REPORT OF I.A.G. SPECIAL STUDY GROUP No.19 ON ELECTROMAGNETIC DISTANCE MEASUREMENT [*]

1960 - 1963

PART I

GENERAL CONSIDERATIONS AND GROUND INSTRUMENTS

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1. — General

This is the second report of SSG 19; the first report, delivered at the 1960 General Assembly at Helsinki has now been incorporated with the proceedings [1]. The present list of members is given at Appendix II. As a result of the Helsinki meeting the scope of the SSG was widened to include fresh developments in airborne and satellite borne systems of distance measurement. A report on these by P. H. KENNEY is given in Part II. The Group has met once since Helsinki, at Munich in October 1962. In the main this report depends on personal communications and discussions, and on published reports, articles, etc. A list of the references consulted is at Appendix V. Apart from this the scope of the report is as in 1960, only fresh developments since then being considered.

2. — Terminology

The terminology and abbreviations used in this report are given below. It is recommended that this terminology be adopted by the I.A.G. for works written in English and that suitable French equivalents be devised and adopted.

a) *Electromagnetic Distance Measurement* (E.D.M.)

Any process or technique of distance measurement which depends on a comparison of signals by electromagnetic means.

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b) *Electro-Optical Distance Measurement* (E.-O.D.M.)

Any method of E.D.M. based on a comparison of light signals.

c) *Microwave Distance Measurement* (M.D.M.)

Any method of E.D.M. based on a comparison of radio microwave signals.

d) *Observation*

A single observation at a single setting of the apparatus.

e) *Set, or Set of Observations*

A set of two or more observations at different settings of the apparatus made in order to eliminate certain errors which, for the apparatus concerned, are inherent in a single observation, e.g. for the tellurometer a set of readings of the four ' A ' patterns at a single carrier frequency, or for the geodimeter a set of readings in the different phase positions and including light conductor readings.

f) *Measurement*

One or more sets of observations with other instrumental settings varied as necessary (e.g. in the case of the tellurometer, carrier frequency) combined with measurements of other relevant quantities (e.g. meteorological measurements) and capable of yielding a precise (even though by itself ambiguous) result.

g) *Determination of Distance*

A series of measuremnts of a distance from which ambiguity has been eliminated and in which external factors such as instruments, direction of measurement, time of day, etc. have been varied in order to minimise systematic error, and to provide a definitive value for use in succeeding calculations.

3. — **Basic Physical Questions**

a) *Velocity of Light*

No new rigorous determination of C_0 has been reported and the best value remains 299 792.5 ± 0.4 km/s. E.D.M. measurements in general do not suggest that the value needs to be changed although PODER [37] has suggested that there is a systematic tendency towards positive error in refractive index determination which might be compensated by the adoption of a slightly higher " geodetic velocity ". (See paragraph 26). Prof. KAROLUS of Switzerland is developing apparatus for remeasuring C_0 [2] but no results have been reported. The Mekometer developed by Dr. FROOME of the U. K. National Physical Laboratory (see paragraph 8) used in conjunction with interferometric measurement using a Laser beam (see paragraph 35) appears potentially capable of a determination to ± 1 part in 10^7.

b) *Refractive index*

The formulae recommended in the 1960 Report have now been adopted in a Resolution of the I.U.G.G. [3]. These formulae are still the best available. It has been pointed out however that the method of applying the recommended formulae for light waves is not clearly indicated in the Report or the Resolution. Both the EDLEN Formula and the BARRELL and SEARS Formula give the refractive index for pure monochromatic light, that is light of a single wavelength. In instruments such as the geodimeter modulated light is used which, even if monochromatically filtered, consists of a group of waves of slightly different lengths. The energy contained in such a group of waves moves with a velocity (the group velocity) slightly different from that of the equivalent monochromatic radiation. This may be compensated by using a special refractive index (n_g) which is related to the refractive index of the equivalent or effective monochromatic radiation as follows :

$$n_g = n_G + \sigma \frac{dn}{d\sigma} = n_G - \Lambda \frac{dn}{d\Lambda}$$

where :

Λ = the equivalent or effective wave length of the radiation in microns
σ = the equivalent or effective wave number of the radiation
n_G = the refractive index of pure monochromatic light of wave length Λ or wave number σ.

Thus using the BARRELL and SEARS Formula the following expression gives n_g :

$$(n_g - 1)\, 10^7 = 2876.04 + \frac{3 \times 16.288}{\Lambda\, 2} + \frac{5 \times 0.136}{\Lambda\, 4}$$

The value of n_g thus obtained should be used and not n_G in computing n_L the refractive index in ambient conditions. An amendment aimed at removing the present ambiguity is being incorporated in Resolution No. 1.

It has also been pointed out by J. MITTER [42] that to obtain absolute uniformity the vapour pressure tables used should be standardised. He recommends those based on the formula of A. SPRUNG [44] for this purpose. He states however that all well-known tables are satisfactory in use with the exception of those of JELINEKS [59] and JORDAN - EGGERT - KNEISSL [60] (upon which the tables of the B.I.P.M. are based) and of ALBRECHT [61]. There seems little to be gained therefore by standardisation although defective tables should clearly not be used.

ELECTRO-OPTICAL DISTANCE MEASURING INSTRUMENTS

4. — The Geodimeter

There have been developments to the Model NASM 4 which was described in the 1960 Report. The Model 4D has been produced with a mercury vapour light source which is said to give a much improved range of up to 5 km by day and 40 km by night. This model has been tested by the United States Coast and Geodetic Survey [4, 5] who have found that it gives good results at 5 km in bright sunlight. On 5 triangulation sides and on a precise traverse in Florida it was found to give extremely consistent results which differed from those of a Model 2A Geodimeter by between + 3 to + 5 cm in the case of the triangulation sides which varied in length from 10 km to 24 km, and by less than 3 cm on the precise traverse with legs varying from 8 km to 14 km. The zero correction obtained was however about 5 cm different from that advised by the manufacturers. From these results it would appear to be confirmed that the Geodimeter NASM 4 is suitable for first order work.

5. — Russian SVV 1 E.-O.D.M. Instrument

This is an improved version of the instrument noted in the 1960 report. It is described by V.A. VELICHKO [6]. The light source has been improved and the transmitting and receiving systems have been made symmetrical and (apparently) interchangeable. As a result, range has been increased to 20 km and accuracy improved to 2 ppm. The instrument has been successfully used to check the scale of triangulation and has been tested against a number of Invar measured bases. The results of these tests are included in Appendix I. A standard error of measurement of ± 1.2 cm ± 0.6 ppm is deduced from these. This is comparable to the estimated p.e. of the Geodimeter NASM 2 in the 1960 Report, i.e. ± 1.5 cm ± 0.7 ppm. On the basis of these results it is considered that the suitability of this instrument for first order work is confirmed.

6. — Czech Technical University Instrument

This is an experimental instrument, developed jointly by the Research Institute of Geodesy and the Institute of Radiotechnics in Prague, which has been described by Borivoj DELONG, Bohuslav SOKOLIK and Premek NEUMANN [7]. It operates on a principle very similar to that of the geodimeter, using light waves modulated at 5 Mc/s by means of an oscillator linked to a Kerr cell. An auxiliary signal about 10 Kc/s different is mixed with the outgoing and returning signals to enable phase comparison to take place at low frequency. The range of the experimental instrument is limited to 250 m and the mean error of a single measurement is said to be ± 5 cm ± 5 ppm. It is thus clearly not a first order instrument in its present form. However it is stated that with improved optics its range could be extended to 2 or 3 km.

7. — The Russian GDM Electro-Optical Instrument

This instrument described by Yu. V. Popov, I. I. Adrianova and I. A. Korolev [8] is a small portable version of an earlier experimental instrument which is incorporated with a theodolite so that both distances and angles can be measured together. It is designed for short distances (up to 2.4 km by day) and has relatively low accuracy. It employs diffraction light modulation at ultra sonic frequency. It is evidently not suitable for first order work.

8. — N. P. L. Microwave Mekometer

This is an experimental instrument which has been constructed at the National Physical Laboratory, Teddington, England. It has been described by K. D. Froome and R. H. Bradsell [9]. The instrument works with a light beam polarisation modulated by passage first through a plane polariser and then through an ammonium dihydrogen phosphate (ADP) crystal to which an alternating electric field of frequency 9.4 Gc/s is applied. The effect of an electric field on the ADP crystal is to render it birefringent. Polarisation thus alternates between the plane and the elliptical and the apparatus is so arranged that the signal returning via the distant reflector again passes through the ADP crystal where, depending on the phase difference of the outgoing and returning signals, the elliptical polarisation is either cancelled or enhanced. The amount of elliptical polarisation remaining is measured by means of an analyser enabling the phase relationship to be deduced with great accuracy. The apparatus has the inherent advantage as regards accuracy that the phase comparison of the outgoing and returning light signals is direct. It is not first necessary, as in the case of the geodimeter, to convert one or other of the light signals to an electric signal. There is thus no problem of uncertain electronic delay. The experimental apparatus operates over a 50 m distance and has been found to be sensitive enough to resolve changes of path length of 0.05 mm. At present absolute accuracy is limited by the performance of the 9.4 Gc/s oscillator used, which is only 3 ppm. There would however be no serious difficulty in improving this to better than 0.1 ppm. Used in conjunction with interferometric measurement of distance, now facilitated by the advent of the Laser with its highly coherent beam, the apparatus appears to have the potential capability of determining the speed of light to better than 1 part in 10^7. The development of the Mekometer as an instrument for distance measurement in the field is being studied by Messrs. Hilger and Watts of London.

