Results of Aperture Area Comparison for Exo-Atmospheric Total Solar Irradiance

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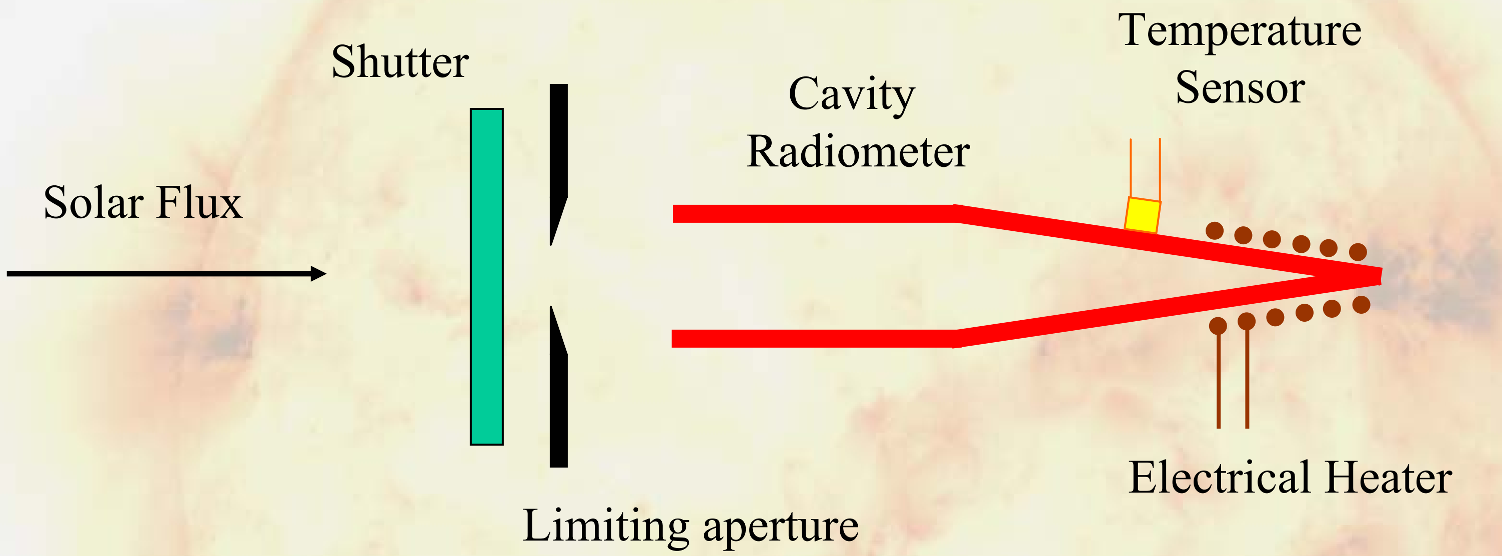
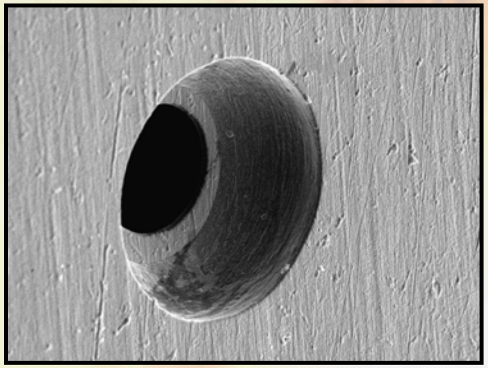
Electrical Substitution Radiometry



- Optical power is compared to electrical power
- Technique at National Metrology Institutes
- NMI's: 0.02 % agreement in power mode with cryogenic radiometers

- For TSI, the aperture area must be known



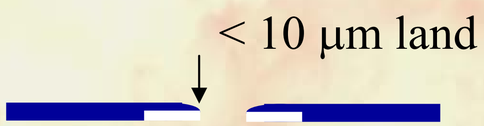
SEM of etched aperture

Aperture Designs

Traditional: machine-turned, ground, lapped

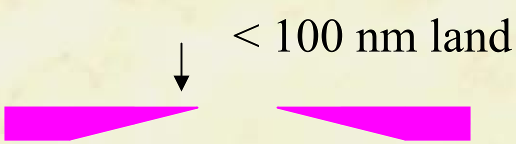
Contact or non-contact measurement technique

