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DEVELOPMENT

OF A

SURFACE PANEL MEASUREMENT SYSTEM

(NASA-CR-163469) DEVELOPMENT OF A SURFACE PANEL MEASUREMENT SYSTEM Final Report (TRW Defense and Space Systems Group) 57 p HC A04/MF A01 CSCL 17I N82-16315

G3/32 Unclas 08824

Final Report

04 August 1981

Prepared by: DL Jones
D. L. Jones
Project Manager

JPL CONTRACT NO. 955987

"This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by the National Aeronautics and Space Administration under Contract NAS7-100."

TRW DEFENSE AND SPACE SYSTEMS GROUP

One Space Park - Redondo Beach, California, 90278

ABSTRACT

This study of reflector measurement systems was performed in support of the reshaping of the 34-meter antenna at Goldstone. The requirements for measurement systems are presented in generalized terms. A survey is made of the surface errors of existing antennas. Reflector measurement systems are divided into three categories. Representative examples of each category are illustrated and discussed. Parametric error analyses are made of selected optical systems.

It is concluded that the existing measurement method using a theodolite at the vertex should be retained as the basic method. A method using a theodolite on the RF cone is a possible variant. A microwave diagnostic technique has good immediate potential. All other methods are either not accurate enough or would require too much development.

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I. INTRODUCTION

This study was performed in support of the reshaping of the 34-meter antenna at Goldstone. The original work statement for the study on the development of surface panel measurement system had three major elements.

- Conduct a state-of-the-art-study of reflector measurement systems.
- Conduct a study of a measurement system which leaves the RF cone in place.
- Develop computer software for the measurement systems.

The initial effort was spent on the state-of-the-art study and on comparative error analyses. A review of this work indicated that there was no new system that would warrant a detailed study and development. The major remaining work was therefore directed toward generalized systems rather than a detailed definition of a specific system.

The main technical content of this report is in the form of presentation charts. They are preceded by a few pages of text describing the charts. The 34 charts are divided into the following seven groups.

		Figure No.
1.	General requirements for reflector measurement systems.	1-3
2.	Surface errors of existing antennas.	4-5
3.	Classification of reflector measurement systems.	6
4.	Mechanical measurement systems.	7-12
5.	Non-mechanical systems, measurements perpendicular to line-of-sight.	12-26
6.	Non-mechanical systems, measurements parallel to line-of-sight.	27-31
7.	Application to the JPL 34-meter antenna.	32-34

An error analysis of measurement systems with optical instruments on the centerline is presented in an appendix. The data from this analysis is used in some of the charts.

II. TECHNICAL DISCUSSION

1. Requirements

Requirements for reflector measurement systems are presented in generalized terms in Figure 1-3. They include a plot of the gain loss as a function of surface error, a listing of typical set of requirements, and a table of required accuracies as a function of frequency. Requirements for a specific antenna can be generated from this information.

2. Surface Errors of Existing Antennas

The surface errors of a selected set of existing antennas are presented in Figures 4 and 5. They include a plot of surface error as a function of diameter and a table which identifies the specific antennas. Most of the antennas are used either for radio-telescopes or for spacecraft communications. The data suggests that a 1/100,000 ratio of surface error to diameter is a practical limit. A notable exception is the 10-meter radio-telescope that was built under the direction of R. B. Leighton at CIT. That one had an error ratio of 2.5/1,000,000.

3. Classification of Reflector Measurement Systems, Figure 6

The measurement systems have been divided into those which are primarily mechanical and those which are primarily non-mechanical. The non-mechanical systems are further subdivided into those with measurements perpendicular to the line of sight and those with measurements parallel to the line of sight.

4. Mechanical Measurement Systems

Mechanical measurement systems are described in Figures 7 through 12. Schematics of six different systems are illustrated in Figure 7. The system most commonly used for small antennas or large antenna panels is some form of a three-axis coordinate measurement system, as illustrated in Figures 9 and 10.

Templates are less commonly used. The system illustrated in Figure 12 is taken from the book, "Mechanical Engineering in Radar and Communications", edited by C. J. Richards (Van Nostrand Rheinhold Company, 1969). The other systems shown on Figure 7 are conceptual and have never been used operationally. The two systems with inclinometers were taken from a report, "Inclinometer Measurements on Parabolic Radio Reflector Surface", by A. Greve, Max Planck Institute for Radioastronomy.

5. Non-mechanical, Measurement Perpendicular to Line-of-Sight

Systems with measurements perpendicular to the line-of-sight are illustrated in Figure 13 through 26. These are all optical systems in which targets are viewed by one or more optical instruments. Five different measurement geometries are illustrated in Figure 14. The one most commonly used for large antennas has an angle-measuring device mounted at the vertex.

A comparative error analysis of the various measurement systems is presented in Figure 15 through 19. A more detailed exposition of this error analysis is given in Appendix A. The results are summarized in Figure 19, which is a plot of measurement error as a function of diameter. This plot also includes mechanical systems and rangefinder systems for reference.

Some special-purpose mechanizations of these systems are illustrated in Figures 20 through 26. The "Pentag" system in Figure 20 is taken from the same text that was referenced for Figure 12. It was also described in two papers in a 1966 IEE Conference on the Design and Construction of Large Steerable Aerials. The Surface Accuracy Measurement System (SAMS) illustrated in Figures 21 through 23 was taken from a Final Technical Report, "Surface Accuracy Measurement Sensor for Deployable Reflector Antennas", Contract No. NAS1-1552 from NASA Langley. It was prepared by R. S. Neiswander at TRW and is dated 25 February 1980. The effort on this system is continuing now.

The Laser/Star Tracker system illustrated in Figures 24 and 25 is a conceptual system. It illustrates what would be required for a fully automatic system. The Camera/Telescope system illustrated in Figure 26 is also conceptual, though similar systems were alluded to in connection with the 210 feet antenna at Parkes, Australia and the 150 feet antenna at Algonquin, Canada.

6. Non-mechanical, Measurements Parallel to Line-of-Sight

Systems with measurements parallel to the line of sight are illustrated in Figures 27 through 31. This is a heterogeneous group that is not easily classified. None of these systems has been commonly used on an operational basis.

A rangefinder system is illustrated in Figure 28. Many such systems have been considered in the technical literature over the last fifteen years. Their actual use has been minimal to date.

A microwave diagnostic technique is illustrated in Figure 29. This is a system that has been developed at the University of Sheffield. The application of this technique to the JPL antennas is the subject of another study by the principal investigators from the University of Sheffield.

A feed mask technique is illustrated in Figures 30 and 31. This is a conceptual extension of the microwave diagnostic technique.

7. Application to the JPL 34-Meter Antenna

The application of this measurement system survey to the JPL 34-meter antenna is presented in Figures 32 through 34. The surface error allocations are listed in Figure 32. They are abstracted from the more detailed presentation in Appendix A. Two configurations were considered. One is with the theodolite at the vertex, which is the existing baseline method. The other is with the theodolite on the feed, 4.7 meters above the vertex. The allowable angular and lineal errors were then calculated. As noted in the appendix, the system is much more sensitive to lineal errors when the theodolite is on the feed.

A discussion of all the measurement system that might be applicable is presented in Figure 33 and 34. The existing method of the theodolite at the vertex is the only method that is both accurate enough and also can be used without further development. Moving the theodolite to the feed would require more accurate measurements of the lengths, but otherwise it is a straight forward variant of the existing method.

The method with the most immediate potential for a rapid automatic measurement system with the required accuracy is the microwave diagnostic system. All of the other methods that were considered are either not accurate enough or would require considerable development.

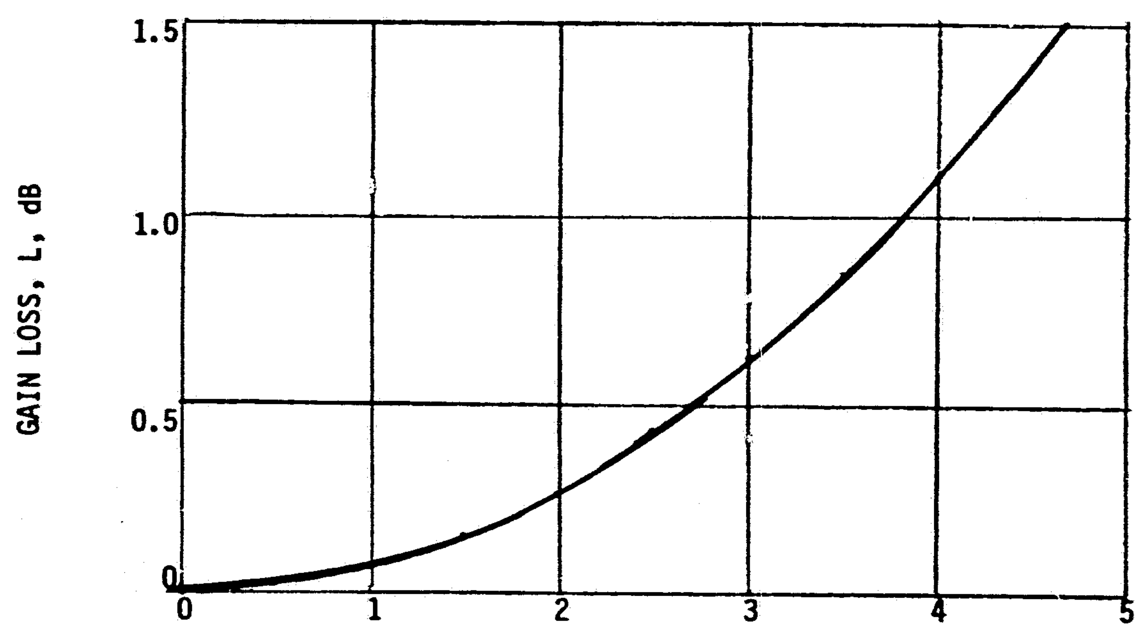

Figure 1 .

TYPICAL ACCURACY REQUIREMENTS

EFFECTIVE SURFACE ERROR OF REFLECTOR

- RMS AVERAGE OVER THE SURFACE
- DETERMINED WITH RESPECT TO BEST FIT PARABOLOID
- DEFINED AS AXIAL COMPONENT OF NORMAL DISPLACEMENT
- OPERATIONAL TOLERANCE IS 2 1/2 PERCENT OF THE WAVELENGTH (0.5 dB LOSS)
- INITIAL SETTING TOLERANCE IS 1/2 OPERATIONAL TOLERANCE
- MEASUREMENT ERROR IS DEFINED AS THE RMS AVERAGE OF ALL ERRORS IN A SET.

FEED AXIAL LOCATION

- AXIALLY ALIGN FEED TO FOCAL POINT OR FOCAL PLANE
- FEED POSITION DEFINED BY RF PHASE CENTER
- FOCAL POINT DEFINED BY BEST FIT PARABOLOID
- OPERATIONAL TOLERANCE IS 25 PERCENT OF THE WAVELENGTH (0.5 dB LOSS)
- INITIAL SETTING TOLERANCE IS 1/2 OPERATIONAL TOLERANCE
- MEASUREMENT ERROR IS DEFINED AS THE PEAK ABSOLUTE ERROR FOR A GIVEN POINT

Figure 2

SURFACE ERROR REQUIREMENTS

Band Designation	Frequency	Wave Length	SURFACE ERRORS, RMS		
			Overall Tolerance	Measurement System Accuracy	
	GHz	mm	mm	mm	Inch
	0.3	1000	25	1.2 to 12	.0500 to .50
UHF					
	1	300	7.5	.38 to 3.8	.015 to .15
L					
	2	150	3.8	.19 to 1.9	.0075 to .075
S					
	4	75	1.9	.10 to 1.0	.0038 to .038
C					
	8	38	.94	.047 to .47	.0019 to .019
X					
	12.5	24	.60	.030 to .30	.0012 to .012
Ku					
	18	17	.42	.021 to .21	.0008 to .0083
K					
	26.5	11	.28	.014 to .14	.0006 to .0056
Ka					
	40	7.5	.19	.010 to .10	.0004 to .0038

