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An atmospheric infrared data link for transmission of beam information
Results of the preliminary test set-up

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1. INTRODUCTION

In a feasibility study for stochastic cooling of bunches in the SPS, [1], it was proposed to transmit beam information along a chord of the machine using an infrared laser beam in the atmosphere. An optical fibre link would be totally inadequate because of the much too long delay (the speed of light in the fiber is about 0.6 to 0.7 c). The total delay of the link (time of flight along the chord, plus electronics and cable delays) should not be greater than the beam time of flight along the arc.

The required bandwidth of the link is in the GHz range [1]. The technology of semiconductor lasers and photodiodes is expanding extremely rapidly, and GHz bandwidths are nowadays common, at relatively low prices. Moreover, compared to a classical microwave link, the optical laser beams have an extremely small divergence and it is conceivable to further increase the link capacity by using several optical beams in parallel (at the same or at different wavelenghts). Compared to a radio link the optical solution is therefore extremely attractive by its simplicity, cheapness and possibilities for further extension.

The price to be paid is, of course the limited availability of the link. In the case of deep fog for instance, the attenuation of near infrared wavelengths, although somewhat better than for visible wavelengths, will be so large over kilometer distances that the transmission will not work. Nevertheless, we believe that a careful investigation of the capabilities of the infrared link was worth the effort for the following reasons:

- Our first objective is to demonstrate experimentally the feasibility of stochastic cooling of bunches in a large machine like the SPS. This experiment can, of course, be performed when the link is available.

- It is important for any future system to assess the availability figures of such a link in the Geneva environment. At this moment the only relevant information we have found was in a commercial leaflet from an american firm [2] [3].

2. THE OPTICAL ELEMENTS

2.1 The Transmitter

The lasers we use have been developed by Philips for digital recording applications [4]. They are Al Ga As semiconductors having a double heterojunction structure which produces a strongly divergent beam from an extremely small emitting area (a few square microns). These devices are equipped with an optical system which corrects the astigmatism of the beam (the laser is a structure with a preferential plane) and makes it almost parallel. The optical system is adjusted and sealed at the factory and the result is a cheap and very small unit (commercially named collimator pen) used for instance in compact disc recording assemblies.

Two versions, which differ by the optical output power are available: the 2mW version is for read and the 20mW for write in digital recording applications. For our application the most relevant parameters are the central wavelength $\lambda \approx 850$ nm (with a very small dispersion, or bandwidth $\Delta\lambda \approx 4$ nm) and the divergence of the beam (~ 0,3 mrad) (Fig.1). Such a small divergence is a very attractive parameter for our application as it gives a beam diameter of the order of one meter at km distances. For these units the firm quotes an operational life time of the order of 10 000 hours [5].

The modulation speed of the Al Ga As semiconductor structure is extremely high (above 1 GHz) [6]. We have measured a cut off frequency of 600 MHz for the collimator pen. This figure is presumably limited by the packaging of the laser; it is nevertheless largely sufficient to test the availability of the link and to perform a stochastic cooling experiment.

The laser is aligned on the receiver using an auxiliary finderscope with reticle. The optical axes of the laser and the finderscope are made parallel on an optical bench (over a 30m distance typically) by adjusting the laser support with micrometric screws (Fig.2). The whole assembly is aligned outdoors on the receiver using the reticle of the finderscope as a reference. Finer adjustments are necessary to optimise the received power. The stability of the mechanism and of the support must be better than 0.1 mrad.

Experiments have been carried out with a laser expander to further reduce the beam divergence. A gain of the received power by a factor up to 10 has been achieved, but at the expense of very critical alignment settings. This is why a laser expander is not considered for our application, in addition to reasons of mechanical complexity.

2.2 <u>The Receiver</u>

The receiver itself is a fast avalanche photodiode (RCA C30921) with a peak response around 800 nm. Typical rise time is 0.5 ns with a sensitivity of 70 A/W.

The package is specially adapted for optical fiber coupling, the diameter of the sensitive area being approximately 0.25 mm. The angular aperture of the diodes, measured in the lab is ± 45°.

The infrared light is collected by a Schmidt-Cassegrain telescope (Fig.2). We have selected a cheap amateur model (C8 from Celestron) and modified the pointing screws to improve the alignment (better stability and reproducibility). Focal length of the primary mirror is 2 m and front lens diameter 20 cm.

Seen from 2 km the laser is a point source, and the size of the image given by the telescope mirror is diffraction limited to a few microns. This is much smaller than the diode diameter (0.25mm) and therefore by simply putting the photodiode at the primary focus of the instrument, all the light collected can reach the sensitive area. However the alignment of the telescope would be extremely critical in this configuration (0,25 mm/2 m ≈ 10^{-4} rad).

Optimum alignment tolerances for the receiver can be calculated using the Abbe sinus law (equivalent to emittance conservation in particle beams) (Fig.3). The maximum "acceptance" at the diode is : sin 45° x 0.25 mm. At the front end of the telescope this acceptance is also: 200 mm (aperture) x sin δ (half angle of the cone) at best. In other words any light ray falling on the telescope with an angle smaller than δ will be collected by the diode. This is equivalent to saying that the tolerable angular alignment error of the telescope is also δ. For a well matched system the misalignment tolerance is therefore $\delta = \pm 1.76\ 10^{-3}$ rad.

To achieve this matching, an intermediate lens is inserted in front of the diode (focal length = 10.3 mm at 860 nm, distance = 10.1 mm); the result is a non critical alignment setting as confirmed by experiments ($\delta \simeq \pm 2$ mrad for complete extinction of the signal).

