CHRONOS

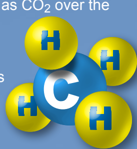
Quantifying changing methane emissions and atmospheric pollution transport for informed air quality, climate and energy policy decisions.

Principal Investigator: Dr. David Edwards, UCAR/NCAR

CHRONOS: Revolutionary Science from Space

Methane (CH_4) and carbon monoxide (CO) are ozone precursors (air pollutants).
- Air pollution directly affects human health.
- Large uncertainties and conflicting estimates exist in current CH_4 and CO emissions inventories.

Methane is a powerful greenhouse gas, 86 times as potent as CO_2 over the 20 year policy-relevant timeframe.
- Reducing CH_4 released to the air mitigates both climate change and air pollution in our lifetimes.

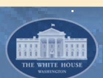


Methane escaping from increasing natural gas production is poorly monitored and highly variable.
- Climate advantages from burning natural gas over coal are lost with as little as 3% fugitive emissions from gas extraction.
- Ground-based CH_4 monitoring shows large inconsistencies.

CO measurements identify regional and urban pollution transport.
- Discriminating between local and transported pollution is fundamental to addressing air quality needs.

Together, CH_4, CO, and CO_2 define the Earth's carbon cycle.
- CHRONOS' CH_4 and CO observations can be combined in a modeling framework with CO_2 observations from other NASA satellites for improved understanding of the Earth's carbon cycle.

CHRONOS Supports Science-Based Decision Making



CHRONOS can provide a NASA contribution to the White House OSTP 2014 **Strategy to Reduce Methane Emissions**, which specifically identified a focus on improving methane measurements.

"Methane emissions come from diverse sources and sectors of the economy, unevenly dispersed across the landscape. These characteristics complicate measurement and attribution and lead to significant uncertainties in estimates of current and projected methane emissions. Better data collection and measurement will improve our understanding of methane sources and trends, and enable more effective management of opportunities to reduce methane emissions."

Compelling Science Goal & Objectives

CHRONOS Science Goal:
Characterize the impacts on air quality, climate and energy policy decisions due to changing emissions of methane and other pollutants in North America from urban sources, wetlands, fires and fossil fuel extraction

CHRONOS Science Objectives:
Quantify the temporal and spatial variations of methane (CH_4) and carbon monoxide (CO) emissions for air quality, climate, and energy policy decisions

Track rapidly changing vertical and horizontal atmospheric pollution transport to determine near-surface air quality at urban to continental spatial scales, and at diurnal to monthly temporal scales

Innovative Investigation Overview

The CHRONOS investigation transforms the assessment of highly uncertain emissions and air quality from space.

Key Feature	New NASA Capability
Hourly temporal resolution	First observations of tropospheric CH_4 and CO with hourly revisit time examines diurnal evolution of emissions and local to continental scale pollution transport.
4 km x 4 km spatial resolution	Fine spatial resolution distinguishes pollution source regions across cities and rural areas.
Multispectral measurements	State-of-the-art multispectral retrieval of CO gives vertical information near the surface and in the free troposphere to distinguish local from transported pollution through horizontal and vertical tracking.
Dense data for model emissions estimates	Comprehensive and self-consistent measurements provide answers to large inconsistencies in reported emissions.
Integrated observing system	Strengthens the international air quality satellite constellation of both LEO and GEO assets with common tools to integrate information.

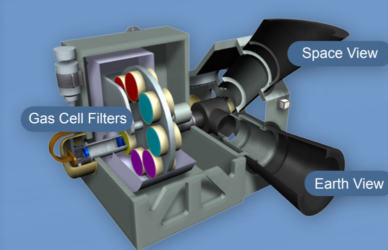
Multi-Disciplinary Science Team

Internationally recognized CHRONOS Science Team delivers compelling science to address national needs.