Figure 3

SURFACE ERRORS OF EXISTING ANTENNAS

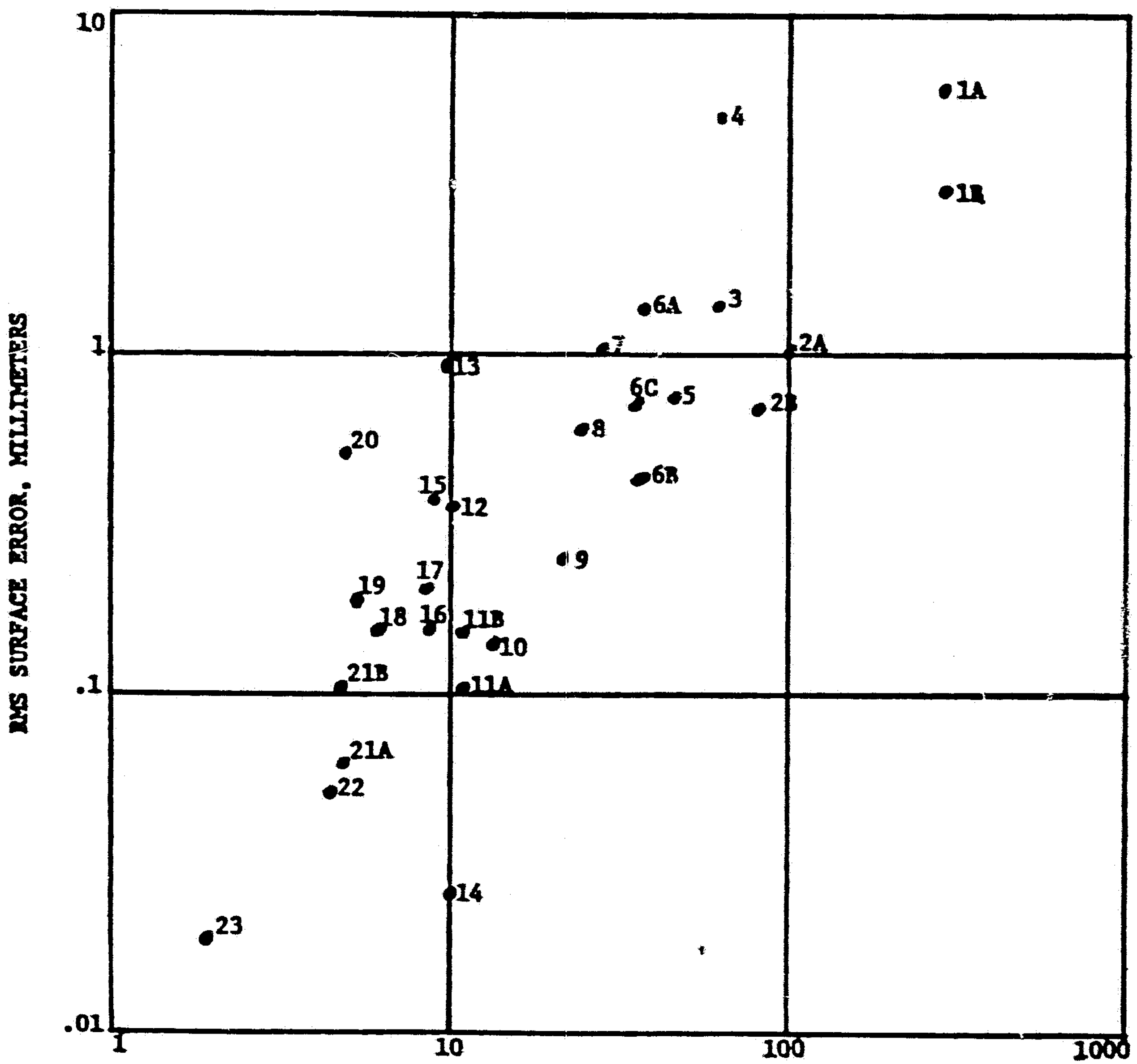

Figure 4

Figure 5

NUMBERING IDENTIFICATION

SURFACE ERROR OF EXISTING ANTENNAS

1.	Arecibo, Puerto Rico	1A	Original	
		1B	Reset	
2.	Effelsberg, Germany	2A	Full Area	
		2B	Partial Area	
3.	JPL, Goldstone, CA			(45° Elevation)
4.	Parkes, Australia			(Effective)
5.	Algonquin, Canada			(Measured)
6.	MIT Haystack, Mass.	6A	Original	(Effective)
		6B	Reset	(Measured)
		6C	Reset	(Effective)
7.	JPL, Goldstone, CA			(Measured)
8.	Raisting, Germany			(Measured)
9.	Crimean RT-22, USSR			(Measured)
10.	ESSCO at Univ. of Mass.			(Measured)
11.	NRAO at Tucson, Arizona	11A		(Measured)
		11B		(Effective)
12.	Bonn University, Germany			(Measured)
13.	RF Systems, Mass.			(Required)
14.	CIT, Owens Valley, CA			(Measured)
15.	CRC, Ottawa, Canada			(Effective)
16.	AFCRL, Mass.			(Measured)
17.	MIT, Lincoln Lab., Mass.			(Measured)
18.	Univ. of CA, Berkeley			(Measured)
19.	JPL, Table Mountain, CA			(Measured and Effective)
20.	TDRSS SA Antenna (Deployable mesh spacecraft antenna)			(Measured)
21.	Univ. of Texas, Austin	21A		(Measured)
		21B		(Effective)
22.	Aerospace Corp. CA			(Measured)
23.	TRW (Special Research Model)			(Measured)

CLASSIFICATION OF REFLECTOR MEASUREMENT SYSTEMS

- MECHANICAL

- NON-MECHANICAL

  A. MEASUREMENTS PERPENDICULAR TO LINE OF SIGHT

  B. MEASUREMENT PARALLEL TO LINE OF SIGHT

Figure 6

MECHANICAL MEASUREMENT METHODS

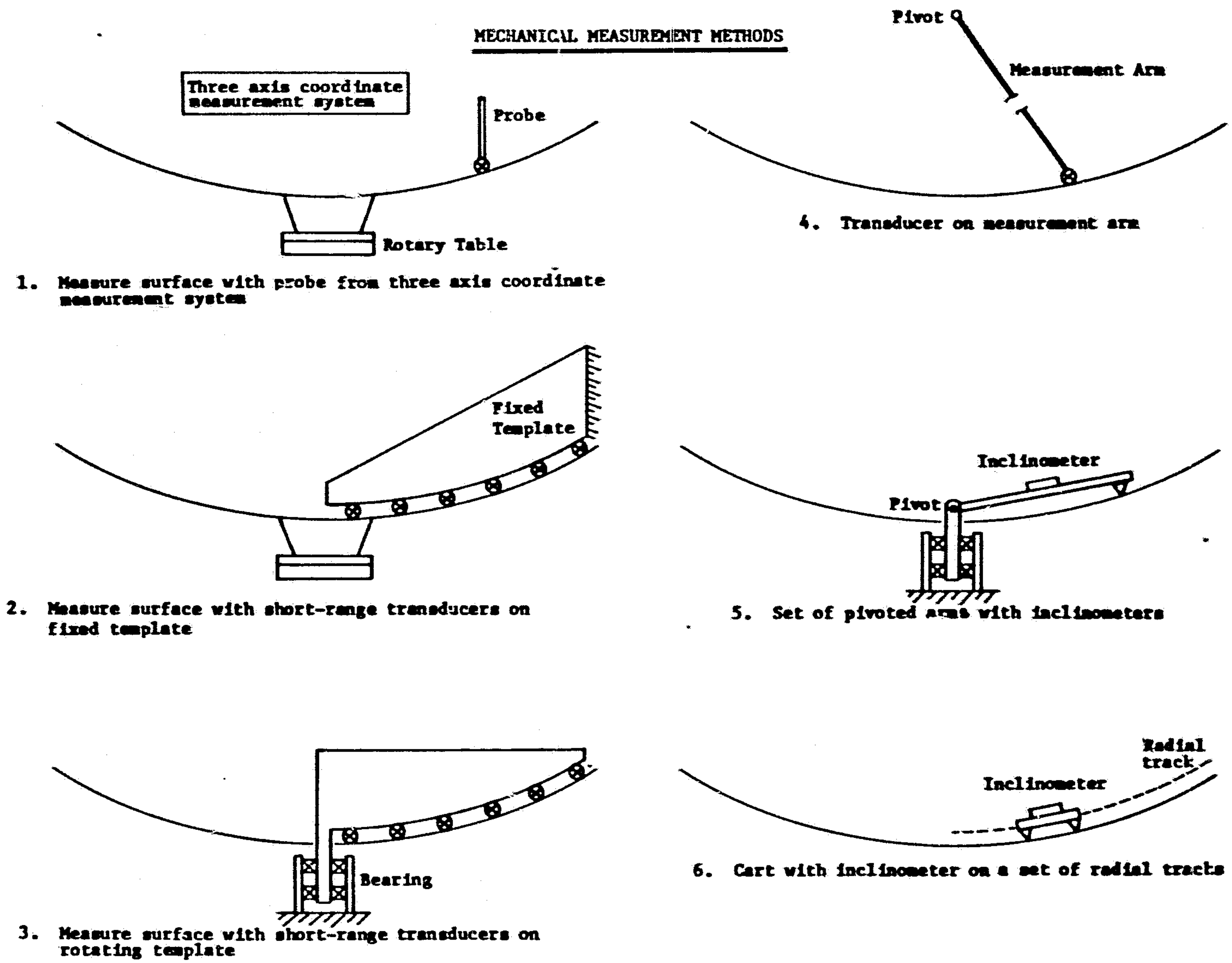

Figure 7

MECHANICAL MEASUREMENT SYSTEMS

- TYPICALLY USED WITH REFLECTORS LESS THAN FIVE METERS IN DIAMETER.
- INCLUDES SYSTEMS WHICH HAVE A MECHANICAL ARM WITH A SHORT-RANGE TRANSDUCER.
- MOST COMMON IS A THREE-AXIS COORDINATE MEASUREMENT SYSTEM SUCH AS THE CORDAX.
- A COORDINATE MEASUREMENT SYSTEM WITH A RANGE OF 15 FEET BY 6 FEET BY 2 FEET WAS REPORTED BY ESSCO.
- A FIXED TRANSDUCER TEMPLATE WITH A ROTATING ANTENNA WAS USED FOR INITIAL MEASUREMENTS OF THE PIONEER JUPITER ANTENNA.
- USE OF A ROTATING TEMPLATE ON A CENTRAL BEARING WAS REPORTED BY THE BRITISH.
- A ROTATING ARM PIVOTED AROUND THE REFLECTOR CENTER OF CURVATURE WAS PROPOSED FOR TRW'S LARGE SOLID DEPLOYABLE REFLECTOR.

Figure 8

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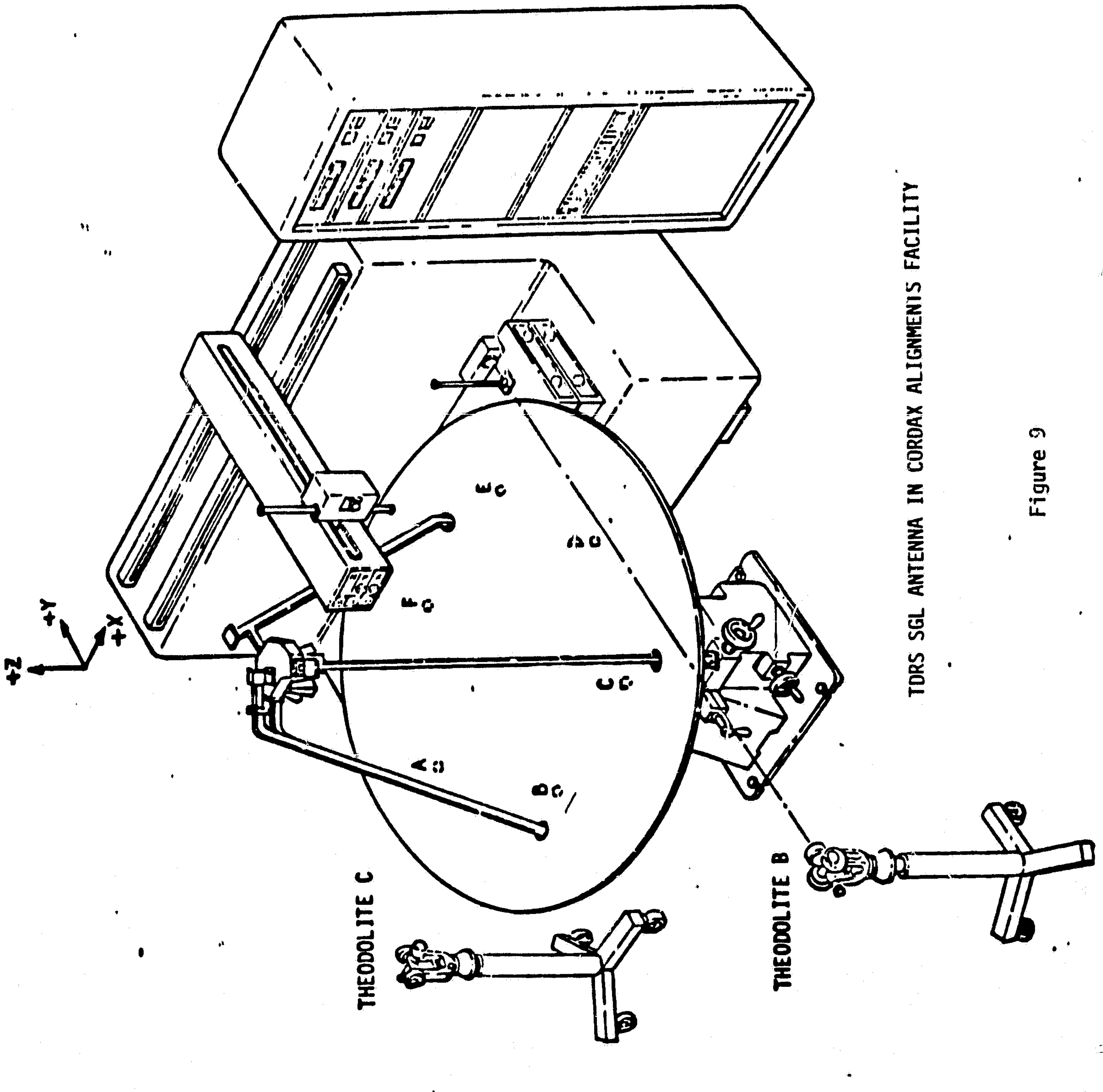

TDRS SGL ANTENNA IN CORDAX ALIGNMENTS FACILITY

Figure 9

THREE AXIS COORDINATE MEASUREMENT SYSTEM

- CORDAX IS THE BRAND NAME OF THE SYSTEM USED AT TRW.
- MEASUREMENTS ARE MADE WITH A DIAL GAGE MOUNTED ON A MEASUREMENT ARM.
- IT IS VERSATILE. IT HAS BEEN USED FOR HUNDREDS OF SHAPE MEASUREMENTS ON DOZENS OF DIFFERENT CONFIGURATIONS.
- IT IS ACCURATE. IT WAS USED TO MEASURE A SPECIAL HIGH ACCURACY REFLECTOR WITH A SURFACE ERROR OF 0.0007 INCH RMS. THE BASIC CORDAX ACCURACY IS PROBABLY LESS THAN 0.0002 INCH RMS. THIS IS BETTER THAN REQUIRED.
- IT HAS DIGITAL OUTPUT FOR INPUT TO COMPUTERS.
- MEASUREMENT RANGE IS EXTENDED BY MOUNTING THE ANTENNA ON A ROTARY TABLE AND USING LATERAL EXTENSIONS ON THE MEASUREMENT ARM.

