Laser Atmospheric Transmitter and Receiver Network (LAnTeRN): A novel hosted-payload active measurement to enhance future space-based GHG emissions monitoring frameworks

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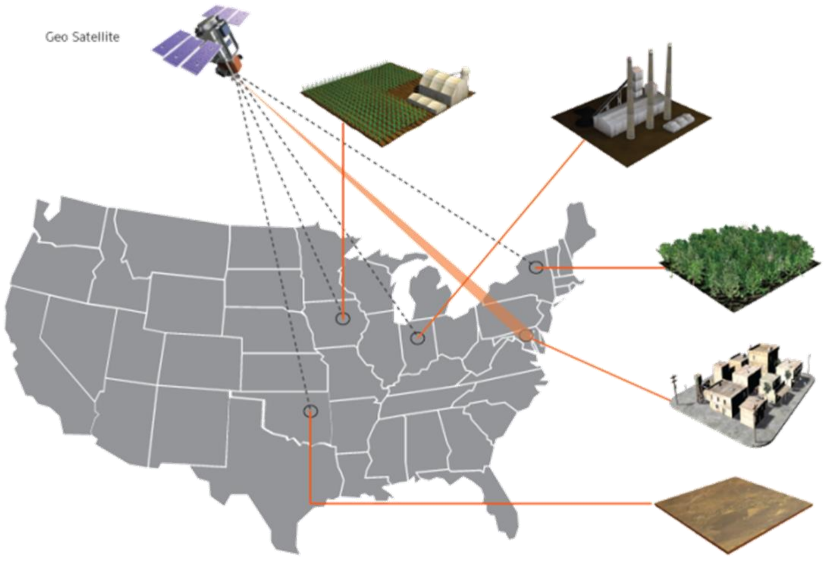
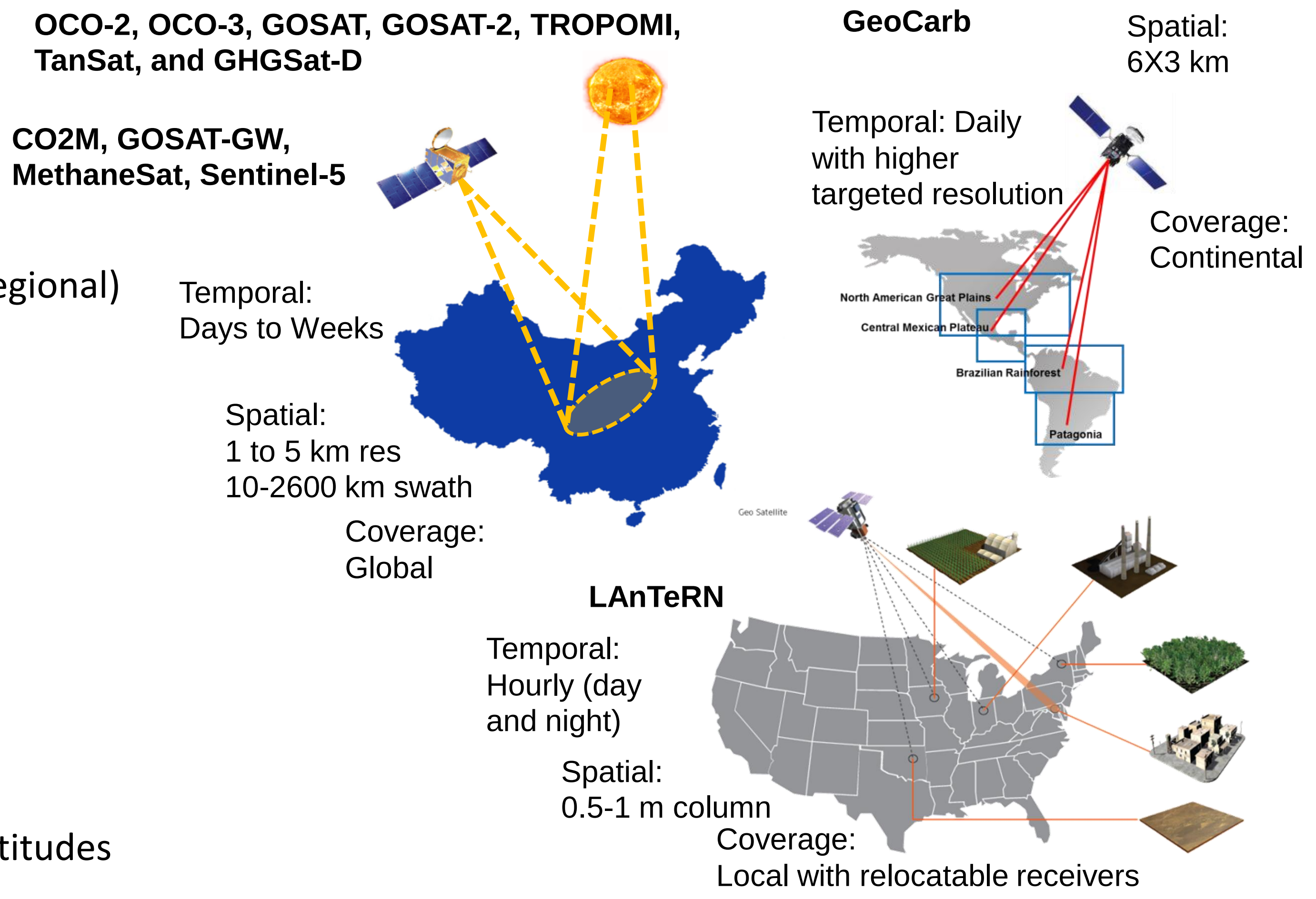
- LAnTeRN is a novel measurement approach enabling column integrated CO_2 (XCO_2) using fiber laser illumination from a Geostationary Orbiting (GEO) satellite
- The Intensity Modulated Continuous Wave (IMCW) approach, developed by ITT Space Systems (now L3Harris) and under license to Spectral Sensor Solutions, has been extensively demonstrated in both airborne and ground-based instrumentation
- Recent airborne validation of the method has shown the ability to provide low-bias, high-precision measurements
- Current work in free-space optical communications (FSOC) is advancing many of the components required to implement a LAnTeRN system, including space-qualified photonics/electronics and integrated ground terminals
- Commercial development for FSOC in the 1.55-um wavelength band significantly reduces risk, cost and development time for implementation of this novel approach



