NATIONAL RADIO ASTRONOMY OBSERVATORY

Charlottesville, Virginia

VLA INTERIM REPORT

May 10, 1968

I. SUMMARY

This report summarizes work done on the VLA since issuance of the VLA proposal in January, 1967. More detailed design information is given in the various internal reports which are appended. The present stage of basic design and feasibility studies should be completed by December, 1968, at which time a final report will be prepared. Feasibility of the concept and of critical elements of the design have now been demonstrated, and prototypes of many of the critical components have been built and tested. With the single exception of the antenna element itself, basic design, prototyping and testing will be complete by December.

The next phase in development of the VLA, detailed design, selection of specific components and engineering of the system, is intimately tied to actual construction of the system, and should not precede it by a long--or indefinite--period of time. Therefore continued extensive work after about next December should be contingent on approval of the project and a reasonable expectation that it can be funded in the near future.

The scientific need for the VLA remains as urgent as it was a year ago--or, if anything, more urgent. Studies of the structure and physics of extragalactic sources, and of their distribution in space; the detection of complex structure in weak "normal" galaxies; the detection of radio fine structure in H II regions and other galactic sources; the detection of polarization fine structure in sources--

these and other recent investigations all emphasize the need for a high resolution, high sensitivity, pencil beam instrument like the VLA, which is also fast enough to acquire the needed data on a reasonable time scale. The extragalactic radio sources--quasars and galaxies--remain as one of the more fundamental and challenging problems of the physical world, and their further study is up against a fundamental limitation in resolution and sensitivity which only a VLA can overcome.

With the basic design and concept of the VLA remaining as described in the VLA proposal, work during the past year has concentrated on further refinement and analysis of some of the basic elements of the array--configuration, side lobe levels, atmospheric effects--and on the design and prototyping of critical electronic systems--IF transmission, local oscillator, delay lines.

II. CONFIGURATION, SIDE LOBES

1. Configuration Studies

The work done during the period under review can be divided into four categories:

(i) Further work has been done using the empirical approach on the lines of the work described in the VLA Proposal. Various distributions of elements along the arms of the Wye were studied. It was felt that although better distributions could be found for specific source declinations, the supplemented Wye was still the overall best configuration. The effect of antenna failure was investigated and found to be small for failure of one antenna out of 36. These results are summarized in VLA Scientific Memorandum No. 7.

(ii) A detailed study was made of the performance of linear correlator arrays. In the supersynthesis mode such arrays have very good performance in a limited declination range. This study has given a good understanding of the working of correlator arrays and has pointed out the limitations of linear arrays. The results are summarized in VLA Scientific Memoranda Nos. 4 and 10.

(iii) The use of complementary arrays has been considered. The required number of antennas can be substantially reduced if the source is observed twice with two different configurations. By superimposing the transfer functions of the two array configurations, a well-filled transfer function can be obtained. However, the total time required per source is greatly increased both because two observations are needed and because of the time expended in changing the configuration, calibration, etc. It was found empirically that 24 antennas used in complementary array configurations could produce a beam pattern comparable to that produced by 36 antennas in a single observation. The results are given in VLA Scientific Memorandum No. 5.

(iv) A new technique for finding an "optimum" configuration using the computer has been developed. This technique, termed Psuedo-Dynamic Programming, selects the best position of an antenna from a given set of possible positions. Thus by using the best configuration found by the empirical approach as the input, and using a set of pre-specified positions as the possible antenna locations, the computer keeps improving the configuration until an optimum configuration is found. A computer program using this technique is now operational. The details of the technique and some results are given in Appendix 1.

2. Side Lobes

Side lobes of the array pattern due to the array configuration itself were discussed in the VLA Proposal. There are other sources of side lobes as well, including those due to antenna surface inaccuracy, atmospheric phase fluctuations, system phase calibration errors, and system phase stability. These have been investigated in some detail, and some results are given in Appendix 2 and VLA Scientific Memorandum No. 6. The general conclusion is that the near side lobes due to "holes" in the uv plane coverage are dominant. Other sources of side lobes can be readily controlled or are negligible compared with the near side lobes, except in a few special circumstances.

III. ATMOSPHERIC EFFECTS

It has been recognized since the beginning of the VLA study that the ultimate limitation on the resolution that can be achieved by such an instrument is established by the inhomogeneous atmosphere. It has also been apparent that certain sites and certain climatic regimes must be better than others and that serious study is needed in order to establish the relationships between climate and VLA performance.

That one-second-of-arc resolution can be achieved is indicated by a variety of evidence, and especially by experience at Green Bank with interferometer baselines yielding fringe periods as short as 2 arc-seconds. Even though the Green Bank climate is far from ideal the fringe stability is good enough to show that extrapolation to 1-second resolution is feasible, especially under better climatic conditions. However, it has always been recognized that an experimental demonstration of 1-second resolution, with adequate phase stability, is needed before a large economic commitment is made to the VLA project.

Serious work on the VLA conceptual design was begun in the fall of 1964, at the same time that the 2-element interferometer came into operation at Green Bank. Simultaneously, planning was begun on an experiment to demonstrate that resolution of one second was possible, even at Green Bank. This experiment has since come to be known as the "42 foot project". The first requirement was a method of transmitting a precise, local-oscillator phase-reference over a baseline long enough to produce 1-second interferometer fringes, at least 22 km in this case. A microwave-link system was indicated, with provision for compensating for atmospherically-induced phase-shifts between the ends of the baselines. The Bureau of Standards (now ESSA) Boulder Laboratories had developed an effective method of measuring the effective length in wavelengths of a tropospheric propagation path. Under contract with NRAO in 1965 they demonstrated that the path-length in wavelengths could be kept constant by insertion of an adjustable phase-shifter controlled by the phase-measuring system. This phase-reference transmission system was demonstrated in Boulder, Colorado over a 15 km path. Subsequently, a system was engineered and produced by Cutler-Hammer Inc. for use at Green Bank. It maintains phase synchronism at both ends of a 12 km baseline to within a couple of degrees.

A portable antenna was also needed to permit measurements at various baseline lengths. Mr. Neil Stafford of San Jose, California designed a portable, paraboloidal antenna 42 feet in diameter, which was built by Peninsula Steel Corp., also of San Jose. This antenna has a polar mount and can track a source at the sidereal rate for five hours. It is presently operating at a site 13 km north of Green Bank, giving a fringe period of two arc-seconds when used as an interferometer with one of the 85-foot antennas. This system has been operated intermittently since November, 1967, with excellent results.

The phase stability is currently being evaluated quantitatively. At present it is possible to say that the phase stability over the 2-second baseline is excellent, though there appears to be somewhat higher scatter than is experienced on the shorter baselines of the 3-element interferometer. The 42-foot system is presently used regularly in conjunction with the 3-element interferometer in astronomical research. It is the longest existing phase-synchronous interferometer, that is, one capable of measuring source positions and of producing data for aperture synthesis.

The 42-foot antenna will be kept at its present site until July 1968, when it will be moved to a position 40 km from the 85-foot antennas. This baseline will produce fringe periods as short as 0.5 arc second.

In order to evaluate atmospheric phase effects at possible VLA sites, the phase stabilities of existing baselines (including the 13 km one) at Green Bank are compared with the gross meteorological parameters (wind, temperature, pressure, humidity and frontal activity). These parameters are relatively easy to determine for the sites, resulting in an indirect appraisal of their suitability for the VLA.

It is known that the refractivity of the air depends mainly upon the water vapor content, so that the inhomogeneous distribution of water vapor is responsible for the atmospherically-induced fluctuation of interferometer phase. Water vapor content can be measured easily and economically by measuring the absorption by the atmosphere of infrared radiation from the sun. To first order, the fluctuating component of phase difference between the ends of a baseline must be proportional to total water vapor content. Therefore infrared hygrometers have been operated for nearly two years on three possible VLA sites in the Southwest in order to determine total water vapor content. The results to date are:

Station No.	Altitude	Average Water Vapor Content Summer 1967	Annual, 1967
Y-15	7000 ft	.68 cm	.44 cm
Y-27	4800 ft	1.25 cm	.72 cm
Y-23	2800 ft	1.57 cm	.83 cm

It is seen that the average total water vapor content decreases monotonically with increasing altitude, confirming earlier measurements published in the VLA proposal.

Six additional infrared hygrometers have been constructed for use at Green Bank and at the Southwestern sites. The Green Bank instruments are being operated in such a manner that total water-vapor content and differential content between two ends of a radio-interferometer can be determined as a function of time. These measurements are compared with the fluctuations in the radio-interferometer phases. The quantitative comparisons are being evaluated; there appears to be a significant correlation between fluctuations in infrared hygrometer readings and radio-interferometer phase. Infrared hygrometers and associated recording equipment will shortly be operated at the Southwestern sites in rotation in order to measure differential water-vapor fluctuations at each site. In this way the relative quality of each site may be established. The hygrometers will be operated through the coming summer, which is expected to be the worst season for VLA operation.

