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A STUDY OF ANTENNA CONCEPTS AND TRADE-OFFS FOR PORTABLE EARTH STATIONS

(Final Report)

Submitted to

DEPARTMENT OF COMMUNICATIONS

by

W.R. Goddard, E. Bridges, S. Thornton-Trump

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Prepared by

W.R. Goddard, E. Bridges, S. Thornton-Trump

DEPARTMENTS OF ELECTRICAL AND MECHANICAL ENGINEERING

UNIVERSITY OF MANITOBA

WINNIPEG, MANITOBA

MARCH, 1978

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PROJECT STAFF

Principal Investigator: Professor E. Bridges,
Department of Electrical Engineering.

Mechanical Design: Professor S. Thornton-Trump,
Department of Mechanical Engineering.

Electrical Consultant: Dr. L. Shafai,
Department of Electrical Engineering.

Research Associate: Dr. W.R. Goddard,
Department of Electrical Engineering.

Graduate Assistant: Mr. T. Lightly,
Department of Mechanical Engineering.

PREFACE

I would like to express my appreciation to all who have assisted in bringing this project to its final report stage. Particularly important is the contribution of Dr. W.R. Goddard who not only put considerable effort into developing the computer programs but into all aspects of the research. Dr. L. Shafai made many valuable suggestions and we are indebted to him for these.

The administrative support of the Office of Industrial Research, particularly of J. Gourlay, is acknowledged. Thanks are due to the Departments of Mechanical and Electrical Engineering and the Computer Centre for the use of various University facilities.

Finally special thanks are due to Mr. O. Roscoe of Space Electronics, DOC, for bringing this interesting project to my attention and to Mr. P. Boudreau, also of Space Electronics, DOC, for his encouragement and guidance during the course of the contract work.

March, 1978 E. Bridges

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1. Introduction

1.1 Design Objective

The essential design objective was to meet the electrical and mechanical performance specifications for the proposed MUSAT portable earth station antenna, as given in Appendix A. We also set out to obtain a relatively simple and reliable, practical design for the antenna. In the electrical design the emphasis was on obtaining maximum gain over both receive and transmit bands, while satisfying the maximum input voltage standing wave ratio (VSWR) requirement. In the mechanical design the emphasis was on meeting the collapsibility and wind gust stability requirements, and to accommodate the electrical requirements. This study concerns the design of tunable Yagi antennas to meet these objectives.

1.2 Literature Search

The objective of the literature search was to obtain sufficient information on Yagi antenna modelling, optimization and active tuning to initiate our own research and design work. The survey of previous work is given in Appendix B. This survey highlights concepts drawn from the literature and indicates how these influenced the direction of our work.

1.3 Selection of Active Antenna Type

In principle, this study was not restricted to active tuning of Yagi antennas with crossed dipoles. The alternatives of a loop element Yagi or other tunable travelling wave antennas were not seriously considered due to lack of information about the design of these antenna types. Hence, all our effort was on the tunable crossed-dipole Yagi antenna.

1.4 Computer Program Development for Electrical Design

The computer program was developed to provide the capability of optimizing the antenna element lengths, positions (spacings), and radii. The measure of performance includes the average and flatness across the receive and/or transmit bands of both the directivity and the antenna feed mismatch loss. The program was developed in a progressive manner from a single frequency case with directivity as a measure to the present stage just described. Section 2 gives the description of the program in more detail, the algorithm, and the objective or cost function definition.

1.5 Mechanical Design

The criteria for the mechanical design were dictated by the choice of the crossed Yagi array. In addition to the specified collapsibility and stability requirements, system reliability was considered of utmost importance. Models for the wind drag were adapted to suit the antenna structure for stability calculations. The approach to design for collapsibility and reliability was to devise several systems with different configurations, mechanisms and materials and choose the best characteristics for the design results, or those that met or exceeded specifications.

1.6 Summary of Results

We have produced an antenna system design with a performance that approaches the 13 dBi gain and meets all the other specifications considered. For example, the 14 element design of the crossed Yagi tunable antenna gives a minimum of 11.5 dBi in the receive band and with a single tuning covers the transmit band with a minimum gain of 12.3 dBi. No matching network is required at the feed port. This antenna has a practical length of 2 metres. De-polarization was not considered.

The resulting antenna system is designed such that normal service should cause no deterioration of performance due to mechanical wear. When collapsed, the system is contained in two packages easily transportable by back pack and of a mass less than ten kilograms.

2. The Computer Program for Electrical Design

The computer program used to obtain the Yagi antenna designs presented in this report searches for the minimum of an objective function, which reflects directivity and mismatch loss criteria, and yields the corresponding antenna parameters. Control parameters specify the selection of optimization frequency bands and choice of antenna parameters to be varied to obtain an optimum. The results of each optimization attempt include, for each frequency, the current coefficients, a printed plot of the H and E plane patterns, forward directivity, efficiency, gain, input impedance, and antenna feed mismatch loss. The resulting antenna parameters are also printed.

The program is written in FORTRAN and all documentation is self-contained. To understand the program thoroughly, one would have to be familiar with the optimization algorithm (Fletcher-Reeves conjugate gradient method [1]), and the method of moments which is used for determining the antenna performance. Appendix C describes the model used for the antenna and cites the work on which the model is based. The program was developed from one provided by Kajfez [2]. A concise description of the algorithm is given in the next section.

The objective function for the optimization routine is defined in Section 2.2. The main skill needed in the use of this objective function is the choice of weights.

2.1 Computer Program Algorithm Description

1. Initialize the antenna parameters, and specify the receive and transmit band limits. Set control parameters for next step. If requested, analyze these parameters using Step 4 and return.
2. Branch to analysis or optimization for receive, transmit, or both bands, and specify element parameters to be varied (any combination of lengths, spacings and radii can be chosen). Specify element parameters that are of common length, or vary independently between each band (this corresponds to the effective lengths for capacitively tuned elements in the transmit band).
3. Minimize the cost function using a conjugate gradient method (Fletcher and Reeves) and three point quadratic estimation. This method determines the class of variable (receive or transmit lengths, spacings, or radii), for

which the largest gradient in the cost function occurs. Then using either steepest descent or a conjugate direction change test parameters are computed for the particular class of variable. As the cost function approaches a minimum three point quadratic estimation is used to approach the minimum. If no reduction of the cost function can be achieved using the above method a random search is attempted.

If the terminating criteria of evaluation limit or minimum change in cost function are not met all previous operations are repeated with new parameter values, otherwise branch to next step.

4. Print performance information for each frequency: H-plane and E-plane patterns, current coefficients, element parameters, input impedance and admittance, mismatch loss, efficiency, forward directivity and gain, and front-to-back ratio of respective directivities.

2.2 Cost Function

The object function of the optimization routine can be viewed as a combination of various measures of performance. The combination represents the relative importance of each measure and whether the quantity is to be maximized or minimized. The measures of performance we have included in our cost function are the average directivities for each passband, the root-mean-square (RMS) deviation of the directivities from these averages, and the mismatch averages and RMS deviations for each passband.

The average directivities for the receive (j=1) and transmit bands (j=2), are the averages of the decibel values, (defined in Appendix D) for D as a function of frequency:

$$\bar{D}_j = \frac{1}{N_j} \sum_{n=1}^{N_j} D_j(f_{jn}) \text{ dB} \quad ,$$

where the f_{jn} are uniformly spaced frequencies in the respective passbands. The RMS deviations from the averages are

$$S_j = \{ \frac{1}{N_j} \sum_{n=1}^{N_j} D_j^2(f_{jn}) - \bar{D}_j \}^{1/2} \text{ dB} \quad .$$

The mismatch loss at the input terminals of the antenna is also important to obtaining the desired gain. The relationship for the mismatch

is given in Appendix D. The expressions for the average R_j and RMS deviations U_j of the mismatch losses are:

$$\overline{R}_j = \frac{1}{N_j} \sum_{n=1}^{N_j} R(f_{jn}) \text{ dB}, \quad j = 1,2 \quad ,$$

and

$$U_j = \{ \frac{1}{N_j} \sum_{n=1}^{N_j} R^2(f_{jn}) - \overline{R}_j \}^{1/2} \text{ dB} \quad .$$

The cost function for each band is obtained by selecting weights for the above expressions to give us the costs

$$C_j = -\overline{D}_j + w_s S_j + w_r \overline{R}_j + w_u U_j \quad ,$$

where $j = 1$ or 2 for receive or transmit values.

The cost function for both receive and transmit bands is given by

$$C = C_1 + w_t C_2 \quad .$$

3. Antenna Design

3.1 Electrical Design

The antenna design was for a crossed Yagi array with sufficient bandpass for either the receive or transmit mode, and director element active tuning to allow switching between the receive and transmit modes. The switching is visualized as being accomplished by centrally loading the directors with varactor capacitance. It was decided that the driven elements and the reflector would not be actively loaded. In the case of the driven elements the high transmit signal levels would result in harmonic generation and produce distortion products. The reflector, it was thought, could be positioned and sized to act commonly for both bands.

Each Yagi in the crossed Yagi array would be designed for an input impedance of 50 ohms with the active element driven in an unbalanced mode. A single 3 dB quadrature hybrid coupler with 40% fractional bandwidth and base impedance of 50 ohms would excite the driven elements in phase quadrature for circular polarization radiation. In the receive mode the hybrid recombines the signal polarization components and provides transmitter-receiver isolation.

The configuration for the integration of the varactors, RF isolators (chokes) for varactor bias and a physical mount for the directive elements is in the form of a cylindrical housing. Figure 3.1 shows a conceptual component layout inside the director support hub. Each director is centrally loaded with two varactors in a series electrical connection which has the advantage of allowing a minimum capacitive loading which is half the minimum varactor capacitance.

The basic approach to the design was to progress from the simplest case to the most complex. Hence, we started with 6 elements and one frequency in either the receive or transmit bands, and used a cost function for directivity only. Through this work we learned the choice of frequency for the optimization that gave the best performance across the band of interest. The number of elements was increased up to 10 elements, the limit of the single frequency version of the program. This version only allowed optimization of element lengths. To accommodate the concept of tuning the directors, we allowed these element lengths to vary independently between the two bands. This approach assumed that we could achieve the desired performance without tuning in either band.

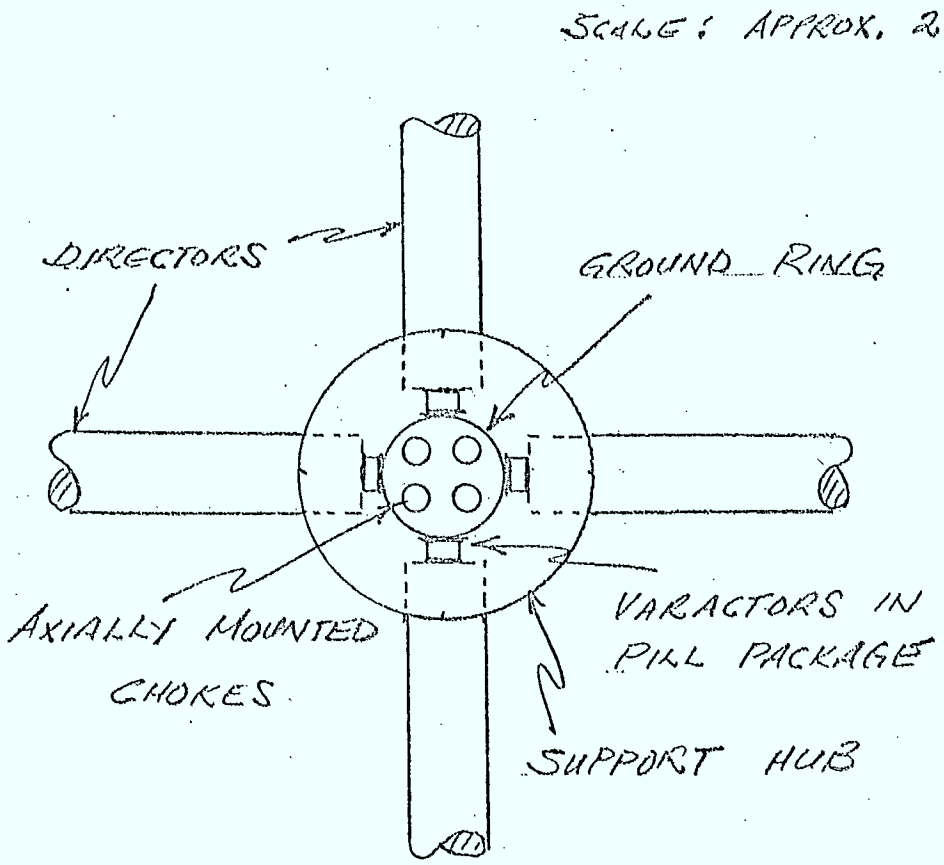


Fig. 3.1 Director support housing with internal component layout.

This single frequency program was modified to use a cost function with directivity and antenna feed mismatch loss. The mismatch results referred to a 50 Ω input impedance for the transmit band showed that even with heavy weighting on the mismatch portion of the cost function, the specified VSWR could not be met. Further, the forward directivity was considerably less along with higher sidelobes than the receive band values. Clearly, some new approach was needed to allow any improvement.

At this stage we chose to add a "transmit band" reflector to improve the directivity and a load element near the driven element to modify its current distribution and give us the desired input impedance. The results were very promising and it became clear that the modified program, being developed at the same time, was necessary to optimize the element spacings and radii to obtain the desired performance.

While this work was progressing, a modified version of the program which uses the cost function described in Section 2.2 was developed. We used the results of the single frequency study to start the design of the antenna to give the desired performance across the receive or transmit bands. The element lengths and spacings were initially optimized in each band. As expected the values for the untuned elements differed for these separate optimizations. To obtain a compromise the program was changed to allow specification of those elements that could be varied in each band but must be common (untuned) for both bands. These common elements include the driven element and the two reflectors. It should be noted that we assumed tuning was unnecessary for the reflectors since their lengths and spacings should dominate in only one band. The driven element cannot be tuned due to the power handling capacity of varactors.

We should point out that the single tuning approach to the design would allow us to use an alternative method for tuning, and this method can also be used for the driven element. In place of the varactors and biasing system we could use fixed capacitive loads, with a PIN diode switch that shorts the load for receive operation, to give the desired tuning. The power handling capacity of these loads would allow tuning of the driven element. Tuning the driven element is most important to the input impedance, and the fixed capacitor/PIN tuning load would give us the extra variable needed to achieve a match, possibly without the use of the parasitic loading element in the present designs. The idea for this approach

occurred near the end of our work and it is not reflected in the optimization work described in the following.

Optimization results for a 10 element 50 ohm input impedance structure showed that the VSWR specification in the transmit band could not be met without adding further matching elements to the structure. (Later numerical experiments on a 9 element structure verified that the mismatch loss could be improved by adding an element between the reflectors and the driven element.)

At this stage we chose to explore a design based on an antenna input impedance of 100 ohms. This requires the driven element to be excited by a balanced generator. A 50 ohm to 100 ohm unbalanced to balanced transformer is required at each quadrature hybrid output. The antenna could be matched to 100 Ω in the receive and transmit bands and optimization of performance was proceeded with for 10, 12, 14 and 16 element structures. Detailed results are reported in Appendix E.

The antenna axial polarization ratio performance was not investigated. The on-axis depolarization is dependent on the cross-polarization due to the gap fields of the driven elements, the amplitude balance and quadrature phase deviation between outputs of the feed network and also the physical misalignment of the antenna elements. The cross-polarization effects are small provided the excitation gaps are in the order of 0.02λ according to Mendelovicz and Adams [18]. Measurements on an antenna model are required to satisfactorily assess this performance factor.

The off-axis depolarization due to the antenna radiation characteristics could have been calculated but manpower and time resources were not available to do so.

3.2 Mechanical Design

The mechanical design criteria for the antenna system concern collapsibility, stability, and reliability. The electrical performance requirements must be accommodated, also. The criteria for collapsibility include constraints on size and weight of the package(s). Since the antenna system is intended to be portable by man on foot, size restrictions dictate that no single package dimension exceed approximately 600 mm. The weight should be minimum for carrying, but sufficient for stability when the antenna is deployed. The criteria for stability are that the wind drag be minimized, and that the centres of drag and gravity be as close to the ground as possible. These criteria influence the selection of a method for collapsing the antenna system. We consider the most important criteria for reliability to be the performance of the antenna system over a large range of temperatures and long periods of time. The following design considerations are based on these criteria.

Initially, during the antenna type selection stage of this work, we considered configurations for backfire and arrays of antennas. The crossed Yagi array antenna was selected for detailed design and most of the mechanical design has been dictated by this choice. Initially, one objective of the design for collapsibility was to keep most of collapsed system connected together for simple and reliable assembly. This approach requires the use of hinges and plug-in elements. For example, with the expected antenna length of 1.5m to 2m , and the constraint on collapsed size, a central mast for the Yagi would have to be broken into at least two segments. Further, the crossed-dipole elements would either have to fold or be removable. Both these mechanisms could lead to poor electrical contact for the function of the varactor biasing system or in contact between the dipole halves. The mechanical positioning and rigidity of mechanical contacts for the desired performance would also be difficult to meet. A large central mast required for mechanical support of hinges would also increase the wind drag, and raise centres of drag and gravity of the system, thereby reducing stability. In order to reduce wind drag and lower the centre of gravity, an open frame support of all but the active element was developed. Since the reduction in wind loading was greater than the reduction in weight the stability of the system was increased. This system

allows all elements to be packaged together in a single container approximately 310 mm deep by 550 mm wide, while maintaining undisturbed electrical contact. The support rods of the frame may then be removed and packaged with the tripod. The method for collapsing the antenna was chosen to maximize electrical performance by avoiding friction contacts such as plug-in elements or hinged elements that were originally considered. This approach also meets the stated reliability objectives for temperature of operation and durability.

4. Antenna Performance Evaluation

4.1 Analysis of Results for 10, 12, 14 and 16 Element Yagi Antenna Electrical Designs

A summary of the antenna parameters for these designs is given in Table 4.1. The antenna configurations are illustrated in Figure 4.1 for the 12 and 14 element designs. The resulting measures of performance are summarized in Table 4.2. Detailed performance results are given in Appendix E.

We are mainly concerned with the antenna directivities, and Figure 4.2 shows how these vary with element number and frequency. These plots show two fundamental characteristics of Yagi antennas. First, the increase in directivity with element number approaches a rate at which it is not worthwhile to add more elements. Second, the directivities for larger electrical spacings (transmit frequency) are greater. Actually, there are peaks in the directivity as this spacing is increased, as shown by King et al [20, page 221].

The results show that the desired gain of 13 dB (minimum) in the receive band cannot be achieved for reasonably sized antennas (the 16 element is 2.5m long) and the single tuning approach. (This does not preclude 13 dB gains, if a multiple tuning approach is used for each band.) The results also show that the improvement of the 14 element directivity in each band over the 12 element directivity was not proportional to the increase from 10 to 12 elements. This is primarily due to the optimization in the transmit band to reduce the mismatch loss. This result was used, without further dual band optimization, to obtain the receive band performance. Hence, it appears that the performance of the 14 element array could be further improved.

The summaries in Table 4.2 indicate that the VSWR specification of 1.5 to 1 maximum, which corresponds to a 0.18 dB mismatch loss, can be met, except for the 0.48 and 0.22 dB values of the 12 element transmit design, a 0.31 dB value in the 14 element transmit design, and a 0.63 dB value in the 16 element transmit design. These results do indicate the relative difficulty we experience in obtaining the required match across the transmit band, compared to the results for the receive band.

The detailed results in Appendix E include the H and E plane patterns. The additional measure of performance available from these is the sidelobe

levels at all the different frequencies for the 10, 12, 14 and 16 element designs. Very few of these levels exceed -10 dB relative to the maximum.

4.2 Emulating the Reactively Loaded Elements

We chose to use effective physical lengths for the antenna elements in both receive and transmit bands. This replacement of the physical length with a load by an effective length over the band does not include the load's frequency dependence and the match points are moved from the physical locations on the actual loaded element. Our concept was that the load could be determined from the difference between input impedances of each director for its actual length and for the effective length. To obtain the input impedances for this difference we consider the element of interest be driven while others are passive. With a unit source voltage the input impedance for the actual length is Z_A, the antenna unloaded impedance. The input impedance for the effective length is $Z_A + Z_L$, where Z_L is the desired load impedance. The element lengths in the receive band are used as the actual lengths. This assumes that for the receive band the directors are unloaded. This unloaded condition could not exactly be achieved with varactors, and possibly a better scheme would be to use PIN diodes to short fixed capacitive loads instead of varactors.

We have computed the required load impedances for the designs with 10 and 12 elements. The capacitances required to obtain the reactive component of Z_{Lm}, for the mth element in each antenna, have also been calculated. The data are presented in Table 4.3. These data show that the capacitances would be easily obtained by commercial varactors since these can provide 0.1 pF to 50 pF. Also fixed or tunable capacitors, with a PIN diode switch, could meet the tuning requirements.

10 ELEMENTS

A		H (REC)		H (TRN)		Y	
CM	INCH	CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	20.800	8.189	-22.600	-8.898
0.500	0.197	17.100	6.732	16.000	6.299	5.400	2.126
0.350	0.138	20.100	7.913	14.600	5.748	11.900	4.685
0.350	0.138	17.600	6.929	17.100	6.732	29.700	11.693
0.350	0.138	20.800	8.189	15.700	6.181	41.800	16.457
0.300	0.118	19.600	7.717	15.000	5.906	54.700	21.535
0.300	0.118	20.600	8.110	16.400	6.457	77.600	30.551
0.300	0.118	19.400	7.638	14.500	5.709	98.700	38.858

12 ELEMENTS

A		H (REC)		H (TRN)		Y	
CM	INCH	CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	20.400	8.031	-22.200	-8.740
0.500	0.197	17.100	6.732	16.200	6.378	5.700	2.244
0.650	0.256	20.000	7.874	14.700	5.787	12.100	4.764
0.650	0.256	17.700	6.969	16.500	6.496	29.700	11.693
0.500	0.197	21.100	8.307	15.500	6.102	41.900	16.496
0.400	0.157	19.700	7.756	15.300	6.024	54.600	21.496
0.650	0.256	20.600	8.110	16.000	6.299	77.200	30.394
0.650	0.256	19.500	7.677	14.800	5.827	98.800	38.898
0.500	0.197	18.900	7.441	14.100	5.551	119.400	46.614
0.400	0.157	19.100	7.520	14.200	5.591	138.800	54.646

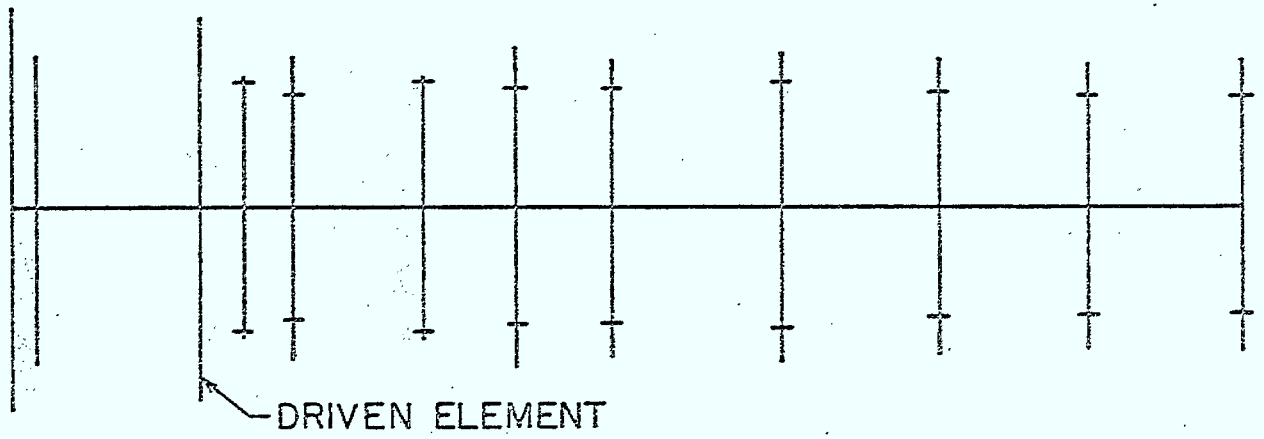
14 ELEMENTS

A		H (REC)		H (TRN)		Y	
CM	INCH	CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.110	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	20.950	8.248	-17.200	-6.772
0.500	0.197	17.200	6.772	16.760	6.598	4.800	1.890
0.400	0.157	19.000	7.480	15.000	5.906	12.100	4.764
0.350	0.138	18.400	7.244	16.970	6.681	25.200	9.921
0.300	0.118	21.800	8.583	15.910	6.264	38.900	15.315
0.350	0.138	20.000	7.874	15.260	6.008	54.100	21.299
0.200	0.079	20.900	8.228	16.490	6.492	73.900	29.094
0.330	0.130	20.500	8.071	14.860	5.850	96.300	37.913
0.300	0.118	19.000	7.480	14.280	5.622	117.800	46.378
0.250	0.098	19.500	7.677	13.880	5.465	140.000	55.118
0.330	0.130	20.200	7.953	14.870	5.854	155.500	61.220
0.330	0.130	19.300	7.598	15.150	5.965	179.600	70.709

16 ELEMENTS

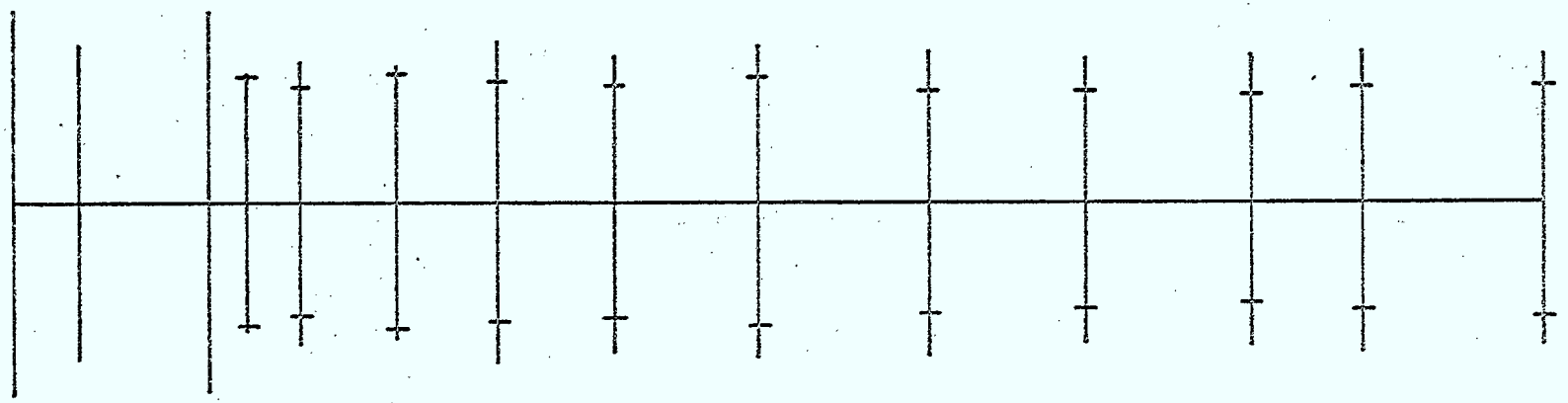
A		H (REC)		H (TRN)		Y	
CM	INCH	CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	25.700	10.118	-26.300	-10.354
0.250	0.098	20.600	8.110	20.900	8.228	-17.900	-7.047
0.510	0.201	17.200	6.772	16.600	6.535	5.600	2.205
0.360	0.142	19.000	7.480	14.900	5.866	11.700	4.606
0.360	0.142	18.400	7.244	17.100	6.732	27.000	10.630
0.360	0.142	21.800	8.583	15.800	6.220	38.900	15.276
0.300	0.118	20.000	7.874	15.200	5.984	54.400	21.417
0.300	0.118	20.900	8.228	16.400	6.457	74.490	29.291
0.300	0.118	20.500	8.071	14.600	5.827	96.800	38.110
0.300	0.118	19.000	7.480	14.200	5.591	117.690	46.299
0.300	0.118	19.500	7.677	13.800	5.433	140.400	55.276
0.300	0.118	20.200	7.953	14.800	5.827	155.200	61.102
0.300	0.118	19.300	7.598	15.100	5.945	180.600	71.102
0.300	0.118	19.700	7.756	15.500	6.102	200.100	78.780
0.300	0.119	20.000	7.874	16.000	6.299	220.900	86.614

TABLE 4.1 ANTENNA PARAMETERS FOR 10, 12, 14, AND 16 ELEMENT DESIGNS.
A IS ELEMENT RADIUS, 2 H(REC) IS RECEIVE BAND ELEMENT LENGTH, 2 H(TRN) IS TRANSMIT BAND EFFECTIVE ELEMENT LENGTH, Y IS ELEMENT POSITION.



Scale: 1mm=1cm

(a) 12 ELEMENT ANTENNA 1.640 m long



(b) 14 ELEMENT ANTENNA 2.058 m long

Fig. 4.1. CONFIGURATION OF OPTIMUM YAGI ANTENNAS. DIRECTOR EFFECTIVE LENGTHS FOR TRANSMIT BAND ARE SHOWN BY TIC MARKS.

