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by

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"SOME METEOROLOGICAL PROBLEMS OF ELECTRONIC SURVEYING"

by

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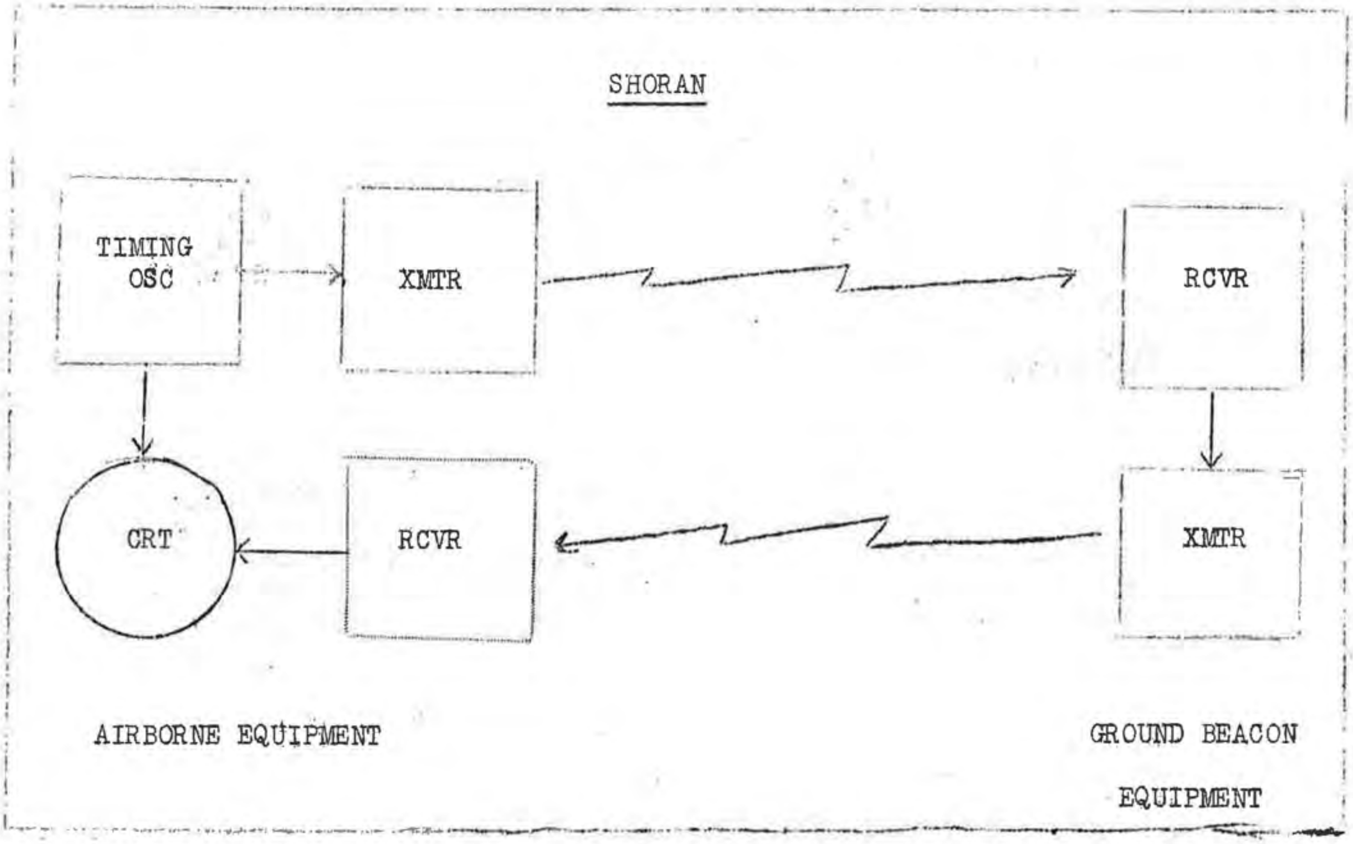
INTRODUCTION

In order that we might get a perspective view of the position of meteorology in relation to electronic surveying, I think it would be wise to start with a brief outline of the purposes of the Geodetic Survey and also give a brief description of the electronic surveying apparatus and the method by which it is employed.

THE GEODETIC SURVEY

One of the primary purposes of the Geodetic Survey is the establishment of geodetic control throughout the country. By control we mean a frame or network of points of accurately known positional coordinates and elevation, for use as reference marks for mapping or other purposes. The Geodetic Survey does not make maps; it does, however, provide the necessary information for the accurate location of latitude and longitude lines and contours on charts, prepared by other surveys.

