INSTRUMENTATION OF THE NINETIES

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1. Introduction

Technological progress, changed measuring tasks and steadily increasing accuracy requirements necessarily lead to the new and continued development of measuring instruments. The following article is intended to provide an outlook on future instruments, this topic being considered from two viewpoints:

1. New development of instruments that will be commercially available in the near future.
2. Publication of some investigation results which provide information about the technical capabilities of measuring principles and methods that might lead to the development of new instruments.

From the viewpoint of new instruments, only the precision inclination meter NIVEL 20 will be briefly described, since the Laser Tracking System also to be expected in 1990 is presented in a separate publication.

A second part describes the technical possibilities for the further development of distance meters based on the measuring principle used in the Mekometer ME 5000. In particular, we will report on the possibilities for the development of a two-color distance meter and a distance meter for short distances (2 m - 200 m) with accuracies in the area of 10-20 μm.

2. Precision Inclination Meter NIVEL 20

2.1 Design and Operation

NIVEL 20 is a high-accuracy sensor for the measurement of deflections of the vertical in two dimensions. The magnitude and the direction of a deflection of the vertical can be determined with one setup of the sensor. The inclination-sensitive element is a liquid in a closed container. The liquid's surface is perpendicular to the direction of the vertical, independently of the sensor's orientation. The inclination of that surface relative to the sensor is measured by optical means. All the optical components needed for that purpose are fastened to the underside of a flat glass plate. The plate also forms the bottom of the container with the transparent liquid. By means of the optical components, the luminous surface of an LED is imaged in a position-sensitive photodiode. The light from the LED is guided from below through the flat glass and the liquid, is totally reflected at the liquid's surface, and then passes again through the liquid and the flat glass. Finally, the photodiode detects the position of the impinging light spot relative to the zero position which was adjusted and calibrated in the horizontal configuration (see Fig. 1).

The flat glass plate, serving as a component and simultaneously as the support for the actual sensor element, is clamped into a trough-shaped metal base. The sensor is set up on three hardened and ground circular support surfaces on the underside of this base. The support surfaces have through holes for M4 screws in the center. On the metal base is placed the printed circuit board with the analog amplifiers and, optionally, a CPU card with a serial interface. The sensor is covered with a plastic hood. The plastic serves primarily as a thermal insulator which is meant to prevent external heat effects from causing nonuniform thermal expansions in the interior of the NIVEL 20 and consequent measuring errors. A temperature sensor is also installed to monitor the sensor's temperature. The direction of the measurement axis X is established by a stop edge on the metal base. The measurement axis Y is perpendicular to it. A bubble level is used for rough determination of the horizontal. The values of inclination in the X and Y directions and the sensor temperature are available as measurement values. The standard version of the NIVEL 20 has and RS-232 or RS-485 serial interface, the latter having the capability of operating up to 32 NIVEL 20s in the same network. A NIVEL 20 with analog outputs is provided for special applications.

