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over a many kilometer path

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A CO₂ laser scintillometer for C_n² measurements
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W. Kohsiek

Abstract

This report gives the technical description of a CO₂ laser scintillometer for the measurement of C_n^2 over pathlengths from 100 m to 10 km. Included are electronical adjustment procedures and discussions of the calibration backgrounds and the operation region of the instrument. The scintillometer has proven to work satisfactory over pathlengths of 449, 5900 and 9700 m.

1. Introduction

A CO₂ laser scintillometer has been developed with the purpose to obtain a path-averaged measurement of the refractive-index structure parameter (C_n^2) for path lengths of several kilometers. By virtue of its long wavelength, 10.6 μm , a CO₂ laser scintillometer largely avoids the problem of saturation of scintillation. Visible or near infrared scintillometers can only cope with the saturation effect if finite, incoherent apertures are used with sizes that become unwieldy large for a many kilometer path.

This report offers a technical description of the CO₂ laser scintillometer. The relation of C_n^2 to the surface fluxes of heat and moisture, and a comparison between the optical C_n^2 and in-situ observations of this quantity have been discussed elsewhere [1,2].

2. Optical configuration

The radiation source (Fig. 1) is a RF excited CO₂ laser. It delivers an output power of 2 W in a 8 mrad divergent beam. The laser requires no water cooling which is an advantage in field measurements. However, the output power of our laser drifted considerably, which behaviour could be suppressed to some extent by cooling the laser head with a ventilator. Due to the slow nature of the drift, it has no direct effect on the measurement of C_n^2 unless the output power is so low that one runs into noise problems. The laser beam is mechanically modulated at 1.6 kHz. Laser head, cooling fan and beam chopper are mounted on an adjustable support together with a rifle telescope.

The receiver (Fig. 2) consists of a Ge focussing lens with a clear aperture of 20 mm and a focal length of 62.5 mm, and a liquid nitrogen cooled HgCdTe detector with a sensitive area of 2 mm diameter. The lens may be omitted if a relatively short path (< 1 km) is used. It was found that the HgCdTe detector is not uniformly sensitive across its surface, so that either defocussing or a very stable mount is advisable. The output signal of the detector is amplified by a battery powered low noise preamplifier located at a short distance from the detector.

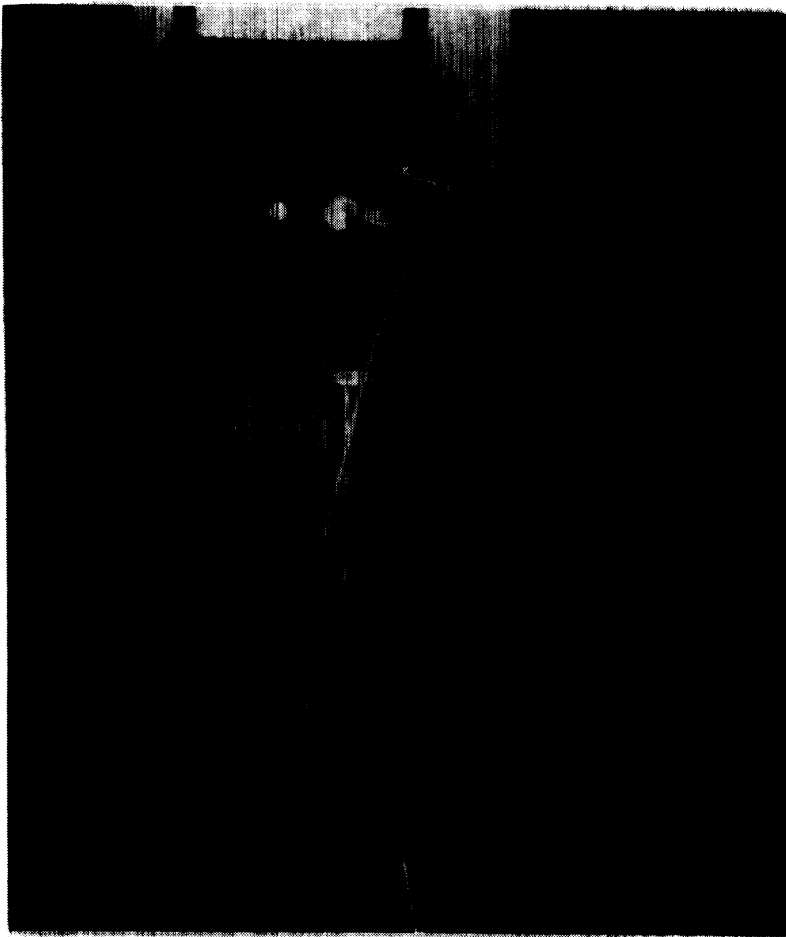


Fig. 1. CO₂ laser assembly. The block-shaped laser head is mounted on a heat sink. Above the laser head a cooling fan (rear) and the beam chopper control unit are placed. The laser beam is directed through the smaller hole (left), the rifle telescope through the larger hole.

