MATCHED FILTER ENHANCED FIBER-BASED LIDAR FOR EARTH, WEATHER AND EXPLORATION

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Abstract: Among the science investigations that are of interest in the NASA Space Science, Earth Science and Planetary Science disciplines are data for surface elevation information, atmosphere chemical composition, atmosphere dynamics and meteorology. A laser sensor architecture has been developed at ITT using both internal and IIP funds which is capable of addressing these science data needs. This architecture also simultaneously transmits online and offline wavelengths. This reduces noise from the atmosphere, target and sensor into a common-mode term which is readily removed. An end-to-end simulation of a multi-channel laser absorption spectroscopy system using amplitude modulated laser beams has been constructed and verified by experimental data from a near IR system tuned to a CO_2 absorption line using telecom laser components (DFB, Modulator, EDFA) and a cooled HgCdTe detector. The verification has been accomplished using multipath absorption cells in the laboratory, horizontal column measurements in the field and vertical column measurements from an aircraft platform. This architecture is also viable in the MWIR wavelength region using readily available sources. In addition, a single channel end-to-end system simulation using pseudo-noise (PN) codes has been developed for ranging applications. Here the information is extracted from the received signal using correlation techniques. This waveform has the promise of being more sensitive than the sinusoidal waveform because digital detection approaches can be used. With sufficient backscatter cross section or laser power this PN waveform can be used to address the need for the distribution of winds in the atmosphere.

I. INTRODUCTION

It is a common misconception that continuous wave (CW) laser sources, such as those used in the telecommunication industry, are not suitable for NASA missions. We have shown that by modulating these sources, and using a matched filter receiver, very sensitive lidar systems can be constructed, using low cost and readily available fiber amplifiers/lasers. The compelling reason to use cw fiber sources is that the tremendous demand for products imposed on telecom industry has forced them to mature the technology and more critically the manufacturing processes to a very high level. The sustained market base ensures that they can routinely deliver a highly reliable product, at a low cost, in a timely manner. [None of these mission enabling criteria can be met for any one-off laser manufactured by industry or the government.] In this period of severe budget constraints, NASA should seek to leverage the industrial base to the maximum extent possible.

II. EXPLOITATION OF LOCK-IN APLIFIER TECHNIQUE TO LIDAR

A. Basics of Lock-In Amplifers

We learn from Stanford Research that "*Lock-in amplifiers are used to detect and measure very small AC signals all the way down to a few nanovolts. Accurate measurements may be made even when the small signal is obscured by noise sources many thousands of times larger. Lock-in amplifiers use a technique known as phase-sensitive detection to single out the component of the signal at a specific reference frequency and phase. Noise signals, at frequencies other than the reference frequency, are rejected and do not affect the measurement.*" [1]

Continuing from Stanford Research, "*typically, an experiment is excited at a fixed frequency (from an oscillator or function generator), and the lock-in detects the response from the experiment at the reference frequency. If the sine output from the function generator is used to excite the experiment, the signal is Vsigsin(ωrt + θsig) where Vsig is the signal amplitude, ωr is the signal frequency, and θsig is the signal's phase.' The lock-in amplifies the signal and then multiplies it by the lock-in reference using a phase-sensitive detector or multiplier. The output of the PSD is simply the product of two sine waves:*

$$V_{psd} = V_{sig}V_L\sin(\omega_r t + \theta_{sig})\sin(\omega_L t + \theta_{ref})$$
$$= ½V_{sig}V_L\cos([\omega_r - \omega_L]t + \theta_{sig} - \theta_{ref}) - ½V_{sig}V_L\cos([\omega_r + \omega_L]t + \theta_{sig} + \theta_{ref})$$

The PSD output is two AC signals, one at the difference frequency (ωr - ωL) and the other at the sum frequency (ωr

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[1] Stanford Research, Application Note #3

$+\omega L$). If the PSD output is passed through a low pass filter, the AC signals are removed. What will be left? In the general case, nothing. However, if ωr equals ωL, the difference frequency component will be a DC signal. In this case, the filtered PSD output will be:

$$V_{psd} = \tfrac{1}{2} V_{sig} V_L \cos(\theta_{sig} - \theta_{ref})$$

This is a very nice signal - it is a DC signal proportional to the signal amplitude.

