Cost-effective, Laser-based Enhancement of Passive Carbon Monitoring Approaches from GEO or LEO Orbits

Dr. Jeremy T. Dobler, Dr. James Nagel, **Mr. Glenn Davis,** Harris Corporation, Environmental Solutions, 1919 West Cook Rd., Fort Wayne, IN, 46801 USA **Jeremy.Dobler@Harris.com**

Introduction

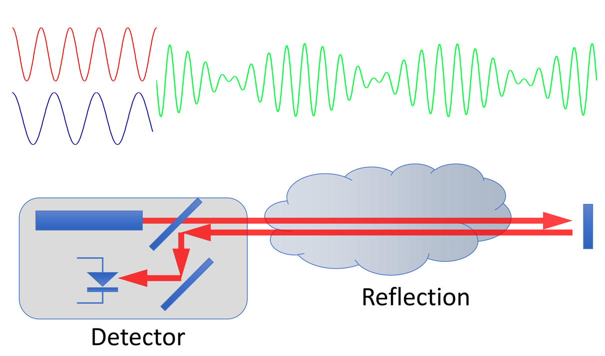
For the past decade, significant advancements have been made toward understanding the global carbon budget using passive remote sensing techniques such as GOSAT and OCO-2. Japan is preparing to launch the follow-on instrument, GOSAT2, and NASA is planning a mission with OCO-3 hosted on the International Space Station (ISS). Although the advancement provided from these sensors has been game changing, these approaches have limitations in terms of temporal coverage and potential for location- and surface-dependent systematic bias from clouds and aerosols, driving column-height uncertainties. Recently NASA announced the selection of the GeoCARB instrument, which will enhance the current record by enabling high-frequency coverage of land, atmosphere, and ocean exchange of carbon, including vegetation health. However, GeoCARB will be affected by similar biases.

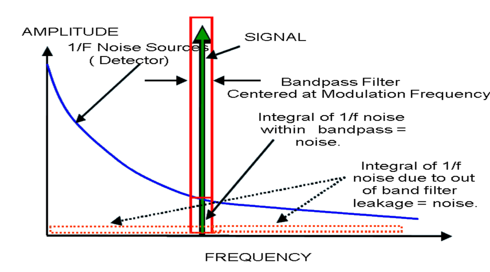
Here we present a cost-effective, laser-based concept aimed at enhancing the GeoCARB mission or other future passive remote-sensing platforms from low or geosynchronous earth orbit (LEO or GEO). Originally developed by Harris in 2011, the Laser Atmospheric Transmitter and Receiver-Network (LAnTeRN) concept uses a single space-based laser transmitter to make total column measurements of CO_2 from GEO between the satellite and a network of ground-based receivers. Following initial development, we demonstrated the LAnTeRN concept through ground-based horizontal path testing. The horizontal testing then led to the Greenhouse-gas Laser Imaging Tomography Experiment, or GreenLITE™, which enables spatial mapping of greenhouse gases including CO_2 and CH_4 over areas of 1 to 25 km^2 and estimates flux from a limited number of dominant sources within the footprint. The LAnTeRN concept is currently implementable using existing high technology readiness level technologies. We will review the LAnTeRN concept and how it might be coupled with GeoCARB, or other similar observations in the future, to eliminate the bias uncertainty inherent in passive measurement systems. We will also discuss how a similar approach might be implemented along with future passive carbon monitoring instruments from LEO platforms as a calibration and validation tool to minimize potential sources of bias.