Discipline	Member & Affiliation
Principal Investigator	David Edwards, P.I., NCAR
Instrument Science	Doreen Neil, (Project Scientist), Co-I., LaRC
	Roger Drake, Co-I., Ball (Instrument Lead)
	John Gille, Co-I., NCAR
	Jim Drummond, Co-I., (contributed) Dalhousie Univ., Canada
Emissions Inventories, Climate and Air Quality	Gregory Frost (lead), Co-I., NOAA
	Drew Shindell, Co-I., Duke University
Chemical Transport Models, Data Assimilation and Inverse Modeling	Daniel Jacob (lead), Co-I. Harvard Univ.
	Daven Henze, Co-I. Univ. Colorado
	Dylan Jones, Co-I, (contributed), U. Toronto, Canada
	Gabriele Pfister, Co-I. NCAR
	Bryan Duncan, Co-I. GSFC
Validation	Jim Crawford, (lead), Co-I. LaRC
	Mike Newchurch, Co-I. Univ. Alabama/AQRSC
	Michel Grutter de la Mora, Co-I., (contributed), UNAM, Mexico
Constellation of Composition Missions	Annmarie Eldering (lead), Co-I. JPL
	Kelly Chance, Co-I. Harvard-SAO
	Cathy Clerbaux, Co-I. (contributed), CNRS, France
	Jhoon Kim, Co-I. (contributed), Yonsei Univ., Seoul, South Korea
Air Quality Applications	Jack Fishman (lead), Co-I., Saint Louis University
	Brad Pierce, Co-I. NOAA
Algorithm Development	Helen Worden (lead), Deputy-PI. NCAR
	Christian Frankenberg, Co-I., Caltech
	Ilse Aben, Co-I. (contributed), SRON, Netherlands
	Louisa Emmons, Co-I. NCAR
	John Worden, Co-I., JPL

Proven Instrument Characteristics

CHRONOS delivers CH_4 & CO measurements using the space-proven Gas Filter Correlation Radiometry technique used by MOPITT. The instrument employs high heritage components and subsystems to achieve a high-performance, low-risk design.



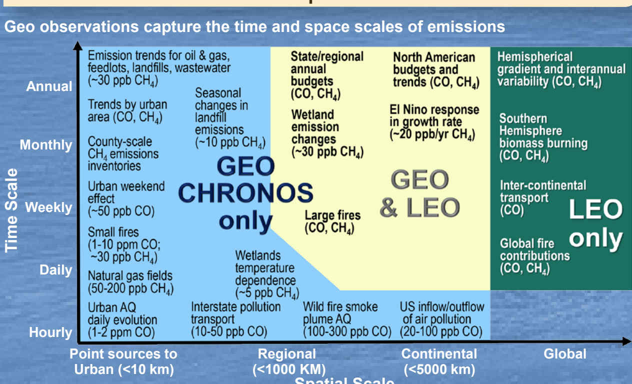
- Simple camera with gas cell filters
- No technology development or advanced engineering
- Build-to-print electronics and mechanism elements
- Benefits from a decade of risk mitigation by NASA ESTO

Parameter	Value
Mass	104.6 kg
Power	209.4 W
Volume	0.9m x 0.7m x 0.9m
Data Rate	59 Mbps (raw, hourly averaged)

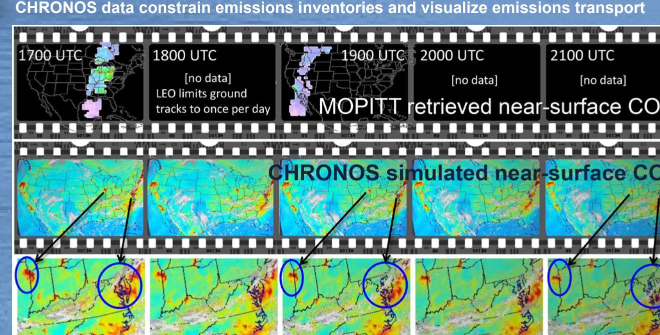
CHRONOS is readily accommodated on commercial GEO spacecraft platforms

