Lumedyne Technologies Incorporated
9275 Sky Park Ct.
Suite 100
San Diego, CA 92123

Oil & Natural Gas Technology

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FINAL Report

Fabry-Perot MEMS Accelerometers for Advanced Seismic Imaging

Submitted by:
Lumedyne Technologies Incorporated
9275 Sky Park Ct.
Suite 100
San Diego, CA 92123

Principal Author: Brad Chisum

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FINAL TECHNICAL REPORT

This report summarizes the technical achievements that occurred over the duration of the project. On November 14th, 2014, Lumedyne Technologies Incorporated was acquired. As a result of the acquisition, the work toward seismic imaging applications was suspended indefinitely. This report captures the progress achieved up to that time.

The sensor development work occurred over a period of roughly six years. During that time the Lumedyne team made a lot of good progress and overcame challenges that ranging from technical issues to supplier delays. This technical report follows the project progression summarized in the table below:

Project Event	Approximate Date
Initial Design for Seismic Imaging	Q2 2009
MEMS prototypes fabricated	Q1 2010
Secondary Cavity Issue Resolution	Q1 2011
Proof Mass Loop Closure Electronics Demonstrated	Q2 2011
Elimination of Resistive Heater	Q3 2011
Project Transition to Time Domain Switched Technology (TDS)	Q1 2014
First TDS prototypes demonstrated	Q2 2014
Lumedyne Acquired & Project Terminated	Q4 2014

