

AN AIRBORNE LASER PROFILE RECORDER.

G.W. McQuistan

SUMMARY. The use of airborne profilers in mapping is described and the advantages of using optical wavelengths is shown. A complete profiler system using a modulated laser beam is outlined, together with a discussion of the various parameters that affect its performance. Possible uses of similar instruments in the general field of surveying are noted.

1. AIRBORNE PROFILING FOR MAPPING.

The usual procedure in map making from aerial photographs is to take a sequence of overlapping photographs from a moving aircraft and to use this sequence to build up a strip of the map. Adjoining strips are combined to fit together to cover the required area or block.

In the process of converting photographs into maps, when a pair of photographs is used, control points are established on successive photographs by transfer from one of the stereo pair to the other. If control points (that is points with known x , y , z coordinates) are first established on the ground in the area of the first photograph, secondary control points can then be established in the second photograph by transfer, and the process repeated successively to the end of the strip where ground control points are again encountered. Comparison of the transferred coordinates with those of the ground survey allows errors to be measured, and these are smoothed out by adjustment over the whole strip. A similar process can be performed with whole areas or blocks and error adjustment made over the whole block.

The process of transfer of control points is most inaccurate in the z coordinate as the accuracy is a function of the parallax between the stereo pair. The process therefore does not give as accurate a measure of height (z) as it does of x and y .

To overcome this inaccuracy, airborne profilers have been used. These determine the height profile of the terrain along a line within the strip. By choosing control points on this line, z is determined and the x and y values of these points are found by the usual transfer process. The line on which the profile is made is usually chosen along the very edge of the strip so it is common to two strips and also each strip has then two lines, one on each side, which have known heights.

To accomplish its purpose the airborne profiler measures its height above the terrain while maintaining its own height above mean sea level. Isobaric surfaces are utilised in keeping the height station and the assumption is made that these surfaces are at constant height above mean sea level, although some adjustments can be made for first and second order deviations.

For a profiling run the general operational sequence would be for the aircraft to take off and climb to a suitable operating height where turbulence was not great (usually between 5,000 and 7,000 feet above the terrain). The system would then be calibrated by flying over an area of known height and the differential barometer set. The aircraft would then have to fly on that isobaric surface (to within about 50 ft.). The runs are straight and usually about 100 miles long and the pilot is required to maintain height, course and altitude to rather tight limits. At the end of the run the system is again calibrated over another area of known height.

2. LIMITATIONS OF MICROWAVE AND OPTICAL PROFILERS.

Airborne profile recorders in current use are of the pulsed microwave type and the best accuracy obtainable with them is about ± 3 metres. The limitation to the accuracy comes from the large angular size of the transmitted beam ($1\frac{1}{2}^\circ$) which results in the received signals being reflected from a large area of ground (a number of acres). Any discontinuities over this area such as houses, small hills and trees, make the origin of the reflected signal uncertain and therefore the height of the terrain uncertain.

To remove this limitation by narrowing the beam is not practical with microwaves, as the beam width is inversely proportional to the diameter of the transmitter, and very large transmitter apertures would be required. However, the beam width is also proportional to the wavelength of the transmitted carrier (microwaves or light) so that if light can be used with a wavelength of only 5×10^{-5} cms a narrow beam can be obtained with an aperture diameter of only a few inches. Until lasers were developed no source was available that was sufficiently bright to be operated in a profiling system in daylight.

With an optical system of only a few inches diameter it is possible to direct the light of a laser into a beam diverging by only a few seconds of arc, but to obtain a divergence of less than about two seconds of arc is not possible because of the limitations of the turbulent atmosphere. At a typical aircraft operating height for a profiler, say 6,000 feet, the spot on the ground from which the reflection is obtained must therefore be larger than 1 inch. In profiling, this size of spot is generally too small, as the detail recorded is too fine. Also the alignment tolerances of the system become severe. The system to be described has a spot on the ground covering about 1 sq. ft.