MICROWAVE DISTANCE MEASURING INSTRUMENTS

9. — Electrotape DM 20

This instrument is produced by the Cubic Corporation of the U.S.A. and is a development of the instrument originally known as Micro-dist (see 1960 Report). The DM 20 is a miniaturised and fully transistorised version of the original instrument and it makes use of a 10 Gc/s (3 cm band) carrier wave. It has a digital read out giving the range in metres based on an assumed refractive index. The carrier wave frequency may be varied from 10-10.5 Gc/s in 8 discrete steps. In trials by the U.S. Army [10] it was used to measure distances from 100 metres to 71 km. (See Appendix I). On lengths from 100 to 500 m it gave mean errors varying from 3 mm to 19 mm. On the Belvoir Taped Base of 1 700 m agreement was 3 mm. For greater lengths (4 900 m to 40 700 m) it was compared with Geodimeter NASM 2 measurements and in one case first order triangulation. The worst difference was 11 ppm on an 8 400 m geodimeter measured length. On the 71 km length measurement was unsuccessful owing to ambiguity. The instrument was less affected by ground reflection than were 10 cm instruments. Electrotape has also been tested by the U.S. Coast and Geodetic Survey [5] on 6 triangulation sides varying in length from 10 km to 24 km. Comparisons with Geodimeter 2A measurements gave agreement varying between 3 ppm and 20 ppm. (See Appendix I).

Tests by the State of Nevada, Department of Highways [43], include comparisons with 10 taped bases (see Appendix I) varying in length from 30 m to 24 km. In general agreement was to 7 ppm or better, the worst being 14 ppm. Some lines, including one of 13 km, proved impossible to measure, presumably as a result of ground reflection, and had to be split into two segments. Lines over water proved difficult to measure when it was windy, possibly because changing reflectivity made the signal unstable. The greatest length measured was 54 km.

The instrument has also been given extensive tests by the Technical University, Hanover [49] in the course of which it was compared with a number of test nets in Germany as well as with certain lines and bases which had been measured by geodimeter, tellurometer and Invar tape. The results of comparisons with geodimeter and Invar tape are included in Appendix I. Of the test net results, only those for the Munich test net are available and here an uncertainty as to the scale of the net prevents very firm conclusions being drawn. It would appear from the results both of earlier tellurometer tests and the Electrotape tests that the scale of the recent (1958) triangulation may be erroneous as the E.D.M. results are consistently greater (by up to 15 ppm). However comparisons with the earlier Bavarian triangulation give agreement ranging from 0 to 6.7 ppm for 11 sides of lengths between 19 km and 58 km. In general the instrument performed satisfactorily and in particular was found to give smaller ground swing than the 10 cm tellurometer.

The results so far reported are insufficient to confirm finally that Electrotape DM 20 is suitable for first order work. Only a few comparisons have been reported, and of these some are outside first order tolerance, but in the absence of fuller details it is impossible to say whether or not this was due to the instrument. In principle there seems no reason why it should not be capable of use for first order work and it is recommended that it be accepted provisionally.

10. — Tellurometer MRA 3

This, the latest version of the tellurometer, operates with a 10 Gc/s (3 cm) carrier frequency in place of the 3 Gc/s (10 cm) frequency used by the earlier MRA 1 and MRA 2 instruments (see 1960 Report). It is fully transistorised and more compact, the antenna being contained within the external fibreglass cover. It is available with either digital read out or a modified cathode ray display, rectilinear in form instead of circular, which can be accurately read with the aid of a parallel cursor. The carrier wave length may be varied from 10 to 10.5 Gc/s. The instrument has been tested in the U.K. on the Ridgeway and Caithness Bases [11] the results being shown in Appendix I. The accuracy seems at least as good as that of the MRA 1 and 2, and the use of the higher carrier frequency seems materially to reduce ground swing. No trouble from this cause was encountered on the Caithness Base which demonstrated excessive ground swing when first measured with the MRA 1 in 1957 (see 1960 Report). The range attainable with the instrument appears comparable with that of the earlier instruments, although possibly slightly less. In some instruments it has been found that the fibreglass cover of the antenna causes error. This is being rectified, but it is suggested that for first order work it is advisable to operate without the cover. No report of any test of attainable range has been received. The results received indicate that the instrument is suitable for first order work and it is recommended that it be accepted provisionally pending confirmation by further results.

11. — Wild Distomat DI 50

This instrument produced by Wild, Heerbrugg in conjunction with Albiswerk, Zurich, works with a carrier wave frequency of 10 Gc/s (3 cm). It has a digital read out, and the following performance claims are made [12] :

Range	100 m to 50 km
Accuracy	2 cm ± between 1 and 10 ppm

The antenna is built as a separate unit from the control unit, being connected to it by a heavy cable which enables the antenna to be placed up to 15 m away from the control unit during operation (e.g. on a mast). No reports of tests have been received and it is not therefore possible to make any recommendation as to its suitability for first order work.

12. — Fairchild Micro-Chain MC-8

This instrument is being developed at the Dumont Laboratories of the Fairchild Instrument Corporation for the U.S. Army. It appears to operate on similar principles to the tellurometer using a variable carrier frequency of 10-10.5 Gc/s. The claimed range is 100 m to 50 km with accuracy to ± 1.5 cm ± 4 ppm. It has a digital read out [30]. No performance figures or further information are available.

RESEARCH INTO E.D.M. ERRORS

13. — Tellurometer Zero Correction

Investigations by a number of authorities indicate that tellurometer zero error varies in a cyclic manner with the 'A' reading, thus :

$$\text{error} = b_0 + b_2 \sin (2\,\alpha)$$

$$\text{where } \alpha = \frac{2\,\pi \times \text{'A' reading}}{100}$$

and b_0 and b_2 are constants.

This suggestion was first made in a report to the I.U.G.G. in 1960 by K. Poder, Chr. J. Lehn and O. Bedsted of the Danish Geodetic Survey. Further investigations by Bedsted and others [13] [14] give the values shown in Table I below for the constants b_0 and b_2 from a number of determinations on lengths varying from 179.82 m to 192.93 m with three instruments in various combinations :

Table I

Date	26-27/4 1960	1-2/6 1960	28/6 1961	28/6 1961	29/6 1961	29/6 1961
Instrument	GI. 2-3	GI. 2-3	GI. 2-3	GI. 2-4	GI. 3-4	GI. 4-3
b_0 cm	— 3.5	— 1.8	— 1.4	— 0.9	+ 1.4	— 0.4
b_2 cm	— 7.6	— 4.9	— 6.2	— 8.0	— 2.0	— 6.7
m.s.e. b_0 cm	± 3.0	± 0.2	± 0.5	± 0.8	± 0.4	± 0.8
m.s.e. b_2 cm	± 1.3	± 0.3	± 0.7	± 1.1	± 0.6	± 1.1

There is stated to be some evidence for an additional term :

$$b_3 \sin \alpha \sin 2\,\alpha$$

The presence of such an error has been confirmed in tests carried out by C. D. Maclellan [15], by the Ordnance Survey of Great Britain [16], by S. Bakkelid of the Survey of Norway [17] [18], by Stig Sundqvist and Ian Brook of Swedish Geographical Survey [19], by H. J. Meckenstock [36] and by the Geodetic Survey of Canada [20]. The British results appear to confirm the presence of the additional term b_3 sin α sin 2 α.

14. — This cyclic zero error therefore seems well established although no firm explanation has yet been given for it. Experiments are being carried out in Denmark to test the theory of K. PODER that it is due to third harmonic distortion of the X and Y amplifiers. It would appear that this type of error has only been observed on the Tellurometer MRA 1 and MRA 2, which is read by means of a circular cathode ray display. It is not known whether any comparable error has been observed in instruments with a linear CRT display or a digital read out. PODER considers the linear display least liable to error [37].

15. — It also appears to be established from the investigations of BAKKELID [17], PODER [37] and MECKENSTOCK [36] that the zero error varies with carrier frequency, apparent transit time usually increasing with increasing frequency. PODER has suggested the term " instrument swing " for this phenomenon which he states arises as a result of the mixing process. The error is eliminated if (as he strongly recommends) the same range of carrier frequencies is used for calibration and for all measurements. BAKKELID suggests that signal strength may also affect zero error, and this perhaps should be investigated.

16. — M.D.M. Ground Reflection Effects

The problem of ground reflection, known also as " ground swing " or " multipath " has received much study. Theoretically ground reflection from land surfaces must be reduced by the adoption of a shorter carrier wave since reflection ceases to be specular if surface irregularities exceed about

$8\lambda \sin g$ where : λ = carrier wave length
g = angle of incidence

Experience with 3 cm instruments such as Electrotape DM 20 and Tellurometer MRA 3 confirms that swing is generally reduced to about 1/3rd of that experienced with 10 cm instruments. The use of a higher frequency also makes a narrower beam possible, thus cutting out reflection altogether on rays which are sufficiently elevated.

17. — It appears to be confirmed by experience of the Ordnance Survey of Great Britain [21] and elsewhere that screening or lowering the instrument to the ground will reduce apparent ground swing when it is excessive, although usually with some loss of signal strength. It is however debatable whether such screening will necessarily improve accuracy. Its effect is probably to produce a complex series of paths due to diffraction and multiple reflection and it is possible that readings which should be taken into account in the mean are eliminated owing to low signal strength. (See paragraph 20). If screening leads to serious loss of signal strength the resulting values must be treated with caution. Investigations by SUNDQVIST and BROOK of the Swedish Geographical Survey [19] indicate that where the cyclic pattern of the swing graph is not clear it is inadvisable

to attempt to restrict the accepted readings to a complete cycle of swing if the amplitude is less than 4 m μ s, but to accept the arithmetic mean of the whole range. This may well be so, particularly on long lines when variations due to varying refractive index are likely to have a marked effect on the "swing graph". The recommendation of the 1960 Report evidently needs slight modification in these respects.