Hosting only the transmitter and leveraging recent commercial FSOC development could enable a rapid, low-cost, demonstration of an active XCO_2 capability, complementing existing and planned measurements.

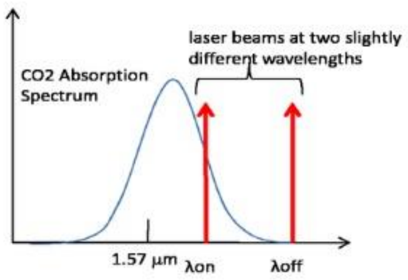
How LAnTeRN measurements fit into future space-based emissions monitoring frameworks?

- Low-Earth Orbit (LEO)
  - offers broad spatial extent (global)
  - sparse temporal coverage (weeks)
- Geostationary Orbit (GEO)
  - offers smaller spatial extent (continental, regional)
  - dense temporal coverage (daily, hourly)
- Passive Measurements
  - provide broad coverage at low resolution
  - limited by clouds and aerosol influence
  - daytime only
- Active Measurements
  - limited coverage at high resolution
  - little influence from clouds and aerosols
  - provide measurements at night and high latitudes

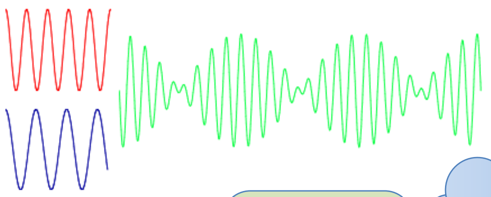


Successful future space-based GHG emissions monitoring frameworks require measurements on multiple temporal and spatial scales and ability to connect them. A range of measurement approaches, new measurement methods, and new methods for cross-calibration are needed.

