Silicate bonding for stable optical systems for space

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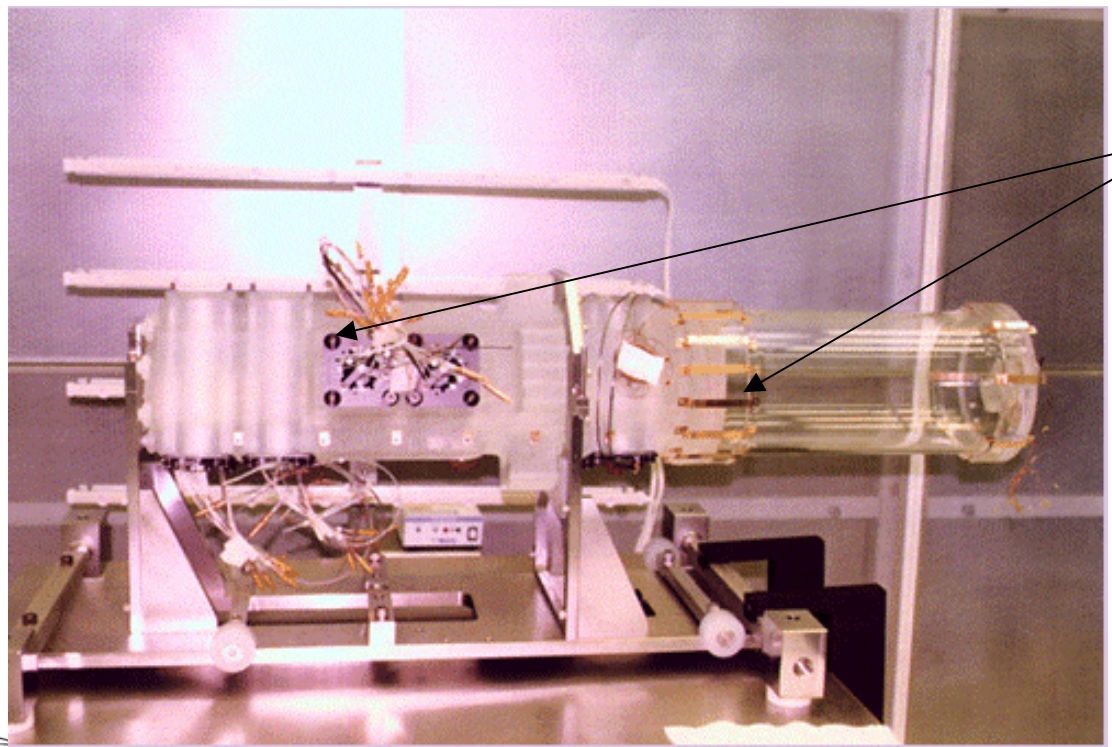
Introduction

- Optical sensing techniques commonly used for precision metrology
- Frequently require components to be jointed with positional precision in a stable manner
- Example of obvious relevance for this meeting is the bonding of components to an optical bench for LISA Pathfinder/LISA
- Driving application for the bonding technique discussed in this talk was the Gravity Probe B experiment

Silicate (Hydroxide-catalysis) bonding

- Technique for bonding oxide materials developed at Stanford University by Dr. Jason (Dz-Hung) Gwo
- Motivation:
  - bond the fused silica components of star-tracking telescopes for Gravity Probe B space experiment



Quartz block containing gyroscopes is attached to a very precise telescope in order to reference the gyro spin directions to a guide star.

Technique was required for bonding silica to silica

Must be:

mechanically strong (withstand launch stresses/thermal cycling)