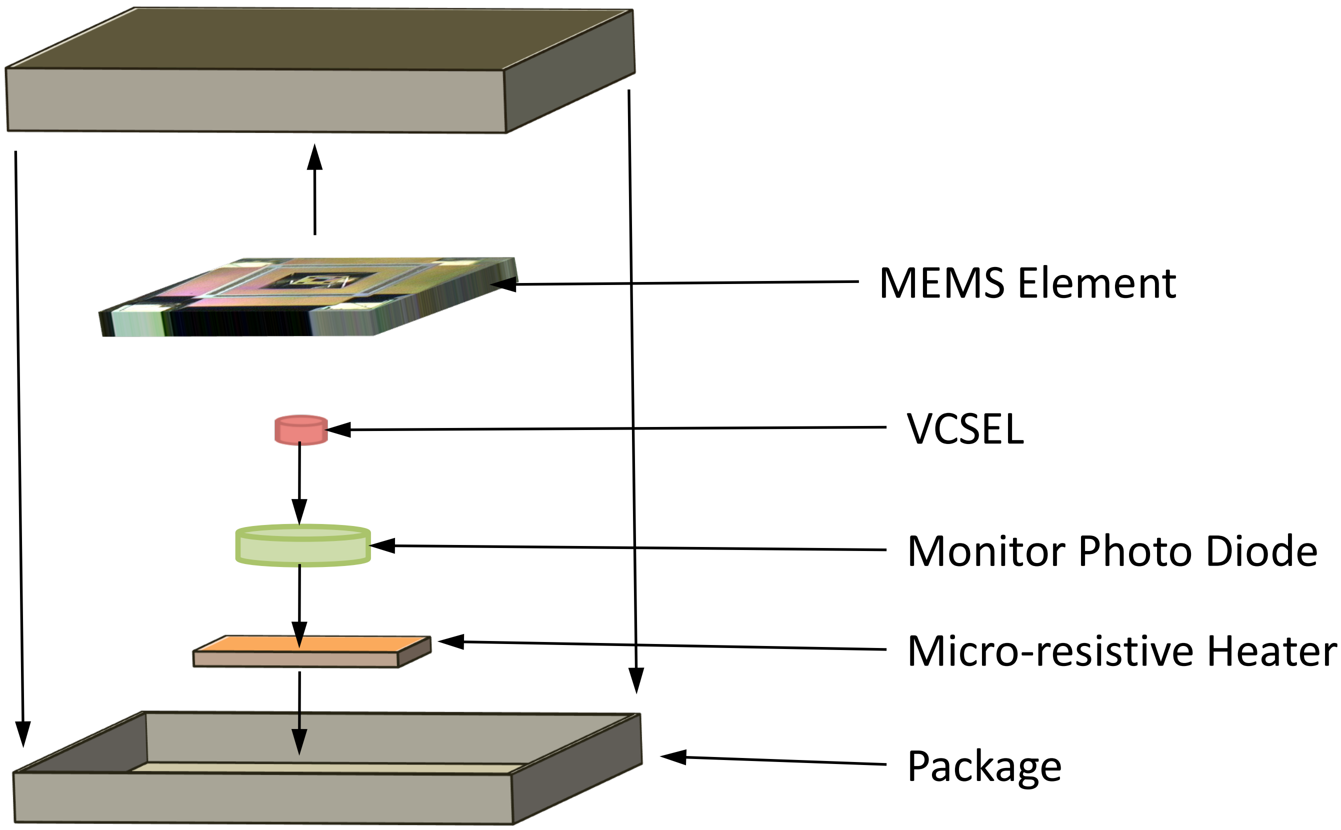
Initial Design for Seismic Imaging

One of the first major efforts of the program was to redesign the Fabry-Perot based accelerometers for seismic imaging applications. This was kicked off with a joint effort with LBNL to develop target specifications to design toward. The specifications are summarized in the table below:

Lumedyne MEMS Seismic Sensor Specification	
Performance	
Full Scale Acceleration	+/- .5 g peak
Digital Quantization	24 Bit (23 +Sign)
Noise	40 ng/√Hz (10 Hz – 750 Hz) 40 ng/√Hz (0 Hz – 10 Hz)
Sample Rate	.5 ms, 1 ms, 2 ms, 4 ms
Frequency Response	0 Hz – .8 Nyquist (-3 dB) all Sample Rates
Equivalent Input Noise	ug rms@ .5 mS, .77 ug rms@ 1mS 548 ng rms@ 2 mS, 387 ng rms@ 4mS

Instantaneous Dynamic Range	113 dB @ .5mS, 116 dB @ 1mS 119 dB @ 2 mS, 121 dB @ 4mS
Total Harmonic Distortion	-94 dB @ 12 Hz, -12 dB RFS
Anti-Alias Filter	.8 Nyquist, Linear Phase, >-128 dB above Nyquist
Tilt	+/- 180^0
Cross Axis Isolation	> 100 dB
Amplitude Accuracy	+/- .25 %
Sensitivity Temp Coefficient	TBD
Offset Thermal Coefficient	TBD
Synchronization	+/- 2 uS relative Sync Input
Calibration Interval	600 S (Min)
Calibration Duration	1S (Max)
Tilt Accuracy	+/- 2^0
Environmental	
Operating Temperature	-40 ^{0}C to + 85 ^{0}C
Humidity	0 to 100 %
Operating Altitude	-100 m to +5500 m
Shock Limit (.5 ms, ½ Sine)	3000 g (peak)
Vibration (20Hz -2000 Hz)	60 g (pk-pk)
Interface	
Command & Control	SPI (Slave)
Data	SPI (Master)
Clock	10.24 MHz (Input)
Sync	Logic Level Sample Rate Clock (Input)
Electrical	
Voltage	3.3V +/- 5%
Power	TBD

With the target sensor specifications established, the next step was a system level design of the sensor. As with all development projects, the design evolved with the project. The drawing below shows an exploded view of the initial packaged MEMS design.