Suppose that instead of being a pure sine wave, the input is made up of signal plus noise. The PSD and low pass filter only detect signals whose frequencies are very close to the lock-in reference frequency. Noise signals, at frequencies far from the reference, are attenuated at the PSD output by the low pass filter (neither $\omega noise$ - ωref nor $\omega noise$ + ωref are close to DC). Noise at frequencies very close to the reference frequency will result in very low frequency AC outputs from the PSD ($|\omega noise - \omega ref|$) is small). Their attenuation depends upon the low pass filter bandwidth and rolloff. A narrower bandwidth will remove noise sources very close to the reference frequency; a wider bandwidth allows these signals to pass. The low pass filter bandwidth determines the bandwidth of detection. Only the signal at the reference frequency will result in a true DC output and be unaffected by the low pass filter. This is the signal we want to measure."[2]

B. Advantages of True Simultaneous Wavelengths

A significant advantage of the ITT architecture is that we achieve true simultaneous transmission and detection of λ_1, λ_2, λ_3. Why is this important? In order to understand the significance of this, we need to examine the entire system – the transmitter, the atmosphere and surface and the receiver – and understand how each affects the received signal.

Let the emitted energy at line-center and off-line be:

$$L_{on}(t) = A \cdot \sin(\omega_1 \cdot t)\ \omega_1$$
$$L_{off}(t) = C \cdot \sin(\omega_2 \cdot t)\ \omega_2$$

Both beams are emitted simultaneously by the same fiber amplifier, transit the atmosphere, are reflected by the surface, transit the atmosphere a second time, and received simultaneously on the same detector.

The on-line signal coming from its lock-in detection system can be represented as:

$$RA = \int_0^{\tau} [[a \cdot \sin(\omega_1 \cdot t) + c \sin(\omega_2 \cdot t)] \cdot \mathrm{X}(t) + \delta_1(t)] \cdot \sin(\omega_1 \cdot t) \cdot dt$$

The off-line signal coming from its lock-in detection system can be represented as:

$$RC = \int_0^{\tau} [[a \cdot \sin(\omega_1 \cdot t) + c \sin(\omega_2 \cdot t)] \cdot \mathrm{X}(t) + \delta_2(t)] \cdot \sin(\omega_2 \cdot t) \cdot dt$$

The "a" and "c" represents the standard laser link equation that characterizes the amount of return laser power that hits the detector and its amplification into an electrical signal. The X(t) represents the effects of scintillation and detector responsivity. Here it has been assumed that the wavelengths of the on-line and off-line are close enough together that the modulation effects are the same for each wavelength, at least to first order. The electronic noise terms generated in the photon to current conversion process are represented by $\delta_1(\tau)$ and $\delta_2(\tau)$, and are considered small.

The on-line lock-in detection system, RA(t), multiplies the input signal with the sine of the on line modulation frequency, similarly the off-line lock-in detection system, RC(t), multiplies the input signal with the sine of the off-line modulation frequency.

Using the trigonometry identity $\sin^2(x) = \dfrac{1-\cos(2x)}{2}$ the ratio of RA and RC can be rewritten as:

$$\frac{RA}{RC} = \frac{a \cdot \int_0^{\tau} [\mathrm{X}(t) - \mathrm{X}(t) \cdot \cos(2 \cdot \omega_1 \cdot t)] \cdot dt}{c \cdot \int_0^{\tau} [\mathrm{X}(t) - \mathrm{X}(t) \cdot \cos(2 \cdot \omega_2 \cdot t)] \cdot dt} \cong \frac{a}{c}$$

The ratio of a/c represents the ratio of the power of the returned on-line to off-line signal and is the transmission of the atmosphere. From the ratio, and using the Beer-Lambert Law, the column density can be determined. Note that any non-spectrally selective modulation created by the laser, atmosphere, surface, and detector, which is represented by X(t), has been eliminated. This represents a significant signal-to-noise-ratio advantage over systems which do not transmit and receive simultaneously.

