Adaptive Tunable Laser Spectrometer For Space Applications

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***Abstract*—An architecture and process for the rapid prototyping and subsequent development of an adaptive tunable laser absorption spectrometer (TLS) are described. Our digital hardware/firmware/software platform is both reconfigurable at design time as well as autonomously adaptive in real-time for both post-integration and post-launch situations. The design expands the range of viable target environments and enhances tunable laser spectrometer performance in extreme and even unpredictable environments. Through rapid prototyping with a commercial RTOS/FPGA platform, we have implemented a fully operational tunable laser spectrometer (using a highly sensitive second harmonic technique). With this prototype, we have demonstrated autonomous real-time adaptivity in the lab with simulated extreme environments.**

I. Introduction

The Tunable Laser Spectrometer (TLS) is a JPL space flight instrument originally built for the Mars Science Laboratory (MSL) mission to Mars in 2011 but is now being considered for many other future flight missions, some involving very challenging environments such as Venus. Although TLS is currently meeting all of its advertised requirements, we have seen some performance variation during extreme parts of the thermal-vacuum testing. None of these issues are necessarily difficult to solve, but optimizing the instrument at this point is problematic, since TLS has already been integrated with other instruments. Access to the instrument is limited and risk to other instruments is a very real concern. To accommodate both re-configurability for new missions as well as post-integration/post-launch optimizations, a new software/electronics platform is needed.

Specifically, our goals are:

(1) Build a system that is, to the extent possible, a completely digital design. This approach is flexible, lowers the cost, the part count, and also decreases the fabrication complexity.

(2) Build a system using hardware that can be reconfigured with software (*via* FPGA technology).

(3) Build a system that can autonomously adapt to changes in its environment by using feedback from housekeeping data sensors and from the collected spectra, which are rich in information.

(4) Build a system that can process data on-the-fly, if necessary, to deal with lower data bandwidth/data volume scenarios.

(5) Build a system that can scale easily, if more laser channels are desirable.

Our development process has two major steps. The first step is rapid prototyping of the laser control and signal processing electronics with specialized commercial hardware. This allows us to efficiently evaluate performance and trade-offs between analog and digital signal processing techniques. We can also experiment with adaptive algorithms that can continually optimize spectral quality in terms of laser power, scan stability and optical fringe reduction. In the second phase, the optimized design will be migrated to a rad-hard RTOS/FPGA based implementation suitable for flight.

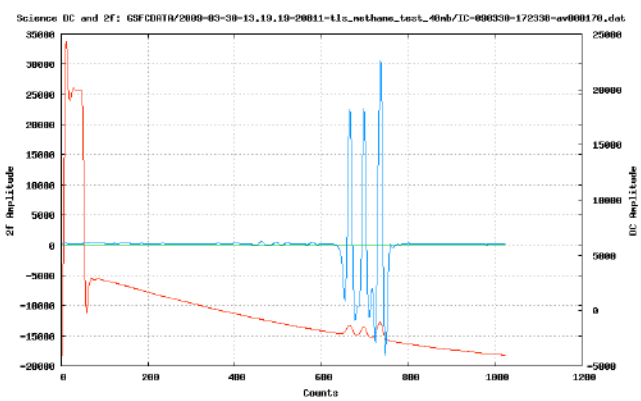
In Section II, we describe the general operation of the Tunable Laser Spectrometer (TLS) and the wavelength modulation spectroscopy technique that is key to the instrument's sensitivity. In Section III, we describe the spectrometer's overall architecture and present our implementation of the modulation and demodulation algorithms. In Section IV we show the results of our prototype work with adaptive algorithms and finally discuss our conclusions in Section V. For a more complete discussion of the existing analog TLS space flight electronics and software implementation see [8].

II. TLS Description

The Tunable Laser Spectrometer, built at the Jet Propulsion Laboratory (Principal Investigator Chris Webster), is one of 3 science instruments that make up the NASA GSFC Sample Analysis at Mars (SAM) instrument suite (Suite Principal Investigator Paul Mahaffy) on the MSL payload [6]. TLS is a 2-channel tunable infrared laser absorption spectrometer with the capability of making accurate measurements of the mixing ratios of several target gases and their isotope ratios.

