

# **Frequency-Agile LIDAR Receiver for Chemical and Biological Agent Sensing**

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# Report Documentation Page

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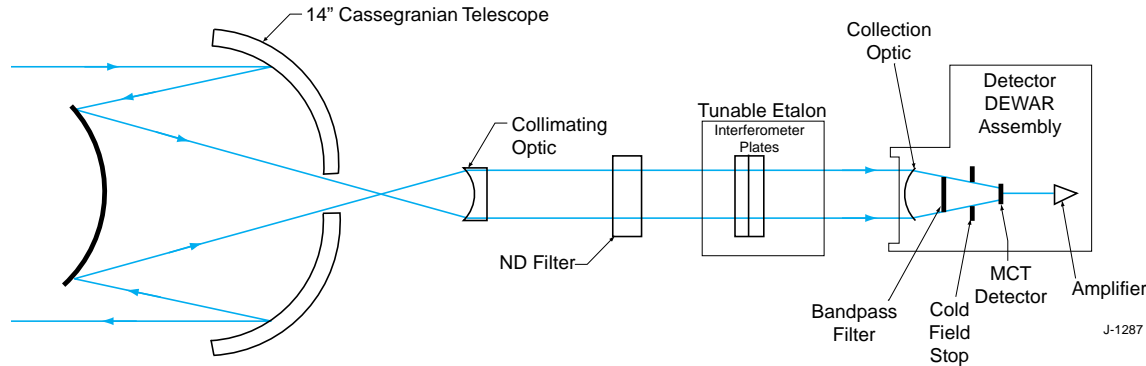
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# Overview

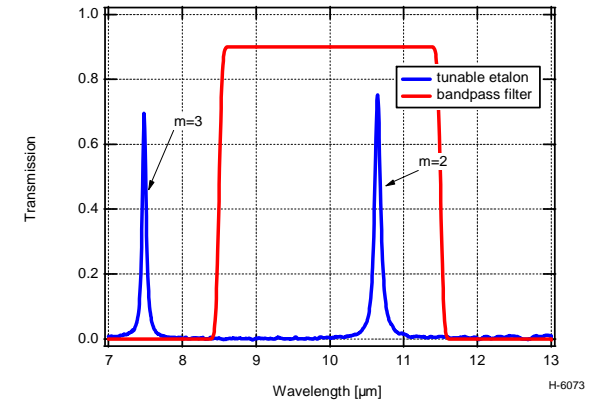
- **Objective: Improve standoff range and chem-bio agent detection limits of direct detection LWIR differential absorption LIDAR systems**
  - Standoff range: ~ 2x increase for fixed chem-bio sensitivity; scales as  $1/\sqrt{\text{NEP}}$
  - CB agent sensitivity: ~ 4x increase for fixed standoff range, scales as NEP
  - Compatible with 200 Hz line-tuned CO<sub>2</sub> laser
- **Technical Approach:**
  - Develop ultra-low noise receiver module (RM)
  - Critical elements of receiver design – required to achieve objectives:
    - Reduce baseline (background) photon flux on detector: Tunable Fabry-Perot etalon in optical train
    - Reduce input-referenced amplifier noise: custom amplifier
    - Reduce detector dark current: High impedance detector
- **Performance Metrics:**
  - Noise equivalent power of receiver system (NEP)
  - Etalon tuning speed/bandwidth and wavelength positioning accuracy
  - Electronics bandwidth

# LIDAR Receiver Concept

## Conceptual Design



## FP Etalon Transmission



$$NEP_{total} = \left[ NEP_{Jsn+Amp+leak}^2 + NEP_{BLIP}^2 \right]^{1/2}$$

- Single element detector (HgCdTe) with band pass filter coupled to low noise custom amplifier → **reduce  $NEP_{Jsn+Amp+Leak}$**
- Insert tunable Fabry-Perot etalon in afocal region of optical train to reduce baseline flux on detector (~30x reduction) → **reduce  $NEP_{BLIP}$** 
  - Etalon tracks 200 Hz CO<sub>2</sub> laser emission wavelength
  - Tunable etalon is PSI innovation
- f/0.9 optical system for full integration with the existing 14'' Cassegrainian telescope currently employed in the ECBC's FAL system

# Fabry-Perot Etalon: Overview

- **Reduction of baseline flux on detector via tunable etalon insertion reduces system noise**

- Photon statistical noise:  $NEP \propto (\text{flux})^{0.5} / (\text{optics transmission})$

- **Transmission maxima fulfill Fabry-Perot resonance condition:**

$$\lambda_m = \frac{2d}{m}$$

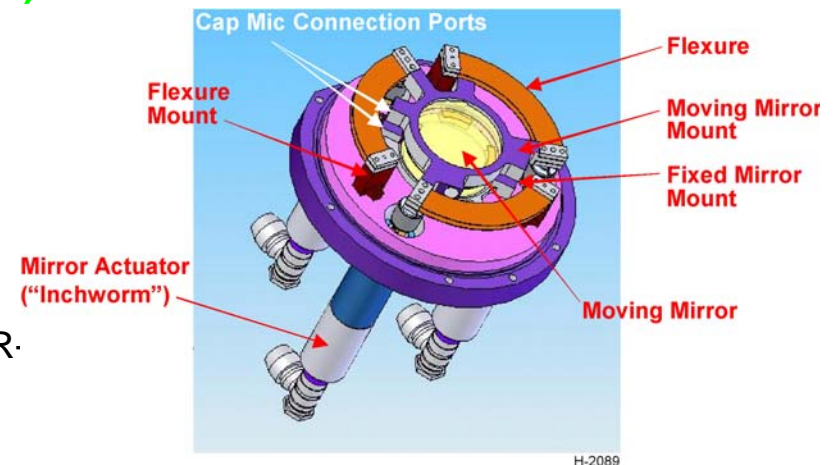
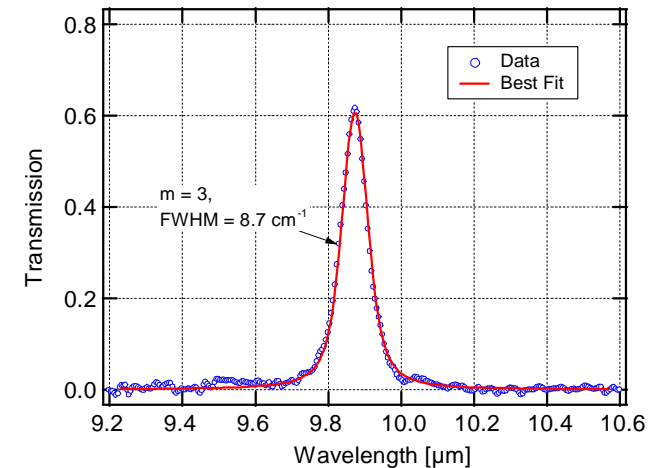
← mirror spacing  
← interference order (integer)

