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Reducing refraction effects in Large Volume Metrology (LVM)

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As part of the EU's recently completed LUMINAR project, a team at University College London (UCL) used simulations and tests to find ways of reducing refraction effects in LVM. Although primarily aimed at photogrammetric methods, the analyses also apply to laser tracking. Results will be taken forward and applied in the UK's Light-Controlled Factory project.

The problem

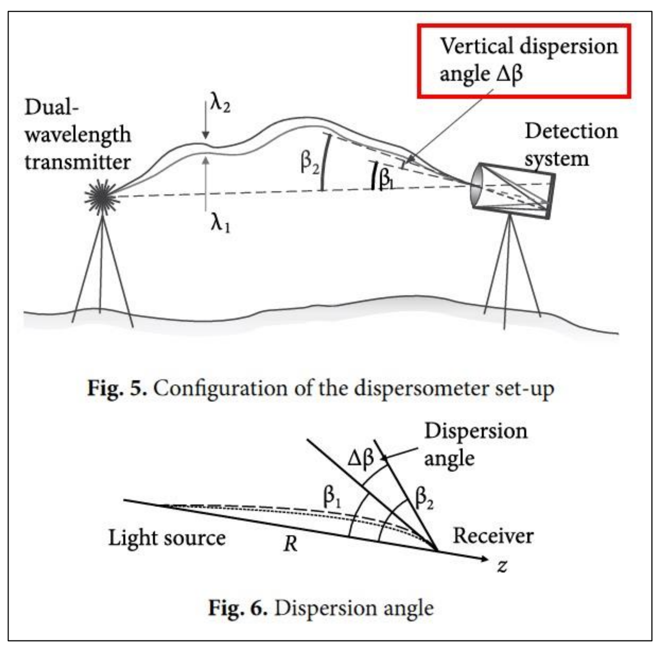
In large volume metrology light rays are assumed to travel in straight lines but refraction due to changes in refractive index of the air causes them to bend. These changes are mainly due to variations in temperature and can be significant over the longer ranges which arise, for example, in aerospace manufacturing.

To put this in perspective, a linear vertical temperature gradient of 1°C per m will deflect a 10m horizontal ray by 50µm and a 30m ray by 0.4mm.

Potential solutions

Significant development has been done in the past on a dual-wavelength (2-colour) solution for geodesy where long measurement ranges and refractive index changes are common. The amount of refraction depends on the wavelength. Blue (shorter) bends more than red (longer).

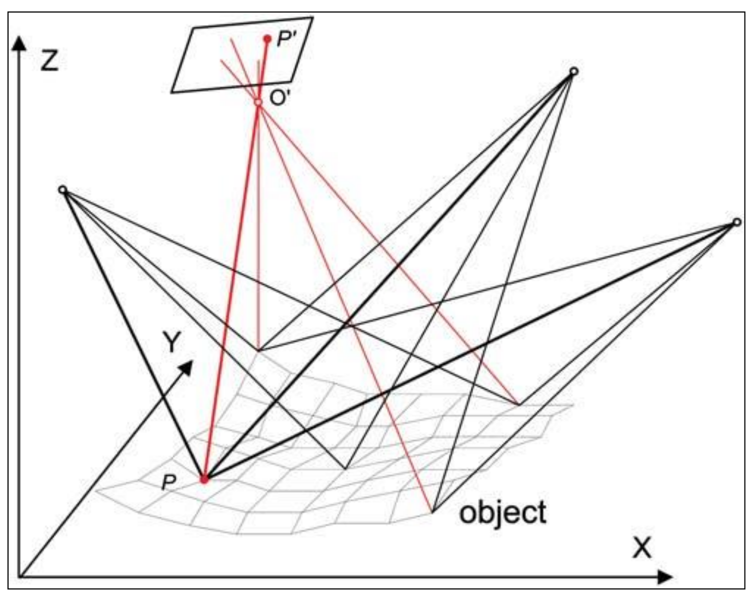
If measurements are made with light of two wavelengths and the refraction difference in angular terms (dispersion) is determined, then the angular pointing error can be calculated. For typical wavelengths used:



Ingensand, 2008.

refraction error = 42 x dispersion angle

Prototype instruments which can correct the error have been built for narrow fields of view (essentially single lines of sight) but the method is not in production. Applying the concept to the wider fields of view used in photogrammetry is a challenge due to the need to detect dispersion which is around 40 times smaller than the refraction error to be corrected. However, this has not been excluded from future development work.



