Carl Zeiss: The Development of Levels during the Past 25 Years, with Special Emphasis on the NI 002 Optical Geodetic Level and the DiNi® 11 Digital Level

Matthias Menzel

1. The History

The history of Germany after World War II is manifest in the history of a number of German companies, including Carl Zeiss. The development of levels is a case in point. After the war, the political situation led to the existence of two companies bearing the name of Carl Zeiss - one in Jena, East Germany, the other in Oberkochen, West Germany. Each of them designed, manufactured and sold surveying instruments levels independently of one another, and not exactly in an atmosphere of mutual friendship. Things changed after the German reunification in 1990. The reunited Carl Zeiss took advantage of the chance to concentrate efforts and develop technically advanced instruments such as digital levels.
My brief historical outline will cover the past 25 years of level design at Carl Zeiss. For better understanding we will occasionally cast a glance further back [6],[7].

From 1973, Oberkochen developed such instruments as the Ni 22 (1966), the Ni 20 (1972) and the Ni 3 (1980). They are all simplified versions of the Ni 2 of 1950, the first engineering level to have a compensator pendulum which automatically keeps the line of sight horizontal. Until today, in 1999, customers in need of a level providing geodetic accuracy have been specifically asking for a Ni 2 - a request that could be satisfied for many years.
With the attached parallel-plate micrometer, the Ni 2 allowed the mean error per kilometre to as low as 0.3 to 0.4 mm. An improvement on this was achieved with the Ni 1, another automatic geodetic level launched in 1967. The difference was in the pendulum suspension: it had crossed steel ligaments instead of the traditional four-bar linkage. Telescope power was increased to 50x, and the micrometer was integrated into the instrument.
In parallel, Oberkochen developed the Ni 4, an automatic construction level launched in 1980. A successor of the Ni 42 of 1971, the Ni 4 now had a conventional levelling base with footscrews. And, not to forget, 1976 saw the launching of a non-automatic "bubble" level Ni 52 for the building industry. The routine levels Ni 30, 40 and 50, with medium and lower accuracies, were added to the line in 1991 and are still part of it.

In the period from 1973, quite a number of levels were designed in Jena too. First and foremost I should mention the NI 002 of 1973, an automatic geodetic level of superior precision. I will deal with it in detail later in my talk. In the years after, a number of further automatic levels were created, such as the NI 020A (1982), the NI 005 A (1983) - actually a NI 020 A with integrated micrometer - and the low-end NI 040 A (1983). Also in 1983, the NI 021 bubble level was launched. The series A levels, from NI 005A to NI 040 A, were accuracy-graded to match different user requirements in the medium-to-low accuracy range. Flexibility in application was ensured by a wide range of accessories. Manufacture of the same series, with a slightly changed styling and a different name, is continued by a company that is a legal successor to the former state-owned "Carl Zeiss Jena" enterprise.
The NI 002 soon came into widespread use. Encouraged by the favourable response, Jena presented two further levels in 1988 forming a design series: the NI 002 A and the RENI 002A. The NI 002 A was a strictly optical level with almost all functions identical to the NI 002. The RENI 002 A, having the same accuracy, was the first step towards a semi-automatic level, with optical staff reading entered into an on-board computer, and digital micrometer reading - features which made operation much more convenient. What remained

for the operator to do was to manually align the telescope crosshairs with the staff graduation. This semi-automatic technique was the state of the art until 1990, when Leica presented the world's first digital level, the Na 2000.
That was the time when not only the two Germanys but also the two Carl Zeiss companies in Jena and Oberkochen were reunited.
The reunited Zeiss made an important decision: to start a development effort for a digital level in 1992. The Jena R&D team had already gained some experience in the years between 1983 and 1985, when the Dresden University of Technology did research into digital levelling for them under a contract. The digital levels DiNi®10 and DiNi®20 were launched at the 1994 Intergeo. A year later, the first digital levelling total station, the DiNi®10T was presented to the surveying community in Dortmund. An upgraded series of digital levels comprising DiNi®11, DiNi®21 and DiNi®11 T were added to the range in1996. Essentially, the upgrading consisted in the use of a PC card as a memory medium for the DiNi®11 and DiNi®11T models, and an increased speed of measurement.
For the sake of completeness, I should mention the development the Ni 10 in 1994, an optical level which has always remained in the shadow of the Ni 2.