Electro-deposition: photo-resist mask on substrate, deposition, etch mask away



Clean edges, good circles, other shapes possible

Diamond turned: diamond tool, ~10 nm resolution, very sharp edges, circular

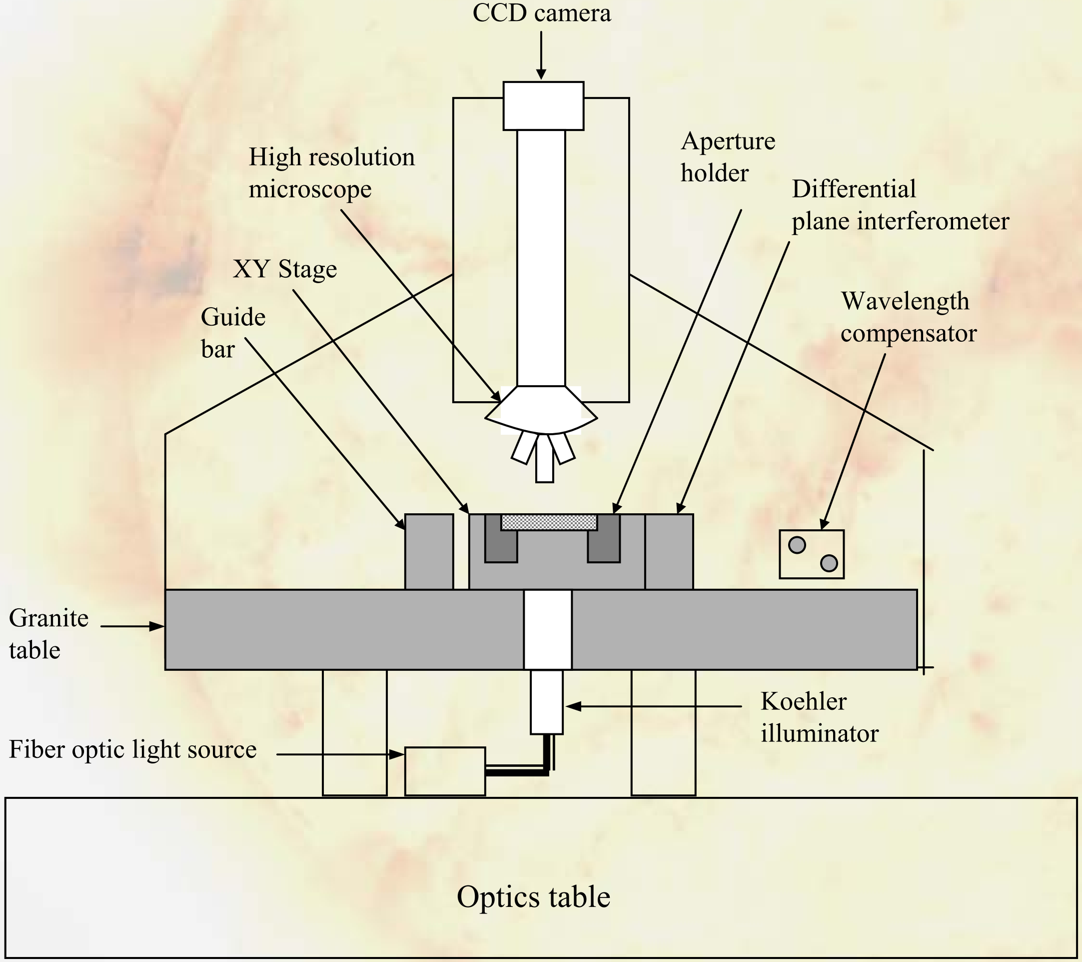


Non-contact method only, no scattering from land

Goals of EOS Comparison

- Common measurement approach
  - aperture & measurement approach are a system
  - however, bias can exist in either component
- Utilize modern, non-contact method
- Measure heritage TSI apertures
- Recognize NMIs participate in international intercomparisons (CCPR-S2)

NIST Geometric Aperture Area Apparatus

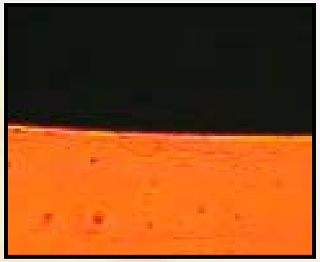


- –Köhler illumination of aperture
- –nested *x*, *y* stage: air bearings & laser interferometer
- –5 nm resolution
- –automated focusing algorithm
- –edge detection from optical microscopy
- –grid plates for calibration
- –relocated in to AML June 2004

Sources of uncertainty

Type	Source of uncertainty
Stage (A)	Instrument, edge quality
Stage (B)	All systematic stage uncertainties including the interferometer, cosine, Abbe offset
Image (A)	Source or detector noise, room noise, etc.
Image (B)	Coherence, magnification, pixel size, stage/camera angle, focus
Temperature (B)	Variation of temperature during measurement
Geometry (B)	Artifact mounting

Example



Diamond-turned, circular copper aperture—R=2.628257 mm

Type	Value nm	u(A)/ A ppm	Comments
Random (A)	13	9.9	Standard deviation of fitted R's (to a circle or ellipse). (TSI study: 6 x 360, rotate in between)
Stage (B)	13.7	10.4	Scales as $2.6 \cdot 10^{-6} \cdot 2R$; scale factor is from rectangular distribution and system specifications
Image (A)	2	1.5	Standard deviation combined with shape of edge waveform
Image (B)	4	3.0	Combined uncertainty of Type B evaluation of coherence, magnification, pixel size, stage/camera angle, and focus effects
Temperature (B)	3	6.6	Temperature difference during measurement and knowledge of thermal expansion coefficient
Geometry (B)	0.06°	1.1	Flatness depends on machining tolerances for the aperture mounting ring
Total (k=1)		16.2	

