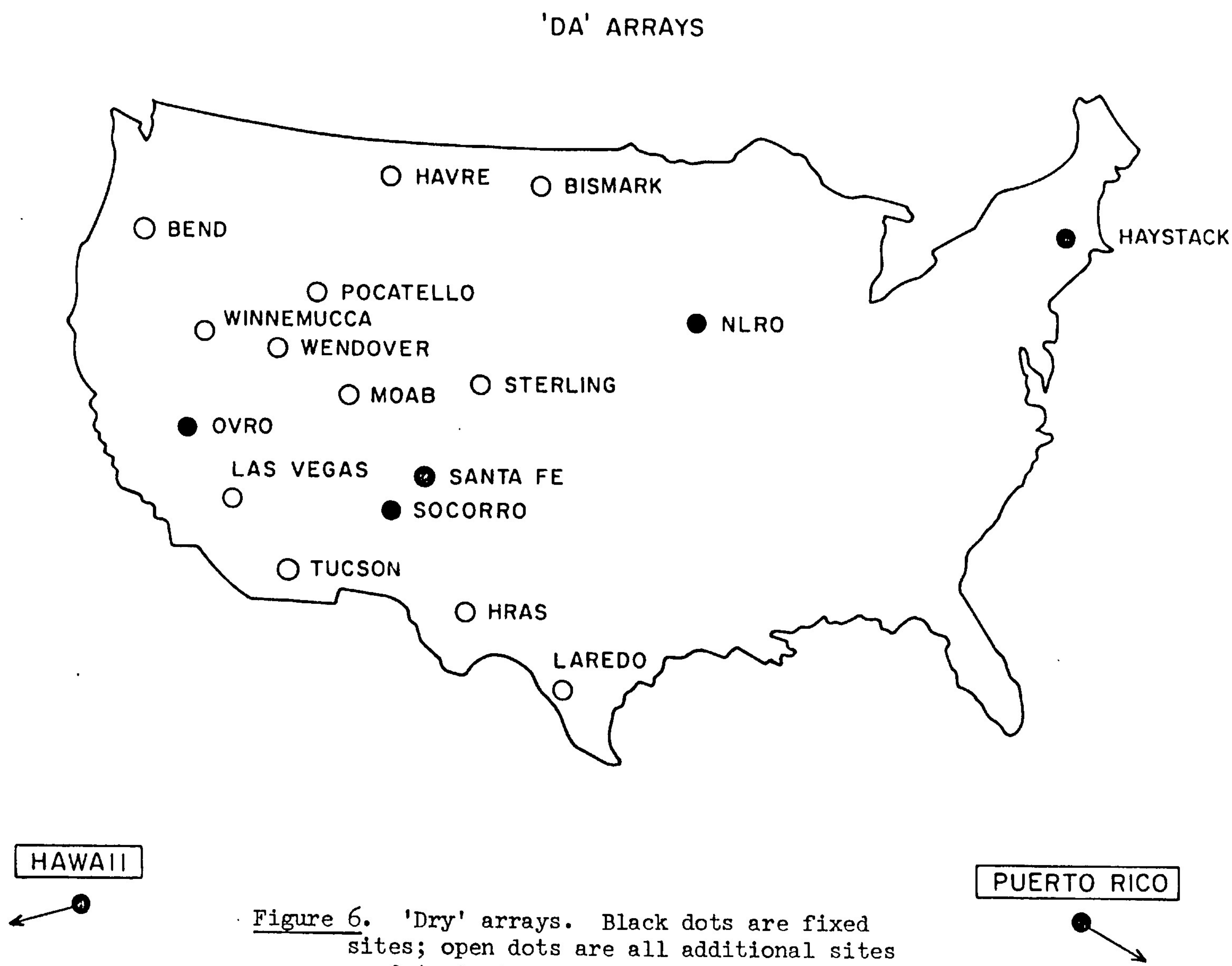

Figure 6. 'Dry' arrays. Black dots are fixed sites; open dots are all additional sites used in test arrays.

