

approximation is based on the assumption that the jitter in the arrival of each photon is independent. Another approximation is based on the assumption that only photon counts over finite time bins are available. Yet another approximation is based on the counts-over-finite-time-bins assumption with the addi-

tional assumption that the counts follow a Poisson distribution. For jitter with a standard deviation of 0.28 of a slot, computational-simulation tests have shown that receivers designed to compensate using the exact or approximate equations would exhibit error-rate reductions, relative to receiver designs based

on neglect of photon-arrival jitter, equivalent to power increases of the order of 1 dB (see figure).

*This work was done by Bruce Moision of Caltech for NASA's Jet Propulsion Laboratory. For more information, contact iaoffice@jpl.nasa.gov.  
NPO-45163*

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## MACOS Version 3.31

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

Version 3.31 of Modeling and Analysis for Controlled Optical Systems (MACOS) has been released. MACOS is an easy-to-use computer program for modeling and analyzing the behaviors of a variety of optical systems, including systems that have large, segmented apertures and are aligned with the technology of wavefront sensing and control. Two previous versions were described in "Improved Software for Modeling Controlled Optical Systems" (NPO-19841) *NASA Tech Briefs*, Vol. 21, No. 12 (December 1997), page 42 and "Optics Program Modified for Multithreaded Parallel Computing" (NPO-40572) *NASA Tech Briefs*, Vol. 30, No. 1 (January 2006) page

13a. The present version incorporates the following enhancements over prior versions:

- A powerful system-optimization facility includes algorithms for linear, nonlinear, unconstrained, and constrained optimization of optical systems under a variety of settings.
- There is now enhanced capability to perturb optical components individually and on subsystem levels, and to optimize system performance by adjusting selected individual components as well as subsystems.
- Capabilities for modeling a variety of new optical aperture types have been added.

- Effects of multilayer thin-film coats on optical surfaces can now be taken into account when tracing polarized rays.
- Major software-engineering work was performed to make MACOS more reliable, flexible, and manageable for purposes of maintenance and further development.

*This program was written by David Redding, John Lou, Scott Basinger and Norbert Sigrist of Caltech for NASA's Jet Propulsion Laboratory.*

*This software is available for commercial licensing. Please contact Karina Edmonds of the California Institute of Technology at (626) 395-2322. Refer to NPO-45030.*

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## Fiber-Optic Determination of N<sub>2</sub>, O<sub>2</sub>, and Fuel Vapor in the Ullage of Liquid-Fuel Tanks

**A fiber-optic sensor provides feedback control of onboard inert gas generation systems (OBIGGS) and reduces aircraft operational costs.**

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

A fiber-optic sensor system has been developed that can remotely measure the concentration of molecular oxygen (O<sub>2</sub>), nitrogen (N<sub>2</sub>), hydrocarbon vapor, and other gases (CO<sub>2</sub>, CO, H<sub>2</sub>O, chlorofluorocarbons, etc.) in the ullage of a liquid-fuel tank. The system provides an accurate and quantitative identification of the above gases with an accuracy of better than 1 percent by volume (for O<sub>2</sub> or N<sub>2</sub>) in real-time (5 seconds). In an effort to prevent aircraft fuel tank fires or explosions similar to the tragic TWA Flight 800 explosion in 1996, OBIGGS are currently being developed for large commercial aircraft to prevent dangerous conditions from forming inside fuel tanks by providing an "inerting" gas blanket that is low in oxygen, thus preventing

the ignition of the fuel/air mixture in the ullage.

OBIGGS have been used in military aircraft for many years and are now standard equipment on some newer large commercial aircraft (such as the Boeing 787). Currently, OBIGGS are being developed for retrofitting to existing commercial aircraft fleets in response to pending mandates from the FAA. Most OBIGGS use an air separation module (ASM) that separates O<sub>2</sub> from N<sub>2</sub> to make nitrogen-enriched air from compressed air flow diverted from the engine (bleed air). Current OBIGGS systems do not have a closed-loop feedback control, in part, due to the lack of suitable process sensors that can reliably measure N<sub>2</sub> or O<sub>2</sub> and at the same time, do not constitute an inherent source of ignition.