C. Modulated compared to Direct and Pulsed Detection

The advantage of the lock-in over direct detection and pulsed detection is illustrated in the following sequence of figures. In the case of direct detection Figure 1 the signal is at DC where all the 1/f noise terms are highest. In the case of pulsed detection, Figure 2, where the bandwidth by necessity is quite large, the integrated value of broadband noise is very high.

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[2] Stanford Research, Application Note #3

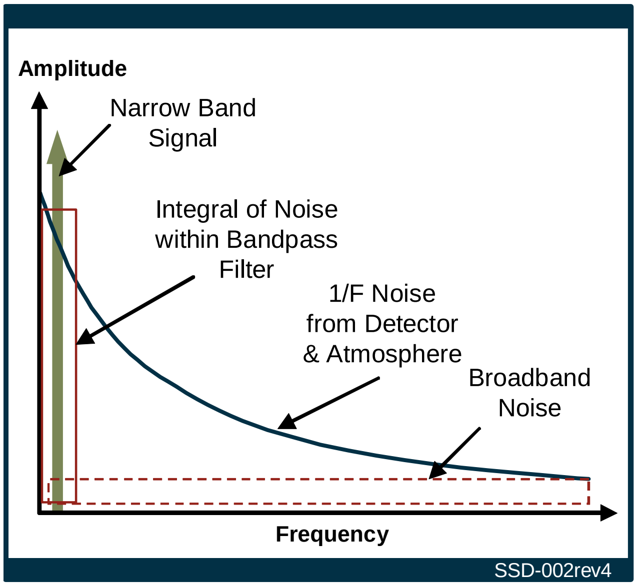

Figure 1 – Illustration of small signal at baseband in presence of large 1/f noise.

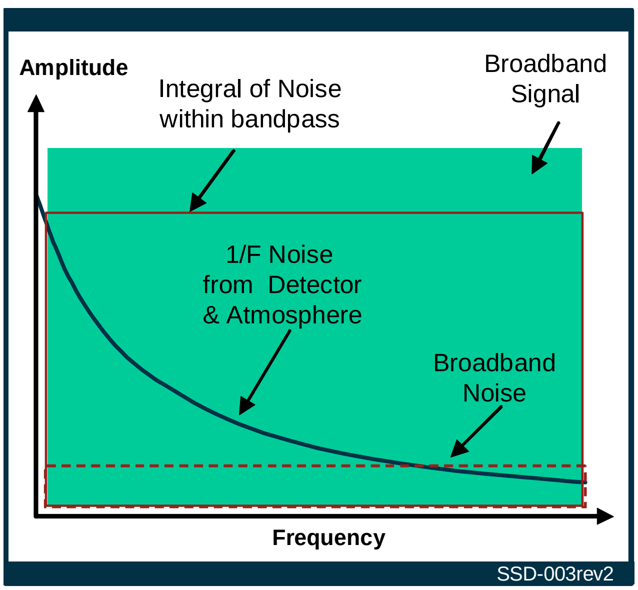

Figure 2 – Illustration large amount of noise when signal is broadband; as required in pulsed lidar.

In the case of MFE, we have chosen the modulation frequency based on two constraints. This is illustrated in Figure 3. First, the modulation frequency should be chosen to be well above the knee in the 1/f curve for detectors and atmosphere. Second, the modulation frequency should be kept low to minimize the engineering challenges. Based on measured PSD noise of transmitter and receiver components, and the atmosphere itself under a wide range of conditions, ITT is working in the region around 50KHz.