18. — The most significant work on ground swing is that by Knud PODER and others, of the Danish Geodetic Survey, which was described in a paper at the Tellurometer Symposium in London in 1962 [22]. Measurements of certain lines by the Ordnance Survey of Great Britain provide good confirmation of PODER's theories [16]. The theory deals with lines measured over simple highly reflective surfaces such as calm sea and shows that, when the reflection coefficient is high and the excess path length appreciable, the swing curve takes a characteristic shape having flat portions alternating with pronounced negative double peaks. The amplitude of the curve depends mainly on the reflection coefficient and its period on the excess path length. In these conditions the arithmetic mean does not give the best value for the line which should be obtained by computing (or selecting) the theoretical curve appropriate to the conditions, and fitting it as closely as possible at the "flat" portion. The position on the actual swing curve of the "zero" value of the theoretical curve then indicates the best value of the transit time. R. C. GARDINER-HILL [46] has derived an expression which gives the distance of the maximum (or flat portion) of the curve above the theoretically correct value for any line, depending on the heights of the terminals and the length. He has tabulated these corrections and produced graphs which may be used for their quick determination. The formulae used to derive the theoretical curve are as follows :

$$\text{Total swing } X = X_M + X_R$$

$$\tan X_M = \frac{a_T \sin \Omega_R Q \, [\cos (\omega_R Q - \pi) + a_T]}{1 + (1 + \cos \Omega_R Q) a_T \cos (\omega_R Q - \pi) + a_T \cos \Omega_R Q}$$

$$\tan X_R = \frac{a_T \sin \Omega_M Q \, [\cos (\omega_M Q - \pi) + a_T]}{1 + (1 + \cos \Omega_M Q) a_T \cos (\omega_M Q - \pi) + a_T \cos \Omega_M Q}$$

where :

X_M = angular phase shift at Master;
X_R = angular phase shift at Remote;
Ω_M = $2\pi \times$ Modulation frequency of Master;
Ω_R = $2\pi \times$ Modulation frequency of Remote;
Q = excess transit time in secs;
ω_M = $2\pi \times$ carrier frequency of Master;
ω_R = $2\pi \times$ carrier frequency of Remote;
a_T = Reflection coefficient.

The reflection coefficient is derived from the geometry of the reflected path (assuming simple reflection at a single point) and the nature of the reflecting surface. For calm sea the following approximate formulae based on an assumed refractive index gradient are used :

$$10^3 \tan g = \frac{(H_1 - C_1) + (H_2 - C_2)}{S} \quad \text{(grazing angle of reflected ray)}$$

$$C_1 = \left(\frac{S_1}{4}\right)^2 \qquad C_2 = \left(\frac{S_2}{4}\right)^2 \quad \text{(curvature corrections to point of reflection)}$$

$$Q = \frac{\delta l}{C_0} \qquad (C_0 = 3 \times 10^8 \text{ m/s})$$

$$\delta l = \frac{2\,(H_1 - C_1)\,(H_2 - C_2)\;10^{-3}}{S} \text{ metres}$$

$$S_1 = \frac{H_1 - C_1}{10^3 \tan g} \qquad S_2 = \frac{H_2 - C_2}{10^3 \tan g} \quad \text{(distances to reflection point)}$$

$$D = \left[1 + \frac{0.247\; S_1\; S_2}{(H_1 - C_1) + (H_2 - C_2)}\right]^{-\frac{1}{2}} \quad \text{(divergence factor)}$$

$$a'_T = 1 - 0.0075 \times 10^3 \tan g \qquad \text{(for calm sea)}$$

$$a_T = a'_T \times D$$

H_1 and H_2 are the heights of the terminals above the reflecting surface, in metres. S is the distance in km. The formula for a'_T is an empirical and approximate one due to R. C. GARDINER-HILL [16] which appears to be accurate enough for practical purposes. The rigorous formula given in PODER is complex.

19. — Applied on lines measured by the Ordnance Survey over the sea, the theory generally produced better agreement with triangulation (corrected for known scale error), in some cases remarkably so, for example in the 29 km line from Carleton Fell to Inshanks where the agreement was improved from 21 ppm to 5 ppm. In one case on a 30 km line the result was made worse (9 ppm to 15 ppm), but in this case the shape of the swing graph was not characteristic and it would appear that the reflection coefficient was not typical for water.

20. — It is emphasised that the method can only be applied for lines singly reflected from simple surfaces such as calm water or smooth level ice or snow. Multiple reflection or reflection from uneven surfaces even if it is strong is too complex for analysis. In such cases it is best to take the arithmetic mean. If reflection is not characteristic the swing graph will show this and provide the necessary warning. The fact that this method is available should not encourage the acceptance of lines with excessive swing. Measurements with normal swing should always be more accurate. However the method does make it possible to measure with good accuracy lines over water which might otherwise be immeasurable. PODER's investigations show that when ground swing is large, error will probably result if the arithmetic mean is used, widely deviating readings being discarded. In effect this is to use only the "flat" portion of the swing

curve and will in general give too high a value. Screening may produce the same effect through a general lowering of signal strength, leading to elimination of deviating readings. Similarly it is bad to select for use only those frequencies which give small swing. If reflection is simple and the swing curve appears to conform to PODER's characteristic pattern it would appear advisable to make at least some measurements with the instruments unscreened, even if swing can be reduced by screening.

21. — The investigations have also demonstrated that where the excess path length is negligible but reflection coefficient close to unity, for example over smooth ice, the reflected signal has opposite phase but almost equal strength to the direct signal which is thus cancelled. This condition is probably the explanation of the loss of signal which has sometimes been observed over such surfaces at quite short range.

22. — **Refractive Index Errors**

A number of investigations into refractive index errors have taken place. BAKKELID of the Geographical Survey of Norway has made a study of temperature anomalies [17] of which he distinguishes three :

$\Delta_1 T$: due to radiation to and from the ground at the terminals;
$\Delta_2 T$: "the peak anomaly" due to wind lifting an air mass up a mountain side and causing its temperature to be adiabatically depressed below that of neighbouring air at the same level;
$\Delta_3 T$: due to thermal convection.

$\Delta_1 T$ can be calculated from the measured temperature gradient at the terminals. It is negative during the day, positive during the night, and zero at some time in the morning and afternoon when the ground temperature is equal to that of the free atmosphere at the same level.

It appears that $\Delta_2 T$ and $\Delta_3 T$ are not generally determinable and that observations should therefore be taken when they are negligible. For $\Delta_2 T = 0$ the weather should be warm with strong convection currents. $\Delta_3 T = 0$ occurs when the air near the ground is cool, that is at night and in the morning and evening.

It is thus impossible to obtain conditions when both $\Delta_2 T$ and $\Delta_3 T$ will simultaneously be zero in mountainous country. In flatter country both anomalies however will be small. $\Delta_1 T$ can be eliminated by either :

a) Measurement of lapse rate and calculation;
b) Observing by day and night and taking a weighted mean;
c) By observing when the temperature gradient near the ground is zero.

BAKKELID does not suggest which is the best course.

23. — In the course of a number of measurements of a 42 km line with terminals at 348 m and 665 m elevation, partial confirmation of the theory was obtained. Inversion occurred at the terminals in the morning and

evening. This resulted in a tendency to measure short. When the difference of the air temperature at the terminals departed markedly from the normal, measures tended to be unreliable. At mid-day measures appeared to be most consistent. Theoretical corrections for $\Delta_1 T$ were computed and applied. They reduced the spread of results slightly but not very noticeably.

24. — Bakkelid also describes experiments in which two 40 km lengths were measured hourly for 24 hours. Terminal heights were 255 m and 327 m for one line and 1666 m and 1545 m for the other. It is clear that terminal measurements fail to correct fully for meteorological variations. The measured transit time reduced to common temperature, pressure and humidity at the terminals, in both cases varies through about 7 ppm during 24 hours. Bakkelid's theories appear to account for some but by no means all of the anomalies noted. For the line at lower altitude it appears that measurements between about 1900 hrs. and 0700 hrs. were the most reliable, but for the higher line no favourable period is discernible.

25. — M. V. Ratynskiy in a review of work carried out for the most part in Russia [35] stresses the great effect that meteorological and topographical conditions have on attainable accuracy. The refractive index of the air is markedly affected by the nature of the underlying surface, especially when the atmosphere is clear and still. There are therefore added difficulties in obtaining representative measurements at the terminals when the line passes over varying terrain. He recapitulates the difficulty of getting representative measures, especially of temperature when the ground at the terminals is considerably elevated, and suggests that it is best to observe soon after sunrise and sunset when the temperature gradient near the surface reverses in sign. He also recommends distributing observations between day and night. The errors due to humidity are, he suggests, minimised in arid regions by observing late at night or in early morning; in mountainous regions 75 % of observations should be taken at night and 25 % in daytime. Ratynskiy also stresses the importance of accuracy in instrumental readings and of ensuring that sufficient temperature readings are taken to eliminate the effects of short-term changes which are often considerable. He gives a table (reproduced as Table II below) of estimated refractive index errors in "average" as well as in "favourable" and "unfavourable" conditions. He defines "average" conditions as being average in the meteorological and topographical sense, with no special precautions for achieving accuracy. "Favourable" and "unfavourable" are correspondingly defined, all recommended precautions being taken in the case of "Favourable conditions and work methods". The term "error" is not exactly defined but is stated to be that which will occur " for the most part ". It would appear therefore roughly equivalent to a mean square error (m.s.e.).

