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ABSTRACT

The development of an experimental full-waveform LADAR system has been enhanced with the assistance of the LadarSIM system simulation software. The Eyesafe LADAR Test-bed (ELT) was designed as a raster scanning, single-beam, energy-detection LADAR with the capability of digitizing and recording the return pulse waveform at up to 2 GHz for 3D off-line image formation research in the laboratory. To assist in the design phase, the full-waveform LADAR simulation in LadarSIM was used to simulate the expected return waveforms for various system design parameters, target characteristics, and target ranges. Once the design was finalized and the ELT constructed, the measured specifications of the system and experimental data captured from the operational sensor were used to validate the behavior of the system as predicted during the design phase.

This paper presents the methodology used, and lessons learned from this "design, build, validate" process. Simulated results from the design phase are presented, and these are compared to simulated results using measured system parameters and operational sensor data. The advantages of this simulation-based process are also presented.

Keywords: laser sensors and systems, validation, LADAR, simulation, radiometry

1. INTRODUCTION

LadarSIM is a Matlab and Simulink-based LADAR system simulator designed and developed by the Center for Advanced Imaging LADAR (CAIL) at Utah State University (USU). This powerful tool for system analysis and error source modeling assists in the design and development of new LADAR systems using pulsed lasers and energy-detection receivers. Unlike many other LADAR simulators such as IRMA, LadarSIM is not primarily concerned with applying detailed physics to simulations, but rather focuses on a quick yet accurate model of the LADAR system being simulated. Because dynamics are included in the simulation, the system modeled can then be tested with a user defined path in a moving environment.

The radiometry simulation within LadarSIM generates signal waveforms that allow LadarSIM to use the shape of the return pulse to accurately model the pulse detection process. From this return waveform, intensity, range error, probability of dropouts, and probability of false alarms are predicted.

With the aid of LadarSIM, the Space Dynamics Lab (SDL) at USU recently developed a new LADAR system called Vehicle Integrated Sensor Suite for Targeting Applications (VISSTA) Eyesafe LADAR Testbed (ELT). Specifications and methods involving the scanning control system, transmitter, and receiver, were determined by the outcomes of system configuration and simulation in LadarSIM. After the ELT was constructed, data was obtained to validate the original design and to quantify system radiometric performance. Thus the VISSTA ELT stands as an example of the "design, build, validate" process.

This paper focuses on two of the three major characterizations of radiometric performance in the ELT – probability of false alarms and range error. Probability of dropouts is not presented in this paper. At the ranges covered in the tests reported here, the signal-to-noise ratio (SNR) did not reach a level low enough for adequate validation of this error.

(a) (b)

Figure 1: The VISSTA van. (a) The ELT aperture can be seen at the right side in the turret behind the cab. (b) Displays used for system control and display of sensor data.

2. THE VISSTA ELT

The VISSTA van was developed to provide a mobile sensor platform for multiple modes of data collection. It currently includes the ELT and an IR camera housed in a movable turret. The van is shown in Figure 1.

The VISSTA ELT contains an eyesafe wavelength LADAR and a visible camera co-boresighted to observe the same field of view. This allows the operator to accurately point the LADAR and capture visible images and LADAR point clouds simultaneously to create 3D "texel images." In addition, the ELT is able to digitize and store LADAR waveform data for off-line processing. This provides an effective means of not only exploring the performance of the LADAR with different targets, but also validating LadarSIM's capability of modeling real systems. Other waveform digitizing LADAR systems such as RIEGL's LiteMapper-5600 are on the market; however, VISSTA ELT is unique in that the 1.5 ns laser pulses are sampled at 2 GHz, providing highly accurate waveform analysis. With stored waveforms, shot independent noise levels can be seen and computed, and parameters such as threshold level and detection method can be modified after data has been taken. In 2007, CAIL validated LadarSIM with a non-waveform processing LADAR device.[1] Until now, however, LadarSIM has not been validated with actual waveform data.

An example of point cloud data obtained with the ELT is given in Figure 2.

3. PARAMETER COLLECTION

To accurately model the device, parameters describing the VISSTA ELT's performance must be found. Measured parameters are desirable; however, not all parameters can be measured and need to be obtained from the manufacturer's specifications. Because this information is competition sensitive, specific parameters will not be discussed in this paper; nevertheless, relative values will be used when needed, and will sufficiently demonstrate the results of validation.

Parameters for the optical design and components in the receiver were obtained from the component manufacturer's specifications. Once the A/D converter was calibrated, the receiver waveform supplied enough data to calculate the noise level in the electronics.

