# Development of an Instrument Performance Simulation Capability for an Infrared Correlation Radiometer For Tropospheric Carbon Monoxide Measurements From GEO

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***Abstract*- We present the progress toward an analytical performance model of a 2.3 micron infrared correlation radiometer (IRCRg) prototype subsystem for a future geostationary spaceborne instrument. The prototype is designed specifically to measure carbon monoxide (CO) from geostationary orbit. The Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission, one of the United States Earth Science and Applications Decadal Survey missions, specifies infrared correlation radiometry to measure CO in two spectral regions for this mission. We have structured this NASA Instrument Incubator Program-funded development project to enable rapid evaluation of future spaceborne instrument designs once the GEO-CAPE mission is determined. The architecture of the performance model and the evaluation of the performance model using test data will be discussed.**

## I. Introduction

Nadir passive geostationary observations of atmospheric trace constituents are particularly difficult due to the great distance from the target (Earth atmosphere). Technologies employed for such geostationary observations operate in a significantly signal-starved milieu. Conversely, technology demonstrations within the atmosphere must be designed for "signal-swamped" operations. Therefore, suborbital technology demonstrations provide little insight into an actual application in geostationary orbit. We suggest that a strategy of suborbital demonstration leading to low Earth orbit demonstration is a valuable step in qualifying a measurement capability to be extended to geostationary observations.

The Infrared Correlation Radiometer for GEO-CAPE (IRCRg) builds on exactly such a strategy. Airborne carbon monoxide (CO) measurements (Reichle, et al., 1986) provided a basis for NASA's Shuttle-based MAPS (Measurement of Air Pollution from Satellites) instrument. MAPS then pioneered the first-ever space based measurements of any trace constituent in Earth's troposphere (National Research Council, 2008). MAPS, also a gas filter correlation radiometer like IRCRg, employed constant-condition gas cells to measure the near-global distribution of carbon monoxide during four flights on Space Shuttle. MOPITT, on NASA's Terra spacecraft, demonstrated the first multispectral CO retrievals from measurements at both 4.6 µm and 2.3 µm (Deeter, et al., 2009). MOPPIT uses pressure and length modulated gas cells for correlation. The MOPITT team estimates a factor of 5 more instrument noise for their measurements at 2.3 µm than for measurements at 4.67 µm. This finding motivated the development of the IRCRg instrument model to identify and minimize 2.3µm measurement noise sources for use in future CO measurements.

As part of NASA's Instrument Incubator Program, we have structured the IRCRg project around an analytical performance simulation model to enable rapid evaluation of design and operating scenarios when the GEO-CAPE mission is defined. Atmospheric CO measurements at 2.3 µm are uniformly sensitive throughout the troposphere, and 4.7 µm CO measurements are most sensitive to the free (mid) troposphere. In combination, the two spectral regions yield information about this Criteria Pollutant near Earth's surface. Performance tests of a 2.3 µm infrared correlation radiometer prototype hardware subsystem will be used to supply essential characterizations for the analytical model. Some tests are designed to separately validate the model.

## II. Analytical Model Concept

Our project requirements focus on developing a software-based IRCR instrument performance simulation model that can be used to simulate end-to-end IRCR system performance and CO measurement capability in a dynamic environment. This capability can quantify individual critical carbon monoxide measurement error sources arising from the "static" state of the instrument as well as the "dynamic" state of the instrument/host vehicle.

The first generation instrument analytical model currently incorporates several noise sources. Detector shot noise derives from photon statistics. Scene irradiance gradients are estimated from terrestrial statistics from currently operating satellites. Read-out noise from the FPA detector as been established from the focal plane array (FPA) detector testing, along with (constant) dark current and non-uniformity factors. Commercial geostationary satellite specifications provided the orbital platform jitter. Optics misalignment (de-focus and FPA tilt allowances) is extracted from computer aided design (CAD) models; thermal expansion is provided from joint runs of ZEMAX and CAD models. Non-uniformity correction and dark current dynamics (perhaps due to fluctuating temperatures, uneven bias voltages, or 1/*f* noise) will be added if laboratory testing indicates they are significant.

