TES Alignment Paper

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Title:

Optical alignment of the TES cryogenic interferometer

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Abstract:

This paper describes the methodology used to align the interferometer optics in the TES cryogenic Fourier Transform Spectrometer. By means of a combination of a laser-based component state-of-alignment measurements and a detailed opto-mechanical model, both geometric & physical optics performance is predicted & optimized. The TES instrument is scheduled to be flown on EOS-CHEM in December 2002.

6.05 Interferometric Systems & Technologies for Remote Sensing

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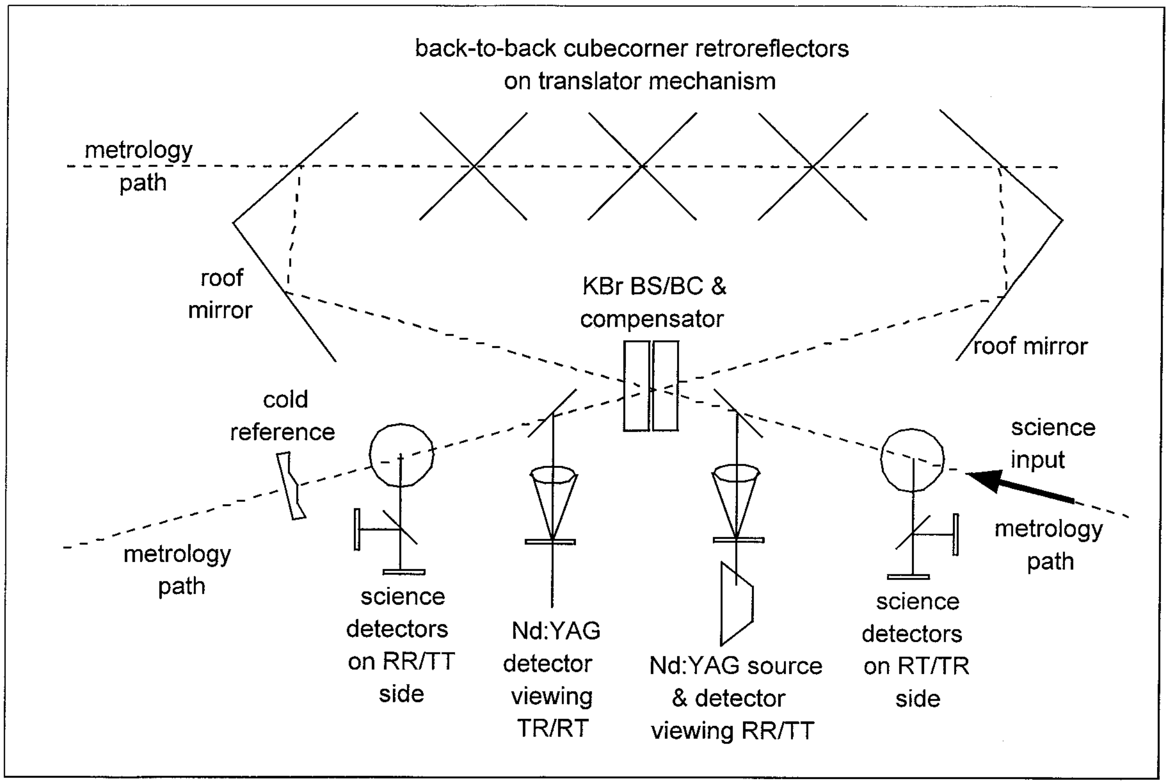
OUTLINE

BACKGROUND

TES Tropospheric Emission Spectrometer is a cryogenic, imaging Connes-type Fourier Transform Spectrometer working at 3 – 16 microns with 0.03 cm-1 spectral resolution designed to measure the state of the earth's troposphere. This satellite instrument will fly as part of NASA's Earth Science Enterprise (formerly "Mission to Planet Earth"), a series of satellite missions which will examine the earth's environment and how it is changing. TES is being built for NASA by the Jet Propulsion Laboratory in Pasadena, California. It is scheduled for launch into polar orbit aboard AURA -- NASA's third earth observing systems spacecraft (EOS-CHEM) in December 2002.