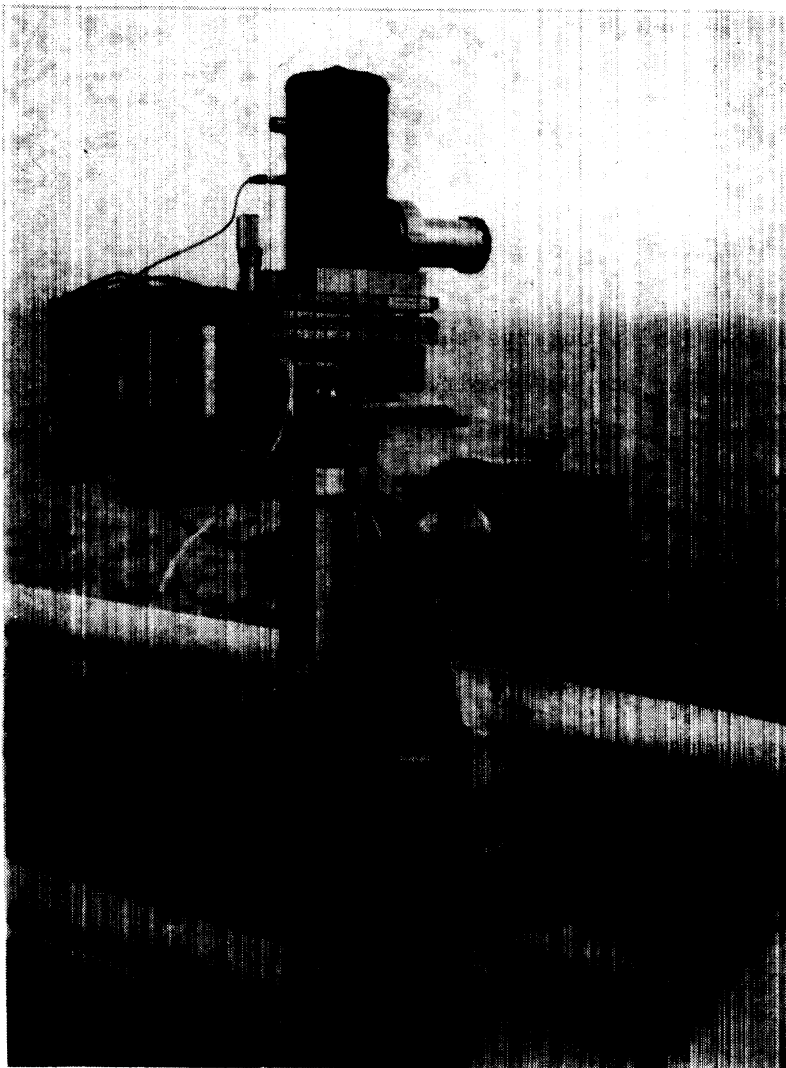


Fig. 2. Detector assembly. The detector proper is the vertical cylinder at the top of the picture. The focussing lens is mounted inside the cylinder that protrudes to the right from the detector. To the left the batteries that power the preamplifier are seen; the preamplifier is placed in between the batteries and the adjustable support for the detector. A second support shown in the middle of the picture is only used for coarse adjustments.

3. Electronics

After the preamplifier, the signal is processed by an analog circuit, which delivers an output voltage that is proportional to $\log C_n^2$. This device is largely a copy of the one described in [3]. It is made up out of 3 parts (circuits): a variable gain amplifier, a second, fixed amplifier followed by a demodulator, and a filter and r.m.s. voltage circuit. The first amplification section originally had an automatic gain control (AGC), but this feature has been replaced by a manually controlled gain because it was observed that the AGC may introduce some non-linear effects. Furthermore some components in the demodulator were adapted to cope with the 1.6 kHz modulation frequency. The demodulated signal is filtered by an active bandpass filter with 3 dB points at 1.5 and 400 Hz. There is virtually no other signal filtering in the amplifier or demodulator section. The filtered signal is measured by a true r.m.s. voltmeter and presented in a linear and log mode on the output jackets. On the circuit boards four potmeters are located that monitor the calibration of the demodulator and the r.m.s. voltmeter. These potmeters are in principle fixed; their adjustment procedure is given in the next section. On the panel a dial potmeter is mounted which has to be set depending on path length and detector aperture. This is discussed in Appendix B.

4. Electronic adjustments

1. Adjustments AD536 demodulator circuit.

- a. Remove op amp 2B
- b. Put +0.1000 volt at pin 1 of the AD536. Observe the signal at pin 6 of op amp 2D. Adjust the 50 k Ω resistor for 0.00 volt.
- c. Put 1.000 volt at pin 1 of the AD536. Adjust the 200 Ω resistor for 2.00 volt at pin 6 of op amp 2D.

2. Adjustment filter and r.m.s. circuit.

- a. Remove op amp E
- b. Put 0.1000 volt at pin 1 of the AD536. Adjust the 50 k Ω resistor for 0.00 volt at pin 6 of op amp H.
- c. Put 1.000 volt at pin 1 of the AD536. Adjust the 200 Ω resistor for 2.00 volt at pin 6 of op amp H.

