National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Space Flight Considerations for Precision Optical Instruments

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KISS workshop on Optical Freq Combs in Space Nov 2, 2015

Topics

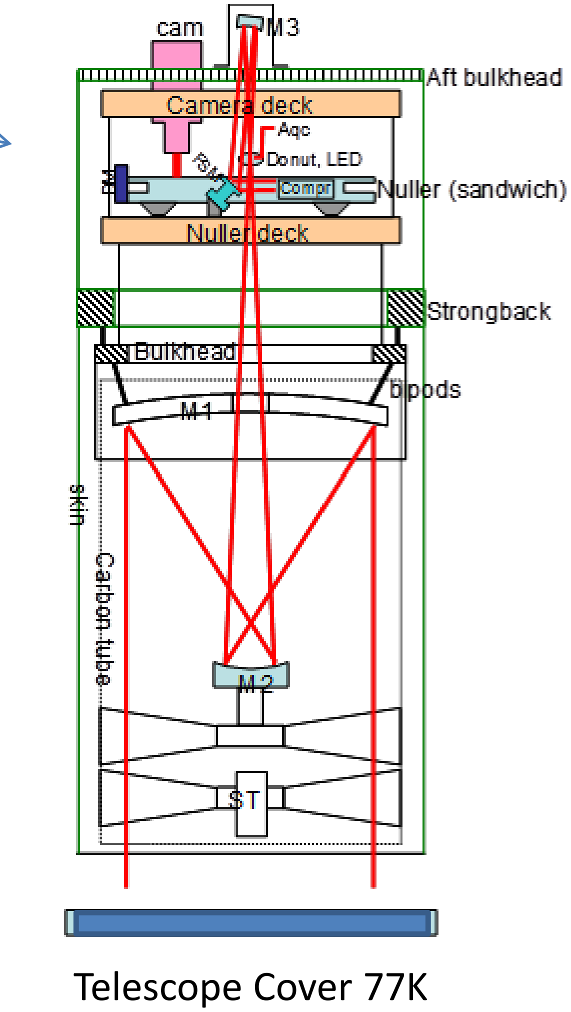
- Optical systems for space (From the Picture project, a sounding rocket with a 50cm telescope and a nulling interferometer coronagraph)
  - Precision alignment
  - Thermal stability
  - Survive Launch (vibration)
- Active components (flight NPRO laser for SIM)
  - Lifetime of semiconductor lasers (pump diodes)
  - Use of redundancy to achieve high reliability and long operating life.

Optical Assemblies in Space

- The assembly was a nulling interferometer to be flown on a sounding rocket.
- Thermally stable
  - No more than 2X worse than an optical bench made entirely of ULE.
  - ULE bench mounted to telescope, should not misalign (warp) when the Telescope structure (alum) expanded/contracted.
- Survive launch (20 Gs random white noise (10~1Khz)) vibration, 9G static load)
  - Maintain alignment through 12G vibration
- No mechanical adjustments after final assembly.

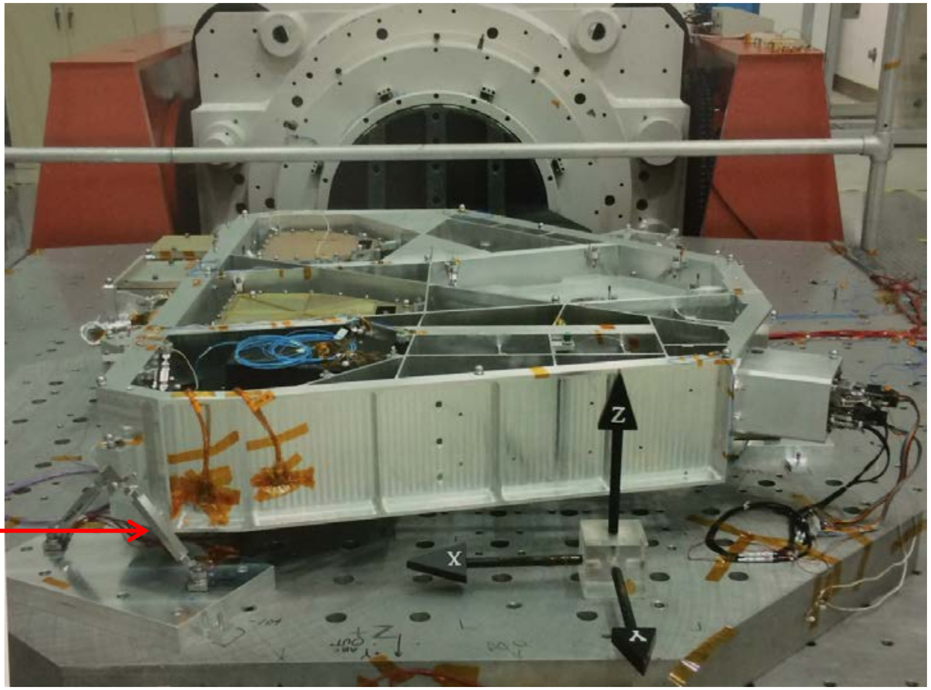
Overview

- Nulling interferometer behind a 60cm telescope.
- PZT tip/tilt mirror between telescope and interferometer.
- Thermal stability within the nulling interferometer to be no worse than 2X ULE.
- Decided to adopt a glass sandwich design.