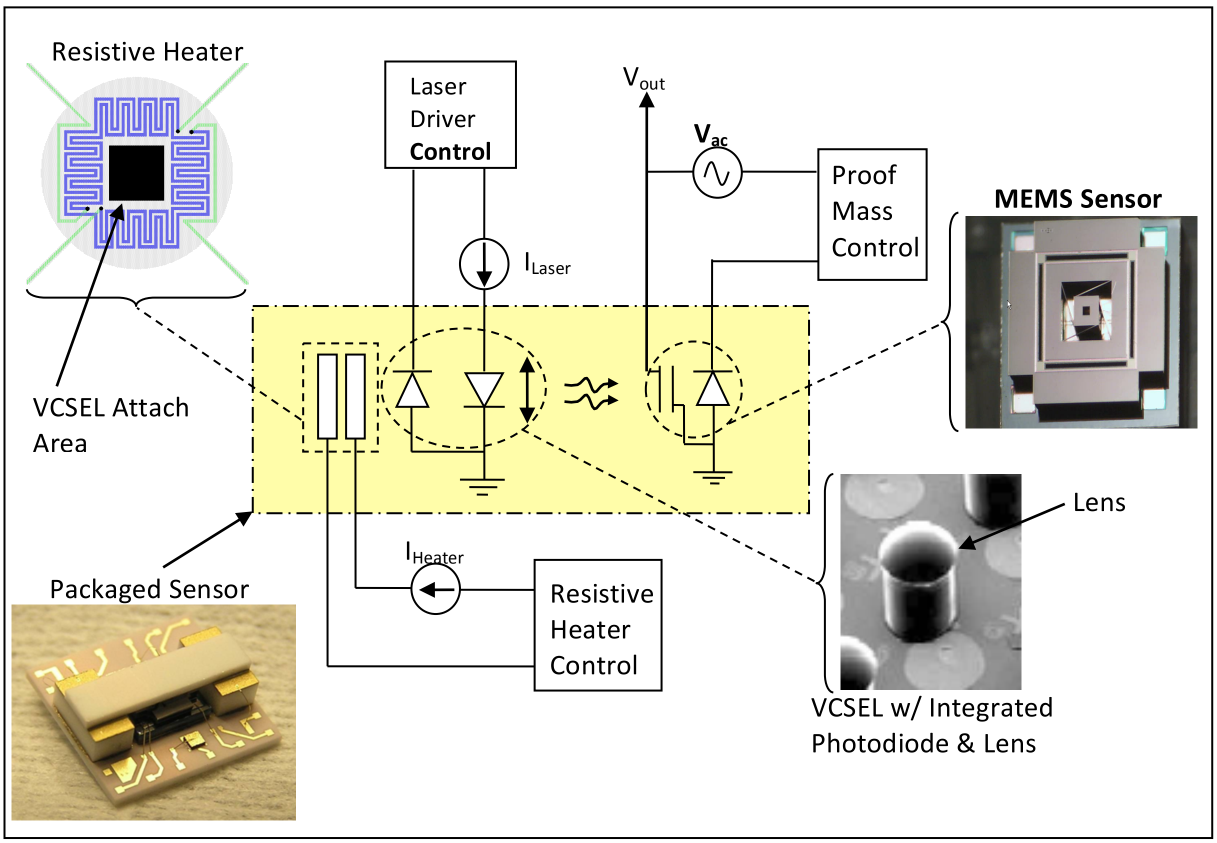


For this configuration, the following list summarizes the system level details:

- MEMS Die has contacts on front and back.
- Back contacts are for Au bump bonds.
- Front side MEMS contacts are wire bonded to package
- VCSEL and photodiode may or may not be pre-bonded (this is TBD).
- VCSEL, Photodiode and Resistive heater all have front side contacts for wire bonding to package.
- Electrical Feed-throughs go to ~12-pin lead frame.
- MEMS Die size ~2.5 x 2.5 mm (thickness is TBD but will be 700-1500 microns)
- VCSEL Die is ~250 x 250 micron by ~125 micron thick
- Photodiode is 200 microns thick
- Resistive heater is 500 microns thick
- Spacing between VCSEL and MEMS die is ~300-500 microns. Tolerance: ±25.4 microns
- VCSEL x,y placement tolerance: ±10 microns
- Mounting Surfaces Flatness Tolerance (for MEMS Die and VCSEL/Heater stack): <25.4 microns

Not included in the drawing above are the electronics. The block diagram below shows the entire sensor design, including the associated control electronics. There are three primary elements of the electronics:

- **Resistive heater control:** The wavelength of the laser changes with temperature and change in wavelength looks like a change in acceleration. By mounting the laser on a resistive heater and holding the temperature of the laser above the operating range, the wavelength output is held constant.
- **Laser driver control:** Any change in the output power of the laser will be indistinguishable from a change in acceleration. The laser driver control loop holds the output power of the laser constant mitigating measurement error from fluctuations in the laser output power.
- **Proof mass control:** The proof mass loop control holds the position of the proof mass constant. This helps linearize the output and extends the dynamic range.