1 LED
2 Imaging optics
3 Liquid
4 Liquid container
5 Biaxial position detector

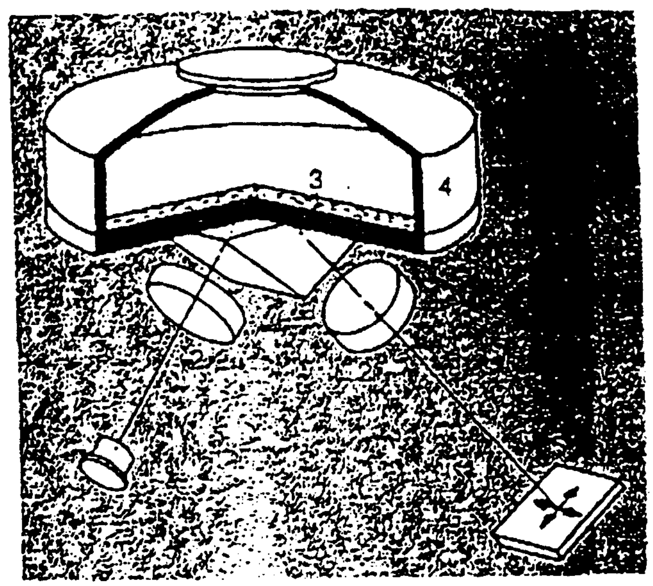


Fig. 1

Functional Principle of the NTVEL 20 Inclination Sensor

2.2 Scope of Application and Specifications

Thanks to its wear-free, sturdy and thermally stable construction, the NIVEL 20 is suitable for use even under extreme conditions in industry, research and construction trades. With available accessories it is possible to put together complete measuring systems suitable for many applications such as the setting up and aligning of machines and systems, flatness measurements on tables, monitoring of systems and structures, and many others.

Sensor Specifications (Valid For Both Measuring Axes):

Measuring range (deflection of the vertical	±1.5	mrad or mm/m
	±5.2	arc min
Linearity error	±(0.005 + 0.5% d.M.W.)[1]	mrad or mm/m
	±(1 + 0.5% d.M.W.)	arc set
Resolution	0.001	mrad or mm/m
	0.2	arc set
Zero-point stability	<0.005	mrad/K
	< 1	arc set/K
Operating-temp. range	-20 to +50	°C
Storage-temp. range	-30 to +60	°C
Relative humidity	10 to 95	%
Dimensions (LxWxH)	ca. 90x90x63	mm
Weight	ca. 850	g
Supply voltage	9-15	V DC

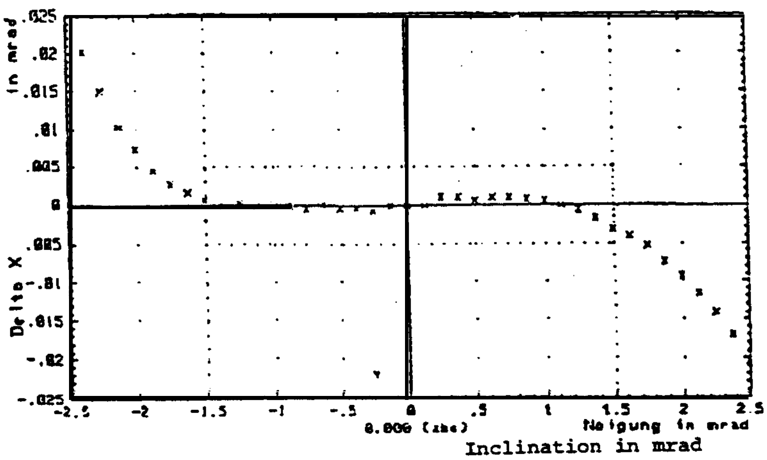
Interfaces:

Analog version	Sensitivity	1000	mV/mrad
Digital version	Serial interface	RS-232 or RS-485	
	Baud rate	2400; 9400; 19200	baud

2.3 **Measurement results**

The graphs of two linearity error measurements shall be used for illustration. The measurements were performed at room temperature on a prototype sensor, once for inclinations in the X direction (Fig. 2) and once for inclinations in the Y* direction (Fig. 3). The tiltings were done without lateral inclinations.

The linearity error and the absolute inclination are indicated in mrad on the vertical and horizontal axes, respectively.