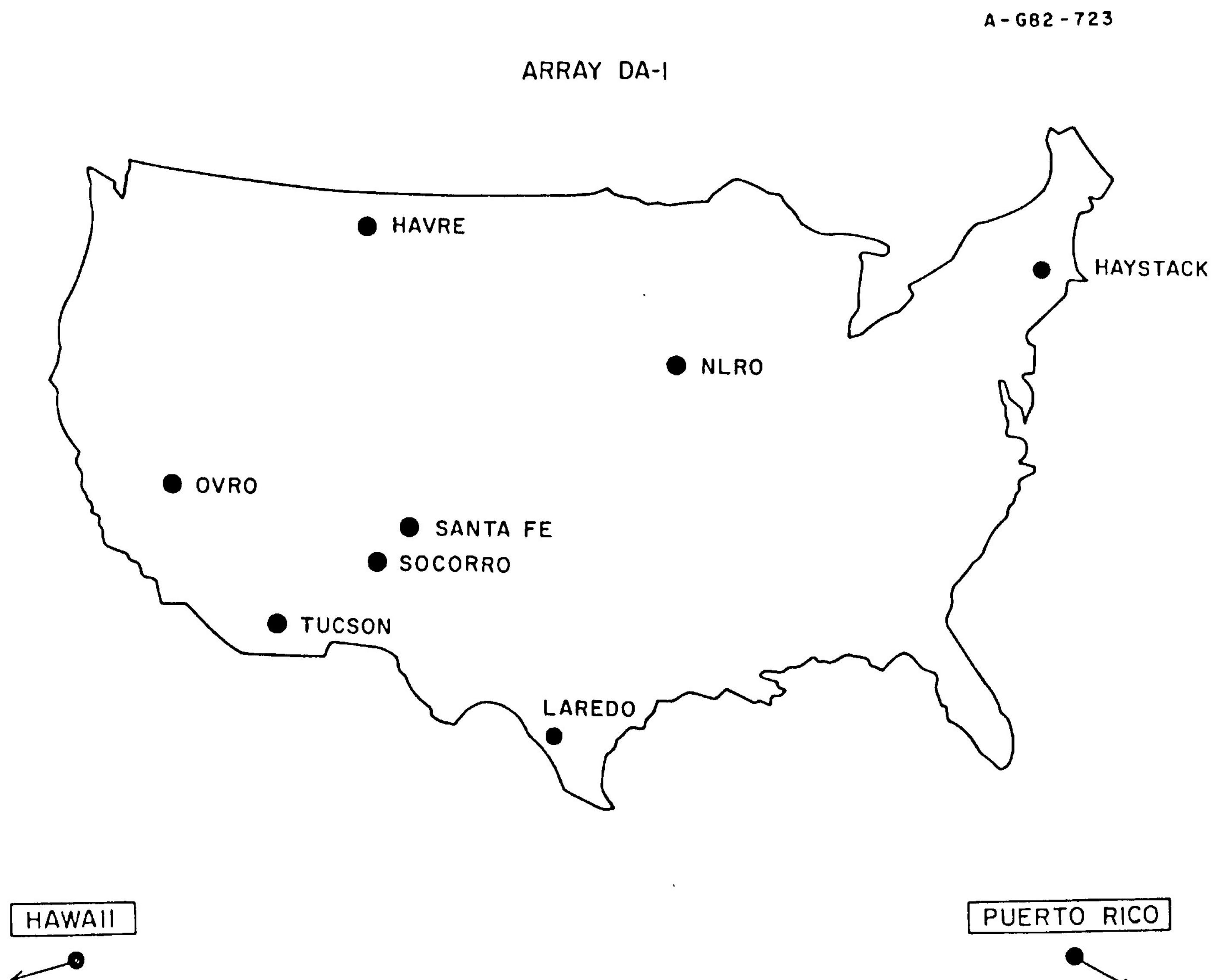

Figure 7. Top-ranked 'dry' array.

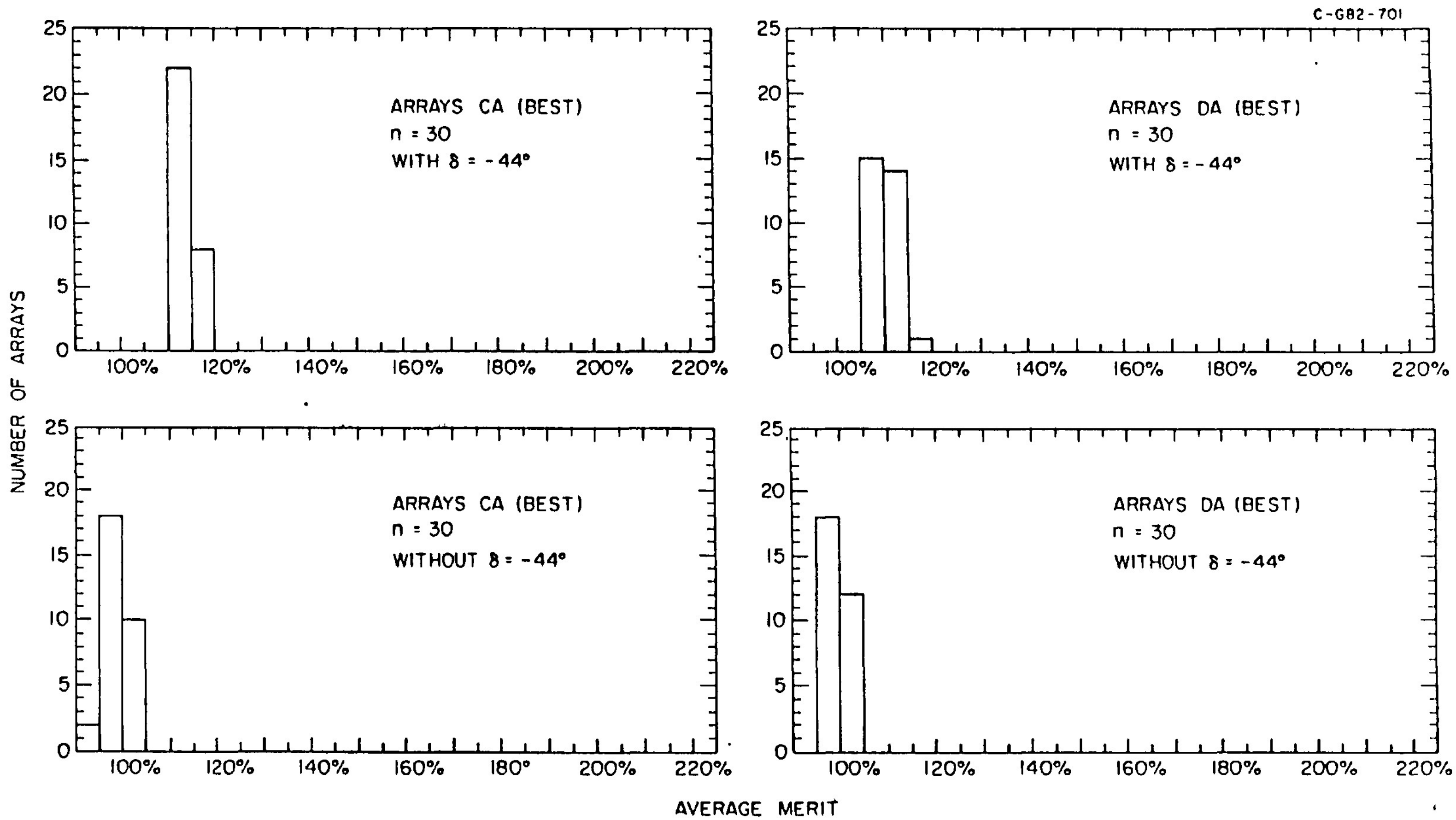

Figure 8. Distribution of best thirty arrays for 'continental' and 'dry' arrays compared with D-2. Separate histograms are shown with and without δ = -44°.