EOS Comparison Results

- Three participants (RMIB, WRC, ERBE)
  - supplied data and uncertainties they would/have used
- Automated NIST procedure:
  - Find geometric center
  - Center each edge x, y in camera's FOV
  - Autofocus
  - Fine positioning and sub pixel correction
  - Repeat every 1°
  - Remove aperture, rotate 59.3°, repeat 6 x
  - Circular and ellipse-fitting routines
- Tour of machine is available

World Radiation Center

Sample	Heritage
PMO609	Rocket flight 1984,1986; SIMBA balloon flight 1985,1988, 1992, 1998; WRR/cryogenic radiometer
PMO611	Rocket flight 1984;SIMBA balloon flight 1998; WRR/cryogenic radiometer comparison; NPL aperture comparison
SOVAR111	SOVA on Eureca 1992-1993; maybe on SOVIM in ISS
SOVAR113	SOVA on Eureca 1992-1993; maybe on SOVIM in ISS
VIRGO2	SIMBA balloon flight 1998; for SOVIM in ISS
VIRGO3	Comparison with NPL; for SOVIM in ISS

All samples were lapped, hardened steel, 5 mm nominal diameter, 0.02mm land; previous measurements used contact methods.

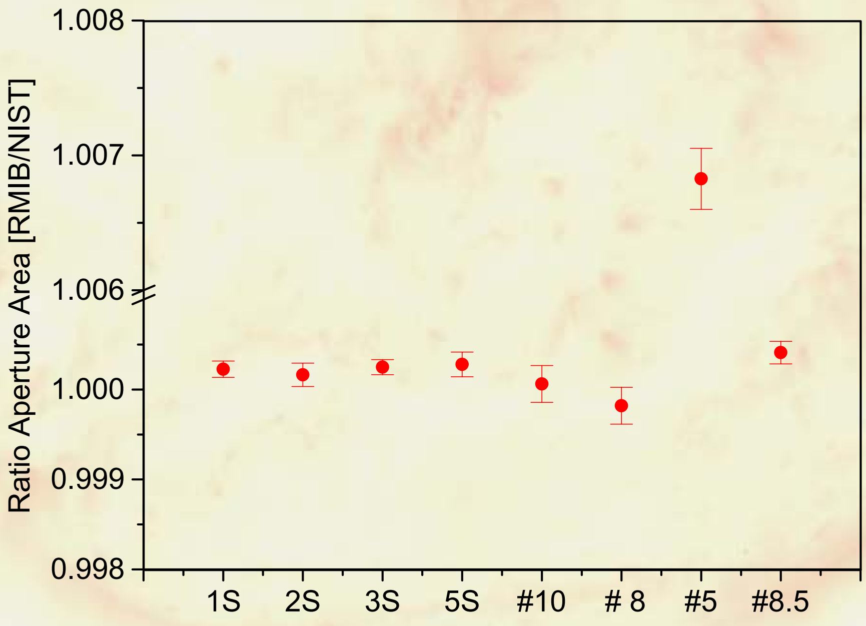
Royal Meteorological Institute of Belgium

Sample	Material	Previous Meas.	Heritage
1S	Ti	NPL, JPL, NASA	For PICARD
2S	Ti	NPL	For PICARD
3S	SST	NPL	For SOVIM
4S	SST	none	
5S	SST	NPL	For SOVIM
6S	SST	JPL, NASA	
#10	SST	ESA-ESTEC	Same series as SOLCON, SOVA1 1992-1998
#8	SST	ESA-ESTEC	Same series as SOLCON, SOVA 1992-1998
#5	SST	Several institutes	SOLCON, SOVA 1992-1998
#8.5	SST	Several institutes	SOLCON, SOVA 1992-1998

Three different size apertures were in the set (nominal diameters = 5, 8.5, or 10 mm).

Royal Meteorological Institute of Belgium

Aperture	NIST Area (mm^2)	NIST Rel uncertainty	Lab Area (mm^2)	Lab Rel uncertainty	Lab/NIST	Ratio Unc
1S	78.7368	8.88E-05	78.7545	1.80E-05	1.00023	9.06E-05
2S	78.7528	1.28E-04	78.7657	2.00E-05	1.00016	1.30E-04
3S	79.3996	8.16E-05	79.4193	1.99E-05	1.00025	8.40E-05
5S	79.4422	1.36E-04	79.4644	1.79E-05	1.00028	1.37E-04
#10	78.4918	4.28E-05	78.4966	2.00E-04	1.00006	2.05E-04
# 8	78.5037	4.25E-05	78.4896	2.00E-04	0.99982	2.04E-04
#5	19.7845	1.08E-04	19.9195	1.99E-04	1.00683	2.26E-04
#8.5	56.7972	4.32E-05	56.8205	1.18E-04	1.00041	1.26E-04