Figure 10

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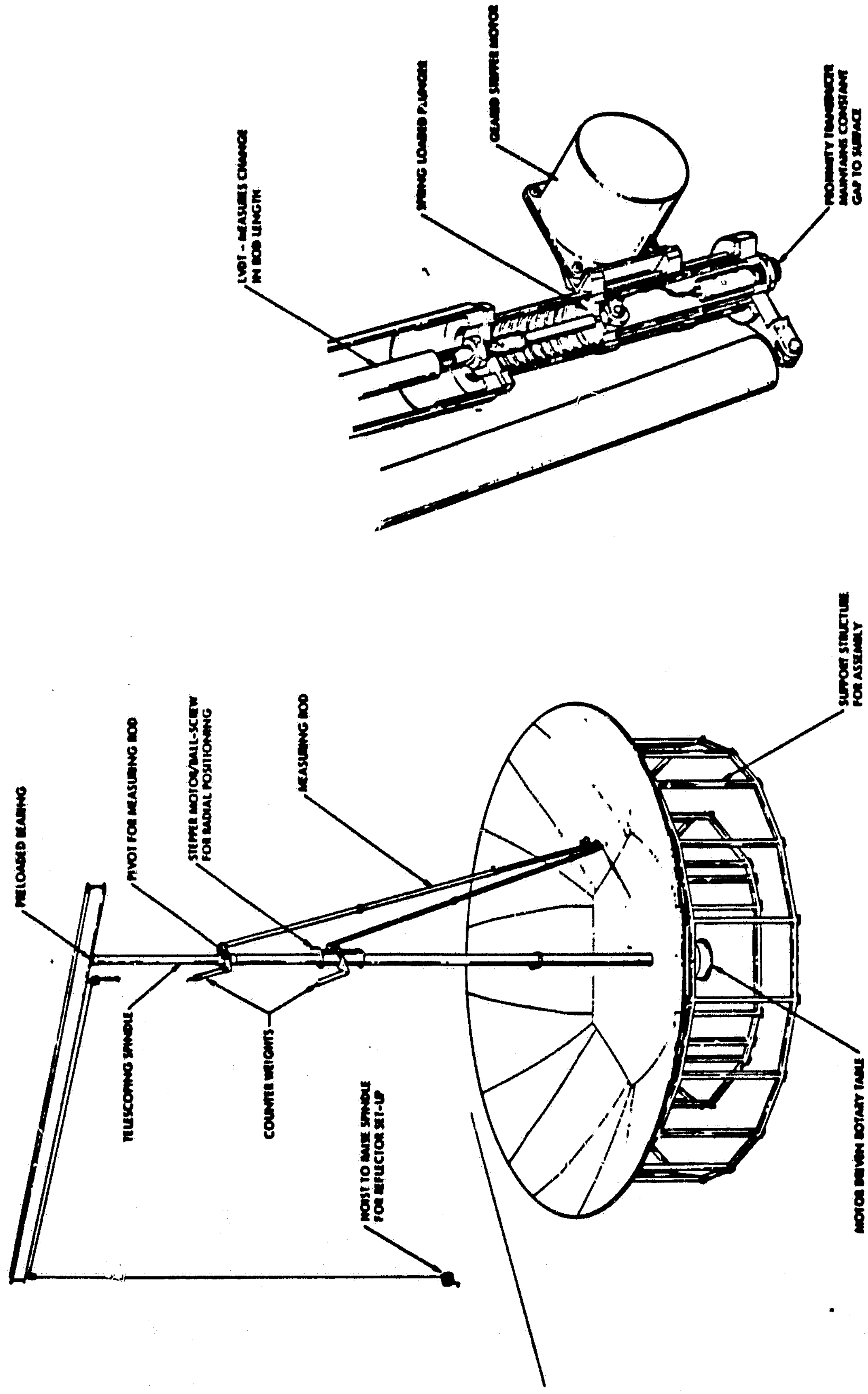

MEASUREMENT SYSTEM PROPOSED FOR LARGE SOLID DEPLOYABLE REFLECTOR

Figure 11

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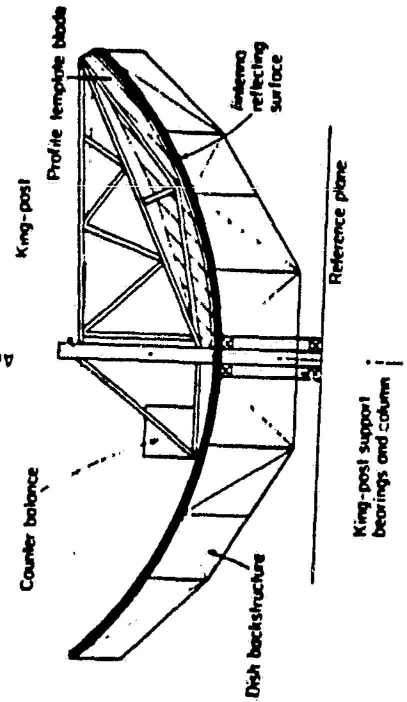


Profile checks, template method

Figure 12

NON-MECHANICAL MEASUREMENT SYSTEMS

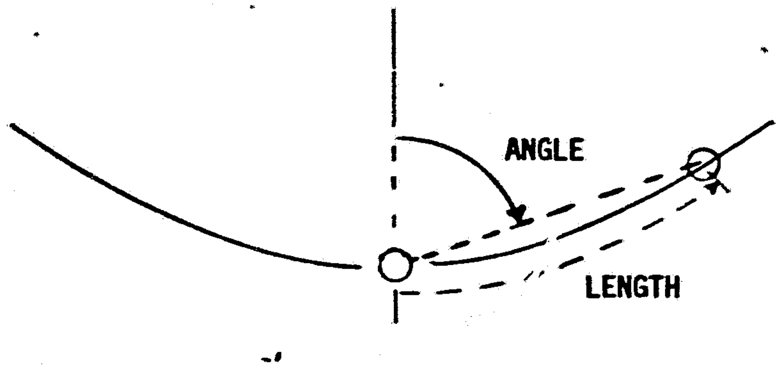
A. MEASUREMENT PERPENDICULAR TO LINE OF SIGHT

- TYPICALLY USED WITH REFLECTORS GREATER THAN FIVE METERS IN DIAMETER.
- MOST COMMON SYSTEM FOR LARGE GROUND ATENNAS HAS AN ANGLE-MEASURING OPTICAL DEVICE AT THE VERTEX VIEWING SURFACE TARGETS THAT ARE AT KNOWN DISTANCES FROM THE VERTEX. THE OPTICAL DEVICES INCLUDE THEODOLITES AND LINE-OF-SIGHT TELESCOPES WITH PENTAPRISMS OR PENTAMIRRORS.
- HEIGHT-MEASURING OPTICAL DEVICES THAT ARE TRAVERSED ALONG TOWERS CAN BE USED IN PLACE OF THE ANGLE-MEASURING DEVICES. HEIGHT-MEASURING DEVICES INCLUDE SIGHT LEVELS AND A LINE-OF-SIGHT TELESCOPE WITH A MOVABLE PENTAPRISM.
- TWO OR MORE EXTERNAL ANGLE-MEASURING DEVICES ARE USED FOR MEASUREMENT BY TRIANGULATION. DEVICES INCLUDES THEODOLITES AND PHOTOGRAMMETRIC CAMERAS.
- A SURFACE ACCURACY MEASUREMENT SYSTEM (SAMS) FOR DEPLOYABLE REFLECTOR ANTENNAS IN SPACE IS BEING DEVELOPED AT TRW UNDER CONTRACT FROM LANGLEY. PRINCIPAL INVESTIGATOR IS R. S. NEISWANDER.

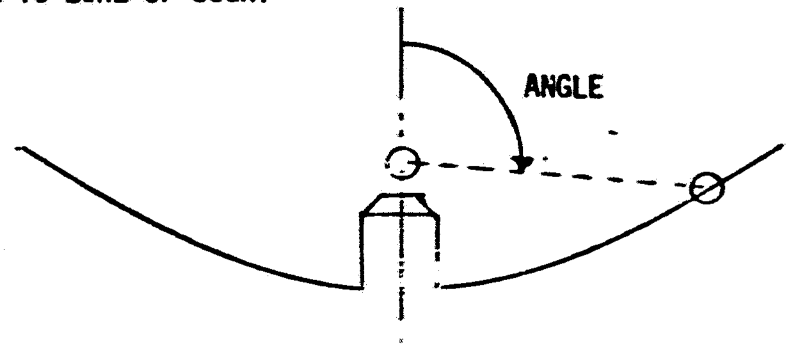
Figure 13

OPTICAL MEASUREMENT SYSTEMS

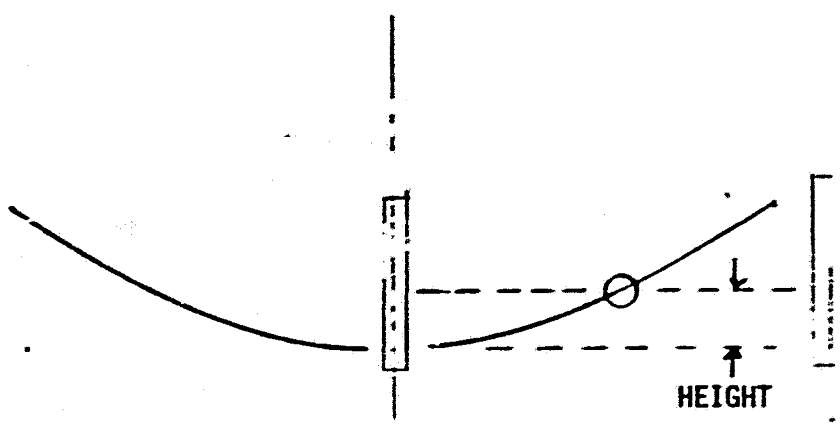
MEASUREMENT PERPENDICULAR TO LINE OF SIGHT



1. MEASURE ANGLE FROM VERTEX
   MEASURE LENGTH FROM VERTEX



3. MEASURE ANGLE FROM ELEVATED INSTRUMENT
   MEASURE LENGTH FROM VERTEX



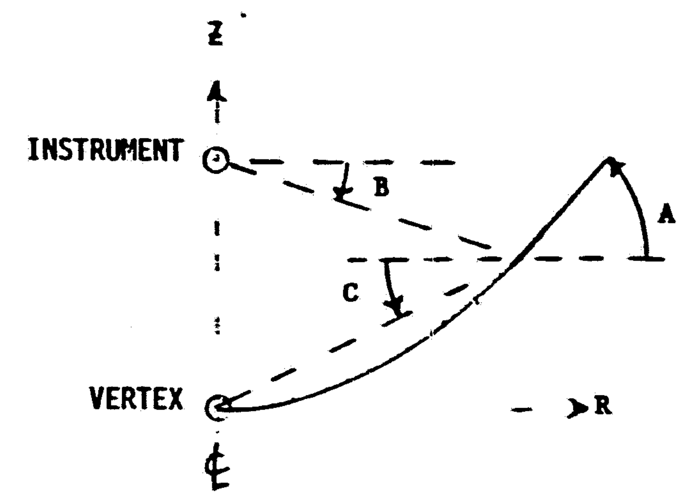
2. MEASURE HEIGHT FROM CENTERLINE OR EXTERNAL TOWER
   MEASURE LENGTH FROM VERTEX

4. MEASURE ANGLES FROM CAMERAS (PHOTOGRAMMETRY)

5. MEASURE ANGLES FROM THEODOLITES

Figure 14

MEASUREMENT SYSTEM GEOMETRY



B = Measurement Angle

S = Arc Length from Vertex

E = Effective Surface Error

= COS (A)*(NORMAL ERROR)

$EB = \partial E/\partial B$

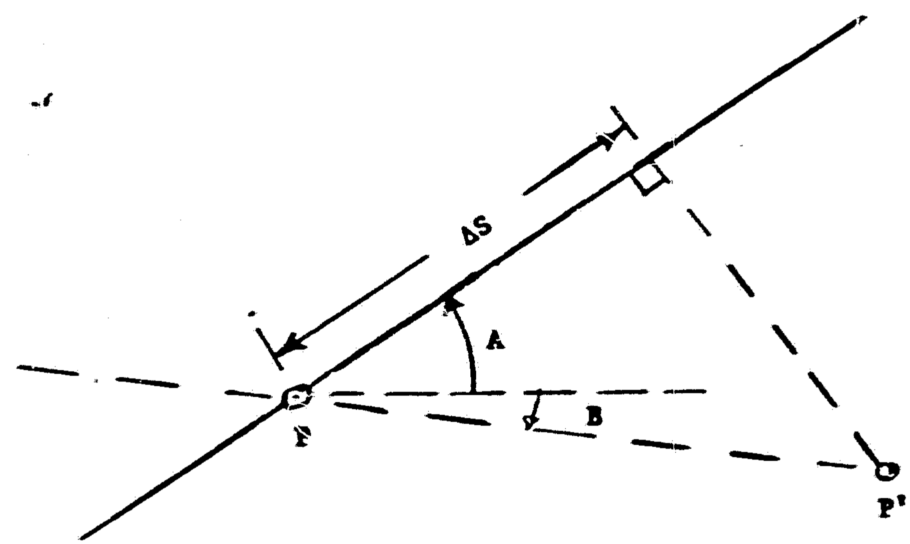
$ES = \partial E/\partial S$

EC = Constant Error Term

$\Delta E = EC + EB*\Delta B + ES*\Delta S$

Figure 15

GEOMETRY OF ERROR IN LENGTH

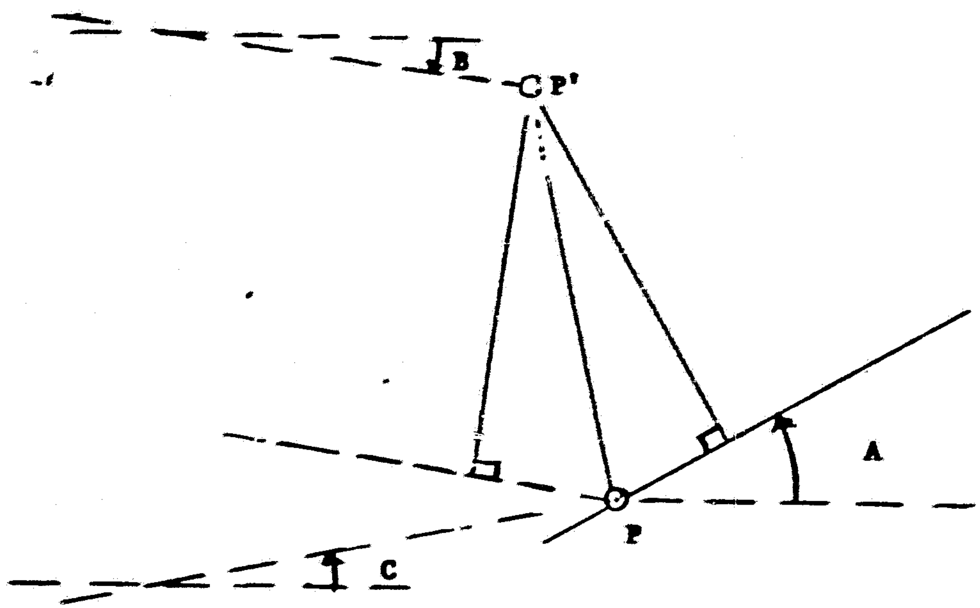


NORMAL ERROR = ΔS *TAN (A + B)

ES = COS(A)*TAN (A + B)

Figure 16

GEOMETRY OF ERROR IN ANGLE



EB = R*COS (A)*COS (A-C)/(COS(B)*COS (B + C))

Figure 17

TYPICAL INFLUENCE COEFFICIENTS FOR OPTICAL SYSTEMS

CONFIGURATION	EB/DIAMETER	ES
1. THEODOLITE AT VERTEX	.29	.19
2. OPTICAL LEVEL	.33	.45
3. THEODOLITE ABOVE VERTEX (HEIGHT = .43 x FOCAL LENGTH)	.33	.74
4. PHOTOGRAMMETRY	1.0	N.A.
5. EXTERNAL THEODOLITES	1.0	0.5

TYPICAL MEASUREMENT ERRORS

$\Delta B = 2 \times 10^{-5}$ RADIAN (4 ARC SECONDS)

