Pulse-polarization ranging for space situational awareness

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ABSTRACT

We describe a non-imaging technique to identify or establish the orientation of an orbiting satellite. This technique involves measuring both the broadening and polarization of pulses reflected from the satellite. As with radar pulses, the laser returns in our scheme are broadened in a way characteristic of the object's structure in the propagation, or range, direction. While the mapping between the return pulse shape and the object or its orientation is not unique, we also measure the polarization of the scattered pulse to reduce the degeneracy of the inverse problem and allow estimation of structural composition or material properties. In this paper, we describe both the concept and the numerical tools we are using to assess its utility.

Keywords: Space situational awareness; laser pulse interrogation; surface scattering

1. INTRODUCTION

Air Force planners anticipate a proliferation of highly-functional satellites ("micro-" or "nanosats") too small to be spatially resolved in images acquired by present ground electro-optical facilities. Also, current US ground SSA facilities are nearly useless for observing foreign satellites over current combat theaters; such a capability would require smaller, transportable telescopes with relatively low spatial resolution. To facilitate intelligence gathering about small satellites or with small, mobile telescopes, we have developed an innovative sensing concept involving laser pulse broadening and polarization measurements. The potential impacts are

- The capacity to estimate satellite sensor pointing or orientation ("pose") with mobile telescope data acquired in a combat theater, allowing inferences of the satellite's tasking and potential enemy knowledge of force deployments,
- The use of orientation information as a constraint in processing data from spatially or spectrally diverse sensors,
- The ability to rapidly detect *a change* in orientation,
- The ability to estimate material composition, properties, or status, including age or anti-satellite battle damage,
- The ability to rapidly detect and estimate velocity changes, indicating a ground station re-tasking, and
- The ability to assess the mission and payload of satellites significantly smaller than those easily resolved with existing ground EO assets.

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We call this technique “pulse-polarization ranging” (PPR).

Observation of reflected laser pulse shapes with high-bandwidth detectors (called “echo imaging” in the medical community) reveals information regarding the structure of the object in the beam propagation (or “range”) direction: Each surface of the satellite may be thought of as reflecting some fraction of the pulse with a relative phase delay proportional to its distance from the surface closest to the observer and an amplitude proportional to the relevant BRDF; the return signal is a convolution of those shifted pulses. Clearly, the return doesn’t uniquely specify the satellite structure or orientation. A simple example would be a flat plate tilted at some angle around some axis in a plane normal to the observer. Given a sufficiently short output pulse and prior knowledge the object is a flat plate, the magnitude but not the direction of the tilt could be estimated from the intensity profile of the return pulse. Consider now the addition of a polarization measurement: If the collection polarimeter is displaced from the illumination source (as would be the case for either passive solar illumination or bi-static laser illumination) and the polarization BRDF is known or can be inferred, both the magnitude and sign of the tilt could be inferred by comparing the output and return pulse shapes and polarizations. Generally, we can estimate three polarization properties from return pulse measurements: Retardance, diattenuation, and depolarization. Estimation of these properties, while requiring more measurements than the pulse profile alone, may carry significantly more information than the pulse profile alone.

In this paper, we describe our scheme, the tools we have developed to analyze its potential, and our progress thus far. In the next section, we show how the broadening of an incident pulse can be used to estimate parameters about the object from which the pulse is reflected and discuss the use of polarization measurements. In Sec. 3, we describe the simulations used to model the relevant physics. In Sec. 4, we describe the use of a vector space approach to quantitatively assess the information carried in the reflected pulse; a related scheme to identify the object or estimate related parameters, such as its orientation or composition, is described in Sec. 5.

2. PPR MEASUREMENTS

2.1. Pulse broadening

In our work, we have formally shown that the return pulse shape is the convolution of the launch pulse with the “surface area density” S. This function is the distribution of surface area pointing in the backscatter direction as a function of “depth,” or distance along the propagation direction. Two plots from our analysis are shown below in Fig. 1. The plots show the return pulse shapes for a cone pointed at the launch telescope (top) and a sphere (bottom). The plots were generated using Gaussian launch pulses with widths of 10, 50, and 100 samples and numerically integrating analytical expressions for the convolution of the launch pulse and S. It is clear that even with a launch pulse having significant length relative to the object, these two shapes can be distinguished. We have also shown that pulse broadening alone can distinguish between different orientations of the cone.

2.2. Polarization measurements

Using conventional technology, we can measure retardance (the relative phase between two orthogonal, linear polarizations), diattenuation (attenuation of one but not both polarizations), and depolarization (decrease of the return pulse from unit degree-of-polarization). In principal, these measurements would add to the Shannon Information in the broadening measurements; potentially adding three times the original information. In practice, measuring these polarization parameters would require launching three pulses with sufficient power in less than the time characteristic of significant atmospheric turbulence evolution. We note that the smaller the telescope diameter, the longer the time available to launch the pulses.

