Design and Specifications of OPCON

An optical system for instantaneous sediment concentration measurements

Report on Investigation

R 716 part VI

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J.J. Bosman

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Statistical notations

\[ E[X] \]  
expected value of random variable \( X \): \([X]\)  
average of a stochastic variable or process over all possible values taken from the same population. Each value is weighted by its probability.

\[ \text{Var}[X] \]  
variance of random variable \( X \): \([X]^2\)  
mean of squared deviations from the expected value.
DESIGN AND SPECIFICATIONS OF OPCON

An optical system for sediment concentration measurements

1. Introduction and conclusions

1.1 Terms of reference

The interaction of water and sand has been subject to many studies, but still the related phenomena are understood only poorly. In particular the behaviour of sandy coasts under wave action suffers from insufficient knowledge. Experimental investigations yield large scatter in the results, which are partly due to the limited capacity of measurement devices. In view of the situation the Ministry of Transport and Public Works - Rijkswaterstaat, Directorate of Water Management and Water Movement - authorized the Delft Hydraulics Laboratory by letter no. 4778, dated September 29th, 1971, to study the possibilities to measure sediment concentrations under wave action in laboratory facilities. The studies are carried out as part of the Applied Research Program of Rijkswaterstaat (T.O.W.).

1.2 Scope of work

The principles of concentration measurements, as known thusfar, have been reviewed by Brolsma (1973). The method of light extinction looked most promising for measurement in situ and especially to study the varying concentration due to waves. The Delft Hydraulics Laboratory tested the commercially available Iowa Sediment Concentration Measuring System (I.S.C.M.S.) developed at Iowa State University. During extensive tests troublesome properties showed up, which are described by Brolsma (1975).

The output of a light extinction device not only carries information on concentration but also on the particle dimensions and velocity. Investigations on these aspects have been carried out with a modified version of the I.S.C.M.S. It has been concluded that in principle the method of light extinction is suitable for concentration measurements, whereas the possibilities on particle size and velocity measurements were not yet clear. However, an apparatus like I.S.C.M.S. was not operational under practical conditions (Wessels, 1976). The
statistical aspects of concentration measurements by optical methods have been studied by Bosman (1981). This study provided the theoretical insight into the statistical fluctuations in such measurements.

The validity of the statistical theory has been tested by Bosman (1984) who showed that it is verified up to a certain concentration upper limit which depends on the particle size.

The present work describes the final result of the former investigations. Proceeding from the correctness of the theory, the optical sensor has been dimensioned and the required accuracy has been interpreted in terms of electronic stability resulting to rather extreme requirements. Much effort has been put in satisfying the requirements. The final result is the optical device OPCON as it is called now. The presently gained experience during its operation for about three years is fully satisfactorily.

Mr. P. Brolsma established the basis for the development of OPCON. Dr. R.H.J. Jansen introduced the application of optical fibres. Dr. J.J. Bosman established the theoretical basis. The technical support of Mr. Der Kinderen has been provided by the Department of Measuring Methods Development of the Delft Hydraulics Laboratory. For their contribution Messrs. Wenneker, Koren and Velberg are mentioned in particular. The major part of the experimental verification tests has been carried out by Mr. Th.E. van Maar. This final report is written by Dr. J.J. Bosman.

1.3 Summary

In Chapter 2 the possible error sources are established which are decisive for the concentration lower measurement limit and the measurement accuracy. The initial requirements (lower limit 100 ppm concentration by volume and accuracy better than 10%) have been interpreted in terms of design requirements for the various contributing elements. As instrumental stability turns out to play a dominant role, special attention is given to it in Chapter 3. The final design of OPCON is elucidated in Chapter 4, both its construction and its electronics. The specifications of OPCON which are important for practical applications are given in Chapter 5. In Chapter 6 the recommended calibration procedure for optical devices is discussed briefly. It is simple and it can be
carried out quickly (typically 5-10 minutes). When concentration measurements are performed, one must know which concentration accuracy is to be accounted for. This is discussed in Chapter 7. Finally, some comments are given on the application of optical devices (not typically OPCON) in Chapter 8. The comments are based on the authors experience during three years of operation with OPCON.

1.4 Conclusions

The optical device OPCON meets the design requirements very well. The lower concentration measurement limit is typically 10-50 ppm, depending on the particle size. The spatial resolution is about 2.5 mm in the vertical direction and in the direction of the water motion. In the horizontal direction, perpendicular to the water motion, the spatial resolution is about 30 mm. Up to sediment particle velocities of 25 m/s, there are no restrictions on the response to concentration variations. The statistical random error in instantaneous measurements is typically 10-50%, depending on the particle size and the concentration. Up to particle velocities of 2.5 m/s, there is no restriction on the response to statistical fluctuations.
2. **Optical concentration measurements**

2.1 **Introduction**

Optical concentration measurements refer to different techniques such as photo or film, light-scattering or light-transmission. All techniques (including non-optical ones, e.g. acoustical techniques) respond to the active sediment particle cross-section (or particle volume). For optical transmission techniques the theory by Bosman (1981) can be applied directly, and the instrument design requirements can be obtained from the concentration accuracy requirements.

2.2 **Terminology in errors and in stability**

2.2.1 **Terminology in errors**

In the discussion a distinction will be made between random and systematic errors. Their meaning and their significance will be discussed shortly here.

Consider a random variable $X$, which is measured at $N$ moments. When the random error is large and the systematic error is small, the measurement results may look as shown in Figure 1A(a): the results scatter largely around the true $X$ (large random error) though their average is about equal to the true $X$ (small systematic error). An under-estimation of the random error may lead to a conclusion as shown in Figure 1A(b). From the same data it may be concluded that $X(t)$ varies sinusoidally.

The situation with small random error and large systematic error is illustrated in Figure 1B(a). The conclusion will be drawn that $X(t)$ is a constant though the value of the constant is wrong.

A large random error obscures any relation except when the measurement density is very large (random errors cancel in the mean; systematic errors do not). To obtain a good understanding, the random error should be small. To get the understanding correct in the absolute sense, the systematic error should be small as well. It is recommended in general to reduce the systematic error below the random error.
2.2.2 Terminology in stability

It happens often that parameters which are supposed to be constant, are not really so, and as a consequence a deviation occurs from the assumed value. Let $X$ be a quantity which is supposed to be constant in time: $X_0$. It is not really stable, but it changes in time: $X = X(t)$. The instability in general contains three contributions: the fluctuation $X_f(t)$, the variation $X_v(t)$ and the drift $X_d(t)$. The instantaneous $X$-value is defined by: $X(t) = X_0 + X_f(t) + X_v(t) + X_d(t)$. The distinction of the various instabilities is determined by the time-scale of the measurements.

During the measurement series, $X$ is assumed to be constant at $X_0$. In reality, $X$ changes in time as depicted in Figure 1C. When the measurement series consists of a number of measurements with a typical time-scale $\tau$ (e.g. the period of averaging), the various instabilities are defined by:

- fluctuation is fast compared with $\tau$ and when averaged over $\tau$ it cancels, i.e. $\bar{X}_f(\tau) = 0$.
- variation is slow compared with $\tau$, but with a time-scale which is smaller than or of about the same order as the duration of the measurement series. Actually it means that it is fully undefined during the measurement series. It certainly does not cancel in averaging over $\tau$: $X_v(\tau) \neq 0$, it may cancel by averaging over the duration of the measurement series.
- drift is very slow compared with the duration of the measurement series and does not cancel anyhow.

The three types of instabilities have to be estimated from separate long time series of $X(t)$. The usual measures for fluctuation and variation can be defined as the averaged amplitude of the high and intermediate frequency instability, respectively, see Figure 1C. Drift is usually specified by the drift-rate, i.e. nett drift per unit of time.

For example, the clean water transmission $V_0$ (Section 2.6.1) acts as an instrumental "constant". Typical time scales are $\tau = 10$ s for time-averaged measurements and a day for measurement series. The instabilities of $V_0$ introduce errors in the measurement of a specific parameter $C$ (concentration here). The undefined part of $V_0$ contributes to the error in $C$. The more or less defined part contributes to the systematic error in $C$. Thus the instabilities can be classified as follows:
- for instantaneous measurements only fluctuation contributes to the random error. Variation and drift determine the systematic error.
- for (short period) time-averaged measurements only variation contributes to the random error in $C$, as fluctuation cancels in the mean. Drift contributes to the systematic error.

2.3 Relation between concentration and light transmission

Sediment concentration is related well with light transmission only in terms of statistical parameters. These relations are given by Bosman (1981):

\[
\begin{align*}
E[V] &= E[V_0] \exp(-\beta), \\
\text{Var}[V] &= \frac{E^2[V]}{E[V_0]} + \left(\frac{\hat{D}}{d}\right)^2 (e^\beta - 1)
\end{align*}
\]

(2.1) (2.2)

where

$V$ = an analogue signal which is proportional to the light transmission,
$V_0$ = the analogue signal for zero-concentration,
$\beta$ = light extinction coefficient due to sediment particles in the light beam.

The notations $E\{ \}$ and $\text{Var}\{ \}$ refer to the "expected value" (mean) and "variance" (mean squared variation), see also the list of symbols.

The extinction coefficient $\beta$ is proportional to the volumetric concentration $C_v$:

\[
\beta = \gamma C_v
\]

(2.3)

where $\gamma$ is a calibration constant which is defined by:

\[
\gamma = \frac{3}{2} \frac{l}{\hat{D}}.
\]

(2.4)

Here $l$ is the transmission length of the light beam and $D^*$ is the particle effective diameter. The light beam diameter is denoted by $d$, and $\hat{D}$ denotes the particle projection diameter which is defined by:

\[
\pi \left(\frac{\hat{D}}{2}\right)^2 = E[A_p] \left[ 1 + \frac{\text{Var}[A_p]}{E^2[A_p]} \right]
\]

(2.5)

Both $D^*$ and $\hat{D}$ must be obtained by calibration (Chapter 6).

