P1.44 CALIBRATION ALGORITHM ACCURACY VERSUS EFFICIENCY TRADEOFFS FOR A GEOSYNCHRONOUS IMAGING FOURIER TRANSFORM SPECTROMETER

Robert Knuteson*, Steve Ackerman, Fred Best, Ralph Dedecker, Ray Garcia, Erik Olson, Hank Revercomb, Maciek Smuga-Otto, and Dave Tobin

Cooperative Institute for Meteorological Satellite Studies (CIMSS)
Space Science and Engineering Center, University of Wisconsin-Madison

Ground calibration algorithms for a geosynchronous imaging FTS are being developed at the Uni. of Wisconsin-Madison Space Science and Engineering Center. This development is being conducted in support of NOAA's GOES-R Risk Reduction program with a focus on the hyperspectral sounder that is anticipated to be a part of the GOES-R Hyperspectral Environmental Suite (HES). The near term objective is to develop calibration algorithms that can be evaluated using thermal vacuum test data from NASA's Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS). The GIFTS is designed to produce 128x128 interferograms in two spectral bands every 11 seconds using a Michelson interferometer and two detector focal plane arrays. Data rates pose a special challenge to the design of the GIFTS ground data processing system which will need to convert the interferograms into radiometrically and spectrally calibrated radiances. This paper will address tradeoffs in accuracy versus processing efficiency for the science algorithms that are under consideration for achieving the desired ground data processing throughput for the GIFTS sensor.

.

1. INTRODUCTION

The U.S. National Oceanic and Atmospheric Administration (NOAA) operates geostationary operational environmental satellites (GOES) for short-range warning and nowcasting, and polar-orbiting environmental satellites (POES) for longer term forecasting. GOES satellites provide continuous monitoring from space in a geosynchronous orbit about 35,800 km (22,300 miles) above the Earth. The current generation of GOES satellites contain separate imager and sounder instruments. The sounder is used to remotely sense the atmospheric thermodynamic state, e.g. atmospheric stability and total column water vapor. A new generation of sensors is under development that will greatly increase the horizontal, vertical, and temporal sampling of the GOES sounder and provide a truly four-dimensional view of the Earth's atmosphere. NOAA's plan for a Hyperspectral Environmental Suite (HES) calls for the replacement of the current GOES instrumentation starting as early as 2013 (Dittberner et al. 2003; Gurka et al. 2003). Meanwhile, NASA's New Millennium Program Earth Observing 3 (NMP EO3) mission is the first step in improving the U.S. geostationary weather observing system. The NMP EO3 mission features the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), an instrument that incorporates new technologies to implement an innovative atmospheric measuring concept proposed by NASA's Langley Research Center (Smith et al. 2000).

* *Corresponding author address:* Robert Knuteson, 1225 W. Dayton St., University of Wisconsin-Madison, Madison, WI 53706; robert.knuteson@ssec.wisc.edu

The NASA GIFTS research instrument will serve as a valuable test bed for the evaluation of approaches to flight hardware and ground data processing in the years preceding the implementation of NOAA's operational Hyperspectral Environmental Suite.

An overview of the algorithm theoretical basis document (ATBD) that is being written by the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (UW-CIMSS) describing the science algorithms required in the ground processing of GIFTS data was presented in Knuteson et al. (2004a). The scope of that document was limited to the algorithms needed for the conversion of raw instrument counts (Level 0 data) to calibrated radiances (Level 1 data). The geo-location approach was described in Limaye et al. (2004) while the science algorithms for higher level products (2+) were described in Huang et al. (2004). This paper will provide more detail on the algorithms being developed for the GIFTS ground data processing with an emphasis on tradeoffs between algorithm accuracy and computational efficiency.