(a) RECEIVE BAND PERFORMANCE SUMMARY 10 ELEMENTS

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
274.00	76.79	9.85	0.0128	-0.0016	0.089	-0.0023	9.92	9.92	11.25
278.00	89.24	10.03	0.0112	-0.0013	0.029	-0.0021	9.93	9.93	11.58
282.00	97.69	6.74	0.0102	-0.0007	0.006	-0.0021	9.91	9.91	11.65
286.00	103.64	0.81	0.0096	-0.0001	0.001	-0.0021	9.89	9.89	11.64
290.00	105.03	-6.14	0.0095	0.0006	0.007	-0.0021	9.87	9.86	11.65

TRANSMIT BAND PERFORMANCE SUMMARY

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
370.00	153.48	-12.12	0.0065	0.0005	0.207	-0.0023	9.79	9.79	13.52
377.50	134.22	-0.20	0.0075	0.0000	0.094	-0.0021	9.93	9.93	14.59
385.00	120.96	16.18	0.0081	-0.0011	0.062	-0.0021	10.16	10.16	16.68
392.50	115.20	30.47	0.0081	-0.0021	0.108	-0.0021	10.43	10.42	21.36
400.00	99.96	28.94	0.0092	-0.0027	0.090	-0.0021	9.97	9.97	22.59

(b) RECEIVE BAND PERFORMANCE SUMMARY 12 ELEMENTS

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
274.00	72.78	8.72	0.0135	-0.0016	0.120	-0.0024	11.20	11.20	13.65
278.00	84.90	10.50	0.0116	-0.0014	0.043	-0.0023	11.29	11.28	13.46
282.00	96.45	7.33	0.0103	-0.0008	0.007	-0.0022	11.32	11.32	12.86
286.00	104.05	-1.31	0.0096	0.0001	0.002	-0.0022	11.30	11.30	12.27
290.00	103.81	-12.68	0.0095	0.0012	0.018	-0.0023	11.24	11.23	11.71

TRANSMIT BAND PERFORMANCE SUMMARY

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
370.00	145.53	6.50	0.0069	-0.0002	0.155	-0.0024	11.35	11.35	16.15
377.50	124.87	22.34	0.0078	-0.0014	0.096	-0.0023	11.50	11.50	16.82
385.00	113.05	47.21	0.0075	-0.0031	0.224	-0.0022	11.76	11.76	18.76
392.50	122.79	72.29	0.0060	-0.0036	0.480	-0.0022	12.15	12.15	24.54
400.00	126.04	32.43	0.0074	-0.0019	0.147	-0.0023	11.86	11.85	20.58

Table 4.2 Summaries of Performance for 10, 12, 14, and 16 Element Yagi Antenna Designs (page 1 of 2)

(c) RECEIVE BAND PERFORMANCE SUMMARY 14 ELEMENTS

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
274.00	70.67	10.39	0.0139	-0.0020	0.146	-0.0031	11.49	11.48	10.11
278.00	85.44	11.09	0.0115	-0.0015	0.042	-0.0030	11.65	11.65	11.27
282.00	98.00	5.83	0.0102	-0.0006	0.004	-0.0030	11.72	11.72	12.10
286.00	104.96	-3.89	0.0095	0.0004	0.004	-0.0031	11.72	11.72	12.58
290.00	104.42	-14.25	0.0094	0.0013	0.023	-0.0032	11.67	11.66	12.84

TRANSMIT BAND PERFORMANCE SUMMARY

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
370.00	154.82	-41.29	0.0060	0.0016	0.318	-0.0031	12.27	12.27	10.46
377.50	110.21	-24.09	0.0087	0.0019	0.067	-0.0030	12.47	12.47	13.24
385.00	88.15	10.14	0.0112	-0.0013	0.040	-0.0030	12.74	12.73	13.44
392.50	97.13	37.29	0.0090	-0.0038	0.154	-0.0031	13.25	13.24	15.77
400.00	70.60	4.26	0.0141	-0.0009	0.134	-0.0032	13.08	13.06	18.53

(d) RECEIVE BAND PERFORMANCE SUMMARY 16 ELEMENTS

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
274.00	73.36	16.37	0.0130	-0.0029	0.142	-0.0031	12.07	12.07	9.40
278.00	89.32	15.86	0.0109	-0.0019	0.044	-0.0030	12.20	12.20	10.59
282.00	100.69	10.02	0.0098	-0.0010	0.011	-0.0030	12.27	12.26	11.99
286.00	106.44	3.12	0.0094	-0.0003	0.005	-0.0030	12.32	12.32	13.65
290.00	102.94	-2.60	0.0092	0.0002	0.009	-0.0032	12.38	12.38	15.29

TRANSMIT BAND PERFORMANCE SUMMARY

FREQUENCY	IMPEDANCE		ADMITTANCE		MISMATCH	EFFICIENCY	DIRECTIVITY	GAIN	FRONT/BACK
370.00	143.36	-41.42	0.0064	0.0019	0.264	-0.0031	12.66	12.66	12.47
377.50	94.91	-18.40	0.0104	0.0011	0.015	-0.0030	12.63	12.62	10.61
385.00	75.37	35.60	0.0108	-0.0051	0.262	-0.0030	12.78	12.78	10.23
392.50	94.77	77.02	0.0064	-0.0052	0.634	-0.0030	13.44	13.44	11.42
400.00	76.49	31.40	0.0112	-0.0046	0.273	-0.0032	12.64	12.63	13.00

Table 4.2 Summaries of Performance for 10, 12, 14, and 16 Element Yagi Antenna Designs (page 2 of 2)

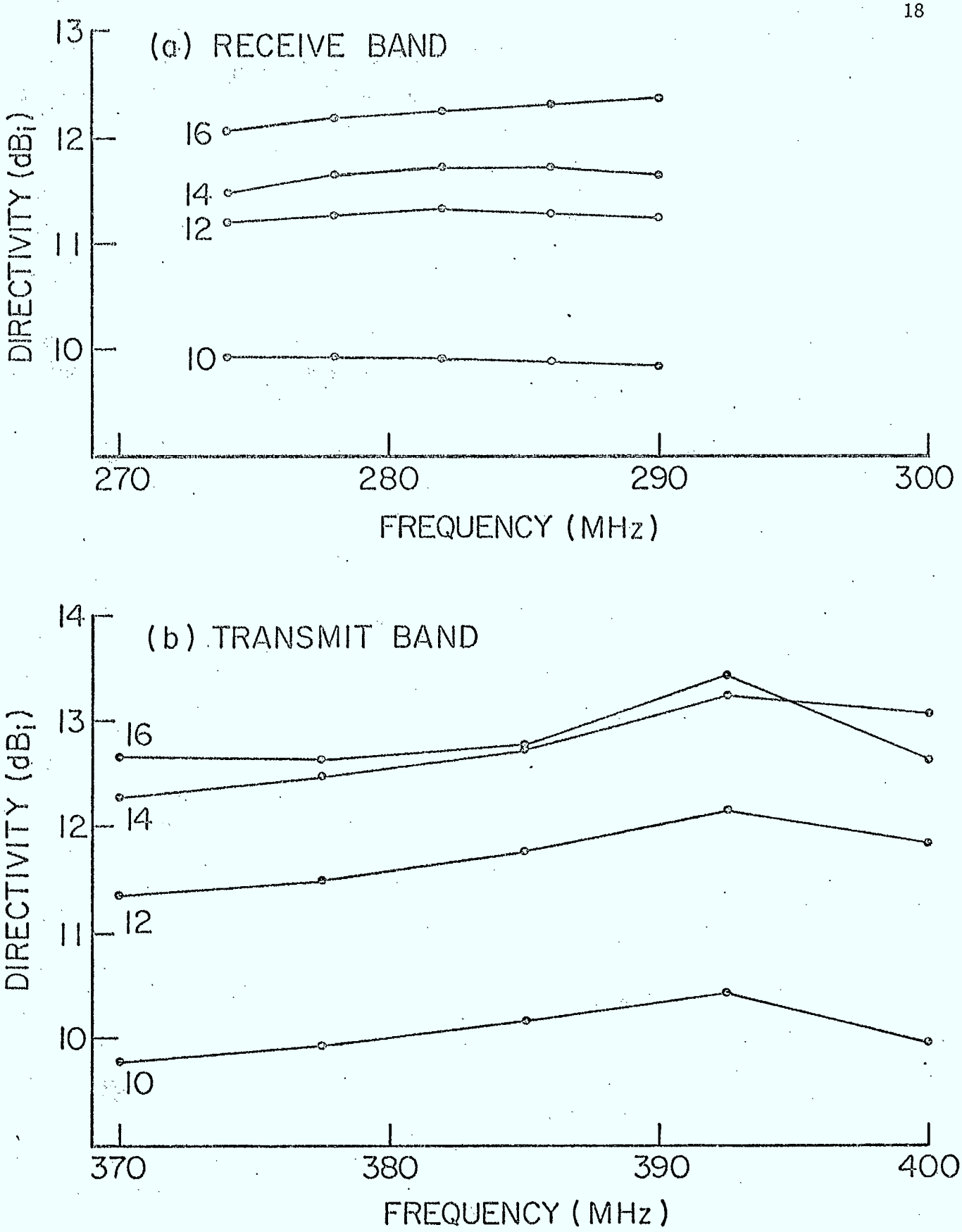


Fig.4.2. DIRECTIVITIES FOR 10, 12, 14 AND 16 ELEMENT ANTENNAS. (a) RECEIVE BAND. (b) TRANSMIT BAND.

EL NO	IMPEDANCE (OHMS)		CAPACITANCE (PF)	FREQUENCY (MHZ)
				370.0
4	-4.809	-31.774	13.5380	
5	-63.853	-190.657	2.2561	
6	-3.039	-14.436	29.7966	
7	-43.036	-160.163	2.6857	
8	-41.640	-153.907	2.7949	
9	-38.166	-145.736	2.9516	
10	-39.804	-160.235	2.6845	
				377.5
4	-5.999	-32.592	12.9358	
5	-80.620	-189.708	2.2224	
6	-2.925	-14.885	28.3236	
7	-50.456	-160.181	2.6320	
8	-42.683	-154.190	2.7343	
9	-43.862	-152.265	2.7689	
10	-37.647	-165.319	2.5502	
				385.0
4	-7.391	-33.155	12.4685	
5	-98.121	-178.944	2.3102	
6	-2.798	-15.469	26.7235	
7	-54.667	-154.461	2.6763	
8	-40.134	-157.510	2.6245	
9	-51.349	-156.384	2.6434	
10	-38.788	-176.693	2.3396	
				392.5
4	-8.453	-33.462	12.1181	
5	-105.453	-160.692	2.5234	
6	-2.638	-16.223	24.9948	
7	-45.595	-148.212	2.7359	
8	-37.936	-170.811	2.3739	
9	-55.194	-155.511	2.6075	
10	-49.536	-186.715	2.1717	
				400.0
4	-8.833	-35.244	11.2896	
5	-112.337	-151.908	2.6193	
6	-2.418	-17.285	23.0190	
7	-29.323	-165.520	2.4039	
8	-54.118	-197.160	2.0181	
9	-44.808	-164.060	2.4253	
10	-55.456	-181.363	2.1939	

Table 4.3 Required Centre Loading Impedances for Transmit Frequency Operation and Corresponding Capacitance Values in the 370 to 400 MHz Band. 10 Element Antenna. (page 1 of 2)

EL NO	IMPEDANCE (OHMS)		CAPACITANCE (PF)	FREQUENCY (MHZ)
				370.0
4	-4.886	-25.931	16.5883	
5	-75.107	-145.000	2.9665	
6	-6.461	-27.757	15.4968	
7	-57.406	-156.313	2.7518	
8	-40.879	-129.500	3.3216	
9	-45.276	-131.906	3.2610	
10	-35.502	-117.521	3.6602	
11	-38.133	-136.724	3.1461	
12	-38.508	-144.372	2.9794	
				377.5
4	-6.259	-26.364	15.9917	
5	-93.865	-135.113	3.1204	
6	-6.313	-29.083	14.4966	
7	-67.999	-149.202	2.8257	
8	-37.287	-129.294	3.2608	
9	-56.268	-138.576	3.0424	
10	-34.126	-128.991	3.2685	
11	-45.104	-134.298	3.1393	
12	-38.582	-154.520	2.7285	
				385.0
4	-7.817	-26.041	15.8744	
5	-103.946	-108.519	3.8094	
6	-6.188	-30.565	13.5249	
7	-67.154	-131.900	3.1341	
8	-29.676	-136.601	3.0263	
9	-70.219	-137.481	3.0069	
10	-44.295	-142.324	2.9046	
11	-42.292	-127.278	3.2479	
12	-51.143	-165.154	2.5031	
				392.5
4	-7.987	-25.056	16.1831	
5	-87.081	-86.985	4.6616	
6	-5.689	-32.489	12.4808	
7	-42.838	-125.966	3.2190	
8	-26.223	-156.288	2.5945	
9	-68.180	-123.557	3.2818	
10	-61.413	-142.932	2.8369	
11	-30.239	-134.843	3.0071	
12	-67.382	-158.806	2.5534	
				400.0
4	-6.599	-27.387	14.5282	
5	-81.216	-97.844	4.0665	
6	-4.925	-35.850	11.0987	
7	-23.349	-154.756	2.5711	
8	-38.012	-191.854	2.0739	
9	-40.306	-146.046	2.7244	
10	-57.842	-125.159	3.1791	
11	-39.317	-156.266	2.5462	
12	-54.694	-148.346	2.6822	

Table 4.3 Required Centre Loading Impedances for Transmit Frequency Operation and Corresponding Capacitance Values in the 370 to 400 MHz Band. 12 Element Antenna. (page 2 of 2)

4.3 Results for Mechanical Design

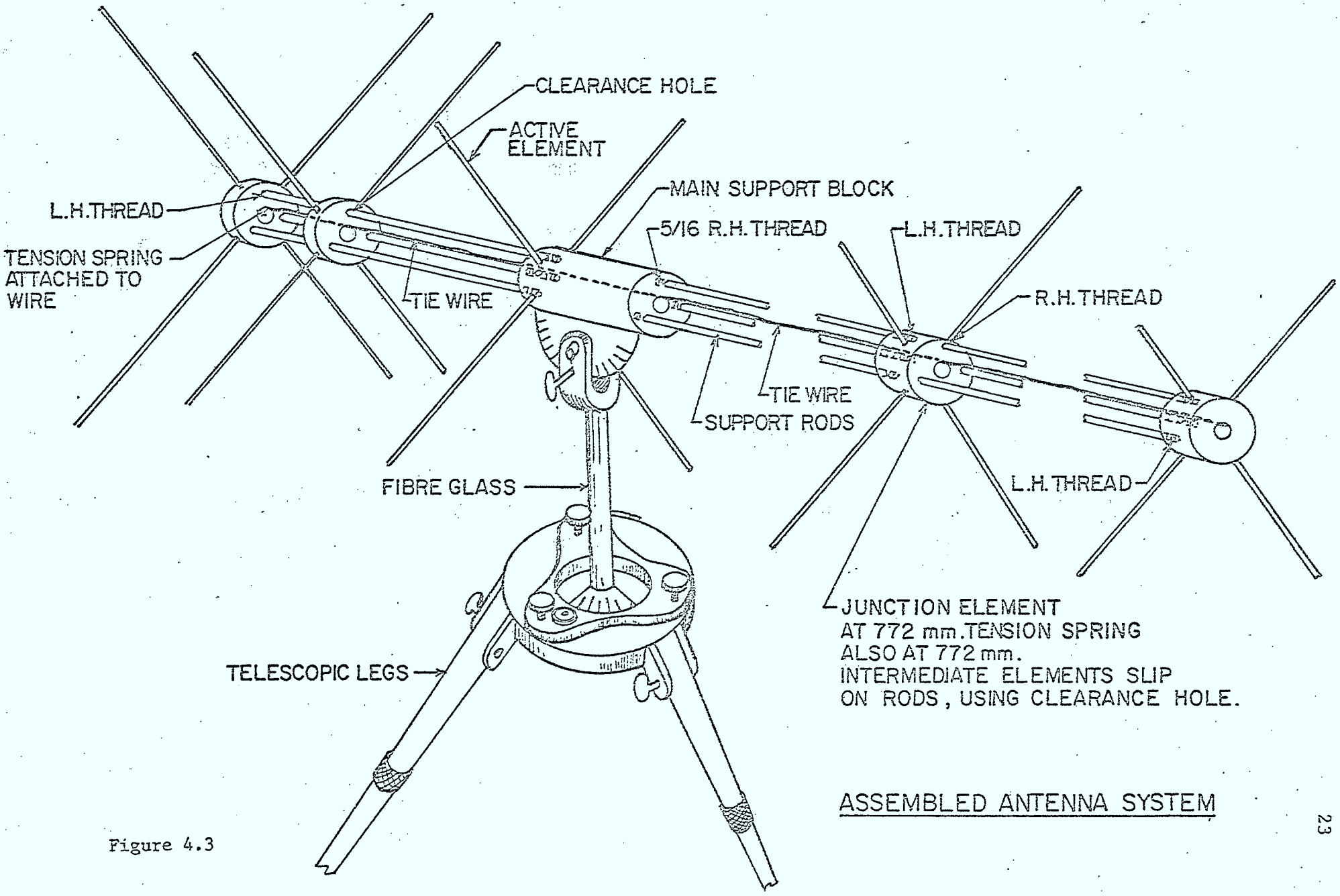
The results of this design work are presented for the 12 element antenna. Some minor modifications for wind loading and tripod base spread would be required for the antennas with different numbers of elements.

In order to ensure good performance, each of the twelve crossed-dipole elements is designed as an integral structure, consisting of a disc of aluminum approximately 12mm thick and 30mm in diameter with a central hole 10mm in diameter. The aluminum rods or tubes forming the elements of the antenna are permanently fastened to the disc. To provide an electrical ground for the varactor biasing system, the discs are joined by a braided, copper coated wire. This wire serves the three purposes of ensuring electrical contact between elements, ensuring proper spacing of the elements and, by fastening each disc permanently to the wire, ensuring that the elements are always maintained in the correct order. The elements can be stacked and placed in a protective container for transport.

The arrangement of the antenna system is shown in Figure 4.3. The antenna has been balanced about the active element to minimize torques produced by both static weight and wind loading. By supporting the antenna at the active element, the physical dimensions required for the electronics for the active elements can also be used to provide strength for structural support and for the elevation mechanism. The forward elements are supported by three rods. These rods are threaded into the support block (active element and support) using a right hand thread and into the end element using a left hand thread. The rods slide through the other elements and are twisted to tighten the threaded connections, thus forming a strong rigid support and maintaining the elements in the proper plane. The rear two elements are attached in a similar manner, using slightly larger diameter rods to improve weight balance. The end elements, both front and rear, are attached to the retaining wire by a spring washer and the rod holes in these rods are threaded using a left hand thread. The spring allows the end element to be displaced sufficiently to assemble and retains sufficient tension on the retaining wire after assembly to maintain proper element spacing.

The support block has a tongue attached which is calibrated for elevation. The tongue is supported on a fibre glass yoke and rod, the yoke incorporating the elevation read out and locking screw. At the lower end,

the rod screws into an azimuth read out plate which can be adapted to a standard tripod head. Fibre glass was chosen for the support rod to insulate the antenna from ground, to interfere as little as possible with the radio signals, and to ensure that the support rod does not fracture easily in cold weather. The calculations of mass, wind loading and tripod leg spread are given in Appendix F along with more detailed drawings of the support system.



ASSEMBLED ANTENNA SYSTEM

Figure 4.3

5. Conclusions and Recommendations

5.1 Electrical Design Conclusion

The electrical design results in the previous section show that a practical antenna with a performance that approaches the specified criteria can be realized. The following two points indicate the degree of our success.

First, our objective of complete transmit band coverage with single tuning of the director loads has been met. A consequence of the simplicity of this tuning is that it restricts the gains which can be achieved. For example, with a practical antenna length, such as the 14 element one, we obtain a minimum gain of 11.5 dBi in the receive band and 12.3 dBi in the transmit band. Clearly, with single tuning, the specified 13 dBi minimum gain cannot be met, but the gain is well above that for a possible 3 dB reduction in this specification.

Second, we have essentially achieved the VSWR specification without the need for any external matching network. Such networks would add loss and complexity to the complete antenna system, and the networks may not be practical. The receive band mismatch loss in all cases is well below the maximum value of 0.2 dB. In the transmit band this value has been exceeded for a few frequencies. Further optimization at a small cost to the transmit band gain would bring these mismatch losses within the VSWR specification.

Antenna depolarization was studied to the extent that we have determined the main causes of depolarization. We have not spent sufficient time on this aspect of the antenna performance to obtain results. Our limited study does not indicate any real difficulties in meeting the desired depolarization performance.

5.2 Mechanical Design Conclusion

A man-portable earth station antenna can be built to withstand 70 mph wind gusts without toppling. The minimum mass required for the structure is approximately 6 kg and the required mass for stability in wind is approximately 10 kg. The crossed Yagi antenna of 12 elements can be collapsed into two packages; one package shaped as a cross 600 mm across each side from tip to tip and the other package 20 mm in diameter and 780 mm long. The system should require less than five minutes to assemble.

5.3 Recommendations

Additional studies are necessary to arrive at a final working antenna. These are:

a) A further development of the computer program to enable it to optimize on the basis of actual element active loading rather than on an effective length basis. (We have given the numerical method for loading in Appendix C.) This extension of the program is important not only to improve the accuracy of the modelling but also to permit an optimization which would allow element tuning in both receive and transmit bands and even multiple in-band tuning. We suggest in-band tuning since it would yield higher antenna gains, possibly in the 14 dBi range, with very few settings per band.

b) The evaluation of the antenna depolarization performance for both on-axis and off-axis cases. This study is necessary in order to set the amplitude balance and quadrature phase deviation performance of the feed network.

c) A parameter sensitivity error analysis should be performed. The effects on antenna performance due to element dimension change and position, tuning device parameter deviation from nominal, temperature changes, etcetera, need evaluation. This evaluation can be performed with a combination of analytical and numerical methods, and confirmed experimentally.

d) A prototype antenna should be constructed and tested to determine the gain, VSWR, polarization and tuning performance.

3) The computer program should be extended to permit analysis of multi-element driven structures. Higher gains, better impedance control and physically shorter structures are expected with this class of antenna.

f) A prototype of the mechanical system should be constructed and tested. Tests should include stability and compatibility with electrical performance requirements.

APPENDIX A

Specifications

1. Electrical

Frequency coverage:		Rx band 274-290 MHz
		Tx band 370-400 MHz
Gain:	Rx band	13 dB_{ic} minimum
		14 dB_{ic} desirable
	Tx band	13 dB_{ic} minimum
Polarization:		Right-hand circular
Axial ratio:		2 dB (max.)
Impedance:		50 ohms
VSWR:		1.5 to 1 (max.)
Power handling capability:		25 Watts p.e.p.

2. Mechanical

Weight:	preferably less than 12 kg.
Size and shape: (collapsed)	suitable for man-portable
Pointing adjustment:	Elevation: 0-60° calibrated
	Azimuth: ±15° about a nominal setting
Environmental:	ability to withstand 45 mph gusts

APPENDIX B

Literature Survey

This survey concerns the pertinent references in the areas of active tuning; Yagi antenna modelling, optimization, and realization; and experimental verifications of the antenna model. A bibliography of unreferenced, but important papers, is also included with the references in Appendix G.

Active Tuning

To design the antenna tuning system we must consider the operating bandwidth at each "setting" of the tuning control, the range of frequencies over which the antenna must perform, and the effects of tuning devices on the antenna linearity and ohmic losses.

Seth [3], [4a,4b] measured the performance of a tunable 6 element Yagi antenna in which each of the 4 directors was centre loaded with a Motorola MV2110 epicap diode. The diodes were all biased with the same voltage. At -25 volts bias the load capacitance was 15 pf, and at -0.5 volt bias the load capacitance was 40 pF. The frequency of the peak gain shifted by 7 MHz from 141 MHz to 148 MHz, which is not in the range of the 100 MHz shift that is required for our design objective (as shown in Section 4, we need capacitances an order of magnitude smaller than these).

Seth also studied the input impedances for various varactor biases, and the results show that one should expect undulating behaviour in the impedance as the frequency changes. The lower capacitance values (10 pF) gave the smoothest variation over the range of frequencies from 125 MHz to 160 MHz, for which the reactance changed from -60 ohms to 100 ohms. These results indicate that care has to be taken to ensure that optimization to obtain a good match at selected points in the band does not produce large mismatches elsewhere in the band.

Seth suggests that negative impedance converters (NIC's) could be used to obtain 2:1 changes in the operating frequency of a Yagi antenna. An NIC is an active device that can give an inductive reactance at lower frequencies in the desired band, and capacitve reactance at higher frequencies. The frequency response over the band can be specified. Podell and Cristal [5] have designed and constructed NIC's, and the problems that they cited are stability, noise and distortion. Further, NIC's are complex to design. We did not pursue these devices further; however, the present state of

development may meet the requirements of active antennas, and these devices should be considered if other simpler methods are not adequate.

Lamensdorf [6],[7] has thoroughly studied the use of varactors for antenna tuning. His approach was to load a transmission line antenna, (folded dipole), hence his results do not directly apply to centre loading of a dipole. However, the measurements on distortion due to the dependence of the varactor capacitance on operating voltage show the significance of varactor nonlinearity for the transmit case. He recommends using a range of DC biases that avoid the most sensitive regions of the varactor capacitance variation. Another important point that he makes is that characteristics of a varactor can vary, and the performance is not always predictable. This is important to the realization of an antenna which would be produced in large numbers, since the calibration of each antenna could be rather lengthy if variations in characteristics are significant. Alternatively, one could have closed-loop control of the load impedance; however, this added complexity should be avoided.

The Integrated Radiator Techniques Study (IRTS) [8] involved experiments with capacitively loaded Yagi antennas. The capacitive loads in the directors could be varied from 0.8 to 10 pF. The directors' half length was 0.105m, and this is 0.87 wavelengths at 620 MHz and 1.26 wavelengths at 900 MHz. Since 0.105m is one-quarter wavelength at 714 MHz, the ability of load capacitors to make the elements electrically shorter does not explain the measured performance of the Yagi over the frequency range. With a 10 pF capacitor the minimum reactive load occurs at 900 MHz ($X_c = 1/\omega c = -18\Omega$), and the maximum reactive load at 620 MHz ($X_c = -320\Omega$). According to an available input impedance chart [9] for an isolated cylindrical dipole the capacitive reactance of -320 Ω would give the $\lambda/4$ effective length cited in the study. This work clearly establishes the basis for the effective length approach that we used in our optimization program.

The study shows how additional gain can be obtained by using parasitic side arrays. It is clear from our work that an alternative approach, such as this one, is needed to obtain the required gain with the constraints on antenna size and the diminishing returns with increasing element numbers.

Design and Optimization

The design of Yagi antennas concerns the choice of reflector and

director numbers, the size limits for element diameters and the antenna length. Given these basic antenna parameters the objective is to determine the values of the parameters which give the specified or best performance. Usually, one finds that for the initial basic antenna, none of the performance requirements can be easily met simultaneously. There are a few papers that consider adding new parameters, such as the parasitic side arrays cited in the IRTS, and the possible improvements obtained with an array of Yagi antennas. We did not pursue a review of these other possible design approaches and we just considered the optimization of a basic Yagi antenna.

Cheng and Chen [10], [11] have optimized element lengths and spacings for Yagi antennas to obtain maximum directivity at one frequency. With a six element antenna the maximum directivity obtained was 15.5 dBi. This shows the potential of narrow band performance for Yagi antennas.

Shen [12] constrained the director lengths and spacings to be uniform, and analyzed the Yagi antenna bandwidth and directivity performances for several antennas. His results show the relatively slow increase in directivity with element number after 14 to 16 elements, and the reduction in bandwidth as the length in increased.

Kajfez has optimized six element Yagi antennas for constrained sidelobe levels [13],and maximum flat gain over a specified passband [14]. Schjaer-Jacobsen and Andersen have also considered various techniques for optimizing Yagi antennas for sidelobe constraints [15]. Both Kajfez [2] and the latter authors [15] have developed numerical methods for fast analysis of these antennas. Since we were interested in a specified gain over a passband, the paper of most interest was the one by Kajfez [14], in which he shows very constant directivities can be obtained in a specified band by varying the element lengths only. For example, with 0.15λ spacing of the directors and 6 elements, the directivity was flat at 9.3 dBi from 280 to 320 MHz. He also considered parameter tolerances and concluded that these are practical. To obtain this optimization he developed a cost function for directivity as we have described in Section 2.2 on the Cost Function.

As a result of our interest in Kajfez's work we obtained a computer program [2] from him for single frequency optimization of directivity for Yagi antennas. We also have acquired a thesis by Yung [16] on optimization methods for Yagi antennas. This thesis is the result of work done with

Kajfez and it gives a very good overview of the optimization methods of Rosenbrock, Fletcher and Reeves, and Davidon (via Fletcher and Powell). The main point he makes is that the parameters of element lengths, spacings and radii must be optimized simultaneously, and sequential optimization usually gives poorer performances.

APPENDIX C

Computer Program for Model of Electrical Performance

The model used for the evaluation of electrical performance of Yagi antennas has the following characteristics. The program is based on a moment-method solution for currents expressed as entire-domain functions [17],[2].

1. The current distribution on the mth of N elements is assumed to be of the form:

$$I_m(z_m) = \sum_{p=1}^{2} b_{pm} \sin\left\{\frac{p\pi}{2}\left(1 - \frac{|z_m|}{h_m}\right)\right\} \quad , \quad m = 1 \text{ to } N \quad , \tag{C.1}$$

where z_m is the position on the mth element and h_m is the element half length. The complex coefficients b_{pm} are to be determined.

This approximation to the actual currents is accurate within 5% as shown by Kafjez [2] in a comparison of measured and computed input admittances. We should note that for dipoles of the order of one-quarter wavelength and feed-gaps > .05λ this model would not be adequate [18]. Our results give elements in the order of half-wavelengths and the feed-gap at the highest frequency can easily be less than .01λ ~ 0.75 cm.

2. The generalized impedance matrix [S] is determined by numerical integration. Three match points are chosen on each element to satisfy Hallén's integral equation. The integration is performed by subdividing each element into 8 (+ multiples of 4) segments. Hallén's equation is, for $n = 1$ to N ,

$$\sum_{m=1}^{N} \int_{z_m=-h_m}^{h_m} I_m(z_m) \frac{\exp[-jkR(z_m,z_n)]}{R(z_m,z_n)} \, dz_m + C_n \cos(kz_n) = -j \frac{V_m}{60} \sin(k|z_n|) \quad , \tag{C.2}$$

where $k = 2\pi/\lambda$ is the free space propagation constant. $R(z_m,z_n)$ is the distance

$$[a_n^2 + (y_m - y_n)^2 + (z_m - z_n)^2]^{1/2} \quad ,$$

corresponding to the antenna parameters shown on the Yagi in Figure C.1. The V_m are impressed voltages at the centres of the elements for any number of driven elements.

The linear equations needed to solve for the coefficients (b_{1m}, b_{2m}) are obtained by substituting the expression (C.1) into (C.2) and then the method of collocation is used to obtain three equations with three unknowns for three match points per element. The c_n's are eliminated by setting $z_{n_3} = 0$, and reducing the three equations to two:

$$\sum_{p=1}^{2} \sum_{m=1}^{N} b_{pm} S^r_{pm}(z_{nq}) = -j \frac{V_n}{60} \sin(k|z_{nq}|) \quad , \quad q = 1,2 \qquad (C.3)$$

The new reduced impedances, $S^r_{pm}(z_{nq})$, are given by

$$S^r_{pm}(z_{nq}) = S_{pm}(z_{nq}) - \cos(kz_{nq})\, S_{pm}(0) \quad , \qquad (C.4)$$

where

$$S_{pm}(z_{nq}) = \int_{-h_m}^{h_m} \sin\left[\frac{p\pi}{2}\left(1 - \frac{|z_m|}{h_m}\right)\right] \frac{\exp[-jkR(z_m, z_n)]}{R(z_m, z_n)}\, dz_m \quad . \qquad (C.5)$$

With these equations for each element we obtain a system of linear equations, and in matrix form we write

$$[S]\ \{b\} = \{V\} \quad . \qquad (C.6)$$

[S] is a square matrix, 2N by 2N ; {b} and {V} are column matrices, 1 by 2N. Since there is only one driven element all the $V_n = 0$, except for V_1, which we set to unity.

This model was based on the solution to Hallén's integral equation proposed by Neff et al [17]. Kajfez [2] reduced the number of current coefficients to two, and developed an efficient numerical integration scheme, plus a fairly accurate three point matching choice for a minimum of eight segments per element. The accuracy is 4% or better, depending on the element length and separations. The lengths should be in the order of half-wavelength and separation of elements not be less than about .08λ. The number of current terms, match point positions, and segments per element were chosen by Kajfez so that the deviation (RMS) of computed admittance from

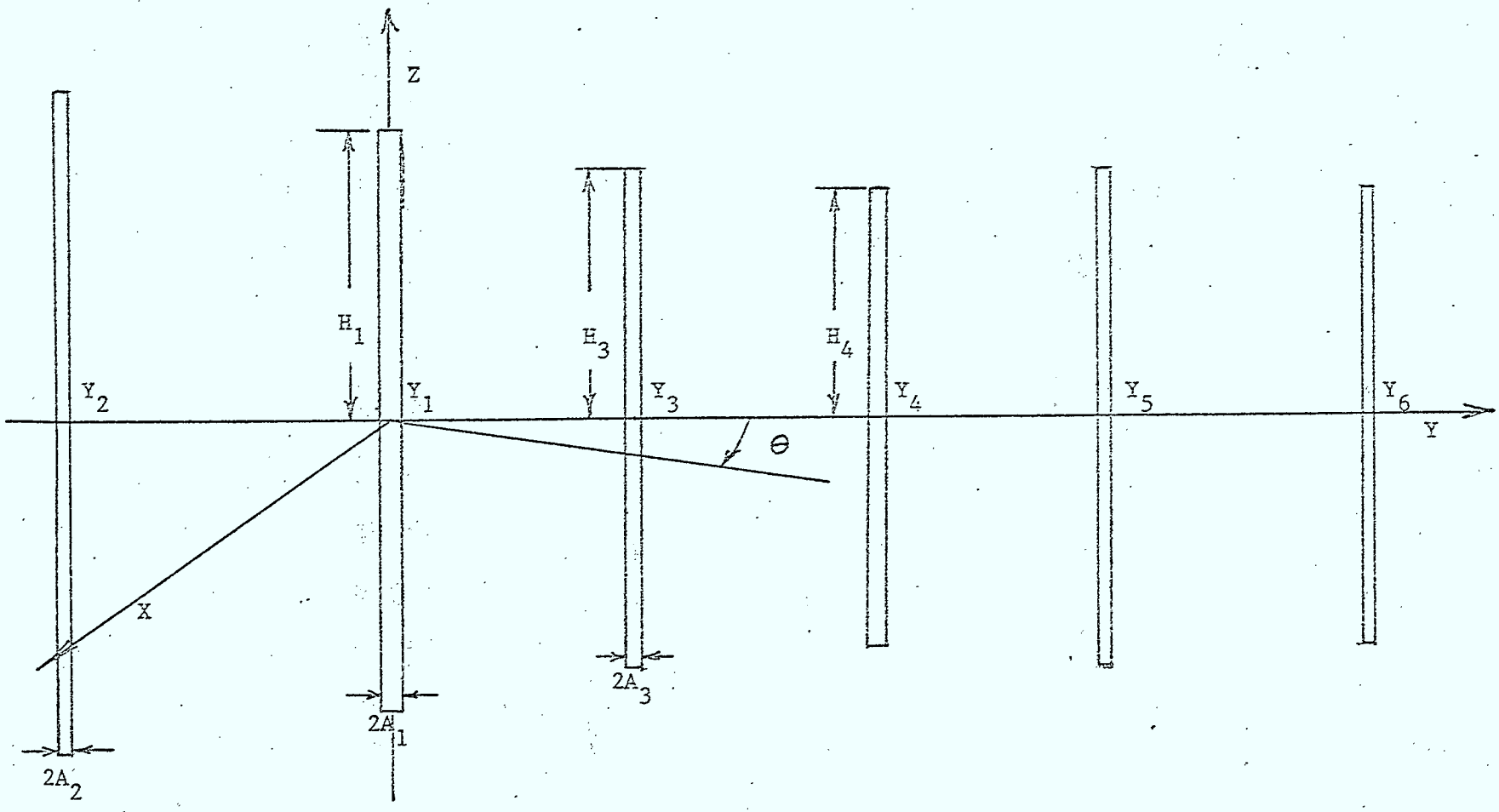


Figure C.1 Yagi Antenna Coordinate System and Antenna Parameters of Element Positions, Half Lengths, and Radii.

experimental data by Mack [19] was less than 5%. Further the input impedance, directivity, and front-to-back ratio for a 10 element Yagi was computed and compared to measured values obtained by King et al [20]. The input resistance agrees within 1%, and the reactance within 1.6%. The directivity computed was 0.4 dB high, and this corresponds to a 3.3% error. Kajfez also compared the performance of the model with experimental values obtained by Schjaer-Jacobsen and Andersen [15] for a 6 element Yagi with 2 reflectors. The directivity computed is 0.3 dB high relative to the one computed by S.-Jacobsen and Andersen, or a 3% difference. The measured gain which would include losses was 0.4 dB less than given by the model. The experiments were with an antenna at 600 MHz, for which the losses would be somewhat more than the operating frequencies we are considering (274 to 400 MHz range).

