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How Surveying Kept Tunnel Builders on the Straight and Narrow – The Albula Tunnel

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Abstract: This year (2024) sees the completion of the new Albula Tunnel under Piz Dschimels (called Giumels in the sources) in the Grisons, Switzerland and is therefore a good opportunity to look back some 120 years at the first Albula tunnel. Construction information and the time line of the original, almost 6 km long, tunnel were published in the Schweizerische Bauzeitung by surveyor-in-charge W. Graf in 1902. One of the many interesting aspects of the tunnel works is how the surveying kept the tunnel builders on the straight and narrow. Graf's article treats us to a glimpse of this in compact form which includes one plate showing the alignments and two photos of some of the surveying equipment used. The surveyors faced similar problems with several longer Swiss tunnels, the Mont Cenis, the Gotthard and the Simplon. A look at the surveying of these and other earlier tunnels also throws light on how the surveyors worked. This paper will attempt to explain how the tunnel portals were located by using triangulation, how the main tunnel axis was set out on site and how the surveyors guided the miners forward. Two teams of miners move along a theoretical common axis towards each other. At the Albula Tunnel one team started from the north-west portal at Preda, the other from the south-east portal at Spinas. The breakthrough took place at 3:30 am on the May 29, 1902. The horizontal displacement of the two halves of the axis was just 50 mm, the vertical just 45 mm. An incredible feat.

Introduction

Having made the decision to build a tunnel, many experts are required to plan and execute the works. One group of experts has the task of guiding the mining works as they blindly proceed towards their target, which can be an exit point on the other side of a hill or mountain or a theoretical point somewhere underground and approached from several directions. Surveyors perfected the art of defining and aligning a tunnel axis, sometimes axes, over many centuries.

Basically the surveyor has to define the position of the start and end of the tunnel and a connecting path between them then guide the miners along that path, usually starting from both ends and sometimes from shafts along the way. Everything is against him. His instruments are not accurate enough, he has no direct line of sight to his target, up until the late 1960s he could not measure great horizontal distances, his plane of reference is not flat or reliably mathematically definable and in the case of working in the Alps, he is either surveying in the worst mountainous weather at high altitude or in hot, humid and smoke filled cramped spaces underground.

1. The first tunnels as a prerequisite to the Albula Tunnel

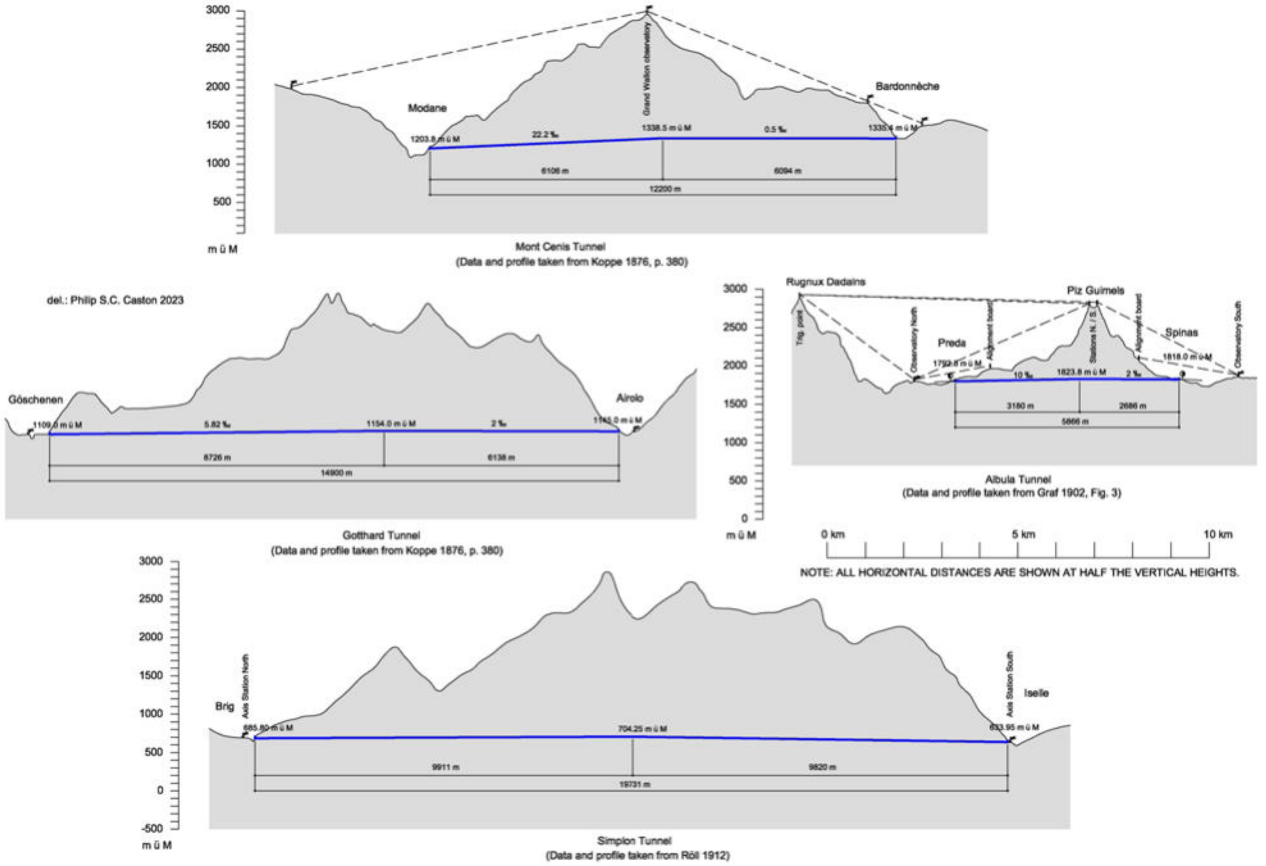
Generally, tunnels were broken down into short sections by excavating shafts along the tunnel axis. Working out from the shafts and from both portals concurrently made the guidance easier and gave the miners more headings. This was a major time saving factor and made the surveying easier. Franz Ržiha's textbook on tunnel works (Ržiha 1872, 173–175) lists 85 well-known tunneling operations in Central Europe and Britain in the years 1770 to 1862 between 100 m and 6000 m in length.