SIM Interferometer (Combiner)

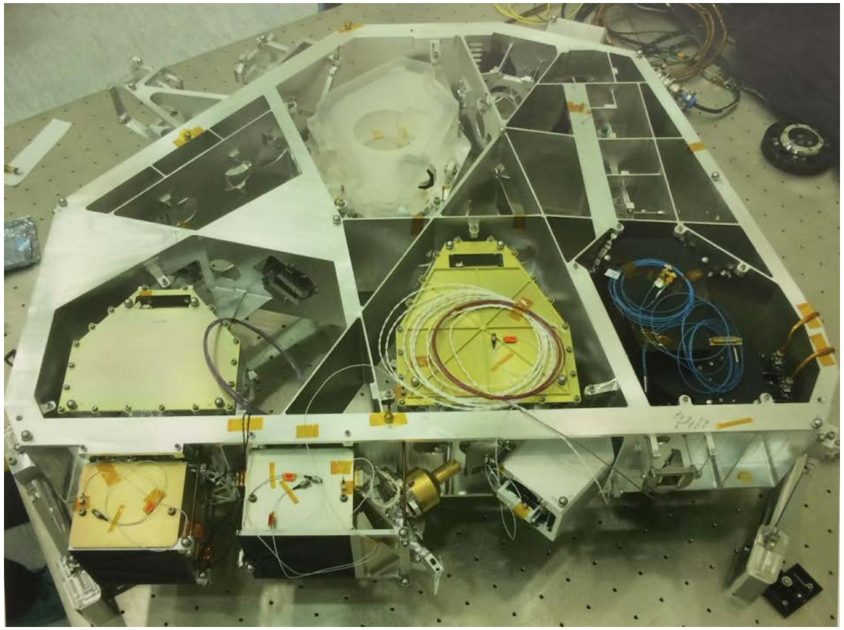
- An example of a brass board interferometer beam combiner that was built and went through flight qualification tests.
- Shown attached to a shake table for vib testing (12G white noise random vib <1khz)
- Common approach to mounting optics and optical assemblies. 3 Bipods constrain 6DOF without warping the optic/structure under either thermal changes or launch loads.



The structure that supports the optics and detectors was carved out of a solid piece of alum.

Undergoing Vib Testing

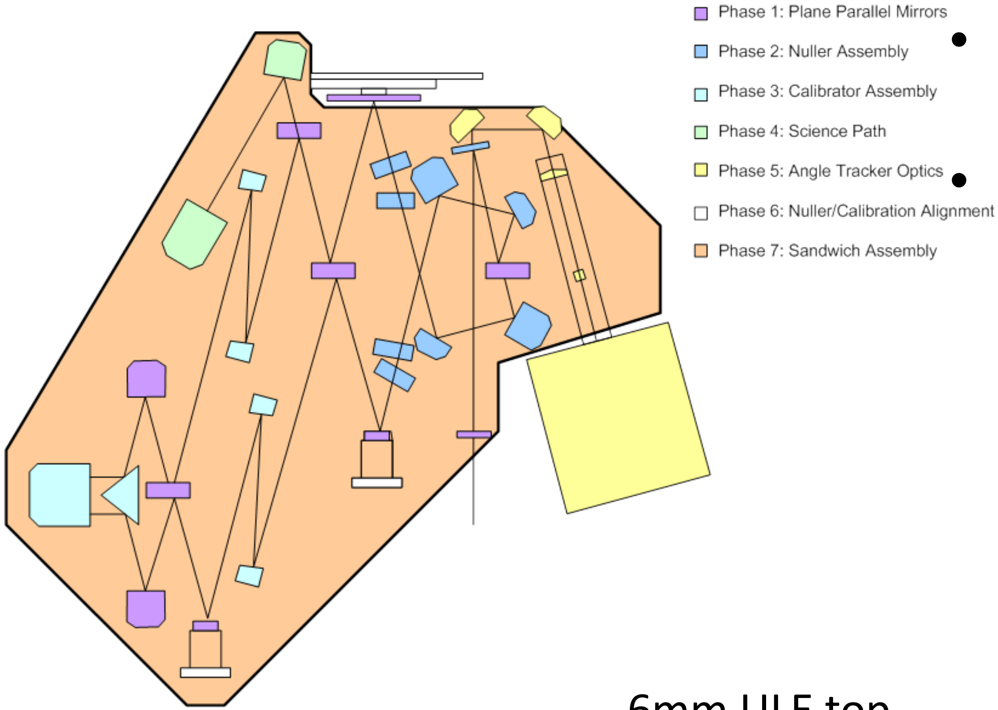
- Because the structural assembly was alum, (not very thermally stable) the interferometer had PZT tip/tilt mirrors and tip/tilt sensors that would correct alignment and OPD shift as the temperature/gradients changed.



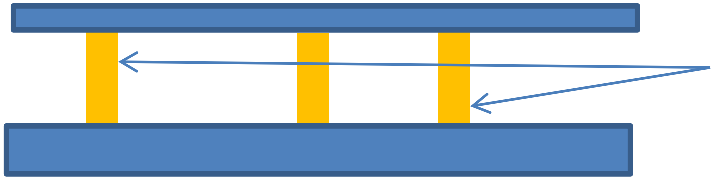
In the end a rather complex (and expensive)

Our sounding rocket experiment had a much smaller budget and tighter thermal stability requirements, and for that we chose a "glass sandwich" approach.

Basic Concept Glass Sandwich



- The optical assembly was moderately complicated.
- The Glass sandwich idea is to use attach all the optics to the ULE baseplate with thin layer of UV curing epoxy.
  - ~10um thick high CTE epoxy would expand but there wasn't much of it.