IV. ELECTRONICS

A system design for the VLA electronics system is presented in the VLA proposal. This design was based on internal studies and a design study contract with ITT Federal Laboratories.

Between March, 1967 and the present time we have attempted to prototype the critical portions of the system in order to test the system feasibility. This phase of the project should be complete by January, 1969. We then plan to perform the final prototyping where much attention will be paid to the problems of packaging, monitoring, and reliability.

The present status of the various subsystems is as follows:

Local-Oscillator System

A portion of the local oscillator system, almost exactly as described in the VLA proposal, has been constructed under contract with the University of Virginia. Construction was completed in November, 1967 and the system has been tested since that time.

The system, without any modifications, operates very well and is certainly feasible for use in the VLA system. Some of the initial tests are documented in VLA Electronics Memorandum No. 8. The phase stability of the system is approximately 1° phase change per °C temperature change; this is entirely adequate.

At the present time some further tests are being made and a lobe rotation system is being incorporated into the design. Some possible improvements in the system are also being examined. A final report is due in July, 1968.

Our future plans call for a final, manufacturing prototype of the system. This final prototype will have a great deal of attention paid to reliability, packaging, and monitoring. It should be identical to the final units used in the VLA.

IF Transmission System

The system design presented in the VLA Proposal has been examined further in VLA Electronics Memoranda Nos. 2, 5, 6 and 7. These memoranda have examined the air link vs. cable choice and the detailed problems of a cable system design. The cable system appears to be feasible and a decision was made in December, 1967 to prototype a 4.8 km segment of a 1-2 GHz cable transmission system.

At the present time we are testing critical components of the prototype transmission system. Our plans are to construct and test the system by January, 1969. A status report on the system is given in VLA Electronics Memorandum No. 9.

Variable Delay System

Proposals were solicited from twelve companies for the construction of a variable delay line suitable for use in the VLA. Responsive bids were received from Microsonics, Inc., and Andersen Laboratories.

A decision was made in September, 1967 to contract both of the above companies for construction of a manually variable delay line meeting the required radio-frequency specifications. After these lines have been completed, one company will be chosen to provide electrical control of the delay line.

Both of the manually variable lines will be completed by July 15, 1968 and it is expected that the prototype electrically variable delay line will be completed by March, 1969.

Correlator System

The correlator designs which were described in the VLA Proposal were constructed and evaluated in the summer of 1967. These results are documented in VLA Electronics Memoranda Nos. 3 and 4. A suitable design has evolved and is presently being refined. Our plans are to prototype a bank of 24 correlators by November, 1968.

Other Portions of the Electronic System

The subsystems described above have been considered to be the critical portions of the electronics system and have received most attention in the past year.

The remaining subsystems are the receiver front-ends and the monitor and control system. No changes in concept regarding these systems has occurred since the writing of the VLA Proposal.

Our present schedule calls for starting detailed design and prototyping of these systems in mid-1968.

V. ANTENNA ELEMENT

In the VLA proposal published in January 1967, a possible antenna element for the VLA was described. A study contract with the Defense Electronic Products Division of the Radio Corporation of America formed the basis of the proposed antenna element. Today, May 1968, the VLA antenna element concept remains essentially unchanged. The work during the last year has not produced anything new and better, and one is led to believe that the proposed concept is close to optimum. Only minor changes are being considered. It seems, for example, advisable to use a more sophisticated moving vehicle than proposed earlier in order to make the moving of the antenna elements between observing stations safer, smoother and more efficient. Furthermore, a study of the operational aspects of the VLA leads to the conclusion that the antenna elements must be designed for much higher reliability than one normally finds in radio telescopes in the 25 m diameter size. Maintenance of the system becomes a prime consideration, and maintenance procedures must be designed into the antennas from the beginning. Thus, the original track plan with side spurs for certain key observing stations has been abandoned. A track system with a perpendicular short cross track between the main track and the observing station, but without costly connecting switches, is now being considered. This system will leave the main tracks open for maintenance vehicles and will also permit easy replacement of any antenna element.

Even an antenna element which has been designed for high reliability will require periodic maintenance. Since it seems reasonable to assume that such preventive maintenance (painting, oil changes, gear adjustments, etc.) should take place at least once every third year, one antenna element per month must go through the maintenance program. Therefore, a rotating maintenance schedule using a spare antenna seems to be an acceptable solution to the maintenance problem.

After the publication of the VLA proposal in January 1967, an attempt was made to obtain a contract with a competent company to design a prototype antenna element based on the VLA proposal concept. Although it was recognized that one contract for both the design and building of a prototype antenna would have been more desirable from a technical point of view, inadequate funding limited the planned effort to the design only. In May 1967, a request for proposal to design the antenna element was sent to 50 comapnies. Twenty-three of these expressed interest in the project and attended a preproposal meeting in Charlottesville on June 12, 1967. Proposals for the design of the antenna were later submitted by the following five companies:

1.	Collins Radio Inc. Dallas, Texas	Proposal Price:	523-0559894-00103P 27 July 1967 $408,379
2.	LTV Electrosystems, Inc. Garland Division Dallas, Texas	Proposal Price:	416-15019 30 July 1967 $379,546
3.	Radio Corporation of America Defense Electronic Products Missile and Surface Radar Div. Moorestown, New Jersey	Proposal Price	DS 105-687-6921 28 July 1967 $595,010
4.	Rohr Corporation Antenna Division Chula Vista, California	Proposal Price:	250-3913-RDH 25 July 1967 $261,297

5. Radiation, Incorporated Melbourne, Florida — Proposal R1 391743-5-31, 28 July 1967, Price: $754,853

The cost of the proposed designs differed considerably. The differences were caused mainly by the level of effort which the various companies proposed to deliver, all considerably higher than was anticipated when the proposal request was sent out by NRAO. The highest bidder, Radiation Incorporated, proposed an antenna element quite different from the general NRAO concept, and it was judged less attractive. It is of interest to notice that the lowest bidder, Rohr Corporation, was the only company with direct experience in designing and building (in quantities) antenna elements of this general class. The other bidders were all systems and large project management companies.

Although Rohr's proposal seemed quite attractive, it was the conclusion of the evaluating team that the cost was too high. At that time it also became evident that the anticipated funding of the VLA project for FY 1968 and FY 1969 would be inadequate to permit both the antenna design and all other activities planned for the VLA project. Following the recommendations of the report of the Dicke panel, it was decided to emphasize the development of the vital and technically difficult electronic components and subsystems, and to continue the antenna element work as an in-house effort with the aid of smaller consultant-type contracts with individuals and/or companies. Accordingly, all proposals submitted for the design of the antenna element were rejected.

The in-house design effort which now is underway will result in detailed specifications of the VLA antenna element and the mobility system. The in-house effort will emphasize the following problem areas which are unique to the VLA:

I. The antenna elements will be produced in a large (36) quantity.

There are several indications that a substantial reduction in unit cost can be achieved. For example, work presently done by Rohr Corporation in this area shows that by cutting the structural members out of steel plates, more efficient use of the material can be achieved. The cutting process, developed by Rohr, adapts itself well to quantity production. Weight reductions of a 25 m parabolic reflector structure similar to that required by the VLA of 30% have been obtained.

II. The antenna elements must be movable over considerable distance.

Although it is clearly possible to move antennas of this size over a rail system as proposed in the VLA proposal, the antenna pedestal must be designed with the movability in mind. Also the replacement and indexing on the observing foundation must be considered early in the design.

III. Various interfaces.

It is of particular importance to design the interfaces between the electronic equipment and the antenna structure. Space for electronics, cables, rotary joints, encoders, etc., must be considered.

IV. Maintenance.

The maintenance of the antennas once the system is in operation is of major concern. The problem has been mentioned earlier in this report, but its importance can hardly be over-emphasized. The required reliability must be considered early in the design phase of the program. The reliability and maintenance considerations are not limited to the antenna element, but must be taken into account at an early stage for all equipment in the VLA system.

The next step in the work on the antenna element should be the manufacture, erection and evaluation of a prototype antenna, possibly erected at the Green Bank site where all laboratory facilities and staff for the evaluation are located. Part of the evaluation program will be to operate the prototype antenna together with the present Green Bank interferometer. After the evaluation is complete, the prototype antenna will be incorporated in the Green Bank interferometer as a fourth element. Funds for the antenna prototype are sought in the FY 1970 budget.

The feed problem is also being studied. One interesting possibility, a novel feed design called Dielguide, developed by Radiation Incorporated, was investigated during 1967. The company submitted a proposal for a study of this feed for the VLA application. The cost quoted for the proposed study was $85,000. After the proposal was evaluated, however, it was concluded that the Dielguide system would be too inflexibile for the VLA application and no contract was awarded.

In July 1967 Collins Radio, Inc., submitted an unsolicited proposal to conduct a VLA feed study for a cost of $75,975. The proposed system was found incompatible with the VLA feed requirements, and no contract was awarded.

