

The laser for long distance alignment— a practical assessment

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Since completing the work described in the Paper the system has been applied to numerous engineering problems requiring static or dynamic measurements, circumstances demanding at times a particularly high accuracy or prolonged observation of a slowly changing situation. For this the equipment has been adapted and developed and, for certain applications, now embodies electro-optic detection of image position.

84. Examples in which the procedure was (or will be) that used in the field experiments include a rocket sled rail, 1 km long, and the rails of certain ship model test tanks, up to 400 m long, at the National Physical Laboratory (NPL). Results to date confirm the accuracy claimed in the Paper.

85. A commercial installation, supported by NPL consultancy, will shortly be made on the wall of the Upper Glendevon Dam, Perthshire, over a base length of 360 m. Displacement in the horizontal plane of seven positions along the wall will be measured once or twice per year. An accuracy of ± 0.5 mm is expected to be achieved without the application of corrections.

86. The first venture into a dynamic situation came with the measurement of hull flexure on a supertanker during launch; using a base length of 120 m, image movement was recorded photographically. Variations of mid-point position, with respect to end references, were assessed to an accuracy of ± 0.25 mm.

87. An application of particularly topical interest was the measurement of box girder form on a number of bridges and viaducts in the UK for the Department of the Environment. The inherent accuracy of the equipment used was ± 0.25 mm, although the roughness of the surfaces to which the magnetic bases were applied caused some degradation. The equipment is compact, portable and rugged, and carries its own power supply; it has been operated over ranges up to 100 m and has functioned well in vibrational conditions which would have made telescope-based equipment inoperable. Very similar equipment has been used to monitor floor movements during structure testing at the Transport and Road Research Laboratory. Due to exceptionally good atmospheric conditions over the 12 m range and the adoption of a procedure for setting the image symmetrically about a reference line on the screen, an accuracy of ± 0.05 m was achieved in those measurements.

88. A 'mini' version, in which the laser source was replaced by a quartz-halogen lamp, has been used for the dual purpose of measuring flatness of large steel plates and calibrating large mechanical flatness-measuring instruments. In this equipment lenses were used as the image-forming element.

89. For the express purpose of providing a facility for long term recording of data and for monitoring image movements faster than can be followed by eye an electro-optic sensor is being further developed, the prototype having been proved in the field in two situations. In the first, the central deflexion of a 30 m open girderwork railway bridge was recorded during passage of rolling stock over it; in the second, sinkage of trial piling over several days was recorded graphically to an accuracy of $\pm 2\%$ of the total movement.

90. Oscillation frequencies up to 50 Hz can be recorded with acceptable attenuation and freedom from the effects of ambient lighting is ensured by modulation of the light source coupled with optical filtering. In its developed form it will be possible to link it with most forms of data logging.

91. Finally, it is hoped to produce a film of the system and its application.

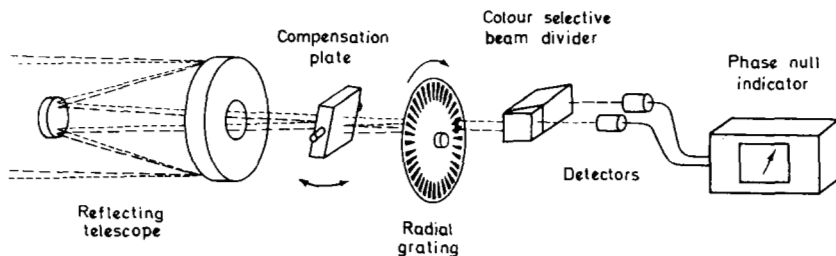


Fig. 7. Schematic diagram of dispersometer

Mr D. C. Williams, Division of Mechanical and Optical Metrology, National Physical Laboratory

In alignment measurements, transverse refractive index gradients are troublesome, and it would be advantageous to be able to make a direct measurement of the amount of bending of the light due to refraction. An attempt is being made at the National Physical Laboratory to do this, based on the fact that blue light is always bent a little more than red.⁵

93. In the presence of refraction, red and blue rays will traverse an alignment path with a slight separation, and arrive at the far end with a small angle between them. If an auxiliary instrument can be placed there to measure this angle using suitable sources, the appropriate correction can be obtained.