From a theoretical point of view only, the accuracy of height measurement for an optical profiler is limited by the atmosphere to a few parts in 10^6 of the height. However, there is a practical limitation of the system set by the accuracy to which the isobaric surface is at constant height above sea level. Reliable data on this is not available and an accurate profiler could assist here.

3. REQUIREMENTS OF THE PROFILER SYSTEM.

The profiler described in the following section has been designed for the Division of National Mapping of the Department of National Development (THONEMANN and McQUISTAN, 1968).

Before describing the various units of the system it is necessary to be more specific about what is required from them. Firstly the accuracy of the heights measured is to be 0.5 metres (rms). This figure results from considerations of the accuracy of the calibration (bench) markers and of what is a meaningful height of an area of one sq. ft.

How frequently should the measurements be made? To answer this question it is necessary to consider the way in which they will be used. The number of control points needed is not high, about one every four miles, but they must be selected with care. Because the control points must be transferred to the mapping photographs, a process in which errors may occur, they should be selected in level areas where small errors in x and y do not give errors in z . Thus the profile must not only allow plenty of latitude in the control point selection but it must also give a general picture of the nature of the terrain. The chosen frequency is 50 points per second, or one point about every four feet of profile run.

To correlate the profile record with the mapping photographs a photographic record of the profile run must also be made simultaneously with the profiling.

The other units of the system must also be designed to meet the above requirements, and particularly, the actual height measuring unit and the barometer must be capable of an accuracy of 0.3 metres, if the whole system is to be accurate to 0.5 metres.

For the system to operate economically it must be capable of being carried in a light twin engined aircraft that can make use of rural airstrips. This requires that the total payload, including crew, should be not more than 1200 lbs. It is also desirable that most maintenance tasks should be possible without ground support facilities.

Although the system is being developed for the typical aircraft environment (temperature, humidity and acceleration) it is only required to operate in good flying conditions. For example it will not be expected to operate under conditions of strong turbulence or through fronts.

4. THE PROFILER SYSTEM.

The various units that make up the profiler system are shown in Fig. 19.1.

Laser. In the profiler the laser is used as a source of light and its property of producing an intense, narrow beam in a narrow spectral range make it very suitable for this purpose. As the light has to be reflected (or scattered) off the natural terrain, which has very poor reflection characteristics, the loss of light is great. Hence a requirement for high intensity. Also the laser light must be detected against a bright background of reflected sunlight and skylight and here the narrowness of its spectral range enable it to be filtered.

The lasers considered for the profiler were the HeNe (6328\AA), ruby (6943\AA), argon (4880\AA), Nd:YAG ($1.06\ \mu$) and the CO₂ ($10.6\ \mu$). The last two lasers are in the infra-red region of the spectrum where the daylight background is favourably low but photoelectric detectors in this region are not very efficient. This ruled out their use for the profiler, but with recent advances in detector technology, these wavelengths may be suitable for future systems. The HeNe laser was rejected as the required power could only be obtained from a laser about 6 feet long, a length that was unsuitable for aircraft mounting. The ruby laser is a pulsed laser and would have been suitable if techniques of pulsing it at 50 pulses per second at the required power had been available. This left the argon ion laser as the choice for the profiler. Argon ion lasers are continuous wave (C.W.) lasers as distinct from the pulsed