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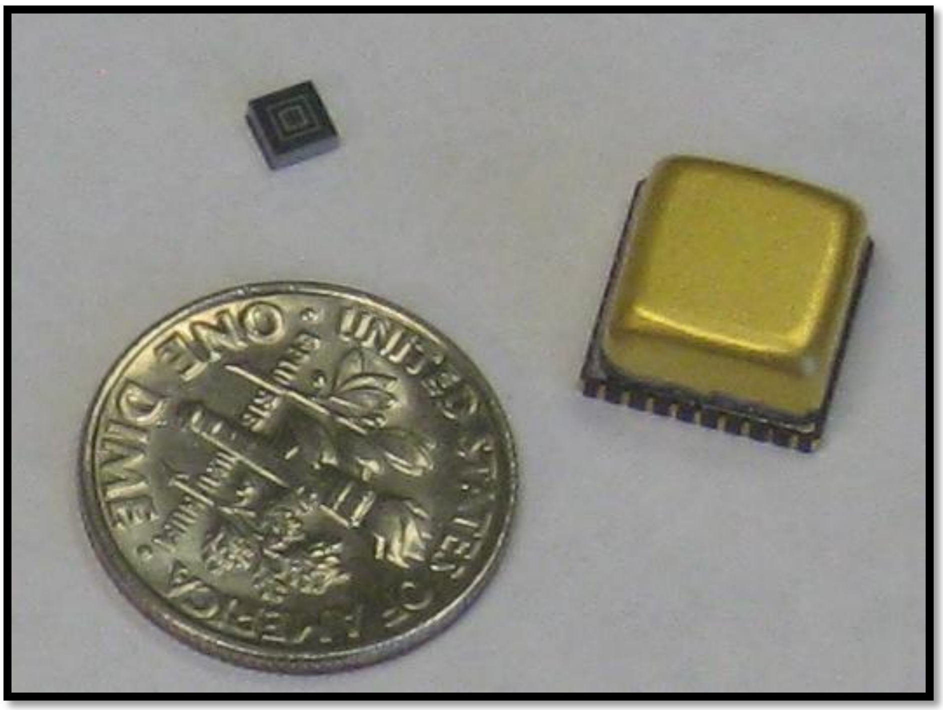
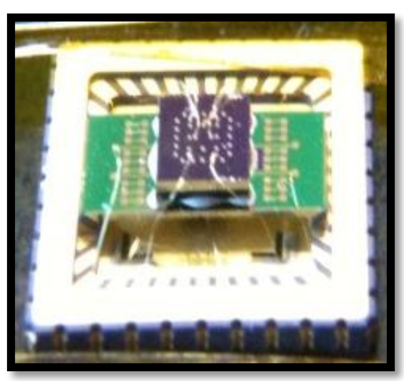
MEMS Prototypes Fabricated

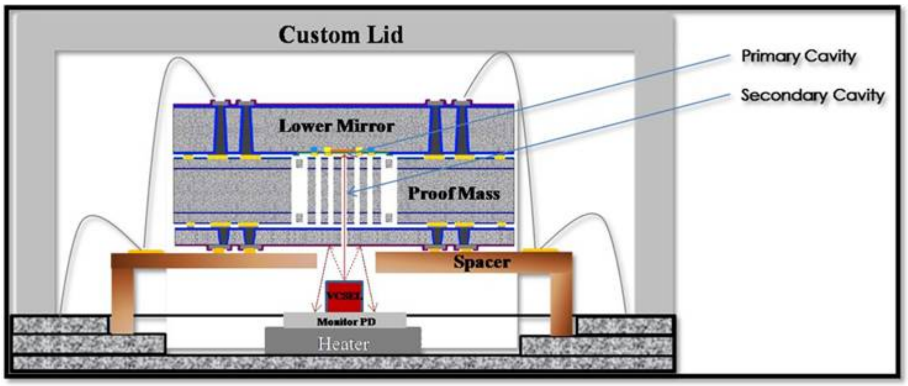
The pictures below show the first fully fabricated MEMS prototypes. There were challenges in the fabrication of these parts that including supplier schedule delays and technical challenges in the fabrication itself. These challenges were largely overcome, but there were some defects in the first parts that limited their performance. Despite these limitations, the prototypes confirmed that the target specifications were achievable and were sufficient to allow other aspects of the sensor (such as the electronics) to continue their development.