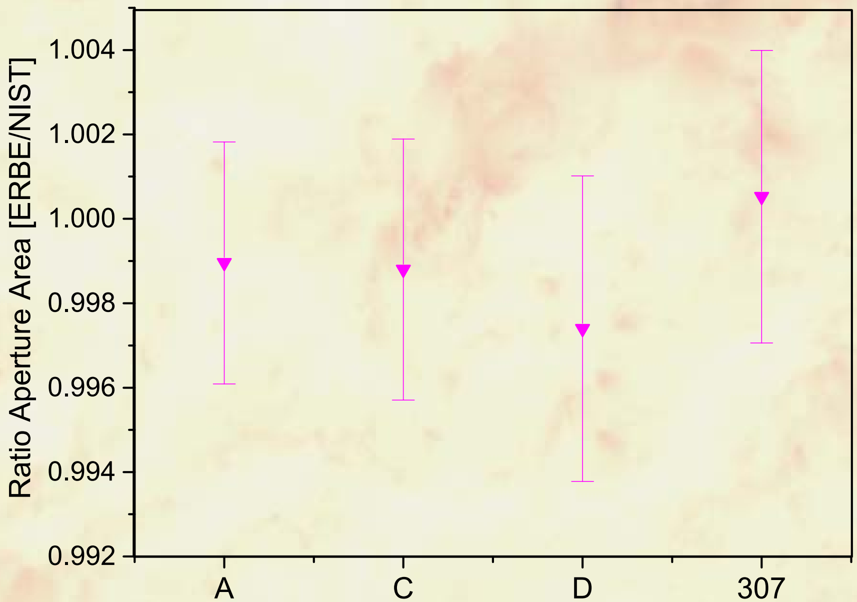
Earth Radiation Budget Experiment

Sample	Material	Previous Meas.	Heritage
A	Al	TRW Boice (contact), comparator, linearscope	ERBE ground spare
C	Al	TRW Boice (contact), comparator	Same series as ERBE flight aperture
D	Al	TRW Boice (contact), comparator	ERBE ground spare
307 NS	Cu	TRW Boice (contact), comparator, linearscope	Ground reference aperture

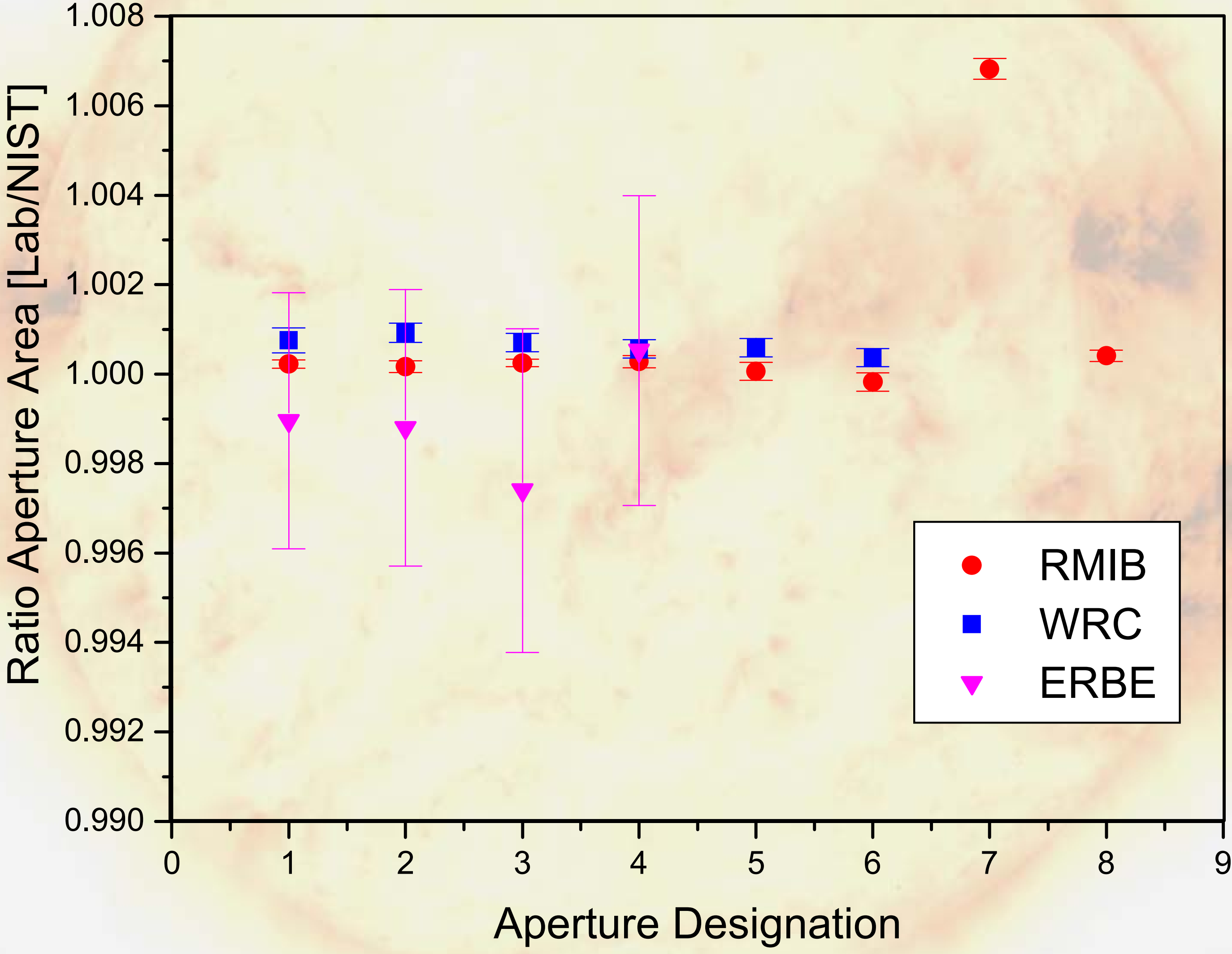
Two different size apertures were in the set (nominal diameters = 6.3 or 8 mm).