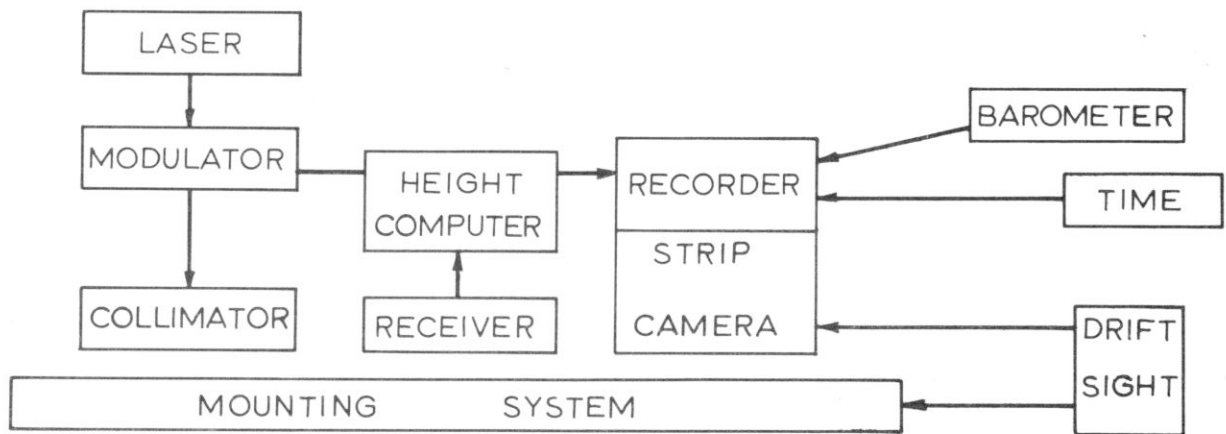


FIG.19.1 LASER TERRAIN PROFILER

type (e.g. ruby). The laser is excited either by R.F. or d.c. power, the former being the preferred method for the profiler. The light is produced in a number of narrow lines, the ones at 4880 Å and 5145 Å being the strongest, but it is only possible to use one of these lines efficiently. The laser cavity, 75 cms long, is part of a hemisphere and the output beam has a divergence of a few milliradians. Water cooling of the laser is necessary to dissipate the heat generated in the gas column.

Modulators. The light from the laser is passed through two modulators which modulate the intensity of the beam at two frequencies 5MHz and 4.5MHz.

The modulators each consist of a birefringent crystal (KDP), to which the modulating voltage is applied, a quarter wave plate and a linear polarized analyser. The polarized light beam from the laser comes out of the modulator with its intensity modulated about the mean value (WOOLLEY, 1967A, p. 7).

Optics. The transmitter optics have the purpose of collimating the beam to a smaller divergence than is produced by the laser. This is accomplished very much in the same way as for a conventional light beam (SEE, 1966). The divergence of the laser beam leaving the collimator is 0.1 milliradians.

The receiver optics is basically a light collector but it also restricts the field of view of the detector, with a focal plane stop, to an area of the terrain where the transmitter spot falls.

The detector itself is a photomultiplier which views the field of view of the receiver through a narrow bandwidth interference filter.

Computer. The height computer is a phase comparator which compares the phase of the outgoing signal with that of the received signal from the photomultiplier.

As the required accuracy of the phase comparison must be equivalent to a range of 0.3 metres (Δh) and if the accuracy to which phase can be measured is .01 (ΔQ), the minimum modulating frequency is given by

$$\begin{aligned} f \text{ min} &= \frac{c}{2\Delta h} \Delta Q && \text{where } c = 3 \times 10^8 \text{ metres/sec} \\ & && = \text{velocity of light} \\ &= 5 \times 10^6 \text{ cycles/second.} \end{aligned}$$

Thus the phase differences is a direct measure of height, with a range of 0.3 to 30 metres. This is the fine height channel. A further coarse, height channel is required which makes use of beat frequency between the 5 MHz and 4.5 MHz modulations to give the height over a range of 3 to 300 metres. Both channels together with the differential height from the barometer are recorded on a UV recorder. Any remaining ambiguity in the height cannot be resolved by the system. It is necessary to use modulating frequencies higher than 1 MHz to avoid modulated scattered light falling onto the detector.

Barometer. At the operating heights of the aircraft the pressure gradient is approximately 0.1 millibars/meter. Two types of instrument are available for measuring to the required accuracy of .03 millibars. These are the hypsometers, which use the boiling point variation in organic liquids as the pressure changes, and the accurate barometers which compare the outside pressure with that in a standard insulated cavity.