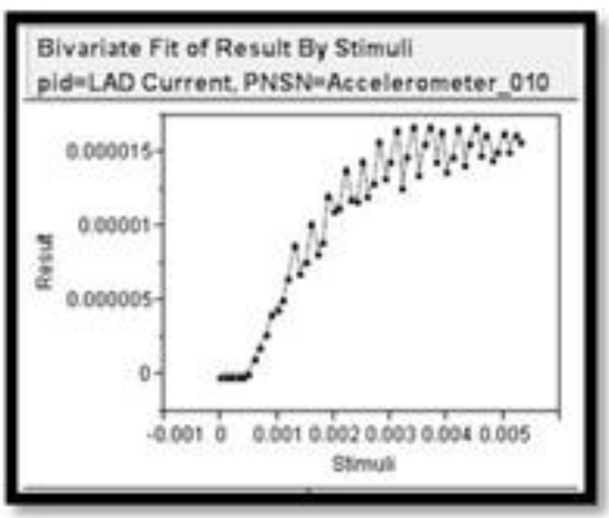


Secondary Cavity Issue Resolution

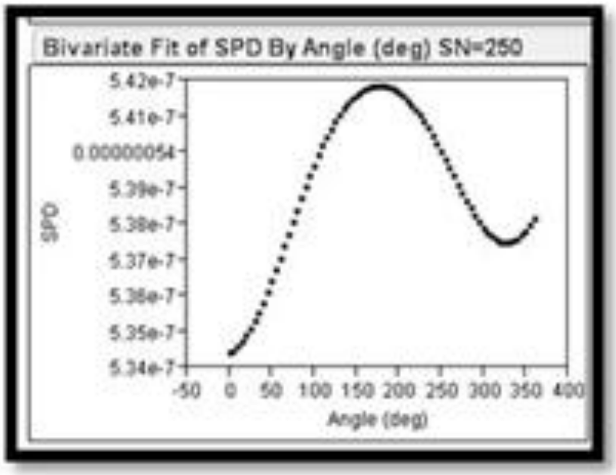
One of the issues that was discovered with the first prototypes was a "Secondary Cavity" problem. With a Fabry-Perot interferometer, there is the intended cavity created by two parallel mirrors. However, the small dimensions of a MEMS based sensor resulted in a situation where a second, unintended, cavity resulted between the output of the VCSEL and the first mirror; as shown in the drawing below.



The secondary cavity creates some undesired effects on the output – essentially, it puts a significant amount of noise on the measurement as shown in the plot below. An ideal plot would be a smooth curve.



The secondary cavity effect was resolved by replacing the VCSEL light source with and RCLED. An RCLED has a coherence that is longer than the intended cavity, but shorter than the secondary cavity. The plot below shows the smooth (and desired) output curve when using an RCLED instead of a VCSEL.



Proof Mass Loop Closure Electronics Demonstrated

The accelerometer uses a proof mass loop closure to extend the dynamic range of the sensor and improve the linearity of the output. The figures below show the electrostatic actuation voltage (blue trace) adjusting the proof mass position to compensate for gravity.

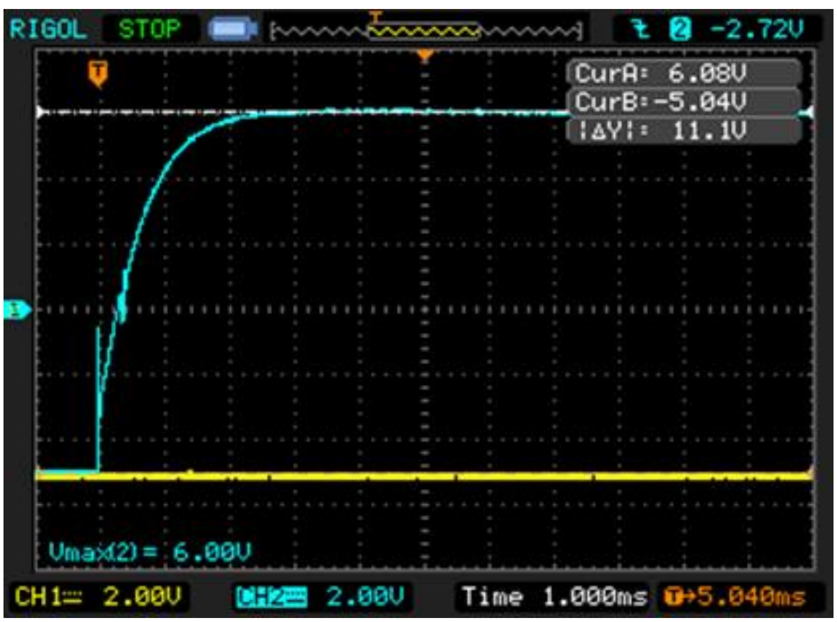


Figure 1: Proof Mass Loop Closure Compensation for Gravity

The plots below show the response to reference step (left image) and 100Hz signal (right image). The pink line represents the acceleration input and the green and blue lines represent the applied voltage of the electrodes controlling the proof mass.