Control is extended throughout the country by precise methods of surveying from the continental reference point, using primary standards of length in the measurement of base lines and the best available instruments and technique for the measurement of angles. In Canada, first order control has been extended throughout the well-populated sections of the country, with some extensions northward. However, the vast expanses of the country from the northern prairies across Hudson Bay to Ungava and to the north have not been tied in to the primary triangulation nets. Before the advent of Shoran, the only control in the North was by astronomic positioning. The accuracy of this method is limited, not by the characteristics of the instruments used, but by the unknown amount of the deflection of the plumb bob from the vertical because of inhomogenieties in the structure of the Earth's crust. Shoran has been chosen as the instrument by which control, of higher accuracy than is possible by astronomic means, is being extended into Canada's north.


SHORAN
TIMING OSC
XMTR
RCVR
CRT
RCVR
XMTR
AIRBORNE EQUIPMENT
GROUND BEACON EQUIPMENT

SHORAN EQUIPMENT

The Shoran equipment indicates distance between two stations by measuring the interval of time required for radar pulses to travel the circuit. The apparatus required to do this is shown in block diagram form on the opposite page. In practice there is a duplicate set of ground equipment at a second ground station and the equipment in the aircraft actually measures the two distances simultaneously. For our purpose it is sufficient to consider only one half of the circuit.

The timing oscillator is the master control of the whole system. This is a quartz-controlled oscillator which is designed to operate at a standard rate maintained constant within narrow limits of error. The crystal is mounted inside a temperature-controlled oven, and all portions of the circuit are designed so that variables will have as little effect upon the frequency of operation as possible. The rate is checked at intervals against the U.S. primary standard of time, WWV - Washington, D.C. The output from this oscillator, in pulse form, is fed to the airborne transmitter and also to the cathode-ray tube circuits. The pulses are spaced in time: the amount required for the radar signal to travel two miles, that is, out and back over a distance of one mile. It will be convenient to think of this interval of time as a distance, and in fact we will speak of it as a "radar mile". The circuits associated with the cathode-ray tube generate voltages which cause the spot to describe a circular track on the tube screen. A complete revolution of this spot corresponds to a radar mile, or a multiple thereof. The pulse from the timing oscillator serves to lock the circular generating voltages in synchronism with the master oscillator and also to provide a reference mark on the circular path in the form of a slight radial displacement of the spot, known as a "pip". The picture appearing on the cathode-ray screen then, due to the pulse from the oscillator, is a circle with an inverted "V" at 12 o'clock. If the rate of the circle-forming voltage is exactly the same as that of the master oscillator this "V" will always appear at the same spot on the screen; if the rates are different the "pip" will drift in a clockwise or counterclockwise manner around the circle depending upon whether the rate is fast or slow. Because the rate is stabilized by the timing oscillator in the Shoran equipment, the reference mark is fixed at 12 o'clock.

Now we will consider the operation of the transmitter. This is a device which is capable of delivering very great amounts of radio-frequency power in the form of pulses of short duration. The transmitter is maintained in a state of readiness, but is inactive or inoperative except when a triggering pulse is received from the timing oscillator. Thus at the same instant that a reference mark is appearing on the screen of the cathode-ray tube, a pulse of energy is released by the transmitter and sent out to the ground beacons.

The ground beacon, as we saw, is simply a transmitter-receiver combination and can be thought of as a mirror. The ground transmitter is normally inoperative and pulses only upon receipt of a triggering signal from its companion receiver, just as the airborne transmitter pulses only when allowed to by the controlling oscillator. To avoid interaction the two transmitters are operated on different but neighboring high frequency channels.

The function of the airborne receiver is to amplify the weak signal received from the ground transmitter, and then apply it as a radial deflection, or pip, to the cathode-ray tube. Now, due to the delay in time between the arrival of the reference pulse and the radio-ed pulse, because of the long path difference involved, there will be an angular displacement between these two "pips". Since the chosen interval is one revolution per radar mile, this displacement will indicate the fractional part of a radar mile separating the two batteries of equipment. The integral number of miles is of relatively minor interest in Geodetic Surveying. This is generally known from preliminary positioning; however, provision is made in the equipment for altering the scale of measurement so that the whole number of miles can be obtained if necessary.