In October 1967, NRAO solicited a proposal for a study and the construction of an engineering prototype VLA feed assembly from 12 companies. Seven companies responded:

1.	TRG Division of Contral Data Corp. 400 Border St. East Boston, Mass.	Proposal: B590 16 November 1967 Price: $82,676
2.	Hughes Aircraft Company Fullerton, California	Proposal: 67CR1B5502-001 16 November 1967 Price: $84,817
3.	Collins Radio Company Dallas, Texas	Proposal: T-0439 14 November 1967 $73,708
4.	Radio Corporation of America Defense Electronics Division Moorestown, New Jersey	Proposal: S-5300 17 November 1967 Price: $87,313
5.	Andrews Corporation P. O. Box 42807 Chicago, Illinois	Proposal: 67-2B 16 November 1967 Price: A - $80,116 B - $65,755
6.	Philco-Ford Corporation WDL Division Palo Alto, California	Proposal: WDL-TP2606 17 November 1967 Price: $42,914
7.	Radiation Incorporated Melbourne, Florida	Proposal: RI-302508-5-31 November 1967 Price: $54,900

The present VLA system requires that the feed presents both left and right hand circular polarization at two frequencies (2695 MHz and 8085 MHz) simultaneously. The circularity specifications are difficult to accomplish, in fact several of the interested companies voiced concern about the polarization requirements. Several of the proposed solutions were based on partly transparent reflectors and/or shaped subreflector, and also in one case a shaped main reflector. These proposals were rejected because of their inherent frequency sensitivity.

One of the companies, RCA, proposed a system which was judged the most attractive because of its simplicity and inherent bandwidth which would enable operation at other intermediate frequencies with very minor modifications. The feed system proposed by RCA also exhibits good circular symmetry which is advantageous to achieving good polarization characteristics. Negotiations with RCA were started in January 1968, and a contract has now been awarded.

VI A SUB-VLA

The nature of the VLA allows it to be built in stages, with each stage itself being a powerful and useful instrument that can at any time be expanded to the full array. Several possible initial "sub-VLA's" have been investigated. Their gross performance characteristics and costs are as follows:

1) An array consisting of one arm of the full Wye and 12 antennas. This system gives a good 1 arc-second beam with low side lobe levels, over a considerable range of declinations. The cost is $19 million.

2) An array consisting of 12 antennas on a Wye configuration with arms 1/3 as long as the VLA. This gives 3 arc-second performance over the whole sky but requires several moves of the antennas. The cost is again $19 million.

3) The full VLA Wye, with 12 antennas. This has all the performance of the VLA except speed. Several moves of the antennas would be required for full synthesis and low side lobe levels. The cost is $27 million.

Any of the above systems could be expanded to the full VLA with almost no loss of money or effort. Various combinations of them are also feasible, at costs ranging between $19 million and $27 million. Costs can be further reduced by about $3 million by initially building only six antennas, but only at the expense of considerably increased observing time. It is probably not feasible to reduce the number of antennas below six and only marginally feasible to reduce the number below twelve.

VII. TIME SCHEDULE AND COST ESTIMATE

The time schedule presented here contains three major decision and funding points:

(i) Selection of a site must be accomplished early in FY 1970 so that detailed site design may be accomplished and building and facilities construction begun in time to meet the array construction schedule. In addition, the prototype antenna must be built in FY 1970. These are the pacing items of the entire schedule--any delay in site selection or the prototype antenna will result in a corresponding delay in the entire project.

(ii) Funds for commencement of site facility construction and computer procurement are required in FY 1971.

(iii) The major funding for electronic and antenna procurement is required in FY 1972.

If funds for the antenna prototype, and a decision on the site, could be obtained prior to FY 1970 the total schedule could be shortened by about six months.

A time and commitment schedule for the one-armed "sub-VLA" is also given.

The table gives a breakdown of current cost estimates.

BASIC SYSTEM VLA – 36 ANT., FULL WYE & PROTOTYPE K $ 4-19-68

	FY 68	FY 69	FY 70	FY 71	FY 72	FY 73	FY 74	FY 75	TOTAL
ANTENNA									
Design & Proto.	140	59	1006	250					1455
Fab. & Erect.					17009				17009
	140	59	1006	250	17009				18464
ELECTRONICS									
Design & Proto.	248	220	470						938
M'fg. & Install.					6184				6184
	248	220	470		6184				7122
COMPUTER									
Design & Proto.	80		100						180
Procure. & Instal.				3598					3598
	80		100	3598					3778
SITE									
Design & Acquisit.	65	120	220						405
Construction				3501	7493				10994
	65	120	220	3501	7493				11399
PROJ. MGMT.									
Sci. Cons., Misc. & Design Cont.	65.5	41.5	311						418
	65.5	41.5	311						418
TOTAL REQUEST	598.5	440.5	2107	7349	23193				41181

BASIC SYSTEM — VLA – 12 ANT., NORTH ARM Y-15, & PROTOTYPE — 4-19-66.

	FY 68	FY 69	FY 70	FY 71	FY 72	FY 73	FY 74	FY 75	TOTAL
ANTENNA									
Design & Proto.	140	59	1006	250					1455
Fab. & Erect.					5583				5583
	140	59	1006	250	5583				7038
ELECTRONICS									
Design & Proto.	248	220	470						938
M'fg. & Install.					2388				2388
	248	220	470		2388				3326
COMPUTER									
Design & Proto.	80		100						180
Procure. & Instal.				2666					2666
	80		100	2666					2846
SITE									
Design & Acquisit.	65	120	180						365
Construction				2301	2457				4758
	65	120	180	2301	2457				5123
PROJ. MGMT.									
Sci. Cons., Misc. & Design Cont.	65.5	41.5	311						418
	65.5	41.5	311						418
TOTAL REQUEST	598.5	440.5	2067	5217	10428				18751

May 10, 1968

PRICE FOR VERY LARGE ARRAY

	Jan. 1967 VLA Proposal (99 Station, 35 Antenna + Prototype) 1966 $	VLA Proposal in 1968 $ 3.5%/yr. Esc.	May 1968 Estimate Full Wye (99 Station, 36 Antenna + Prototype) 1968 $	May 1968 Estimate Full Wye (99 Station 12 Antenna + Prototype) 1968 $	May 1968 Estimate North Arm (33 Station 12 Antenna + Prototype)
Antenna System					
Design & Prototype - Antenna	$ 1,648,000	$ 1,765,000	$ 1,285,000	$ 1,285,000	$ 1,285,000
Design & Prototype - Transport	147,500	158,000	170,000	170,000	170,000
Construction - Antenna	15,204,000	16,283,000	16,749,000	5,583,000	5,583,000
Construction - Transport	59,500	64,000	260,000	- -	- -
Subtotal	$17,059,000	$18,270,000	$18,464,000	$ 7,038,000	$ 7,038,000
Electronic System					
LO	$ 1,132,000	$ 1,212,000	$ 1,376,000	$ 1,010,000	$ 517,000
Front Ends	878,000	940,000	923,000	315,000	315,000
IF & Delay	2,493,000	2,670,000	2,896,000	1,936,000	1,026,000
Correlators	256,000	274,000	211,000	50,000	50,000
System Monitor	328,000	351,000	278,000	230,000	180,000
System Integration	500,000	500,000	500,000	400,000	300,000
Design & Prototype	- -	- -	938,000	938,000	938,000
Subtotal	$ 5,587,000	$ 5,947,000	$ 7,122,000	$ 4,879,000	$ 3,326,000
Computer System					
Main Computer	$ 2,140,000	$ 2,292,000	$ 1,522,000	$ 1,432,000	$ 1,432,000
Communications	1,269,000	1,359,000	1,705,000	986,000	863,000
Programming	300,000	321.000	551,000	551,000	551,000
Subtotal	$ 3,709,000	$ 3,972,000	$ 3,778,000	$ 2,969,000	$ 2,846,000
Site					
Buildings	$ 977,000	$ 1,046,000	$ 1,046,000	$ 1,046,000	$ 1,046,000
Wye	6,733,000	7,211,000	7,493,000	7,493,000	2,457,000
Utilities & Facilities	1,916,000	2,052,000	2,455,000	2,455,000	1,255,000
Site Acquisition	100,000	107,000	405,000	405,000	365,000
Subtotal	$ 9,726,000	$10,416,000	$11,399,000	$11,399,000	$ 5,123,000
Project Management	$ - -	$ - -	$ 418,000	$ 418,000	$ 418,000
Total Basic Array	$36,081,000	$38,605,000	$41,181,000	$26,703,000	$18,751,000
Continuum Research Equipment*	$ 2,525,000	$ 2,704,000	$ 3,166,000	$ 1,589,000	$ 988,000
Spectral Line Research Equipment*	$ 3,300,000	$ 3,534,000	$ 3,534,000	$ 1,178,000	$ 1,178,000
Spent through December 1967	$ 577,000	$ 577,000	$ 577,000	$ 577,000	$ 577,000

*Desirable, but not essential.