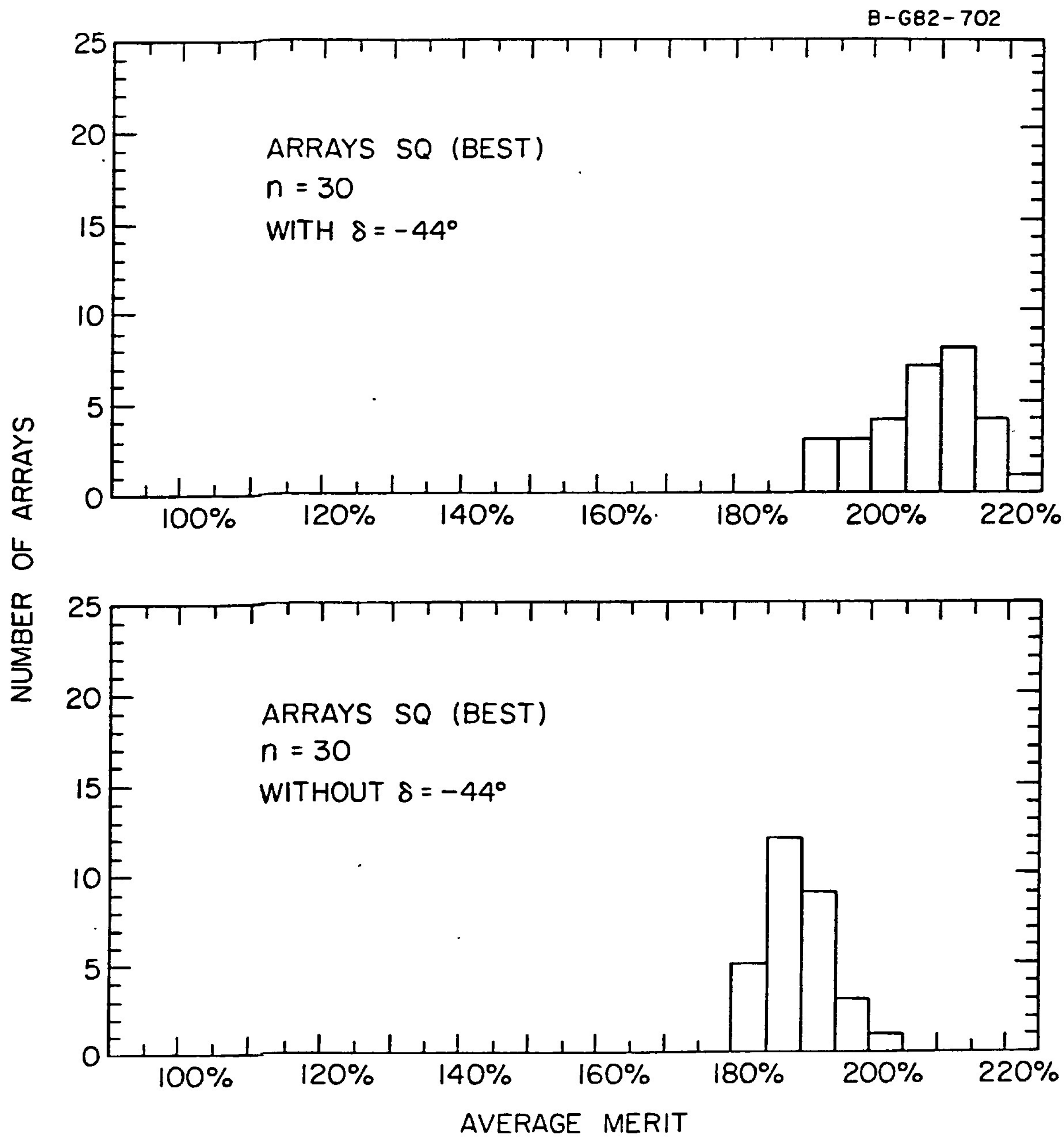

Figure 9. Same as Figure 8, but with best thirty 'southern' arrays.

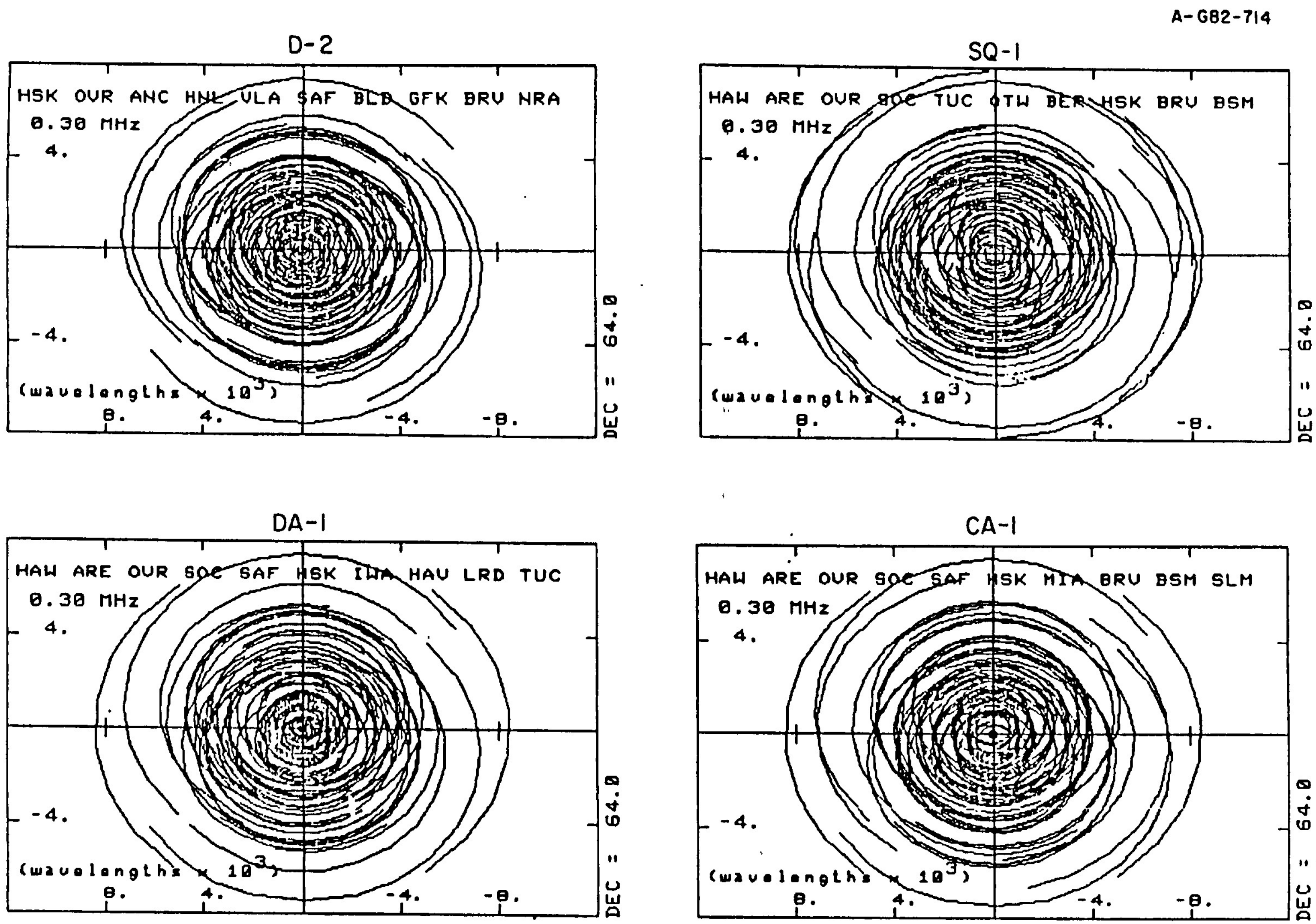

Figure 10. Transfer functions for arrays SQ-1, CA-1, DA-1, and D-2 at nine declinations (+64°, +44°, +30°, +18°, +6°, -6°, -18°, -30°, and -44°).