It is obvious from Eq. (2.1) that the concentration is related exponentially
to the averaged light transmission. For practical reasons the OPCON output is linearized, that is, it provides the linearized transmission \( W = \ln V \) instead of \( V \). The averaged linearized transmission and its variance are given by:

\[
E[W] = E[a_c] \beta , \quad (2.6)
\]

\[
\text{Var}[W] = \text{Var}[W_0] + E^2[a_c] \left( \frac{d}{d} \right)^2 (e^\beta - 1) , \quad (2.7)
\]

where \( a_c \) is an electronic conversion factor.

In an extensive measurement series Bosman (1984) showed that the given relations, Eqs. (2.1-2) and Eqs. (2.6-7) are justified up to an upper concentration limit which depends on the sediment particle size and which is different for the expected value and the variance. This concentration limit is of the order of 1%. Above this limit the deviation from the theoretical relation increases very fast. Thus far no explanation has been found for these anomalies.

2.4 The accuracy of optical concentration measurements

The relation between concentration and light transmission is described by Eq. (2.1). The equation can be considered as a good approximation for the instantaneous relation, provided that its approximating character is taken into account. By substitution of \( \beta \), Eq. (2.3), the instantaneous relation is:

\[
C_v = \frac{1}{\gamma} \ln \frac{V_0}{V}. \quad (2.8)
\]

The four error sources to be studied are:

- The approximation, Eq. (2.8), for the relation between instantaneous transmission and concentration. This is referred to as the statistical concentration error.
- The error due to \( V_0 \) is called the instrumental concentration error, as in principle, \( V_0 \) is an instrumental constant.
- The accuracy of the \( V \)-measurement is referred to as the read-out concentration error.
- The error due to \( \gamma \) is called the calibration concentration error.

Except for the statistical concentration error, all error contributions are
more or less fixed during the measurement. The statistical concentration error is purely random and can be minimized by elongating the period of averaging. Thus the statistical error is the critical one, that is, other error contributions must be small compared with the statistical one. Therefore the next section will deal with the statistical concentration error. In Section 2.6 the other error contributions will be discussed and their significance will be estimated by comparison of their contributions to the concentration error.

In balancing the errors it should be kept in mind that \( V_o, V \) and \( \gamma \) can not be affected during the measurement. Thus the errors which either of them introduces must be considered in the design stage. This is described earlier by Bosman (1979).

The lower measurement limit is defined as the concentration for which the random error (excluding the statistical contribution) is half of the concentration itself, that is \( \Delta C_v^{\frac{1}{r}} = \frac{1}{2} C_v \). The lower concentration limit has been specified for \( C_v = 10^{-4} \) (100 ppm), thus the requirement is

\[
\left| \Delta C_v \right|_r < 5 \times 10^{-5}, \text{ for } C_v = 10^{-4} .
\]

(2.9)

2.5 The statistical concentration error

This aspect is discussed extensively by Bosman (1981) thus only a summary is presented here. The relative concentration error due to the random positioning of particles in space is given by:

\[
\frac{\Delta C_v}{C_v} \text{stat} = 1.24 \frac{\hat{D}}{\hat{d}} f_n(\beta) ,
\]

(2.10)

where \( f_n(\beta) \) is a function of \( \beta \) only, and is minimum unity for \( \beta = 1.6 \), see Figure 2. The relative statistical error in instantaneous concentrations is minimum in the order of 10% (for \( \beta = 1.6 \)).

The statistical error can be reduced either by time-averaging or by enlarging the light beam diameter. As a consequence in both cases part of the measurement resolution is lost, either in time or in position. The resolution loss can be minimized by a good scaling of the \( \beta \)-range in the measurements. The optimum \( \beta \)-ranges for concentrations varying over 1 decade, 2 and 3 decades are indicated in Figure 2. A 2-decades measurement range will be adopted as a
starting point. This range is specified by its lower $\beta$-limit at $\beta = 0.065$. The corresponding optimum choice for $\lambda$ can be obtained from Eqs. (2.3) and (2.4):

$$\lambda = 0.043 \frac{D^*}{C_v,\text{min}} \quad (2.11)$$

where $C_v,\text{min}$ is the lower concentration limit to be measured. For $C_v,\text{min} = 10^{-4}$ and the practical range of sediment sizes ($50 \ \mu m \leq D^* \leq 400 \ \mu m$), it means that $\lambda$ should be chosen in the range of 20 mm to 160 mm. When $\lambda$ is not matching the optimum choice, concentration measurements are still possible, but at the cost of time- and/or position-resolution.

As a good compromise the OPCON has been designed with a transmission length of $\lambda = 30 \ \text{mm}$ which is very suitable for the finer particles (say, for sizes up to 200 $\mu m$). For the coarser particles it is still suitable at the cost of (time-)resolution to achieve the same accuracy.

In the past optical sensors such as I.S.C.M.S., see Glover et al (1969), usually had transmission lengths of a few millimeters which is far too small with respect to the statistical error since $\beta$ in general is small ($\ll 1$). Also such a sensor is much more sensitive for instrumental instability, see Section 2.6.1.

An optimum two-decade measurement-range from $\beta = 0.065$ to $\beta = 6.5$ will be considered (other scalings of the measurement-range are worse). To facilitate accurate concentration measurements it will be required that the statistical error can be reduced under 5% by time-averaging. To leave the leading role in the choice of $C_v$-accuracy to the statistical error, all other random error contributions should contribute less to the concentration error:

$$\left| \frac{\Delta C_v}{C_v} \right|_r < 5\%, \text{ for } 0.065 < \beta < 6.5. \quad (2.12)$$

The lower index $r$ refers to random error contributions from other sources than the statistical one.

A consequence of a right scaling of the $\beta$-range ($\beta$ of the order unity) is that the exponential character in Eq. (2.1) cannot be approximated simply by a linear relationship. In a practical design it is recommended to linearize the
light transmission which results to Eq. (2.6). It is also obvious from Eq. (2.1) that light transmission for a 2-decades β-range varies over almost 3 decades. Hence in optical devices the receiver part (photo-receiver and amplifier) should be linear over preferably 3 decades.

2.6 The other error sources

2.6.1 The error sources and the requirements

Besides of the statistical error, the other errors originate from V, V₀ and γ , see Eq. (2.8). The design requirements are given by Eqs. (2.9) and (2.12). For each error source the strongest requirement must be fulfilled.

2.6.2 The read-out concentration error due to V

The influence of a deviation in the actual V-value in the measurement can be calculated easily from Eq. (2.8):

\[
\frac{\Delta C_V}{C_V} = -\frac{1}{\beta} \frac{\Delta V}{V} .
\]

The accuracy of the V-value in the measurement depends on the read-out unit, that is, ΔV is the purely random accuracy \( \Delta V_r \) of the read-out unit. By substitution of the basic relation as defined by Eq. (2.1) it is obtained:

\[
\frac{\Delta C_V}{C_V} = -\frac{1}{\beta} e^\beta \frac{\Delta V_r}{V_0} ,
\]

where \( \frac{\Delta V_r}{V_0} \) is the relative full-scale read-out accuracy. As Eq. (2.12) appears to be the strongest, it is found:

\[
\left| \frac{\Delta V_r}{V_0} \right| < 0.05% .
\]

This read-out accuracy means that a digital display requires at least 4 significant digits and when the signal is digitized the AD-converter requires at least 12 bits. Note that these are the requirements for the full dynamic range without intermediate rescaling of the read-out accuracy.
2.6.3 The instrumental concentration error due to $V_o$

A deviation $\Delta V_o$ of the true $V_o$-value from its calibration-value, introduces an error $\Delta C_v$ in the concentration. According to Eq. (2.8) their relation is:

$$\frac{\Delta C_v}{C_v} \left( \frac{V}{V_o} \right) = \frac{1}{\beta} \frac{\Delta V_o}{V_o},$$

(2.16)

which defines the relative concentration error due to instrumental instability. Obviously $1/\beta$ acts as an amplification factor on the instrumental instability in its contribution to the concentration error. It explains the problems with instrumental instability in the past with too small transmission lengths (small $l$ results to small $\beta$).

After substitution it is found that the requirement by Eq. (2.12) is stronger than the one by Eq. (2.9). It yields:

$$\left| \frac{\Delta V_o}{V_o} \right| r < 0.3\%.$$

(2.17)

Both instrumental fluctuation and variation should satisfy this requirement. To follow the general recommendation, instrumental drift should be kept under 0.3% as well, though this is not strictly necessary.

2.6.4 The calibration concentration error due to $\gamma$

The true value of $\gamma$ in the calculation of $C_v$ from Eq.(2.8) may differ from the substituted value $\hat{\gamma}$ which is obtained in advance through calibration. It is seen easily from Eq. (2.8) that a deviation $\Delta \gamma$ from $\hat{\gamma}$ introduces a relative concentration error which is given by:

$$\frac{\Delta C_v}{C_v} \hat{\gamma} = - \frac{\Delta \gamma}{\gamma}.$$

(2.18)

Three error sources may be responsible for a deviating $\gamma$-value. The first one is the accuracy of the $\gamma$-measurement in the calibration. The calibration yields $\gamma$ with a random and systematic error. The total relative calibration error contributes relatively equally in the concentration error but only purely systematically. Thus the total relative calibration error $(\Delta \gamma / \gamma)_{c, \text{tot}}$ should be a few percent at most.
As can be seen from Eq. (2.4), \( \gamma \) depends on the effective particle diameter \( D^* \) and on the transmission length \( l \). As the latter is merely a matter of instrument stability, its influence will be discussed in Chapter 3. The particle size distribution may happen to change during the measurement. For example, with natural sediment, significant segregation in terms of \( D^* \) over the vertical direction occurs, see e.g. Bosman (1982b). From Eqs. (2.4) and (2.18) it is seen that a change \( \Delta D^* \) introduces an error \( \Delta C_v \) according to:

\[
\left( \frac{\Delta C_v}{C_v} \right)_D^* = \left( \frac{\Delta D^*}{D^*} \right)_D^*.
\]

(2.19)

It is a systematic error which is not constant as it depends on the conditions (\( \Delta D^* \) depends on the measurement position and on the fluid motion). To keep the systematic concentration error negligibly small, Eq. (2.19) requires that the relative change in \( D^* \) should be less than about 2%. When segregation occurs, it is easily of the order 10-50%. Thus when segregation occurs, a systematic concentration error of the order of 50% must be taken into account.