26. — Poder [37] also stresses the importance of accuracy of instruments and of calibration, pointing out that inaccurate calibration, especially of

TABLE II

Meteorological elements	Unfavourable conditions			Average conditions			Favourable conditions and work methods		
	Error in determination of mean values of the meteorological elements	Corresponding relative error in determination of index of refraction (and distance)		Error in determination of mean values of the meteorological elements	Corresponding relative error in determination of index of refraction (and distance)		Error in determination of mean values of the meteorological elements	Corresponding relative error in determination of index of refraction (and distance)	
		for light range	for radio range		for light range	for radio range		for light range	for radio range
Temperature	± 2°,0	± 2,0 $\cdot 10^{-6}$	± 2,6$\cdot 10^{-6}$	± 0°,7	± 0,7$\cdot 10^{-6}$	± 0,9$\cdot 10^{-3}$	± 0°,2	± 0,20$\cdot 10^{-6}$	± 0,26$\cdot 10^{-6}$
Pressure	± 1 ,0 mm Hg	± 0,4 $\cdot 10^{-6}$	± 0,4$\cdot 10^{-6}$	± 0 ,5 mm Hg	± 0,2$\cdot 10^{-6}$	± 0,2$\cdot 10^{-6}$	± 0 ,1 mm Hg	± 0,04$\cdot 10^{-6}$	± 0,04$\cdot 10^{-6}$
Pressure of water vapour	± 1 ,5 mm Hg	± 0,08$\cdot 10^{-6}$	± 8,7$\cdot 10^{-6}$	± 0 ,8 mm Hg	± 0,04$\cdot 10^{-6}$	± 4,6$\cdot 10^{-6}$	± 0 ,3 mm Hg	± 0,02$\cdot 10^{-6}$	± 1,7$\cdot 10^{-6}$
Total relative error in determination of index of refraction (and distance)		± 2,0 $\cdot 10^{-6}$ (1/500 000)	± 9,1$\cdot 10^{-6}$ (1/110 000)		± 0,7$\cdot 10^{-6}$ (1/1 400 000)	± 4,7$\cdot 10^{-6}$ (1/210 000)		± 0,20$\cdot 10^{-6}$ (1/5 000 000)	± 1,7$\cdot 10^{-6}$ (1/600 000)

thermometers, may introduce appreciable systematic error. He estimates the accidental component of refractive index error of a tellurometer measurement as ± 2 to 3 ppm (m.s.e.), citing the case of Denmark where for 800 measurements of 125 sides it was ± 2.2 ppm. He considers that there is also a systematic component due to the fact that the negative refractive index gradient is much steeper in the first 15 m (approx.) above the ground than above this height. Thus measurements at terminals tend to give too high a value of refractive index. The effect is similar both during the day and at night when temperature inversion is normally present. He roughly estimates this error, on the basis of work by BEST [47], as + 2 ppm and finds confirmation in the fact that the comparison of E.D.M. and triangulation in Denmark reveals a systematic discrepancy of this order. He suggests that a method of dealing with this would be to adopt a " geodetic " value for C_0 of 299 793.1 km/s instead of the *in vacuo* figure of 299 792.5 km/s.

MECKENSTOCK [36], basing his conclusions on the work of BEST [47] and FRANKENBERGER [48], also considers for similar reasons that there is the strong likelihood of a systematic tendency to measure short with the geodimeter unless special measures are taken, citing in support of this view the geodimeter measurements reported to SSG 19 in 1960 [1] which indicate that the adopted light velocity is too low by 0.2 km/s. He considers that the likelihood of such a systematic error when using microwaves is much less owing to the fact that measurement is normally made in the middle of the day when the refractive index gradient is smallest and when its variations are random in nature. The tellurometer measurements of the 1960 Report certainly do not suggest that a higher value for C_0 is required, in fact the reverse.

It would appear therefore that at present there is insufficient evidence to justify the adoption of a slightly higher "geodetic" value for C_0, although it may well be that geodimeter measurements based on the accepted value will tend to be slightly short if ground level terminal measurements of refractive index are relied on.

27. — To sum up, these investigations, and others in France [30] and Germany [36] [40], in general confirm the conclusions of the 1960 Report, and make apparent the difficulties and uncertainties (in any but flat and uniform terrain) of attempting to determine corrections to terminal refractive index measurements on the basis of an atmospheric model inferred either theoretically or from limited measurements of lapse rates, etc. It is best to make measurements in conditions, both topographical and meteorological, which are as good as possible. In particular, overcast windy weather is preferable. Meteorological measurements should if possible be taken some metres clear of the ground so as to minimise the effect of local surface anomaly. If conditions are unavoidably poor their effect should be minimised by repeating measurement on different days and times of the day and night. The recommendation of the 1960 Report is confirmed that it is more important to choose suitable observing weather

than to attempt to choose a favourable time of the day. RATYNSKIY has suggested that observations should be made soon after sunrise and sunset (para. 25 above) but at these times the atmosphere is often very still and markedly stratified. Such conditions are in general less favourable than when there is a good breeze and a well mixed lower atmosphere.

28. — The need for accurate instruments — especially wet and dry bulb thermometers — and accurate calibration of them, as well as accurate observation, is emphasised. The use of microwave refractometers has been suggested [23] [36] and may be convenient in some circumstances, but the accuracy of about ± 3 ppm reported appears insufficient for first order work.

29. — There have been various suggestions for directly obtaining the total refractivity of a line from measurements made at its terminals. These include measurement of the atmospheric reflection coefficient [41] in order to determine the gradient of the refractive index along the ray path, the use of sound waves in conjunction with electromagnetic waves for a similar purpose and simultaneous measurement on a number of frequencies chosen in relation to the absorption bands of the various atmospheric constituents in order to enable their contributions to the total refractivity to be separately assessed. Though no doubt theoretically possible it would appear that such methods present great practical problems and are a long way from realisation.

30. — **Wave Path — Geodetic and Atmospheric Corrections**

Since the refractive index varies with height the path of an electromagnetic wave through the atmosphere is normally curved. If the mean of the terminal values of the refractive index is adopted for a line it is necessary to apply geometric corrections to reduce to horizontal and spheroid level and also two further corrections :

a) A correction (K_g) to reduce from measured arc length along the ray path to spheroid arc length;

b) A correction (K_v) arising from the fact that since the curvature of the earth is normally much greater than that of the ray path, the latter dips into atmosphere with a refractive index in general greater than the terminal mean.

J. SAASTAMOINEN [24] [25] derives the following values for these corrections :

$$K_g = \frac{1 - k^2}{24\,R^2}\,S^3$$

$$K_v = \frac{k\,(1 - k)}{12\,R^2}\,S^3$$

$$K = K_g + K_v = \frac{(1 - k)^2}{24\,R^2}\,S^3$$

where :

R = the radius of curvature of the earth;

ρ = the radius of curvature of the path;

k = the coefficient of refraction $= \dfrac{R}{\rho}$ (assumed constant for any line);

S = the measured distance.

S. Bakkelid [17] derives similar formulae, but from evidence of measured lapse rates concludes that for M.D.M. serious error does not result if the value $\rho = 4\,R$ is accepted in calculating k (i.e. $k = 0.25$). Saastamoinen suggests that this may not be so, but it is normally extremely difficult to measure k for microwaves, and since the resulting errors are probably no greater than those of assuming that k is constant along the line, the adoption of a value of $k = 0.25$ seems reasonable. This gives :

$$K = \frac{S^3}{43\ R^2}$$

This correction is also given by the common practice of treating the ray path as straight and assuming an earth radius of $\dfrac{4R}{3}$, i.e.

$$K = \frac{S^3}{24\left(\dfrac{4R}{3}\right)^2} = \frac{S^3}{43\ R^2}$$

Note however that if terminal means are not used, but instead the mean of several refractive index measurements along the ray path, the need for correction K_v is eliminated and :

$$K = K_g = \frac{1 - k^2}{24\ R^2}\ S^3$$

$$= \frac{S^3}{25.6\ R^2} \qquad \text{when } k = 0.25$$

A more rigorous formula for reducing M.D.M. measurements has been derived by Poder, Lehn and Andersen [13] from an atmospheric model suggested by Hotine, but it would appear that the simpler approximate formulae are adequate for normal purposes.

For E.-O. D. M. it is possible to derive k from theodolite vertical angle measurements if the heights of the terminals are accurately known. Saastamoinen [25] recommends this course but it appears that the present distance limitations of E-O.D.M. render the path curvature correction unimportant, certainly in relation to errors arising from other causes such as those due to local temperature anomalies.

31. — **Modulation Frequency Error**

Since an error in the assumed frequency of modulation for any E.D.M. instrument produces a proportionate error in the distance, frequency during measurement must be accurately known. Modulation frequency is normally controlled by a thermostatically heated crystal. Gerke [45] and others have shown that in ordinary conditions the frequency should remain constant to within 1 ppm for a long time. However there is undoubtedly a tendency for frequency to drift slightly over a period of months — possibly owing to variations in heater and thermostat operation. Moreover a number of organisations have noted sudden marked changes of frequency which may quite readily result from knocks or bumps, from damage to the temperature control system, or from mishandling of the equipment. It therefore is most advisable to check modulation frequency at close intervals before, during and after periods of field operation. PODER suggests [37] about once every week or fortnight. For this purpose when the instrument is used in areas where laboratory testing facilities are not at hand it appears advisable to make use of field calibration equipment. No equipment appears to be marketed specifically for this purpose, but a number of users have devised their own equipment, for example the Royal Danish Geodetic Institute [26]. This equipment has an accuracy of 1 to 3 parts in 10^7 — an accuracy which is limited by the phase stability of the received wireless signal used for calibration. This of course is affected by atmospheric conditions. Using their equipment, results reported reveal short term changes of Tellurometer MRA 1 frequencies of 25 c/s or 2.5 ppm.

32. — **Freak Lines**

A number of authorities have reported the occasional occurrence of "freak" lines which give inexplicably large errors when measured with M. D. M. equipment. Such instances are probably the result of some peculiarity of microwave propagation on the line in question. The possibility of their occurrence emphasises the importance of not relying on single M.D.M. measured lengths to control scale. (See paragraph 47 (a) of 1960 Report).

33. — **Estimates of Errors**

PODER [37] and RATYNSKIY [35] have made estimates of some of the errors inherent in E.D.M. In Table III below these estimates are compared with those of a single measurement given in the 1960 Report of SSG 19. The latter were given as probable errors but have been approximately converted to m.s.e.'s, for the purpose of comparison, by multiplying by 1.5.