Modified System of Equations for Centre Loading of Directors

The Hallén integral equation (C.2), can easily accommodate a voltage drop at the centre of each director. The voltage drop for a load in the mth element would be

$$V_m = I_m(0)\, Z_{Lm} \quad ,$$

for which the right-hand-side of (C.2) is replaced by $+ j \frac{V_m}{60} \sin(k|z_n|)$, for the directors. Z_{Lm} is the impedance of the load at the mth director, which for capacitive loads is

$$Z_{Lm} = \frac{1}{j\omega C_m} \quad .$$

To obtain the modified system of equations we recognize that $I_m(0) = b_{1m}$. Then, for $m = n \neq 1$, and $p = 1$, the impedance elements of equation (C.4) become:

$$S^r_{1n}(z_{nq}) = S_{1n}(z_{nq}) - \cos(kz_{nq})\, S_{1n}(0) - j \frac{Z_{Ln}}{60} \sin(k|z_{nq}|)$$

For $m \neq n$ or $n = 1$, $S^r_{pm}(z_{nq})$ is given by equation (C.4). Let us call the new impedance matrix $[S]_L$. Then the required solution for the current coefficients is given by

$$\{b\} = [S]_L^{-1} \{V\} \quad ,$$

where {b} and {V} are the same column matrices as defined for equation (C.6).

APPENDIX D

Antenna Gain and Directivity

The gain and directivity are the same for a lossless antenna. Once the current coefficients have been determined as described in the section on the antenna model the radiation pattern, for frequency f_j, is given by

$$P(f_j,\theta) = \frac{4}{\pi} \sum_{m=1}^{N} h_m (b_{1m} + b_{2m}) \exp[jk_j y_m \cos\theta] \quad ,$$

where b_{1m} and b_{2m} are functions of frequency. The gain is the ratio of the power radiated per unit solid angle for $\theta = 0$, to the average input power. Without losses, and input impedance $Z_i(f_j)$

$$G(f_j) = D(f_j) = 10 \log_{10} \{ \frac{\pi Z_{fs}}{Re(Z_i(f_j))} \left| \frac{P(f_j,0)}{\lambda_j b_{11}} \right|^2 \} dB$$

gives the gain or directivity in decibels. Z_{fs} is free space impedance.

Antenna Gain for a Lossy Structure

The current distributions on the antenna are determined for a perfect conductor, on which the tangential electric field is zero. With a lossy structure, the tangential fields are non-zero and the generalized impedance matrix can be modified to account for this boundary condition. The self impedance terms for a segment of length $\Delta\ell$ would be increased by

$$Z_p = \left(\frac{j\omega\mu_0}{\sigma} \right)^{1/2} (\Delta\ell) \quad ,$$

where $\mu_0 = 4\pi \times 10^{-7}$ henry/m and σ is conductivity of the metal.

We chose to neglect the effect of the finite conductivity on the boundary condition and use the perfect conductor current distributions to obtain the power loss. Then the efficiency of the antenna gives the power gain in decibels

$$G = \eta + D$$

where the efficiency is given by

$$\eta = 10 \log_{10} \{ 1 - \frac{P_{loss}}{P_{in}} \} dB \quad .$$

The power loss at a particular frequency is given by

$$P_{loss}(f_j) = \left(\frac{f_j}{40\sigma}\right)^{1/2} \sum_{m=1}^{N} \left(\frac{h_m}{a_m}\right) \{|b_{1m}|^2 + |b_{2m}|^2 + \frac{16}{3\pi} \mathrm{Re}(b_{1m} b_{2m}^*)$$

for f_j in MHz. The input power is

$$P_{in}(f_j) = \frac{1}{2} |I(0)|^2 \, \mathrm{Re}(Z_1(f_j)) \quad ,$$

which reduces to $\frac{1}{2} \mathrm{Re}(b_{11})$ for unit voltage excitation. All the coefficients b_{pm} are functions of frequency.

Antenna Feed Mismatch Loss

The feed mismatch loss depends on the reflection coefficient Γ, which is given by

$$|\Gamma(f_{jn})| = \left| \frac{Z_1(f_{jn}) - Z_0}{Z_1(f_{jn}) + Z_0} \right| = \frac{\mathrm{VSWR} - 1}{\mathrm{VSWR} + 1} \quad ,$$

where $Z_1(f_{jn})$ and Z_0 are the input impedance and the characteristic impedance of the feed line, respectively. The mismatch loss is given by

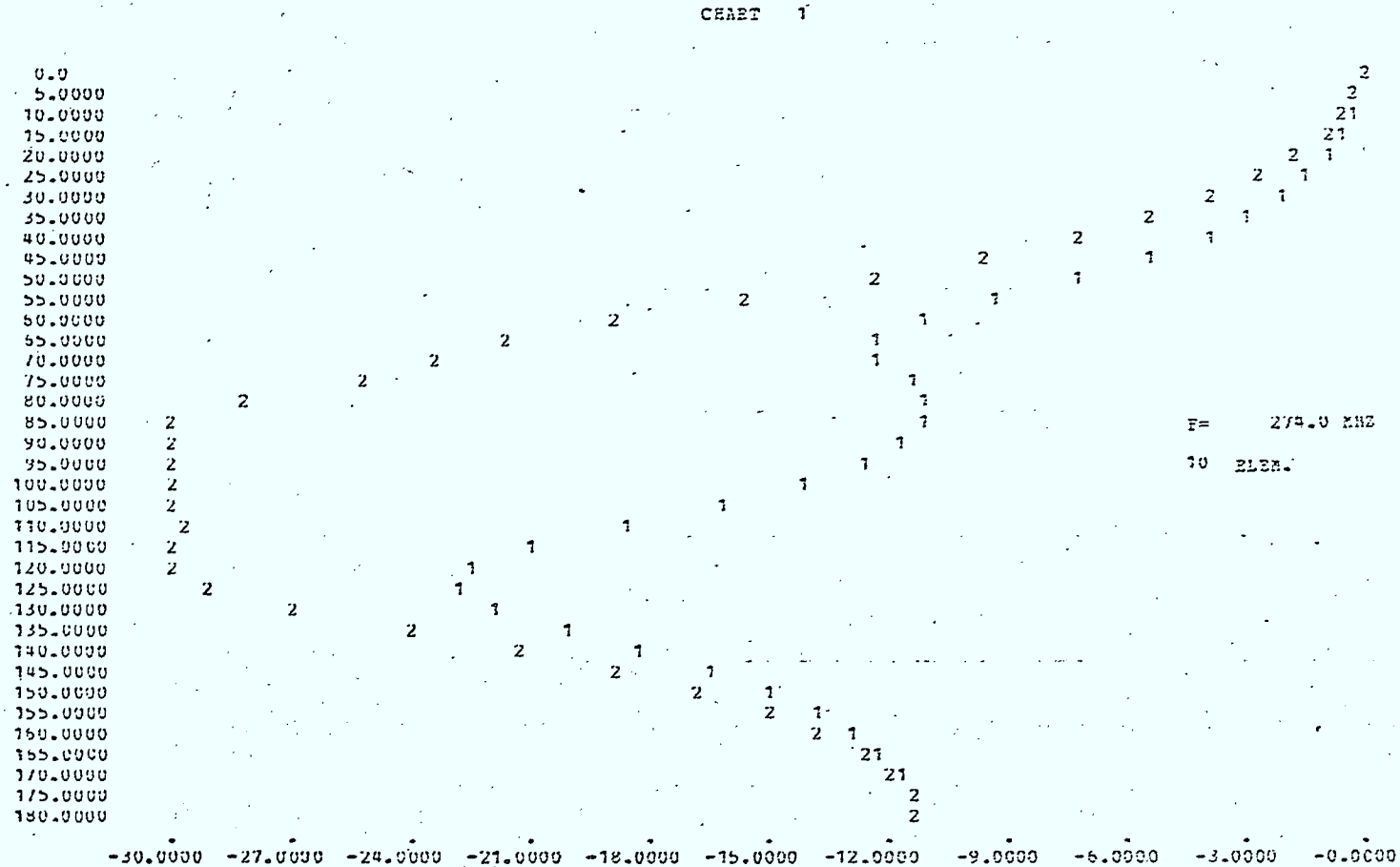
$$R(f_{jn}) = 10 \log_{10} \left\{ \frac{1}{1 - |\Gamma_{jn}|^2} \right\} \quad ,$$

where $j = 1$ and 2 for receive and transmit bands, respectively.

APPENDIX E

Data for Yagi Antenna Electrical Designs

This appendix contains the H and E plane patterns for Yagi antennas with 10, 12, 14 and 16 elements. Each plot is accompanied by a list of the element radii (A), lengths (H), and locations (Y). The performance measures of forward directivity, gain, efficiency, front-to-back ratio, input impedance and mismatch loss are also included. The performance has been evaluated at five frequencies in both the receive and transmit bands. The H and E plane patterns are plotted with numbers 1 and 2, respectively.



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	17.100	6.732	5.400	2.126
0.350	0.138	20.100	7.913	11.900	4.685
0.350	0.138	17.600	6.929	29.700	11.693
0.350	0.138	20.800	8.189	41.800	16.457
0.300	0.118	19.600	7.717	54.700	21.535
0.300	0.118	20.600	8.110	77.600	30.551
0.300	0.118	19.400	7.638	98.700	38.858

FORWARD DIRECTIVITY= 9.92 DB

FRONT TO BACK RATIO= 11.25 DB

FORWARD GAIN= 9.92 DB

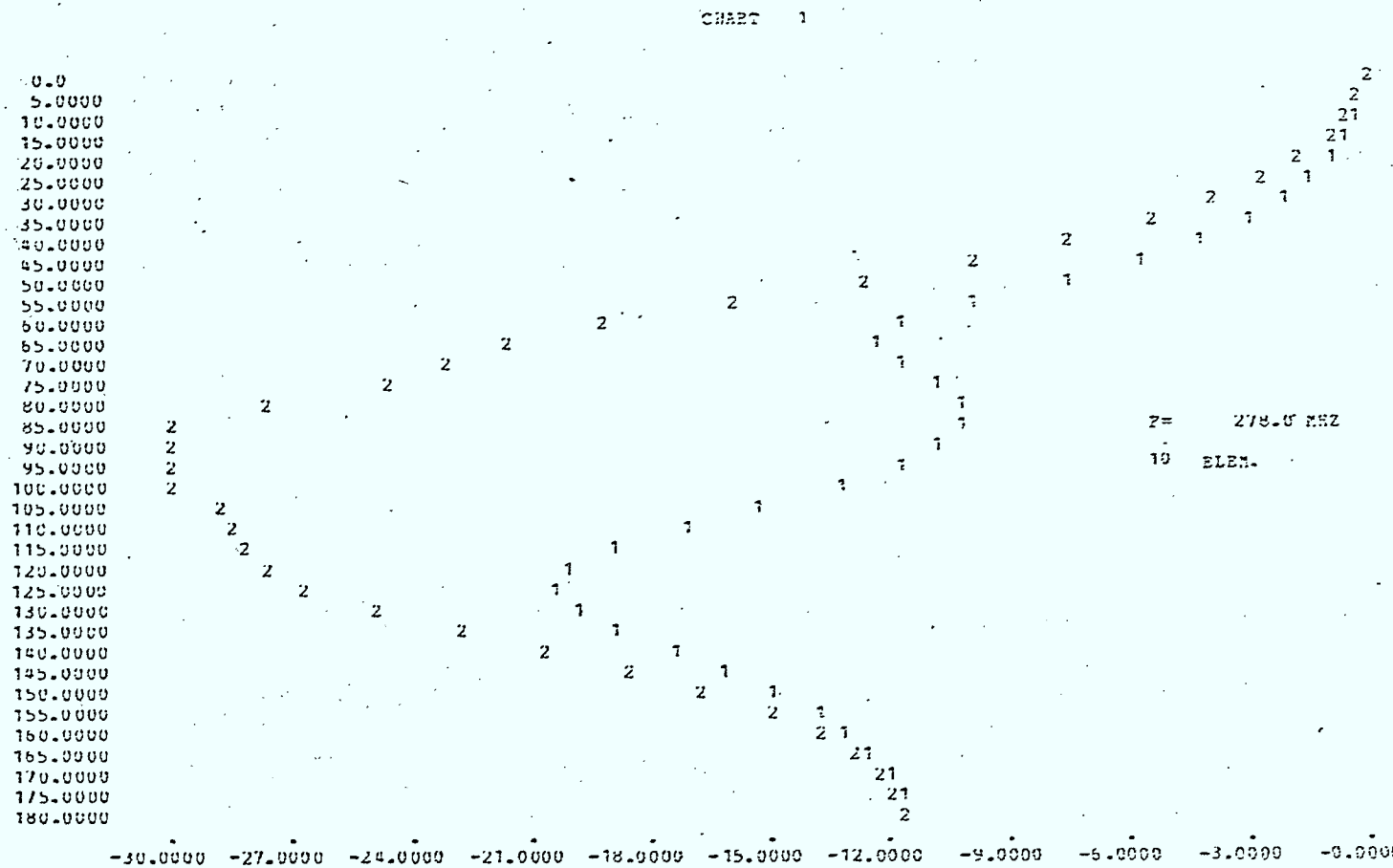
EFFICIENCY= -0.0023 DB

INPUT IMPEDANCE= 76.79 9.85 OHMS

INPUT ADMITTANCE= 12.81 -1.64 MILLISIEMENS

MISMATCH LOSS= 0.0890 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	17.100	6.732	5.400	2.126
0.350	0.138	20.100	7.913	11.900	4.685
0.350	0.138	17.600	6.929	29.700	11.693
0.350	0.138	20.800	8.189	41.800	16.457
0.300	0.118	19.600	7.717	54.700	21.535
0.300	0.118	20.600	8.110	77.600	30.551
0.300	0.118	19.400	7.638	98.700	38.858

FORWARD DIRECTIVITY= 9.93 DB

FRONT TO BACK RATIO= 11.58 DB

FORWARD GAIN= 9.93 DB

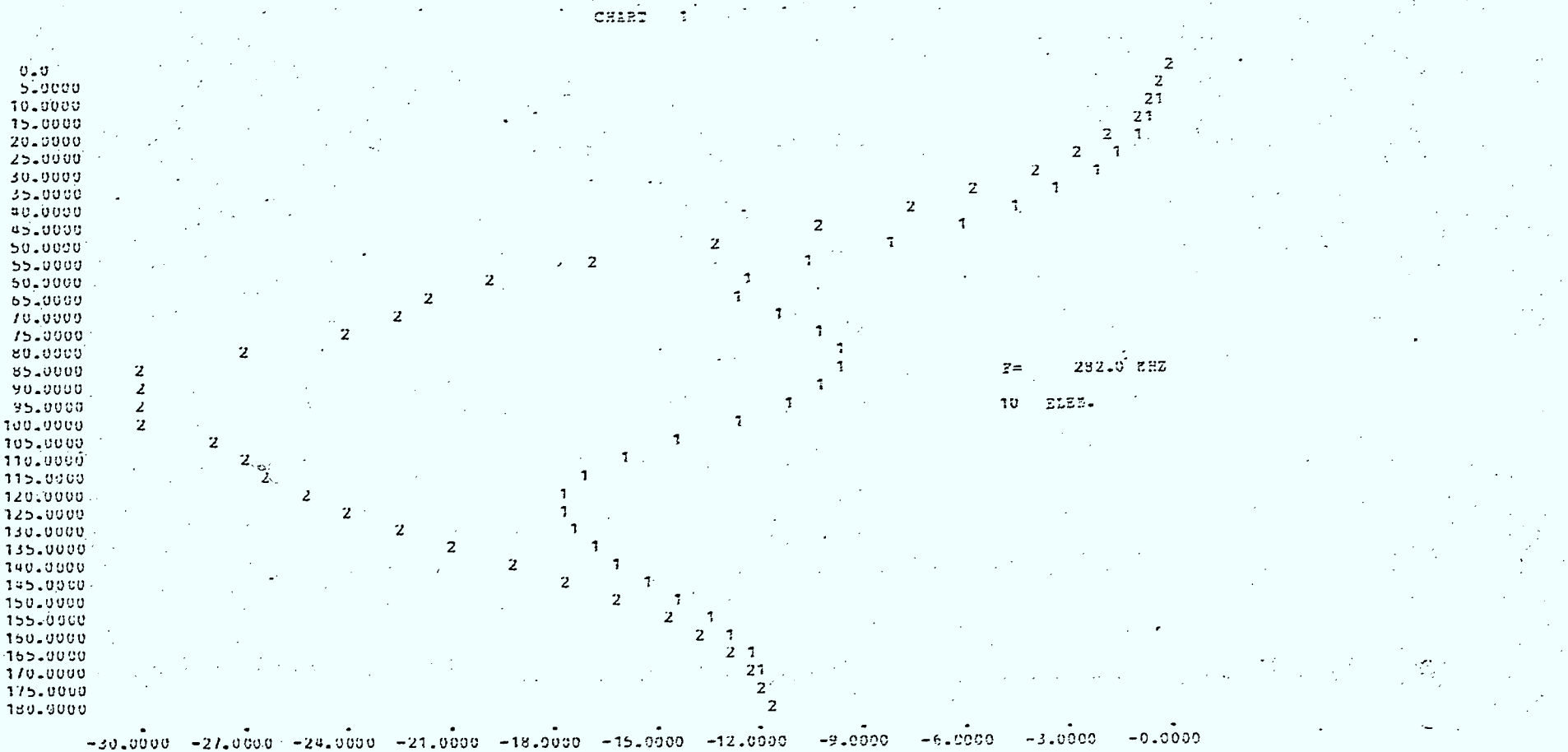
EFFICIENCY= -0.0021 DB

INPUT IMPEDANCE= 88.24 10.03 OHMS

INPUT ADMITTANCE= 11.19 -1.27 MILLISIEMENS

MISMATCH LOSS= 0.0293 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		V	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	17.100	6.732	5.400	2.126
0.350	0.138	20.100	7.913	11.900	4.685
0.350	0.138	17.600	6.929	29.700	11.693
0.350	0.138	20.800	8.189	41.800	16.457
0.300	0.118	19.600	7.717	54.700	21.535
0.300	0.119	20.600	8.110	77.600	30.551
0.300	0.118	19.400	7.638	98.700	38.858

FORWARD DIRECTIVITY= 9.91 DB

FRONT TO BACK RATIO= 11.65 DB

FORWARD GAIN= 9.91 DB

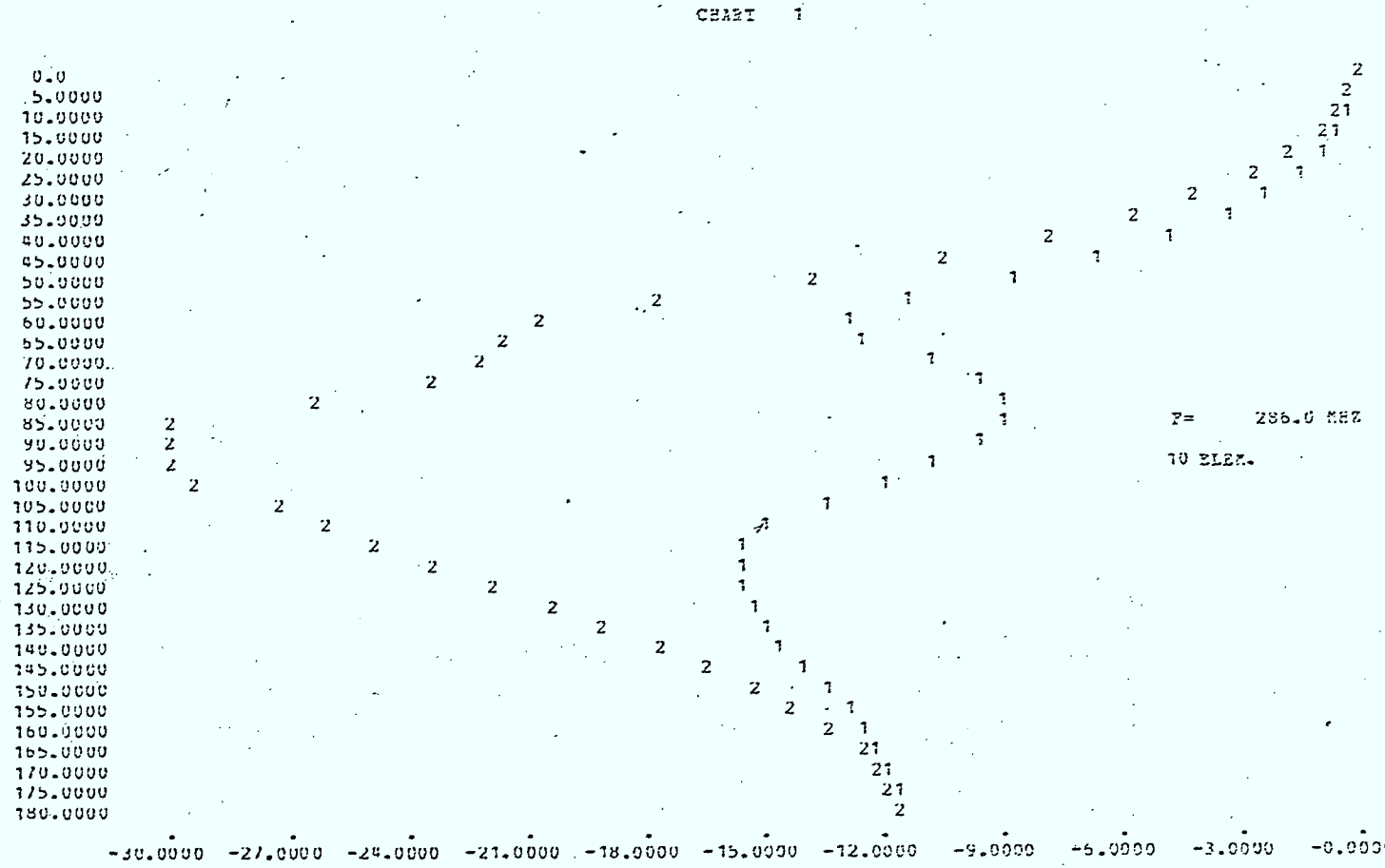
EFFICIENCY= -0.0021 DB

INPUT IMPEDANCE= 97.69 6.74 OHMS

INPUT ADMITTANCE= 10.19 -0.70 MILLISIEMENS

MISMATCH LOSS= 0.0056 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	17.100	6.732	5.400	2.126
0.350	0.138	20.100	7.913	11.900	4.685
0.350	0.138	17.600	6.929	29.700	11.693
0.350	0.138	20.800	8.189	41.800	16.457
0.300	0.118	19.600	7.717	54.700	21.535
0.300	0.118	20.600	8.110	77.600	30.551
0.300	0.118	19.400	7.638	98.700	38.858

FORWARD DIRECTIVITY= 9.89 DB

FRONT TO BACK RATIO= 11.64 DB

FORWARD GAIN= 9.89 DB

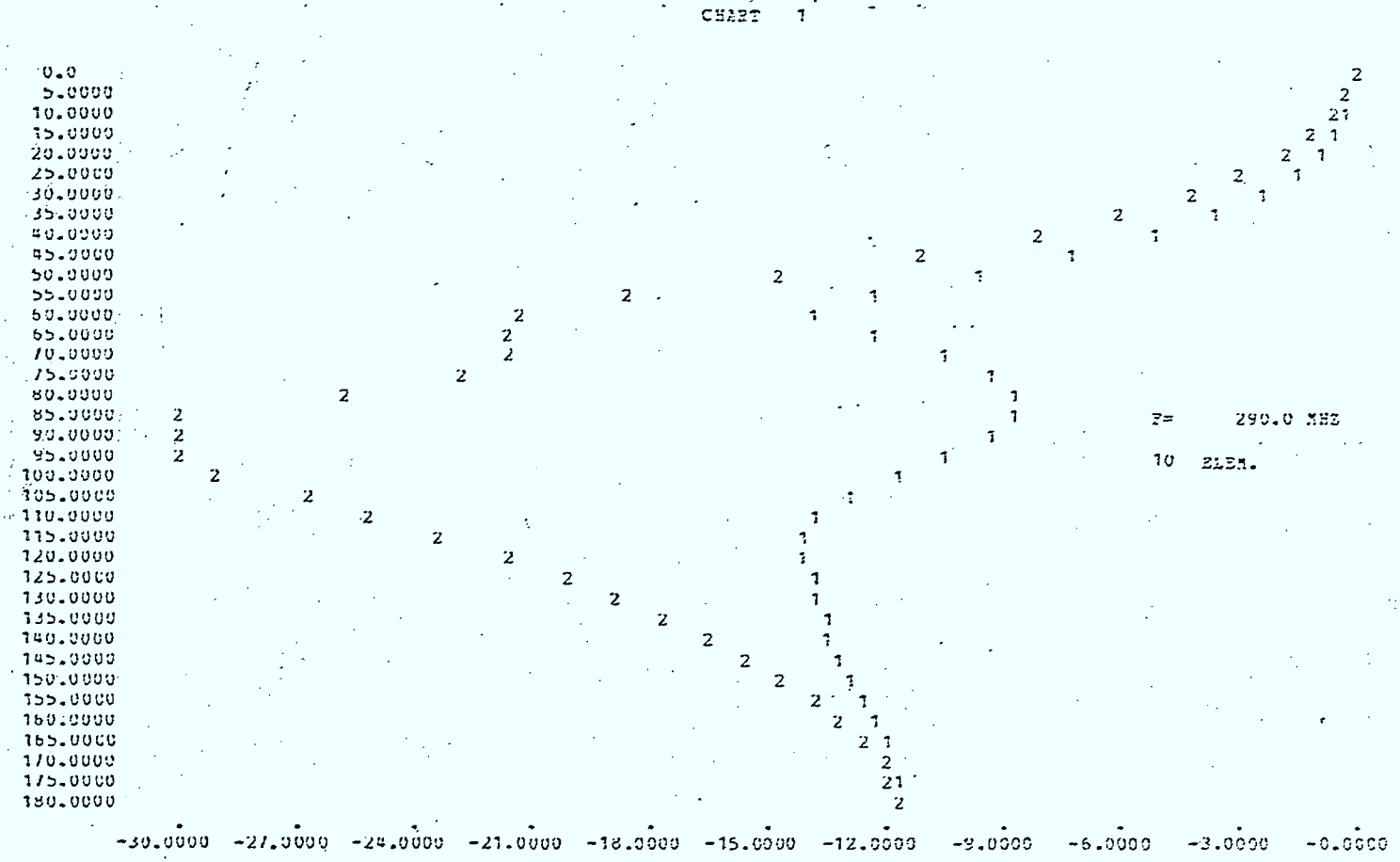
EFFICIENCY= -0.0021 DB

INPUT IMPEDANCE= 103.64 0.81 OHMS

INPUT ADMITTANCE= 9.65 -0.08 MILLISIEMENS

MISMATCH LOSS= 0.0018 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	17.100	6.732	5.400	2.126
0.350	0.138	20.100	7.913	11.900	4.685
0.350	0.138	17.600	6.929	29.700	11.693
0.350	0.138	20.800	8.189	41.800	16.457
0.300	0.118	19.600	7.717	54.700	21.535
0.300	0.118	20.600	8.110	77.600	30.551
0.300	0.118	19.400	7.638	98.700	38.858

FORWARD DIRECTIVITY= 9.87 DB

FRONT TO BACK RATIO= 11.65 DB

FORWARD GAIN= 9.86 DB

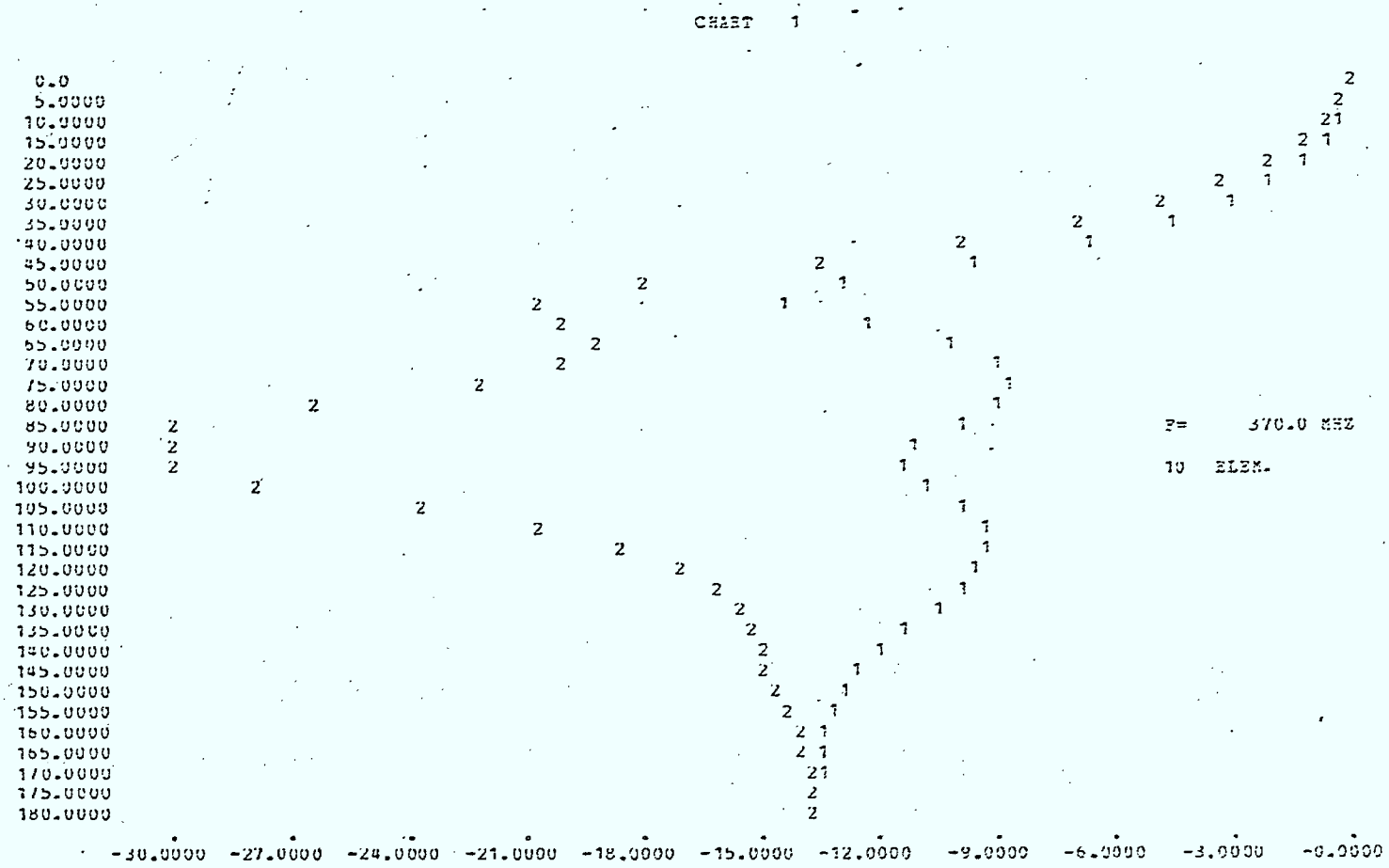
EFFICIENCY= -0.0021 DB

INPUT IMPEDANCE= 105.03 -6.14 OHMS

INPUT ADMITTANCE= 9.49 0.56 MILLISIEMENS

MISMATCH LOSS= 0.0065 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		T	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.500	-8.858
0.500	0.197	16.000	6.299	5.400	2.126
0.350	0.138	14.800	5.748	11.900	4.685
0.350	0.138	17.100	6.732	29.700	11.693
0.350	0.138	15.700	6.181	41.800	16.457
0.300	0.118	15.000	5.906	54.700	21.535
0.300	0.118	16.400	6.457	77.600	30.551
0.300	0.118	14.500	5.709	98.700	38.858