One of the earliest tunnels mentioned is the 3620 m long Thames and Medway Tunnel in the county of Kent, England, started in 1822. A description of the surveying was published in 1838 by Fredrick Simms, which includes a plate showing the transit instrument used (Simms 1838, plate 85). The tunnel headings were started from both entrances and from nine shafts sunk along the main axis.

The axis was initially set out by mounting the transit on a wooden frame and projecting the axis along the ground by rotating the telescope around its horizontal axis starting with a backsight to the entrance and ending with a foresight to a second transit station. The transit was then moved to the new station and the axis continued by backsighting to the previous station then foresighting to the second entrance.

The result was not satisfactory. After days of thinking about the causes, the surveyor and engineer William Clark eventually realized that the wooden frame was not sufficiently stable and suffered from temperature related expansions and contractions. The transit was then fixed to a stone capped pillar, which eliminated the problem (Simms 1838, 2). Simms describes the design and adjustment of the transit in detail in his treatise on mathematical instruments (Simms 1844, 68–77).

We are treated to another insight into the surveying of two mid-nineteenth Century tunnels by Simms in his report on the construction of the Blechingley and Saltwood tunnels



Mont Cenis Tunnel
(Data and profile taken from Koppe 1876, p. 380)

Gotthard Tunnel
(Data and profile taken from Koppe 1876, p. 380)

Albula Tunnel
(Data and profile taken from Graf 1902, Fig. 3)

Simplon Tunnel
(Data and profile taken from Röll 1912)

Figure 1. Comparative terrain profiles and longitudinal tunnel sections: Mont Cenis, Gotthard, Albula and Simplon (Delineated: Author).

(both part of the South-Eastern Railway between London and Dover) (Simms 1859). Both tunnels follow a straight axis. The 1211 m long Blechingley tunnel was started in 1840 and the heading completed by Christmas (Simms 1859, 9), the 873 m long Saltwood tunnel was started in 1842 (Simms 1859, 13). Both tunnels ranged the axis overland, each using a transit instrument with 30 inches (762 mm) of focal length with a cast-iron stand set up on the highest spot. The Saltwood transit was set upon a stone cap atop a brick pier over 30 ft. (9.2 m) high. A wooden shelter encased the pillar and transit and was independently supported (Simms 1859, 21–22).

Due to the relatively shorts lengths of these early tunnels and the simple sighting no trigonometrical surveys were required or complicated angles needed to be measured or calculations undertaken. A lesson clearly learned for practical surveying was the necessity to rest the transit instrument on an absolutely stable base.

When it came to tunneling through the Alps to connect Northern and Southern Europe by rail, shafts were no longer viable. The first long tunnel attempted (between Modane in France and Bardonnèche in Italy – the Mont Cenis or Fréjus Tunnel), c. 40 years before work started on the much shorter Albula Tunnel, had just two headings and a 12.2 km straight axis (Fig. 1).

Clues to the surveying can be found in American engineer Charles Storrow's report on European tunnels published during the tunneling operations in 1862. In it he states that the length of the tunnel was determined by triangulation, one base measured by engineers, another taken from government surveys. An observatory was set up on the highest summit (Storrow 1862, 78).