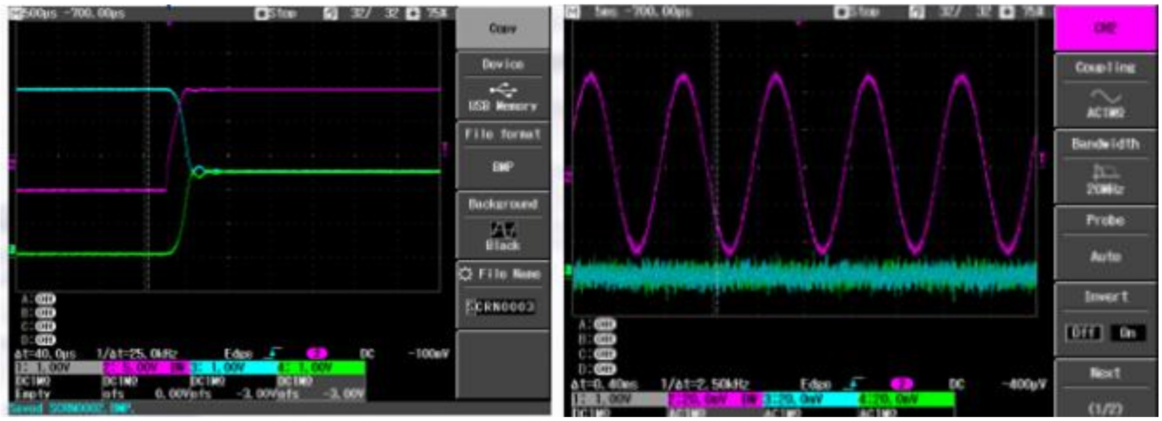


Figure 2: Response of Proof Mass Loop Closure

Elimination of Resistive Heater

The resistive heater was incorporated in the original design to prevent optical power fluctuations due to light source temperature changes from occurring. The Lumedyne team discovered a very strong correlation between the Monitor Photodiode and the electrode voltage over temperature. This correlation can be used to compensate for temperature effects using electronic data processing, which would consume less power and resulting is a less expensive design. As can be seen in the charts below, there is a decent linear fit over temperature between the voltage of the electrode used to control the position of the proof mass (ELM) and the monitor photodiode (MPD). As a result, the actual electrode voltage can be compensated as a function of the voltage change on the monitor photo diode.

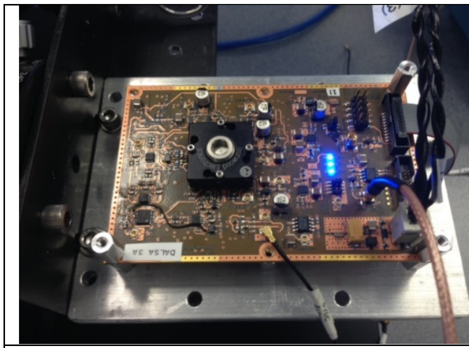
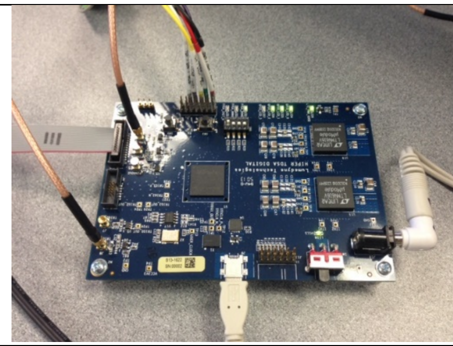
Project Transition to Time Domain Switched Technology (TDS)

In 2014, NETL and Lumedyne agreed to transition the core technology inside the accelerometer from the Fabry-Perot approach to a new technique Lumedyne had discovered called "Time Domain Switched" (TDS). The TDS approach could leverage some of the Fabry-Perot development work and offered the following benefits:

- Improved Low Frequency Response
- Lower Power Consumption
- Lower Unit Cost
- Longer Product Life

First TDS Prototype Demonstrated

The TDS prototype demonstration was performed with PCB level electronics whose noise floor was limited to about 5 micro-g's per root-hertz. However, the MEMS sensor noise floor is less than 30 nano-gs per root-hertz. The MEMS noise floor can be reduced further and, ultimately, the electronics noise floor will be matched to that of the MEMS.