It is possible, in principle, to measure sediment concentrations without any calibration, see Bosman (1984). It looks worthwhile when significant segregation occurs. But more investigation is required on that possibility. Also, the influence of segregation can be eliminated by separate calibrations for suction samples of the specific conditions. This method is very straightforward, but it is laborious.

### 2.7 Concentration error contribution

The various error contributions have been summarized in Table 1. It is complete, except for the contribution from the instability of the transmission length, which will be discussed in Section 3.3. Apart from the statistical error, all random error contributions should satisfy the requirements by Eqs. (2.9) and (2.12). The systematic error contributions are recommended to satisfy the same conditions, though this is not a strong requirement.

The obtained design requirements for OPCON are:
- read-out accuracy must be better than 0.05%, i.e. minimum 4 significant digits read-out or 12 bits AD-conversion,
- instrumental instability less than 0.3%.

The consequences for instrument design are established in Chapter 3.
More generally for optical methods attention should be paid to:
- accurate calibration (few per cent total error at most),
- $\delta^*$ in the measurements, especially when segregation is to be expected.
These two aspects contribute to the systematic error only.
3. **Instrumental stability**

3.1 **Introduction**

Accurate concentration measurements require that the instrumental instability is less than 0.3%. The instability sources are the instrumental 'constant' $V_o$ and the transmission length $\lambda$. The bottlenecks to meet the requirement will be traced and the consequences for the instrumental design are discussed.

3.2 **Stability of $V_o$ excluding transmission length**

3.2.1 **The constituent parts**

The zero-concentration ("clean" water) transmission is given by:

$$V_o = I_e I_r e^{-k\lambda},$$  \hspace{1cm} (3.1)

where

$I_e$ = a factor containing all electronics and optics at the photo-emitter side, thus including power supply and light source.

$I_r$ = a factor containing all electronics and optics at the photo-receiver side, thus including photo-PIN-diode, photo-amplifier, operational amplifier.

$k$ = light extinction coefficient in water. (The term extinction refers to the depletion of energy both by absorption and scattering).

$\lambda$ = light transmission length (here considered as a constant).

The parameters $I_e$, $I_r$ and $k$ depend on various conditions, e.g. on temperature. Let $x$ denote any physical condition (e.g. temperature) which influences the three parameters. When $x$ changes over $\Delta x$, there is a resulting change $\Delta V_o$ in $V_o$ which according to Eq. (3.1) is:

$$\left(\frac{\Delta V_o}{V_o}\right)_x = \frac{1}{V_o} \frac{\partial V_o}{\partial x} \Delta x = R_x(I_e) \Delta x + R_x(I_r) \Delta x - k\lambda \cdot R_x(k) \Delta x,$$  \hspace{1cm} (3.2)

where $R_x(Y)$ denotes:
\[ R_x(Y) = \frac{1}{Y} \frac{\partial Y}{\partial x} \quad \text{(3.3)} \]

which is the relative \( x \)-coefficient of an arbitrary variable \( Y \). For example, \( R_T(I_e) \) is the relative temperature-coefficient of the emitter part (in percent per kelvin). Eq. (3.2) describes the total relative instrumental instability due to \( x \).

The parameters \( x \) which may be thought of to influence possibly \( I_e, I_r \) and \( k \) are temperature and time.

The influence of temperature is obvious from the temperature coefficients of electronic components and light extinction in water. Temperature changes in general are slow compared with the time-scale of measurements, hence temperature-coefficients may contribute to the instrumental variation and drift. The influence of time consists of a changing characteristics of the specific component. For electronic components it may be indicated by "aging". For the water it may consist of a changing amount of contained impurities. The influence of time is expected to be slow anyhow compared with the duration of measurement series, thus contributing to instrumental drift only.

Note that besides of these, other instabilities may occur: electronic noise (for the emitter and receiver part) and water impurities (for the water). Such instabilities are very fast and thus contribute to instrumental fluctuation.

### 3.2.2 Stability of emitter part

As a light-source a LED (Light Emitting Diode) has been chosen because: it is small and cheap, it has a long life-time, it has small power consumption and it can be modulated if required. It lends itself well to stabilization. A disadvantage is its rather limited radiation power. The LED power-supply is not expected to give rise to significant instrumental instability.

Temperature coefficients of LED's typically are of the order 0.3% - 1.0% per kelvin. It will be obvious that this temperature coefficient may be a serious problem contributing both to variation and to drift.

Aging of light-sources is well-known. In addition, it has been found in the present investigation, at least for the selected light source, that the angular distribution of the emitted light changes slightly in time too. Thus the emitter part may contribute significantly to drift.
A quite different error contribution originates from a varying ambient light level. It is classified with the emitter part as it acts as an additional, but unstable light source. The ambient light varies as a function of time only and it may be of different origin:
- artificial light varies rapidly, thus contributing to "instrumental" fluctuation only,
- daylight changes slowly in time, though sometimes changes happen quite abruptly (e.g. due to moving clouds). It contributes to variation.
Also the ambient light contribution should be constant within 0.3%.

3.2.3 Stability of receiver part

For the receiver a photo-PIN-diode (PIN = Positive-Intrinsic-Negative) has been chosen. These light sensitive semi-conductor elements have an output current which over a rather wide range is proportional to the incident light energy. In addition they are small and cheap, and quite fast (wide bandwidth). A fast receiver is desired to enable measurement of the statistical variance of light transmission. Their temperature sensitivity is typically of the order -0.2% per kelvin. It will be obvious that the photo-diode temperature coefficient may contribute significantly both to variation and to drift. (Photo-transistors are more sensitive, but their linearity is confined to a rather narrow range. In addition they are less stable and relatively slow).

3.2.4 Stability of the extinction coefficient of water

The possible instability in time depends on the impurity density variation in water only. This contributes to drift.

The relative light transmission $T_r$ in water is defined by $T_r = \exp(-k \ell)$. Due to its temperature coefficient, $k$ (thus $T_r$) depends on the temperature. The temperature coefficient $R_T(k)$ depends on temperature also. To obtain a representative impression, it will be assumed that $T_r$ and $R_T(k)$ concern $T = 10^\circ C$. In addition, $k$ depends on the radiation wavelength (excitation of rotational bands in water molecules). A lot of investigation has been carried out in the past on the temperature dependence of molecular absorption, e.g. Collins (1925), from which the relative temperature coefficient $R_T(k)$ has been derived as a function of the radiation wavelength. For a given tempera-
ture variation $|\Delta T|$, it can be calculated what the clean water transmission $T_{w0}$ must be at least to meet the instrumental stability requirement. Also, for various transmission lengths $\lambda$, the transmission can be calculated as a function of the light wavelength. The results are shown in Figure 3 for $\lambda = 10$ mm, $\lambda = 50$ mm and $\lambda = 100$ mm. When the transmission lines are in the dashed area defined by $T_{w0}$, the stability requirement is violated. To construct Fig. 3, it is assumed that $|\Delta T| = 1\%$. When $|\Delta T|$ is larger the dashed area increases too. When the water temperature differs from the assumed $T = 10^\circ C$ the dashed area peaks move slightly either to the left or to the right. From the figure windows can be defined for suitable wavelengths. The windows depend on the transmission length. In general, the following windows can be defined.

$$\gamma < 700 \text{ nm}, \quad (3.4a)$$

$$760 \text{ nm} < \gamma < 830 \text{ nm}, \quad (3.4b)$$

$$850 \text{ nm} < \gamma < 910 \text{ nm}, \quad (3.4c)$$

$$990 \text{ nm} < \gamma < 1010 \text{ nm}. \quad (3.4d)$$

The latter window is small compared with possible shifts of the peaks, hence it is not of practical use (except for very small $\lambda$).

Thus with a proper choice of the light source with respect to its peak wavelength, the influence of the temperature coefficient of the clean water extinction coefficient is no problem.

3.3 Stability of transmission length

The calibration constant $\gamma$ and the instrumental constant $V_o$ depend on the transmission length $\lambda$, see Eq. (2.4) and Eq. (3.1), respectively. A changing $\lambda$ results to an error $\Delta C$ in the concentration, which is given by:

$$\left(\frac{\Delta C}{C}\right)_\lambda = -\left(1 + \frac{k\lambda}{\beta}\right) \frac{\Delta \lambda}{\lambda}. \quad (3.5)$$

The relative concentration error is maximum for minimum $\beta$ ($\beta = 0.065$). Since $k\lambda = 0.1$, Eq. (3.5) turns into:
\[ \frac{\Delta C_v}{C_v} \ll 2.5 \left| \frac{\Delta l}{l} \right| . \]  

(3.6)

With a rigid construction \( l \) may change only by high frequency vibration with small amplitude. Thus the stability of the transmission length may contribute to fluctuation only, not to variation and drift. To satisfy the stability requirement:

\[ \left| \frac{\Delta l}{l} \right| < 2\% , \]  

(3.7)

This requirement should not be difficult to match in a rigid construction.