FORWARD DIRECTIVITY= 9.79 DB

FRONT TO BACK RATIO= 13.52 DB

FORWARD GAIN= 9.79 DB

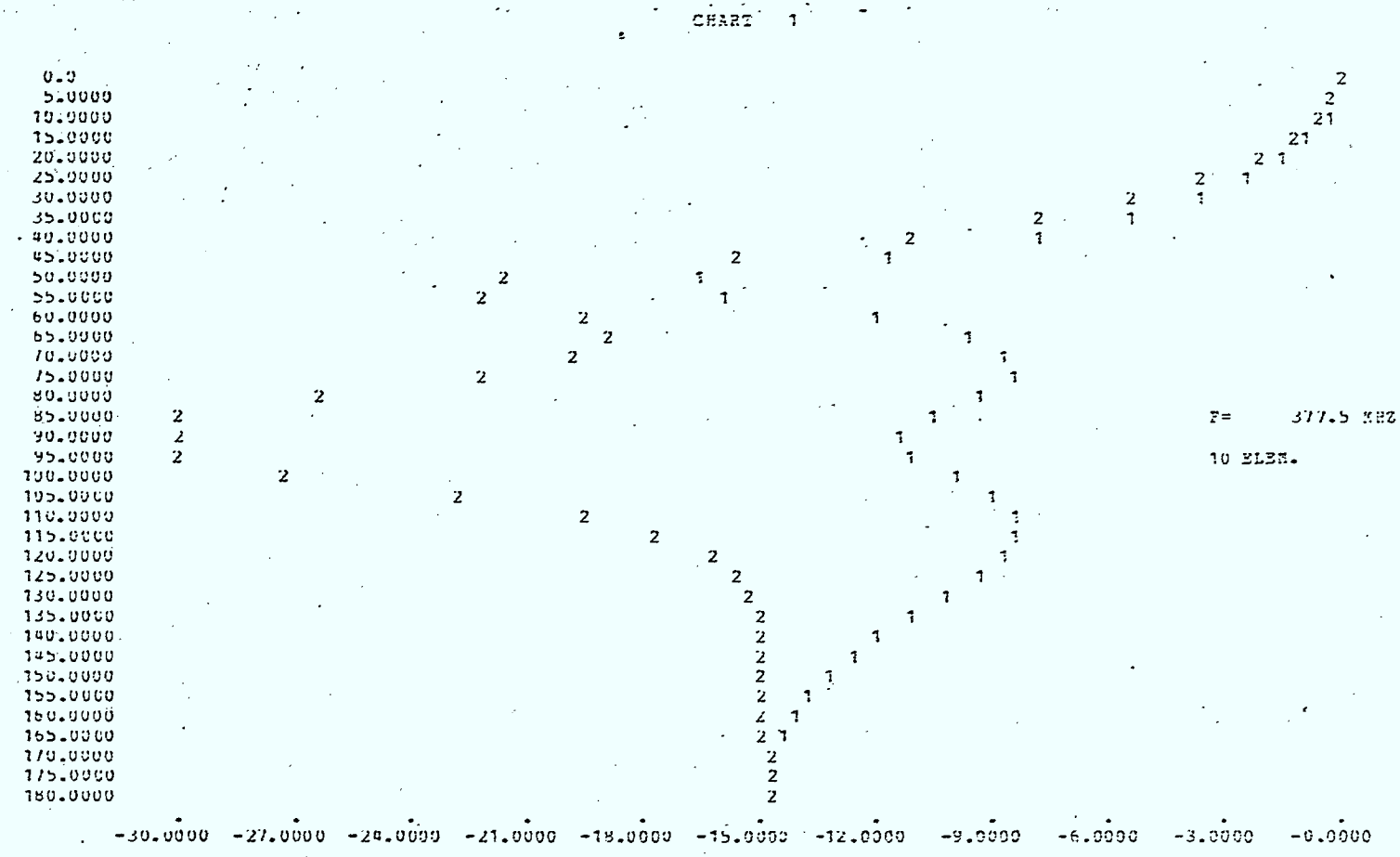
EFFICIENCY= -0.0021 DB

INPUT IMPEDANCE= 153.40 -12.12 OHMS

INPUT ADMITTANCE= 6.48 0.51 MILLISIEMENS

MISMATCH LOSS= 0.2072 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	16.000	6.299	5.400	2.126
0.350	0.138	14.600	5.748	11.900	4.685
0.350	0.138	17.100	6.732	29.700	11.693
0.350	0.138	15.700	6.181	41.800	16.457
0.300	0.118	15.000	5.906	54.700	21.535
0.300	0.118	16.400	6.457	77.600	30.551
0.300	0.118	14.500	5.709	98.700	38.858

FORWARD DIRECTIVITY= 9.93 DB

FRONT TO BACK RATIO= 14.59 DB

FORWARD GAIN= 9.93 DB

EFFICIENCY= -0.0025 DB

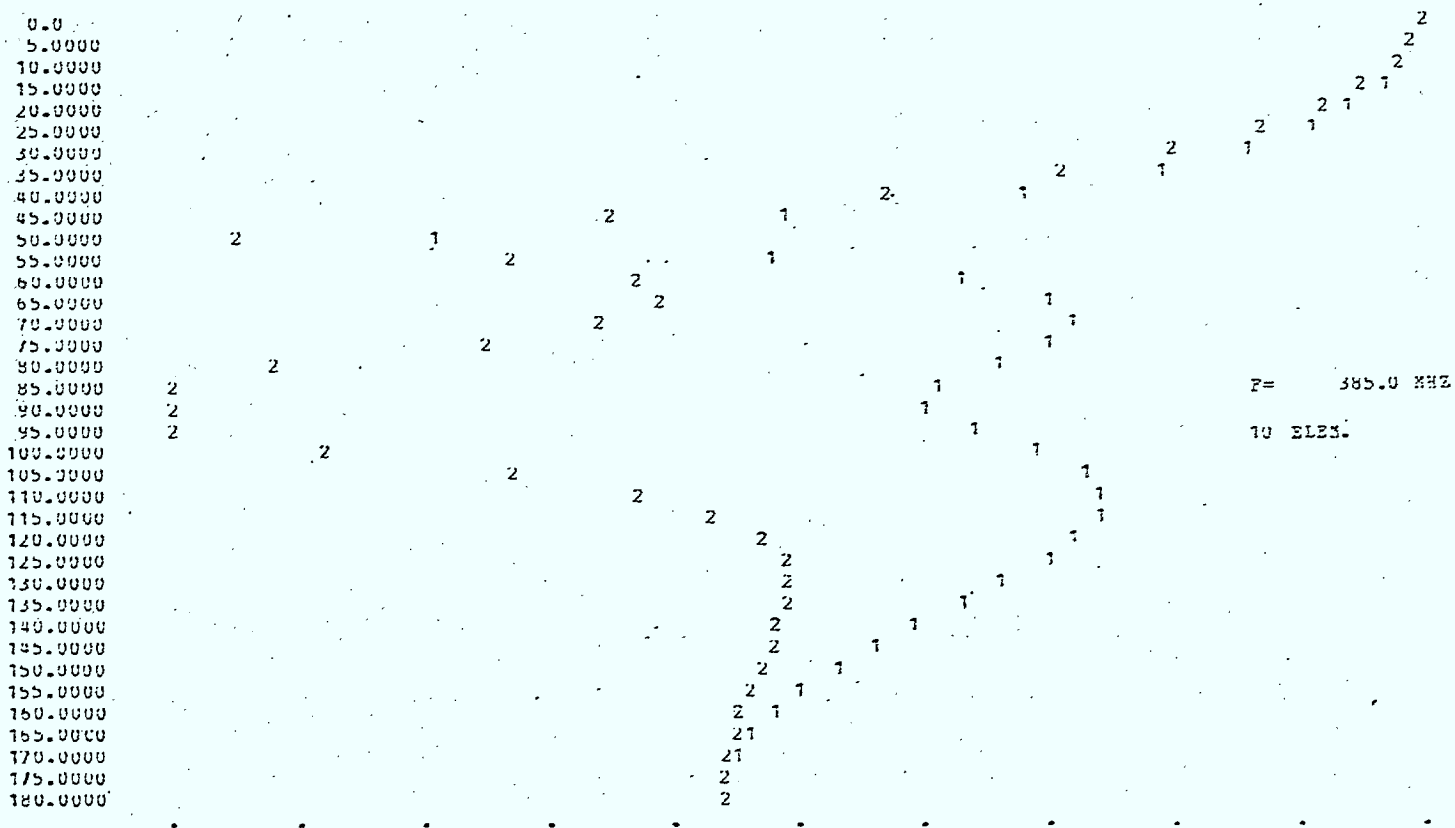
INPUT IMPEDANCE= 134.22 -0.20 OHMS

INPUT ADMITTANCE= 7.45 0.01 MILLISIEMENS

MISMATCH LOSS= 0.0937 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

CHART 1



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	16.000	6.299	5.400	2.126
0.350	0.138	14.600	5.748	11.900	4.685
0.350	0.138	17.100	6.732	29.700	11.693
0.350	0.138	15.700	6.181	41.800	16.457
0.300	0.118	15.000	5.906	54.700	21.535
0.300	0.118	16.400	6.457	77.600	30.551
0.300	0.118	14.500	5.709	98.700	38.858

FORWARD DIRECTIVITY= 10.16 DB

FRONT TO BACK RATIO= 16.68 DB

FORWARD GAIN= 10.16 DB

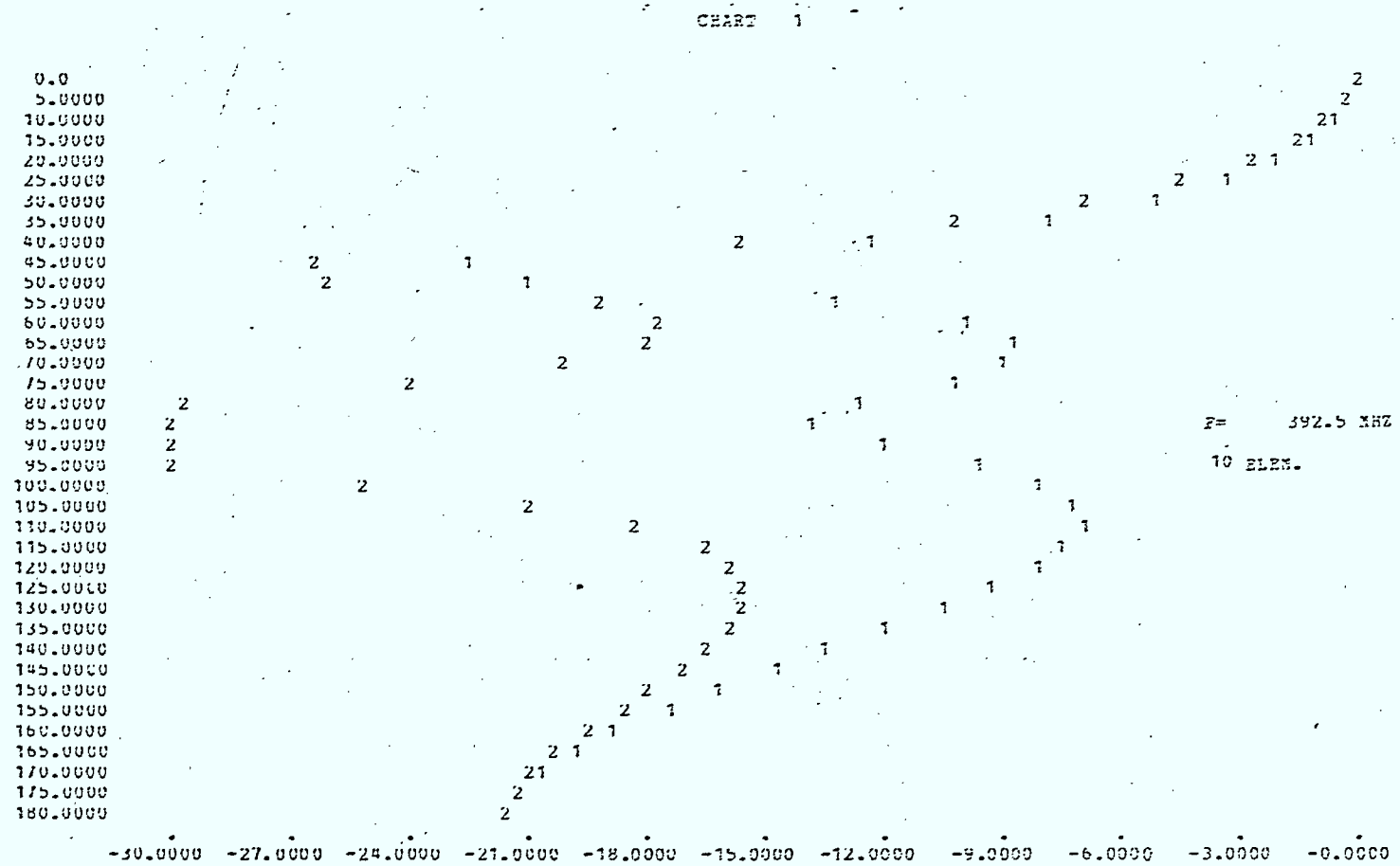
EFFICIENCY= -0.0031 DB

INPUT IMPEDANCE= 120.96 16.18 OHMS

INPUT ADMITTANCE= 8.12 -1.09 MILLISIEMENS

MISMATCH LOSS= 0.0625 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	16.000	6.299	5.400	2.126
0.350	0.138	14.600	5.748	11.900	4.685
0.350	0.138	17.100	6.732	29.700	11.693
0.350	0.138	15.700	6.181	41.800	16.457
0.300	0.118	15.000	5.906	54.700	21.535
0.300	0.118	16.400	6.457	77.900	30.551
0.300	0.118	14.500	5.709	98.700	38.858

FORWARD DIRECTIVITY= 10.43 DB

FRONT TO BACK RATIO= 21.36 DB

FORWARD GAIN= 10.42 DB

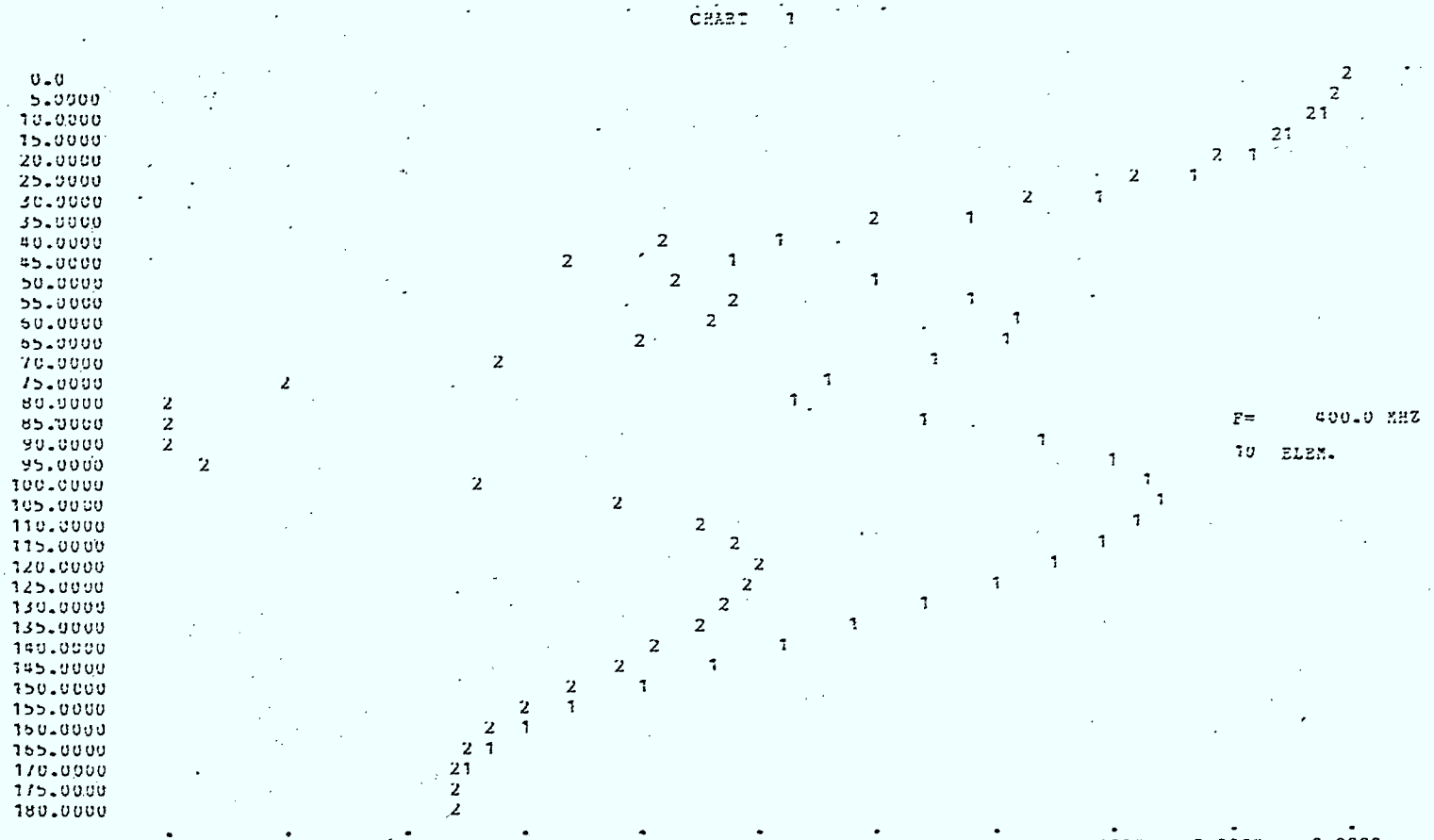
EFFICIENCY= -0.0043 DB

INPUT IMPEDANCE= 115.20 30.47 OHMS

INPUT ADMITTANCE= 8.11 -2.15 MILLISIEMENS

MISMATCH LOSS= 0.1079 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.000	-9.843
0.250	0.098	20.800	8.189	-22.600	-8.898
0.500	0.197	16.000	6.299	5.400	2.126
0.350	0.138	14.600	5.748	11.900	4.685
0.350	0.138	17.100	6.732	29.700	11.693
0.350	0.138	15.700	6.181	41.800	16.457
0.300	0.118	15.000	5.906	54.700	21.535
0.300	0.118	16.400	6.457	77.600	30.551
0.300	0.118	14.500	5.709	98.700	38.858

FORWARD DIRECTIVITY= 9.97 DB

FRONT TO BACK RATIO= 22.59 DB

FORWARD GAIN= 9.97 DB

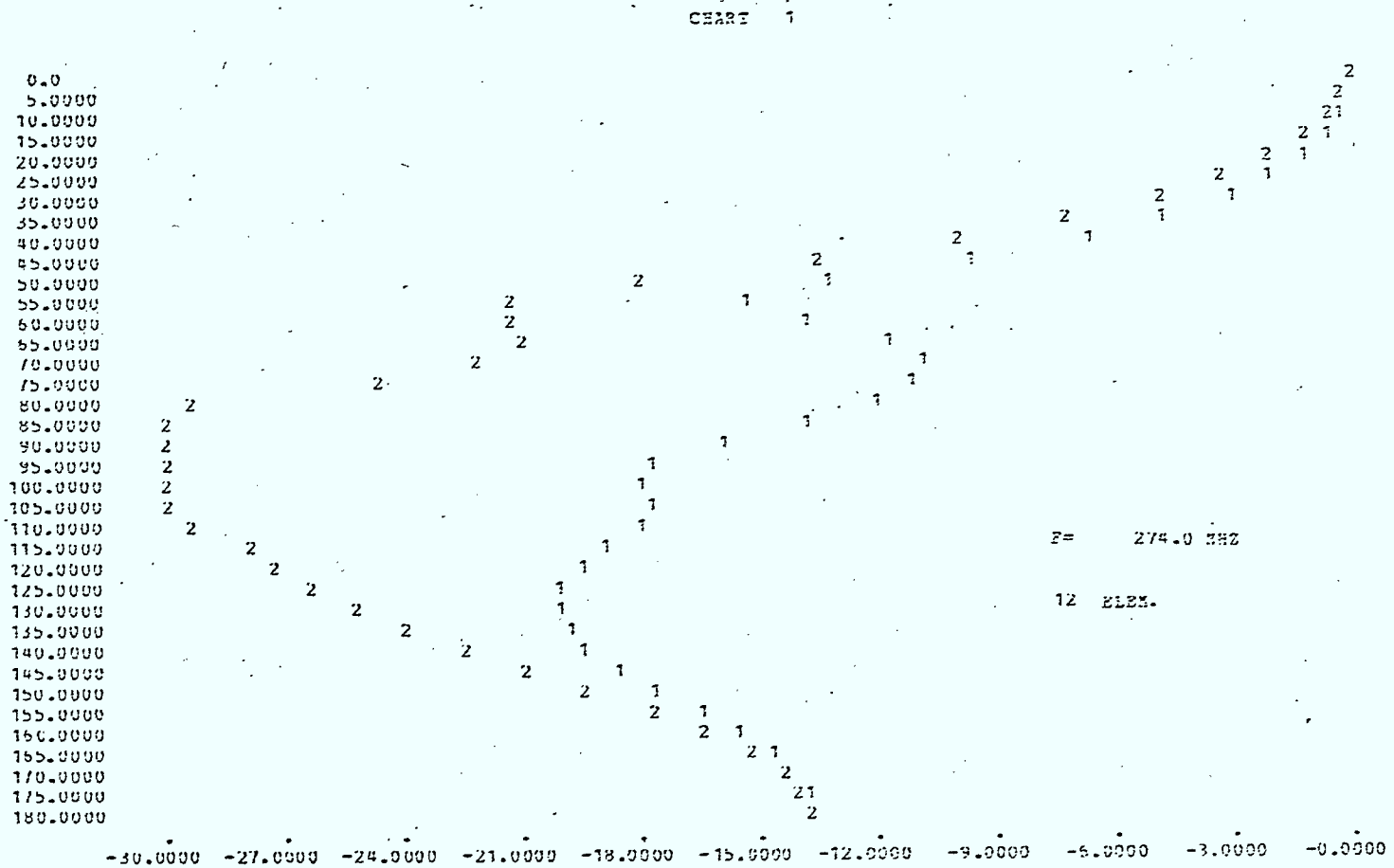
EFFICIENCY= -0.0067 DB

INPUT IMPEDANCE= 99.96 28.94 OHMS

INPUT ADMITTANCE= 9.23 -2.67 MILLISIEMENS

MISMATCH LOSS= 0.0900 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	17.100	6.732	5.700	2.244
0.650	0.256	20.000	7.874	12.100	4.764
0.650	0.256	17.700	6.969	29.700	11.693
0.500	0.197	21.100	8.307	41.900	16.496
0.400	0.157	19.700	7.756	54.600	21.496
0.550	0.256	20.500	8.110	77.200	30.394
0.650	0.256	19.500	7.677	98.800	38.898
0.500	0.197	18.900	7.441	118.400	46.614
0.400	0.157	19.100	7.520	138.800	54.646

FORWARD DIRECTIVITY= 11.20 DB

FRONT TO BACK RATIO= 13.65 DB

FORWARD GAIN= 11.20 DB

EFFICIENCY= -0.0024 DB

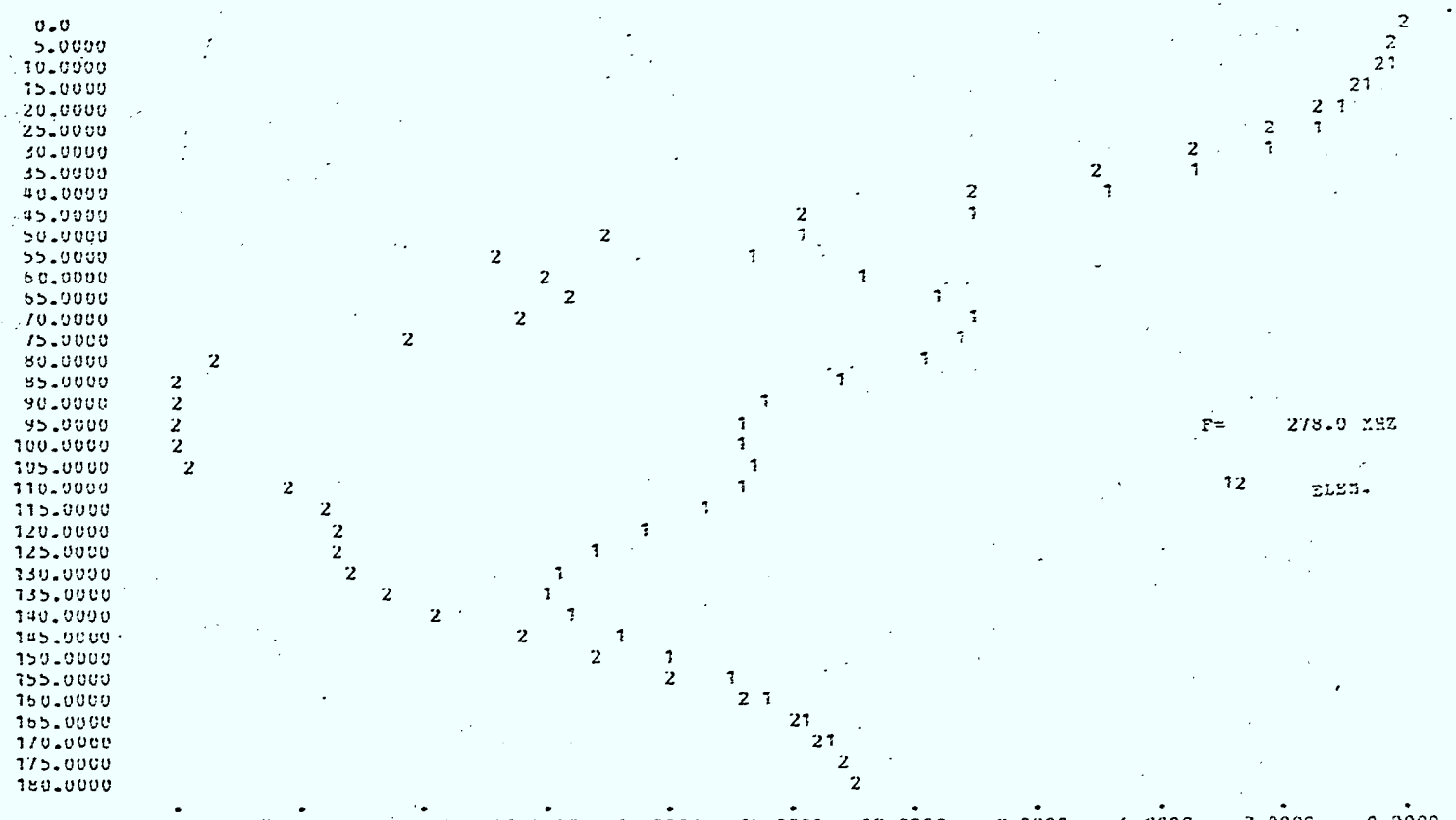
INPUT IMPEDANCE= 72.78 8.72 OHMS

INPUT ADMITTANCE= 13.55 -1.62 MILLISIEMENS

MISMATCH LOSS= 0.1292 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

CHART 1



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	17.100	6.732	5.700	2.244
0.650	0.256	20.000	7.874	12.100	4.764
0.650	0.256	17.700	6.969	29.700	11.693
0.500	0.197	21.100	8.307	41.900	16.496
0.400	0.157	19.700	7.756	54.600	21.496
0.650	0.256	20.600	8.110	77.200	30.394
0.550	0.256	19.500	7.677	98.800	38.898
0.500	0.197	18.900	7.441	118.400	46.614
0.400	0.157	19.100	7.520	138.800	54.646

FORWARD DIRECTIVITY= 11.29 DB

FRONT TO BACK RATIO= 13.46 DB

FORWARD GAIN= 11.28 DB

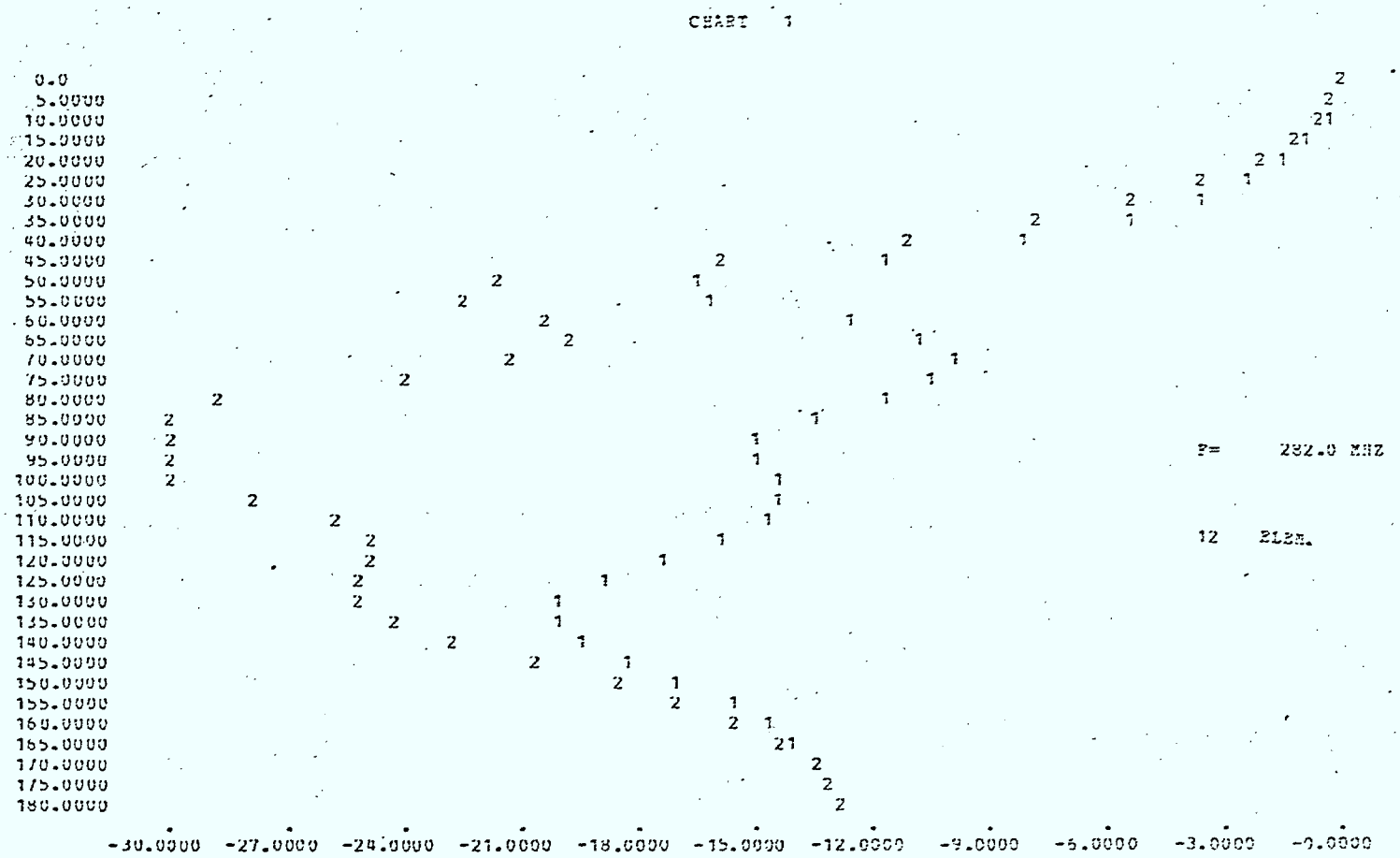
EFFICIENCY= -0.0023 DB

INPUT IMPEDANCE= 84.90 10.50 OHMS

INPUT ADMITTANCE= 11.60 -1.43 MILLISIEMENS

MISMATCH LOSS= 0.0431 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	17.100	6.732	5.700	2.244
0.650	0.256	20.000	7.874	12.100	4.764
0.650	0.256	17.700	6.969	29.700	11.693
0.500	0.197	21.100	8.307	41.900	16.496
0.400	0.157	19.700	7.756	54.600	21.496
0.650	0.256	20.600	8.110	77.200	30.394
0.650	0.256	19.500	7.677	98.600	38.818
0.500	0.197	18.900	7.441	118.400	46.614
0.400	0.157	19.100	7.520	138.800	54.646

FORWARD DIRECTIVITY= 11.32 DB

FRONT TO BACK RATIO= 12.86 DB

FORWARD GAIN= 11.32 DB

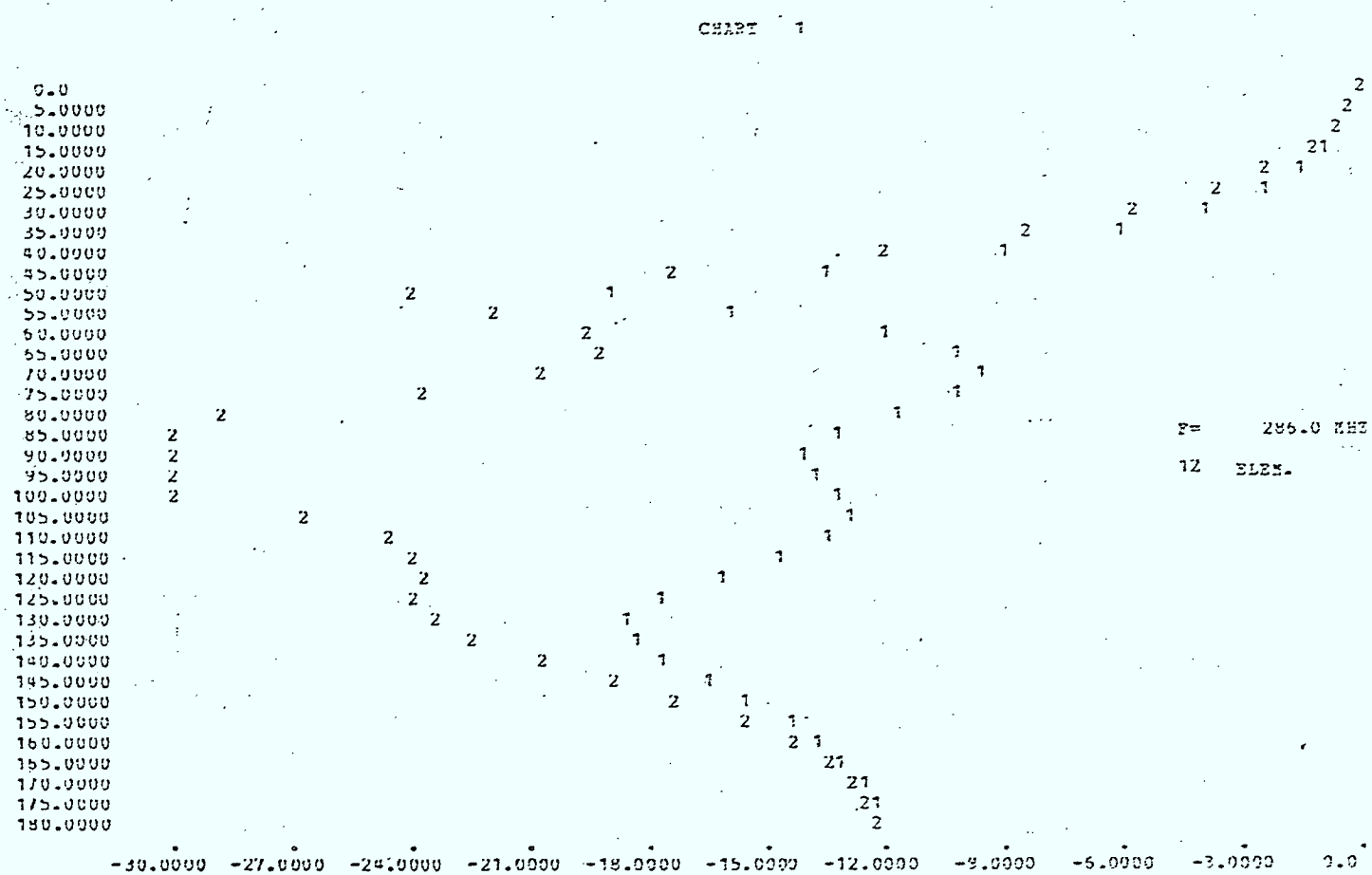
EFFICIENCY= -0.0022 DB

INPUT IMPEDANCE= 96.45 7.33 OHMS

INPUT ADMITTANCE= 10.31 -0.78 MILLISIEMENS

MISMATCH LOSS= 0.0075 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	17.100	6.732	5.700	2.244
0.650	0.256	20.000	7.874	12.100	4.764
0.650	0.256	17.700	6.969	29.700	11.693
0.500	0.197	21.100	8.307	41.900	16.496
0.400	0.157	19.700	7.756	54.600	21.496
0.650	0.256	20.600	8.110	77.200	30.394
0.650	0.256	19.500	7.677	98.800	38.898
0.500	0.197	18.900	7.441	118.400	46.614
0.400	0.157	19.100	7.520	139.800	55.039