94. The angle between blue and red has to be multiplied by 65 to obtain the actual refraction angle which is required. This factor is constant for an atmosphere of given composition, irrespective of detailed conditions along the path, and variations due to humidity are not serious.

95. To measure the dispersion,⁶ the red and blue beams enter a receiving telescope at slightly different angles (Fig. 7) and are brought to a focus in the image plane. The red and blue image spots will have a slight separation which must be measured, bearing in mind that they may be moving about. The composite spot is chopped by a rotating radial metrological grating, and the red and blue beams are passed to separate detectors. This gives two approximately sinusoidal signals with a small phase difference proportional to the spot separation.

96. It would not be satisfactory to rely on electronics to measure the phase difference, so a null measurement is made by placing just before the image plane a tilting glass plate which introduces refraction to compensate that due to the atmosphere. The rotation required to give zero phase difference is a measure of the amount of refraction. At present the plate is rotated manually by a micrometer head, but in principle this can be done automatically with a servo loop, giving continuous read-out.

97. Initial experiments have been performed with a tungsten source, which works well in the laboratory, but the signal/noise ratio would be barely adequate for field conditions and one would have to work at night. Therefore experiments are planned using laser sources. For the red, the helium-neon laser is suitable and, for the blue, a fairly portable helium-cadmium laser has recently been acquired.

98. The order of accuracy aimed at is $1 \mu\text{rad}$ of refraction, which corresponds to $1/65 \mu\text{rad}$ between red and blue, and the principal problem is that the two sources must appear to be in the same place in the absence of refraction to this accuracy. The two beams are therefore passed through a common defining pinhole and allowed to spread. The smaller the pinhole, the greater the spread, so that there is a trade-off

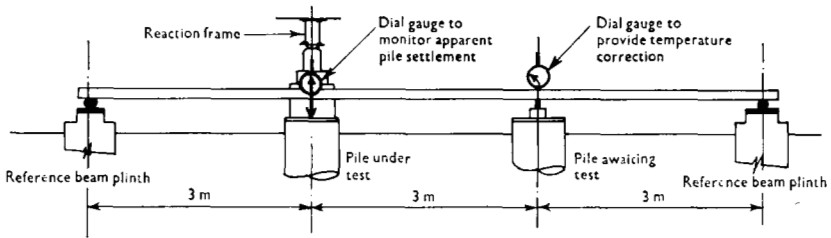


Fig. 8. Diagram of settlement measurement using the long beam

between the amount of light received by the instrument and the accuracy to which the source positions are defined. However, it is possible to work in daylight using band filters and still achieve adequate superposition of the sources.

99. Furthermore, one can put in front of the source pinhole a prism which gives a mirror inversion of the beams. If the prism is rotated by 90° , the beams rotate through 180° , so that the asymmetry is reversed and a mean reading can be obtained which should be correct. Continuous rotation is possible, which also eliminates asymmetry in the prism itself.

100. The two sources do not give ideal point images in the instrument, but diffraction patterns, and the degree of accuracy required is a very small fraction of their widths. Any asymmetries in the diffraction patterns caused by imperfections in the telescope will be different for the red and for the blue, and systematic error will result. This problem can be overcome by placing another inverting prism in front of the instrument and reversing the input beams with different orientations of the prism. Alternatively, the instrument itself can be rotated if it can be made sufficiently compact.

Mr R. B. Dixon, Assistant Bridge Engineer, Kent County Council Sub Unit, SERCU, Department of the Environment

My interest in the equipment outlined in the Paper arises from work currently being undertaken as a joint venture between the Department of the Environment and Kent County Council as site investigation work for the proposed M25 motorway in Kent.

102. Long term vertical maintained load testing is proceeding in Gault clay. In the vertical tests displacement was monitored initially by reference to a datum beam 3 m long, with each end mounted on stub piles. When the first pile was loaded, it became apparent that settlement per increment of load was small, about 0.2 mm, and that the datum piles were moving, owing to ground movement associated with the pile being loaded.