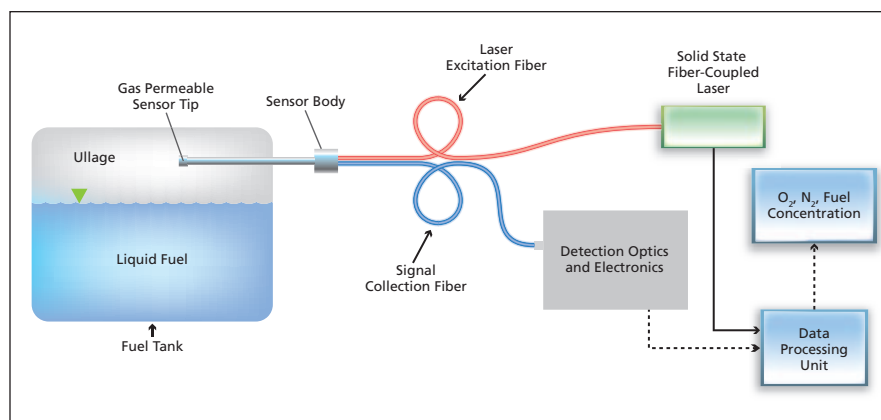
Thus, current OBIGGS operate with a high factor-of-safety dictated by process protocol to ensure adequate fuel-tank inerting. This approach is inherently inefficient as it consumes more engine bleed air than is necessary compared to a closed-loop controlled approach. The reduction of bleed air usage is important as it reduces fuel consumption, which translates to both increased flight range and lower operational costs.

Numerous approaches to developing OBIGGS feedback-control sensors have been under development by many research groups and companies. However, the direct measurement of nitrogen (N<sub>2</sub>) is a challenge to most OBIGGS ullage sensors (such as tunable diode laser absorption) as they cannot measure N<sub>2</sub> directly but de-

pend on the measurement of oxygen ( $O_2$ ). The problem with a singular measure of  $O_2$ , is that as the concentration (number density) of  $O_2$  decreases due to the inerting process or due to lower pressures from high altitudes, the precision and accuracy of the  $O_2$  measurement decreases. However, measuring  $O_2$  density in combination with  $N_2$  density (which is more abundant in air and in a  $N_2$ -inerted fuel tank) can provide a much more accurate and reliable determination of the OBIGGS efficacy.

Perhaps the most important advantage that the present technology has over competing single molecule sensors is the built-in redundancy of the simultaneous  $O_2$  and  $N_2$  measurement, which minimizes the possibility of false high-oxygen OBIGGS alarms, and its impact on airline operational costs that can result from a safety-required takeoff abort or forced-landing. The fiber-optic sensor system described here is inherently reliable as it has no moving parts or sensor materials that wear out or are consumed. Furthermore, the system is compact, lightweight, and requires little power (<20 W) for use aboard aircraft. The sensor technology itself does not present an intrinsic fire or explosion safety hazard compared to electrically based sensors that require wiring, which can serve as ignition sources within a fuel tank.

The present technology provides a fiber-optically-coupled gas sensor head that uses a low power (<30 mW) solid-state laser and optical detection system to yield high signal-to-noise ratios ( $10^4$ ) of multiple gas densities in a real-time mode. The optical signals from the sensor system are then digitized and processed by a rugged embedded micro-



**Schematic of the Fiber-Optic Ullage Oxygen/Nitrogen Sensor System** shows the sensor probe head mounted in the fuel tank through a bulkhead fitting. The laser and detection optics and electronics can be mounted remotely from the fuel tank in the avionics compartment. Multiple fiber optics sensor heads (up to 8) can be connected to a common detection optics unit for cost-effective deployment in configurations with multiple fuel tanks or multiple locations within a fuel tank.

controller unit (MCU). The MCU provides quantitative data streams representing the measured species concentration of  $N_2$ ,  $O_2$  for active-feedback control, and an alarm signal for aircraft operations.

In operation, the sensor probe head is mounted in the fuel-tank ullage, using a bulkhead flange type mount. The laser and detection optics and electronics can be mounted remotely in the avionics cabinet, away from the harsh environment that surrounds the fuel tank. The remote fiber-optic mounting enhances serviceability and provides system installation flexibility. This flexibility includes the ability for a single detection optics unit to monitor up to eight separate probe heads for a cost-effective deployment. Finally, the present system can also be used to reliably detect fires in inaccessible locations aboard an aircraft (engine nacelle, cabling and hydraulic line compartment, wheel well, and the

like) by detecting low  $O_2$ , with enhanced  $CO_2$  and CO, both by-products of combustion and fires.

As an added benefit, the present technology can also measure the concentration of chlorofluorocarbons (CFC's) that are used to suppress fires to confirm that fire-suppression measures have been properly executed. Such a fire detection system also has the advantage of very low false-alarm rates as multiple chemical species are detected and required to trigger a fire alarm.

*This work was done by Quang-Viet Nguyen of 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: Steve Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17826-1.*