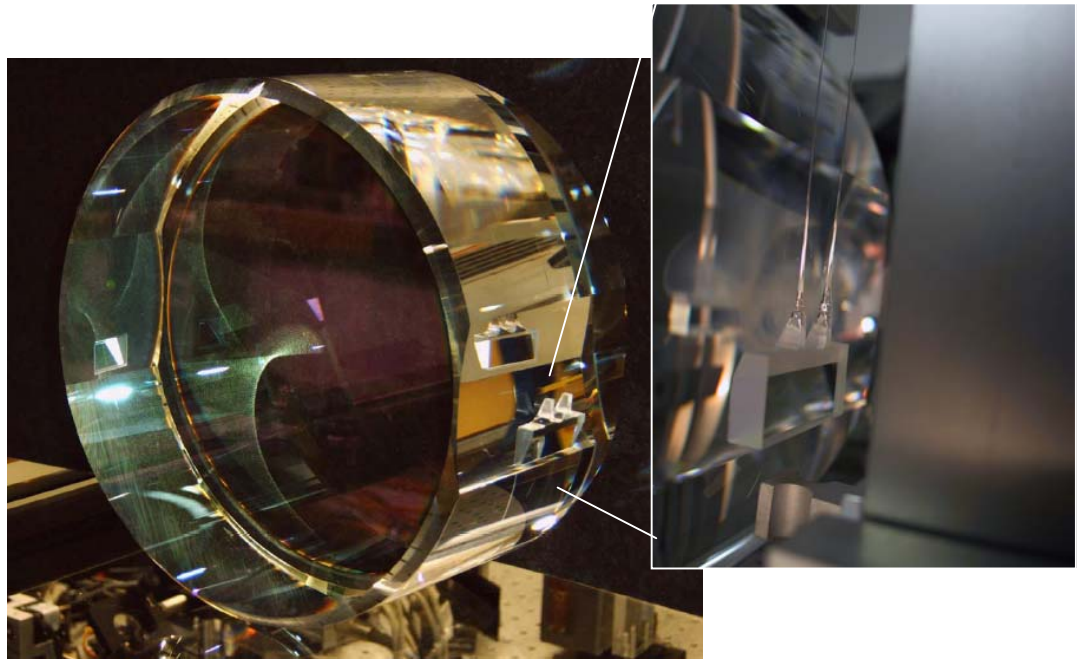
mechanically stable

Silicate bonding

- A small amount of dilute aqueous alkali-metal hydroxides eg: potassium, sodium, lithium etc hydroxide, or sodium silicate (NaOH + colloidal silica filler) solution is introduced between two surfaces of a suitable oxide material
- Surfaces to be bonded should be polished to a flatness of ~λ/10 and thoroughly cleaned
- Silicate or 'hydroxy-catalysis' bonding takes place between the surfaces
- Suitable oxide material? - typically an oxide which will allow an anion involving it to be formed eg silica (silicate), sapphire (aluminate) etc

Developments at Glasgow

- Technology transferred to Glasgow for use in construction of monolithic optics for use in ground based GW detectors (GEO600)



- Application to other materials – sapphire and silicon (Adv. LIGO, future detectors)

- Found application in the construction of the stable optical platforms needed for LISA pathfinder/LISA (see talks by G. Heinzel, D. Robertson, poster from Astrium D, C. Braxmaier)

- Extension to silicon carbide

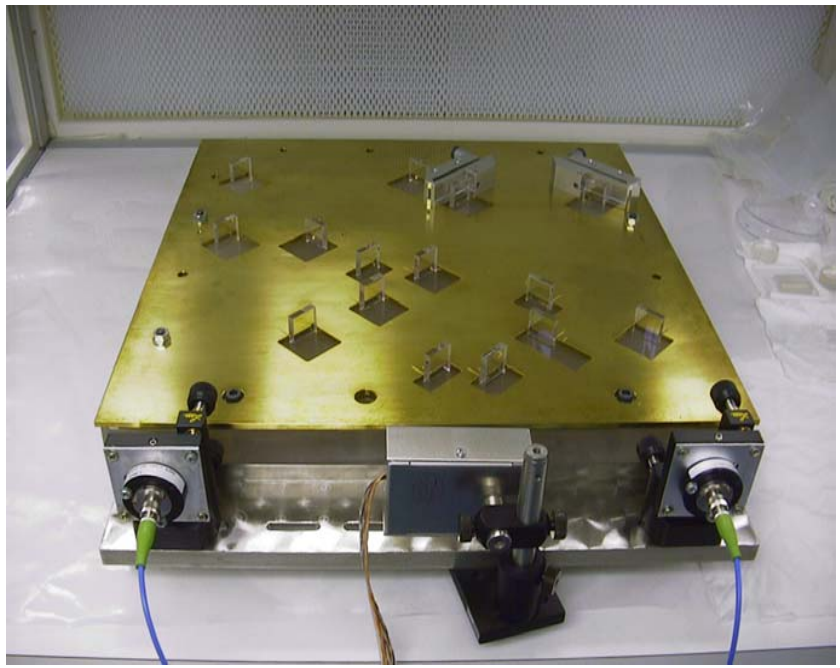
Properties of silicate bonds

- When used for bonding silica:
  - Strength – Bond strength comparable with bulk silica. See talk by G. Heinzel on LPF.
  - Stability – Glasgow interferometer sees no change (<1%) in visibility over long timescales (~ year)- see talk by Dave Robertson on Glasgow test bench.

