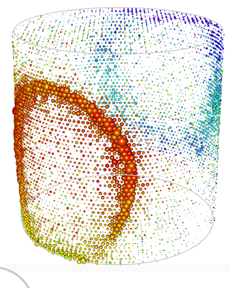

A novel water-Cherenkov detector design with retro-reflectors to produce antipodal rings

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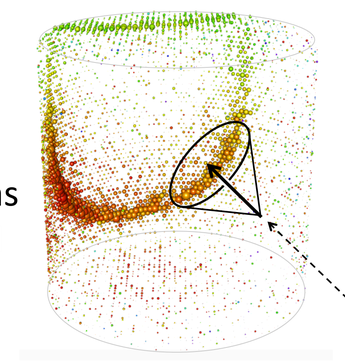
1

Problems with water-Cherenkov detectors

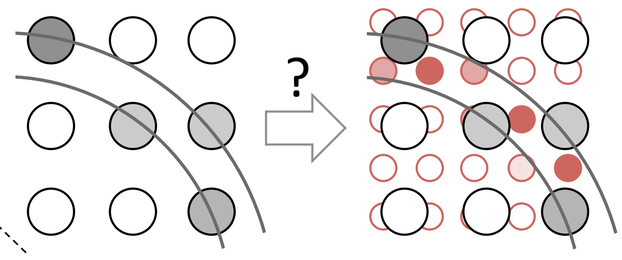
Basic design of water-Cherenkov detectors has not changed for a long time.



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 greater ring resolution due to effectively smaller PMT sizes and parallax?

2

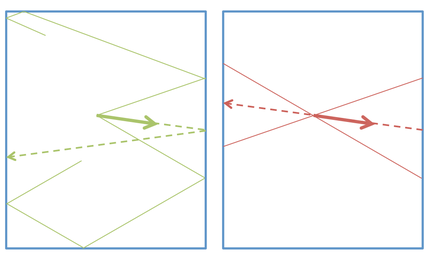
Problems with normal mirrors ⇨ Solution: **Retro-reflectors**

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

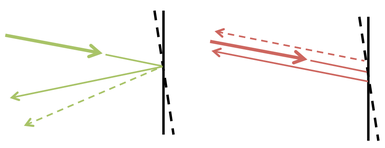
Even 1° misalignment causes ~1 m deviation of the light path over 30 m.

Residual light decreases contrast for other rings.

→ impractical



↑ Reflected light path for normal mirrors (left) and retro-reflectors (right).



↑ Angle of reflected light when slightly changing the alignment.

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.

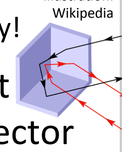
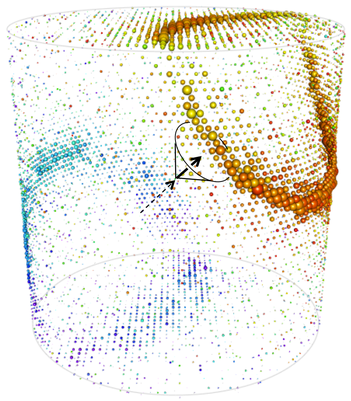
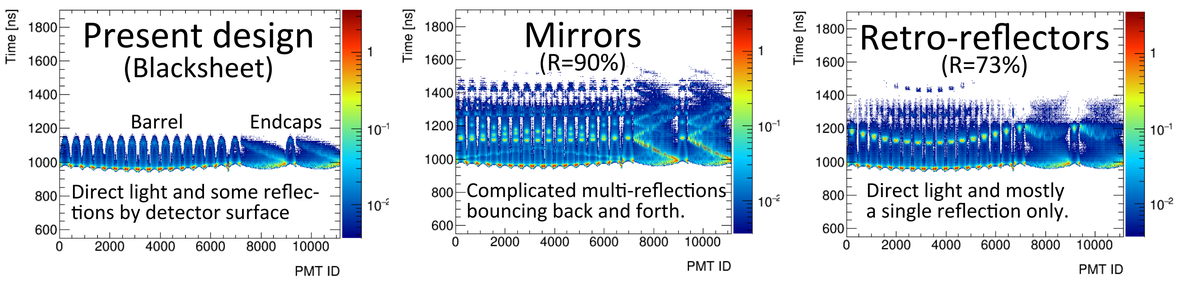


Illustration: Wikipedia





With retro-reflectors (right) the reflected light is well separated in time.