$\Delta S = 2 \times 10^{-5} \times$ DIAMETER

EC = 0.1 MILLIMETER

Figure 1B

TYPICAL ERRORS OF EXISTING MEASUREMENT SYSTEMS

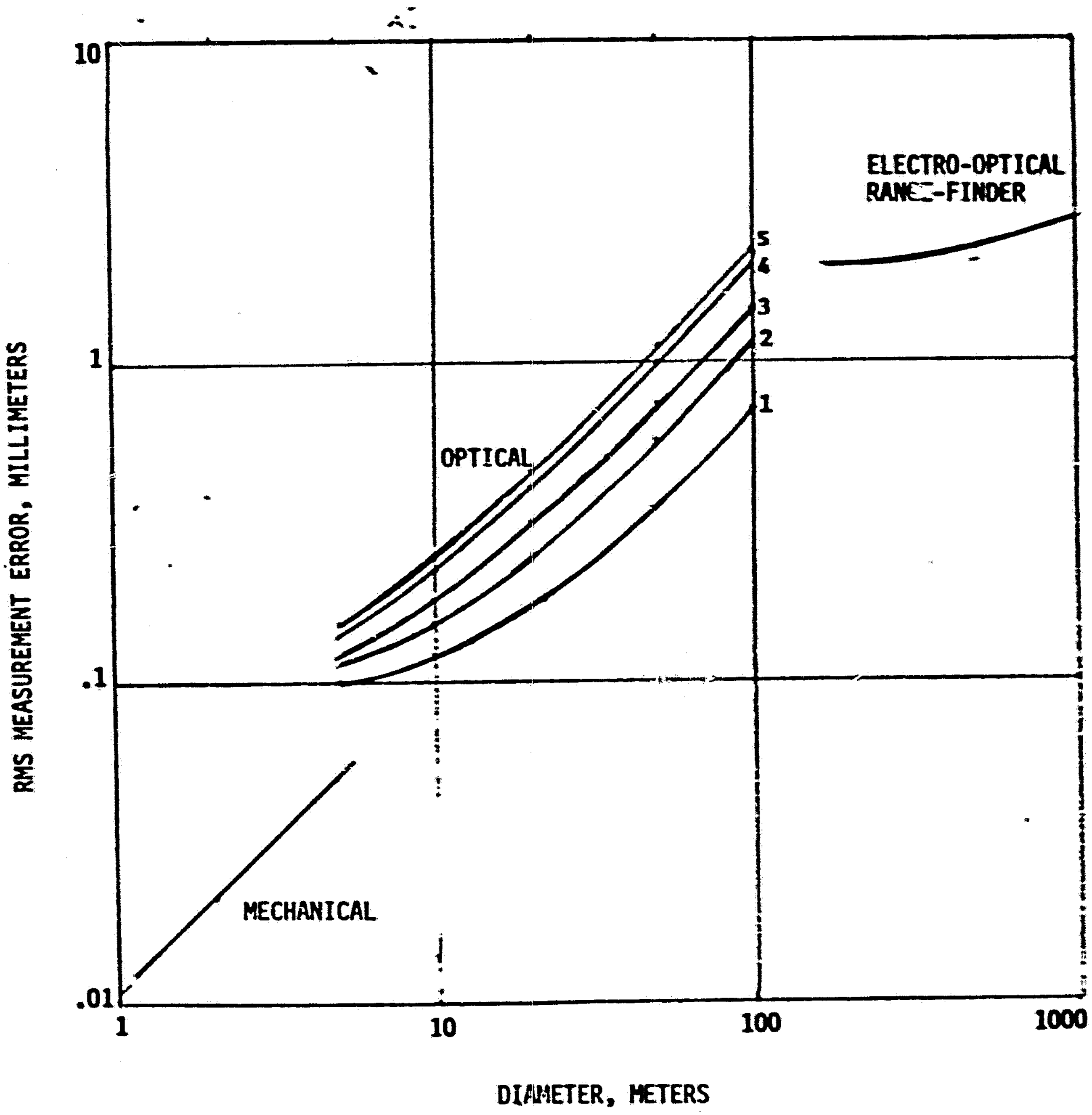
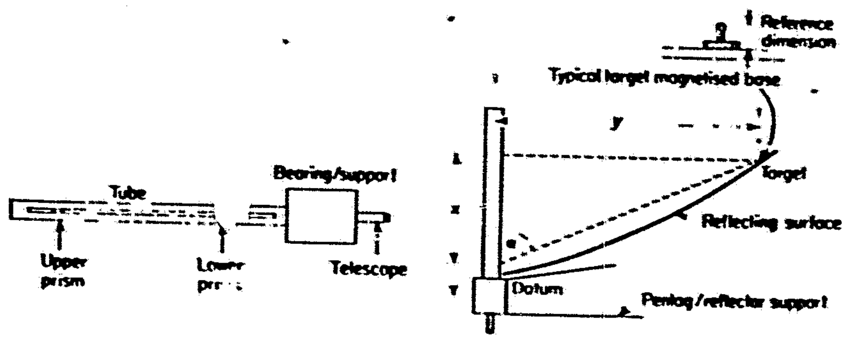


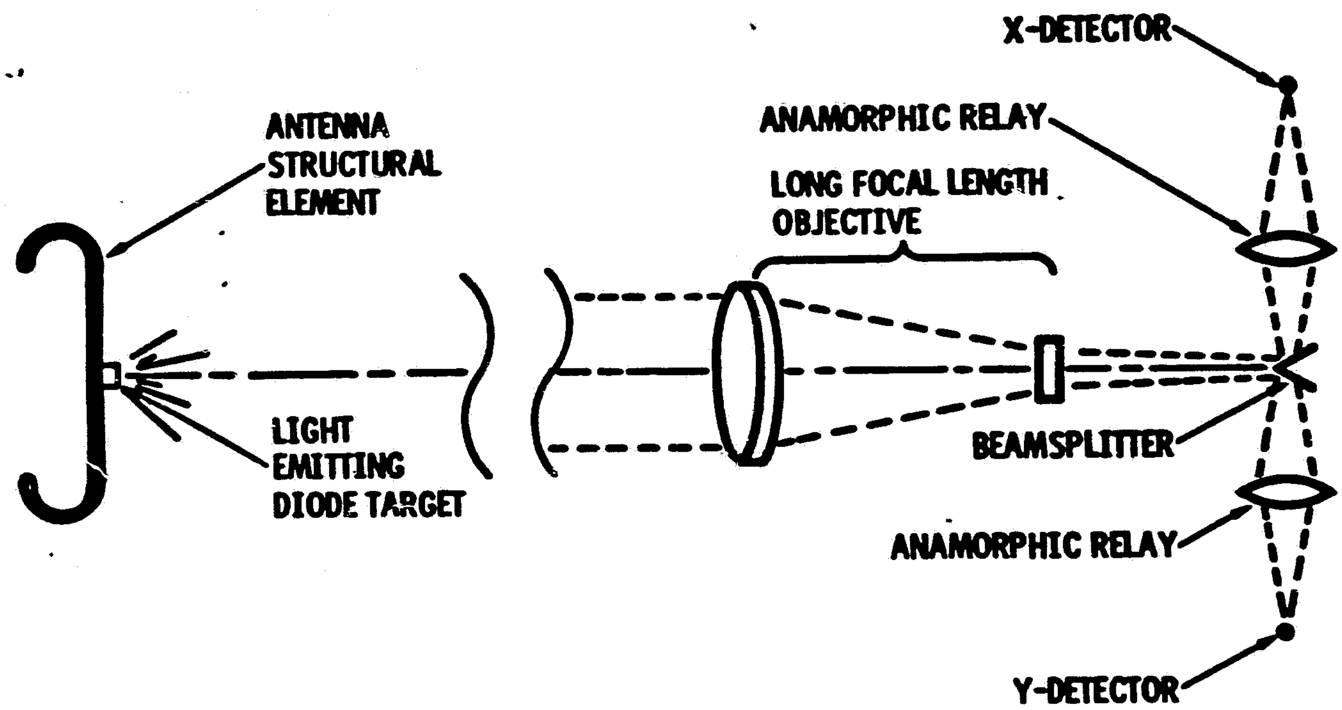
Figure 19



Profile checks, optical method

Figure 20

SURFACE ACCURACY MEASUREMENT SENSOR (SAMS)



Receiver Optics Schematic

Figure 21

SAMS

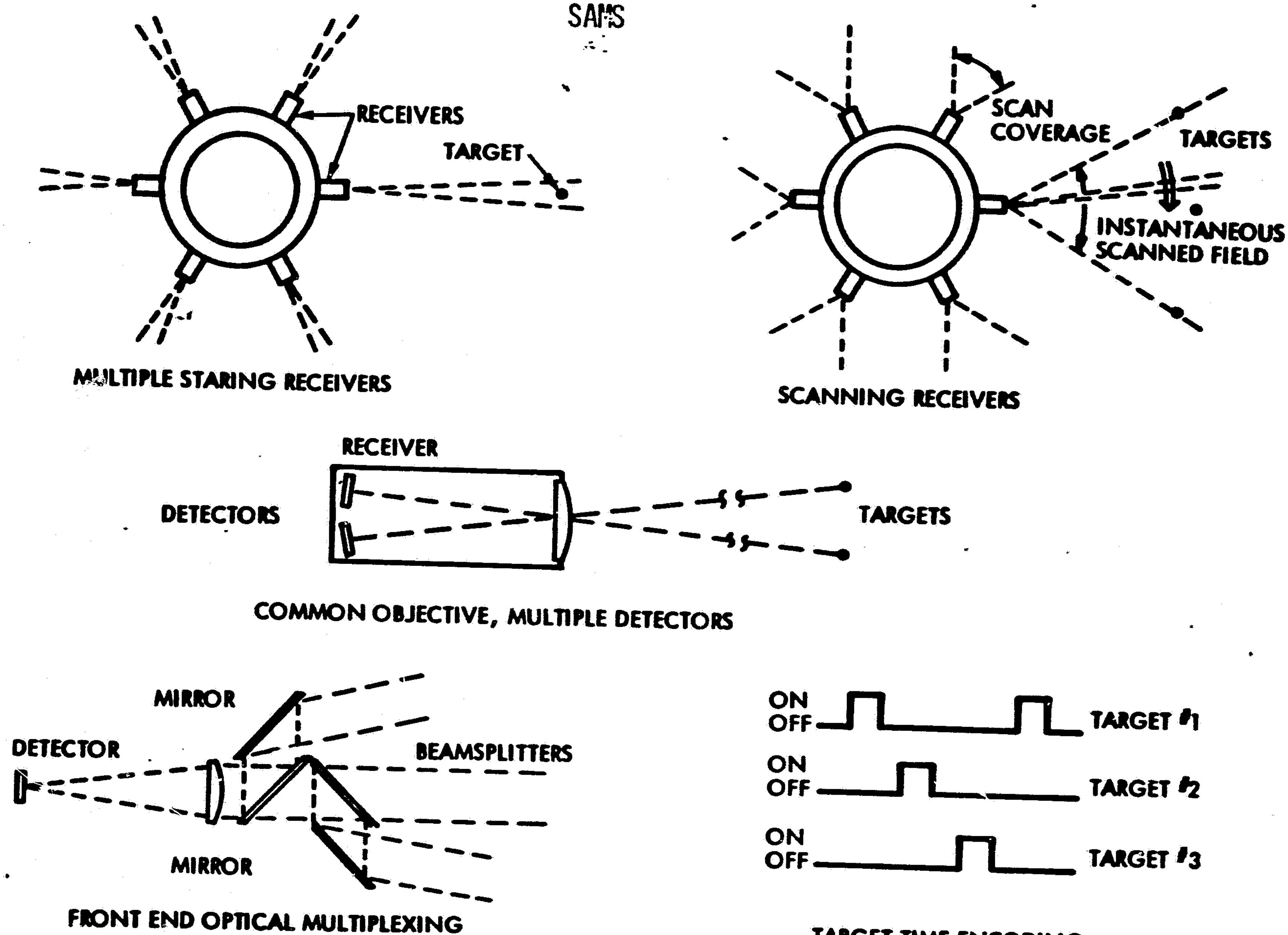
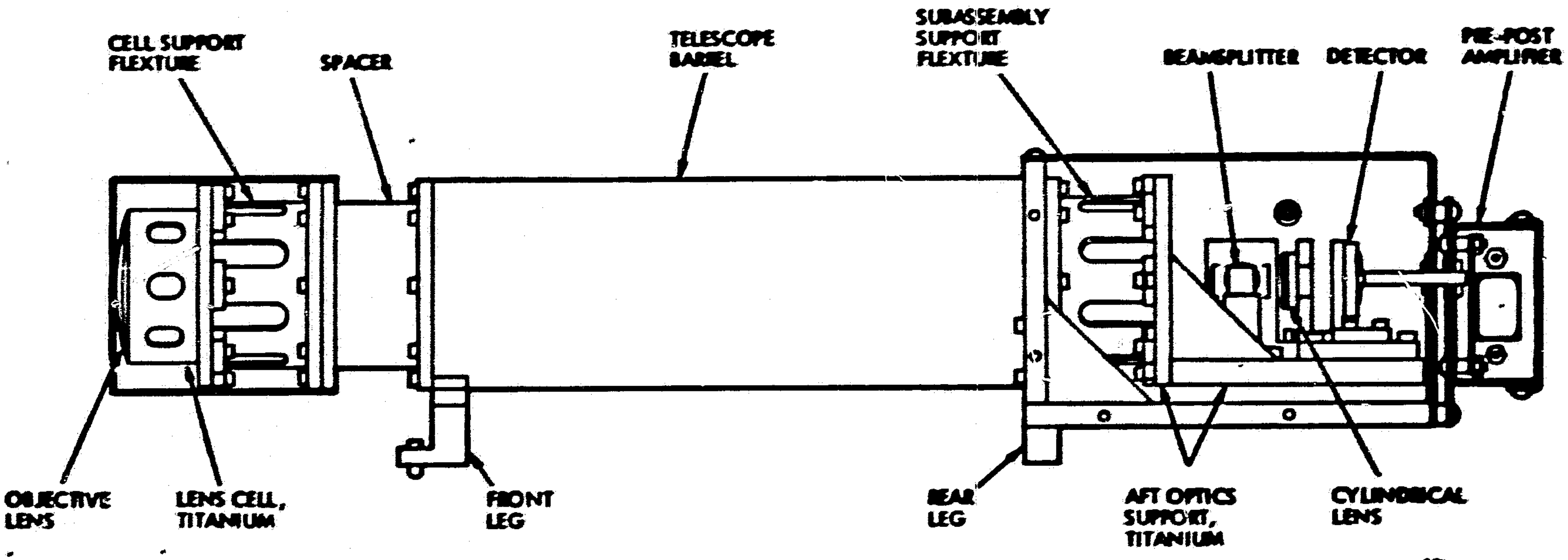