3. Adjustment variable gain circuit.

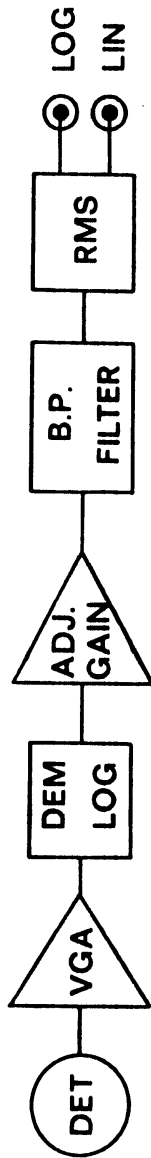
As mentioned afore, the AGC provision has been omitted and the two FET's that used to control the gain of op amps 1A and 1B have been replaced by one fixed and one variable resistor, respectively. The latter resistor, a 10 k Ω one turn panel potmeter labelled "GAIN", is to be set so that the linear signal level at pin 8 of the AD536 of the demodulator circuit is about 1 volt. The signal is available at the output plug labelled "DEM.A".

Note: the adjustment of the two AD536 depends on the power supply voltage, which is fixed at + and - 15 V (the electronics described in [3] run on + and -5 V).

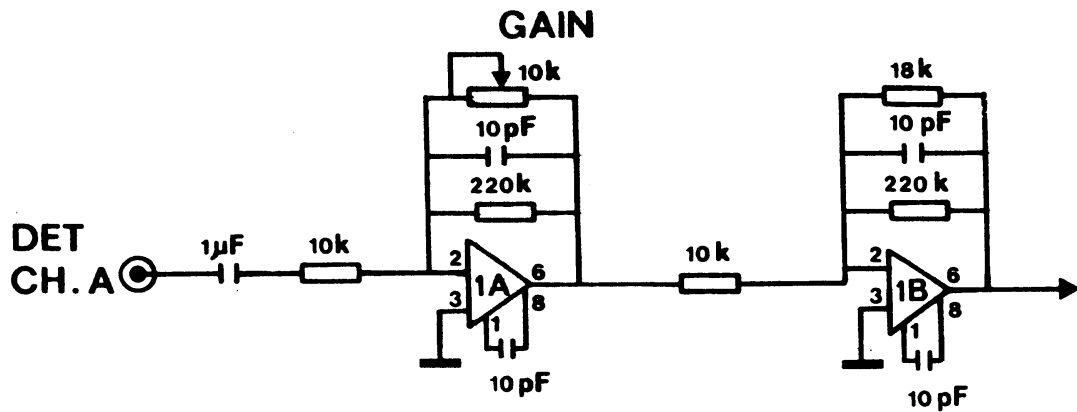
APPENDIX A

1. Block diagram of C_n^2 system
2. Variable gain amplifier
3. Demodulator
4. Filter and r.m.s. voltmeter
5. BNC connectors
6. Panel functions

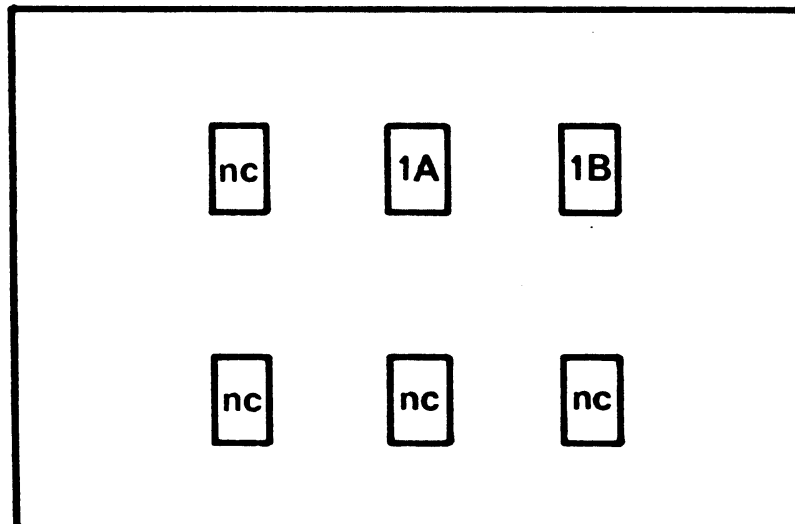
1. Block diagram of C_n^2 system.