103. A beam 9 m long was adopted for subsequent measurement and although this eliminated the error due to ground movement, it introduced error due to temperature effect which was swamping the pile settlement. This was overcome to a certain degree by mounting the beam on datums so that the pile under test was offset from the centre point of the beam, as shown in Fig. 8. At the same offset, on the opposite side of the centre line, its displacement purely due to temperature was monitored relative to a deep datum in this case test pile awaiting test, thus providing a temperature correction. The system was not very satisfactory, being reliant on the symmetrical behaviour of the beam; in addition, measurement was being made at a 250 mm cantilever to one side of the beam.

104. The Optical Metrology Department of the NPL was approached as it appeared that a light beam orientated system would obviate much of the difficulty

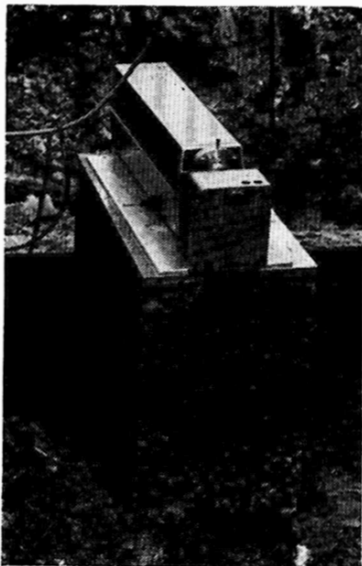


Fig. 9

experienced. On the Authors' recommendation, two systems were investigated; one was a variation of the box girder type of equipment using a quartz iodine source. This device is currently being evaluated in the field. The second system employs a laser source and, having a high beam intensity, auto recording is possible. Datums for the system were a redundant pile and a 5 m³ concrete base.

105. The laser was mounted on one datum (Fig. 9) 6 m from the lens which was contained in a mild steel pack (Fig. 10), so that the lens was positioned at the centre of the pile below the hydraulic jack applying the test load. The sensor was mounted on the remaining datum (Fig. 11) a further 6 m from the lens, thus deflexion measurement was monitored at the point where it was required, that is, at the centre of the pile.

106. After electronic processing of the signal from the sensor, an analogue of pile settlement was displayed on a 250 mm bed chart plotter which was located remote from the test in an instrument house. A second pen on the recorder provided continuous monitoring of the signal strength arriving at the sensor. Beam interruptions could be isolated easily from sudden pile movements since signal intensity dropped simultaneously.

107. The instrument was calibrated so that a pile deflexion of 1 mm produced a full width deflexion in the chart plotter. Increments of force of 150 km were applied and maintained until settlement decayed to 0.1 mm/day, usually taking about 48 hours. The trace resulting on the chart recorder had a noise oscillation superimposed on it of amplitude equivalent to a pile movement of 0.015 mm; in addition, there was a diurnal variation which was difficult to quantify since it could be partly attributed to small variation in applied load due to temperature effects in the load application system. It is felt that both the noise and diurnal variation could be attributed to the proximity of the laser beam to the ground in this case only (75 mm). The position of the beam was fixed because the present test rig was not designed to accommodate an optical measurement system, and on future applications the beam would be repositioned by elevating the three units or excavating a trench beneath the light path.

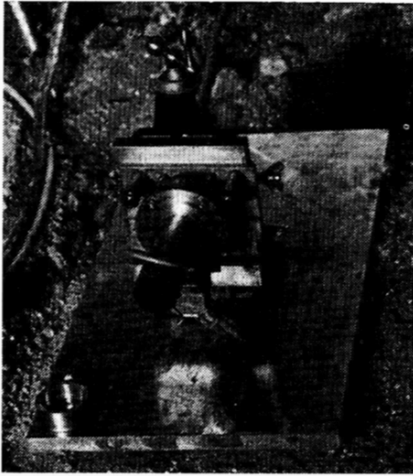


Fig. 10

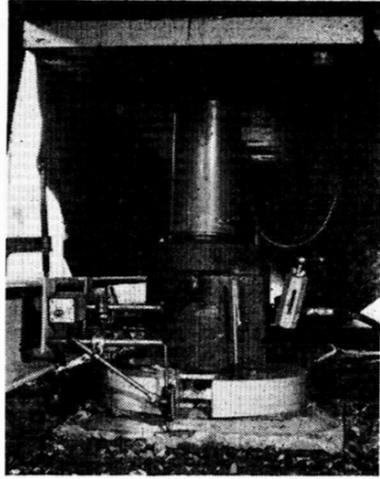


Fig. 11

108. The equipment was running for 16 days continuously and was left unattended at night between 17.30 and 08.30 h. The only problem arose from blockage of the pen system on the recorder, about ten hours trace being lost during the 16 day period. The equipment was calibrated twice during the test and at the conclusion and was found to be satisfactorily calibrated on all occasions.