CHRONOS in GEO Reveals Comprehensive Picture of Emissions

Geo observations capture the time and space scales of emissions



CHRONOS data constrain emissions inventories and visualize emissions transport



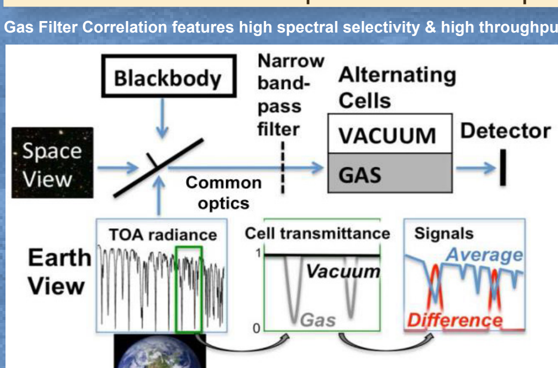
CHRONOS provides observations everywhere over greater North America every hour, compared to LEO gaps. Hourly frames, depicting CO surface data, illustrate CHRONOS' value to observe anthropogenic and transient emission sources and track air pollution transport. Reds indicate high pollutant levels. Circled areas show CO pollution from Chicago moving south, while afternoon clouds sweep through Washington DC, clearing the air.

CHRONOS significantly advances the NASA goal of scientific discovery

NASA 2014 Earth Science Goals	NRC 2007 Questions	CHRONOS Science Objectives	CHRONOS Measurements	LEO Heritage	Synergy with Global Air Quality Constellation
Advance the understanding of changes in the Earth's radiation balance, air quality, and the ozone layer that result from changes in atmospheric composition	How will continuing economic development affect the production of air pollutants?	**O1.** Quantify the temporal and spatial variations of CH_4 and CO emissions for air quality, climate, and energy policy decisions	*CH_4 total column abundance: (O1)* **Benefits:** Unprecedented capability for quantifying North American emissions	**SCIAMACHY** SWIR CH_4 (2002-2012); **GOSAT** SWIR CH_4 (2009-2014)	*Correlative LEO measurements:* EUMETSAT **IASI** and **IASI-NG** TIR CO, O_3, NH_3 + METOP (2018-2035); NASA **OCO-3** CO_2, (2017-?); ESA S5-P **TROPOMI** SWIR, UV-Vis CO, CH_4, O_3, +, (2016-2023); JAXA **GOSAT-2** SWIR CO_2, CH_4, CO, + (2018-2023)
Further the use of Earth system science research to inform decisions and provide benefit to society	How will [air] pollutants be transported across oceans and continents?	**O2.** Track rapidly changing vertical and horizontal atmospheric pollution transport to determine near-surface air quality at urban to continental, spatial scales, and at diurnal to monthly temporal scales	*CO total column and tropospheric abundance in up to 3 layers with near surface sensitivity: (O1 & O2)* **Benefits:** Outstanding tracer of pollution with required temporal and spatial resolution to test predictions of air quality.	**MAPS** TIR CO GFCR on Shuttle (1981-1994); **MOPITT** TIR & multispectral CO (1999-2020(?)); **SCIAMACHY** SWIR CO (2002-2012); **AIRS/TES/IASI/CrIS** TIR CO (2002-?)	*CHRONOS provides the only CH_4 and CO measurements in the GEO constellation:* Korean **GEMS** UV-Vis O_3, aerosols +, MP-GEOSAT (2018-2027); ESA/EUMETSAT **S4** UV-Vis O_3, aerosols,+ MTG/TIR O_3, aerosols, CO + (2021-2028); NASA **TEMPO** UV-Vis O_3, aerosols, + ; (2019-?)

