P14.5 Geostationary Interferometer 24-Hour Simulated Dataset for Test Processing and Calibration

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The UW-Madison CIMSS is producing simulation datasets as a part of the risk reduction effort in the NOAA GOES-R program. One of the potential baseline sounder designs for the GOES-R Hyperspectral Environmental Suite (HES) is a geostationary imaging Fourier transform spectrometer. This paper describes a simulation based on the specifications of the existing NASA GIFTS instrument, which is currently undergoing thermal vacuum testing. The initial step of the preparation uses a Weather Research and Forecasting (WRF) model simulation covering most of the North and South American continents to provide internally consistent atmospheric profiles over a potential geostationary imaging area. Next, the GIFTS forward radiative transfer model calculates the outgoing radiance spectra at the top of the atmosphere. Finally, a detailed mathematical model of the instrument is used to calculate the resulting raw signal sent down from the satellite. The intended use of this 24 hour dataset is to test science algorithms and data processing software.

1. Introduction

The GOES-R program specifications include a requirement for a baseline sounding instrument capable of approximately 1 cm^{-1} resolution in a number of possible wavenumber regions. An imaging Michelson interferometer is one of the two primary sounder technologies which can meet this need. This paper focuses on simulation data synthesis for the GIFTS instrument, which is currently in thermal vacuum testing at the Utah Space Dynamics Laboratory. A considerable amount of the detailed design work, fast forward model development, instrument model refinement, and science algorithm testing has already been achieved by the sounding community for the GIFTS instrument. This makes the imaging interferometer design an attractive choice for a potential component of a complete next generation geostationary meteorological suite.

While deciding on the parameters of this dataset we solicited input from various research groups representing a range of interests in the meteorological and atmospheric science communities. The large spatial coverage of the dataset will provide a sufficient number of cases for testing the pattern matching algorithms used in the wind vector determination program. Large variations in surface conditions and a broad latitude range provides a variety of conditions for profile retrieval algorithm testing.

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While the quantity of data contained in our 24 hour datasets dataset is more than sufficient for science algorithm testing, the size of the dataset is necessary for testing prototype software for science and environment data processing. Exercising the modules that make up this processing system with a self-consistent 24-hour dataset will help identify problems posed by large datasets in general.

Throughout the creation of this test dataset we strived to produce data that is representative of what an operational imaging interferometer will produce. The numerical weather model is unlikely to reproduce the exact atmospheric and cloud conditions that happened in the real world on the chosen day, but we feel the profiles are a good example of potential conditions. The subsequent radiative transfer and instrument modeling steps were designed to give our best estimate of GIFTS instrument data output for the given atmosphere and cloud property profiles. Further refinements to this modeling can be made as the GIFTS instrument ground-test data is analyzed.

The creation of the simulated datasets is comprised of three steps. After the numerical weather model produces atmosphere and cloud profiles (described in section 2), a regression analysis-based fast radiative transfer model produces top of atmosphere (TOA) radiance spectra (sections 3 and 4). The final step is to model the GIFTS optics and detectors to produce interferograms, which are described in sections 5 and 6.

2. Cloud Particle and Atmospheric Profile Modeling with WRF

The Weather Research and Forecasting (WRF) model is used to generate realistic high-resolution temperature and water vapor profiles covering a large geographical domain. Post processing of the model simulated data is performed in order to provide climatological ozone estimates and also to calculate effective particle diameters for each microphysical species.

Due to inaccuracies inherent in all numerical weather modeling systems, the primary objective of this work is to produce *realistic* simulated datasets that contain mesoscale cloud, temperature, and water vapor structures representative of a real atmosphere. The ability to reproduce the *exact* atmospheric state for a given situation is constrained by several model limitations. For example, even the most sophisticated bulk microphysics schemes in the WRF models contain numerous assumptions that simplify cloud morphology and cloudy radiative transfer processes. Another serious limitation is the observation that model grid *spacing* (Δx) is not synonymous with grid *resolution* (Grasso 2000).

