



### Computational Ghost Imaging for Remote Sensing

**Ghost imaging is used in encryption, remote sensing, and biomedical imaging applications.**

*NASA's Jet Propulsion Laboratory, Pasadena, California*

This work relates to the generic problem of remote active imaging; that is, a source illuminates a target of interest and a receiver collects the scattered light off the target to obtain an image. Conventional imaging systems consist of an imaging lens and a high-resolution detector array [e.g., a CCD (charge coupled device) array] to register the image. However, conventional imaging systems for remote sensing require high-quality optics and need to support large detector arrays and associated electronics. This results in suboptimal size, weight, and power consumption.

Computational ghost imaging (CGI) is a computational alternative to this traditional imaging concept that has a very simple receiver structure. In CGI, the transmitter illuminates the target with a modulated light source. A single-pixel (bucket) detector collects the scattered light. Then, via computation (i.e., post-processing), the receiver can “reconstruct” the image using the knowledge of the modulation that was projected onto the target by the transmitter. This way, one can construct a very simple receiver that, in principle, requires no lens to image a target.

Ghost imaging is a transverse imaging modality that has been receiving much attention owing to a rich inter-

connection of novel physical characteristics and novel signal processing algorithms suitable for active computational imaging. The original ghost imaging experiments consisted of two correlated optical beams traversing distinct paths and impinging on two spatially-separated photodetectors: one beam interacts with the target and then illuminates on a single-pixel (bucket) detector that provides no spatial resolution, whereas the other beam traverses an independent path and impinges on a high-resolution camera without any interaction with the target. The term “ghost imaging” was coined soon after the initial experiments were reported, to emphasize the fact that by cross-correlating two photocurrents, one generates an image of the target. In CGI, the measurement obtained from the reference arm (with the high-resolution detector) is replaced by a computational derivation of the measurement-plane intensity profile of the reference-arm beam. The algorithms applied to computational ghost imaging have diversified beyond simple correlation measurements, and now include modern reconstruction algorithms based on compressive sensing.

The physical principles underpinning CGI are as follows: the transmitter, by use

of a spatial light modulator, projects a spatiotemporally varying speckle pattern on the target. The scattered light from the target is collected with a simple bucket detector offering no spatial resolution. The photocurrent, whose fluctuations in excess of the shot-noise floor are proportional to the sum of the fluctuations seen in the transmitter-generated speckles, is then processed to resolve the transverse profile of the object. This signal processing can take on a rather elementary linear form such as cross-correlation, or can be more complex and nonlinear, such as L1-norm minimization. The latter form of ghost imaging is known as compressive, as it utilizes techniques developed for compressive imaging. Turbulence near the target has negligible impact on ghost imaging. The most restrictive source of speckle in remote sensing is that induced by the diffuse surface scattering from the target itself. It is evident from earlier analysis that once the speckle is fully developed, no additional gain is possible from integration, and de-correlated speckles must be obtained by using angular, spectral, or polarization diversity.

*This work was done by Baris I. Erkmen of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact [iaoffice@jpl.nasa.gov](mailto:iaoffice@jpl.nasa.gov). NPO-48157*

### Digital Architecture for a Trace Gas Sensor Platform

*John H. Glenn Research Center, Cleveland, Ohio*

A digital architecture has been implemented for a trace gas sensor platform, as a companion to standard analog control electronics, which accommodates optical absorption whose fractional absorbance equivalent would result in excess error if assumed to be linear. In cases where the absorption (1-transmission) is not equivalent to the fractional absorbance within a few percent error, it is necessary to ac-

commodate the actual measured absorption while reporting the measured concentration of a target analyte with reasonable accuracy. This requires incorporation of programmable intelligence into the sensor platform so that flexible interpretation of the acquired data may be accomplished.

Several different digital component architectures were tested and implemented. Commercial off-the-shelf digi-

tal electronics including data acquisition cards (DAQs), complex programmable logic devices (CPLDs), field-programmable gate arrays (FPGAs), and microcontrollers have been used to achieve the desired outcome. The most completely integrated architecture achieved during the project used the CPLD along with a microcontroller. The CPLD provides the initial digital demodulation of the raw sensor signal,

and then communicates over a parallel communications interface with a microcontroller. The microcontroller analyzes the digital signal from the CPLD, and applies a non-linear correction obtained through extensive data analysis at the various relevant EVA operating pressures. The microcontroller then presents the quantitatively accurate carbon dioxide partial pressure regardless of optical density.