Intensity Modulated Continuous Wave (IMCW) Laser Absorption Spectroscopy (LAS) measurement methodology

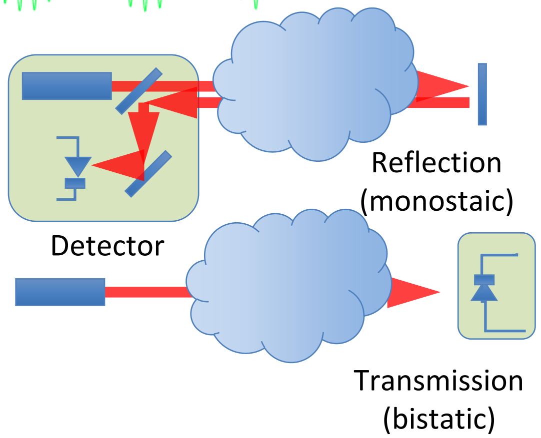


- Two (or more) wavelengths chosen (~25 to 75 pm separation)
- One is absorbed by the target gas, and the other is not



- All wavelengths are uniquely encoded and combined into a single amplitude-modulated waveform

Simultaneous transmission and reception allows for multiplicative correlated noise sources to cancel in the ratio, leading to increased measurement precision, and near-immunity to scintillation



- Combined waveform is propagated to a target and reflected back (monostatic) for collection or is directly collected (bistatic) by a single telescope and common detector
- Ratio of normalized signals is proportional to the number of gas molecules present through a Beer-Lambert retrieval

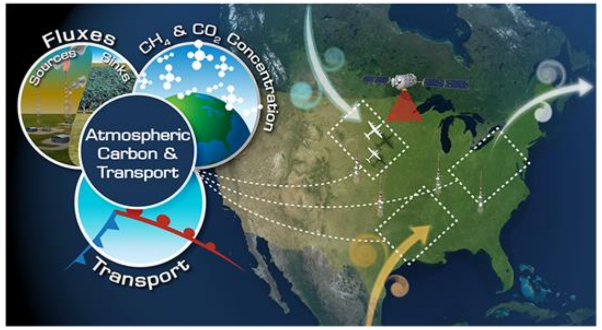
The IMCW LAS method is ideally suited for low-power differential measurements over long open paths, with low bandwidth detection.

Recent validation of IMCW method

- Airborne validation of the IMCW method through the NASA Earth Venture Suborbital ACT-America demonstrated precision of 1.2, 0.43, and 0.26 ppmv for 1, 10, and 60 second averages, respectively.
- After calibration, the measurements were shown to be unbiased with a 1σ standard deviation of 0.8 ppm.
- Calibration campaign-to-campaign (year-to-year) was stable within about 0.5 ppm

  (see Campbell et al., Earth and Space Science, 2020)
- These results are consistent with, and show improvement over, previously reported validation work which showed agreement of the airborne data to the in situ derived values to 0.67 ppmv ±1.7 ppmv

  (see Dobler et al., Applied Optics, 2013)
- Similar signal-to-noise levels can easily be achieved for the LAnTeRN concept leveraging recent technology developments in FSOC

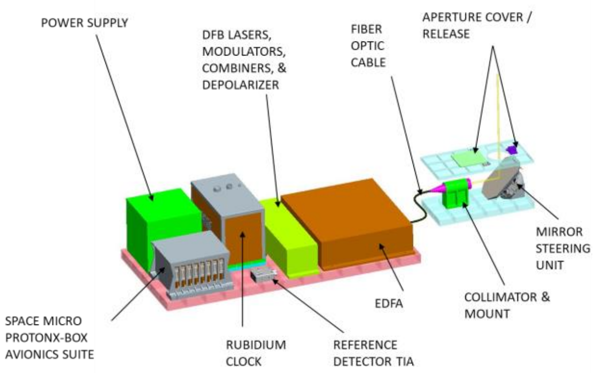


Extensive flight campaigns with NASA have demonstrated the IMCW method has potential to provide high-accuracy, high-precision vertical column XCO_2 measurements under a range of conditions.