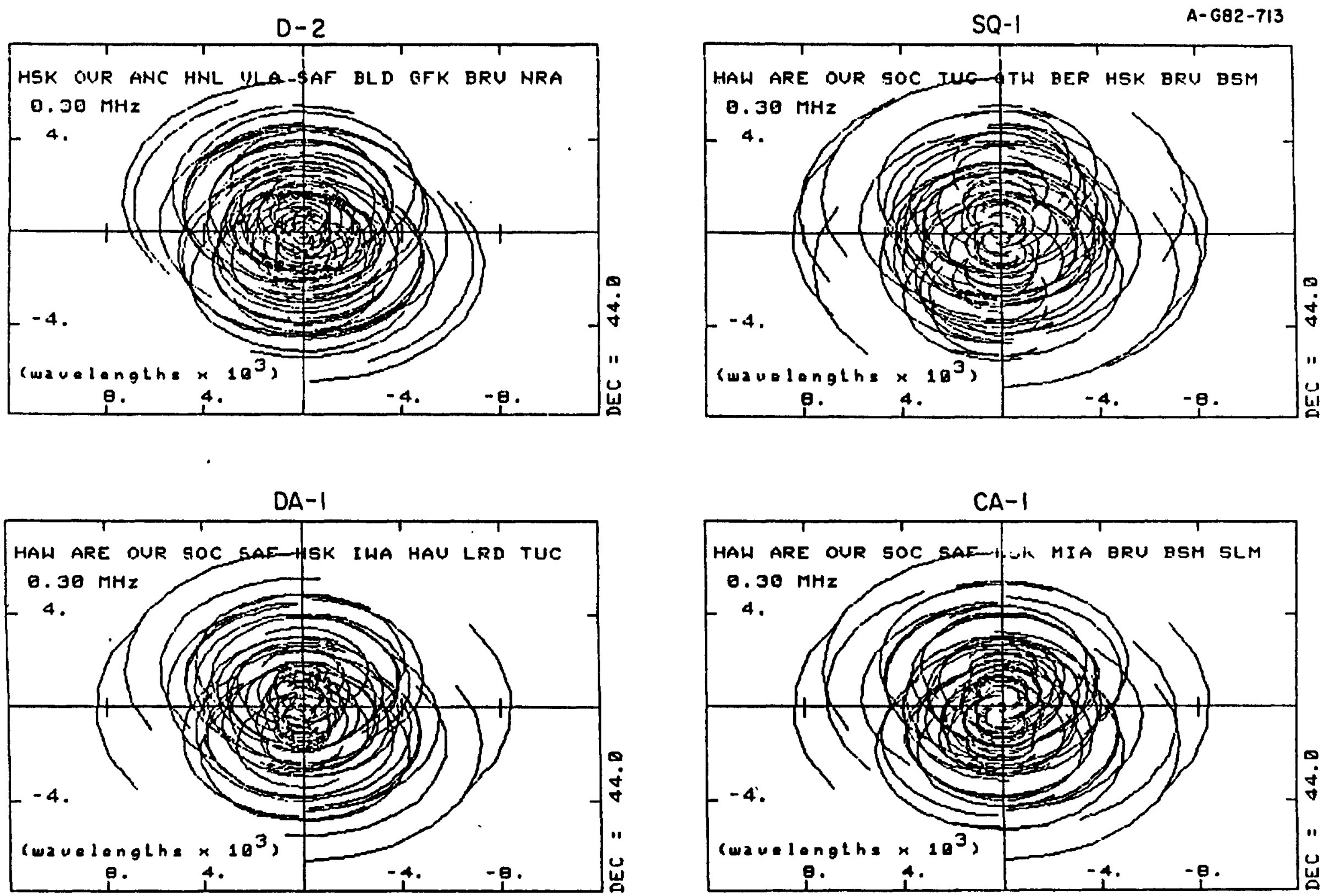

Figure 10 (continued)

