Compensating for the effects of refraction in photogrammetric metrology

Stephen Kyle

University College London

s.kyle@ucl.ac.uk

Co-authors:

Stuart Robson (UCL)

Lindsay MacDonald (UCL)

Mark Shortis (RMIT University)

3D Imaging, Metrology & Photogrammetry
applied coordinate technologies

The task for UCL in the LUMINAR project

LUMINAR: **L**arge volume **U**nified **M**etrology for **I**ndustry, **N**ovel **A**pplications & **R**esearch

“Large volume” means 3D metrology in large manufacturing spaces. The Airbus image (right) shows a typical example.

In these large spaces we use optical methods such as laser tracking and photogrammetry but there’s a problem:

We assume light travels in straight lines, but it doesn’t.

Temperature variations in the local atmosphere are a particular source of variations in refractive index which causes light rays to bend.

The UCL task:
Find ways to mitigate the negative effects of refraction by measuring and modelling it, and then compensating for it in multi-camera networks used for 3D location and tracking in the on-going Light-Controlled Factory project.

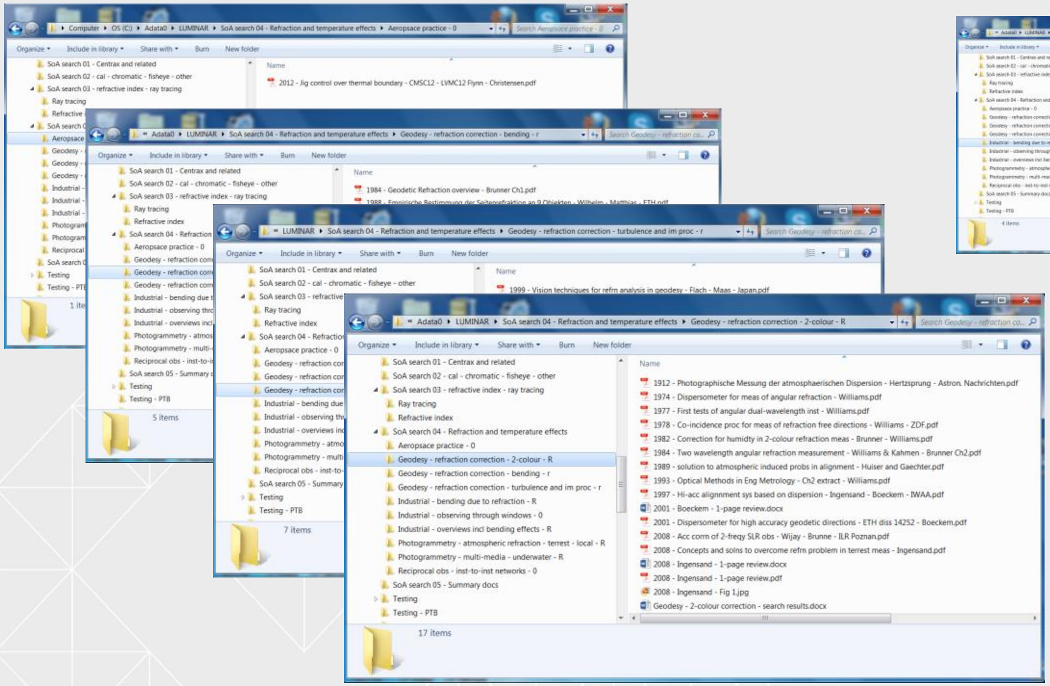
Presentation overview

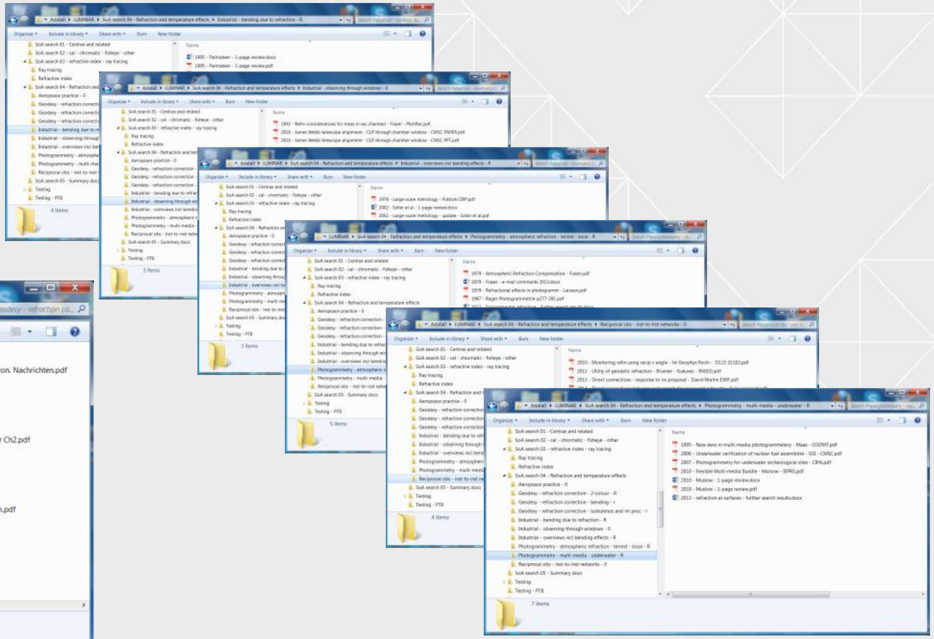
This following items will be discussed

1. Background
2. Refraction simulation
3. Experimental work
4. The Light-Controlled Factory
5. Further potential work

1: Background

Literature review – refraction effects





47 publications in 10 categories covering issues such as:

- Geodetic work – ray bending, turbulence and 2-colour correction
- Photogrammetric work – terrestrial effects, underwater photogrammetry
- Refraction in an industrial context – general bending, through windows, evaluations in aerospace environments

Apparent target errors

- Palmateer suggests vertical temperature gradients (cold on floor, warm under roof) are fairly typical of assembly halls at Boeing [1]
  - In relatively small areas refraction errors are not significant
  - For full aircraft measurement effects can be significant, e.g. 0.26mm
- 0.5°C per m vertical temperature gradient
  - Over a 10m horizontal line, apparent target deflection is 50µm
  - Over a 30m horizontal line, deflection is 0.4mm
- 1.5°C per m vertical temperature gradient (approx. 10°C over 6m)
  - At 15m horizontally and 6m vertically, deflection is 0.175mm

[1] John Palmateer, Boeing Commercial Airplane Group
Effect of stratified thermal gradients on measurement accuracy with application to tracking interferometer and theodolite measurement
7 Congrès de Métrologie, 1995

The 2-colour solution

2-colour correction in geodesy

- A measurement beam with 2 colours (wavelengths) of light bends slightly differently for each colour
- From the bending difference (dispersion) at the instrument, the refraction error can be calculated
- *For typical frequencies: error = 42 x dispersion*
- Huiser and Gächter at Wild Leitz (now part of Hexagon MI) built a working dispersometer in 1989