For the MSL mission, specific target gases are H2O, CH4, and CO2, along with their isotopes [3].

TLS is a harmonic absorption spectrometer. A full description of the technique can be found in Webster et al. [1], but we describe it briefly here. Lasers are selected to tune through infrared regions of the electromagnetic spectrum where the target gases are known to absorb light. Gas is injected into a multipass Herriott cell [2] and the lasers tune "through" the spectral absorption lines either by changing the ramp current (changing the index of refraction of the laser cavity) or with temperature (changing the length of the laser cavity). Normal operation is to hold temperature constant with a PID circuit and then tune only with the current ramp through the laser. For greater sensitivity, TLS uses Wavelength Modulation Spectroscopy (WMS) [4]. A small amplitude sinusoidal wave of frequency *f* is superimposed on the laser current ramp. This technique carries the signal into a higher frequency, away from *1/f* noise. The detector is then demodulated at twice the laser modulation frequency (second harmonic spectroscopy) and the signal is bandpass filtered around this 2f frequency. Using this method, TLS can detect absorption levels of many gases at the parts per billion level. Figure 1 shows a typical TLS spectra with the direct absorption in red, with the second harmonic spectra in blue. The second graph shows the same spectra with the *2f* signal magnified. Note that the *2f* signal can detect absorptions too small to be seen in direct absorption. Because very small gas concentrations are to be measured, TLS also records reference spectra by beam-splitting a percentage of the laser light through a small cell of known gas composition and concentration. This can be used to correlate between scans if lines are noisy and need averaging or integrating.



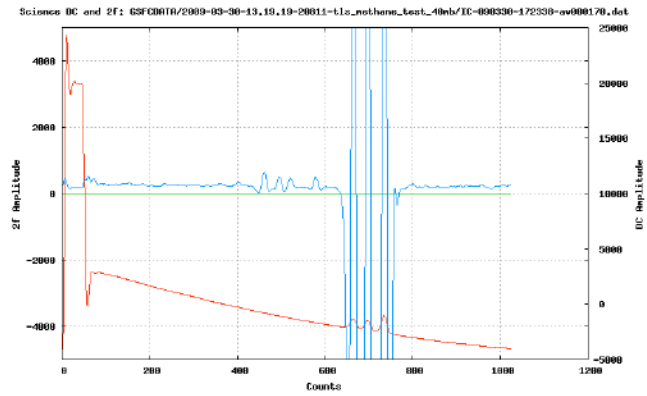


Figure 1. TLS Methane Spectra

III. Implementing the Next Generation TLS

For the prototyping platform we chose the CompactRIO system from National Instruments [7]. The CompactRIO is a reconfigurable embedded system containing three main components: a real-time controller, a reconfigurable field-programmable gate array (FPGA), and industrial I/O modules. The real-time controller contains a PowerPC processor 533MHz running VxWorks to deterministically execute LabVIEW Real-Time applications. The reconfigurable Virtex-5 LX FPGA chassis is directly connected to the I/O modules for high-performance access to the I/O circuitry of each module and can control timing, triggering, and synchronization. I/O modules contain signal conditioning and conversion circuitry such as 4-Channel, 16-bit per channel analog output for the laser excitation and a 32-Channel, 16-bit analog input Module for the detector signal chain and the house keeping data.

For our purposes, the main advantages of the CompactRIO platform are the programmatic control of all hardware components and the hard real-time capabilities of the programming environment and the operating system.