INTRODUCTION

The TES interferometer alignment challenge results from the following constraints:

1. Sensitivity analyses result in alignment tolerances at the micro-radian and micrometer level. Generally, these tolerances cannot be met by simple bolt-in installation to an accurately machined barrel or optical chassis. Instead, elements must be serially installed, evaluated & adjusted in order to predict & achieve a given level of instrument performance. Additionally, because the optical elements are all enclosed in a housing with limited viewing apertures, alignment assessment opportunities are limited. For example, packaging prevents normal-incidence theodolite or autocollimator measurements of optical element tip/tilt.

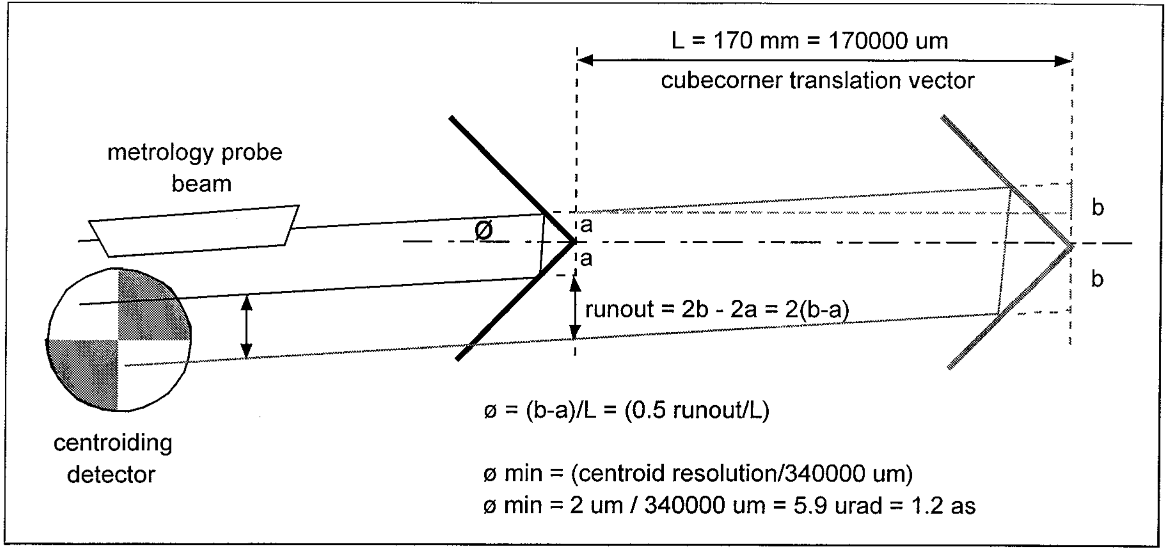
2. TES interferometer is NOT an athermal design:

Since alignment is temperature-dependent, the metrology system must be capable of collecting measurements of the interferometer optics under cold operating conditions that are accurately traceable to those same measurements made at room-temperature-in air (installation & adjustment conditions).

3. The best-fit retroreflector translation vector uniquely defines the optical axis of the instrument and thus is the reference for the system alignment. Once the cubecorner is installed in the system, all beams launched into the optical train are "perfectly" retroreflected back to the source. Thus tip/tilt errors of any element in the path would go undetected by a theodolite. Tip, tilt and decenter of a given element must then be deduced from a detailed analysis of the emerging beam as it passes thru the system including a MOVING retroreflector. See Figure.

4. Alignment correction is typically achieved by means of careful shimming. In order to deterministically achieve repeatable alignments, installation procedures & metrology must be systematically controlled.

Specifically, by measuring transverse beam runout as the metrology probe beam is returned by the moving cubecorner, we can determine angular errors associated with any newly-introduced reflective element in the path.



Translator stroke & centroiding detector sensitivity determine the fundamental angular measurement sensitivity according to:

Min. detectable angular sensitivity ~ centroid sensitivity / translator stroke. Given 2 micron centroid sensitivity and 17 mm stroke, angular sensitivity is ~1.2 as.

In general, with an explicit description of the position & direction of the beam being launched into the system, measurements of runout & absolute position of the returning beam incident on the quad cell can be inverted to determine the errors from the nominal in tip, tilt & piston of the newly integrated reflecting element. In this manner, the optomechanical model is built up as each new element is installed in the system.