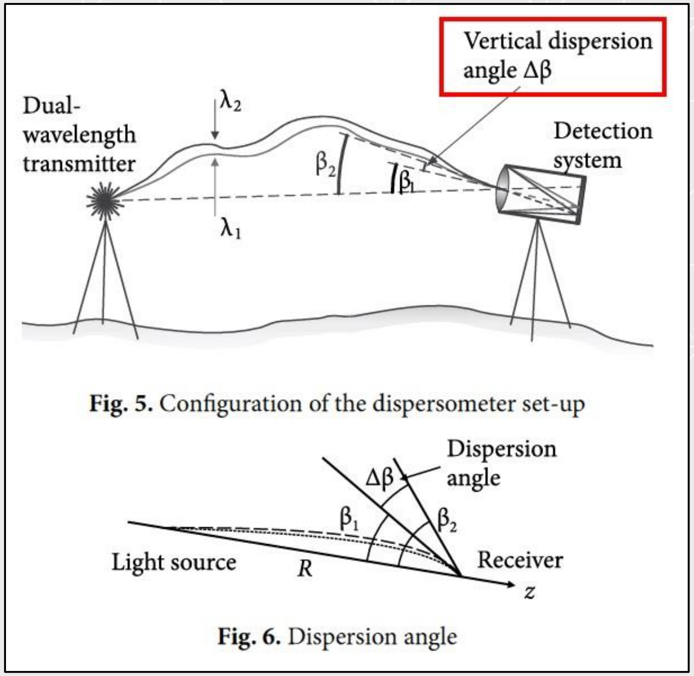


Fig. 5. Configuration of the dispersometer set-up

Fig. 6. Dispersion angle

The challenge in photogrammetry - example

- For previous example of 1.5°C/m, 15m (H), 6m (V), dispersion corresponds to around 5µm at target
- For test camera with 75mm lens, a 2.2 µm pixel with 1/50 interpolation factor corresponds to approx. 9µm at target
- Demanding but worth investigating

Illustration source:
Ingensand, H.
Concepts and solutions to overcome the refraction problem in terrestrial precision measurement.
Geodezija ir Kartografija / Geodesy and Cartography, 2008, 34(2): 61 – 65

2: Refraction simulation

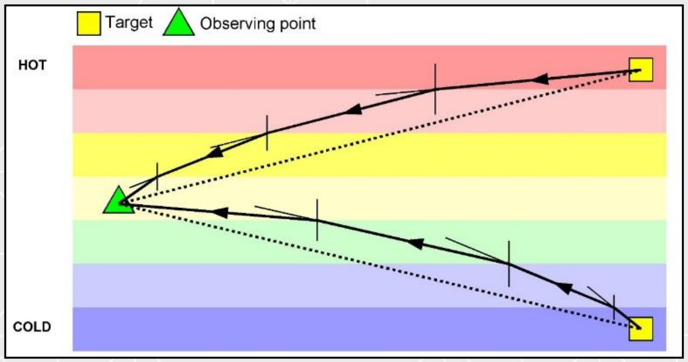
Refraction simulation - basics

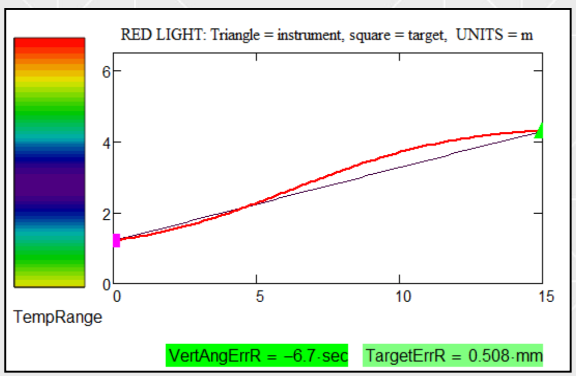
Refractivity function: Boensch & Potulski

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

v is the wavenumber (inverse wavelength) in μm^{-1}, i.e. $v = 1/\lambda$
P is ambient pressure, assumed constant in the simulations
T is the temperature at which refractivity and refractive index is to be evaluated

$N = 1 + \text{Refractivity\_BP}(\nu, P, T)$ where N is the refractive index





The refractive index of air depends on temperature, pressure and humidity. Temperature is most critical. UCL simulations only use temperature as a variable.

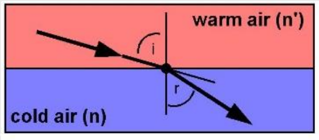
On the left is Bönsch and Potulski's formulation, a modification of Edlén's.

The starting model for simulation is horizontal layers of air at different temperatures with rays traced using Snell's Law. See centre diagram.

The lower diagram shows a MathCAD simulation of ray bending caused by a layer model. (Bending exaggerated for visualization.)

