Optical calibration from tens to hundreds of meters for a neutrino telescope

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Abstract

A critical review of the available optical calibration techniques is given in the context of the Neutrino Burst Experiment. We will discuss the effects of the optical properties of water on different candidate light sources and the challenges from an engineering point of view. The merits of candidate light sources will be compared.

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1. Introduction

The Neutrino Burst Experiment (NuBE) [1] (Fig. 1) will be composed of four 32-meter diameter NESTOR ‘floors’ [2], stacked vertically 30 meters apart, and four 400m tall autonomous strings located on a rectangle centered around the tower with 600m diagonal. Each string will be composed of two nodes separated vertically by a distance of 300 meters. A node consists of two clusters of eight photomultipliers each. The two clusters of each node are 10m apart. The tower is connected to shore with an electro-optical cable and can communicate acoustically with the autonomous strings. For power consumption as well as symmetry reasons we consider placing one light beacon above and one below the NESTOR tower in order to provide light pulses that will be used for temporal calibration and

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synchronisation of the strings with respect to each other and to the tower.

Having the upper beacon situated 60 meters above the topmost NESTOR floor the total distance of the beacon from the lowest floor is 150 meters. With the distance of the lowest floor from the ocean bottom being equal to that between the lowest node in a NuBE string from the ocean bottom, the upper beacon has equal distances to all the nodes on the four strings. In this detector geometry the optical modules of the top floor form an angle of approximately 30 degrees as viewed from the upper beacon. Based on this configuration the distances between the upper beacon and the optical modules are shown in table 1. In this document we will focus our discussion on this geometry.

In addition to timing calibration with fixed light beacons, light beacons can be used to crosscheck positioning calibration. Autonomous battery-operated light beacons will be deployed in free fall. Once they reach the sea bottom, acoustic releases will allow for retrieval of the beacons for future use. The trajectory of each beacon will be continuously monitored acoustically and the calibration light pulses detected by NuBE will be compared with the acoustic data. The positioning accuracy of a Long BaseLine (LBL) acoustic positioning system is better than 1m, which is adequate for NuBE

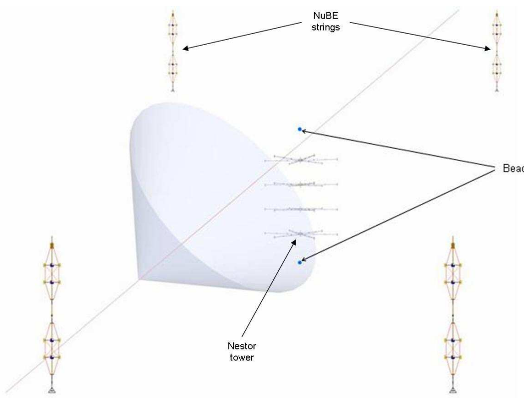

Fig.1 - Schematic diagram of NuBE with the two beacons. The cone corresponds to a Cerenkov light cone of a particle moving along the grey line. Not to scale

Table 1. Distances from the upper beacon to the optical elements of NuBE

Floor 1 (top)	Floor 2	Floor 3	Floor 4 (bottom)	Any NuBE string node
62 m	91 m	121 m	151 m	335 m

2. Light beacon requirements

The beacon that will be used to calibrate NuBE must satisfy two basic requirements, sufficient light intensity to be detected by all the optical modules, some of which are situated over 300m away and a light pulse short enough for accurate timing calibration.

In order to set the requirements for the beacon we have to consider the effect of the optical properties of water on the light pulse. This pulse will be affected by:

1. Attenuation: this will affect the required intensity which depends on the chosen emitted light wavelength.
2. Scattering: this will affect the pulse duration over long distances since a photon can be scattered before it is detected. However, in the deep ocean for the 300m distances involved, scattering is not important.
3. Dispersion: this will also affect the pulse duration since different wavelengths travel at different speeds. A source with narrow spectral width is preferable to reduce the effect of dispersion.