From this Table it might seem that the 1960 Report is slightly pessimistic, but the results of reported comparison with taped measurements etc. do not support this (see Appendix I). A number of recently reported results in fact fall well outside the estimate. It is recommended therefore that the 1960 estimates be retained. These are restated below as standard (or mean square) errors as follows (for a full determination of distance in accordance with recommendation) :

Geodimeter NASM 1	± 4.5 cm ± 1 ppm
Geodimeter NASM 2	± 2.2 cm ± 1 ppm
Tellurometer MRA 1 and 2	± 3.0 cm ± 3 ppm

TABLE III

Error	SSG 19 Report 1960 (converted to m.s.e.)		Poder	Ratynskiy Average conditions	
	E-O.D.M. (NASM 2)	M.D.M.	M.D.M.	E-O.D.M.	M.D.M.
Instrumental error (including zero error, phase display error and " instrument swing ")	± 2.1 cm	± 1.8 cm	± 2.1 cm	not stated	
Refractive Index error due to :					
Temperature	± 0.7 ppm	± 1.2 ppm	not stated	± 0.7 ppm	± 0.9 ppm
Atmospheric pressure	± 0.3 ppm	± 0.4 ppm	not stated	± 0.2 ppm	± 0.2 ppm
Humidity	nil	± 6.0 ppm	not stated	± 0	± 4.6 ppm
Total refractive index error	± 1.0 ppm	± 6.1 ppm	+ 2 ± 2.2 ppm	± 0.7 ppm	± 4.7 ppm
Ground swing error	—	± 4.6 ppm	not stated	—	not stated

GENERAL E.D.M. RESEARCH

34. — Optimum Wavelength M.D.M. Instruments

Four M.D.M. instruments now employ a 10 Gc/s (3 cm) carrier wave, Electrotape DM 20, Tellurometer MRA 3, Wild Distomat DI 50 and Fairchild Micro-Chain MC-8. Present indications are that for first order work, on balance, the higher frequency provides advantage because of reduced ground reflection. Range however is somewhat reduced and cloud penetration is said to be poor. The higher the frequency the lower the klystron efficiency, but this has been compensated in the present instruments by the use of transistors instead of valves and by a slight narrowing of the beam. The adoption of even higher frequencies (of the order of 1 cm) might be advantageous. The beam angle could be reduced to about 1 degree which would prevent an excessive power requirement and virtually eliminate ground reflection. However difficulties of alignment in poor visibility might result which would handicap lower order work. The advent of an instrument of this type would be a most interesting development.

35. — Masers and Lasers

Maser (Microwave Amplification by Stimulated Emission of Radiation) action depends upon the fact that if certain substances, solid, liquid, or gaseous, are energised in a suitable manner by irradiation or by an electric discharge, the distribution of their active components (atoms, ions or molecules) among the various allowed energy levels may be inverted from the normal state, causing the system to become unstable. In these conditions, if a radiation is applied at the frequency of transition between two energy levels, whose particle populations have been inverted by this disturbance, it will stimulate the substance to emit radiation at this same frequency but with considerable amplification. By this loss of energy the substance tends to return to a stable state [28]. In the case of the Maser the amplified signal is of microwave frequency. In the case of the Laser (Light Amplification by Stimulated Emission of Radiation) it is a light signal, but the general principle of operation is the same.

Because its frequency must be precisely that of the transition between two energy levels, a Maser or Laser emission is of a very narrow band width. By suitably shaping the substance used (e.g. ruby crystal), or its container in the case of a gas, it acts as a resonator causing the emission to build up into a coherent and (in the case of the Laser) narrow, concentrated and highly directional beam (beam angle $< 0^{\circ}.1$). These characteristics offer possibilities for E.D.M. In clear weather the very concentrated beam of the Laser could be detected and used for distance measurement at considerable ranges (of the order of 40 km) even in daylight. Its high degree of coherence allows the use of very high modulation frequencies, and also raises the possibility of using Laser light for measurement by direct interferometric methods of much greater lengths than is possible with ordinary filtered light. The beam can be focussed to a fine point, split or deflected by means of a prism, without dispersion. It is thus possible to produce a concentrated double beam diverging at an accurately known angle and to use this to measure distances by a modified subtense method, the stadia intercept being read directly by observing the points on the stadia scale at which the twin beams impinge [29]. The accuracy of such observation would decrease much more slowly with increased distance than would that of optical observation of the subtense angle.

36. — At present no E.D.M. apparatus based on the Maser or Laser has been reported but the intense study being given to the subject appears to ensure that such devices will make their appearance in the near future.

37. — **Measurement of Long Lines**

Since 1960 the Tellurometer (MRA 1 and MRA 2) has been successfully used for the measurement of lines of the order of 100 km. For such lines the use of a large (48″) reflector is advantageous. The Ordnance Survey of Great Britain obtained a difference (Tell.-Trig.) of 1 ppm from first order triangulation for a line of 103 km over the sea [34]. The scale of the triangulation may be in error by about + 3 to + 5 ppm. On such long lines the excess signal path length is normally negligible and ground reflection therefore does not affect the measurement. However the determination of refractive index presents unusual problems. The Ordnance Survey made use of a ship near the point of minimum clearance to take additional meteorological observations about 10 m above the sea surface. The line clearance was about 43 m. The influence of these on the result was insignificant and it seems questionable whether such observations are worth while for a homogeneous line over the sea, particularly if terminal observations can be made at a sufficient height above the ground (e.g. on 30 m towers) to ensure that they are free of local anomaly. For a long non-homogeneous line over land, or if the meteorological conditions at the terminals are likely to be anomalous, central measurements are probably worth while, a lapse rate correction for temperature and barometric pressure being applied to reduce the measurements to signal path height. Water vapour pressure may be accepted as observed. Further research in this field would be valuable.

38. — A line-crossing technique has been successfully used by the Royal Danish Geodetic Survey for measuring a line of about 70 km across water [27]. Two Tellurometer MRA 1 master sets were operated on fixed frequencies from the bridge of a ship; remotes were on land. The line-crossing measurement, a mean of 7 crossings, differed from the mean of 12 direct measurements by — 18 cm.

39. — **Practical Considerations — Frequency Allocation**

In certain highly developed countries clearance for the use of M.D.M. instruments has produced difficulty. This particularly applied to instruments operating in the 10 cm and longer wave bands. Instruments such as the tellurometer and Electrotape require to operate over a disproportionately wide band owing to the need to vary carrier frequency to eliminate the effects of ground reflection. The international authority for allocation of frequency bands is the International Telecommunications Union (I.T.U.). National authorities allocate frequencies within their own countries in general conformity with the allocations of the I.T.U. The frequency bands at present used for M.D.M. purposes and the other main users of these bands at present are shown below. (Details of I.T.U. allocations in these bands are given in Appendix IV) (*).

	Frequency Band	*Other Uses*
Tellurometer Aero Dist	1.2-1.4 Gc/s	Aero Radio Navigation and Radio Location
Tellurometer MRA 1 and 2	2.8-3.2 Gc/s	
Tellurometer MRA 3	10.0-10.5 Gc/s	Radio Location (Primary) Amateurs (Secondary)
Electrotape DM 20		
Wild Distomat DI 50		
Fairchild Micro-Chain MC-8		

(*) *IHB Note.* — This appendix is not reprinted in the present volume.

In certain countries there are definite objections to the use of aerial navigation frequencies for M.D.M. purposes since in such cases safety to life is a consideration.

40. — This problem cannot yet be described as serious, but it would seem inevitable that as the use of M.D.M. becomes more widespread and other microwave users more numerous it will be aggravated. It therefore appears advisable to take steps towards securing international allocation of suitable frequencies specifically for the use of M.D.M. equipment.

41. — This question was discussed at the Tellurometer Symposium held in London on 30th July - 3rd August 1962, and as a result a resolution was passed (Appendix III) (*). It is recommended that the I.A.G. take note of this and request the I.U.G.G. to take the matter up with the I.T.U. It is believed that such action is necessary if hampering restrictions upon the use of M.D.M. and upon the development of new equipment in the future are to be avoided.

CONCLUSIONS AND RECOMMENDATIONS

42. — The following is a summary of the conclusions and recommendations that are either new or which modify the conclusions of the 1960 Report, paragraphs 44 to 50. Otherwise the latter are confirmed.

43. — The following additional instruments are acceptable for first order work :

a) *E-O.D.M. Instruments*

Geodimeter NASM 4	(paragraph 4)	
Russian SVV 1	(paragraph 5)	

b) *M.D.M. Instruments*

Electrotape DM 20	(provisionally)	(paragraph 9)
Tellurometer MRA 3	(provisionally)	(paragraph 10)

44. — **Range**

The maximum range at which accurate measurements can be made with 3 Gc/s instruments such as the Tellurometer MRA 1 and 2 now appears to be about 100-110 km. It is not however recommended that measurements at such distances be accepted unless special precautions are taken to obtain an accurately representative value of refractive index (paragraph 37).

(*) *IHB Note.* — This appendix is not reprinted in the present volume.

45. — Ground Reflection

a) It is recommended that PODER's method (paragraphs 18 to 20) of correcting for ground swing be adopted when conditions indicate that this is appropriate, i.e. for measurements with large excess path length over highly reflective surfaces and when the form of the ground swing graph is characteristic. Otherwise the arithmetic mean should be employed.

b) Screening or lowering the instrument to the ground to reduce ground swing should be adopted only with caution (paragraph 20).

c) The same range of cavity settings should be used for all work, including calibration (paragraph 15) and no attempt should be made to discard incomplete cycles of ground swing unless the amplitude exceeds 4 m μs and the cyclic pattern is clearly marked (paragraph 17).

46. — Zero Error

It is recommended that for the Tellurometer MRA 1 and 2 zero error should be calculated on the assumption that its behaviour is cyclic (paragraphs 13 and 14). Further investigation of zero is required for instruments of other types.