Figure 22 - Concepts for Handling Multiple Targets



:Figure 23. Layout, Receiver, SAMS DRA Breadboard

LASER/STAR TRACKER
REFLECTOR MEASUREMENT
SYSTEM

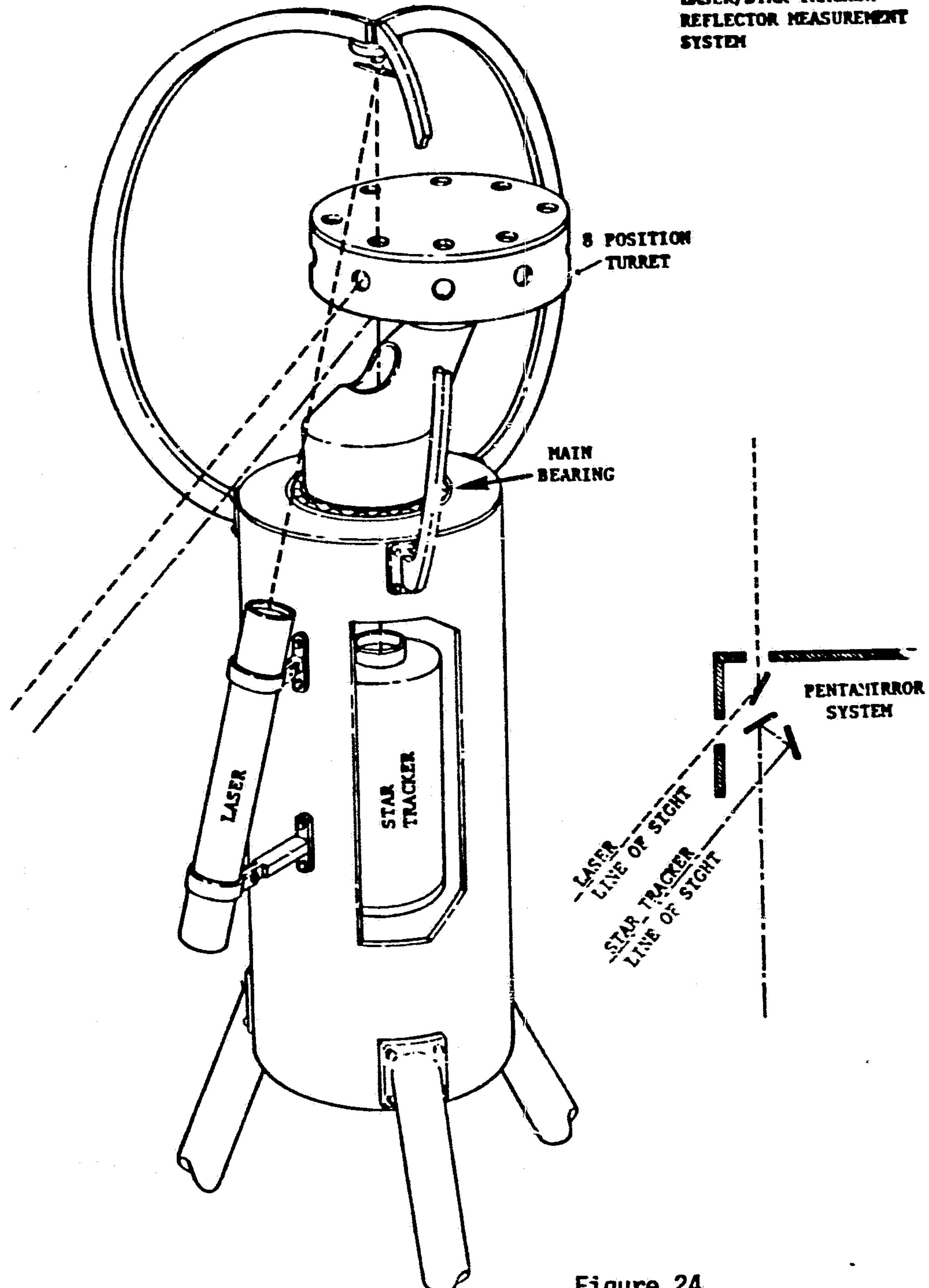


Figure 24

LASER/STAR TRACKER MEASUREMENT SYSTEM BEING USED IN A GROUND STATION ANTENNA

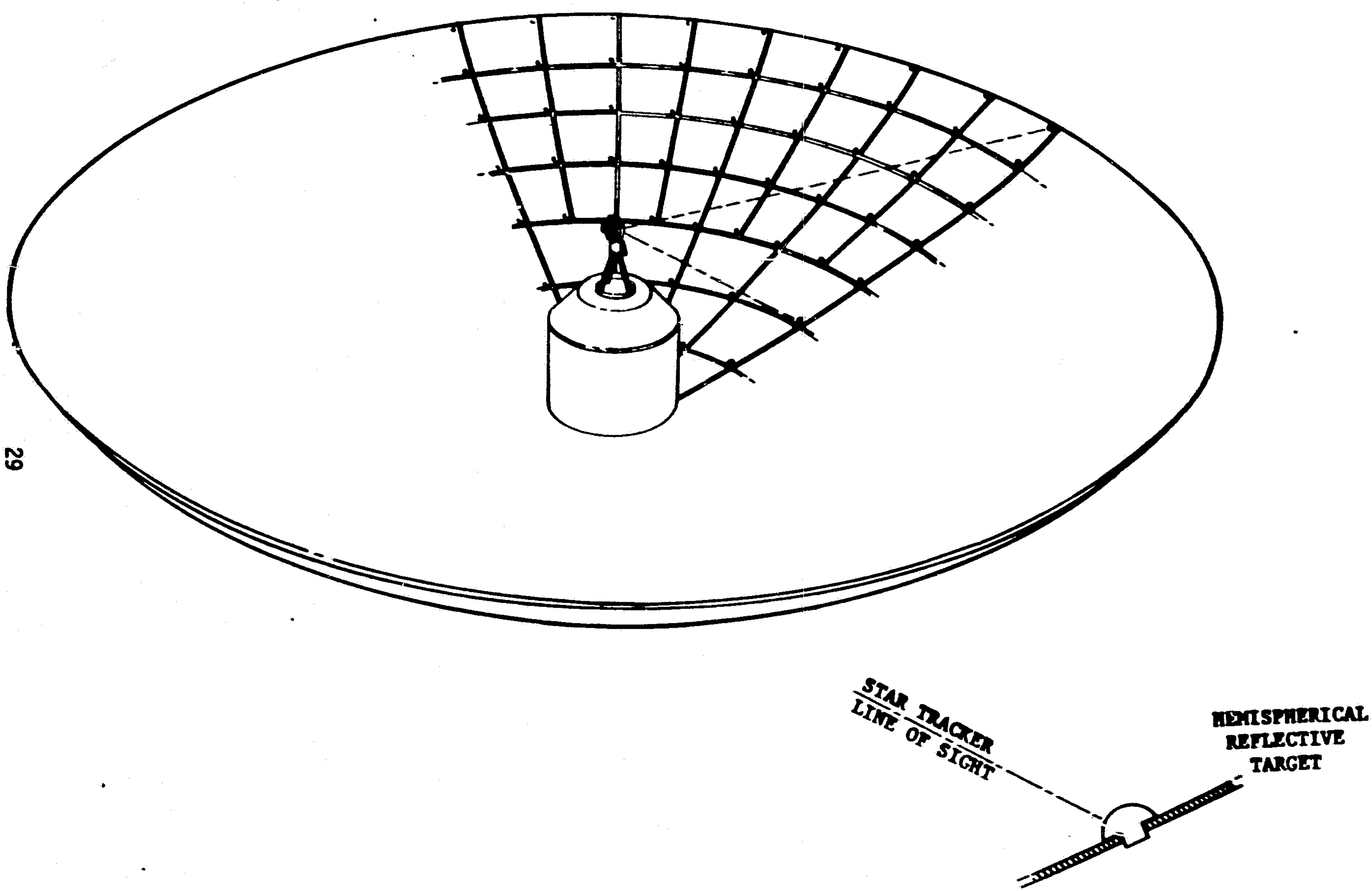


Figure 25

CAMERA/TELESCOPE REFLECTOR MEASUREMENT SYSTEM

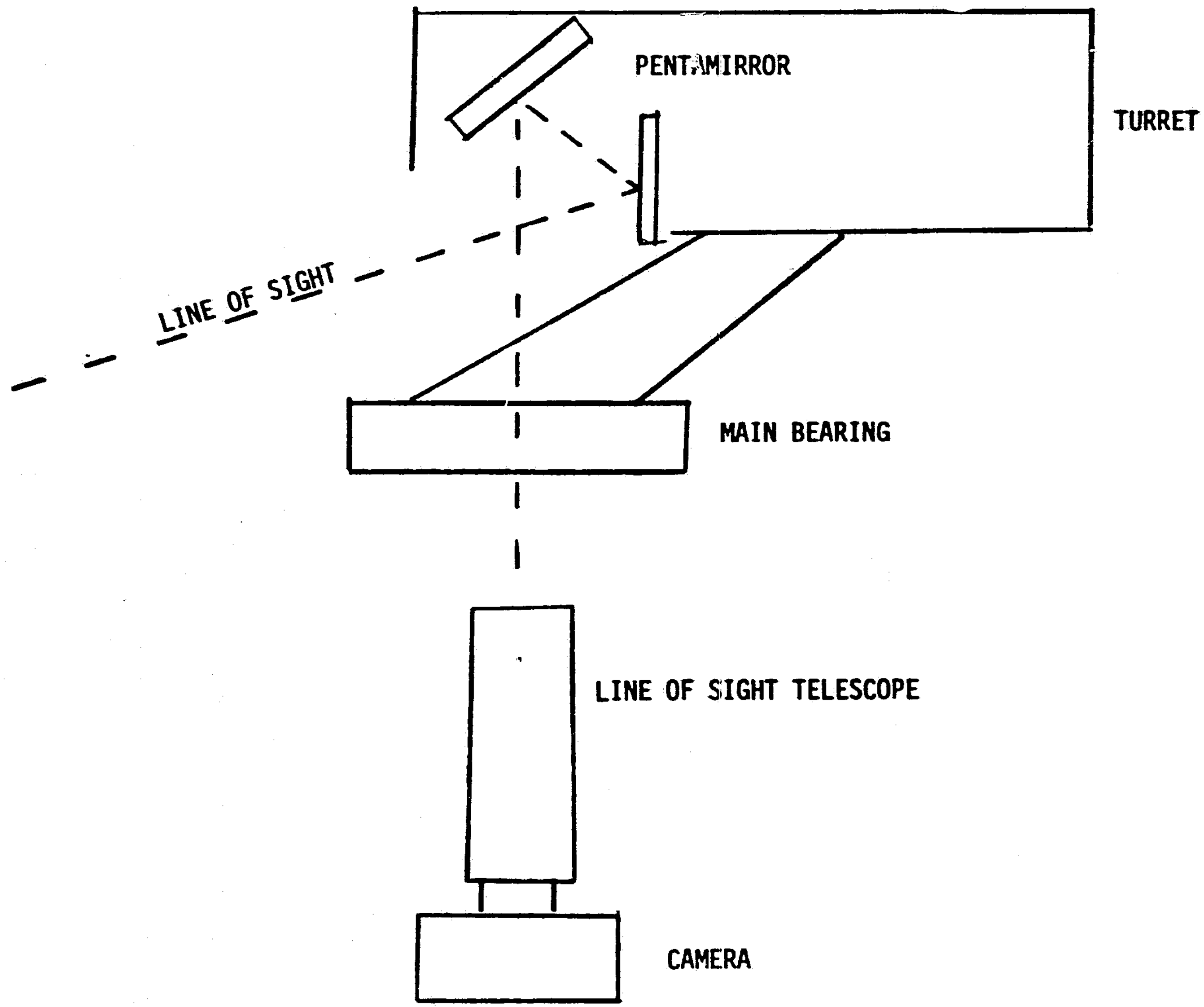


Figure 26

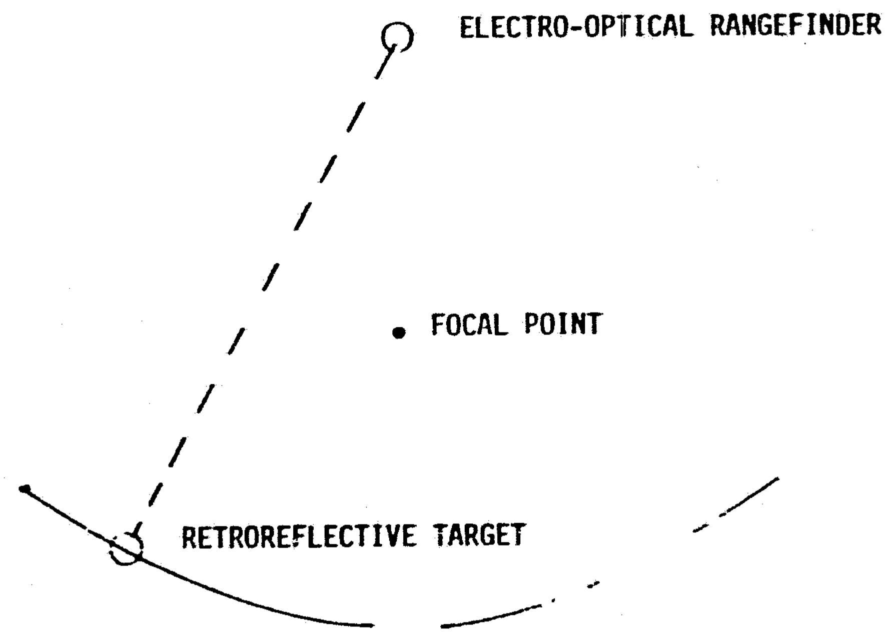
NON-MECHANICAL MEASUREMENT SYSTEMS

B. MEASUREMENTS PARALLEL TO LINE OF SIGHT

- SUCH SYSTEMS ARE NOT NORMALLY USED OUTSIDE THE UNIVERSITY SYSTEM.
- A LASER RANGE FINDER SYSTEM CUSTOM-DESIGNED AT CORNELL WAS USED TO RESET THE 305 METER ARECIBO REFLECTOR FROM 6 MM TO 3 MM RMS.
- A LASER INTERFEROMETER SYSTEM CUSTOM-DESIGNED AT CIT WAS USED TO SET A 10 METER ANTENNA TO 25 MICRONS RMS.
- A MICROWAVE DIAGNOSTIC TECHNIQUE DEVELOPED AT THE UNIVERSITY OF SHEFFIELD WAS USED TO MEASURE A 25 METER ANTENNA WITH AN ACCURACY BETTER THAN 0.01 WAVELENGTH.
- NEAR FIELD ANTENNA TESTING CAN BE INTERPRETED AS A FORM OF SURFACE MEASUREMENT.
- COMMERICALLY AVAILABLE ELECTRO-OPTICAL RANGE FINDERS WITH DIGITAL OUTPUT HAVE A FIXED ERROR TERM ON THE ORDER OF 5 MILLIMETERS THAT MAKES THEM UNSUITABLE FOR FREQUENCIES HIGHER THAN UHF.
- THE TECHNICAL LITERATURE INCLUDES MANY PROPOSALS AND FEASIBILITY STUDIES FOR HIGHER ACCURACY RANGE FINDERS.