Earth Radiation Budget Experiment

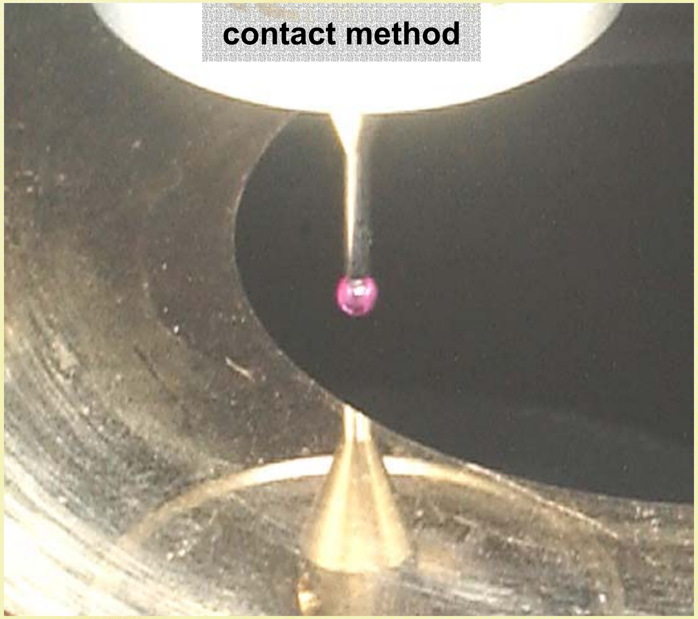
Aperture	NIST Area (mm^2)	NIST Rel uncertainty	Lab Area (mm^2)	Lab Rel uncertainty	Lab/NIST	Ratio Unc
A	50.6091	1.34E-03	50.5563	2.53E-03	0.99896	0.00287
C	51.3081	1.80E-03	51.2464	2.52E-03	0.9988	0.00309
D	51.2711	2.60E-03	51.1377	2.52E-03	0.9974	0.00362
307	31.6357	1.33E-03	31.6523	3.20E-03	1.00053	0.00347