47. — Path and Earth Curvature Corrections

It is recommended that the principles of correction indicated in paragraph 30 be adopted.

48. — Frequency Control

It is recommended that suitable field equipment be developed and used to control modulation frequency when E.D.M. equipment is used in areas where laboratory calibration equipment is not readily accessible (paragraph 31).

49. — Future Research

It is recommended that research into E.D.M. be energetically continued especially in the following fields :

a) Use of carrier frequencies of the order of 36 Gc/s (paragraph 34)

b) Application of Laser to E.D.M. (paragraph 35)

c) Measurement of refractive index in various conditions (paragraphs 22-29)

d) Ground reflection (paragraphs 16-21)

e) Zero error (paragraphs 13-15).

50. — Frequency Allocation

It is recommended that the I.A.G. approach the I.T.U. through the I.U.G.G. with a view to the allocation of frequencies for E.D.M. purposes in accordance with Resolution No. 1 of the Tellurometer Symposium (Appendix III).

PART II

AIR AND SPACE SYSTEMS

by P. H. KENNEY

INTRODUCTION

1. — At the I.U.G.G. General Assembly in Helsinki in 1960, SSG 19 reported on the various ground based electromagnetic distance measuring instruments of geodetic significance then available.

Up to that time airborne instruments had been excluded from the terms of reference of the Study Group, but at the Helsinki meeting it was agreed to widen the terms of reference to cover new developments in these systems. In the three years since the Helsinki meeting there have been not only developments of airborne systems but also proposals for systems used in conjunction with artificial satellites. This report therefore covers developments in both airborne and satellite-borne systems.

AIRBORNE SYSTEMS

General

2. — All airborne systems of distance measurement operate by timing the transmission of signals between an aircraft and stations upon the ground. The transmitter is normally (but not necessarily) in the aircraft and the ground stations are normally transponder beacons. Airborne systems have the obvious advantage over ground based systems that they can operate on a " line of sight " basis at much greater ranges (of the order of 500 km or more), but they suffer from inherent inaccuracy due first of all to uncertainty as to the mean refractive index along the asymmetric signal path, one end of which may be at 6 000 m and the other near sea level; and secondly to the difficulty of operating from a fast moving platform from which, amongst other things, it is extremely difficult to obtain accurate observations of ambient meteorological conditions.

3. — Distance measurements using airborne systems are also inherently difficult to combine with angular measurements because they are only geodetically accurate when made between points which are too far apart to be intervisible. Azimuth is thus difficult to determine accurately. Some promising experiments have however been carried out in which azimuth has been obtained by simultaneous theodolite observation from both ends of a long line on to a flare target towed across it by a high flying aircraft. The correct azimuth of the line is indicated when the azimuths from each end (after allowing for convergence) are supplementary. Alternatively the flare or high intensity strobe lamp may be photographed against the star background, from each end of the line, and the azimuth obtained analytically [50].

Systems hitherto in Use

4. — Airborne systems have their origin in wartime bombing and navigational devices. The British systems OBOE and GEE H were the first to be adapted for mapping purposes although they were never put to strictly geodetic use. The U.S. system Shoran was the first to be used purely for distance measurement by the well known line-crossing technique. With various refinements this system has been used to make trilateration connections in a number of areas where ordinary triangulation is impossible, for example between the North American continent and Europe, via Greenland, Iceland and the Faeroes. It has also been used as a temporary substitute for a basic triangulation framework in certain continental areas, e.g. Canada, to enable 1/250 000 scale mapping to proceed without waiting for first order triangulation to be completed. The most advanced form of the system is known as Hiran. In this the transmitter is carried in the aircraft and it interrogates transponder beacons located on the ground. It operates at a frequency of between 300 and 400 Mc/s, using a pulsed signal. A system of " gain riding " or automatic compensation for varying signal strengths is incorporated. The system however can only achieve an accuracy at maximum range about 20 ppm or thereabouts (this accuracy falling off as range decreases). It is thus not strictly up to first order standards.

Shiran [50] [55]

5. — The USAF, in conjunction with industry, have laid down specifications for a more accurate system to replace Hiran. Work is now proceeding on the development of a frequency modulated continuous wave (f.m.c.w.) system, working between 3.0 and 3.5 Gc/s in which the transmitter operates at 3.312 Gc/s and the transponder at 3.087 Gc/s. The object is to obtain the distance between the aircraft, which carries the master station, and the ground station, with a standard deviation of 4 m. It is planned to transmit to up to four ground stations which may be at distances of 40

and 1 000 km from the aircraft. In addition to the airborne distance measuring equipment, it is intended to carry an electronic computer in the aircraft, the object of which will be to compute preliminary results and thus to check the performance of the system in the air. This system is in the manufacturing stage and it is unlikely that results will be available before 1964.

Aerodist [51] [52]

6. — Aerodist has been developed by the Tellurometer Company and is based in principle upon the tellurometer system. It consists of an airborne master instrument which interrogates two or three remote stations. In operation it produces a continuous measurement of the distance between the master and any remote station. In its simpler mode (two channel) it may be used for measuring the distance between two remote ground stations by the normal line-crossing technique. In the three channel mode the system may be used for fixing the position of a third remote station with respect to the known positions of the first two remote stations.

7. — Aerodist is designed to work up to a maximum ground-to-air distance of 300 km, though it may be used at much shorter ranges. It works at frequencies between 1.20 and 1.47 Gc/s, modulated at about 1.5 Mc/s. Its proposed accuracy is 1 m ± 1/100 000, for any air/ground distance. This accuracy would be geodetically useful when the instrument is used at ranges approaching the maximum. Over short ranges the errors would scarcely be acceptable. To achieve this accuracy it may prove necessary to make meteorological observations at different heights between the ground and flying station. Also, further investigation is necessary into taking truly representative meteorological observations in the aircraft.

8. — Another problem is that of aligning the remote station on the master. The full range will only be achieved if this alignment is accurate within 15° (beamwidth 30°). Otherwise signal strength may be too weak for measurement, though speech may still be possible.

9. — The problem of ground reflection arises with Aerodist as with the tellurometer, and is to some extent accentuated by the fact that with a moving master station the technique of varying the carrier wavelength to eliminate ground swing becomes inapplicable. It appears that instead line crossings will have to be made at different points in order to vary reflection conditions. The problem needs further study.

10. — There is also the problem of aircraft height. At present it would appear that there is no satisfactory alternative to the use of barometric methods, or possibly the aircraft's own altimeter, although clearly some more precise and positive method would be an advantage.

Aerodist Trials

11. — Aerodist equipment has been tested in the air in three countries, U.S.A., U.K. and Canada.

U.S. Trials (1960)

12. — Tests were carried out with prototype equipment by Gimrada [51] and produced accuracies well below the predicted 1 m ± 1/100 000.

U.K. Trials (1961)

13. — These tests were carried out by Fairey Aviation Ltd. on behalf of Tellurometer Ltd. [4]. Line crossings were flown over the six lines forming a braced quadrilateral, in western U.K. The following table gives details of the results.

Ordnance Survey Distance (corrected for known scale error)	'Aerodist' Mean Reading	Accuracy of Mean Reading	Error of Mean Reading
89 890.121	89 892.977	1/41 000	+ 2.856
102 242.050	102 250.066	1/13 000	+ 8.016
212 187.979	212 192.403	1/48 000	+ 4.424
148 674.858	148 680.473	1/26 000	+ 5.615
182 135.324	182 138.572	1/56 000	+ 3.248
182 135.324	182 135.068	1/711 000	— 0.256
132 974.837	132 972.642	1/61 000	— 2.195
170 928.542	170 924.668	1/44 000	— 3.874

U.K. Trials (1962)

14. — In the summer of 1962 a 3-channel Aerodist system was tested in the U.K. A quadrilateral consisting of 4 first order geodetic stations was selected, with average side length of about 120 km. Each of the six lines of this quadrilateral were measured with up to 13 crossings of each line. Flying heights were varied between 600 and 2 000 metres. Meteorological observations were taken on board the aircraft with psychrometers and survey barometers, as well as readings of the aircraft's altimeter, compass and air speed instruments. Computations of the refractive index for the preliminary results so far available depended upon an assumed linear gradient between the aircraft and ground stations. Before the trials could be carried out some difficulty was experienced in obtaining frequency clearance, and ultimately authority was only given on a day-to-day basis. In this trial, production models of the Aerodist equipment were used. These produce a large quantity of paper traces which require lengthy analysis. A digital read-out, possibly in the form of punched tape, might be more easily processed. The preliminary results of these trials which are given in the following table show little significant difference from the results obtained in the Fairey trials of the previous year when prototype equipment was being tested.

Corrected Triangulation distance	Aerodist distance	Difference	Accuracy
111 021.97	111 021.51	— 0.46	1/241 000
144 618.92	144 615.29	— 3.63	1/40 000
174 003.88	173 994.20	— 9.68	1/18 000
190 220.33	190 212.80	— 7.53	1/25 000
137 186.45	137 177.93	— 8.52	1/16 000
120 552.04	120 552.82	+ 0.78	1/155 000

Other Trials

15. — Other trials have been carried out as follows but so far no results have been reported : U.S. (1961); Canada (1962).

SATELLITE-CARRIED SYSTEMS

General

16. — The range of ground-based electromagnetic distance measuring equipment has been increased tenfold by placing such systems in aircraft, and a further order of range increase seemed to be feasible if it proved possible to put the necessary instruments in satellites. By such means it is hoped that points anywhere over the earth's surface may be connected via an artificial satellite, either directly or by orbital extrapolation. The use of a satellite for this purpose produces its own inherent difficulties. In the first place the platform now moves at a speed of about 8 km/s instead of perhaps 100 m/s. The problem of instantaneous location is thus much greater. Ordinary atmospheric refraction problems are simplified since the signal for its greater part travels in space or near-space. However radio waves are refracted in their passage through the ionosphere by considerable but varying amounts, depending on the state of the ionosphere, the angle of passage and the wavelength employed.