Inclination in X Direction

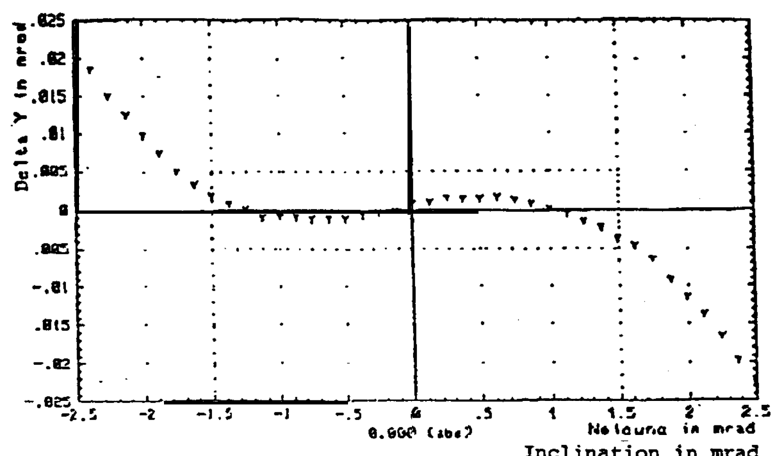


Fig. 2

Inclination in Y Direction

* 1 Tr. note: Probably stands for “des Mittelwert” (of the mean value) or “des Maximalwert” (of the maximum value).

3. Tests With A Two-Color Distance Meter

3.1 General Discussion of Two-Color Distance Measurement

In the two-color method a distance is measured simultaneously with red and blue light /1/. The different propagation speeds of the light waves in the atmosphere result in two different distance values. The basic formulas (e.g., of Owens /2/) for calculating the propagation speed of light in the atmosphere as a function of wavelength, temperature, pressure and humidity are known for distance measurement with one color. The same formulas are used as the basis for calculating the distance in the two-color method. The reduction of a two-color measurement is very simple if a common propagation path is assumed.

We have:

$$D = L_{red} - A \cdot (L_{blue} - L_{red})$$

with

$$\frac{A = N_{red}}{(N_{blue} - N_{red})}$$

D = reduced distance

L_{red}, L_{blue} =	are distances measured with red and blue light and calculated with the speed in vacuum
N_{red}, N_{blue} =	are the indices of refraction refraction reduced by 1, calculated by the formula of Owens (n - 1)

Since the refractive index for both colors depends linearly on the air density, i.e., on the temperature and air pressure, the coefficient A is independent of pressure and temperature in first approximation. However, the water vapor causes another wavelength dependence, and the influence on the factor A is determined primarily by the variation of the mixture ratio of the atmosphere.Differences of 1º C or 1 hPa cause a distance change of about 0.001 ppm, while a change of the water-vapor partial pressure by 1 hPa results in a distance change of about 0.1 ppm.

Due to the refraction gradients in the zenith direction, the blue light beam deviates upward by about 10 cm at a distance of 30 km. This effect must be taken into consideration in an exact two-color distance formula /3/. The neglect of this effect results in an error of <l mm ($3 \cdot 10^{-8}$) for a distance of 30 km.

As is evident from formula (l), the atmospheric correction results from the difference between "red" and "blue" measurements and from the factor A. Since the factor A in our setup (HeNe and argon lasers) is about 34, the error in the difference measurement due to the distance reduction of 0.1 mm is increased to 3.4 mm.

The first setup of a two-color distance meter was intended to allow basic tests of such a measuring system, to discover critical points and to create the foundations for estimating the attainable accuracies.

3.2 Description of the Two-Color Distance Meter

In principle, distance meters based on the FIZEAU principle offer high resolution and accuracy. The objective was to develop a measuring system that can measure the red-blue difference to an accuracy of about 0.05 mm at 15 km. This value corresponds to a distance uncertainty of 1.5 mm ($1 \cdot 10^{-7}$).

FIZEAU System

In the FIZEAU system (see Fig. 4) a light wave is modulated twice, once at transmission and the second time at reception.

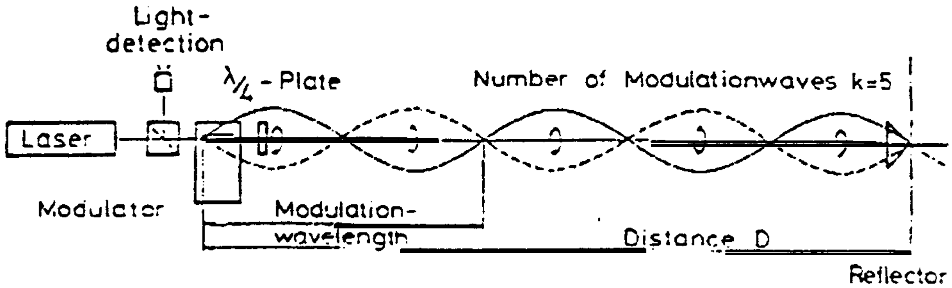


Fig. 4.