2. The NI 002 (NI 002 A / RENI 002 A) Geodetic Level

Figure 1: NI 002 A

When the NI 002 was presented to the surveying community in 1973, nobody foresaw that this opened a new chapter in geodetic levelling. Despite probable conjecture to the contrary, the instrument had not been designed with suitability for *motorized levelling* in mind, although tests with motorized levelling, using other levels, had been made already in the late sixties, by a team headed by Prof. Peschel of the Dresden University of Technology. The NI 002 was designed to satisfy the most exacting demands of height transfer in general. The fact that it also met the requirements of motorized levelling was merely, and almost incidentally, an added advantage of the concept. A detailed description of the NI 002 family and their performance parameters can be found in the literature [4, 5 and 1]. Let us focus here on those features of the instrument that bear upon its scope of applications.

The instrument's well-proven accuracy of ± 0.2 mm/km is achieved by its design concept, which includes the unique reversing mirror compensator (with the pendulum mirror suspended at half the focal distance, and measurements made with the mirror in an initial and a reversed position), the designed-in accuracy of this compensator, system focusing by means of shifting the pendulum mirror, and an objective micrometer. These elements provide what is called a "quasi-absolute horizon". The mean of the two readings is nearly independent of the distance between instrument and levelling rod. The features described eliminated the need to keep the backsight and foresight distances exactly equal and raised horizon stability to a new level of quality. With the NI 002 it is thus possible to carry out precise lines of levels without equalizing backsight and foresight distances to within 10 cm. The greater freedom of instrument stationing is an advantage also in industrial applications. Before, precise area levelling was only possible with relocating the instrument several times, while the NI 002 and its successors can remain at a single station, from which sightings can be taken to targets at different distances.

3. The DiNi®11, DiNi®21 and DiNi®11T Digital Levels

3.1 Instrument features

Comprehensive descriptions of the Zeiss digital levels, their mode of operation and accuracies are given elsewhere [2 and 3].
In this context I want to point to some particular features. For measurement, the DiNi® needs a staff segment of only 30 cm, which is frequently an important advantage under practical surveying conditions. This type of staff reading is very close to the common classical method. The user interface with its four-line graphic capability display and the extensive key panel leave nothing to be desired. The on-board software includes all surveying methods you can think of, and different language versions are a matter of course. Users of instruments purchased some time ago can order updates so as to keep their software at the latest state. The DiNi®11 and DiNi®11T models have PC cards as memory media, allowing the user to work on any number of projects (i.e. with any number of data files).
These features have meanwhile earned the DiNi® a high reputation worldwide.

Figure 2: DiNi®11 T Digital Level with horizontal circle

Frequently, questions are raised on the accuracy of height and distance measurements as a function of the sighting distance, also in connection with the use of the DiNi®11T (DiNi®10T) with expanded staff segment. The DiNi®11T (DiNi®10T) is used with a staff segment of 100 cm for greater distance accuracy. Height reading, however, still uses the 30 cm segment only. Questions about the obtainable accuracy arise where digital levels are to be used not only for lines of levels but also for structure monitoring and special measurements. It is difficult to make generally valid statements on accuracy, because it depends on various parameters. The next graph illustrates the accuracy of a single height measurement, determined from repeated sightings, as a function of distance.