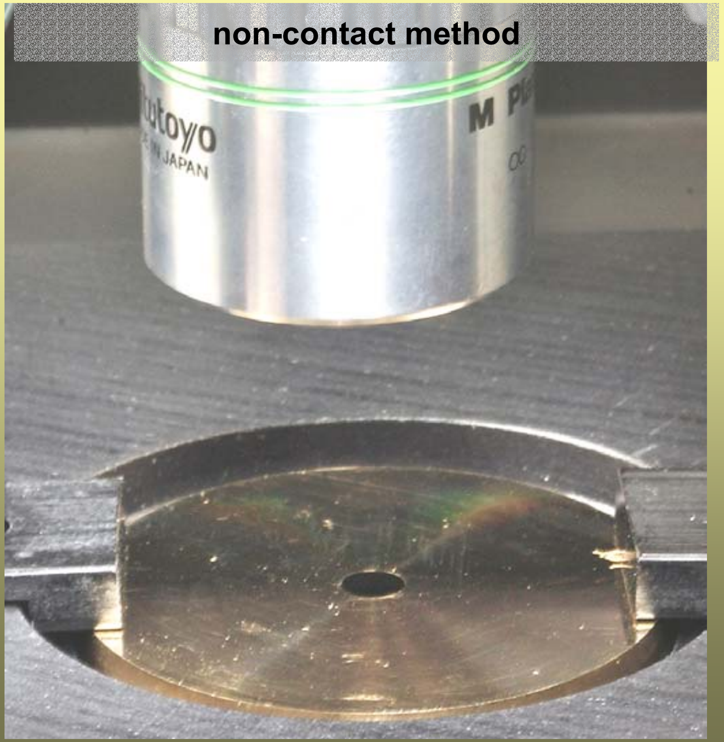
Composite Results



Discussion



edge location through contact probe



edge location using optical contrast

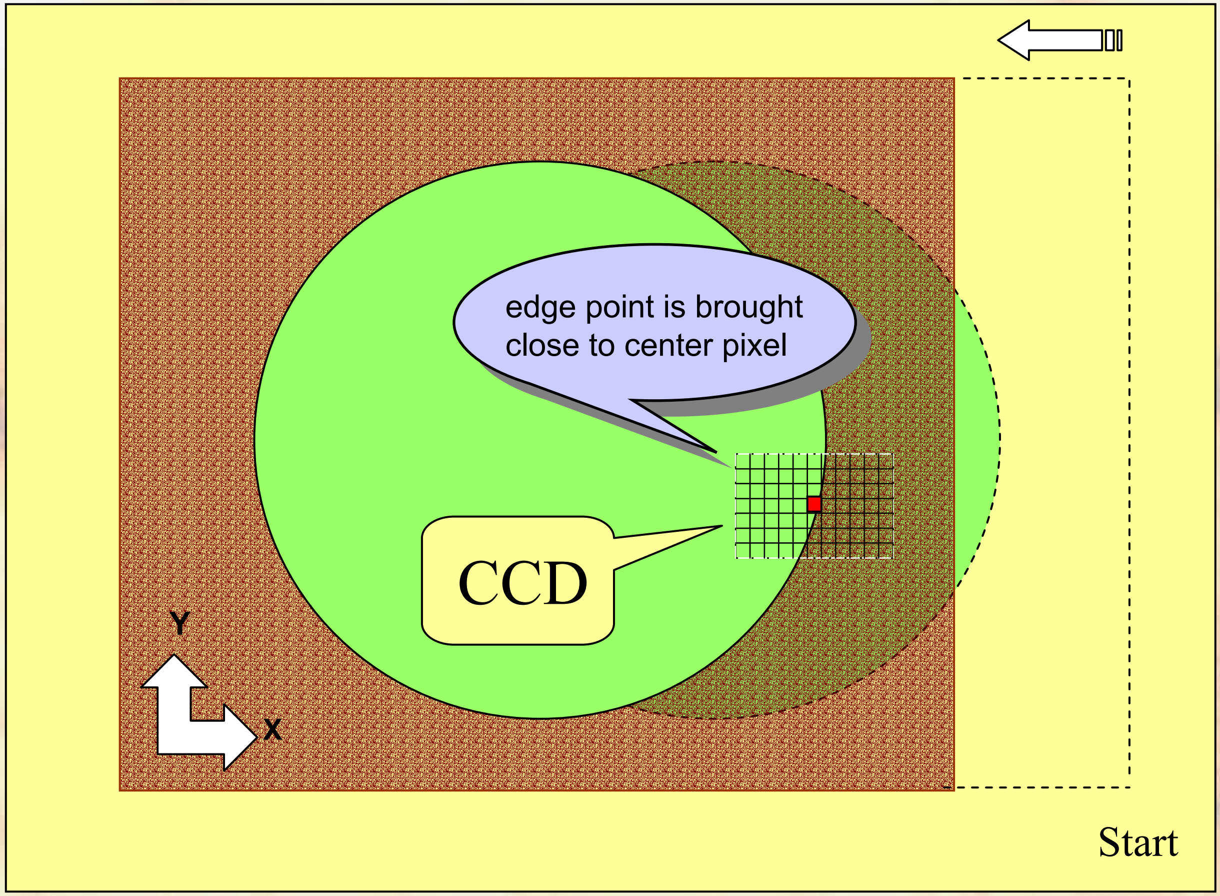
In the CCPR-S2 comparison (Draft A is in circulation), apertures with lands and diamond-turned apertures were circulated. Contact and/or non-contact methods were used by the participants.

Conclusions

- Some results discrepant given stated uncertainties
- If area was overestimated in previous determinations, then TSI was underestimated
- Does not resolve the TIM discrepancy with ACRIM III and the composite VIRGO result
- Send ACRIM apertures to NIST ASAP
- Possible expansion of Round Robin
  - NIST re-measure TIM apertures
  - JPL ROI machine measure NIST apertures

Back Up Slides

Determining distance



An edge point is brought to

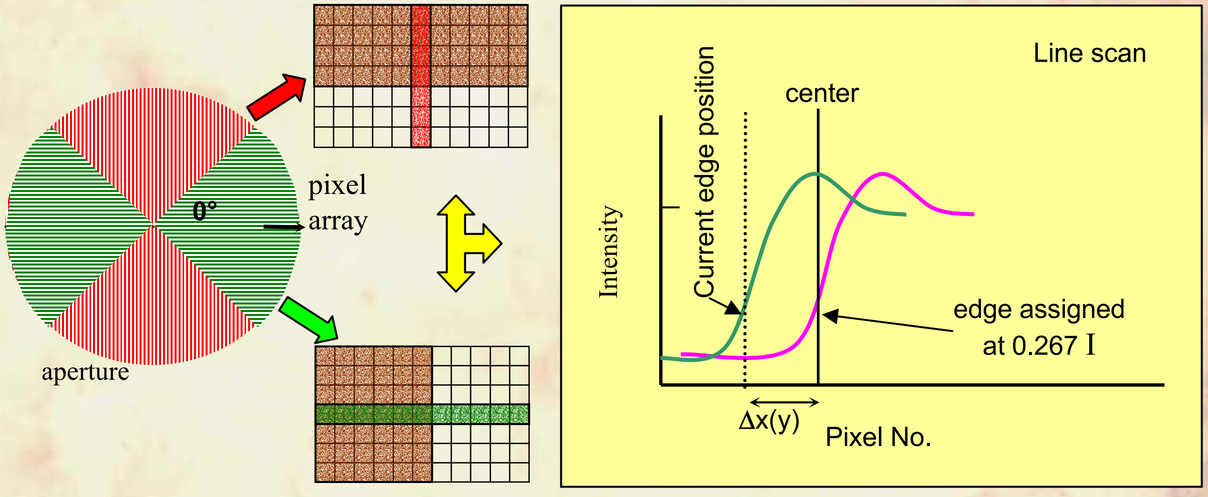
center of camera's field of view for coarse positioning;