APPENDIX 2

SIDE LOBES OF THE VLA

E. J. Blum*

The VLA Proposal examines the effects and the level of side lobes in several chapters, but some related questions are not studied. I do not intend to exhaust the subject, but I would like to present here a comprehensive view with the idea of VLA dynamic range in mind.

The VLA will be able to detect objects down to a flux threshold of 10^{-4} f.u. On the other hand, some strong radio sources exist with flux around 10^{3} f.u. The quiet sun radiates 10^{5} f.u. from its whole surface, and when disturbed relatively narrow regions may have also flux up to 10^{5} f.u. So, we have to think about dynamic ranges of dB during the night and much more during the daytime, with 90 dB possible.

VLA side lobes come from different physical processes, and we may classify them, not too arbitrarily, in the following way:

I. Diffraction side lobes

II. Near side lobes due to holes (incomplete coverage of UV plane)

III. Side lobes due to phase or amplitude errors

IV. Far side lobes due to incomplete coverage of UV plane

* On leave from the Observatoirè de Meudon, Meudon, France.

Categories I and III apply to the array as well as to individual dishes. The last category being closely related to II and III.

I. Diffraction Side Lobes

Diffraction side lobes are produced by an ideal array of perfect dishes. In principle their effect may always be supressed by a proper mathematical or physical processing.

(a) Dish diffraction side lobes may be reduced by tapered illumination, and also by filtering the data or convolving it with a synthetic lobe. The measurement over a field of several beam widths is necessary to reach a reasonable reliability.

(b) Array diffraction side lobes are reduced by tapered illumination. During data processing the weight of spatial harmonics is decreased according to their length.

As diffraction side lobes may be corrected and decrease rapidly with distance from the main beam, we will not consider them in the following analysis.

II. Holes Side Lobes

As dishes are full apertures, they do not produce such side lobes. The array is the only source, and the magnitude of the side lobes has been evaluated in the VLA proposal (Appendix F, p. 6.20 ∝ Sq.). Their rms value is for $\frac{\pi N^2}{8} = 22{,}000$ and $n = 3{,}300$ (15% holes_, $\sqrt{\bar{B}^2} = \frac{1}{500}$ or 27 dB. Table 6.2 gives values from computed models ranging from 16 to 25 dB. If the pattern of holes side lobes is precisely known, a restoration might be done.

The restored field will look smoother, but the lack of information due to holes cannot be replaced.

Another way to make the estimate is to consider the vector resulting from the addition of random unit vectors, each coming from one hole, and representing the lack of information introduced by holes. The sum vector is $\sqrt{n}$, compared with main lobe amplitude $\frac{\pi N^2}{8} - n$, so rms value of holes side lobe is $\frac{\sqrt{n}}{\frac{\pi N^2}{8} - n}$ in good agreement, within a factor $\sqrt{2}$, to appendix F result. Finally the holes side lobe field may be taken with a rms value 25 to 27 dB.

III. Side Lobes Due to Phase and Amplitude Errors

(a) Dishes. We follow Ruze in Jasik (Antenna Engineering Handbook, p. 2.37)

$$\bar{P}(\phi) = P_o(\phi) + S(\phi) \frac{c^2 \pi \bar{\delta}^2}{\eta_A} \exp - \frac{\pi^2 c^2}{\lambda^2} \sin^2 \phi \qquad (1)$$

where

$\bar{P}(\phi)$ is the power pattern for average system

$P_o(\phi)$ is the power pattern for system without error

$s(\phi)$ slowly varying function

c correlation interval

η_A effective area of dish

$\bar{\delta}^2$ mean square error radian squared

Assuming $c/\lambda = 1$, with $\lambda = 0.1$ m, surface errors of 3 mm rms or $\bar{\delta}^2 = 0.04$, effective area 1/2 500 m^2 (Chapt. 11 of VLA Proposal), the rms value of the side lobes is:

53 dB close to main lobe

60 dB at $\sim$ 20°

70 dB at $\sim$ 40° (assuming $S(\phi) = 1$)

When used in an array, dishes errors side lobes are added randomly if the dishes inaccuracies are random. This is probably not quite true, chiefly for deformations which are due to structure common to all dishes. So, we think it will be safe not to add any extra attenuation to values above, and even to decrease slightly these values to take care of possible large scale deformations ($c > \lambda$).

It is interesting to note that the same formula, applied to West Ford dish (PIEEE <u>52</u>, 589, 1966) gives 50 dB at 10° and 70 dB at 45° from the main lobe, which is very close to measured values. As the low efficiency of this antenna is probably due to surface inaccuracy, we have assumed a rms error of $\lambda/10$, with $c/\lambda = 1$ (λ = 4 cm).

(1) may be written, close to main lobe,

$$\bar{P}(\phi) = P_o(\phi) - S(\phi)\,\frac{c^2\pi\bar{\delta}^2}{\eta_A}\left(1 - \frac{\pi^2 c^2}{\lambda^2}\,\phi^2\right)$$

So, in this zone there will be an increase of side lobes when increasing c. For instance, at an angle of 3 main beams: $\phi = 3 \times 20'$ or $= \frac{1}{100}$ rad, if $c/\lambda = 10$ side lobe level is $\sim$ 33 dB.

On the contrary, far from main lobe increasing, c has the effect to decrease side lobe (but it may be questioned if formula (1) established on

statistical basis is still valid for dish diameter $\stackrel{\sim}{\sim}$ 250 λ and $c/\lambda \stackrel{\sim}{\sim} 10$).
In fact c is not really a parameter; it will be fixed mainly by the dishes construction technique.

(b) Array. Let us consider the measurement of some sky distribution $T(\theta,\phi)$ by a correlation interferometer, each antenna giving a voltage output $\gamma(\theta-\theta_o,\phi-\phi_o)$ from the direction θ,ϕ; θ_o,ϕ_o being some reference direction.

We have $u_{\theta_o\phi_o} = \iint \gamma_1(\theta-\theta_o,\phi-\phi_o)\ \gamma_2\ (\theta-\theta_o,\phi-\phi_o)\ T\ (\theta,\phi)\ d\theta d\phi$. Where $u_{\theta_o\phi_o}$ is the power output of the system pointed in the direction $\theta_o\phi_o$. With a correlation array, with N pairs

$$U\ (\theta_o\phi_o) = \sum_N u_{\theta_o\phi_o} = \iint T\ (\theta,\phi) \sum_N \gamma_1\gamma_2\ d\theta d\phi$$

Looking to Fourier transforms:

with $w\ (u,v) = TF\ (\Sigma\ \gamma_1\gamma_2)$

$\beta\ (u,v) = TF\ (T\ (\theta,\phi))$.

We have: $B\ (u,v) = w\ (u,v)\ \beta\ (u,v)$ and

$$U\ (\theta_o\phi_o) = \iint B\ (u,v)\ e^{2\pi i\ (u\theta_o + v\phi_o)}\ du\ dv$$

To study side lobes, we choose $T\ (\theta,\phi) = \delta$, or $\beta = 1$.

$$U(\theta_o\phi_o) = \iint w\ (u,v)\ e^{2\pi i\ (u\theta_o + v\phi_o)}\ du\ dv$$

Now the transfer function may be separated into three parts, w_1, w_2, iw_3. w_1 is the specified transfer function, w_2 corresponds to amplitude errors in the function, iw_3 to phase errors.

As we know $U(\theta_o \phi_o)$ is a real quantity, we may write:

$$U(\theta_o, \phi_o) = \iint w_1 \ (u,v) \cos 2\pi \ (u\theta_o + v\phi_o) \ du \ dv +$$

$$+ \iint w_2 \ (u,v) \cos 2\pi \ (u\theta_o + v\theta_o) \ du \ dv$$

$$- \iint w_3 \sin 2\pi \ (u\theta_o + v\phi_o) \ du \ dv$$

The normalized output for a perfect array ($w_2 = w_3 = 0$), in its main lobe ($\theta_o = \phi_o = 0$), is $U_o = \iint w_1$. And the side lobe pattern is given by the variation of $U(\theta_o, \phi_o)$.

The first term of $U(\theta_o, \phi_o)$ corresponds to diffraction and holes side lobes we have already estimated. We are interested now in the two following terms, which take respectively into account amplitude and phase error effects on the transfer function. We know that amplitude errors are relatively small -- a few percent on each spatial harmonic -- phase errors are greater. For one peculiar set of u,v, we have a value of w_3 which is εw_1, ε in radians with $|\varepsilon| \approx 0{,}1$, so we may neglect the amplitude error term. We will neglect also the effect of phase error on amplitude (decrease of w_1 by $1 - \varepsilon^2$). So, we want now to evaluate

$$\bar{E} = \iint w_3 \; (u,v) \; \sin 2\pi \; (u\theta_o + v\phi_o) \; du \; dv,$$ compared to $\iint w_1$; w_3 is a random function which may be positive or negative for each set of u,v. For a given value of $\theta_o \; \phi_o$, the product by $\sin 2\pi \; (u\theta_o + v\phi_o)$ may be considered as a frequency change, which is not affecting the statistical properties of w_3. (This is true only if θ_o, ϕ_o are not too small, i.e., not too close to main lobe.) Then:

$$\bar{E} \approx \frac{2}{\pi} \iint w_3 \; (u,v) \; du \; dv.$$

The factor $\frac{2}{\pi}$ comes from the mean value of sin.