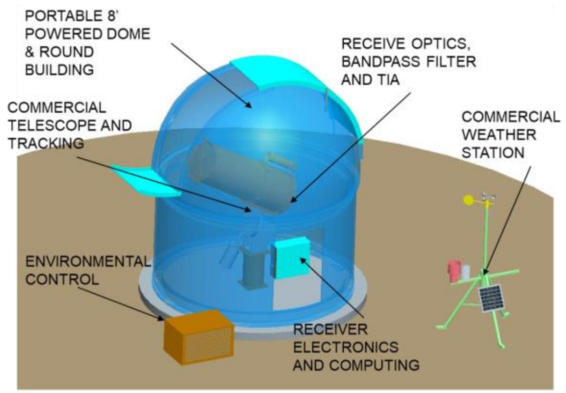
Laser Atmospheric Transmitter and Receiver Network (LAnTeRN) performance

Baseline Instrument Parameters		
Transmitter	**Value**	**Units**
Online Wavelength 1 (–3pm)	1571.109	nm
Online Wavelength 2 (–10pm)	1571.102	nm
Offline Wavelength 3 (–70pm)	1571.042	nm
Total Optical Power	6.4	W
Individual Channel Optical Power	3.24,1.44,1.72	W
Individual Channel Modulation Frequency	187, 200, 223	kHz
Laser Linewidth	10	MHz
Laser Frequency Stability	3	MHz
Transmitter Efficiency	95	%
Transmitter Divergence (1/2 angle)	1400	urad
Receiver	**Value**	**Units**
Receiver Efficiency	0.64	
Receiver Aperture Diameter	0.4064	m
Center Obscuration Diameter	20	%
Receiver FOV (1/2 angle)	2.44	mrad
Detector Diameter	1	mm
Electronics Bandwidth	0.4	MHz
Responsivity	1	A/W
Reverse Leakage Current	1.00E-10	A
Detector Temperature	293	K
Transimpedance Amplifier (TIA) Feedback Resistance	1.00E+07	Ohm
TIA Feedback Resistor Temperature	293	K
Detector Capacitance	3.00E-11	F
TIA Voltage Input Noise	5.00E-09	V/rtHz
Integration Time	1.0	min
Optical Bandpass Filter Width	1.0	nm
Other	**Value**	**Units**
Orbit Longitude	-112	deg
Ground Sensor Elevation Angle (Philadelphia, Indianapolis, Rural East U.S.)	30.4, 32.9, 41.0	deg
Aerosol OD @ Nadir	0.3 - 0.4	

Transmitter



Notional Receiver



Example scenario estimates for 2 min integration

Science Requirement	Location	Season	Aerosol OD @ Nadir	Online Position	Required Instrument Uncertainty (ppm)	Modeled Instrument Uncertainty* (ppm)
Urban 0.2 ppm / 3 mo	Philadelphia	Summer	0.4	–3 pm	5.42	1.56
				–10 pm	5.97	2.32
	Indianapolis	Winter	0.3	–3 pm	3.19	1.14
				–10 pm	4.06	1.81
Biogenic 0.1 ppm / yr	Rural Eastern U.S.	Summer	0.4	–3 pm	4.60	1.00
				–10 pm	5.91	1.96
	Rural Eastern U.S.	Winter	0.4	–3 pm	4.60	1.00
				–10 pm	5.91	1.95

*Uncertainty values shown include retrieval uncertainty estimates, 120-sec integration, use end-of-life (EOL) transmit powers defined as 20% degradation from the beginning of life power, and an elevation angle of 30°.

A baseline architecture that leverages primarily mature commercial off-the-shelf components has been formulated, and performance estimates have been run for a number of scenarios using a physics-based optical communication model and realistic parameters.

Current state of the technology

- Free-Space Optical Communications (FSOC) is fueling industry development of space qualified photonics components
  - There has been significant advancement in commercially-available space-qualified photonics over the past 5+ years, including:
    - Lasers, amplifiers, pump diodes, fused fiber components, polarization control, and detectors
  - Significant reduction in size, weight and power has also been achieved
  - Additional developments related to universal ground terminals that could be leveraged are in work (recent examples: Proceedings Volume 11678, Free-Space Laser Communications XXXIII; 116780L (2021) https://doi.org/10.1117/12.2577512)
- Although similar to an optical comm link, LAnTeRN has a simpler modulation/demodulation scheme, low frequency requirements, and significantly reduced pointing requirements
- LAnTeRN relies on a proven measurement methodology, is relatively inexpensive to execute compared to other active measurement approaches, and could be implemented on a short timescale leveraging recent advancements in FSOC

LAnTeRN would complement current and planned space-based GHG measurement capabilities toward a global GHG emissions monitoring framework and provide the only persistent day and night measurement of column XCO_2 at the local scale for key locations.