VLB ARRAY MEMO No. 97

AN ATLAS OF TRANSFER FUNCTIONS FOR POSSIBLE VLBI ARRAYS

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Turn back now all ye who despise u-v tracks!

INTRODUCTION

Many possible arrays have been explored during the VLBA configuration studies. Some of these have proven useful and appear in the proposal, in the design studies that preceeded the proposal, or in other documents related to the Array. Others have not proven useful and have not appeared where persons not working actively on configuration studies can find them. Questions often arise about the usefulness of particular stations. The object of this document is to describe some of the considerations that go into the selection of a configuration and to answer some of the questions on the effects of particular sites.

This document is only concerned with u-v tracks for possible configurations. There is no attempt to use more sophisticated and computationally intensive array comparison methods. For details and applications of those methods, refer to the design studies (Cohen 1980, Kellerman 1981), and to VLBA documents by Linfield on the effects of the use of closure parameters in the mapping and by Mutel and Gaume on a u-v plane based quality measure. U-v tracks are the computationally easiest way to compare arrays and give the most insight into the effects of particular stations and therefore are the most useful way of comparing a large number of configurations.

The u-v tracks shown in this document are all plotted in a consistent manner in order to facilitate comparisons. The tracks for each array configuration are computed at 8 declinations, each of which represents the center of a strip of sky containing 10 percent of the total area of the sky. Therefore there should be approximately equal numbers of extragalactic sources to observe at each of the declinations plotted. Galactic sources are concentrated in the galactic plane and tend to have low declinations where the performance of most arrays is relatively poor. There are only three different scales on which most of the tracks are plotted and Array D2, which is the array of the NRAO design study (Kellermann 1981), and is the array used for demonstration purposes in the VLBA proposal, is shown at each of the scales. The largest scale is appropriate for showing global arrays with baselines up to 11,000 km (the scale actually goes to 16,000 km). The next scale is appropriate for arrays confined to U. S. territory and shows a maximum baseline of 10,000 km. A smaller scale, with a maximum baseline of 2000 km, is used to show the short baseline coverage of some arrays. In addition to these three scales, the coverage of the VLA and the VLA plus nearby stations are shown on smaller scales. All u-v tracks are plotted to scales given in km in order to be independent of frequency.

This report begins with a description of the process by which Array D2 was chosen. Many of the factors that should be considered in deriving any configuration are described. The constraints under which the Array configuration should be chosen are summarized in Table 1. The rest of the report is devoted to showing the u-v tracks for many possible arrays. The text related to the u-v tracks is entirely contained in the figure captions. The figures are divided into 6 groups and are listed in Table 2. The names, abbreviations, latitudes, and longitudes of the stations used in the arrays displayed are given in Table 3.

ARRAY D2

Array D2 is the configuration used for demonstration purposes in the VLBA proposal and in the NRAO VLBA design study (Kellermann 1981). It contains antennas at the locations listed in the caption of Figure I-1. Many of the considerations that go into the selection of a configuration can be described nicely by discussing the process by which Array D2 was found.

One of the most important constraints on the configuration is that it provide the highest resolution possible. For east-west baselines, this can be most effectively met with stations near the equator, but a constraint that all antennas should be on U. S. territory has been placed on the initial design studies. The effects of relaxing this constraint will be shown in the figures where the value of foreign stations is shown. Under the U. S. territory constraint, the longest baselines are from either New England or Puerto Rico to either Alaska or Hawaii. Puerto Rico to Hawaii is the longest and Hawaii to New England is a reasonable second. At the time D2 was chosen, there was some fear that there may be complications operating in Puerto Rico (although a major U. S. observatory, Arecibo, is there) and that the high frequency observing conditions might be poor there, so the Hawaii to New England baseline was selected. The effects of choosing Puerto Rico will be shown later and Puerto Rico is prominent in the alternative arrays shown in the figures.

In order to minimize operating problems and expenses, it is desirable to place as many antennas at existing observatories as possible. For this reason, Haystack Observatory in Massachusetts was selected as the New England site, causing a small but acceptable loss in resolution over using a site in Maine. Similarily, the Owens Valley Radio Observatory in California and the National Radio Astronomy Observatory in Green Bank, West Virginia were selected as sites. Several other existing sites, such as North Liberty Radio Observatory in Iowa, the Harvard Radio Astronomy Station in Fort Davis, Texas, and the Hat Creek Radio Observatory in California were also considered but did not work well with Array D2 as it was being formulated. Doubtless other arrays with performance similar to Array D2 could be found in which some other combination of existing sites is used.

There is significant debate as to whether existing sites should be used. The existing site could provide technical support and manpower which helps reduce expenses and reduce the time needed for repairs requiring skilled personel. On the other hand, if an antenna is built at the site of an existing antenna, that existing antenna is no longer useful as a part time addition to the array for experiments requiring the highest possible dynamic range and sensitivity. Also, many of the existing sites do not meet the accessibility requirements that will be placed on new Array elements. For example, there is a six hour drive involved in getting to OVRO and Green Bank in not much better. An attractive alternative is to place the new antennas near the existing observatories in order to obtain local support, but far enough away to provide interesting short baselines for low resolution experiments at the lower frequencies where the existing antennas can operate.

One observatory which should have Array antennas nearby is the VLA near Socorro, New Mexico. The VLA is a very powerful interferrometer with baselines up to 35 km in length and with antennas very similar to those proposed for the VLBA. Scientifically, the ideal VLBA configuration would cover all baselines from 35 km to the nearly 8000 km Hawaii to New England baseline and the short baselines would be near the VLA so that the combined instruments would smoothly cover all possible spacings. This is not possible without increasing the number of antennas and the cost of the VLBA significantly. However, by placing the shortest spacings of the VLBA near the VLA, some of the intermediate spacings can be acquired. For this reason, there is an element of Array D2 at Socorro, somewhat less than 100 km from the VLA, and other elements of Array D2 are placed in New Mexico and adjoining states. The VLBA and the VLA, both of which will be NRAO instruments, can be operated in several modes: as separate instruments, as a sensitive VLBI instrument using the entire VLA in phased array mode as one VLBA element, as a somewhat higher resolution version of the VLA by using a nearby VLBA antenna as a VLA element (meanwhile the VLBA may be using one of the 27 VLA antennas), or as a very powerful combined instrument studying a source over many orders of magnitude in angular scale.

Another important feature of the VLBA will be the ability to observe sources at low declinations. East-west arrays with relatively small numbers of elements can be devised which provide very good coverage over a wide range of baselines for northern sources. This is the type of array proposed by the Canadian Long Baseline Array project because of the very limited north-south extent of accessible territory in Canada. Arrays of this type were also proposed in some early U. S. array studies. Providing good coverage for low declination sources is much more difficult. The antennas must be well distributed in two dimensions, greatly increasing the complexity of the configuration selection process. While optimal one-dimensional geometries, such as minimum redundancy geometries, are known, no optimal two-dimensional geometries have been presented. The VLA logarithmic wye is a very good configuration if the antennas must be moved. However the radial arms concentrate most of the baselines along a small number of radial directions in short observations leading to non-optimum beams. With an array of fixed antennas such as the VLBA, such concentrations of baselines should be avoided.

In order to observe low declination sources, sites well dispersed in the north-south direction are required. The longest available north-south spacings available on U. S. territory are from Hawaii to Alaska and from Puerto Rico to New England. The latter baseline is significantly shorter than the former but has the advantage that sources farther to the south can be seen from New England than from Alaska. For Array D2, Alaska was chosen for the northern station. Next, a baseline with the greatest possible north-south extent within the contiguous 48 states should be chosen so there is not a large gap between the Hawaii-Alaska baseline and the next shorter north-south baseline. Southern Texas and Florida are the southern-most possible sites with Texas prefered because it has a drier climate and because is it closer to the VLA. A southern Texas station should be complemented by a station along the Canadian border. Eastern Washington or Idaho would be preferred for operational and climatic reasons but the baselines to that area and to sites near the VLA from Hawaii or from the Northeast are nearly equal for high declination sources and the uniformity of coverage for such arrays is poor. A rough line of sites running from northeast of the VLA and ending in North Dakota provides much better coverage. Stations at Los Alamos, New Mexico; Denver, Colorado; and Grand Fork, North Dakota were selected to provide the desired coverage. Many other possible sites in the Southwest were tried in a search for good intermediate spacings that interact well with the rest of the array, but those chosen seem to be the best. Sites in the Northwest, rather than North Dakota, do seem to work well in arrays that include Puerto Rico.

Array D2 provides good coverage of the u-v plane and would be acceptable as a final array configuration, assuming the U. S. territory constraint is kept. Other U. S. only arrays can be found that are as good or maybe even slightly better, but there is little chance that a very much better array can be found. However, Array D2 has some operational difficulties that would be nice to avoid and further efforts to find a better configuration will continue. The most obvious problems are that the North Dakota station must be operated in a rather extreme winter environment (worse that the Alaska station) and that the south Texas station and some of the others are not in optimal high-dry sites for observations at the highest frequencies. Also the coverage provided by a station in Puerto Rico on low declination sources and the enhancement of the coverage that Puerto Rico provides when possible new antennas to the south are used is sufficiently good that such a station should probably be included in the final configuration.

TABLE 1

ARRAY CONSTRAINTS SUMMARY

I. All configurations to be studied in the effort to find a final configuration for the VLBA will satisfy the following constraints:
   - A. Ten stations.
   - B. Most sites on U.S. territory.
   - C. Maximum spacing greater than 7500 km.
   - D. Minimum spacing less than 200 km.
   - E. Two dimensional for low declination coverage.
   - F. Short spacings near the VLA.
   - G. Sites should be as far south as possible for good low declination coverage.
   - H. Inner third provides good coverage.
   - I. Sites are near good transportation.
   - J. As many high-dry sites as possible.
   - K. Sites are near existing technical facilities.
   - L. Array interacts well with other observatories.
     1. Europe.
     2. Japan.
     3. Canada.
     4. Possible southern stations to be added later.

II. Arrays satisfying each of the following constraints concerning existing observatories will be studied.
   - A. Sites at existing observatories where possible.
   - B. Sites near but separated from existing observatories (ones that will survive) for short spacings.

III. Arrays satisfying each of the following geographic constaints will be studied.
   - A. All sites on U.S. territory.
   - B. One site near Mexico City.
   - C. Two or three sites in Canada.
   - D. One site in Mexico and some sites in Canada.
   - E. No geographic constraint on a few sites.

IV. Sites will be located in the following areas in all configurations that will be studied:
   - A. Hawaii (Specific location within Hawaii not important).
   - B. Within 100 km of VLA.
   - C. Within 200 km of fixed site B.
   - (D. Puerto Rico - feasibility must be verified)

TABLE 2.

Summary of Figures

Figure #	Scale max. (km)	Description
Section I:	Array D2 and variations.	
I-1	10,000	Array D2
I-2	16,000	Array D2 - Large scale.
I-3	2,000	Array D2 - Inner portion
I-4	10,000	Array D2 Green Bank --> Jacksonville FL.
I-5	10,000	Array D2 Grand Fork --> Spokane WA.
I-6	10,000	Array D2 Brownsville --> Laredo TX.
I-7	10,000	Array D2 Anchorage --> Arecibo PR.
I-8	10,000	Array D2 OVRO --> Clark Lake, CA.
I-9	10,000	Array D2 Green Bank --> Michigan.
I-10	10,000	Array D2 Hawaii and Anchorage --> Bonn and Arecibo.
I-11	10,000	Array D2 u-v coverage with 10% bandwidth.
Section II:	Other arrays.	
II-1	10,000	Array 13 from Caltech design study (Cohen 1980)
II-2	10,000	Array 13 + Socorro NM and Arecibo PR.
II-3	10,000	A reasonable 8 station array.
II-4	10,000	A 10 station array that has two Hawaii sites.
II-5	2,000	Inner portion of II-4.
II-6	10,000	A strongly centrally condensed array.
II-7	2,000	Inner portion of II-6.
II-8	10,000	A 10 station array with Mexico and Northern Canada.
II-9	10,000	A 10 station array of nested triangles.
II-10	10,000	A 10 station with a N-S line plus other sites.
II-11	10,000	A 10 station wye configuration.
Section III:	Arrays based on existing stations:	
III-1	10,000	5 station U. S. Network experiment.
III-2	10,000	7 existing stations - typical network plus Europe experiment.
III-3	10,000	15 existing stations - maximum, low freq. effort.
III-4	10,000	10 existing US sites + Hawaii and Puerto Rico.
III-5	10,000	The 7 stations of III-4 that would work at 1.3 cm.

TABLE 2 (Cont.)

Figure #	Scale max. (km)	Description
Section IV:	Arrays using South American and Pacific sites.	
IV-1	16,000	Array D2 + Galapagos.
IV-2	16,000	Array D2 + Easter Island.
IV-3	16,000	Array D2 + Galapagos and Easter Island.
IV-4	16,000	Mutel Array SG-1: 10 stations with Galapagos.
IV-5	16,000	IV-4 with Quito instead of Galapagos. (SQ-2)
IV-6	16,000	Mutel Array SE-1: 10 stations with Easter Island.
IV-7	16,000	Mutel Array SEG-1: 10 stations with both Galapagos and Easter Island.
IV-8	16,000	Array D2 + Argentina.
IV-9	16,000	Array D2 + Argentina and Quito.
IV-10	16,000	Array of Fig. II-4 + Argentina and Quito.
IV-11	16,000	Array D2 + Itapatinga, Brazil.
Section V:	Array D2 plus other sites.	
V-1	10,000	Mexico City.
V-2	10,000	Acapulco.
V-3	10,000	Edmonton, Alberta.
V-4	10,000	Newfoundland.
V-5	10,000	Yellowknife, Northwest Territories.
V-6	10,000	Penticton, British Columbia.
V-7	10,000	Algonquin Radio Observatory, Ontario.
V-8	10,000	Newfoundland, Algonquin, Yellowknife, and Penticton.
V-9	16,000	Bologna, Italy (Similar to any European station).
V-10	16,000	Bonn, West Germany.
V-11	16,000	Jodrell Bank, England.
V-12	16,000	South Africa.
V-13	16,000	Tokyo, Japan.
V-14	16,000	Tidbinbilla, Australia.
V-15	10,000	The proposed Canadian Long Baseline Array.
V-16	2,000	Center portion V-16.
Section VI:	VLA plus other sites.	
VI-1	50	9 elements of VLA — every third element.
VI-2	200	VLA (9 elt) + Socorro
VI-3	2,000	VLA (5 elt) + Array D2

TABLE 3

Station Locations

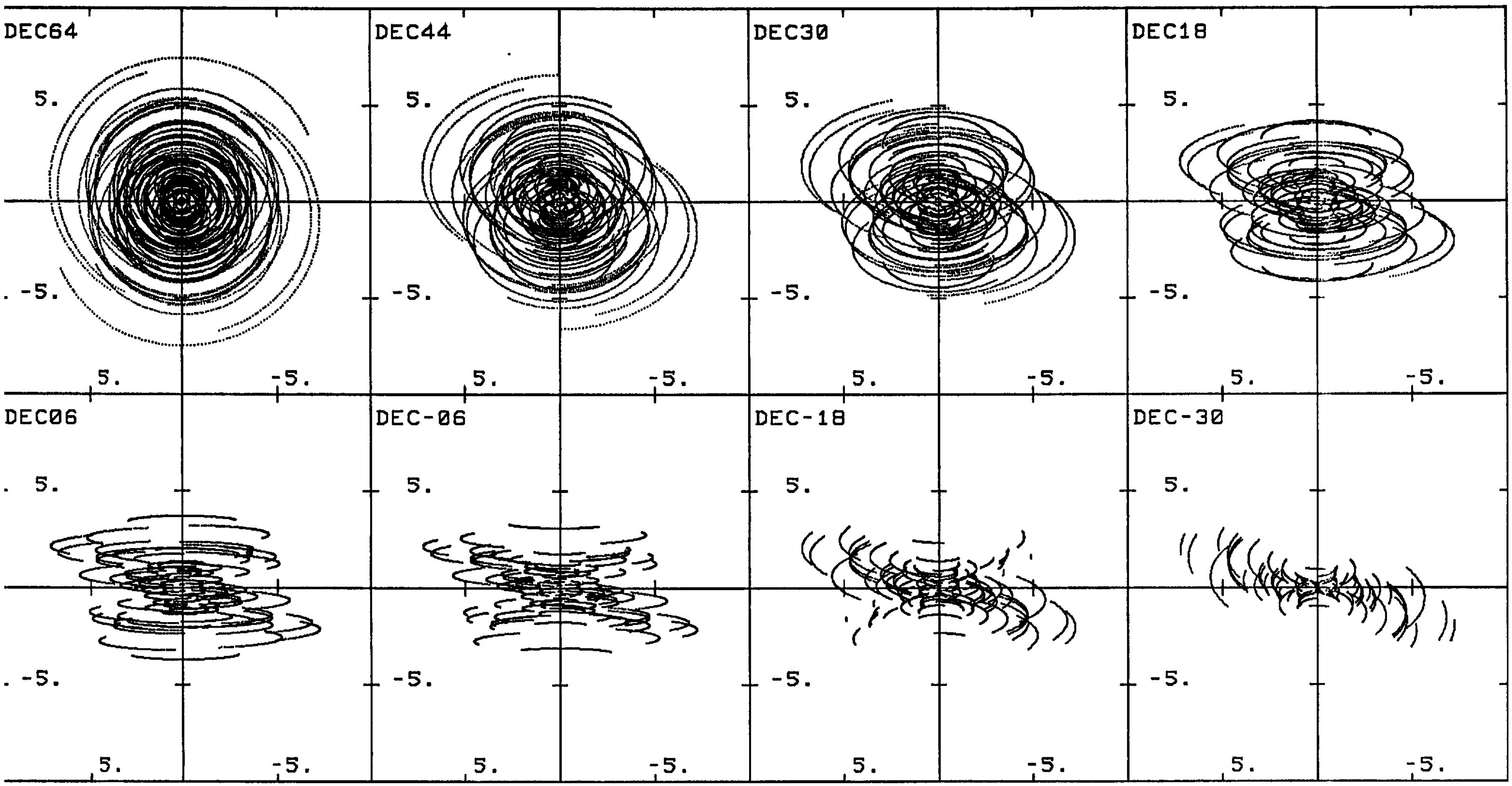
Abbr.	Station	Latitude	Longitude
AE3	VLA station AE3	34.0667	107.5861
AE6	" " AE6	34.0389	107.5167
AE9	" " AE9	34.0000	107.4083
AN3	" " AN3	34.1056	107.6222
AN6	" " AN6	34.1583	107.624
AN9	" " AN9	34.2444	107.633
AW3	" " AW3	34.0639	107.6444
AW6	" " AW6	34.0278	107.7083
AW9	" " AW9	33.9722	107.8083
ACAPUL	Acapulco, Mexico	17.5	100.0
ANCH	Anchorage, Alaska	61.	150.
ARECIBO	Arecibo Observatory, Puerto Rico	18.3435	66.7533
ARGENT	Observatory, Western Argentina	-32.	69.
ARO	* Algonquin Radio Observatory, Ont.	45.95	78.07
ATIK	* Atikokan, Ontario	48.94	91.80
BANGOR	Bangor, Maine	44.8	68.8
BGNA	Bologna, Italy	44.5	-11.3
BISMARCK	Bismark, North Dakota	46.8	100.8
BLDR	Boulder, Colorado	40.0036	105.2617
BOIS	Boise, Idaho	43.6	116.2
BONN	100 m telescope, Bonn, West Germany	50.3360	-6.88444
BRVL2	Brownsville, Texas (slightly inland)	26.2	98.0
CAPECAN	Cape Canaveral, Florida	28.5	80.5
CHURCH	Churchill, Manitoba	58.9	94.0
CLARK	Clark Lake Observatory, California	33.3	116.2
COME	* Come By Chance, Newfoundland	47.36	54.76
DALLAS	Dallas, Texas	32.6	96.6
DSS14	Goldstone DSN Station, California	35.2444	116.8895
DSS43	Tidbinbilla DSN Station, Australia	-35.2210	211.0187
DWINGELOO	Dwingeloo Observatory, Netherlands	52.6276	-6.3967
EASTER	Easter Island, Pacific Ocean (Chile)	-27.	110.
EDMT	Edmonton, Alberta	54.5	114.0
FDVS	Fort Davis, Texas (HRAS)	30.4678	103.9472
GALAPA	Galapagos Islands, Equador	-1.0	92.0
GRFALL	Great Falls, Montana	47.5	111.3
GRFK2	Grand Forks, North Dakota	48.0	97.1
HAWAII	Near Mona Kea, Hawaii	19.8	155.5
HILO	Hilo, Hawaii	19.5	155.0

* Proposed Canadian Long Baseline Array Stations

TABLE 3 (cont)

Abbr.	Station	Latitude	Longitude
HSTK	Haystack Observatory, Massachusetts	42.4317	71.4881
HCRK	Hat Creek Observatory, California	40.6276	121.4733
IOWA	North Liberty Observatory, Iowa	41.5805	91.5745
ITA	Itapatinga Observatory, Brazil	-23.2	46.55
JODRELL	Jodrell Bank, England	53.0516	2.3066
JCKVLE	Jacksonville, Florida	30.0	81.8
KAUAI	Kauai, Hawaii	22.0	159.6
LASL	Los Alamos, New Mexico	35.9	106.4
LETH	* Lethbridge, Alberta	49.23	112.39
LRDO	Laredo, Texas	27.5	99.5
LVGS	Las Vegas, Nevada	36.2	115.2
LVNM	Las Vegas, New Mexico	35.6	105.2
MEXDF	Mexico City, Mexico	19.5	99.0
MICHNEW	Dexter, Mich. (U of Mich Rad Ast Obs)	42.3979	83.9350
NEWF	Newfoundland	48.	57.
MHAT	* Medicine Hat, Alberta	49.21	110.06
NPLAT	North Platte, Nebraska	41.3	101.
NRAO	Green Bank, West Virginia	38.2508	79.8358
NRL	Maryland Point, Maryland	38.3739	77.2333
OKLA	Oklahoma City, Oklahoma	35.2	97.5
OMAHA	Omaha, Nebraska	41.3	96.0
OVRO	Owens Valley Obs., California	37.0465	118.2824
ONSALA	Onsala Observatory, Sweden	57.2184	-11.92
PENT	* Penticton Obs., British Columbia	49.3	119.6
PUEBLO	Pueblo, Colorado	38.3	104.5
QUITO	Quito, Equador	-0.2	77.0
SAFR	Hartebeesthoek, South Africa	-25.7393	-27.4407
SALEM	Salem, Oregon	45.0	123.0
SASK	* Western Saskatchewan	49.20	109.05
SDGO	San Diego, California	33.0	117.0
SOCORRO	Socorro, New Mexico	34.1	106.9
SPKN	Spokane, Washington	47.7	117.4
TOKYO	Tokyo, Japan	36.0	-140.0
TOPEKA	Topeka, Kansas	39.0	95.7
TUSC	Tuscon, Arizona	32.7	111.0
TUSCNE	Near Tuscon, Arizona	32.5	110.5
VLA	VLA Site, New Mexico	34.079	107.618
VLASW	Southwest of VLA, New Mexico	33.4	108.3
WEYB	* Weyburn, Saskatchewan	48.94	91.8
YELKNF	* Yellowknife, Northwest Territories	62.7	114.5

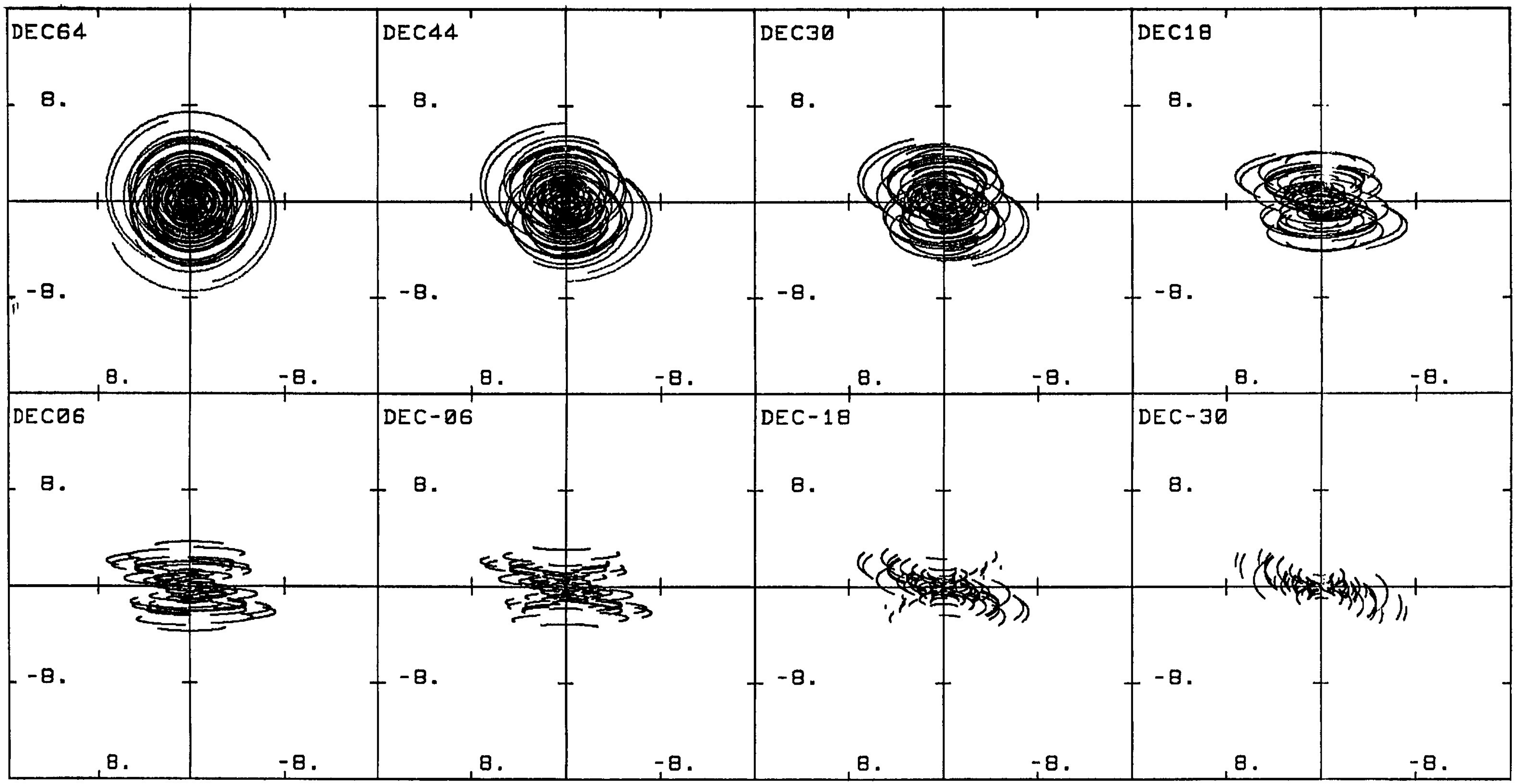
* Proposed Canadian Long Baseline Array Stations



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

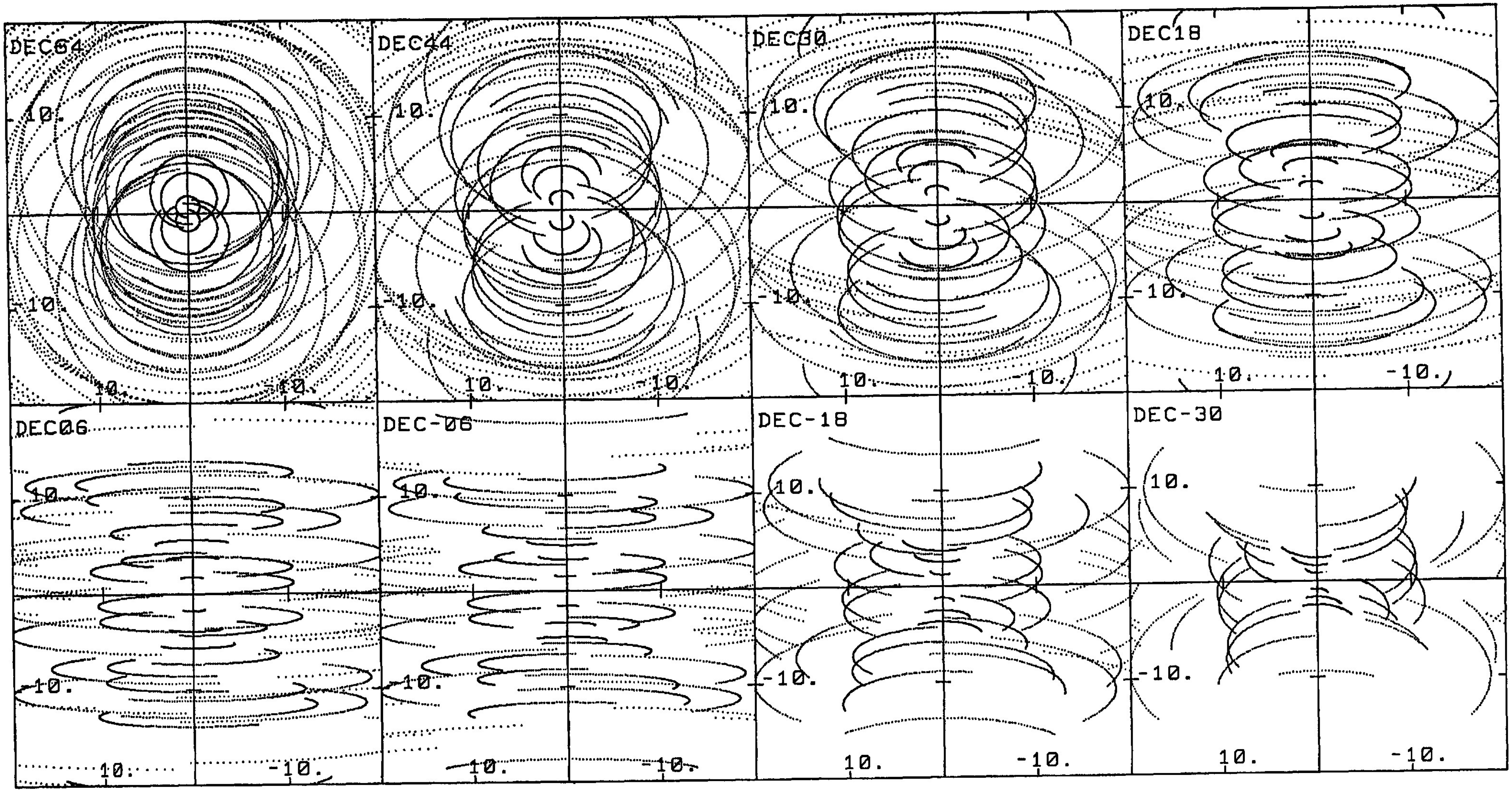
Figure I-1: Array D2 at the scale appropriate for plots of US arrays. The scale maximum is 10,000 km.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

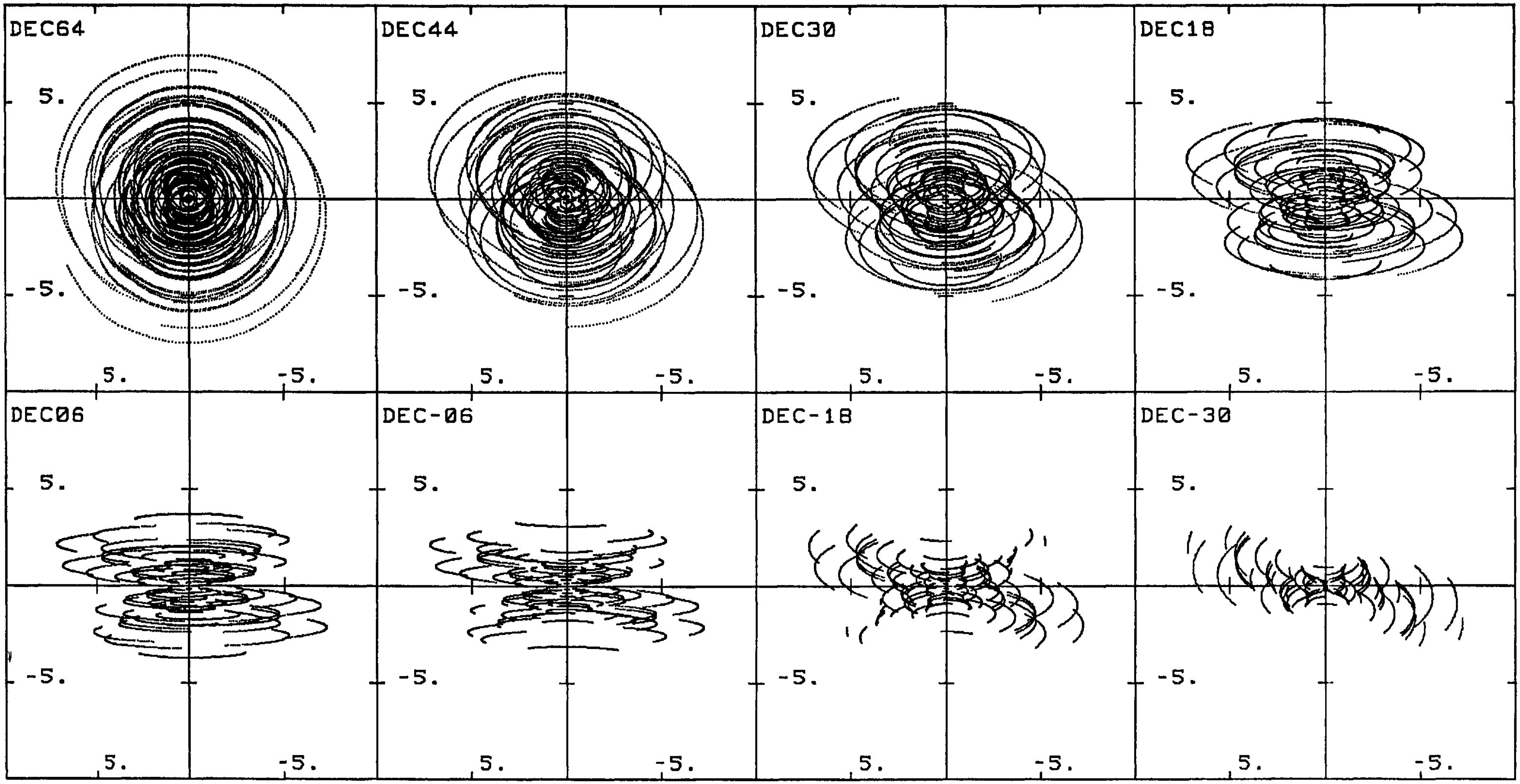
Figure I-2: Array D2 at the scale appropriate for plots of arrays that use the full size of the Earth. The scale maximum is 16,000 km.