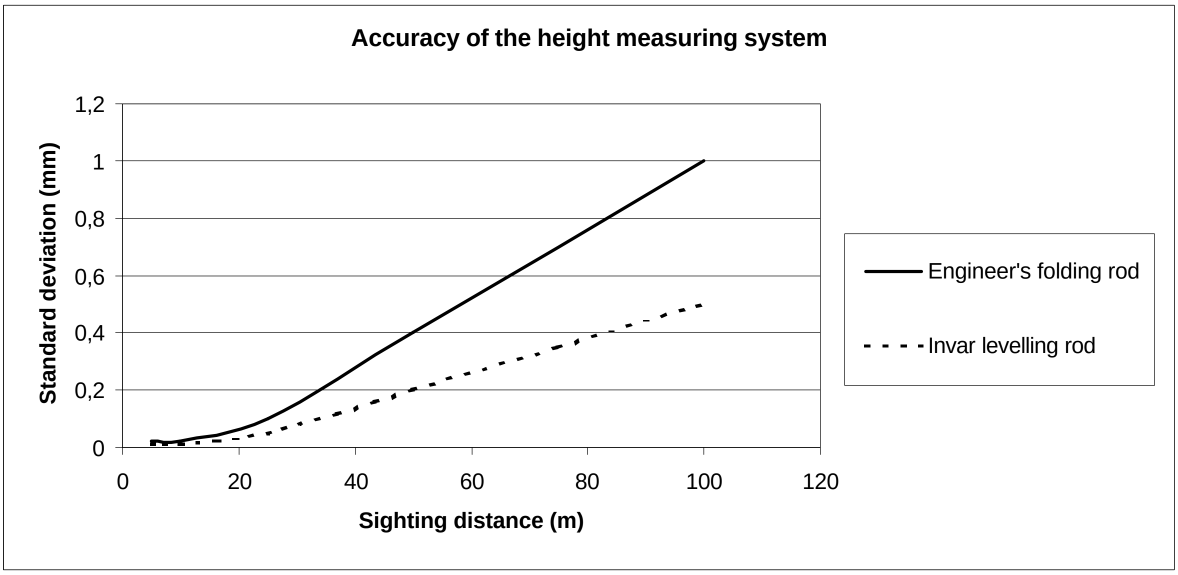

Figure 3: Obtainable accuracy of the height measuring system as a function of sighting distance and type of staff, determined from repeated sightings

Whether these accuracies can be achieved in a specific surveying job in a specific field situation remains to be analyzed by the user. Factors to be considered include the different sighting distances to be used, and the accuracy to which the line of sight can be adjusted.

The next illustration shows the distance measuring accuracies obtainable with the DiNi®11 and DiNi®11T instruments and the two different staff types.
These accuracies can also be described as follows:

DiNi®11T with Invar staves: $\sigma = 0.5\ D * 0.01$ (D in m)

DiNi®11 with Invar staves: $\sigma = (0.005 + 0.00002\ D + 0.00003\ D^2) * 100$ (D in m)

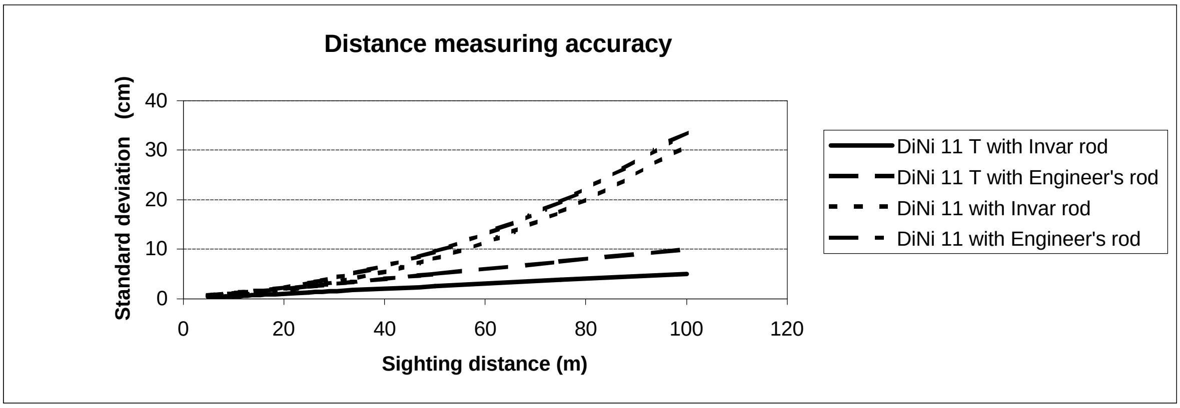

Figure 4: Obtainable distance measuring accuracy as a function of sighting distance and staff type

3.2 Remarks on using digital levels

While the DiNi® has a highly accurate electronic staff reading system, its mechanical and optical design is that of any other ordinary level and quite unlike that of the NI 002. Digital levels are therefore prone to influences known from other precise levels of earlier make.
One of the parameters to be considered is the instrument's temperature behaviour. Given the existence of an on-board computer with memory and an automatic reading system, it suggests itself to make allowance for the inclination of the line of sight with temperature (known as temperature response), and correct it. This is possible provided that this effect remains constant throughout the instrument's lifetime, and provided the availability of a simple function that efficiently corrects the error. The deviation of the line of sight from the horizontal due to temperature has various reasons. The error determined by the user or manufacturer results from different factors, such as the accumulated effect of thermal expansion coefficients of the various materials involved (glass, metal, plastics). Rarely ever can the individual causes of the temperature response be singled out. The history of instruments has seen mechanical temperature compensators, in which different materials were used deliberately to move some element in a staff reading raypath and thus produce an effect counteracting the temperature response. Attempts were made in the past to prevent temperature responses in precise levels from exceeding 0.3 " to 0.5"/K. Given the capabilities of the digital level, these effects can now be reduced even further. This has been accomplished for the DiNi®11 and DiNi®11 T levels. Fig. 5 shows, for example, the temperature responses for a DiNi®11 with correction.