All the light coming from objects inside the cone of half angle δ will be collected by the receiver; therefore the larger the δ the less critical the alignment, as we already said, but also the larger the spurious light collected from other sources, or in other words the smaller the signal-to-noise ratio. This effect is clearly observed when measuring the incoming light with a radiometer at the focus of the primary mirror. With the large sensitive area of the radiometer ($1cm^2$), the signal to noise ratio is poor because of the large δ (10 mm/2 m = 5.10^{-3}). To improve the signal to noise ratio we use an infrared filter (cut off wavelength 780 nm). A better solution would be a narrow band interferometric filter ($\Delta\lambda$ < 10nm) exactly matched to the laser wavelength.

3. ATMOSPHERIC CONTAMINATION

The test link chosen was between the auxiliary building BA3 on the SPS site and the water tower near the ISR(distance L = 2.6 km). The emitter is housed in an insulated plexiglas box mounted on the geodetic pillar on top of BA3 (Fig. 2). The alignment mechanism is directly clamped onto the pillar for optimum stability. Inside the box where the electronic equipment is located, the air temperature is adequate in winter as well as in summer (hot air is coming out of the building through the pillar sheath).

The observation deck at the top of the water tower provides a convenient place to house the telescope and electronic equipment for long term recordings.

The first outdoors transmission tests showed immediately a large fluctuation of the received power (the variance of the power fluctuation being comparable to the mean power). The spectrum of the fluctuation is given in Fig. 5 and Fig. 4 shows typical waveforms.

We first suspected the laser to be responsible for the fluctuation (partition noise from one longitudinal mode to the next which would give at long distances a different interference pattern). This explanation was soon discarded, [6], and the effect is now believed to be the scintillation of the atmosphere, also responsible for the twinkling of stars.

Scintillation is the result of diffraction of light on refractive irregularities on the light path. A very simple introduction to this theory is given in reference [7]. The relevant irregularity size is that of the Fresnel zone radius $\sqrt{\lambda L}$ where L is the path length and λ the wavelength ($\sqrt{\lambda L}$ = 4.6 cm in our case). Typical fluctuation frequencies $f = v/\sqrt{\lambda L}$, where v is the speed of the moving air are in the several ten Hertz range for v = 1m/s. This is consistant with the observations (Fig. 5).

The size of the resulting scintillation pattern r_p at the receiving end is given by : [7]

$$r_p = \sqrt{\frac{L}{Z} - 1}\,\sqrt{\lambda L}$$

where Z is the distance of the perturbing object from the source (fig.6).

If the receiver area is large compared with r_p, there is some averaging effect between the different pictures of the pattern, the extreme case being when all the emitted power is collected by the receiver. In this situation the scintillation effect is zero. The influence of the receiver area has been observed on our link by reducing the useful aperture of the telescope: the result is that the relative fluctuation increases as expected. A "diversity" reception system, using several receivers in parallel would give results equivalent to that of a much larger aperture telescope. However these approaches are relatively expensive.

Most of the scintillation effect is given by pattern sizes which are of the order of (or greater than) the telescope aperture because there is no averaging in this case. From Fig.6 it is clear that these large patterns are created by atmospheric irregularities near the source. If we use several laser beams in parallel as indicated on Fig.7 these irregularities near the source, of size $\sqrt{\lambda L} \simeq 4,6$cm, will not be correlated if the beams separation is larger than $\sqrt{\lambda L}$.

An experiment was set up using two identical lasers aligned on the telescope. The distance x between the two lasers could be varied from 1 m down to 5 cm (Fig.7). Each laser was modulated at a different RF Frequency (10 MHz and 300 MHz) and, at the receiver end two tuned receivers were used to monitor simultaneously the fluctuations of the two beams (Fig.4). The result which is in full agreement with the simple theory mentioned above was that the two signals were completely uncorrelated except at very small distances (Fig. 5, x = 5 cm).

Pratically this means that the signals from the two lasers never vanish simultaneously: there is always a useful signal available, although with a fluctuating amplitude. With several lasers in parallel the effects of scintillation of the atmosphere can be largely eliminated at a moderate price.

The long term fluctuations of the received signal are due to meteorological conditions and alignment stability. Rain is not very harmful, but heavy snow falls or deep fog renders the link inoperative. It is interesting to mention that transmission at 800 nm wavelength is better than in the visible: a useful signal was received on the telescope although the BA3 buildings could not be seen from the water tower. One could consider working at higher wavelengths to further gain some factor on the bad weather transmission. For the moment the technology at, say 1300 nm, is not yet available or too expensive.

A thorough study of alignment stability has not been attempted yet, but the present results seem to indicate that, for relatively short periods (compatible with a stochastic cooling experiment) no servosystems are necessary to keep the lasers and telescope on axis, if they are installed on buildings.

4. ELECTRONIC CIRCUITY.

4.1 Laser Drive

The laser diode is driven by a current source which is switched by the modulating signal through a differential transistor pair (Fig.8). By sensing the average light power emitted with a photodiode built in the laser package, it is possible to stabilize the laser and avoid thermal run-out. The photodiode signal is compared to a reference, then amplified and finally controls the intensity of the current source.

For the particular application of stochastic cooling of bunches, the link only operates for short intervals (typically 400 ns)just at the bunch passage. We make use of the rest of the time (> 90%), when the link is idle, to transmit the clock frequency. This has the advantage that the average power, which only depends upon the ON-OFF ratio of the clock pulses, is practically constant and therefore well suited for the regulation circuity.

Just after the bunch passage, the beam information will be converted from parallel (output of analog to digital converters) into serial form for transmission with the link. To validate the transmission it is intended to transmit, just before the beam information, a coded word (header) which would be recognized at the receiving end. The number of bits of this header depends on the degree of confidence in the validity of the transmission which is required. In our experiments to assess the availability of the link we decided that four bits would be sufficient to validate the transmission, and that a clock frequency of 200 MHz, for which complex logic functions already exist, would be high enough to demonstrate the principle.