Figure 27

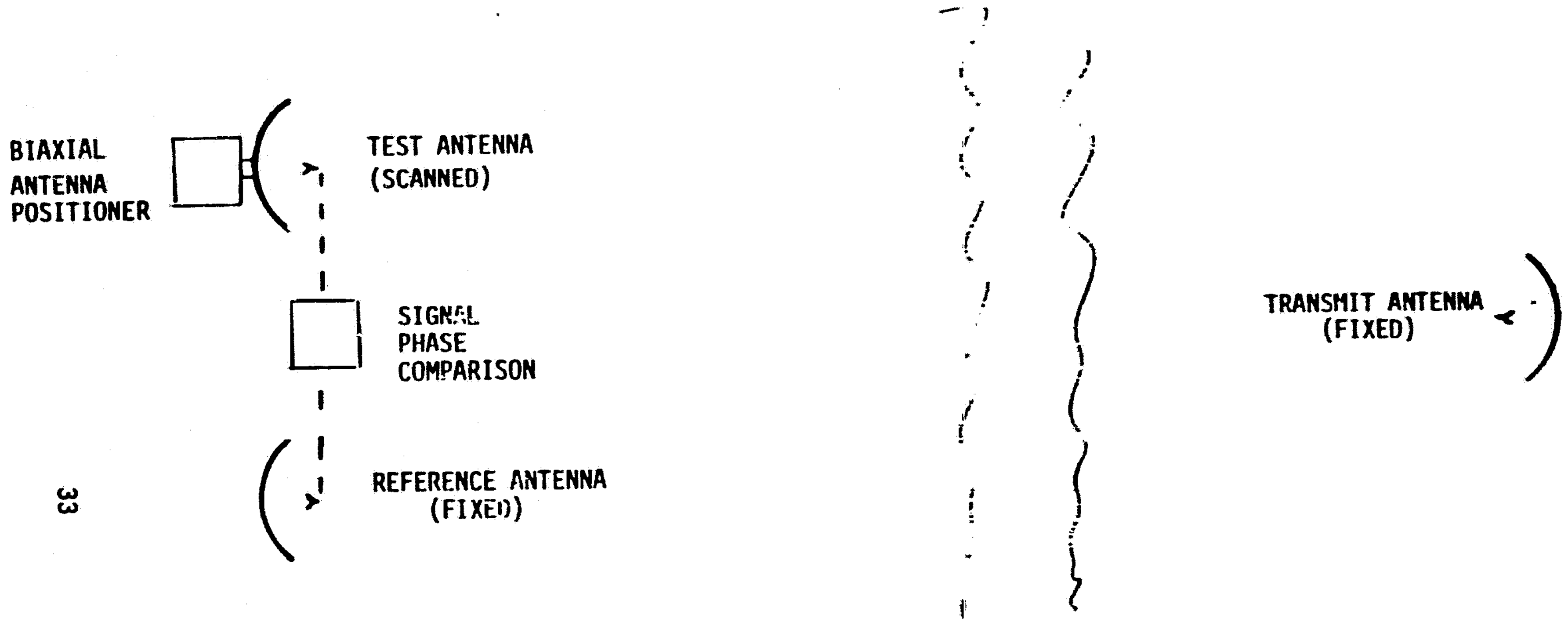
REFLECTOR MEASUREMENT WITH RANGEFINDER



- MEASURE DISTANCE FROM RANGEFINDER TO TARGET
- MEASURE DISTANCE FROM VERTEX TO TARGET

Figure 2B

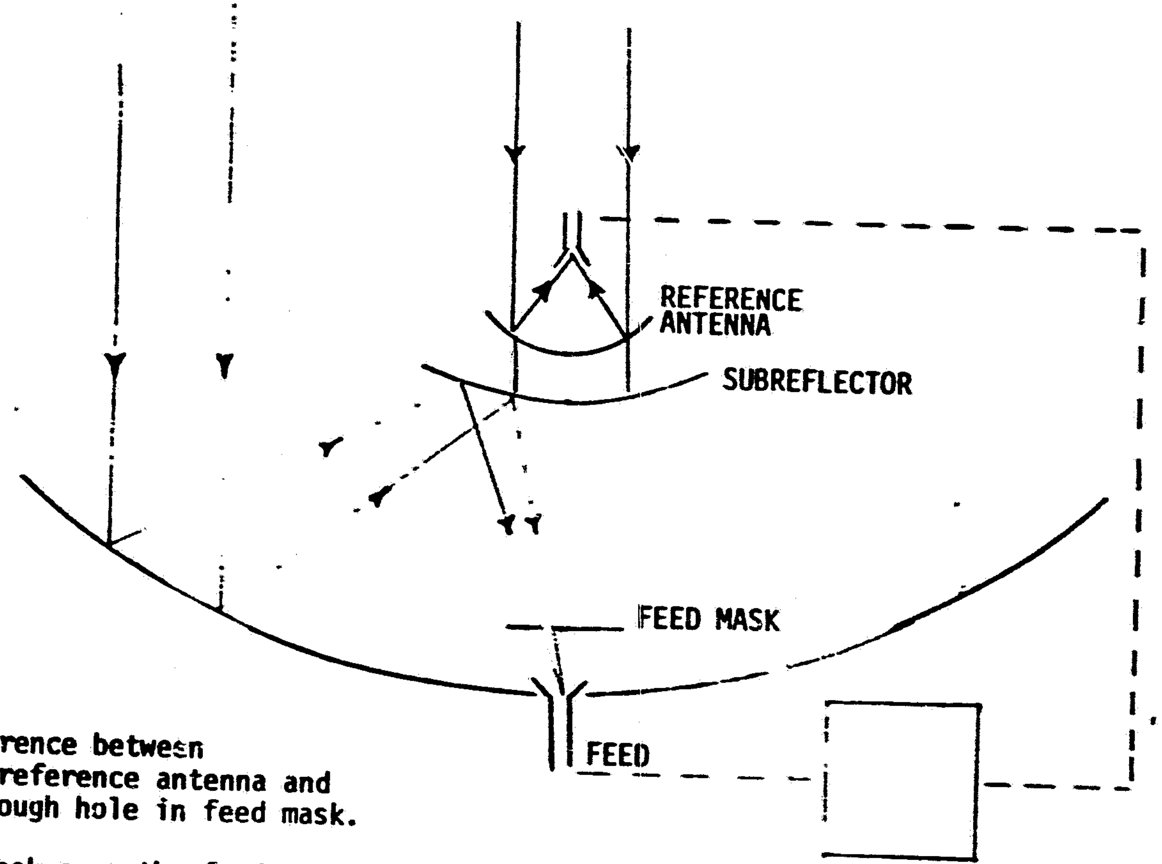
MICROWAVE DIAGNOSTIC TECHNIQUE



- SCAN ANTENNA OVER A TWO-DIMENSIONAL ARRAY WITH 100 x 100 READINGS.
- MEASURE PHASE DIFFERENCE AT EACH READING.
- CALCULATE REFLECTOR SHAPE MISALIGNMENT AND FEED POSITION MISALIGNMENT.

Figure 29

FEED MASK TECHNIQUE



- Measure phase difference between signal received by reference antenna and signal received through hole in feed mask.
- Scan hole in feed mask over the feed aperture.
- Calculate reflector shape misalignment and feed position misalignment,

Figure 30

FEED MASK TECHNIQUE

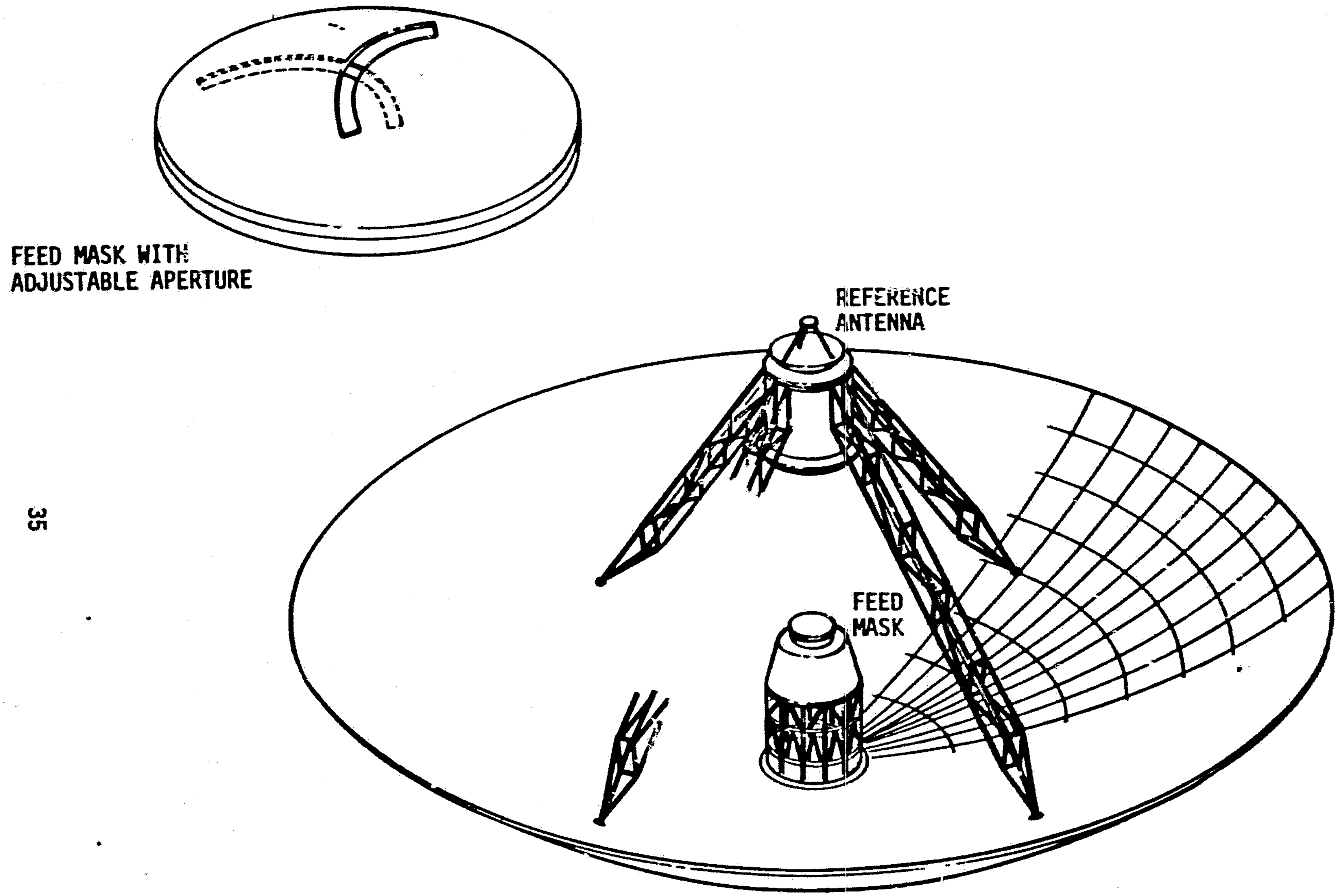


Figure 31

34 METER ANTENNA SURFACE ERROR ALLOCATIONS

OPERATIONAL TOLERANCE FOR 1/2 DB LOSS	0.6 MM (.024 INCH) RMS
PANEL SETTING TOLERANCE	0.3 MM (.012 INCH) RMS
ALLOWABLE SURFACE MEASUREMENT ERROR	0.3 MM (.012 INCH) RMS
DUE TO ANGULAR MEASUREMENT	0.2 MM (.008 INCH) RMS
DUE TO LINEAR MEASUREMENT	0.2 MM (.008 INCH) RMS
ALLOWABLE ANGULAR ERROR	
THEODOLITE AT VERTEX	4.3 ARC SECONDS RMS
THEODOLITE ON FEED	3.9 ARC SECONDS RMS
ALLOWABLE LINEAR ERROR	
THEODOLITE AT VERTEX	1.1 MM (.044 INCH) RMS
THEODOLITE ON FEED	0.28 MM (.011 INCH) RMS

Figure 32

MEASUREMENT TECHNIQUES

THEODOLITE ON CENTERLINE

- AT VERTEX - EXISTING METHOD.
- ON FEED - MORE SENSITIVE TO LINEAL ERRORS.

MICROWAVE DIAGNOSTICS

- BASIC METHOD DEVELOPED AT UNIVERSITY OF SHEFFIELD.
- FEED MASK IS A CONCEPTUAL VARIANT.

ANGULAR TRANSDUCERS ON CENTERLINE

- SURFACE ACCURACY MEASUREMENT SENSOR (SAMS) BEING DEVELOPED AT TRW UNDER CONTRACT FROM LANGLEY.
- LASER/STAR TRACKER IS A CONCEPTUAL VARIANT.
- CAMERA/TELESCOPE IS A SEMI-AUTOMATIC SYSTEM.

Figure 33

MEASUREMENT TECHNIQUES (CONTINUED)

ELECTRONIC RANGING

- EXISTING EQUIPMENT NOT ACCURATE ENOUGH.
- DEVELOPMENT OF NEW SYSTEMS BEING PERFORMED AT JPL.

MECHANICAL TEMPLATES (INCLUDING LASER INTERFEROMETER)

- NOT PRACTICAL BECAUSE OF LARGE SIZE.

EXTERNAL TRIANGULATION

- NOT ACCURATE ENOUGH.
- THEODOLITE MOUNTS NOT STABLE.
- PHOTOGRAMMETRY NOT SUITED FOR ADJUSTMENT

Figure 34

III. CONCLUSIONS AND RECOMMENDATIONS

The existing method of shaping antennas uses a theodolite at the vertex. It is the only method that is both accurate enough and also can be used without further development. This method should be retained as a basic measurement method.

Moving the theodolite to a position on top of the RF cone would require more accurate measurements of the lengths, but otherwise would require minimal development. This should be the basic method to be used if the theodolite cannot be placed at the vertex.

The method with the most immediate potential for a rapid automatic measurement system with the required accuracy is the microwave diagnostic system being developed at the University of Sheffield.

All other methods that were considered are either not accurate enough or would require considerable development. They should be reviewed for long-term potential, but no immediate action is recommended.

APPENDIX A

PRELIMINARY ERROR ANALYSIS OF REFLECTOR MEASUREMENT SYSTEMS

Introduction

This report is a preliminary error analysis of measurement systems for the 34 meter reflector. The analysis is made in a parametric form so that it applies to a variety of systems that could be chosen. The main emphasis is on systems with a theodolite mounted on the feed rather than its usual position at the vertex. One purpose of the report is to provide information that will be helpful in choosing a system. Another purpose is to provide reference data for the final error analysis that will be made when a specific technique is chosen.

Effective Surface Error

Errors in the reflector surface measurement system cause the surface to be distorted from its ideal shape. The amount of distortion is defined by the normal deviation, ND, between the ideal surface and the distorted surface. The effective surface deviation, E, is defined as one half the change in the RF path length between these two surfaces. It is also equal to the axial component of the normal deviation.

General Description of Measurement System

For the purpose of this error analysis, the surface to be measured, is taken as a paraboloid with a focal length, F. A theodolite or other optical instrument is mounted on the centerline a distance, ZT, above the vertex. A measurement point on the surface is viewed with the theodolite and the angle, B, from the aperture plane is measured. The arc length, S, to the same point is also measured. The arc length is measured from the vertex in a radial direction along the surface. The reflector shape is determined as a function of the angle and length measurement to each point.