3

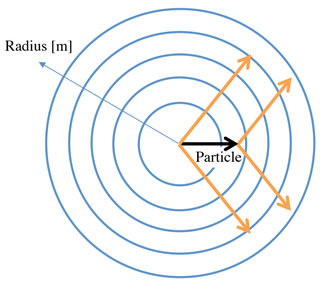
Verification of multi-reflection cancellation

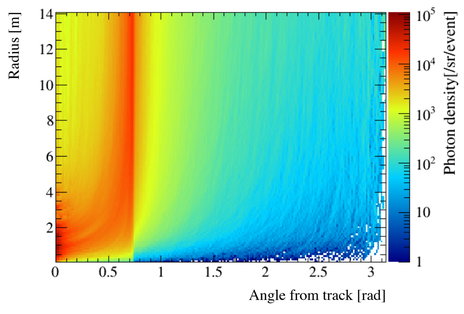
Simulation using Geant4[1]-based WCSim[2]. Blacksheets between PMTs are replaced with reflective materials. The complicated multi-reflection time signatures due to mirrors disappear almost completely with retro-reflectors. (side-going electron in SuperK[3] sized detector)

4

Cherenkov profile

For precise modeling of the cherenkov profile, we simulate moving particles in Geant4[1], and fit flux and timing distributions of photons with zonal harmonics for each radial slice about the vertex.





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

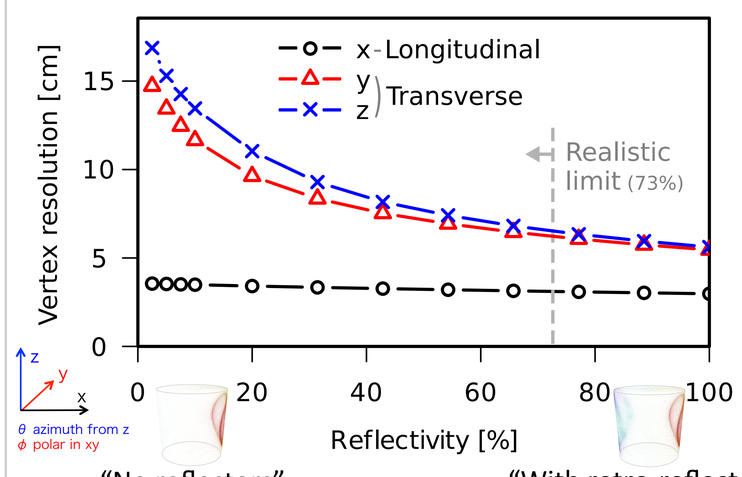
Analysis method

Using the Cherenkov profile model, the expected charge and timing distributions for all PMTs are calculated for track parameters $\eta = (t, x, y, z, E, \theta, \phi)$ and the detector configuration. This is used to construct a likelihood function $L(\eta, \eta_{\text{true}})$, whose second derivative is used to compute the ring reconstruction sensitivities.

5

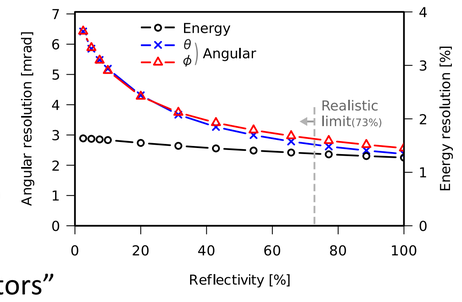
Ring reconstruction sensitivity

All following plots are for 500 MeV electrons in a SuperK[3] sized detector.



<u>Great enhancement</u> of transverse position and anglular resolution.

Longitudinal position and energy resolution improve only slightly.