    Precise quantification using lasers locked to cavities planned by Univ. Florida in collaboration with Univ. Glasgow.
  - Resistance to large temperature fluctuations (from cryogenic to 800C)
  - Forms a very thin bond – < approx 80-100nm
  - Relatively low effect on system mechanical dissipation – hence use in GEO, see talk by H. Grote
- Properties appear to carry forward to other materials e.g. sapphire, silicon, silicon carbide etc

Further Developments at Glasgow

- Disadvantage – for the construction of *precisely aligned* optical systems there are a number of difficulties:



1) If alignment is carried out with bonding solution in place, settling time must be long enough to allow necessary adjustments.

   However bonds typically take only ~30 sec to set - after this time pieces can no longer be adjusted.

2) If initial alignment is carried out with pieces dry, optical contacting may occur, resulting in damage

- Thus the precision positioning of highly polished, very clean pieces can be problematic

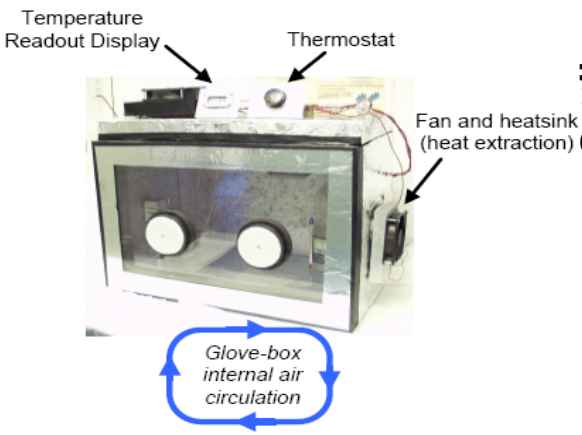
Method 1) can be practical if bond setting time can be increased by:

- using temperature dependence of reaction
- changing concentration of reactants

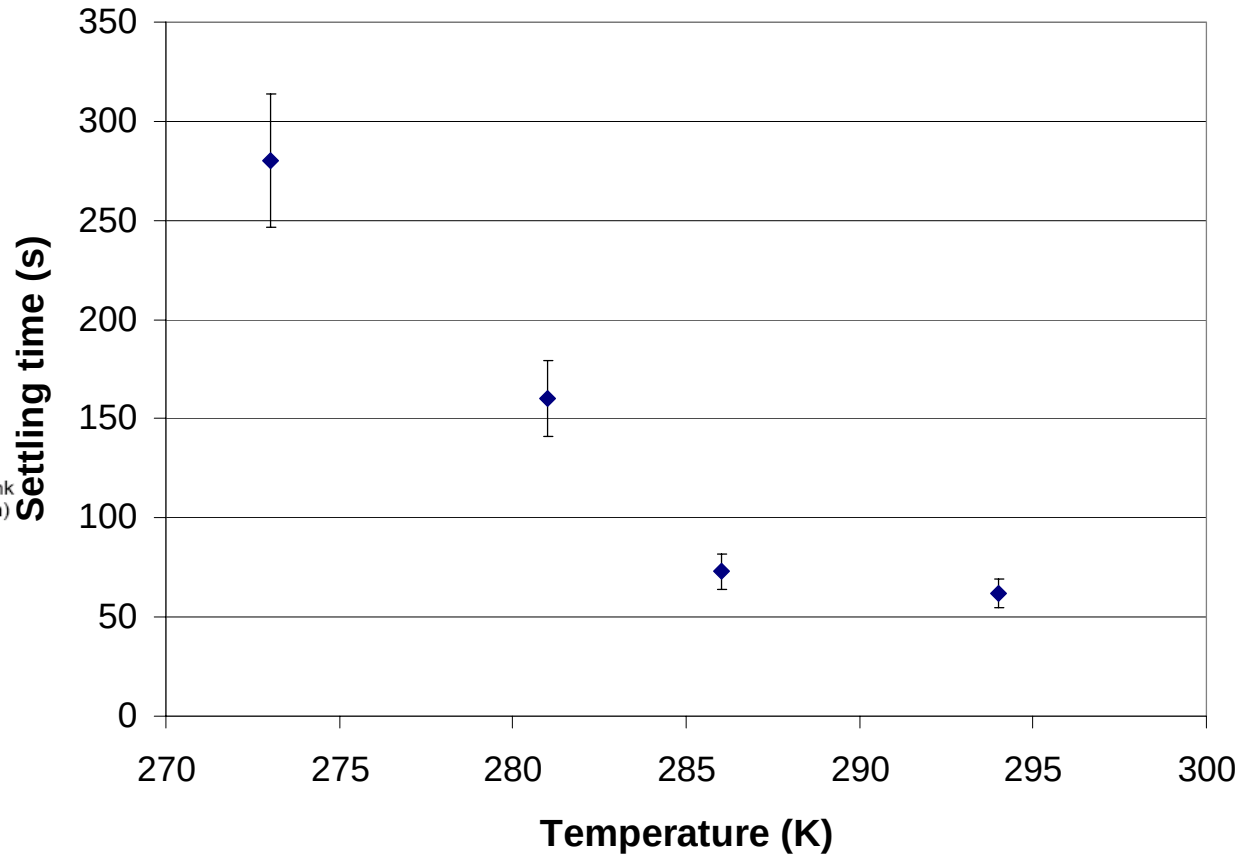
Temperature dependence of reaction

- Bonds between silica pieces were formed using dilute NaOH solution

- Bonding carried out in a controlled temperature environment



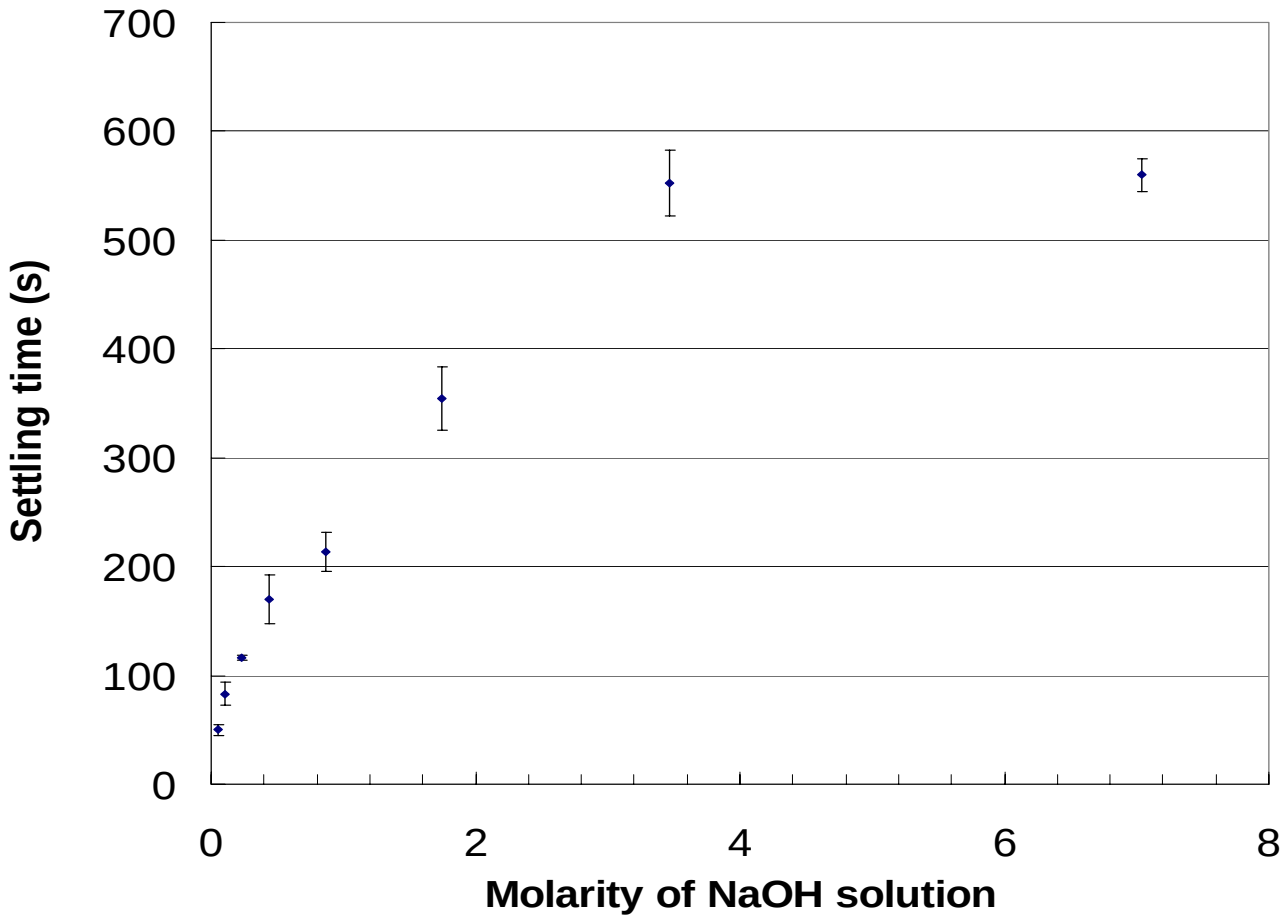
Graph shows measured 'settling' time of bonds as a function of temperature