Harris Active Remote Sensing Technology

The Harris Intensity Modulated Continuous Wave (IMCW) Laser Absorption Spectroscopy (LAS) approach is predicated on heritage principles used in radar signal processing while also combining decades of investment in the telecommunications industry. The fiber-based architecture enables a robust instrument design while the continuous wave (CW) aspect enables reliable narrow line width , low-peak power operation, not susceptible to misalignments or component damage that traditional free-space optics and high peak power pulsed systems are. The basic principles of the measurement are as follows:

- Two or more fixed wavelength lasers are uniquely encoded and combined into a single output waveform
- Reference measurement is taken to characterize the relative amplitudes of each outgoing channel using single reference detector
- Combined waveform is transmitted to target, reflected back, and collected by a single telescope onto a single science detector
- Detector signal is amplified and then digitized
- Reference and reflected signals are spectrally separated using correlation with encoded waveforms
- Reflected signals are normalized by reference signals from respective wavelengths
- Ratio of normalized signals, when using at least one wavelength in high absorption and at least one with low absorption, is directly related to number density of the absorbing gas(es)
- Proper absolute and relative spectral selection can minimize influence of other gases
- Knowledge of atmospheric state allows inversion to concentration
- IMCW approach offers simultaneous ranging via encoded waveforms (e.g., Chirp, PN codes)





$$N = \int_0^z \rho(z')dz' = \frac{1}{2\left(\sigma_{on}^{eff} - \sigma_{off}^{eff}\right)} \ln\left(\frac{S_{off}(z)}{S_{on}(z)}\right)$$

N is the number density, ρ is the differential transmission, σ is absorption cross section, and S is reference normalized signal

IMCW enables many of the advantages of coherent detection (high gain, high background rejection) without the increased cost and complexity, in addition to being implementable in all optical fiber, resulting in a simpler more robust design.

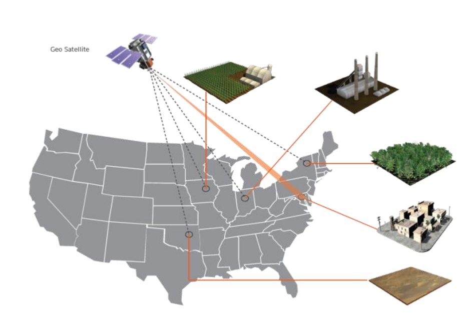
Multi-Functional Fiber Laser Lidar (MFLL)

MFLL is an all fiber-based airborne demonstrator utilizing the IMCW approach. The system was built by Harris (previously ITT) in 2004 as a proof-of-concept to demonstrate measurements with similar power levels to those expected from a space implementation and has since participated in dozens of extensive airborne campaigns in conjunction with NASA Langley Research Center. Most recently MFLL has been participating in the NASA Earth Venture Suborbital program Atmospheric Carbon Transport across America (ACT-America). The system currently utilizes a CO_2 absorption line near 1571 nm, but could also be easily implemented at the 2050 nm strong absorption band. Mentioned here for completeness, MFLL has been described in detail elsewhere. See for example *(Dobler et al., Appl. Opt.* ***52****, 2874-2892, 2013)*. MFLL is the basis from which the following unique measurement approaches were derived.

LAnTeRN

LAnTeRN is a concept developed by Harris in 2011 as a derivative of the MFLL measurement, seeking to eliminate partial path effects on the Integrated Path Differential Absorption (IPDA) measurements. LAnTeRN is a bistatic implementation of the IMCW approach where the measurement is made in transmission rather than reflection. For space, LAnTeRN was initially conceived as a transmitter located on a hosted payload in a geostationary orbit, and a network of ground-based receivers. Some key advantages of this approach are:

- Having the receiver on the ground reduces cost and risk significantly by eliminating the need to launch meter + class telescope and other electronics for receiver, and 3-7X optical power requirement reduction
- GEO orbit enables long-term integration over a fixed path to achieve very high precision measurements that are not susceptible to bias from clouds and aerosols
- LAnTeRN in GEO offers an opportunity for independent validation of bias not feasible for any other existing or planned approach
- LAnTeRN offers a low cost pathfinder for future backscatter missions