3. Effects of attenuation and dispersion

In order to calculate the required light intensity for the beacon we have to consider light attenuation in the water. For a point source the light intensity I at distance R can be described by eq. (1):

$$I = \frac{AI_0}{4\pi R^2} e^{-R/L} \qquad (1)$$

Where I is the light intensity at distance R from the source, I_o is the light intensity emitted at the source, A is the target area and L the transmission length - the path length within the medium over which the number of photons has decreased to 37% (i.e. 1/e) due to absorption, assuming that scattering, although present, contributes minimally to the loss of photons.

In the NESTOR site the transmission length *L* at 460nm is about 55 meters [3]. With this value one can calculate that from a 2nJ light pulse at 460nm, which produces about 5×10^9 photons, assuming they are distributed uniformly on a spherical surface, only 5000 will be emitted into the solid angle defined by a 15 inch photomultiplier tube (PMT) at 335 meters. Furthermore, because of attenuation, only about 10 photons will reach the photocathode of the PMT at that distance. These ten photons suffice to produce a single photoelectron. We distinguish signal from background from coincidence in time of multiple OMs.

From our measurements of water salinity, temperature and pressure at the NESTOR site we have found the variation of the refractive index versus wavelength [4] (Fig.2). Based on these values of the refractive index we can calculate the speed of light in water for each wavelength and estimate that the dispersion at the site is about 0.2ns per nm*km. For a source with spectral width of 20nm the difference in traveling time for the different wavelengths for a distance of 335m would be less than 1.3ns.

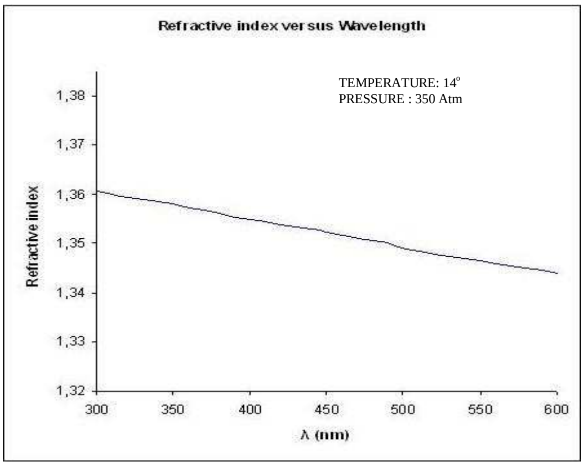

Fig.2 - Plot of refractive index versus wavelength for the NESTOR site.

4. Potential light sources, advantages and disadvantages

Typical features of all the potential light sources discussed here can be found in Table 2.

4.1. LEDs

Light Emitting diodes are the cheapest of the potential light sources with cost for a single unit of about 0.5 Euro. An LED has low power consumption and low heat dissipation. They are small in size and weight, exhibit very good shock resistance and can easily become part of a custom electronic circuit. Their intensity is such that a number of about 30 LEDs would be needed to reach the intensity required of the NuBE beacon. An LED typically has a spectral width of 10-20nm and will be affected more by dispersion compared to the laser sources.

4.2. Semiconductor lasers

Laser diodes in the UV/blue wavelength region with power output (for continuous wave operation) of about 500mW are now available for about 1000 Euro per unit. It should be noted, that new high density optical disc drives use lasers with wavelengths around 405nm. Mass production should drive the prices down. Like LEDs they are small in size and weight and can easily become part of a custom electronic board. They are more powerful than LEDs and only about 3 units would be sufficient to reach the required intensity for the NuBE beacon. Their spectral width is about 1nm resulting in sub-nanosecond dispersion for the NuBE strings. As with any laser however a diffuser will be necessary, as lasers emit light in a collimated beam.