3.4 Consequences for instrumental design

3.4.1 Some considerations on instrument design

The temperature sensitivities of the emitter and receiver part are most troublesome. One possibility is to attempt to stabilize the temperature. Due to the LED's own energy dissipation this is hardly possible. For example, both the LED and the photo-diode may be brought in good thermal contact with the flowing water in which the measurement is performed. The large heat capacity of the water will stabilize the temperature of the components. However, due to its heat dissipation the LED temperature will be (slightly) larger than that of the water. The heat dissipated by the LED must be removed by the water. As a consequence, cooling depends on the water velocity too and due to its small heat capacity the LED temperature varies with water velocity. This might explain the velocity dependence of L.S.C.M.S., as encountered by Broksma (1975). In principle, it may be rectified by enlarging the LED heat capacity. On the other hand, it would take quite a long time for the instrument to get stable after the initial switch-on.

Therefore, it has been decided to keep the LED and the photo-diode out of the water. Optical fibres (Jansen, 1977) should perform the light conduction to and from the sensing volume. Thus two problems remained to be solved: how to reduce the temperature coefficients and how to reduce the finally remaining temperature coefficient. The first problem is discussed in Sections 3.4.2 and 3.4.3. The final reduction will be introduced here and elaborated in Section 3.4.5.
As can be seen from Eq. (3.1) the instrumental "constant" \( V_0 \) is proportional both to the emitter term \( I_e \) and to the receiver term \( I_r \). Thus when an additional reference signal \( V_r \) is available, which in the sense of temperature sensitivity is identical, all temperature instability should cancel in the ratio \( V_r/V_0 \), provided that corresponding components are thermally tightly coupled.

The first set-up was quite simple. The reference signal consisted of an identical LED and an identical photo-diode. The LED power supply was common. Both LED's were mounted close in a brass block as a thermal link. The two photo-diodes were mounted similarly. The identical photo-amplifiers were mounted quite close in a single box. Yet, the resulting temperature sensitivity of the ratio \( V_r/V_0 \) appeared to be only half of the circuits individually. This was mainly due to the two LED's, as the differences amongst their individual characteristics were too large.

The second set-up applied a single LED for the two circuits: the main light beam supplied the measurement circuit \( V_0 \), whereas the straylight supplied the reference circuit \( V_r \). The attempt failed as it turned out that the directional light intensity distribution of the LED changed in time, thus introducing a new instability of the same order as the temperature instability.

In the final design, a single LED is supplying both circuits. A small amount of light is taken out of the measurement beam to supply the reference circuit. This is achieved in the following way. At the entrance of the optical fibre a small prism has been mounted such that one of the rectangular sides matches the fibre. The LED is installed in front of the other rectangular side such that the light beam enters perpendicular. Inside the prism almost total reflection occurs at the hypothenuse. Some loss (about 2%) occurs due to Fresnel reflection. This outcoming light supplies the reference circuit. At this stage the headlines of the design are established. The final design is sketched schematically in Figure 4.

3.4.2 The emitter part

The power output of a LED is approximately proportional to the LED current. The proportionality factor depends on the temperature: with increasing temperature and constant current the power output decreases. To stabilize the
power output, the LED current should increase with temperature. In addition, the voltage-current relation of a LED depends on temperature too. As a consequence, to stabilize the power output of the LED, its voltage and current should be adjusted for each temperature.

This can be achieved by a constant voltage supply with a series resistance. When the temperature increases, the LED-voltage decreases, so the voltage over the series resistance increases. As a consequence the current through the resistance (and thus through the LED) increases. By the right choice of the series resistance the LED current follows the LED voltage along the required trajectory. As a matter of fact the temperature sensitivity of the photo-diode has been included in the choice of the series resistance.

3.4.3 The receiver part

The efficiency of a photo-diode depends on the temperature. Considering the combination emitter/receiver as a whole, its temperature sensitivity can be reduced through the choice of the series resistance in the LED power supply. Instead of choosing the series resistance on basis of a stable LED power output, it has been chosen on basis of a stable current output of the photo-diode.

Still the optimum series resistance depends on the region of temperature variation. For example, it is different for the situation with the ambient temperature varying around 10°C (e.g. 5-15°C as in winter) and the situation with the temperature varying around 25°C (e.g. 20-30°C as in summer). As a decisive temperature, 15°C has been chosen to find the optimum series resistance from a measurement series in a temperature-controlled room. With a LED current of 50 mA, the temperature coefficient of the combination around 15°C could be reduced to 0.02 pct/K.

Even without incident light, the photo-diode provides a very small, so-called dark current. This dark current is relatively sensitive for temperature variations compared with the sensitivity of the photo-efficiency. For large concentration the light transmittance of the water is only small. The resulting small photo-current may differ hardly an order of magnitude from the dark-current. As a result the temperature sensitivity of the dark current is
dominant over the reduced sensitivity of the emitter/receiver combination. Thus the dark current should be kept as small as possible.

Usually photo-DIN-diodes operate with a reversed bias voltage. As a result the diode capacity decreases and the diode becomes faster (wider bandwidth). In addition, however, the dark current increases. As the selected photo-PIN-diode for the present purposes is expected to be sufficiently fast even without reversed bias, this usual bias has been omitted.

The diode current is converted into a voltage by a low-noise, low-drift photo-amplifier with wide bandwidth. The diode capacity (without reversed bias) and the required bandwidth determine the feedback resistance, which fixes the transfer function. With a single amplifier the obtained voltage level is too low to supply the log/divider amplifier for linearization and stabilization. Therefore, a second low-noise voltage amplifier is added. The bandwidth of the system has been measured to be 56 kHz and the noise output has been found to be 0.06 mV_{RMS}.

3.4.4 Reduction of ambient light influence

To eliminate the influence of the ambient light, modulation of the light source is applied often. Because the required additional electronics, considering the required stability and bandwidth, would be rather complex and expensive, it has been attempted to reduce the ambient light influence in a more simple way.

The first element in the solution is the choice of the photo-diode, which is insensitive for wavelengths below $\lambda = 750$ nm by an optical filter. For wavelengths above $\lambda = 950$ nm the 'natural' environment of the sensing volume (i.e. the water) acts as a filter, see Fig. 3.

The second element in the solution is the choice of the optical fibre. By choosing fibres with small numerical aperture, light can enter the receiving fibre under a small angle only. Thus the influence of ambient light is confined to a small solid angle. This direction can be shielded easily when the ambient light level is troublesome. The applied fibres have a numerical aperture (N.A.) of 0.21 in air. This means that in water the fibre acceptance
angle is smaller than 10°. The fibres have a core of 0.07 mm and have been bundled to a total optical diameter of 3 mm.

3.4.5 Stabilization by dividing/Linearization

The remaining instabilities after reduction can be minimized by applying a reference circuit \( V_r \) which is proportional to \( V_o \) and which follows the instability of \( V_o \). Let \( a_r \) be an amplification constant not depending on \( V_r \) nor on \( V_o \). Dividing the reference signal, \( a_r V_r \), by the instantaneous transmission signal, Eq. (2.1) becomes:

\[
E\left[ \frac{a_r V_r}{V}\right] = E\left[ \frac{a_r V_r}{V_o}\right] \exp(\gamma C_v),
\]

where Eq. (2.3) has been substituted for \( \beta \). In principle \( V_o \) and \( V_r \) follow identically any change of conditions, so the remaining instability in \( E[a_r V_r/V_o] \) is actually due to \( a_r \) only. Thus the instrumental instability is reduced.

In a clean water measurement \( (C_v = 0) \) \( a_r \) can be adjusted such that \( a_r V_r = V_0 \). By proper adjustment the concentration is given by:

\[
C_v = \frac{1}{\gamma} \ln E\left[ \frac{a_r V_r}{V}\right].
\]

Thus the concentration is obtained correctly only when the ratio \( a_r V_r/V \) is averaged first and linearized by the log-operation afterwards. But this is very unpractical considering instantaneous outputs. Bosman (1984) showed both theoretically and experimentally that the sequence of the operations can be exchanged with negligible error. Thus the equation above can be replaced by:

\[
C_v = \frac{1}{\gamma} E\{\ln \frac{a_r V_r}{V}\}.
\]

If \( W \) denotes the linearized output of OTPCON, i.e. \( W = a_c \ln (a_r V_r/V) \) then:

\[
E[W] = a_c \gamma C_v,
\]

which is identical to Eq. (2.6). For the variance of the linearized transmission it results to Eq. (2.7).
The stabilization by dividing and linearization by log-operation according to Eq. (3.9) has been performed in a single analogue function integrated circuit: Burr-Brown Logarithmic Amplifier 4127KG.
4. Design of OPCON

4.1 Introduction

In this chapter the various design aspects are discussed concerning both the optics, mechanics and electronics. Specifications as obtained with this design are to be found in Chapter 5.

4.2 The OPCON-probe

The schematic set-up of OPCON is shown in Fig. 4. Three aspects are very essential in the OPCON-design:
- rigid probe construction
- electronic components outside the water,
- light guidance through glass fibres.
These aspects will be discussed successively.

4.2.1 The probe-mechanics

The probe, see Photo 1, consists of two stainless steel tubes (6 mm Ø), containing the glass fibres, and an aluminium probe-head containing the opto-electronic components, see Fig. 5. The emitter tube is straight, whereas the receiving tube is bended faintly twice to achieve the required 30 mm length of the sensing volume. The two tubes have been embedded in a single stainless steel jacket (15 mm Ø) which is only for practical ease. At the two sensing ends of the probe tubes small prism holders have been mounted. As can be seen from the figure, these holders are edged in order to minimize scour when the measurement position is close to a loose bed.