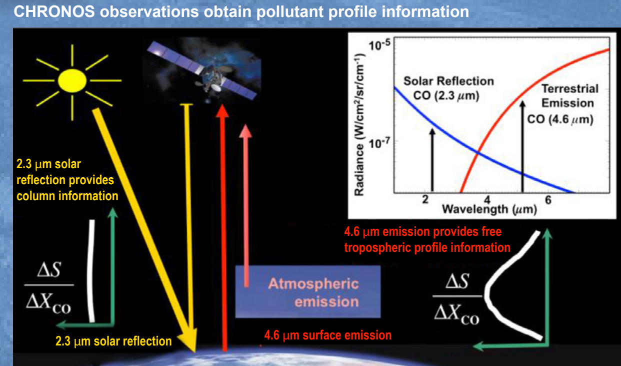
CHRONOS Measurement Concepts Build on Extensive Space Heritage

Gas Filter Correlation features high spectral selectivity & high throughput



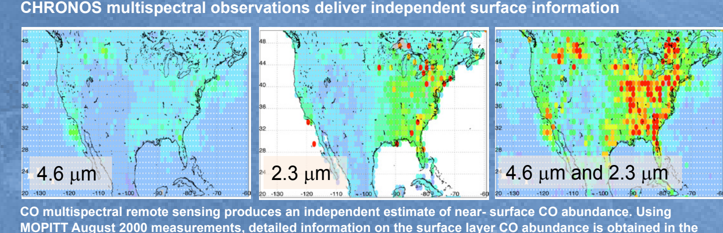
CHRONOS uses the Gas Filter Correlation Radiometer (GFCR) technique with schematic above showing GFCR signals from a single gas cell/vacuum cell pair. Upwelling atmospheric radiance passes through a narrow bandpass filter, selected for the target gas spectral range, then passes through a target gas cell and on to a detector pixel. Within 60 msec, the atmospheric radiance passes through an identical reference vacuum cell and identical bandpass filter and falls on the same detector pixel.

CHRONOS observations obtain pollutant profile information



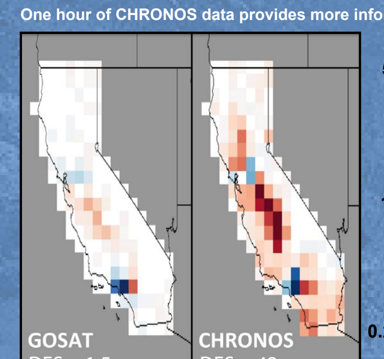
At 2.2 and 2.3 μm, measurement signals rely on daytime reflected solar radiation and weak spectral features. Changes in CH_4 and CO mixing ratios produce uniform signal sensitivity throughout the vertical profile, including near the surface. At 4.6 μm (2170 cm^{-1}), signal sensitivity is usually greatest in the middle troposphere. CHRONOS 2.2 μm (4400 cm^{-1}) CH_4 retrievals use the solar reflected radiance to provide a true total column. Multispectral CO retrievals combine the measurements from 2.3 μm (4250 cm^{-1}) and 4.6 μm (2170 cm^{-1}) to increase the sensitivity to near surface CO. This increased sensitivity typically provides substantially improved information about air pollution emissions and transport.

CHRONOS multispectral observations deliver independent surface information



CO multispectral remote sensing produces an independent estimate of near- surface CO abundance. Using MOPITT August 2000 measurements, detailed information on the surface layer CO abundance is obtained in the 4.6-μm and 2.3-μm multispectral retrievals, but is absent in the single channel retrievals.

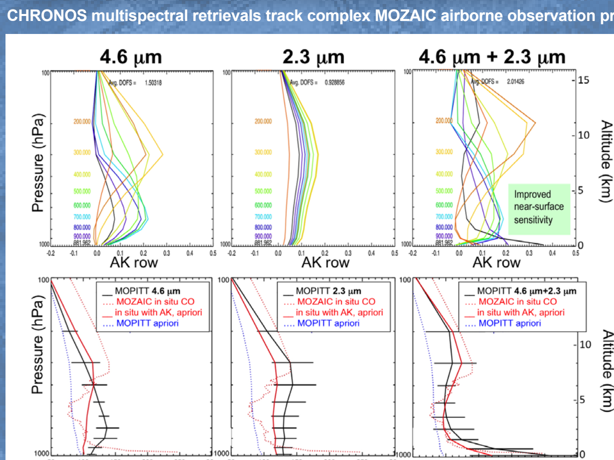
One hour of CHRONOS data provides more information than 1 year of LEO data



CHRONOS simulated observations demonstrate ability to update CH_4 emission estimates in California. Figure shows correction factors to the EDGAR v4.2 CH_4 inventory at 0.5° × 0.6° resolution from 1 year of GOSAT satellite observations, and 1 hour of simulated CHRONOS data. In optimal estimation retrievals, "DFS", the degrees of freedom for signal, denotes the number of independent pieces of information available in an observing system. The high CHRONOS DFS indicates a more observationally constrained retrieval. CHRONOS OSSE estimates were within 10% of the simulation "truth."