The July 1871 edition of Harper's New Monthly Magazine (Harper's 1871, 170), published just two months prior to the tunnel opening for traffic gives us more details: "In engineering phrase, the horizontal axis of the tunnel was to be fixed; that is, a line was to be marked out over the crests right under which, no matter how far below, the tunnel should run. In fixing this line the two engineers, Copello and Borelli, to whom the work was confided, encountered great difficulties. […] But it was at length performed, and from the summit of the Great Vallon, 11,000 feet [3352 m] above the sea, down the slope on either side, a line was marked out, right under which the tunnel should run. That the tunnel should nowhere deviate a foot to the right or the left from following this line, lay fairly within the known limits of engineering skill."

Following the opening, the September 21, 1871, edition of Nature (Nature 1871, 415) devoted two whole pages of detailed information to the technical aspects from which the following facts are taken.

The Italian engineers planning the tunnel in 1857 had identified three main problems that the surveyors had to solve: "(1) To fix across the mountain several points which would all be contained in the vertical plane drawn through the axis of the tunnel. (2) To obtain the exact length between the openings. (3) To know the precise difference of level between the two extremities of the tunnel, so as to obtain the proper gradients."

The solution was to first perform a trigonometrical survey, the preparation of which (building stations at each trigonometrical point to support a theodolite and target pole to measure horizontal angles) was completed by the end of 1857. Over the following winter a system or network of 28 triangles incorporating 68 measured angles was surveyed. To improve the accuracy most of the angles were measured 10 times, some 20 and key angles some 60 times over. This must have generated an inordinately huge amount of calculations to obtain accurate axis azimuths, but the effort clearly paid off as the lateral displacement of both headings amounted to "half a yard" (c. 45 cm).

The relative heights at each end of the tunnel were determined by levelling over the summit. This was done once in 1857 and again as a check in 1858 by Signor Mondina. The difference between to two results was 3.93 inches (99 mm), an excellent result over a distance of 12 km. After breakthrough of the two headings during the morning of the 26th of December 1870 the vertical difference between the two levels was established at c. 60 cm. This is equivalent of an angular displacement of less than one arc second over the whole distance. The main vertical plane, which defines the tunnel axis also incorporated one observatory at each end of the tunnel. Each was placed with a line of sight into the tunnel works and consisted of a large masonry pedestal and marble top engraved with orientation lines to align the "instrument" within the vertical plane. The "instrument" is described as being similar to a theodolite, it had a telescope with crosshairs and sat on two supports mounted on a tripod. This could be called a transit scope.

To start projecting the plane into the tunnel the telescope is firstly mounted on the pedestal, then aligned with a signal (at the Modane end, signal Lachalle halfway up the mountain was used), then angled downwards into the tunnel. A cramp iron was attached to the ceiling in the tunnel from which a plummet hung. The plummet was moved along the notched cramp iron until it was visually covered by the cross hairs. This was done by transmitting the instructions by telegraph or horn signals.

The success of the surveying at the Mont Cenis Tunnel came when planning for the next major Alpine tunnel, the Gotthard Tunnel (between Göschenen, Canton Uri and Airolo, Canton Ticino, Switzerland) was finally getting under way (Fig. 1). Surveyor Otto Gelpke (1840–1895) was commissioned to undertake a preliminary survey in 1869. He had previously been engaged in triangulation work for the Swiss Federal Topographic Office. He spent July, August and September planning a trigonometrical survey consisting of a network of triangles and a base line, then supervising the construction of the required trigonometrical point signals, measuring the angles and the length of the base line (Gelpke 1870). The net consisted of 11 triangles and 33 angles. Using his 9-inch (c. 23 cm) diameter theodolite he could take readings of down to 10".

No surveying instrument is 100% accurate and will therefore cause systematic (or mechanical) errors. Similarly, the surveying conditions are not always ideal, which causes accidental errors. Large surveys have to factor in the curvature of the earth and compensate. The measuring of an angle is often a complicated affair. It is usually calculated from at least two angular directions read from a graduated horizontal circle. Sometimes tens of directions are compounded together.

When surveying a net of triangles in a flat plane the sum of all the three internal angles in each triangle should equal exactly 180°. No matter how good a surveyor's measurements are the systematic errors will always inhibit an exact match, in other words the angles won't add up. The minute differences have to be compensated for by spreading them around the system and adjusting the results to take up the compensation. This is a science in itself and the methods employed were highly contested at the end of the 19th Century.

Gelpke gives us some insight into his method. In repeatedly measuring the same angle the collection of results will vary, if ever so small. His solution was to take the average of each set of measurements and use probability calculation and weighted values to even out the adjustments to achieve 180° exactly in each triangle. Then, using the measured base line as one side of one triangle, the coordinates of each of the main trigonometrical point stations were calculated. Similarly, the secondary coordinates and the two observatories were determined, the length of the tunnel between them calculated and the azimuth of the tunnel axis from both ends fixed.