The latter type has been chosen for the profiler system and it is necessary to use one with a temperature above ambient as those that require ice cooling are not logistically practical.

This barometer has a range of ± 40 metres and the aircraft is required to keep to the isobaric surface within this range to prevent interruption of the reference to the initial surface.

Recording Camera and Drift-Sight. To photograph the ground, a strip camera is used with the speed of the film matched to the speed of the image of the terrain. A strip of terrain 0.5 km across is recorded on 70 mm film. The line profiled is indicated near the centre of the strip.

A beam splitting mirror in the camera is used to form an image of the terrain from which the drift and required camera film speed are deduced.

Power Supply. The laser is a very inefficient device for converting electrical power into light and although the Argon ion laser is one of the more efficient the present design calls for an input of 4.8 kW, for a light output of only 40 mW.

To produce this 4.8 kW of R.F. power at 27 MHz from a d.c. supply by conventional means would require heavy generators and transformers. To overcome this problem of weight and also to use the available power more economically a novel R.F. generator using a multi-transistor modulator transmitter arrangement is being developed. This will be powered directly from the aircraft's 28V d.c. generator, will be water cooled and work at 70% overall efficiency. The main problems of combining many transistor outputs in parallel and matching of the laser gas column RF impedance, have all been overcome and a complete transmitter is being built to weigh less than 100 lbs (including cooling).

5. SYSTEM ANALYSIS.

If P_t is the power transmitted by the system then the power received P_r is given by:

$$P_r = P_t a T_\lambda^2 T_o A_r / \pi H^2$$

where a is the reflectance or albedo of the terrain (typically about 0.1)
 T_λ is the transmission of the atmosphere at the carrier wavelength (0.7)
 T_o is the transmission of the optical system including the interference filter
 A_r is the receiver area, about 0.3 metres²
 H is the height above the terrain.

This power (P_r) must be detected by the photomultiplier against a background of reflected sunlight. The power of the background P_b is given by

$$P_b = b_\lambda T_\lambda^2 T_o a A_r \delta \Omega / \pi$$

where b_λ is the solar constant within the wavelength range of the filter (power/unit area/unit wavelength)
 δ is the filter bandwidth
 Ω is the solid angle of acceptance of the detector as determined by the receiver optics.

While this background can be considered constant during the measurement period and can therefore be biased off electrically, it has intrinsic noise on it, and it is against this background noise that the modulated return signal must have its phases measured. The required output power to enable this to be done is about 40 milliwatts for practical values of the above parameters.

6. PROFILERS AND GENERAL APPLICATIONS.

The system described in this paper has been designed for a specific purpose in mapping but the parameters can be varied to suit other applications. For example, from lower operating heights greater height accuracy can be obtained, but the isobaric surfaces could not be used to control aircraft height in this case.

Uses of profiling for surveying and quantity surveying are obvious for such purposes as roads, railways, pipe lines and power transmission lines. Also because of its small spot size on the ground it will be capable of measuring heights of small ground features such as trees.

A further development of such system would be to scan the terrain laterally and build up a complete map from the two-dimensional profiles.

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SURVEYING APPLICATIONS OF THE
LASER TERRAIN PROFILER.

L. G. Turner.

SUMMARY. This paper describes, in general terms, the requirements for a laser terrain profiler and its application to the problem of providing adequate and timely vertical control for 1:100,000 scale mapping in Australia.

1. DEVELOPMENT.

The provision of vertical control for mapping has long posed a problem in arriving at an economic, practical and accurate solution, particularly in respect of medium scale standard mapping in a vast area such as Australia.

The use of photogrammetry has provided a practical solution to the compilation of planimetric 1:250,000 scale maps but with the requirement for contours to be added to the new 1:100,000 map series, considerable demand for vertical control for this purpose has led to the development of airborne methods which can produce the required density and accuracy within a reasonable time scale and without the obstacles imposed by terrain and difficult access.