- **Tuning range = Free Spectral Range:**

$$\Delta\lambda \equiv \lambda_{\max,m} - \lambda_{m+1}(\lambda_{\max,m}) \approx \frac{\lambda_{\max,m}}{m+1}$$

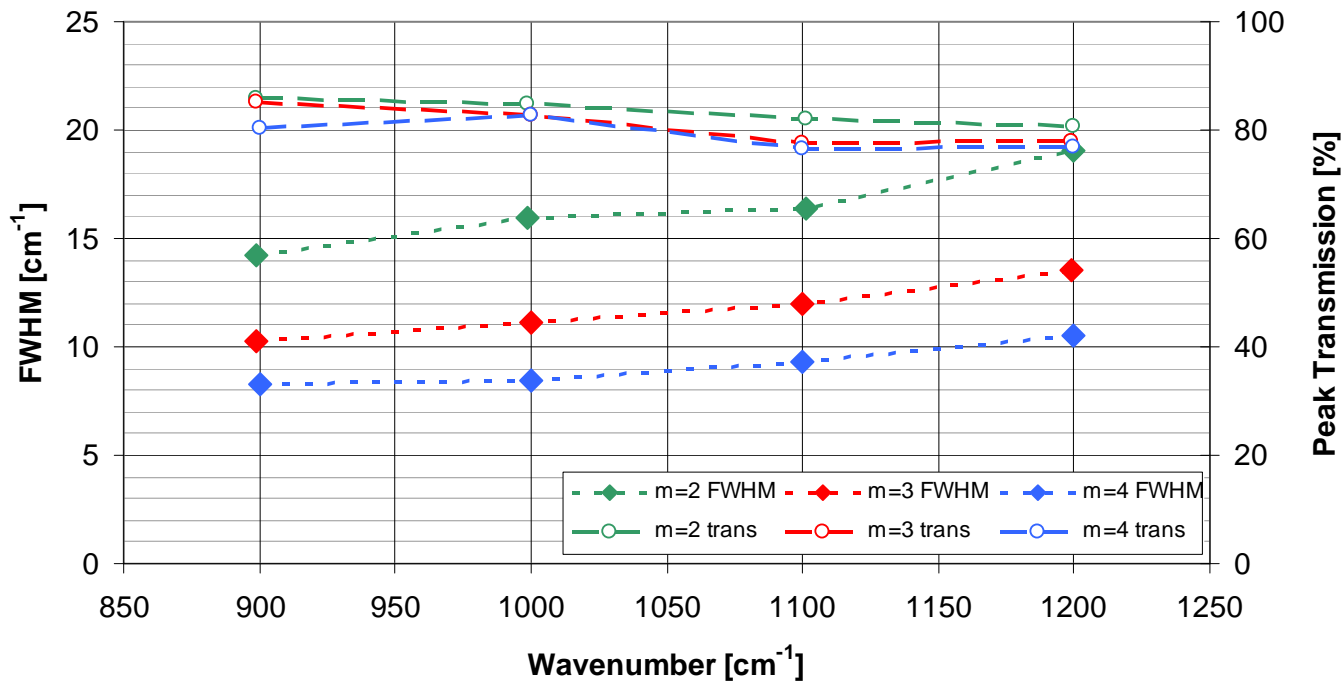
- **PSI etalon design:**

- Optics: 50 mm dia x 8 mm thick ZnSe, central 36 mm HR-coated
  - Electronics: FPGA-based control system increases the bandwidth of the etalon control loop and maintains active, continuous alignment of the etalon mirrors (control bandwidth between 2 kHz and 5 kHz)



# Fabry-Perot Etalon: Spectral Performance Characteristics

1559 Etalon Performance, December 09

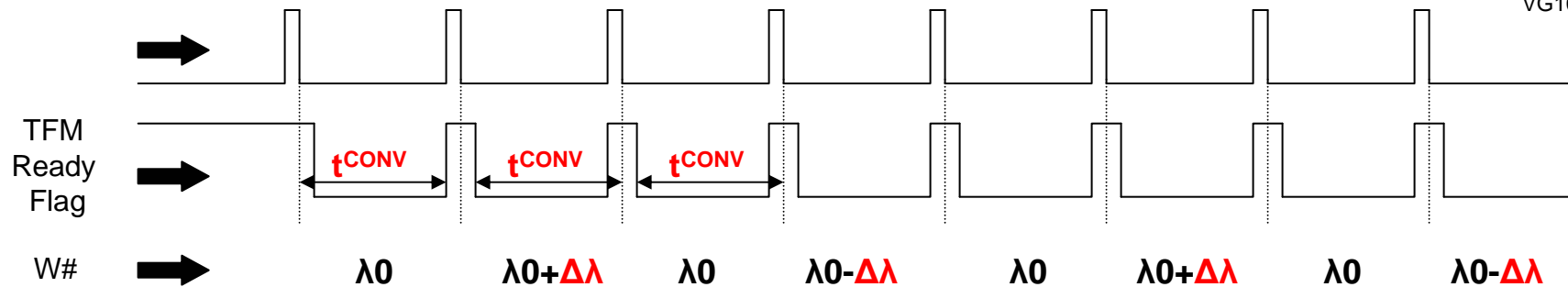


## Conclusions:

- Transmission ~ 80% for all orders across tuning range
- FWHM (m=2): 15 – 19  $\text{cm}^{-1}$
- FWHM (m=3): 10 – 14  $\text{cm}^{-1}$
- FWHM (m=4): 8 – 11  $\text{cm}^{-1}$

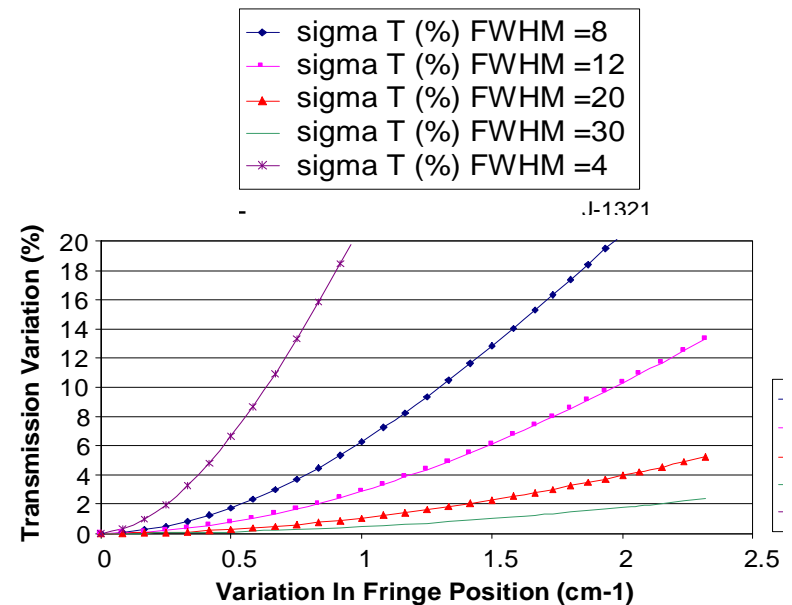
# Fabry-Perot Etalon: Derived Requirements