Scale Maximum 2,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

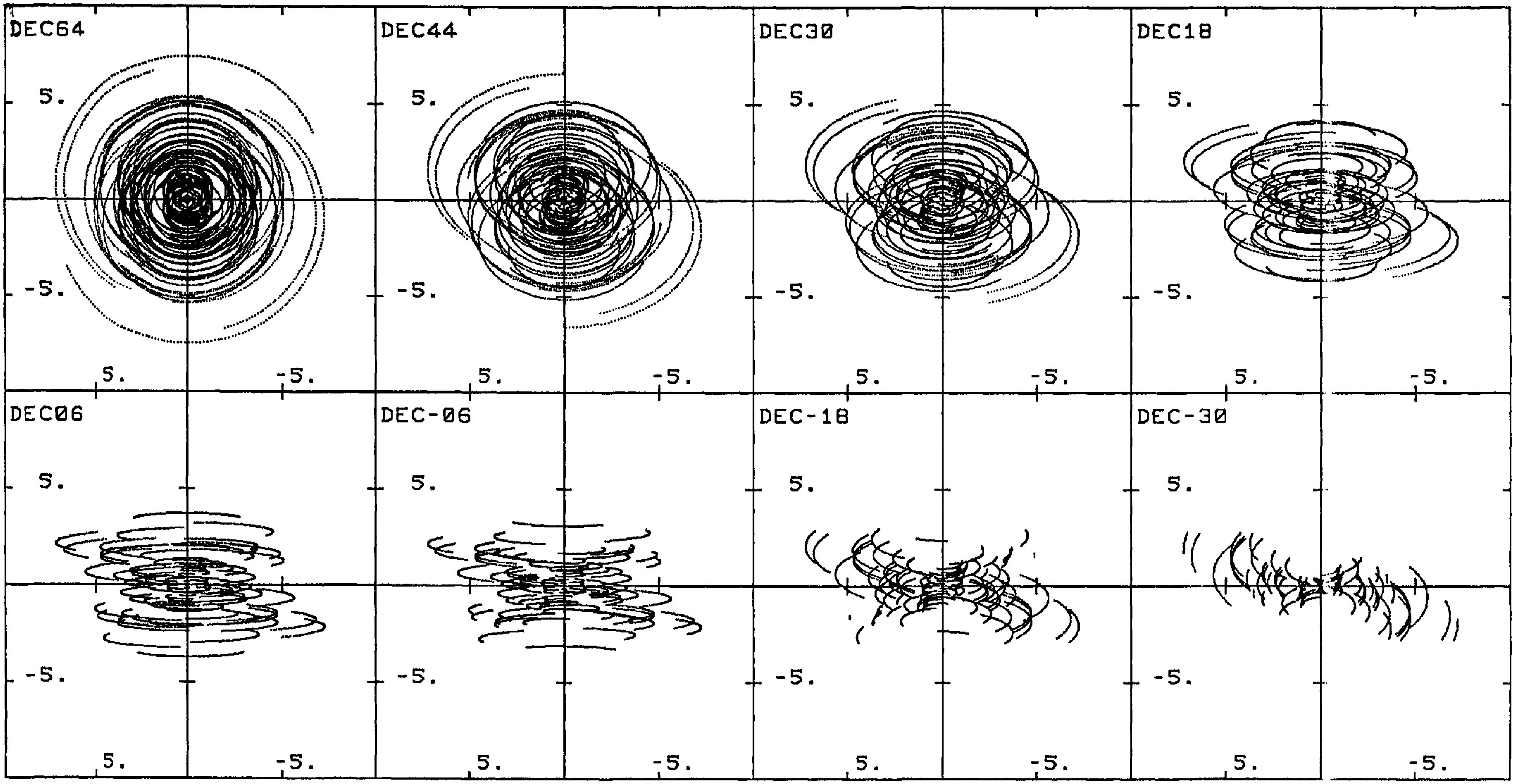
Figure I-3: Array D2 showing the coverage out to a maximum of 2000 km.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 JCKVLE HSTK BRVL2

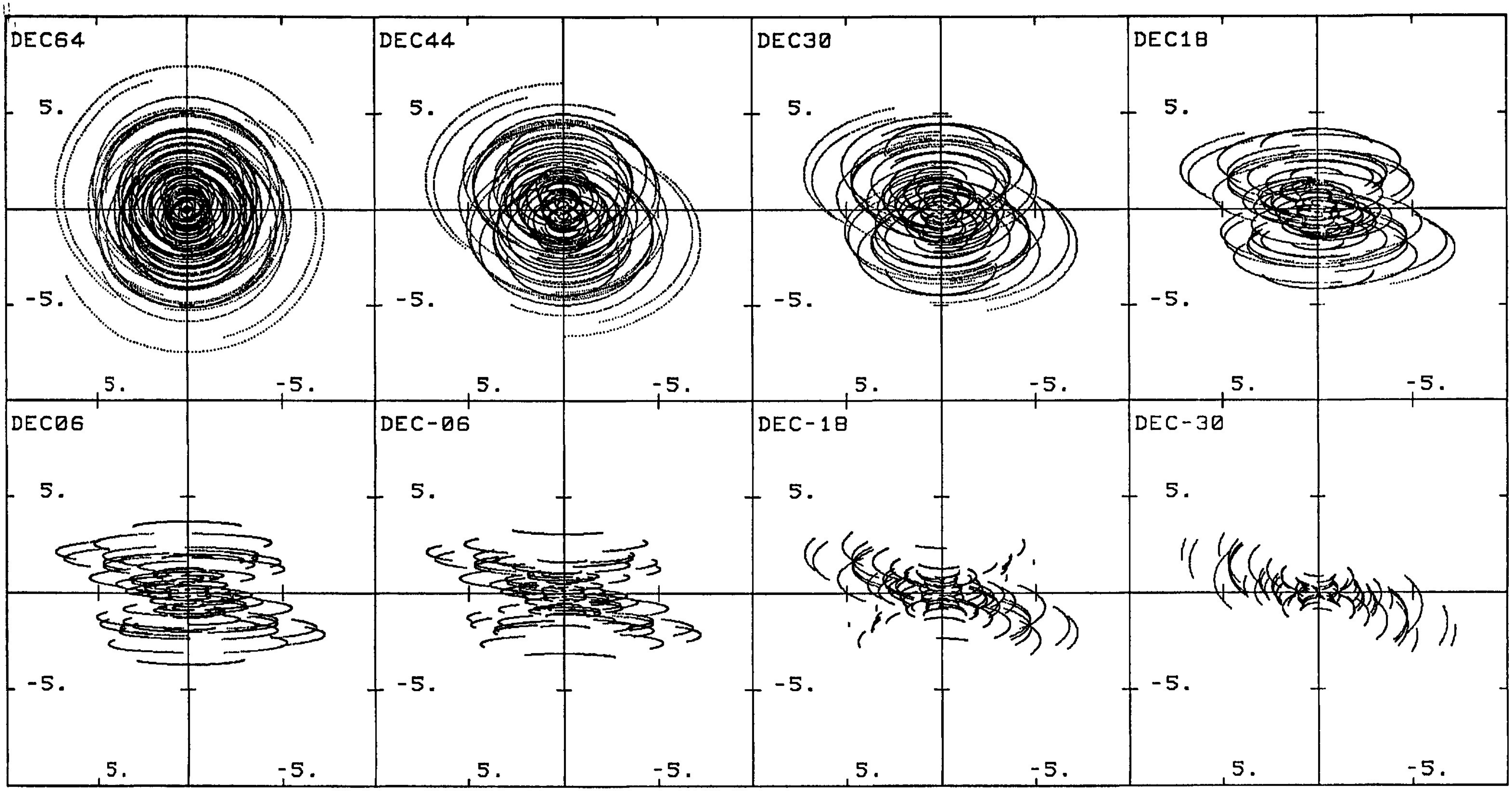
Figure I-4: Array D2 with the Green Bank, WV station moved to Jacksonville FL. This is a good alternative to Green Bank although the technical support available at Green Bank would be lost. However it may be useful not to use the sites of existing observatories so that they can be used as additions to the array.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR SPKN NRAO HSTK BRVL2

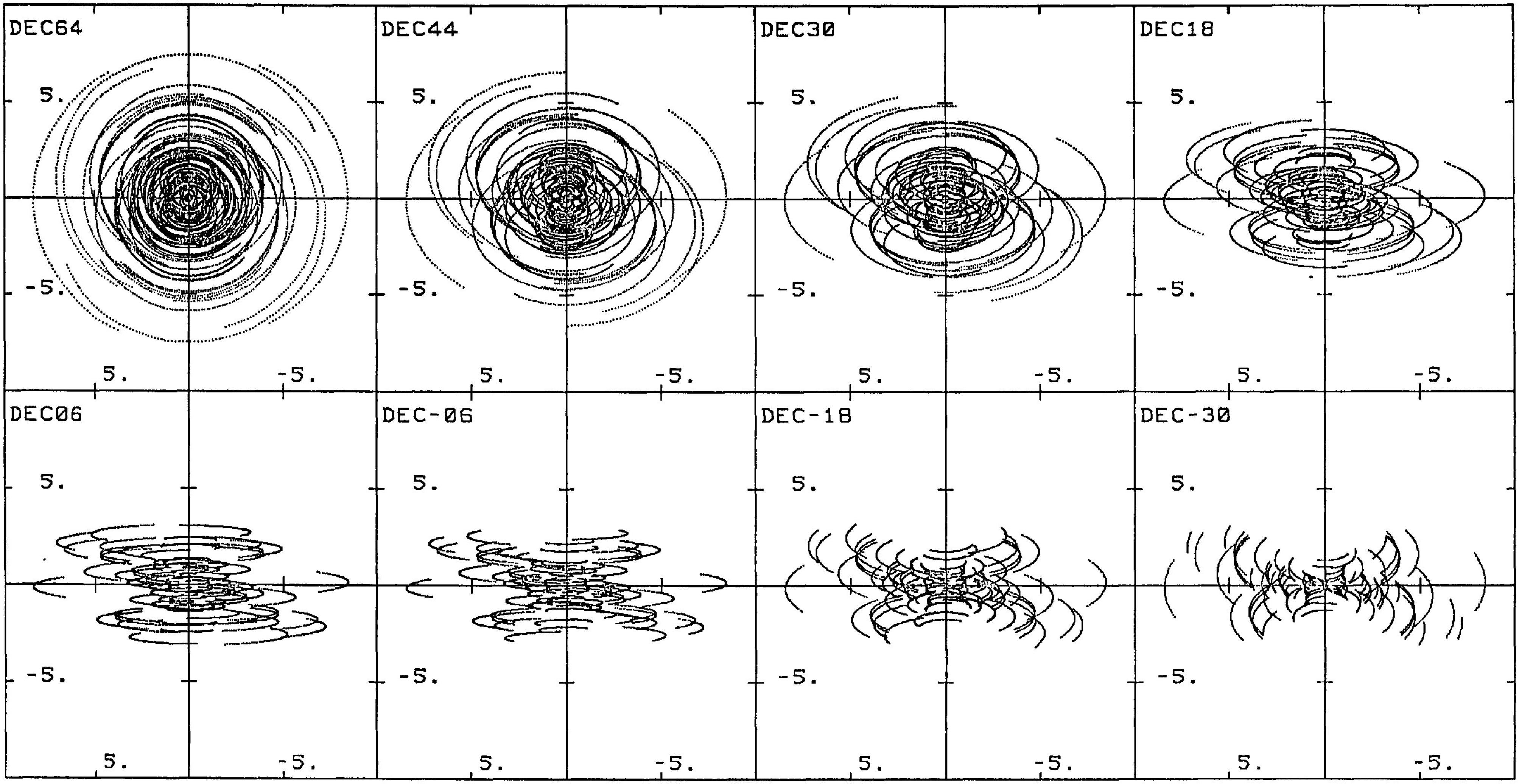
Figure I-5: Array D2 with the North Dakota station moved to Spokane, Washington. This move would be desirable for climatic and operational reasons but it produces holes in the coverage at the higher declinations. A northwest station can be used in arrays that include Puerto Rico as will be seen in later



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK LRDO

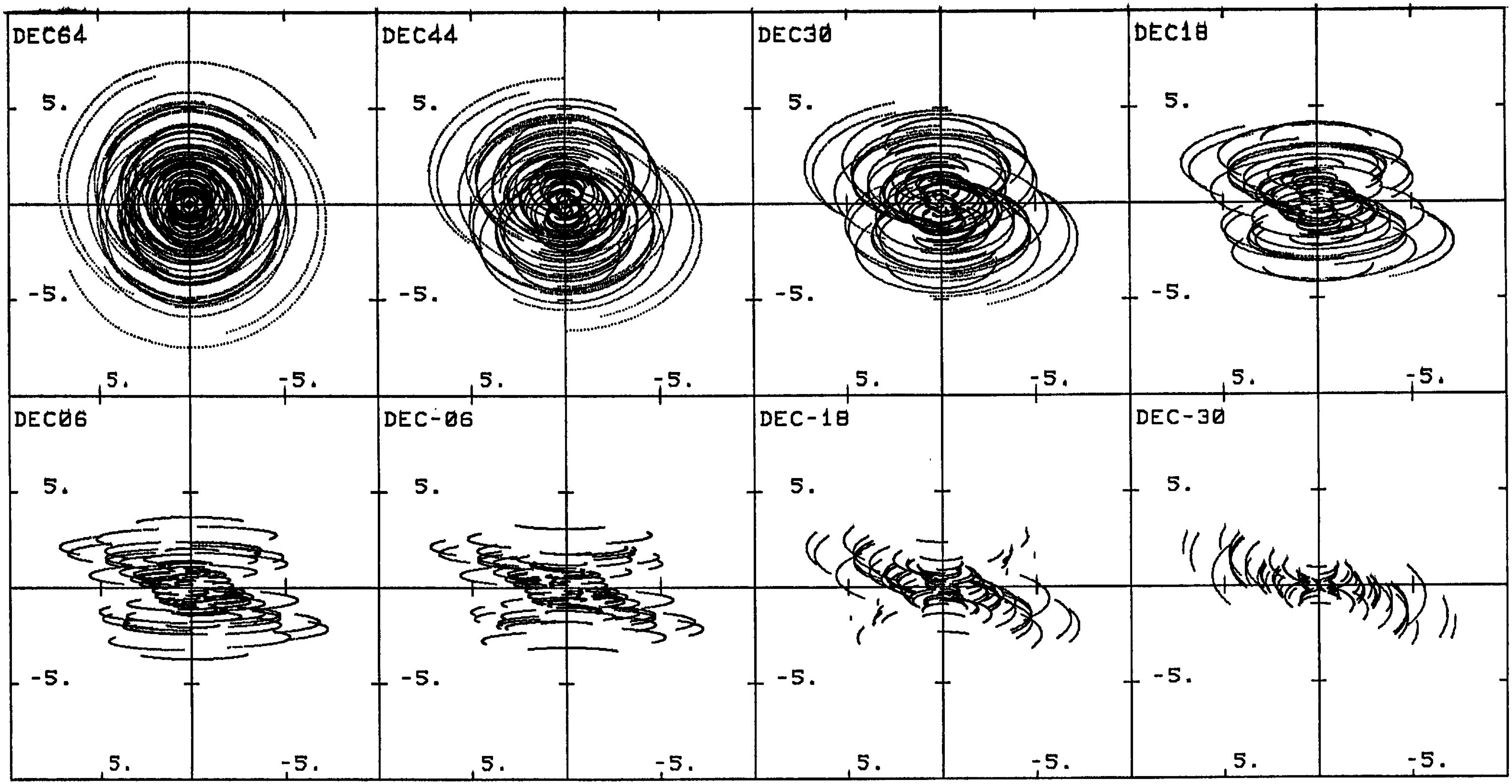
Figure I-6: Array D2 with the Brownsville, Texas station moved inland and north to Laredo, Texas. This causes a small reduction in the maximum north-south baselines at the lowest declinations but may be worthwhile for climatic reasons.



Scale Maximum 10,000 km.

HAWAII ARECIBO OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

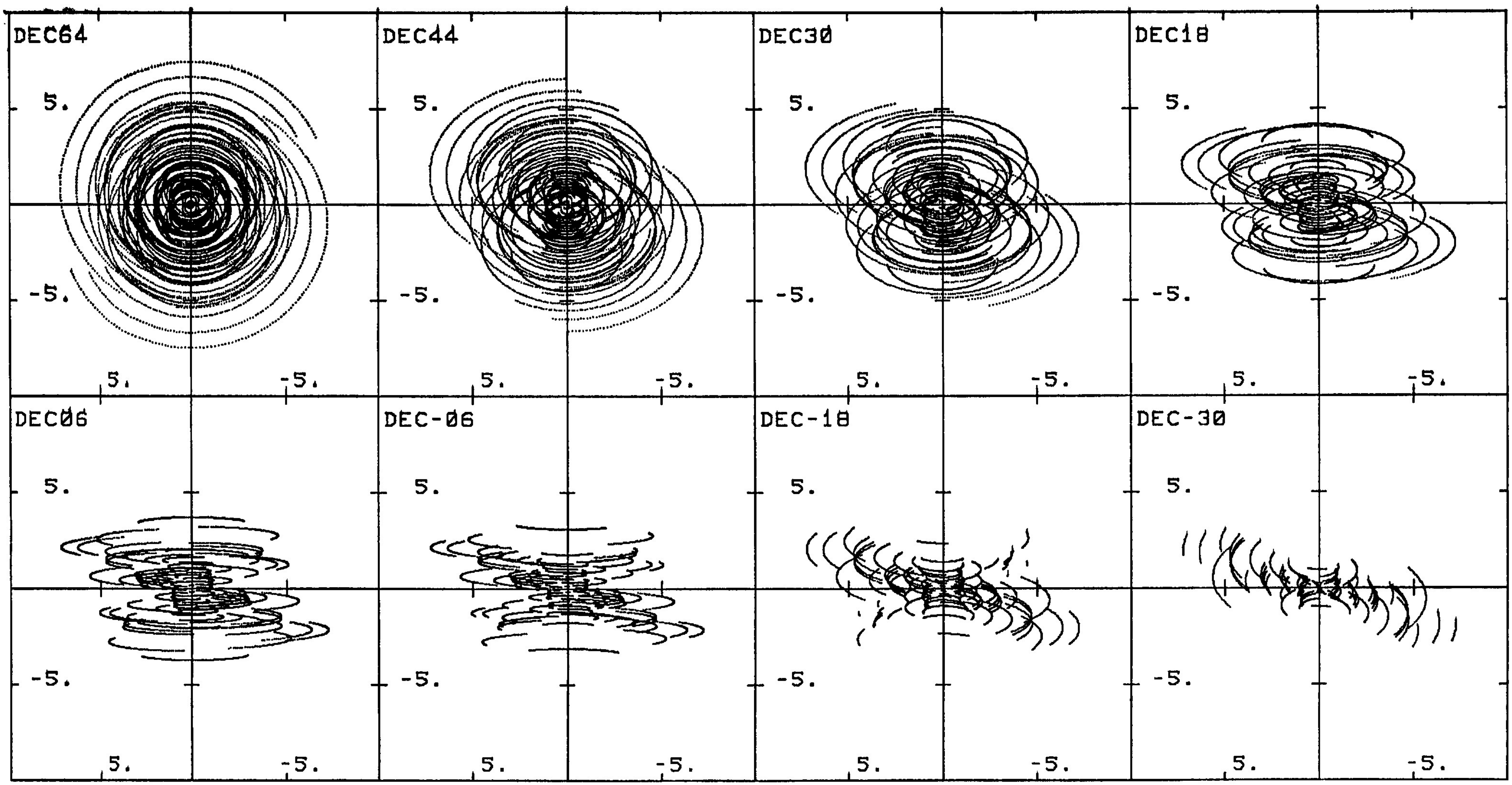
Figure I-7: Array D2 except that the Anchorage station is replaced with Arecibo. The maximum north-south spacing is shorter than with Anchorage but, at the lowest declinations, the effect is reduced because of projection effects. The maximum east-west baseline is a bit longer and Arecibo can see stations far to the south and has a milder climate than Alaska so such an array has advantages and should be considered. As will become apparent later in the discussion of South American stations, an array that includes a site in Puerto Rico is much better than Array D2 when used with stations to the south. The large holes in the coverage shown here show that if a Puerto Rico site is used, several of the other sites must also be moved to obtain good, uniform coverage.



Scale Maximum 10,000 km.

HAWAII ANCH CLARK SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

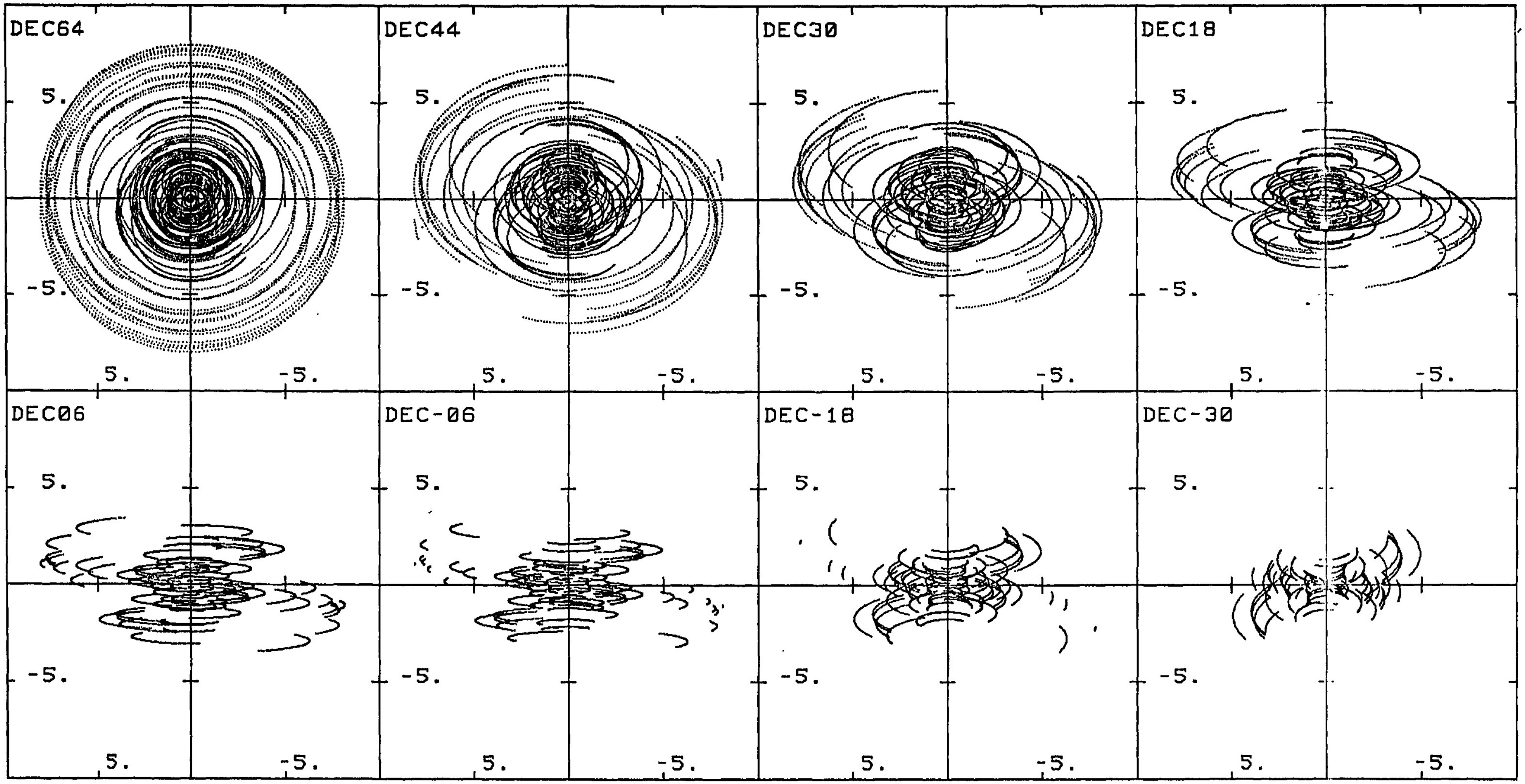
Figure I-8: Array D2 with the OVRO antenna moved to Clark Lake in Southern California. This move opens up some small holes at all declinations. It is likely that if a Southern California site were desired, a good array could be found with one, but more than just the OVRO site must be changed. Clark Lake has existing radio astronomy facilities but is at a very low elevation. Other Southern California sites would probably offer a better environment and greater accessibility.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 MICHNEW HSTK BRVL2

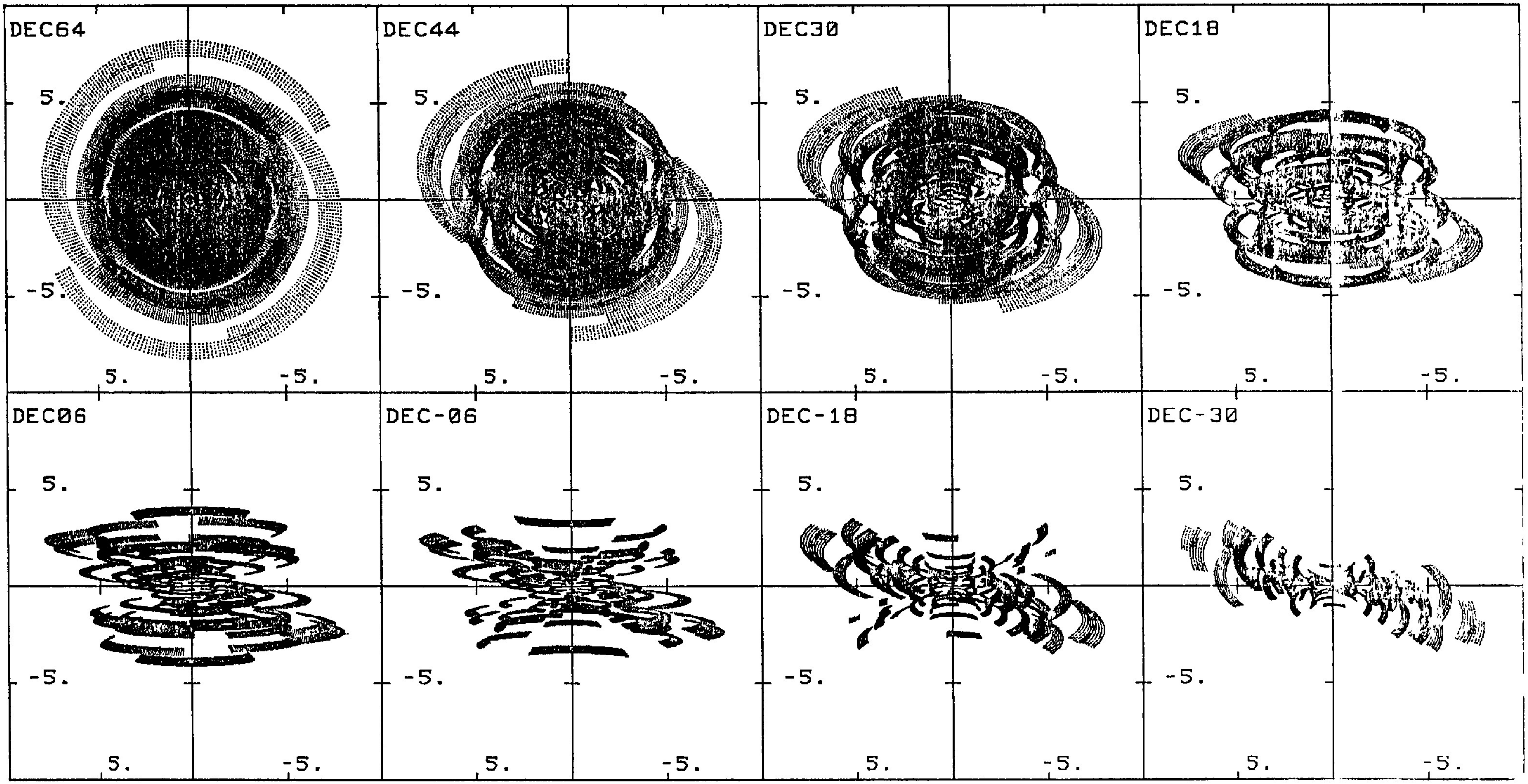
Figure I-9: Array D2 with the Green Bank antenna moved to the University of Michigan Radio Astronomy Obs. site. This move most seriously affects the high declination coverage. As does Figure I-8, this figure demonstrates that if one station of a good array is moved, others must also be moved in order to maintain good coverage.



Scale Maximum 10,000 km.