2. Variable gain amplifier.

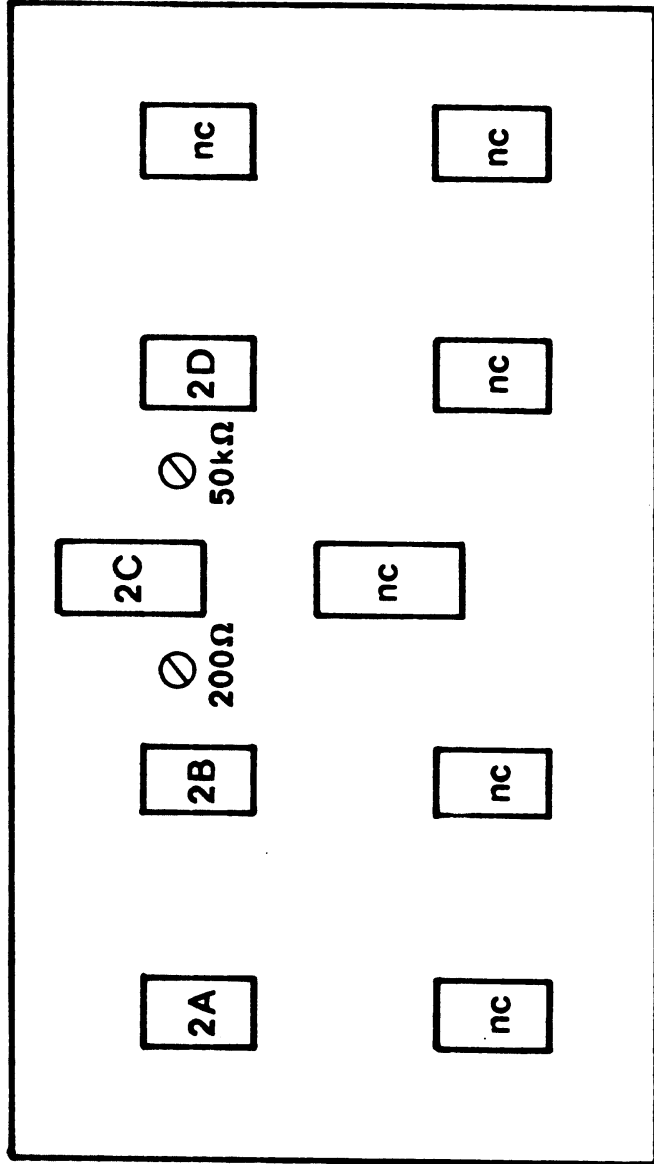
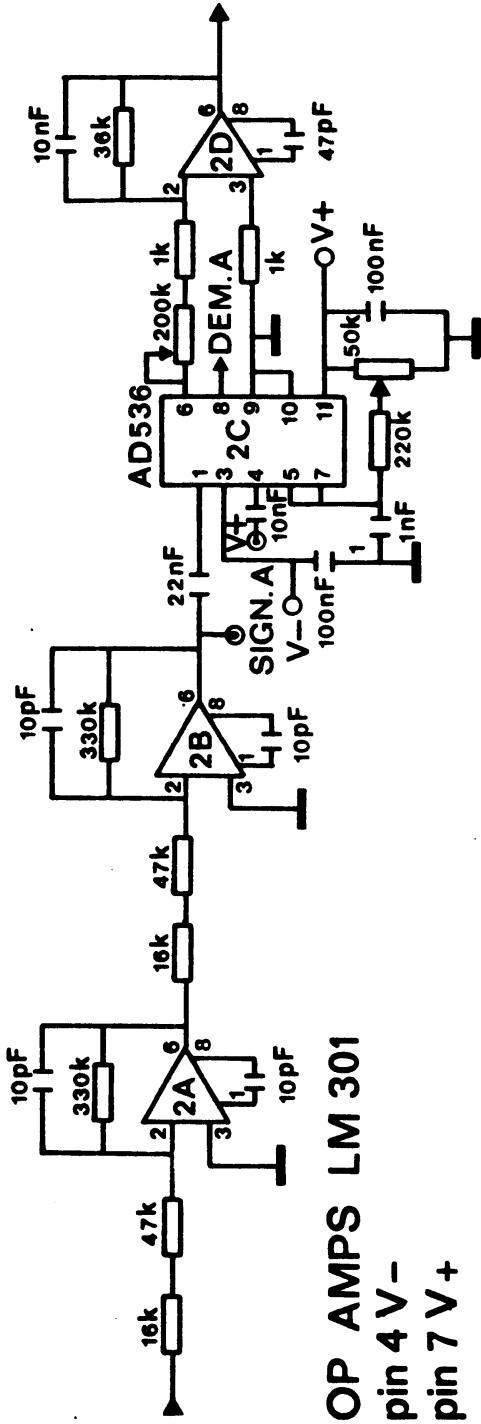