The noise model used in LadarSIM is given in Figure 3. In the model, the blocks represent the transfer functions of each of the receiver components that can be modeled: the avalanche photodiode (APD), transimpedance amplifier (TIA), a power amplifier, and the discriminator circuit (including any matched filtering). The noise sources modeled are given as follows:[2]

e_{sig} = Shot noise due to the signal,

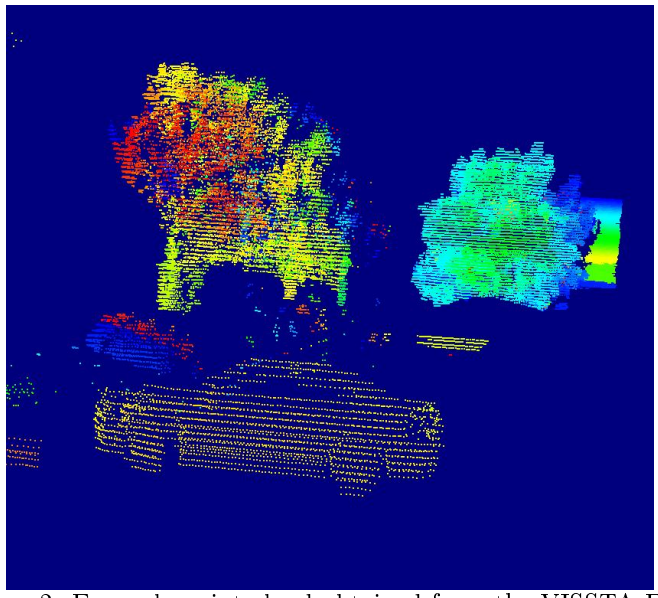

Figure 2: Example point cloud obtained from the VISSTA ELT.

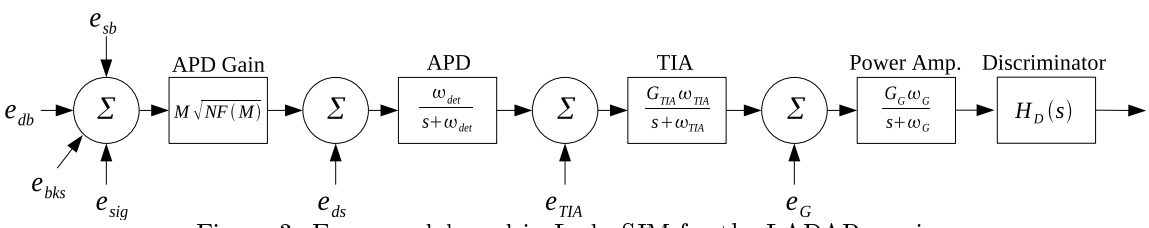

Figure 3: Error model used in LadarSIM for the LADAR receiver.

e_{bks} = Laser pulse backscatter,

e_{sb} = Solar background noise,

e_{db} = Bulk dark current noise,

e_{ds} = Surface dark current noise,

e_{TIA} = TIA noise,

e_G = Power amplifier noise.

Values for the bandwidths and gains in the LadarSIM noise model,

M = APD avalance gain,

$NF(\cdot)$ = APD noise factor,

ω_{det} = APD bandwidth,

G_{TIA} = transimpedance amplifier gain,

ω_{TIA} = transimpedance amplifier bandwidth,

G_G = power amplifier gain, and

ω_G = power amplifier bandwidth

were determined from the measurement of return pulses, known settings on the amplifiers, and from the datasheets for the components in the receiver.

To eliminate any error due to pointing, the VISSTA ELT was set to fire pulses without scanning. A large testboard with an estimated reflectivity of 0.7 was assembled and placed at various ranges. Before firing pulses

at each range placement, the aperture was covered to obtain a waveform containing only dark current noise. This was done to measure the effect of the noise in the electronics (e_{db}, e_{ds}, e_{TIA}, and e_G). The measured dark current noise level was found to be slightly larger than the specifications used in the ELT design phase. This measured noise level was then used to match the electronics noise level used by LadarSIM to compute range error and probability of false alarms for validation.

After obtaining the dark current waveform, solar background noise was found by uncovering the aperture and recording without firing pulses. Solar background noise was found to be negligible compared to the dark current noise. The LadarSIM model also reported solar background noise as negligible to the overall noise level. The two noise sources that are modeled by LadarSIM but were unable to be measured are backscatter (e_{bks}) and shot noise from the signal (e_{sig}).

Pulses were then fired and the waveforms corresponding to both the pulse exiting the aperture (start pulse) and the return pulse for each shot were digitized. These waveforms were analyzed to validate the performance of the ELT against the predictions from LadarSIM used during the design phase.