Figure 1 illustrates the major architecture of the performance model. The high resolution hypercube radiance model is an atmospheric forward radiance model based on the HITRAN spectral line database overlying a variety of surface conditions (BRDF). The space platform jitter model, based on commercial geostationary satellite specifications, is convolved with the optically designed field of view to produce realistic scenes for evaluation by the synthetic instrument, which is represented by the remaining detector and readout terms. The model is proving particularly useful in assessing operating modes of the selected focal plane array detector.

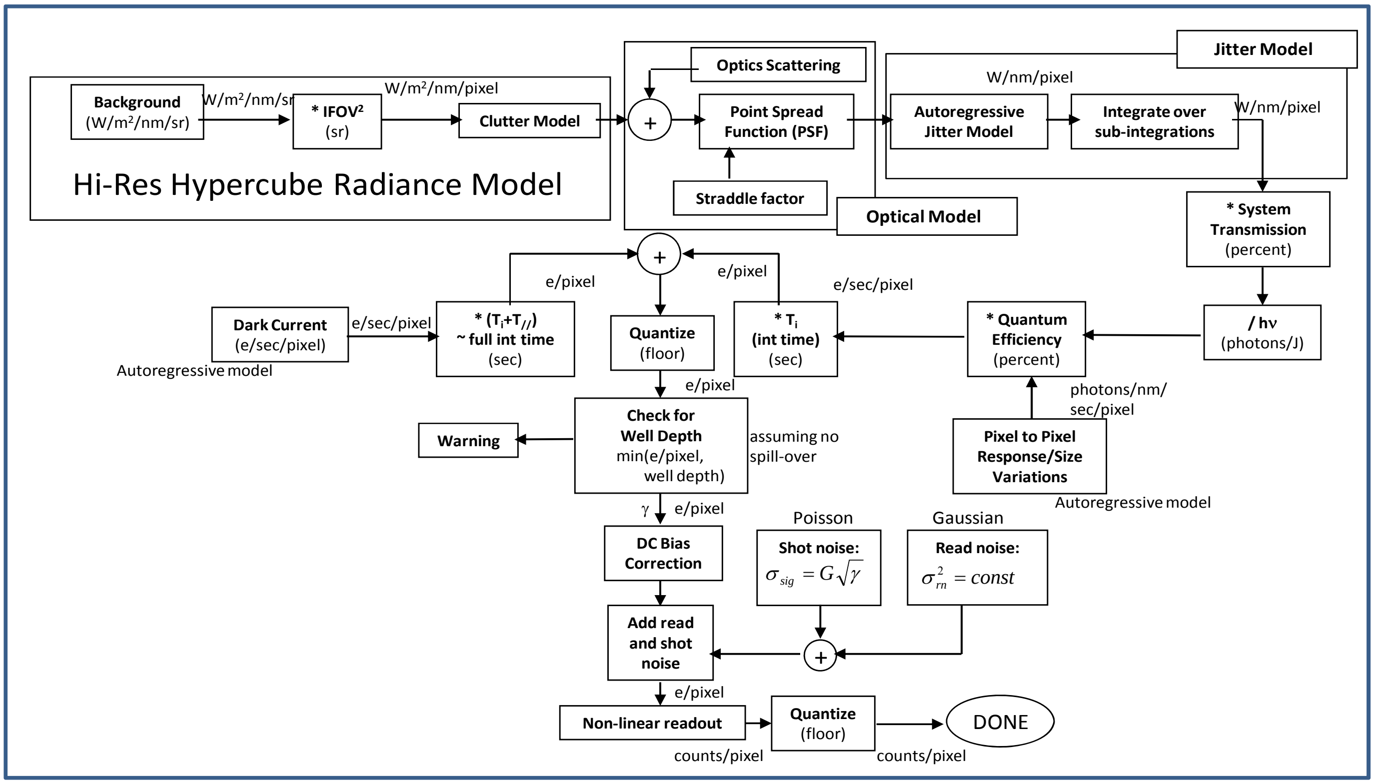


Fig. 1 IRCRg performance model architecture combines target (atmosphere and surface) properties with dynamic performance of the spacecraft platform, and actual instrument capabilities, to evaluate observing strategy for geostationary observations.