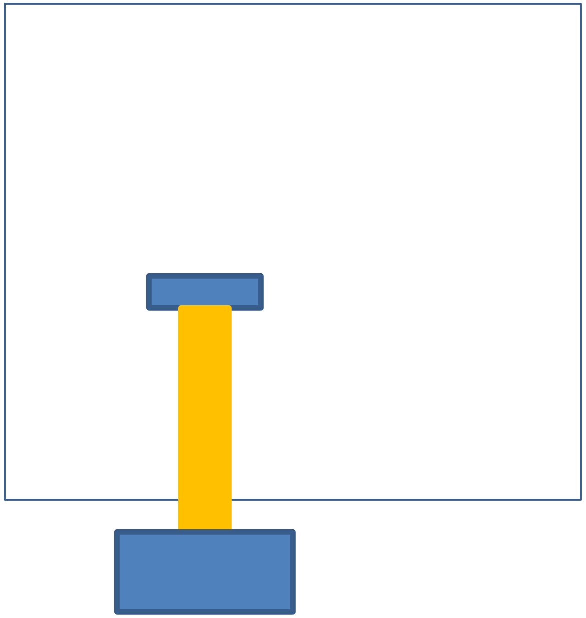
6mm ULE top

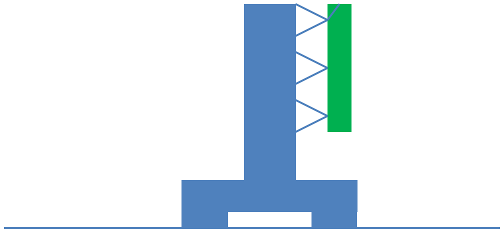
Fused silica reflective & trans optics

12mm ULE baseplate
Spacing and alignment determined
By ULE baseplate.

Alignment of Optics

- Optical assemblies in space are fixed, no micrometers or screws. (one arm of the interferometer did have a pzt)
- In our case, we used attached a pzt piston/tip/tilt stage via a long post with a “weak” adhesive to the optic being aligned. The optic position was monitored with an interferometer and when it was in the “right” place, we turned on the UV lamp to cure the UV epxoy.

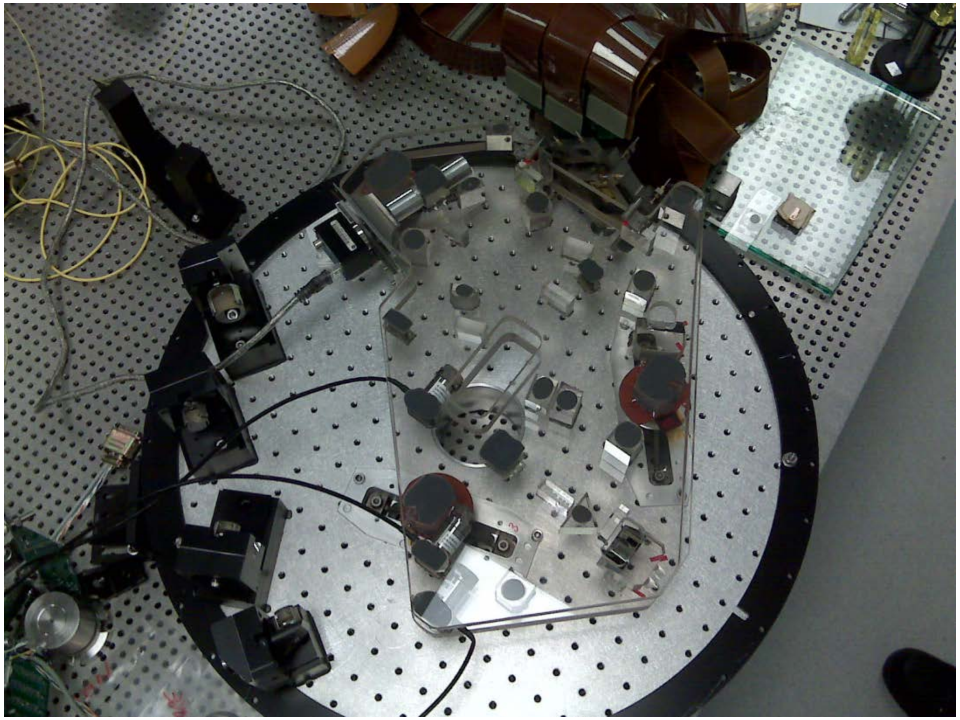




Normal flight Optic.

Nulling Interferometer Glass Sandwich

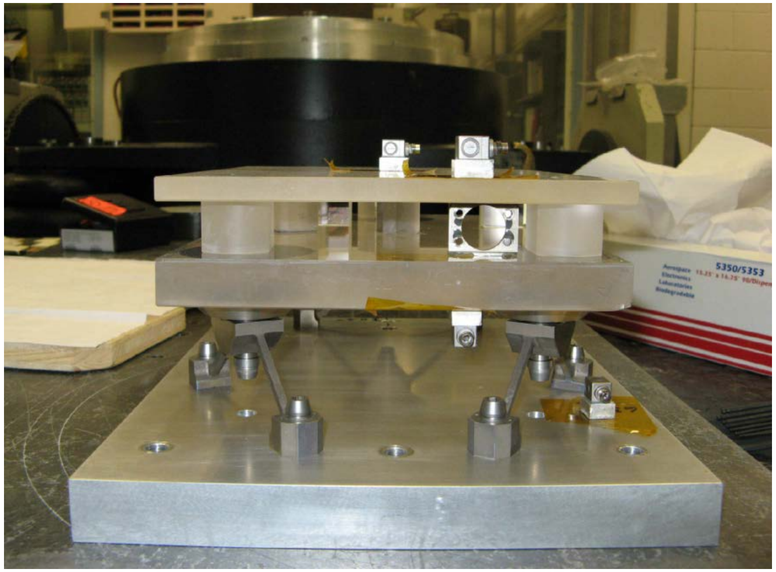
- So we worked out a way to assemble the optics and align it.
- Next we had to show it could survive launch.
- 12G white noise < 1khz and 9G static load.
- Before testing the final glass sandwich we conducted a series of tests with a “prototype” that we assembled without careful alignment of the optics.



