SPIRIT-LEVELLING OPERATIONS

OF THE

GREAT TRIGONOMETRICAL SURVEY OF INDIA.

By MAJOR A. W. BAIRD, R.E., F.R.S., &c.,

DEPUTY-SUPERINTENDENT, SURVEY OF INDIA.

SPIRIT-LEVELLING OPERATIONS OF THE GREAT TRIGONOMETRICAL SURVEY OF INDIA.

By Major A. W. Baird, R.E., F.R.S., etc.

(Deputy Superintendent, Survey of India.)

These operations have for their object the connection of the several Tidal Stations by Lines of Spirit-Levels running along the Coast, and across the continent of India from sea to sea: also the connection of the principal stations of the Great Triangulation which fall in the neighbourhood of the lines of levels, with a view to the rectification of the differences of height, which have already been determined by the less accurate trigonometrical method. Collaterally with these operations a great number of the bench marks of the Irrigation, Railway, and other branches of the Department of Public Works have been connected, with a view to their general combination and reduction to a common datum.

From the origin of the Trigonometrical Survey in India up to the year 1858 all heights were invariably determined by the method of reciprocal vertical angles, between the principal stations of the triangulation. This method is based on the supposition that the back and forward angles are equally refracted, and that the refraction is consequently eliminated in deducing the angle subtended by the excess of the higher station over the lower. But the anomalies and irregularities of the trajectories of light in the lower strata of the atmosphere render it highly improbable that the refraction can be equal in the back and forward observations.

In 1858 the Great Trigonometrical Survey of India commenced a series of Spirit-levels, which up to May, 1862, had been so far extended that the Chach Base line near Attock, the Dehra Dun, and the Sironj, base lines, had all been connected with the Mean Sea Level at Kurrachee, making a total of 1998 miles of double levelling, executed by two and sometimes three independent observers working with different instruments and staves on the same points.

The following is a brief description of the rigorous method of procedure which was laid down by General Walker, and has been adopted in carrying out the levelling.

The instruments employed are Standard Levels, by Messrs. Troughton and Simms, of 22 inch focal length, and power averaging 42—very superior to ordinary levelling instruments. The levels are fitted with finely graduated scales, and have their runs determined by a series of observations on the vertical circle of a large theodolite, and sometimes by a great number of observations to a graduated staff generally set up at exactly 10 chains distant from the instrument. From the mean value of the "run" subtense tables are constructed for use in the field, showing the corrections for dislevelment which are applied to every observation.

As this necessitates a certain amount of computation on the ground, a trained native recorder accompanies each observer, thus dividing the labour, and enabling the surveyor to concentrate his attention on the actual manipulation of, and observations with, the instrument.

To guide in obtaining a true perpendicular the staves are supplied with plummets let into the sides, and visible through glass doors. Swivels are fixed to the tops of the staves for four guy ropes, by means of which they are adjusted and kept steady when once properly fixed. Whenever the staff is set up a wooden peg is previously driven well into the ground, and into the head of the peg is fixed a hemispherical brass brad—which presents a smooth surface, or point on which the brass shoe of the staff rests, and can rotate freely. If the staff is to be set up on a permanent bench mark cut on a stone, the head of a brad from which the spike has been removed is placed on the bench mark, so that the staff may always have a point to rest on.

Starting from a bench mark a brad is used, and also the same precaution is taken when closing on a bench mark. Thus as the levelling operations merely determine differences of height, the levels of the two bench marks "intense" are obtained.

To prevent the possibility of errors in reading the staves escaping detection, the staves are graduated on both sides, one side having a white ground and black divisions (feet, tenths, and hundredths), numbered from 0·00 foot to 10·00 feet; the reverse side having a black ground with white divisions, numbered from 5·55 to 15·55 feet.

Both faces of each staff are observed: thus, two independent values of difference of level are obtained at each station when the instrument is set up, and this forms one set of observations.

The staves are read off to the third place of decimals of a foot, and if the difference between the two values obtained, after the correction for dislevelment has been applied, amounts to ·006, *i.e.* $\frac{6}{1000}$ of a foot, the invariable rule is to repeat the observations. Should the day be unfavourable, sometimes four or five sets of observations have to be taken at a station, and the mean of all the sets taken as the true value.