The success of gas filter correlation techniques used for tropospheric CO measurements in the 2.3 μm spectral region depends on the ability to account for surface albedo variation combined with platform jitter. The following simulation illustrates the utility of our software simulator to evaluate the instrument measurement performance. The simulation performed here includes full radiance simulation as well as a detailed sensor model with all reasonable sources errors (i.e. detector shot noises, readout noises) and spacecraft jitter.

Figure 2 provides a synthetic scene calculated in our simulator. The synthetic scenes for the instrument are constructed to have reflectivity with a similar variability as a large set of MODIS images in the 2 micron band. Typical atmospheres (with respect to major and trace gas constituents, and physical structure) are laid over these scenes, generating top-of-the-atmosphere radiance for presentation to the instrument. This modeled, upwelling top-of-the-atmosphere radiance on 2-km grid is analytically passed through the

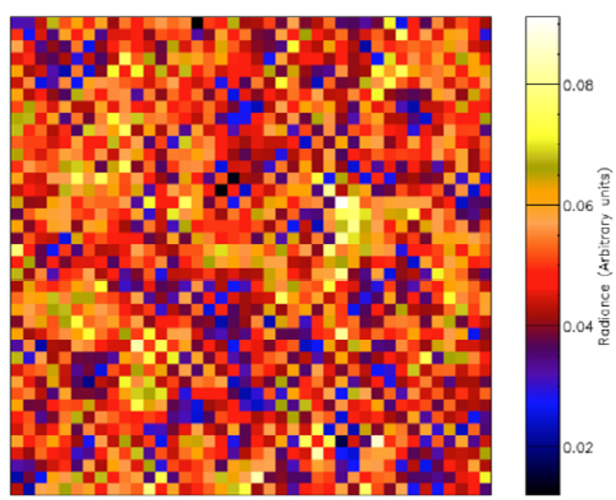


Figure 2. Sample synthetic scene observed at GEO.

geostationary instrument's "vacuum" channel. CO mixing ratios in the scene atmosphere are held constant, so all of the structure in the scene results from structure in the surface reflectivity. This scene represents what would be detected through the "vacuum" channel of the IRCRg in geostationary orbit. The horizontal and vertical axes on the plot are simply distance in each of two horizontal directions as seen from space. The color bar provides radiance in arbitrary units.

Instantaneous pointing is calculated for subdivided detector integration intervals. (Sample spacecraft pointing error is displayed in Figure 3.) The point spread function for the optical system spreads the atmospheric flux across the focal plane as a number of photoelectrons. The process is repeated until all rays and all sub-integration times have been computed, then the loop advances to the next gas cell. When the scene loops are complete, the dark current, shot noise, readout noise, well depth, analog to digital gain curves, and detector non-uniformities are added to the calculation. Recall that this instrument images a scene using 1024 x 1024 pixels. Spectral content is derived from the spectral correlation between signatures of all gases present (the "vacuum" channel) and the known signature of the gas of interest (CO). (Neil et al., 2002)

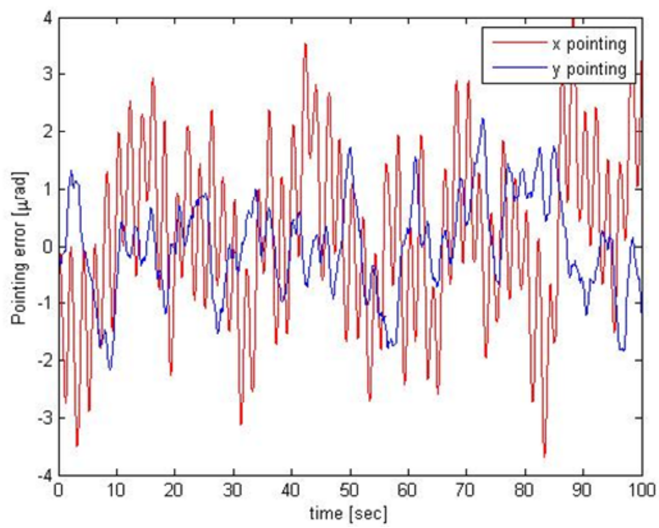


Fig. 3 Sample geostationary satellite pointing performance.