While ULE was very thermally stable, glass in general is not recommended for use as structural material because the tensile strength is very low. (and small cracks will grow under high G vibration)

Prototype Glass Sandwich
(Launch loads)

- We built a prototype glass sandwich to test our ideas on how to make a glass sandwith survive launch loads.
- A sounding rocket payload is the opposite of a NASA flagship mission. While detailed FEM simulations can be very accurate, predicting when a where a failure might occur, they are also moderately expensive.
- The sounding rocket program provides "free" shake tests for experimenters.

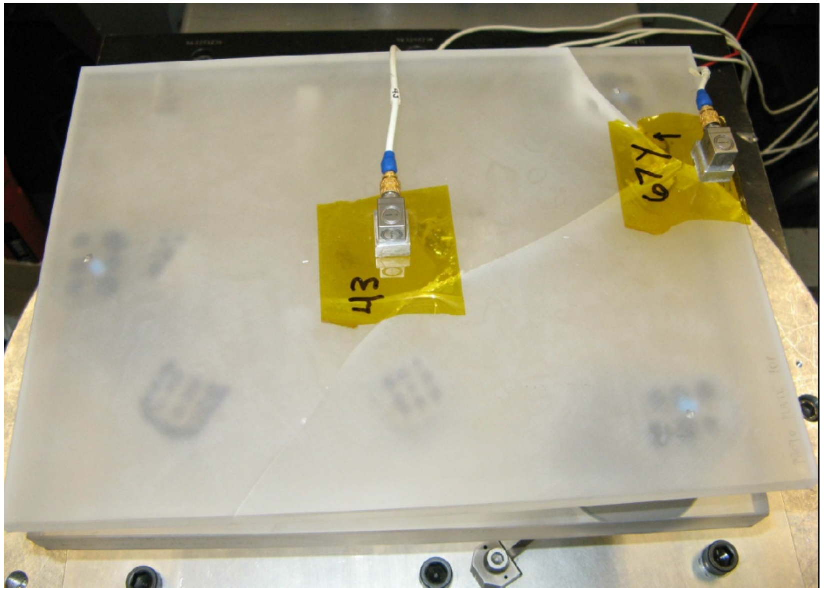


During the shake test(s) two iterations of shake tests were conducted, we identified three major design flaws that would result in fracture of the glass sandwich.

This was trial and error engineering.

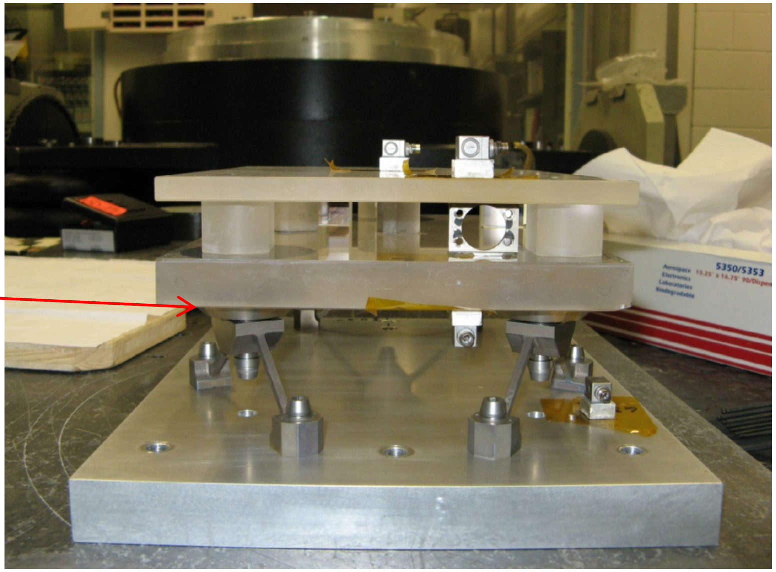
Problems Identified During Shake Tests

- Although the vibrations were 12Gs any high Q mechanical resonances in the structure can result in much high G forces.
  - Accelerometers recorded acceleration of ~250Gs at the principle resonance (~140hz) (bipod).
- Epoxy strength. There are a number of “flight approved” epoxies, high strength over a wide temperature range.
  - None of them were UV cured epoxies.



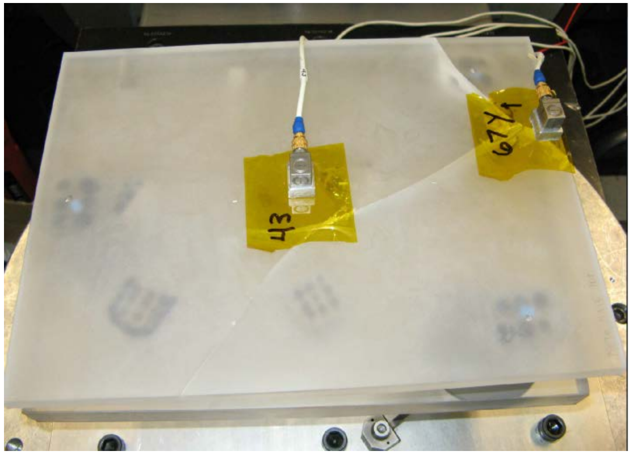
Solution/work around

- The Q of the resonance was reduced by using a thick layer of flight approved RTV to bond the bipod to the bottom glass plate.
  - This reduced the maximum G forces to ~70Gs.
- The optics in the glass sandwich served both as optical elements and structural elements. When all the structural elements were attached using UV curing epoxy some of the UV epoxy bonds broke. But we also had purely structural elements in the sandwich. When these were bonded using the stronger non-UV curing epoxy all the bonds held.