The ability of a model to resolve small scale structure effectively (relative to the grid spacing) is limited by the dissipation mechanisms used by that model, including both explicit smoothers and explicit and implicit dissipation inherent to a given integration scheme. It should be noted, however, that even with these limitations, sophisticated numerical models still represent an excellent method to generate physically realistic atmospheric datasets with fine spatial and temporal resolution.

Version 2.1 of the WRF model was used to produce a realistic simulation of atmospheric conditions on the chosen day. The simulation was initialized at 00 UTC on 24 June 2003 with 1° Global Forecasting System (GFS) analyses and then run for 30 hours on a single 1580 x 1830 grid point domain with 8-km horizontal grid spacing and 50 vertical levels. The simulation employed the WRF Single-Moment 6-class microphysics scheme (Hong et al. 2004), the Yonsei University PBL scheme, the RRTM longwave and Dudhia shortwave radiation schemes, and the Noah LSM. No cumulus parameterization scheme was used so only explicitly resolved convection was modeled during the simulation.

The domain chosen for this simulation encompasses a very large geographical area that contains regions of clear and cloudy-sky conditions. Fig. 1 shows the WRF-simulated vertically-integrated cloud microphysical content at 1400 UTC on June 24, 2003. Inspection of this figure reveals the presence of substantial cloud-cover over a large portion of the ocean while large regions of clear sky conditions are present over North and South America. It is also interesting to note the well-defined Intertropical Convergence Zone (ITCZ) extending across the domain at approximately 10° N. In figure 2, colored isosurfaces are plotted for a total cloud microphysical content (summation of the cloud water, rain water, ice, snow, and graupel mixing ratios) of .01 g kg^{-1}. The color is a function of temperature, ranging from warm (yellow) to cold (blue).

Simulation Domain

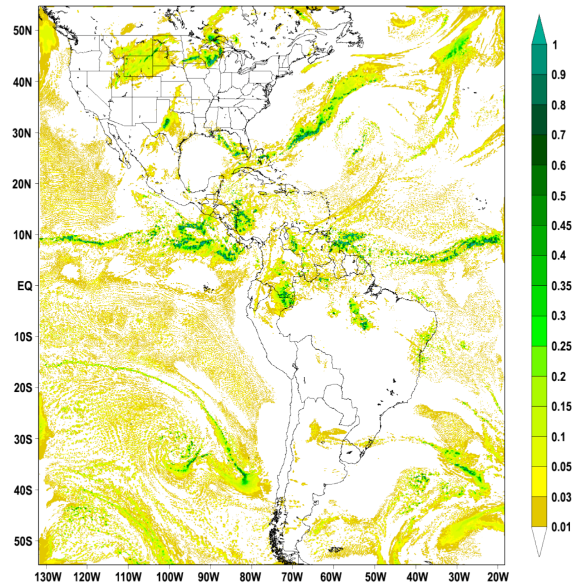

Fig. 1: WRF simulated vertically integrated cloud microphysical content valid at 1400 UTC on 24 June 2003.