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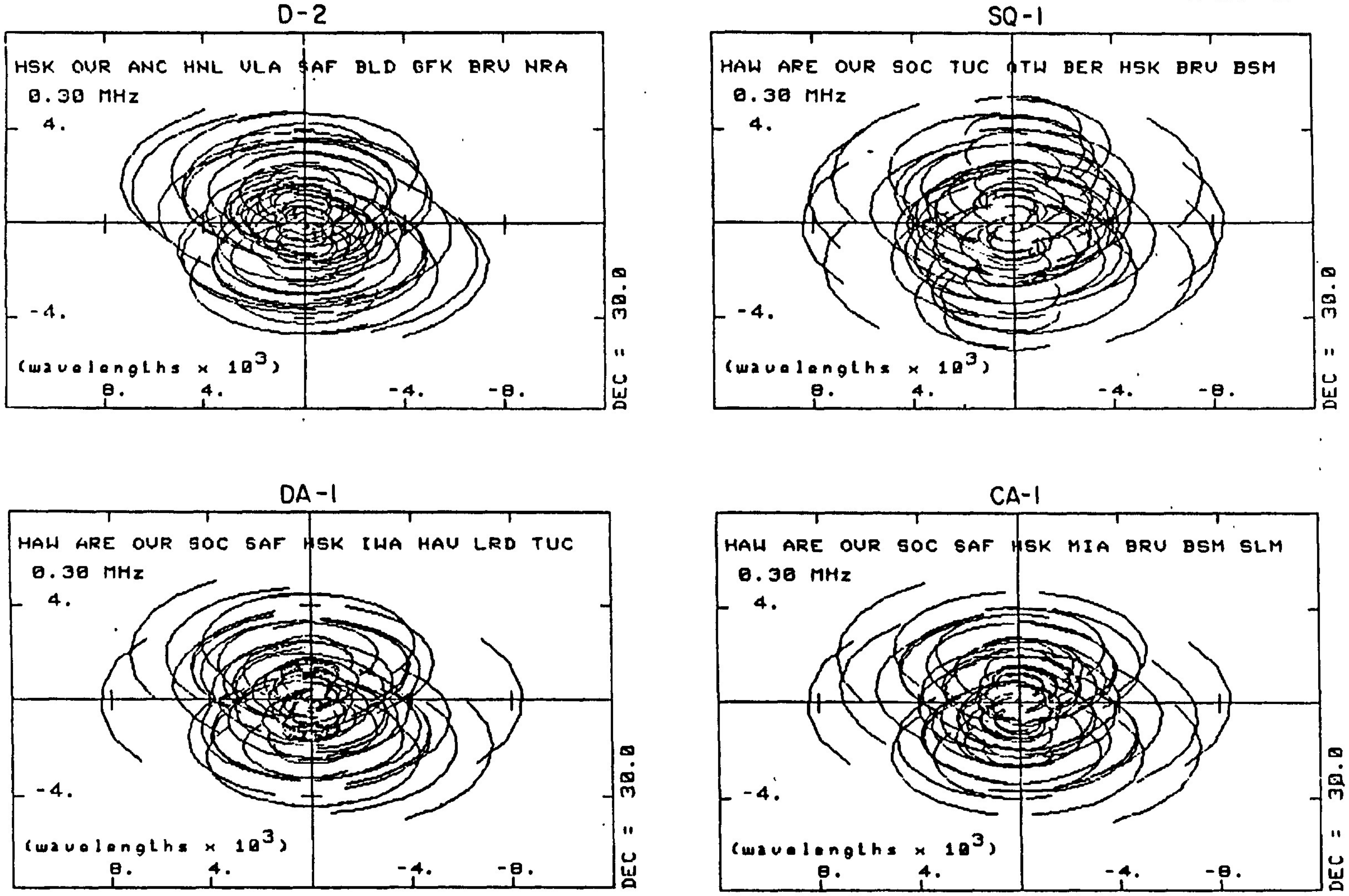

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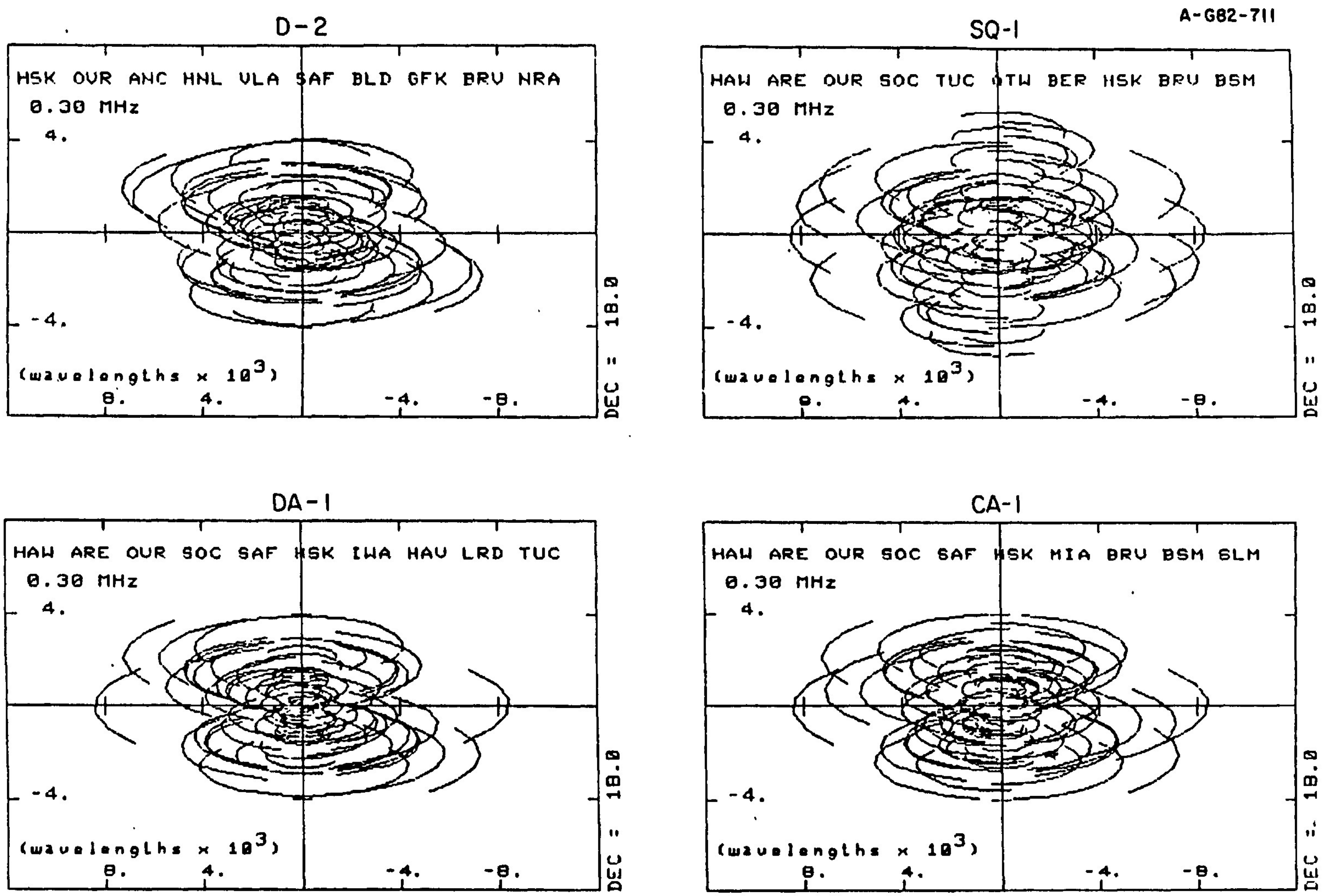