The instrument is invariably put midway between, or at equal distances from, the back and forward staves, the distance to each staff —which is always carefully measured with a chain—varying from 10 or 12 chains in a clear morning and over fairly level ground, to 3 or 4 chains between 10 and 11 o'clock in the forenoon, when it begins to warm up. The rate of progress is not as rapid as in ordinary levelling operations, but four miles a day may generally be reckoned on.

A second observer with a separate instrument, recorder, staves and khalassies (the men who carry the instrumental equipment of the party) follows the first observer, over the same ground, resting his staves on the same pegs and brads that were used by his predecessor, and carefully comparing the results. Whenever a difference exceeding 0·006 of a foot appears between the results of the two observers the observations are repeated, and should the discrepancy still remain, the prior observer is called back to re-observe, and the second leveller takes the lead. But as a matter of fact this is a rare occurrence.

The rule of equal distances between instrument and each staff eliminates all collimation error in the level, and it also eliminates the effects of the curvature of the earth and all constant refraction.

The line of levels is divided as nearly as possible into equal sections, and adjacent sections are levelled over in opposite directions. Thus, supposing the general direction of the work is from east to west, four miles will be carried out from east to west; the next day four miles from west to east will be levelled over, and so on. Of course the distance one day may be a little more or less than the distance the next day, but it is arranged that the total of all the sections in one direction will be as nearly as possible equal to the total distance of the sections in the opposite direction. Not only is this system carried out in sections, but it is followed to a certain extent at each alternate station throughout the section. Thus in commencing it is usual to observe the back staff first; at the next station the forward staff is observed first; at the third station the back staff is again first observed, and so on.

This system was devised to guard against the accumulation of small constant errors, as it has been found that levelling steadily in one direction is liable to give a different result from what is obtained when levelling in the opposite direction.

It involves a great deal of extra marching (as the whole ground has to be twice gone over), but this is deemed essential for the acquisition of really trustworthy results.

It has been already stated that 1998 miles of levelling had been carried out from the commencement in 1858 up to May, 1862. Between 1862 and 1865 the line of levels had been extended from Agra via Patka Gerouli and Tilliagarhi (near Sahibgunge) to Calcutta, thus adding another 931 miles of levelling to the main line, besides connecting various stations of the Great Triangulation by means of branch lines. The terminal station at Calcutta was the sill of the Kidderpore Dock; but the mean level of the water at Kidderpore is of course very much higher than the mean level of the sea, as although the Hooghly is a river, in which the influence of the tide is felt much beyond Calcutta, yet from the sea proper at the head of the Gulf of Bengal to Calcutta is over 100 miles. Thus no very reliable test of the accuracy of the work could yet be obtained.

Between 1865 and 1872, the levelling operations were for the most part carried out in the North of India. Thus lines of levels from Ferozepore to Lahore and Mean Meer, from Mooltan to Dehra Gazi Khan, and also from Delhi to Meerut, and Saharunpore to Umballa were carried out in one season. Next year from Meerut to Moradabad, Bareilly and Pilibhect was completed, and the following year from Bareilly to Cawnpore via Shajehanpore, Sectapore and Lucknow was finished; the last-named line was continued the next season to Fyzabad and Goruckpore, and on to Dildarnugger. Afterwards the levelling was carried from Goruckpore to Bettia and Mozufferpore to Darbhanga: and next year this was continued to Sahibganj, Purniah and Karagolaghat to Pirpanti, on the main line of levels from Kurrachee to Calcutta.

This completed the levelling in the North of India, and if we include the short line of 71 miles which was carried out in the South of India from Tuticorin to the Cape Comorin Base Line, during the season 1869–70, we have 1705 miles to add to the total of the levelling done up to 1872.