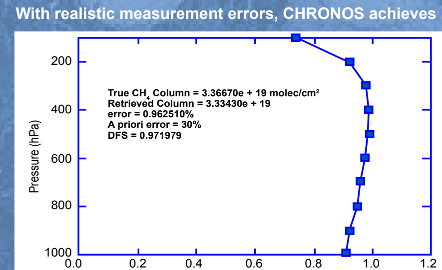
Well-Understood CO and CH_4 Retrievals

CHRONOS multispectral retrievals track complex MOZAIC airborne observation profiles



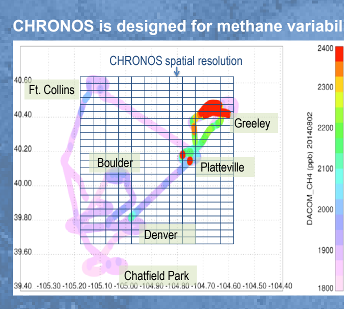
MOPITT Averaging Kernel (AK) rows (top) showing vertical sensitivity to CO abundance as a function of atmospheric pressure and altitude for 4.6 μm (left), 2.3 μm (middle) and 4.6 μm + 2.3 μm multispectral (right) retrievals. The bottom panels show the corresponding CO profile retrievals as compared to MOZAIC in situ CO measurements taken within 100 km of the MOPITT data.

With realistic measurement errors, CHRONOS achieves high information content



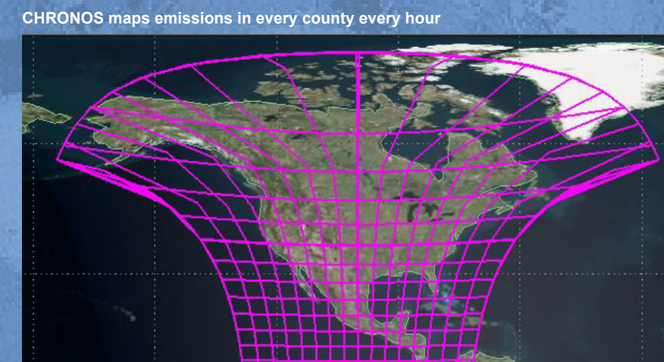
Methane retrieval column averaging kernel assuming CHRONOS measurement precision and a priori covariance with 30% diagonal errors and 500 hPa correlation length. Since the signal source is solar reflectance, the response is nearly uniform vertically, giving true total column information for CH_4 with DFS close to 1.

CHRONOS is designed for methane variability seen in FRAPPE/DISCOVER-AQ



CHRONOS column methane measurements have the spatial resolution and precision (1%) to distinguish hourly differences in city-scale methane abundances. Aircraft in situ measurements of CH_4 in ppb from FRAPPE-DISCOVER-AQ in the Colorado Front Range on August 2, 2014. Vertical profiles were measured over cities, identified by spiral flight tracks. Total column CH_4 computed from the vertical profiles is different by 4.9% between Ft. Collins and Greeley. CHRONOS spatial resolution is indicated by the overlaid grid.

CHRONOS maps emissions in every county every hour



CHRONOS maps emissions in the smallest US county with more than 3 pixels every hour, and the largest US county with over 1500 pixels every hour. The CHRONOS measurement domain at a nominal location of 100°W extends over greater North America and includes adjacent ocean to observe pollution inflow and outflow. Each grid box represents 125 × 125 data points (pixels).

CHRONOS EVI-3 could launch in 2022 at a NASA instrument investigation cost of $97M.