OP AMPS LM 301
 pin 4 V-
 pin 7 V+



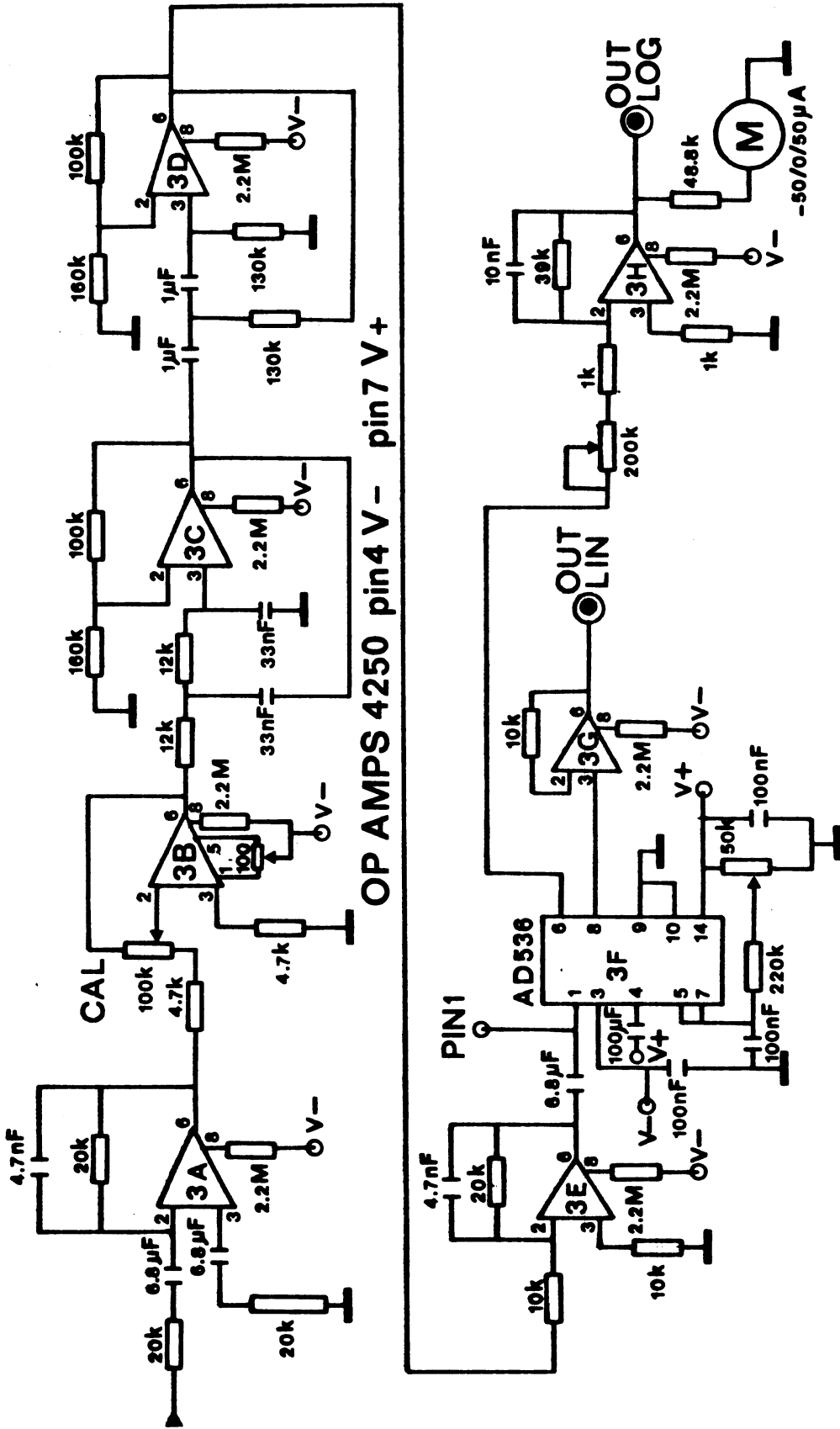
circuit board layout

3. Demodulator.

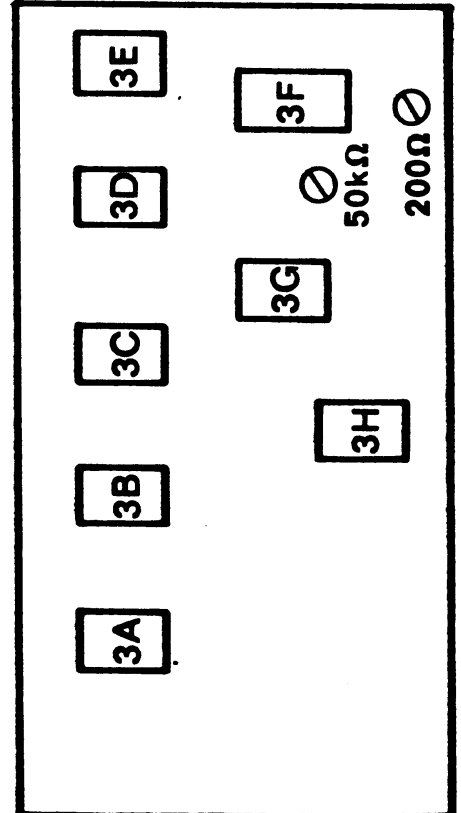


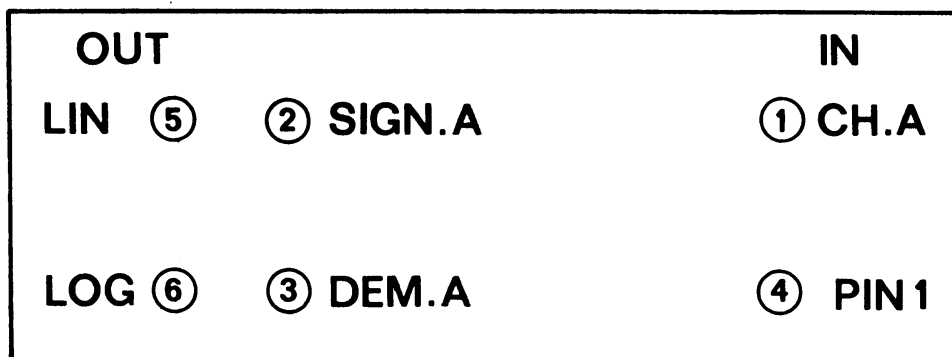
circuit board layout

4. Filter and r.m.s. voltmeter.

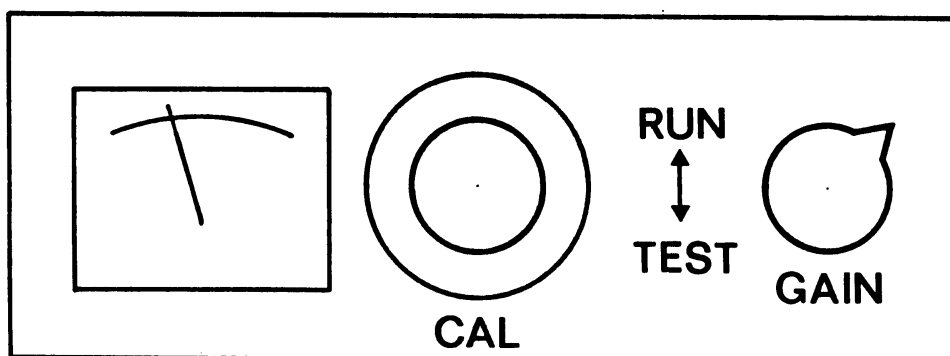


circuit board layout



5. BNC connectors

- 1: signal input
 2: modulated signal after amplification
 3: demodulated signal, linear
 4: demodulated, filtered signal, log, to be presented to r.m.s. voltmeter
 5: linear output
 6: log output

6. Panel functions

From left to right:

- Voltmeter, parallel to LOG OUT, ± 2.5 V full scale
- Dial potmeter for calibration (Appendix B)
- Switch, not used, leave in position "RUN"
- One turn potmeter for gain adjustment (Section 4.3)

APPENDIX B

Calibration backgrounds

In this Appendix the line of reasoning presented in [3] is closely followed. Because some of the steps involved here are different from [3], it was considered appropriate to give the complete derivation of the calibration at this place again rather than referring to [3] only.

There are basically two differences between the scintillometer discussed in [3] and the CO₂ scintillometer: the former makes use of a finite aperture transmitter and two finite aperture receivers, whereas the latter only has one receiver while the apertures, to start with, will be considered as infinitely small.

For the present scintillometer the log-amplitude variance of the irradiance, σ_X^2 , is given by [4]