This development has proceeded through barometric heighting by helicopter and airborne profile recording by radio altimeter to radar profile recording. Barometric heighting and radar profiling are still employed today and each is playing a part in the production of vertical control.

Barometric heighting produces results with a mean square error of approximately ± 2 metres but in order to be an economic proposition, provision of ground control is limited and requires extension by photogrammetric methods to obtain the required density of four vertical control points per photogrammetric model. Radar profile recording can produce results with a mean square error of approximately ± 3 metres and theoretically provide the required density of model control but in practice is limited by lack of resolution and inaccuracies due to the comparatively wide beam of the radar system. This led to investigations of the potential of the laser as a terrain profiler to provide the required accuracy and density of vertical control for systematic mapping at medium scales.

The Division of National Mapping has sponsored the development of a laser terrain profiler through the scientific and research facilities of the Weapons Research Establishment of the Department of Supply. A technical description of the equipment being developed is given in a paper by Mr. G. McQuistan (Paper No.19).

The limitations of radar profiling will be virtually overcome by the use of a laser system which, with a beam of only 10^{-4} radians, will obviate the requirement for extensive datum areas and enable positive ground heights to be obtained even in areas of open timber. One most important aspect of this development is that sponsorship by a surveying and mapping organisation will ensure that a practical field surveying system is produced and not a laboratory type equipment modified for use in an aircraft. Emphasis will be placed on compactness and lightweight rugged construction, facility of field operation and simplicity of field maintenance.

The development of recording methods and ancillary equipment in the laser system will add to the accuracy and simplicity of procedures. As it is being designed as a surveying instrument in the first place, it will have numerous refinements for practical surveying not normally found in the systems developed from modifications to equipment originally designed for other purposes.

Australia is generally a very good country for obtaining vertical control using methods based on barometric height determinations, particularly in the inland where normally fine weather prevails throughout the winter with low isobaric gradients. However, air turbulence is also very prevalent in these areas up to levels of 6000 to 7000 feet. As a stable flying platform is essential to the accuracy of airborne profiling equipment, a unique feature of the equipment being developed for the Division of National Mapping will be its ability to avoid the air turbulence by operating with a high degree of accuracy and resolution at heights of between 7000 to 10,000 feet.

2. USES IN NATIONAL MAPPING.

The Division is currently engaged on a programme to produce 1:100,000 maps of Australia with contours at 20 metre intervals. As this will be the first fully contoured series published in Australia, the provision of accurate and extensive vertical control for contouring is of major importance to the programme.

Superwide angle aerial photography is being used exclusively for the programme and is taken on a basic standard flight pattern of east-west runs with the unit for area coverage being the 1:250,000 map sheet. This involves 8 runs of photography and lends itself ideally to the provision of laser terrain profiles along the side lap of the photographic runs. From these profiles ample vertical control can be obtained to fully control each photogrammetric model.

This will be the major role of the laser terrain profiler in the Division for the duration of the current mapping programme.

The distinct advantage of terrain profiling over other methods of providing vertical control, is the ability to provide individual vertical model control directly from the profiles without further processing or photogrammetric procedures. This advantage is greatest when used in conjunction with analogue methods of establishing horizontal model control. The combination provides full model control for direct use in plotting instruments without the necessity to introduce photogrammetric methods of control intensification or have access to more costly comparator type instruments and electronic computers.

Another role for the Laser Terrain Profiler which may well develop within the Division is the provision of selected terrain profiles for use as an accuracy check on the manuscript map compilation. This will provide a ready means of comparing the terrain profile with its representation on the manuscript map.

3. PROCEDURE.

The equipment has been designed to operate from a light twin-engined aircraft which, apart from very worthwhile economics in aircraft operation, will permit the use of smaller airstrips with the consequent savings in unproductive flying. A combination of strip mosaics from existing photography and the 1:250,000 series maps will be used for navigation by visual flight rules and this will ensure accurate tracking over the prescribed flight lines.