Cloud Isosurfaces

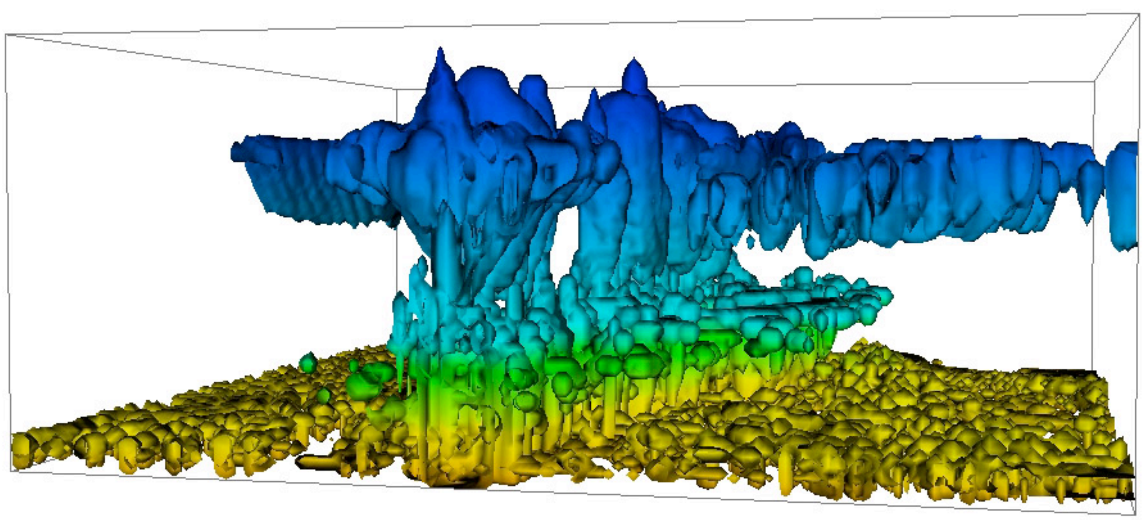

Figure 2: 3-D representation of the simulated cloud profile for structure along the ITCZ over the eastern Pacific. Ocean at 1400 UTC on 24 June 2003.

Although the 8-km horizontal resolution of this simulation is not sufficient to fully resolve the atmospheric detail that the GIFTS instrument's 4-km pixel footprint will be able to reveal, it is clear that this simulation still contains a substantial amount of fine-scale atmospheric structure. Future versions of the 24-hour dataset will include sub-domains with substantially finer horizontal resolution (< 2 km).

The last part of the WRF simulation breaks up the full domain outputs into a horizontal grid of 128 by 128 "cubes". This represents the number of detectors in the GIFTS detector arrays, but has four times the ground coverage due to the GIFTS 4 kilometer spatial resolution and the WRF grid spacing of 8 kilometers. The GIFTS cubes are aligned side by side, and their edges match up exactly. This arrangement differs from the actual viewing pattern of GIFTS, which will have overlapping cubes to improve the quality of the spatially resampled image mosaics. When more details about the telescope pointing mechanism on GIFTS are known a simulation study of the optimum overlap amount can be performed.

3. Clear Sky Model

The GIFTS clear sky forward model is a LBLRTM based Pressure Layer Optical Depth (PLOD) fast model. At fixed pressure layers, regressions are made to line-by-line transmittance calculations obtained with LBLRTM. The line-by-line transmittance data are monochromatic values, and need to be mapped to the GIFTS spectral domain. The mapping has an effective spectral resolution of 0.6 cm^{-1}, and the results are apodized prior to performing the regression analysis.

We use 32 training profiles from a NOAA database. Each profile has 100 vertical layers and is calculated at 6 satellite view angles. The predictors generated from the profiles are the same ones used for the AIRS instrument.

Three regressions are made at every layer for 3073 channels between 587 and 2347 cm^{-1}: one for fixed gases, one for H_2O, and one for O_3. Each gas type has its own set of predictors, and therefore, its own regression coefficients.

Figure 3 displays the current planned spectral coverage of GIFTS measurements with clear-sky brightness temperature calculated from the U.S standard atmosphere.

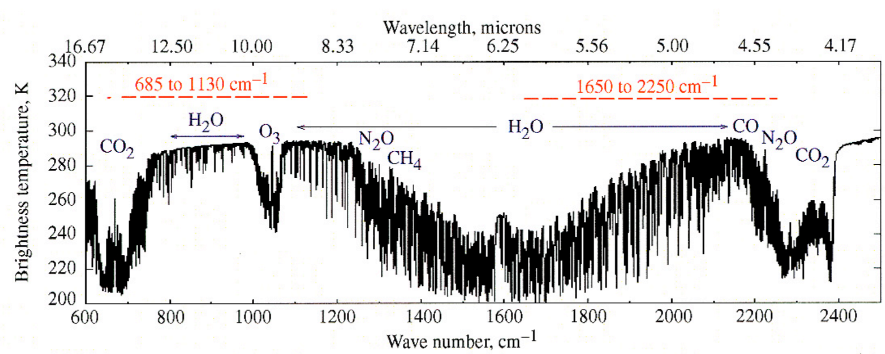

Fig. 3: GIFTS spectral coverage and its brightness temperature spectrum.