3. SIMULATIONS

3.1. Atmospheric propagation

The atmosphere induces two sources of noise. First, tip/tilt and higher-order aberrations in the near field of the telescope cause random speckling and beam wander in the plane of the object. This means the illumination intensity is a random process, with the correlation between pulses depending on the repetition rate. Our turbulence models the atmosphere as several discrete layers, with Fraunhoffer propagations between them. Examples of the laser irradiance after passing through a number of phase screens are shown in Fig. 2.

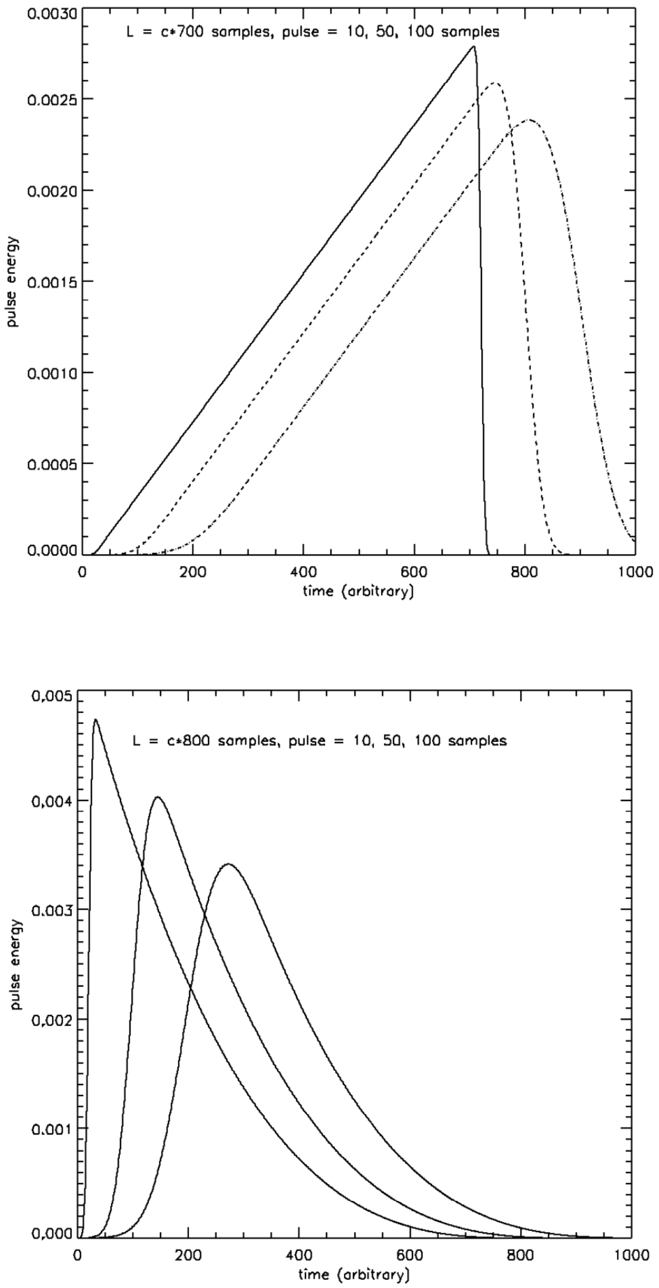

Figure 1. Laser pulse shapes in the near-field of the object for (top) a cone, pointed toward the launch telescope and (bottom) a sphere. The incident pulses are Gaussian with 1/2-widths of 10, 50, and 100 samples.

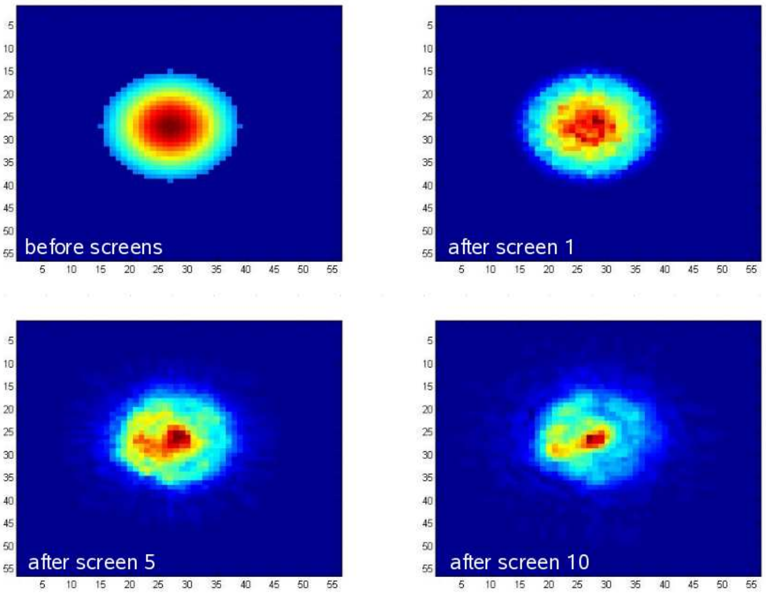

Figure 2. Simulated launch beam irradiance profiles after passing through 1, 5, and 10 phase screens.