Before discussing the further progress of the levelling, it should be mentioned that the heights in the Great Trigonometrical Survey of India up to 1874 were dependent on determinations of sea-level which were obtained from personal observations on a graduated pole, taken generally at every quarter of an hour day and night for a few days, or at most for one semi-lunation. These observations were carried out at several places on the coast line, viz.: Diu Harbour (in Kattyawar), Karwar, and Mangalore, all on the West Coast; at Vizagapatam on the East Coast, and at Tuticorin near the extreme South of India. At only one place (Kurrachee) had observations been taken with a Self-Registering Tide Gauge previous to 1869; the value of Mean Sea Level which had been deduced from the Kurrachee work was obtained from observations taken over two semi-lunations with that gauge; and on this value depend all the heights in Sind, Panjab, &c.

Systematic Tidal observations by means of Self-Registering Tide Gauges were commenced by the Great Trigonometrical Survey in 1873, when gauges were set up at three places in the Gulf of Cutch. An account of these operations, which were carried out for a special purpose, was given in a paper which the writer read before the Physical Section of the British Association at Glasgow in 1876.

It may be said that at Okha, the station at the mouth of the Gulf of Cutch, the first very accurate determination of mean level of the sea was obtained. Subsequently, in 1877, the Government of India ordered that a systematic record of Tidal observations at selected places all round the coasts of India and Burmah should be carried out. It is unnecessary to refer here to these operations, except in so far as they are considered with regard to determining the exact value of mean sea level at certain places; but it may be stated that Tidal observations are being carried out simultaneously at 20 stations on the coasts of India, Ceylon, and Burmah, including Aden and Port Blair in the Andaman Islands. Besides these, observations have been completed at four other stations, in addition to the three places in the Gulf of Cutch.

As a rule the minimum time of observation is taken to be five years, for the mean level of the sea can be very accurately determined during this period. The mean level as derived from Tidal observations for one year differs slightly from that obtained from observations from the preceding or succeeding year, but the fluctuation in the value is very slight. Thus at Kurrachee, where observations were made during 16 years, the highest level in any year only differed to the extent of 0·148 foot from the mean of all the years, and the lowest differed 0·132 foot; the fluctuations thus amounting to 0·280 foot.

It is a happy coincidence that the hitherto provisionally accepted value of the Kurrachee mean sea level as derived from two semi-lunations agrees closely with the accurate determination from 16 years' observations, and thus all the heights given in the published pamphlets of the levelling operations in Sind, Panjab, North-West Provinces, and Bengal are practically correct.

Between 1873 and 1875 over 600 miles of levelling had been done in Madras, viz.: from Gooty to Bellary, Dharwar and on to Karwar, and also from the Bangalore Base Line via Tumkur and Honoro to Bellary, and thence via Adoni to Raichore.

During this time also the line of levels round the Gulf of Cutch had been carried out, which extended to 304 miles, making with the Madras levelling 905 miles to be added to the total of levelling up to 1872.

The line of levels during the next two seasons had been carried from Torya on the Gulf of Cutch through Kattyawar and on nearly to Bombay, and besides this a large loop line from Shikarpur on the Runn of Cutch to Patri and Viramgam, thus adding 778 miles to the work already executed.

During the next four seasons which ended in 1880–81 the work had been extended to Bombay, and from Bombay to Madras, with a branch line from Poona via Sattara and Belgaum to Dharwar, to join the line of levels from Bellary to Bangalore; and also branch lines from Sholapur to Rijapur, and from Gulbarga to the Bider Base Line had been carried out: and the main line was extended from Kalyan near Bombay to Chikalvohol near Malegam in Khandesh, making in all 1796 miles of levelling for the four seasons.

From 1881 up to the season which has just closed (1884–85), the levelling has been carried from Chikalvohol near Malegam to Mhow and Indore, and on to join the Sironj Base Line in Central India, where the levels from Agra terminated.

Also False Point Tidal Station had been connected with Kidderpore, so as to make the line of levels from Kurrachee to Calcutta end at a tidal station at the sea coast on the east side of India. Lines of levels were carried to Dublat and Diamond Harbour Tidal Stations, and also along both banks of the Hooghly, so as to give bench marks for the river surveyors.