Alignment Approach & Implementation

We declare the instrument to be "fully aligned" when physical & geometrical optical performance is optimized under operational temperature conditions. In order to do this, we strive for deterministic positioning of all optical components in all critical DOF's by means of accurate measurement techniques & repeatable, kinematic adjustment mechanisms.

The optomechanical computer model is continually updated to include the most accurate SOA position & thermal behavior. With this information, end-to-end instrument performance can be predicted & compared to experimental results.

TES element SOA is inferred from the following Integration & Test (I&T) procedure:

Both the TES instrument & the alignment metrology are fixed to a COMMON vibration-isolated optical bench. Bench & alignment metrology remain at rm. temp. inside vac chamber.

The metrology system includes the following elements: (See Figure)

Fiber-optic fed collimated beam launcher (840 nm laser diode; 30 mw)

Accurately encoded Linear & rotary stages for accurately launching beam into TES and locating return beam

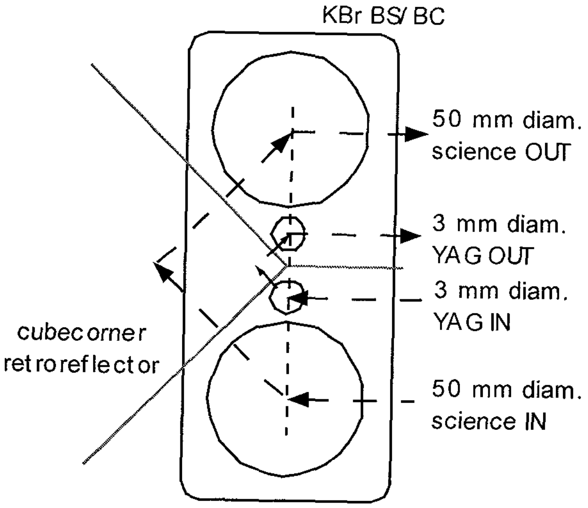
Position sensing detectors: quad cells, lateral effect detectors, CCD

Interferometer components installed, adjusted & evaluated SERIALLY

Components are aligned at 300K for null retroreflection from accurately launched & detected probe beam ("laser CMM")

This small collimated laser metrology beam is accurately launched into the TES optical train, typically following the path of either the science or reference beam chief rays. In general, this beam is sequentially reflected by the elements installed in the interferometer. After the three reflections in the cubecorner retroreflector, the metrology beam emerges anti-parallel to it's entering path. The transverse offset is typically either 38 mm (corresponding to the reference laser channel path) or 108 mm (corresponding to the science channel path) . Beamsplitter coatings are optimized for 1.064 um at the 38 mm offset; and optimized for 3-16 micron science light elsewhere.

Schematically showing Science & YAG beam paths thru KBr BS/BC & cubecorner



"Accuracy" here includes knowledge and/or consideration of . . .

» test temp. vs. operational temp.

» alignment wavelength vs. operational wavelength

» component "as-manufactured" intrinsic errors
current state-of-alignment completeness

I&T in vac chamber configured for minimum disruption of metrology setup between 300K & 180K

Use of diffraction grating & corner cube (DGMA) to separate component motions from optical bench motions

For each optical element, we perform " The TES 4-STEP " . . .
Step 1 – Install & Align optical element @ 300K ,
Step 2 -- Check optical element @ 180K ,
Step 3 -- Tweak optical element @ 300K ,
Step 4 -- Re-check optical element @180K

The position & runout of the beam returning to the metrology detectors is recorded. This information can then be used to infer optical element SOA.

[E. Motts add quad cell details here: varying beam radius hassles, non-linearity, limited range; would use larger, linear detector or CCD next time]

Variations in SOA of each element in going from room-temperature to cold conditions must be measured after the installation of each new element. (This is Step 2 outlined above.) Assuming this room-to-cold temperature alignment change is repeatable, the warm SOA of a given element can be adjusted (Step 3) so as to leave the element at the optimum SOA under cold operating conditions (Step 4). This four-step process is repeated with each new optical element introduced into the system.

With the addition of each new element we assume the behavior of the previously-installed element is unchanged. Once the interferometer is fully assembled, SOA of individual elements can no longer be directly measured. Alignment errors can only be inferred from the ensemble of optical performance measurements in the science & YAG channels.