The block diagram of the electronics on the laser side is given Fig. 9a. From the 200 MHz clock frequency a trigger pulse is derived, every 23 μs (revolution period) with a standard SPS unit. The four bit shift register where the header word is stored is then triggered, and the output serial code replaces the 200 MHz clock frequency (Fig. 10a).

4.2 Receiver

At the receiving end, the first problem is to take care of the large dynamic range due to scintillation and weather changes. With an almost constant duty cycle, AC coupling and a hard limiter provide easily more than 40dB dynamic range (Fig. 9b). AC coupling also reduces the influence of the steady background light.

With the logic signal from the limiter the clock frequency is reconstructed with a phase lock circuit. The lock-in time is made small compared with the distance between two bunches to provide immediate recovery after an interruption. On the other hand the phase variation of the clock frequency should be negligible (maximum measured 20°) during the transmission of the useful message (header plus beam word). These two contradictory requirements are met in our design, for which no gating of the loop amplifier is necessary. The advantage of such a solution is that the clock is transmitted independently from the message, in a time sharing sequence: coding of the message is straightforward and there is no loss of speed as opposed to the standard combined transmission codes (e.g. Manchester code) where more bandwidth is necessary.

Figure 10b shows the digital sequence at the receiving end, namely a train of clock pulses followed by the four bit word "9" (1001) used to validate the transmission. By a straightforward expansion of the present circuitry, it is possible to transmit longer words, as required for stochastic cooling tests. The data transmission rate is, at present 200 Mbits/s (1 bit per clock pulse) although the bandwidth capability of the link is 400 Mbits/s (1 bit per clock transition).

5. RESULTS AND CONCLUSIONS

Although it is still too early to draw firm conclusions on the long term behaviour of the link, we already know that uninterrupted periods of the order of 24 hours are realistic. Stability of the optical axes of the lasers and the telescope are satisfactory. No realignment is necessary even after one week of operation.

A typical winter recording is given in figure 11 showing the output signals of the radiometer and of the avalanche photodiode. In addition, the logic detector signal indicates, with a vertical bar when the coded word has not been recognized (periods of snow and fog).

The probability of an horizontal visibility smaller than a given distance has been estimated for the Geneva-Cointrin Airport [8]. The results, summarized on figure 12 indicate that for the proposed link (1 to 2 Km distance) the availability of the transmision should be of the order of 99%, even in winter.

Even in good weather conditions, operation with one laser only occasionally suffers short interruptions, but with two lasers in parallel those disappear completely, showing the effectiveness of the multilaser solution.

In conclusion the atmospheric infrared link offers a cheap and convenient way to transmit high data rates over kilometer distances, with an availability figure sufficient to implement a stochastic cooling experiment in the SPS.

ACKNOWLEDGEMENTS

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REFERENCES

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COLLIMATOR PEN

The collimator pen CQL13A is used for reading applications such as: data retrieval, video-audio disc applications, optical memories, security systems etc.

The pen is mounted in a non-hermetic encapsulation, specifically designed for easy alignment in an optical read or write system, and consists of a lens system and a laser device. The lens system collimates the diverging laser light. The wavefront quality is diffraction limited. A cylindrical lens is used for correction of the astigmatism of the laser.
The housing is circular and precision manufactured with a diameter accuracy between + 0 and −11 μm.

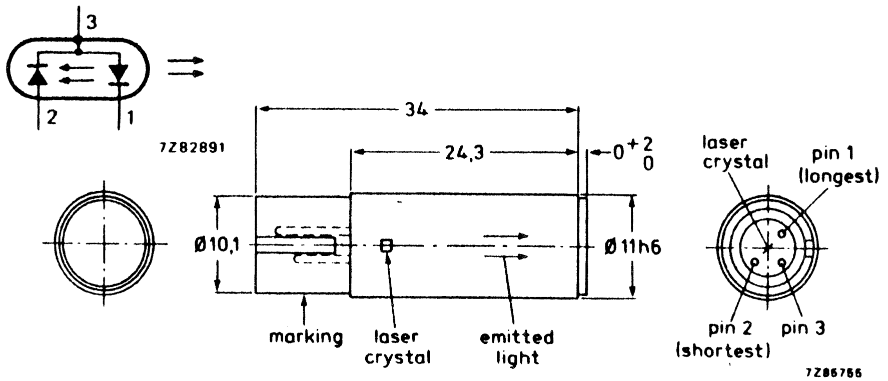
QUICK REFERENCE DATA

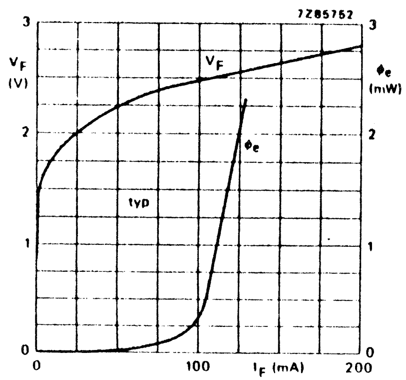
Output power ϕ_e		2 mW		**20 mW**
Current at output power ϕ_e = 2 mW and temperature of 60 °C	<	175 mA	**<**	**200 mA**
Wavelength at peak emission λ_{pk}	typ.	820 nm	**typ.**	**865 nm**
Wavefront form of bundle (non-convergent) divergence	<	0,3 mrad	**<**	**0,3 mrad**