FORWARD DIRECTIVITY= 11.30 DB

FRONT TO BACK RATIO= 12.21 DB

FORWARD GAIN= 11.20 DB

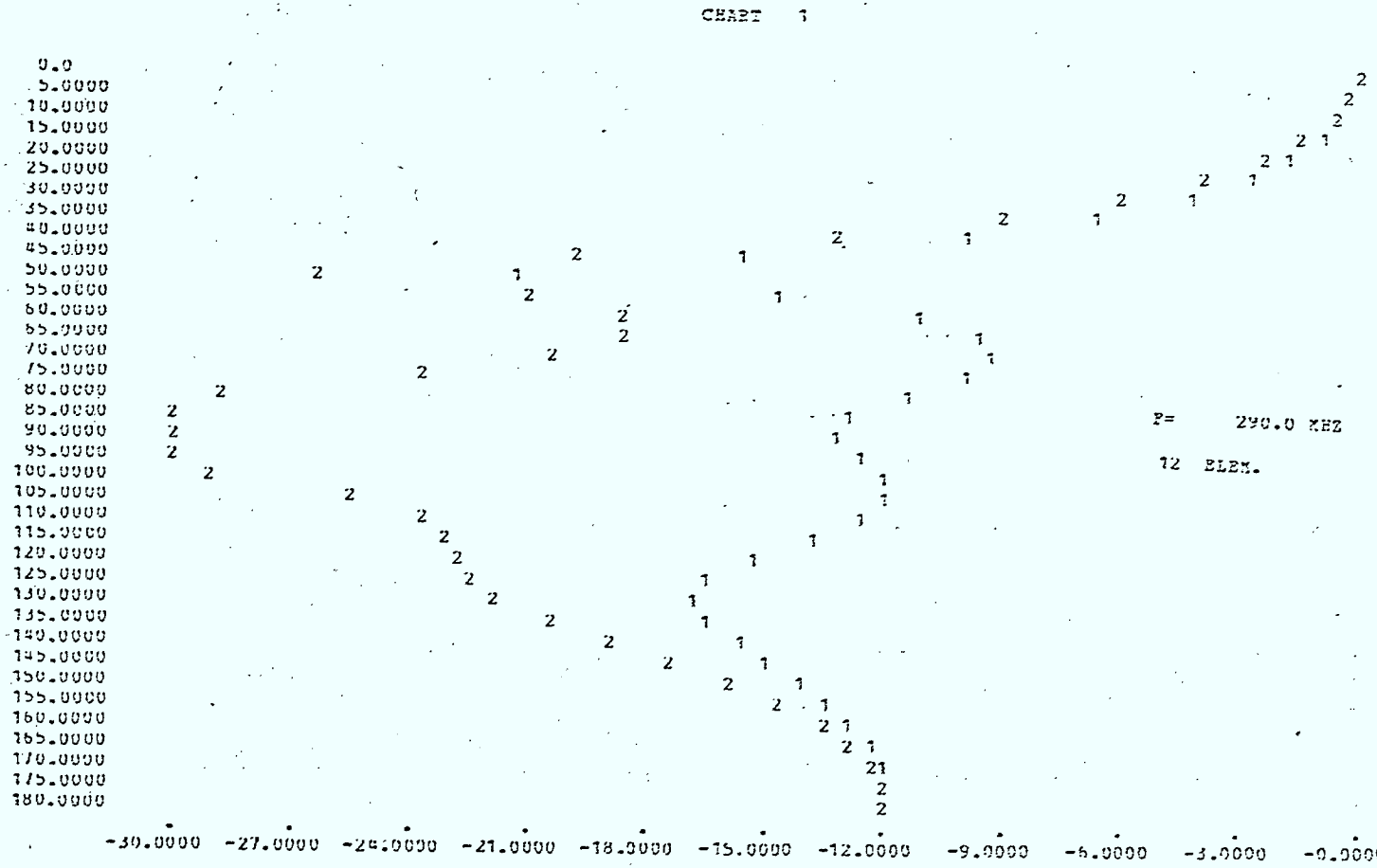
EFFICIENCY= -0.0022 DB

INPUT IMPEDANCE= 104.05 -1.31 OHMS

INPUT ADMITTANCE= 9.61 0.12 MILLISIEMENS

MISMATCH LOSS= 0.0019 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	17.100	6.732	5.700	2.244
0.650	0.256	20.000	7.874	12.100	4.764
0.650	0.256	17.700	6.969	29.700	11.693
0.500	0.197	21.100	8.307	41.900	16.496
0.400	0.157	19.700	7.756	54.600	21.496
0.650	0.256	20.600	8.110	77.200	30.394
0.650	0.256	19.500	7.677	98.800	38.898
0.500	0.197	18.900	7.441	118.400	46.614
0.400	0.157	19.100	7.520	138.800	54.646

FORWARD DIRECTIVITY= 11.24 DB

FRONT TO BACK RATIO= 11.71 DB

FORWARD GAIN= 11.23 DB

EFFICIENCY= -0.0023 DB

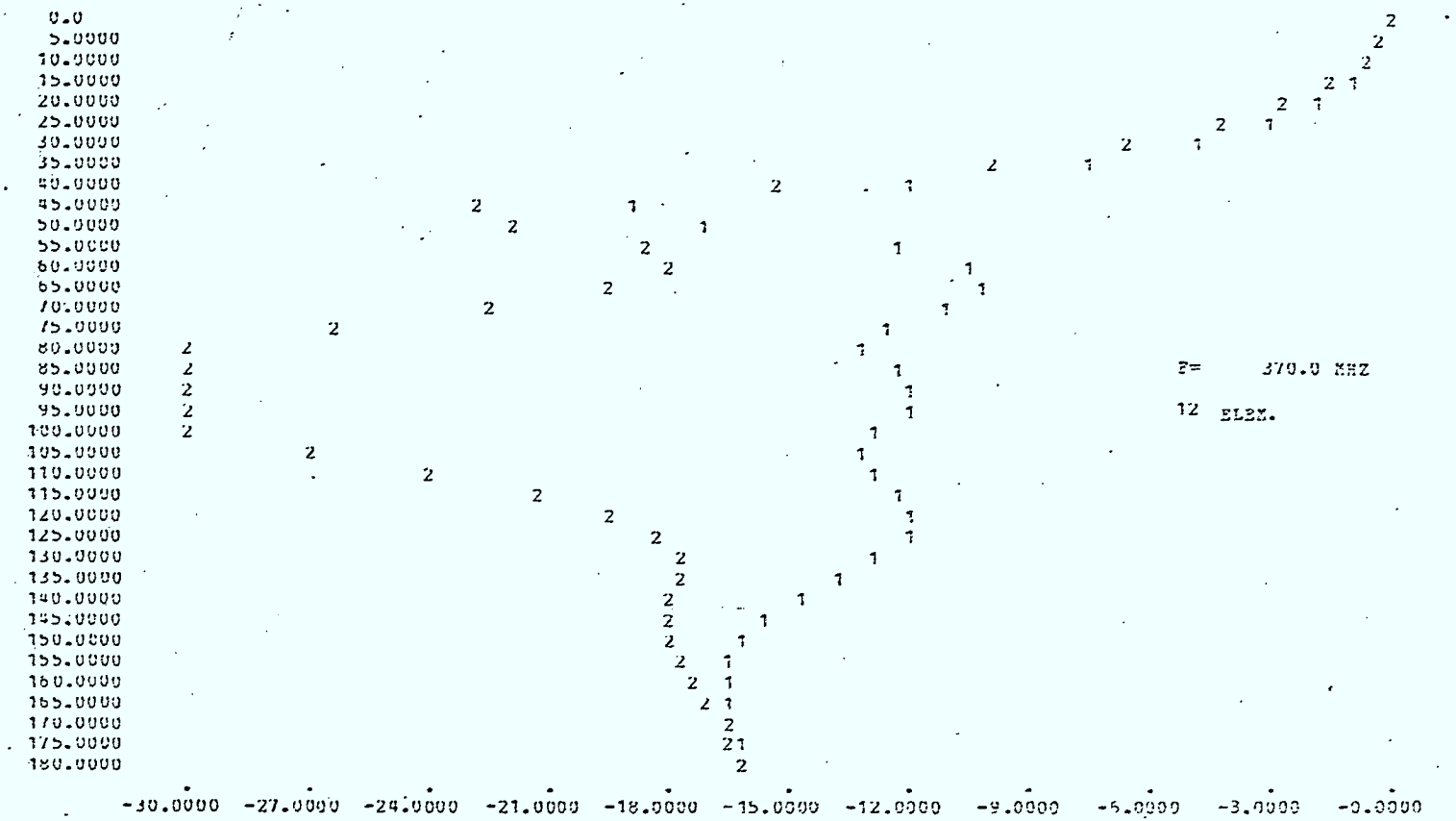
INPUT IMPEDANCE= 103.81 -12.68 OHMS

INPUT ADMITTANCE= 9.49 1.16 MILLISIEMENS

MISMATCH LOSS= 0.0183 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

CHART 1



F= 370.0 MHZ

12 ELEM.

A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	16.200	6.378	5.700	2.244
0.650	0.256	14.700	5.787	12.100	4.764
0.650	0.256	16.500	6.496	29.700	11.693
0.500	0.197	15.500	6.102	41.900	16.496
0.400	0.157	15.300	6.024	54.600	21.496
0.650	0.256	16.000	6.299	77.200	30.394
0.650	0.256	14.800	5.827	98.900	38.937
0.500	0.197	14.100	5.551	118.400	46.614
0.400	0.157	14.200	5.591	138.900	54.685

FORWARD DIRECTIVITY= 11.35 DB

FRONT TO BACK RATIO= 16.15 DB

FORWARD GAIN= 11.35 DB

EFFICIENCY= -0.0024 DB

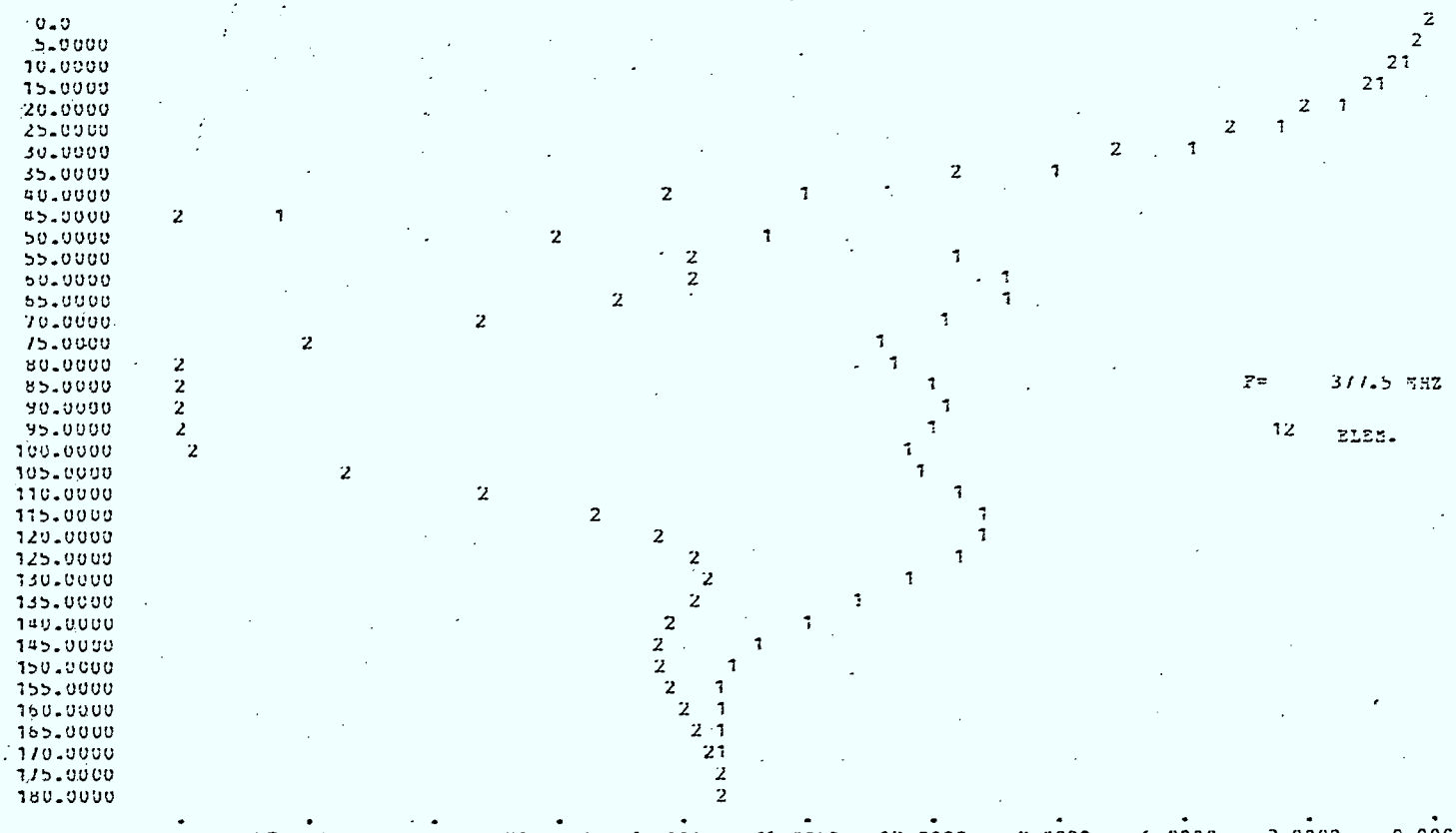
INPUT IMPEDANCE= 145.53 6.50 OHMS

INPUT ADMITTANCE= 6.86 -0.31 MILLISIEMENS

MISMATCH LOSS= 0.1550 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

CHART 1



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	16.200	6.378	5.700	2.244
0.650	0.256	14.700	5.787	12.100	4.764
0.650	0.256	16.500	6.496	29.700	11.693
0.500	0.197	15.500	6.102	41.900	16.496
0.400	0.157	15.300	6.024	54.600	21.496
0.650	0.256	16.000	6.299	77.200	30.394
0.650	0.256	14.900	5.867	98.800	38.898
0.500	0.197	14.100	5.551	118.400	46.614
0.400	0.157	14.200	5.591	138.800	54.646

FORWARD DIRECTIVITY= 11.50 DB

FRONT TO BACK RATIO= 16.82 DB

FORWARD GAIN= 11.50 DB

EFFICIENCY= -0.0026 DB

INPUT IMPEDANCE= 124.87 22.34 OHMS

INPUT ADMITTANCE= .76 -1.39 MILLISIEMENS

MISMATCH LOSS= 0.0461 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

CHART 1

A		R		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	16.200	6.378	5.700	2.244
0.650	0.256	14.700	5.787	12.100	4.764
0.650	0.256	16.500	6.496	29.700	11.693
0.500	0.197	15.500	6.102	41.900	16.496
0.400	0.157	15.300	6.024	54.600	21.496
0.650	0.256	16.000	6.299	77.200	30.394
0.650	0.256	14.800	5.827	98.800	38.898
0.500	0.197	14.100	5.551	118.400	46.614
0.400	0.157	14.200	5.591	138.800	54.646

FORWARD DIRECTIVITY= 11.76 DB

FRONT TO BACK RATIO= 18.76 DB

FORWARD GAIN= 11.76 DB

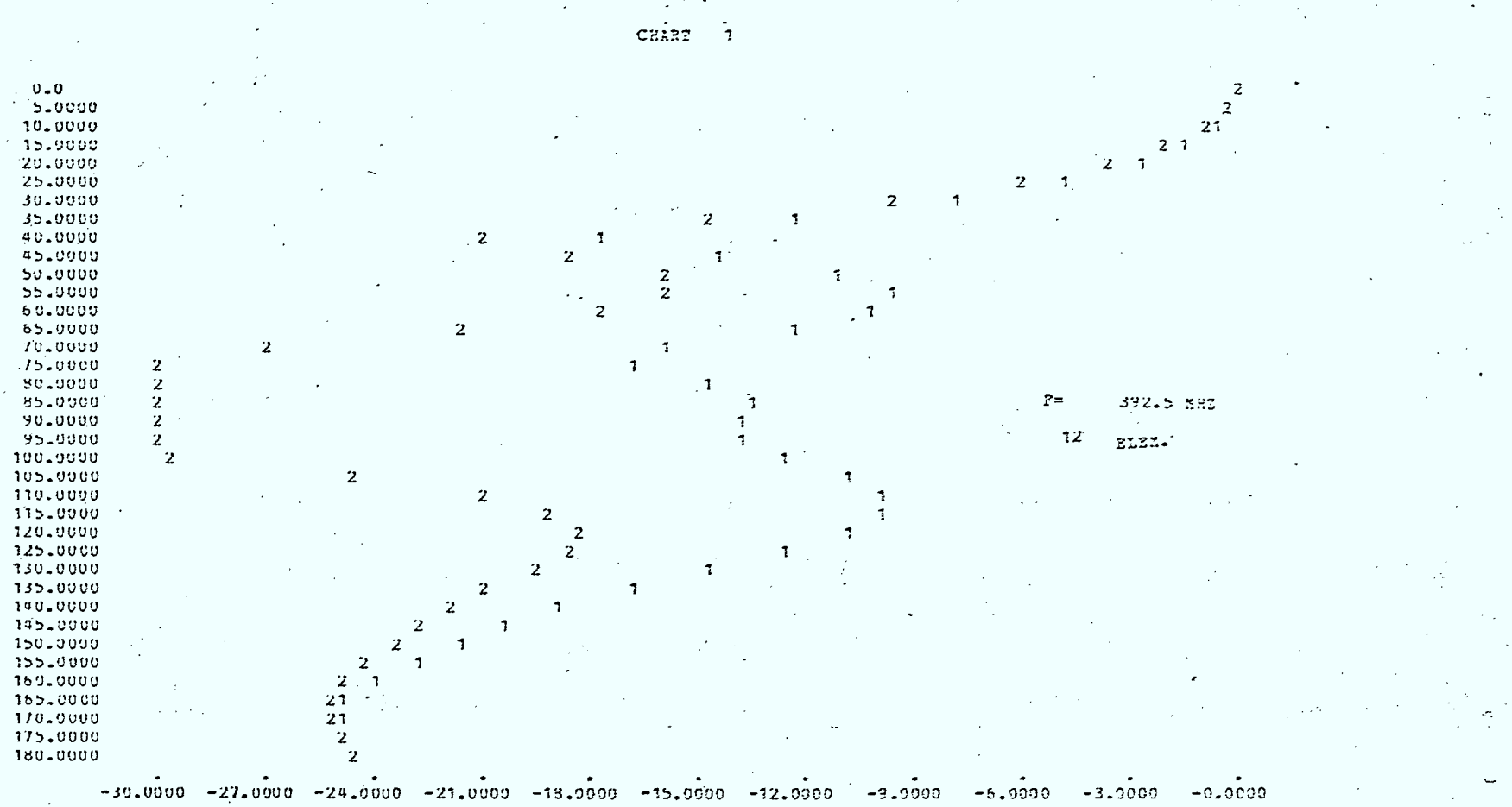
EFFICIENCY= -0.0032 DB

INPUT IMPEDANCE= 113.05 47.21 OHMS

INPUT ADMITTANCE= 7.53 -3.15 MILLISIEMENS

MISMATCH LOSS= 0.2245 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	16.200	6.378	5.700	2.244
0.650	0.256	14.700	5.787	12.100	4.764
0.650	0.256	16.500	6.496	29.700	11.693
0.500	0.197	15.500	6.102	41.900	16.496
0.400	0.157	15.300	6.024	54.600	21.496
0.650	0.256	15.900	6.299	77.200	30.394
0.650	0.256	14.800	5.827	98.600	38.819
0.500	0.197	14.100	5.551	119.400	46.614
0.400	0.157	14.200	5.591	138.800	54.646

FORWARD DIRECTIVITY= 12.15 DB

FRONT TO BACK RATIO= 24.54 DB

FORWARD GAIN= 12.15 DB

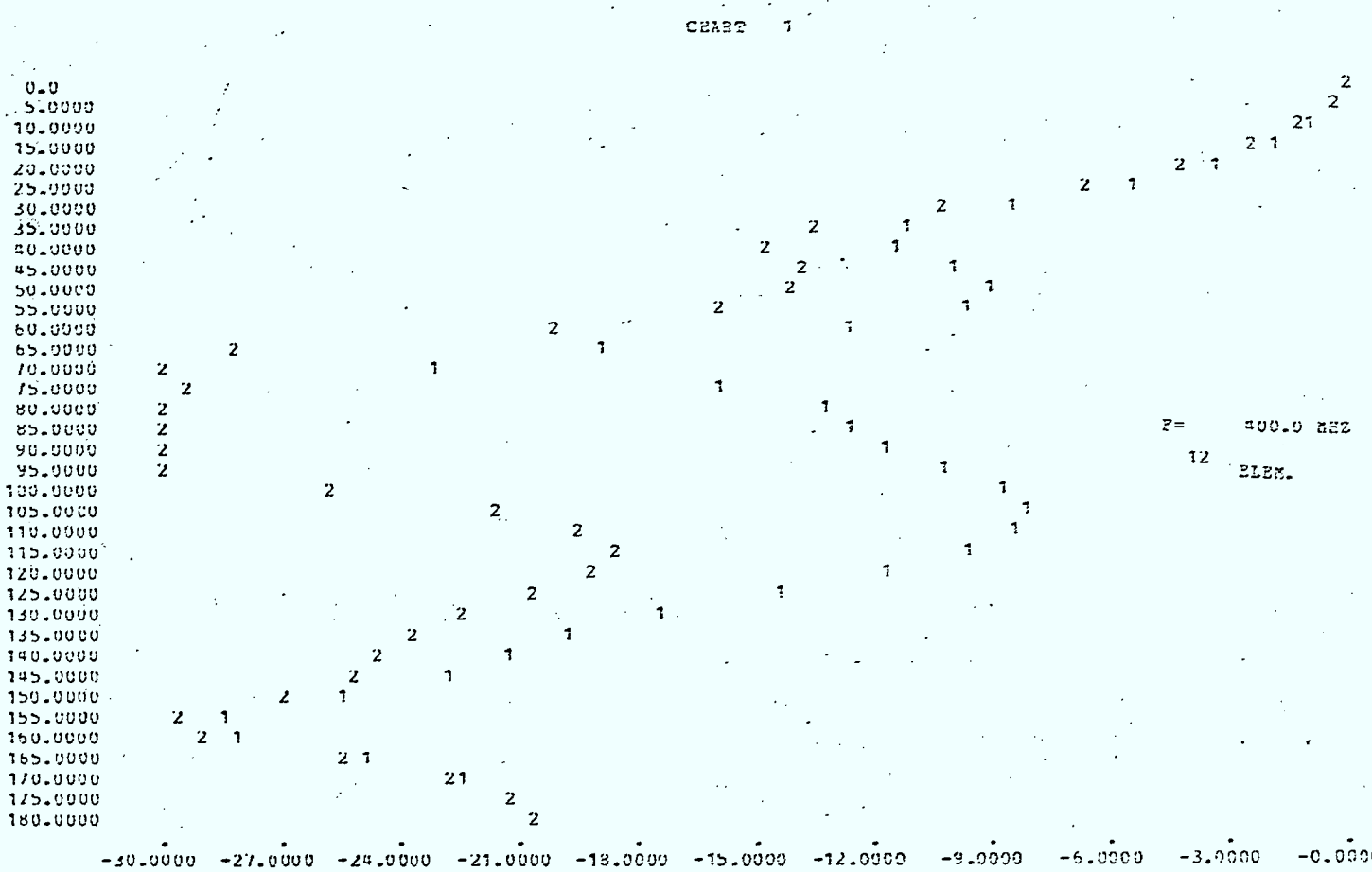
EFFICIENCY= -0.0044 DB

INPUT IMPEDANCE= 122.79 72.29 OHMS

INPUT ADMITTANCE= 6.05 -3.56 MILLISIEMENS

MISMATCH LOSS= 0.4804 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.300	9.961	0.0	0.0
0.400	0.157	26.500	10.433	-25.200	-9.921
0.150	0.059	20.400	8.031	-22.200	-8.740
0.500	0.197	16.200	6.378	5.700	2.244
0.650	0.256	14.700	5.787	12.100	4.764
0.650	0.256	16.500	6.496	29.700	11.693
0.500	0.197	15.500	6.102	41.900	16.496
0.400	0.157	15.300	6.024	54.600	21.496
0.650	0.256	16.000	6.299	77.200	30.394
0.650	0.256	14.800	5.827	98.800	38.898
0.500	0.197	14.100	5.551	118.400	46.614
0.400	0.157	14.200	5.591	138.800	54.646

FORWARD DIRECTIVITY= 11.86 DB

FRONT TO BACK RATIO= 20.58 DB

FORWARD GAIN= 11.85 DB

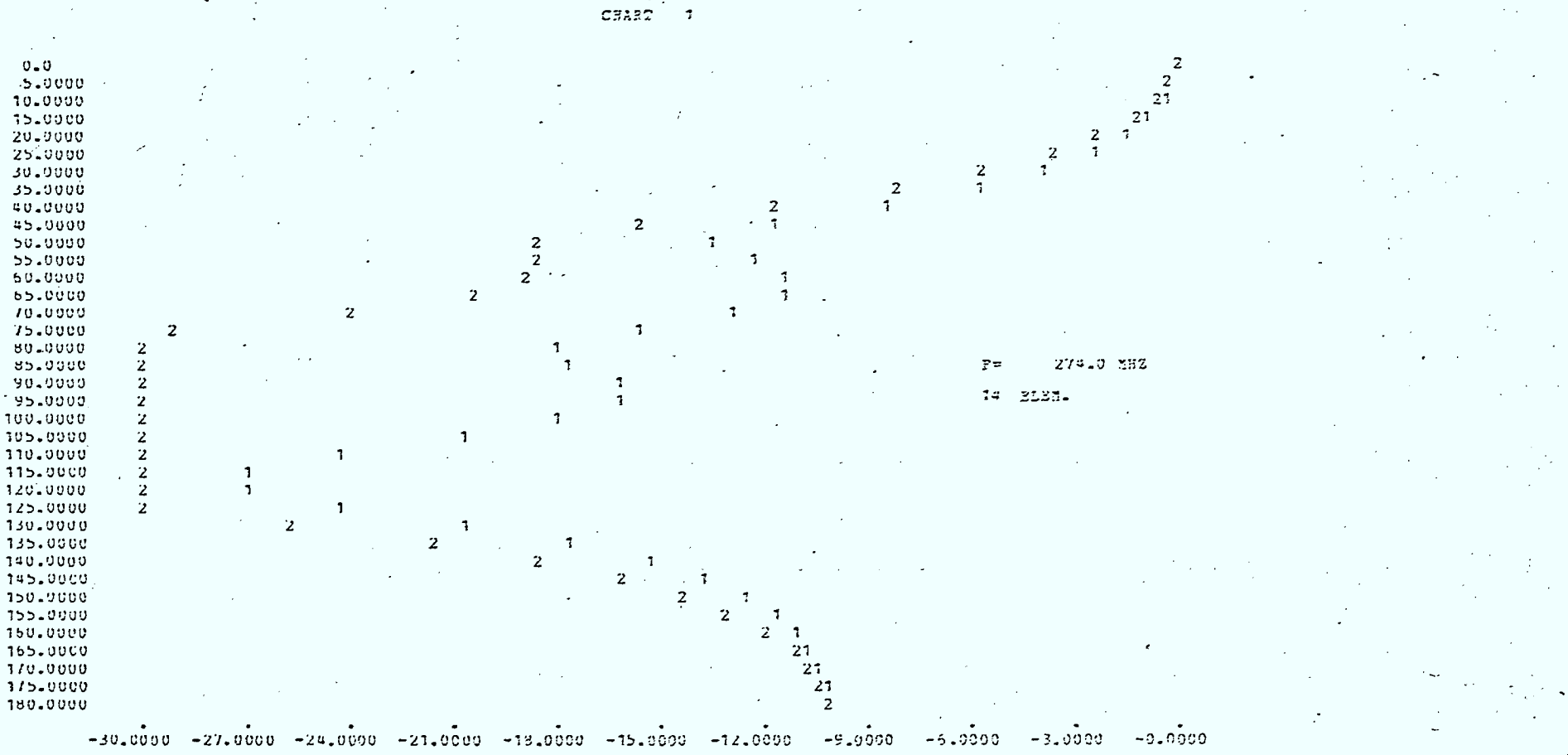
EFFICIENCY= -0.0074 DB

INPUT IMPEDANCE= 126.04 32.43 OHMS

INPUT ADMITTANCE= 7.44 -1.91 MILLISIEMENS

MISMATCH LOSS= 0.1465 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	17.200	6.772	4.800	1.890
0.400	0.157	19.000	7.480	12.100	4.764
0.350	0.138	18.400	7.244	25.200	9.921
0.300	0.118	21.800	8.583	38.900	15.315
0.350	0.138	20.000	7.874	54.100	21.299
0.200	0.079	20.900	8.228	73.900	29.094
0.330	0.130	20.500	8.071	96.300	37.913
0.300	0.119	19.000	7.480	117.800	46.378
0.250	0.098	19.500	7.677	140.000	55.114
0.330	0.130	20.200	7.953	155.500	61.220
0.330	0.130	19.300	7.598	178.600	70.709