The detailed procedures of operation have yet to be determined after operational testing of the equipment but will probably follow closely those used in radar profiling. This will involve commencing a survey flight over a pre-selected datum, proceeding along the survey line and closing with a further datum run. The continuous strip positioning photography will enable differential stereoscopic transfer of selected points to mapping photography and these points can be simply related to the profile record by common fiducial markers.

A major factor in the operation of radar profiling is the necessity to use large datum surfaces which may be some distance from the survey line and involve expensive flying time, less production, more computation of corrections and inaccuracies due to greater dependence on drift determination of the isobaric gradients.

With the possibility of datum measurements over virtual pinpoint targets with the laser terrain profiler, a multiplicity of datums are available from the national levelling programme and other sources not available to radar profiling. This will mean savings in unproductive flight times between datums and survey lines and less dependence on uncertainties of isobaric gradients over long distances, a factor which is vital to the final accuracy of the profiles.

Additional cross-tie profiles will be run at intervals, again commencing and terminating over a known datum, and these will provide a basis for comparison of the profiles at cross-over points and adjustment, if required.

4. REDUCTION.

The reduction of observed profiles will take the same form as that carried out for radar profiling. This will involve corrections for changes in the isobaric surface as determined from aircraft drift, and latitude corrections combined in the formula:

$$\Delta Z = 0.035 \times \text{Sin Lat.} \times \text{Sin Drift Angle} \times \text{True Air Speed} \times \text{Distance.}$$

The correction ΔZ is applied as negative for port drift and positive for starboard drift.

The deviations of the aircraft from the isobaric surface are corrected automatically on the profile record from hypsometer measurements during the profiling operation. Application of the drift corrections between datum runs will allow a closing error to be determined, which, if acceptable, can be distributed linearly along the survey line.

With the pattern of cross-ties a comparison can be made between reduced profile values at the point of intersection and, where necessary, this procedure lends itself to an adjustment of the network either by simple mathematical adjustment or a more sophisticated least squares solution. It is expected that with the accuracy of the laser terrain profiler this latter type of adjustment will be unnecessary for our requirements which are for control suitable for 20 metre contours.

The final corrections to each profile will normally be drawn as a graph so that the required correction can be read off the graph to coincide with any selected control point.

5. THE FUTURE.

The future uses of the laser terrain profiler are of course a subject for conjecture but in the survey field some that come to mind may be worthy of mention.

The accuracy and resolution of the equipment are the key to its potential which could well include providing vertical control profiles for large scale project mapping or the determination of profiles along proposed high tension transmission line routes and clearance profiles for micro-wave radio links.

A further possible use which may well appeal to the forester is the measurement of tree heights in areas of open timber and even the samples of counting of tree crowns where these are sufficiently definite to be resolved from the profile chart.

DISCUSSION: PAPERS 19 and 20.

Chairman: Major G.J.F. Holden

McQUISTAN: Laser Terrain Profiler

TURNER: Profiler Applications

POWELL: The terrain profiler is an impressive piece of equipment, but because its use depends on the isobaric surfaces, calibration checks will be very important. With APR water surfaces are used for calibration. Is this possible with the laser profiler?

TURNER: We don't really know whether the laser will penetrate water surfaces. Calibration checks might be carried out by flying over a point of known height where a set of retro-reflectors had been set out.

McQUISTAN: The behaviour of the profiler over water surfaces is one of the questions which will, we hope, be answered in the tests of the apparatus due to take place shortly.

PUTTOCK: The U.S. Air Force in tests with laser beams found that the water surface was useless as a reflector. The return signal was a mixed jumble of reflected rays and spurious reflections and was not usable.

POWELL: The dependence on isobaric surfaces still worries me. Discrepancies will result between longitudinal and cross profiles and will require adjustment.

TURNER: The isobaric surface is not expected to give any difficulty. I do not expect any adjustments will be necessary. The calibrations at the beginning and end of a run should overcome the difficulties.