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- **Etalon transmission fringe needs to track CO<sub>2</sub> emission wavelength**
  - 200 Hz laser → etalon needs to reach commanded wavelength in < 5 msec
  - CO<sub>2</sub> laser lines:
    - Four branches: 9R, 9P, 10R, 10P
      - ~ 50% CO<sub>2</sub> lines require < 5 cm<sup>-1</sup> jumps
      - ~ 80% CO<sub>2</sub> lines require < 10 cm<sup>-1</sup> jumps
- **Achieve < 1% transmission error due etalon wavelength position uncertainty**
  - If the transmission varies from shot to shot, then the wavelength variation aliases as measurement noise and degrades CB agent detection sensitivity

$$\sigma_p \propto \frac{\sigma_{I/I_0}}{(I/I_0)} = \frac{\sigma_T}{T}$$



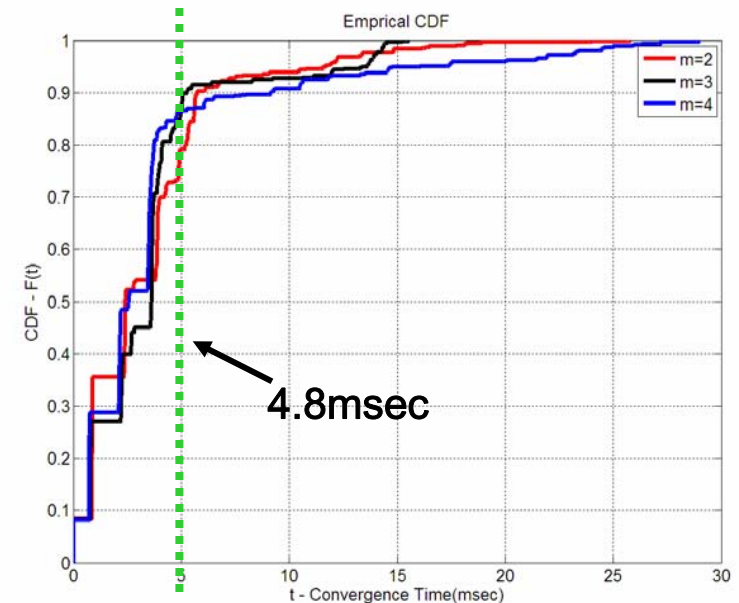
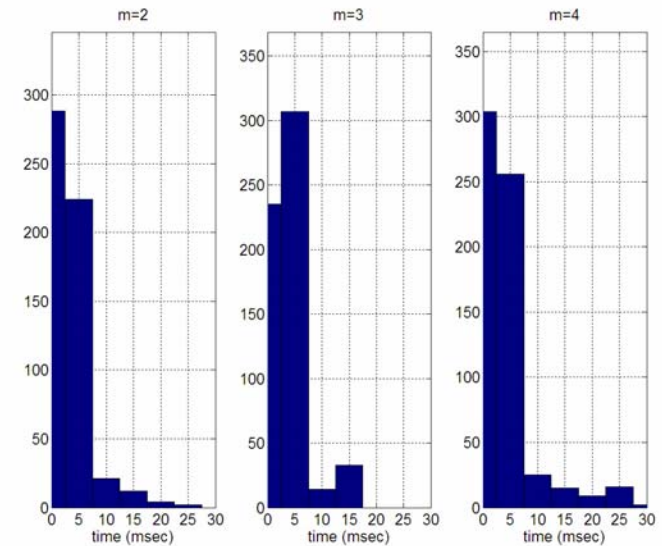
# Fabry-Perot Etalon: Tuning Speed

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	m=2	m=3	m=4
5cm <sup>-1</sup> Jump	< 4ms	< 3.5ms	< 3ms
10cm <sup>-1</sup> Jump	< 5ms	< 4ms	< 4ms
40cm <sup>-1</sup> Jump	< 10ms	< 15ms	< 20ms
ECBC Wavelength List	< 5ms (80%)	< 5ms (85%)	< 5ms (85%)

- **Etalon Tuning Performance:**

- Less than 5 ms convergence time for 10cm<sup>-1</sup> and smaller jumps
- Technical requirement successfully achieved
- Non-lasing laser trigger pulses are required for jumps greater than 10cm<sup>-1</sup>
  - Slightly reduced the system duty cycle

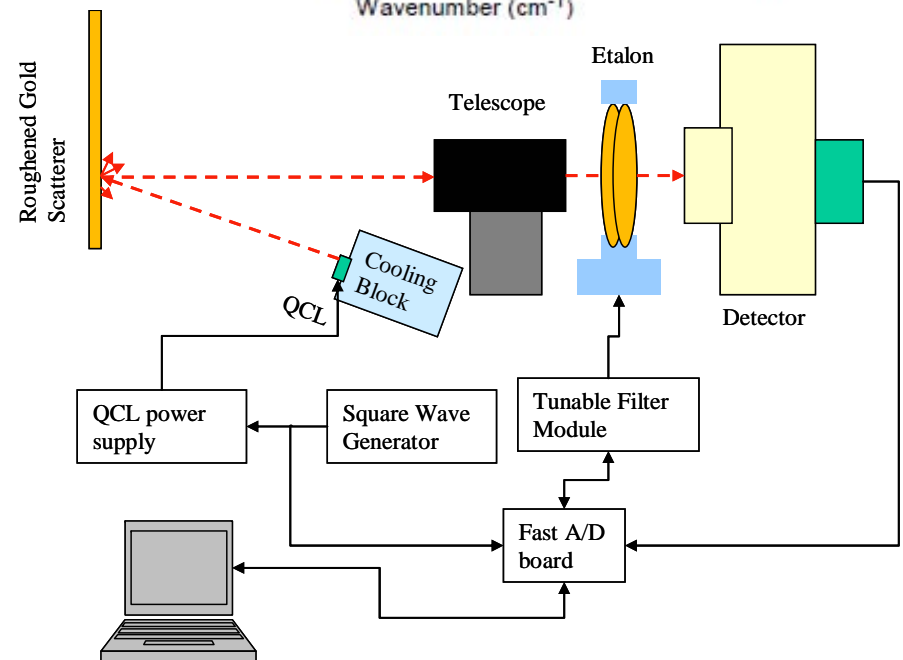
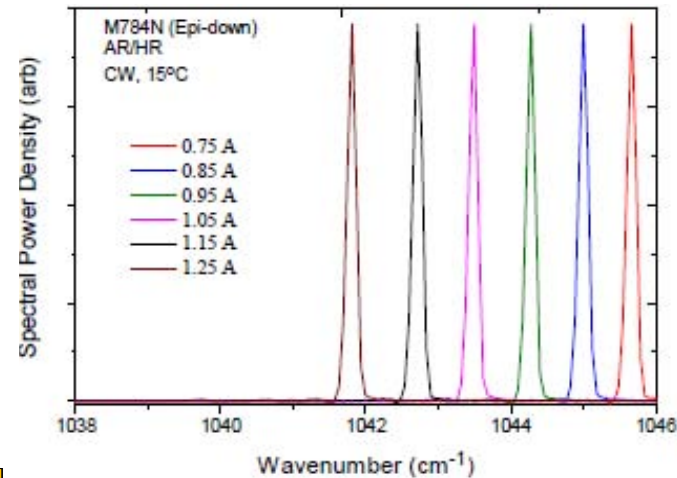