The probe-head is a bold aluminium block acting as a thermal link between the LED and the two photo-PIN-diodes. It can be easily taken off the probe tube. The submersible length of the probe is 0.95 m. There is no objection for any other desired length. The only limitation is the available fibre length.
4.2.2 The probe-electronics

The probe-head contains a single LED, General Electric, type F5D1, which has been selected on maximum light output within a small solid angle and the wavelength criteria given in Section 3.2.4. The most important factory specifications (for the purpose of OPCON) have been listed in Table 5. The LED power supply is part of the OPCON input/output system, see Section 4.3.1.

The probe-head contains two identical photo-PIN-diodes, Siemens, type BP104, which have been selected on sensitive area and sensitivity for the wavelength of the light. The most important factory specifications (for the purpose of OPCON) have been listed in Table 6.

The dual photo-amplifier for the sensor and reference photo-diodes has been attached to the probe-head in order to minimize the lead capacitance for maximum bandwidth. The electronic scheme has been given in Fig. 6a. By the choice of the resistance $R_\star$, the amplifier output can be scaled into the desired range. It is of the order of 1MΩ for about 5V output.

4.2.3 The probe-optics

The most important part of the probe optics consists of the fibre bundles, Scott Mainz, type K2. Important specifications have been listed in Table 4. The fibres have been selected mainly because of their small numerical aperture through which the ambient light sensitivity could be reduced considerably.

The two prisms in the probe-head are clear as they should reflect the light beam over 90°. A small (Fresnel) light loss at the hypothenuse at the emitter side is required to supply the reference diode.

Each prism holder at the sensing end of the probe tubes contains a silvered prism to reflect the light beam over 90°. The hypothenuses have been silvered to avoid condensation on the surface when the probe is put from room temperature into the relatively cold water.
4.3 The OPCON input/output system

The OPCON input/output system is a cabinet with plug-in units, which is suitable also for 19 inch rack-mounting. It is connected with the OPCON-probe by a single demountable cable, carrying both the probe-input (LED and pre-amp power supplies) and the probe-output (measurement signal and reference signal). The input/output system contains standard units and a few optional plug-in units, which are not required for OPCON itself, but which are usually applied in practice. The input/output system is shown on Photo 2.

Two standard units are essential in the operation of OPCON:
- The LED power supply designed to minimize the temperature sensitivity of the emitter/receiver combination, see Subsections 3.4.2 and 3.4.3. Its electronic scheme is shown in Figure 6b.
- The log-amplifier/divider acts both as a stabilizer and as a linearizer, see Subsection 3.4.5. Its electronical scheme has been given in Figure 6c. Its two inputs are the measurement signal and the reference signal. Its output is the linearized analogue signal W. By a single switch it is chosen either for the external (from the probe) reference signal or for an internal reference signal in case of checking for good operation. By a 10-turn potentiometer the clean water output is adjusted to zero. The output sensitivity is 3V/decade. The log-amplifier/divider can be used also independently, i.e. for application to other purposes.

In practical applications OPCON is often used in combination with other electronic devices for the ease of data-handling. The elements which are applied frequently are available as plug-ins for the same cabinet. They can be used also for other purposes. The three optional units are:
- adjustable large bandwidth amplifier to achieve an easy output scaling,
- a time averager over time intervals 10-20-30-60-90-120 seconds,
- digital voltmeter with 1 mV accuracy (4½ digits).
5. Specifications of OPCON

5.1 Introduction

In this chapter the specifications of OPCON are discussed as far as they are important for sediment concentration measurements. As a consequence, the limits of capability have not been established when they were found outside the practical range of interest. The OPCON specifications are summarized in Table 3.

5.2 Response time

Usually the light source is modulated to measure the response time. However, this is not the operation condition for OPCON as the light emission is fixed.

So the response time has been tested for the receiver part separately. The present tests have been performed by interrupting the beam by a light blocking stripe which is attached to a lucite disc. The disc has been rotated with adjustable velocity. The stripe blocks the light beam each lap. The stripe width \( w \) is larger than the beam diameter \( d \):

\[
w = (4.85 \pm 0.03) \text{ mm}.
\]  

(5.1)

The pulse in light transmission which is generated by the passing stripe has been sketched in Fig. 7. To simplify the illustration, the stripe is kept fixed whereas the light beam is moving with linear velocity \( v \). From the figure it is seen that:

\[
v t_{f_0} = v t_{r_0} = d,
\]

(5.2a)

\[
v t_{z_0} = w - d.
\]

(5.2b)

The relations assume that the receiver follows exactly the changing light transmission. When the receiver is too slow for high velocity, a delay occurs both in \( t_f \) and in \( t_r \) as indicated in Fig. 7. For a number of velocities in the range 1.7 m/s - 26 m/s the time parameters \( t_f, t_z \) and \( t_r \) of the pulse have been measured by means of an oscilloscope. It turned out that within the
measurement accuracy $t_r = t_f$. If the delay-times for $t_f$ and $t_r$ are identical, it is found:

\[ t_r(v) = t_f(v) = t_f + \Delta t(v), \quad (5.3a) \]

\[ t_z(v) = t_z - \Delta t(v). \quad (5.3b) \]

The averaged rise-time $\bar{t}_r$ is defined by $\bar{t}_r = (t_r + t_f)/2$. As $t_z(v)$ is decreased by a possible delay $\Delta t$, whereas $t_z(v)$ is increased, the time-ratio $t_z(t)/\bar{t}_r$ is most sensitive for delay-occurrence. By definition of the relative delay-time $\Delta t_r(v) = \Delta t(v)/\bar{t}_r$, the time ratio can be approximated well for small delay-times by:

\[ \frac{t_z}{t_r} \approx \frac{t_z}{t_r} - \left(1 + \frac{t_z}{t_r}^2\right) \Delta t_r(v). \quad (5.4) \]

For a perfectly following receiver ($\Delta t_r = 0$), the time-ratio is given by:

\[ \frac{t_z}{t_r} = \frac{w}{d} - 1, \quad (5.5) \]

no matter what the actual velocity $v$ is. Substitution into Eq. (5.4) yields:

\[ \frac{t_z}{t_r} = \frac{w}{d} - 1 - \frac{w}{d} \Delta t_r(v). \quad (5.6) \]

The time-ratio as measured for velocities up to $v = 26$ m/s are shown in Fig. 8. As $t_z$ and $\bar{t}_r$ have been determined on the same oscilloscope time base, the calculated time-ratios do not depend on the oscilloscope calibration. The measurement accuracy (4 - 8%) is mainly due to the precise definition of $t_f$, $t_z$ and $t_r$.

Considering the measurement accuracy, the one conclusion is that the time-ratio is constant (0.86). Then it is found from Eqs. (5.1) and (5.5) for the light beam diameter: $d = (2.61 \pm 0.06)$ mm.

The other conclusions might be that the time-ratio is about constant (0.92) for small velocities ($v < 6$ m/s) and that it decreases linearly for larger velocities, as indicated by the dashed line in Fig. 8. As this behaviour looks rather systematic in spite of the large errors, it may be significant. The
linear decrease corresponds with a time-delay increase of 0.3% per m/s velocity above \( v_0 = 6 \text{ m/s} \). The total relative time-delay for a velocity \( v = 26 \text{ m/s} \) would be less than 6%. For small velocities the receiver follows exactly. Hence, according to Eqs. (5.1) and (5.6), the light beam diameter is: 
\[
d = (2.53 \pm 0.06) \text{ mm.}
\]
Finally, it is assumed for the light beam diameter:
\[
d = (2.57 \pm 0.05) \text{ mm.} \tag{5.7}
\]
Considering the measurement accuracy and the small differences between the two possible interpretations (3% in \( d \); less than 6% in time-delay), it will be assumed that the receiver part follows perfectly up to the velocities \( v = 26 \text{ m/s} \) when the transmission changes from full \( (V = 4 \text{ Volt}) \) to completely zero \( (V = 0 \text{ Volt}) \).

In order to follow fast concentration variations (e.g. moving suspension clouds) the OPCON should be able to respond fast to sudden changes in light transmission. Under most extreme conditions this response time concerns the change from full light transmission (zero-concentration) to no transmission at all (very large concentration). In practice, changing sediment concentrations are not that extreme, thus it is concluded:

**Varying sediment concentrations are followed exactly up to particle velocities of at least 25 m/s.**

The typical time scale for concentration-variations is determined by the light beam diameter \( d \) and the sediment particle velocity \( v_5 \). Statistical fluctuations have a time-scale which is determined by the diameter \( D \) of sediment particles and their velocity. Furtheron, transmission variations are only small, and far from the tested extreme. As the ratio \( D/d \) is of the order of 0.1 \( (D = 0.2 \text{ mm, } d = 2 \text{ mm}) \), it is concluded that:

**Statistical fluctuations (single particle influence) are followed exactly up to particle velocities of at least 2.5 m/s.**

5.3 Instrumental stability

5.3.1 Output stability and concentration

An instability \( \Delta W \) in the OPCON-output can be expressed in terms of concentration by means of Eq. (3.11):
\[ \Delta C_v = \frac{\Delta W}{\gamma a_c}, \]

(5.8)

where \( \gamma \), given by Eq. (2.4), depends on the particle size and should be obtained by calibration. As a consequence, the interpretation of the instability \( \Delta W \) in terms of \( \Delta C_v \) depends on the particle size. To provide a decisive figure, the OPCON-instability will be expressed in terms of concentration for particles of sizes around \( D^* = 0.1 \) mm. With \( \lambda = 29.6 \) mm and \( a_c = 2605 \) mV for the tested OPCON, it is found that 1 mV output instability corresponds with \( \Delta C_v = 8.6 \times 10^{-7} \).