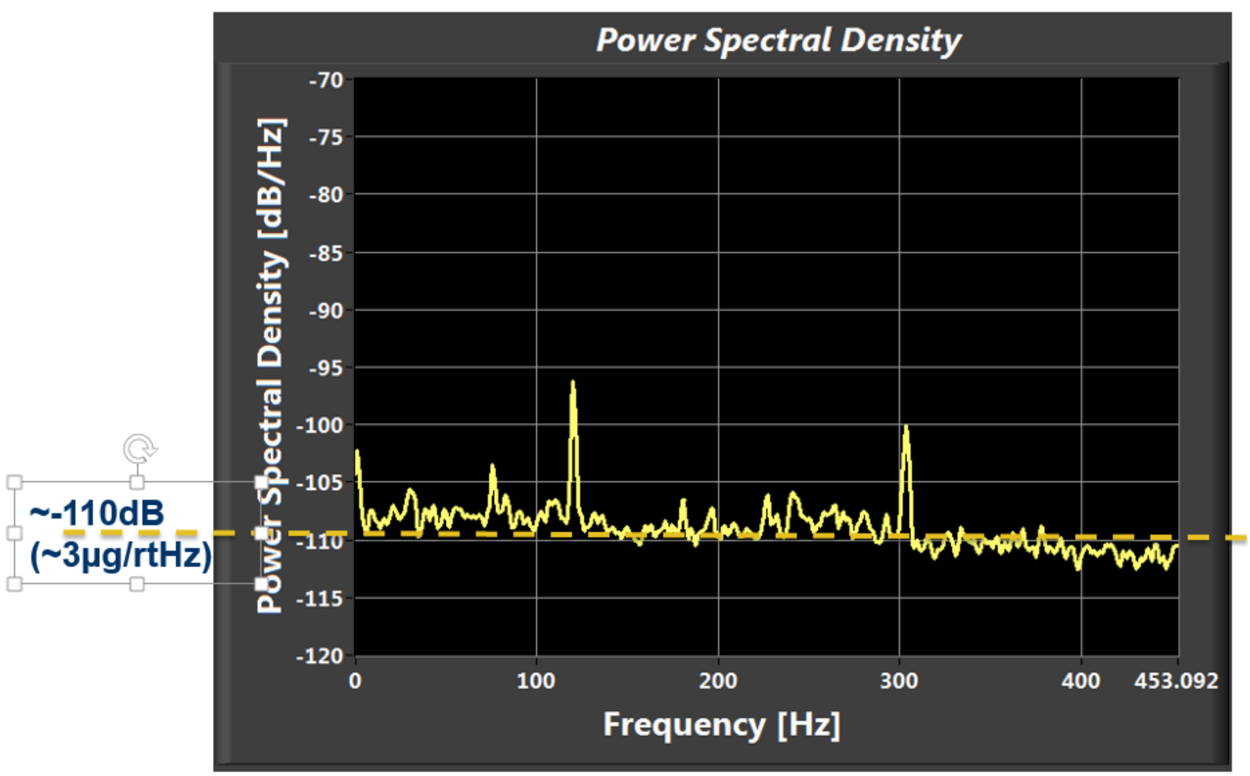
	
Analog PCB with MEMS	Digital TDC FBGA

Measurement results to date demonstrate the following characteristics of TDS:

- Improved 1/f performance: the 1/f knee is <0.003 Hz!
- Improved performance over temperature: Very little change in output over temperature and no observable hysteresis!
- Excellent measurement repeatability.
- No measurement offset error.

Measurement Results:

The power spectral deisity plot below shows a noise floor of approximately 3mg/rtHz with a bandwidth of 450 Hz.



To demonstrate the 1/f knee performance advantage, a low frequency PSD was taken vs. a Colibrys SF 1500 (see the chart below). The Colibrys accelerometer has a 1/f knee at about 3 Hz (normal for MEMS based sensors) and the Lumedyne prototype demonstrates a 1/f knee below 0.003 Hz. To Lumedyne's best knowledge, this is the lowest 1/f knee ever measured by a MEMS device.

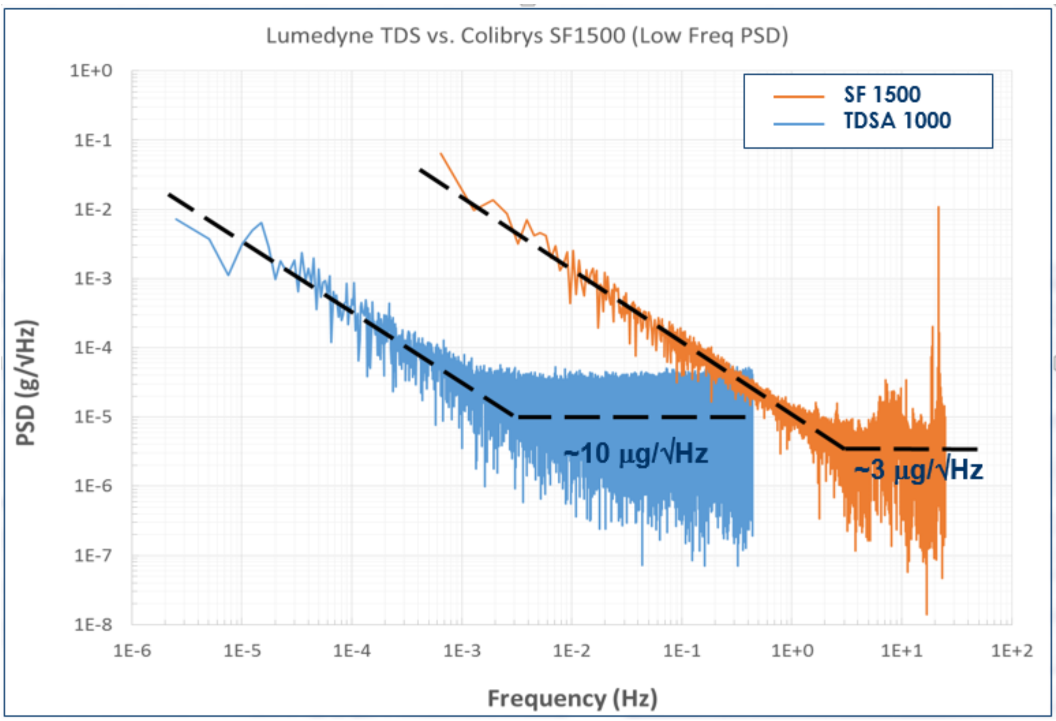


Figure 3: TDS vs Colibrys SF1500

Temperature Sweep Test:

The TDS technology is inherently immune to the impact of temperature changes. Perhaps more important, however, is that he technology does not exhibit temperature historesis. The plots below show Lumedyne's TDS vs. an Invensense MPU-6500 undergroing a temperature sweep from 15 degrees C to 65 degrees C and back down. The MPU-6500 displays a classic eye-diagram while the Lumedyne TDS does not.

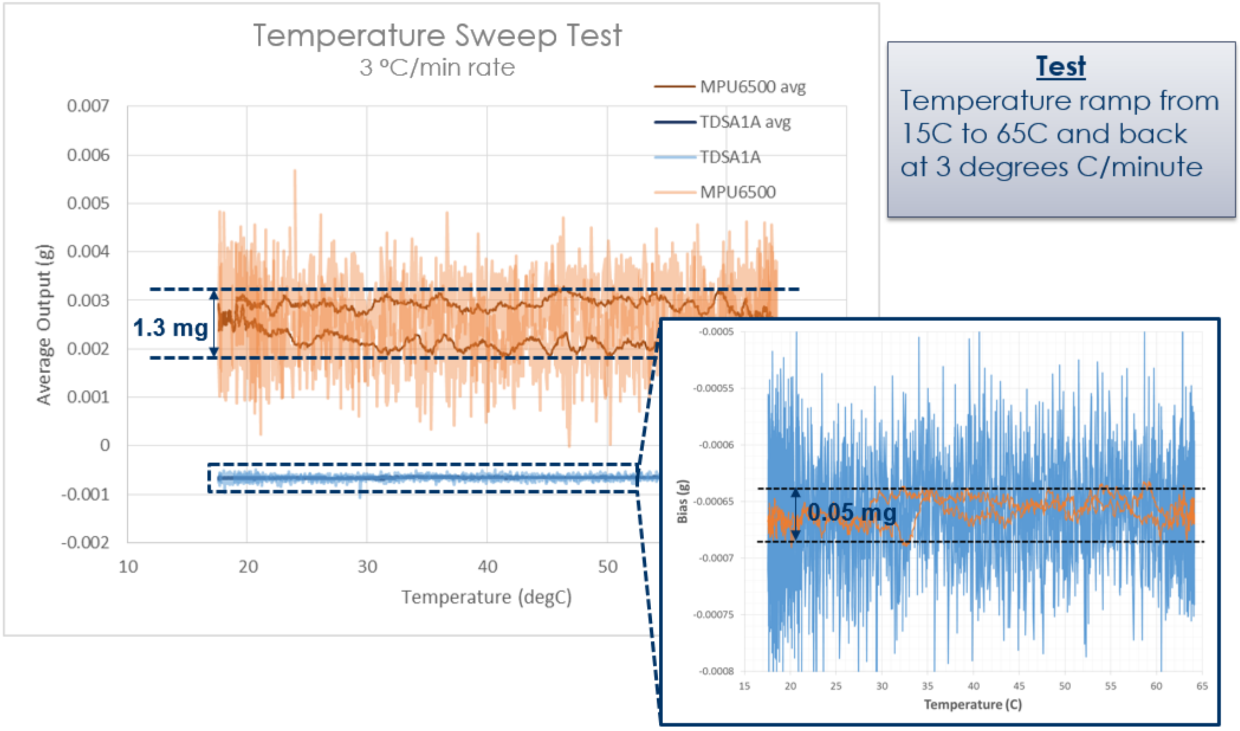


Figure 4: Temperature Sweep Test

Lumedyne Technologies Acquired and Project Terminated

On November 14th, 2014, Lumedyne Technologies was acquired. While the acquisition was a result of the technical accomplishment of the TDS technology, the new company elected to suspend the development of the technology for seismic imaging applications. Development of the TDS technology for other applications continues.

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

One West Third Street, Suite 1400
Tulsa, OK 74103-3519

1450 Queen Avenue SW
Albany, OR 97321-2198

2175 University Ave. South
Suite 201
Fairbanks, AK 99709

Visit the NETL website at:
www.netl.doe.gov

Customer Service:
1-800-553-7681