Let us consider first phase errors not varying with time: imperfect phasing and positioning; these errors are permanently applied to the 630 fundamental harmonics of the VLA. During synthesis, harmonics move in UV plane, but always with the same error. Therefore we have only 630 errors. Moreover these errors are not independent. They come from linear combination of 36 independent errors given by the 36 antennas.*

---

* It may be noted that the One mile telescope has about the same number of independent pairs (∿ 60 different positions).

If all harmonics are equal (no taper), and if errors have the same mean value $\sqrt{\varepsilon^2}$ on all UV plane, we have

$$\sum\sum w_3 = \frac{2\varepsilon}{\pi} \sqrt{\eta} \text{ and } \iint w_1 = n, \text{ with } n = 36$$

or a mean side lobe level of $\frac{2\varepsilon}{\pi\sqrt{\eta}}$.

In fact, there will be some taper, and errors will increase certainly with spatial frequency. The preceding level has to be increased, chiefly because of taper; the variation of errors with spatial frequency may be taken into account by a proper choice of ε. For side lobes coming from time varying phase errors ε_1 (due to propagation through atmosphere), if we suppose that the time scale of variation is of the same order of magnitude as the mean sampling time of a cell (12 mn), a similar approach gives a side lobe level of $\frac{2\varepsilon_1}{\pi\sqrt{N}}$ with N = 22,000, negligible compared with preceding values.

If we come back now to the general case, i.e., close to the main lobe: $\overline{E} = \iint w_3 \sin 2\pi\ (u\theta_o + v\phi_o)\ du\ dv$, one can see that for small values of $\theta_o\phi_o$ the side lobe level decreases.

Finally in taking $\frac{2\varepsilon}{\pi\sqrt{36}}$ as an estimate of side lobe level, we have:

20 dB assuming ε = 0.1 (6° rms)

23 dB " ε = 0.05 (3° rms)

Considering the effect of taper, it seems that 18 to 20 dB rms is a conservative value. However, if several calibrations of the system made on precisely known fields, are possible during one synthesized field observation, then preceding side lobes value may be slightly increased.

IV. Far Side Lobes

Far side lobes are due to array discontinuous coverage; the preceding analysis of holes and errors side lobes have been made under the assumption of narrow band. This assumption is no longer valid far from main beam, as the pattern is smeared by the bandwidth. To estimate side lobes far from main beam, we will again consider the array as formed by small antennas; dish influence being treated separately. Then to remove the smearing effect we will split the bandwidth in n channels of frequency, each channel corresponding to an instrument without smearing. Each instrument gives in any direction of space, far from main lobe, a pattern obtained by random sum of 22,000 cells, though of rms amplitude $(22,000)^{-1/2}$ compared with main lobe. If there are some grating effects, i.e., some regularity in the summation, amplitude may be increased. Now we have n instruments at n different frequencies, so we have to add quadratically their contribution again and the total rms level of far side lobes is $(22,000 \times n)^{-1/2}$. n varies with distance of main lobe, between 1 and 3000 for the VLA configuration 20' x 10", 100 MHz bandwidth.

(Length of one arm in wavelengths: 20.000 - coherence condition $\frac{b}{F} \sim \frac{1}{4} \frac{1}{20.000}$ $b = \frac{2700}{80.000}$ MHz, $\frac{B}{b} = n_{max} = \frac{80.000}{27.000} \times 100 = 3000$). At 10° of main lobe the side lobe level is then 33 dB; and 39 dB at 90°.

V. Total Side Lobe Pattern

For small n the preceding estimate has no meaning, for the random assumption is no longer valid, and only the sum of holes S.L. and errors S.L.

are to be considered in the main lobe region. For large n, on the contrary this estimate takes into account holes and errors S.L. which are no longer separable. For moderate n values, transition between dish main beam field, and far field, we may also consider several systems with bandwidth narrow enough to have no smearing effect, each of these systems with side lobes due to holes, and phase errors, and add them randomly. With this crude estimate, we can draw two figures to summarize the whole preceding analysis. (In the case of array field equal to dish main lobe.) Fig. 1 indicates the side lobe, 2° and more from main lobe, Fig. 2 close to main lobe. As all values are rms, the total side lobe contents have peaks which may sometime reach -5 dB (shaded zone).

It is clear from the figures that the dishes side lobes give the main protection against strong source radiation, when holes and phase errors cause rather high S.L. level. In the far zone any reduction of bandwidth gives an increase in S.L. up to the holes and phase errors side lobe level value, for very narrow bandwidth.

During the day, the sun, at 20° or less from the main lobe, may give unwanted signals. During the night there will be probably no difficulty anywhere. However, as the dish protection is the most efficient, it seems important to specify the dish far side lobe level. For instance, if in some regions side lobes of dishes are only 45 dB, daylight observations may have trouble in any solar position, and by night measurements at less than 5 or 10° of a strong source may be disturbed. The same situation may occur within 2° of main lobe if dish diffraction side lobes are not corrected (Fig. 2, assuming 20 dB and 26 dB and so on for diffraction side lobes: total side lobe, dashed curve).

It may be questioned if the criterion we have taken: rms side lobe level, measured by its average power, is a good one in a correlation system which gives positive and negative side lobes, and perhaps all preceding values, at least for the array, are slightly pessimistic.

VI. Conclusion

In this paper we have studied various aspects of side lobe levels for the VLA as it is described in the VLA proposal. We have derived some characteristic values of side lobe levels from various approaches. As some of these approaches are rather crude we would not guarantee a high accuracy for these values. Nevertheless, several points seem quite clear:

1) In the field of dish beam width (20' x 20') observations with dynamic range greater than 16-20 dB have to be made with great care.

2) If a strong source is within 2° of the main lobe, dish diffraction side lobes are to be corrected.

3) If the sun is within 20° of the main lobe there may be trouble.

4) A reduction of the bandwidth of the array would cause a noticeable increase of the side lobe level.

5) Dish errors side lobes, due to structure and common to all dishes are to be more than 50 dB.

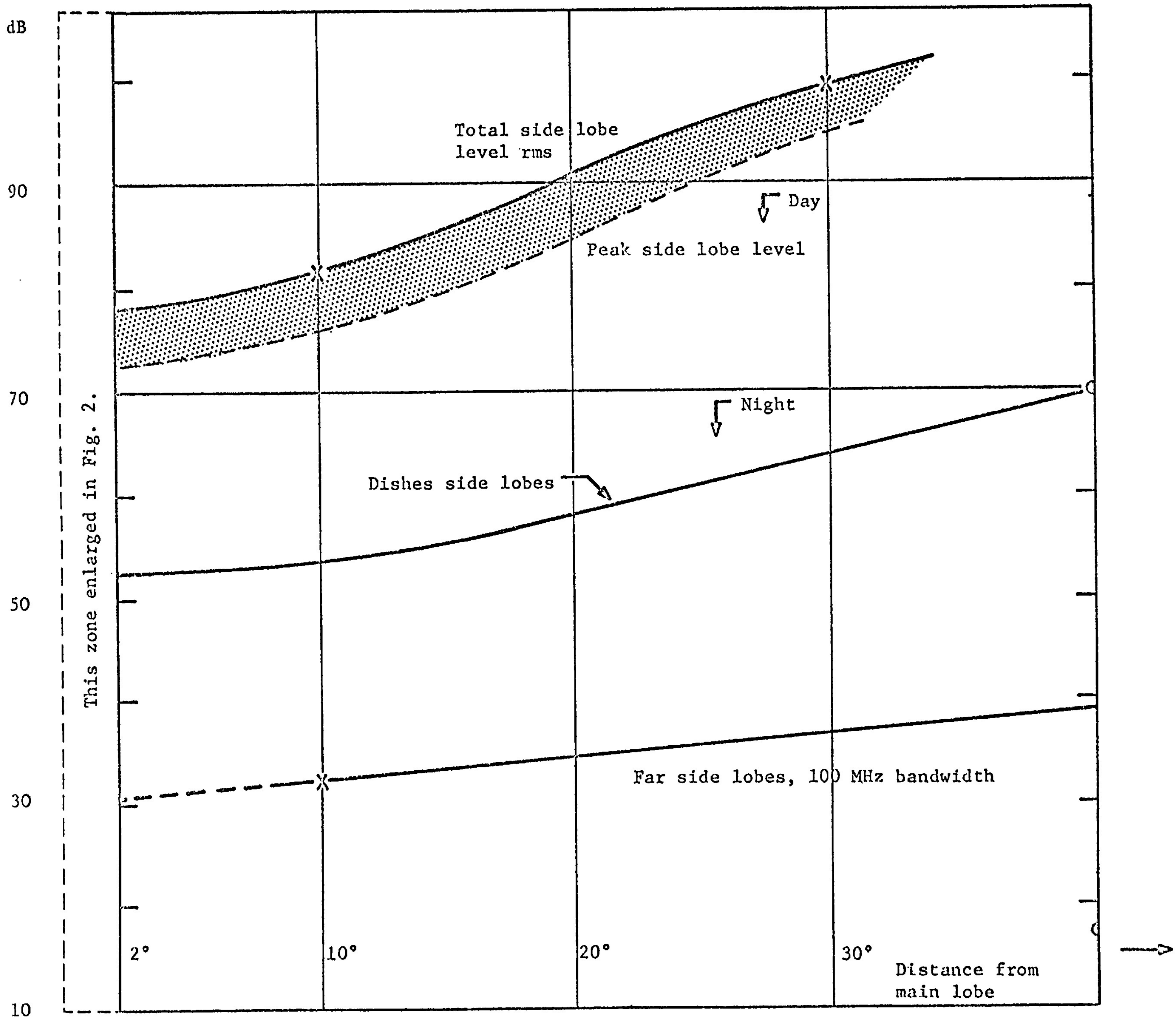
dB
90
70
50
30
10
This zone enlarged in Fig. 2.
Total side lobe level rms
Day
Peak side lobe level
Night
Dishes side lobes
Far side lobes, 100 MHz bandwidth
2°
10°
20°
30°
Distance from main lobe