FORWARD DIRECTIVITY= 11.49 DB

FRONT TO BACK RATIO= 10.11 DB

FORWARD GAIN= 11.48 DB

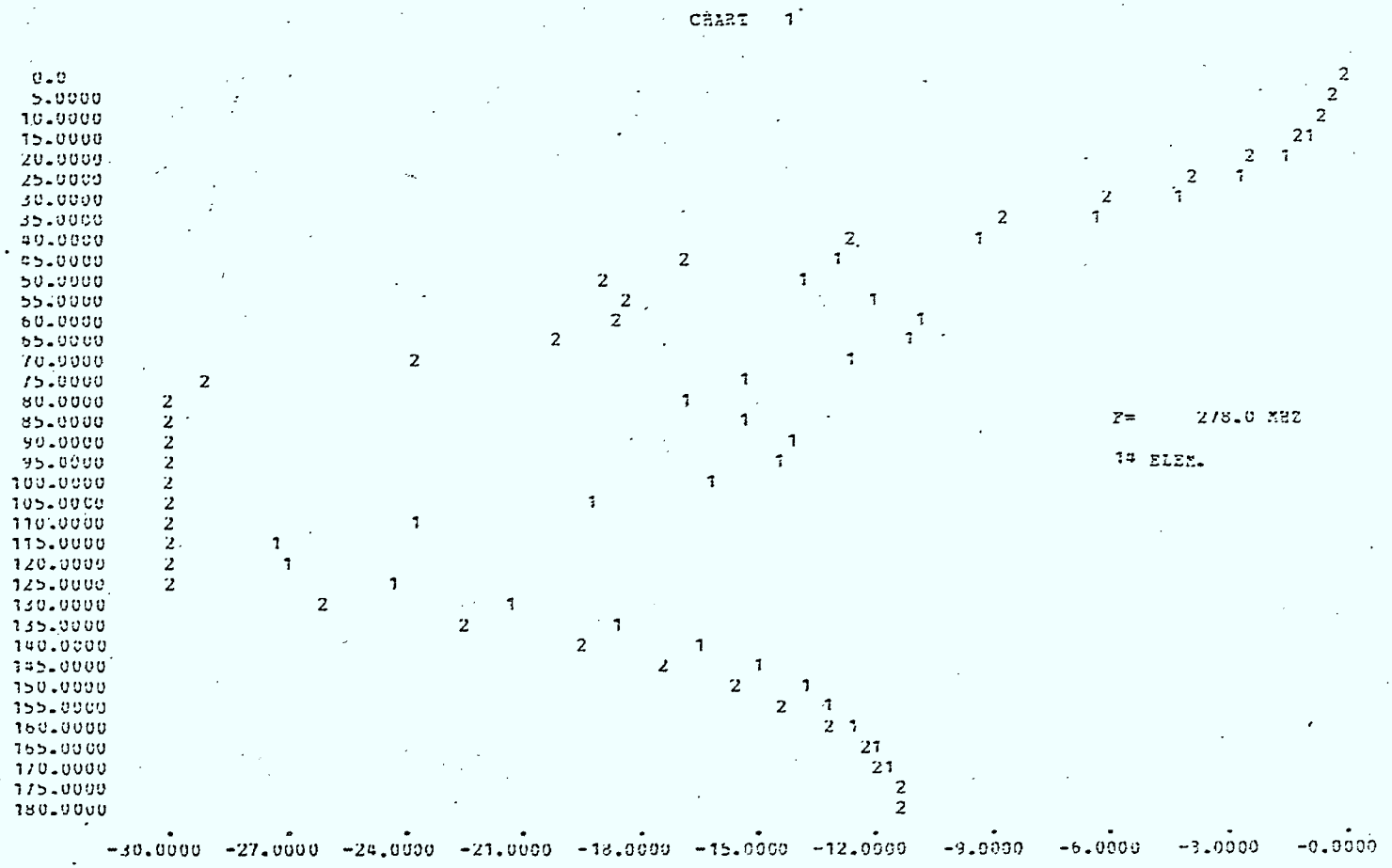
EFFICIENCY= -0.0031 DB

INPUT IMPEDANCE= 70.67 10.39 OHMS

INPUT ADMITTANCE= 13.95 -2.04 MILLISIEMENS

MISMATCH LOSS= 0.1462 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	17.200	6.772	4.900	1.890
0.400	0.157	19.000	7.480	12.100	4.764
0.350	0.138	18.400	7.244	25.200	9.921
0.300	0.118	21.800	8.583	38.900	15.315
0.350	0.139	20.000	7.874	54.100	21.299
0.200	0.079	20.900	8.228	73.900	29.094
0.330	0.130	20.500	8.071	96.300	37.913
0.300	0.118	19.000	7.480	117.600	46.378
0.250	0.098	19.500	7.677	140.000	55.118
0.330	0.130	20.200	7.953	155.500	61.220
0.330	0.130	19.300	7.598	179.600	70.709

FORWARD DIRECTIVITY= 11.65 DB

FRONT TO BACK RATIO= 11.27 DB

FORWARD GAIN= 11.65 DB

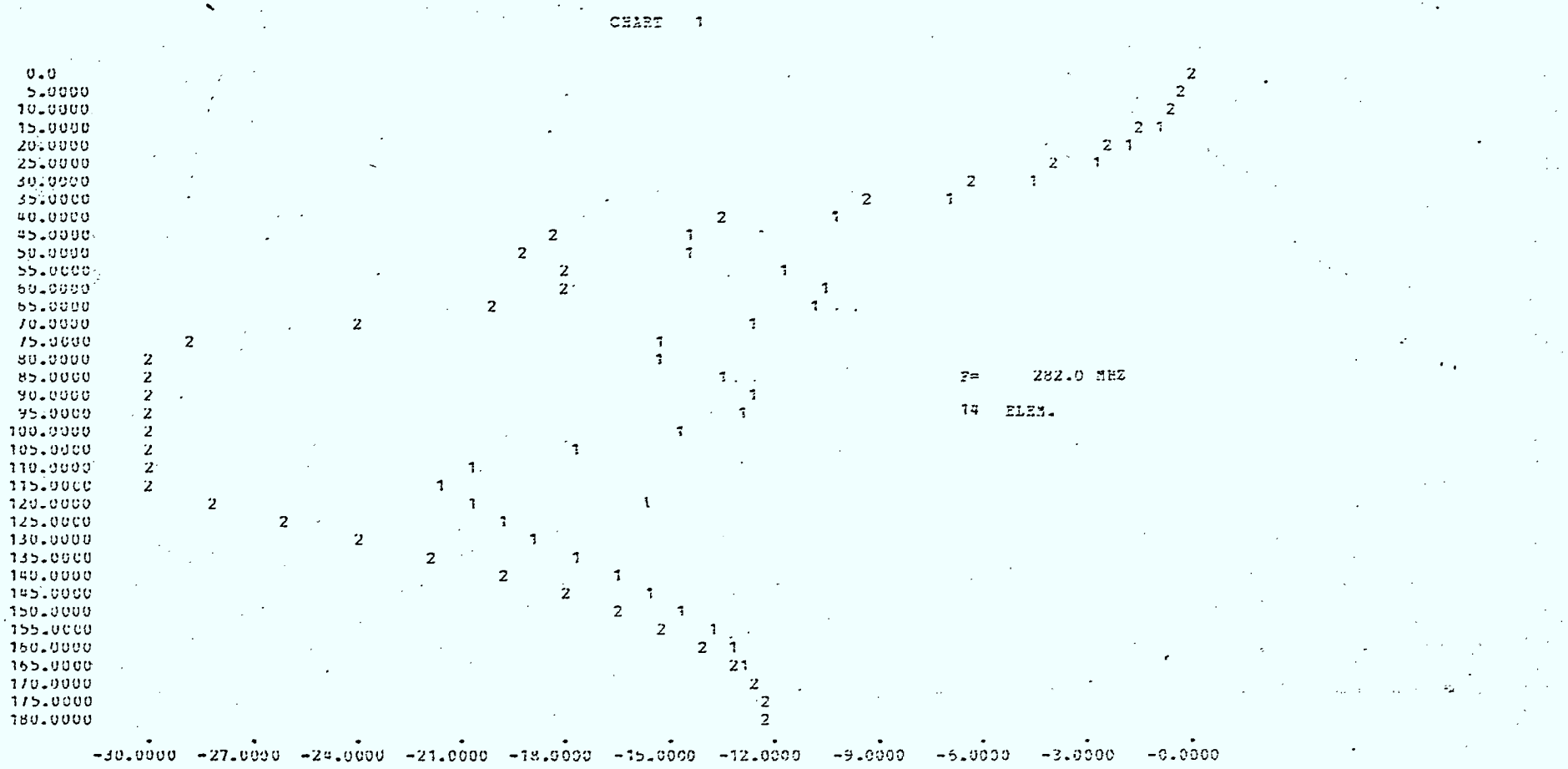
EFFICIENCY= -0.0030 DB

INPUT IMPEDANCE= 85.44 11.09 OHMS

INPUT ADMITTANCE= 11.51 -1.49 MILLISIEMENS

MISMATCH LOSS= 0.0424 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		V	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	17.200	6.772	4.800	1.890
0.400	0.157	19.000	7.480	12.100	4.764
0.350	0.138	18.400	7.244	25.200	9.921
0.300	0.118	21.800	8.583	38.900	15.315
0.350	0.138	20.000	7.874	54.100	21.299
0.200	0.079	20.900	8.228	73.900	29.094
0.330	0.130	20.500	8.071	96.300	37.913
0.300	0.118	19.000	7.480	117.800	46.378
0.250	0.098	19.500	7.677	140.000	55.118
0.330	0.130	20.200	7.953	155.500	61.220
0.330	0.130	19.300	7.598	179.600	70.709

FORWARD DIRECTIVITY= 11.72 DB

FRONT TO BACK RATIO= 14.10 DB

FORWARD GAIN= 11.72 DB

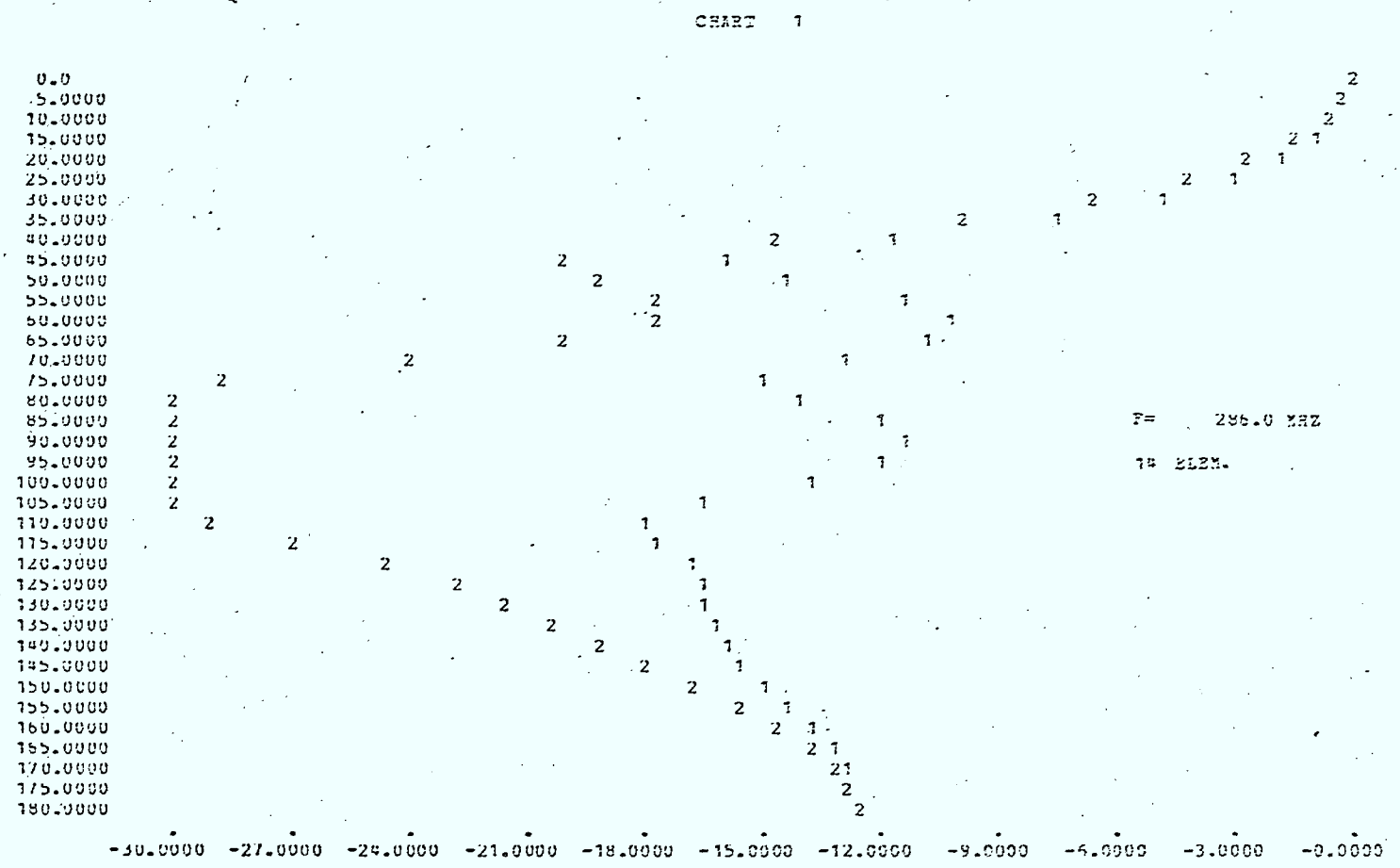
EFFICIENCY= -0.0030 DB

INPUT IMPEDANCE= 99.00 5.83 OHMS

INPUT ADMITTANCE= 10.17 -0.60 MILLISIEMENS

MISMATCH LOSS= 0.0042 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	17.200	6.772	4.800	1.890
0.400	0.157	19.000	7.480	12.700	4.764
0.350	0.138	18.400	7.244	25.200	9.921
0.300	0.118	21.800	8.583	38.900	15.315
0.350	0.138	20.000	7.874	54.100	21.299
0.200	0.079	20.400	8.228	73.900	29.094
0.340	0.130	20.500	8.071	96.600	37.913
0.300	0.118	19.000	7.480	117.800	46.378
0.250	0.098	19.500	7.677	140.300	55.118
0.330	0.130	20.200	7.953	155.500	61.220
0.330	0.130	19.300	7.598	179.600	70.709

FORWARD DIRECTIVITY= 11.72 DB

FRONT TO BACK RATIO= 12.56 DB

FORWARD GAIN= 11.72 DB

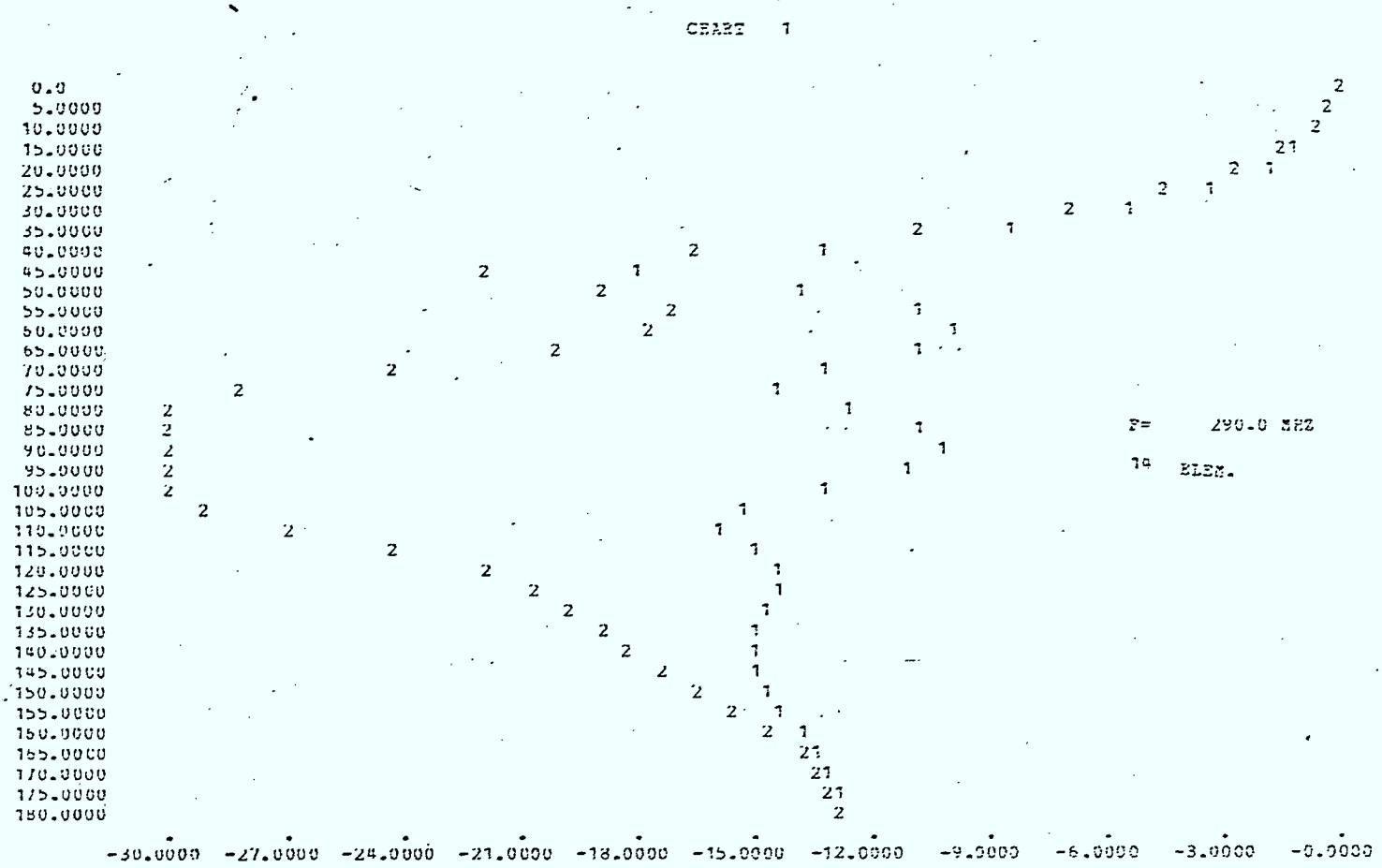
EFFICIENCY= -0.0031 DB

INPUT IMPEDANCE= 104.96 -3.89 OHMS

INPUT ADMITTANCE= 9.51 0.35 MILLISIEMENS

MISMATCH LOSS= 0.0041 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	17.200	6.772	4.800	1.890
0.400	0.157	19.000	7.480	12.100	4.764
0.350	0.138	18.400	7.244	25.200	9.921
0.300	0.118	21.800	8.583	38.900	15.315
0.350	0.138	20.000	7.874	54.100	21.299
0.200	0.079	20.900	8.228	73.900	29.094
0.330	0.130	20.500	8.071	96.300	37.913
0.300	0.118	19.000	7.480	117.800	46.378
0.250	0.098	19.500	7.677	140.000	55.118
0.330	0.130	20.200	7.953	155.500	61.220
0.330	0.130	19.300	7.598	179.600	70.709

FORWARD DIRECTIVITY= 11.67 DB

FRONT TO BACK RATIO= 12.84 DB

FORWARD GAIN= 11.66 DB

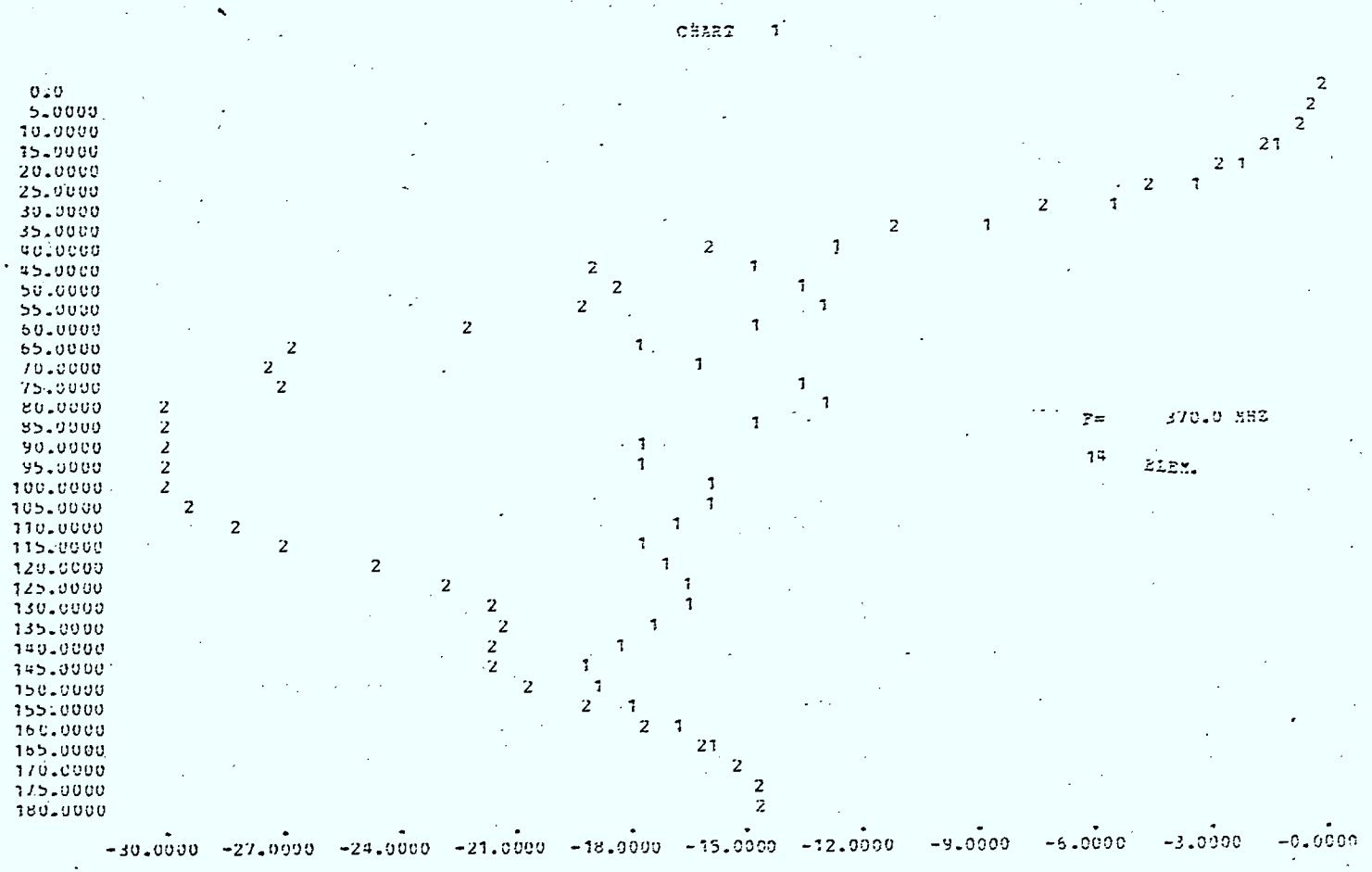
EFFICIENCY= -0.0032 DB

INPUT IMPEDANCE= 104.42 -14.25 OHMS

INPUT ADMITTANCE= 9.40 1.28 MILLISIEMENS

MISMATCH LOSS= 0.0231 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		V	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	16.760	6.598	4.800	1.890
0.400	0.157	15.000	5.906	12.100	4.764
0.350	0.138	16.970	6.681	25.200	9.921
0.300	0.118	15.910	6.264	38.900	15.315
0.350	0.138	15.260	6.008	54.100	21.299
0.200	0.079	15.490	6.492	74.900	29.094
0.330	0.130	14.850	5.850	96.300	37.913
0.300	0.118	14.280	5.622	117.800	46.378
0.250	0.098	13.880	5.465	140.000	55.118
0.330	0.130	14.870	5.854	155.500	61.220
0.330	0.130	15.150	5.965	179.600	70.709

FORWARD DIRECTIVITY= 12.27 DB

FRONT TO BACK RATIO= 14.45 DB

FORWARD GAIN= 12.27 DB

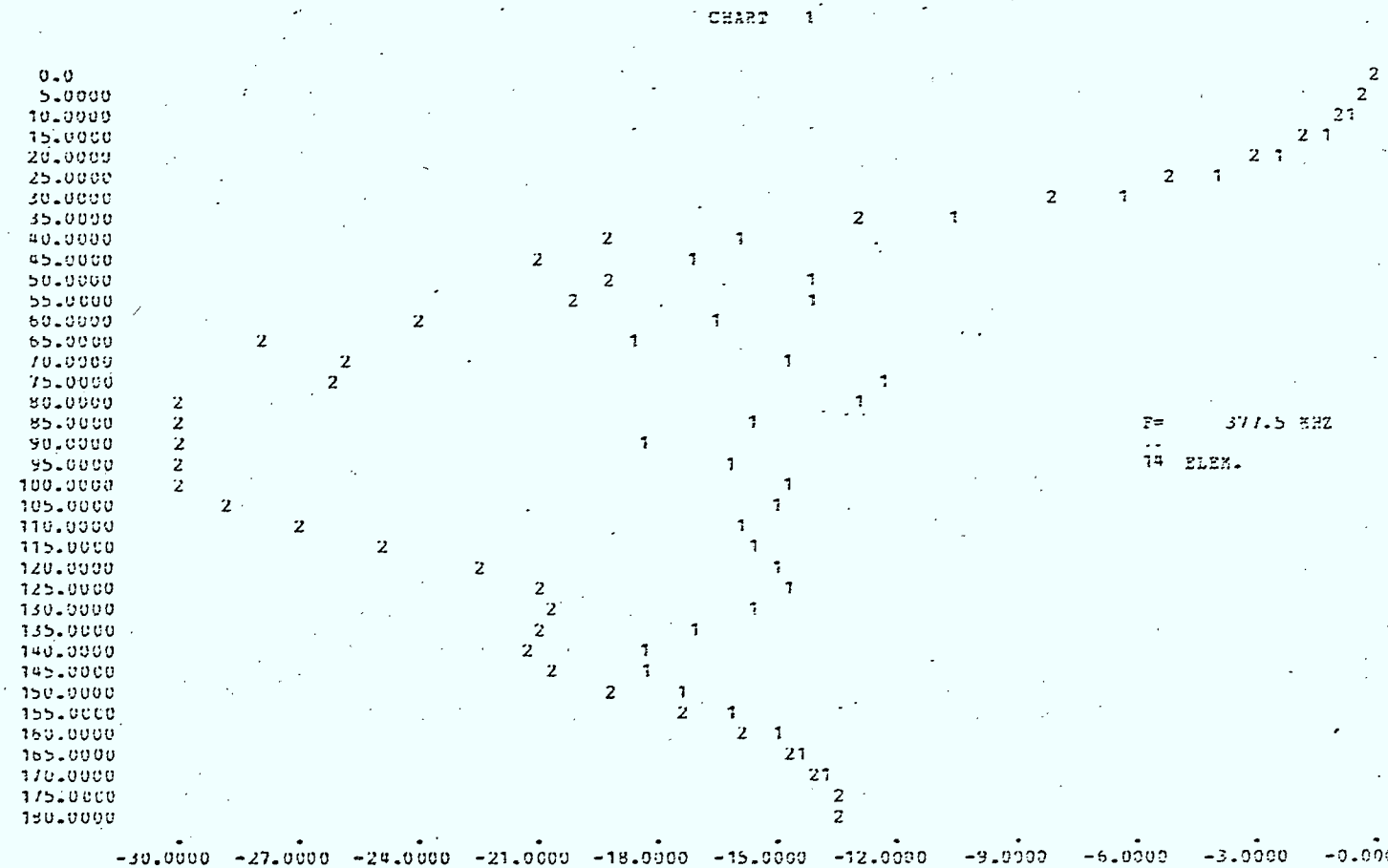
EFFICIENCY= -0.0034 DB

INPUT IMPEDANCE= 154.82 -41.29 OHMS

INPUT ADMITTANCE= 6.03 1.61 MILLISIEMENS

MISMATCH LOSS= 0.3164 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		I	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	16.760	6.598	4.880	1.890
0.400	0.157	15.000	5.906	12.100	4.764
0.350	0.138	16.970	6.681	25.200	9.921
0.300	0.118	15.910	6.264	38.900	15.315
0.350	0.138	15.260	6.008	54.100	21.299
0.200	0.079	16.490	6.492	73.900	29.094
0.350	0.140	14.860	5.850	96.300	37.913
0.300	0.118	14.280	5.622	117.600	46.378
0.250	0.098	13.880	5.465	140.000	55.118
0.350	0.140	14.870	5.854	155.500	61.220.
0.350	0.140	15.150	5.965	179.600	70.709

FORWARD DIRECTIVITY= 12.47 DB

FRONT TO BACK RATIO= 13.24 DB

FORWARD GAIN= 12.47 DB

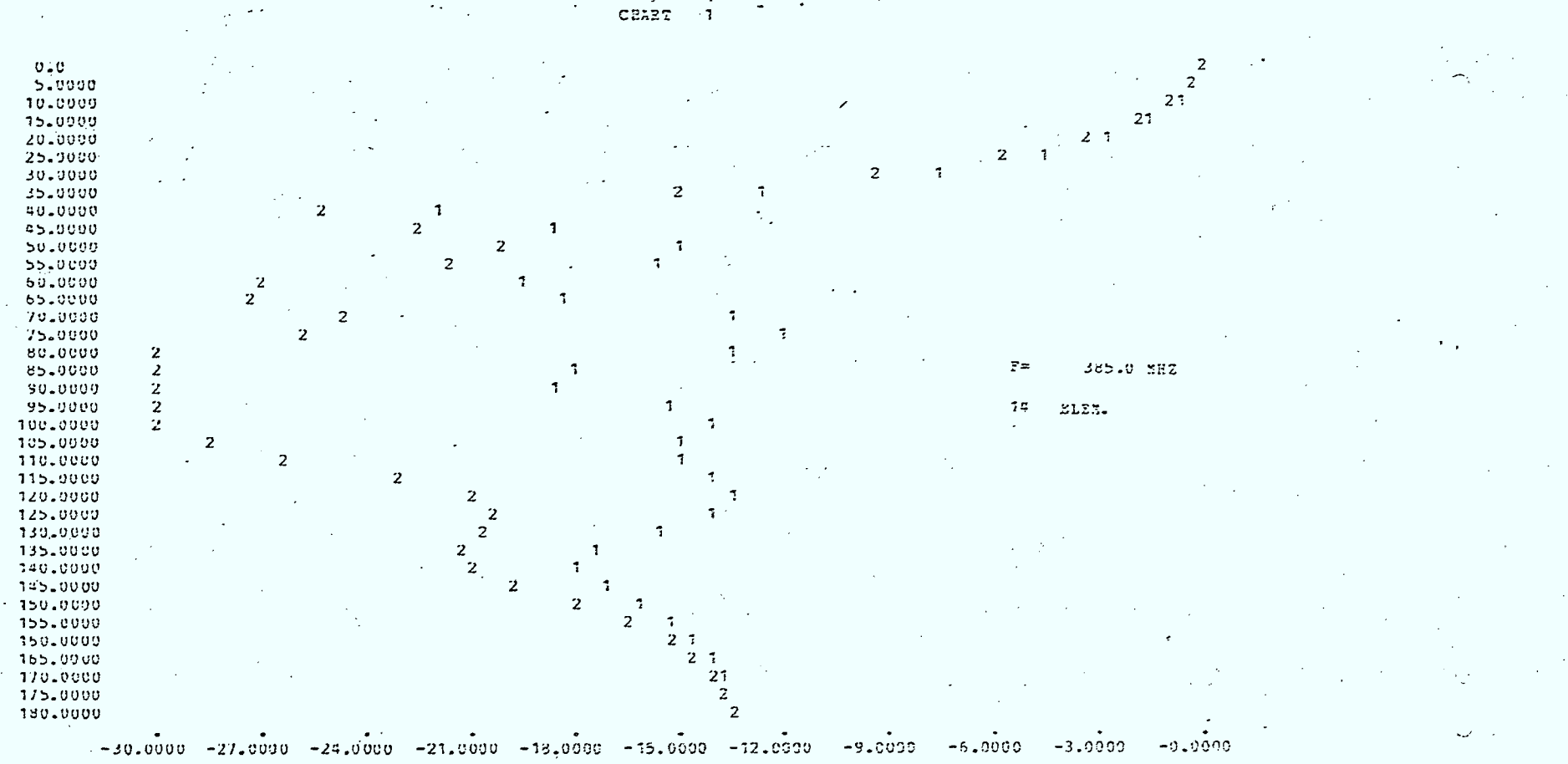
EFFICIENCY= -0.0042 DB

INPUT IMPEDANCE= 110.21 -24.03 OHMS

INPUT ADMITTANCE= 8.66 1.89 MILLISIEMENS

MISMATCH LOSS= 0.0667 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	16.760	6.598	4.800	1.890
0.400	0.157	15.000	5.906	12.100	4.764
0.350	0.138	16.970	6.681	25.200	9.921
0.300	0.118	15.970	6.264	39.900	15.315
0.350	0.138	15.280	6.008	54.100	21.299
0.200	0.079	14.490	5.492	73.900	29.094
0.330	0.130	14.560	5.850	96.300	37.913
0.300	0.118	14.280	5.622	117.800	46.378
0.250	0.098	13.880	5.465	140.000	55.118
0.330	0.130	14.870	5.854	155.500	61.220
0.330	0.130	15.150	5.965	179.600	70.709