TECHNIQUE OF MEASUREMENT

Because of the nature of the equipment and of the problem, it is not practicable to determine the separation of the ground stations by a single measurement. It is impossible to determine exactly when the aircraft is in the vertical plane containing the ground stations. In order to surmount this difficulty and also to improve the precision of measurement, the following technique is used. The aircraft proceeds to the approximate center (of the line joining the two ground beacons) by ordinary navigation methods, aided by Shoran during the latter stage of the journey. An elevation at which suitably strong return signals from the ground beacons are available is chosen as the operating altitude. The aircraft then commences to execute a "figure of eight" flight path in a horizontal plane, with the vertical axis of the "8" at right angles to the line between stations. Continuous recordings are made of the sum-distance to the two ground stations during the three-minute period (approximately), centered in time at line crossing. The four possible methods of crossing are repeated twice, making a total of eight crossings. This whole process, repeated on another day, brings the complete set to sixteen crossings. Automatic photographic equipment is installed in the plane for the purpose of providing a permanent record, on 35mm film, of the necessary data required in the computations.

The sum-distance (that is the distance from one ground beacon to the aircraft plus the aircraft to second beacon Shoran distance) decreases to a minimum as the aircraft approaches the line and increases again beyond the line. The curve obtained when the sum-distance is plotted against the time is very closely approximated, in the vicinity of the minimum point, by a parabola. The minimum distance for each of the sixteen crossings is determined by choosing a series of observations over which the half-distance varies by one whole mile, then fitting a parabola by a least squares curve-fitting process, and obtaining the minimum sum-distance from the best-fit parabola. The one-mile interval is chosen in order to eliminate inherent cyclical errors which would otherwise require tedious application of corrections to the individual measurements. From each set of eight crossings the following is determined:- the mean pressure altitude at operating altitude and the minimum Shoran distance. The latter is in reality a time, converted to a distance under the assumption of a constant velocity of propagation. What is required is the geodetic map distance between the two beacon stations.

If the aircraft elevation were known accurately, and if the radio waves travelled at a fixed speed in a straight line, the problem of the reduction of these measured quantities to the geodetic map distance would be a simple problem in geometry, and meteorology would not enter the picture at all. As you know, altimeters do not indicate true elevation, except occasionally by accident, perhaps, and also radio waves are affected by the state of the atmosphere (as those of you who have watched television at points distant from the transmitting site are well aware) so we can see that the problem is not that simple. The elevation of the aircraft has to be determined by the application of the principles of barometric altimetry, and corrections must be applied for the refraction of the ray in the atmosphere. This is one reason why it was deemed necessary to second a meteorologist from the Meteorological Service to the Department of Mines and Technical Surveys to work with the Shoran Project.

AIRCRAFT ELEVATION

The elevation of the airborne station is obviously an important factor in the reduction of the Shoran to map distance. Actually for a 250-mile line, an error of 100 feet at 15,000 feet in the aircraft elevation will result in an error of approximately 7.7 feet in the reduced map distance. A rough working rule used in the field states that one-tenth the error in aircraft elevation is felt in the reduced map distance. The actual factor, of course, depends upon the elevation and the length of the line, or their ratio.

The two known methods of determining aircraft elevation suitable for Shoran are: the narrow beam radar altimeter, and pressure altimetry. The radar altimeter can not be used conveniently except over water surfaces of known elevation; thus the pressure-operated altimeter has been chosen for use in the Shoran project.

The altimeters used in the Shoran aircraft are, of course, calibrated at periodic intervals. This work is done in the National Research Council laboratories, where accurate standards are available.

The instrument is used basically to indicate the pressure at operating elevation. In order to evaluate the elevation, it is necessary to know in addition the pressure at a reference elevation near ground level, and the relation between the density and pressure or height in the vertical column of air between these two pressures.

We will first consider the determination of the pressure at the low reference level, or the base correction as it has been termed for convenience. This could be determined rapidly from the analyzed synoptic surface charts of the Meteorological Service, for most locations in southern Canada; however, in the area in which Shoran surveying is being done, the network of reporting stations is too sparse for an accurate pressure analysis. In addition, the elevations of many of the barometers in the north country are not known accurately, and this introduces a further hazard to exact analysis. In order to improve this situation, the operators of the Shoran beacon stations are trained in weather observing, and during the period of line crossing, surface observations are taken at the synoptic hours at each ground beacon station. The observations from these stations are transmitted to base, and used in conjunction with the regular observations from the Department of Transport network. Although only two ground stations are involved in the line crossing, there may be up to ten ground stations in the field at one time, so that very considerable help is obtained in the analysis from these additional reports. It has been found that somewhat better accuracy is obtained by dealing with altimeter corrections at a reference level near the mean station elevation, rather than with reduced sea level pressures. This eliminates the possibility of errors arising by returning from sea level pressure to station pressure by means of a different rule than was used in the original reduction from station pressure. A set of graphs prepared from the sea level reduction tables facilitates the computations. The base correction at the mid-point of the Shoran line is then determined by interpolation from an analyzed iso-correction chart drawn at, say, 1000 feet of pressure altitude. The contour pattern on this chart generally resembles the sea level pressure pattern; thus the latter may be used as a guide in its preparation.