Fig. 1

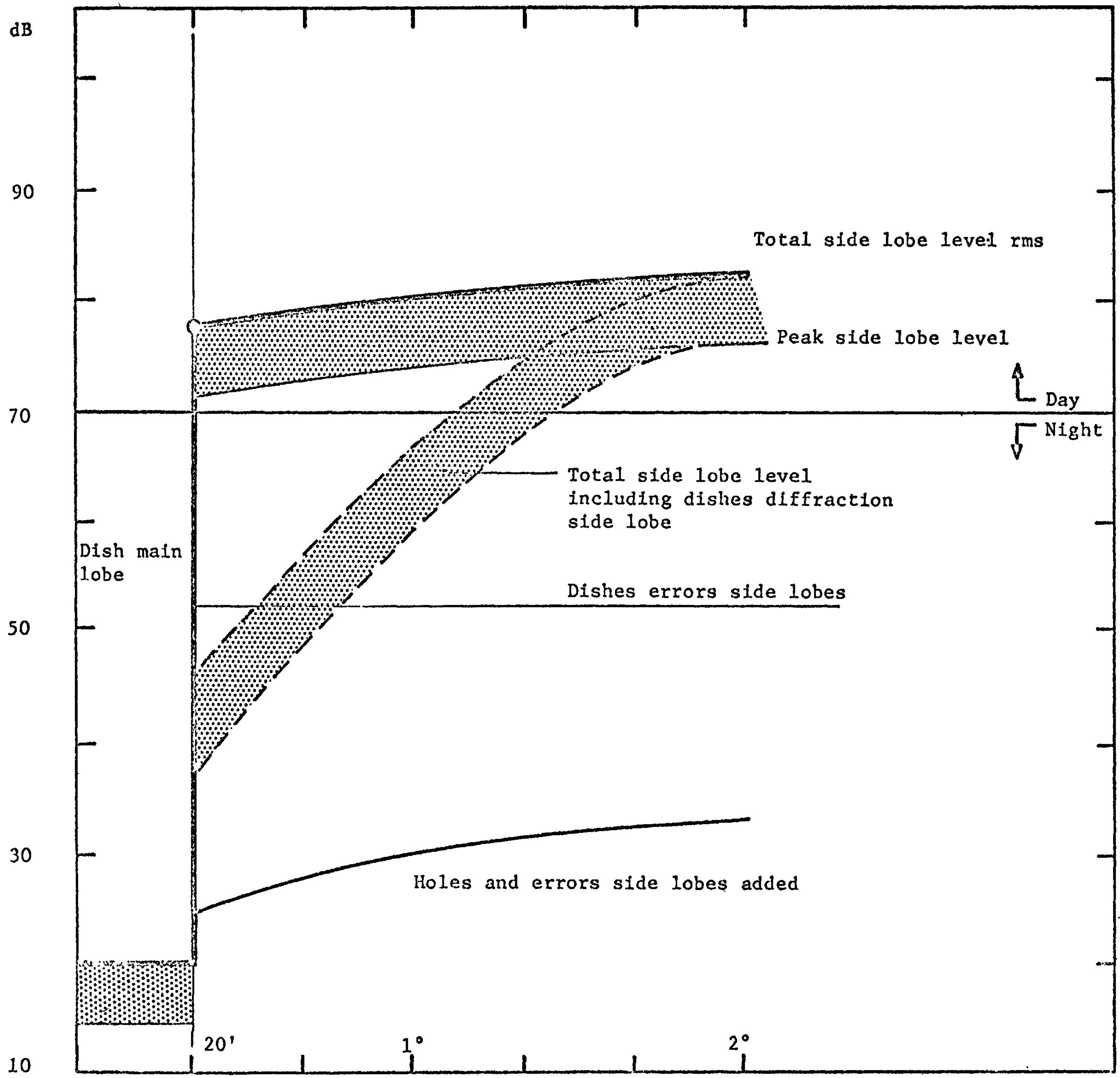
dB
90
70
50
30
10
Total side lobe level rms
Peak side lobe level
Day
Night
Total side lobe level including dishes diffraction side lobe
Dish main lobe
Dishes errors side lobes
Holes and errors side lobes added
20'
1°
2°

Fig. 2

APPENDIX 1.

THE USE OF PSEUDO DYNAMIC PROGRAMMING FOR VLA CONFIGURATION DESIGN

Introduction

The VLA is an antenna array having a beam narrow enough to resolve sources separated by one second-of-arc and yet pure enough to keep the side-lobe response to a minimum. Specifically, it has four resolutions, 1", 3" 9", and 27", and has mean sidelobe level far from the beam but within the field of view less than -30 db, and with the peak sidelobe level less than -15 db within the field of view. The configuration study is aimed at finding the antenna configuration which will produce such a beam at the minimum cost.

The design of antenna arrays to achieve specific beam characteristics has been the subject of intensive research in the past decade.[1-7] In a linear additive array, the characteristics of the beam depend upon the locations and excitations of the elements of the array. No unique technique has yet been developed for finding the optimum array configuration. The various approaches used in array synthesis work can be broadly classified into three categories: (i) analytical approach, (ii) statistical approach, and (iii) computer optimization.

The analytical approach has been tried by several workers.[1,5,8,9,10] Although partial success has been achieved, the arrays designed by the analytical approach do not perform better than arrays designed by other approaches.[7] The chief difficulty is that analytical methods cannot handle a large number of parameters and that the designs produced are often impractical due to very close antenna spacings which result in mutual coupling.

The statistical or probabilistic approach in general leads to arrays with performance comparable to those designed analytically.[7,12,13] They bring out the statistics of the performance of different types of arrays without actually specifying an array which could be termed optimum in some sense.

Computer techniques used in optimization have used empirical approaches and perturbation methods.[4,6] Since computers can handle large numbers of antennas and also take care of many parameters simultaneously, they are well-suited for large arrays. Within a certain restricted sense they lead to optimum array configurations. However, for any rigorous optimization, the computing time soon becomes very long. For similar sized arrays, computer techniques have yielded array configurations which perform as well as arrays designed by any other technique.

It is clear that in the present state of the art the design of an optimum antenna array (even a linear additive array) remains a challenging unsolved problem. The problem of designing the VLA configuration is more involved than that of the linear additive array since the VLA is to be used as a correlator array in the supersynthesis mode. The two main complicating factors are:

(i) The beam pattern, as a function of the element locations, is much more involved for the correlator array than for the linear additive array.

(ii) When used in the supersynthesis mode, the synthesized beam depends not only upon the configuration but also upon the declination of the source and the hour angle range over which it is observed.

It is not possible to write a simple mathematical expression giving the beam pattern as a function of antenna locations, declination of source and tracking time. This makes any analytical approach towards optimization hopelessly difficult. The best approach is the use of a large sized high speed computer which can be programmed to compute the beam pattern of a given configuration for specified declination and tracking time. Such an approach has been used for the VLA configuration study using the IBM/360 computer. A pseudo-dynamic programming technique is being used which produces an "optimum" configuration within the framework of restrictions discussed below:

<u>Pseudo-Dynamic Programming</u>

The pseudo-dynamic programming technique efficiently utilizes the capabilities of the computer to find an optimum configuration. The optimum configuration defines the locations of the antennas which produce the best beam characteristics. In general, if N antennas can occupy any of P possible positions, the number of different possible arrangements is

$$ {}^{P}C_{N} = \frac{P\,(P-1)\,(P-2)\cdots(P-N+1)}{N!} $$

The value of P is governed by the resolution and field of view specifications. Even for relatively small values of P, the above number becomes astronomically large and it is obviously impossible to study all these configurations. One can, therefore, choose the optimum configuration from these ${}^{P}C_{N}$ possibilities by one of three ways:

(i) Random selection: In this approach N numbers are selected at random out of the given P numbers and the transfer function corresponding to these N positions is computed. By considering a large number of random choices, the one yielding the best sampling in the spatial frequency plane (tranfer function) can be chosen as the final configuration.