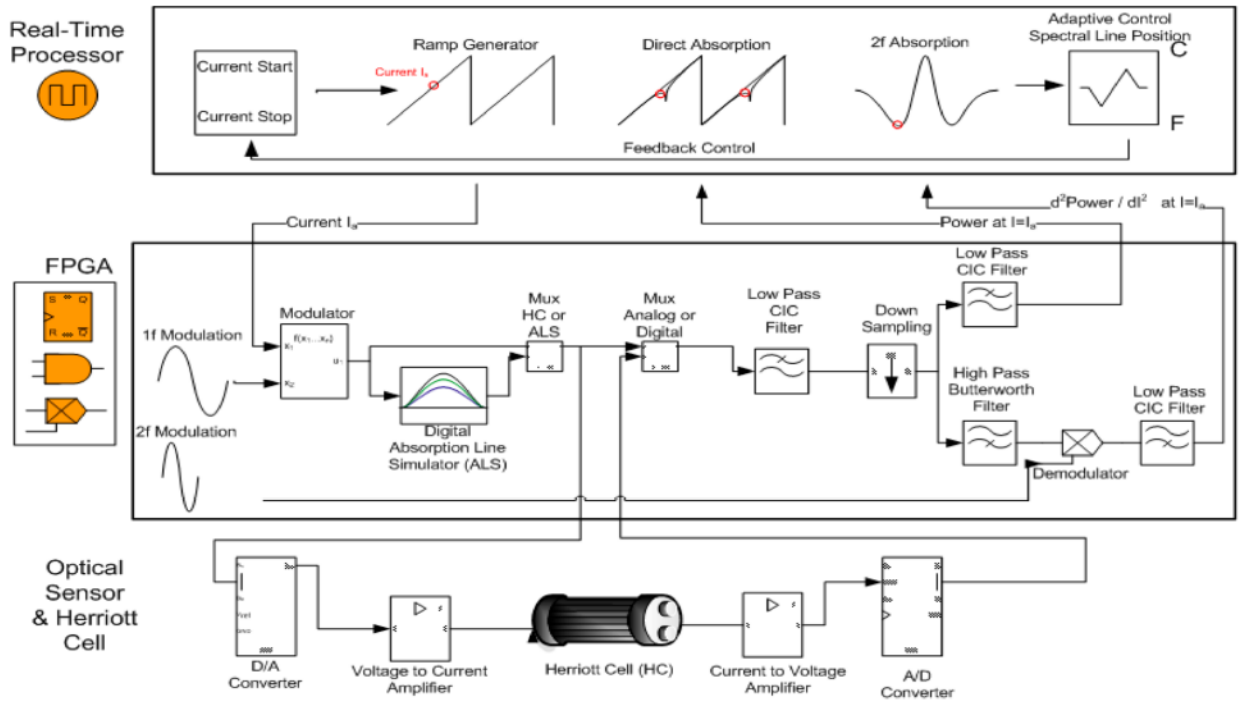
A. Architecture

The block diagram of the adaptive TLS is based on 3 main components:

1. The Real-Time Operating System simultaneously handles communication with the user, controls precision timing for ramp generation and adaptive algorithms, and provides a simple interface to the reconfigurable hardware.

2. The digital reconfigurable hardware implements the real-time modulation of the laser current and demodulation of the detector signal with all of the necessary digital filtering for signal processing.

3. The Input/Output interface converts between the analog and digital domains. We use a 16bit digital to analog converter (DAC) with analog drive circuitry to control the laser current output. The detector signal is measured by a photodiode whose signal is immediately amplified and then converted into a voltage and digitized by a 16 bit analog to digital converter (ADC).



B. *Laser Current Scan and Modulation*

The laser current ramp is a composite signal comprised of two repeating and reprogrammable look-up tables. The first look-up table is stored on the RTOS processor and contains a trapezoidal current ramp of programmable amplitude. The second programmable look-up table is stored on the FPGA and implements a sinusoidal modulation waveform (*1f*). In a loop on the RTOS processor, each laser ramp value is sent to the FPGA. In a second asynchronous loop executed on the FPGA, the *1f* values are retrieved from the modulation table and then offset by the current laser ramp value. This new value is then written to the 16 bit DAC.

In contrast with recording *2f* spectra using the traditional analog approach (where an asynchronous current modulation was added to a time varying current ramp), the digital approach allows us to modulate and measure the *2f* spectra for each individual laser ramp value. This "point-by-point" approach has several benefits:

1. Since the value of the laser current ramp is held constant during modulation, we avoid any low frequency contribution from the laser current ramp to affect the 2f spectra.
2. We can explicitly control the frequency, resolution and timing of both the 1f and 2f frequencies. Both are generated in lookup tables and indexed simultaneously. This synchronous approach makes our design less sensitive to jitter.
3. Because we generate the modulation "point-by-point", we do not have to generate nor store large arrays in memory. This approach effectively decouples the laser current ramp size from the fidelity (i.e. number of points) of the sinusoidal modulation. This conserves memory and reduces the communication overhead between the RTOS and the FPGA.