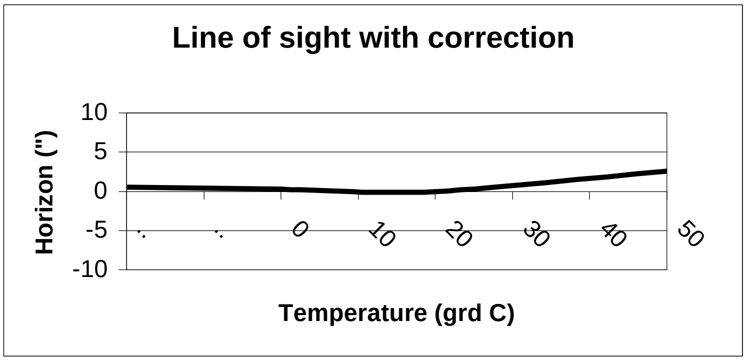

Figure 5: Temperature responses for a DiNi®11 with correction

The presently used correction procedure is backed by investigations that involved measurements at a great number of temperature intervals and included extremely stressed instruments to simulate a long lifetime. The validity of the correction is checked by consistent quality inspection. One should mind, however, that the correction works only with an instrument that has had time to adopt the ambient temperature. There is no possibility to shorten this time. The thumb rule still applies that the waiting time for precise levelling should be 2 minutes per degree of temperature difference. Temperature balance may be achieved slightly faster in this or that instrument, but this does not lead to any significant differences.

Another problem to be always considered in "normal" precise levels is the residual compensator error. The pendulum movements in precise levels are almost linear in the range in which the pendulum is to correct the instrument's inclination. Manufacturers take every effort to make the pendulum set to the horizontal as precisely as possible. Despite adjustment to a pendulum factor of 1 (for both the mechanical and optical effects), and despite meticulous care in designing and assembling the pendulum and the vertical axis system, a tiny angular error of 0.1 to 0.15" may occur between foresight and backsight. Provided that lines of levels are run with consistent procedures, this angle constitutes a systematic error. A residual

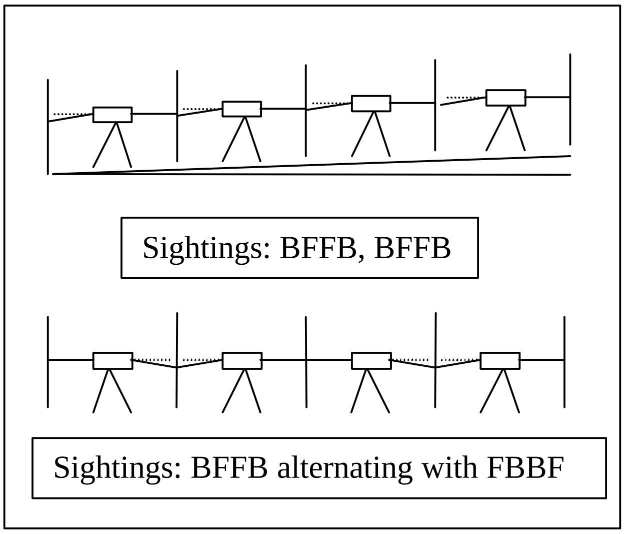

Figure 6: Measurement methods

compensator error of 0.2" means a misclosure of a circuit of levels of about 1 mm. The advantages of the digital level (fast measurement, no subjective errors) help identify this error better than ever before. In the past, these errors were part of the random error and could not be ascertained, while now they can be found out even if they are very small. The conclusion to be drawn from this is that precise levelling jobs with a digital level of known make should in any case be performed by the alternating method (back/fore/fore/back - fore/back/back/fore), also known as the "red pants" method.

The accuracy obtainable with a level is implemented via the correct horizontal alignment of its line of sight. It is impossible, however, to keep the line of sight absolutely stable over many hours of work and at any temperature.
It is therefore necessary to check and correct the line of sight from time to time, especially before running precise lines of level under conditions with heavy temperature fluctuations, and after excessive mechanical stresses.
In optical precise levels known so far, users have made measurements by the familiar methods (Förstner etc.) and shifted the crosshairs to the nominal reading by a small amount. The crosshair line thickness is about 2" to 3". Accordingly, the changes and settings made with an optical level in the past must have been in the order of several seconds of arc.
With digital levels, the digital form of results gave rise to some uncertainty, as there is no experience with the necessary amount of correction in digital terms. In the digital level, adjustment of the electronic horizon is made by a computed off-centre position of the linear CCD array, which plays the part of the crosshairs in the electronic system. Where the instrument is used for optical measurements, the crosshairs can be shifted to the nominal staff position after the electronic adjustment. A graphic representation of the changes observed against time provides a good overview and helps to make the right decision. Adjustment measurements repeated in succession yield differences of 2" to 3" under normal ambient conditions. With measurement under identical conditions, changes from day to day should not exceed 3" to 5".