# Fabry-Perot Etalon:

## Transmission Uncertainty Measurements (1)

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- **Make use of Quantum Cascade Laser (QCL, Maxion P/N M784) which emits at 9.6  $\mu\text{m}$** 
  - Direct measurement of the desired performance one can expect with the ECBC's FAL CO<sub>2</sub> laser
  - Multiple etalon scans over laser line
- **Laser output was directed onto a roughened gold scattering screen**
  - QCL was mounted to a cooling block and directed through a collimating lens onto the screen
  - A N<sub>2</sub>(l)-cooled LWIR camera was used to monitor the onset of lasing and to adjust the lens
- **The laser power supply was modulated with a square wave to +/- 30mA at 10 kHz**
  - Laser turned on and off in a binary fashion with a 50% duty cycle
  - Produced a detectable AC signal well above the detector's high pass cutoff frequency of 500 Hz



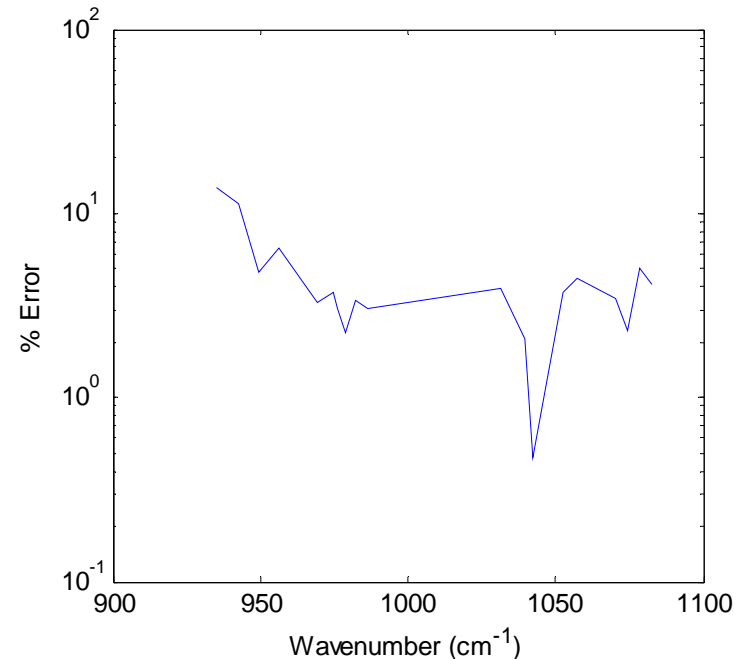
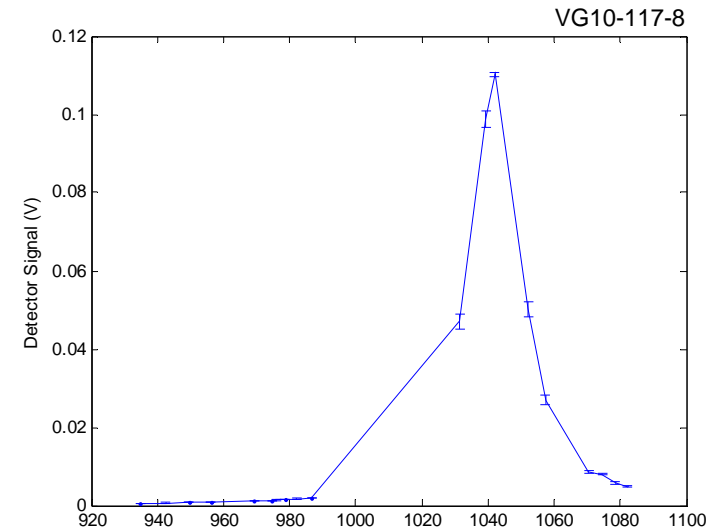
# Fabry-Perot Etalon:

## Transmission Uncertainty Measurements (2)

- The QCL emission is significantly narrower than the etalon transmission bandwidth
  - Shape of the peak represents the etalon transmission function
- Each wavelength data point is an average of 32 separate measurements (etalon scans) and error bars are the standard deviation:

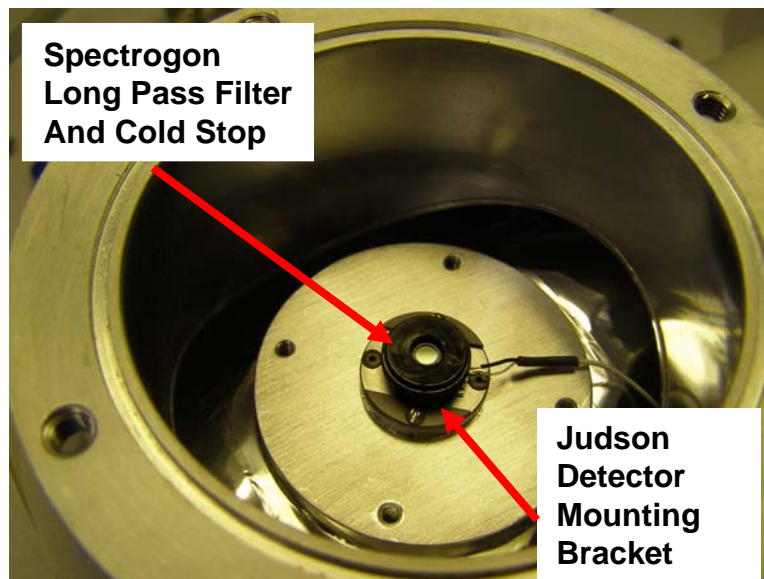
$$\% Error = \left( \frac{\sigma(stdev)}{Mean} \right) \cdot 100$$

- The transmission error due to etalon wavelength position uncertainty is ~ 0.5%
  - Successfully meet derived requirement
- The etalon convergence criteria is determined based on optimization of both tuning speed and position accuracy