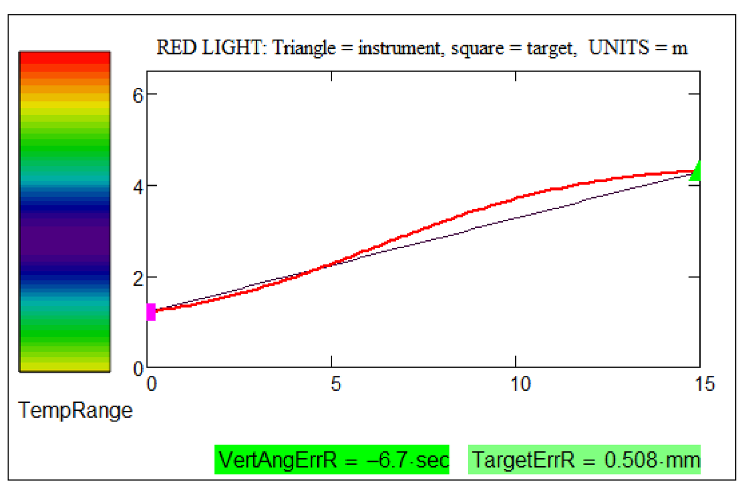
Another possible solution for photogrammetry would utilize the redundancy in multi-camera measurement networks.

Here features of interest are intersected from many camera locations. Two intersections are a minimum so that more may offer information about refraction errors.

In practice the least-squares analysis used to calculate camera and feature locations tends to absorb refraction errors by modifying camera and target coordinates. They are therefore not easily filtered out.

Currently the working solution is to sample temperatures throughout the working space and calculate refraction errors by ray tracing.

The diagram (right) shows a calculation using MathCAD ©. Ray bending due to the vertical temperature profile shown has been magnified to help visualization.