Fizeau System in the Tuned State

As with the Mekometer ME 5000, this system works with a variable-frequency polarization modulation of the light in the 500 MHz range. The frequency is shifted until the light detection is minimal (minimal point or 0 phase). This means that at this frequency there is a whole number of modulation wavelengths in the measurement path between the modulation crystal - reflector - modulation crystal.

We have:

$$2 \cdot D = k \cdot \text{modulation wavelength}$$

with

modulation wavelength = c/f

K = number of mod•wavelengths in 2•D = f/df

f = modulation frequency

df = frequency difference between 2 minima

The variation of the modulation frequency and thus of the modulation wavelength can occur only within the limits of the modulation bandwidth.

Determination of the Distance

To determine a distance it suffices to measure the frequency of a minimal point (fine measurement) and to measure the frequency difference between two minimal points (coarse measurement). At large distances especially (> 10 km), a somewhat greater effort in the measurement of this frequency difference is necessary to avoid coarse measurement errors.

In our case, the determination was made via “quasi”- simultaneously measured pairs of minima at a maximally large frequency spacing. “Quasi”-simultaneous means alternating measurements at the lower and upper modulator band limits. After the measurement of 5 adjacent minima at the lower and upper band limits, the “spacing” of these groups is performed by seeking out and measuring other minima at doubled frequency spacings until the middle of the band is reached. Thus, for a distance of 5 km another 12 measuring points are obtained until the overlap in the middle is reached. Thus, a distance measurement of 5 km consists of 22 “red” and 22 “blue” frequency measurements distributed over the entire modulator range. The individual frequency measurement consists of an averaging of 4 frequency values weighted with the corresponding O-phase deviation. All measurements and the complete measurement sequence of the two-color distance meter are controlled by a laptop computer. A complete measurement takes about 10 minutes.

System Design

In a first test the setup shown in Fig. 5 was tested. It involves two complete FIZEAU systems which have common optics and two lasers as light sources (HeNe 7 mW, argon 5 mW). The advantage of two complete systems lies in the continuous and simultaneous measurement of the distance with two colors. The disadvantage lies in the possibly less stable difference of the mechanical-geometrical addition constants.