In using several trigonometrical points already established and measured by the Swiss Federal Topographic Office and the Swiss Geodetic Commission Gelpke had a reference to check his results. The largest discrepancy was a 4 cm difference in length over a 10.5 km distance – a negligible amount. In comparing his trigonometrical levelling there was a similar small discrepancy of 97 mm. A further test involved staking out the route based on the triangulation and calculated azimuths overland, but the difficult terrain made it impossible to complete.

As the preparations for work on the tunneling progressed it was decided to rotate the tunnel axis slightly causing the southern observatory to be moved. It was also decided to execute a second, independent trigonometrical survey. This time Gelpke's former assistant Carl Koppe (1844–1910) would undertake the work, which would be published in the Zeitschrift für Vermessungswesen (Journal of Surveying) starting in 1874. He would turn to advanced theory, which at the time was still anchored in academic circles, and use the Method of least squares and equations of condition to solve the calculation of observations. His employer granted him several months leave to attend lectures in Berlin to help him improve his understanding of these calculations (Kobold 1982, 52).

Koppe finally got underway in 1874 with the first trigonometrical station measurements and completed the rest the following year. The result of using the complicated methods and equations was that he could define the accuracy of the network of triangles and the alignments. He calculated the most probable divergence of both tunnel headings at their meeting point to be just ±1.059" (about 40 mm). This is based upon all additional factors, such as projecting the alignment into the tunnel, being perfect (Koppe 1875, 441).

Koppe undertook a test of his calculations by staking out the alignments overland. The modified tunnel axis made this more likely to succeed. The axis was projected from the southern end using four intermediate stations to the summit at Kastelhorngrat. At the northern end, the axis was projected out of the valley to the north to a new station. From there the telescope was aligned back with the axis at the tunnel portal then swung up and compared with the station summit. It revealed a three arc second offset (c. 100 to 150 mm) horizontal displacement (Koppe 1876, 359).

With the new axis sufficiently defined and proven the next challenge was to project it on to the working faces. The method is identical to that already described for the Mont Cenis Tunnel. The transit scopes from that project were modified and reused. The telescopes with their 50× magnification had illuminated cross-hairs.

Each of the two observatories was a starting point for the staking out. The alignments were marked further out along the axis in the solid rock and over both portals, all being periodically re-checked for position. From then on it was just a matter of working forward, but the damp and particle-filled air reduced the lines of sight and cost either precious time in ventilating the headings or setting up multiple new stations (Dolezalek 1878, 186). One technical innovation made the communication between the staking out team considerably easier than before. As of 1875 the different stations could communicate via electric cables using morse.

Section-engineer Carl Dolezalek's 1878 report written after several years of tunneling operations and experience gained reveals the major problem: Time. The equipment needs to work efficiently and accurately. New brightly burning petroleum lamps proved their worth, but had to be modified to keep the flame stable. It was hoped that electric light would improve the performance in the future. Improvements for a more practical tripod were suggested and a design offered. To help adjust the position of the lamp in the axis a finely moveable plate, adjusted using a thread, should be attached to the tripod (Dolezalek 1878).

The probe breakthrough between the headings took place on the February 28, 1880, the main breakthrough a day later. It was clear that the length of the tunnel had been miscalculated by 7.1 m (longer than predicted), but it would take several days before the alignment of the two axes to each other could be established. The comparison was made by levelling between the last benchmark in each heading. The result was a 50 mm difference (Gelpke 1880).

The lateral difference was quickly established to be 25–30 cm or nine arc seconds. In practical terms not a serious problem and the breakthrough was considered a success, but for the two surveyors many questions arose as to where the problems lay. These were never answered as the staking out quickly disappeared in enlarging the headings to a full section tunnel. The tunnel was opened to traffic on January 1, 1882.

Seven years later new surveying work commenced simultaneously on two new alpine tunnels some 135 km apart, the Simplon Tunnel (between Brig in Canton Wallis, Switzerland and Iselle di Trasquera, Italy) and the Albula Tunnel (between Preda and Spinas, Kanton Grisons, Switzerland). Both tunnels have a straight axis but completely different lengths (Fig. 1). Simplon's unbroken 20.1 km length was clearly going to push the surveying to a new level of expectation. It was matched by Swiss engineer Max Rosenmund (1857–1908) who achieved a discrepancy in the length (calculated/measured) of just 0.79 m, a difference in height of the two headings of 90 mm and a lateral displacement of just 50 mm (Rosenmund 1905).