Refraction simulation – 3D ray bending

Snell's Law

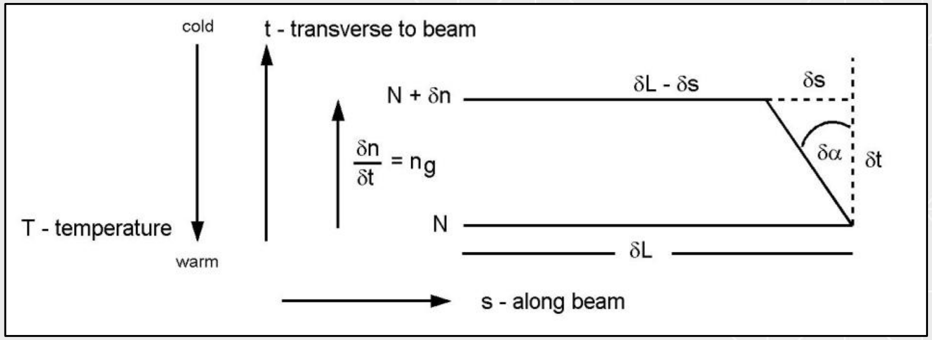


$$n' \cdot \sin(i) = n \cdot \sin(r)$$

Not ideal

- (Near) horizontal rays in a layer model remain within the layer and do not bend, even though there is a transverse refractive index gradient causing bending.
- Oblique rays at layer interfaces are difficult to model.

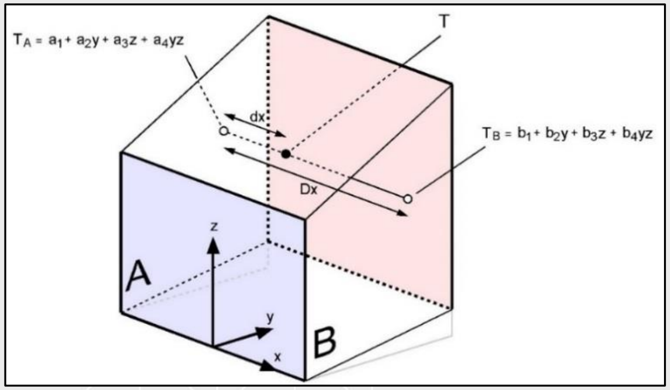
Williams' differential bending formulation



A better, general approach

- The diagram shows air at different temperatures either side of a light beam.
- On the colder side the refractive index is higher and the beam travels more slowly, hence a bend angle δα.
- It is easily shown that: $\delta\alpha = \frac{\delta L}{N} \cdot n_g$
- Note: the refractive index gradient is the *transverse component* of the spatial refractive index gradient.

Interpolation of temperature



From bilinear interpolation on the A and B faces:

$$T_A = a_1 + a_2 \cdot y + a_3 \cdot z + a_4 \cdot y \cdot z$$

$$T_B = b_1 + b_2 \cdot y + b_3 \cdot z + b_4 \cdot y \cdot z$$

hence linear interpolation between T_A and T_B:

$$T = k_1 + k_2 \cdot x + k_3 \cdot y + k_4 \cdot z + k_5 \cdot x \cdot y + k_6 \cdot y \cdot z + k_7 \cdot z \cdot x + k_8 \cdot x \cdot y \cdot z$$

k_1 .. k_8 found by solving 8 equations for the 8 temperature at the corners.
Hence the spatial temperature gradient:

$$\frac{dT}{dx} = k_2 + k_5 \cdot y + k_7 \cdot z + k_8 \cdot y \cdot z$$

$$\frac{dT}{dy} = k_3 + k_5 \cdot x + k_6 \cdot z + k_8 \cdot x \cdot z \qquad \frac{dT}{dS} = \begin{pmatrix} \frac{dT}{dX} \\ \frac{dT}{dY} \\ \frac{dT}{dZ} \end{pmatrix}$$