$$\sigma_X^2 = 0.124 k^{7/6} L^{11/6} C_n^2, \quad (1)$$

where $k = 2\pi/\lambda$, λ is the wavelength of the radiation, L is the path length and C_n^2 the refractive-index structure parameter. By definition,

$$\sigma_X^2 = (\ln A - \overline{\ln A})^2, \quad (2)$$

where A is the radiation amplitude and the overbar denotes a time average. Because we measure irradiance $I \propto A^2$ and $\ln A = 2.3026 \log A$, we can write

$$\sigma_X^2 = 2.3026^2 (\log I^{\frac{1}{2}} - \overline{\log I^{\frac{1}{2}}})^2 \quad (3)$$

$$= \frac{2.3026^2}{4} (\log I - \overline{\log I})^2. \quad (4)$$

The output voltage of the demodulator is such that 2 volts is one decade of I . Furthermore, the bandpass filter removes $\overline{\log I}$, thus the input voltage to the r.m.s. voltmeter, V_3 , is

$$V_3 = 2 K \log I, \quad (5)$$

where K is the total gain between the demodulator output and the r.m.s. voltmeter input. The linear output of the voltmeter, V_4 , is equal to $\sqrt{V_3}$. Combining (5) and (4) it follows that

$$\sigma_X^2 = \frac{2.3026^2}{4} \frac{V_4^2}{4K^2}. \quad (6)$$

The instrument calibration is chosen as

$$C_n^2 = 10^{-12} V_4^2. \quad (7)$$

Combining (1), (6) and (7) it follows that the gain K is

$$K = 1.635 \times 10^6 k^{-7/12} L^{-11/12}. \quad (8)$$

The log output of the r.m.s. voltmeter, V_5 , is related to V_4 by

$$V_5 = 2 + 2 \log V_4, \quad (9)$$

thus $V_5 = 0$ V if $V_4 = 0.1$ V and $C_n^2 = 10^{-14} \text{ m}^{-2/3}$, and V_5 changes 1 volt when C_n^2 changes one decade.