FORWARD DIRECTIVITY= 12.74 DB

FRONT TO BACK RATIO= 13.44 DB

FORWARD GAIN= 12.73 DB

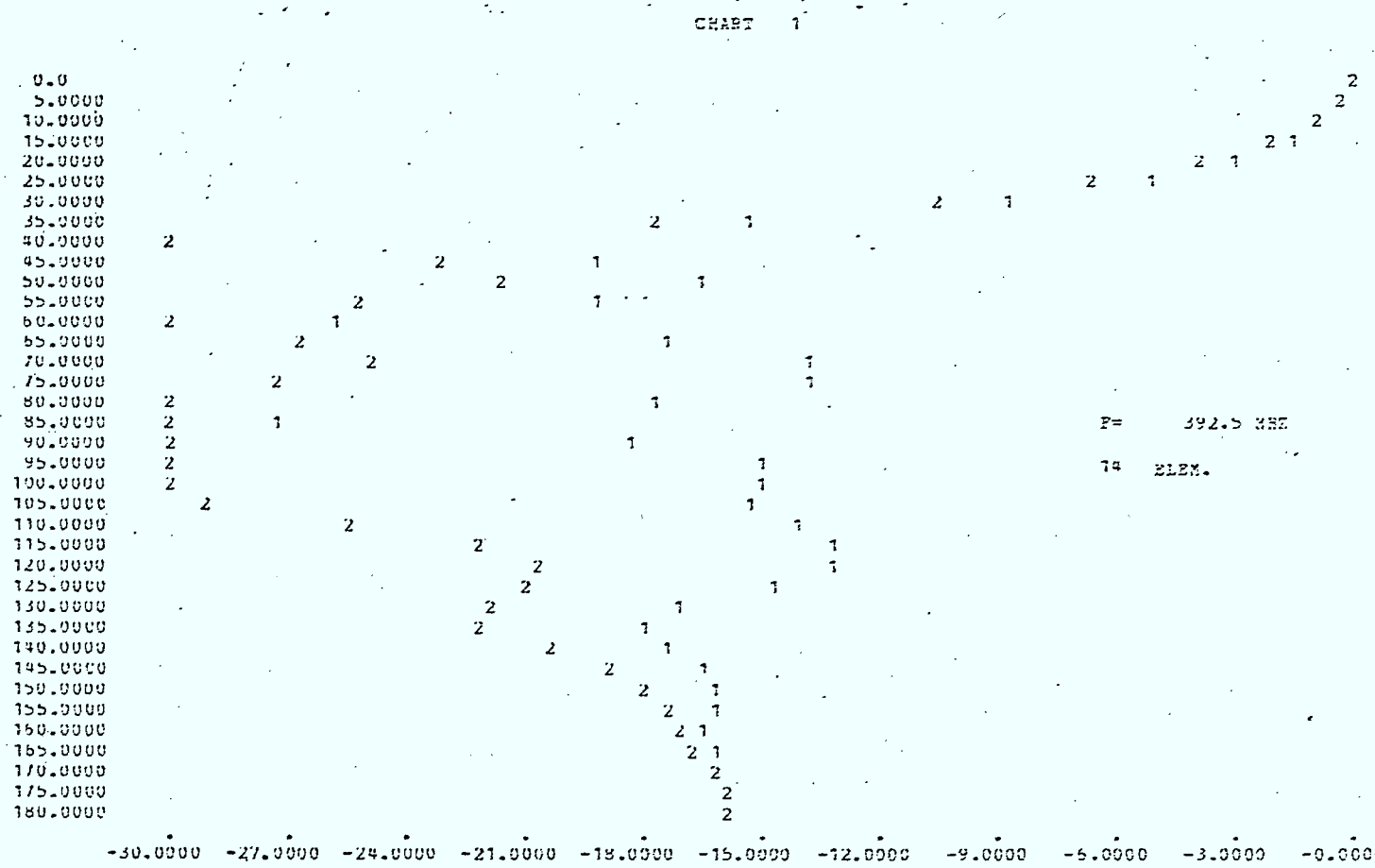
EFFICIENCY= -0.0053 DB

INPUT IMPEDANCE= 88.15 10.14 OHMS

INPUT ADMITTANCE= 11.20 -1.29 MILLISIEMENS

MISMATCH LOSS= 0.0299 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.249	-17.200	-6.772
0.500	0.197	16.760	6.598	4.800	1.890
0.400	0.157	15.000	5.906	12.100	4.764
0.350	0.138	16.970	6.681	25.200	9.921
0.300	0.118	15.910	6.264	38.900	15.315
0.350	0.138	15.260	6.008	54.100	21.299
0.200	0.079	16.450	6.477	73.900	29.094
0.330	0.130	14.860	5.850	96.300	37.913
0.300	0.118	14.250	5.622	117.800	46.378
0.250	0.098	13.880	5.465	140.000	55.118
0.330	0.130	14.870	5.854	155.500	61.220
0.330	0.130	15.150	5.965	179.600	70.709

FORWARD DIRECTIVITY= 13.25 DB

FRONT TO BACK RATIO= 15.77 DB

FORWARD GAIN= 13.24 DB

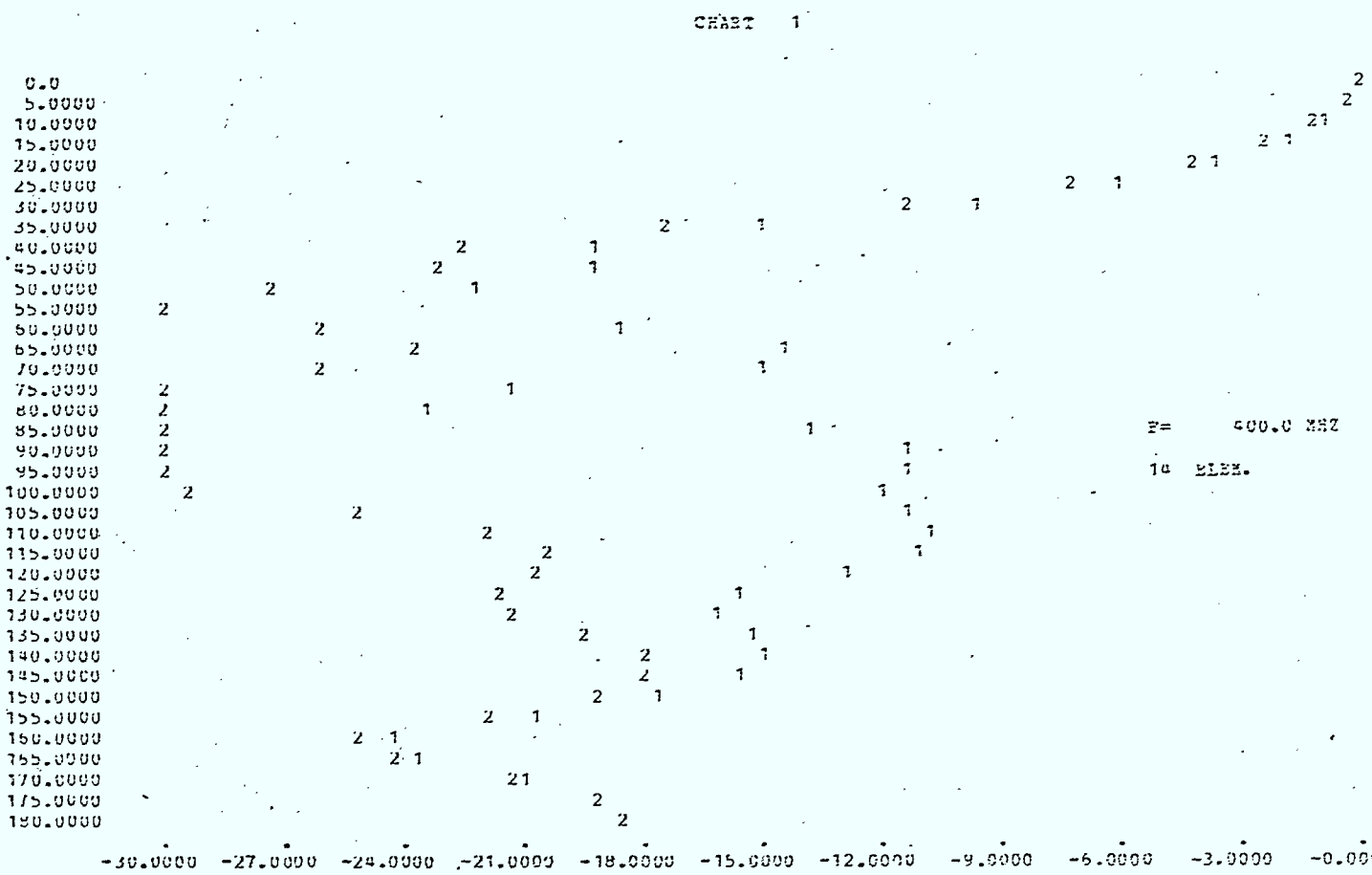
EFFICIENCY= -0.0075 DB

INPUT IMPEDANCE= 97.13 37.29 OHMS

INPUT ADMITTANCE= 8.97 -3.44 MILLISIEMENS

MISMATCH LOSS= 0.1536 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.400	0.157	25.700	10.118	-26.200	-10.315
0.300	0.118	20.950	8.248	-17.200	-6.772
0.500	0.197	16.760	6.598	4.800	1.890
0.400	0.157	15.000	5.906	12.100	4.764
0.350	0.138	16.570	6.681	25.200	9.921
0.300	0.118	15.910	6.264	38.900	15.315
0.350	0.138	15.260	6.008	54.100	21.299
0.200	0.079	16.490	6.492	73.900	29.094
0.350	0.138	14.960	5.858	96.300	37.913
0.300	0.118	14.280	5.622	117.800	46.378
0.250	0.098	13.860	5.465	140.000	55.118
0.330	0.130	14.870	5.854	155.500	61.220
0.330	0.130	15.750	5.965	179.600	70.709

FORWARD DIRECTIVITY= 13.08 DB

FRONT TO BACK RATIO= 18.53 DB

FORWARD GAIN= 13.06 DB

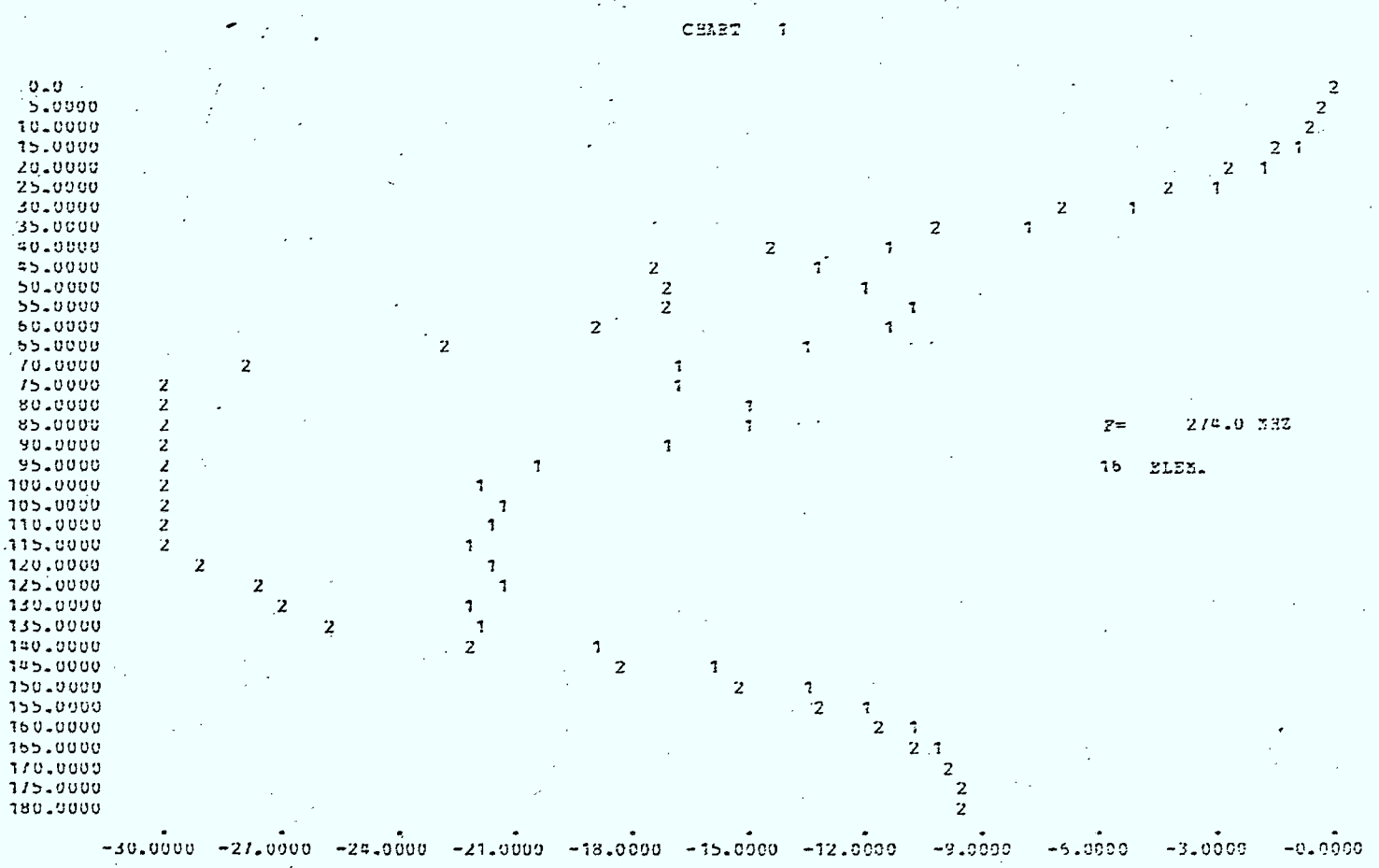
EFFICIENCY= -0.0143 DB

INPUT IMPEDANCE= 70.60 4.26 OHMS

INPUT ADMITTANCE= 14.11 -0.85 MILLISIEMENS

MISMATCH LOSS= 0.7336 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



X		Y		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.600	8.110	-17.900	-7.047
0.510	0.201	17.200	6.772	5.600	2.205
0.360	0.142	19.000	7.480	11.700	4.606
0.360	0.142	18.400	7.244	27.000	10.630
0.360	0.142	21.800	8.583	38.800	15.276
0.300	0.118	20.000	7.874	54.400	21.417
0.300	0.118	20.900	8.228	74.400	29.291
0.300	0.118	20.500	8.071	96.800	38.110
0.300	0.118	19.000	7.480	117.600	46.299
0.300	0.118	19.500	7.677	140.400	55.276
0.300	0.118	20.200	7.953	155.200	61.102
0.300	0.118	19.300	7.598	180.600	71.102
0.300	0.118	19.700	7.756	200.100	78.780
0.400	0.118	20.000	7.874	220.000	86.614

FORWARD DIRECTIVITY= 12.07 DB

FRONT TO BACK RATIO= 9.40 DB

FORWARD GAIN= 12.07 DB

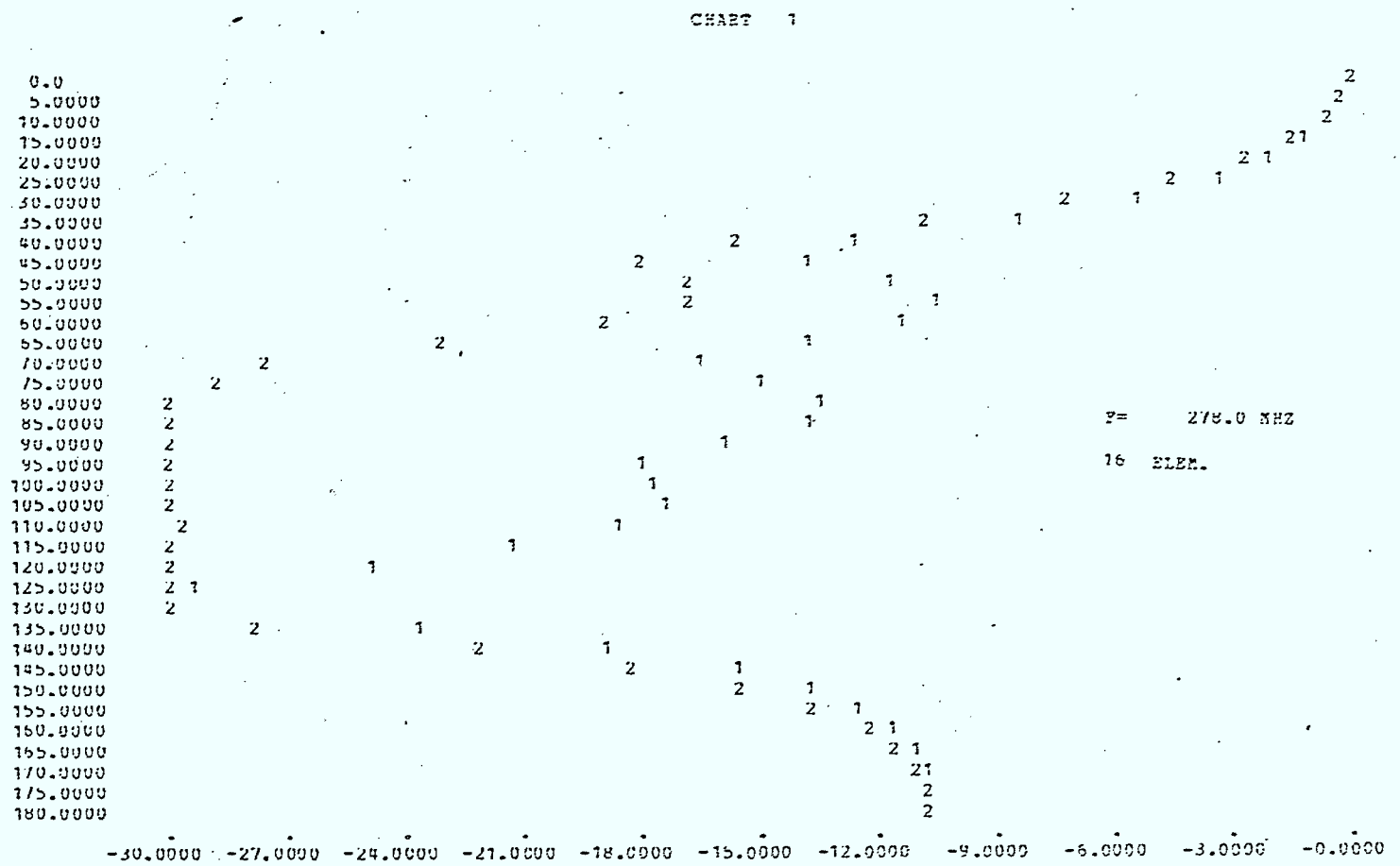
EFFICIENCY= -0.0031 DB

INPUT IMPEDANCE= 73.36 16.37 OHMS

INPUT ADMITTANCE= 12.99 -2.90 MILLISIEMENS

MISMATCH LOSS= 0.7423 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.600	8.110	-17.900	-7.047
0.510	0.201	17.200	6.772	5.600	2.205
0.360	0.142	19.000	7.480	11.700	4.606
0.360	0.142	18.400	7.244	27.000	10.630
0.360	0.142	21.800	8.583	38.800	15.276
0.300	0.118	20.000	7.874	54.400	21.417
0.300	0.118	20.900	8.224	74.400	29.291
0.300	0.118	20.500	8.077	96.800	38.110
0.300	0.118	19.000	7.480	117.600	46.299
0.300	0.118	19.500	7.677	140.400	55.276
0.300	0.118	20.200	7.953	155.200	61.102
0.300	0.118	19.300	7.598	180.600	71.102
0.300	0.118	19.700	7.756	200.100	78.780
0.300	0.118	20.000	7.874	220.000	86.614

FORWARD DIRECTIVITY= 12.20 DB

FRONT TO BACK RATIO= 10.59 DB

FORWARD GAIN= 12.20 DB

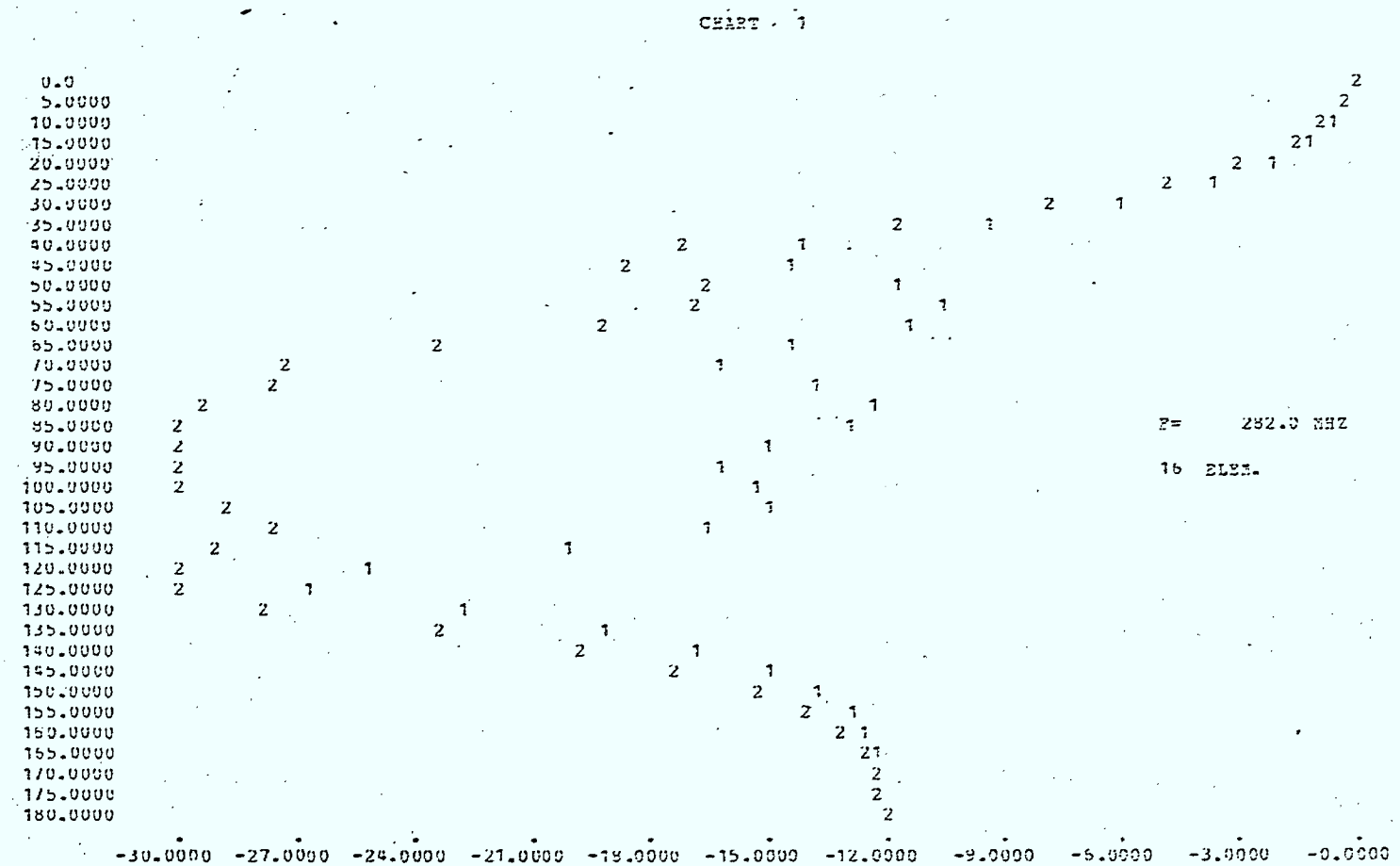
EFFICIENCY= -0.0030 DB

INPUT IMPEDANCE= 89.32 15.86 OHMS

INPUT ADMITTANCE= 10.85 -1.93 MILLISIEMENS

MISMATCH LOSS= 0.0442 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.600	8.110	-17.900	-7.047
0.510	0.201	17.200	6.772	5.600	2.205
0.360	0.142	19.000	7.480	11.700	4.606
0.360	0.142	18.400	7.244	27.000	10.630
0.360	0.142	21.800	8.583	38.800	15.276
0.300	0.118	20.000	7.874	54.500	21.457
0.300	0.118	20.900	8.228	74.400	29.291
0.300	0.118	20.500	8.071	96.800	38.110
0.300	0.118	19.000	7.480	117.600	46.299
0.300	0.118	19.500	7.677	140.400	55.276
0.300	0.118	20.200	7.953	155.200	61.102
0.300	0.118	19.300	7.598	180.600	71.102
0.300	0.118	19.700	7.756	200.100	78.780
0.300	0.118	20.300	7.992	220.900	86.969

FORWARD DIRECTIVITY= 12.27 DB

FRONT TO BACK RATIO= 11.99 DB

FORWARD GAIN= 12.26 DB

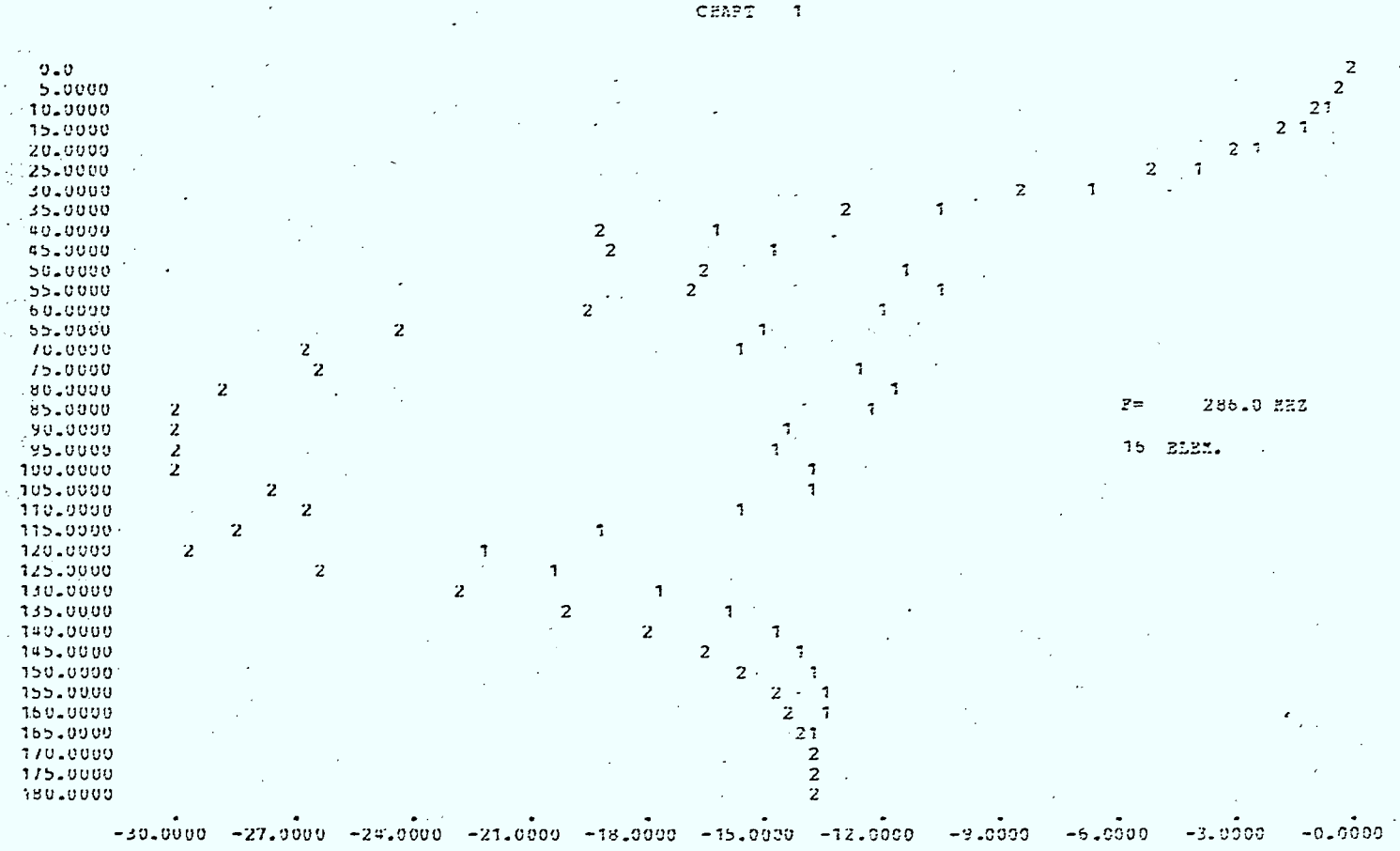
EFFICIENCY= -0.0030 DB

INPUT IMPEDANCE= 100.69 10.02 OHMS

INPUT ADMITTANCE= 9.93 -0.98 MILLISIEMENS

MISMATCH LOSS= 0.0109 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.600	8.110	-17.900	-7.047
0.510	0.201	17.200	6.772	5.600	2.205
0.360	0.142	19.000	7.480	11.700	4.606
0.360	0.142	18.400	7.244	27.000	10.630
0.360	0.142	21.800	8.583	38.800	15.276
0.300	0.118	20.000	7.874	54.400	21.417
0.300	0.118	20.900	8.228	74.400	29.291
0.300	0.118	20.500	8.071	96.800	38.110
0.300	0.118	19.000	7.480	117.600	46.299
0.300	0.118	19.500	7.677	140.400	55.276
0.300	0.118	20.200	7.953	155.200	61.102
0.300	0.118	19.300	7.598	180.600	71.102
0.300	0.118	19.700	7.756	200.100	78.780
0.300	0.118	20.000	7.874	220.000	86.614

FORWARD DIRECTIVITY= 12.32 DB

FRONT TO BACK RATIO= 13.65 DB

FORWARD GAIN= 12.32 DB

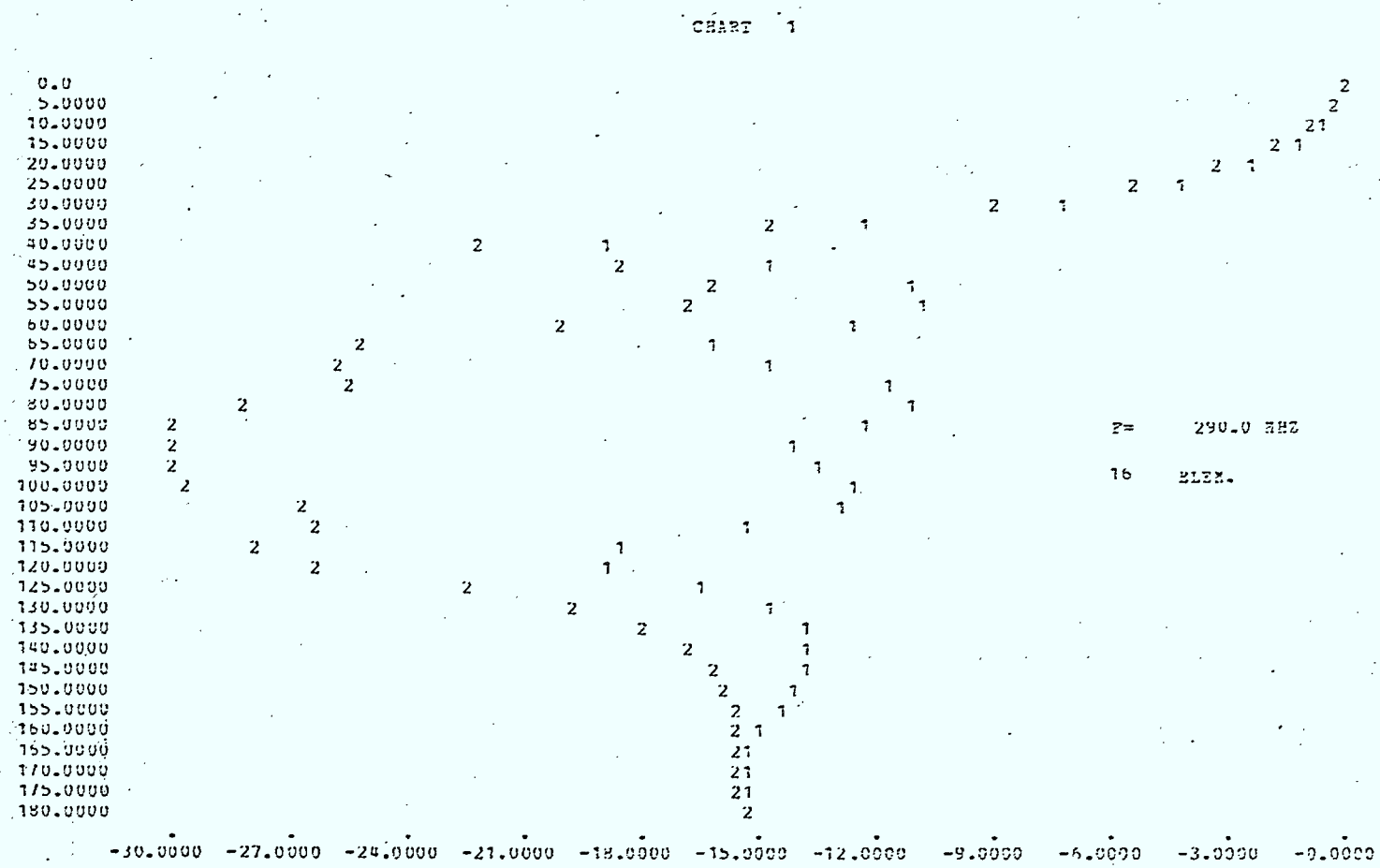
EFFICIENCY= -0.0030 DB

INPUT IMPEDANCE= 106.44 3.12 OHMS

INPUT ADMITTANCE= 9.39 -0.28 MILLISIEMENS

MISMATCH LOSS= 0.0052 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.600	8.110	-17.900	-7.047
0.510	0.201	17.200	6.772	5.600	2.205
0.360	0.142	19.000	7.480	11.700	4.606
0.360	0.142	18.400	7.244	27.000	10.630
0.360	0.142	21.800	8.583	39.800	15.276
0.300	0.118	20.000	7.874	54.400	21.417
0.300	0.118	20.900	8.228	74.400	29.291
0.300	0.118	20.500	8.071	96.200	34.110
0.300	0.118	19.000	7.480	117.600	46.299
0.300	0.118	19.500	7.677	140.400	55.276
0.300	0.118	20.200	7.953	155.200	61.102
0.300	0.118	19.300	7.598	180.600	71.102
0.300	0.118	19.700	7.756	200.100	78.780
0.300	0.118	20.000	7.874	220.000	86.614