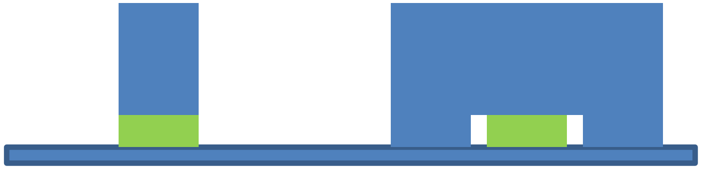


Problem 3 What Caused the Glass Fracture?

- Epoxy shrinks when it cures
  - The approach on the right will "pull" the two pieces together as the epoxy cures.
  - In theory it's more thermally stable than the approach on the left.
- The problem is that under 250Gs, the epoxy will stretch so there is a few um gap between the two pieces. We then have two hard materials hitting each other 140 times a second. The glass fractured after 35 sec of vibration.



25mm height glass

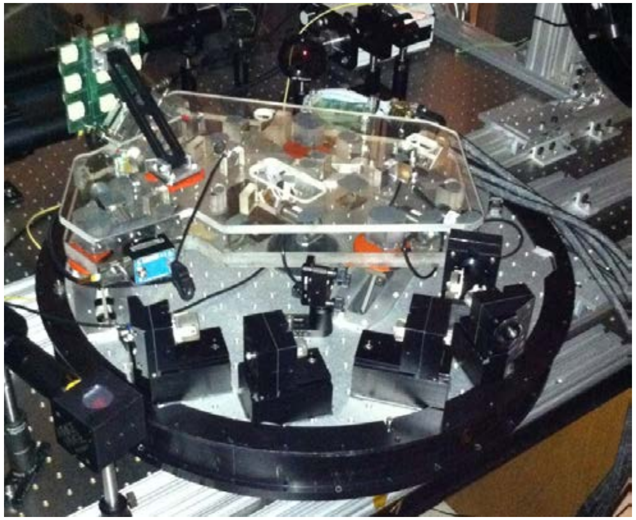


10um adhesive layer

1mm adhesive layer

The most Challenging Vib/Shock Test

- We fixed all the problems we found during the vibration tests.
- Spent a lot of time aligning the optical elements in the interferometer and shipped the instrument to B.U. (for integration with the telescope)
- When it arrived there was a very small crack in the glass base plate.
- FedEx was our most challenging vib/shock test.



Once in Space the Mech Environ is Very Quiet

- All the mechanical noise you bring with you.
- At high freq, (10’s hz) the major noise sources are reaction wheels.
- At low freq, items like deployed solar panels, high gain antenna for communication etc. (if the s/c undergoes a thermal shock (eg in LEO going in/out of Earth’s shadow) the thermal shock can produce mechanical noise.
- For SIM (long baseline interferometer) we needed a structure that had < 10nm (λ/60) (rms 100hz>f>1hz) Coincidentally, we tested the seismic environment on Mauna Kea after Keck I was built but before Keck II was built. (a few 10’s nm)
  - SIM needed 2 levels of passive isolation for the reaction wheels.
  - If a much quieter mechanical environment is needed, several options are available, but it would not be a “standard” spacecraft.
    - One option is a S/C with no moving parts
    - Another is a spacecraft there is no mechanical connection between the S/C bus (that has moving parts) and the optical payload.
    - Most extreme would be drag free spacecraft.

Lifetime Requirements for Class A/B Missions

- SIM was a class A/B mission with a 5 year primary mission with consumables to last 10yrs.
- SIM used a NPRO (1.32um) laser for metrology.
- NASA/JPL life time requirements for the laser was
  - 3 sigma for 5 years + ground testing/launch etc. AND a spare laser
  - 99.7% probability the laser will last for 5+2 years. And a spare laser
- Starting looking into laser reliability ~2004~2007. A few years earlier, JPL flew a commercial NPRO laser in a FTS (earth science instrument) and the unit failed after ~ 2years in space.
- Laser diode pump lifetime was identified an issue that needed to be addressed is a systematic way.

COTS Laser Diodes

- The 1.32um NPRO (Yag) laser used a 808nm pump laser. About ~1W of pump power was needed for our application (for 30~40 metrology beams on SIM) (expected 200mW of 1.32um light for 1W 808nm pump.)
- Laser diode lifetimes are quite long (MTTF ~ 100,000 hrs) But this means the laser has a ~50% probability of failure in ~11 years. The probability of failure after 5 yrs is >> 0.3%.
  - Using standard models for the failure of high power semiconductors, a laser diode that has 0.3% chance of failing in 5 years has only a 2% chance of failing in 10 yrs.
  - We need a laser diode pump ‘system’ that is much more reliable than the ‘average’ single laser diode at that time. (a lot of progress has been made since then)

Failure Rate of Semiconductor Devices

- The most relevant region for lifetime estimates for laser diodes is the “random failure” region.
- The MTTF (mean time to failure) is when the integral of the failure rate is 50%. Many laser diodes have a MTTF of ~100,000 hrs
- For semi-conductor lasers e_a the activation energy ~0.7 ev
- The Arrhenius model is used to interpret the data from accelerated lifetime tests where the laser diodes are operated at temperatures (and current) above their normal operating point.