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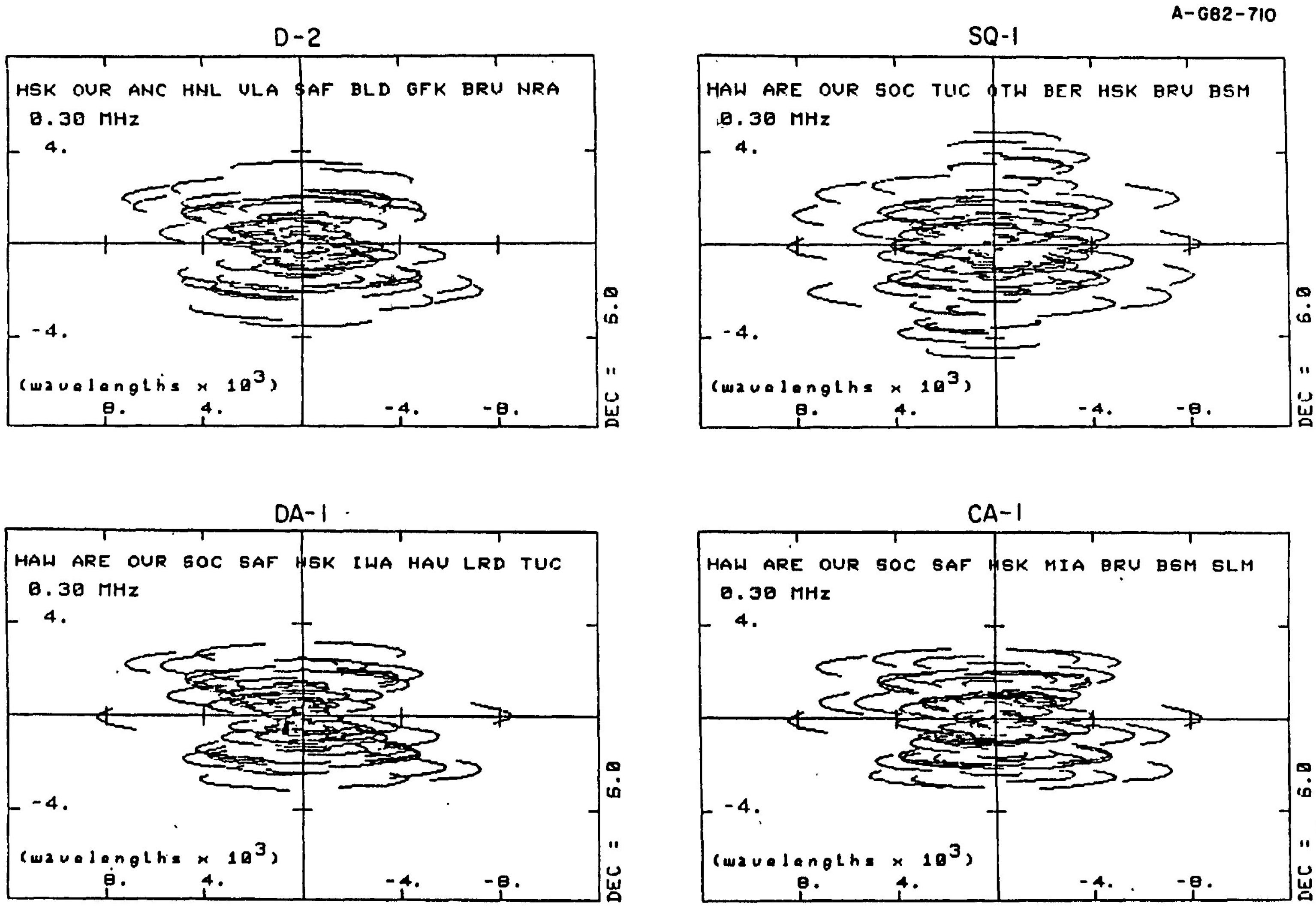
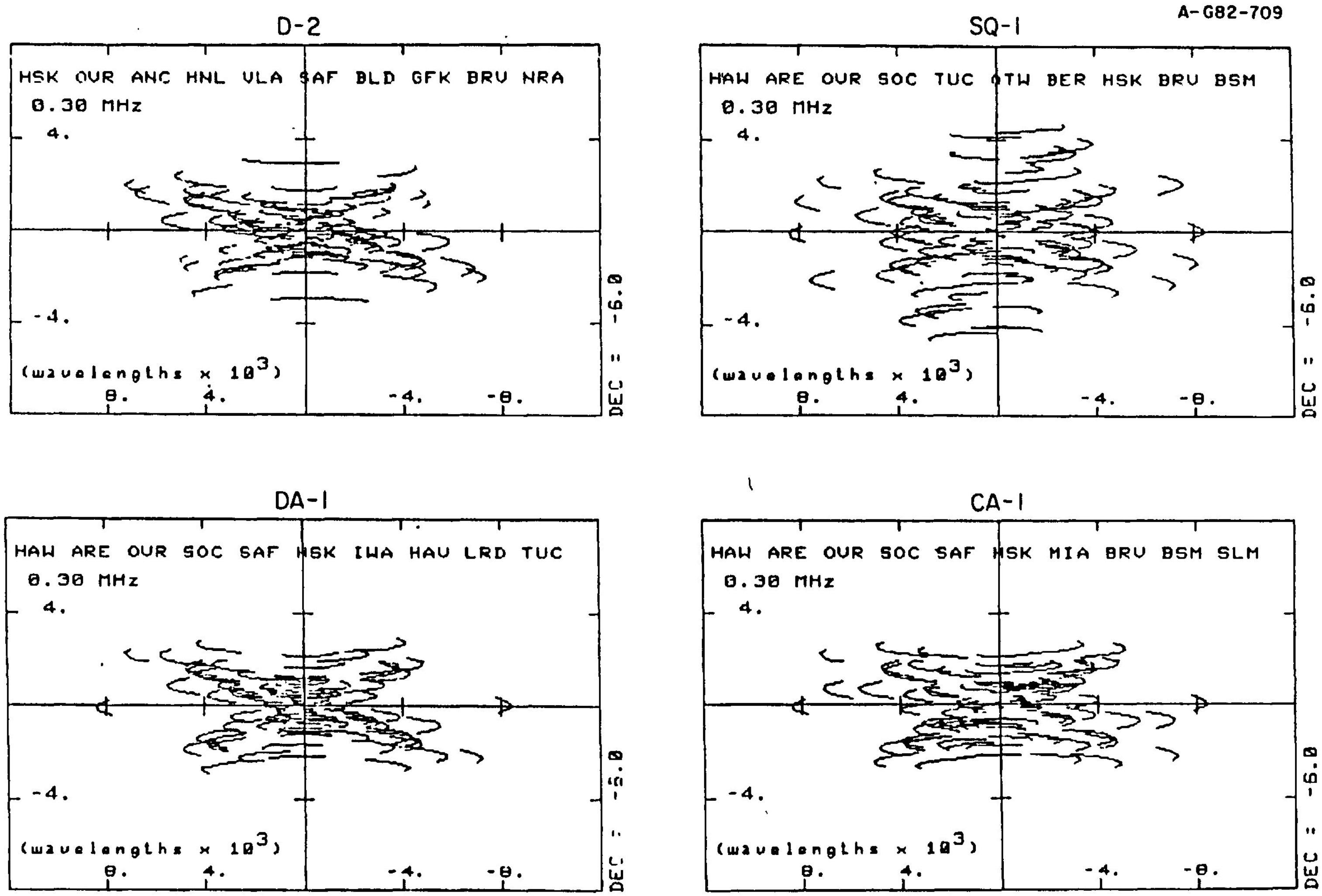