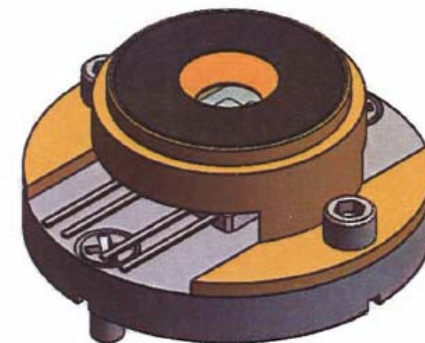


# Detector

- **Judson single element PVMCT, 0.5 mm diameter**
  - Capacitance ~ 200 pF
  - 77K resistance @ 0 VDC: 11 k $\Omega$
- **The detector mounting bracket was custom designed to support the integration of the collection lens assembly inside the dewar for reduction of self-radiance of optical components**

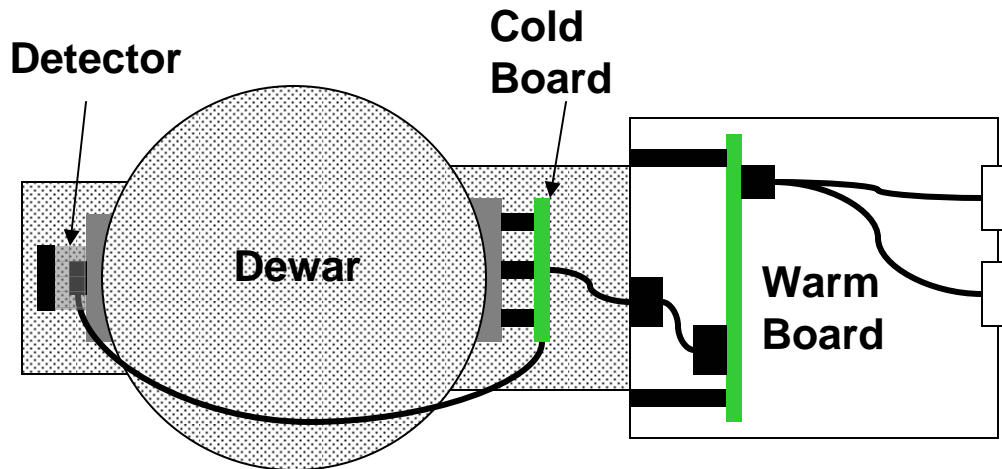


**Lens and cold filter/stop  
Mounting bracket**



# Custom Preamplifier

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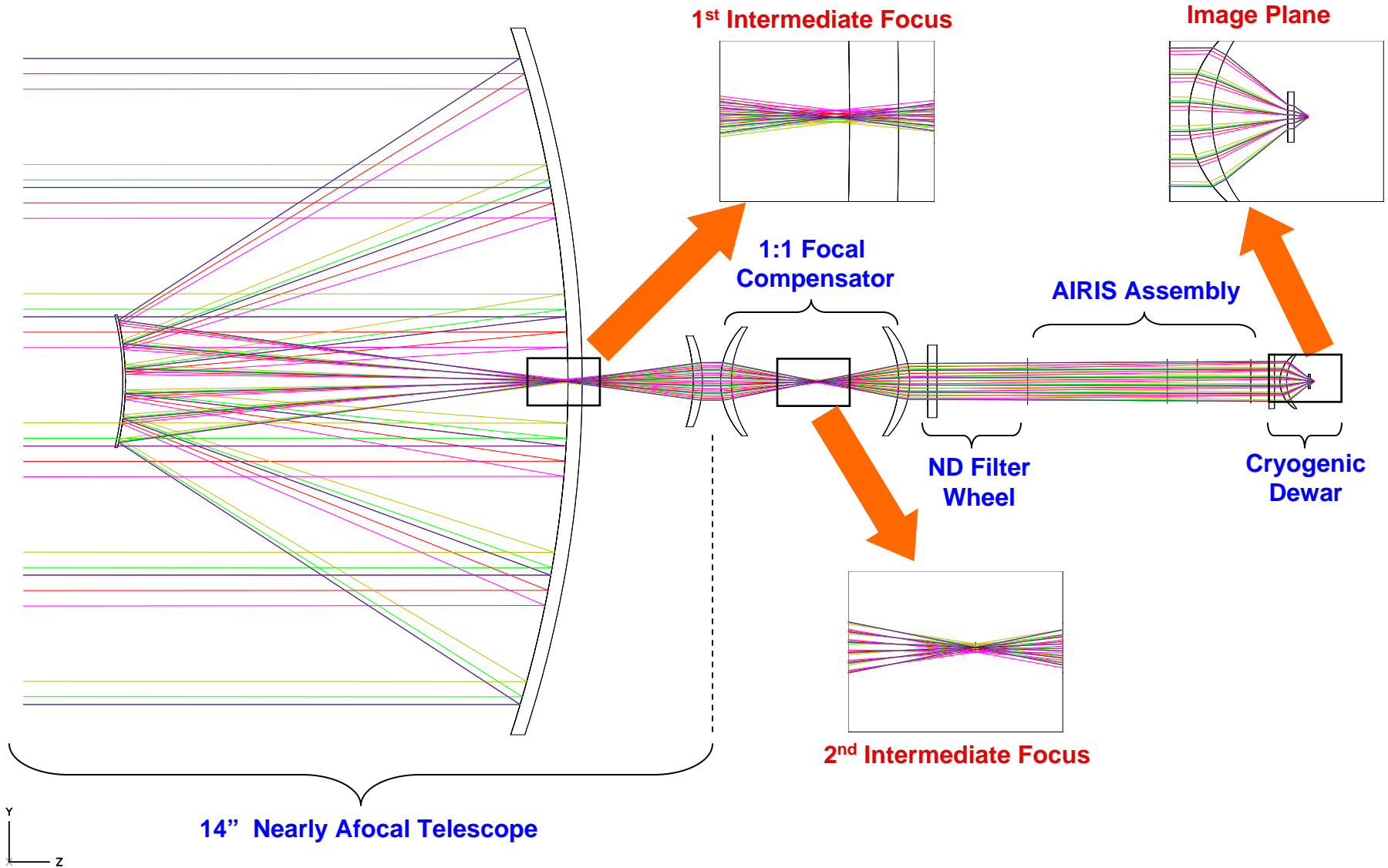


	Single Ended	Differential
Signal Bandwidth	>5MHz (Pref. 20MHz)	>5MHz (Pref. 20MHz)
Output Voltage Range	+3V to -3V	+/-1.13V
Common Mode Voltage	N/A	0V
TIA Gain	200k $\Omega$ / 50k $\Omega$	20k $\Omega$ / 5k $\Omega$
Output Connector & Cable	Triaxial	Triaxial (2X)
Termination Resistance	50 $\Omega$	50 $\Omega$
Bias	0V to -350mV – Pot Adjusted	
Voltage Noise	~ 0.8nV/√Hz	
Cold PCB Temperature	140K to 180K	
Power Dissipated on Cold PCB	< 650mW	
Warm PCB Size	3.5" X 2.5"	
Cold PCB Size	1" Diameter	
Power Requirements	+/-15V, <5mVrms noise, <200mA	