MECHANICAL DATA

Dimensions in mm

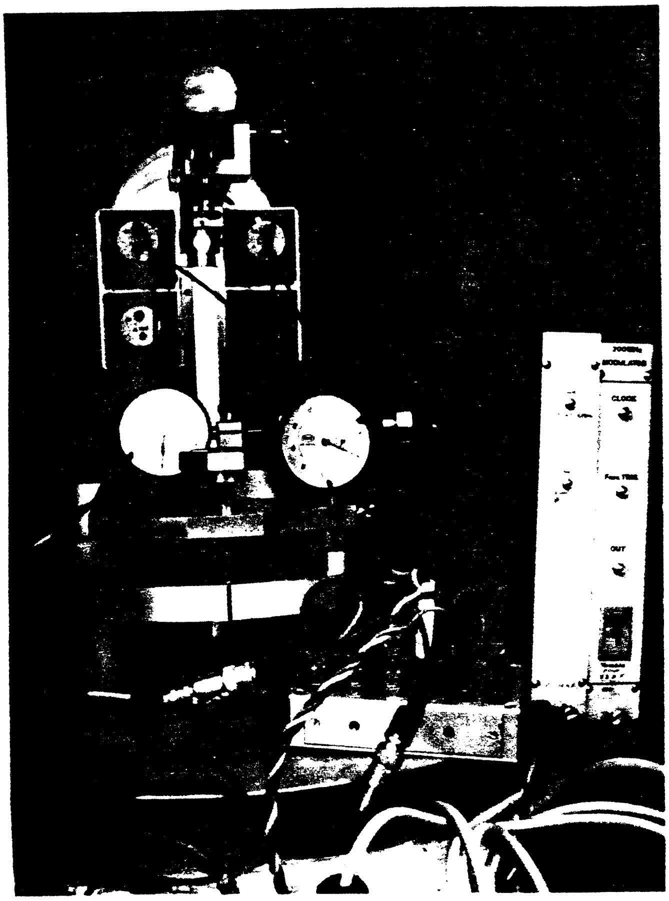
Fig. 1.



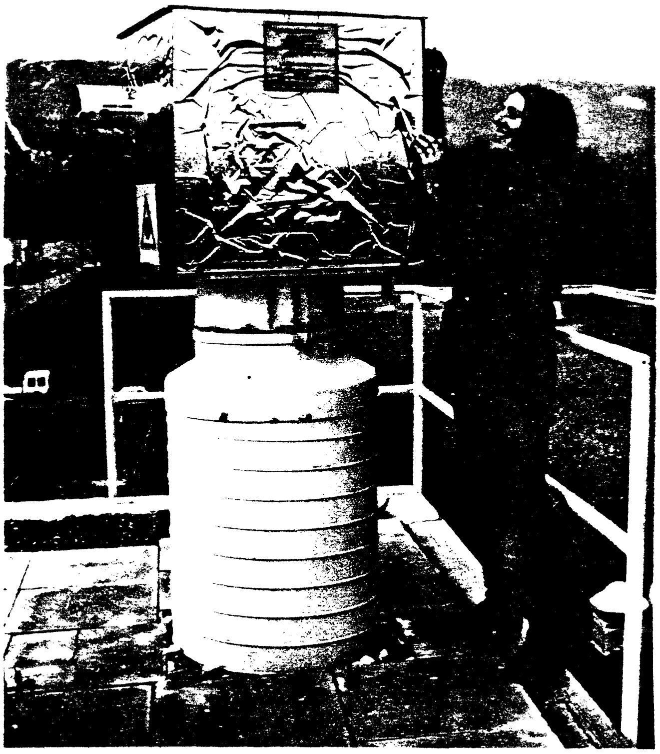


Mass	max. 8 g
Concentricity	angle between the mechanical and optical axis ≤ 10 mrad
Marking	type number CQL13A and serial number
Mounting	on a p.c. board by means of a specifically designed connector