<u>Figure 10</u> (continued)



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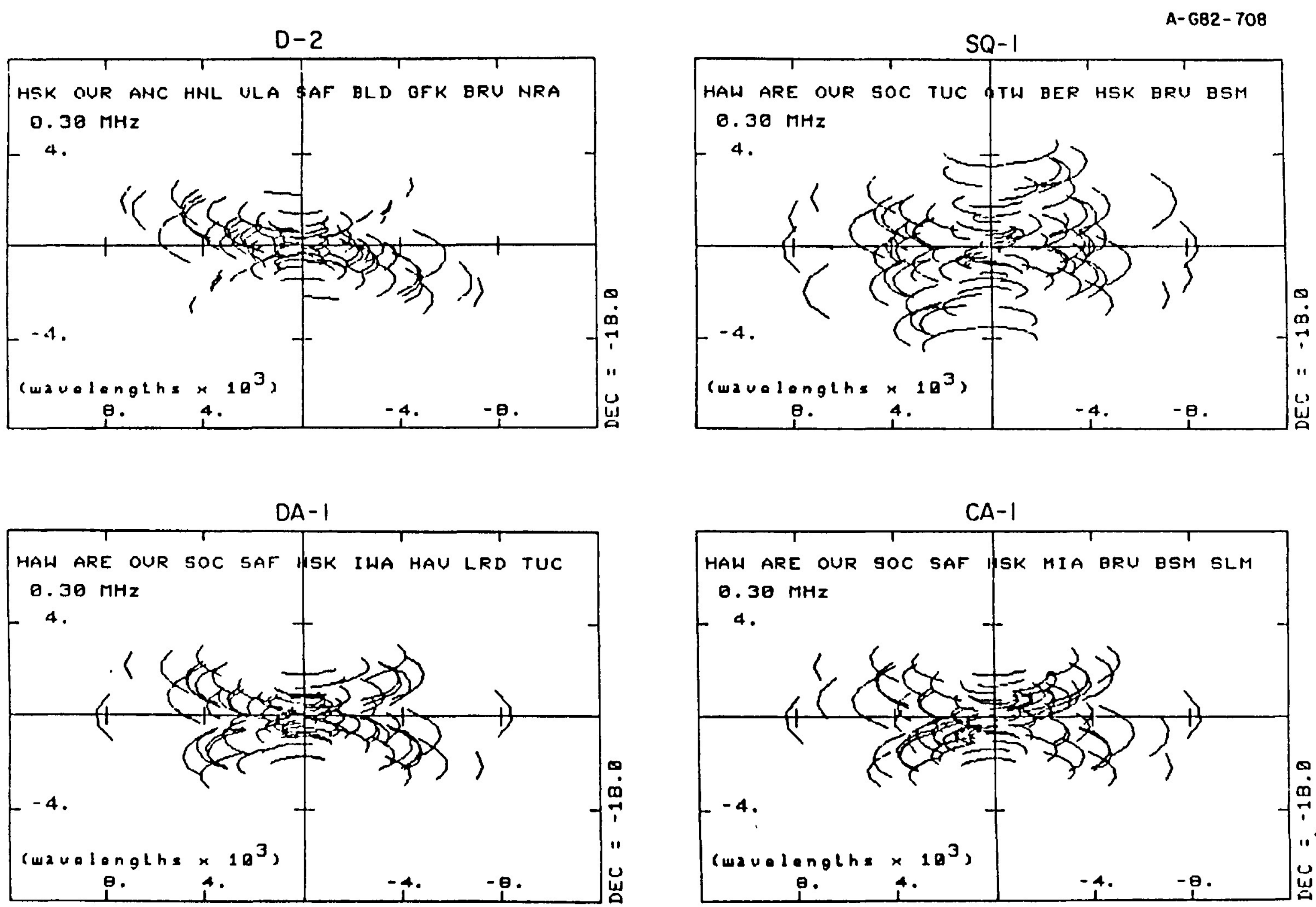