These measurements include: Modulation vs. wavelength, field position, OPD as well as ZPD position & boresight registration.

OPTO-MECHANICAL MODELING [S. Larson inputs here]
Crucial to the determination of interferometer SOA is a detailed opto-mechanical computer model. The ASAP optical modeling software package (Breault Research Corp.) was chosen for it's ability to trace rays non-sequentially as well as it's ability to do the physical optics modeling (modulation predicts) Distinct from the nominal optical design model, { ML White comments on CODEV design model here??? } the informed with the following knowledge:

1. Component fabrication errors: Wavefront, wedge, thickness, index, coating performance

2. Component SOA knowledge (from metrology measurements and independent surveys)

3. Component mechanism model: Location of tip/tilt/decenter adjustment mechanisms is explicitly modeled enabling direct calculation of alignment-correcting shims.

4. Detector & Stimulus modeling:
Active area of every pixel in the interferometer focal plane is modeled assuming a uniform top-hat sensitivity function. External stimuli are modeled as well (including source geometry & wavelength, optical train), enabling an explicit prediction of detector signal output.

Limitations: Not all degrees of freedom measured.

The ASAP model is continually updated to include the most accurate SOA position & thermal behavior. { one Model at room temp., second model at cold temp.? } With this information, end-to-end instrument performance can be predicted & compared to experimental results.

PHYSICAL OPTICS PERFORMANCE

Signal modulation and boresight registration between the four detector arrays are the primary performance metrics for the interferometer.

Modulation predicts are calculated based on …

Stimulus configuration
- Source geometry, wavelength
- Stimulus optics

Interferometer configuration including
- Optical element inspection reports (wavefront quality, thickness, coatings)
- Optical element SOA (warm & cold measurements)
- Retroreflector position (OPD±17 cm)

Each pixel is conjugate to an extended source in object space and so pixel output is estimated as follows:

Is the sum of an array of 8 point sources at 8 discrete field positions. (Figure)

Integrate an ensemble of point sources over pixel angular subtense

Pixel signal(wavelength, field position, OPD)
For a given retroreflector position, trace monochromatic wavefronts thru both arms of the interferometer (OPD's range from –34 cm to 34 cm) and coherently add to determine net PSF at focal plane.

After a small number of iterations in retroreflector position, maximum & minimum pixel outputs can be determined. This enables a modulation prediction for that particular configuration.

M(pixel, SOA, wavelength, OPD, …)

Nd:YAG

To enable transformation of the raw science-channel interferograms into accurate tropospheric spectra, an OPD tracking 1.064 um reference laser is installed in the interferometer. It too must be deterministically aligned within the optical train so as to provide a stable, robust reference signal at operating temp (180K) and over the 5 year life of the instrument.

Nd:YAG light in a collimated gaussian beam of 3 mm diameter (e-2) is introduced into the interferometer immediately before the BS, and the two interfering beams are extracted immediately after the BC. Nominally, the YAG beam travels parallel to the retroreflector translation vector which, again is nominally parallel to the science optical axis/boresight. A small patch of BS/BC surface specially coated for 1.064 um interferometry and lying just outside the science CA is devoted to this laser reference channel.

COLD MODULATION RESULTS

PARAMETER	PREDICTION	MEASURMENT
10.6 um	0.60	0.60
intermediate wavelengths		
3.3 um	0.10	0.10
1.064 um on RR/TT		
(+OPD)	0.20	0.20
(ZPD)	0.20	0.20
(-OPD)	0.20	0.20
1.064 um on RT/TR		
(+OPD)	0.30	0.30
(ZPD)	0.30	0.30
(-OPD)	0.30	0.30

SUMMARY & CONCLUSIONS

The alignment methodology described above has enabled us to both predict & optimize performance of the TES interferometer to a high degree of accuracy.

Alignment of a non-athermalized optical system comprised of small-tolerance components is a vastly time consuming & painstaking process. The problem is exacerbated by the inability to independently assess (much less correct) individual optical element SOA at any given time in the course of instrument integration.

Design of the interferometer housing or optical bench should commence only after the design of alignment adjustment mechanisms are complete.

Interface envelopes allocated to the optical elements (including their integral alignment adjustment mechanisms) should not be frozen until element opto-mechanical design is complete.

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.