BONN ARECIBO OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

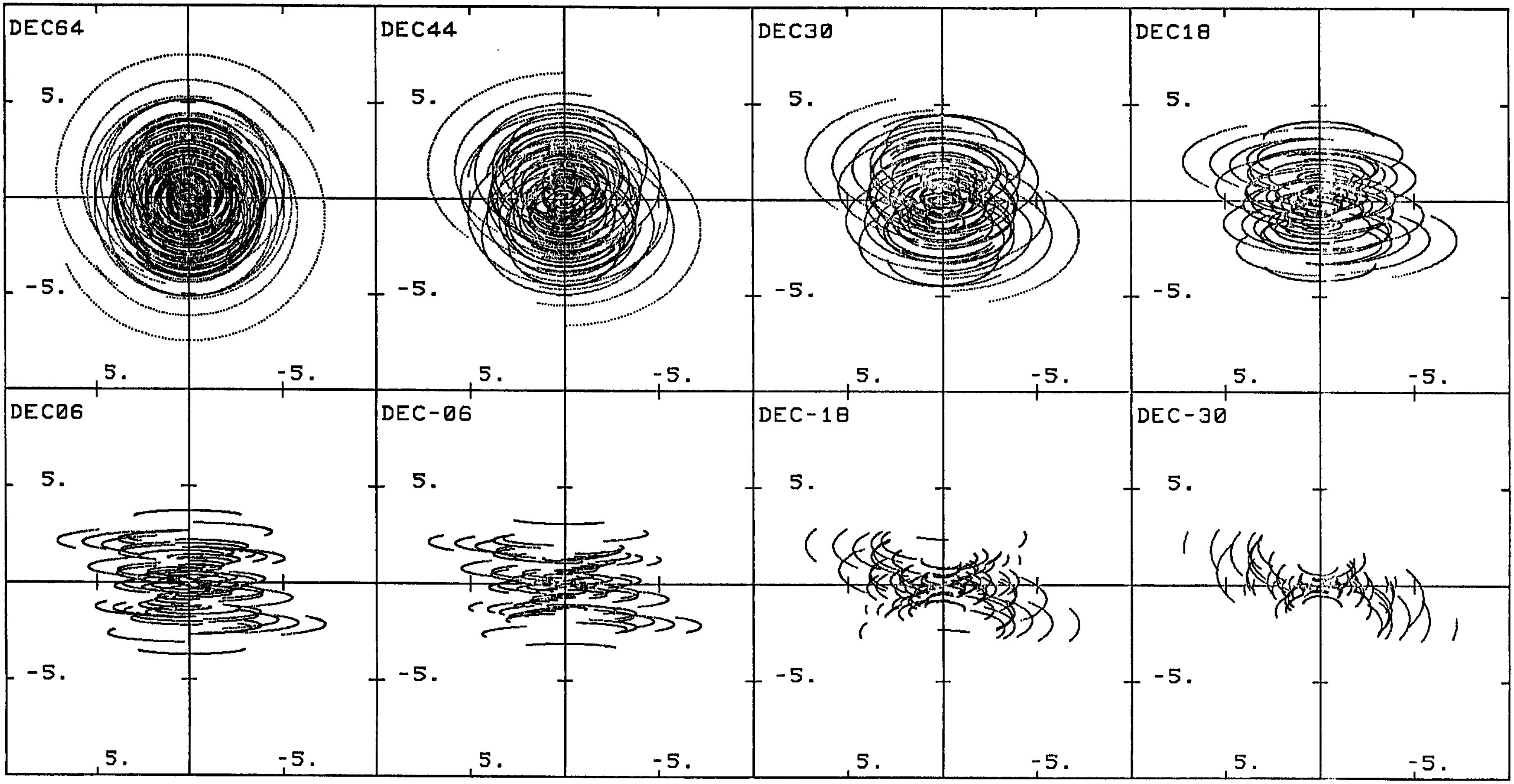
Figure I-10: Array D2 with the long baselines toward the east rather than the west. Hawaii and Anchorage have been replaced by Arecibo and Bonn. Such a configuration has the advantage that there are several active VLBI observatories in Europe so there would be much local support. However there are significant dissadvantages, mostly because of the high latitude of Europe, that make the long baselines to Hawaii much more attractive. The baselines to Europe are similar in length to those to Hawaii so the resolution is similar at high declinations, but the change in longitude is much higher. Therefore, not only does Europe not see nearly as far south as Hawaii, but the time of mutual visibility for low declination sources is much lower. This leads to the very short u-v tracks seen at declinations of 18 degrees and lower. These short tracks are one of the big problems faced in current VLBI work.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2

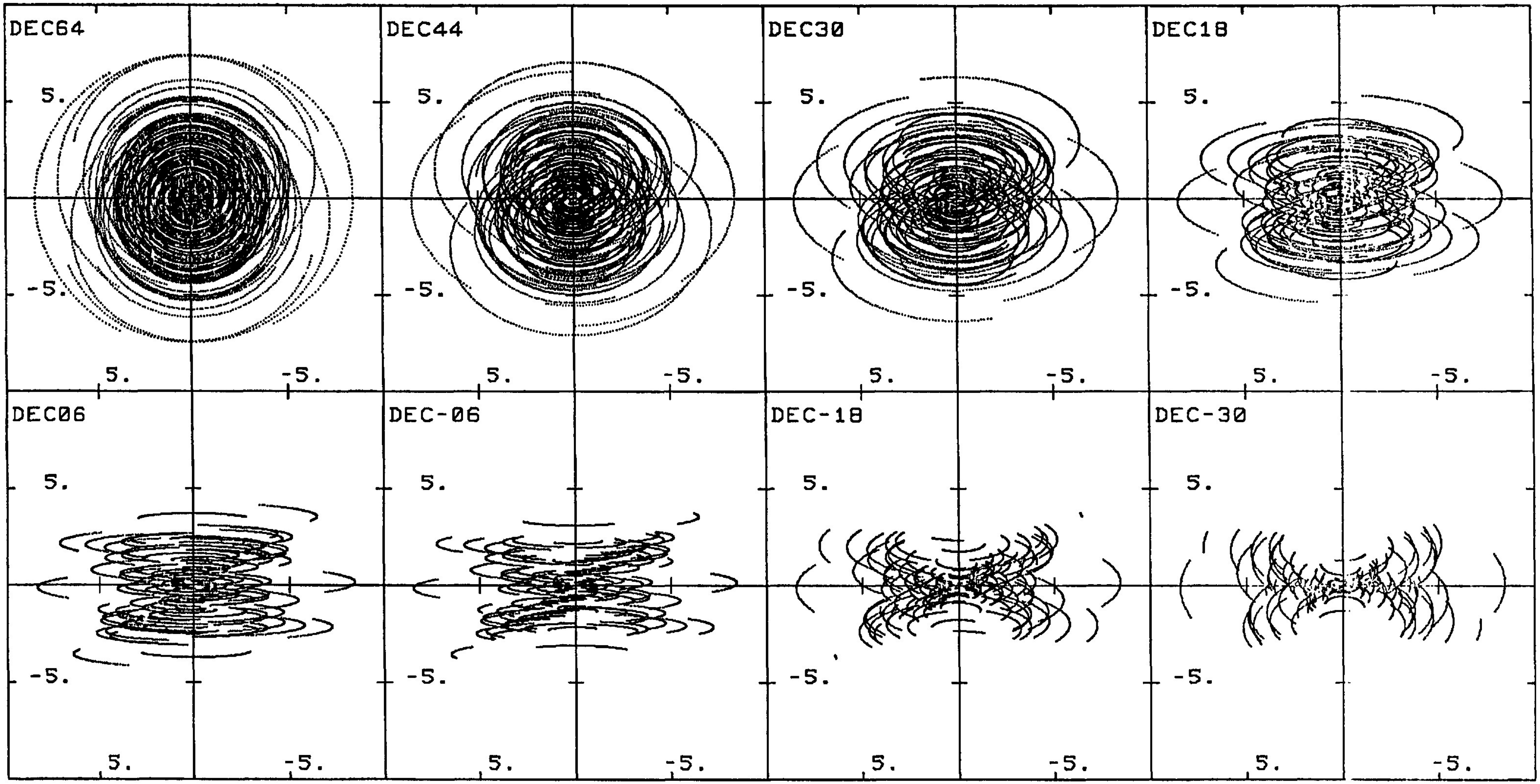
Figure I-11: Array D2 showing the u-v coverage that could be obtained if several frequencies spaced over 10 precent of the observing frequency were used. The increase in u-v coverage is very interesting but there will be serious complications in dealing with sources whose spectral index varies with position. Also the technique cannot be used on spectral line sources.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SALEM BOIS BLDR DSS14 IOWA HSTK LRDO

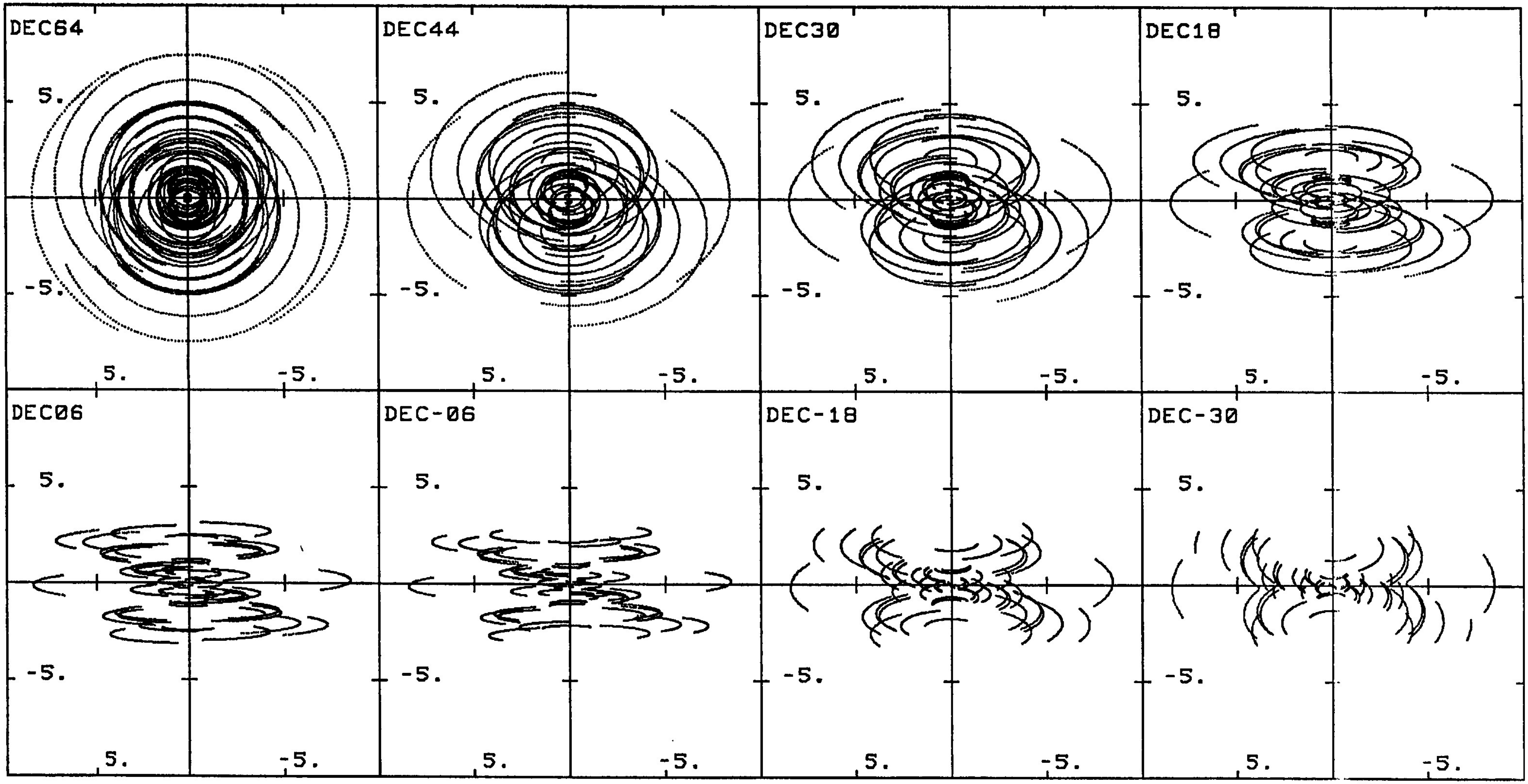
Figure II-1: Array 13 from the Caltech design study (Cohen 1980). This was the best of the arrays found in the early VLBA design effort. It was derived under the constraint that the short baselines are in California rather than near the VLA. In performance, it is similar to Array D2, but it does not interact well with the VLA so it will not be seriously considered.



Scale Maximum 10,000 km.

SOCORRO ARECIBO HAWAII ANCH OVRO SALEM BOIS BLDR DSS14 IOWA HSTK LRDO

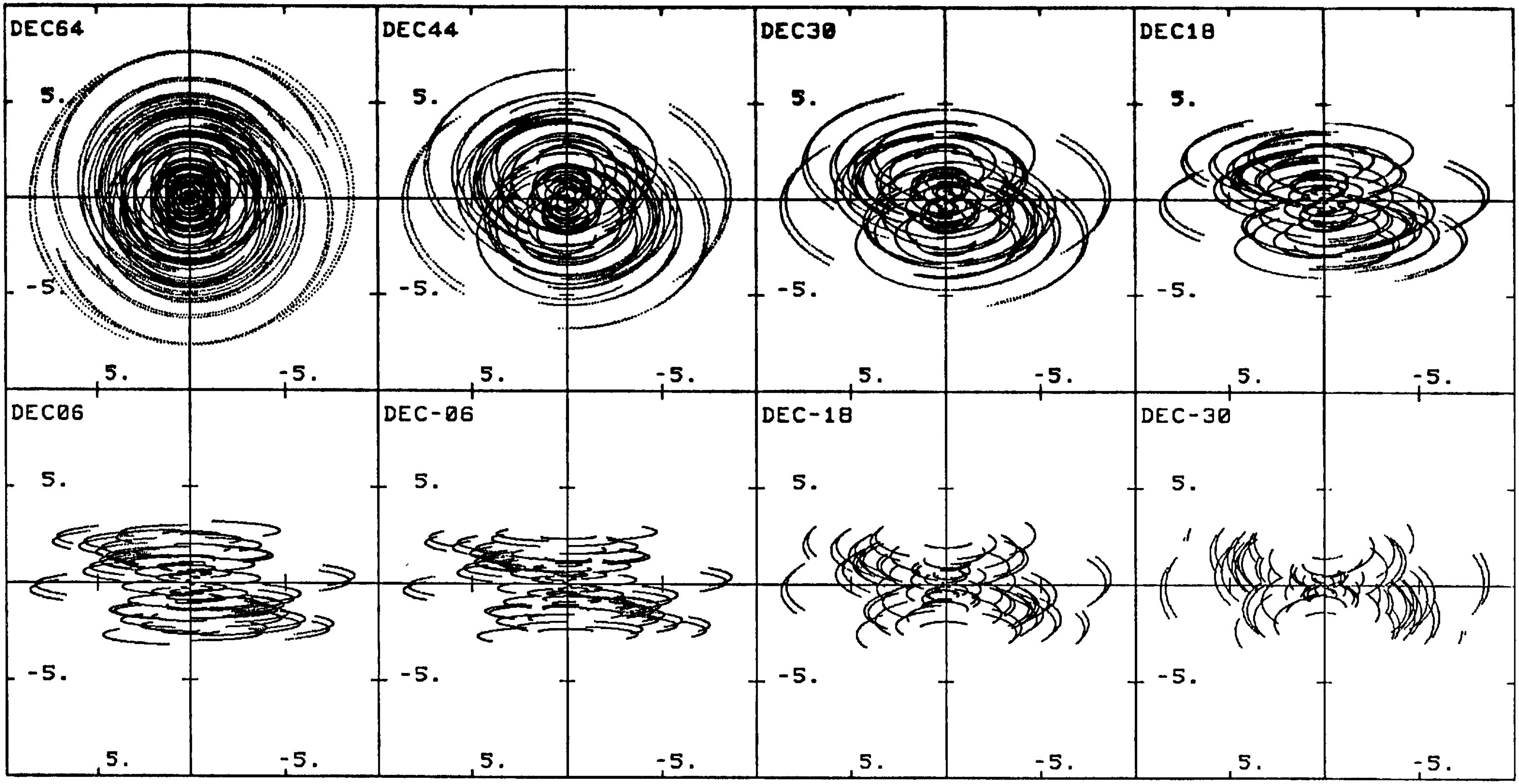
Figure II-2: Array 13 plus Arecibo, Puerto Rico and Socorro, New Mexico. This is a reasonably good 12 array based on Array 13 but with some of the lack of interaction with the VLA corrected by adding a station in Socorro and with improved long spacing coverage obtained with the addition of Arecibo. Comparison with Array 13 shows dramatically the advantage of having Puerto Rico for low declinations.



Scale Maximum 10,000 km.

ARECIBO HAWAII GRFALL HSTK SOCORRO IOWA LVGS LVNM

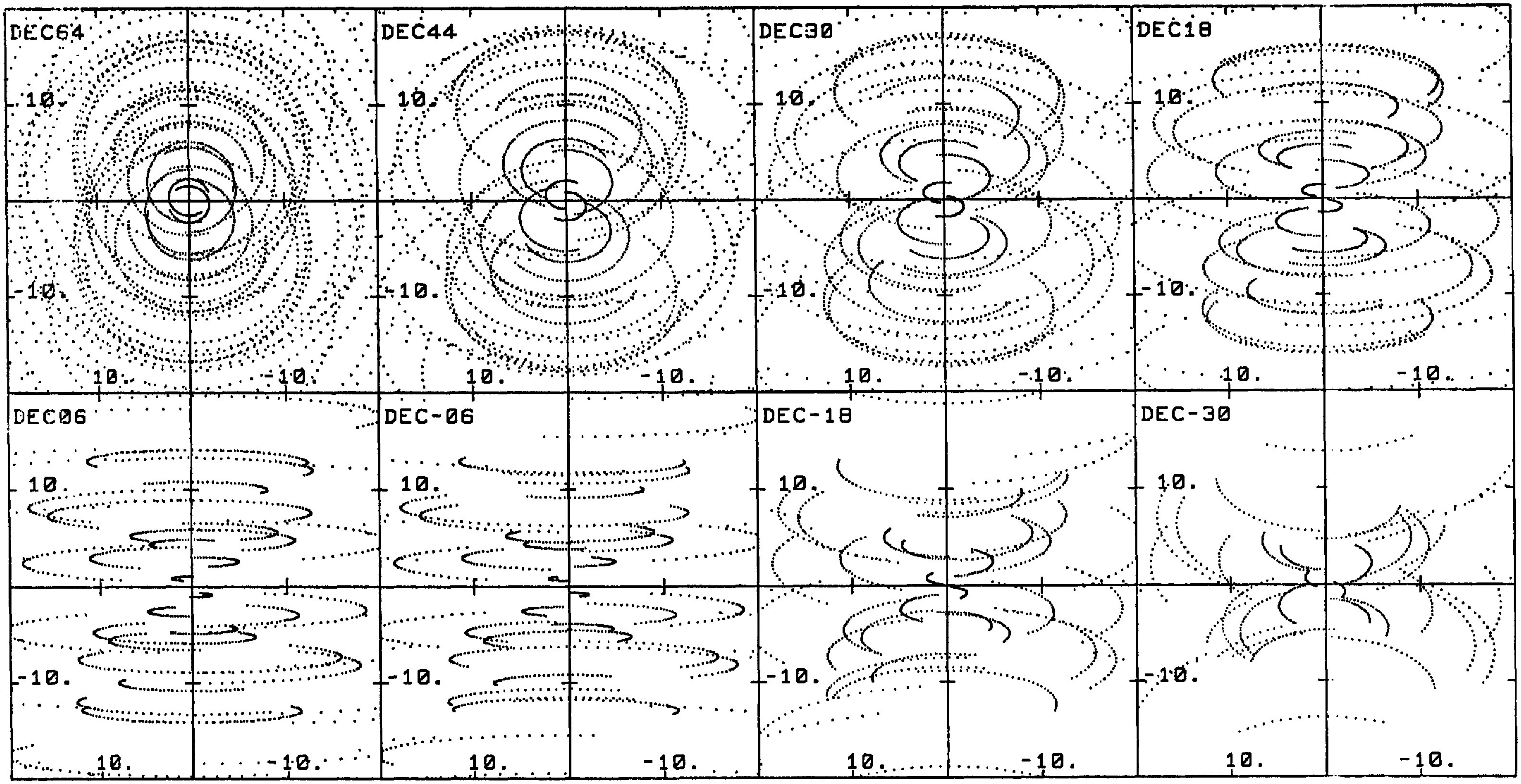
Figure II-3: A good 8 station array derived under the constraints applied to the other arrays. Note the sparse and non-uniform coverage. With the wide range of spacings desired, some stations must be close together so it is not possible to get good uniform coverage with this few sites.



Scale Maximum 10,000 km.

KAUAI HILO SPKN TUSCNE VLASW LRDO IOWA BANGOR ARECIBO PUEBLO

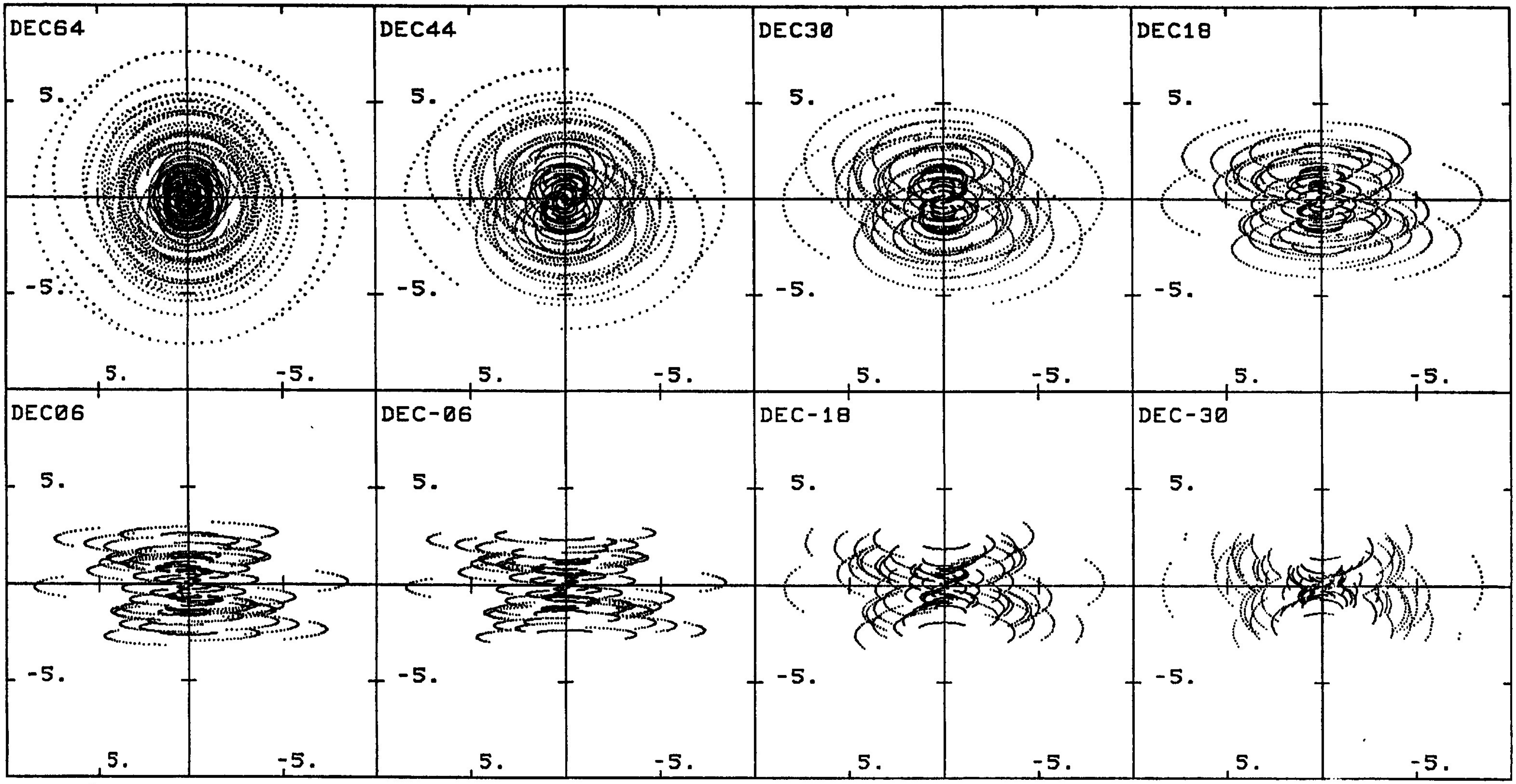
Figure II-4: A ten station array that has two sites in Hawaii. This is a reasonably good 10 station array that is very different from Array D2 and Array 13 but that has similar, although not quite as good, performance. It shows a possible configuration using Puerto Rico and shows what might be done if it were decided that isolated stations (a long way from other stations) are poor for calibration reasons. This is not considered a problem using current techniques.



Scale Maximum 2,000 km.

KAUAI HILO SPKN TUSCNE VLASW LRDO IOWA BANGOR ARECIBO PUEBLO

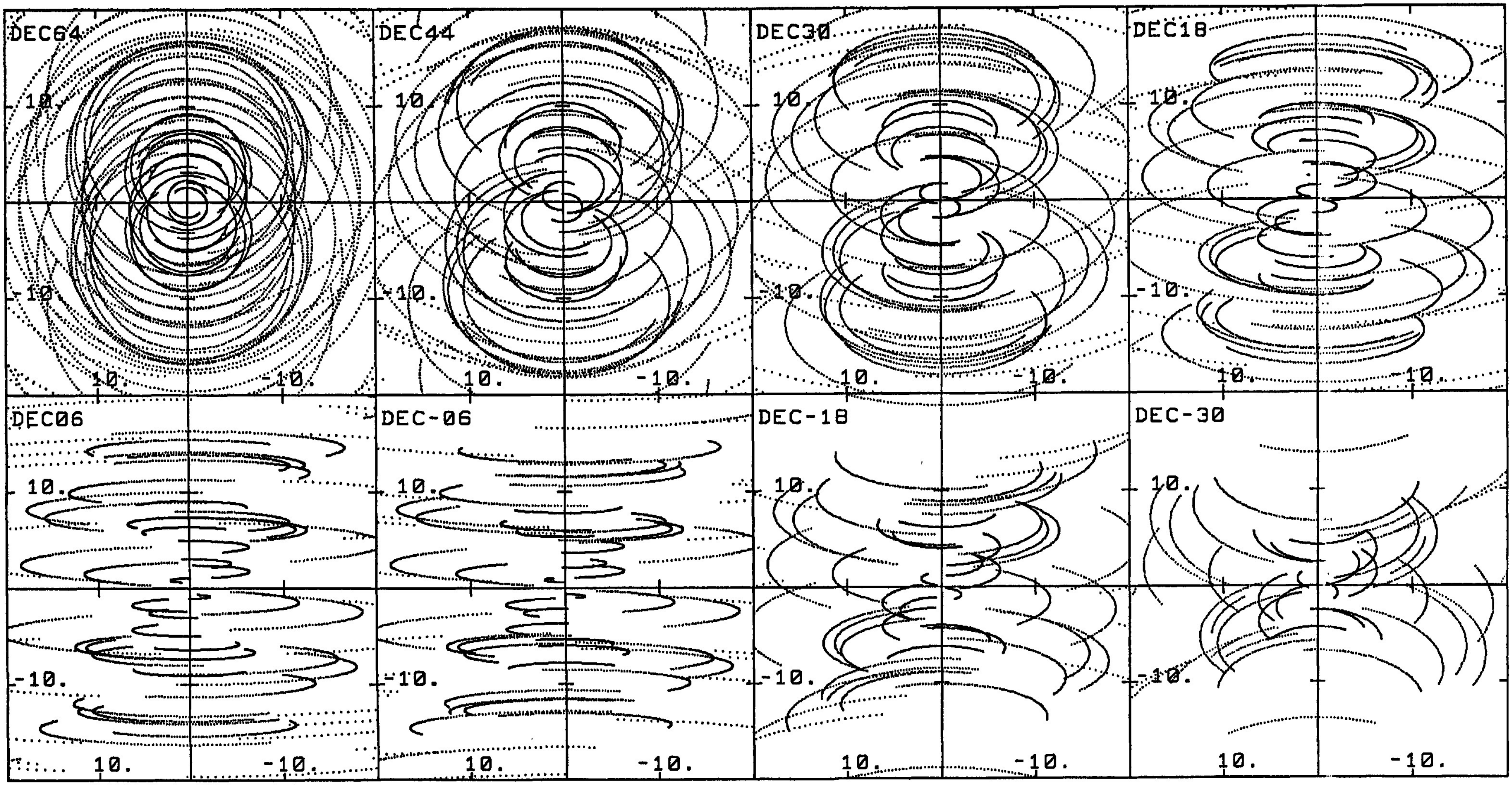
Figure II-5: The inner 2000 km of the array of Figure II-4. With the large scale plots, it is easy to miss poor aspects of the coverage at short spacings. As can be seen here, this array has reasonably uniform coverage at the shorter spacings.



Scale Maximum 10,000 km.

HAWAII ARECIBO SPKN BANGOR BRVL2 VLASW IOWA TUSCNE FDVSNEW BLDR

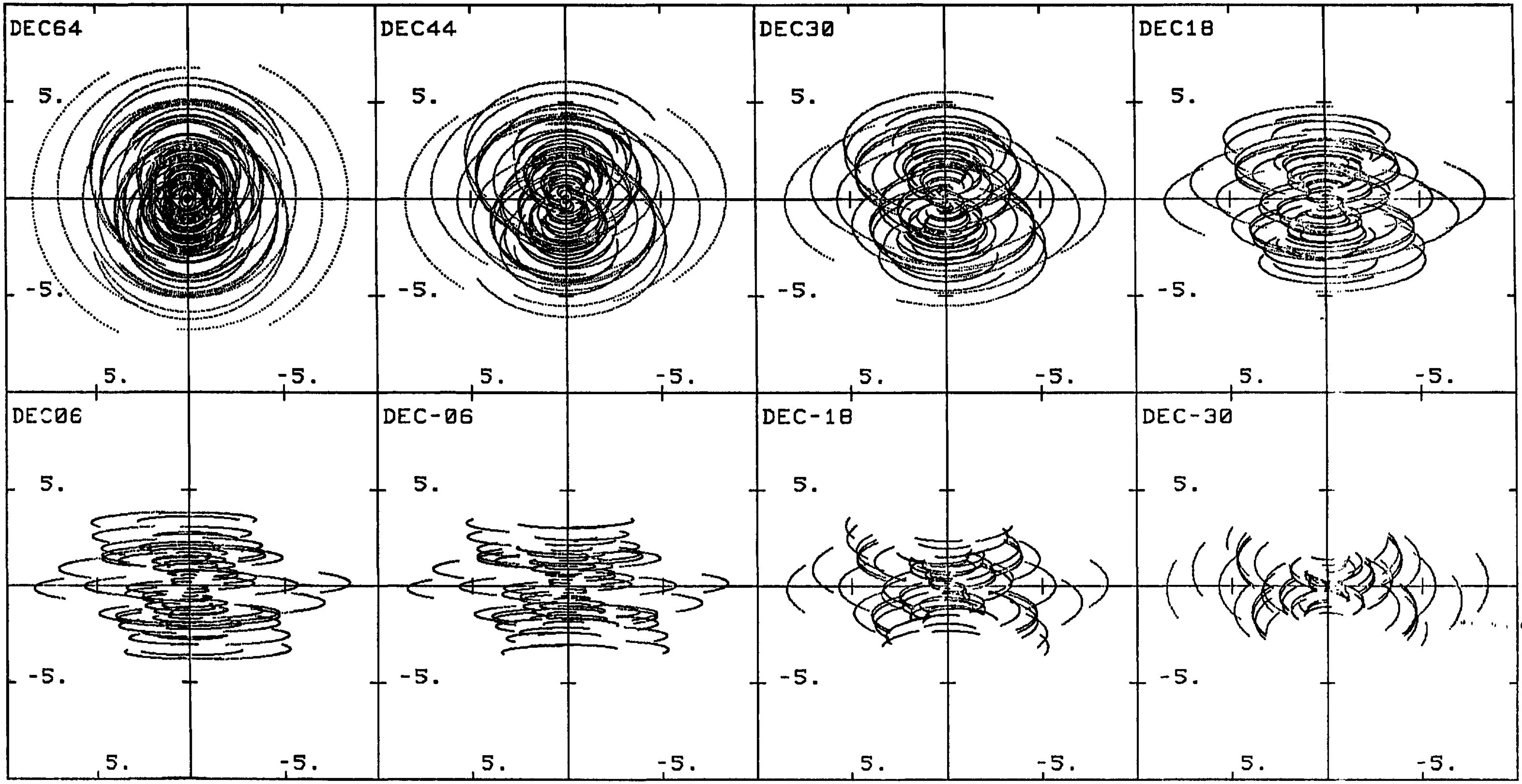
Figure II-6: A strongly centrally condensed ten-station array. This is a configuration that sacrafices some coverage at the longer spacings in order to improve the short spacing performance. This may be desirable in order to map sources over a wide range of scale sizes. This configuration shows what can be done but it is not highly optimized.