central pixel for fine positioning

Distances are measured by the displacement of x,y stage

Determining edge coordinates

Scan intensity of pixel array horizontally for right or left quadrants of the circular aperture, or vertically for top and bottom quadrants to locate edge and generate line scans

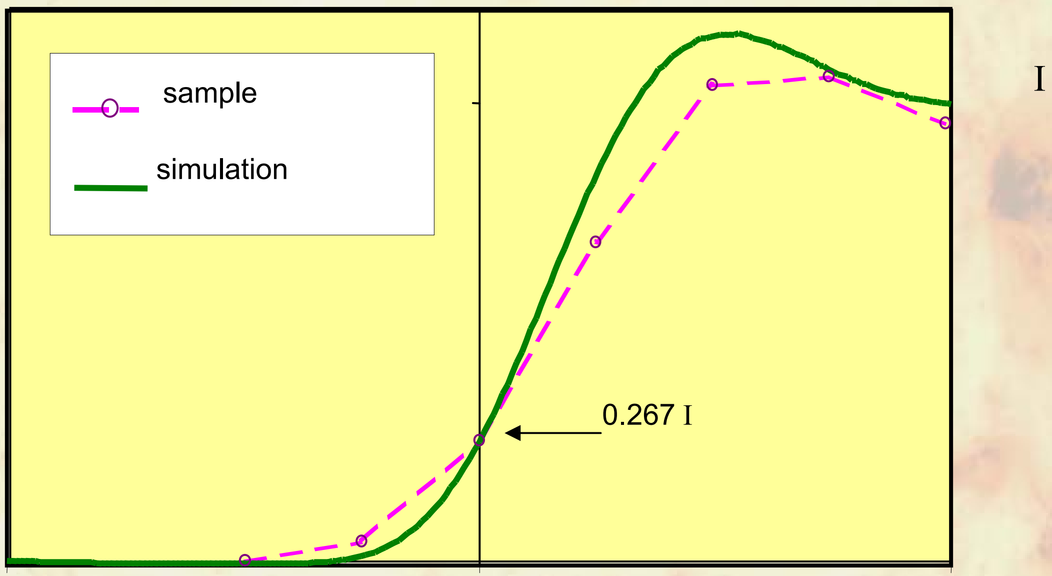


Calculate Δx or Δy to bring edge to center pixel

Current edge location: Stage position + Δ pix

Scan and move until edge is at center pixel

Determining location of edge from light intensity



Due to partial coherence of light in image, edge assignment according to intensity is determined from edge waveform simulations

Subpixel length correction

$x(y)_{\text{coordinate}} = X(Y)_{\text{stage position}} \pm$ subpixel length correction

Minimum stage motion : 25 nm

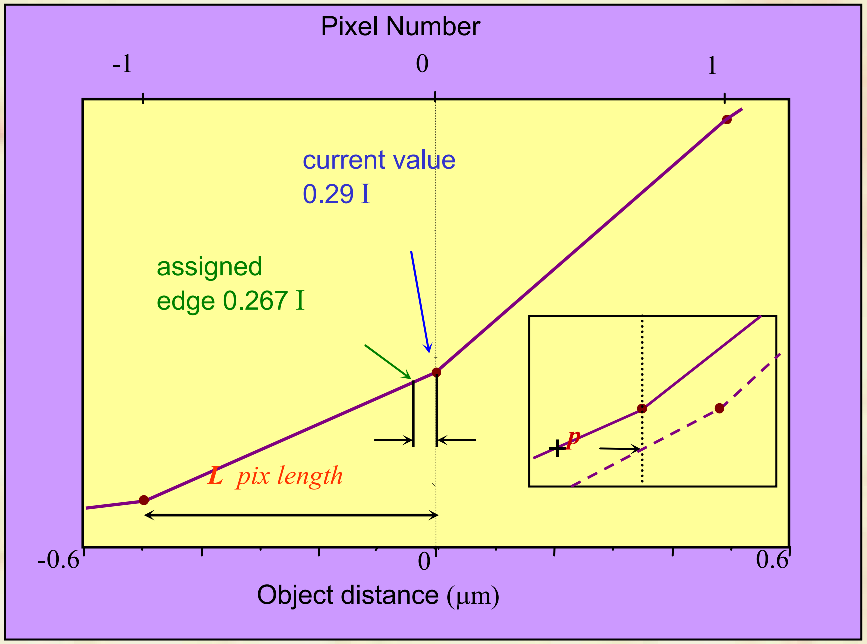


Illustration of subpixel length correction. After final stage move to bring the edge point to the center, the edge may not be at the center pixel. ***p*** is the fraction of pixel length, converted to object distance, that the assigned edge is offset from the center.