Secor [53] [54] [56]

17. — The Cubic Corporation of the United States has developed this system, in conjunction with the Army Map Service, in which it is planned to have up to four ground based stations interrogating a transponder carried in a satellite in orbit at a height of about 1 000 km. F.m.c.w. signals are used, and phase comparison of the transmitted with the received signals at the ground station provides a measure of the distance of the satellite. Thus successive positions of the satellite can be fixed by means of synchronised observations from three or more known ground stations. If synchronised observations are also taken from a further ground station the position of the latter can then be fixed by a form of resection from the successive known satellite positions.

18. — The carrier wave transmission frequency is about 450 Mc/s, and four modulation frequencies are used in order to obviate ambiguity in the measured distances. Ionospheric refraction, it is hoped, will be eliminated by using two retransmission frequencies from the satellite, i.e. 449 Mc/s and 224.5 Mc/s. Though some satellite-borne experiments have been carried out, so far no accuracy data is available. It is hoped that distances between points 1 000 km or more apart will be achieved to an accuracy of about 30 m.

Transit [53] [54] [57] [58]

19. — This system, being developed by the U.S. Navy, is based on the Doppler effect. A satellite is put into orbit at a height of about 1 000 km and the orbit is very carefully monitored by ground stations. The satellite is equipped with a crystal-controlled clock and with means of recording data regarding its own orbit, supplied by monitoring stations. On passing such stations the satellite is fed with the latest data regarding its orbit with respect to time. In the course of subsequent orbits, every 90 seconds it broadcasts information including the time, and its own height and position at the time of transmission, computed by extrapolation from the stored data. In addition it transmits four ultra stable frequency signals.

20. — A ground station wishing to fix its position will tune in to the satellite's transmission and record the transmitted data, and in particular the stable frequency signal. As the satellite passes, the Doppler effect will cause the frequency of these signals to drop. By measurement of the maximum rate of change of frequency, the distance of the observing station from the satellite can be computed. At the moment of maximum change the station must lie on a circle centred at a point on the orbit, with this distance as radius, in a plane at right angles to the orbit. The centre of this circle may be determined from the orbital data transmitted by the satellite. The circle will intersect the earth at two points, one to the east and one to the west of the satellite's orbit. The point which corresponds to the station may be determined from a plot of the rate of change of frequency. If the observer were stationary with respect to the orbital plane, this plot would be symmetrical about the point of maximum change. However, because of the earth's rotation, the ground station moves towards or away from the orbit, thus making the Doppler variation asymmetric about the maximum point. The direction of asymmetry indicates whether the observing station is to the east or west of the orbit.

21. — The use of four transmission frequencies enables the effect of ionospheric refraction to be computed and eliminated. This and other factors greatly complicate the computation of results, and if the full accuracy inherent in the system is to be attained an electronic computer is required. With such equipment it is hoped that accuracies of 50 m or better will be achieved. Practical experiments with the system have been

going on for several years although accuracy data are not yet published. Once the system becomes available for civil use, possibly within a year, a means of fixing position to an accuracy approaching that required for geodesy will be available for general use.

Anna [53] [54]

22. — The geodetic satellite Anna, sponsored jointly by the U.S. Army, Navy, Air Force and NASA, carries both Secor and Transit systems in addition to a flashing beacon for optical observation. The satellite was launched on 31st October 1962 and is in orbit at a height of 1 100 km with an angle of inclination to the equator of 50.2°, but so far no results have been announced.

Appendix I

A. — MICROWAVE DISTANCE MEASUREMENTS

Date	Country and Organisation	Instrument	Base or line	Length km	No. of Days	No. of Measures	Diff. MDM-Tape etc.		M.s.e. of single obs.		Remarks
							cm	ppm	cm	ppm	
1958	D.F.R. Geod. Institute, Frankfurt [32]	MRA 1	Munich	8.2			— 3	— 3.7	2.7	2.2	Taped bases
1959	” ” ” ”	”	Heerbrugg	7.3			+ 17	+ 23.3	8.7	11.9	
1960	” ” ” ”	”	Meppen	7.0			+ 10	+ 14.6	2.3	3.3	
	” ” ” ”	”	Gottingen	5.2			+ 18	+ 34.6	7.8	15.0	
1960	Ordnance Survey of N.I. [33]	MRA 1	Lough Foyle	12.6	14	20	+ 2.4	+ 1.9	1.4	1.1	Base measured with compensation bars
1962	Tellurometer Ltd. & O.S. [11]	MRA 3	Ridgeway Base	11.2	2	6	— 2.0	— 1.8	1.1	1.0	Taped bases
1962	” ” ”	MRA 3	Caithness Base	24.8	3	8	— 6.2	— 2.5	4.5	1.8	
1962	U.S. Army [10]	Electrotape DM 20	Belvoir Base	1.7		8	— 0.3	— 1.8			Taped base
	” ”	”	Leesburg Ecc-Westbase	4.7		7	+ 0.2	+ 0.4			Comparison with Geodimeter NASM 2
	” ”	”	Leesburg Ecc-Orchard	4.9		8	+ 4.3	+ 8.8			
	” ”	”	Ferry-Wheat	7.3		8	— 2.3	— 3.2			
	” ”	”	Leesburg Ecc-Fairall	8.0		8	+ 4.7	— 5.9			
	” ”	”	Leesburg Ecc-Hamilton	8.4		8	+ 8.9	+ 10.6			
	” ”	”	Clark-Robinson	20.3		10	+ 7.6	+ 3.7			Trig. : accuracy 1/225 000
	” ”	”	Clark-Fork	40.7		8	+ 11.9	+ 2.9			
June 1962	U.S. Coast & Geodetic Survey	Electrotape DM 20	Cheyenne Well-Monotony	15.7		14	— 5.1	— 3.2			Comparison with Geodimeter NASM 2
	” ” ” ”	”	Houston-Crowder	18.6		11	—17.3	— 9.3			
	” ” ” ”	”	Elkreek-Sink	16.2		20	—11.2	— 6.9			
	” ” ” ”	”	Colby Base	10.6		9	—14.1	—13.3			
	” ” ” ”	”	Lebanon-Old Well	24.3		6	—51.6	—21.3			
	” ” ” ”	”	Blixt-Halliwill	23.6		24	—17.7	— 7.5			
1962	Tech. Hochschule, Hannover [49]	Electrotape DM 20	Munich	8.2	2	8	— 3.1	— 3.8	2.0	2.4	Taped base
	” ” ”	”	Base N - Parsdorf	9.0	1	4	— 5.6	— 6.2	2.8	3.0	Comparison with Geodimeter NASM 2
	” ” ”	”	Base S - Parsdorf	10.3	1	4	— 6.1	— 5.9	3.2	3.1	
	” ” ”	”	Gottingen Test net								
		”	Base N - BUF 140	1.8			+ 1.5	+ 8.2			Taped lengths
			BUF 140 - BUF 87	1.3			— 1.4	—10.8			
			BUF 87 - Base S	2.1			— 4.8	+ 22.9			
	” ” ”	”	Cuxhaven Leuchturm - Döse, Pfeiler	2.9			+ 1.0	+ 3.5			Comparison with geodimeter
	” ” ”	”	Cuxhaven Radar - Döse, Pfeiler	2.8			— 2.2	— 7.9			
1962	State of Nevada, Dept. of Highways [43]	Electrotape DM 20	State Base	30 m	1	7	Nil		Spread	3.3 cm	Sun, cool breeze
			” ”	76 m	1	10	Nil		”	2.7 cm	” ” ”
	” ”	”	” ”	152 m	1	14	— 0.1	— 6.6	”	5.0 cm	Cloudy, cool
	” ”	”	” ”	335 m	2	10	+ 0.2	+ 6.0	”	3.4 cm	Sun, warm calm breeze
	” ”	”	Humboldt Base	3.2	2	32	— 0.6	— 1.9	”	3.3 cm	Overcast, calm, rain, cool
	” ”	”	Elko Base	7.0	2	32	—10.0	—14	”	11.7 cm	” ” ”
	” ”	”	Reed Base	8.9	2	32	+ 4.1	+ 4.5	”	6.5 cm	Cloudy, breezy, clear, warm
	” ”	”	Ely Base	13.4	2	8	—12.9	— 9.7	”	2.9 cm	2 Segments, clear, cool
	” ”	”	Reese River Base	17.9	1	32	—12.0	— 6.7	”	11.3 cm	Clear, cool, including mid-course wet
	” ”	”	Pahrump Base	24.2	1	10	— 3.4	— 1.4	”	5.7 cm	Clear, strong wind, dusty. Dust storm eventually made null meter readings too unstable for measurement.

APPENDIX I

Comparisons of Electronic Distance Measurement with measurements by other Methods

B. — *ELECTRO-OPTICAL DISTANCE MEASUREMENT*

All comparisons against taped bases

Date	Country and Organisation	Instrument	Base or line	Length km	Diff. Geod. Tape	
					cm	ppm
6/60	U.S. Coast and Geodetic Survey [5]	Geod. 2	Patrick, Florida	18.2	— 3.4	— 1.9
7/62	" " " "	"	Titusville, Florida	10.9	+ 5.2	+ 4.8
3/60	" " " "	"	Colby, Kansas	10.6	— 0.3	— 0.3
6/61	" " " "	"	Boundary, Mont.	13.8	+ 7.4	+ 5.4
6/62	" " " "	"	G.B.I., B.W.I.	14.9	— 7.2	— 4.8
1960	U.S.S.R. [6]	SVV-1	Transpolar	7.2	+ 1.4	+ 1.9
	"	"	Steppe Zone :			
			May	10.3	— 1.4	— 1.4
			June	10.3	— 0.1	— 0.1
			August	10.3	+ 1.2	+ 1.2
	"	"	Wooded Steppe Zone	10.7	+ 1.5	+ 1.4
	"	"	Taiga Regions :			
			June	7.5	— 0.3	— 0.4
			August	7.5	— 1.5	— 2.0
	"	"	Semi-desert Steppe	10.0	— 3.5	— 3.5

Appendix II

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APPENDIX V

References

[1] Travaux de l'Association Internationale de Géodésie, tome 21. Published by the Secretariat of the Association.