Scale Maximum 2,000 km.

HAWAII ARECIBO SPKN BANGOR BRVL2 VLASW IOWA TUSCNE FDVSNEW BLDR

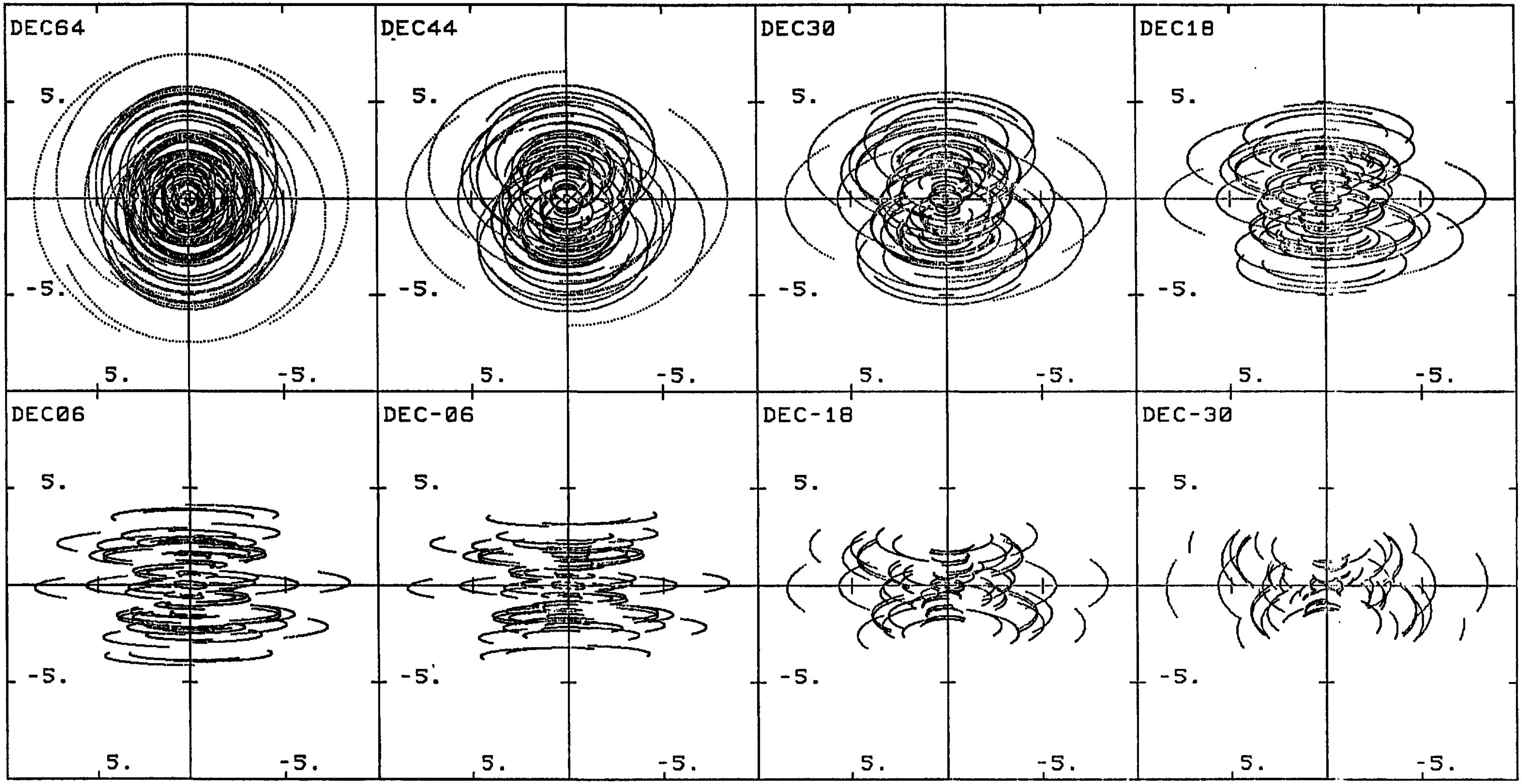
Figure II-7: The inner 2000 km of the centrally condensed array of Figure II-6. This shows the relutively dense coverage in the inner regions.



Scale Maximum 10,000 km.

HAWAII BLDR SDGO SOCORRO LASL CHURCH GRFK2 ARECIBO MEXDF CAPECAN

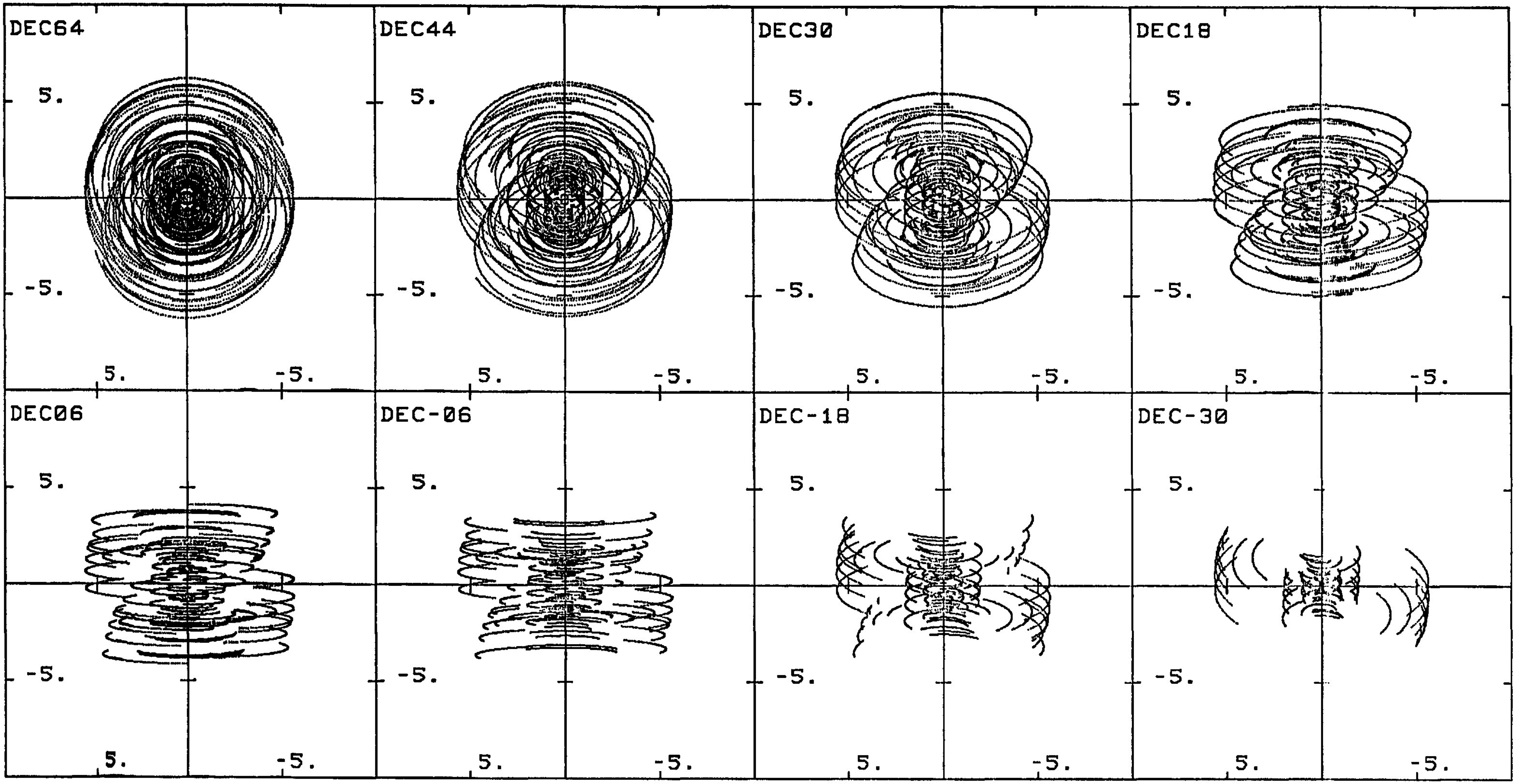
Figure II-8: A 10 station array that includes stations in Mexico and Canada. Note the improved performance near u=0 for low declination sources. Use of Mexico is very desirable because it allows observations of sources further to the south than can be seen from some US sites and because it provides a good high-dry site to replace the southern Texas station needed in all US configurations. Canada also helps improve the north-south coverage for moderately low declination sources although it is too far north to see the lowest declinations. While the latitude of any reasonably accessable site in Canada is no higher than Alaska, it is directly north of the main concentration of sites in the southwestern US, giving better interaction with those stations. There is also strong interest in VLBI in Canada and a Canadian VLBI array may be built.



Scale Maximum 10,000 km.

HAWAII YELKNF ARECIBO HSTK SPKN MEXDF LASL OKLA NPLAT SOCORRO

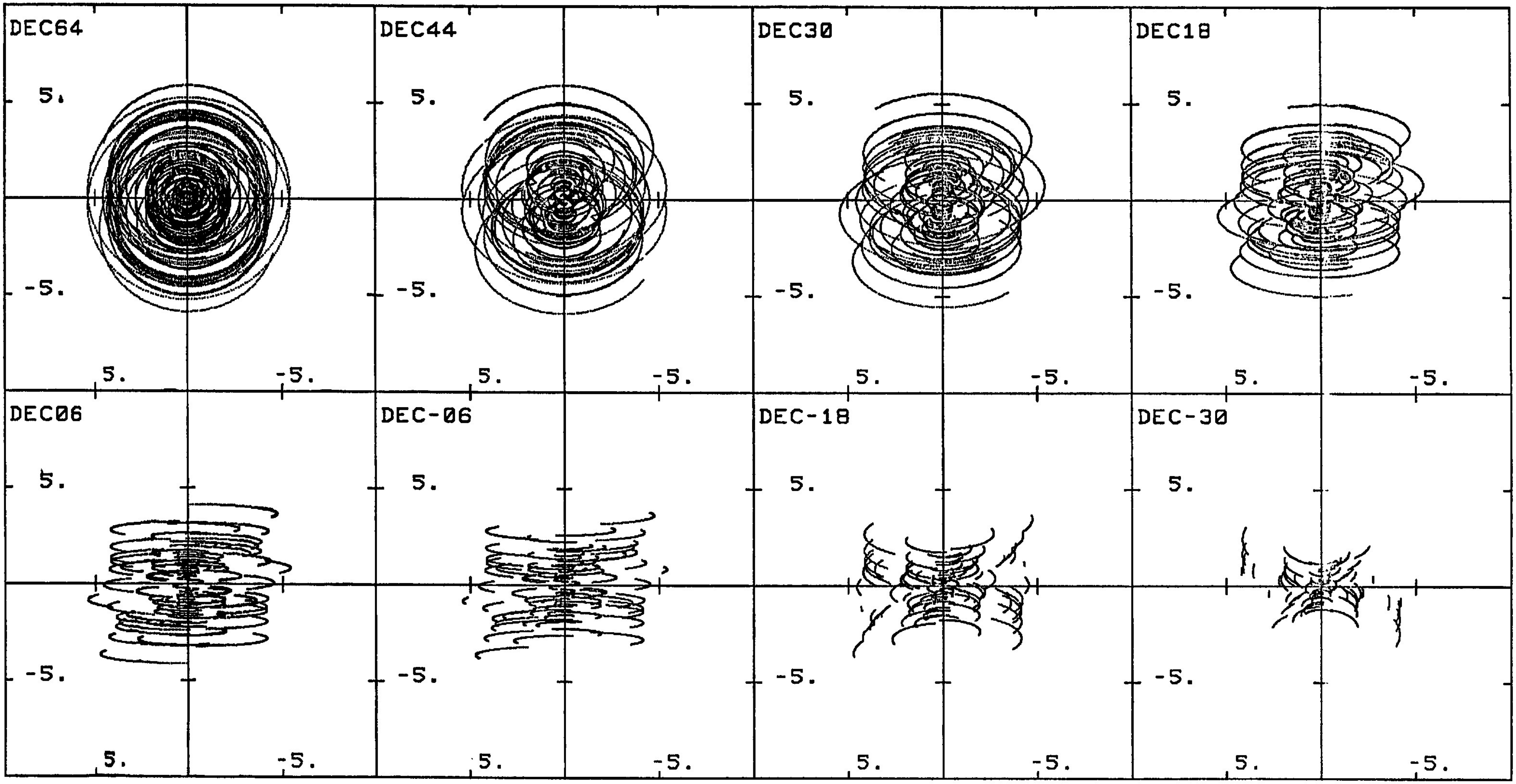
Figure II-9: This is a ten station array formed of nested triangles. It was one of several attempts to explore regular geometries. The outer triangle is Hawaii-Yellowknife-Arecibo. Inside this, but off center, is Haystack-Spokane-Mexico City, a triangle that is inverted relative to the largest one. The inner triangle is Los Alamos-Oklahoma City-North Platt. A tenth station at Socorro provides short baselines and a tie to the VLA. The coverage is not bad but the uniformity would have to be improved to match the better optimized arrays, especially in the short spacings.



Scale Maximum 10,000 km.

CHURCH GRFK2 OMAHA TOPEKA DALLAS BRVL2 ACAPUL HAWAII ANCH OVRO SOCORRO

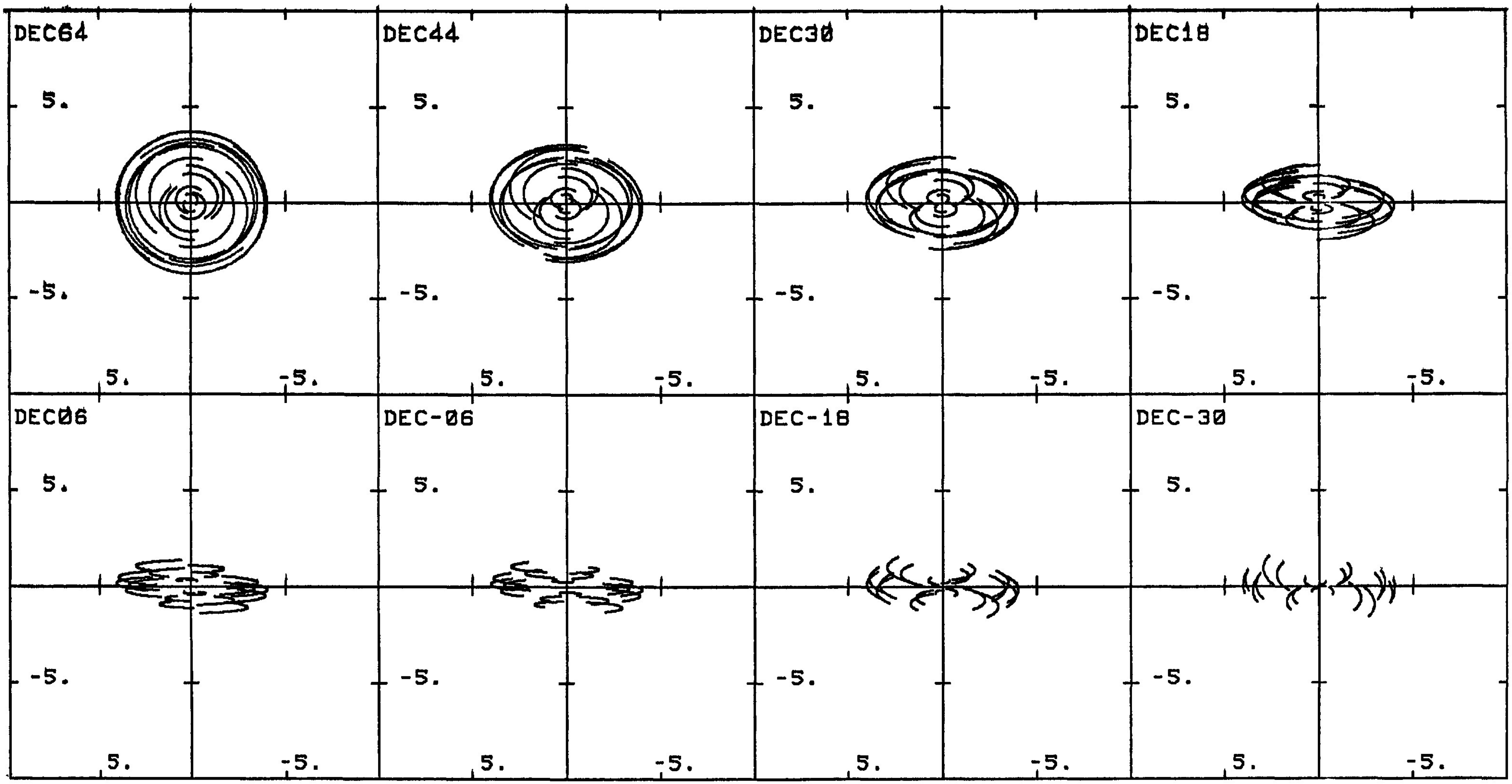
Figure II-10: This array consists of a north-south line of sites from Churchill, to Acapulco, Mexico plus 4 stations stretching east-west. The regularity can be seen in the systematic groups of tracks. The coverage is poor - there are too many north-south baselines relative to east-west baselines and there are big gaps. In general, lines of stations are poor because they give a concentration of baselines along the line. This is seen in VLA snap-shots (short observations) where there are 6 radial concentrations of u-v points. The lines of stations are needed at the VLA because the antennas must be moved to change configurations and the lines minimize the amount of track needed. For the VLBA, there is no such constraint so a more distributed pattern of antenna locations is preferred.



Scale Maximum 10,000 km.

STAT 1 STAT 2 STAT 3 STAT 4 STAT 5 STAT 6 STAT 7 STAT 8 STAT 9 STAT10

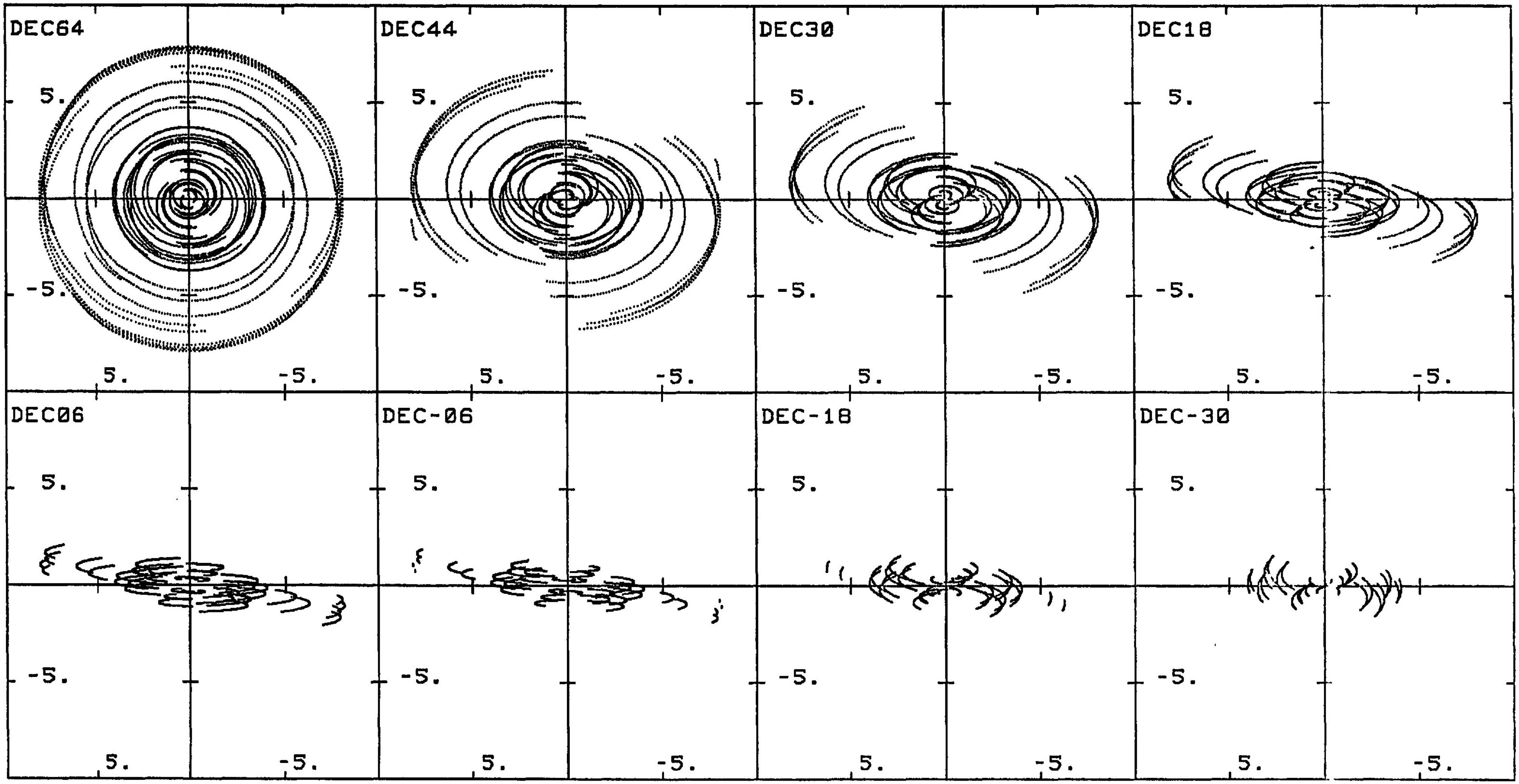
Figure II-11: This array is a 10 station power law wye with the junction of the arms at Socorro and the ends of the arms at Anchorage, Newfoundland, and Acapulco. (The station locations are not listed in the stations list.) As in the last figure, the effects of the regularities are apparent and there are large gaps at the low declinations. Note the contrast between the coverage of this wye which has arms that curve with the Earth, and the coverage of the VLA (Figure VI-1), which has sites that are effectively on a plane.



Scale Maximum 10,000 km.

HCRK OVRO FDVS NRAO HSTK

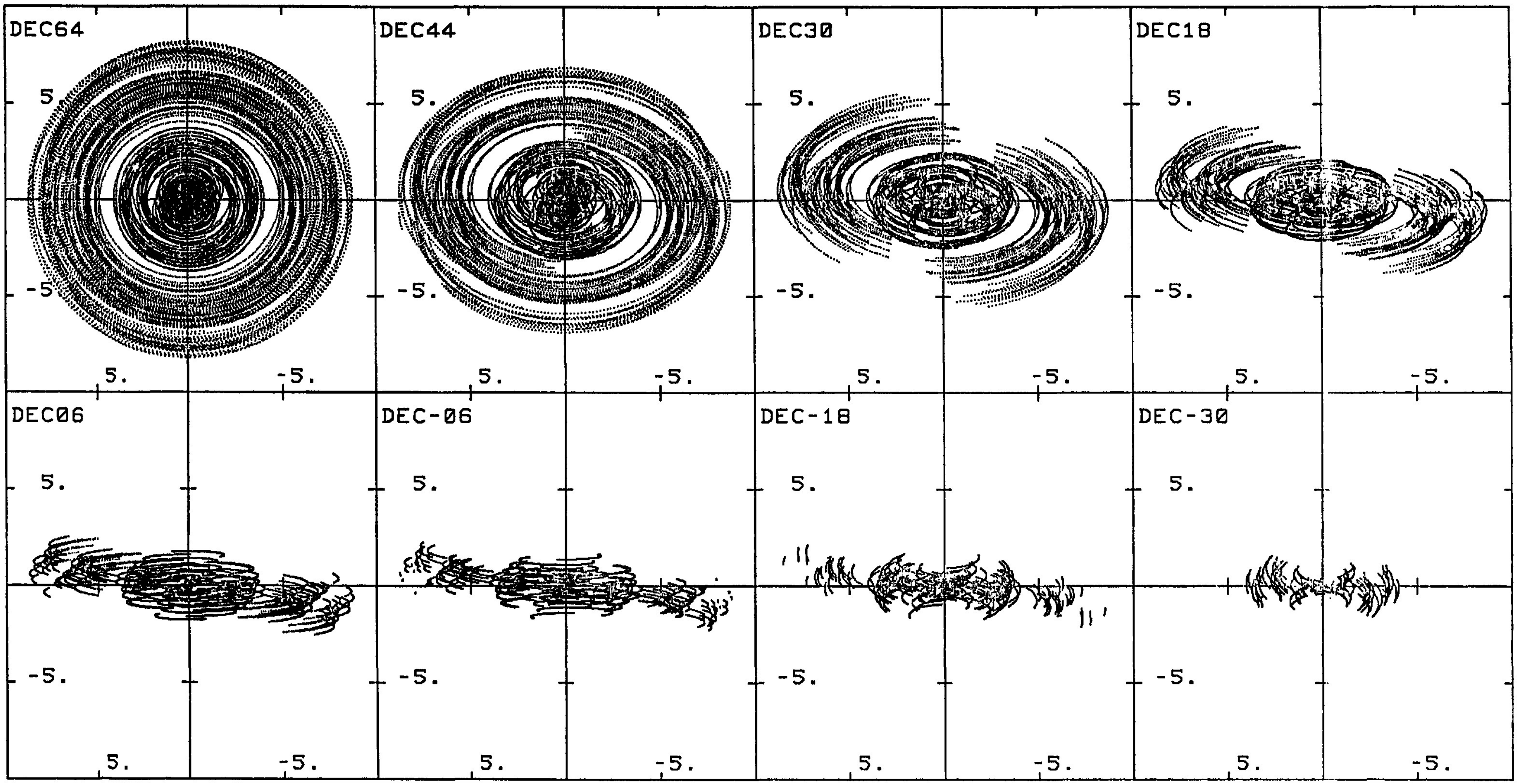
Figure III-1: The coverage of a U. S. VLBI Network experiment that uses the 5 most active stations and does not use a European station. With only 10 baselines the coverage is sparse. The sites of the stations were not chosen with VLBI in mind so the uniformity of the coverage is poor. At high declinations the large holes due to the 'midwest gap' can be seen. Iowa fills these holes but has poor frequency coverage and low sensitivity. Without Europe, the resolution is severely limited by the lack of a Hawaii site.



Scale Maximum 10,000 km.

HCRK OVRO VLA FDVS NRAO HSTK BONN

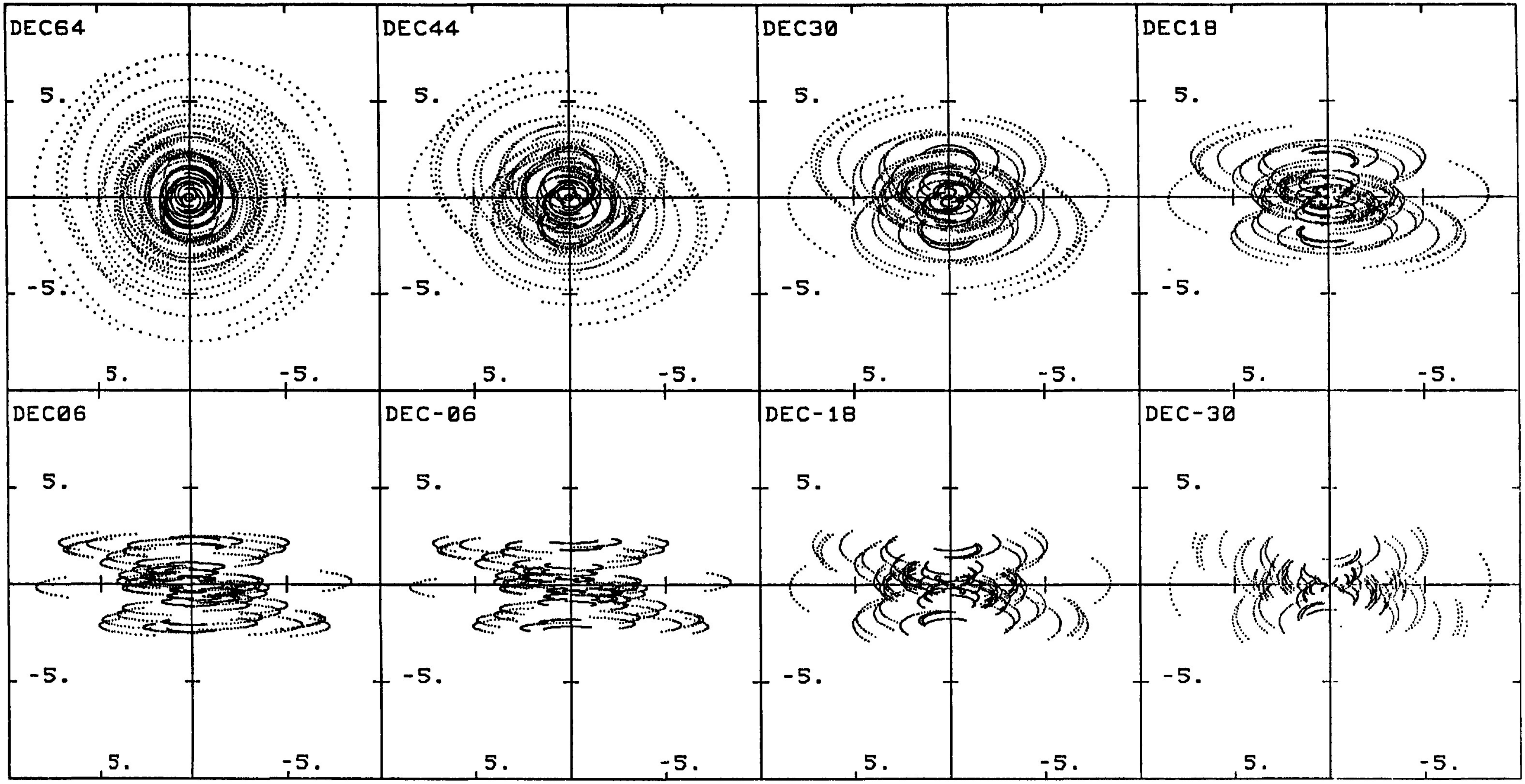
Figure III-2: The u-v coverage of seven existing stations that are commonly used in current VLBI Network observations at frequencies below 10 GHz. The VLA and Bonn have been added to the usual Network stations shown in the last figure because, although they are not full Network stations, they are used in a large fraction of current experiments. Note the large gaps and the poor north-south distribution at low declinations. Also note the loss of long spacings at low declinations that is a result of the high latitude Europe. The performance of some of the antennas is poor at frequencies of 10 GHz and higher.



Scale Maximum 10,000 km.

