Temperature-dependent refractive index of Cleartran® ZnS to cryogenic temperatures

Doug Leviton and Brad Frey / NASA Goddard Space Flight Center

doug.leviton@nasa.gov

The Cryogenic High-Accuracy Refraction Measuring System (CHARMS) at NASA GSFC
... but first, let’s talk about the CHARMS facility at NASA’s Goddard Space Flight Center

- Cryogenic, High-Accuracy Refraction Measuring System (CHARMS)
- design features for highest accuracy and precision
- technologies we rely on
- data products and examples
- optical materials for which we’ve measured cryogenic refractive index
CHARMS fact sheet

- developed in ~2003 to provide design refractive indices of ZnSe, LiF, BaF2 for two triplet lenses in JWST’s Near Infrared Camera (NIRCam) at 38 K
- CHARMS is a differential, absolute, minimum deviation refractometer
- provides dense sampling of index in both wavelength and temperature
- wavelength coverage:
  - 400 nm (violet) to 5.6 µm in mid-IR
  - plans to extend range to 120 nm in FUV, and 20 microns in mid-IR
- temperature coverage:
  15 K to 330+ K (60 C)
- accuracy in n(λ,T)
  +/-0.000002 to +/-0.0001 depending on material and temperature
JWST NIRCam lens materials

ZnSe - 29°  BaF₂ - 58°  LiF - 60°
Minimum deviation refractometry

- apex:
  - measure angle of prism face A
  - measure angle of prism face B
  - measure direction of **undeviated** beam
  - measure direction of **deviated** beam
  for each wavelength

\[
n(\lambda, T) = \frac{\sin (\alpha/2 + \delta/2)}{\sin (\alpha/2)}
\]
Limits on accuracy with minimum deviation method

- \( n(\alpha, \delta(\lambda, T)) \)
- \( dn \) contains ...
  - \( \frac{dn}{d\alpha} \cdot \Delta \alpha \)  
    Prism apex
  - \( \frac{dn}{d\delta} \cdot \Delta \delta \)  
    Deviation angle
  - \( \frac{dn}{d\lambda} \cdot \Delta \lambda \)  
    Spectral dispersion
  - \( \frac{dn}{dT} \cdot \Delta T \)  
    Thermo-optic coefficient
- uncertainty should be listed as a function of both wavelength AND temperature
### Bookkeeping error budget

Uncertainty governed by all eight quantities in the red box for each measurement for a given specimen (green box).

So, refractometers should not list just a single number for accuracy.

#### Table:

<table>
<thead>
<tr>
<th>Index n</th>
<th>Apex α</th>
<th>Sensitivity</th>
<th>dn/dλ</th>
<th>dn/dT</th>
<th>dn/da</th>
<th>dn/dδ</th>
<th>dλ</th>
<th>dT</th>
<th>da</th>
<th>dδ</th>
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For specified prism:

- dn

For specified prism:

- 0.0014 deg
- 0.5 sec
- $\delta$
On precision ...

• precision often well exceeds accuracy; do not confuse with accuracy
• CHARMS precision for fused silica at a given wavelength is \(~1E-7\)
CHARMS design approach / measurement technique

- limit contribution of each error source by design / know each contributor well
  - automate to eliminate human factor
  - build best practical machine for measuring apex angle
  - use similar hardware for measuring beam direction in refractometer
  - use multiple, calibrated high accuracy temperature sensors on prism
  - calibrate monochromator carefully with laser lines and measure only at wavelengths for calibrated (order number x wavelength)

- make differential measurements
  - have access to undeviated beam and refer to it frequently!
  - measure spectral index over and over as temperature of sample slowly drifts in temperature – builds rich data set for fitting

- immerse entire refractometer in vacuum
  - measurements thus absolute
  - no window effects
  - eliminates most environmental effects
  - all reflective design is broadband and achromatic
CHARMS optical layout

- cryo-refrigerator
- chamber
- monochromator
- exit slit
- flat
- flat
- flat
- UVIS camera
- MIR camera
- slit image
- rotating flat
- prism

- $f = 1.1 \text{ m}$
- $f = 1.5 \text{ m}$
- 0.5 m
CHARMS opto-mechanical layout

- rotating fold flat
- sample chamber “shield”
- cryo refrigerator
- “focus” flat
- camera mirror
- detector
- select mirror
- fixed fold flat
- collimator
- UVIS camera
- MIR camera (not shown)

monochromator (not shown)
Technologies we rely on

- high accuracy, high resolution, absolute Leviton encoders installed on
  - apex measuring setup (0.3 arcsecond apex accuracy)
  - rotating fold mirror spindle (0.8 arcsecond deviation accuracy)
  - sample stage
  - monochromator grating shaft
- absolute electronic autocollimator
- long focal length collimating and camera mirrors
- high accuracy calibrated Si diode temperature sensors
- CCD for NUV / Vis / NIR wavelengths
- InSb array camera for NIR to mid-IR wavelength
- QTH and globar light sources
- numerous order sorting filters
Calibrated monochromator