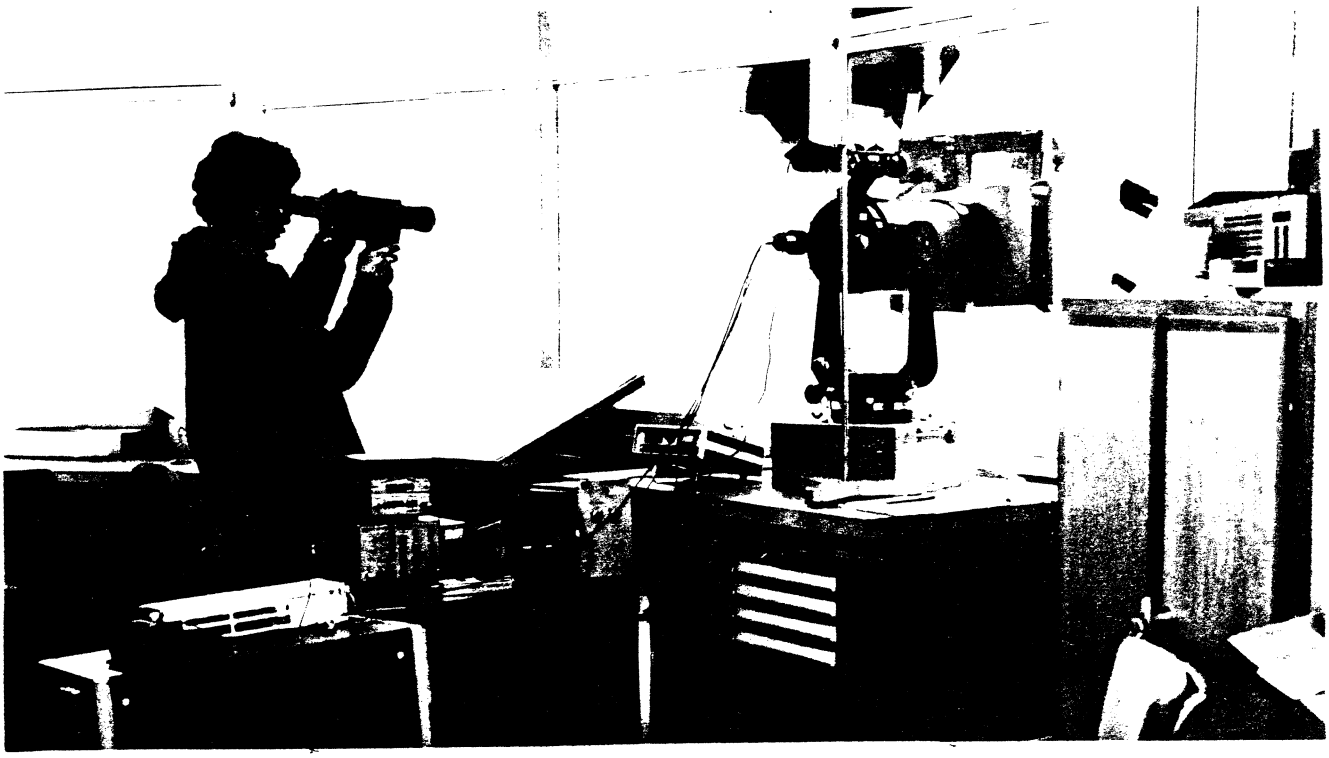
Fig. 1



The alignment mechanism for the lasers



Housing of the lasers on the roof of BA3



Telescope and electronics in the water tower

Fig. 2

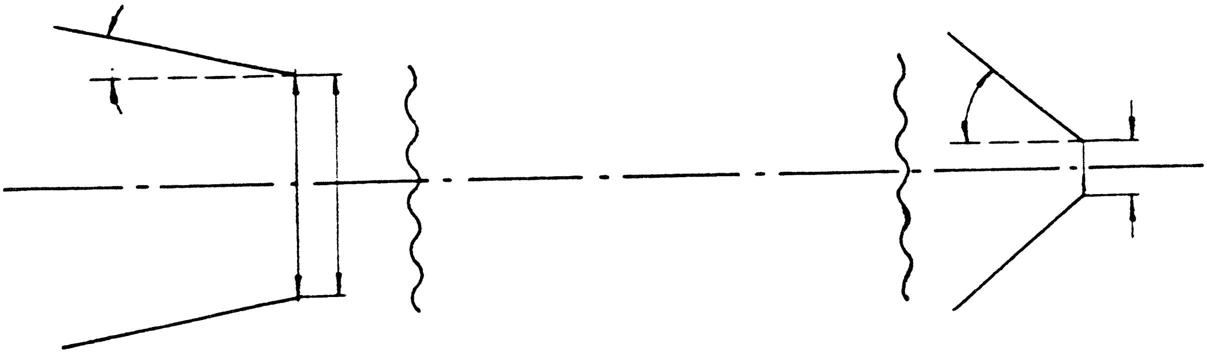
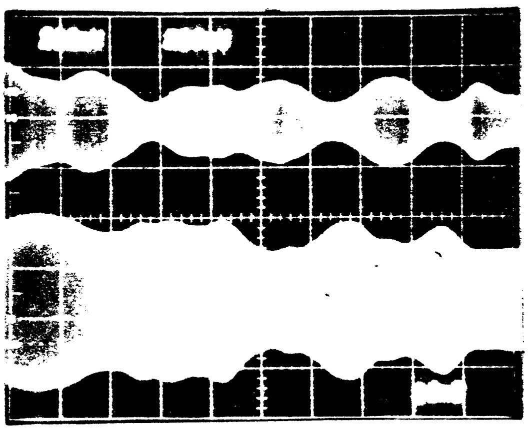


Fig. 3

Abbe sinus law or " acceptance conservation" in matched optical systems

D sin = d sin



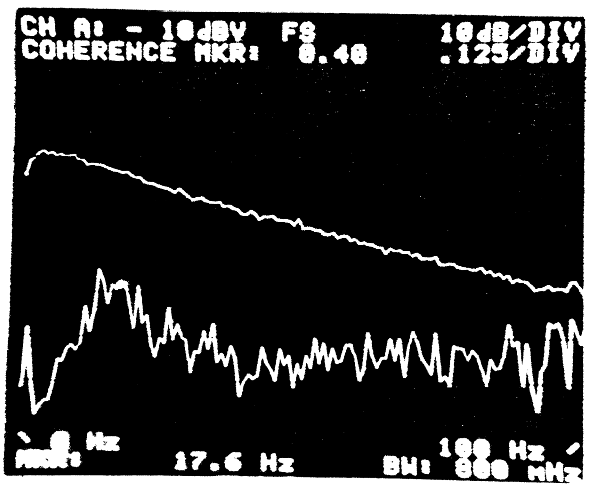
Laser A

Laser B

Fig. 4

Typical fluctuation waveforms at the receiver

(L = 2.6 km) 10 ms/div



Top :

Spectrum of

fluctuations

Bottom:

Coherence laser A - Laser B

(distance x=5cm)