2. The Albula Tunnel

The surveying work on the much shorter 5866 m long Albula Tunnel on the other hand would seem not to be so challenging and efficiency would even dictate a reduction in effort. This is a different kind of challenge but which can also lead to innovation. In preparation for the Albula Tunnel, surveyor Robert Wildberger from Coire undertook a preliminary triangulation net survey in 1896 which defined an observatory each on the tunnel axis at Preda and Spinas (Caprez 2014). None of these original calculations appear to have survived, or at least they are not in the Rhaetian Railway archives in Coire (Chur). Wildberger also staked out a provisional axis plane overland in September 1898 to confirm the preliminary alignments. It allowed work to start on the headings a few weeks later (Hennings 1908). To get the whole Albula Railway project started as quickly as possible, the Rhaetian Railway managed the construction project and further planning using in-house personnel. In July 1898 German born senior engineer Friedrich Hennings (1838–1922) was appointed to run the project's technical department. Surveyor W. Graf oversaw the tunnel surveying and worked in collaboration with Colonel Robert Reber (1850–1911) from the Swiss Topographical Office to measure angles and calculate the length of the tunnel. Graf published valuable data and an insight into the surveying in the Schweizerische Bauzeitung (Swiss Journal of Construction) in 1902, from which the following facts are taken (Graf 1902).

Much work on preparing and calculating the triangulation network was saved by collaborating with the Swiss Topographical Office, who were working on their 3rd order triangulation. By connecting in four new trigonometrical points around each observatory, the observatory coordinates could be easily calculated, then used to calculate the distance between them and from that the exact length of the tunnel. There would be no need to measure a base line distance.

The first angle measurements were made September 3–16 and December 5–8, 1898. By then manual work had started on site. Further measurements were taken in June and July the following year. Unfortunately, Graf's report in the Schweizerische Bauzeitung does not go into the details of calculating the coordinates, but a look Rosenmund's report on the Simplon Tunnel published a year earlier might throw some light on the methods and work undertaken (Rosenmund 1901).

The preliminary field work on the Simplon Tunnel took place between June 17 and July 11, 1898, and included building 11 new signals at the trigonometrical points. The triangulation network would connect into the Swiss triangulation of the 1st order by defining two axis stations (one at each end) using three triangulation trigonometrical points. The first angle measurements were made August 14 September 4 and from September 23 to the October 11.

The surveying teams at both tunnels used 21 cm diameter theodolites, designed for the repetition of angles, manufactured by Kern & Co. AG in Aarau (Fig. 2). Rosenmund recorded that the surveyors measured each angle individually for three reasons: 1) to concentrate on each angle at the best time of day when the signals can be optimally seen, 2) to not be delayed by waiting for sequenced signals to become visible and 3) so that the surveyor does not have to repeatedly change his position.

To make the calculation of the angles in the network easier, all the angles should end up with the same weighting, which would be equivalent to a single angle being measured 48 times. The measurements to be taken at every station were planned in advance. Rosenmund's report contains all the details of the measurements at each signal, the systematic errors and the corrected final angles.