- The transimpedance preamplifier architecture was optimized around the selected IR detector diode
  - Input-referenced noise density of 0.8 nV/ Hz<sup>0.5</sup>
- A portion of the preamplifier was physically located within the cryogenic dewar with the IR photodiode
  - Stage consists of a JFET transistor with the detector attached to its gate
    - Thermal noise from this stage and any stray capacitance at the input are reduced
    - Reductions help to lower the input referred noise added by the preamplifier.
- The other portion of the preamplifier was located directly outside the dewar and was operated at room temperature
  - The majority of the preamplifier circuitry is located on this PCB
    - Circuitry to control and adjust bias condition
    - Monitor dewar temperatures
    - Buffer the preamplifier output

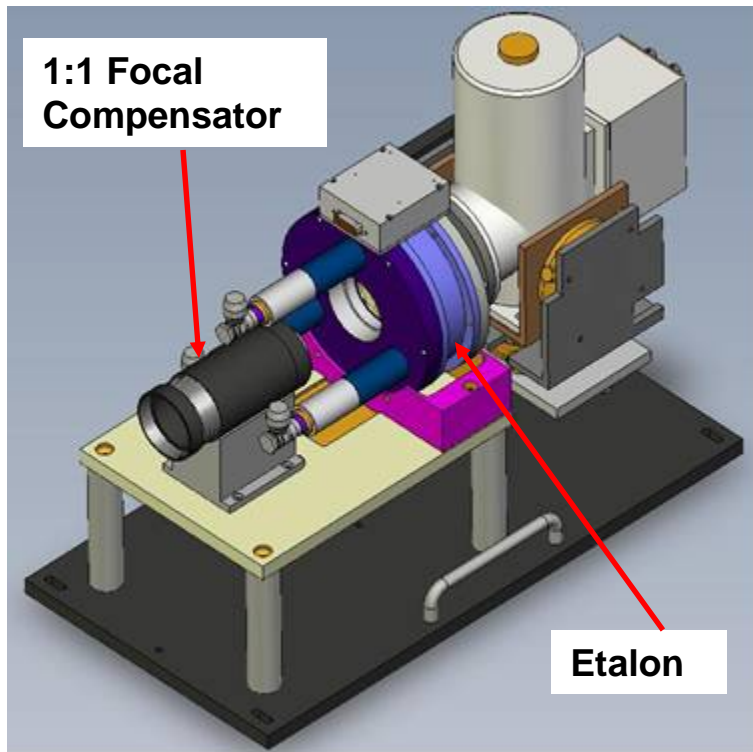
# Optical Layout: Designed for Retrofitting into Existing FAL Receiver

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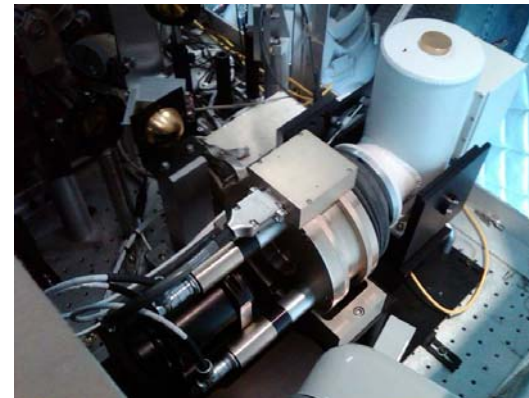
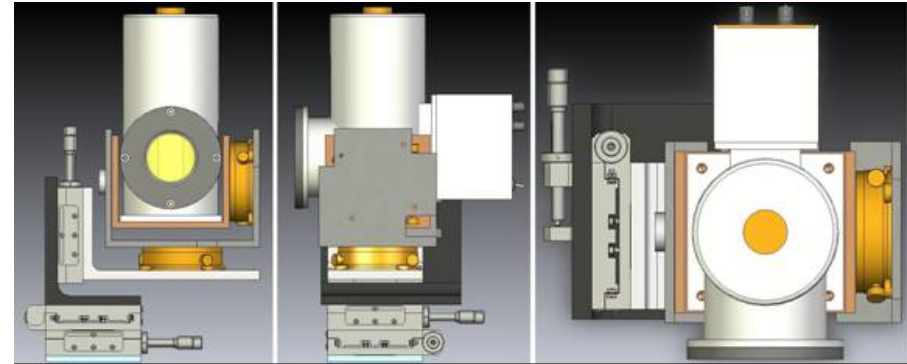


# Receiver Module Mechanical Configuration

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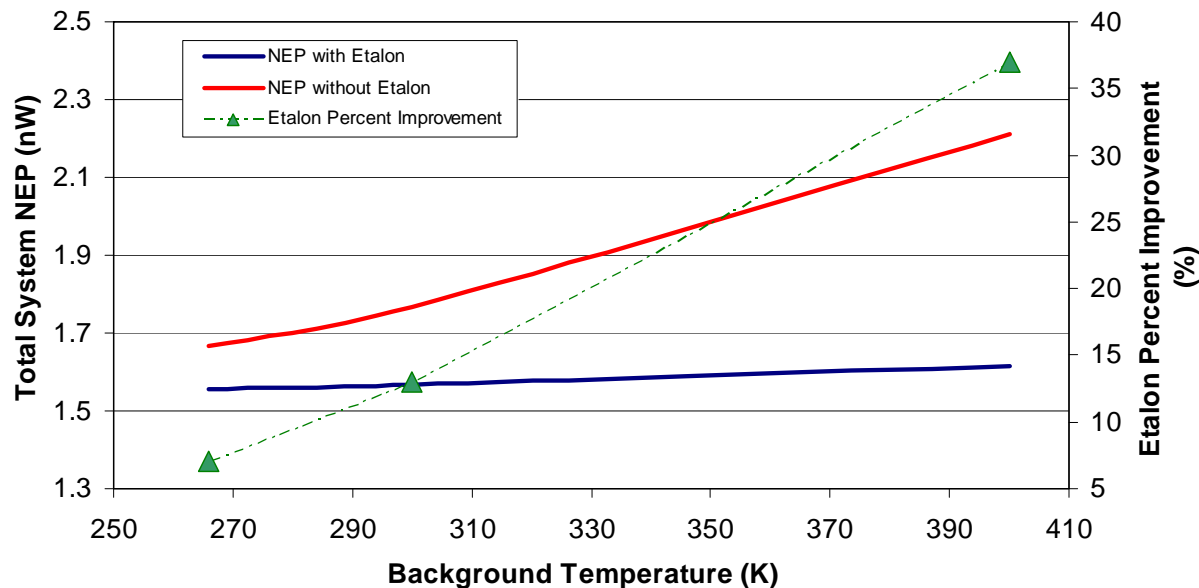
## Detector Mounting Stage