$$\frac{dT}{dz} = k_4 + k_6 \cdot y + k_7 \cdot x + k_8 \cdot x \cdot y$$

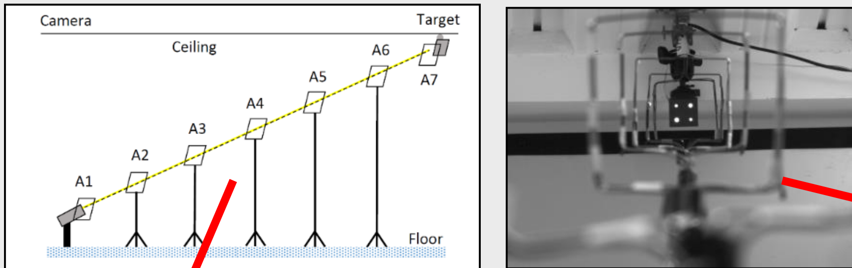
- The measurement space is divided into cuboidal voxels
- Rays are divided into successive linear segments
- Temperature T for the current segment is interpolated from 8 thermocouple readings at the voxel corners using trilinear interpolation
- Williams' equation requires the refractive index N and its vector gradient transverse to the beam.
- The interpolated temperature gives the refractive index N using Bönsch and Potulski's formula
- From this formula the gradient of N w.r.t. T is calculated.
- From the interpolation equation for T, the vector gradient of T with respect to the 3D space is calculated.
- From these two gradients the refractive index gradient is:

Spatial gradient of N

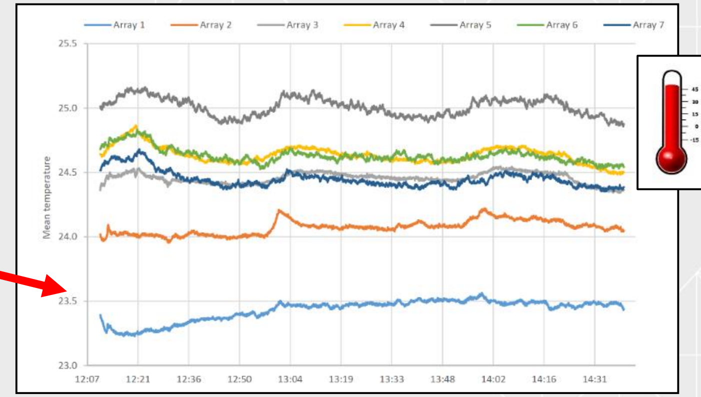
$$\frac{dN}{dS} = \frac{dN}{dT} \cdot \frac{dT}{dS} \quad \text{where} \quad \frac{dN}{dT} = \frac{-0.11413375528178 \cdot P^2 - 34125.86506 \cdot P}{(341.2586506 \cdot T + 93214.6)^2} \cdot \left[80.9233 + \frac{23339.83}{(130 - \nu^2)} + \frac{155.18}{38.9 - \nu^2} \right] \cdot 10^{-6}$$

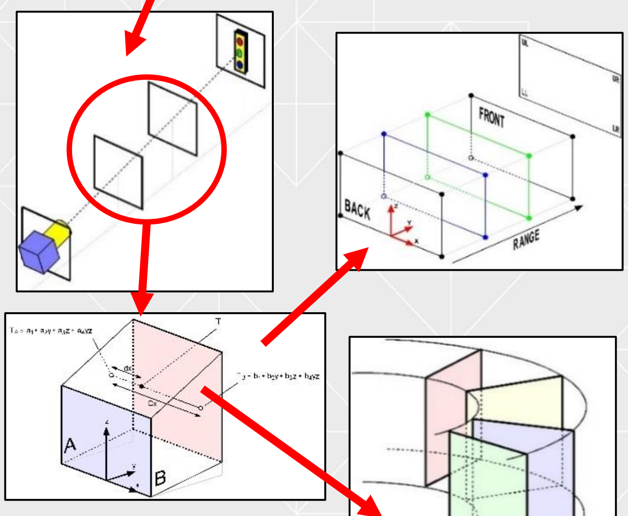
3: Experimental work

Tests at UCL



Testing





Modelling

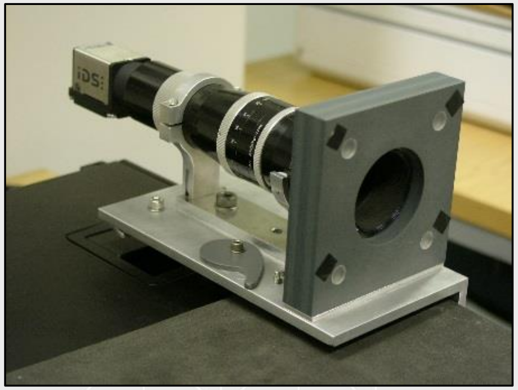
A cluster of 4 LED targets (violet and IR) is imaged by a telephoto lens through an array of “quad” thermocouples.