[2] A. KAROLUS and D. FRIES : "Eine neue Anordnung zur Bestimmung der Lichtgeschwindigkeit". *Annalen der Physik,* 7 Folge, Bd. 4, 1959.

[3] Resolution No. 3 of IUGG XIIth General Assembly, Helsinki, 1960.

[4] Austin C. POLING : "Report on Model 4-D Geodimeter and Electrotape Tests in conjunction with Model 2 Geodimeter". Unpublished U.S. Coast and Geodetic Survey Report.

[5] B. K. MEADE, U.S. Coast and Geodetic Survey. Unpublished Communications dated 2nd November 1962 and 1st March 1963.

[6] V. A. VELICHKO : "The measurement of the sides of second order triangulation with the SVV 1 geodimeter-type instrument". *Geodesia e Kartografia,* No. 7-8, July-August 1961.

[7] Borivoj DELONG, Bohuslav SOKOLIK and Premek NEUMANN : "Electro-optical Distance Meter with Quartz Modulator". *Studia Geoph et Geod* 5 (1961).

[8] Yu. V. POPOV, I. I. ADRIANOVA and I. A. KOROLEV : " The Small GDM Geodimeter-type Instrument ". *Geodesia e Kartografia,* No. 3-4, March-April 1961.

[9] K. D. FROOME and R. H. BRADSELL : "Distance Measurement by means of a light ray modulated at a microwave frequency". *Journal of Scientific Instruments,* Vol. 38, pp. 458-462, December 1961.

[10] Engineering Test Report, Electronic Ranging Equipment Electrotape. 16th January 1961, U. S. Army GIMRADA Report.

[11] WADLEY, T. L., HOLSCHER, H. D. : " MRA 3 Tellurometer Measurements on the Ridgeway and Caithness Bases". C.S.I.R. Special Report No. T. 28, Johannesburg, 1962.

[12] " Wild Distomat DI 50 ". Wild Heerbrugg leaflet.

[13] K. PODER, Chr. J. LEHN and O. BEDSTED : "Some preliminary results and considerations of the Tellurometer investigations". Report to IAG General Assembly, 1960.

[14] Ole BEDSTED : "A note on the Cyclic Error". Paper No. 11. Tellurometer Symposium, London, 30th July-3rd August, 1962.

[15] C.D. MCLELLAN : " The Tellurometer in Geodetic Surveying ". *Canadian Surveyor,* Vol. XV, No. 7, 1961.

[16] R. C. GARDINER-HILL : " Refinements of Precise Distance Measurement by Tellurometer ". Paper presented at Commonwealth Survey Officers Conference, London, 1963.

[17] S. BAKKELID : " Preliminary Results of Studies of some Tellurometer Problems ". Geodetic Publication No. 13, Geographical Survey of Norway.

[18] S. BAKKELID : Unpublished Report Ref. VIII/GL/SL dated December 1962.

[19] Stig SUNDQVIST and Ian BROOK : " Some preliminary results of measurements carried out by the Swedish Geographical Survey to determine Index error in Tellurometer MRA 2, 462 and MRA 2, 444 ". October 1962. Unpublished Report.

[20] J. E. LILLY, Dominion Geodesist, Canada. Unpublished communication 16th November 1962.

[21] J. KELSEY : " A method for reducing ground swing on Tellurometer measurements". *Empire Survey Review,* No. 112, 1958.

[22] Knud PODER : "Reflections". Paper to Tellurometer Symposium, London, 30th July-3rd August, 1962.

[23] M.J. VETTER and M.C. THOMPSON, Jr. : "Absolute Microwave Refractometer". *Review of Scientific Instruments,* Vol. 33, No. 6, pp. 656-660, June 1962.

[24] J. SAASTAMOINEN : "Reduction of Electronic Length Measurements". *Canadian Surveyor,* Vol. XVI, No. 2, March 1962.

[25] J. SAASTAMOINEN : "Curvature correction in electronic distance measurement". Paper presented to IAG General Assembly, 1963.
[26] Knud PODER and Ole BEDSTED : "A Frequency Measuring System". Paper presented at the Tellurometer Symposium, London 30th July-3rd August, 1962.
[27] Knud PODER and Ole BEDSTED : "A Line-crossing Experiment". Paper presented at the Tellurometer Symposium, London, 30th July-3rd August, 1962.
[28] K.D. HARRIS : "Lasers - Review of Recent Developments". *Electronic Technology,* March 1962, Vol. 39, No. 3, pp. 86-94.
[29] K.M. WALLACE : "Maser Surveying". *Surveying and Mapping,* December 1962.
[30] M. DECK : "Works of the IGN (France) on Tellurometer 1958-1962". Paper presented at the Tellurometer Symposium, London, 30th July-3rd August 1962.
[31] H. DRAHEIM : "Twenty-four hour test of Tellurometer at 1-hour intervals". Paper presented at the Tellurometer Symposium, London, 30th July-3rd August 1962.
[32] K. GERKE : "Tellurometer measurement in base line extension figures". Paper presented at the Tellurometer Symposium, London, 30th July-3rd August 1962.
[33] W.R. TAYLOR : "The remeasurement of the Lough Foyle Base Line". *E.S.R.*, No. 126, Vol. XVI, October 1962.
[34] R.E. LOWER : "Report on the Measurement by Tellurometer of the Line Dunnose-Beachy Head, a distance of 103.5 km.". Unpublished Ordnance Survey Report.
[35] M.V. RATYNSKIY : "The problem of the determination of the index of refraction of the air during distance measurement with electro-optical and pulsed wave range-finders". *Geodesia e Aerophotosemka,* Moscow Institute of Geodetic, Aerial and Cartographic Engineers. Publication No. 2 of 1962.
[36] H.J. MECKENSTOCK : "Untersuchung uber die Fehlereinflusse und Reduktionen dei der elektrischen Entferningsmessung fur geodatische Zwecke". Geodatisches Institut of the Technischen Hochschule, Aachen.
[37] K. PODER. Unpublished communication dated 29th March 1963.
[38] K. PODER. Unpublished communication dated 27th May 1963.
[39] Fairchild. Dumont Laboratories Product Data Pamphlet.
[40] J. MITTER : "Uber die Bestimmbarkeit der Ausbreitungsgeschwindigkeit der Tragerwellen bei elektronischen Entferningsmessungen". *Allgemeine Vermessungsnachrichten* Karlsruhe.
[41] R.S. BROWN and E.J. MARTIN, Jr. : "Research Studies related to mapping, geodesy and position determination". Mid-west Research Institute. Project for U.S. Army GIMRADA.
[42] J. MITTER : "Zur Bestimmung des atmospharischen Dampfdurckes mittels Psychrometern — Uber die Psychrometerformel und ihre Auswertung". *Allgemeine Vermessungsnachrichten,* 1963, Vol. 79, No. 3.
[43] Paul J. DUBE : "Results with a model DM 20 Electrotape Control extension in Nevada". State of Nevada, Department of Highways Report.
[44] SPRUNG, A. : "Uber die Bestimmung der Luftfeuchtigkeit mit Hilfe des Assmannschen Aspirationspsychrometers". *Das Wetter,* 5 (1888).
[45] K. GERKE : "Tellurometer frequency checking". Verlag des Instituts fur Angewandte Geodasie, Frankfurt A/M, Series II, No. 8.
[46] GARDINER-HILL, R.C. Unpublished communication.
[47] BEST, A.C., KNIGHTING, E., PEDLOW, R.H., STORMOUTH, K. : "Temperature and humidity gradients in the first 100 metres over S.E. England". *Geographical Memoirs,* No. 89, London 1952.
[48] FRANKENBERGER, E. : "Uber vertikale Temperatur-, Feuchteund Windgradienten in den untersten 7 Dekametern der Atmosphare, den Vertikalaustausch und den Warmehaushalt an Wiesenboden bei Quickborn/Holstein 1953/54. *Berichte des Deutschen Wetterdienstes,* 3, (1955), Nr. 20.
[49] H. SEEGAR : "First Experiences with the Electrotape Model DM 20". Communication dated March 1963, from the Geodetic Institute of the Technical University, Hanover.
[50] WILLIAMS, D.W. : Geodesy, Progress and Promise. 1962.

[51] Instrument Manufacturing Corporation of South Africa. Report on Tellurometer Aerodist system. 1962.
[52] Fairey Air Surveys. Aerodist Evaluation Trials. 1961.
[53] Williams, D.W. : Preliminary report on the optical system for the Anna Geodetic Satellite. 1962.
[54] Edgerton, Germeshaussen & Grier Inc. (U.S.A.). Satellite Anna optical programme. 1962.
[55] Duffie, C.A.P. : Airborne distance measuring and data processing developments in U.S.A. 1962.
[56] Henriksen, S.W. : Secor distance measurement. 1961.
[57] Kershner, R.B. and Newton, R.R. : "Transit system". *Journal of the Institute of Navigation.* April 1962.
[58] Nickolson, W. : "First attempt to obtain a fix from Transit". *Journal of the Institute of Navigation.* April 1962.
[59] Jelineks Psychrometer-Tafeln (6).6. Auflage, Herausgegeben von W. Trabert, Leipzig 1911, S.3-4.
[60] Jordan-Eggert-Kneissl : Handbuch der Vermessungskunde. 10 Ausgabe, Stuttgart 1956, Bd.III, Anhang Tafel (14).
[61] Albrecht, Th. : Formeln und Hilfstafeln fur geographische Ortsbestimmungen, 4. Auflage, Leipzig 1908, Hilfstafel 34 : Tafel fur den Dunstdruck.