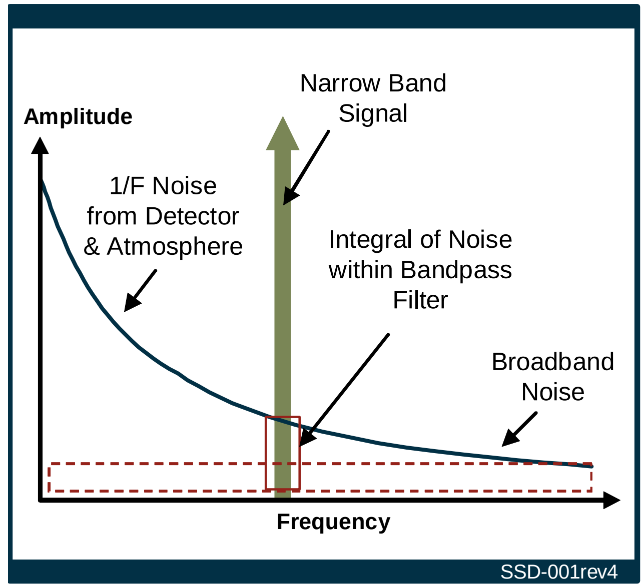

Figure 3 – Illustration of advantage of placing a narrow band signal well above the knee in the 1/f noise.

In summary, we have successfully constructed and demonstrated several lidar systems, using lock-in amplifiers, which have sensitivities several orders of magnitude greater than direct detection (at comparable received power).

In the next two sections we will report on the status of two programs which exploit cw lasers and various forms of modulation.

III. EARTH SCIENCE MISSIONS ENABLED CW SOURCES AND LOCK-IN AMPLIFIERS

A. ACCLAIM - Mapping Sources and Sinks of CO2.

The objective of the ACCLAIM mission is to accurately measure the total column and lower troposphere concentration of CO2. [3] To date, we are using a technique called Laser Absorption Spectroscopy or LAS. This method, like DIAL, requires multiple wavelengths, which are commonly 'tuned' to line center (λon) and to the non-absorbing baseline (λoff). In the case of ACCLAIM, we transmit at several wavelengths λ_1, λ_2, $\lambda 3$ which are independently modulated at ω_1, ω_2, ω_3.

[3] Browell, et al

1) System Overview: Using internal funds, ITT has developed, perform significant risk reduction, and validated through test and flight, and end-to-end lidar system.[4]

The transmitter subsystem consists of a Distributed Feedback Diode and Modulator for each wavelength, λ1, λ2, through λn. The modulated outputs are combined into a single fiber, which is input to several multi-watt fiber amplifiers, whose outputs are NOT coupled and which remain independent. The transmitter is 100% fiber; there are no discrete optical elements until the output lens. In addition to the multi-watt output, each amplifier has a low power output which is used to normalize the received signal. The fiber amplifiers are very robust, having reached TRL 5 to 6. The fiber amplifiers are very efficient and compact, producing 5-10 watts per 8 x 10 x 1 inch module, at 10% total electrical to optical efficiency.

The receiver subsystem consists of a telescope, an optical bandpass filter, APD Detector fabricated in HgCdTe and low noise amplifier. One unique aspect of the ITT implementation is the use of a proprietary APD detector, which provides single digit photon sensitivity, with zero excess noise. A second unique aspect of the ITT implementation is that each wavelength λ1, λ2, λ3 are readily separated by the electrical subcarrier, versus complex optical filters and etalons. The signal processing subsystem consists of a multi-channel lock-in amplifier, which provides the modulation signal to the modulators, and performs the lock-in process on the received signal.

Note that this modular architecture has several demonstrated advantages:

- the architecture is independent of the system wavelength
- supports multiple species simultaneously, as long as the transmitter has spectral bandwidth; which is yet another advantage of fiber amplifiers/laser over bulk lasers
- easily supports the N+1 redundancy

2) Physics-Based Modeling and System Validation using 3rd Generation EDU: ITT has invested in the evolutionary development of the engineering development unit. The EDU used to validate physics-based, high-fidelity, end-to-end performance model. In the present model, there is a signal and, or noise term for every component (e.g. wavelength control, fiber amplifier, optics, atmosphere, sun/moon, surface, responsivity, and dark current, 1/f, electronics, etc.). Each term has been validated using measured data. We do not rely on vendor data. Then each subsystem was validated in the lab and field. Then the system was validated in the field and airborne campaign. We have developed a robust set of validation methods which we continually reuse to develop performance data, and long term trends.