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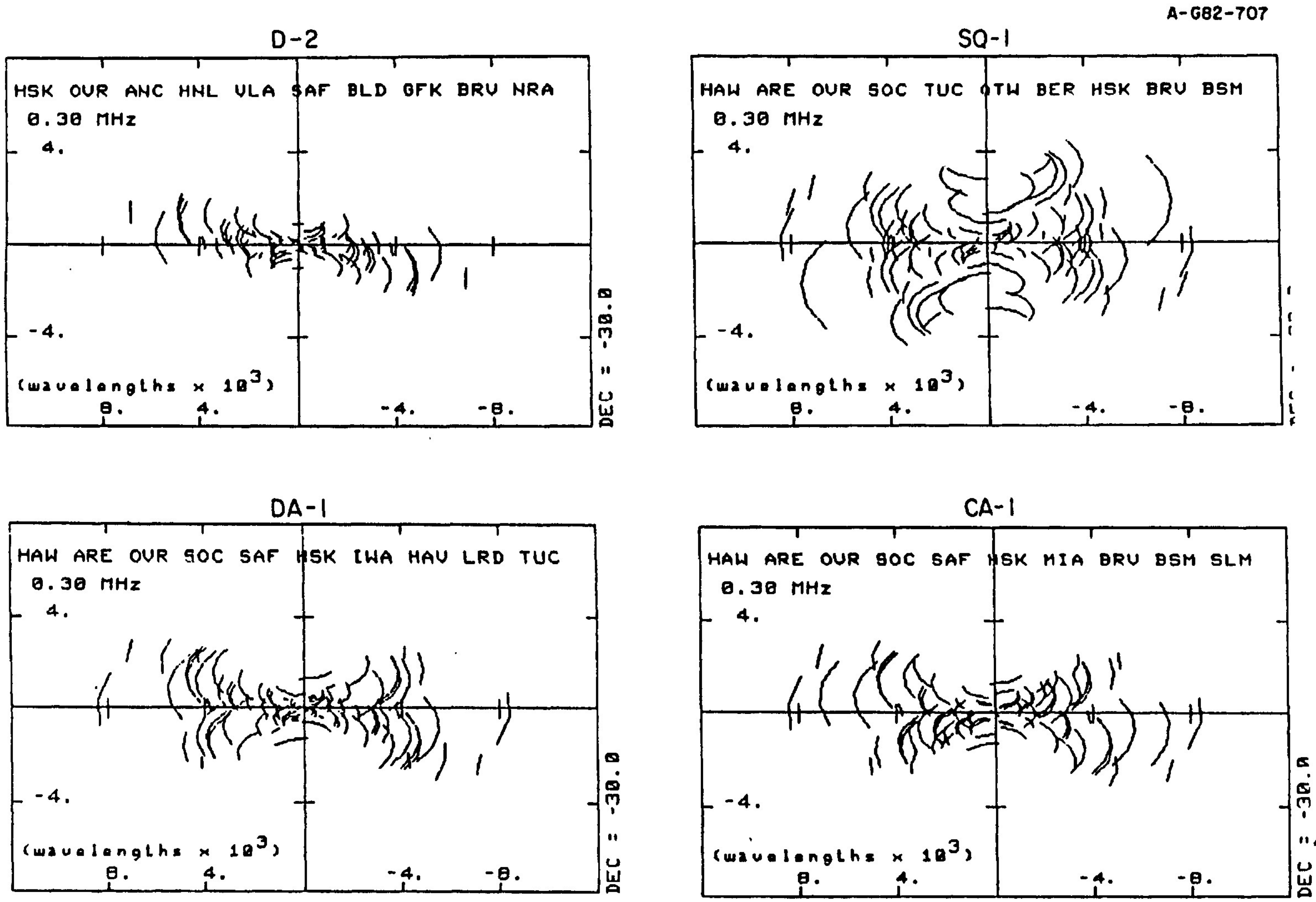

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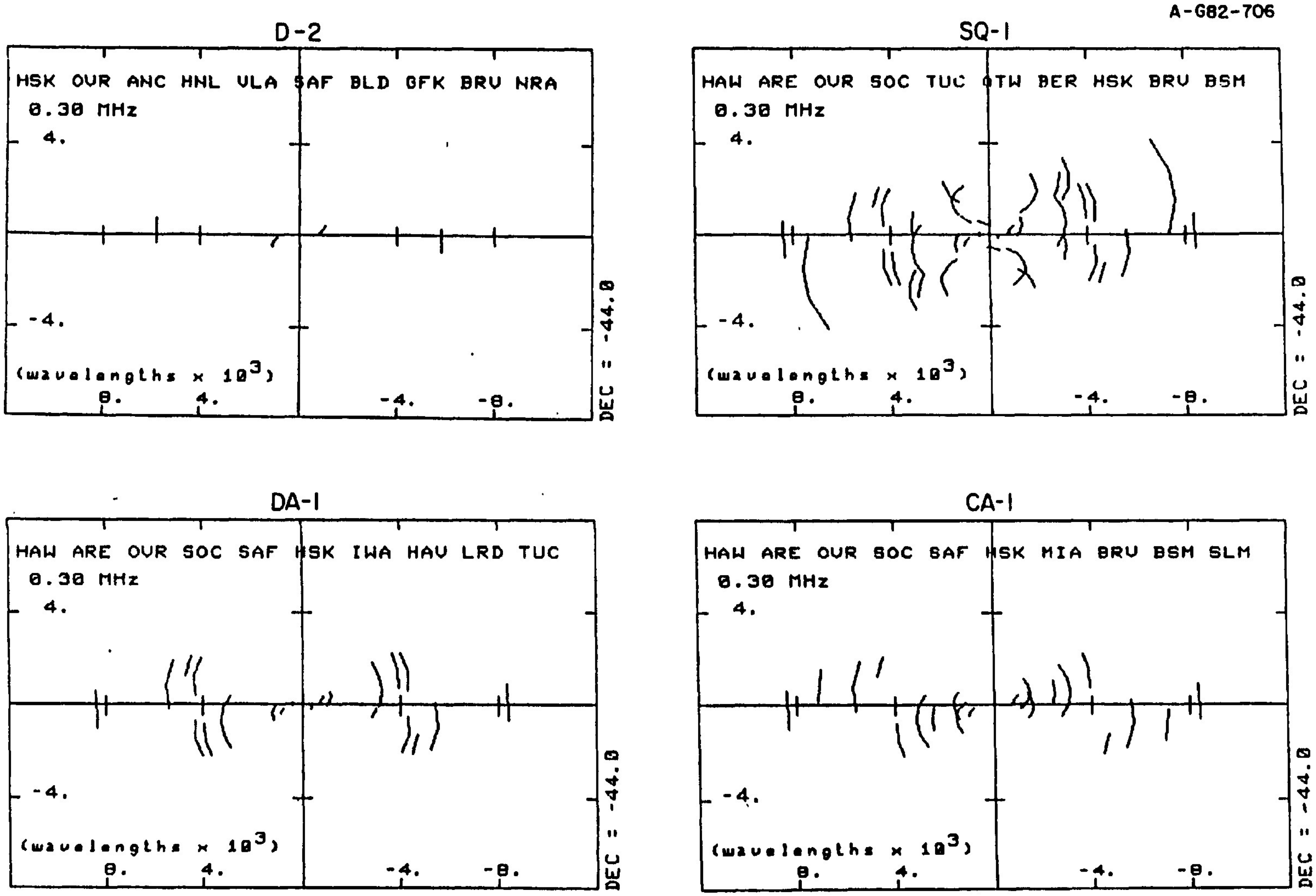

Figure 10 (continued)