VIRGO	NTS 96 035	1/7

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Date: 15/5/96

Subject :

Do we really need to place the photodiodes inside vacuum ?

1 Introduction

The use of photodiodes inside the vacuum system have several drawback these there are problems like power dissipation, cabling, accessibility etc. etc. photodiodes outside the vacuum tank will make the operation of VIRGO simpl increase the duty-cycle. As a general rule one should place something inside chamber only if it is really needed. The aim of this note is to have a deeper photodetector noise specifications and to see if we really need to place them ir

2 Signal Modulation: Specifications

Placing the photodetectors outside the vacuum system will have as consec the interferometer output beam will propagate in air for about 1 m length. acoustic noise acting on the photodetector itself and on the optical path may i and/or amplitude modulation of the output beam. Since the GW signal is e demodulation of the signal at high frequency (~6 MHz), one has to look at th and phase modulation that any external perturbation may produce on thi component of the signal.

In the ideal case of an interferometer perfectly locked on the dark fringe signal is perfectly held at zero and obviously no phase or amplitude modul signal may be produced by variation of the optical path or vibration of the support.

In a more realistic case, the interferometer is not perfectly held on the c
and a small quasi-static 6 MHz signal is always present in the interferometer o
As a consequence any fast (0.1 ms to 0.1 s time scale) amplitude or phase mo
this signal may cause a spurious signal in the frequency range of operation of

If no perturbation is present the 6 MHz component of photodiode curre
by the following simple expression:

$$I_\Omega(t) = \eta\, P_\Omega(t)\, \sin(2\pi\, \Omega\, t)$$

where Ω is the modulation frequency ($\approx$6 MHz), η the photodiode efficiency a
the signal one looks for. If the interferometer is perfectly held on the dark
$P_\Omega(t)\approx 0$ and external perturbations will have any effect. In a more realistic
contains a quite big low frequency component due to the low frequency oscill
suspended mirrors and a small high frequency component due to thermal
noise and, if present, gravitational waves. The ratio between the low frequ
variation $P_\Omega^{(rms)}$ and the high frequency spectral density $\tilde{P}_\Omega(f)$ in this interferometer
spectral dynamic. The exact value of this ratio will depend on the gain of t
feedback. Typical conservative values are:

$$\frac{\tilde{P}_\Omega(f)}{P_\Omega^{(rms)}} \leq \begin{array}{l} 3\cdot 10^{-7}\,\mathrm{Hz}^{-1/2} \quad f=10\,\mathrm{Hz} \\ 10^{-8}\,\mathrm{Hz}^{-1/2} \quad f=100\,\mathrm{Hz} \end{array}$$

Any external perturbation will produce amplitude and/or phase modulation
beam and so of the photodiode output current:

$$I_\Omega(t) = (1+a(t))\, \eta\, P_\Omega(t)\, \sin(2\pi\, \Omega t + \phi(t))$$

where $a(t)$ and $\phi(t)$ are the small amplitude and phase modulation induced by
perturbation. This current signal once properly amplified is sent to the
demodulated at Ω using a reference signal $V_{ref}\sin(2\pi\,\Omega t + \Delta)$, where Δ is so
offset introduced by the electronics. Apart for a constant factor the signal at
the mixer will be given by:

$$\begin{aligned} &(1+a(t))\, \eta\, P_\Omega(t)\, \cos(\Delta - \phi(t)) \\ &\approx \eta\, P_\Omega(t)\, (1+ a(t) + \Delta\, \phi(t)) \end{aligned}$$

The second and third term in the parenthesis are the noise terms due respe amplitude and phase modulation of the output beam while the first term is th that one wants to measure. The mixing of the great low frequency compone $(=P_{\Omega}^{(rms)})$ with the high frequency part of the external amplitude and modulation (a(t) and/or $\phi(t)$) may produce a spurious signal in the frequen interest. The noise terms will not degrade the interferometer noise perform following condition is fulfilled:

$$P_{\Omega}^{(rms)} \cdot (\Delta a(f) + \Delta \phi(f)) < \tilde{\Omega} P(f)$$

Notice that the ratio $\tilde{\Omega} P(f) / P_{\Omega}^{(rms)}$ is the interferometer dynamic range (express spectral units) previously introduced. Using the conservative values given previous condition becomes:

$$(\Delta a + \Delta \phi) \leq \begin{matrix} 3 \cdot 10^{-7} \, Hz^{-1/2} \; f=10Hz \\ 10^{-8} \, Hz^{-1/2} \; f=100Hz \end{matrix} \qquad (**)$$

Some possible sources of amplitude or phase noise are considered below:

3 Phase modulation sources

3.1 Acoustic noise

The propagation in air will produce a phase noise due to the fluctuation refraction index. The phase noise amplitude is given by the following expressi

$$\tilde{\varphi} = \tilde{\delta} n \frac{2\pi}{\lambda_{mod}} l$$

where $\tilde{\delta} n$ is the index of refraction fluctuation and l is the path length in air. A noise having a very high intensity (130 dB) produce a local variation of pres order of $6 \cdot 10^{-4}$ Atm. As a consequence the air index of refraction n will cha amount $\delta n = (n-1) \cdot \delta P / P \approx 20 \cdot 10^{-8}$. Using λ_{mod}=48m and l=2m one founds ϕ=5 value which fulfils condition (**) even if Δ is equal to 12°.