The remaining information required in the determination of the aircraft elevation is the relation between the density and pressure (or height) between the base level and the aircraft operating level. The density of upper air observations is not sufficiently high for the evaluation of this from radiosonde data; thus it is necessary to obtain the information by direct measurement. The standard procedure is to make a sounding at the mid-point of the line before and after crossing operations. Under conditions favourable to light horizontal density gradients, a sounding on an adjacent line can be substituted for one of these, for reasons of economy of flying time. The Shoran aircraft is fitted with a psychrometer mounted on a sliding frame, operated from inside by the navigator, such that the thermometers can be brought inside the plane for application of water to the muslin, and pushed out again into the airstream for reading. The aircraft commences the ascent sounding at approximately 300 feet above ground level, or at the minimum safe altitude, and flies a helical climb to operating level. Readings of the wet and dry bulb thermometers are taken at every thousand-foot interval of pressure altitude, at which the aircraft levels off to allow temperatures to reach equilibrium. The wet bulb, the dry bulb air temperatures, the pressure altitude and the indicated air speed are noted, along with pertinent remarks on cloud structure, etc., and are recorded on forms which are turned over, along with the developed films, to the computation centre at base.

As you know a thermometer mounted outside a moving aircraft does not indicate the true air temperature. Due to the rapid relative motion there is experienced a dynamic heating at the thermometer bulb. Application of the first law of thermodynamics and Bernouilli's theorem indicates that this heating is proportional to the square of the true air speed. The factor of proportionality depends upon the structure of the thermometer and the characteristics of the aircraft, and is very sensitive to position, and obviously cannot be calculated from basic principles. The actual value of this factor is found by experiment made prior to the field season. This experiment is performed under stable conditions, during which the aircraft is flown at various speed within its range. A plot of the recorded temperature against the square of the true air speeds yields a straight line; thus the proportionality factor is determined, and from this the ambient temperature at any air speed may be derived. The correction applied to the wet bulb thermometer is less than that applied to the dry, the ratio between the corrections being equal to the ratio between the dry and wet adiabatic lapse rates, at the pressure and temperature concerned. Occasionally, straight application of the corrections will yield a dry bulb temperature lower than the wet. When such conditions are encountered it is assumed that partial wetting of the dry bulb has taken place, and the air is considered saturated at the corrected wet bulb temperature.

The actual computation of the aircraft elevation is reduced to a graphical integration of the hypsometric equation over the limits set by the base correction and the calibrated reading of the aircraft altimeter. It is seen that the altimeter is used as a pressure-measuring device only, and that the aircraft height is obtained by resorting to the basic pressure-height relationship. The one assumption we are forced to make is that the effect of vertical accelerations upon the results is negligible. It should be noted, for the record, that a correction is applied to the computed elevations for the difference between the mean value of "g" and the assumed constant value used in the standard atmosphere pressure-height relationship.

ELEVATION OF GROUND STATIONS

Many of the Shoran beacon sites are located at points far distant from elevation reference marks. The elevation of these stations is required for two reasons: firstly, the pressure observations used to help determine the base correction must be given a reference value; secondly, the reduction to the map distance depends upon the elevation of the beacon station. When it is not practicable to carry out a spirit-levelling survey to the nearest known water surface or bench mark, the elevation is determined by pressure altimetry. The programme followed in this case is as described.

After the site has been chosen, a party of observers is left at the location for a two-week period. During this time, when the Geodetic Monument is constructed, the area is cleared of trees, if any, and other preparations are made for its later use as a beacon station. Weather observations are made at three-hour intervals coincident with the synoptic times. These observations are recorded and turned over to the Meteorological Service. The ground station elevation is obtained as follows:- the reports are plotted on analyzed surface charts; then, after making minor adjustments to draw in the new data, if necessary, the observed pressures are compared with the interpolated sea level pressure. This is done for each observation in the two-week period, yielding about 112 differences, from which the mean is obtained. The mean dry bulb temperature is also computed; then a procedure which amounts to the inverse of the usual method of reduction from station to sea level pressure is applied, yielding the station elevation.