The clear sky top of atmosphere radiance is currently broken down into three terms: the atmospheric contribution, the surface emissions, and the surface reflected contribution. As our modeling of the surface emissivity becomes more sophisticated, we need to include a more accurate calculation of the reflected term. The downwelling flux at the surface is now calculated via a two point Gaussian quadrature approximation with the assumption of a Lambertian surface.

The surface reflected term requires knowledge of the downwelling flux, upwelling transmittance and reflectance of the surface. It would be too time consuming to run a dedicated fast model for the downwelling calculations so the existing fast model is used instead. Three sources of potential error arise from this computational shortcut. First, the fast model has a built-in directionality - the model is designed for TOA radiances, and is based on a level to space regressions rather than independent layer terms. Depending on the application (micro-window or on/off line), using upwelling transmissivity for downwelling radiance may be reasonable. Second, the fast model calculations are made at the instrument resolution, whereas preferably it should be the product of the flux and transmissivity terms that are convolved to instrument resolution. Without creating a separate model with downward directionality, these errors cannot be further reduced. A third, smaller, source of error comes from using a low order Gaussian Quadrature approximation. They have decided that the two point approximation is a good trade-off between error and computational resources.

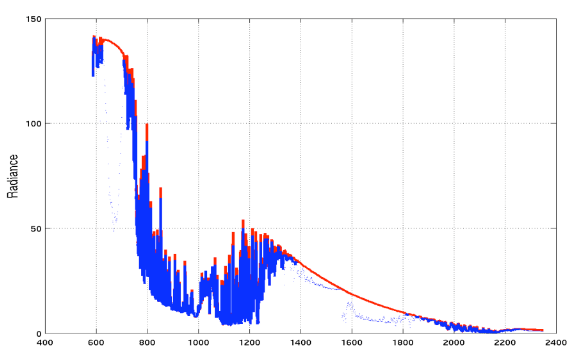

Fig. 4: Comparison of downwelling clear sky model (blue) and LBLRTM calculations (red).

4. Cloudy Sky Model

For the two layer cloudy sky GIFTS forward model, the standard 100 layers of the atmosphere are divided into five groups. These groups are the layers below the lower cloud base, the lower cloud, the layers between the clouds, the upper cloud, and the remaining layers above the upper cloud.

Output from the WRF models includes profiles of mixing ratios for rain water, ice, cloud water, snow, and graupel. To determine the phase at each layer the following quantity is calculated:

$$\text{phase \#} = \frac{\sum_{habit} category * mixing\ ratio}{\sum_{habit} mixing\ ratio}$$

where the category number is 2.0 for ice, snow, and graupel, and 1.0 for water mixing ratios. If the phase number is greater than 1.5, then the cloud group layer is modeled as ice. All other cloud group layers are modeled as water clouds. The mixing ratio profiles are also used to calculate the visible optical depth and effective particle size.

The cloud upper and lower boundaries are determined by grouping cloudy atmospheric layers into one or two cloud layer groups. Adjacent atmospheric layers containing clouds of similar phase are grouped together. Only the two cloud groups with the largest optical depths are considered. The two layer model also ignores any cloudy layers that have visible optical depths less than 0.5 for water and 0.01 for ice. Total visible optical depth and effective size for both of the clouds (if two exist) are calculated from the individual layer properties.