- Assembly designed for ease of integration into FAL system
- Detector mounted on a Yaw, Tilt, XYZ translation stage for easy optical alignment

# FAL Receiver Module: Performance Characterization, System Model

- **Model system performance**
  - Model developed in Matlab
  - Model calculates  $NEP_{BLIP}$  given specific system input parameters
- **System NEP improvement most significant when observing warmer backgrounds which add significantly to the BLIP noise**
  - ~37% improvement at  $T_{bkgd}=400K$
  - ~6% improvement at  $T_{bkgd} = 266K$



- **Experimentally determine system NEP for an electronic bandwidth of 5 MHz and compare with model predictions**

# FAL Receiver Module: NEP Asymptote Measurement

- **Measure NEP contributed by detector thermal noise and preamp. noise (Johnson, voltage, current and leakage noise) – no BLIP noise**
  - Replace cooled lens with blackened piece of aluminum
- **Capture noise density using spectrum analyzer (PSD)**

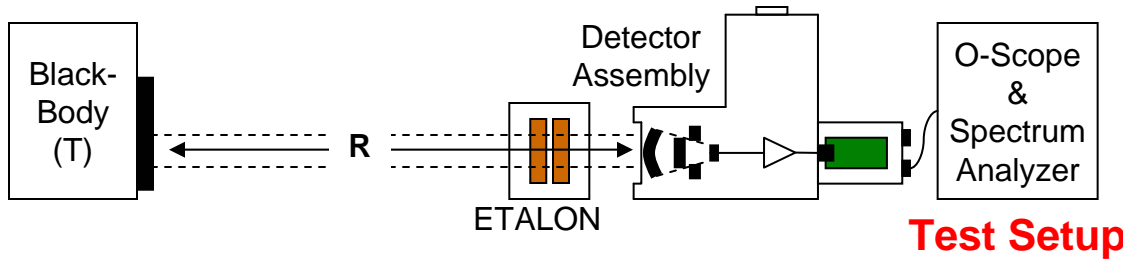
$$\Rightarrow NEP_{total} = \left[ NEP_{Thermal+AmpV,I,Js n+Leak}^2 + \underbrace{NEP_{BLIP}^2}_{\sim 0} \right]^{1/2}$$

$$\Rightarrow NEP_{total} = \frac{1}{R} \left[ \int_0^{5MHz} PSD(f) df \right]^{1/2}$$

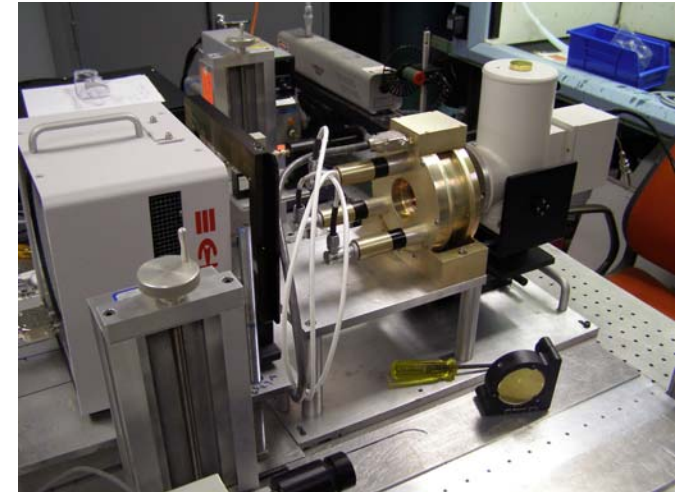
	Gain (Low)	Gain (High)	Bandwidth	NEP (@ 80K) 5 MHz, High Gain
Single Ended	52.98kΩ	213.1kΩ	~16MHz	<b>1.54 nW</b>
Differential	4.64kΩ	18.56kΩ	~20MHz	*

# FAL Receiver Module: NEP<sub>BLIP</sub> Measurement

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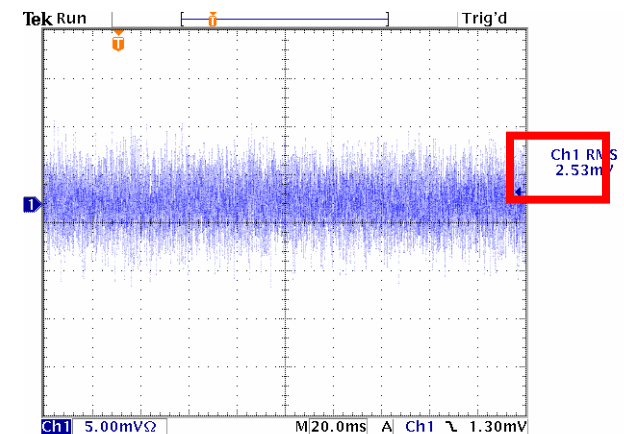


$$NEP_{BLIP} (nW) = \frac{\sqrt{(RMS_{Total})^2 - (RMS_{Gold\_Mirror})^2}}{D_{responsivity} (A/W) \cdot Gain(k\Omega) \cdot (10^6)}$$



- Measure noise baseline by observing gold mirror (looking at ~77K target) positioned in front of detector window
- Tune Etalon to a single wavelength and observe 400K Blackbody
- Measure total NEP using noise PSD captured by spectrum analyzer (or RMS noise on O-scope) with and without etalon inserted in the optical train
- Calculate NEP<sub>BLIP</sub> with and without etalon

## O-scope RMS Noise, Etalon @ m=2



14 Nov 2008  
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# FAL Receiver Module: Performance Characterization Summary