- Insulated 'glove box' with Peltier units used to cool system

Setting time of bond as a function of concentration of bonding solution

- Concentration of NaOH present in bonding solution successively increased
- Settling time of bond observed also to **increase**
- At first seems counterintuitive
- Consider chemical reaction steps



Chemistry of the Bonding Process 1

- Etching Phase
  - Basically the OH^- ions etch the silica

    $SiO_2 + OH^- + 2H_2O \rightarrow Si(OH)_5^-$
  - i.e. silicate ions formed in the fluid between the surfaces and as this happens the OH^- concentration decreases or the pH decreases

- Bonding Phase
  - When pH falls below 11 the silicate ion dissociates:

    $Si(OH)_5^- \leftrightarrow Si(OH)_4 + OH^-$ (R. Iler, 'Chemistry of silica', 1979)
  - $Si(OH)_4$ then 'polymerises' in the gap between surfaces: rigid -Si-O-Si – chains formed and water is released
  - The bond is then setting

Chemistry of the Bonding Process 2

- Note:
  - The higher the initial pH the longer it takes to fall to 11 and so the longer the settling time till ‘polymerisation’ takes place
  - Original OH^- is recreated after dissociation of silicate ion: OH^- acts as a catalyst
  - Free OH^- finally attaches to silica substrates and is part of the final bond
  - Where does the water go? Some evaporates, some is absorbed by silica

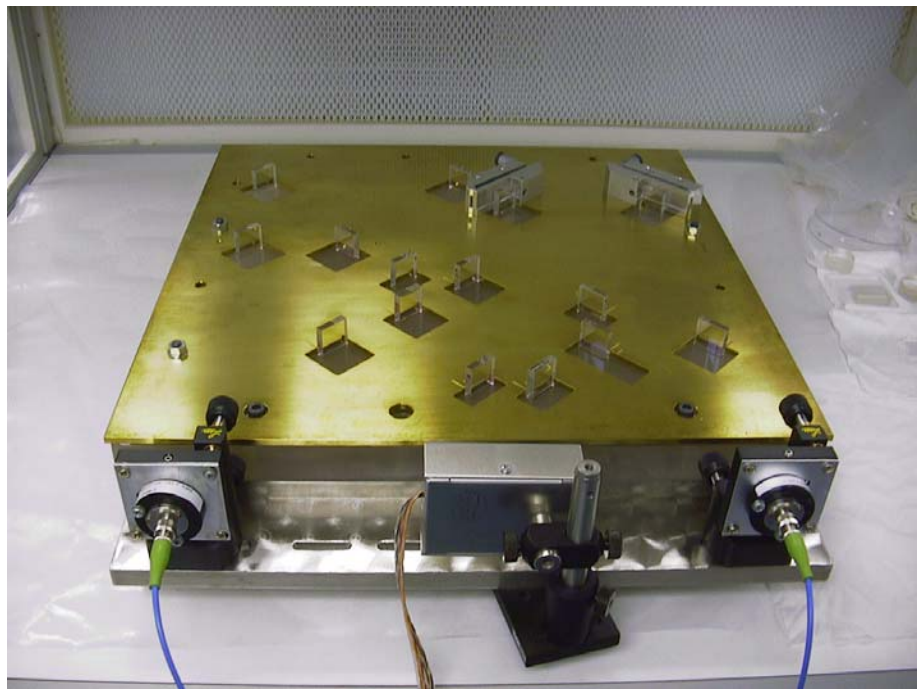
Extending time available for component positioning

Alternative approach:

- Method 2) develop technique to allow pre-positioning of components without presence of bonding solution

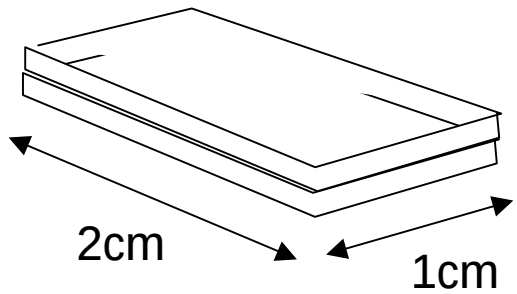
  - Recall surfaces to be bonded are both globally flat (~λ/10) and typically locally 'smooth' (~Angstrom micro-roughness) - such surfaces if placed together dry are likely to optically contact.