The gain K is controlled by the dial potmeter on the panel labelled "CAL":

$$K = 5.27 \frac{101.6 - 1.01 R}{4.7 + 1.01 R}, \quad (10)$$

where R is the position of the dial (0 - 100). The factor 5.27 in (10) represents the measured gain of the circuit with the exception of the stage that incorporates the potmeter.

From (8) and (10) follows the relation between R and the path length L; in case of $k = 2\pi/10.6 \times 10^{-6} \text{ m}^{-1}$:

$$\begin{aligned} R &= \frac{530 - 4.65 K}{5.27 + K} \\ &= \frac{530 - 4.65 \times 701 L^{-11/12}}{5.27 + 701 L^{-11/12}} = \frac{530 - 3264 L^{-11/12}}{5.27 + 701 L^{-11/12}}. \end{aligned} \quad (11)$$

Note: if the path is many kilometers long, the potmeter has to be set at high values (> 90) and (10) gives inaccurate results due to small deviations of the potmeter from linearity. For those settings it is advised to measure the resistance of the part of the potmeter connecting to the $4.7 \text{ k}\Omega$ resistor directly and calculate the gain from

$$K = 5.27 \frac{101.36 - R_m}{4.7 + R_m}, \quad (12)$$

where R_m is the measured resistance. For a chosen K , R_m is given by

$$R_m = \frac{534.17 - 4.7 K}{5.27 + K} \quad (13)$$

When measuring R_m , remove op amp 3B!

In the foregoing, the receiver and transmitter apertures were supposed to be infinitely small, that is much smaller than the size of the first Fresnel zone $\sqrt{\lambda L}$. The transmitter aperture is equal to the laser beam diameter, which is about 1.5 mm and indeed can be considered small if compared to $\sqrt{\lambda L}$ (for example, $\sqrt{\lambda L}$ is 73 mm for a 500 m path). The receiver aperture is 2 mm if no focussing lens is used and 20 mm with lens. In the latter case σ_x^2 is overrated by (1) if the pathlength is shorter than several kilometers. The appropriate correction to R as a function of L can be expressed as

$$\Delta R = -9174 L^{-1.357}. \quad (14)$$

ΔR is the amount by which the setting of the potmeter has to be changed (decreased) to give the proper gain.

APPENDIX C

Operation region.

The usable path length is controlled by several factors such as laser power, detector- and electrical noise and saturation. Here, a quantitative presentation of the measurable C_n^2 for any path length will be given. The following parameters are introduced:

Effective laser power (including reduction by chopper)	$P_1 = 1 \text{ W}$
Laser beam divergence	$\delta = 8.5 \text{ mrad}$
Path length	$L(\text{m})$
Atmospheric transmission	$t(-)$
Receiver diameter	$D = 2 \times 10^{-2} \text{ or}$ $2 \times 10^{-3} \text{ m}$
Detector sensitivity	$S = 220 \text{ V/W}$
Detector noise	$N = 1.6 \times 10^{-11}$ $\text{W/Hz}^{\frac{1}{2}}$
Detection bandwidth	$\Delta f = 400 \text{ Hz}$

1. Long path limit

a. Limit imposed by instrumental factors

Let \bar{P}_d be the average radiation power on the detector's surface and $\sigma(P_d)$ the r.m.s. noise of the detector. Due to this noise only, an apparent log amplitude variance $\sigma_{\chi,r}^2$ is measured which is related to \bar{P}_d and $\sigma(P_d)$ by

$$\sigma_{\chi,r}^2 = \frac{1}{2} \sigma^2(\ln P_d) = \frac{1}{2} \sigma^2\left(\ln \frac{P_d}{\bar{P}_d}\right) \sim \frac{1}{2} \frac{\sigma^2(P_d)}{\bar{P}_d^2} \quad (15)$$