During the last field season Madras and Beypore have been connected, and a branch line was taken from Jollarpet to Bangalore, thus connecting Karwar with Madras and Beypore. This has added 1567 miles to the levelling operations, making in all the magnificent total of 9680 miles of double levelling executed by the Trigonometrical Survey between 1858 and the present year. Besides this some 300 miles of single levelling by branch lines to trigonometrical stations have been levelled over. During this period, there were only two seasons in which levelling operations were not prosecuted. Thus the time occupied in carrying out this vast amount of work has been exactly a quarter of a century.

To give a practical and familiar illustration of the magnitude of these operations, taking the line which runs from Kurrachee up the Indus to Mithankote, and onwards via Ferozpore, Agra, Allahabad, Monghyr and Calcutta to False Point is 2300 miles in length. If this distance be converted into longitudinal degrees for the latitude of London, it represents, say, 53° of longitude; and if stretched out eastwards, would reach from London straight across the Channel through Germany and all Russia to Astrakan. It is most probably the longest line ever run between two seas, and the error in levelling does not exceed 1 foot 8 inches, or under one inch per one hundred miles.

Again, the line of levels taken from the Chach Base near Peshawar, in the extreme North, and extending to Beypore in the South, represents over 22° of latitude, a distance greater than that embraced between the most northerly point of Scotland and the most southerly point of Spain.

The difficulties experienced in carrying out this enormous piece of work have at times been very considerable. Bad roads or want of roads, and having to carry the levels through long grass, and crossing large rivers, such as the Kosi, and more especially the Ganges; and the Hooghly occasioned great trouble. In taking the observations across these large rivers special arrangements had to be made, by pasting on the staves slips of paper divided only into feet and tenths, as of course the smaller divisions on the staves could not be recognised. On these occasions about fifty sets of observations by each leveller had to be made at each long crossing. In going from False Point to Calcutta, and down the banks of the Hooghly to Dublat in Sangor Island, the work was exceptionally troublesome. First of all a very difficult network of creeks at the mouth of the Mahanadi had to be crossed, until "terra firma" was reached on the banks of the Kendrapara Canal. This necessitated wading for about eighteen miles through an extensive jungly swamp, which is wholly covered with water at spring tides, and is never entirely free from it. The stands of the instruments had frequently to be set up in water about two feet deep; and as the soil below was loose and slushy, so that any movement on the part of the observer disturbed the level of the telescope, the first observer had to summon his coadjutor from a station in rear, to read the level at the moment he was reading the staves with the telescope, and then he had to return and perform the same duty for his coadjutor. Various creeks and rivers, ranging from a quarter to three-quarters of a mile in breadth, had to be crossed before Kakrahati was reached, but in all cases the crossing was accomplished by direct spirit-levelling, though occasionally staves with the broad graduation slips had to be used.

To cross the Hooghly in this manner was found impracticable, as the river was considerably over one mile in width at its narrowest part. Temporary tide gauges were set up on both banks, at a part where the main channel and the banks were parallel to each other. Simultaneous readings of the level of the water on both gauges were taken by the two levellers at high water, and also during rising and falling tides. The surface of the water was very smooth, and upwards of 300 observations, extending over four days, were taken. A difference of level of nearly two inches was found between rising and falling tides, but the mean of both differed by only two-thirds of an inch from the level at the top of the tide when the surface of the river was neither rising nor falling; and the general mean may be accepted as within half an inch of the truth, and is probably much more exact than any result which might have been obtained by measuring the vertical angles across the river by any other process.

The following season similar difficulties were experienced along both banks of the Hooghly. But from what has already been said it will be seen that considerable skill is frequently necessary to overcome the obstacles that occur; and indeed at times it was only from the zeal, activity, and good management of the assistant in charge of the detachment that the difficulties were overcome. In 1882-83 the surveyors were harassed and exposed to an extent which induced bad health, panic, and desertion, and it was with very great trouble that the season's work was completed.

Now with regard to some of the results of the operations.

From the mean sea level of the tidal station at Okha, at the entrance of the Gulf of Cutch to that at Bombay, there is an apparent rise of 0·33 of a foot, *i.e.* 4 inches in a length of line of 530 miles.

From the mean sea level Bombay to that of Karwar there is an apparent rise of 0·93 of a foot, or 11 inches in a length of line of 530 miles.

From Kurrachee to False Point there is an apparent rise of 1 foot 8 inches in 2300 miles.