  - Problem can be reduced by using an alkane of moderately low vapour pressure and low viscosity (octane or decane) to 'float' the components.
  - However this is not ideal – can lead to errors in component alignment



Possible solution – use of finely ground surfaces

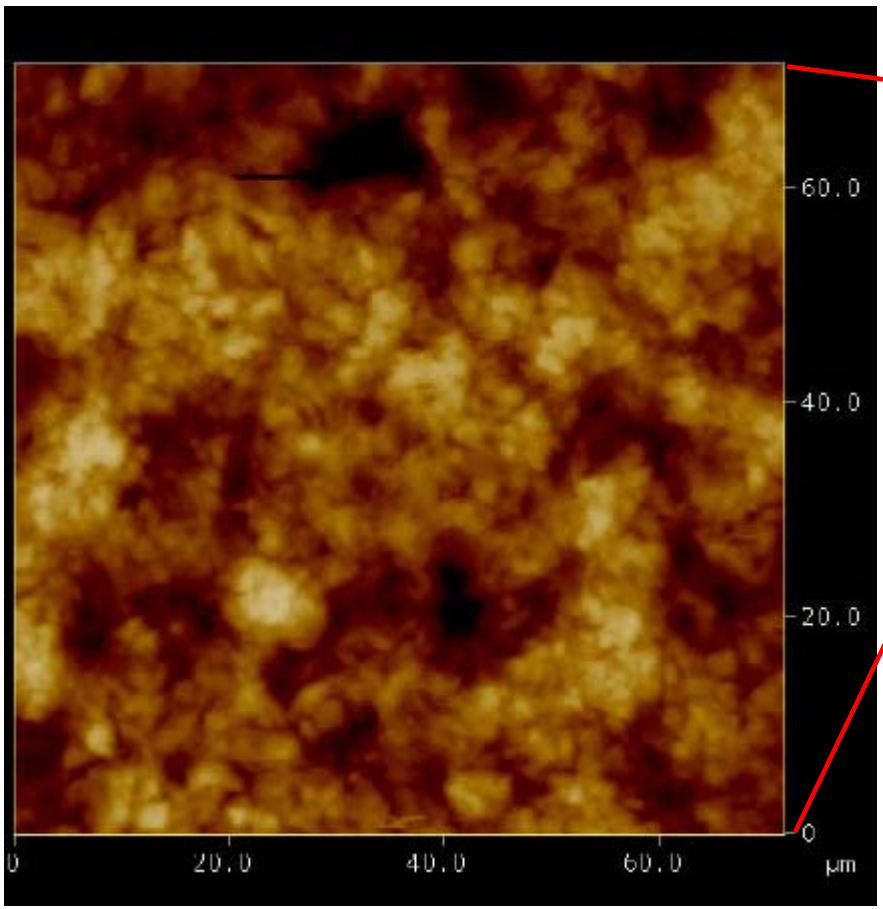
- Still require surfaces to be bonded to have a global flatness of ~$\lambda/10$
- However, apply a fine grind to the surfaces, increasing the micro-roughness of one or both surfaces to be jointed
- Tests carried out on bonding pairs of ground fused silica pieces
- Successfully bonded using sodium silicate solution



- Surface roughness of each face to be bonded was characterised using Atomic Force Microscope

Surface roughness characterisation

- Typical surface roughness ~500nm rms measured over an area of ~70 x 70 microns



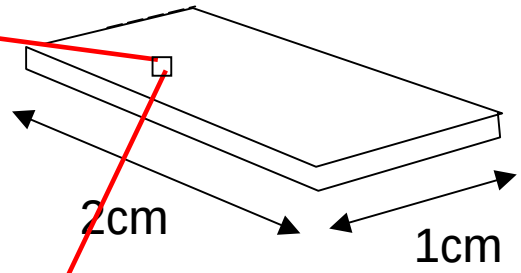


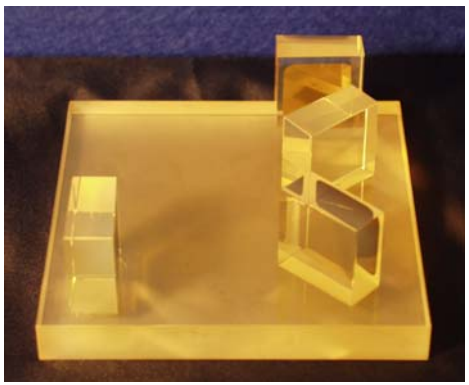
Image Statistics

Img. Z range	3.525 µm
Img. Rms (Rq)	489.55 nm
Img. Ra	387.32 nm
Img. Srf. area	5639.8 µm²