HCRK OVRO VLA FDVS NRAO HSTK BONN PENT ARO NRL ONSALA JODRELL IOWA DWINGELO BGNA

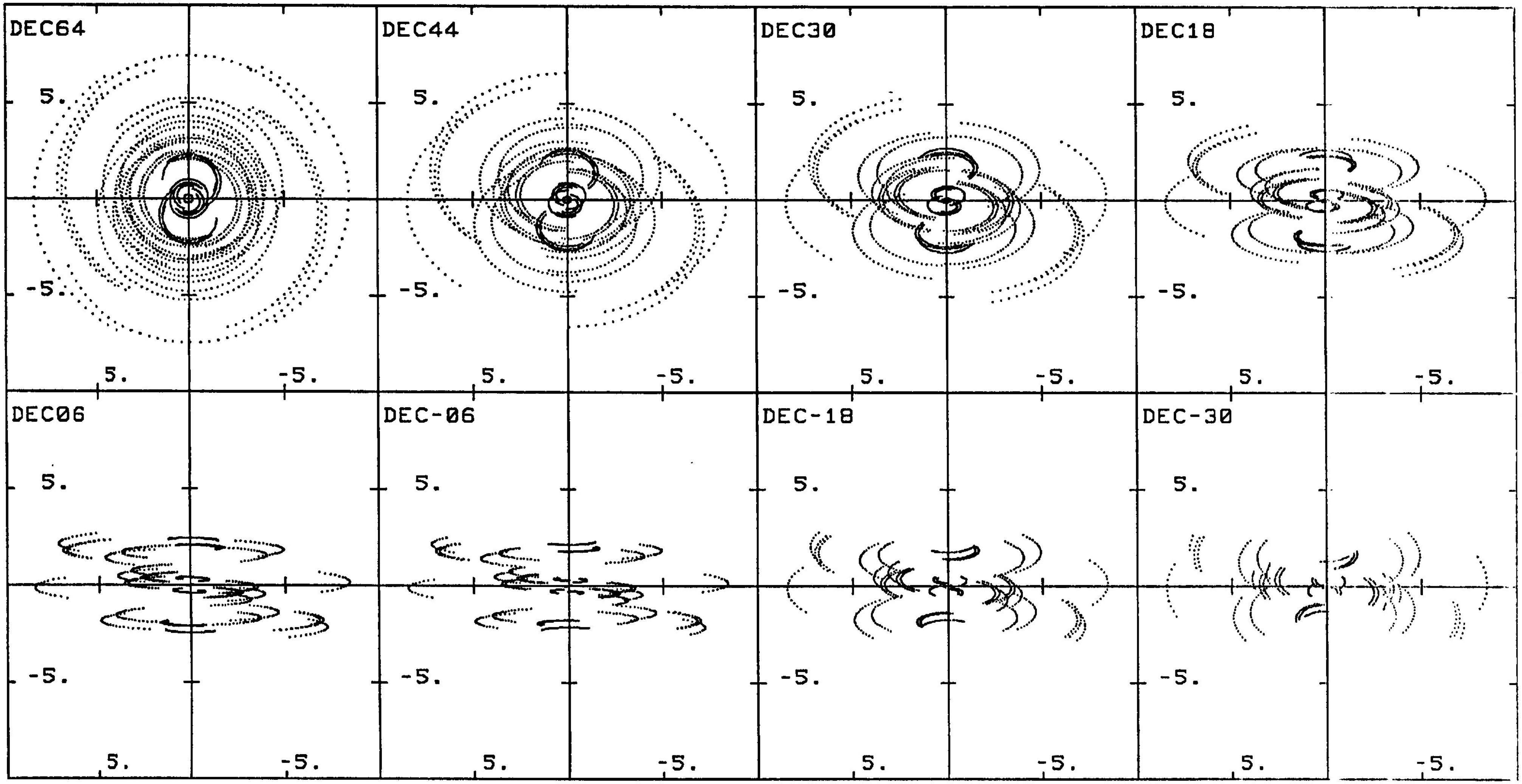
Figure III-3: The u-v coverage of a very large experiment that might be done with existing observatories at low frequencies (such an experiment has been proposed for a source at 4 degrees declination). Note that there are still gaps corresponding to the midwestern United States and to the Atlantic Ocean. An experiment of this magnitude can only be done at low frequencies (eg 1650 MHz) and only with cooperation from many observatories. With current facilities, such experiments will be rare.



Scale Maximum 10,000 km.

ARECIBO HAWAII OVRO HCRK VLA FDVS IOWA NRAO NRL HSTK

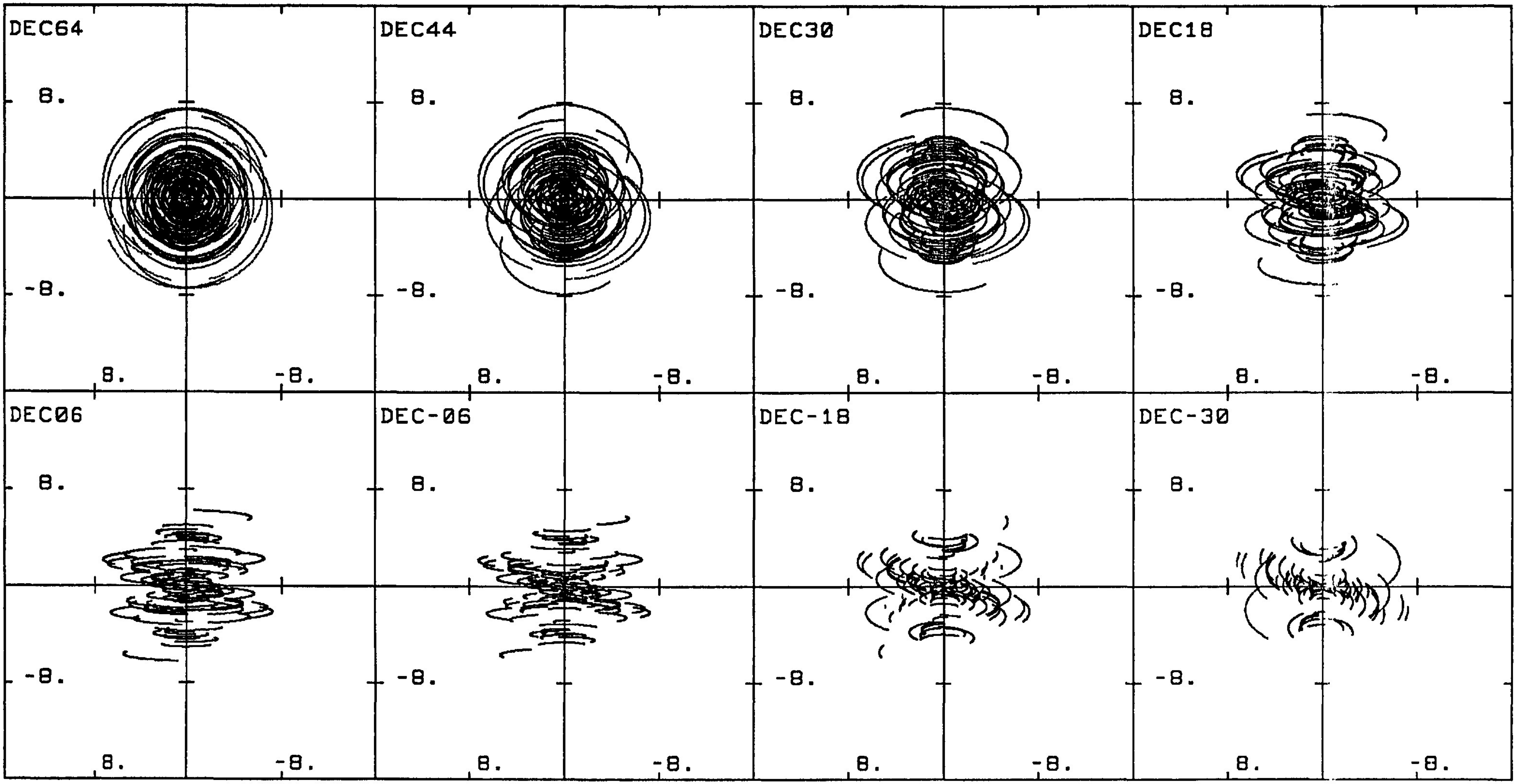
Figure III-4: An array consisting of 8 existing U.S. observatories plus new antennas at Arecibo and Hawaii (Note that the new Arecibo antenna is at an existing observatory - the current antenna has very limited hour angle coverage). The coverage is not as uniform as the coverage obtained with an optimized array but is very much better that what is currently available. Note that the well-known 'midwest gap' is filled by the 60 foot antenna at Iowa which is being upgraded for use at 5 GHz and maybe higher. The coverage shown here could only be obtained at frequencies below 5 GHz (or 10 GHz with poor performance at some sites).



Scale Maximum 10,000 km.

ARECIBO HAWAII OVRO VLA NRAO NRL HSTK

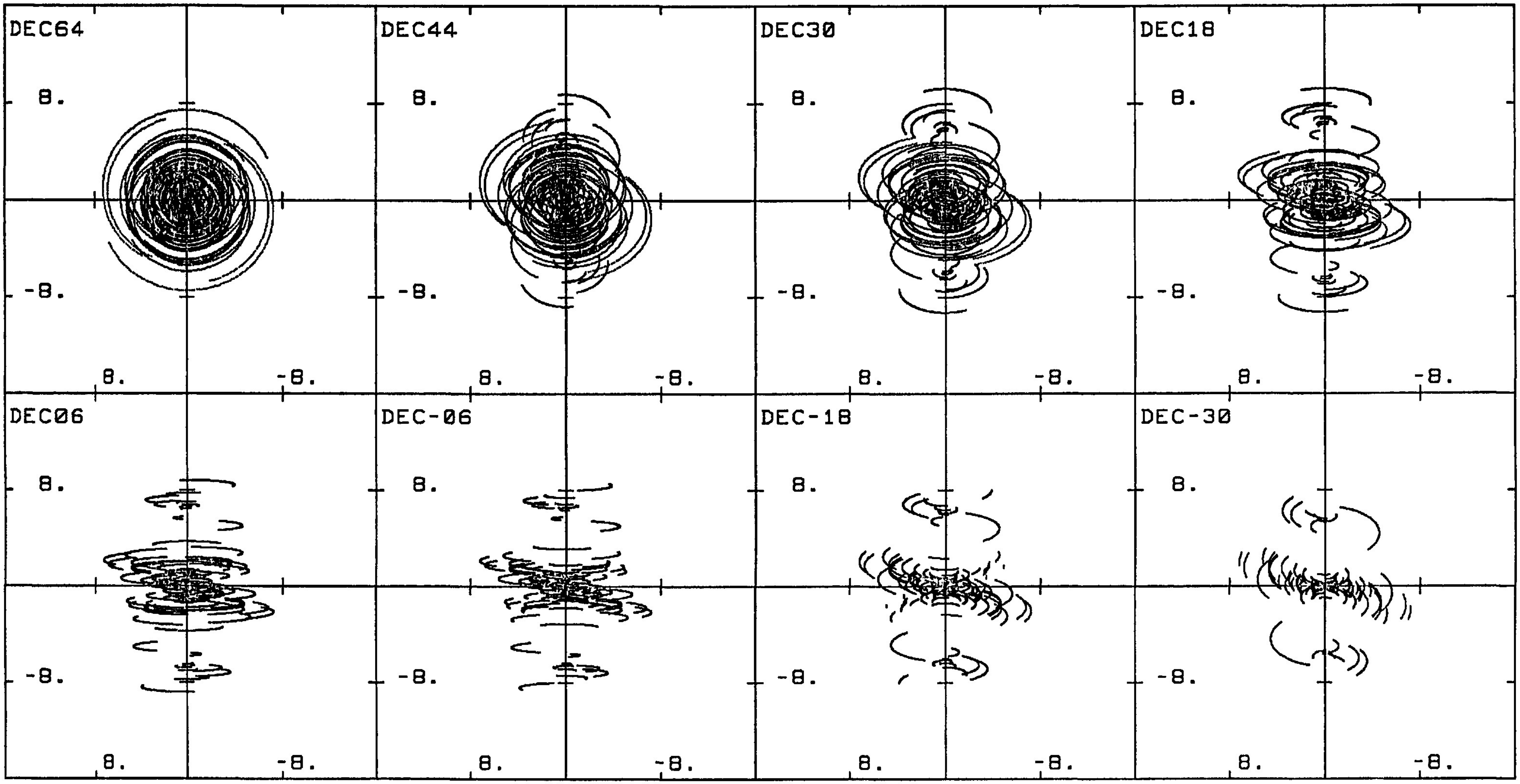
Figure III-5: The coverage of the 7 antennas of the array of Figure III-3 that would give useful performance at 22 GHz (eg the H2O maser frequency). Now the coverage is very poor.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 GALAPA

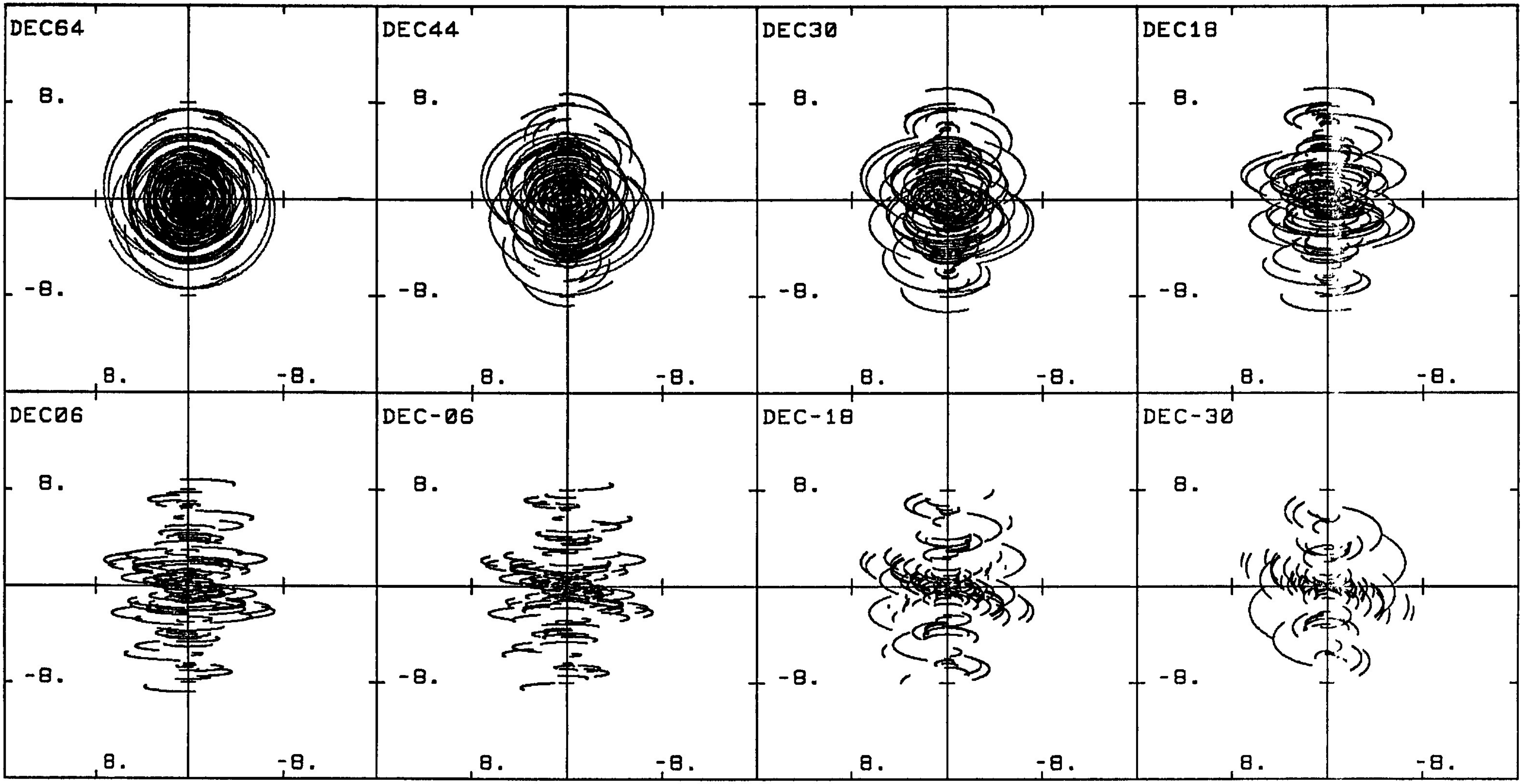
Figure IV-1: This is the first of several figures showing what could be gained by using stations in South America and/or on islands west of South America. This figure shows the u-v coverage of Array D2 plus a station in the Galapagos. The north-south coverage is improved dramatically at low declinations although there is a large gap. That gap can be avoided with a suitable choice of U.S. stations as will be shown in later figures - the inclusion of a Puerto Rico station seems to be the key. The Galapagos are owned by Equador and are serviced by daily flights to Quito.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 EASTER

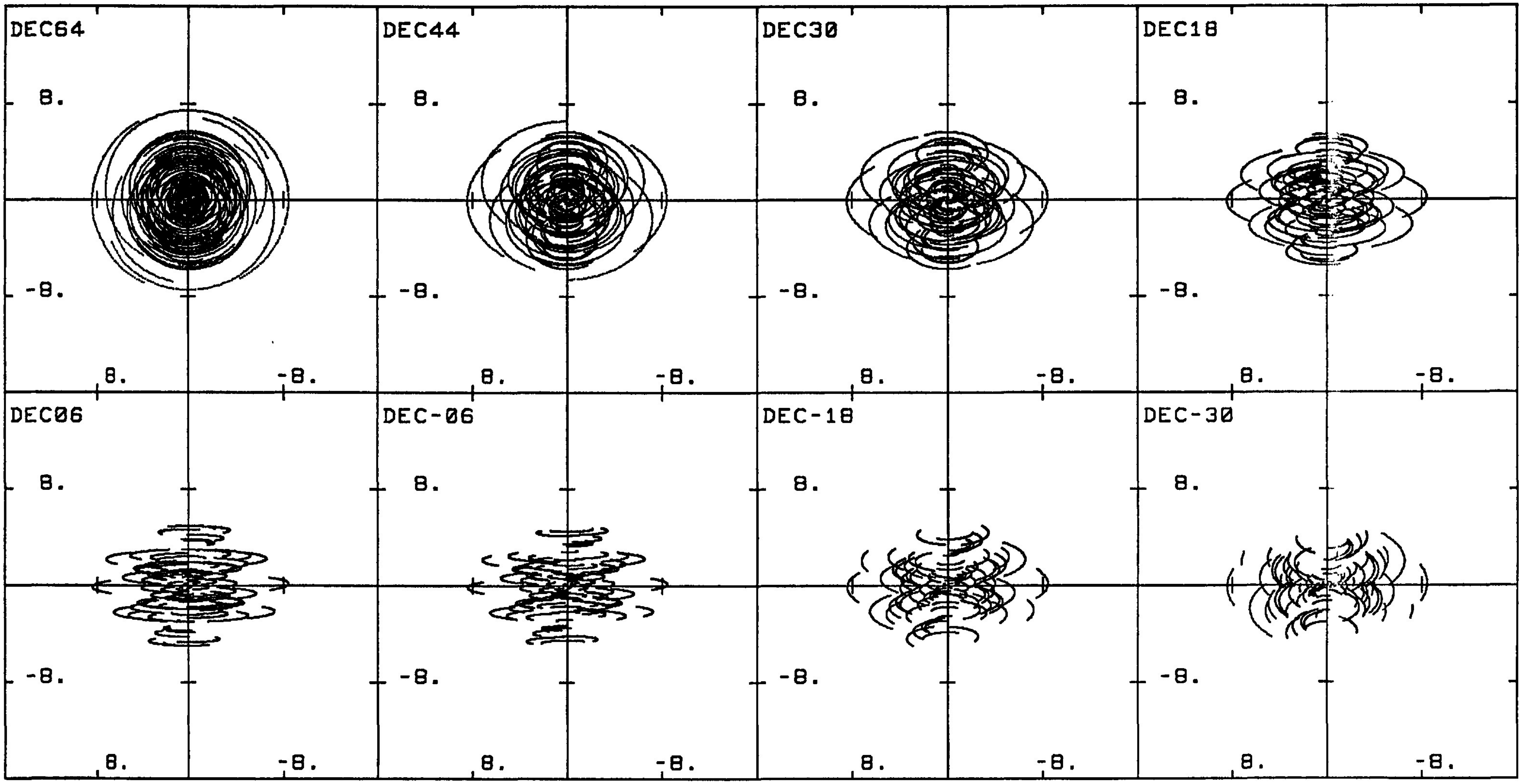
Figure IV-2: Array D2 plus Easter Island. This provides very long north-south baselines but leaves a large gap. Easter Island is owned by Chile and is serviced by several flights a week from Chile.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 GALAPA EASTER

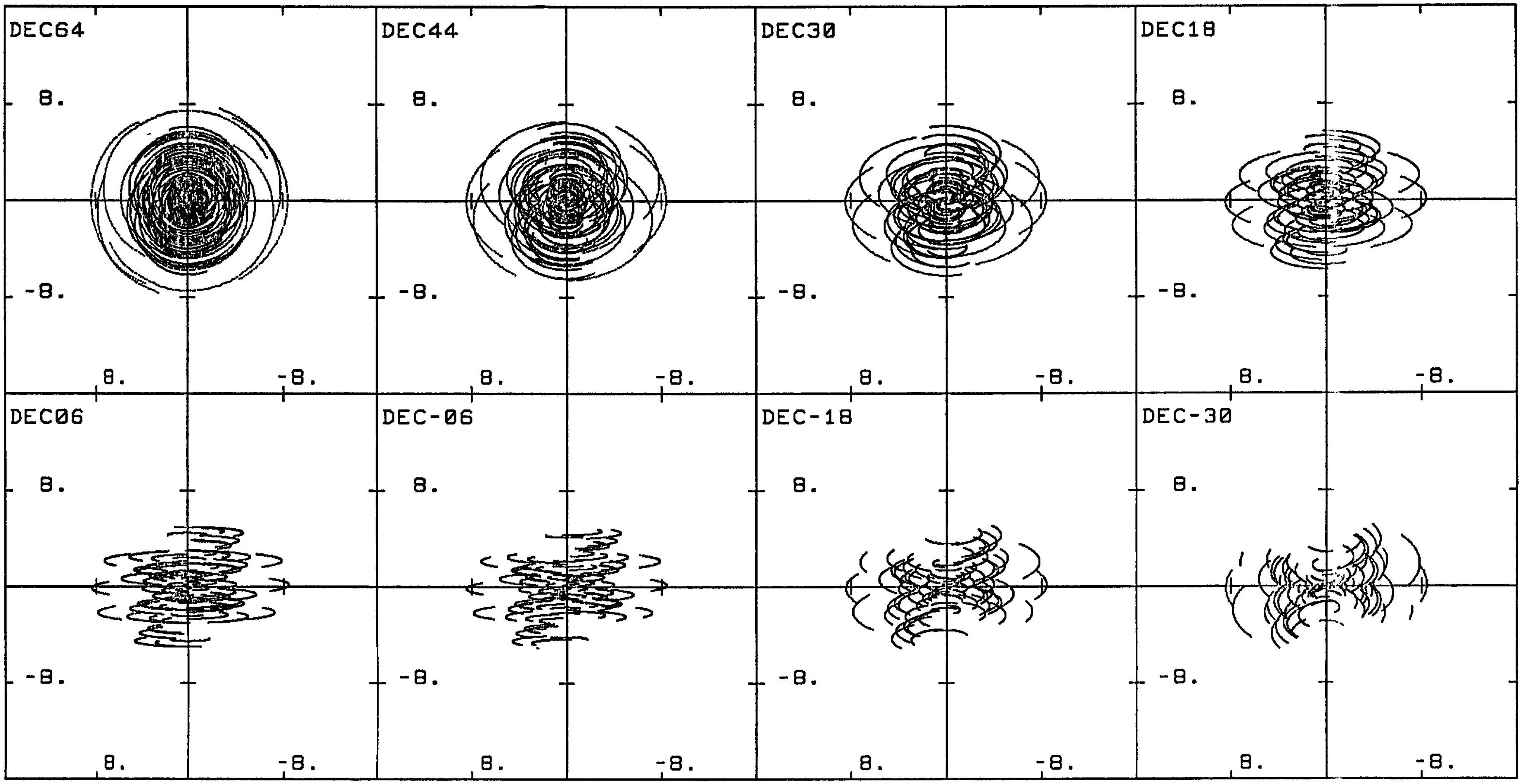
Figure IV-3: This shows the coverage of Array D2 plus antennas in the Galapagos and on Easter Island. The north-south coverage is significantly improved over that of Figure IV-1. Again the gaps can be avoided with a suitable choice of North American sites. More discussion of the use of the Galapagos and Easter Island can be found in Mutel and Gaume (1982). South America is much more to the east of North America than most people realize and stations on the mainland are not as good as station on these islands.



Scale Maximum 16,000 km.

HSTK OVRO SALEM HAWAII VLA TUSC BRVL2 ARECIBO GALAPA BISMARCK

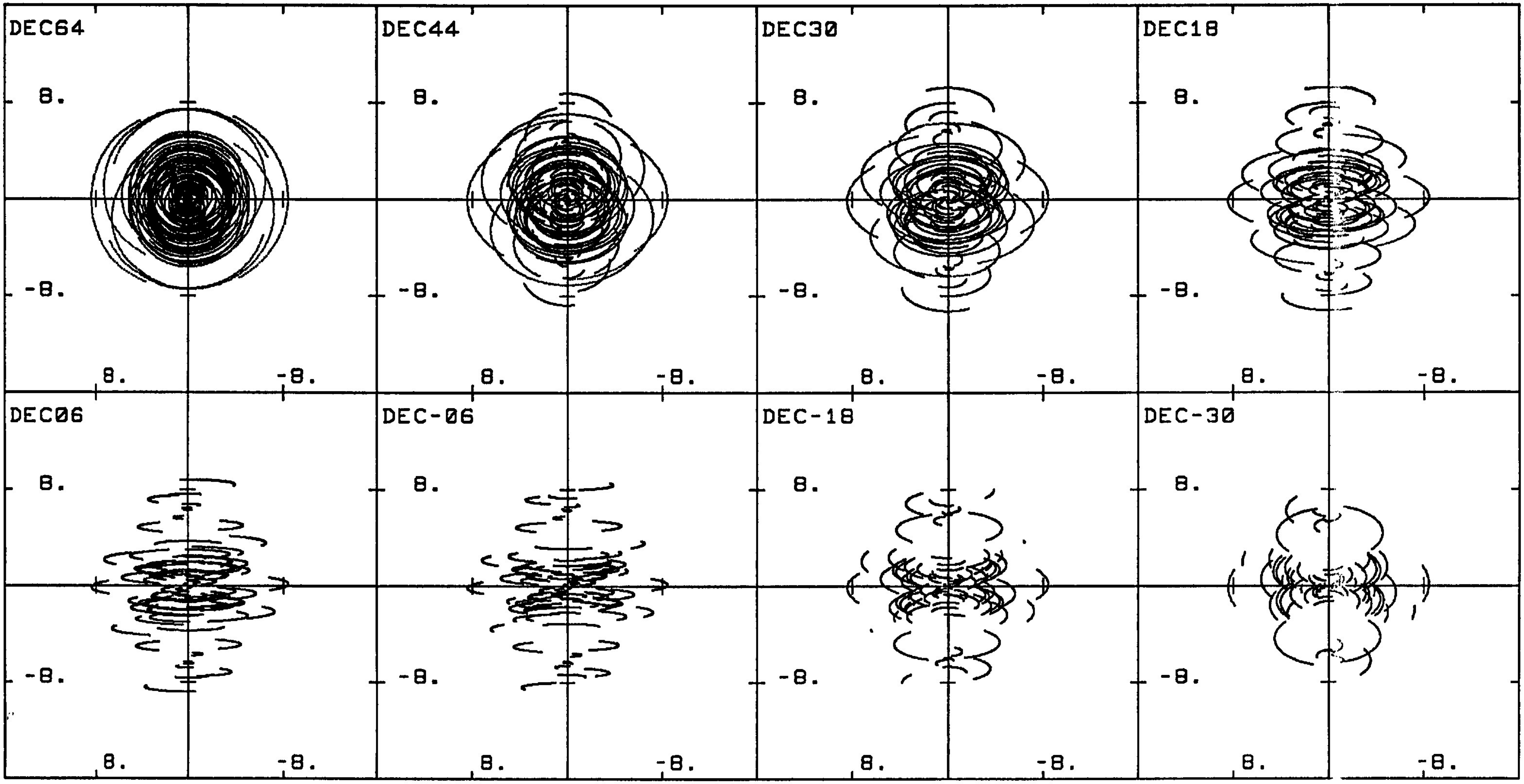
Figure IV-4: Array SG-1 of Mutel and Gaume (1982). This is a 10 station optimized array that uses the Galapagos.



Scale Maximum 16,000 km.

HSTK OVRO SALEM HAWAII VLA TUSC BRVL2 ARECIBO QUITO BISMARCK

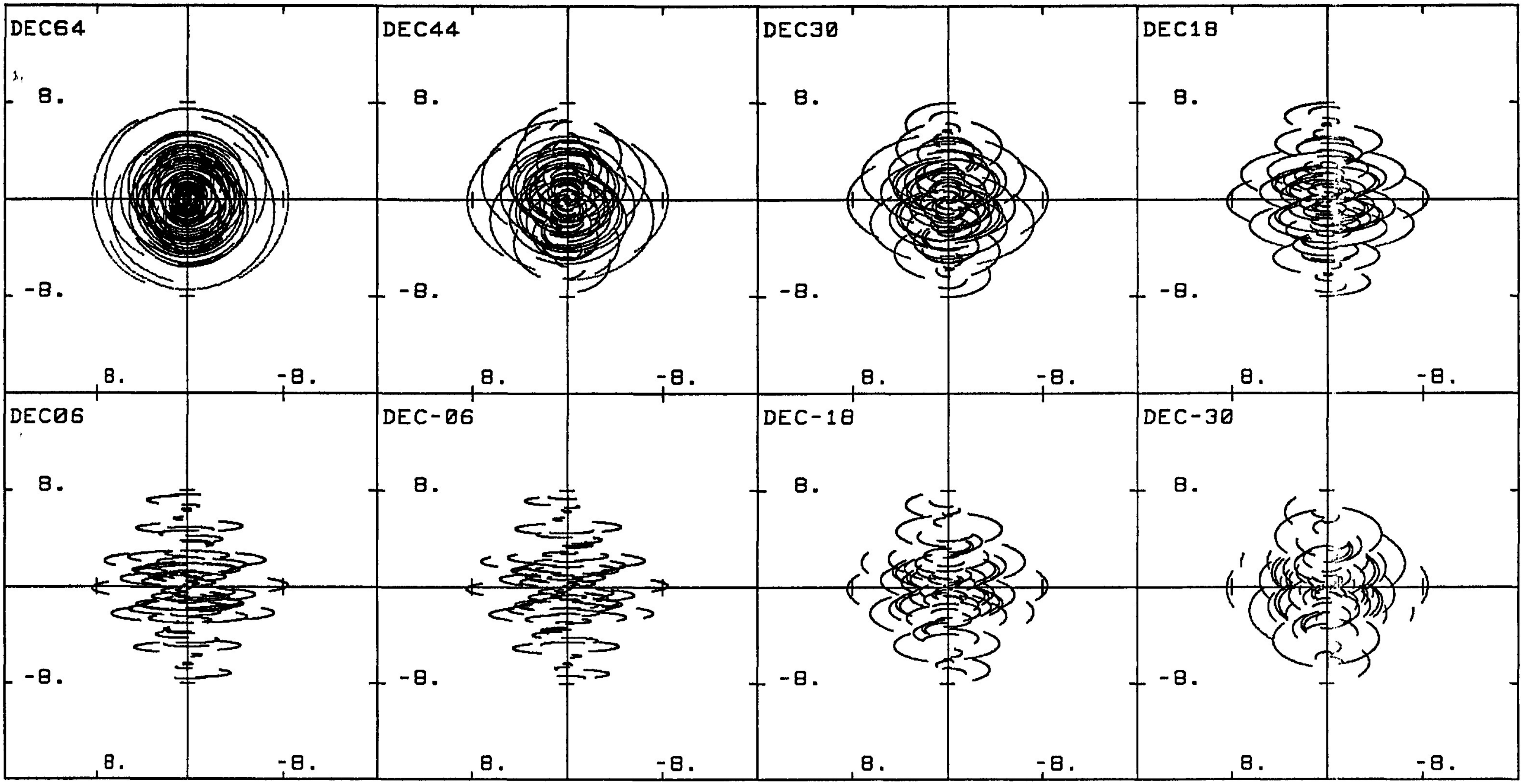
Figure IV-5: Array SG-1 (Figure IV-4) with Quito instead of the Galapagos (SQ-2 of Mutel and Gaume). The coverage is not as good as with the Galapagos because of the more easterly location of Quito but it is good enough that Quito may be preferred for logistical reasons.