for $\sigma(P_d) \ll \bar{P}_d$. Substitution of

$$\bar{P}_d = P_1 t\left(\frac{D}{\delta L}\right)^2, \quad (16)$$

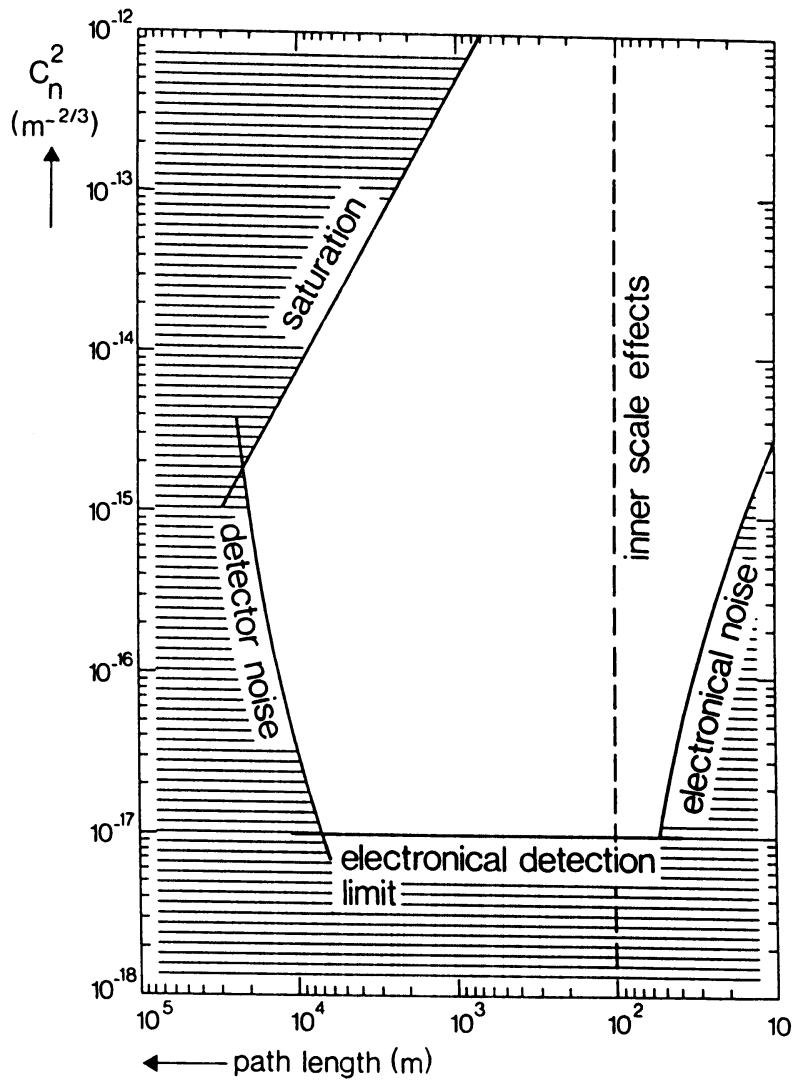


Fig. 3. Operation region of the CO₂ scintillometer with a 2 cm receiver aperture.

$$\sigma(P_d) = N \Delta f^{\frac{1}{2}} \quad (17)$$

into (15) gives

$$\sigma_{\chi,r}^2 = \frac{1}{4} \frac{N^2 \Delta f}{P_1^2 t^2} \left(\frac{\delta L}{D}\right)^2 \quad (18)$$

The log amplitude variance is interpreted in terms of C_n^2 through

$$C_n^2 = \sigma_{\chi}^2 \frac{1}{0.124} k^{-7/6} L^{-11/6} f^{-1}(D,L), \quad (19)$$

where $f(D,L)$ is the correction factor due to the finite receiver diameter. Combination of (18) and (19) gives

$$C_{n,r}^2 = \frac{N^2 \Delta f \delta^4 k^{-7/6}}{0.496 P_1^2 D^4} t^{-2} f^{-1}(D,L) L^{13/6} \quad (20)$$

The transmission t is a function of path length through

$$t = e^{-\alpha L}, \quad (21)$$

where α is the absorption coefficient of the atmosphere at the wavelength of interest. Its magnitude mainly depends on the humidity; at a water vapour density of 10 g/m^3 , $\alpha \sim 10^{-6} \text{ cm}^{-1}$ [5]. The reduction factor f was calculated as a function of L , assuming a receiver diameter of $2 \times 10^{-2} \text{ m}$. Using the above given values for the other quantities involved in (20), $C_{n,r}^2$ was calculated as a function of L . These values, multiplied by a factor of 10, have been graphed in Fig. 3. and labelled "DETECTOR NOISE".

b. Saturation limit

No saturation effect is assumed to be present if $\sigma_{\chi}^2 < 0.1$. From Eq. (19) then follows a relation between the value of C_n^2 , above which saturation is likely to occur, and the path length L . The relation is displayed in Fig. 3 for a receiver diameter of $2 \times 10^{-2} \text{ m}$ (label: SATURATION).

2. Short path limit

In case of a short path noise produced by the electronical unit becomes a limiting factor. The electronical noise has been determined experimentally in terms of C_n^2 . The observed values were multiplied by 10 and graphed in Fig. 3 (label: ELECTRONICAL NOISE).

3. Other limits

The minimum output voltage of the electronical unit is - 4V, corresponding to $C_n^2 = 10^{-18} \text{ m}^{-2/3}$. As a safe minimum detectable C_n^2 , a ten times larger value is adopted, viz. $C_n^2 = 10^{-17} \text{ m}^{-2/3}$ (label: ELECTRONICAL DETECTION LIMIT).

If the path length is very short, Eq. (1) may fail because the size of the first Fresnel zone, $\sqrt{\lambda L}$, is not anymore much larger than the inner scale of the turbulence. As a (rather arbitrary) minimum value of L , 100 m is adopted. The first Fresnel zone is 3.3 cm in that case. The inner scale length usually varies between 0.1 and 1 cm in the surface layer.

References

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