This technique could extend the linear dynamic range of typical absorption

spectrometers, particularly those whose low end noise equivalent absorbance is below one-part-in-100,000. In the EVA application, it allows introduction of a path-length-enhancing architecture whose optical interference effects are well understood and quantified without sacrificing the dynamic range that allows quantitative detection at the higher carbon dioxide partial pressures. The digital components are compact and allow reasonably complete integration with separately developed analog control

electronics without sacrificing size, mass, or power draw.

*This work was done by Paula Gonzales, Miguel Casias, Andrei Vakhtin, and Jeffrey Pilgrim of Vista Photonics, Inc. for Glenn Research Center. Further information is contained in a TSP (see page 1).*

*Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steven Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-18730-1.*

## Dispersed Fringe Sensing Analysis — DFSA

*NASA's Jet Propulsion Laboratory, Pasadena, California*

Dispersed Fringe Sensing (DFS) is a technique for measuring and phasing segmented telescope mirrors using a dispersed broadband light image. DFS is capable of breaking the monochromatic light ambiguity, measuring absolute piston errors between segments of large segmented primary mirrors to tens of nanometers accuracy over a range of 100 micrometers or more.

The DFSA software tool analyzes DFS images to extract DFS encoded segment piston errors, which can be used to measure piston distances between primary mirror segments of ground and space telescopes. This information is necessary to control mirror segments to establish a smooth, continuous primary figure needed to achieve high optical quality.

The DFSA tool is versatile, allowing precise piston measurements from a variety of different optical configurations. DFSA technology may be used for meas-

uring wavefront pistons from sub-apertures defined by adjacent segments (such as Keck Telescope), or from separated sub-apertures used for testing large optical systems (such as sub-aperture wavefront testing for large primary mirrors using auto-collimating flats). An experimental demonstration of the coarse-phasing technology with verification of DFSA was performed at the Keck Telescope.

DFSA includes image processing, wavelength and source spectral calibration, fringe extraction line determination, dispersed fringe analysis, and wavefront piston sign determination. The code is robust against internal optical system aberrations and against spectral variations of the source. In addition to the DFSA tool, the software package contains a simple but sophisticated MATLAB model to generate dispersed fringe images of optical system configurations in order to quickly estimate the

coarse phasing performance given the optical and operational design requirements. Combining MATLAB (a high-level language and interactive environment developed by MathWorks), MACOS (JPL's software package for Modeling and Analysis for Controlled Optical Systems), and DFSA provides a unique optical development, modeling and analysis package to study current and future approaches to coarse phasing controlled segmented optical systems.

*This work was done by Norbert Sigrist, Fang Shi, David C. Redding, Scott A. Basinger, Catherine M. Ohara, Byoung-Joon Seo, Siddarayappa A. Bikkannavar, and Joshua A. Spechler of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov.*

*This software is available for commercial licensing. Please contact Daniel Broderick of the California Institute of Technology at danielb@caltech.edu. Refer to NPO-48019.*

## Indium Tin Oxide Resistor-Based Nitric Oxide Microsensors

**Applications for these sensors include engine emission and environmental monitoring.**

*John H. Glenn Research Center, Cleveland, Ohio*

A sensitive resistor-based NO microsensor, with a wide detection range and a low detection limit, has been developed. Semiconductor microfabrication techniques were used to create a sensor that has a simple, robust structure with a sensing area of  $1.10 \times 0.99$  mm. A Pt interdigitated structure was used for the electrodes to maximize the sensor signal output. N-type semiconductor indium tin oxide (ITO) thin film was sputter-deposited as a sensing material on the electrode surface, and be-

tween the electrode fingers. Alumina substrate (250  $\mu$ m in thickness) was sequentially used for sensor fabrication.

The resulting sensor was tested by applying a voltage across the two electrodes and measuring the resulting current. The sensor was tested at different concentrations of NO-containing gas at a range of temperatures. Preliminary results showed that the sensor had a relatively high sensitivity to NO at 450 °C and 1 V. NO concentrations from ppm to ppb ranges were detected with the

low limit of near 159 ppb. Lower NO concentrations are being tested.

Two sensing mechanisms were involved in the NO gas detection at ppm level: adsorption and oxidation reactions, whereas at ppb level of NO, only one sensing mechanism of adsorption was involved.

The NO microsensor has the advantages of high sensitivity, small size, simple batch fabrication, high sensor yield, low cost, and low power consumption due to its microsize. The resistor-based