Fig. 5

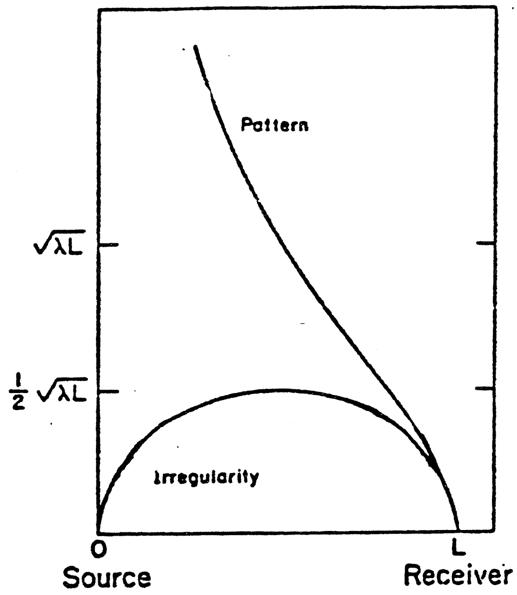


Fig. 6

Size of the most effective irregularity and of the resulting scintillation pattern(r_p), from reference 7

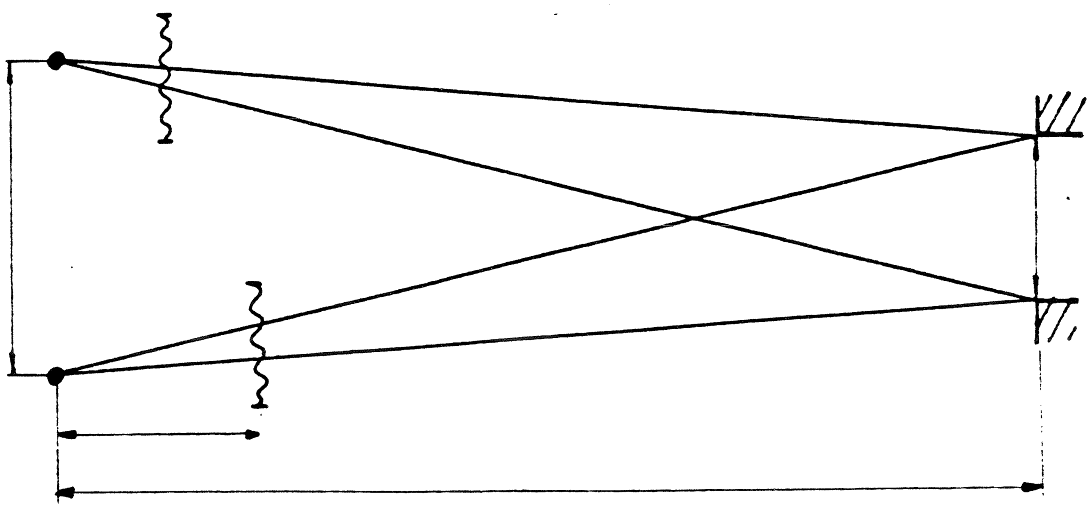
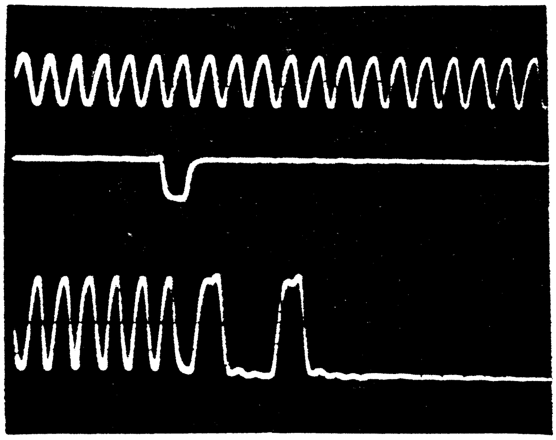
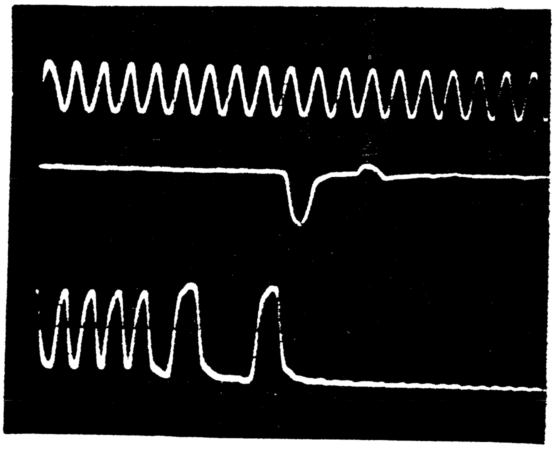


Fig. 7

The beams of lasers A and B are separated, near the source.
Uncorrelated patterns at the receiver if x , typically.