The quads (A1 .. A7) are clusters of 4 thermocouple sensors which provide 3D sensing of the atmosphere in an air “duct” between camera and target.

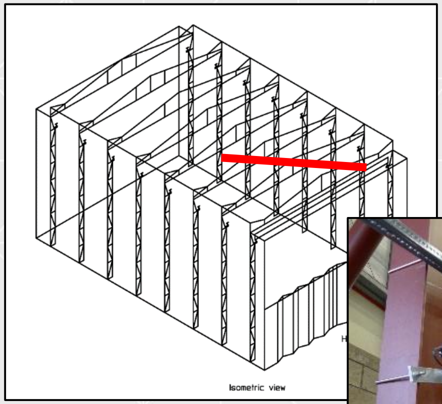
“Snapshots” of the duct’s thermal state are used to model refraction and correlate these against image movements.

Thermal distortions of the camera made results unclear.

Tests at Airbus UK



- The system was extended to use two cameras with LED targets around their lenses
  - Image on right shows Kern 75mm lens



- This gave a mutually pointing camera/target configuration at each end of a 40m test line
  - Images on right show diagrammatic layout in hangar and the actual situation

- Analysis not yet complete

4: The Light-Controlled Factory

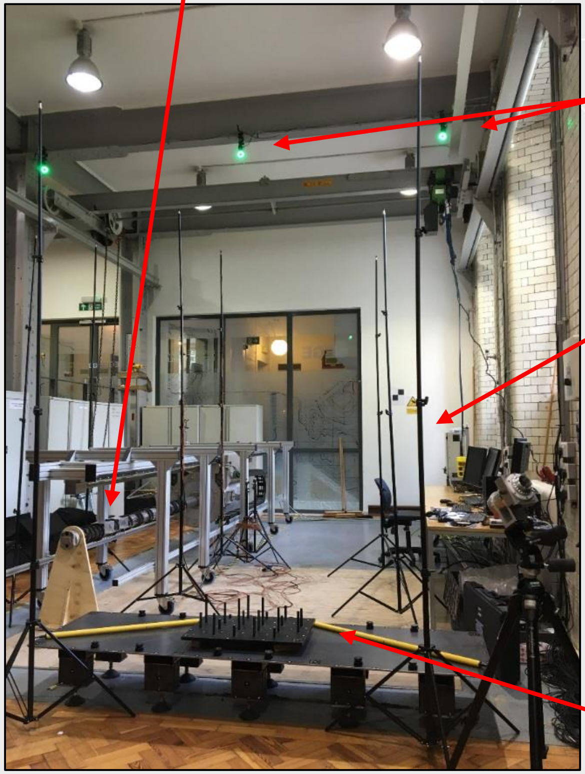
Photogrammetry in the factory

- In the Light-Controlled Factory project, multiple individual parts and objects such as robots will be tracked by cameras in 7 degrees of freedom (7DoF)
  - 6 DoF with real-time monitoring of change
- Commercial systems already exist but do not cover the larger spaces of interest to the project
  - Images from Creaform (now part of Ametek) and Aicon (now part of Hexagon MI)

UCL test area

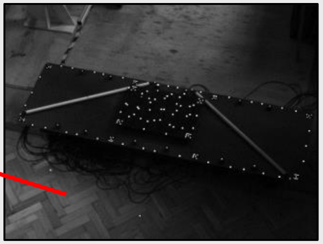
- At UCL, a snake-arm robot with on-board cameras will be monitored by external cameras as it analyses a test object
- The monitored test space is roughly a cube of 4m side length
- 12 telescopic stands, each 4m high and with 4 thermocouples attached, will provide snapshots of the thermal state of the cube to enable 3D ray refraction to be calculated
- Refraction correction will be applied to a constantly updated camera network to improve spatial accuracy at the test object

Snake-arm robot



Standard cameras with LED ring illumination monitor the movement of retro-reflective targets