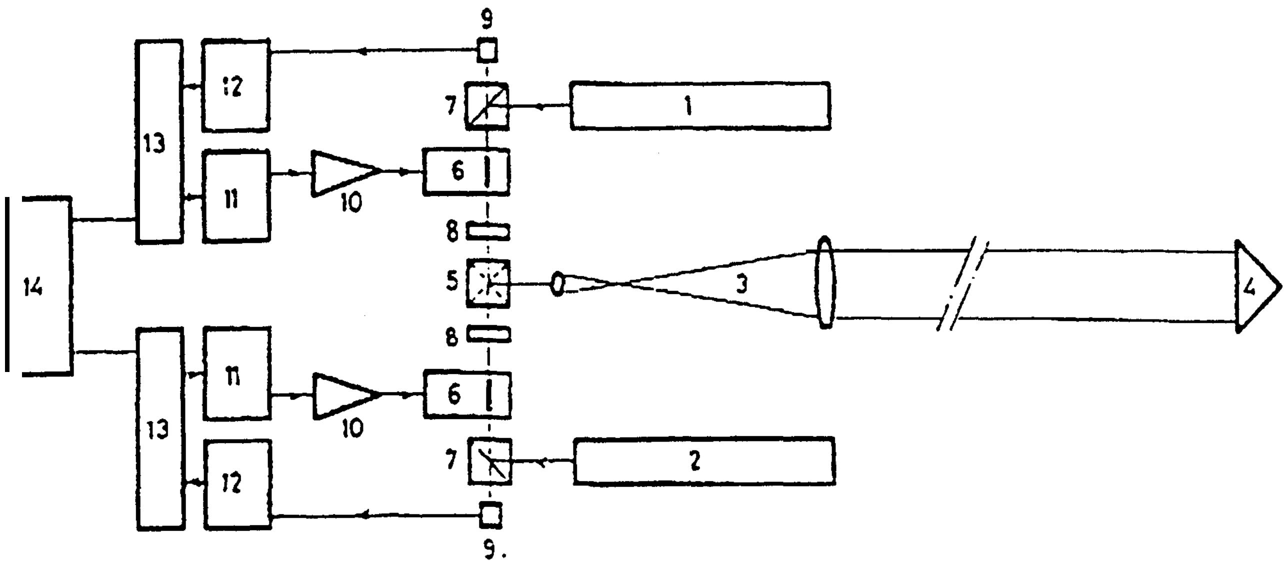


Fig. 5

Block Diagram of the Distance Meter with Two Modulators

(1) Red laser (He-Ne)
(2) Blue laser (argon)
(3) Transmit/receive optics
(4) Reflector
(5) Red-blue splitter
(6) Modulator
(7) Pol. beam splitter

(8) $\lambda/4$ plate
(9) Light detector
(10) Power amplifier
(11) Synthesizer
(12) Lock-in detector
(13) Controller
(14) Laptop computer

3.3 Results and Knowledge Gained

With this two-color distance meter built from two Mekometer ME 5000 electronic assemblies, a series of test measurements was performed at distances between 200 m and 10 km on different days. Some considerable inaccuracies were found, and the average errors reached values on the order of 3-4 mm. These results were basically within the expected range, and the actual primary goal of investigating the overall system and discovering the critical points was largely reached. A detailed working paper was produced with a number of points to be noted in developing such an instrument. In the following we report only on the crucial information for the user.

To estimate the maximum attainable accuracy, the master oscillator (10 MHz quartz crystal) was replaced by a Hewlett-Packard synthesizer, thus making it possible to perform the phase-O tuning in extremely small frequency steps.

The maximum measured distance resolution was about 0.02 ppm at 5 km, i.e., 0.1 mm. When a “red” and a “blue” minimum were measured simultaneously, atmospherically determined short-term drifts of equal order of magnitude could be found with an uncertainty of about 0.1 mm. By integrating over a measurement time of 5-10 minutes, a maximum resolution in the red-blue difference of 0.05 mm can be envisaged. This means that the basic accuracy of a two-color distance meter is about 1 mm, if an extrapolation factor of A = 22 can be assumed (see Equation (1)). However, especially in the measurement of large distances, calm atmospheric conditions are necessary to achieve this order of magnitude. Thus, the two-color instrument unfortunately is also again dependent on the atmospheric parameters.

For distances over 10 km, the signal quality necessary for optimal accuracy can be obtained only with correspondingly large reflectors. An array of 3 x 3 reflectors with a diameter of 60 mm each seems about right from the size standpoint. However, if the alignment is not sufficiently good, problems may arise for the red-blue difference because of the previously discussed divergence between the red and blue light beams.

A better solution is the Cassegrain configuration known from the Terrameter /4/. Besides treating the red and blue light waves identically. it also yields no additional polarization components.

4. Precision Distance Meter for Short Distances

The Mekometer ME 5000 was originally designed and developed as an exact distance meter for the measurement range of from 20 m to 8000 m. The first experiences with the ME 5000 already showed that the potential hidden in this instrument far exceeds what is guaranteed by its specifications. By using a computer to control the ME 5000's measurement sequence, a certain expansion of its measuring range and possible applications could be achieved. In the meantime, the Development Department of KERN had begun to build a functional sample to be used to estimate the possibilities of this measuring principle. For this reason, the results of a series of test measurements are available which serve as the basis for the development of a precision distance meter for short ranges.