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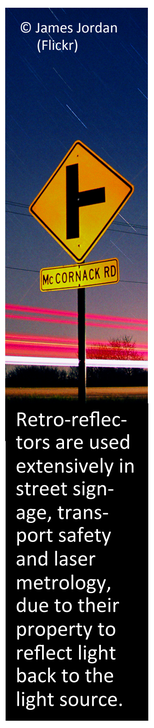
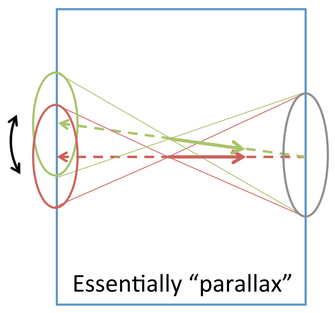


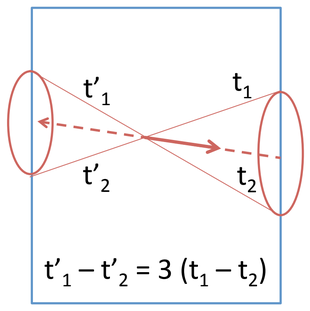
Retro-reflectors are used extensively in street signage, transport safety and laser metrology, due to their property to reflect light back to the light source.

Origin of enhanced sensitivity



Sensitivity to <u>photon direction</u>

- Without reflectors, a change in z can be compensated by a change in θ.
- Adding reflectors resolves this degeneracy by causing the antipodal ring to move (same for y,ϕ)



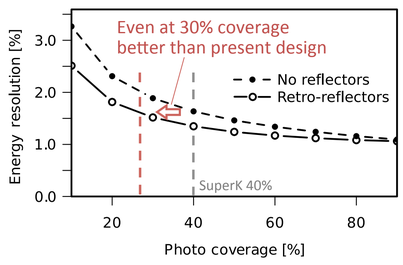
Sensitivity to timing differences

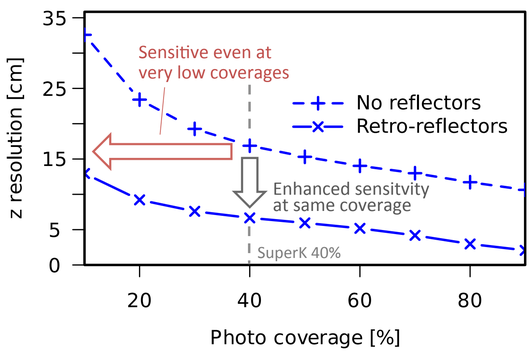
- Normally vertex sensitivity comes from timing difference $t_1 - t_2$
- Reflected light has 3x path length

→ 3x sensitivity to timing differences at same time resolution.

7

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 sensitvities converge.

The enhanced position and angle sensitvities due to parralax 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, <u>reducing the cost</u> of water-cherenkov detectors significantly.

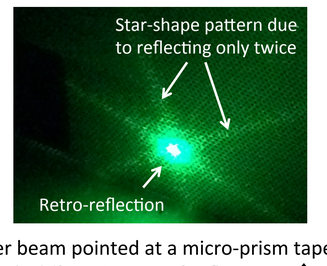
(cost of retro-reflectors about 1/10 of PMTs)

8

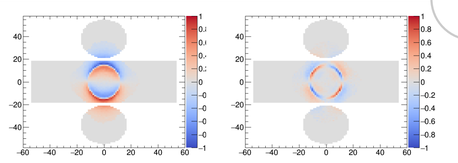
Practical challenges

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.

Suppression methods (e.g. blinds) might need to be developed.



Laser beam pointed at a micro-prism tape reveals different types of reflections. ↑



↑ Some variational modes of the Cherenkov profile for a side-going electron.

Variations of the cherenkov profile due to electromagnetic showering etc. were ignored in this analysis, and can have an impact on the sensitivity.

9

Summary

- By adding reflectors between PMTs, it might be possible to improve vertex and angular resolution ~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

[1] S. Agostinelli et al. [GEANT4 Collaboration], Nucl. Instrum. Meth. A 506 (2003) 250.
[2] T. Dealtry et al., https://github.com/WCSim/WCSim/blob/develop/doc/DetectorDocumentation.pdf (2016).
[3] Fukuda S. et al. [The Super-Kamiokande Collaboration], Nucl. Instrum. Meth. A 501 (2003) 418.