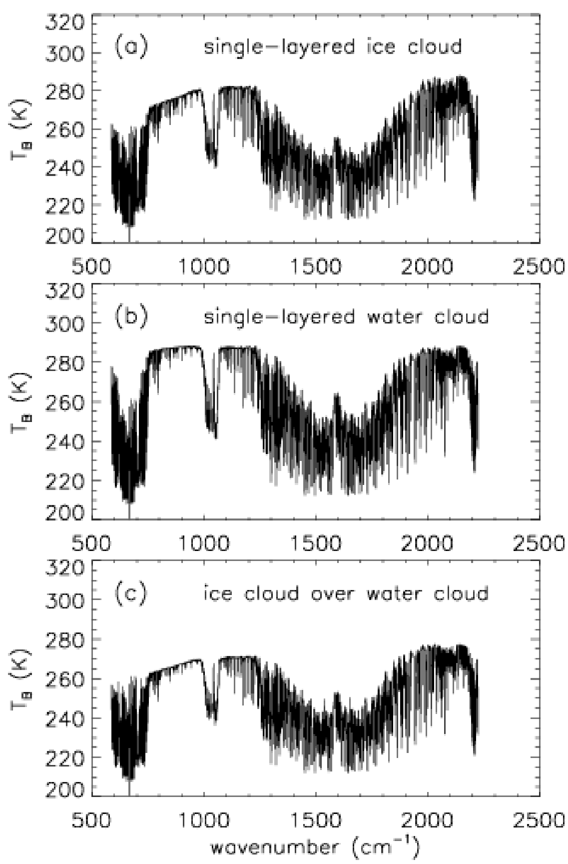

Fig. 5: Sample brightness temperature spectra for three cloud combinations.

The final optical depths and particle effective sizes are used to determine the radiative properties of the cloud. A multi-dimensional look up table (LUT) of the spectral transmittance and reflectance values is provided by Ping Yang (Yang et. al. in press). The ice cloud table covers an optical depth range of 0.04 to 100 and an effective size range of 10 – 157 microns. For water clouds the ranges are 0.06 – 150 and 2 – 100 microns. Multiplying the cloudy transmittance values by the clear sky transmittance values yields a transmittance profile for the TOA radiance calculations. For cloudy conditions, the surface reflection term is much smaller than for clear sky, so we approximate the downwelling radiance to be the same as the upwelling radiance for the pertinent layers. Figure 5 shows TOA radiances computed for three different atmospheric conditions. Panel *a* is for a single layer ice cloud at a height of 12 km with an optical depth of 1 and effective size of 40 μm. Panel *b represents* a water cloud at a height of 2 km, optical depth of 5 and effective particle size of 10 μm. The last panel (*c*) is a two layer cloud combination, with a 50 μm effective particle size ice cloud layer like panel *a* overlying a water cloud layer with the same properties as the cloud in panel *b*.

5. Surface Emissivity Model

In order to increase the realism of the infrared emission spectrum over land, a global emissivity database developed at UW SSEC is used to characterize the surface infrared properties below each of the NWP profiles prior to computing top of atmosphere radiance. The latitude and longitude of each profile is used to select from the gridded emissivity database. The database is derived from a combination of high spectral resolution laboratory measurements of selected materials, and multiple years of MODIS (MOD11) observed land surface emissivities at 3.7, 3.9, 4.0, 8.5, 11.0 and 12.0 micron wavelengths. For a given month, a continuous spectrum of emissivity from 3.7 to 14.3 microns is available from this database for every latitude/longitude point globally at 0.05 degree resolution (Wetzel-Seemann et al., 2006).

6. Instrument Model

The modeling of the instrument and the data that is output from the instrument is broken into two parts. The first part models how the optics of the instrument will affect the observations. The second half of the instrument model covers most of the detector related effects. The model for the GIFTS instrument developed at the UW-CIMSS represents an abstraction of the actual instrument to represent the key features of an imaging FTS sensor but is not intended to capture all the technical details of the sensor under development at Utah State Space Dynamics Laboratory.