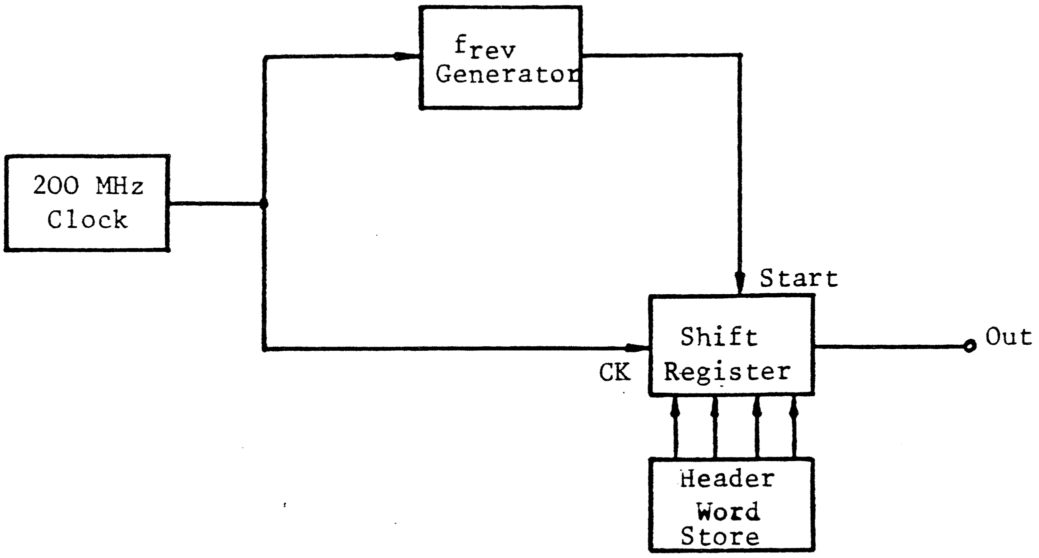


a) emission

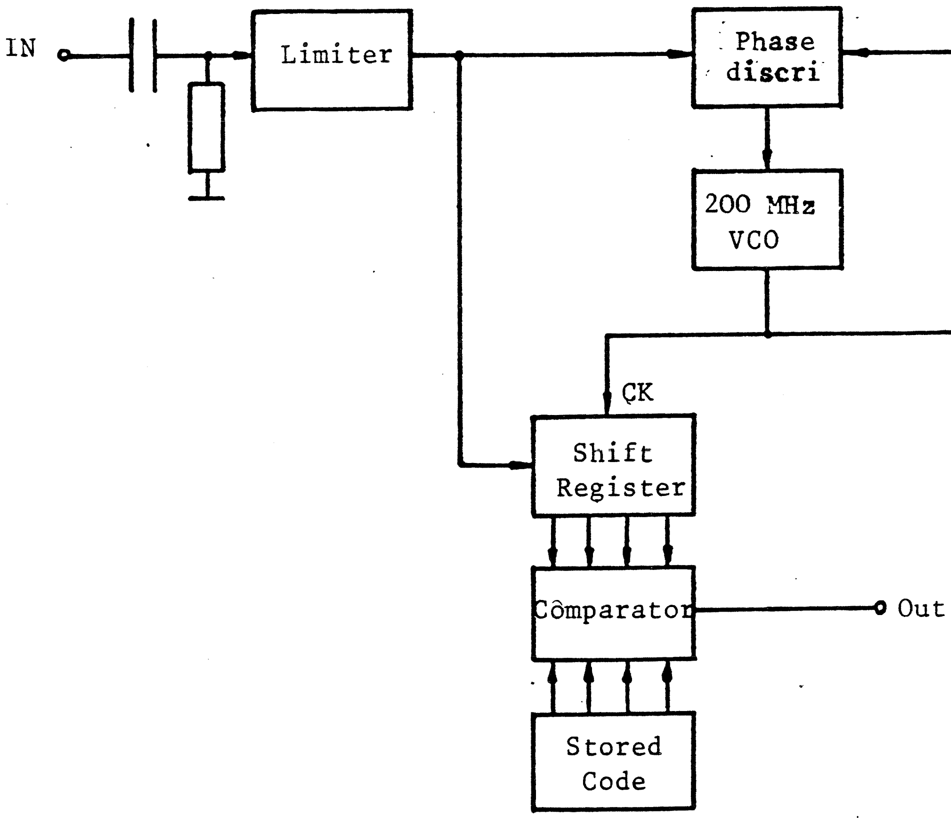


b) reception

Fig. 10 Digital transmission waveforms, 10 ns/div



a) emission



b) reception

Fig. 9

Schematics of the electronics for coding and decoding

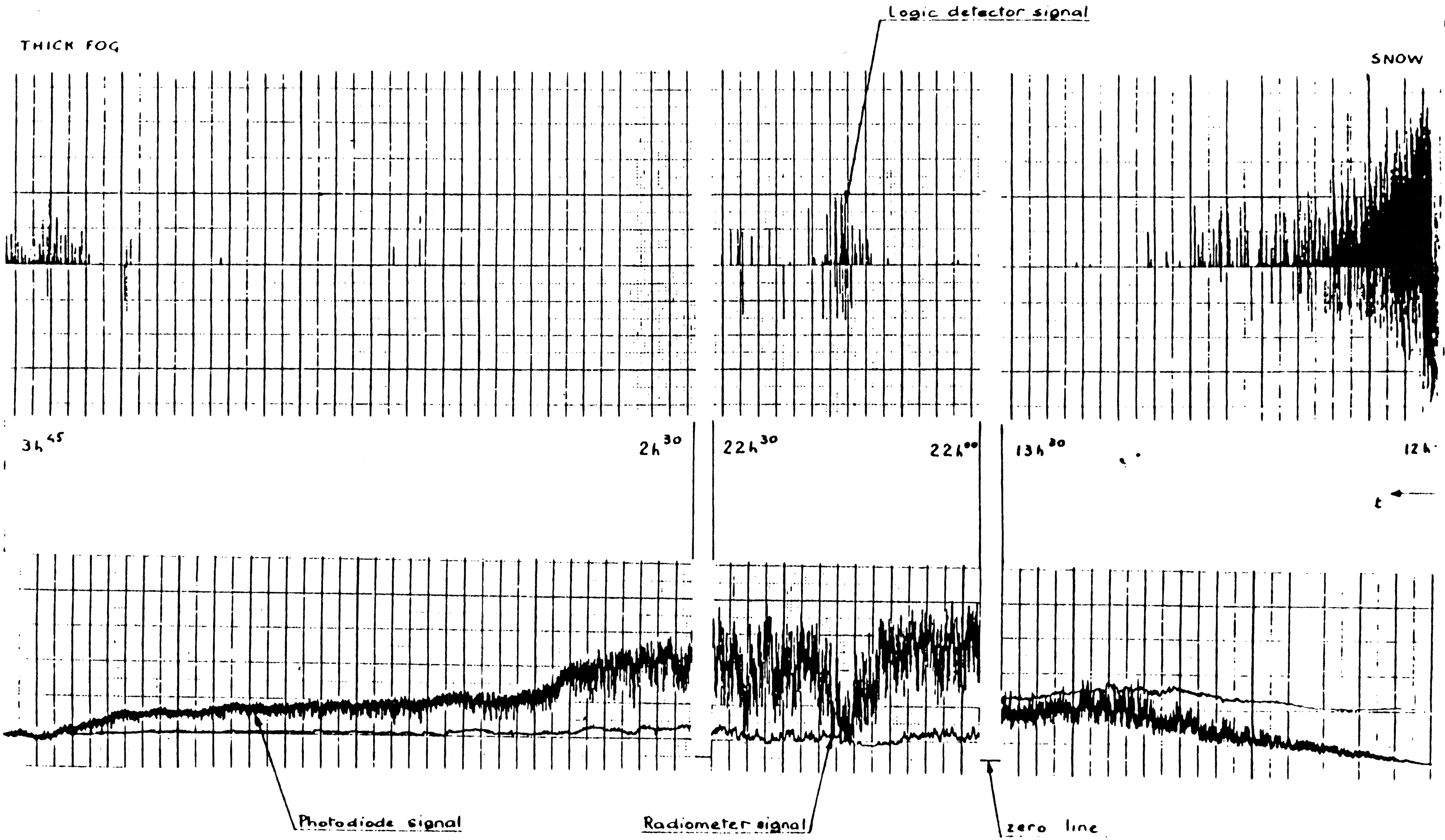