Scale Maximum 16,000 km.

HSTK OVRO EASTER HAWAII VLA TUSC BRVL2 ARECIBO ANCH BISMARCK

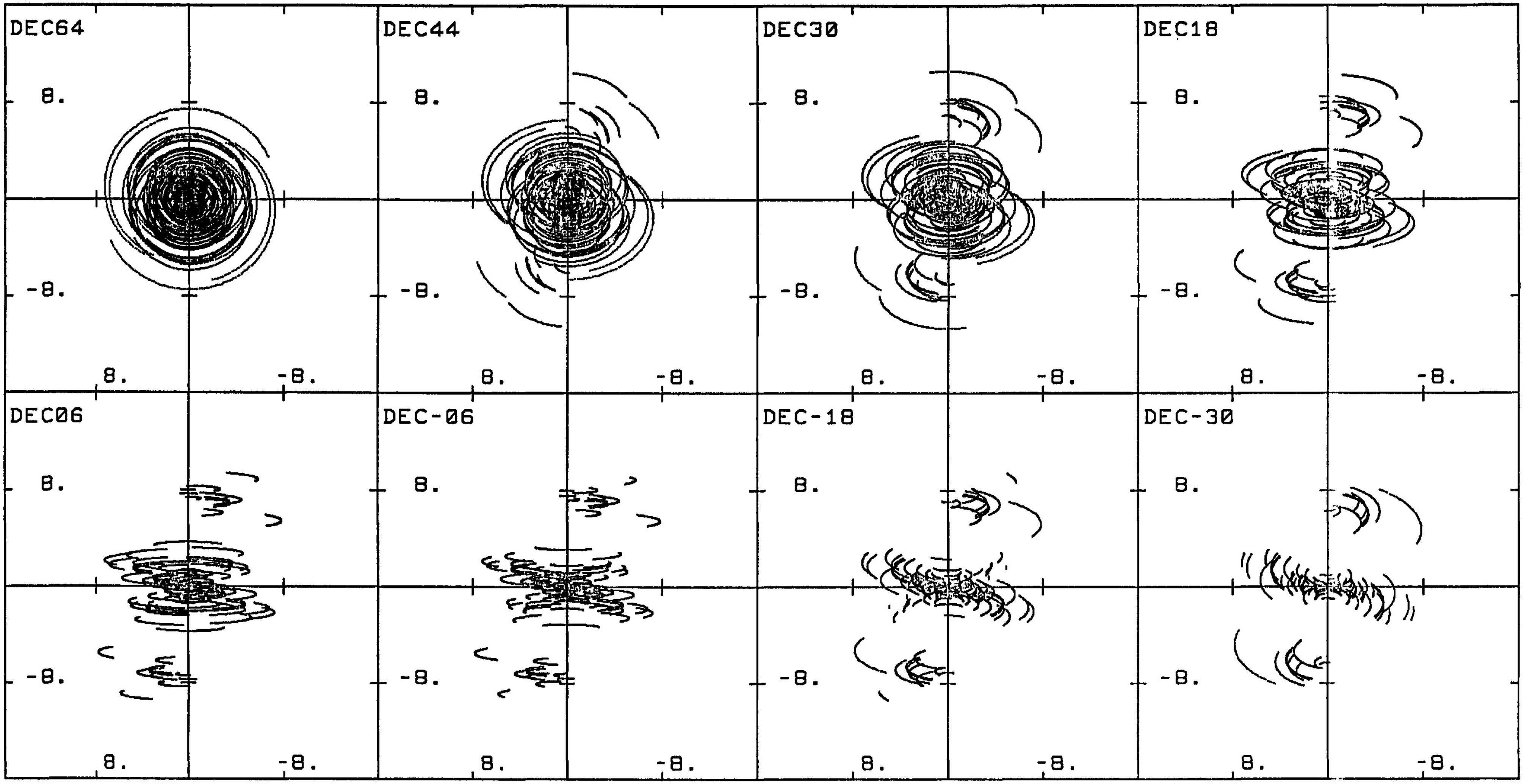
Figure IV-6: Array SE-1 of Mutel and Gaume (1982). This is basically the same array as that shown in Figure IV-4 except that Easter Island is included and the Galapagos are not.



Scale Maximum 16,000 km.

HSTK OVRO EASTER HAWAII VLA TUSC BRVL2 ARECIBO GALAPA BISMARCK

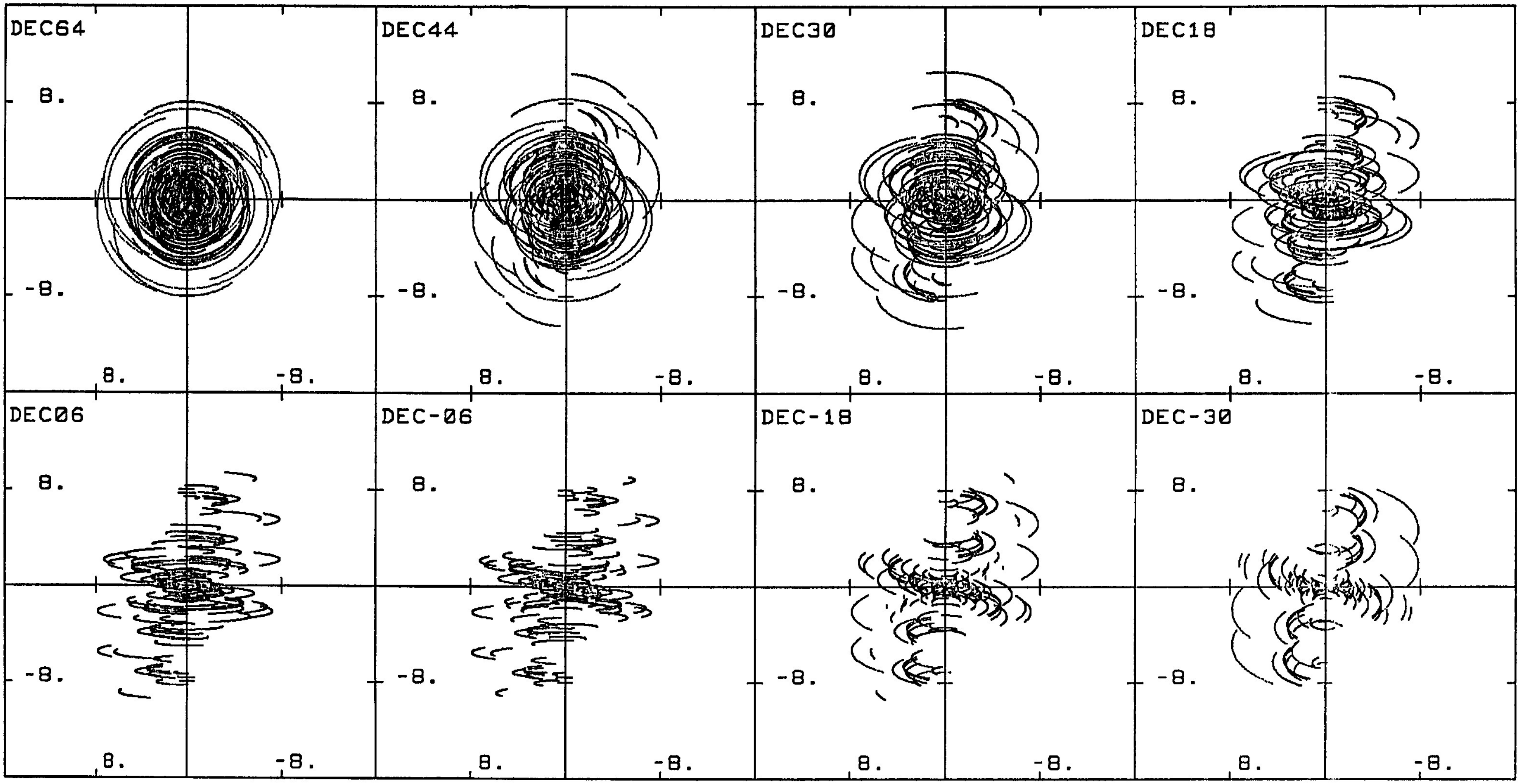
Figure IV-7: Array SEG-1 of Mutel and Gaume (1982). This is a 10 station optimized array that includes both the Galapagos and Easter Island. The coverage at low declinations is very much better than anything that is possible with an Array confined to U.S. territory. It may not be realistic to try to put some of the original 10 antennas of the array in such remote locations but the possibility of adding such stations later, possibly in cooperation with the countries involved, should be kept in mind.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARGENT

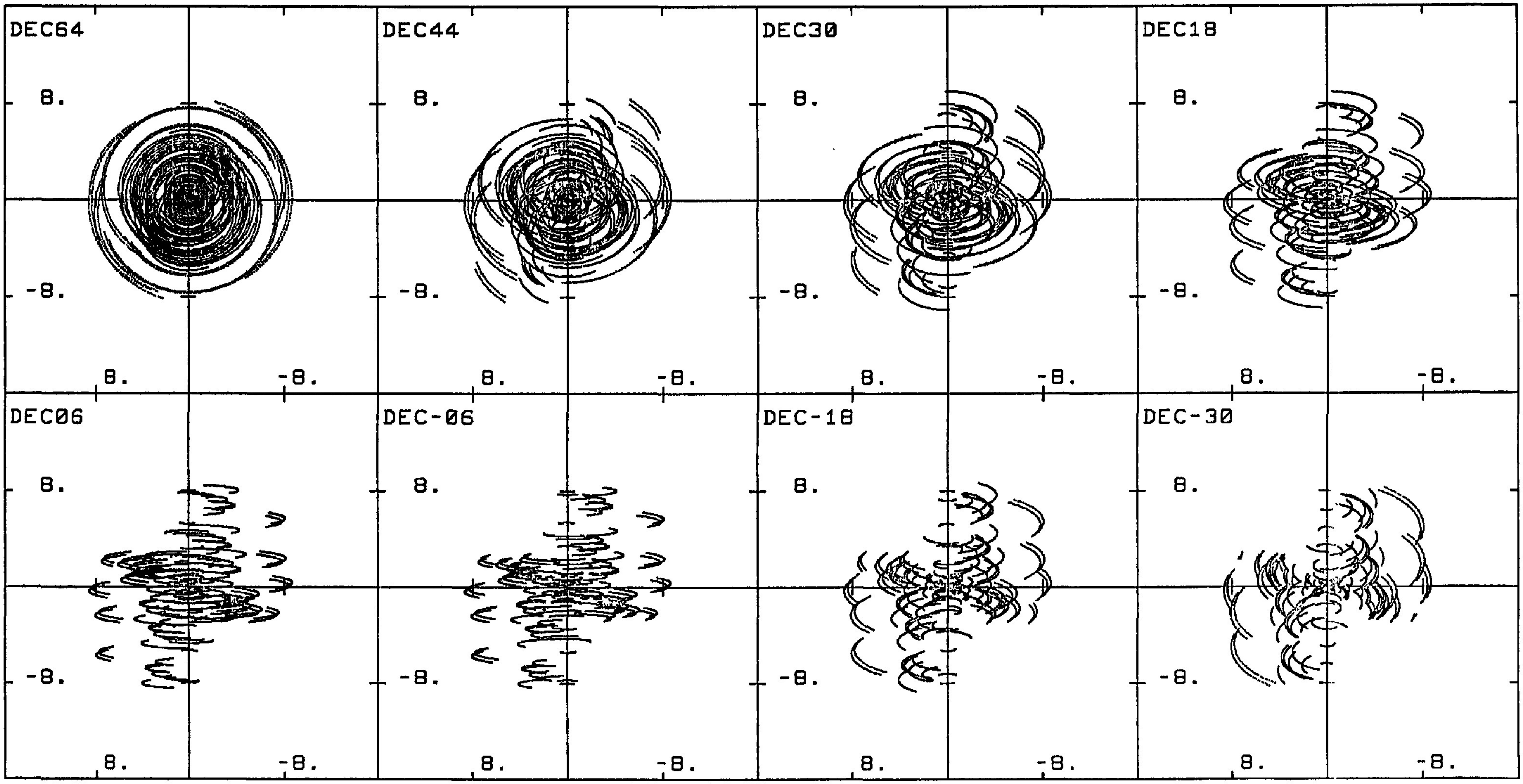
Figure IV-8: This plot shows the coverage of Array D2 plus a station in western Argentina at a site that is being developed for astronomy and has been suggested by the Argentines as a possible site for a VLBI station. The station, used without other southern stations, leaves large gaps and would be poor for image formation. See the next two figures for some possible fixes.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARGENT QUITO

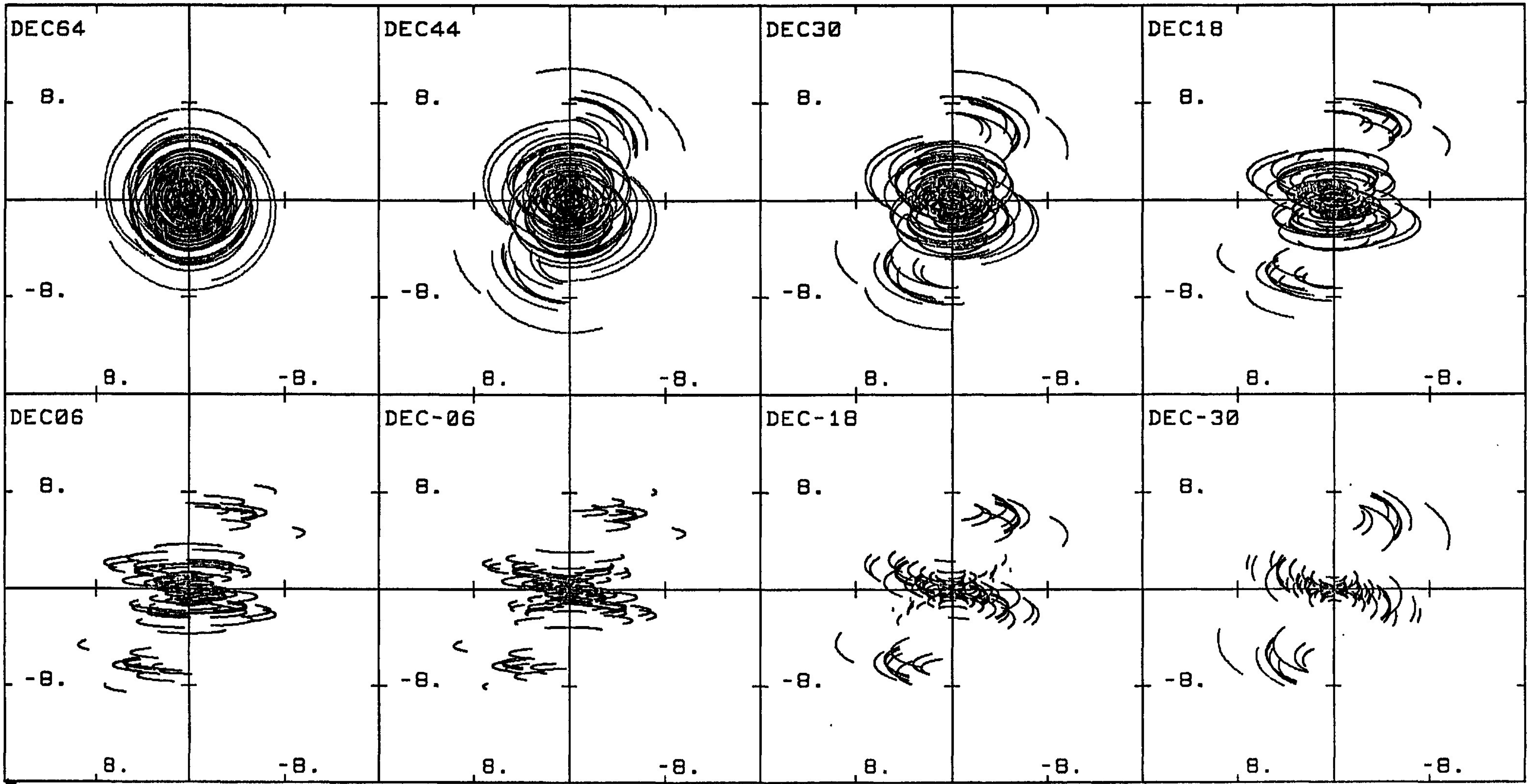
Figure IV-9: For this figure, a station in Quito, Equador has been added to the array of Figure IV-8. Much of the big north-south gap has been filled. The major hole is in the northwest and southeast quadrants. This is the result of the eastern location of South America and shows why Easter Island is preferred. The holes might be filled by another southern station in the Pacific, perhaps at an easily accessable site such as Samoa, Fiji, or Tahiti or perhaps at some U. S. military base. Australia may be too far west although it would help.



Scale Maximum 16,000 km.

KAUAI HILO SPKN TUSCNE VLASW LRDO IOWA BANGOR ARECIBO PUEBLO ARGENT QUITO

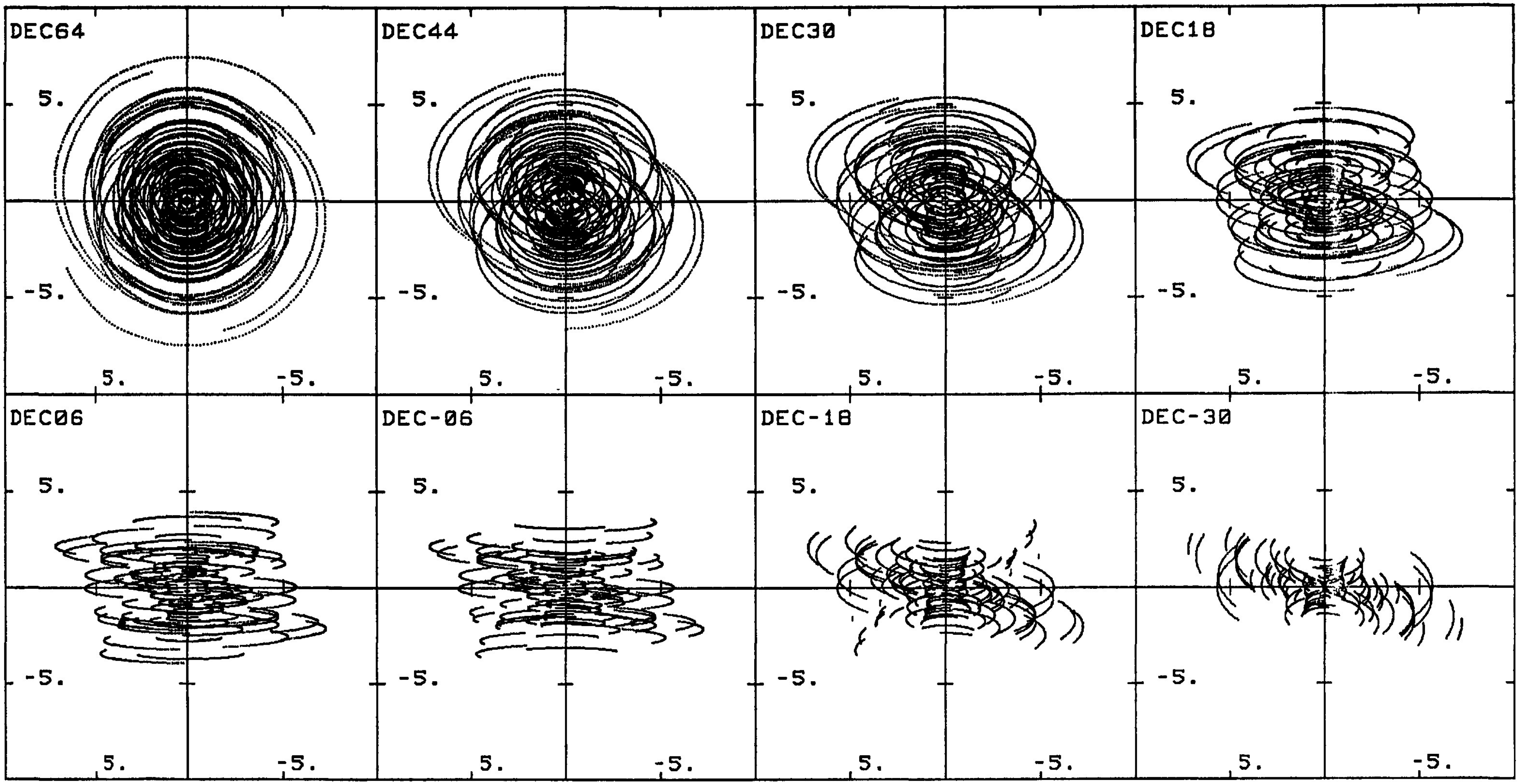
Figure IV-10: This shows the coverage of a U.S. 10 station array that includes Arecibo (the array of Figure II-4) with Quito and Argentina added. The east-west gaps seen in the last figure, which are related to the similar gaps in Figure IV-3, are gone showing that the major problem with South American sites is the missing quadrants.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ITA

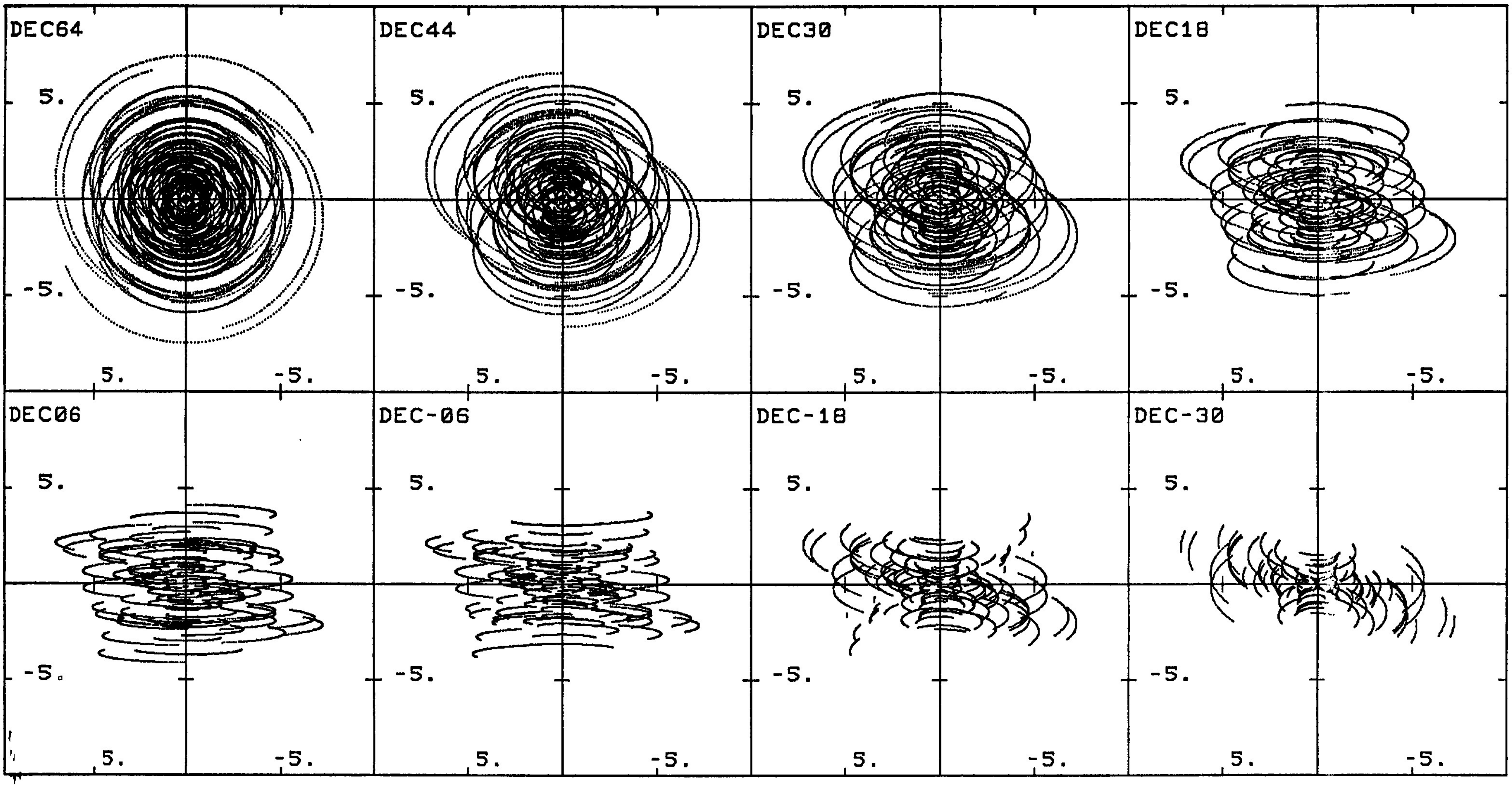
Figure IV-11: The coverage of Array D2 plus an antenna at the observatory at Itapatinga in Brazil. VLBI experiments have already been done to this station. The coverage has the same problems and advantages as the coverages for the station in Argentina. The observatory is farther east than the Argentina site so the problem with the missing quadrant is worse. However, the presence of local, interested personel and possible support make these sites worth considering for antennas that might be used with the array, although probably not for one of the original 10.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 MEXDF

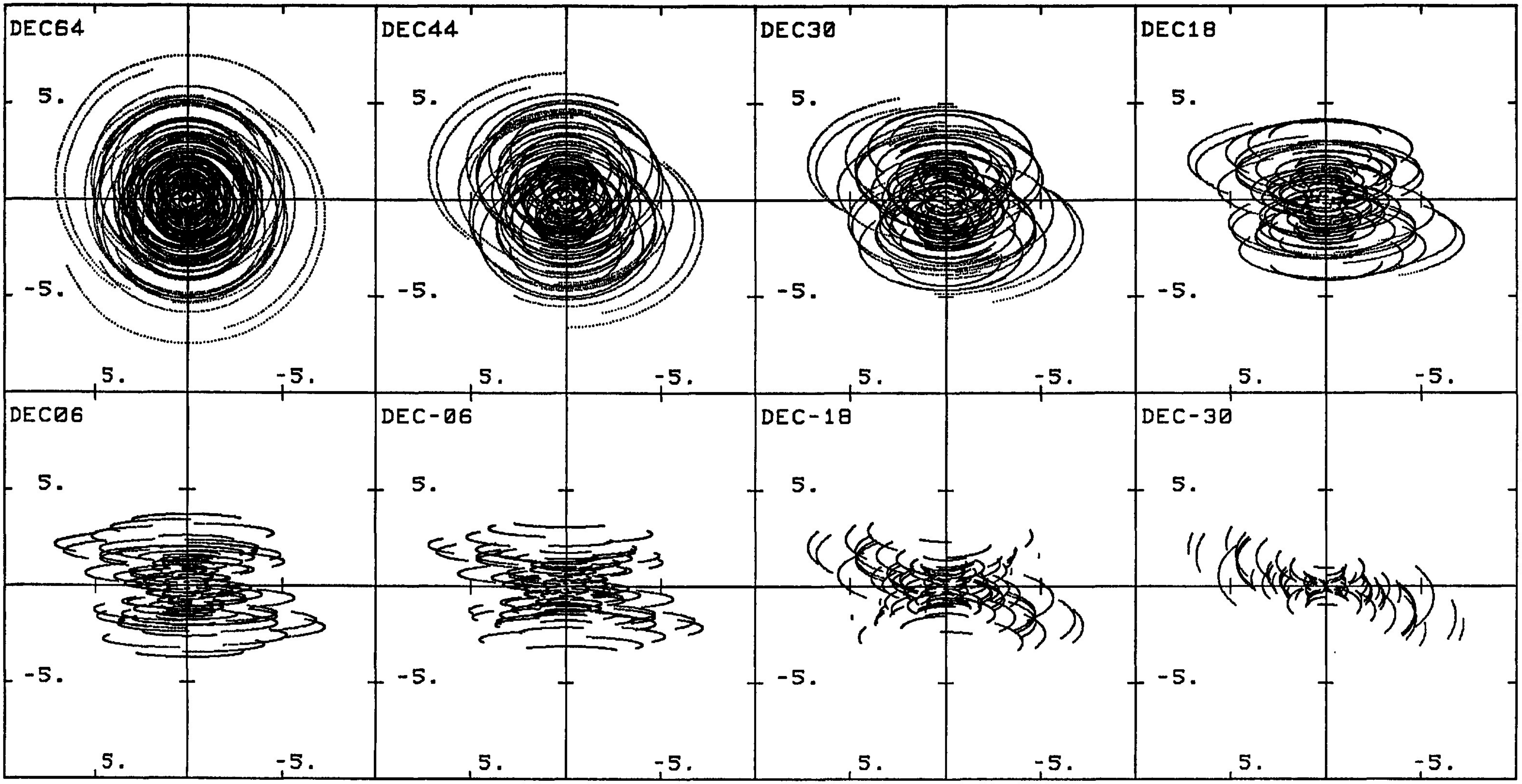
Figure V-1: The coverage of Array D2 plus a station in Mexico City. A Mexico site adds to the north-south coverage at low declinations and adds intermediate spacings. As discussed in the caption of Figure II-8, a Mexico site could have significant advantages as one of the original 10.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ACAPUL

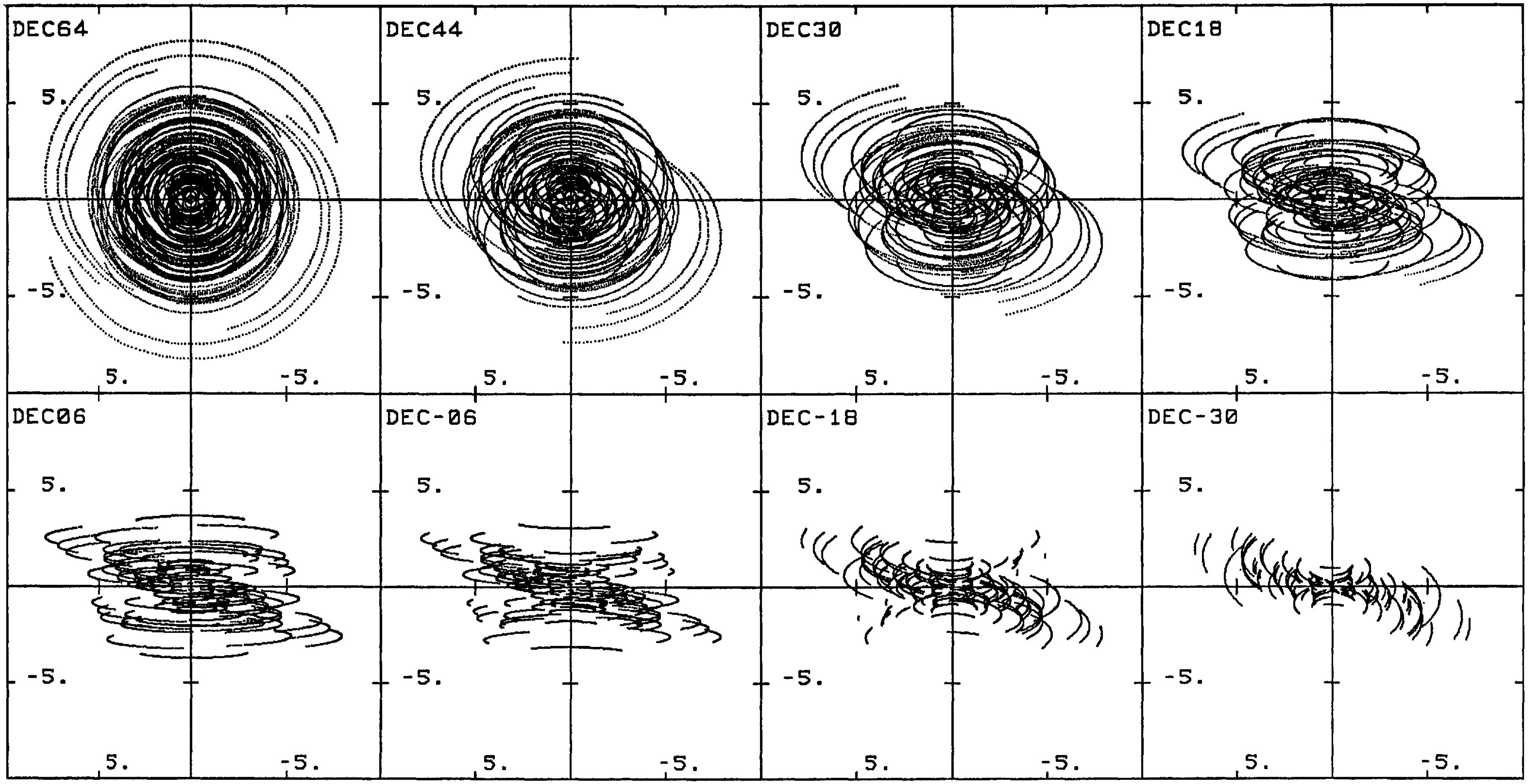
Figure V-2: The coverage of Array D2 plus a station in Acapulco. Acapulco is about as far south as one can get in Mexico and it has good transportation so it is attractive as a site although it is not a great deal from different from Mexico City.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 EDMT