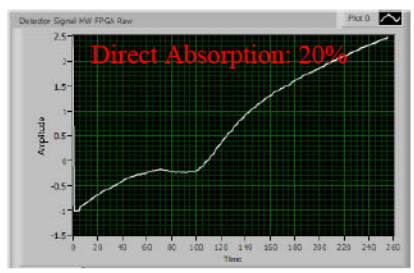


Figure 2. Direct Absorption Spectra

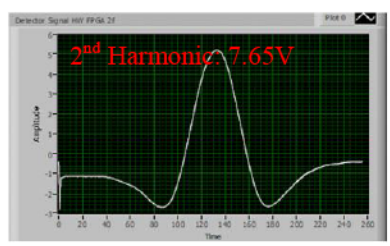


Figure 3. Second Harmonic Absorption

C. *Signal Detection*

The output of the Herriott Cell detector is converted to the digital domain through a current to voltage amplifier and a 16-bit ADC. The digital signal is processed through a programmable staged cascaded integrator comb (CIC) finite impulse response (FIR) low pass filter and is then down-sampled to reduce white noise. Next, the signal is processed through a 16 stage CIC FIR low pass filter to produce the DC component (direct absorption) of the spectra shown on Figure 3. This value is returned to the RTOS processor. The same down-sampled digital signal is simultaneously processed through a Butterworth infinite impulse response (IIR) high pass filter to produces the AC component (*2f* absorption) of

the spectra. Demodulation is then accomplished by multiplying this AC component by the *2f* modulation waveform retrieved from a third lookup table that implements a frequency twice that of the *1f* table. Because the two values are accessed during the same loop iteration, they are guaranteed to always have the same phase relationship, regardless of jitter. Finally, this signal is passed through another CIC FIR low-pass filter and the resulting *2f* modulation component response is sent to the RT processor.

IV. Results

We tested our adaptive TLS implementation both for signal to noise ratios (SNR) and adaptive performance. For these early tests, we analyzed analog signals (through commercial DAC and ADC hardware) using a Herriott Cell in the testbed shown on Figure 4. The testbed also includes an infrared tunable laser with a TEC that is controlled by a commercial ILX Lightwave laser driver. The cRIO software sends out the ramp and modulates the laser current as explained in the previous section and after gas absorption in the cell, the detector measures the power from the photodetector through the current to voltage preamplifier. Finally the user graphical interface is run on the laptop controlling the interface of cRIO.

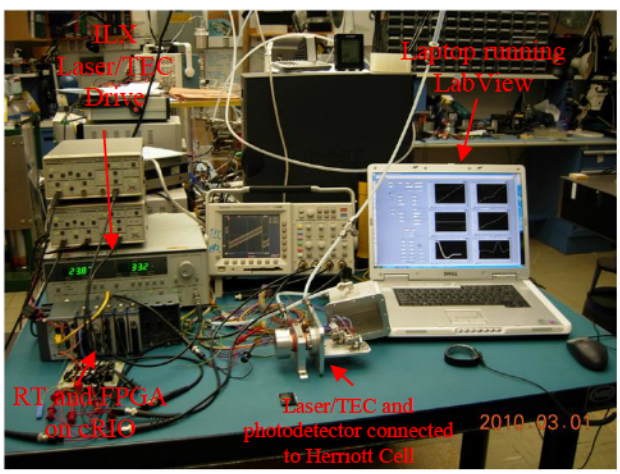


Figure 4. TLS Testbed

A. Signal to Noise

Table 1 below shows the SNR performance of Digital TLS as a function of the scanning speed. For our tests, we used a 2 percent absorption signal and a ramp refresh rate of 23 Hz. (This current scan rate is limited by the 200kHz sampling rate of the DAC and ADC of the cRIO platform).

At low scan rate (and large number of samples up to 10^6), the table shows that the digital implementation achieves an electronics system noise level on the final 2f spectra of less than 3.6 parts in 10e5 of the power reaching the detector in a 6 seconds average. These early results compare favorably with the existing analog design.