From Bombay to Madras the discrepancy was very great, being nearly 3 feet in 730 miles; also an apparent rise.

From Karwar via Bellary, Bangalore, and Jollarpet to Madras there is a rise of 0·55 of a foot, or nearly 7 inches in 519 miles.

It must be here mentioned that in all these cases it is the southern stations which appear raised above the northern stations. On the other hand the following cases show a reverse result, that is, the southern stations are lower than the northern.

From Kurrachee via Mithankot, Ferozpore, and Agra to Sironj and Bombay there is a fall of 0·62 foot, or 7½ inches in 2030 miles.

From Madras to Beypore a fall of 0·658 foot, or 8 inches in 407 miles.

From Karwar via Bellary, Bangalore, Jollarpet and on to Beypore there is only a fall of 0·1 of a foot, that is, a little more than one inch in 663 miles; or the mean sea level at Karwar and Beypore are almost identical as determined by spirit-levelling.

The first five lines, in each of which the mean sea at the southern station appears to be higher than at the northern, were those first completed. General Walker commented on them in his Annual Report to the Government of India for 1880–81, and suggested that the discrepancy was chiefly due to errors in the levelling operations, caused from a liability to personal misapprehension in reading the bubble of the spirit-level, which may tend to produce a considerable accumulation of error on lines of which the general direction is either towards the sun or opposite to the sun. Owing to the spirit-level being placed above the telescope, the observer gets a side view of the bubble refracted obliquely through the thickness of the glass tube, which is not so sharply defined as the look down view from above. The rim round the bubble, caused by the adhesion of the liquid to the sides of the tube, becomes so prominent that its extremities may be observed instead of those of the bubble. When light falls obliquely on the instrument and either end of the instrument is pointed towards the light, the outer edge of the rim at the end of the bubble towards the light is more clearly defined than the inner, while at the opposite end of the bubdle the inner edge of the rim is the more clearly defined. Consequently there is a tendency to assume the instrument to be level when in reality the end towards the light is depressed, and, though the tendency would probably vary in magnitude with different persons, it is likely to affect all persons more or less. Obviously it is uninfluenced by reversing the direction of the operations, though it disappears when the direction of levelling is at right angles to that of the light.

This illumination error is a maximum on the meridian, and vanishes on the prime vertical. However great its magnitude it is non-apparent in a circuit of levels, and is only apparent on lines starting from and closing on the mean sea, which affords an independent check on the levelling operations. When the operations are carried on between sunrise and mid-day, as is usually the case in India, the direction of the line of average effect would be south-east and north-west; and the result would be to apparently raise the southern stations relatively to the northern ones, though not to the same extent as if operations were carried on throughout the entire day.

It is to be noted, however, that so small an error of level adjustment as 1″·2 of arc recurring with the same sign at only one-fourth of the stations at which the instruments were set up, would produce a discrepancy such as had been met with in the line between Bombay and Madras.

When General Walker made this suggestion, the raising of the southern stations had been found to occur in a greater or less degree on all the lines of levels connecting the tidal stations. Since then, however, the Kurrachee-Bombay line, the Madras-Beypore line, and the line from Karwar to Beypore via Bellary, Bangalore, and Jollarpet have been executed. In the first two of these lines the southern stations are lowered relatively to the northern stations, and in the last line the northern and southern stations are practically identical.

Thus the operations since 1881 throw a doubt on the southern stations being apparently raised relatively to the northern, and the explanation of the Bombay-Madras discrepancy of sea level must be sought for otherwise.