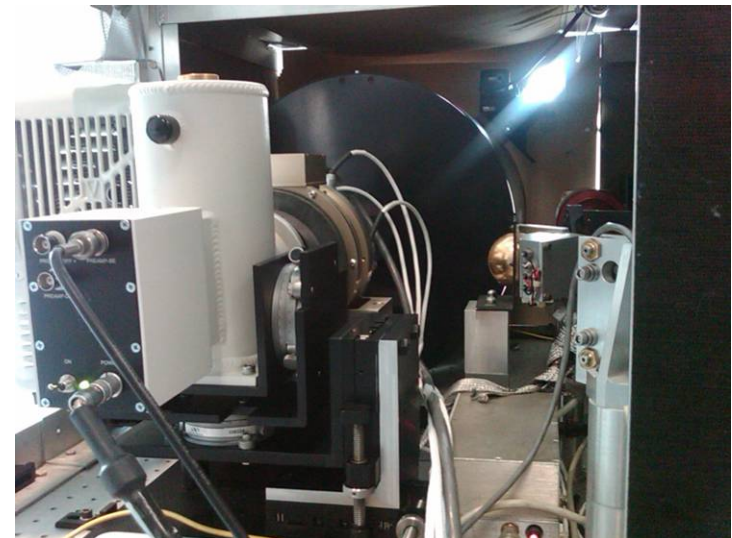
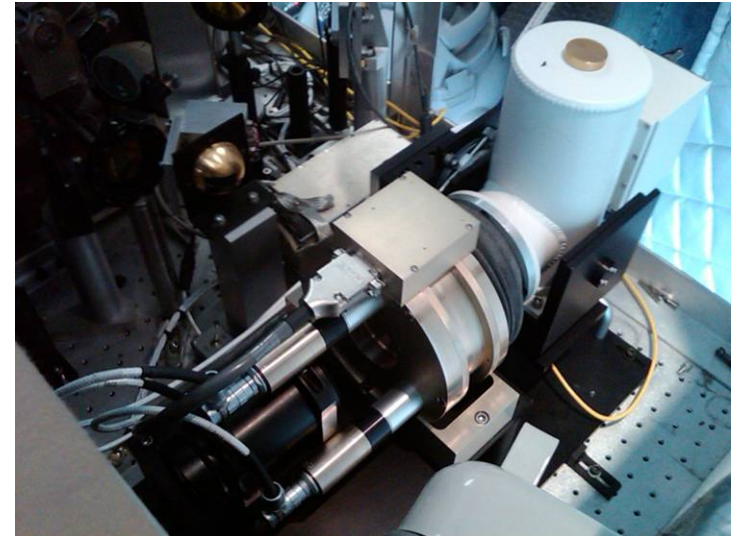
@5MHz, $T_{\text{bkgd}}=400\text{K}$	m=2	m=3	m=4	No Etalon
NEP-Det/Preamp	1.54nW	1.54nW	1.54nW	1.54nW
NEP-Blip (Measured)	0.73nW	0.64nW	0.61nW	1.86nW
NEP-Blip (Modeled)	0.48 nW			1.59nW
Measured NEP <sub>total</sub>	1.70nW	1.67nW	1.66nW	2.42nW
Modeled NEP <sub>total</sub>	1.61nW			2.21nW

- **Objective: NEP  $\leq$  1.5nW for 5 MHz bandwidth**
- **Overall NEP is ~13% higher than design goal**
  - Higher detector capacitance than expected increased NEP
- **Measured NEP improvement through the use of etalon consistent with expected performance**
  - ~ 37% NEP improvement when  $T_{\text{bkgd}}=400\text{K}$

# RM Integration into FAL System

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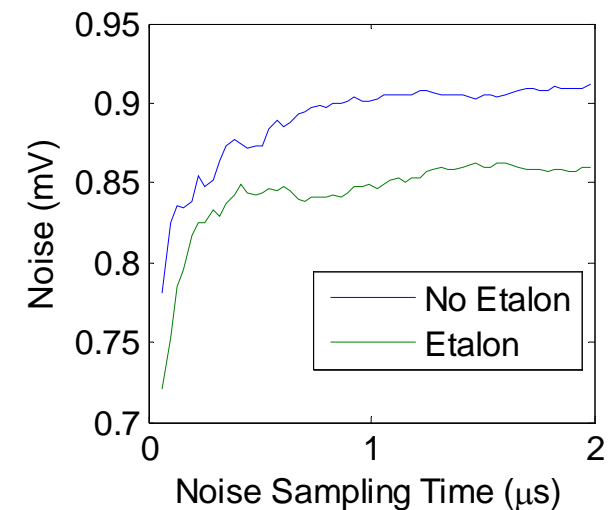
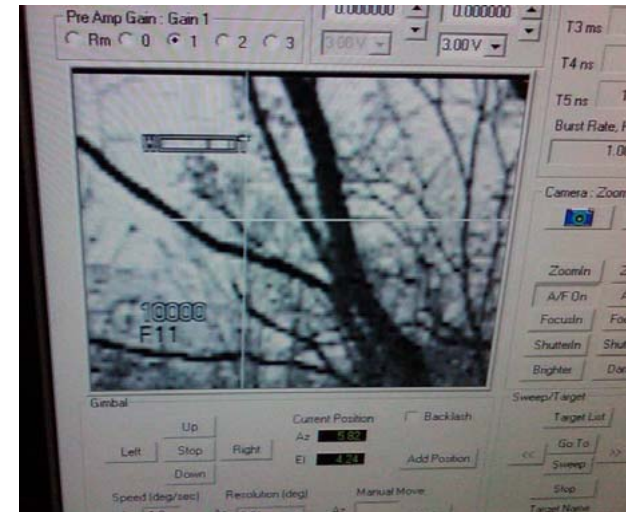
- **Receiver Module (RM) transported to ECBC for full system integration**
  - Dec 16 – 18, 2009
- **Successfully performed system optical alignment**
  - Developed alignment procedure
  - Demonstrated the ability to remove RM in & out and retain the integrity of the optical alignment
- **Successfully integrated RM/TFM with FAL software/hardware**
  - Confirmed TFM can be controlled by FAL software
    - Using DLL functions developed by PSI
  - Characterized integrated TFM operation (with FAL laser on)
    - TFM Convergence time and sigma values
    - Burst and Laser Triggers – with non-lasing triggers inserted
    - Etalon scanning and transmission measurements error against known FAL laser line/s



# RM/FAL System: Performance Characterization

VG10-117-18

- **Performed system characterization**
  - Goal: Characterize FAL/RM system noise and overall improvement due to the use of the etalon
- **Targets:**
  - Hard target @ ~ 400 m (tree branch)
  - $T_{\text{bgd}} \sim 266\text{K}$
- **System Measurements:**
  - Single laser shots (10R20) with etalon fixed at  $975\text{ cm}^{-1}$
  - Single laser shots (10R20) with etalon tuning across the laser line
  - Laser scanning (9 lines) with etalon synced and scanning
- **Blip noise measurements are made by analyzing the noise in the digitizer's traces in the absence of laser light**
- **Analyzed noise gives a good estimation of the Noise Equivalent Voltage, which can be converted to NEP**
  - It is important that laser returns be negligible by  $t_1$  so that the time dependent laser return signal does not contribute to the measured noise.
  - Results demonstrate a ~ 6% NEP improvement through the use of PSI's etalon in the FAL system
  - Results consistent with modeling predictions when system observing a  $T_{\text{bgd}} \sim 270\text{ K}$
- **RM successfully demonstrated expected BLIP noise reduction**



# Conclusions

- **Successfully developed low noise receiver module for FAL**
- **Receiver module is fully compatible with 200 Hz line tuned CO<sub>2</sub> laser**
- **Receiver module achieves total system NEP ~ 1.7 nW for an electronic bandwidth of 5 MHz**
- **NEP<sub>Blip</sub> reduction consistent with modeling predictions**
- **Receiver module was successfully integrated with the ECBC's FAL system**