4. PROBABILITY OF FALSE ALARMS

False alarms are defined as any detection caused by anything except the reflected pulse off an object in the scene. This may come from noise in the electronics, back scatter noise, or solar background noise. In LadarSIM, the probability of false alarm is determined using a cumulative Poisson distribution as in[3]

$$P_{fa} = 1 - exp(-\Delta t \cdot \Lambda), \tag{1}$$

where

Δt = time interval (gate) that the waveform is recording (sec), and

Λ = the false alarm rate.

LadarSIM models three general discrimination methods–leading edge, constant fraction, and crossover.[4] For this paper, only the leading edge detection method is presented. Assuming Gaussian white noise, the equation for the false alarm rate is given by[5]

$$\Lambda = \frac{B_{sys}}{\sqrt{3}} \cdot exp(-\frac{1}{2} \cdot TNR^2), \tag{2}$$

where

B_{sys}= the receiver noise equivalent bandwidth, and

TNR = detection threshold to noise ratio.

In LADAR systems that do not capture waveforms, the TNR must be set before a point cloud is acquired, often according to system noise measurements. Therefore, ELT waveform data collected without pulses present was used to evaluate the P_{fa} in the ELT for different values of TNR. These same TNR settings were used in LadarSIM, along with the system gain settings and the range gate setting used in the ELT.

Several values of the TNR were used to experimentally exploit the full range of P_{fa} from 0 to 1, and the percentage of pulse detections was computed from the data. Note that without waveform data, this procedure would not be possible.

Figure 4 compares LadarSIM's prediction to the measured values. The starred plot in the figure gives the P_{fa} predicted during the ELT design phase from LadarSIM using only manufacturers specifications. It is important to note that the data points plotted in the figure represent quantized TNR values. The plot shows that LadarSIM under-estimated the occurances of false alarms; however, the two data sets track each other well.

A closer look at the VISSTA ELT data revealed small, unmodeled increases in noise power at random locations as shown in Figure 5. Because a false alarm will occur at the spot of highest noise and the noise observed is time varying, more false alarms are expected to occur at these unmodeled "noise bursts" than with Gaussian white noise.

5. RANGE ERROR ANALYSIS

Range error is a measurement of the precision and repeatability of the system range measurements. In LadarSIM, the range error is defined as the standard deviation of range measurements from pulses hitting a surface at the same range. The range error is dependent on the system noise as well as the slope of the pulse at the detection point. This directly corresponds to the SNR, and the shape and rise time of the pulse. For that reason, systems with narrow pulses and low noise levels produce little range error. For the leading edge discrimination method, range error is given by[6]

$$\sigma_R = \frac{c}{2} \cdot \left. \frac{\sigma_d(t_p)}{\left|\frac{d}{dt} v(t_p)\right|} \right|_{t=t_p}, \tag{3}$$

where

c = the speed of light,

$\sigma_d(t_p)$ = the detection noise at the timing point t_p, and

$v(\cdot)$ = the pulse waveform.

To calculate the range error of the sensor data and compare with LadarSIM, tests were conducted on the test board without scanning. Because all points have the same true range, any error present was directly from the system and not from other factors such as uneven surfaces or differences in the angle from the surface to the sensor. For accurate results, approximately 100,000 shots on the surface were used for calculation.

Comparing the results from the VISSTA ELT to LadarSIM was done in two steps. First, the range error was calculated in LadarSIM using manufacturer's specifications. Second, the LadarSIM noise parameters were

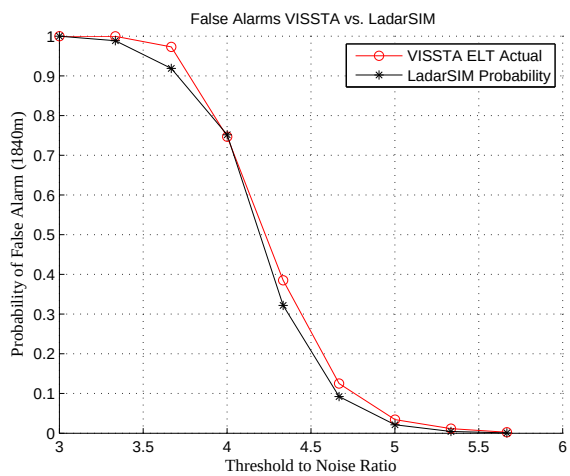

Figure 4: Probability of False Alarms.