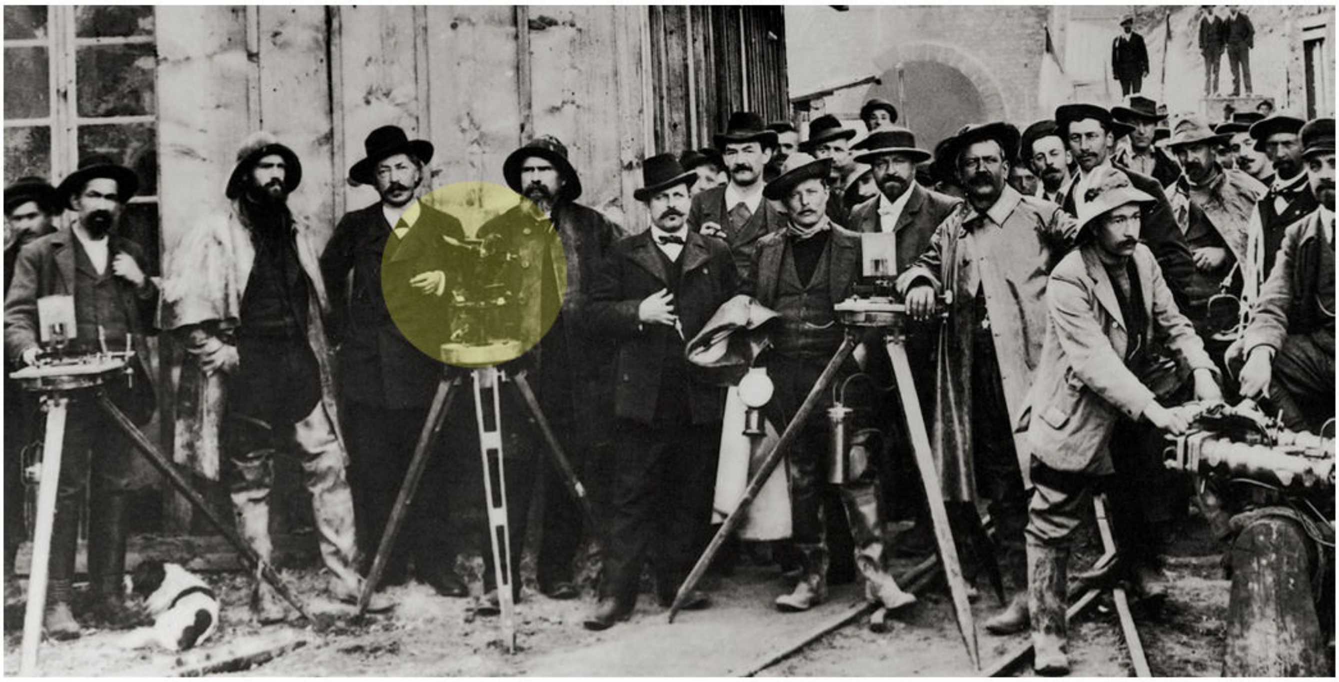


Figure 2. Surveyors and workers display their instruments and tools in Preda, probably just after breakthrough in 1902. Tunnel entrance in background. Detail from a larger site photograph (archives of the Rhaetian Railway, Coire (Chur), reproduced with kind permission).

27 triangles could now be calculated that would make up the triangulation network. On a plane surface all internal angles add up to exactly 180° but over large areas the plane has to be considered as irregular, ellipsoidal or at least spherical. This introduces an excess factor making the sum of the angles larger than 180°. This spherical excess is proportional to the size of the triangle. The largest excess was only 0.25", but an accurate triangulation includes every known variable in the quest for perfection.

Another variable and source of inaccuracy is the directional variation of the pull of the earth, usually directly downwards, but subtly changed by large masses (such as mountains). The effect was calculated for each trigonometrical point, the maximum value being five arc seconds.

Finally, to calculate the triangulation the whole network was projected on to a flat plane intersecting two of the trigonometrical points and the remaining trigonometrical points then being expressed as coordinates in Cartesian form (x and y axes at right-angles). The angle corrections were applied to calculate the final angles with the highest probability. The final result was an average error of ± 0.70" and the most probable error of ± 0.45" over a distance of 20,091 m (between the two axis points). This is equivalent to a lateral divergence at the meeting of the projected axes at the middle of the tunnel of ± 46 mm (not including staking out errors). The highest probable error in calculating the length was 0,56 m and a maximum height divergence of 90 mm. The closeness of the final results (see above) is a testament to the method and the surveying.

Having measured and calculated the positions of the two main trigonometrical points on the theoretical tunnel axis (called observatories in Graf's report and axis stations in Rosenmund's report) and calculated the angles to at least three surrounding trigonometrical points and the tunnel axis itself (azimuth), the next step in the surveyor's work is to physically mark the tunnel axis on site and undertake the staking out the axis as guidance for each heading.

The Albula tunnel axis was set out from both observatories. A theodolite was placed at each observatory, the telescope of which was then orientated to each of the trigonometrical points in turn and rotated around the vertical axis by the calculated angles to point at the tunnel axis. Although not specifically stated in Graf's report this process would have been repeated many times with each alignment being marked in some way, then the average of the multiple markings taken as the definitive alignment. Graf describes an axis point in the vicinity of the heading, but does not describe it in any detail.

Once the axis points are established, the theodolite's telescope can be used to project the axis plane overland, ideally both planes would intersect at a common point and confirm the axis. The Albula tunnel axis runs directly under the western of the two Piz Dschimels peaks, slightly offset to the southwest of the summit (2777 m above sea level). At almost 1000 m higher than the Preda portal the axis intersects the ridge at one point giving a clear line of sight to the Preda observatory, but then runs along a slope and intersects with another ridge which blocks the line of sight to the Spinas observatory. This meant that two stations, 15 to 20 meters apart, had to be set up each with its line of sight to its own observatory.

Colonel Reber and surveyor Graf used a theodolite with a 24 cm diameter graded horizontal circle. The stations were marked with poles firmly cemented to the granite rock. These poles would serve as the main targets in the tunnel axis plane for the theodolite at each observatory.

In addition, a secondary target called an alignment board was set up between the observatory and the main target each at approximately one kilometer distance from the tunnel portal in the hills for orientation in bad weather when the summit was not visible. Each of the two alignment boards consisted of a white one m^2 panel marked with a 20 mm wide black stripe. The stripe was established by repeated alignment (ten times) from each observatory.

Figure 3. Theodolite pillar, 29. August 2018 (Image: Author).

The first new station in the staking out of each axis was set in the heading at circa 60 m from the portal. As the heading followed the tunnel invert and the sides and roof would be chopped out later to form the full tunnel section the stations were set in the floor. The station consisted of a 30 cm diameter block 50 to 70 cm long set into the floor in concrete. Iron nails with a five to six cm diameter head were sunk headed into the log, then marked to define the axis.