4.1 Possible Specifications as Basis For Development

The objectives in building the mentioned functional sample were oriented primarily toward the characteristics of an instrument for the general geodesy market. Only after the merger of WILD LEITZ with KERN did the aspect of maximum attainable accuracy become more important again. For this reason, with respect to instrument size and measuring time and also with respect to accuracy and shortest measurement distance, realistic requirements that far exceed the usual improvements made in a developmental step can be imposed as a. basis for development. The most important specification features as well as a few key words indicating how the technical solution is possible are listed below.

The FIZEAU principle already described in Section 3.2 and the distance-determination solution applied in the Mekometer ME 5000 serve as the basis.

Shortest Measurement Distance < 2 m:

The raising of the modulation frequency from ca. 500 MHz to 1.3 GHz the modified construction of the modulator and the special programmability of the frequency drift for the zero-point detection permit unambiguous measurement of distances < 2 m.

Measuring Time < 5 Seconds:

The time needed for the measurement of a distance depends on the speed of the synthesizer, the time for the signal integration, the measurement algorithm and the computation speed of the CPU. A completely new synthesizer circuit design with transient buildup times in the range of 1 millisecond and the test results with correspondingly short integration times make the requirement for a measuring time of < 5 seconds seem realistic.

0.001 mm Resolution Time of the Measuring System:

The special coupling of the synthesizer circuit makes possible not only the relatively large frequency steps that are necessary for high speed, but also an extremely small step on the order of 0.1 ppm, which corresponds to a distance resolution of ca. 0.001 mm at 5 m. Under the assumption of an averaging of several measurements and taking into consideration the influence of temperature (0.2° C corresponds to 0.001 mm at 5 m), this value is surely sufficient.

Measuring Accuracy <0.01 mm + 0.1 ppm:

The tests showed that the temperature compensation by means of a $\lambda/4$ plate with a semiconductor laser works better. Ideas also exist concerning a better optical isolation of the sensor beam from the reflected light.

The coupling with an exact angle-measuring system,
the use of small reflectors
and the instrument size of 120 x 120 x 70 mm are other specification features.

4.2 Results of Test Measurements

A series of test measurements was performed with the available functional sample. Although the controller software of this instrument setup met only the simplest requirements, informative results were obtained.

At ranges between 2 m and 200 m a large number of measurements was performed in which individual instrument parameters were tested at a wide variety of settings. Figures 6 and 7 show two representative results.

5. Summary

The new NIVEL 20 and Laser Tracking System instruments document that in the field of instrument development technological progress necessarily leads to a continuous improvement of instruments and measuring methods.

The descriptions of the possibilities for further development of the Mekometer principle provide evidence that much more could be realized technically. Another prerequisite for the beginning of a new instrument development is that corresponding results can be expected on the economic balance sheet. Unfortunately, at this time there is no funding plan for the two possibilities presented here for the development of distance meters, and so for the time being there are no plans to implement these projects.