- monochromator grating
- encoder scale
- encoder LED illumination
- encoder camera
Windowless prism assembly

- Sample chamber
- Prism
- Sample platform
- Sample isolator
- Scale hold-down
- Encoder scale
- Precision bearing
- Thermal isolators
CHARMS automation

Rack contains:
- control PC
- motor controllers
- encoder readouts
- temperature monitors
- programmed power supplies
- turbopump control
- pressure gauges
- monochromator control
Measurement campaigns to date

- JWST / NIRCams
  - ZnSe, BaF₂, LiF, Si, Ge, Cleartran ZnS (2 prisms each)
- Ball Aerospace / Kepler Photometer
  - Corning 7980 fused silica (5 samples from 1 m corrector boule)
- ESO / ESA
  - ZnSe
- UC Lick Observatory
  - CaF₂, S-FTM16 (2 prisms), S-FPL15
- Harvard College Observatory
  - S-TIM28
- University of Oxford
  - BaLKN3, E-SF03, N-BK7, SF15
- NASA proposals
  - Corning 7940, CaF₂, Infrasil 301, SF4, SF6, S-TIH1
- Lockheed Martin
  - Infrasil 301, ZnSe

20 different materials and counting
Cleartran ZnS

- Cleartran (ZnS) is a water-clear form of CVD ZnS
- made by Rohm and Haas (formerly CVD, Inc.), now a subsidiary of Dow Corporation
- different from conventional CVD ZnS by about 0.001 to 0.002 in index
Noteworthy applications for Cleartran ZnS

- Infrared Array Camera (IRAC) on the Spitzer Space Telescope
- Near-InfraRed Imager and Slitless Spectrograph (NIRISS) (replacement for Tunable Filter Imager (TFI) for James Webb Space Telescope)
- Gemini Planet Imager (GPI) for the Gemini South telescope
What previous cryogenic index studies are there?

- None for Cleartran ZnS at cryogenic temps :-(

- Room temperature for conventional CVD ZnS
CHARMS data products

• spectral index over temperature from 20 to 300 K, and wavelength from 0.5 to 5.6 μm
• 3-term Sellmeier fits to measured data with 4\textsuperscript{th} order temperature dependence
• spectral dispersion tables over temperature
• spectral thermo-optic coefficient tables over temperature

\[ n^2(\lambda, T) - 1 = \sum_{i=1}^{3} \frac{S_i(T) \cdot \lambda^2}{\lambda^2 - \lambda_i^2(T)} \]  
this functional form

these coefficients  
\[ S_i(T) = \sum_{j=0}^{4} S_{ij} \cdot T^j \]

\[ \lambda_i(T) = \sum_{j=0}^{4} \lambda_{ij} \cdot T^j \]
# Index uncertainties

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<tr>
<th>Wavelength [µm]</th>
<th>30 K</th>
<th>75 K</th>
<th>100 K</th>
<th>150 K</th>
<th>200 K</th>
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</table>
Absolute spectral refractive index of Cleartran® ZnS with temperature
Spectral dispersion of Cleartran® ZnS with temperature

Thermo-optic coefficient (dn/dT) of Cleartran® ZnS with temperature
Coefficients of wavelength and temperature-dependent Sellmeier fit

Coefficients for temperature dependent Sellmeier equation for Cleartran ZnS

Applicability: 20 K ≤ T ≤ 300 K; 0.50 μm ≤ λ ≤ 5.6 μm

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>S&lt;sub&gt;1&lt;/sub&gt;</th>
<th>S&lt;sub&gt;2&lt;/sub&gt;</th>
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Three rules for using these coefficients:

1. Do not use outside the identified range of applicability, i.e. do not extrapolate
2. Use all listed significant figures for each coefficient
3. Make sure you can reproduce all of the index value in accompanying table which were generate with the fit
Comparison of CHARMS and Rohm & Haas refractive index for Cleartran® ZnS at room temperature

Ratio of measured dispersion of Cleartran® to that of CVD ZnS at 293 K
Conclusions

1. first cryogenic measurements of Cleartran ZnS refractive index
2. dispersion and thermo-optic coefficient of Cleartran quite similar to conventional CVD ZnS
3. CHARMS measurements agree very well with those of material manufacturer at room temperature
4. would be prudent to measure more than one sample before concluding that we know Cleartran at cryo (boule-to-boule variability)