To establish each mark as the stations progressed along each heading three teams of surveyors were required as described above, one operating a lamp at the backsight, one operating the theodolite and one operating a sliding plate marker on a tripod at the foresight. Communication between the survey teams took advantage of telephone. The cables were limited to 600 m in length. Back- and foresight lighting was still not electric, but achieved by a recently patented acetylene gas powered lamp.

Graf reports that the theodolite telescope was turned around both axes to eliminate non-collimation during the staking out process and repeated twice each time with the horizontal circle moved through 60°. Each reading was marked on a strip of paper alongside the sliding plate at the foresight. This whole process was repeated four to six times depending on the importance of the accuracy of each station.

A plummet transmitted the average of the markings on the paper strip to the nail heads in the floor. In addition to the main stations which guided the axis along the projected route and which where the domain of Graf, intermediate stations were projected forward by the construction team to guide the miners. At intervals of 300 m these would be checked by Graf and if necessary corrected.

The final set of stations were staked out March 28–31, 1902. The headings then continued forward until they met on the May 29. Breakthrough took place at 3:30 am. It just remained to continue the alignment from the last stations forward to determine the exact deviations and the surveyor's honour or shame.

The lateral deviation measured 50 mm, the difference in height 48 mm the length discrepancy turned out to be 1.15 m (shorter).

In terms of lateral deviation per kilometer: Albula = 8.3 mm; Simplon = 10,0 mm; Gotthard = 22 mm and Mont Cenis = 33 mm.

In terms of difference in height per kilometer: Gotthard = 3.3 mm; Simplon = 4.5 mm; Albula = 8 mm and Mont Cenis = 49 mm.

In terms of distance per kilometer: Simplon = 39 mm; Albula = 192 mm; Gotthard = 473 mm and Mont Cenis = unknown.

The variance in the values between the tunnels is not relative to their actual length. Other factors such the quality of the mathematics used, the quality of the surveying equipment and the accuracy with which the measurements were made determines the outcome. Of the four tunnels under consideration here the Albula scored the best in the lateral deviation, was behind the Gotthard and Simplon in the difference of height and lay between the Simplon and Gotthard in the distance per kilometer.

3. Physical remains of the surveying operations

It is theoretically possible that the station blocks with their metal nails are still buried in the invert, but as the tunnel is still in service, it is not possible to determine any remains. I could find no evidence of the alignment boards. It is not clear how they were anchored to the ground. Using GPS, it is possible to calculate positions along the tunnel axis close to where Graf describes both of them. The terrain also narrows their location down to a searchable area, but despite repeated searches I could find no trace of any foundation or pillar that could have supported a board. There is also nothing left of the southern observatory.

A pillar is however located at the northern observatory at approximately N46°35.556' E009°45.990' (Fig. 3). Graf describes the construction of the signal pillars in his report as a stone and mortar pillar with an 80 mm diameter iron pipe at its center, in which a 75 mm diameter, two meters tall, wooden target post could be inserted (Graf 1902, 285). The accompanying illustration shows a section through the construction. A truncated pyramid one meter high with a flat upper surface 50×50 cm sits on a 80×80 cm, one meter deep foundation. There must have been an adapter for centering the theodolite over the pipe of which there is no record. The simplest device could have been a plate with a pin on its underside to center the plate in the pipe and three engraved radial lines to centre the theodolite over the pin/plate. Possibly it was more complicated.

Having found the northern observatory, I had hoped that the stations on the summit of Piz Dschimels would similarly still be there, but according to a local mountain guide there are no remains of any pillars, just a plateau where possibly a pillar could have been erected.

Graf also gives us an insight into the surveying equipment used with an image of a foresight station sliding plate illuminated target along with the acetylene gas generator canister required to generate the gas for the extremely bright flame. The gas generator was an innovation, patented by Dr. Rudolf Gerster on June 3, 1899 (Patent 1899) after work on the headings had started, just in time for use by the surveyors as the headings proceeded forward. The sliding plate target is similar to the design used by the Gotthard Tunnel surveyors (Dolezalec 1878, plate 744).

Figure 4. Surveyors with a level at the place of breakthrough (photograph in the archives of the Rhaetian Railway, Coire (Chur), reproduced with kind permission).

Graf's report also treats us to an image of the smaller of the two theodolites used during the surveying work - the 21 cm diameter graduated horizontal circle with a 10 arc second resolution used in the staking out of the tunnel axis in the heading (the second larger 24 cm diameter graduated horizontal circle theodolite with a five arc second resolution was used at the Piz Dschimels summit stations). This theodolite can be seen in a group photo of the miners and engineers taken in front of the northern portal, probably taken after breakthrough in May 1902 (Fig. 2). The fore- and backsight tripods with their sliding plates are also proudly presented.