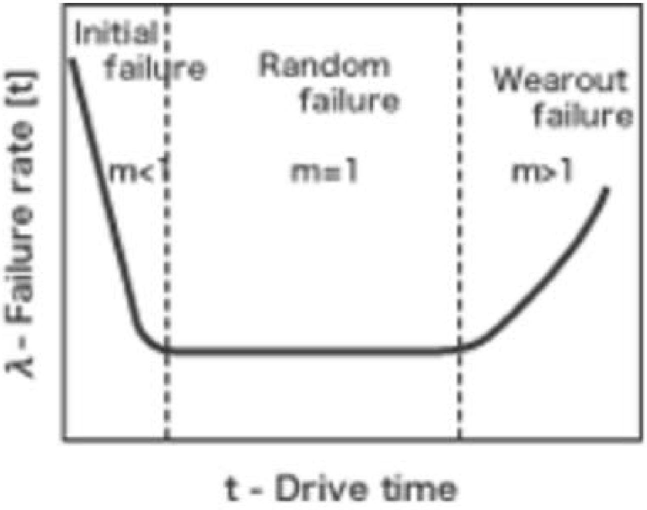


Fig. 2 Failure Rate vs. Time for Parts

$$t_f = A\,exp\left(\frac{e_a}{kT}\right)$$ Arrhenius model

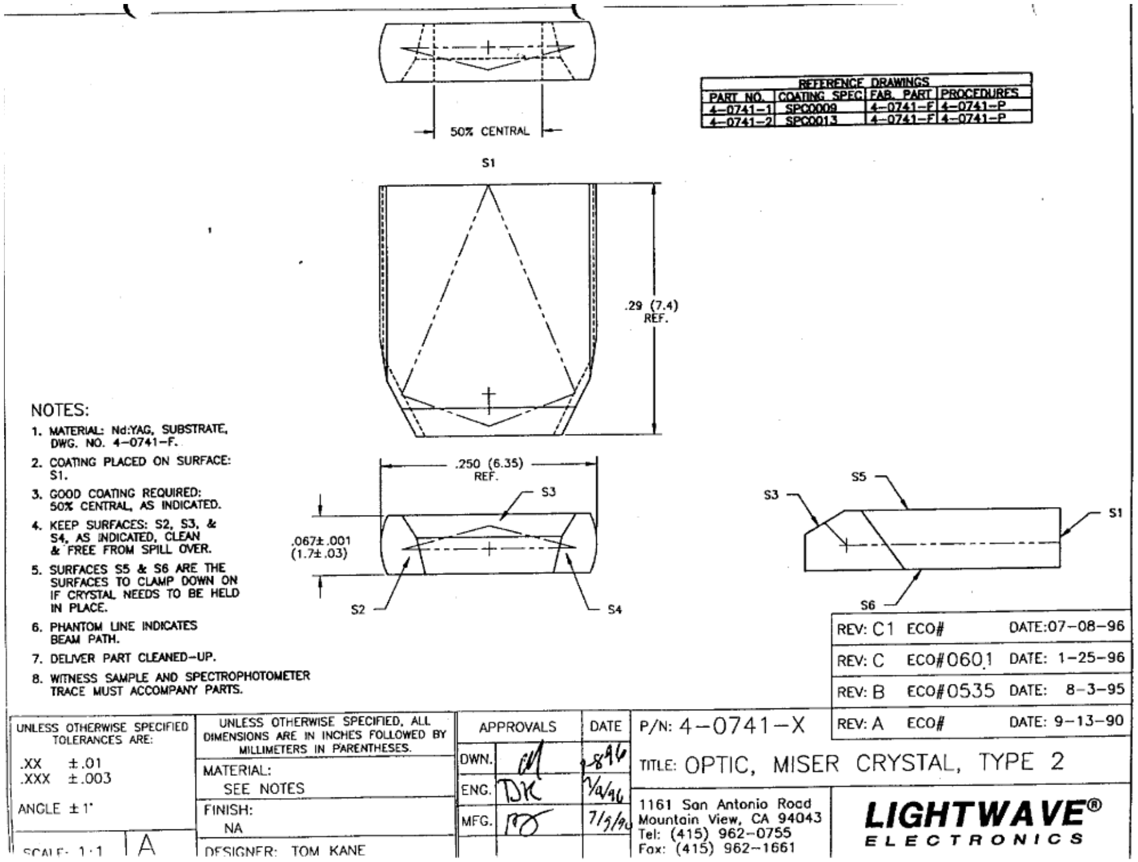
Where,

t_f = Time to failure [hours]
A = Scaling factor
e_a = Activation energy [eV]
k = Boltzmann’s constant [8.617×10^{-5} eV/K]
T = Temperature [Kelvin]

Steps Towards a Laser with 3σ 5year life

- To obtain a 99.7% probability of survival after 5 years means the MTTF ~ 83 years. The question was how to use multiple laser diodes to provide a ~90 year MTTF pump system.
  - Run multiple diodes at the same time (at low power) or substitute a new diode as the prior one failed.
- The Arrehenius model provides a strategy for increasing the lifetime of the pump laser. Operate the laser diode at a lower current/temperature than the nominal rating of the laser where the MTTF is ~100,000 hrs.
  - The product of laser power * time increased as the current to the laser was reduced.
- At the time we were looking at a flight laser for SIM, we couldn’t get the needed pump power from a single laser diode (operating far below nominal power). Multiple diodes were needed.
  - Next is using multiple pump lasers to pump a NPRO laser.