First we measured the performance of each component, individually and in combination, to insure that each component and any interactions were properly accounted for. Next, we measured the performance of the system under a wide variety of conditions (received power, surface reflectivity, sunlight, weather, environmental) to ensure that these terms also were accounted for properly. Finally, we accumulated hundreds of hours of operational time on the system. The measured performance and retrieved CO2 matches the predicted performance and CO2 truth data.

3) Status: Based on the results for the work up through the May 2005 flight and subsequent outdoor field testing:

- We have validated the performance model under a wide range of operational conditions.
- We demonstrated that the system routinely makes measurements with a precision of 0.1% This is consistent with the requirement for mapping of sources and sinks of CO2 at 1-ppm level, with margin.
- We demonstrated that the system is very stable. We can integrate over many 10's of minutes. This means that the system is largely free of non-random noise processes. This also means that periodic (re)calibration would not take a large percentage of the available observation time.
- We have demonstrated that the system has an accuracy of 1.5% against column integrated in-situ data.
- We have completed our first Integrated Design Center run, which confirmed that the payload poses no unique challenges and is affordable.

Following May 2005 flight we captured the lessons learned and submitted a plan for additional investment by ITT and others. The plan called for replacing the borrowed detector, eliminate the LN2 cooling, continue to improve the stability, and incorporate additional diagnostics. We have completed these upgrades and are preparing the payload for our second science flight.

B. Multi-Functional Fiber Laser Lidar (MFLL) for Ice Sheet Topographic Mapping

The objective of the MFLL is to develop and demonstrate

[4] ITT has been awarded several patents relating to this architecture.

robust and affordable solution for precision mapping of ice sheets and similar challenging topography from UAV and satellites. This project is in its first year.

For the MFLL we again chose to modulate a continuous output fiber amplifiers/laser. However, to accomplish ranging, rather than use sinusoid amplitude modulation, we used pseudo-random code sequence and digital modulation.

1)Requirements Capture: ITT uses several processes including Voice of the Customer and Quality Functional Deployment to interview potential users. The VOC is a set of processes for helping the integrated product team (IPT) focus on critical customer wants and needs. The is a method of prioritize customers requirements. From these processes, we determined that the key performance metrics were; 10 cm vertical resolution, high area coverage rate, and simultaneous cross track and fore and aft measurements

2)System Overview: For this mission, we explored three architectures including FM Chirp using a long pulse fiber laser, PN encoding using single photon counting detectors, and PN counting using the APD array from ACCLAIM. Very early in the program, each architecture was modeled and performance metrics were developed. These metrics included range resolution as a function of received power, which leads to area coverage rate, and the maturity of the components. We chose to implement the PN encoded system with a single photon counting detectors.

Then we explored several tradeoffs including reflectivity versus wavelength, NEP of various detectors versus wavelength, and commonality with ACCLAIM. Because we need to achieve wide area coverage, we chose to operate in the 1um region which offers the advantage of higher reflectivity from ice and snow, readily available single photon counting detectors, and very efficient fiber amplifiers.

We are presently exploring the trade offs between bit rate, code length,

3). Physics Based Modeling and System Validation using 3rd Generation EDU: As previously mention, the team developed physics-based, high-fidelity, end-to-end performance models for each architecture. In the present models, there is a signal and, or noise term for every component (e.g. wavelength control, fiber amplifier, optics, atmosphere, sun/moon, surface, responsivity, and dark current, 1/f, electronics, etc.). We are presently validating the performance model, and as shown in Figure 4, we are now getting very good agreement between the model and observed performance. The next steps will be to use the validated model to develop nomagrams will illustrate the performance as a function of ‘constraints’ (standoff distance, GSD, power-aperture-time product), ‘controls’ (bit rate, code length), and ‘noise’ (background, dark current).