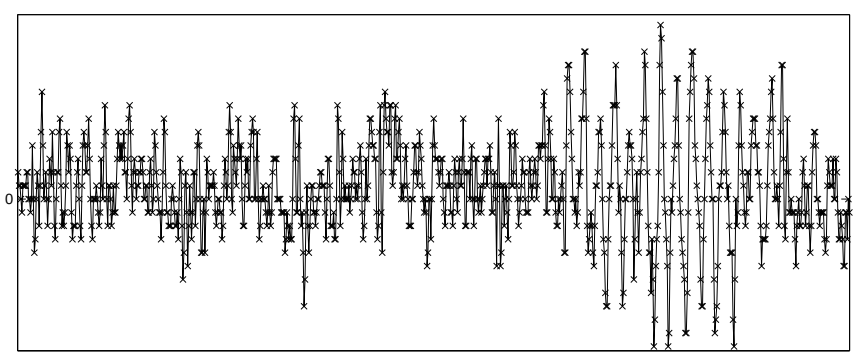

Figure 5: Noise Signal from the VISSTA ELT.

updated with the measured data from the dark current waveform. Not all parameters could be updated because data such as the shot noise could not be measured; however, adding in the dark current noise provides a more realistic model.

Figure 6 compares the VISSTA ELT range error to the expected range error calculated in LadarSIM. The

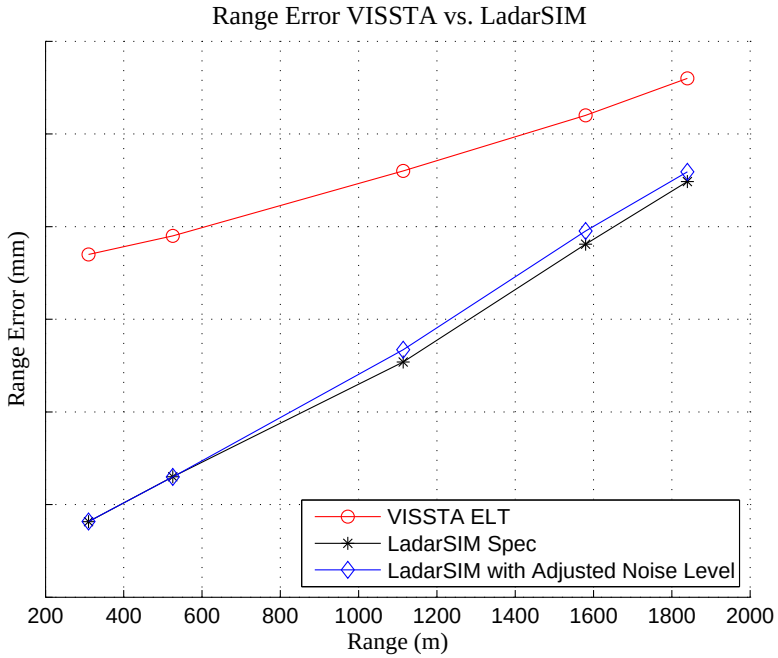

Figure 6: Range error of VISSTA and LadarSIM at various ranges.

starred plot is the data modeled in LadarSIM from the manufacturer's specifications. Since the VISSTA ELT was designed with the aid of LadarSIM, this set of data represents the performance expected from the original design. Adding the additional dark current noise measured from the ELT data to the LadarSIM parameters lead to a slightly higher range error prediction, as indicated in the diamond plot. This is expected since the measured noise in the ELT was slightly higher than the noise assumed in the original design of the ELT.

The measured data from VISSTA ELT is given in the circle plot in Figure 6. The difference in the simulated performance and the actual performance is on the order of one to three milimeters. These differences are likely due to the range error sources which are not modeled in LadarSIM. These could include error sources such as cable noise, errors in the parameters taken from data sheets that were not measured, and noise due to measurement of the start pulse timing point.

It is interesting to note that the simulation error is larger at shorter ranges and decreases as the ranges increase. This result was unexpected; we are currently investigating the causes of this effect.

6. CONCLUSION

Results from our investigation have confirmed the value of the design, build, validate concept for LADAR system design. The performance of the VISSTA ELT was predicted using LadarSIM during the design stage, and those predictions guided the engineering tradeoffs necessary during that stage of development. After the ELT was constructed, data were taken to validate the usefulness of the LadarSIM predictions. We observed that the false alarm performance of the ELT was very close to the simulated values, with the difference possibly resulting from unmodeled noise bursts found in the data. This observation allows us to look for sources of these bursts in the ELT to effectively lower the P_{fa}.

The results of the range error investigation indicate that the performance of the ELT is within milimeters of the design performance. These differences are likely due to the additional noise that is inevitably found in

a completed design and from sources that are not modeled by LadarSIM. These results have led us to consider adding noise sources to our simulation, including a model of pulse jitter and the the start pulse detection error present in many systems, including the VISSTA ELT. In addition, we have become aware of the different slopes of the performance curves of the actual and simulated range error plots. We expect to continue the investigation of this phenomenon with additional data collects.

Overall, we have found that design with the assistance of a tool such as LadarSIM to be very beneficial to achieving the goals of a LADAR system development.

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