NPRO Crystal



REFERENCE DRAWINGS			
PART NO.	COATING SPEC	FAB. PART	PROCEDURES
4–0741–1	SPC0009	4–0741–F	4–0741–P
4–0741–2	SPC0013	4–0741–F	4–0741–P

NOTES:

1. MATERIAL: Nd:YAG, SUBSTRATE, DWG. NO. 4–0741–F.
2. COATING PLACED ON SURFACE: S1.
3. GOOD COATING REQUIRED: 50% CENTRAL, AS INDICATED.
4. KEEP SURFACES: S2, S3, & S4, AS INDICATED, CLEAN & FREE FROM SPILL OVER.
5. SURFACES S5 & S6 ARE THE SURFACES TO CLAMP DOWN ON IF CRYSTAL NEEDS TO BE HELD IN PLACE.
6. PHANTOM LINE INDICATES BEAM PATH.
7. DELIVER PART CLEANED–UP.
8. WITNESS SAMPLE AND SPECTROPHOTOMETER TRACE MUST ACCOMPANY PARTS.

REV: C1	ECO#	DATE:07–08–96
REV: C	ECO#0601	DATE: 1–25–96
REV: B	ECO#0535	DATE: 8–3–95
REV: A	ECO#	DATE: 9–13–90

UNLESS OTHERWISE SPECIFIED TOLERANCES ARE:
.XX ±.01
.XXX ±.003
ANGLE ± 1°

SCALE: 1:1
A

UNLESS OTHERWISE SPECIFIED, ALL DIMENSIONS ARE IN INCHES FOLLOWED BY MILLIMETERS IN PARENTHESES.

MATERIAL: SEE NOTES

FINISH: NA

DESIGNER: TOM KANE

APPROVALS		DATE
DWN.		7-8-96
ENG.	DK	7/9/96
MFG.		7/5/96

P/N: 4–0741–X

TITLE: OPTIC, MISER CRYSTAL, TYPE 2

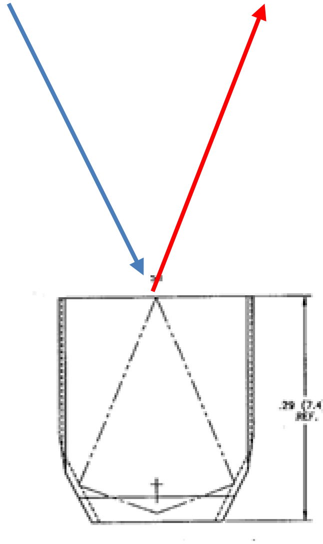
1161 San Antonio Road
Mountain View, CA 94043
Tel: (415) 962–0755
Fax: (415) 962–1661

LIGHTWAVE® ELECTRONICS

An NRPO laser was used on MISER an Earth science thermal IR FTS instrument

That laser failed after ~2.5 yrs.