3.2 Longitudinal Seismic Noise

Seismic induced vibrations of the photodetector in the beam direction produce a phase modulation of the signal. In this case the expected phase m given by the following expression:

$$\tilde{\phi} = n\frac{2\pi}{\lambda_{mod}}\tilde{\delta x}$$

where $\tilde{\delta x}$ is the seismic noise vibration of the photodetectors. Assuming a "st seismic noise level $\tilde{\delta x} = 10^{-6}/f^2$ m/√Hz one finds $\tilde{\phi} = 1.25 \cdot 10^{-11}$ (100Hz/f)^2 /√Hz which fulfils condition (**) even for very large values of Δ.

4 Amplitude modulation sources

The vibration of the photodetectors in a direction perpendicular to the produce a modulation of the 6 MHz signal amplitude due to different me Among these there are:

1. photodetector edge effect
2. presence of dust on the photodetector
3. non-uniformity of the photodetector efficiency

4.1 Photodetector edge effect

Due to the photodetector finite size, a lateral vibration of the photodetect a variation of the signal amplitude. This amplitude modulation a depen photodetector size $S=\pi R^2$, the beam size w and the displacement amplitude given by the following expression:

$$a = \int_S I(x,y)\,dx\,dy \Big/ \int_S I(x-\delta x,y)\,dx\,dy$$

$$\text{with } I(x,y) = \frac{2}{\pi w^2}\exp\left(-2\frac{x^2+y^2}{w^2}\right)$$

where δx is the lateral displacement of the photodetector, I(x,y) is the n gaussian intensity and the integral is done on the photodetector surface S. By the integral one founds:

$$a = \left(2\frac{R}{w}\right)^2 \exp\left(-2\frac{R^2}{w^2}\right)\frac{\delta x^2}{w^2}$$

Notice that the effect is a second order one (a depends on δx^2). Assuming F founds for a

$$\tilde{a} = 16\, e^{-8}\frac{2\cdot\Delta x\cdot\delta x}{w^2}$$

where Δx is the static offset of the beam position respect to the photodiode ce is the spectral density of the photodetector vibration at the frequencies Assuming Δx=100 μm, $\tilde{x}=10^{-6}/f^2$ m/√Hz and w=R/2=0.75 mm one founds:

$$\tilde{a}(f) = 1.9\cdot 10^{-10}\left(\frac{100\ \mathrm{Hz}}{f}\right)^2$$

value which satisfy the required condition by two orders of magnitude.

4.2 The effect of dust

The presence of dust particles on the photodetector has to effects: first it photodiode active area by covering it, second it induces a signal amplitude when, due to the seismic noise, the photodetector vibrates laterally.

The first effect may be easily evaluated; the signal lost is given by:

$$\text{losses} = \left(\frac{\sigma^2 N}{\pi R^2}\right) \approx 1.5\cdot 10^{-3}\left(\frac{\sigma^2 N}{10^{-8}\mathrm{m}^2}\right)$$

Where N is the number of dust particles, σ their size and, as in the previous we have assumed $R=1.5.10^{-3}$ mm. In order to have signal losses $\leq 10^{-3}$ the pr should be less than 10^{-8} m^2. For example this means:

$N \leq 1$ (per photodiode) if $\sigma=100$ μm

$N \leq 10$ (per photodiode) if $\sigma = 10\ \mu m$
$N \leq 100$ (per photodiode) if $\sigma = 1\ \mu m$

The second effect may also be easily evaluated by considering that tl variation induced by a transverse vibration of the photodiode is equal to the signal lost due to presence of the dust. If N particles of dimension σ are attac photodetector at the locations $(x_i, y_i, i=1,N)$ then a vibration $\delta x(f)$ will generate a signal amplitude variation equal to:

$$\tilde{a}(f) = \delta x(f) \frac{d}{dx}\left(\sum_{i=1}^{N} \sigma^2 I(x_i, y_i) \right)$$

$$= \delta x(f) \frac{2}{\pi} \frac{\sigma^2}{w^2} \sum_{i=1}^{N} \frac{4x_i}{w^2} e^{-2\frac{x_i^2 + y_i^2}{w^2}}$$

Assuming a random distribution of the dust particles on the photodetecto standard seismic noise level ($\delta x = 10^{-6}/f^2$) and $w = R/2 = 0.75$ mm one founds:

$$\tilde{a}(f) = 1.6 \cdot 10^{-10} \left(\frac{\sigma}{10\ \mu m} \right)^2 \left(\frac{N}{10^3} \right)^{\frac{1}{2}} \left(\frac{100\ Hz}{f} \right)^2$$

To fulfil condition (**) the product $\sigma^2\sqrt{N}$ should be less than $2 \cdot 10^{-7}$ a requir strict than the previous one.

4.3 The effect of efficiency non-uniformity

Non-uniformity of the photodiode efficiency makes the 6 MHz signal a sensitive to lateral displacement of the photodetector. Let's assume a linear in photodiode efficiency from one side of the detector to the other by 2 percent:

$$\eta(x) = \bar{\eta}(1 + \alpha\, x/R) \qquad \text{with } \alpha = 10^{-2}$$

A seismic vibration of the photodiode in the x direction will generate a modul signal amplitude given by the following expression:

$$\tilde{a}(f) = \frac{\alpha}{R} \delta x(f) \approx 6 \cdot 10^{-10} \frac{100\ Hz^2}{f^2}$$

a value which fulfils condition (**) by a factor 4.5 @ 10 Hz and by a factor 1
Hz. A linear increase of efficiency of the photodiode from one side to the o
detector seems quite pessimistic. Nevertheless measurement are foreseen i
verify this hypothesis.

5 Conclusions

The effects of acoustic and seismic noise on the photodetectors ha
considered in this note: these effects turns out to be negligible. Consequentl
the photodiode inside the vacuum system is, at present, not justified.