To facilitate the following discussions it will be applied that the instrumental instability amounts \( \Delta C_v = 10^{-6} (= 1 \text{ ppm}) \) per mV OPCON-output instability. This figure is rather correct for particle sizes near 0.1 mm (but half for \( D^* = 0.05 \) mm and double for \( D^* = 0.2 \) mm).

### 5.3.2 Stabilization after switch-on

After switch-on and proper zero-adjustment, the output of OPCON has been recorded for 25 hrs, the optical sensor being placed in clean water. The measurement results are schematized in half hour registrations which are shown in Fig. 9. The measurement accuracy is about 0.3 mV. As can be seen from the figure, the OPCON-zero drifts rather fast immediately after switch-on. The drift-rate is about 2 mW/hr, or in terms of concentration about 2 ppm/hr. After about ten hours the drift rate is reduced considerably down to about 0.1 ppm/hr. Thus is is concluded that the typical stabilization time after switch-on is about ten hours.

The stabilization time is due to the heating of the thermal link block by the LED dissipated energy. The heat capacity of the thermal link is large compared with the heat dissipation rate of the LED. As a consequence it takes a rather long time to stabilize after switch-on. On the other hand the large heat sink stabilizes against rapid temperature variations in the environment. Thus it is dissuaded to reduce the heat capacity of the thermal link.

### 5.3.3 Instrumental fluctuation

Without discriminating amongst the various sources, the total fluctuation can be measured in a "clean" water AC-RMS-measurement. Such measurements include
the contributions from "impurities" and small air bubbles in the tap water. In terms of the OPCON-output fluctuation it was found that the pure instrumental fluctuation is about 0.8 mV whereas the water contribution varies up to 2 mV ultimately. Thus in terms of concentration the instrumental fluctuation is less than 1 ppm, and the "clean" water fluctuation is less than 2 ppm. The total concentration fluctuation was found to be less than 2.5 ppm.

5.3.4 Instrumental variation

With the optical sensor in clean water, the OPCON-output signal W has been recorded continuously over a period of 150 hrs under normal measurement conditions. The environmental humidity and temperature have been recorded simultaneously. The measurement results are shown in Fig. 10. The measurements have been carried out in the month of December, and cover a period from Tuesday 9 a.m. up to next Monday noon. The low temperature (10 - 11°) periods are during the night, the higher temperatures (≈ 14°C) are during day. The relative environmental humidity is following the temperature rather precisely, though inversely. The longer period with low temperature at the end of the measurement series covers the weekend.

It is obvious from Fig. 10 that the OPCON-output signal varies with the environment, which most likely is due to temperature only, and not due to humidity. It is obvious also that the OPCON variation is much slower and a little delayed relative to the temperature variation. Some drift occurs, which will be discussed in the next subsection. Around the drift some instrumental variation is obvious. This instrumental variation is estimated from the figure to be less than 5 mV, which in terms of concentration amounts 5 ppm. This variation contributes to the random error in the concentration (stability of zero-concentration). The systematic concentration error contribution is given by the drift-rate, see Subsection 5.3.5.

As the OPCON-output variation is not following precisely the environmental temperature, it is not quite possible to relate the instrumental variation to the temperature. Nevertheless a rough estimate can be given from Fig. 10 yielding that the instrumental temperature sensitivity is about 5 mV over 3°C, or in terms of concentration, the temperature sensitivity is about 2 ppm per 1°C. Before starting and after stopping measurements, the zero-concentration
usually will be re-adjusted, thus it seems sensible to consider the OPCON-stability also over a workday. From the recordings in Fig. 10 the parts covering a workday have been selected and shown separately in Fig. 11. For the first day (Tuesday) no data on environmental humidity and temperature were available. When the environmental temperature is rather stable the OPCON-output is very stable too, see Saturday and Sunday in Fig. 11. Under normal conditions the OPCON-output varies over a workday, which may consist both of mainly variation (Tuesday) and of mainly drift (Wednesday, Thursday and Friday). The random and systematic concentration errors are estimated to be less than 5 ppm over a workday.

5.3.5 Instrumental drift

The long-term (1 week) instrumental drift is estimated in Fig. 10 by the driftline. The total drift amounts -5 mV over 150 hrs. Thus the long-term drift rate is about -0.8 ppm per day (24 hrs).

The short-term drift, which is actually due to long-term variation, is discussed in the preceding subsection. It depends strongly on the environmental conditions. It amounts typically less than 5 ppm over a workday.

5.4 Instrumental linearity

Two aspects should be distinguished in instrumental linearity. The first concerns the linearity of the receiver part, i.e. the linearity of the transmission signal V which may vary over more than two decades. This aspect has not been tested separately as it is hard to perform.

The second aspect concerns the signal linearization, i.e. the log-conformity of the applied amplifier, which is within 1% over two decades at least.

In an extensive study Bosman (1984) reported that no significant instrumental alinearility has been found in the practical operating range of the OPCON.

5.5 Ambient light sensitivity

Under normal conditions, no significant contribution from daylight and room lightening has been found. Usually, it is rather constant, and it is corrected for by the zero-adjustment of OPCON, see Section 6.4. Its variation is
included in the instrumental fluctuation, see Subsection 5.3.3.

When a strong light beam is directed towards the OPCON receiver side under a small angle, the ambient light influence is obvious (e.g. when films are being made). Elimination can be achieved by:
- keeping the lightening constant and zero-re-adjustment, see Section 6.4,
- protection of the receiver side for small angle incident light by a small light blocking shield opposite to the receiver side.

5.6 Flow velocity influence

As flow velocity influence is expected to be very small, it is hard to detect amongst other environmental influences. Hence flow velocity influence has been investigated in the wavetunnel of the Delft Hydraulics Laboratory. In the tunnel the water velocity has been varied sinusoidally with a period of ten seconds (as a possible influence is expected to be slow) and a velocity amplitude of 1 m/s. The instantaneous OPCON-output has been recorded for half a day. No significant 10 s-variation could be detected.
6. Calibration

6.1 Introduction

An extensive study on the calibration of optical devices (not typically OPCON) has been carried out by Bosman (1984). Some headlines of this study will be recalled here.

6.2 The suspension vessel

To obtain accurate calibration results the concentration should be known well in the calibration. As a consequence the spatial homogeneity of the concentration in the calibration process should be within 10%. To accomodate this requirement, Bosman (1984) designed a small suspension vessel in which sediment can be brought into suspension with a concentration homogeneity varying from a few percent for small sediment particles up to ten percent for coarse particles. The suspension vessel is small and easy to operate.

6.3 The calibration procedure

In a known clean water volume, the OPCON-output is adjusted to zero, which actually means that the reference signal \( a_{r} V_{r} \) is adjusted equal to the zero-transmission signal \( V_{o} \).

A known amount of the studied sediment is added to the water and brought into suspension. The (averaged) OPCON-output is proportional to the concentration. To obtain accurate results the sensor position should be varied. This can be done discretely (e.g. take 10 positions) or continuously (moving the sensor during averaging). This way a calibration accuracy within a few percent can be achieved easily. From the averaged OPCON-output and the known concentration, the calibration constant is calculated easily. For accurate calibrations a concentration by volume in the range 0.1% - 1% is recommended.

6.4 Maintaining the calibration in measurements

"Measurement water" is defined as the water during the measurement when all studied sediment has settled. The measurement water can be clean water. But often the measurement water is more or less turbid. Small particles are very
effective in light extinction. Thus even when the small particles concentration is extremely small (e.g. visually undetected) its influence on light transmission may be appreciable. It means that the zero-transmission is affected, i.e. \( V_0 \) in the measurement water differs from that in clean water. To correct for the influence, it suffices to adjust the OPCON-output to zero in the measurement water. **This is not affecting the calibration constant.**

It is recommended to adjust the OPCON-output to zero in the measurement water before starting measurements. This corrects for the long-term change of the water transmission and for instrumental drift. The calibration constant is maintained as long as the studied sediment is identical to that in the calibration.
7. Concentration accuracy

7.1 Introduction

When concentration measurements are performed with OPCON, it is of great importance to know what errors should be taken into account. This is discussed for both instantaneous concentrations and for time-averaged concentrations.

7.2 Concentration errors

7.2.1 The error contributions

Generally, the instantaneous relation between the OPCON-output and the sediment concentration is given by:

\[ W = W_o + a_r \gamma C_v, \]  

(7.1)

where \( W_o \) is the zero-concentration output. Adjustment of \( W_o \) to zero means to adjust \( a_r \) such that \( a_r v_r = v_o \). Due to instrumental instability in \( v_o \), see Section 3.4.5, \( W_o \) will not be stable and equal to zero during the measurements.

The various error contributions can be defined. The first error contribution is due to statistical fluctuations as Eq. (7.1) is valid only on the average, see Section 2.5. This fluctuation contributes to the random error only and its relative contribution is denoted by \( (\Delta C_v/C_v)_{stat} \). From Eq. (7.1) the other error contributions can be derived. Instrumental instabilities through \( W_o \) contribute to the relative concentration error as:

\[ \left| \frac{\Delta C_v}{C_v} \right|_{instr} = \frac{1}{\beta} \left| \frac{\Delta W_o}{C_v} \right|, \]  

(7.2)

The instrumental instability \( \Delta W_o \) contains fluctuation, variation and drift. Instrumental instabilities in \( a_r \) are included in the instrumental instability \( \Delta W_o \). The read-out accuracy \( \Delta W_r \) of the OPCON-output contributes to the random concentration error only:
\[
\frac{\Delta C_v}{C_v} \Big|_{\text{read}} = \frac{1}{\beta} \frac{\Delta W_r}{a_c}. 
\]

The calibration accuracy \( \Delta \gamma \) leads to a concentration error:

\[
\left| \frac{\Delta C_v}{C_v} \right|_{\text{cal}} = \left| \frac{\Delta \gamma}{\gamma} \right|.
\]

The calibration accuracy \( \Delta \gamma \) is purely systematic in the concentration error. In principle \( \Delta \gamma/\gamma \) consists of two parts, see Subsection 2.6.4:

- \( |\Delta \gamma/\gamma|_C \): the relative accuracy with which \( \gamma \) is determined in the calibration. In a good calibration procedure it is typically 5%.
- \( |\Delta \gamma/\gamma|_D = |\Delta D^*/D^*| \): the deviation of \( \gamma \) in the measurement from the \( \gamma \) in the calibration due to segregation. With a few percent segregation (in terms of \( D^* \)), this \( |\Delta \gamma/\gamma|_D \) is dominating in \( |\Delta C_v/C_v|_{\text{cal}} \).