Measurement System Geometry

The geometry of the measurement system is illustrated in Figure 1. All of the angles are measured from the aperture plane. The angle, A, is defined by the local slope of the surface. The angle, B, is the measurement angle from the theodolite. The angle, C, is defined by the line from the vertex to the point. The origin of the coordinate system is at the vertex. Cylindrical coordinates with radius, R, and height, Z, are used.

Measurement Configurations

Three measurement configurations are used in this analysis. They are:

- Theodolite at height, ZT

  This is the baseline configuration discussed above.

- Theodolite at vertex

  This configuration is obtained by setting ZT = 0, so that B + C = 0.

- Sight level

  This configuration is obtained by setting ZT = Z, so that B = 0.

Partial Derivations of Effective Surface Error

The effective surface error, E, is a function of the angle, B, and the length, S.

$$E = F(B,S)$$

Both of these measurements have associated errors, DB and DS. The error, DE, in the effective surface error is then given by,

$$DE = DB*EB + DS*ES$$

Where EB and ES are the partial derivations of E with respect to B and S. They may also be considered as influence coefficients, since they determine the influence that B and S have on E.

Length Influence Coefficient

The geometric factors which determine the length influence coefficient, ES, are illustrated in Figure 2. A target is actually located at the point, P. It is mislocated at point, P', because of an error, DS, in the length. The resultant normal deviation, effective error and influence coefficients are:

$$ND = DS*TAN(A + B)$$

$$E = ND*COS(A)$$

$$ES = COS(A)*TAN(A + B)$$

Angle Influence Coefficient

The geometric factors which determine the angle influence coefficient, EB, are illustrated in Figure 3. A target is located at point P. It is mislocated at point, P', because of an error, DB, in the angle. The resultant normal deviations are:

- Normal to theodolite line of sight

  R/COS(B)

- Normal to line of sight from vertex

  R/(COS(B)*COS(B + C)

- Normal to local surface

  R*COS(A - C)/(COS(B)*COS(B + C)

The resultant influence coefficient is

EB = R*COS(A)*COS(A - C)/(COS(B)*COS(B + C)

Computer Program, PART

A computer program called PART which calculates the influence coefficients over a range of parameters has been written in FORTRAN. Listings of the symbolic input and the computer output are presented in Appendix A. The numerical values that were used as input are included as DATA statements in the program so that no separate input was required. All dimensions are in meters.

The reflector was divided into 20 equal-area annular rings going from a minimum radius of 1.9 meters to a maximum radius of 17 meters. The minimum radius was determined by the subreflector shadowing. Influence coefficients, EB and EL, were calculated for each of these rings and for each of the three measurement configurations described earlier. The following letters were used to identify the measurement configuration:

Z - theodolite at height, ZT

V - theodolite at vertex

L - sight level

The influence coefficient, EB, for angle is therefore labeled as EBZ, EBV, and EBL for each of the configurations. Similarly, the influence coefficient, ES, for length is labeled as ESZ, ESV, And ESL.

Input Data

The following numerical values were used as input data to the programs:

Reflector diameter	34 m
Focal length	11 m
Subreflector diameter	3.8 m
Theodolite height above vertex	4.7 m

Angular Error Influence Coefficient

The angular error influence coefficient, EB, is plotted in Figure 4 as a function of the area ratio. It has units of length, since it is the effective surface error per unit of angle in radians. It may also be thought of as an effective radius. The actual radius is also plotted in Figure 4 for reference.

Length Error Influence Coefficient

The length error influence coefficient, ES, is plotted in Figure 5 as a function of the area ratio. It is non-dimensional, since it is the effective surface error per unit of length error. The configuration with the theodolite on the feed has much higher coefficients than the other configurations for small radii.

The integral of ES with respect to the area ratio is plotted in Figure 6. This plot makes it convenient to determine the effective coefficient for hybrid systems that use a combination of configurations.

Preliminary Error Allocation

The influence coefficients were used to make the preliminary error allocation shown in Table 1. Some arbitrary assumptions and allocations were required. These results are summarized and compared to the configuration with the theodolite at the vertex as follows:

Allowable angular error, arc seconds RMS	
Theodolite at vertex	4.3
Theodolite on feed	3.9
Allowable lineal error, mm (inch) RMS	
Theodolite at vertex	1.09 (.044)
Theodolite on feed	
Case I	0.28 (.011)
Case II	0.35 (.014)

Case I is the baseline configuration with the theodolite being used for all measurements. Case II is a hybrid configuration in which an optical sight level is used for inner tenth of the reflector area.

Conclusion

Moving the measurement theodolite from its usual position at the vertex to an auxiliary position on the feed increases the sensitivity of the measurement system to angular and lineal errors. The increase is small for angular errors, and so an angular measurement system that was satisfactory at the vertex should also be satisfactory on the feed. The increase is large for lineal error, and so errors that were acceptably small when the theodolite was at the vertex may be unacceptably large when the theodolite is on the feed.

TABLE 1

PRELIMINARY ERROR ALLOCATION FOR SURFACE ERROR

1. Operational tolerance

   - Assume 2½ percent of wavelength (0.5 dB loss)
   - Minimum X band wavelength = 24 mm
   - Operational tolerance = 0.6 mm (0.024 inch) RMS

2. Allowable measurement system error

   - Assume ½ of operational tolerance
   - Allowable error = 0.3 mm (0.012 inch) RMS

3. Allocation of errors to angle and length

   - Allocate equal effects to angle and length
   - Assume angle and length errors are not correlated
   - Allowable error for each effect = $0.3/\sqrt{2}$ = 0.21 mm RMS

4. Allowable angular error

   - Average value of EBZ = 11.2 meters (effective radius)
   - Allowable angular error = (0.21/11,200) radian
     = 3.9 arc second RMS

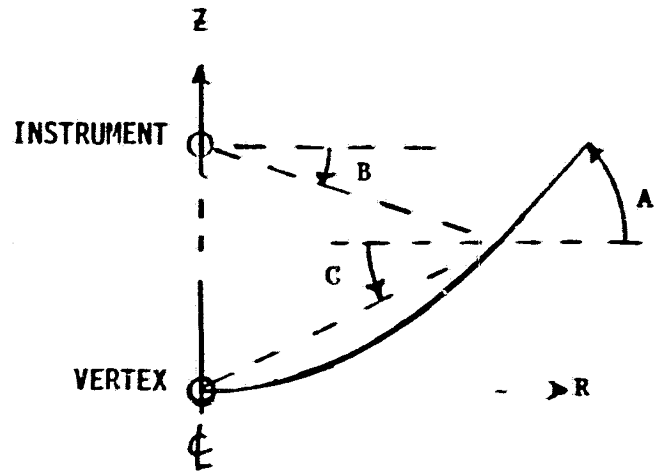
5. Allowable lineal error (Case I)

   - Average value of ESZ = 0.74
   - Allowable linear error = 0.21/0.74 = 0.28 mm (.011 inch)

6. Allowable lineal error (Case II)

   - Use level for inner tenth of area
   - Average value of ES = 0.60
   - Allowable linear error = 0.21/0.60 = 0.35 mm (.014 inch)

MEASUREMENT SYSTEM GEOMETRY



B = Measurement Angle

S = Arc Length from Vertex

E = Effective Surface Error
  = COS (A)*(NORMAL ERROR)

EB = ∂E/∂B

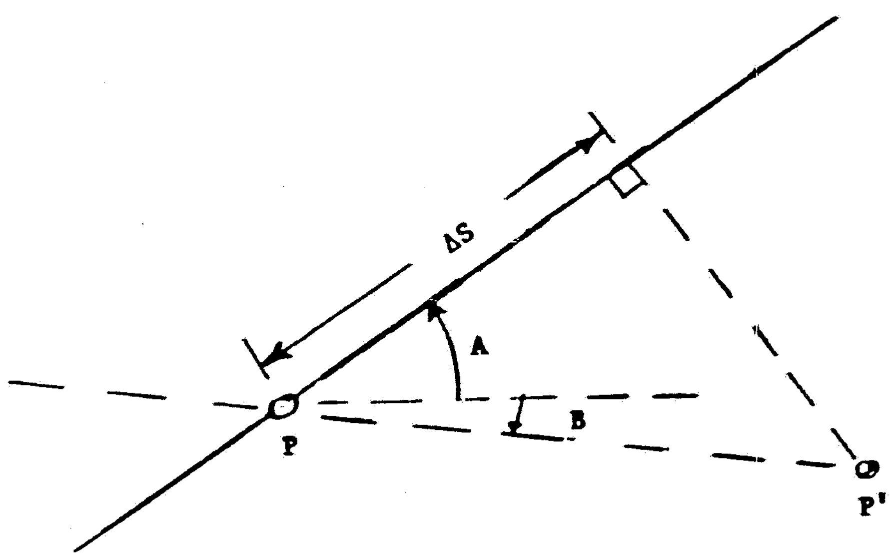
ES = ∂E/∂S

EC = Constant Error Term

ΔE = EC + EB*ΔB + ES*ΔS

Figure 1

GEOMETRY OF ERROR IN LENGTH

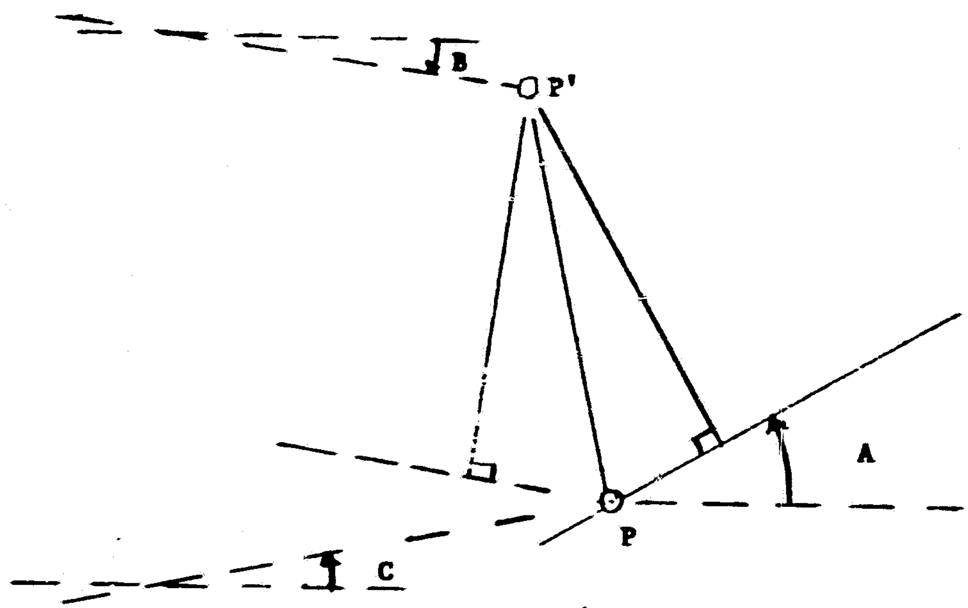


$$\text{NORMAL ERROR} = \Delta S * \text{TAN}(A + B)$$

$$\text{ES} = \text{COS}(A) * \text{TAN}(A + B)$$

Figure 2

GEOMETRY OF ERROR IN ANGLE



EB = R*COS (A)*COS (A-C)/(COS(B)*COS (B + C))

Figure 3

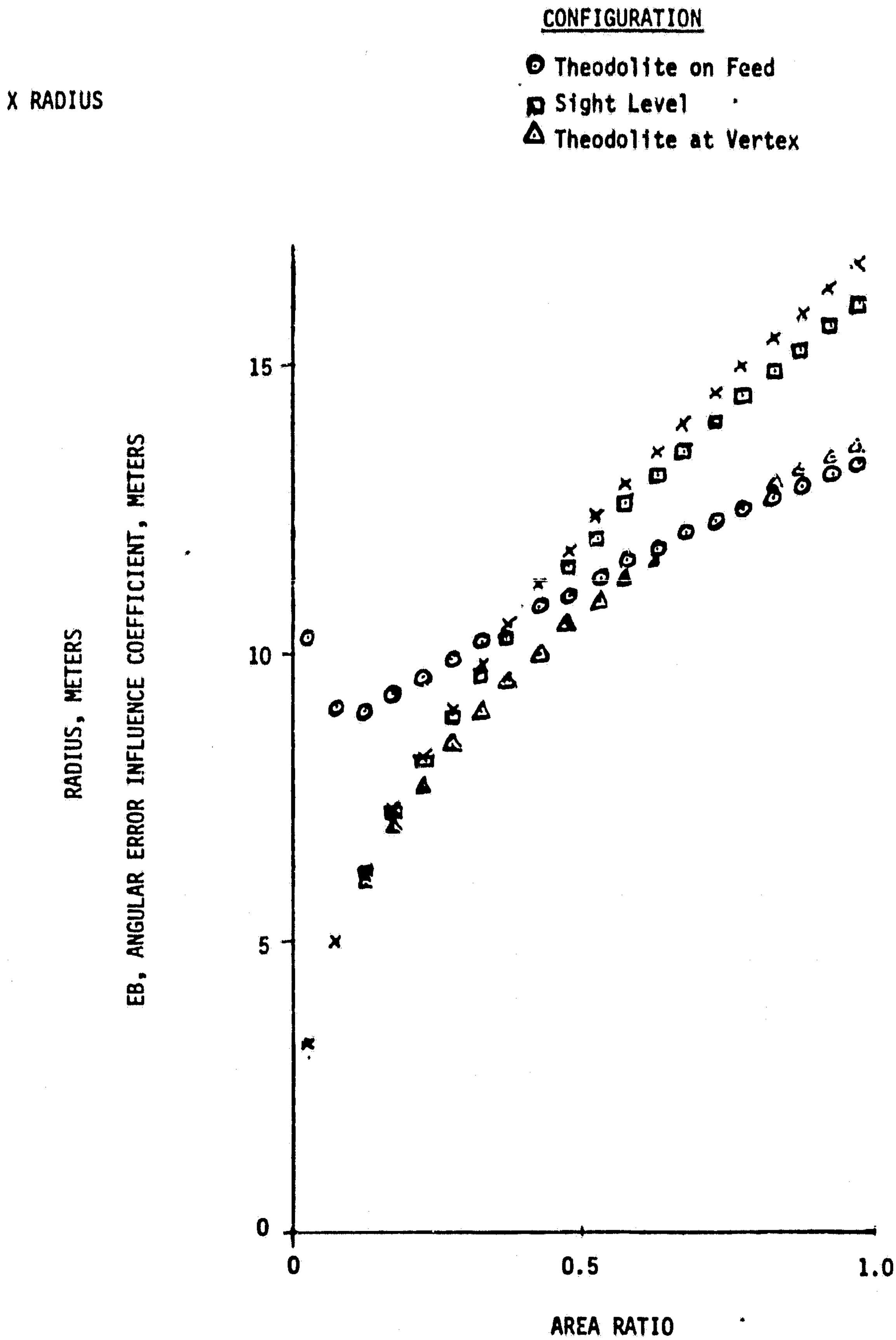

CONFIGURATION
Theodolite on Feed
Sight Level
Theodolite at Vertex
X RADIUS
RADIUS, METERS
EB, ANGULAR ERROR INFLUENCE COEFFICIENT, METERS
15
10
5
0
0
0.5
1.0
AREA RATIO