The process is similar to that employed at many of our own stations in the North, whose elevation has had to be calculated from the barometer readings, after installation. A further complication arises, however, in the establishment of Shoran stations, as it is not considered practicable to use mercury barometers. Instead, a battery of three Kollsman altimeters is used to measure the pressure. On account of the fact that these instruments are subject to many sources of error, from which mercury barometers are free, it is particularly necessary to use great care in the interpretation of the results. Experience with these instruments indicates that they will show good agreement with a mercury instrument over a period of time, then suddenly shift and continue to agree, but with a fixed difference, for a further long period. The shifts seem to be associated with rapid, wide, pressure variations, such as are encountered during flights. In order to detect these jumps in calibration it is necessary to compare the aneroid instruments with a mercury standard before and after the field season, and also to compare the instruments in one battery with one another during the field programme. It is hoped to reduce this difficulty in future by transporting the instruments in air-tight containers.

REDUCTION OF SHORAN TO MAP DISTANCE

Next we come to the problem of the reduction of the Shoran distance to the Geodetic Map distance. If radio signals were unaffected by the atmosphere this would not be a difficult problem at all; in fact it could be solved by the application of elementary geometry. However, just as light is refracted in passing through the earth's atmosphere, so are radio signals. The amount of curvature and the variations in the speed of the waves as they pass through the different layers is very small, but not small enough to be negligible in geodetic surveying. The refractive index of air, at frequencies used in Shoran, depends upon the air temperature, the total pressure, and the partial pressure of water vapour. The form of the relationship is readily derived from fundamental principles but the constants are obtained from actual measurements. On account of the high value of the dielectric constant of water, the vapour pressure (though small in comparison to the total pressure) exerts an important effect upon the refractive index. The curvature of a ray passing through a stratified atmosphere at a small horizontal angle is equal to the vertical rate of change of the refractive index (approximately). Under average conditions the distribution of temperature, pressure and vapour pressure with elevation is such that the curvature is nearly constant over the ranges of elevations encountered. Thus the path of the ray can be represented to a high degree of precision by a circular arc. However, under some conditions the curvature varies over a wide range, especially in the low levels and a more complicated curve results.

The conditions favourable for a small radius of curvature are: (a) a rapid vertical decrease in the water vapour pressure; (b) a strong vertical increase in dry bulb temperature. The range over which the curvature varies, in the types of atmospheres encountered in Northern Canada in summer, is from about 10,000 miles to about 30,000 miles, the average being about 22,000 miles.

The conventional method of reduction of the Shoran to map distance is as follows. The radius of curvature of the ray is assumed to be 3.91 times the Earth's radius. The refractive index of the air is assumed to be constant at the value existing at N.T.P. Then the map distance is obtained through the application of geometry. To this reduced distance two corrections are applied: one for the actual curvature of the ray, and one for the actual velocity. It is assumed that the ray is an arc of a circle, the radius of which is calculated from the values of the measured refractive index at the two extremities of the sounding. With the aid of tables prepared beforehand, the portions of the ray cut off by each 1000-foot layer of the atmosphere are available and thus the average value of the refractive index along the ray can be computed. The averaged refractive index is almost always less than that at N.T.P. so that the "velocity correction" is generally positive. The curvature correction is positive or negative depending on whether the calculated radius of curvature is greater or less than 3.91R (15,500 miles).

It will have been noted that data from the mid-point sounding is used to evaluate the refractive index at points along the ray up to distances of 150 miles away. The error resulting from this is not serious unless there exist strong horizontal gradients of refractive index, since the velocity correction is of relatively small magnitude.

The above method has its limitations. It is based upon the assumption that the ray path can be approximated by a circular arc. Under some conditions, when the radius of curvature of the ray varies over wide limits, the above method of calculating the mean curvature does not lead to a representative mean value, and in order to get accurate results a more basic approach must be used. Much work has been done on this problem and various methods are available for the reduction of Shoran to map distances in almost any type of horizontally stratified atmosphere.

CONCLUSION

I have endeavoured to give a picture of all the phases of Shoran electronic surveying from a meteorologist's point of view, and since the subject is of such wide scope, touching on so many fields, it has been necessary to deal but lightly with the various phases. I think that you will agree that this is a most interesting project, and that it is unique, in that it offers an opportunity for the application of meteorology toward a very practical result: that of obtaining geodetic control over our vast country in a fraction of the time that would be required by older methods.

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