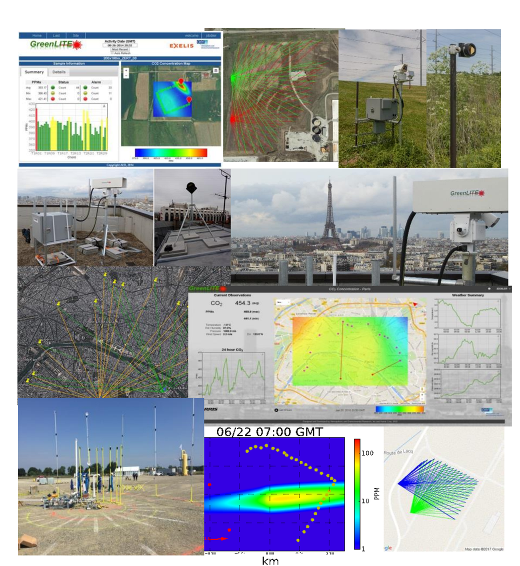
Dobler et al. Remote Sens., ***5****(12), 6284-6304; 2013*

GreenLITE™

GreenLITE™ is an offshoot of MFLL and LAnTeRN developed by Harris and Atmospheric and Environmental Research (AER) starting in 2013. The development was partially funded through a cooperative agreement with the U.S. Department of Energy (DOE) as a means to offer continuous monitoring and leak detection for ground carbon sequestration sites up to ~1 km^2.

The GreenLITE™ concept uses a set of two or more IMCW monostatic transceivers and a series of reflectors in order to establish a horizontal grid of gas density measurements, which are then used to provide an estimate of the 2-D spatial distribution of the gas within the footprint of the site configuration using sparse tomographic methods. It has since been expanded through Harris and AER funding to a demonstration of full-scale urban monitoring and high-accuracy, precision measurements of CH_4 or CO_2. It also provides estimates of the spatial distribution of the gases over areas from 0.04 to 25 km^2.

Additional details on GreenLITE™ CO_2 deployments can be found in *(Dobler et al. Journal of Applied Remote Sensing, 11(1), 2017)* and *(Dobler et al., EPJ Web of Conferences* ***176****, 05013, 2018)*, including information on the recent addition of methane. The Harris and AER team have also recently demonstrated the ability to estimate flux during the Gas Leak Detection Campaign hosted by TOTAL in Lacq, France, June 2016. Details are available in *(Watremez et al., Society of Petroleum Engineers; Doc. ID* ***SPE-190496****-MS, Abu Dhabi, UAE, 16-18 April, 2018)*.



Active Calibration Approach

The LAnTeRN concept from GEO can enable the following unique calibration opportunities:

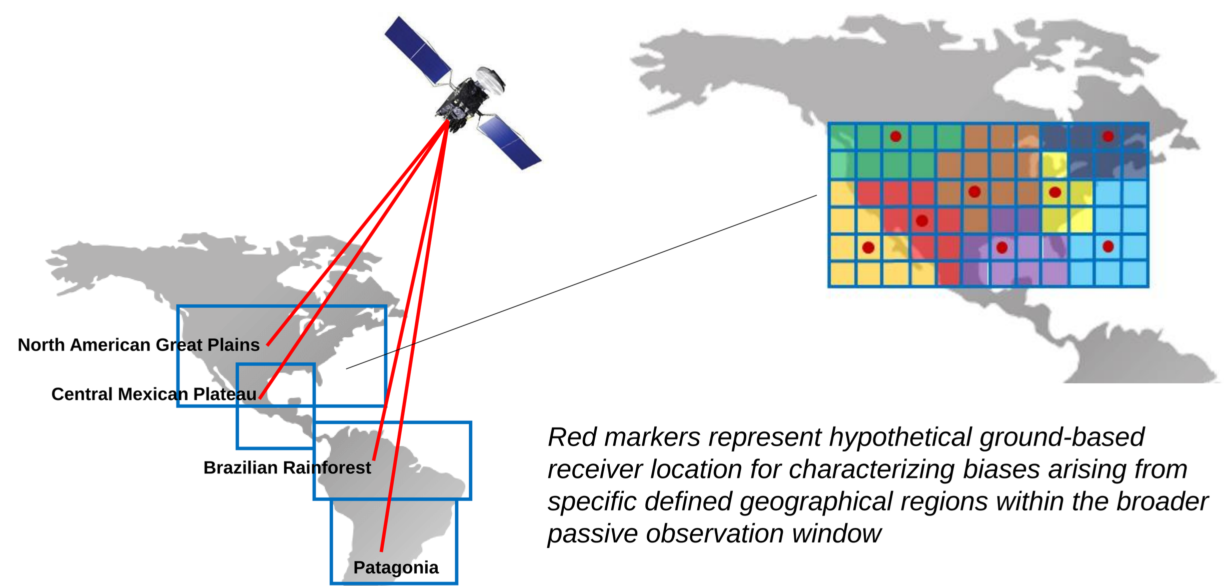
- Collocation of all ground transceivers during initial calibration to establish cross-calibration between receivers before distributing them
- Long-term integration allowing random noise to be minimized to unprecedented levels for a remote sensing measurement
- Continuous viewing along a fixed path, which supports the ability to use existing technologies (Aircraft in situ, flasks, AirCore, etc.) for extensive column characterization and obtaining a clear evaluation of the absolute bias of the active system
- Portability of the ground sensors enable the process above to be repeated to validate the stability of the cross-calibration over the mission lifetime

Need for Active-Passive GHG Remote Sensing from Space

- Passive measurements from LEO or GEO are impacted by uncertainties in the column length caused by the influence of clouds and aerosols
- Additional biases can arise from rapidly changing topography and different surface types
- Validation approaches using Total Column Carbon Observing Network are only available during a limited time of day due to solar tracking and varying air mass making it difficult to assess potential time of day or solar angle biases
- The active component would provide diurnal measurements not currently available to the passive sensors

Active-Passive GEO Scenario 1

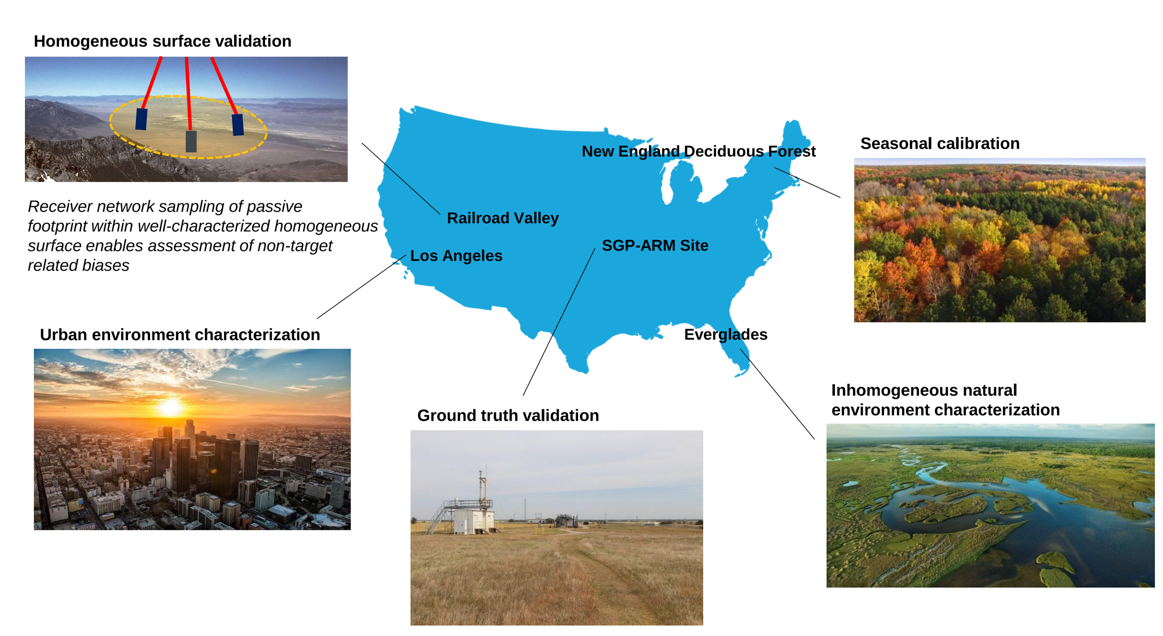
- GEO passive measurement validation through comparison of strategically placed expandable network of receivers
- Intelligent receiver placement within a given spatial observation window gives comparison data for defined geographical sub-sections (e.g. desert, ocean, mountain, etc.), enabling passive bias characterization under varying conditions
- Allows for isolation of components contributing to passive bias that can then be used to partially correct the measurements coming from the passive sensor