Figure 4

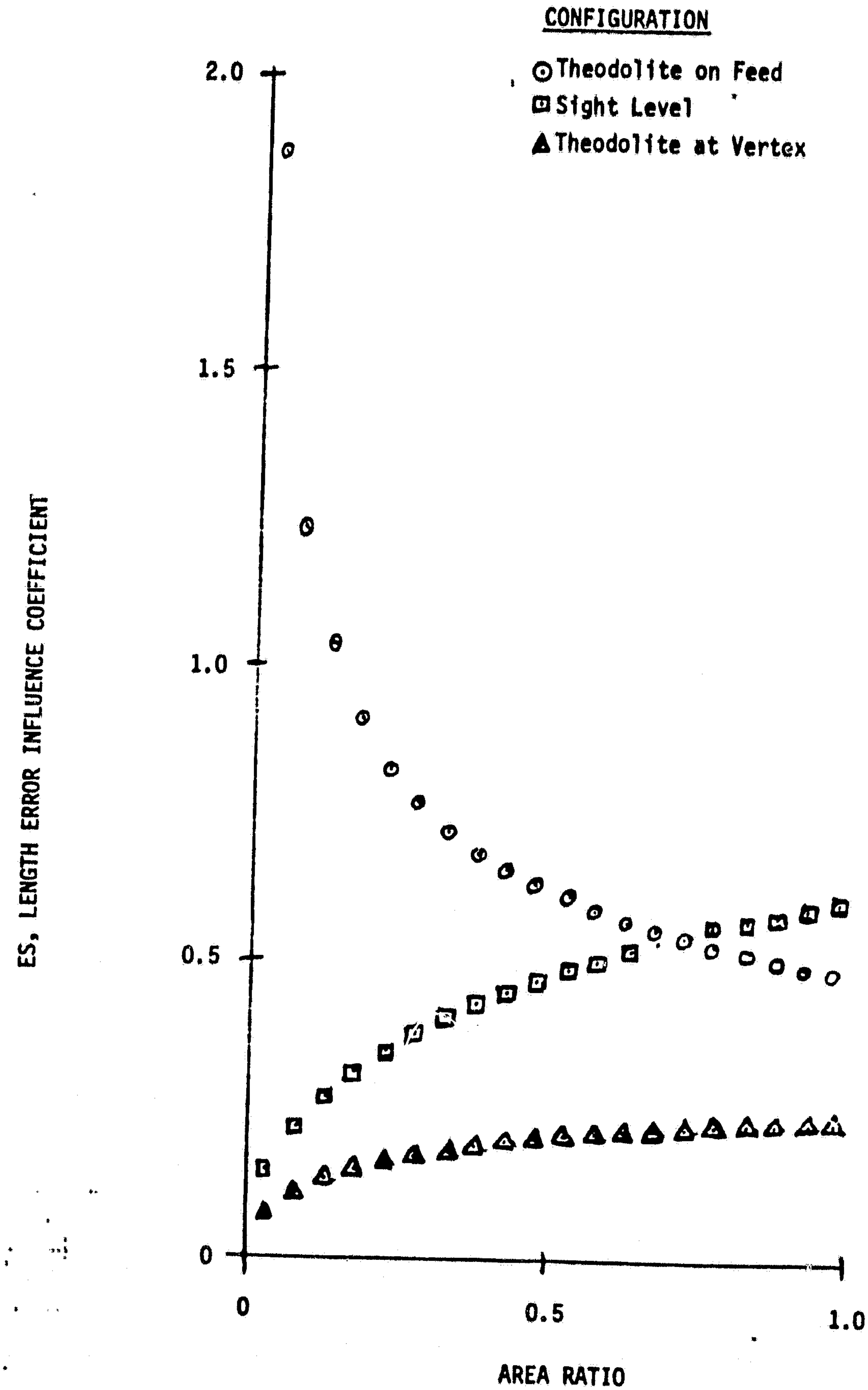

CONFIGURATION
Theodolite on Feed
Sight Level
Theodolite at Vertex
2.0
1.5
1.0
0.5
0
0
0.5
1.0
ES, LENGTH ERROR INFLUENCE COEFFICIENT
AREA RATIO

Figure 5

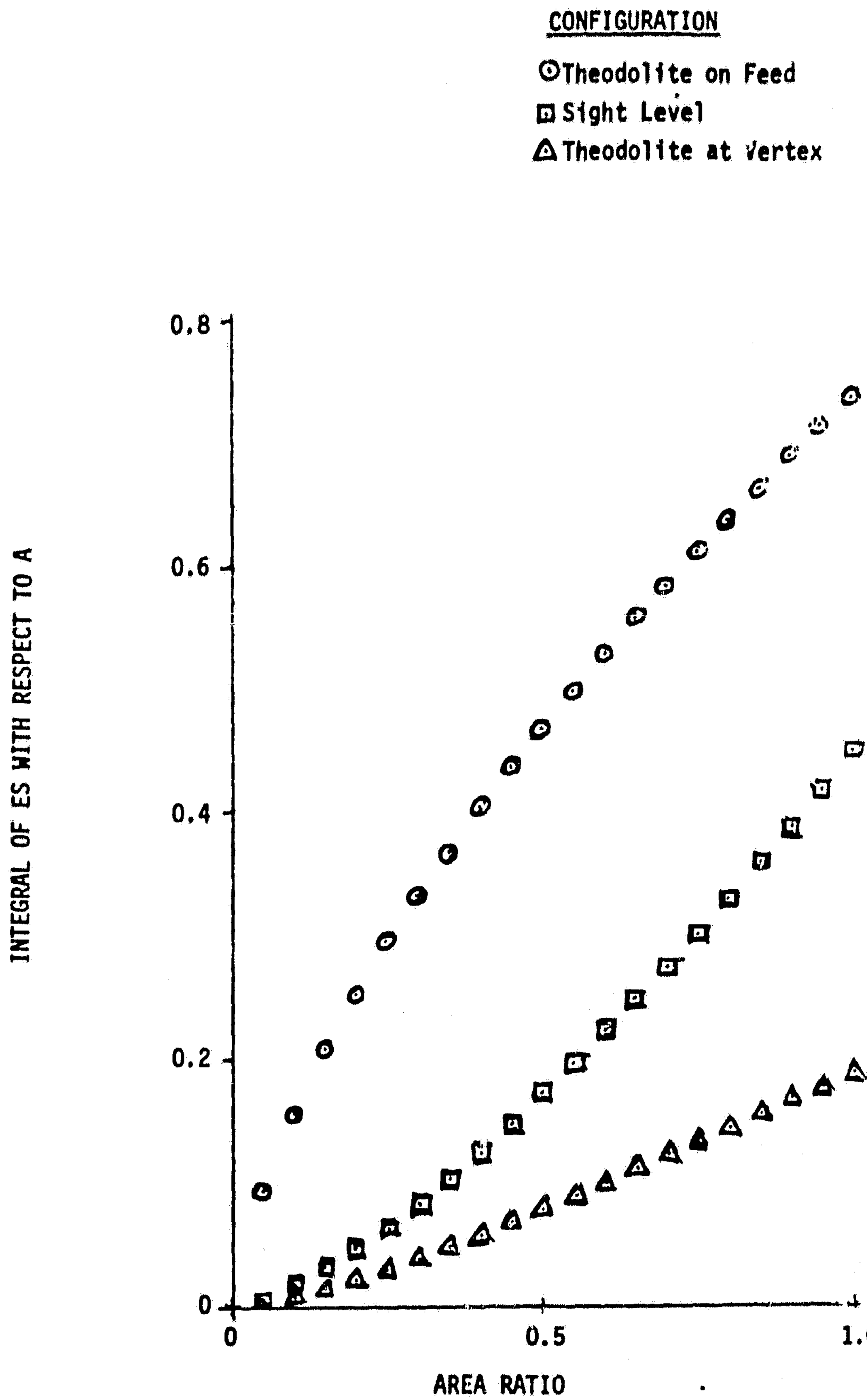

CONFIGURATION
Theodolite on Feed
Sight Level
Theodolite at Vertex
INTEGRAL OF ES WITH RESPECT TO A
0.8
0.6
0.4
0.2
0
0
0.5
1.0
AREA RATIO

Figure 6

```
RUNX COMPILER (VER.2.3M)                10/27/80. 12.06.16.

      PROGRAM PART(OUTPUT)
*
*  CALCULATE THE PARTIAL DERIVATIVES, EB AND ES, OF THE EFFECTIVE SURFACE
*  ERROR, E, WITH RESPECT TO THE ANGLE, B, AND LENGTH, S.
*
*  USE THREE MEASUREMENT CONFIGURATIONS.  IN ALL THREE CONFIGURATIONS
*  THE ARC LENGTH IS MEASURED ALONG THE SURFACE.  THE HEIGHT IS THEN
*  MEASURED BY ONE OF THE THREE FOLLOWING METHODS:
*
*     L      SIGHT LEVEL
*     V      THEODOLITE AT VERTEX
*     Z      THEODOLITE AT HEIGHT, ZT
*
*     F = FOCAL LENGTH
*     RMIN = MINIMUM RADIUS
*     RMAX = MAXIMUM RADIUS
*     ZT = THEODOLITE HEIGHT
*
      DATA F,RMIN,RMAX,ZT /11.,1.9,17.,4.7/
*
*  SET SUMS TO ZERO
*
      DATA EBLS,EBVS,EBZS,ESLS,ESVS,ESZS /6*0./
*
*  CALCULATE INCREMENT, DRR, IN RR=R**2 FOR 20 EQUAL AREAS.
*
      DRR = (RMAX**2 - RMIN**2)/20.
*
*  SET INITIAL RR AND INDEX
*
      RR = RMIN**2 - DRR/2.
      PRINT 1000
      DO 100 K=1,20
      RR = RR + DRR
*
*  CALCULATE RADIUS, R,HEIGHT, Z, AND SLOPE, DZDR.
*
```

```
        R = SQRT(RR)
        Z= .25*RR/F
        DZDR = .5*R/F
*
*  CALCULATE THE GEOMETRIC ANGLES, A, B, C.
*
        A = ATAN(DZDR)
        B = ATAN2(ZT-Z,R)
        C = ATAN2(Z,R)
*
*  CALCULATE PARTIAL DERIVATIVES, EB AND ES, FOR CONFIGURATIONS L, V, Z.
*
        EBL = R*COS(A-C)
        EBV = EBL*COS(A)/COS(C)
        EBZ = EBL*COS(A)/(COS(B)*COS(B + C))
        ESL = SIN(A)
        ESV = COS(A)*TAN(A-C)
        ESZ = COS(A)*TAN (A + B)
*
*  CALCULATE SUMMATIONS FOR AVERAGING
*
        EBLS = EBLS + EBL/20.
        EBVS = EBVS + EBV/20.
        EBZS = EBZS + EBZ/20.
        ESLS = ESLS + ESL/20.
        ESVS = ESVS + ESV/20.
        ESZS = ESZS + ESZ/20.
*
        PRINT 1100,K,R,Z,DZDR,EBL,EBV,EBZ,ESL,ESV,ESZ
100     PRINT 1200,EBLS,EBVS,EBZS,ESLS,ESVS,ESZS
        STOP
*
*
1000    FORMAT(7X,1HK,5X,1HR,7X,1HZ,4X,4HDZDR,7X,3HEBL,5X,3HEBV,5X,3HEBZ,5
+       X,3HESL,5X,3HESV,5X,3HESZ//)
1100    FORMAT(6X,I2,3F8.2,3F8.1,3F8.3)
1200    FORMAT(32X,3F8.1,3F8.3)
        END
```

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K	R	Z	DZDR	EBL	EBV	EBZ	ESL	ESV	ESZ
1	3.28	.24	.15	3.3	3.2	10.3	.147	.073	1.871
				.2	.2	.5	.007	.004	.094
2	5.00	.57	.23	5.0	4.9	9.1	.222	.108	1.265
				.4	.4	1.0	.018	.009	.157
3	6.27	.89	.28	6.2	6.0	9.0	.274	.132	1.038
				.7	.7	1.4	.032	.016	.209
4	7.32	1.22	.33	7.2	7.0	9.3	.316	.150	.912
				1.1	1.1	1.9	.046	.023	.254
5	8.24	1.54	.37	8.1	7.7	9.6	.351	.164	.829
				1.5	1.4	2.4	.065	.031	.296
6	9.06	1.87	.41	8.9	8.4	9.9	.381	.176	.769
				1.9	1.9	2.9	.085	.040	.334
7	9.82	2.19	.45	9.6	9.0	10.2	.407	.185	.724
				2.4	2.3	3.4	.105	.049	.370
8	10.52	2.51	.48	10.3	9.5	10.5	.431	.194	.687
				2.9	2.8	3.9	.126	.059	.405
9	11.18	2.84	.51	10.9	10.0	10.8	.453	.201	.657
				3.5	3.3	4.4	.149	.069	.438
10	11.80	3.16	.54	11.5	10.5	11.0	.473	.207	.632
				4.0	3.8	5.0	.173	.079	.469
11	12.39	3.49	.56	12.0	10.9	11.3	.491	.212	.610
				4.7	4.4	5.5	.197	.090	.500
12	12.95	3.81	.59	12.6	11.3	11.6	.507	.216	.590
				5.3	4.9	6.1	.223	.101	.529
13	13.49	4.14	.61	13.1	11.6	11.8	.523	.220	.573
				5.9	5.5	6.7	.249	.112	.558
14	14.01	4.46	.64	13.5	12.0	12.1	.537	.223	.558
				6.6	6.1	7.3	.276	.123	.586
15	14.51	4.78	.66	14.0	12.3	12.3	.551	.226	.544
				7.3	6.7	7.9	.303	.134	.613
16	14.99	5.11	.68	14.5	12.6	12.5	.563	.229	.531
				8.0	7.4	8.6	.331	.146	.639
17	15.46	5.43	.70	14.9	12.9	12.7	.575	.231	.519
				8.8	8.0	9.2	.360	.157	.665
18	15.92	5.76	.72	15.3	13.2	12.9	.586	.232	.508
				9.5	8.7	9.8	.389	.169	.691
19	16.36	6.08	.74	15.7	13.4	13.1	.597	.234	.497
				10.3	9.3	10.5	.419	.180	.716
20	16.79	6.41	.76	16.1	13.7	13.3	.607	.235	.485
				11.1	10.0	11.2	.450	.192	.740

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