The source image was passed through the simulator for 1000 realizations of the shot noise and platform jitter for the "vacuum" ($N_2O$) and CO filters based on an IRCR sensor with 8 km measurement resolution (oversampled over the 2 km resolution radiance image shown in Figure 2). Figure 4 shows the difference between the averaged ratio of the 1000 frame pairs (CO to vacuum) from the true ratio (a uniform value of 0.953361) that was input into the simulation.

Analysis has shown that the variation over the image is almost entirely due to attitude jitter.

Figure 4 indicates the precision with which we can determine the radiance ratio for the situation that we have simulated and with the very simple post processing techniques applied here. This particular simulation has shown that for the simulated

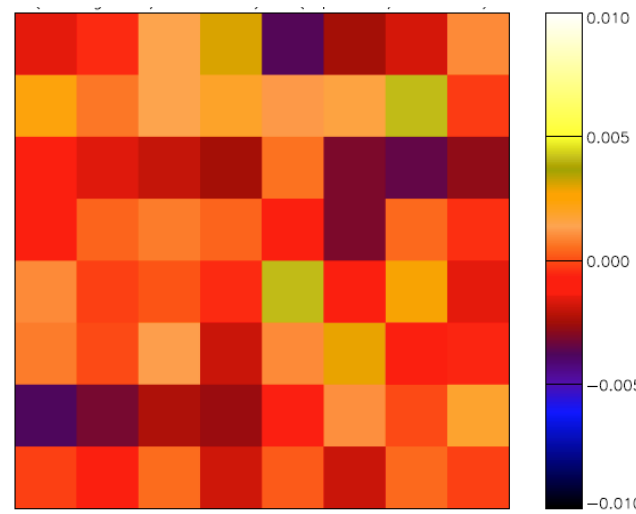


Fig. 4 Measurement error with system noise and spacecraft motion indicates the IRCRg system can achieve the required system performance. Color represents error in a spatial pixel. The horizontal and vertical axes on the plot are distance in each of two horizontal directions as seen from space.

circumstances, attitude jitter is the most important factor in producing spread in the detected radiance ratio. With the individual frames that have been output from the simulations, we have been able to construct processing techniques that can reduce the spread (error) in the radiance ratio by an order of magnitude. Preliminary analysis of the simulated measurements suggests that our strawman instrument design would meet the measurement accuracy and precision requirements of +/- 10 % under the given surface albedo variability and spacecraft jitter power spectral density.

## III. Test Plans

To support this analytical model, we are constructing the bench-top laboratory IRCRg instrument that will be used to characterize important tropospheric CO measurement error sources arising from the instrument design and fabrication. The bench top instrument will provide data to test the IRCR performance simulator. Fabrication and test will raise the TRL of the components for a future system to provide continental-scale CO mapping from a geostationary platform.

The test procedures will be used to demonstrate sufficient optical and detector performance of the prototype IRCR instrument design. The overall test plan will demonstrate optical focus; obtain baseline point source images, show they are the expected size and ensquared energy; demonstrate detector stability and stability of non-uniformity correction and dark current; demonstrate sufficiently low detector noise and sufficiently large well-depth for the intended uses; demonstrate that there are no gross stray light issues; test response linearity with a variety of input levels; and if time permits, simulate a real world data collection and retrieval using external gas cells to represent the atmosphere.

## IV. Summary

This Instrument Incubator project prototypes gas filter correlation radiometer channels for measurement of carbon monoxide (CO) at 2.3 µm as part of a multispectral instrument evaluation. The measurement technique is mature and well-validated. The focus of this work is to enable suitable signal-to-noise for a system (instrument and spacecraft) operating at geostationary orbit (35,786 km), fifty times more distant than the EOS observations from low Earth orbit.

An instrument analytical model that is populated by test and characterization data supports "what-if" scenario testing and cost effective decision making for GEO-CAPE. Instrument plus platform simulation capability provides realistic measurement assessment for GEO.

## V. ACKNOWLEDGEMENTS

This work is funded by NASA's Earth Science Technology Office (Instrument Incubator Program) and by NASA Langley Research Center internal funds.

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