It is quite likely that the theodolite is unit number 16659, made by Kern & Co. AG in Aarau and delivered to the Rhaetian Railway in March 1899. Such an instrument is recorded in the original order book (no. 28) held in the Kern & Co. AG assets collection in the Aarau City Museum. The order book contains a brief description of the instrument and its type number: 172.

This can be cross-checked with Kern's own price-courant brochure (Kern 1897). By chance Kern produced a brochure in 1897 with a detailed description of the instrument. Number 172 is the only 21 cm diameter graduated horizontal circle instrument with two Vernier scales on opposite sides of the circle listed. By the order date of the theodolite in 1899 the headings had progressed circa 180 m inward from the Preda portal and circa 100 m inward from the Spinas portal (Hennings 1908, plate 24) and by its delivery at the end of May the Preda heading had progressed another 700 m. This instrument was possibly ordered to specifically take over the staking out deeper into the headings, although the timing could just be a coincidence. The theodolite cost 945 Swiss francs.

The Kern order book also records a second order by the Rhaetian Railway nine months later for the week beginning on Tuesday, January 2, 1900. Two levels, type number 111, unit numbers 16856 and 16867 were to be delivered. These could have been used in the tunnel or elsewhere along the line. Unit number 16867 and its carrying case are on display in the Albula Railway Museum exhibition in Bergün. At 190 francs it was almost five times less expensive than the 21 cm theodolite.

This same order also includes five construction theodolites type number 141 (costing 456 Swiss francs each and less than half the price of the 21 cm theodolite). The 1897 Kern price-courant brochure gives its price three years earlier as just 400 Swiss francs and includes an illustration of the instrument. The construction theodolite is listed under the heading Universal Level Instruments. Its telescope can be angled up and down slightly but cannot be fully rotated vertically through 180°. The smaller 12 cm diameter graduated horizontal circle is limited to one arc minute resolution. The instrument is clearly not good at measuring horizontal angles with great accuracy. It is a level and designed to project a horizontal or tilted plane. Its balance screw allows the crosshairs to be adjusted vertically. Of the five instruments produced for that order unit number 16872 has survived and is also on display in the Albula Railway Museum exhibition in Bergün.

This could be the construction theodolite level shown at the breakthrough of the two headings in a second image stored in the Rhaetian Railway's archives (Fig. 4). This image also includes three gentlemen seen in the figure 2, one wearing a Homberg style hat (W. Graf?) and two with beards and long coats. Whilst der 21 cm theodolite staked out the tunnel axes laterally, the level would have transferred the heights and gradients forwards at the same time.

These two images confirm the instruments used in the staking out operations. The actual level or at least one from the same original order has also survived and allows a haptic encounter (even if it is currently behind glass). With a little imagination to fill out the details one can visualise the theodolite at the northern observatory, it being aimed at a target on the summit of Piz Dschimels then aimed down into the heading. Then the long projection of the axis into the rock using back- and foresight moving forward with every new station. Every step is a challenge to the success of accurately following the tunnel axis plane. After three years and mounting excitement came the breakthrough and the final result. Was it to be a vindication or a major embarrassment?

Conclusion

The surveyors involved in guiding the miners towards a common meeting place underground from two starting points almost 8 km apart had to be confident of their methods to achieve success. This involved designing and building a triangulation network of stations, then taking readings at the stations of the other stations to calculate angles, recalculate the angles to azimuths, staking out the two tunnel axis azimuths, then projecting them underground to meet at the desired place.

The instruments used were at their limits and had to be used carefully. Only the clever use of surveying theory stopped blunders and eliminated or minimised systematic errors. Once underground there was no way of orientating directly with the calculated target. The alignments had to be correct. The project depended on the surveyor's ability. The correct meeting of both tunnel axes would not only minimise the completion work to be done but define the surveyor's reputation.

After three years of planning, measuring and staking out surveyor W. Graf, responsible for the operations at the Albula Tunnel, must have been anticipating the outcome. The approaching headings would have been increasingly audible as they closed in on each other. That would be a first indication that the alignments were at least reasonably correct. Work stopped on the Spinas heading a couple of days before the breakthrough and deliberately overshot the meeting point. Now the Preda heading had to continue forward to intercept the Spinas heading. On the May 29, 1902, at 03:30 am at breakthrough any doubts about the surveying would have been quickly dispelled as it was instantly clear that both headings were visibly perfectly aligned. Later a 50 mm lateral displacement and 48 mm height difference would be calculated. That is the equivalent of 1.29" error over the eight kilometers between the observatories or a quarter of the smallest measurable angle using the 24 cm theodolite. An incredible achievement.

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