FORWARD DIRECTIVITY= 12.38 DB

FRONT TO BACK RATIO= 15.29 DB

FORWARD GAIN= 12.38 DB

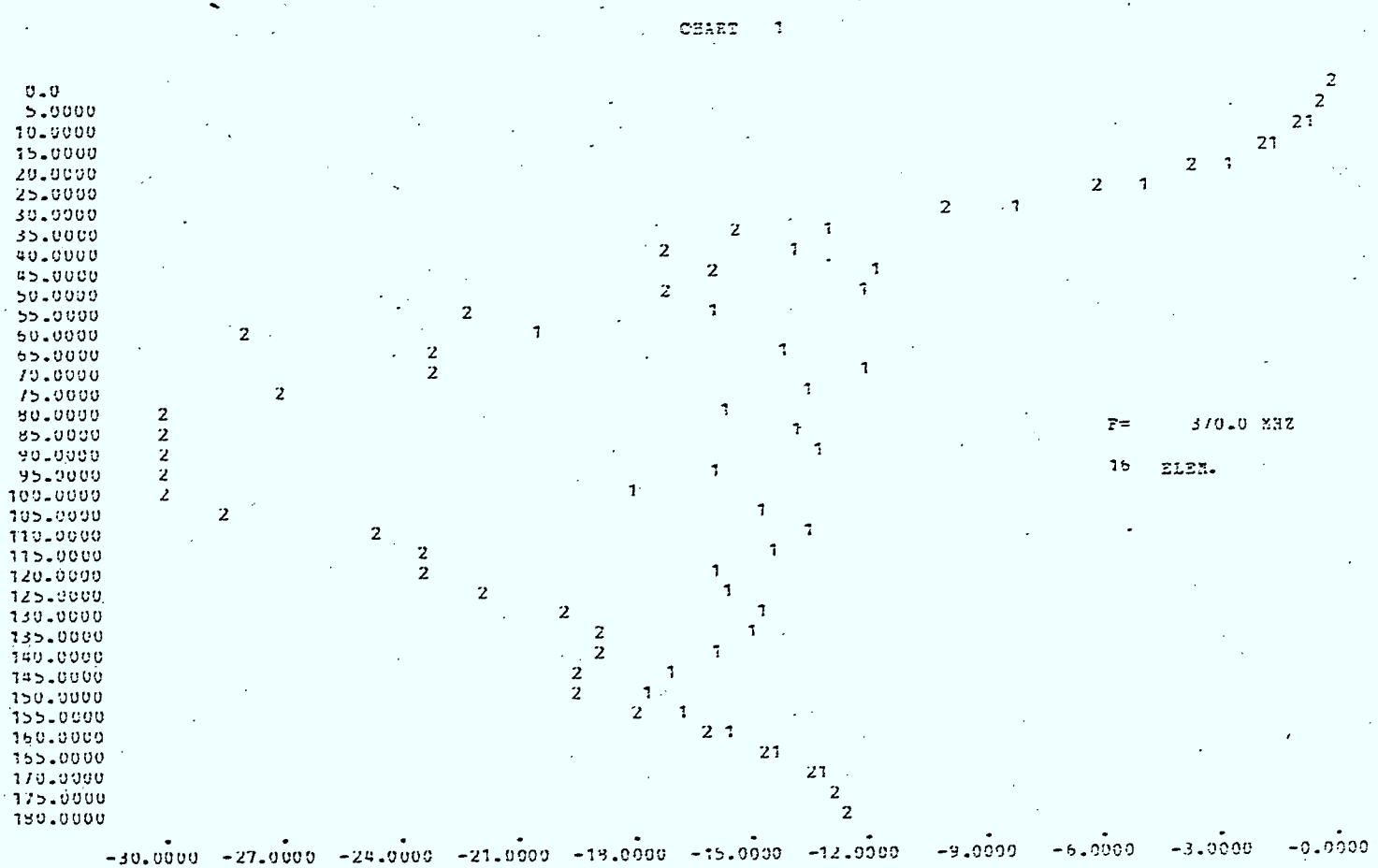
EFFICIENCY= -0.0032 DB

INPUT IMPEDANCE= 108.94 -2.60 OHMS

INPUT ADMITTANCE= 9.17 0.22 MILLISIEMENS

MISMATCH LOSS= 0.0086 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.900	8.228	-17.900	-7.047
0.510	0.201	16.600	6.535	5.600	2.205
0.360	0.142	14.900	5.866	11.700	4.606
0.360	0.142	17.100	6.732	27.000	10.630
0.360	0.142	15.800	6.220	38.500	15.276
0.300	0.118	15.200	5.984	54.900	21.417
0.300	0.118	16.400	6.457	74.400	29.291
0.300	0.118	14.600	5.827	96.300	38.110
0.300	0.118	14.200	5.591	117.600	46.299
0.300	0.118	13.800	5.433	140.400	55.276
0.300	0.118	14.800	5.827	155.200	61.102
0.300	0.118	15.100	5.945	180.600	71.102
0.300	0.118	15.500	6.102	200.100	78.780
0.300	0.118	16.000	6.299	220.000	86.614

FORWARD DIRECTIVITY= 12.66 DB

FRONT TO BACK RATIO= 12.47 DB

FORWARD GAIN= 12.66 DB

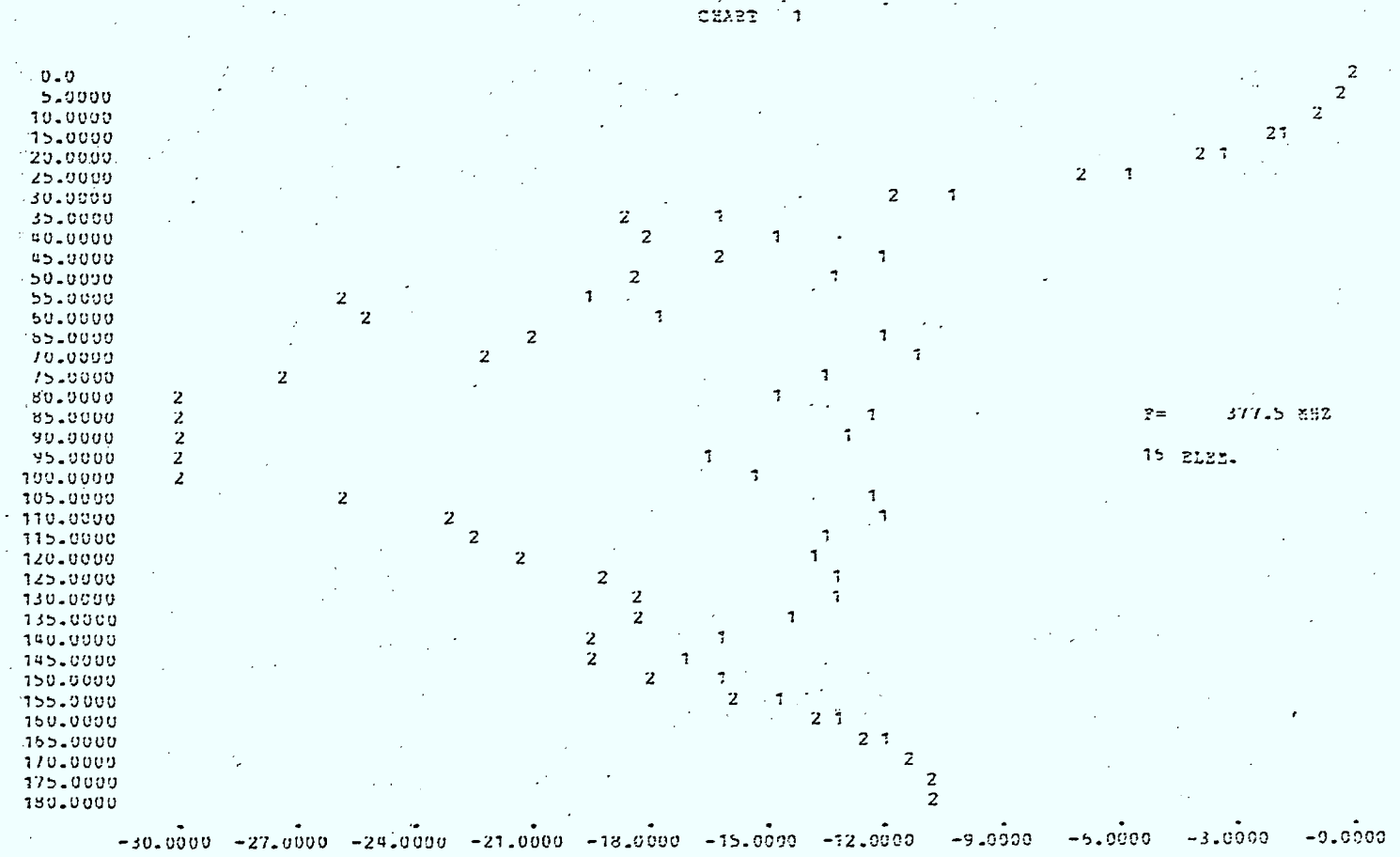
EFFICIENCY= -0.0034 DB

INPUT IMPEDANCE= 143.36 -41.42 OHMS

INPUT ADMITTANCE= 6.48 1.86 MILLISIEMENS

MISMATCH LOSS= 0.2647 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		H		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.358
0.250	0.098	20.900	8.228	-17.900	-7.047
0.510	0.201	16.600	6.535	5.600	2.205
0.350	0.142	14.900	5.866	11.700	4.606
0.360	0.142	17.100	6.732	27.000	10.630
0.360	0.142	15.800	6.220	38.800	15.276
0.300	0.118	15.200	5.984	54.400	21.417
0.300	0.118	16.400	6.457	74.400	29.291
0.300	0.118	14.800	5.827	96.800	38.110
0.300	0.118	14.200	5.591	117.600	46.299
0.300	0.118	13.800	5.433	140.000	55.276
0.300	0.118	14.400	5.827	155.200	61.102
0.300	0.118	15.100	5.945	180.600	71.102
0.300	0.118	15.500	6.102	200.100	78.780
0.300	0.118	16.000	6.299	220.300	86.732

FORWARD DIRECTIVITY= 12.63 DB

FRONT TO BACK RATIO= 10.61 DB

FORWARD GAIN= 12.62 DB

EFFICIENCY= -0.0041 DB

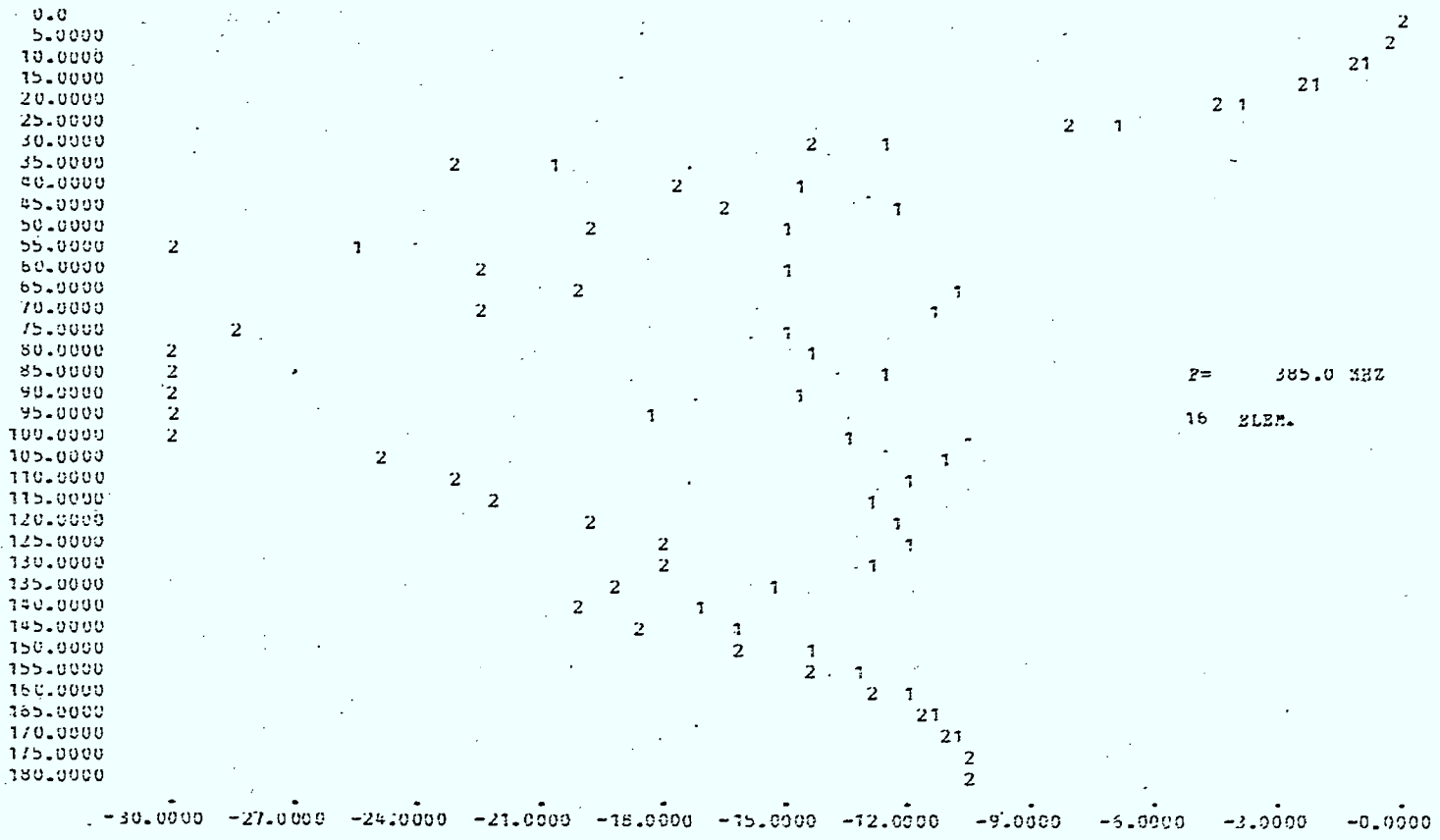
INPUT IMPEDANCE= 98.91 -10.40 OHMS

INPUT ADMITTANCE= 10.41 1.14 MILLISIEMENS

MISMATCH LOSS= 0.0153 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

CHART 1



F= 385.0 MHZ

16 ELEM.

A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.900	8.228	-17.900	-7.047
0.510	0.201	16.600	6.535	5.600	2.205
0.360	0.142	14.900	5.866	11.700	4.606
0.360	0.142	17.100	6.732	27.000	10.630
0.360	0.142	15.800	6.220	38.800	15.276
0.300	0.118	15.200	5.984	54.400	21.417
0.300	0.118	16.400	6.457	74.400	29.291
0.300	0.118	14.800	5.827	96.800	38.110
0.300	0.118	14.200	5.591	117.600	46.299
0.300	0.118	14.800	5.833	140.500	55.276
0.300	0.118	14.800	5.827	155.200	61.102
0.300	0.118	15.100	5.945	180.600	71.102
0.300	0.118	15.500	6.102	200.100	78.780
0.300	0.118	16.000	6.299	220.000	86.614

FORWARD DIRECTIVITY= 12.78 DB

FRONT TO BACK RATIO= 10.23 DB

FORWARD GAIN= 12.78 DB

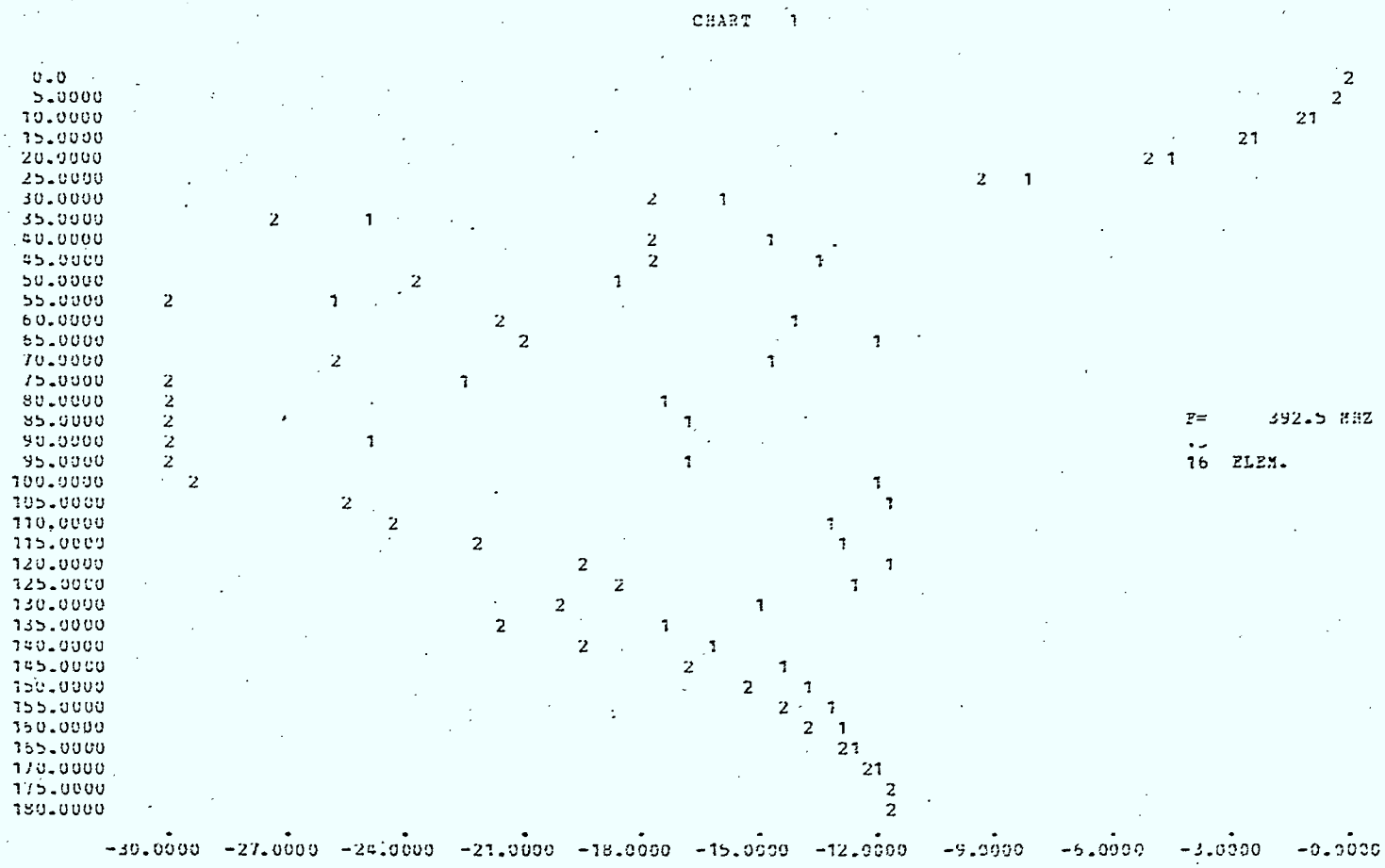
EFFICIENCY= -0.0051 DB

INPUT IMPEDANCE= 75.37 35.60 OHMS

INPUT ADMITTANCE= 10.85 -5.12 MILLISIEMENS

MISMATCH LOSS= 0.2614 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.900	8.228	-17.900	-7.047
0.510	0.201	16.600	6.535	5.600	2.205
0.360	0.142	14.900	5.866	11.700	4.606
0.360	0.142	17.100	6.732	27.000	10.630
0.360	0.142	15.800	6.220	38.800	15.276
0.300	0.118	15.200	5.984	55.000	21.417
0.300	0.118	16.300	6.457	74.400	29.291
0.300	0.118	14.900	5.927	96.800	38.110
0.300	0.118	14.200	5.591	117.600	44.299
0.300	0.118	13.800	5.433	140.400	55.276
0.300	0.118	14.800	5.827	155.200	61.102
0.300	0.118	15.100	5.945	180.600	71.102
0.300	0.118	15.500	6.102	200.100	78.780
0.300	0.118	16.000	6.299	220.000	86.614

FORWARD DIRECTIVITY= 13.44 DB

FRONT TO BACK RATIO= 11.42 DB

FORWARD GAIN= 13.44 DB

EFFICIENCY= -0.0073 DB

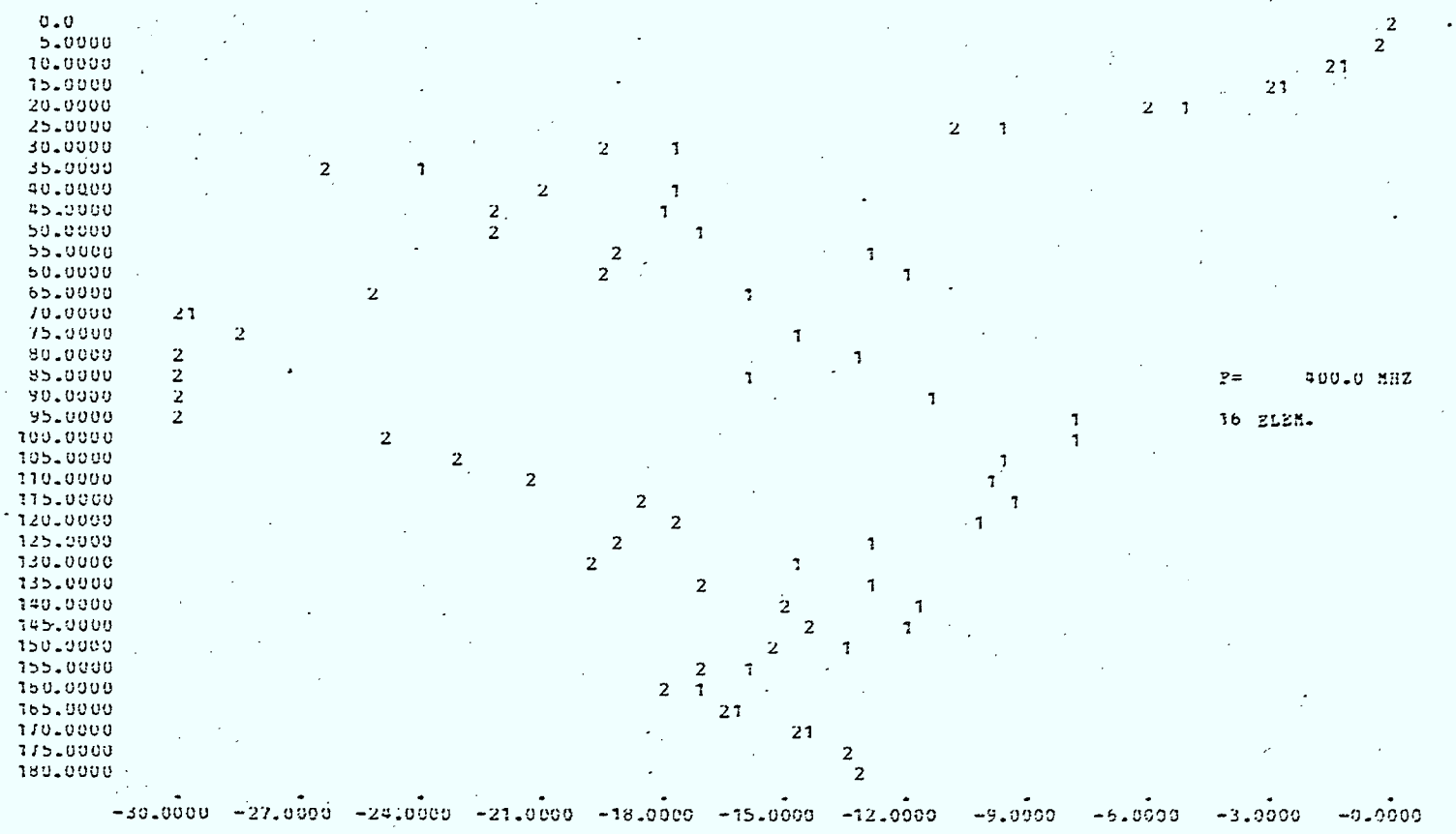
INPUT IMPEDANCE= 99.77 77.02 OHMS

INPUT ADMITTANCE= 6.35 -5.16 MILLISIEMENS

MISMATCH LOSS= 0.6340 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

CHART 1



A		B		Y	
CM	INCH	CM	INCH	CM	INCH
0.650	0.256	25.200	9.921	0.0	0.0
0.410	0.161	25.700	10.118	-26.300	-10.354
0.250	0.098	20.900	8.228	-17.900	-7.047
0.510	0.201	16.600	6.535	5.600	2.205
0.360	0.142	14.900	5.866	11.700	4.606
0.360	0.142	17.100	6.732	27.000	10.630
0.360	0.142	15.800	6.220	38.800	15.276
0.300	0.118	15.200	5.984	54.400	21.417
0.300	0.118	16.400	6.457	74.000	29.291
0.300	0.118	14.800	5.827	96.900	38.113
0.300	0.118	14.200	5.591	117.600	46.299
0.300	0.118	13.800	5.433	140.400	55.276
0.300	0.118	14.800	5.827	155.200	61.102
0.300	0.118	15.100	5.945	180.600	71.102
0.300	0.118	15.500	6.102	200.100	78.780
0.300	0.118	16.000	6.299	220.000	86.614

FORWARD DIRECTIVITY= 12.64 DB

FRONT TO BACK RATIO= 13.00 DB

FORWARD GAIN= 12.63 DB

EFFICIENCY= -0.0129 DB

INPUT IMPEDANCE=	76.49	31.40 OHMS
INPUT ADMITTANCE=	11.19	-4.59 MILLISIEMENS

MISMATCH LOSS= 0.2131 DB

CHARACTERISTIC IMPEDANCE = 100.00 OHMS

APPENDIX F

F.1 Wind Load Calculations

Maximum Wind Load Occurs in Cross Wind

Drag Force $D = C_D\, q\, S$

where C_D - drag coefficient for section = 1.22

q - dynamic pressure due to wind

S - projected area of strut

D - total drag force

Toppling moment $M = D \times h$

where M - moment about ground

h - centroidal height of structure being considered

Calculation: $q = \frac{1}{2} \rho V^2$ $\rho = .003$ slug/ft^3 for air at -60°C

$V = 45$ mph $= 66$ fps

Therefore $q = 6.53$ lb$_f$/ft^2

	S ft^2	D lb$_f$	M ft lb$_f$
Support rods; centroid at 4 ft	.365	3.00	12.00
Fibre glass rod: C at 3.5 ft	.125	1.00	3.50
Tripod Legs: C at 1.5 ft	1.00	7.97	12.00
Element discs: C at 4 ft	.083	0.66	2.65
Main Support Block: C at 4 ft	.054	.43	1.72
Tripod head: C at 3 ft	.05	.40	1.20
		13.46	33.07
Design Figures		14 lb$_f$	35 ft lb$_f$

Leg Spread of tripod = 3 ft

Assume antenna at 4 ft above ground:

$w \times \ell \sin 30 =$ total moment $w =$ weight $= 24$ lb$_f$

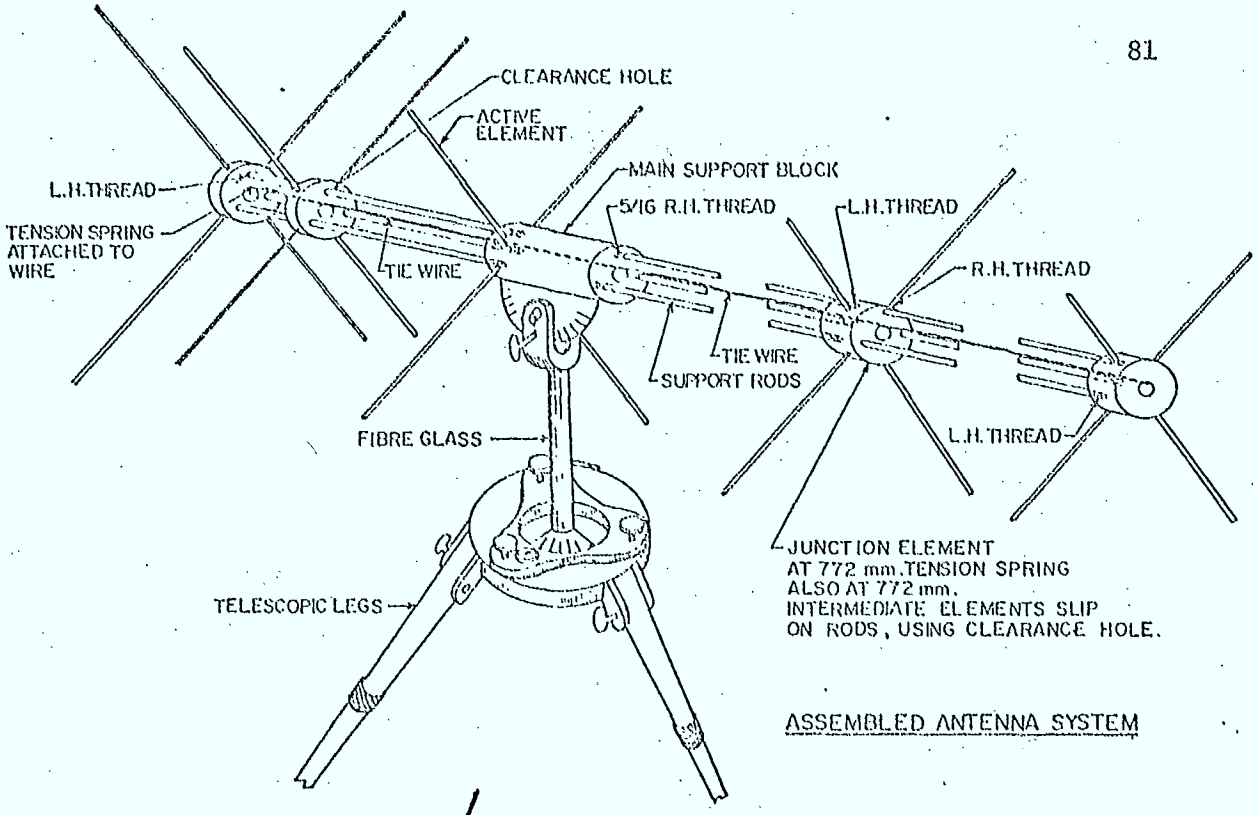
$\ell = 35/(24 \sin 30) = 2.89$ ft from centroid of equilateral triangle described by leg positions on ground.

F.2 Mass Calculations for Antenna with Aluminum Material

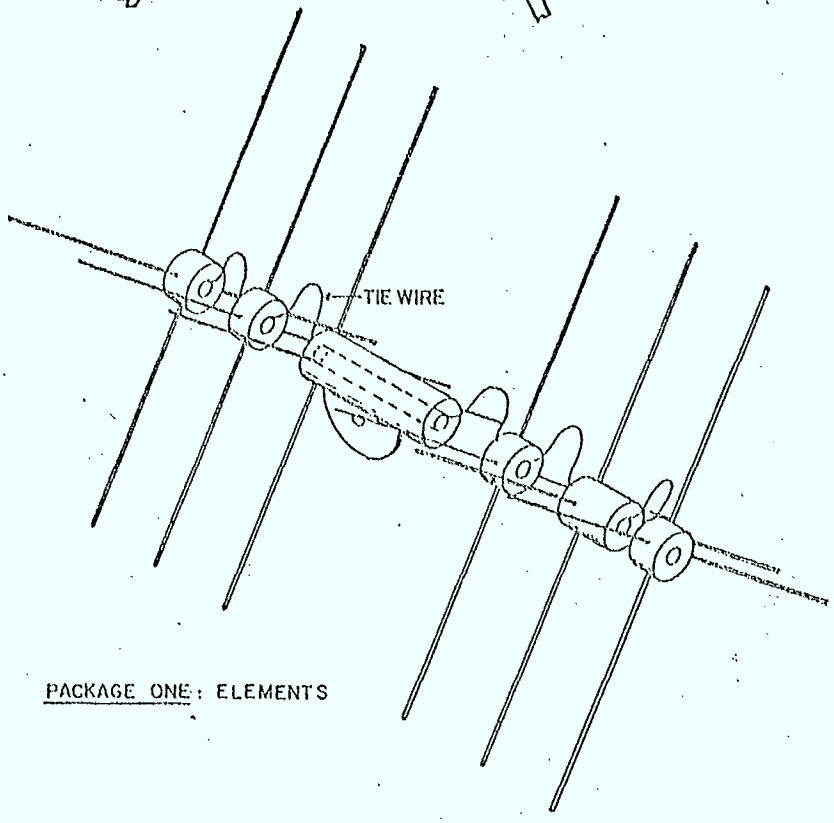
Element		Length	dia.	+%	Vol.	mass in grams
1	tube	506 mm	6.5	10	9.54	75.9
2	tube	530 mm	4	8	5.83	46.6
3	rod	416 mm	2.5	8	4.08	32.9
4	tube	342 mm	5	10	4.83	39.0
5	rod	402 mm	3.5	8	7.74	61.6
6	rod	352 mm	3.5	8	6.77	55.0
7	rod	416 mm	3.5	8	8.00	63.6
8	rod	392 mm	3.0	8	5.54	44.3
9	rod	412 mm	3.0	8	5.82	46.5
10	rod	388 mm	3.0	8	5.48	43.8
11	Tripod					3632.0
12	main block					1000.0
13	Fibreglass rod (1" ø 1/8 wall)					700.0
						5841.2

mass of system - 6 kg.

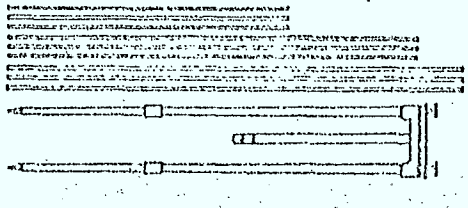
For stability, tripod legs must be weighted to bring mass of system to - 10 kg.



ASSEMBLED ANTENNA SYSTEM



PACKAGE ONE: ELEMENTS



PACKAGE TWO: RODS AND TRIPOD

APPENDIX G

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