109. The vertical test programme lasted for about four months during which the site was visited day and night. Savings on supervision cost alone would have been considerable had an investment been made in this equipment from the outset. It would also have been necessary to provide only the two datums instead of five for the vertical testing on the four piles and therefore considerable effort could have been expended to ensure that these datums were free from temperature and ground movement effects.

110. A continuous plot of pile movement would have been produced and operator mistakes eliminated. I feel that, for this type of application, development of a set of equipment recording on paper or magnetic tape suitable for computer input, in conjunction with some form of real time visualization, would be welcomed; perhaps the Authors would comment on any developments in this direction.

Mr J. E. Cheney, Geotechnics Division, Building Research Station

I would like to summarize the requirements for deformation measurement that geotechnics research demands. I use the term 'deformation measurement' deliberately as the need for true alignment, defined as a requirement to place three or more points of a geotechnic structure very accurately in a straight line, is very rarely required in geotechnics. Those involved in geotechnics require measurement of deformation over periods of

- (a) 3-6 hours for a constant rate of penetration pile test
- (b) 1-30 days for an incremental load pile test and to study the effects of tunnelling on adjacent ground
- (c) 1-3 years for construction of large works, such as earth- or rockfill dams and motorways
- (d) an indefinite time measured in tens of years for monitoring behaviour of such latter structures.

112. Concerning pile tests, the current method is to measure the settlement of the pile by manually-read dial gauges or recorded transducers supported from the centre of a steel beam which straddles the test area and has its ends supported on surface pads or piles at a distance judged to be reasonably out of ground movement influence of the pile tested. The beams used are currently, depending on the diameter of the pile and type of test, about 10–20 m long. For many tests these lengths are sufficient.

113. Work by Mr R. W. Cooke and Mr G. Price, of the Building Research Station (BRS), suggests that, when testing a typical pile of 1 m dia., ground uplifts at 10 pile diameters away of the order of 0.05 mm or more can be expected.

114. For research purposes the BRS would like to establish the reference ends at about 15 diameters away. This involves an overall reference length of about 30 m. I think that this length is beyond the limit of practicable beams and the BRS is optimistic of the development of the Authors' system for pile test work.

115. The Authors are suspicious of reference beams and, although I share some of their doubts, much good work has been done using beams fitted with screens and covers to minimize the effects of differential temperature and wind. I am not in any way detracting from the Authors' excellent system when I suggest that, for pile test purposes, the measurement of vertical temperature gradients is not practicable. The sight line in general will have to pass through a *mêlée* of test equipment.

116. I understand that the Authors think that for such relatively short lengths DC or quasi-static refractive curves will be insignificant, but I feel that trouble may be experienced on some sites, particularly in urban areas. It is also not feasible on some sites to await good metrological conditions to time a pile test. I would welcome the Authors' comments as to the suitability of the component parts of their system being established in a near vacuum or a major part of the light path being in vacuum.

117. Mr H. S. H. Thomas, of the BRS, is developing and testing a field vacuum system, utilizing plastic drain pipes, for one of the BRS's optical telescope alignment systems over a distance of about 30 m. I suggest that the Authors' system, particularly in its latest form incorporating accurate optic-electronic sensing, married to vacuum work, may provide the universal pile test reference beam of the future which could be used in any site conditions.

118. Concerning the use for dam and motorway cutting work, where lengths of up to 1 km or so may be involved, I think it would be interesting to try to find a site where the NPL system could be installed. This could be compared with precision levelling for vertical deformation and mekometer electro-optical distance measuring from stable monuments downstream of the dam, or laterally away from the cutting, for the determination of horizontal movement.

119. With regard to the degree of accuracy required in geotechnics, in general, centimetres are of no use, millimetres are useful, tenths of millimetres are very useable and, in certain types of geotechnics work, even hundredths of millimetres are desirable.