4.3. Solid state lasers[1]

Solid state lasers are very powerful compared to semiconductor sources and a single unit is capable of providing the light intensity required for the NuBE

[1] Semiconductor lasers are laser diodes while solid state lasers are the lasers whose active material is a rare earth element doped crystal, such as Nd:YAG..

beacon, with a pulse duration as short as a few femtoseconds. In order to emit in the UV/blue region second harmonic generation is required, increasing the laser's complexity and the cost. Due to their construction they are sensitive to shock due to the carefully aligned mirrors defining the laser cavity. A solid state laser's operational lifetime is similar to that of a semiconductor laser and is determined by the lifetime of the pump, which is usually a semiconductor laser.

4.4. Gas lasers

A single gas laser is also capable of providing the light intensity required for the NuBE beacon and the pulse width can be less than a nanosecond. Gas lasers are bigger than semiconductor and most solid state lasers and their length often exceeds 1m. To accommodate a gas laser special housing may be needed. They require a high voltage power supply and they dissipate heat requiring a cooling system. Also, as with the solid state lasers, they are more sensitive to shock than semiconductor devices.

4.5. Dye lasers

Dye lasers can produce very short (<1ns) pulses with more than adequate intensity for the NuBE light beacon. The most useful feature of dye lasers is their ability to tune the emitted wavelength over a wide range. The main disadvantage of dye lasers is the rapid degradation time (few operational hours) of the dye. Once the dye is degraded, the laser must be opened to replace the dye. Furthermore, many laser dyes are classified as hazardous chemicals and require special handling.

5. Geometrical and electronic aspects

As shown in table 1, for the case where the upper beacon is 60m above the topmost floor, the distance of optical modules from the beacon differ significantly for optical modules in different parts of NuBE. In this arrangement, if the light output from the beacon is uniform over a solid angle, optical modules in floor 1 (top) would receive at least 3000 times more light than the optical modules in the strings due to the distance attenuation and difference in the solid angle. So the position of the light beacon should be carefully selected and, possibly, different intensities should be emitted at different angles to avoid over-illuminating optical modules which are close to the beacon.

In order to use LEDs as the light source of the beacon, one must create short (few ns) pulses from multiple LEDs and synchronise them in order to appear as a single pulse. A similar issue arises with semiconductor lasers but fewer lasers would be needed than LEDs.

6. Conclusions

Based on the characteristics of all the available sources, a beacon based on a semiconductor laser appears to be the best option. A semiconductor laser is powerful enough so only a few units are needed to reach the required light intensity. They can produce pulses of about 1ns, which is more than adequate for our application and it is possible to construct a beacon with low power consumption and heat dissipation which can fit in a standard 17 inch glass sphere [5].

An alternative would be an LED based beacon, with the added complexity of creating short pulses with each LED and having to synchronise tens of different LED units.

Either of these two beacons can be constructed as autonomous, battery operated beacons, to be used in free drop deployments.

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Table 2. Typical features of the potential light sources for the calibration beacon of NuBE.

	Energy per pulse	Pulse duration	Operational lifetime	Price	Other
LED	50 – 100pJ	~ 10 ns[a]	up to 100.000 hours	~ €0.5	Small size and weight, good shock resistance, low power/heat
Laser Diode	<500 pJ	<1ns	>10.000 hours	~ €1000	Small size and weight, good shock resistance, low power/heat
SS laser	>1mJ	Few fs	>10.000 hours[b]	~ €5000 - €50000	SHG[c] needed, can be very big, shock sensitive
Gas laser	100s µJ	<1ns	1.000s of hours	>€10000	Can be very big, shock sensitive, high power, cooling may be needed
Dye laser	100s µJ	<1ns	Few hours	>€10000	Can be very big, shock sensitive, high power, cooling needed, rapid dye material degradation

[a]LEDs with pulse duration as short as about 1ns are available but pulse intensities are low

[b]Operational lifetime limited by the lifetime of the pump, usually a laser diode.

[c]Second Harmonic Generation, or Frequency doubling

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