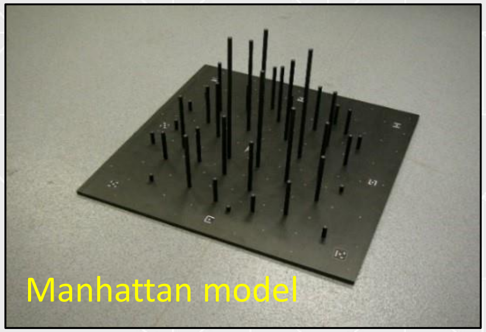
Telescopic stands for thermocouples

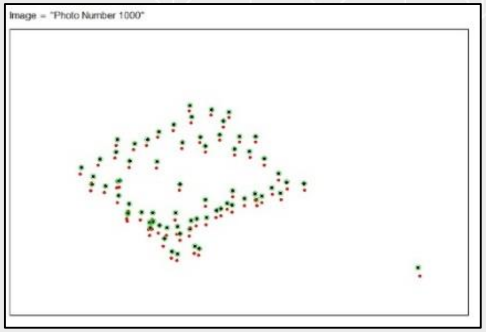


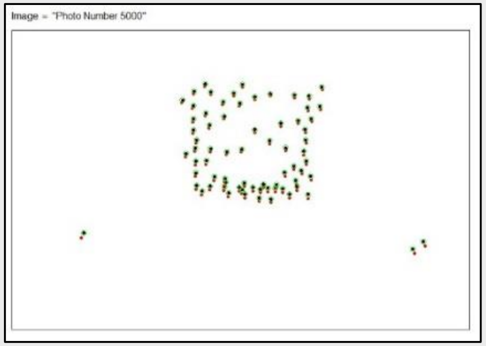
Test object

Multi-intersection analysis

- Multi-camera networks, with multi-ray intersections, are typically analysed by least-squares “bundle adjustment”
  - Generates all target and camera location data
- Attempt to filter out refraction errors from this analysis
  - Simulate images of a test object, with and without a thermal distribution causing refraction
  - Compare results to see if refraction can be identified
- A simulated, scaled-up version of a 3D target artefact was simulated with a 30m height separation to the cameras and 60°C vertical temperature difference
- Due to nature of least-squares analysis, refraction errors are absorbed in new camera and target locations
- Best option currently is to measure the thermal state of the environment, then calculate refraction errors







5: Potential further work

Further work

- Investigate alternative imaging techniques more sensitive to dispersion measurement
  - Directly capable of eliminating refraction errors
- Verify simulation against laser tracker measurements
  - Correction for laser tracker measurement is also important
  - It may be easier to eliminate the issue of instrument deformation confusing results
- Implement MathCAD simulations in MatLAB for online refraction correction
  - Local network of temperature sensors provides real-time snapshots of environment
- Confirm validity of interpolating temperature from a 3D network of sensors
- Evaluate techniques for remotely sensing temperatures in a 3D work space
  - Avoid the need for physical sensing
  - Physically positioned sensors may be an inconvenient addition to the workspace

- **Investigate areas such as accelerator alignment for application of refraction correction**

Acknowledgements

LUMINAR project

An EU EMRP project jointly funded by the EMRP participating countries within the EURAMET and the European Union.

EURAMET

EMRP
European Metrology Research Programme
Programme of EURAMET
The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union

The Light-Controlled Factory project

EPSRC grant EP/K018124/1

.. if you liked this

- .. then take a look at S Kyle's poster later today:
  www.3dimpact-online.com: a knowledge base of 3D metrology

- .. and consider attending the 3D Metrology Conference www.3dmc.events
  Aachen 22 – 24 November for more great presentations such as:
  - NPL: Evaluating the measurement process
  - Sigma3D: VDI guideline for end users of large-scale metrology
  - Hexagon: 3D metrology for automated assembly
  - FFT Production Systems: In-line laser radar
  - Nuclear AMRC: In-Process inspection of large high-value components
  - Insphere: Confidence in Additive Manufacturing
  - Etalon: Laser metrology for on-machine measurements
  - IK4 Tekniker: Advances in metrology of large parts
  - PTB: Intrinsic refractivity compensation for distance metrology

- Thanks for your attention – merci beaucoup – Danke vielmals