7.2.2 **Magnitude of error contributions**

The **statistical concentration error** is discussed extensively by Bosman (1981). The explicit expressions are repeated here:

- for instantaneous concentration measurements:

\[
\left| \frac{\Delta C_v}{C_v} \right|_{\text{stat,i}} = \frac{\hat{D}}{d} \frac{1}{\beta} \sqrt{\frac{\beta}{e-1}}. 
\]

For OPCON \( d = 2.6 \) mm and in practice \( \hat{D} \) is usually of the order 0.2 mm. Thus \( \hat{D}/d \) is of the order 0.1. As a consequence, the instantaneous statistical error varies usually from about 10% for \( \beta = 1.6 \), up to about 50% for \( \beta = 0.05 \) and \( \beta = 5 \).

- for time-averaged concentration measurements:

\[
\left| \frac{\Delta C_v}{C_v} \right|_{\text{stat,a}} = \frac{1}{\sqrt{1 + \frac{4\pi\tau}{\pi d}}} \frac{\hat{D}}{d} \frac{1}{\beta} \sqrt{\frac{\beta}{e-1}}, 
\]

where \( \tau \) is the averaging time-interval and \( v \) is the (averaged) absolute flow velocity-component perpendicular to the light beam. For \( vt \gg d \):

\[
\left| \frac{\Delta C_v}{C_v} \right|_{\text{stat,a}} = \frac{\hat{D} \sqrt{\pi}}{2\sqrt{v\tau}} \frac{1}{\beta} \sqrt{\frac{\beta}{e-1}}. 
\]

The statistical error can be reduced by \( \tau \), however, at the cost of time-resolution.
The **instrumental concentration error** is given by Eq. (7.2). The various instrumental instabilities $\Delta W_o$ have been specified in Subsections 5.3.3, 5.3.4 and 5.3.5. By substituting $a_c = 2605$ mV the instrumental error contributions are given by:

- the instrumental fluctuation contribution, Subsection 5.3.2:

\[
\frac{\Delta C_v}{C_v} \bigg|_{i,f} < \frac{0.03}{\beta} \% \text{ purely instrumental,} \tag{7.8a}
\]

\[
< \frac{0.08}{\beta} \% \text{ due to water impurity.} \tag{7.8b}
\]

- the instrumental variation contribution, Subsection 5.3.4:

\[
\frac{\Delta C_v}{C_v} \bigg|_{i,v} < \frac{0.2}{\beta} \% \text{ over a workday and longer.} \tag{7.9}
\]

- the instrumental drift contribution, Subsection 5.3.5:

\[
\frac{\Delta C_v}{C_v} \bigg|_{i,d} \begin{cases} 
= \frac{0.0012}{\beta} \% \text{ per hour for the long term,} & \tag{7.10a} \\
< \frac{0.2}{\beta} \% \text{ over a workday.} & \tag{7.10b}
\end{cases}
\]

The **read-out concentration error** is given by Eq. (7.3) and depends on the user's choice. Instead, the relevant read-out accuracy will be given in the next sections, depending on the type of measurement.

The **calibration concentration error**, given by Eq. (7.4), depends on the user too.

7.3 **Instantaneous concentration accuracy**

7.3.1 **Random error**

The random error contributions to the instantaneous concentration are:

- the instantaneous statistical contribution given by Eq. (7.5), amounts typically 10 - 50%.

- the instrumental fluctuation contribution, given by Eqs. (7.8a-b) amounts typically less than $0.09/\beta$%,
the read-out accuracy, specified by Eq. (7.3).

Except for extremely small values of $\beta (\beta \ll 10^{-3})$ the instrumental fluctuation contribution can be neglected with respect to the statistical random error. Under practical conditions this is justified. For particle sizes of the order 0.05 mm, it can be relevant only for $C_v << 2$ ppm, and for particle sizes of 0.5 mm only for $C_v << 20$ ppm.

Similarly, when the read-out accuracy is of the same magnitude as the instrumental fluctuation contribution, it can be neglected too. As the instrumental fluctuation is less than 2.5 mV, a read-out accuracy $|\Delta W_r|$ within 3 mV suffices under practical conditions for instantaneous measurements.

The relevant total random error for instantaneous concentration measurement is summarized in Table 2a.

7.3.2 Systematic error

The systematic error contributions to the instantaneous concentration are:
- the instrumental variation, given by Eq. (7.9). As instantaneous measurements are short term measurements, instrumental drift is included in the instrumental variation.
- the calibration contribution, given by Eq. (7.4).

Similar to the procedure in the former section, it can be shown that the systematic error due to instrumental variation can be neglected under practical conditions as it is much smaller than the random (statistical) error. For practical sizes of 0.05 mm it can be relevant only when $C_v << 100$ ppm, and for particle sizes near 0.5 mm, only when $C_v << 1000$ ppm.
Thus practically the calibration contribution is the only one to account for.

The pure calibration accuracy is of the order of a few percent in a good calibration procedure, so it can be neglected with respect to the random error. When the diameter $D^*$ is not identical in the calibration and in the measurement, the relative deviation $\Delta D^*/D^*$ is important. When significant segregation ($>5\%$) occurs a relative systematic concentration error of the same magnitude as the relative segregation $\Delta D^*/D^*$ should be taken into account.
The relevant systematic error for instantaneous concentration measurements is given in Table 2a.

7.4 Time-averaged concentration accuracy

7.4.1 Random error

The random error contributions to the time-averaged concentration are:
- the statistical contribution, given by Eqs. (7.6) and (7.7),
- the instrumental variation contribution, given by Eq. (7.9),
- the read-out accuracy contribution, given by Eq. (7.3).

It is found easily from Eqs. (7.3) and (7.9) that the contribution from the read-out accuracy $\Delta W_r$ can be neglected relative to the variation contribution when $|\Delta W_r| < 5$ mV. The instrumental variation contribution is largest for minimum $\beta$, see Eq. (7.9). For $\beta = 0.065$ it is less than 3%. For $\beta = 0.01$ it may contribute up to 20%. The magnitude of the statistical error is up to the users choice for the averaging time-interval. But it makes no sense to reduce the statistical error under the instrumental contribution (a waste of time-resolution). By equating Eqs. (7.6) and (7.9) it is found for a sensible choice:

$$\nu \tau \lesssim \frac{25\pi D^2}{4d} (e^\beta - 1) \times 10^4 - \frac{1}{4} \pi d. \quad (7.11)$$

For $D = 0.2$ mm and $d = 2.6$ mm and for concentrations above $C_v = 10$ ppm, Eq. (7.11) can be approximated well by:

$$\nu \tau \lesssim 2 \times 10^6 C_v \text{ (mm).} \quad (7.12)$$

Thus for concentrations near $C_v = 1000$ ppm and velocities of the order of 0.5 m/s, it makes no sense to choose an averaging time-interval longer than 4 seconds.

The random concentration error for time-averaged concentrations is summarized in Table 2b.
7.4.2 **Systematic error**

The systematic error contributions to the time-averaged concentration are:
- the instrumental drift contribution, given by Eqs. (7.10a-b),
- the calibration contribution, given by Eq. (7.4).

The instrumental drift contribution can be neglected with respect to the total random error. The relative calibration accuracy $|\Delta \gamma / \gamma|_c$ can be neglected as well, though it may be dominant at large concentrations. But even then it is of the order of only a few percent in a good calibration procedure. Thus the relative calibration error due to deviating particle size (segregation) remains. It can be neglected when segregation is less than a few percent. Otherwise, the relative concentration error is $|\Delta D^* / D^*|$.  

The systematic concentration error in time-averaged measurements is summarized in Table 2b.
8. Remarks on application of optical devices

8.1 Introduction

Besides of the discussion of the specific device OPCON, it is worthwhile to put some remarks on the application of the optical method for sediment concentration measurements. The remarks are based upon a three years operation experience with OPCON, during which it has been applied in various experiments. Some of the remarks apply to other measurement methods as well.

8.2 Background turbidity

Optical transmission depends both on the concentration and on the particle size. The light extinction is inversely proportional to the particle size diameter. Thus smaller particles are much more effective in light extinction than coarser particles. Even when the concentration of very small particles during the concentration measurements (background turbidity) is extremely small it may result into a considerable light extinction.

Except when the used sediment has been washed thoroughly, it is experienced that turbidity occurs in the measurements. This is not necessarily a problem provided that its contribution to light extinction is constant. Then it can be corrected for easily by proper zero-adjustment. It has been experienced also, however, that with natural sands the turbidity varies in time (with the fluid motion). Then it acts as an instrumental variation. Thus it is negligible only when the light extinction due to turbidity varies less than 0.5%. In practice this variation is usually much larger, introducing a large random error in the measurements.

It is concluded that optical methods can be applied under conditions with turbidity, provided that attention is paid to its extinction variation.