Fig. 11 Typical transmission recording (winter season). Bad transmission corresponds to the vertical bars on the logic signal. Note the large steady signal on the radiometer in day light conditions.

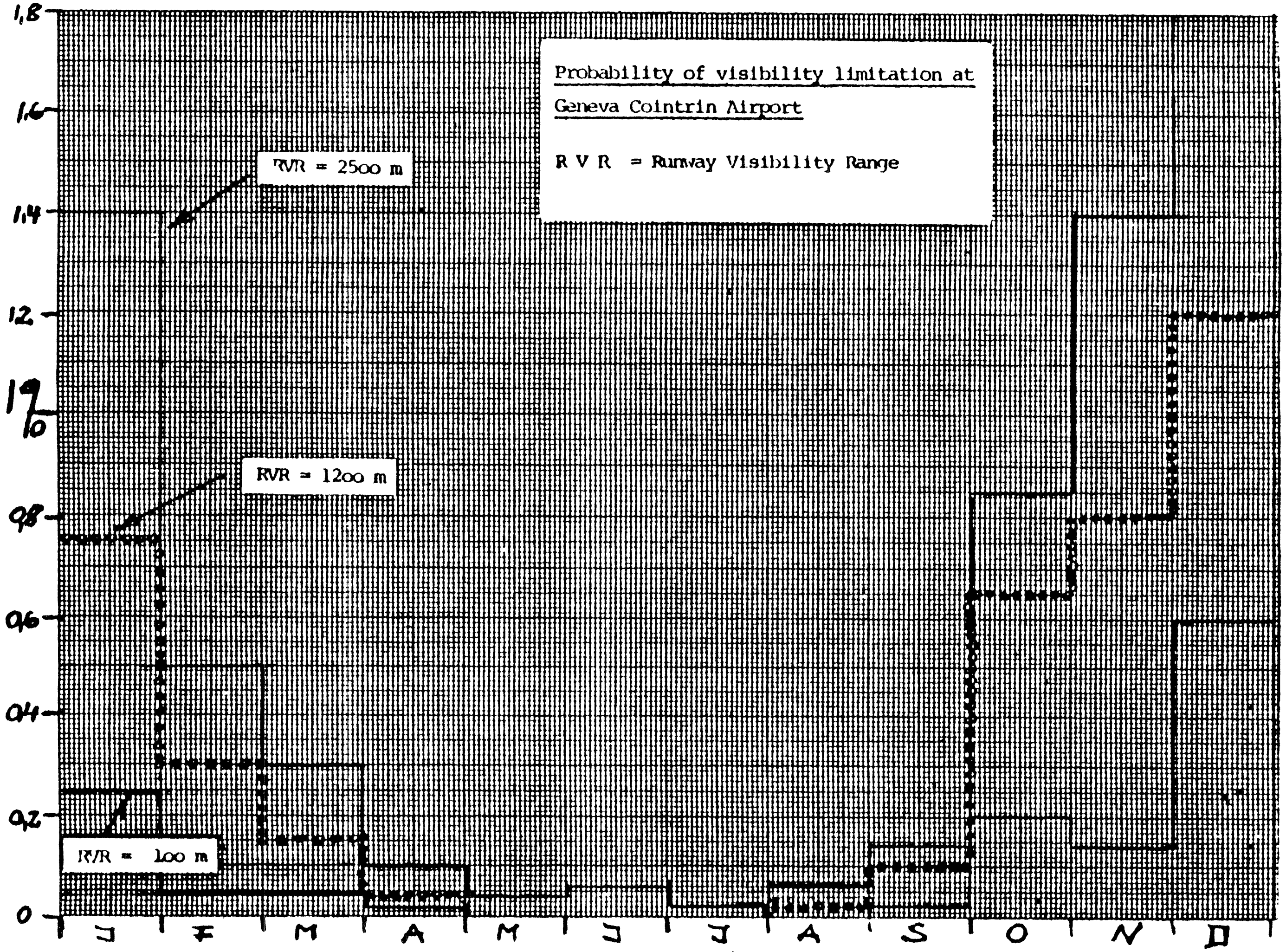


Fig. 12   From reference 8