(ii) Empirical approach: In this approach the N elements are placed in different geometrical forms (for example, along the circumference of a circle or along radial arms, etc.) and the geometrical form giving the best transfer function is selected. Further improvement of the transfer function is then effected by trying various distributions of the elements on the basic geometrical form selected and choosing the best distribution for the configuration.

(iii) Perturbation method: In this approach one starts with an arbitrary configuration. The position of each element is then perturbed by small amounts and the element is then left in a position which improves the transfer function. The final configuration incorporates the result of these perturbation studies.

The first approach obviously lacks any logic and even if a very large number of random configurations is tried, the final configuration cannot be termed optimum in any sense. The second approach points out the classes of geometrical forms which are better than other classes. The third approach improves a given configuration by introducing small perturbations. However, in effecting a small perturbation about the mean position of an antenna, only a local optimum position can be obtained.

The pseudo-dynamic programming combines the second approach with an improved version of the third approach. Basically, the computer selects the optimum location of an antenna from (P-N+1) possible locations for a given arrangement of (N-1) antennas, a given declination and a given tracking time. The starting positions of the N antennas are selected using approach (ii). By optimizing the positions of all antennas successively, a configuration is obtained which is optimum over the P positions for the declination and tracking time considered.

The shortcomings of this technique are (i) that the final optimum configuration obtained depends upon the starting configuration and (ii) that the optimization of one antenna depends upon the location of all others. Thus after optimizing the first antenna, when the second is moved to the optimum position, the position of the first may no longer be optimum.

In actual practice it is found that these two shortcomings have very insignificant effect on the result. It is found that the performance of beams of several optimized configurations for which different starting configurations were chosen are similar to within a fraction of a db. Also, once all N antenna positions have been optimized, we can start from the first antenna again and thus keep optimizing by performing several runs of the N antenna loop until no further improvement is possible. It is found that, depending upon how good the starting configuration is, one reaches a configuration, after about two runs, which cannot be substantially improved by further runs. It is also of interest to note the result of this pseudo-dynamic programming when applied to a linear, non-tracking array. The optimum positions for such an array are given from the theory discussed by Leech[14]. The program came out with these optimum positions after two runs only.

Procedure and Results

An exhaustive empirical study of various types of configurations has been done using digital computers. The results of this study are summarized in the VLA Proposal[15]. That study forms the starting point for the use of pseudo-dynamic programming. It is apparent that in view of the requirement of four configurations giving resolutions of 1", 3", 9", and 27", expandability of the array is very important. It has been shown that a three arm array in the form of a symmetrical Wye offers the best and cheapest layout for the track on which the antennas can be moved. The empirical study concluded that 36 antennas will be needed to achieve the desired beam characteristics in one day's observation.

With this background, the basic layout of the track has been taken as a symmetrical wye with one arm rotated 5^{o} east of the north-south direction. On each arm 42 possible positions (equispaced) have been taken (making P = 126). Optimization has been carried out mainly at a declination of 0^{o} although other declinations have also been used. This is because a well-filled transfer function is almost difficult to achieve at 0^{o}. Several different starting configurations have been tried.

The computation of the beam pattern from a given transfer function is a time consuming process on the computer. Therefore, we cannot use the sidelobe levels as a criterion for optimization. The sidelobe levels depend both upon the number and distribution of the unsampled spatial frequencies (holes) in the transfer function. In general, holes near the center of the transfer function cause greater sidelobes than holes far from the center. A count of the number of holes in which greater weighting is given to the holes near the center, serves as a good criterion for optimization. Such a criterion using a gaussian weighting (termed weighted holes) has been used as a criterion and Figure 1 shows the decrease of the weighted holes as more and more antennas are optimized in a 30 element array. It is clear that no further improvement results after the 30 antennas have been run twice through the optimizing loop.

Two approaches have been used to arrive at a final configuration. In one, one starts with a large number of antennas (N = 30, was chosen) and keeps optimizing until no further improvement is possible. Thus each antenna is optimized with respect to the 29 others. In the other approach, one starts with a small number of antennas and optimizes their configuration. Then additional antennas are added, one at a time, each placed at the optimum position as given by the computer. Thus one gets the beam characteristics as a function of the number of elements. This relationship is shown in Figure 2 for 0^{o} declination. It should be noted that Figure 2 is strictly true for 0^{o} only and gives little information about performance at other declinations.

The performance of a 30-element array, optimized according to the first approach, is shown as a function of declination in Figure 3. For comparison, the performance of the 36-element array (termed supplemented Wye) as proposed in the VLA Proposal is also shown in Figure 3.

The pseudo-dynamic programming technique is a simple procedure for getting the best of a set of possible configurations. Its potentialities are vast and are limited mainly by the size of the computer and the amount of computer time available. This procedure, while bearing some similarity to the techniques of dynamic programming as proposed by Bellman[16], is not really the same since the Principle of Optimality is not satisfied. Nevertheless, with reference to the problem of VLA configuration, it appears to be the best approach.

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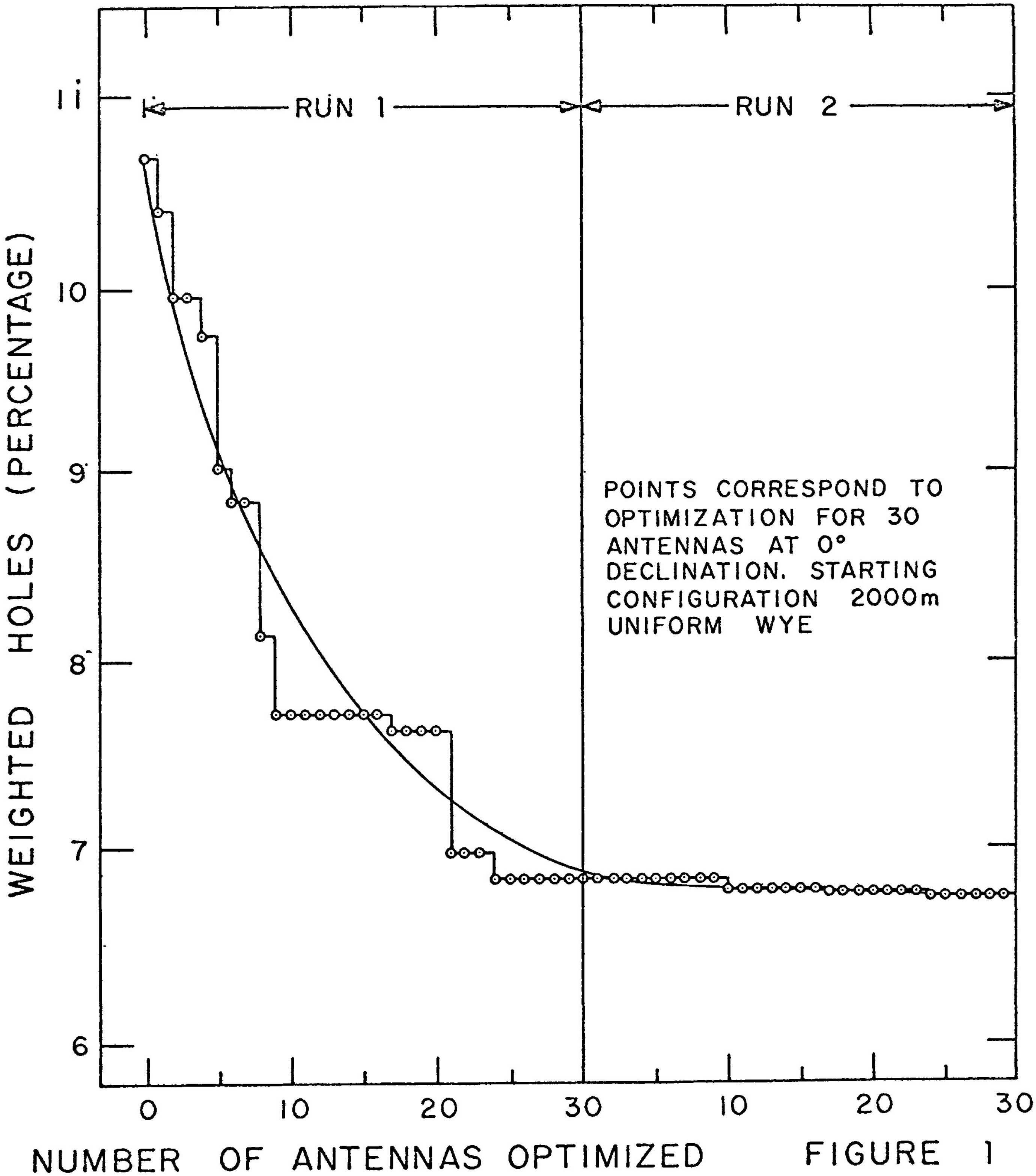
RUN 1
RUN 2
WEIGHTED HOLES (PERCENTAGE)
11
10
9
8
7
6
0
10
20
30
10
20
30
NUMBER OF ANTENNAS OPTIMIZED
POINTS CORRESPOND TO
OPTIMIZATION FOR 30
ANTENNAS AT 0°
DECLINATION. STARTING
CONFIGURATION 2000m
UNIFORM WYE