3.2. Surface interaction model

The surface interaction model is critical to understanding the utility of polarization measurements and implementing an inversion algorithm. As discussed in Sec. 5, the surface interaction model can also be used to generate the databases needed to implement our algorithm to invert pulse measurements to objects or object parameters. The model has been developed by generalizing current scattering models to include polarization effects and double-bounce scatter. The generalized models were implemented using graphics processing hardware, Open-GL, the Open GL Shader Language, and the NVIDIA CUDA applications programming interface. The model is described in detail in Stryjewski, et al.[1] in these proceedings.

4. SHANNON INFORMATION CALCULATION

To quantify the utility of the PPR concept and our ability to distinguish among objects or parameters, we calculate Shannon Information (SI) associated with the return pulses. The SI is given by

$$I_X \ = \ \sum_x \, p_x \, \log_2 \, p_x, \tag{1}$$

where X is the relevant random process, the x are sample functions of X, and p_x is the probability associated with any random sample function x. In this case, the random process is the return pulse energy distribution, sampled N times by the detector. The probability p_x is then the joint probability of measuring the N sampled energies associated with the return pulse sample function x. Note that if the sampled energy distributions of pulses reflected by all objects in any orientation are identical, the probability distribution is a delta function and

$$I_X \ = \ \sum_x \, \delta(x - x') \, \log_2 \, \delta(x - x') \ = \ 0, \tag{2}$$

so zero SI indicates a complete inability to distinguish among the objects or possible orientations or compositions based on PPR measurements.

Although SI is ideal for quantifying PPR's fundamental limits, there is a significant obstacle to its use: For N detector samples, a dynamic range of b bits, and two polarizations, there are $(2^b)^{2N}$ elements in the associated probability density function (pdf). For $N = 32$ samples and 128 grey levels for each sample, this means there are 2^{448}, an indescribably huge number. Rather than allocate the space required for the pdf and counting occurrences in the associated cells, we represent the return pulse as a vector in an N-dimensional space (2 N if two polarizations are measured). Then, we need only count the number of vectors that are identical (same direction and length).

With M pulses to examine, searching the list for duplication is an $M!$ problem; still daunting. To address this problem, we make use of the fact that if two vectors point to the same point in the vector space, they must have the same magnitude. The magnitude of each of the M pulse "vectors" is calculated and sorted to place same-magnitude vectors in adjacent bins on a list. Sorting the list is an $M \log M$ problem; much more manageable. This approach allows us to calculate the SI in polynomial time with no impractical space requirements.

Finally, we note that in addition to the information carried by the set of return pulses, we also wish to quantify the information transmitted from the object near field to the actual noisy detector. In other words, the SI allows us to quantify our ability to distinguish among objects and their parameters based on a quantized measurement of the pulse shape with using different polarization. The mutual information, or MI, allows us to account for detector noise and turbulence fluctuations. If the random process at the detector is Y, and its sample functions are denoted by the variable y, the mutual information transmitted from the object near field to the detector is given by

$$I_{XY}^{m} = \sum_{x} \sum_{y} p_x \log_2 \left\{ \frac{p_{xy}}{p_x p_y} \right\}. \tag{3}$$

Our final simplification is to avoid the complication of calculating the joint probability p_{xy} by calculating the normalized autocorrelation between the p_x and p_y distributions.

5. INVERSION ALGORITHM

The algorithm to invert the mapping from objects and their parameters is related to our Shannon Information implementation. Our approach is to again treat the measured data like vectors. Then, controlled observations and the surface interaction model can be used to develop "basis vectors" spanning the measurement space. The data can then be compared to the database vectors using a computationally simple inner product.

To utilize a time series of measurements as the objects tracks across the sky, we further generalize the vector space concept to form "trajectories" from the points traced through the vector space in by the "tips" of the individual pulse returns. We can then quantitatively compare the trace of the measured time series, after filtering to attenuate noise, with our library of traces using a distance metric.

6. PROGRESS AND FURTHER WORK

We have developed an innovative concept to identify or estimate parameters of interest, such as orientation and material composition, using a non-imaging laser interrogation technique. We have created significant extensions to scattering models and implemented a versatile surface interaction model using advanced computational techniques. Finally, we have also developed a new, efficient, and practical Shannon Information calculation and used those concepts to formulate an inverse algorithm.

Analysis of the following optimization problems is critical for a complete understanding of our technique's potential:

- Quantify the optimal projection telescope diameter by trading loss of power from beam spreading (relatively small telescope) with random noise from atmospheric turbulence modes subtended by the pupil of a relatively large telescope.
- Quantify the optimal number of pulse time samples by trading aliasing of the pulse shape (relatively fewer samples) with increased noise in relatively more samples.

- Quantify optimal regularization parameters for deconvolving the launch pulse from the measured return pulse. This involves the usual tradeoff for inverse processing: Relatively less regularization will sharpen the pulse features, making the returns from different objects easier to distinguish, but more regularization will suppress measurement noise.

In addition to these trades, experimental work with test targets in the lab and on ranges, as well as actual orbiting objects, would be invaluable. Finally, we note the surface interaction model could be used for a.) modeling scenes and targets for laser engagement collateral damage simulations, and b.) simultaneous modeling of emission and reflection from both rocket hardbodys and plumes.

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