Next steps

- Previously:

  tests on bonded monolithic Zerodur interferometer with bonds between polished surfaces



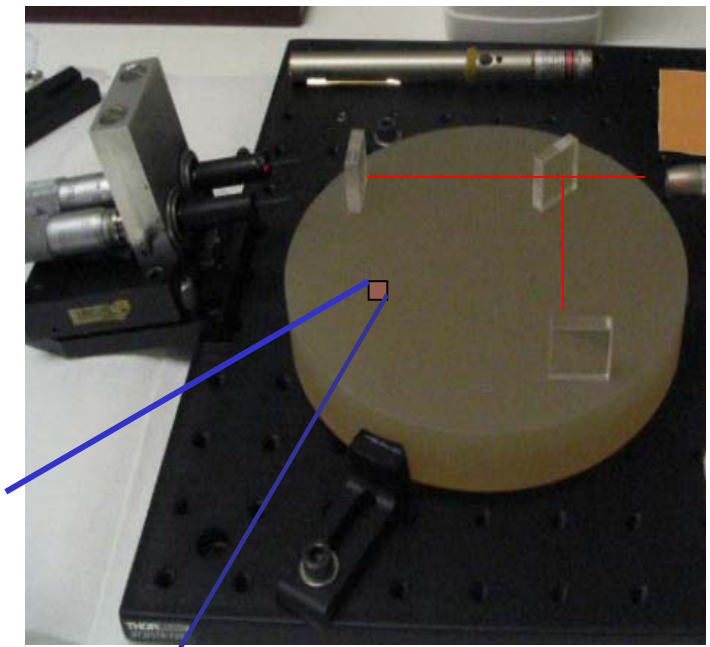
The interferometer passed a shake test/thermal cycling to ESA specification ESA A0/1-3446/99/NL/FM with no measurable change in alignment

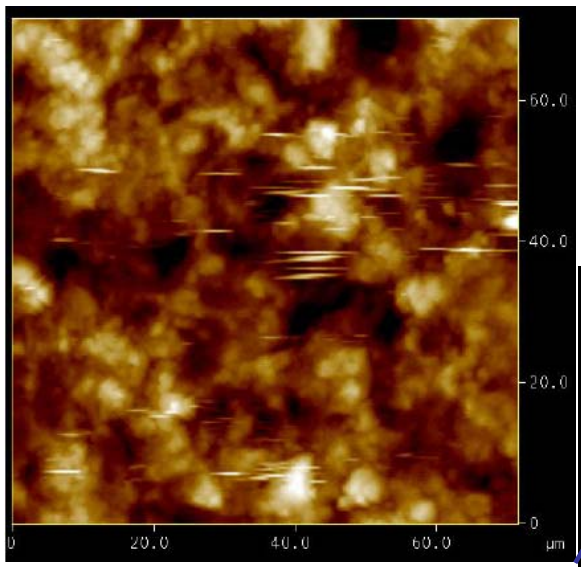
- Plan:

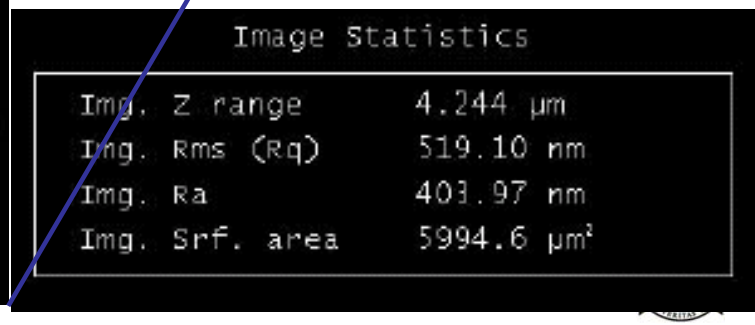
  to test bonds to ground surfaces in a similar fashion -construct a small bonded interferometer

Zerodur baseplate with ground surface

Fused silica optics (coated for 1micron)