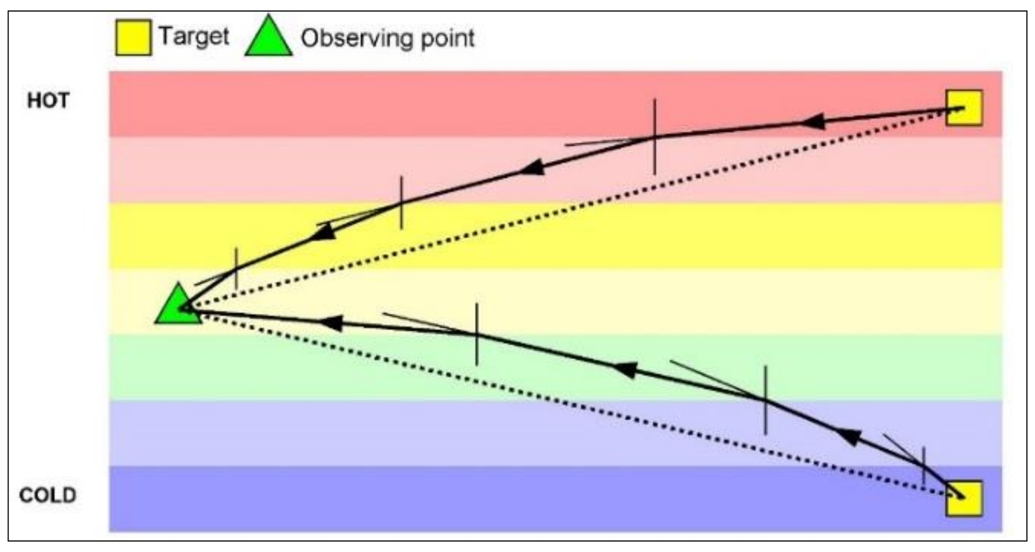


Simulation

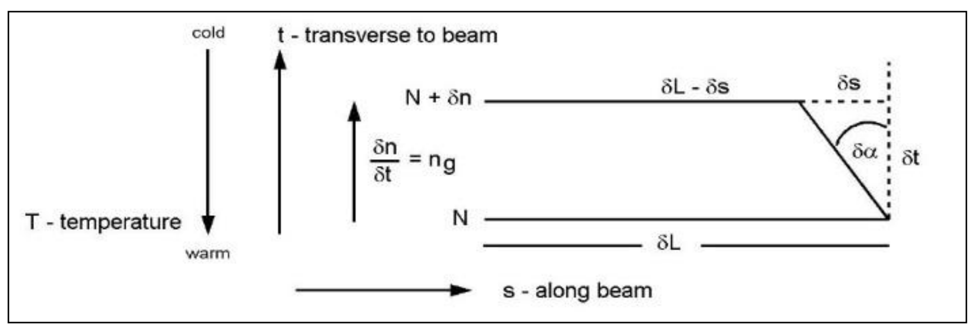
A temperature distribution is defined for the simulated workspace and a ray traced through this. Temperature is the most critical parameter defining the refractive index of air which, at any position, can be calculated with a simplified formula for refractivity (= 1 - refractive index). The following is due to Boensch and Potulski. Only temperature is varied, with air assumed dry and at a standard pressure of 1013 mbar.

$$\mathrm{Refractivity\_BP}(\nu,p,T) := \frac{100p\cdot\left[1+p\cdot(61.3-T)\cdot 10^{-8}\right]}{93214.6\cdot(1+0.003661T)}\cdot\left[80.9233+\frac{23339.83}{(130-\nu^2)}+\frac{155.18}{(38.9-\nu^2)}\right]\cdot 10^{-6}$$

The initial model assumed horizontal layers of air at different temperatures and Snell's Law was used to trace a ray through these. The following diagram illustrates the procedure. In practice, many thin layers are defined to create a more realistic simulation.



Snell's Law is not an ideal tool to use. For example there is no bending of a nearly horizontal ray within the locally defined layer. Modelling was therefore changed to use a differential bending formulation by Williams.

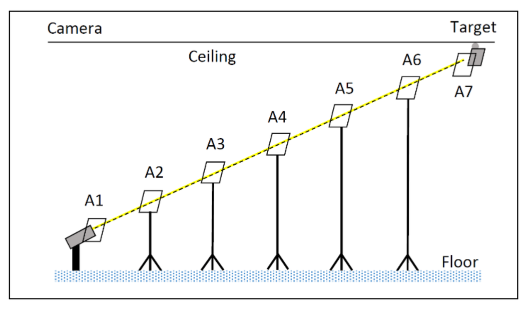


$$\delta\alpha = \frac{\delta L}{N}\cdot n_g$$

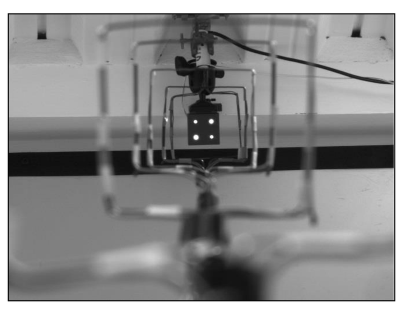
Williams' formulation also requires calculation of the spatial gradient of the refractive index at right angles to the ray's direction of propagation. This enables ray bending to be calculated in any 3D direction.

Testing

The simulation uses standard physical principles and is expected to be accurate. However, it will also be compared with experimental tests and this aspect of the work is still ongoing. Most recent experiments were made on site at Airbus.



For the experiments measurement "corridors" were created, with temperatures sensed at the corners of simple frames arranged along the line of sight from a camera to a target cluster.



The Light-Controlled Factory (LCF)

The image (right) shows an AICON multi-camera system in a factory configuration. The LCF project aims to use much larger camera networks working across bigger spaces where refraction is likely to be an issue and the LUMINAR analysis can be applied.

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EMRP European Metrology Research Programme
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