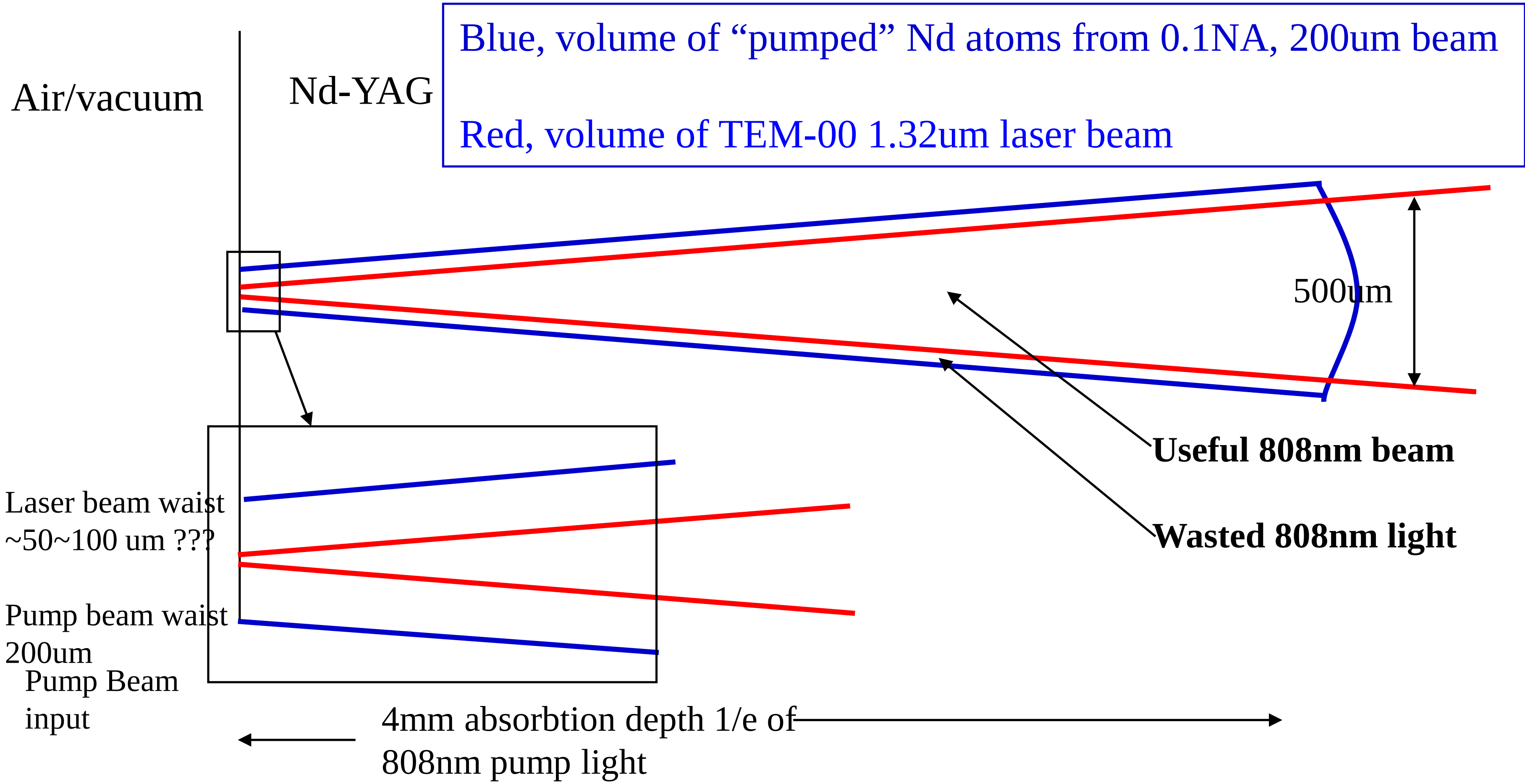
808 nm pump



1.32um out

A*Omega of NPRO

From NPRO Data Sheet



Blue, volume of “pumped” Nd atoms from 0.1NA, 200um beam

Red, volume of TEM-00 1.32um laser beam

Air/vacuum

Nd-YAG

500um

Useful 808nm beam

Wasted 808nm light

Laser beam waist
~50~100 um ???

Pump beam waist
200um

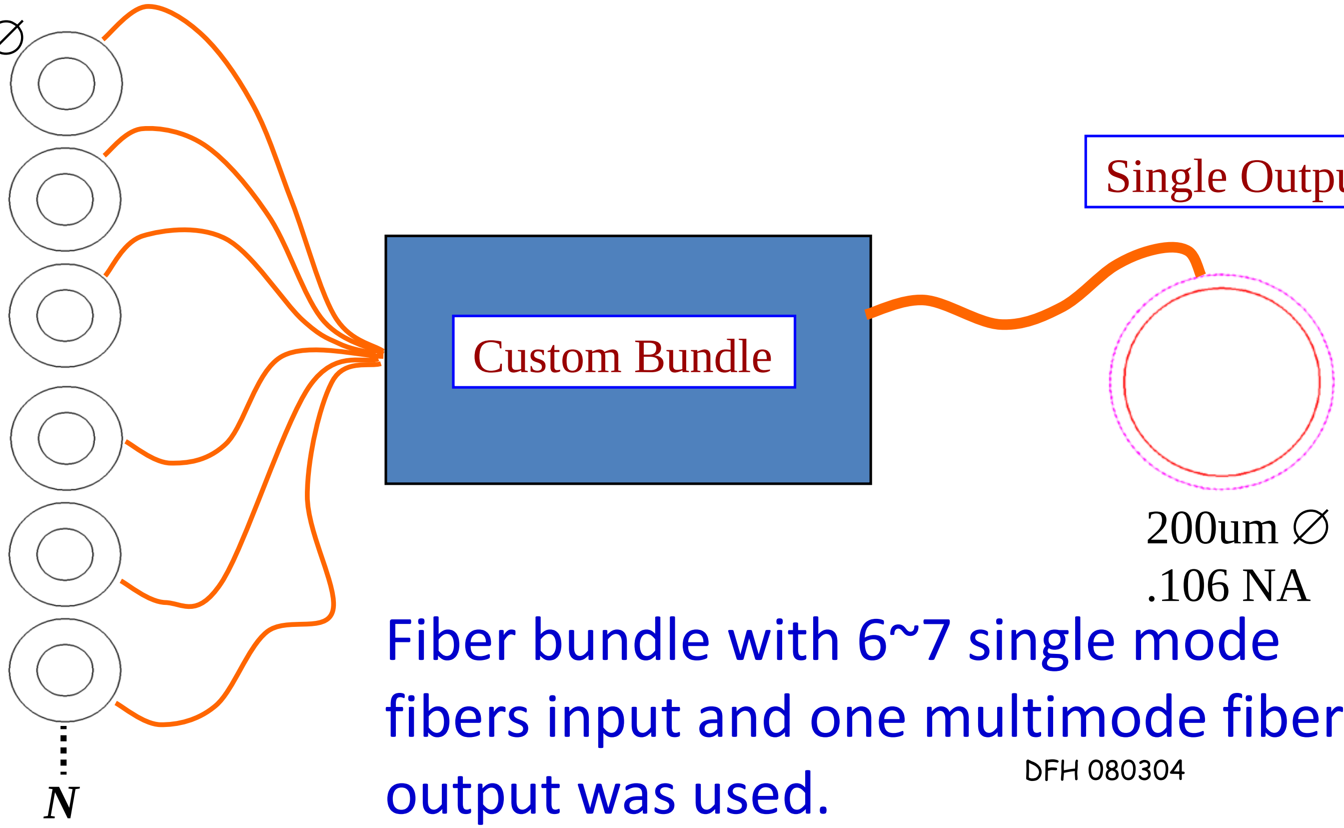
Pump Beam
input

4mm absorbtion depth 1/e of
808nm pump light

Many Options, Fiber Combiner

Multiple Inputs (N)

$$\left(\sqrt{N}\right) * D_{input} * NA_{input} \le D_{output} * NA_{output}$$



105um ∅
.08 NA

Use multiple
Single mode diode
Lasers

Custom Bundle

Single Output

200um ∅
.106 NA

N

Fiber bundle with 6~7 single mode fibers input and one multimode fiber output was used.

DFH 080304

What was the best choice in 2007 may not be the best choice in 2015.

Summary

- In building optical instruments for space one should keep in mind.
  - Surviving launch. A popular way to mount optics (3 bipods) can have a very high mechanical Q, resulting in 100’s of g’s of acceleration during launch.
    - But once in space the mechanical environment can be very quiet (you bring the noise with you)
  - Thermal control. In general the space environment can be made extremely stable, much better than in the lab. (except for LEO, low Earth orbit)
  - For active components, redundancy can provide extreme reliability and may be required for some space missions.