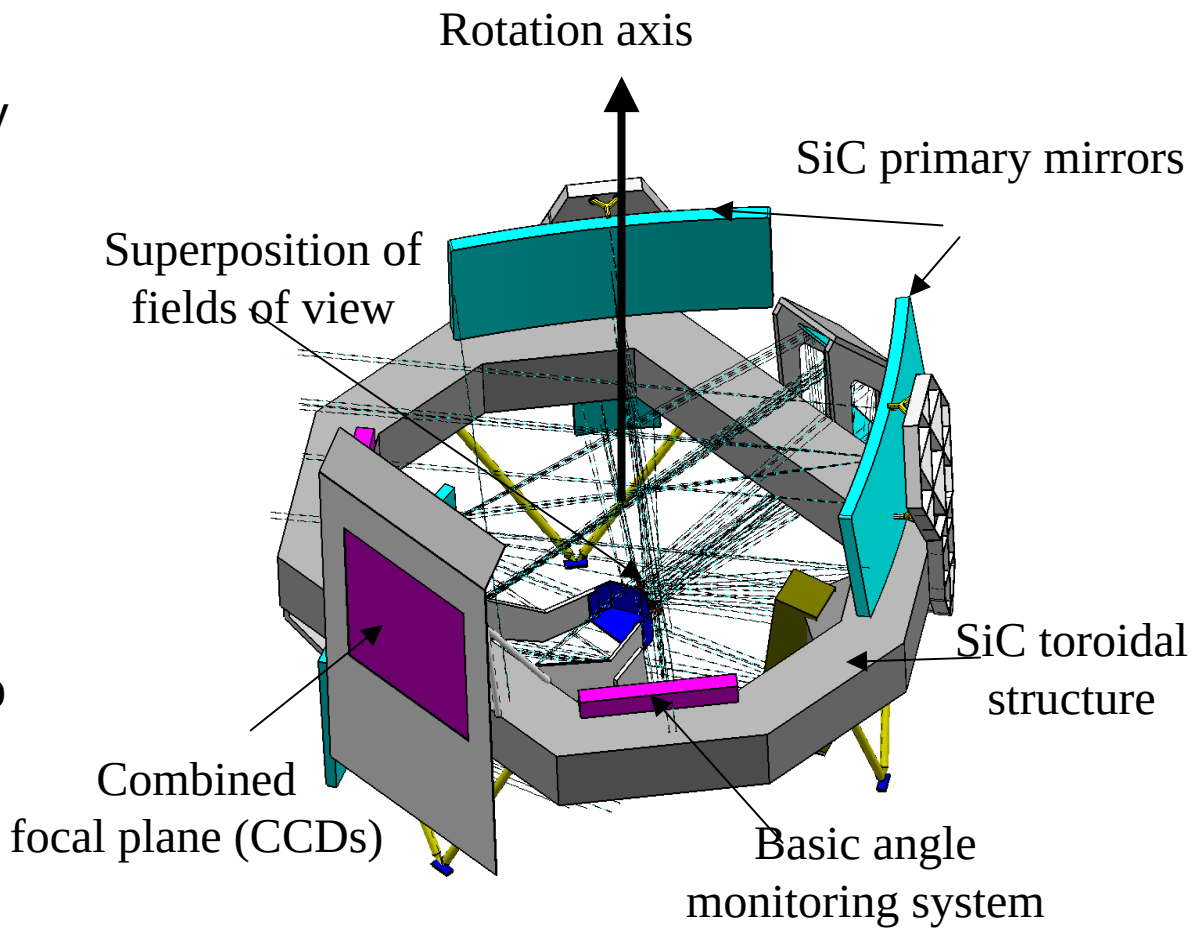






Bonding of silicon carbide

- GAIA - Mission objectives – census of stars in our galaxy
- Contract from Astrium France to develop bonding process to joint silicon carbide
- (Patent application filed by Glasgow)
- University of Florida plan to study stability of silicon carbide structures for possible use in fabricating the primary and secondary mirrors in LISA



Summary

- Demonstrated possibility of extending setting times of silicate bonds by either:
  - lowering temperature of system
  - altering concentration of bonding solution
- Demonstrated possibility of bonding between ground surfaces – allows precise positioning of pieces without danger of optical contacting
- Further work:
  - Strength tests of bonds between ground/ground or ground/polished surfaces
  - (Can fluid be ‘wicked’ into components already in place?)
  - Fabrication of test interferometer – shake and bake tests
  - Possible application to construction of LPF/LISA – may allow benefits of stable bonding technique whilst considerably easing task of positioning pieces