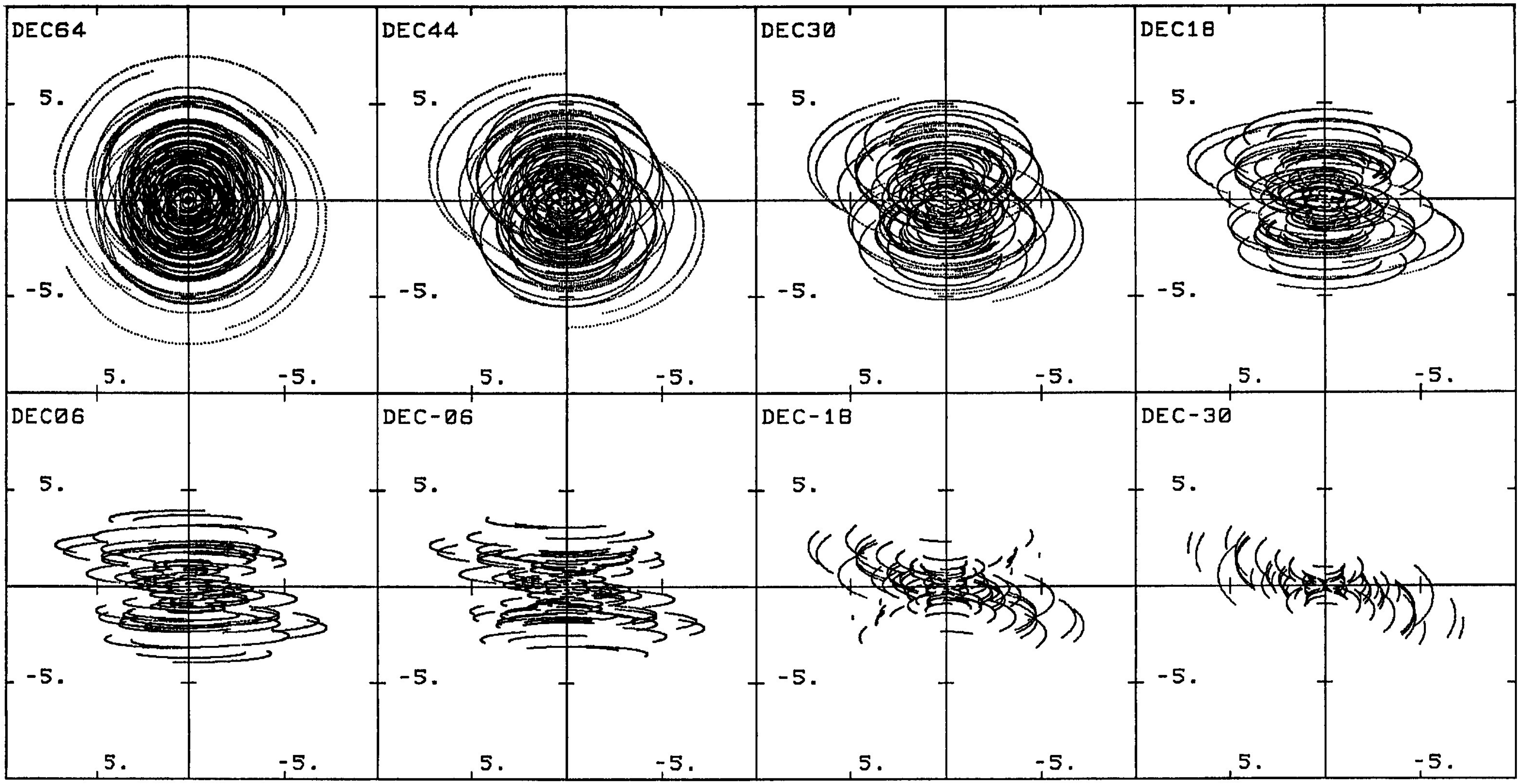
Figure V-3: The coverage of Array D2 plus a station in Edmonton, Alberta. Edmonton is one of the most northern, large population centers in Canada although it is not all that far north of the U.S. border. Any stations significantly north of the border add to the north-south coverage. Use of Canada has the advantage of the presence of interested Canadian astronomers and large pool of trained technicians. However, the Canadians have their own array project and the politics of cooperation on a formal level are not clear at this time. At the level of individual scientists and engineers, there is much ongoing communication and cooperation.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 NEWF

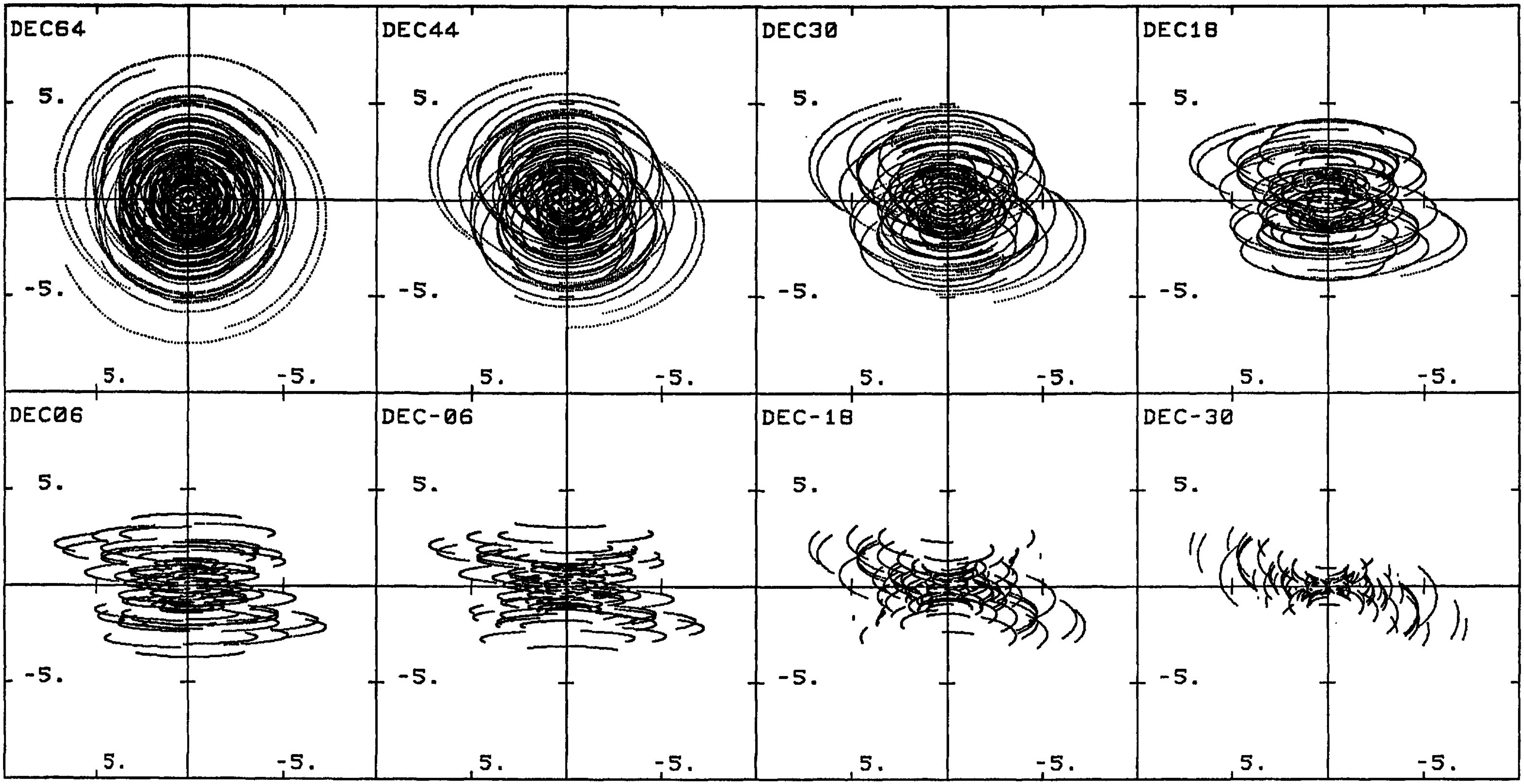
Figure V-4: The coverage of Array D2 plus a station in Newfoundland. This station mostly adds to the east-west coverage of a U.S. array. It would also add to the north-south coverage if a Puerto Rico site were included in the VLBA.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 YELKNF

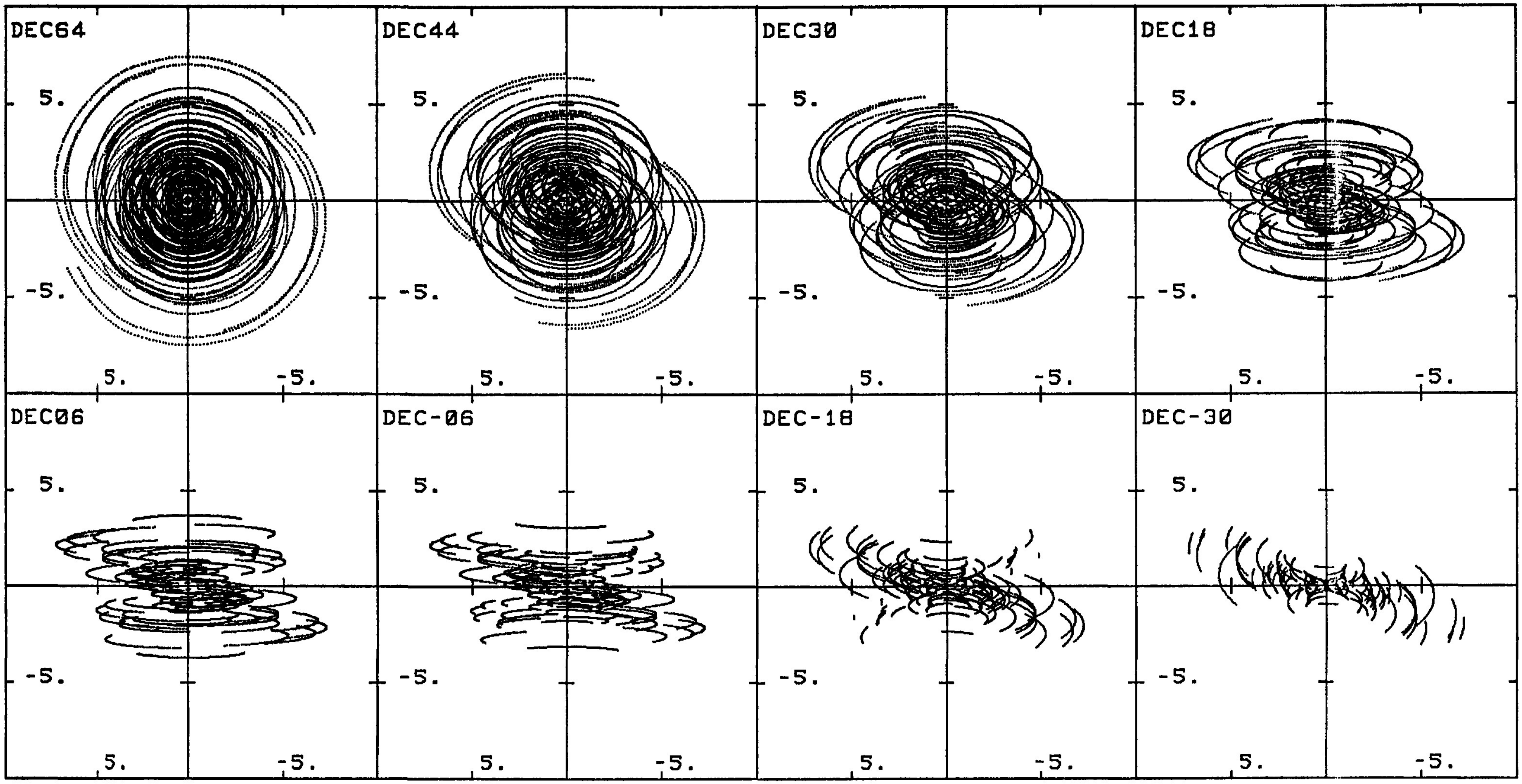
Figure V-5: The coverage of Array D2 plus a station in Yellowknife, Northwest Territories. This station is about as far north as one can go in Canada and have regular transportation and a local infrastructure of technical support. The Canadian VLB array will probably have a station in Yellowknife at the urging of the geophysicists. There is a large geophysics station in the area that could provide local support. A station this far north in Canada would make an Alaskan station unnecessary.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 PENT

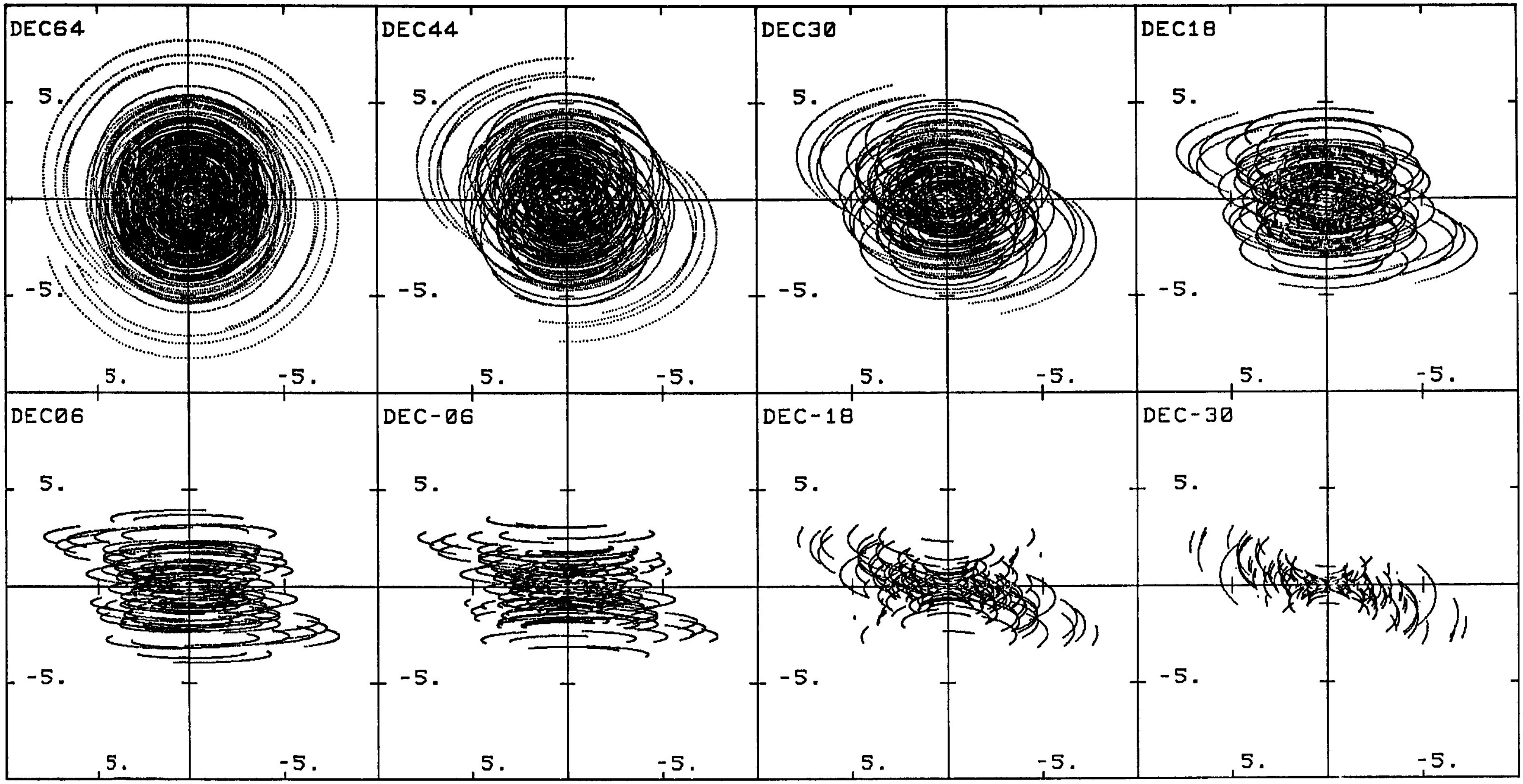
Figure V-6: The coverage of Array D2 plus a station at the radio astronomy observatory in Penticton, British Columbia. This station does not add significantly to the north-south coverage of the array because it is near the U. S. border as are most of the sites in the proposed Canadian VLB Array. However it is a developed site with local support that would make sense in a cooperative effort as long as the rest of the configuration is compatible with a Northwest station. The existing antenna at Penticton has been used for VLBI in Canada and could be used with the array at low frequencies.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARO

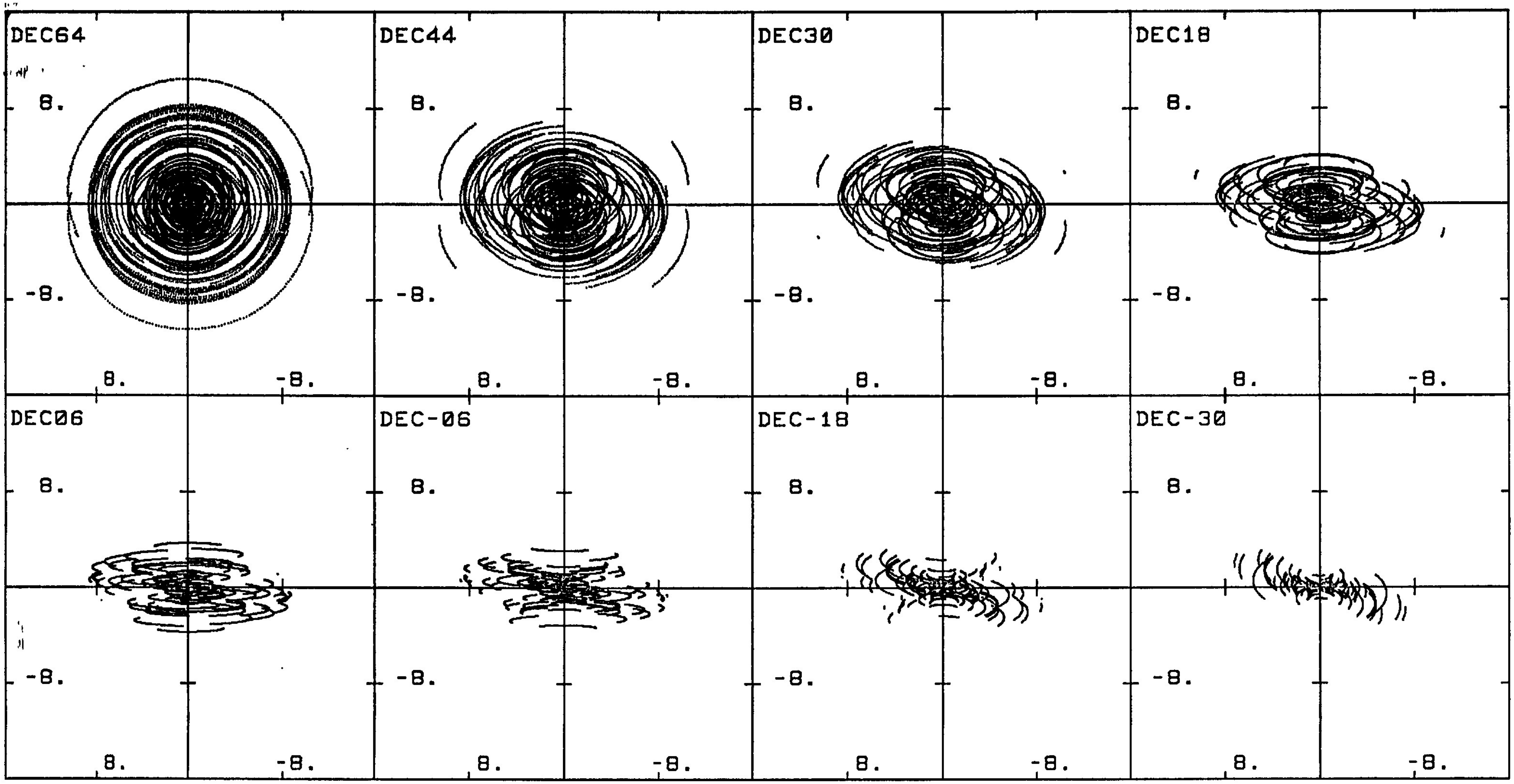
Figure V-7: The coverage of Array D2 plus a station at the Algonquin Radio Observatory. The same comments made for Penticton in Figure V-6 apply to Algonquin except that the existing antenna works up to 22 GHz and may work at much higher frequencies by the time the VLBA is built so it would make a good observatory for occasional experiments that require extra antennas.



Scale Maximum 10,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 ARO NEWF YELKNF PENT

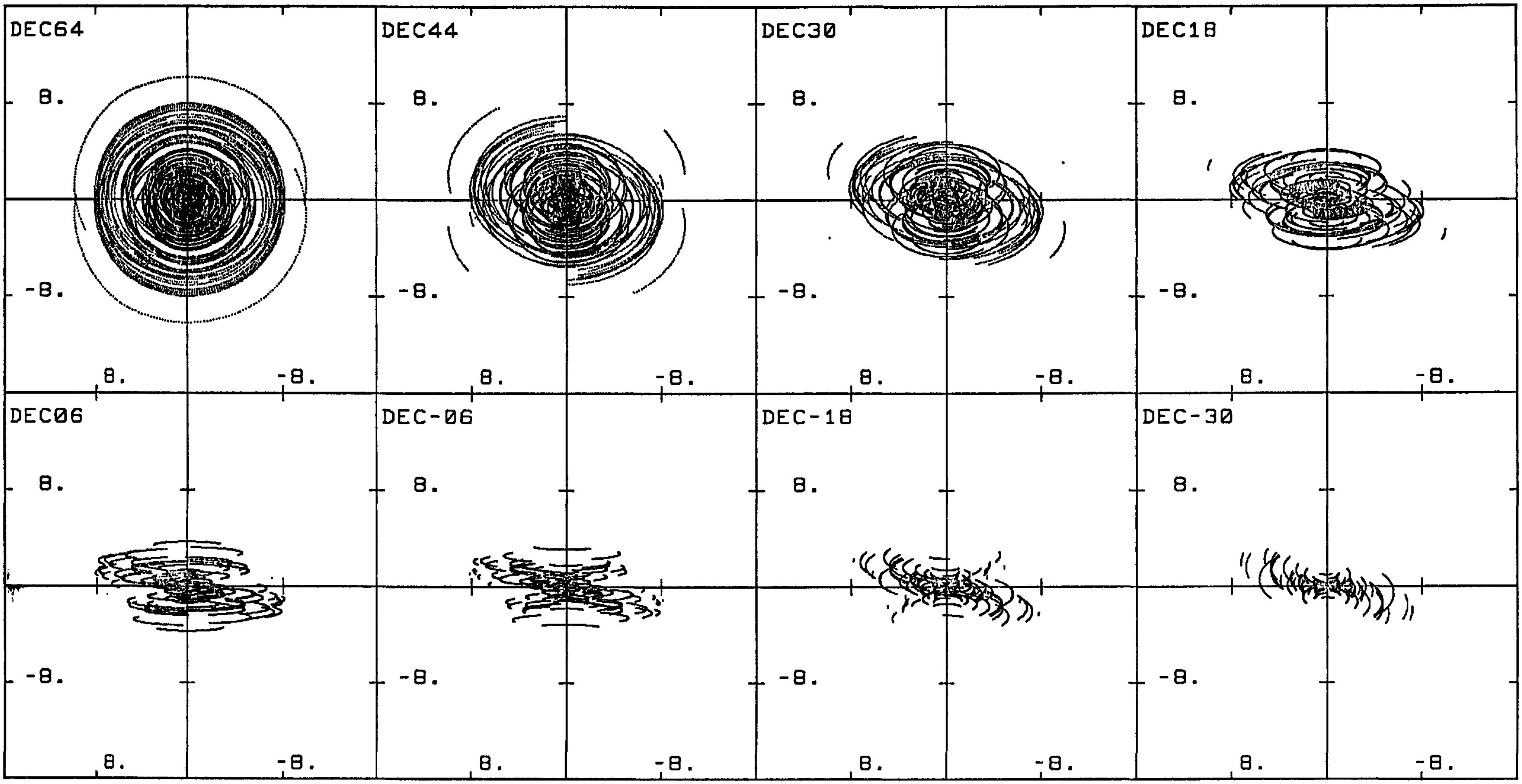
Figure V-8: The coverage of Array D2 plus the four stations shown in the last four figures - Newfoundland, Algonquin, Yellowknife, and Penticton. The main effect is to increase the density of tracks which will lead to much improved dynamic range of the maps that are made with all of these stations. The coverage shown here will be similar to the coverage that would be provided be combined observations with the proposed Canadian VLB array and the VLBA except that four additional stations would be added. The additional stations would provide short and intermediate baselines as the configuration shown includes sites near the ends of the CLBA. See Figure V-15.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 BGNA

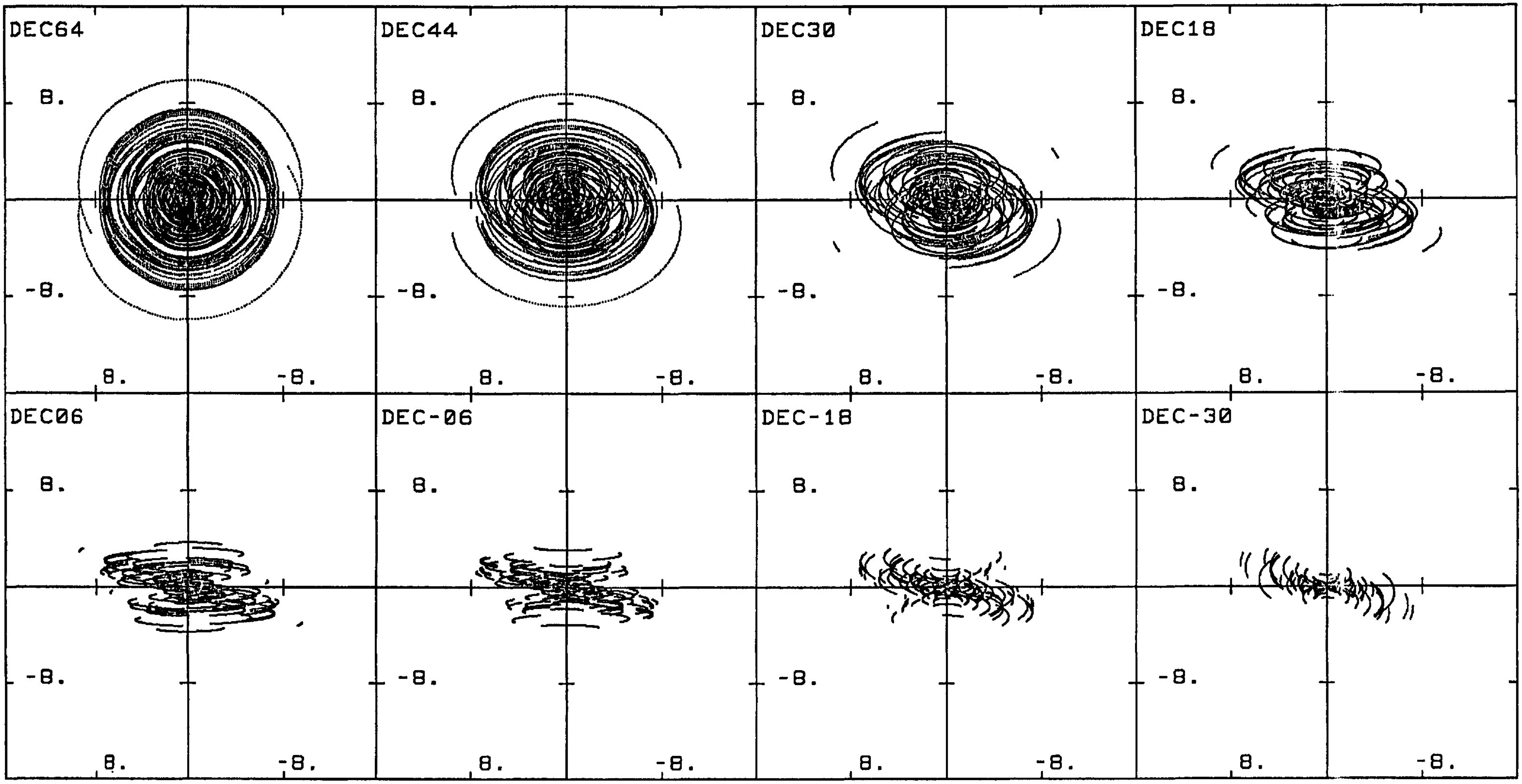
Figure V-9: The coverage of Array D2 plus a station in Bologna, Italy where a dedicated VLB antenna is currently under construction. This station has the advantage that is will be an existing, dedicated VLBI facility, but it shares the problems of all European stations - high latitude and low mutual visibility with U.S. sites for low declination sources.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 BONN

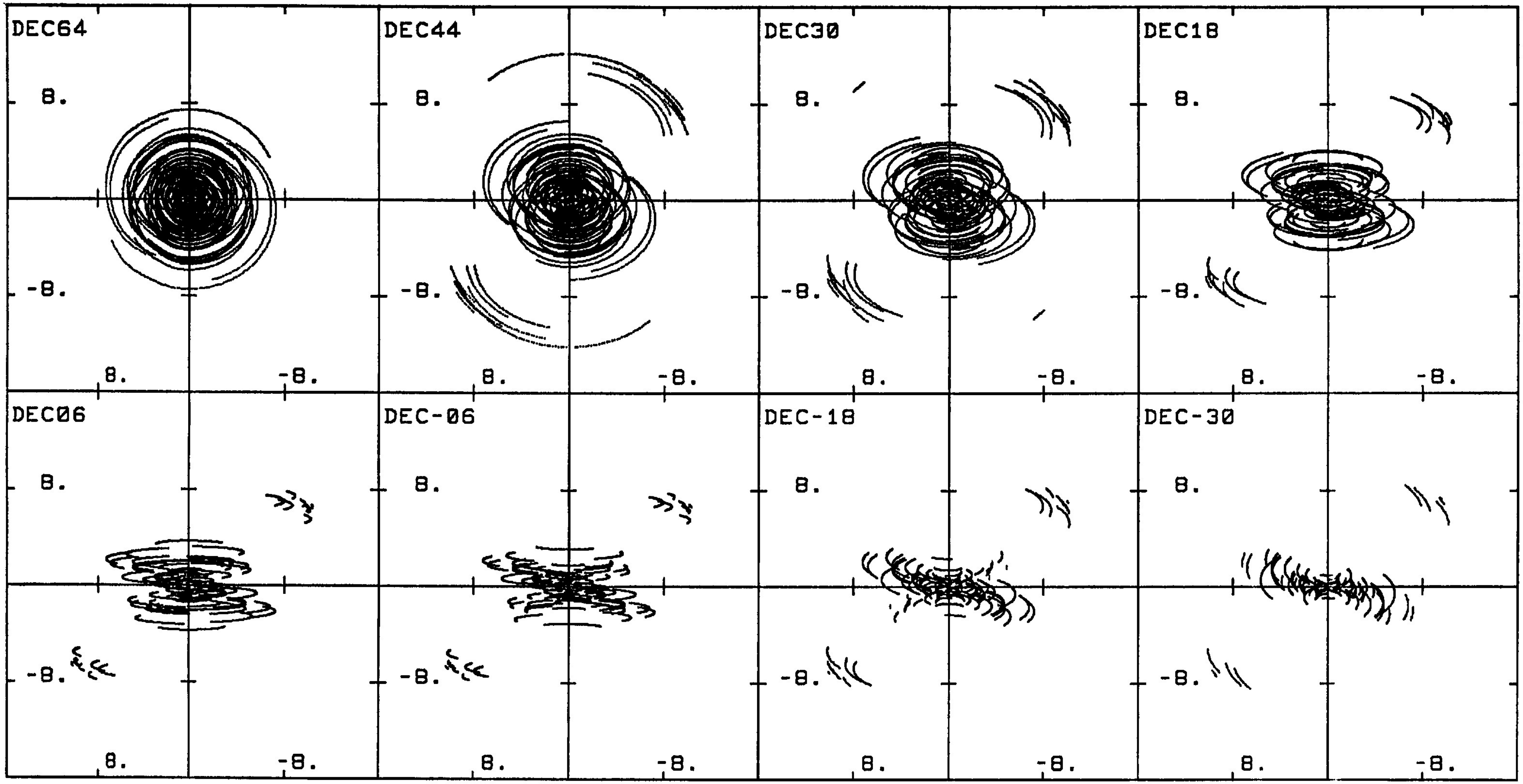
Figure V-10: The coverage of Array D2 plus a station at Bonn, West Germany where the worlds largest fully steerable antenna is now located. Observations with Bonn are hampered by the problems with Europe that have been mentioned but will be valuable, especially for high declination sources, because of the great sensitivity of the Bonn antenna.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 JODRELL