Red markers represent hypothetical ground-based receiver location for characterizing biases arising from specific defined geographical regions within the broader passive observation window

Active-Passive GEO Scenario 2

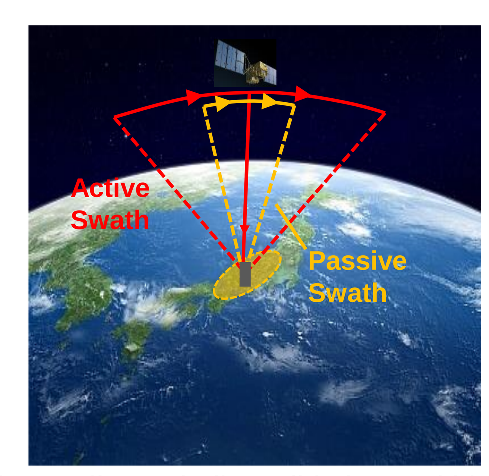
- Relocatable ground sensors supporting targeted observations of both homogeneous and inhomogeneous environments
- Enables long-term characterization of specific areas of interest and calibration opportunities focused on identifying potential bias over a specific target area or type



Active-Passive LEO Scenario 3

A bi-static instrument co-hosted with a dedicated passive instrument in LEO is more challenging and loses some of the benefits of the GEO case.

This scenario can still provide important enhancements and maintains the benefit of only having the transmitter on orbit, which reduces size, weight, power, and cost. The required laser power is higher than for the GEO case due to shorter integration periods, but still significantly lower than for the surface reflection-based active measurements.



Other considerations include:

- Ability to strategically position ground receivers offer periodic validation and bias correction of the passive measurements
- Receivers can be placed in areas where passive measurements are restricted such as the polar and mid-latitude regions for added science value
- Shorter dwell times may require a swath in space that is wider than the passive instrument to obtain reasonable SNR
- Advancements in pointing and tracking coming from free-space optical communications may reduce required dwell time and swath

Conclusions and Future Work

- We present a concept for enhancing existing or planned passive GHG sensing capabilities through the integration of a laser transmitter with the payload and the use of a network of receivers on the ground
- Measurements in transmission are not susceptible to bias from clouds and aerosols
- The fixed relation from a geosynchronous orbit offers very long integration times without the need for a cloud and low-aerosol environment, rarely possible with a passive system
- Allows for additional scientific measurements and characterization in certain critical areas of interest not accessible to passive techniques or at night
- The Harris IMCW approach enables the use of fiber laser technology that exists at a high technology readiness level today and can be easily scaled to other spectroscopic wavelengths (e.g., 2050 nm)
- The proposed concept can be achieved at a significantly lower cost in comparison to a purely active system using surface reflection IPDA
- Implementation of the LAnTeRN concept in conjunction with GeoCARB or a similar mission would serve as a technological "stepping-stone" and low-cost precursor to a future full active instrument in LEO