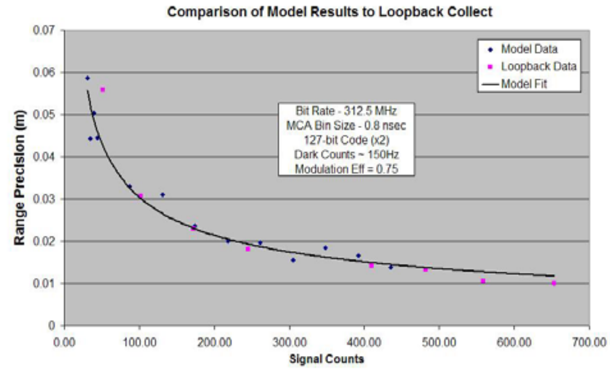

Figure 4 – Illustration of close comparison between model and measured data for PN lidar.

In addition to the performance model, we developed a simulation which allows the team to configure and fly the simulated instrument over known terrain. The tool was designed as a systems engineering tool, where the user can input parameters into a spreadsheet. The program then ingests the specified DEM file, and runs all the cases in the spreadsheet. The tool outputs both graphical and numerical data for further analysis. We have included just two of the many outputs available. Figure 5 is an overview of the terrain and the flight path, and is used to put the data into context with respect to the overall terrain. Figure 6 is a plot of the residual or difference between measured and truth for a specified track. With this tool, we can quickly explore and quantify the improvement to the representation of the ice sheet as a function of vertical resolution, ground sample distance, number of pixels and pixel separation.

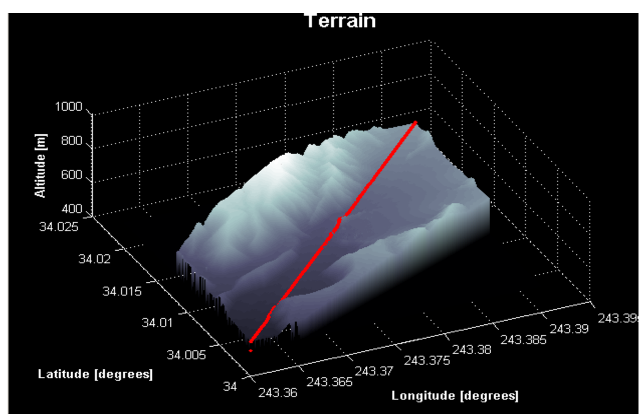

Figure 5 –Example simulation output which projects flight path over terrain.

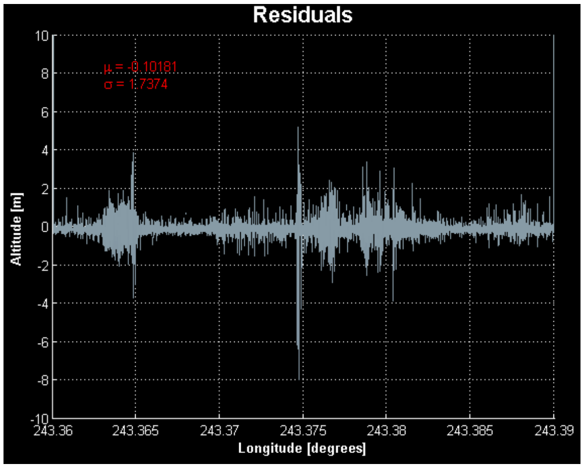

Fig 6 – Example simulation output which compares measured to truth

*4)Status:*Once the PN system was chosen, the team acquired the necessary components, integrated them into the first evolution of the system, and is currently characterizing components and end-end performance prior to a engineering test flight planned for this summer. Following that flight, the instrument will be transferred to an aircraft which is already outfitted with a mapping lidar and operating in the artic. The two systems will fly together to validate the PN system. From there, we will upgrade the instrument to the full wide swath capability in anticipation of deployment in late 2007 or early 2008.

<u>The project year end report will include much more detail on the results of the trade studies, on-going validation work and plans for the next grant year.</u>

IV. SUMMARY

In summary, we believe that with the application of signal processing techniques such as lock-in amplifiers, PN encoding, and matched filters in general, that we have enabled the use of continuous output laser for a wide range of NASA and other government agency missions. This work enables the exploitation of robust and reliable, high-volume, high low-cost fiber amplifiers/lasers for a multitude to missions.

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REFERENCES

1 Stanford Research, Application Note #3
2 Stanford Research, Application Note #3
3 Browell, et al
4 ITT has been awarded several patents relating to this architecture.