8.3 Segregation

With unsorted sediment in suspension, segregation occurs. In terms of the particle effective diameter \( D^* \), segregation has been often found in the range 20 - 60%. Considerable systematic errors are introduced when segregation is
not corrected for. Thus samples should be tapped from the suspension at each measurement height and for each fluid motion. This is quite laborious.

8.4 Instantaneous measurements

An important reason to apply optical methods is that it allows to measure the variation of concentration in time. It has been found by Nakato et al (1977) that the instantaneous concentration shows a relatively large random error. This has been confirmed by Bosman (1982) who concluded that this random error is certainly not due to particles positioning in space as has been assumed before. Bosman concluded that the relatively large random error (50 - 150%) is an inherent characteristic of the suspension process. Only part of the process can be described in a deterministic way as far as it is determined by the (averaged) water motion. But the other part (usually the major part) is due to the loose boundary both with respect to the small scale water motion (turbulence structure) and with respect to the bed (dynamic state variable). Maybe measurement of the concentration variation in time is not so useful.
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<td>read-out unit</td>
<td>$\frac{\Delta V_r}{V_o}$</td>
<td>$\frac{1}{\beta} \frac{\Delta V_r}{V_o}$</td>
<td>random</td>
</tr>
<tr>
<td></td>
<td>$d$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>calibration</td>
<td>$\frac{\Delta \gamma}{\gamma}$, tot</td>
<td>$\frac{\Delta \gamma}{\gamma}$, tot</td>
<td>systematic</td>
</tr>
<tr>
<td></td>
<td>$\frac{\Delta D^<em>}{D^</em>}$</td>
<td>$\frac{\Delta D^<em>}{D^</em>}$</td>
<td>systematic</td>
</tr>
</tbody>
</table>

Table 1  Concentration error contributions

Note: $^+$ only relevant for instantaneous measurements
**instantaneous measurements**

<table>
<thead>
<tr>
<th>random error</th>
<th>purely statistical</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \frac{\Delta C_v}{C_v} ]</td>
<td>[ \frac{\hat{D}}{d} \frac{1}{\beta} \sqrt{e^{\beta} - 1} ]</td>
</tr>
</tbody>
</table>

| systematic error | \[ \frac{\Delta C_v}{C_v} \] | \[ = 0 \] when \[ \frac{\Delta D^*}{D} \] \[ < 5\% \] +) |
| | \[ \frac{\Delta C_v}{C_v} \] | \[ = \frac{\Delta D^*}{D} \] when \[ \frac{\Delta D^*}{D} \] \[ > 5\% \] +) |

| recommended | read-out accuracy \[ \frac{\Delta W}{W} \] < 3 mV |

Table 2a Error table for instantaneous concentration measurements

**time-averaged measurements**

\( \tau = \) averaging time-interval
\( v = \) time-averaged (over \( \tau \)) absolute velocity-component perpendicular to the light beam

| random error | \[ \frac{\Delta C_v}{C_v} \] | \[ = \frac{1}{\beta} \left[ \frac{\pi D^2}{4 d v \tau} (e^{\beta} - 1) + 4 \times 10^{-6} \right] \] |

| systematic error | \[ \frac{\Delta C_v}{C_v} \] | \[ = 0 \] when \[ \frac{\Delta D^*}{D} \] \[ < 5\% \] +) |
| | \[ \frac{\Delta C_v}{C_v} \] | \[ = \frac{\Delta D^*}{D} \] when \[ \frac{\Delta D^*}{D} \] \[ > 5\% \] +) |

| recommended | read-out accuracy \[ \frac{\Delta W}{W} \] < 5 mV combine Bosman's (1981) uncertainty relations with \( \nu \tau \lesssim 2 \times 10^6 C_v \) (mm) |

Table 2b Error table for time-averaged concentration measurements

\(^{+})\text{Note: } \Delta D^* \text{ is the difference in particle size between the calibration and the actual measurement. An important practical origin is segregation}\)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1100 g</td>
</tr>
<tr>
<td>Submersible length</td>
<td>0.95 m</td>
</tr>
<tr>
<td>Light transmission length</td>
<td>(29.6 ± 0.3) mm</td>
</tr>
<tr>
<td>Light beam diameter</td>
<td>(2.57 ± 0.05) mm</td>
</tr>
<tr>
<td>Light peak wavelength</td>
<td>880 mm</td>
</tr>
<tr>
<td>Power requirement</td>
<td>(50 - 60 Hz/10 W)</td>
</tr>
<tr>
<td>Output-sensitivity</td>
<td>3 V/decade</td>
</tr>
<tr>
<td>Output-range</td>
<td>0 - 13 V</td>
</tr>
<tr>
<td>Stabilization after switch-on</td>
<td>&lt; 10 hrs</td>
</tr>
<tr>
<td>Fluctuation*</td>
<td>&lt; 1 mV</td>
</tr>
<tr>
<td>Variation*</td>
<td>&lt; 5 mV</td>
</tr>
<tr>
<td>Drift-rate*</td>
<td>&lt; 0.03 mV/hr</td>
</tr>
<tr>
<td>Particle size range</td>
<td>0.05 mm - 0.5 mm</td>
</tr>
<tr>
<td>Lower concentration limit for particle size</td>
<td>10 ppm</td>
</tr>
<tr>
<td>of 0.1 mm (other sizes in proportion)</td>
<td></td>
</tr>
<tr>
<td>Upper concentration limit</td>
<td>none</td>
</tr>
<tr>
<td>Linearity</td>
<td>within 1% for concentrations up to 10,000 ppm</td>
</tr>
<tr>
<td>Response to concentration gradients</td>
<td>no restriction for particle velocities up to 25 m/s</td>
</tr>
<tr>
<td>Response to statistical variations</td>
<td>no restriction for particle velocities up to 2.5 m/s</td>
</tr>
</tbody>
</table>

Table 3  OPCON-specifications

*Note: relation output/concentration: \( W = K \cdot C_v \),

\( K = \) calibration constant, depending on particle size \( (K = 116 \text{ V/D; D in mm}) \),

fluctuation/variation/drift-rates in terms of concentration: \[ |\Delta C_v| = |\Delta W|/K \]
<table>
<thead>
<tr>
<th>Specification</th>
<th>All glass/Schott Mainz K2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Fibre core</td>
<td>70 μm</td>
</tr>
<tr>
<td>Bundle diameter</td>
<td>3 mm</td>
</tr>
<tr>
<td>Relative attenuation</td>
<td>0.1 %/m</td>
</tr>
<tr>
<td>Numerical aperture</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Table 4 Fibre bundle specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>LED/GENERAL ELECTRIC F5DI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Continuous power output</td>
<td>12 mW (100 mA)</td>
</tr>
<tr>
<td>Peak wavelength</td>
<td>λ_p = 880 nm</td>
</tr>
<tr>
<td>Spectral bandwidth (50%)</td>
<td>Δλ_50 = 80 nm</td>
</tr>
<tr>
<td>Temp. coeff. peak wavelength</td>
<td>0.3 nm/K</td>
</tr>
<tr>
<td>Half intensity beam angle</td>
<td>θ_1/2 = 20°</td>
</tr>
</tbody>
</table>

Table 5 Emitter specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Si-PIN-diode/SIEMENS BP104</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td></td>
</tr>
<tr>
<td>Sensitive area</td>
<td>5 mm²</td>
</tr>
<tr>
<td>Peak wavelength</td>
<td>λ_max = 950 nm</td>
</tr>
<tr>
<td>Spectral bandwidth (50%)</td>
<td>Δλ_50 = 100 nm</td>
</tr>
<tr>
<td>Lower sensitivity limit</td>
<td>λ_low = 760 nm</td>
</tr>
<tr>
<td>Sensitivity at λ = 880 nm</td>
<td>80%</td>
</tr>
<tr>
<td>Temp. coeff. sensitivity</td>
<td>-0.2%/K</td>
</tr>
<tr>
<td>Half sensitivity beam angle</td>
<td>θ_1/2 = 60°</td>
</tr>
<tr>
<td>Dark current</td>
<td>2 nA</td>
</tr>
</tbody>
</table>

Table 6 Receiver specifications
1A. large random error/small systematic error

1B. small random error/large systematic error

1C. X - instabilities
NORMALIZED BEHAVIOUR OF STATISTICAL FLUCTUATIONS AS A FUNCTION OF $\beta$

DELFt HYDRAULICS LABORATORY

R 716-VI FIG. 2
SUITABLE WAVE-LENGTH WINDOWS

DELFt HYDRAULICS LABORATORY

R 716-VI FIG. 3
L - light source (LED)
P_c, P_r - photo-diodes
A_c, A_r - photo-amplifiers
D - diaphragm
f - 3mm Ø glass fibers
P_1 - clear prism
P_2 - silvered prism

SCHEMATIC SET-UP OF OPCON

DELFIT HYDRAULICS LABORATORY
OPCON
OPTICAL CONCENTRATION PROBE
DELFT HYDRAULICS LABORATORY
R 716-VI FIG. 5
MEASURED TIME RATIO AS A FUNCTION OF VELOCITY

DELFT HYDRAULICS LABORATORY

R 716-VI FIG. 8
opcon linearized output W (mV)

- 0.1 mV/hr

- 2 mV/hr

time after switch-on (hrs)

STABILIZATION OF OPCON AFTER SWITCH-ON

DELFIT HYDRAULICS LABORATORY

R 716-VI FIG. 9
LONG-TERM STABILITY OF OPCON

DELFT HYDRAULICS LABORATORY

R 716-VI FIG. 10

relative humidity(%) ambient temperature(°C) opccon linearized output W (mV)
1 The OPCON - probe
2 The OPCON input/output system