FIGURE 1

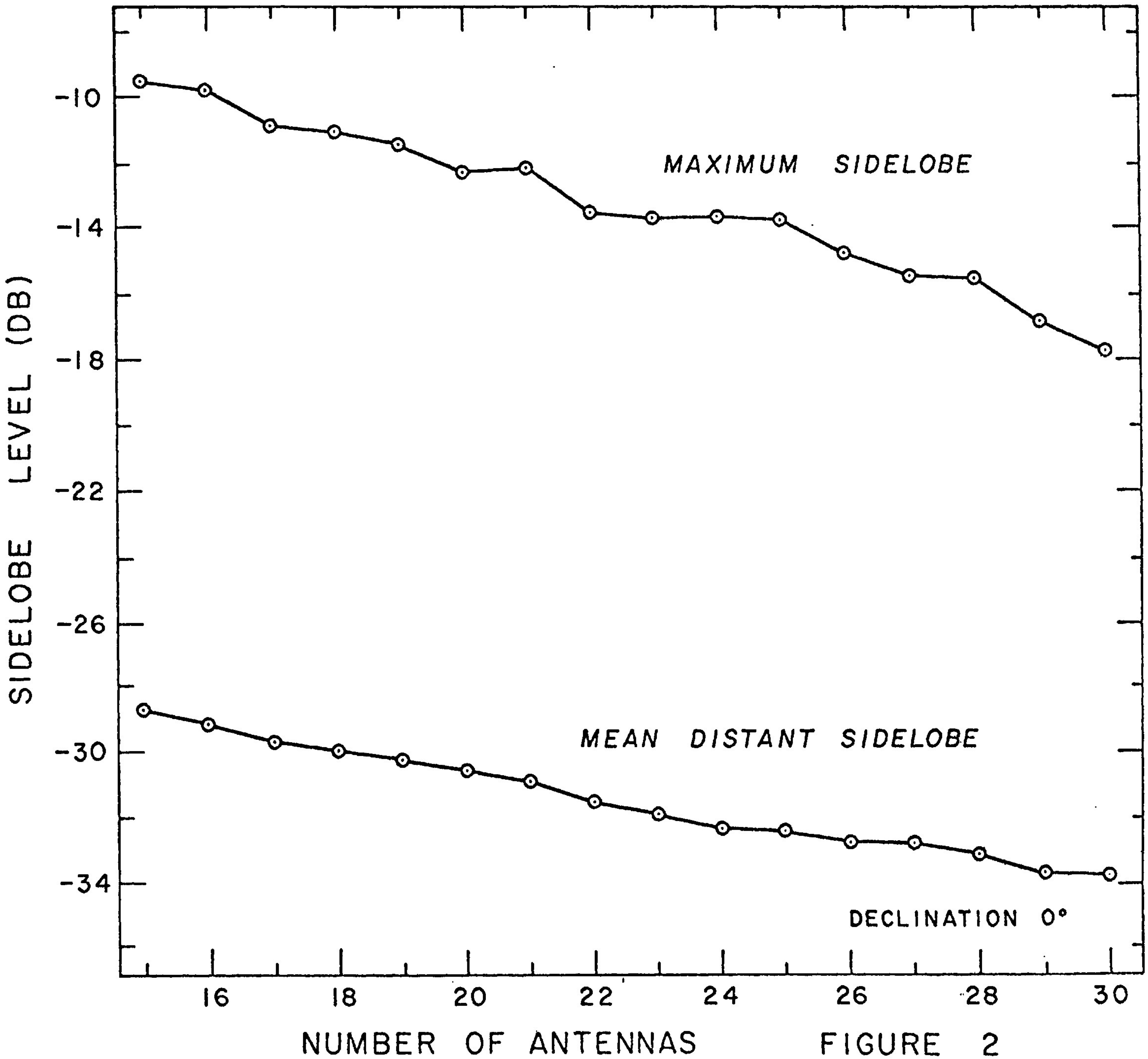
SIDELOBE LEVEL (DB)
-10
-14
-18
-22
-26
-30
-34
MAXIMUM SIDELOBE
MEAN DISTANT SIDELOBE
DECLINATION 0°
16
18
20
22
24
26
28
30
NUMBER OF ANTENNAS

FIGURE 2

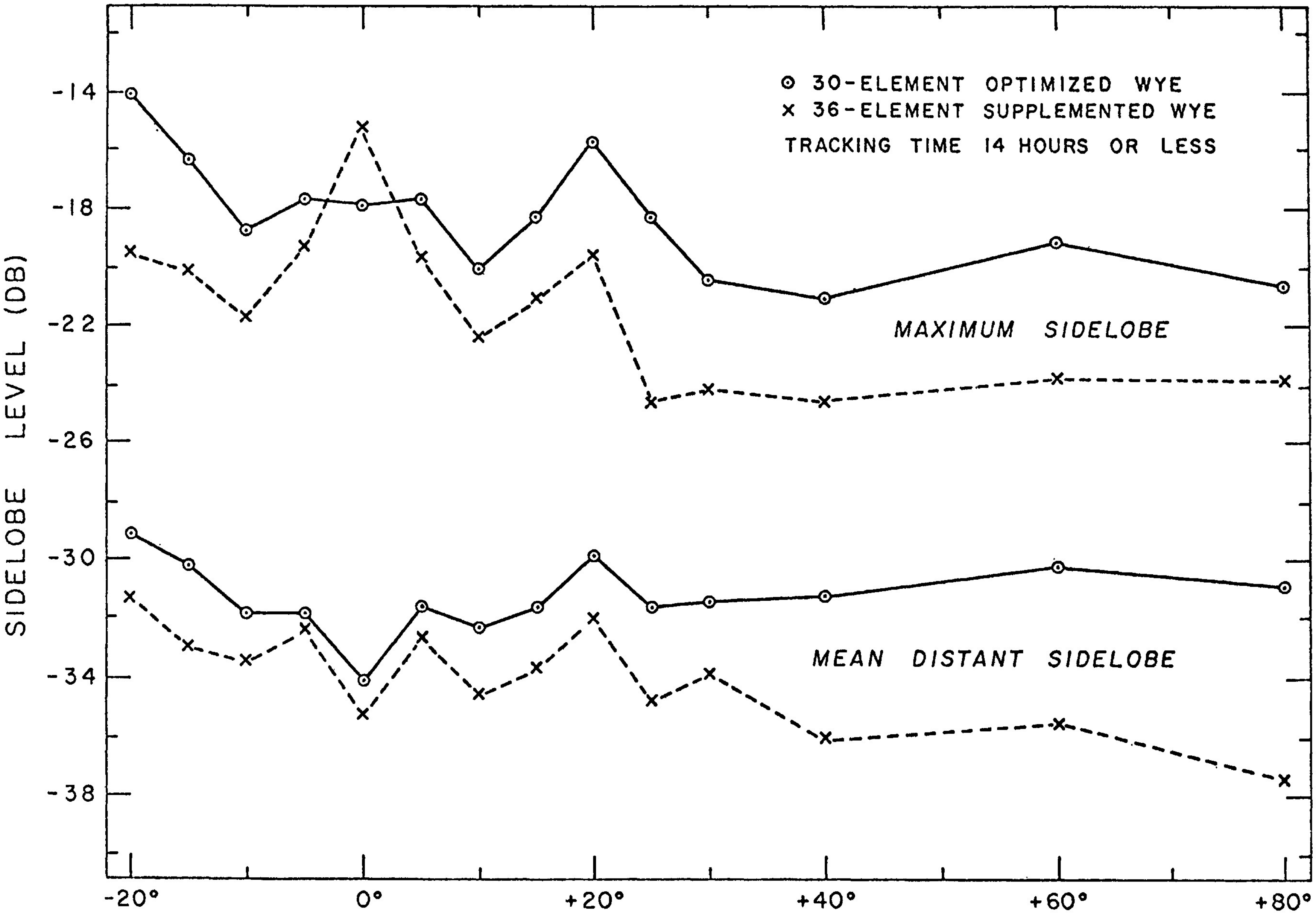
30-ELEMENT OPTIMIZED WYE
36-ELEMENT SUPPLEMENTED WYE
TRACKING TIME 14 HOURS OR LESS
MAXIMUM SIDELOBE
MEAN DISTANT SIDELOBE
SIDELOBE LEVEL (DB)
-14
-18
-22
-26
-30
-34
-38
-20°
0°
+20°
+40°
+60°
+80°
DECLINATION

FIGURE 3