TABLE I. Singal To Noise Performance

Scan Frequency**		SNR rms *
23	Hz	460
7	Hz	1079
0.23	Hz	8920
0.02	Hz	25000

*measured for 2% deep H2O absorption line
** used 128 samples per current ramp

B. Adaptibility

As mentioned earlier, adaptability is a vital goal for next generation tunable laser spectrometers. For our early implementation efforts, we have built a simple algorithm to control the position of the target spectral lines in the scan window. Recall that tunable lasers tune both with current and temperature. While the design tries to hold the laser temperature constant, thermal "sneak-paths" or poor performing electronics can cause the lasers to operate at the wrong temperature and tune over regions that miss the target lines. This could be disastrous for missions with short, critical measurement opportunities.

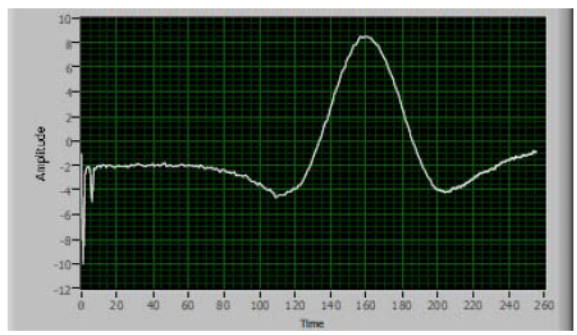


Figure 5. Spectral Line is locked at position 160

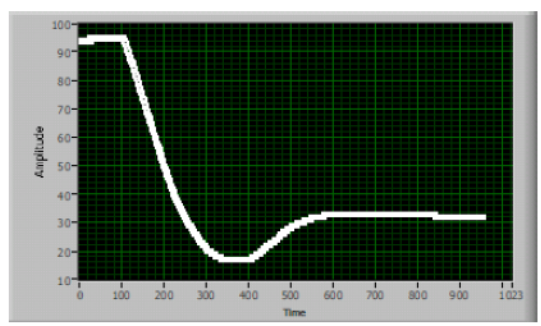


Figure 6. Autonomous Adjustment of current to maintain position of 160

We can mitigate against this problem by "locking and tracking" an absorption line in the reference spectra. This reference scan, which has a constant, known composition and concentration, provides strong detectable features at all times during the mission. We save a typical reference scan in non-volatile memory and use it during every initialization to locate the correct scan window with our target lines. This is the locking phase where we correlate the stored reference scan with the most recently retrieved reference scan, stopping

when we have found the optimum correlation. After locking, the tracking phase follows where the error is used as feedback in a software-implemented PID control loop to follow any small variation of the target lines.

Figures 5 and 6 show the response of the system to a controlled thermal disturbance of the laser temperature. In Figure 6, the x-axis shows the time and the y-axis displays the current offset added to the entire laser current ramp to keep the spectral feature from moving. Initially, the line has stabilized at a position of 160 as shown on Figure 5 with a current offset of 95. Since the temperature of the laser has been changed, the algorithm detected that the spectral line shifted by a very small amount during one scan time (100ms). The algorithm compensates immediately by adjusting the laser current offset. The feedback value from the PID loop is immediately added to the current offset of the laser start and end current. For our chosen set of PID tuning parameters, the system is able to track the change of temperature and to keep the line at index 160. Of course, the PID parameters can be tuned to have either gentler or more aggressive results, based on the needs and behaviors of the individual system.

Using this and other adaptive techniques (e.g. correlation, FFT analysis, empirical heuristics) we plan to extend adaptivity to many other performances issues common to laser absorption spectrometers such as pressure dependent modulation, automatic gain adjustment and adjustment of modulation frequency in response to signal quality.

V. Conclusion

Our goal has been to design and build an autonomously adaptive digital spectrometer for space applications using, in a first step, a flexible and adaptive digital TLS on a rapid prototype platform. Our early results compare favorably with that of the existing analog version of TLS and demonstrate that the digital system is able to adapt to change in the environment. Our future work will include continuing to experiment with transforming traditional analog spectroscopy techniques into the digital realm and add more of the adaptive features mentioned above to our existing prototype. Also, we plan to fabricate a proto-flight spectrometer and fly this spectrometer on high-altitude aircraft and balloon platforms.

Acknowledgment

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