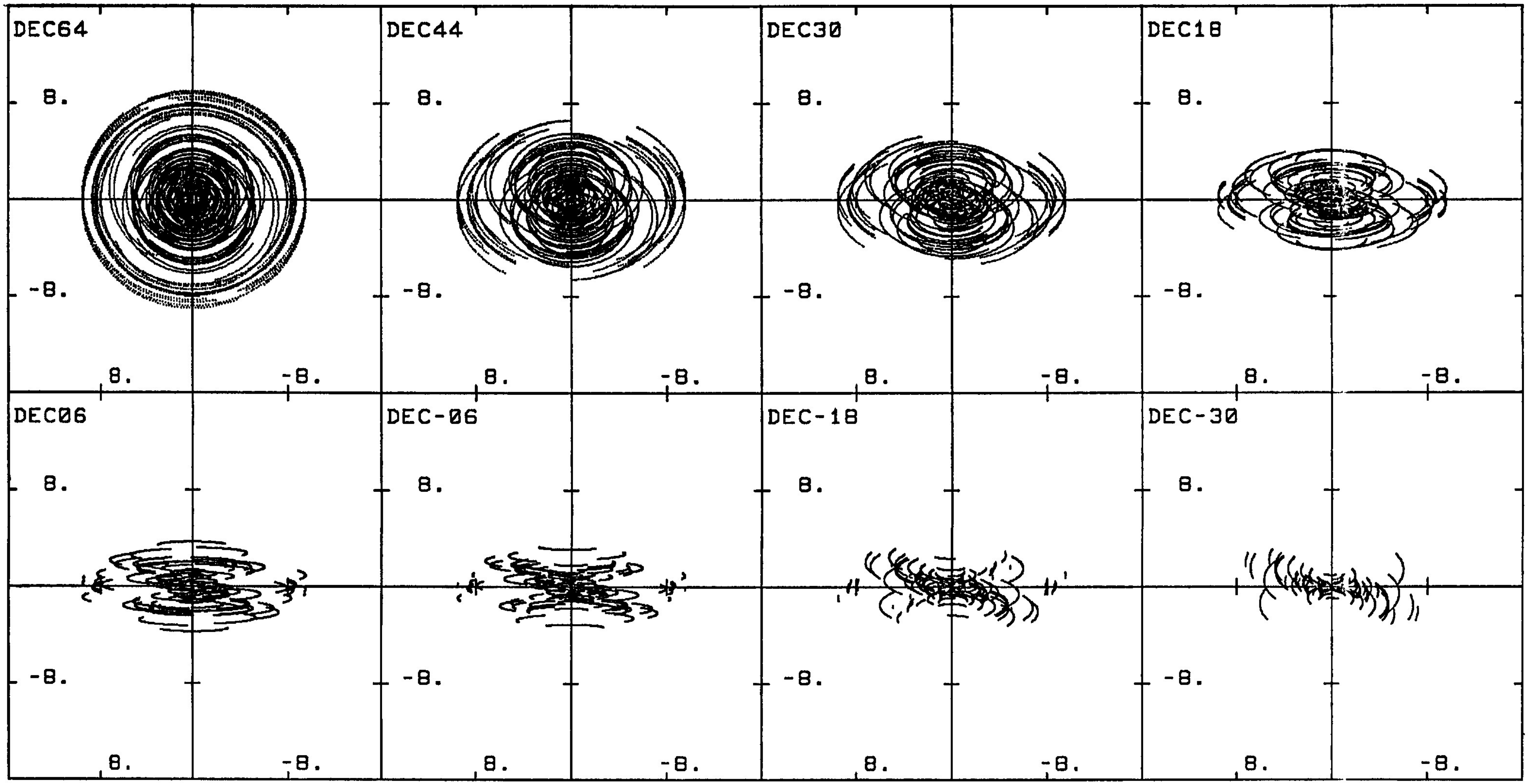
Figure V-11: The coverage of Array D2 plus a station at Jodrell Bank, England where there are several existing telescopes and the headquarters of the Multi-Telescope-Ratio-Linked-Interferometer (MTRLI) which is the major instrument capable of filling the gap in spacings between the VLA and the VLBA.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 SAFR

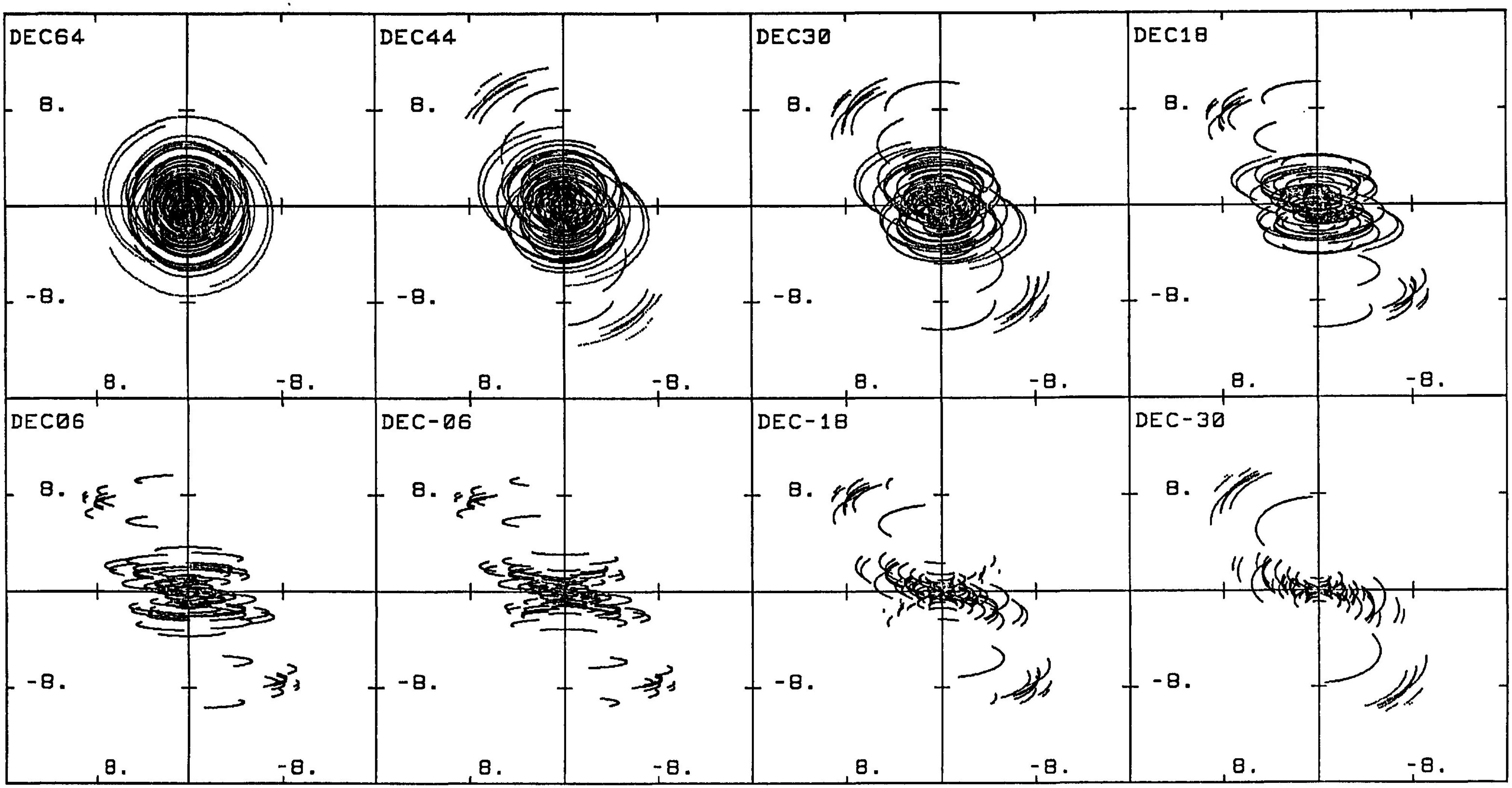
Figure V-12: The coverage of Array D2 plus a station in South Africa where there is an old NASA tracking station which is now used by the South Africans for radio astronomy, including VLBI. South Africa is so far from the U. S. that the tracks are short and there is a huge gap between the South African tracks and the tracks from stations in the VLBA. For this station to be useful, several other southern and, perhaps, European stations would be needed in order to obtain more uniform coverage.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 TOKYO

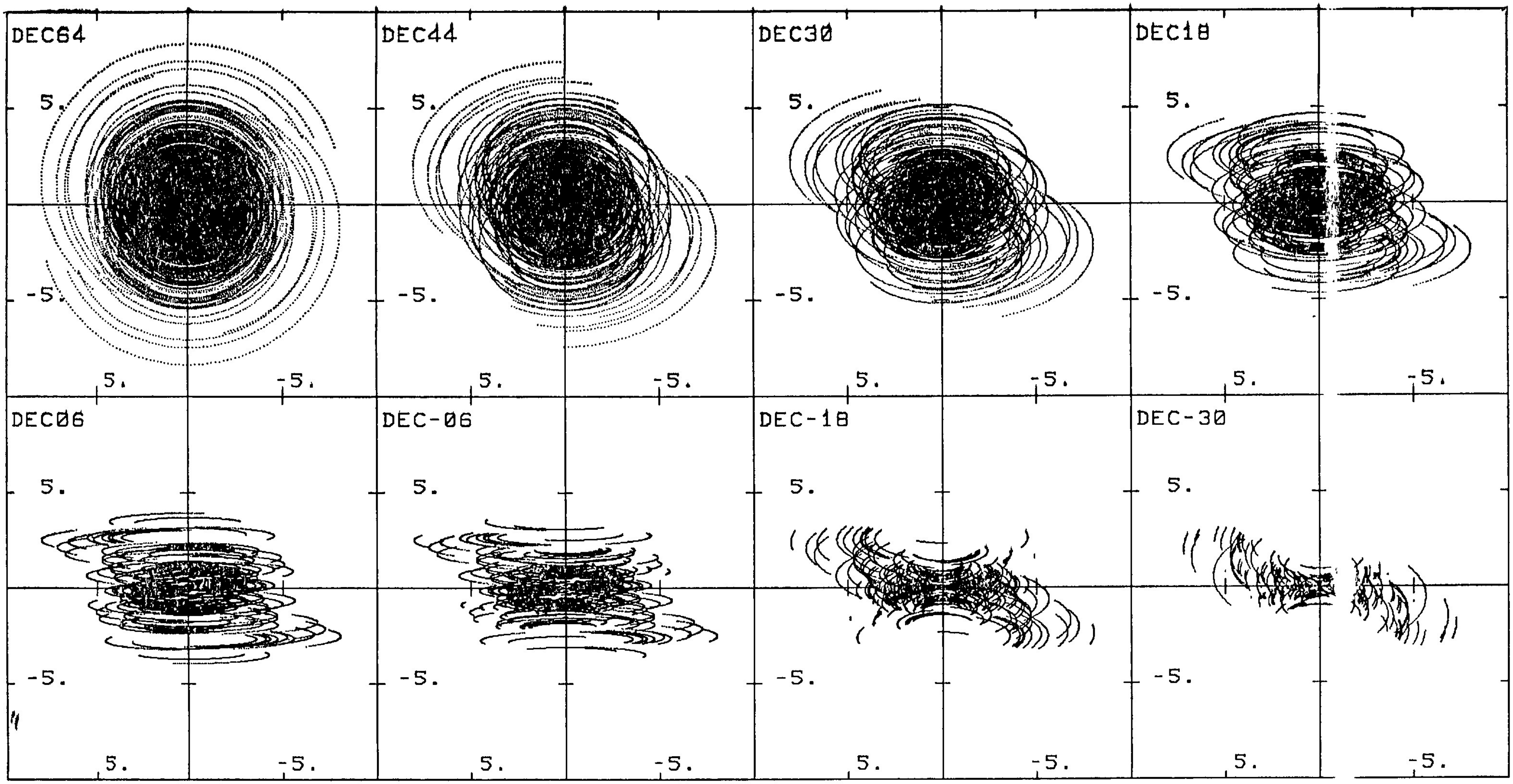
Figure V-13: The coverage of Array D2 plus a station in Japan. Japan provides some long baselines but does not dramatically help the overall u-v coverage of the VLBA. The large longitude difference between Japan and the U. S. limits mutual visibility just as in the case for Europe. However, an array of antennas scattered among Pacific islands including Japan, Hawaii, and many others plus western U.S. sites can provide very interesting coverage - much like that shown in Figure IV-7 for an array including southern stations.



Scale Maximum 16,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 DSS43

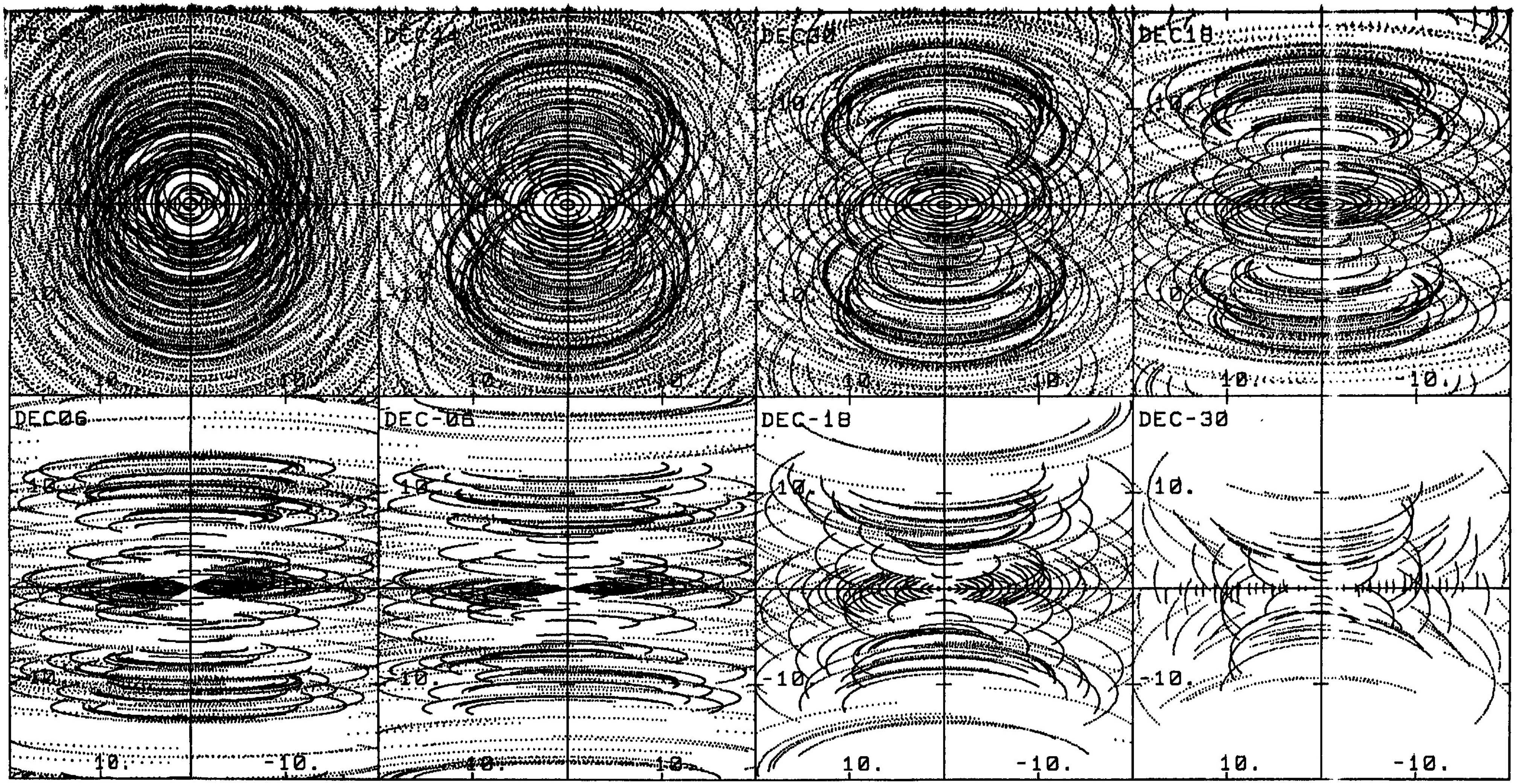
Figure V-14: The coverage of Array D2 plus a station at Tidbinbilla in Australia where NASA's Deep Space Network tracking station is located. The coverage provided by other Australian stations is similar. Australia is too far from the U.S. to provide good coverage without intermediate stations.



Scale Maximum 10,000 km.

PENT LETH MHAT SASK WEYB ATIK ARO COME YELKNF HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK NRAO HSTK

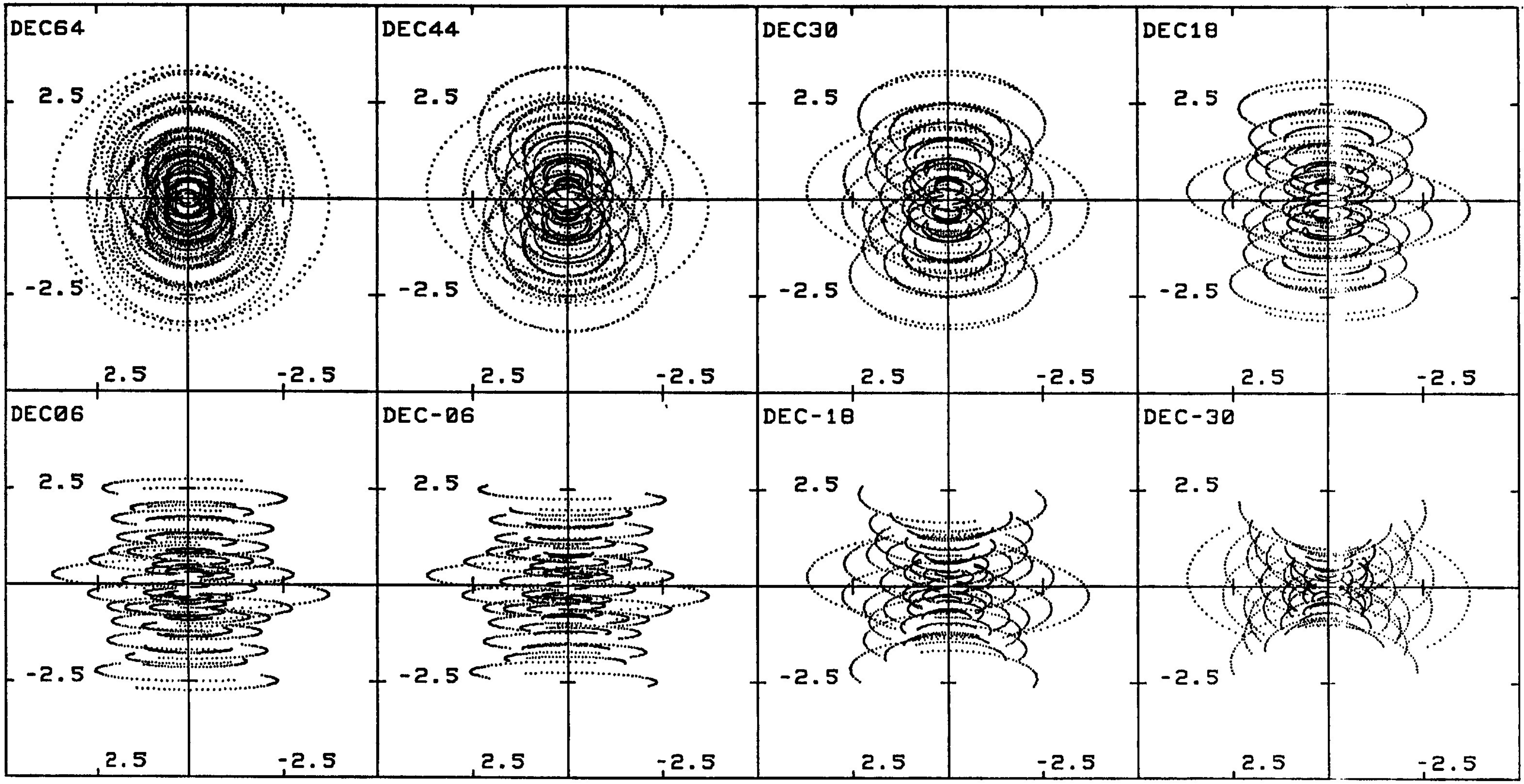
Figure V-15: The coverage of the Array D2 plus the proposed Canadian Long Baseline Array (CLBA). The CLBA has eight stations in a linear east-west configuration across Canada plus a ninth station in Yellowknife, primarily for geodedic observations. Note the great increase in the density of u-v tracks when the number of stations is nearly doubled. The number of baselines has gone up by nearly a factor of four. With the increased number of tracks, the dynamic range of maps made using both arrays will be very good. The overall boundaries of the u-v coverage of the combined array are similar to those of Array D2 alone since the CLBA does not add stations significantly outside the boundaries of Array D2. The range of spacings is increased because the CLBA has a shorter minimum spacing than Array D2.



Scale Maximum 2,000 km.

PENT LETH MHAT SASK WEYB ATIK ARO COME YELKNF HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK

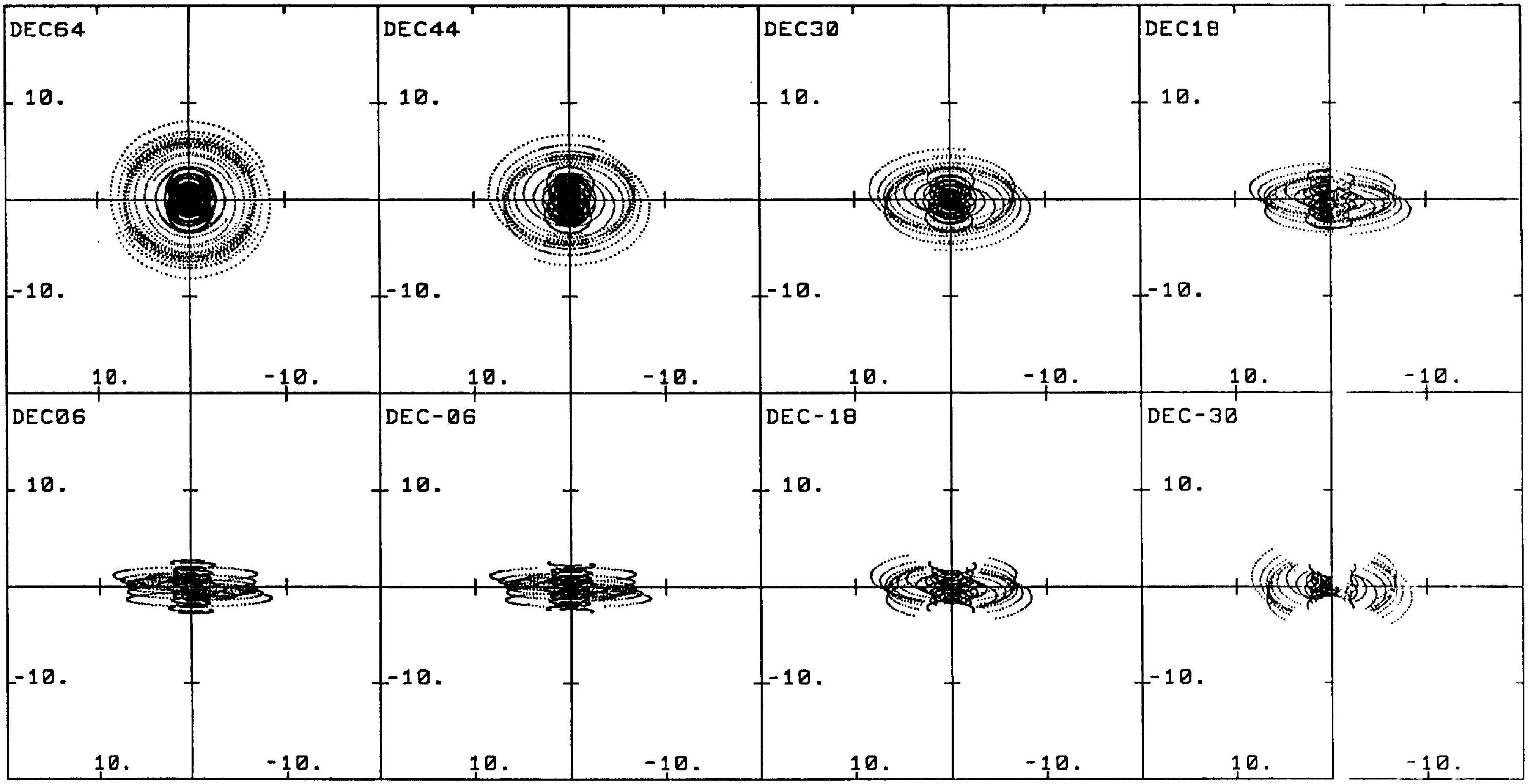
Figure V-16: The inner 2000 km of the coverage of the Array D2 plus the CLBA. Note the high density of tracks. Maps made from such coverage will begin to approach maps from the VLA in dynamic range although the VLA still has 8 more antennas than the combined VLB arrays so they still won't be as good.



Scale Maximum 50 km.

AE3 AE6 AE9 AN3 AN6 AN9 AW3 AW6 AW9

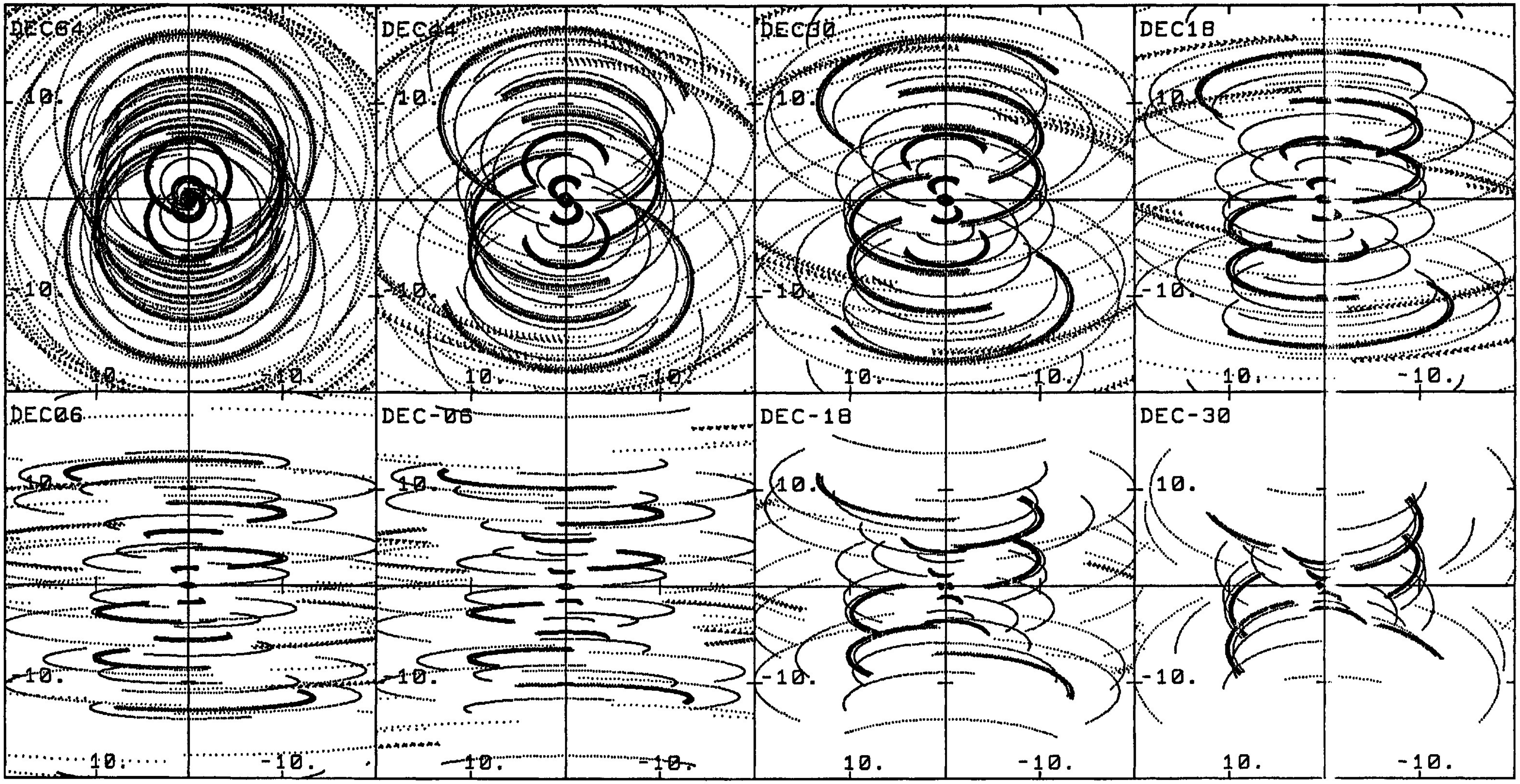
Figure VI-1: The coverage of the VLA in the A array with a scale going to 50 km. Only the tracks of every third element are shown so the overall shape and uniformity of the coverage is representative of what is normally obtained with the VLA but the density of tracks is very much lower than what is actually obtained with all 27 antennas. As can be seen, there are clear advantages in not having the geographically imposed constraints that affect the VLBA.



Scale Maximum 200 km.

AE3 AE6 AE9 AN3 AN6 AN9 AW3 AW6 AW9 SOCORRO

Figure VI-2: The coverage of the same 9 VLA antennas of Figure VI-1 plus the Socorro VLBA antenna. This may be a common observing mode for extended resolution observations with the VLA. While such observations are made, one or more of the VLA's 27 antennas could be used to replace the Socorro antenna for the ongoing VLBA observations.



Scale Maximum 2,000 km.

HAWAII ANCH OVRO SOCORRO LASL BLDR GRFK2 NRAO HSTK BRVL2 AE9 AW9 AN9 AE3 AW3

Figure VI-3: The coverage out to 2000 km of Array D2 plus 5 antennas of the VLA, including the end antennas of each arm in the A configuration. The VLA plus Socorro coverage shown in Fig. VI-2 is only the dark area at the very center. There is a range of spacings arround 100-200 km that is poorly sampled.