Quoting from General Walker's note already referred to, he says:—
"That there are variations in the general level of the surface of the ocean at different places, so that if compared with the surface of the spheroid or other geometrical figure which most closely corresponds with the figure of the earth the surface of the ocean will in some places be above and in other places be below that of the figure, is probable enough: and indeed this must certainly happen whenever the attracting influences of mountains and other irregularities of the earth's surface on the water of the ocean are not counteracted by deficiencies of density in the strata below the elevated masses. But as the surface of the ocean is everywhere maintained in equilibrium—excepting, of course, the oscillations of the tide—there can be no flow of water from one point to another: thus there can be no sensible differences of level, though some points on the surface may be materially higher than other points as referred to a hypothetical geometrical surface, or, say, the earth's centre. *The differences of height, however considerable, must be insensible, because they cannot be measured by instrumental means; for the causes by which they would be produced must equally affect both the spirit-levels of the instruments and the water-levels of the ocean, whenever both are subjected to the same influences.* Thus if the spirit levels had been carried without error along the coast from Bombay via Cape Comorin to Madras, they must have shown identity of mean sea level at Bombay and Madras, just as has been met with in the Red Sea and the Mediterranean, on opposite sides of the Isthmus of Suez; and in the Atlantic and the Pacific Oceans, on opposite sides of the Isthmus of Panama. And this identity would be obtained even if there were actually a considerable difference of height, as is very possible: for the Western Ghats (or Mountains) and the general greater elevation of the

western as compared to the eastern half of the Peninsula are sources of attraction which if not counteracted must raise the mean sea at Bombay more than 31 feet (as calculated by Mr. Hennessey) above mean sea level Madras."

There seems to remain only two possible explanations of the discrepancy between Bombay and Madras.

First, that it is due to the proximate and local attractions of the hills and table-lands over which the line of levels was carried, and which must exercise some influence on the instrumental levels over and beyond the general influence that is exerted alike on both the instrumental and ocean levels.

Or (second) that the error is due to some accidental gross error in the levelling.

Regarding the former of these two explanations, the spirit levels were carried from Bombay up the short and abrupt ascent to the crest of the Western Ghats near Poona, and then down the long and gentle decline to the east coast at Madras. Thus, while subject to the same general attractive influence of the continental masses as the ocean levels, they are subject also to the more immediate influence of local inequalities in the configuration of the ground passed over.

With regard to the second explanation, it seems improbable that the discrepancy can be due to an accidental gross error, seeing the special precautions which are taken, by the employment of two independent operators and instruments, and the use of double-faced staves, to guard against such errors. Moreover the most probable locus of such an error was believed to be in the section over the Ghats, and this was re-levelled, with the result that the two measurements were identical. Quite lately, too, the last portion of the line (about 50 miles) near Madras was re-levelled, the results of the first and second levelling being identical.

The levelling which has yet to be done to complete the whole scheme is as follows :—

From False Point Tidal Station via Vizagapatam and Coconada Tidal Stations to Madras (see broken lines on the map). Then Erode via Trichinopoly to Negapatam, thus connecting Madras and Negapatam Tidal Stations, and also Beypore and Negapatam.

From Trichinopoly via Madura to Paumben Tidal Station, and from Madura to Tuticorin, where a Tidal Observatory is to be set up.

Also from Nowanar Tidal Station through Cutch via Lakpat to Tatta, to join the line of levels in Sind from Kurrachee to Mithankot, &c.

And a branch line from Marmagão (near Goa) Tidal Station to Dharwar, to join the line from Bombay to Karwar: and at the same time Marmagão and Karwar will be directly connected.

If besides these lines the levels are carried across country from the Bider Base line to Vizagapatam, the whole system will be most complete and tied together in a most thorough manner.

Four, or at most five seasons should be sufficient to finish the whole of this work, and when completed it is likely that the portion of the line between Bombay and Madras, where the discrepancy is generated, may be sufficiently localized as to make it worth while having it further examined; and if with the result of no gross error being found, then it seems to me the only conclusion which can be come to is, that the local attractions on the line operated over has been sufficient to disturb the spirit levels to a very sensible extent.*

* The identity of the mean sea level on opposite sides of the Isthmus of Suez and that of Panama having been questioned during the discussion which followed the reading of this paper at the meeting of the British Association, General Walker has obtained the following information on the subject from the Engineer of the Suez Canal, through Major-General Sir John Stokes, K.C.B., R.E.

1° Le niveau moyen annuel de la mer Mediterranée, à Port Saïd, est le même que le niveau moyen annuel de la mer Rouge, à Suez.

2° D'après les études de la Compagnie du Canal de Panama, il n'y a pas de différence de niveau sensible entre l'océan Atlantique, à Colon, et l'océan Pacifique, à Panama.