The TOA radiances produced from the GIFTS fast model are used as a starting point. The optics model then adds the instrument background contribution, a phase shift, a spectral smearing, and a spectral shift. The spectral smearing and shift are due to self apodization by the instrument optics. We also apply the detector responsivity and numerical filter effects at this point, but in the future we plan to move these steps to the detector part of the instrument model. The final product is a group of raw instrument interferograms.

The data from the GIFTS instrument is sent to the ground processing system as interferogram counts. The main function of the calibration software is to convert the interferograms to spectra in physical units and use the blackbody observations to remove the instrument background contribution. The temperature of the instrument optics follows a diurnal pattern as the amount of solar illumination on instrument components changes over the orbital path. The change in the optics temperature is used to vary the background contribution to the interferogram signal. Figure 6 shows a model estimate of how the optics temperatures might change over 24 hours. A simple lookup table for the optics temperature is used to vary the instrument background term of the output signal.

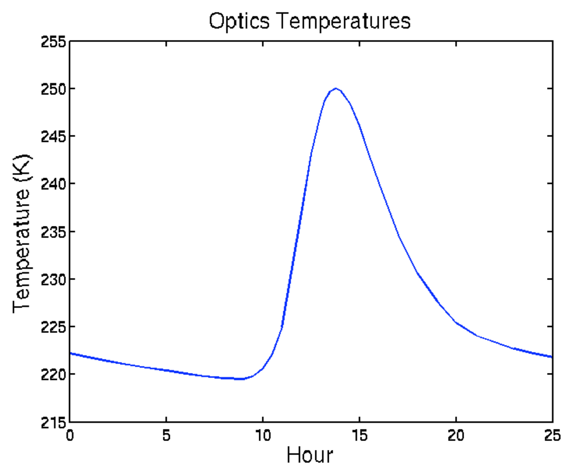

Fig. 6: Change in instrument optics temperatures over 24 hours. The temperatures over the last hour are just a repeat of the first hour.

We also we simulate the off-axis effect common to imaging interferometers in the data. Calculation of the off-axis effect involves very large Fourier transforms, so we perform this step for only part of the dataset. For the rest of the data a smaller FFT is done to produce real interferograms.

The final part of the instrument model simulates the effects of the detectors. Since the responsivity and numerical filter have already been applied, the main procedure is to apply the variations in gains and offsets throughout the detector array. This is done with Gaussian distribution gain factors, from 0.5 to 1.5 randomly spread across the detector array. The detector signal offsets are also random values between zero and 50. For each individual detector in the array, the gain and offset values remain constant throughout the 24 hour dataset.

The last two steps in the detector model are to add the noise inherent in the detector and simulate the quantization of the interferometer converting the analog signal to a digital stream. The noise added is a Gaussian distribution of noise equivalent radiance multiplied by the square root of the number of interferogram points.

The blackbody view data is an integral part of the simulated dataset. The GIFTS instrument is designed to have three in-flight calibration sources. These are two heated cavities that bound typical atmosphere temperatures as well as a deep space viewing option. The viewing schedule for a geostationary interferometer is likely to include blocks of blackbody views once about every 30 minutes. To provide the ability to test a variety of calibration schedules as well as predictive calibration algorithms, a series of 4 hot, 4 warm, and 4 space views are simulated to occur every 10 minutes for the 24 hour dataset.

Conclusions

The 24 hour GIFTS simulation dataset represents our efforts to provide realistic idea of what data from a geostationary interferometer as part of the GOES-R program would give to research efforts. The data is designed to help advance wind vector determination research as well as a range of single field of view retrieval algorithms. The size of the dataset also provides the groups working on design of data processing systems with a realistic volume of data.

In subsequent versions of the test dataset we hope to add some more detail to the simulations. A higher spatial resolution WRF simulation for a small subsection would complement the full disk data well. With the higher resolution data, we can simulate the effect of viewing geometry on the data for larger viewing angles.

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