CHAIRMAN: The difficulty of the isobaric surface cannot be dismissed so lightly. After all we have an instrument designed to measure a height difference to 0.5 metres, a very high precision, in fact. The object is to measure the height of the ground surface, but the datum used for the horizontal transfer of heights is the isobaric surface, a very inaccurate datum. Investigations in connection with APR by Dr. Jerie of I.T.C. show that the errors to be expected are of the order of several metres. Is the drift measured, and if so, how? Also, trying to set the laser beam on to a mirror on the ground would be an almost impossible task, since the beam is only a foot across, and swings in an arc as the plane tilts.

McQUISTAN: The isobaric surface does present a weakness and is the limiting factor in the accuracy of the results.

ANGUS-LEPPAN: Investigations in our Department of Surveying into barometric heighting have indicated that the isobaric surface generally has a slope of the order of 0.5 feet per mile, and is fairly uniform. However if it increases above 1 foot/mile, the surface is buckled, and results will be unpredictable. Unless special measurements are taken, it will not be known whether the surface is plane or buckled.

BENNETT: The investigations referred to were made on the ground and one should be careful in applying them at 10 000 feet altitude. Have you any knowledge of the tilt of the isobaric surface at this height?

TURNER: We can calculate the tilt from the drift of the aircraft. It is likely to be more stable at 10 000 feet. In the centre of Australia we expect the isobaric surface to be very stable.

POWELL: What is the method of recording the profile?

McQUISTAN: The height record will be on a graphical profile. However, some further development is taking place and a digital record may be added later.

OWENS: There has been mention of the signal-to-noise ratio. One way of improving the ratio is to use the synthetic amplitude which could be produced using transmitters in the wing tips of the plane. Is this a possibility?

McQUISTAN: I am not an expert on microwaves but there are some formidable problems in this approach.

POWELL: Could the equipment be used to follow a specific line so as to produce a profile along it? How accurately can it be guided?

TURNER: The flying can be fairly precise. There is no difference between navigating for this measurement and for aerial photography.

HARLEY: If the profiler were used during the aerial photo flights then the heights could be used to scale the model as well as to set it horizontal. Is the maximum measuring height above 10 000 feet?

TURNER: The photo flights are at 25 000 feet and this is well beyond the capabilities of the instrument.

LYONS: The Third Order Levelling has not yet been adjusted, and in the centre of Australia the errors can be quite large. Is it intended to assume the present values are error free?

LAMBERT: Present Third Order values are quite good enough. The mapping only calls for control accurate to 10-15 feet, which is the sensitivity in the plotting instruments.

LYONS: But this is a very different figure from the 0.5 feet mentioned earlier.

PUTTOCK: It will be necessary to record the roll and pitch of the aircraft, since the vertical component is required. Have there been tests in the air, or on the ground.

McQUISTAN: Ground tests have been carried out, with encouraging results. It has been necessary to improve the signal-to-noise ratio, and a test flight in a Dakota will take place shortly.

TURNER: With a good pilot, there will be very little roll and pitch.

(Experience with aerial photography indicates that with good flying, tip and tilt is normally of the order of 1° . On 10 000 feet, the correction will amount to 1.5, 3.4 and 6.1 feet for tilts of 1° , $1\frac{1}{2}^{\circ}$ and 2° resp. - Ed.)

EDITOR'S COMMENT: It is clear that, with present techniques, the precision of

0.5 metres which the apparatus aims to achieve, cannot be utilised; and moreover it is not necessary in the immediate application to 1/100 000 mapping. However, it may be a valuable asset in later applications, where precise corrections will be applied for tilts of the isobaric surface and of the beam.

OVINGTON: Will the profiles measured for the 1/100 000 mapping be available to private companies?

LAMBERT: Yes, the results of all National Mapping control surveys have always been available to the public.

GALE: A fitting final comment for this conference which has brought participants from a number of countries: the airborne profile recorder (APR) was an idea which originated in Australia, and which was developed by Canadian companies.