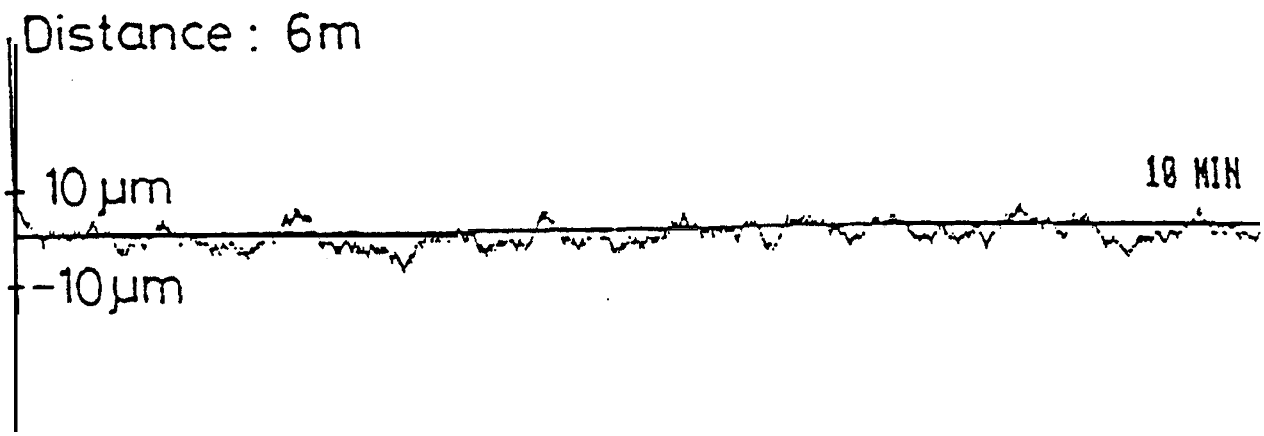


Fig. 6

Continuous Measurement For 10 Minutes

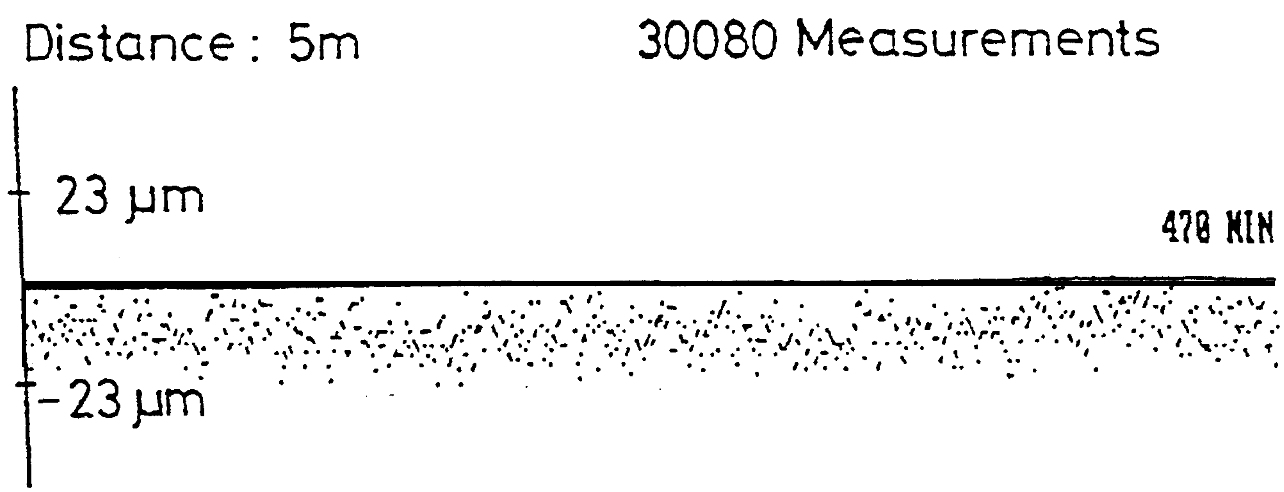


Fig. 7

Continuous Measurement For 8 Hours

Selected literature:

1. Owens, J.C. : Laser Applications in Metrology and Geodesy. Published by Ross M. Academic Press, NY/London (1971)

2. Owens, J.C. : Optical refractive index of air. Applied Optics, vol. 6, No. 1, pp. 51-59 (1967)

3. Hübner, W. : On the use of dispersion for electromagnetic measurement. DGK, Series C, No. 310, Munich (1985)

4. Huggett, G.R. and Slater, L.E.: Recent advances in multiwavelength distance measurement. Proc. Int. Symp. on EDM and the Influence of Atmosph. Refr., Netherlands Geod. Comm. Published by Richardus P, Wageningen, pp. 141-152 (1977)

5. Meier, D. and Loser, R. : The Mekometer ME 5000 - A new precision distance meter. AVN, no. 5, May 1986

6. Meier, D. and Loser, R. : Experiments with a two-color distance meter. Ingenieurvermessung 88 published by Schnädelbach/Ebner, Vol. 1, Dümmler Verlag, Bonn

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