A novel water-Cherenkov detector design with retro-reflectors to produce antipodal rings

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Problems with water-Cherenkov detectors

Basic design of water-Cherenkov detectors has not changed for a long time.

With ~40% photocoverage, we are losing ~60% of photons.

During a ring event, only a fraction of all PMTs provide information.

Idea: Mapping lost photons onto PMTs outside the ring

Can we collect lost photons by placing mirrors in the unused 60%?

Can we expect a greater ring resolution due to effectively smaller PMT sizes and parallax?

Problems with normal mirrors

Need to keep track of ~4 reflections, which is difficult to model correctly, efficiently.

Even 1° misalignment causes ~1 m deviation of the light path over 30 m.

Residual light decreases contrast for other rings.

→ impractical

Solution: Retro-reflectors

Reflect light back into same direction. What does not hit PMT gets trapped in reflectors.

→ 1 reflection only

Robust against change in reflector orientation.

Could in principle be fit as another ring.

Verification of multi-reflection cancellation

Simulation using Geant4-based WCSim. Blackshells between PMTs are replaced with reflective materials. The complicated multi-reflection time signatures due to mirrors disappear almost completely with retro-reflectors.

Cherenkov profile

For precise modeling of the cherenkov profile, we simulate moving particles in Geant4, and fit flux and timing distributions of photons with zonal harmonics for each radial slice about the vertex.

Analysis method

Using the Cherenkov profile model, the expected charge and timing distributions for all PMTs are calculated for track parameters \( \eta \) and \( \phi \), and the detector configuration. This is used to construct a likelihood function \( L(\eta, \phi) \), whose second derivative is used to compute the ring reconstruction sensitivities.

At each solid angle we measure not only the photon flux but also their direction distribution, which allows modeling of reflections including scattering effects.

Origin of enhanced sensitivity

Sensitivity to photon direction

• Without reflectors, a change in \( \eta \) can be compensated by a change in \( \phi \).

• Adding reflectors resolves this degeneracy by causing the antipodal ring to move (same for \( \nu \) direction).

Sensitivity to timing differences

• Normally vertex sensitivity comes from timing difference \( t_1 - t_2 \).

• Reflected light has 3x path length \( \rightarrow 3x \) sensitivity to timing differences at same time resolution.

Sensitivities with different photo-coverages

Energy resolution mostly depends on the number of collected photons. The more PMTs we have the less reflectors we can place, so the sensitivities converge.

The enhanced position and angle sensitivities due to parallax result from a new information class (photon direction) and are thus effective for a wide range of coverages.

The improved reconstruction sensitivity means one can reduce the number of PMTs by introducing retro-reflectors, reducing the cost of water-Cherenkov detectors significantly.

(cost of retro-reflectors about 1/10 of PMTs)

Practical challenges

Corner cube retro-reflectors have most accurate retro-reflection. However, if the incident light reflects less than three times, it will not be retro-reflective.

Superposition methods (e.g. blind) might need to be developed.

Summary

• By adding reflectors between PMTs, it might be possible to improve vertex and angular resolution \( \rightarrow 2x \) in water-Cherenkov detectors.

• Problems like multiple reflections and alignment difficulties are elegantly solved by using retro-reflectors instead of normal mirrors.

• Research for solving practical difficulties in implementation and data-analysis is ongoing.

• Improvements should help with kinematic selection of multi-ring events and reduce cost of water-Cherenkov detectors by requiring less PMTs.

References