Circle fitting

Equation of a circle

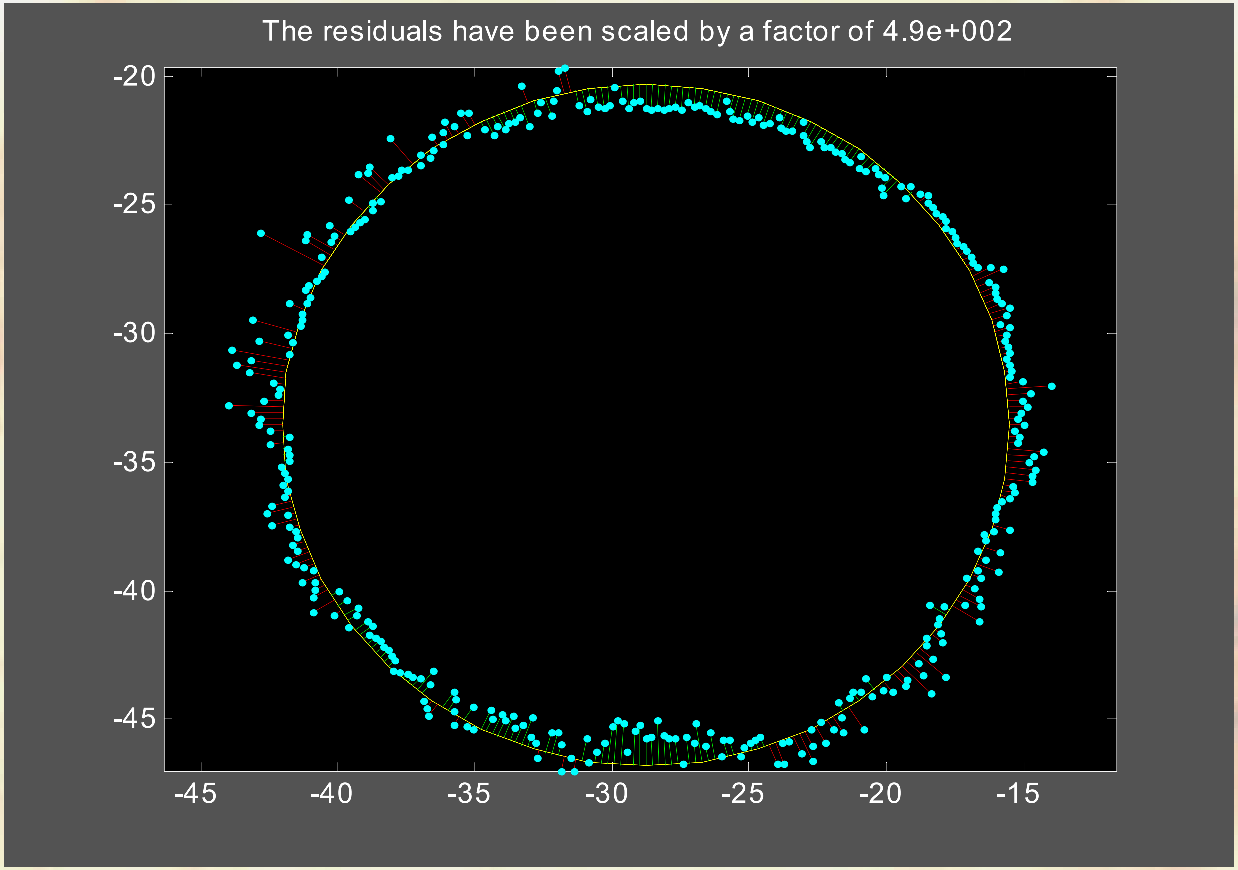
$$R^2 = (x - x_0)^2 + (y - y_0)^2$$

where x_0, y_0 is the center of the circle

Least-squares algorithm is used to find the best circle

$$\sum_{i=1}^{N} (R_i^2 - R^2) = \min$$

Results from Circle-fitting



The residuals are scaled by a factor of ~500 for illustration purposes

Bootstrap Method

Determining standard uncertainty of the radius

After a single circle fitting, residuals of the radius from each x,y point is generated

The residuals are randomized and applied to the best-fit circle to generate a new “noisy” circle

Find best-fit circle again, generating new radius and residuals

Repeat 5000 times

Find standard deviation of the fitted radii (n=5000)