3.3 Use of digital levels for special jobs

Digital levels can be used for checking and monitoring heights on structures and other objects. The DiNi®11T (DiNi®10T) with its digital horizontal circle is particularly suitable for such jobs. Two stepping motors can be attached to drive the lateral slow-motion and focusing screws. A control computer can be programmed for taking sights and readings at any number of staff segments fixed at the structure points to be checked. After program teach-in by carrying out a manual cycle of measurements, the computer will repeat the cycle any number of times at user-determined time intervals. The computer releases the instrument and recording functions via the RS232 interface. The necessary equipment configuration is available from manufacturers collaborating with Carl Zeiss.

Figure 7: DiNi® 10T modified for the monitoring of structures

4. Comparison between NI 002 and DiNi®11

From the explanations given it is obvious that the NI 002, by its very design, has the edge over the DiNi®11 on accuracy, whereas its lack of automatic reading relies heavily on the operator's concentration and involves the risk of subjective error.

Figure 8: A DiNi in field use, Denmark, 1998

In addition to digital reading, digital levels have the decisive advantage that they register the complete data in a form capable of electronic processing and in a minimum of time. The results are less affected by staff subsidence and similar effects. Since the digital level brought automation to levelling procedures, many users have come to appreciate its capabilities for smooth, reliable and accurate surveying, the more so as does not take days to learn its operation. Although accessories such as the right-angle eyepiece are available and, in fact, employed in *motorized levelling*, digital levels are still little used for this method, compared to the NI 002 and its successors. This is for reasons that have little to do with the different capabilities of digital levels. On a worldwide scale, the present demand for large precise levelling projects is very low. In addition, motorized levelling takes too much manpower - a factor that will probably lead to a future phase-out of the method. A third reason is that historically developed attitudes towards *motorized levelling* in general differ from country to country. Some countries do not use it at all.

5. Summary and Outlook

After a look back on the history of level designing at Carl Zeiss in the past 25 years, I have discussed some technical details of the NI 002 and DiNi®11 instruments and their applicability, including their usefulness for the well-known method of *motorized levelling.* Although they differ by their technical capabilities, both instruments can be used for *motorized levelling.*

The new DiNi® digital levels, which almost come up to the accuracy of the NI 002, make levelling jobs considerably easier for the surveyor. Their data logging, storing and processing capabilities and the elimination of subjective errors are of crucial importance to all applications of precise levelling. In top-precision surveying jobs involving widely differing sighting distances, the present digital levels cannot replace the NI 002 family.

References:

[1] Feist, W.: Das Präzisionsnivellier Ni 002A - ein Instrument für hochgenaue Höhenbestimmung in der Meßtechnik. AVN 2/1994. S. 56-63.

[2] Feist, W., Glimm, A.., Marold, T., Rosenkranz, H.: Die Total Level Station DiNi®10 T - Das erste digitale Nivelliertachymeter. VR 58/1. S. 1-7.

[3] Feist, W., Gürtler, K., Marold, T., Rosenkranz, H.: Die neuen Digitalnivelliere DiNi®10 und DiNi®20. VR 57/2. S. 78-89.

[4] Hüther, G.: Das neue Präzisionskompensatornivellier NI 002 des VEB Carl Zeiss Jena. Jenaer Rundschau. Sonderheft zur LFM 1973. Jena 1973. S. 56-60.

[5] Hüther, G.: RENI 002A und NI 002A - zwei neue Präzisionskompensatornivelliere. Jenaer Rundschau. 1988. Heft 4 S. 160-164.

[6] Jenaer Rundschau. 1983 Heft 1. Beilage der Jenaer Rundschau 75 Jahre Zeiss-Jena-Vermessungsgeräte.

[7] Köhler, H., Meier, H.-K.: 30 Jahre Forschung und Entwicklung im Zeiss Werk Oberkochen, Kapitel 7.6 Geodätische Instrumente. Carl Zeiss Oberkochen 1990.

[8] ZEISS Vermessungs-Instrumente. Firmenkatalog Nr. 520431 CARL ZEISS Oberkochen/Württ. 1969.

Address of the author:
Dipl.-Ing. Matthias Menzel, Carl Zeiss Jena GmbH, Geschäftsbereich Geodätische Systeme, Tatzendpromenade 1a, D-07743 Jena, Menzel@Zeiss.de .