Dr A. D. M. Penman, Building Research Station

I want to discuss measurements of movements of a rockfill dam during construction. We had thought that the laser or straight line approach might be useful but realized that a serious limitation was that the reference points on either side of the valley would have to be very close to the dam. In these positions they would be liable to movements caused by the weight of the dam and impounded water and would also be liable to accidental damage due to the construction process.

121. In order to measure surface movements of Llyn Brianne Dam (currently the highest dam in Britain) we established stable reference pillars founded on bedrock at distances of 200–500 m from the dam. The pillars were positioned so that movements could be measured by angular changes or by changes in measured distances. A Kern DKM2A theodolite was used to measure angles and a Tellurometer MA100 electronic distance measuring instrument to measure distances. A Wild N3 precise level was also used to measure settlements. Changes in the three co-ordinates of each

of the points on the dam were found by three methods: by three-dimensional trilateration, by two-dimensional trilateration plus levelling and by three-dimensional triangulation. These methods gave results which agreed to within ± 2 mm of movement and details have been given by Penman and Charles.⁷

122. The sight paths between the pillars and from the pillars to the dam were mainly well clear of the ground surface so that shimmer was not a serious problem and presumably errors due to refraction were minimized. With the alignment system, the sight path would have to be fairly close to the surface all the way and it was thought that this would cause excessive refraction.

123. The potential high degree of accuracy of the surveying instruments could easily be wasted by inaccurate methods of locating the instruments and their targets on the pillars and the points on the dam. In order to minimize these inaccuracies we had avoided the use of tripods and had fitted all the pillars and points on the dam with special centring plates which accepted spigots on the bases of the instruments to close tolerances.

124. I should like to ask the Authors first, if they agree with using alignment close to the surface of a dam or would they use a system where the laser beam was away from the surface? Second, would they comment on the use of portable tripods to support accurate instruments?

Professor A. L. L. Baker, Imperial College of Science and Technology

I should like to ask the Authors under what circumstances is the laser technique better than the theodolite technique? I should think that it is not often worth while to use laser techniques for these very accurate measurements over long distances when the traditional theodolite techniques are still adequate.

Messrs Harrison, Tolmon and New

The point we would stress is that when sighting through the atmosphere over long path lengths, refraction problems will inevitably be present, but that the zone plate system is no worse influenced than others. However, the image on our screen makes their presence more apparent than, say, when viewing through a telescope.

127. We should like to underline the fact that there are several things which can go wrong with an instrument on a tripod. It is being asked to define not only the end of the reference axis but the direction in which it is going. In the system described, where the axis is defined by two units well separated from each other, possibly by many metres, small twists of the units have no effect on the direction of the reference axis. For example, no doubt when the system was used in box girder bridges the latter were vibrating, but this had no influence on the image at the screen. We think that, in this sort of situation, it is a powerful technique overcoming serious shortcomings of instruments such as a tripod-mounted theodolite.

128. When precision levelling, the sight line may curve due to atmospheric refraction. Probably the curvature will be similar when fore sighting and back sighting, and therefore the technique tends to eliminate error. Much survey work does not follow precision levelling procedures, yet we are unaware that any attempt is made to derive corrections by monitoring the atmosphere.

129. **Dr Penman** questioned the desirability or otherwise of carrying out alignment measurements with the 'sight line' close to the surface. Much of our work was done at about 1.3 m but we would prefer 2 m, especially from the viewpoint of safety. Undoubtedly, atmospheric troubles tend to lessen further away from the ground.

130. On the question of tripods and concrete pillars, there are circumstances where the mobility afforded by the tripod is essential. When this is not a consideration, we would choose a concrete plinth every time.

131. **Mr Cheney** spoke of an exercise comparing techniques in situations such as

DISCUSSION

cuttings. If it is essential to be able to operate the system under any climatic conditions, then if a cheap and easily assembled vacuum system can be produced, that is the solution: perhaps the BRS has already accomplished this. To date, we have been diffident about advising the adoption of a vacuum system. The reference alignment bench at the NPL, in which 16 positions over about 150 m are monitored, is, with the exception of laser and detector, completely operating in vacuum, and the image is beautifully steady as a consequence.

References

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