2. INSTRUMENT DESCRIPTION

The GIFTS instrument is an imaging Fourier Transform Spectrometer (FTS) designed to provide significant advances in water vapor, wind, temperature, and trace gas profiling from geostationary orbit. Imaging FTS offers an instrument approach that can satisfy the demanding radiometric and spectral accuracy requirements for remote sensing and climate applications, while providing the massively parallel spatial sampling needed for rapid coverage of the Earth disk, as well as more frequent coverage of selected regions. The GIFTS baseline design uses focal plane detector arrays to cover two broad spectral regions; a longwave infrared band (685–1129 cm^{-1}) and a midwave/shortwave band (1650–2250 cm^{-1}). Each focal plane array contains a grid of 128 × 128 elements for a total of 16,384 fields of view with a nominal field of view diameter of 4 km at the sub-satellite point. Details of the initial instrument design are described elsewhere (Bingham et al., 2000; Best et al., 2000, 2004; Knuteson et al., 2004b). Figure 1 shows the spectral coverage of the GIFTS sensor. The longwave (LW) band covers the traditional "temperature sounding" region for the characterization of atmospheric temperature from the top of the atmosphere to the surface and includes the 8-12 μm IR window for the characterization of land surface and cloud top temperature and emissivity. The shortwave/midwave (SMW) band includes a non-traditional coverage of the shortwave side of the "6.3 μm water vapor sounding" region. The short-midwave band coverage (1650-2250 cm^{-1}) was shown by analysis to be optimal for three reasons; 1) this region avoids the interference of "fixed" gases N_2O and CH_4 which degrade the water vapor sounding performance, 2) the shorter wavelength leads to better signal to noise performance for the detectors chosen, 3) and it provides coverage of carbon monoxide thereby allowing the tracking of air pollution plumes from source to sink.

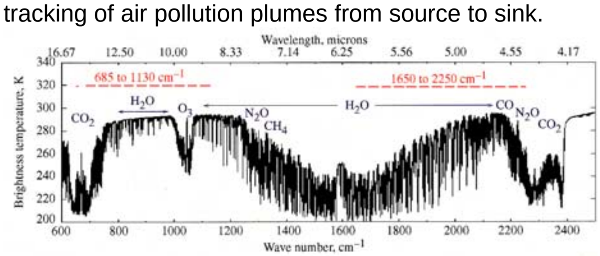

Figure 1. A calculation of the top of atmosphere radiance emitted by the standard atmosphere in units of equivalent brightness temperature (Kelvin). The dashed lines indicate the two spectral bands selected for the NASA GIFTS sensor.

3. ALGORITHM OVERVIEW

The GIFTS sensor will sample the interferogram from each detector as a function of optical path delay and numerically filter the data in real-time to reduce the data rate before transmission to the ground-based X-band receiver. The sensor will obtain views of the onboard calibration references and deep space at regular intervals interleaved with the observations of Earth scenes. The ground reception facility will decode the telemetry stream and pass the GIFTS sensor data in real-time to a ground data processing facility. The GIFTS Level 0 to 1 ground data processing is anticipated to include the following tasks: i) Fourier transform of the GIFTS interferograms, ii) application of a non-linearity correction to the sensor data, iii) radiometric calibration, iv) spectral calibration, v) instrument line shape correction, and vi) spectral resampling to a common wavenumber grid. This paper will focus on two algorithms under consideration for the implementation of the spectral resampling. Tradeoffs between algorithm accuracy and computational performance will be described.

4. WAVENUMBER RESAMPLING METHODS

Once the spectral calibration (i.e. wavenumber sampling scale) is determined for each of the GIFTS fields of view, the calibrated radiance spectrum can be re-sampled from the original sampling interval to a pre-specified reference wavenumber scale (Tobin et al., 2003). The re-sampling can be performed in software using a double FFT and linear interpolation of an over-sampled spectrum. An alternative approach using a convolution rather than an FFT to resample the spectra is being evaluated for potential performance advantages. The result of the wavenumber resampling operation will be that all of the GIFTS spectra have a common wavenumber scale independent of their location in the focal plane array. This is essential for the routine comparison of observations and radiative transfer calculations needed in the production of Level 2 products, e.g. temperature and humidity profiles.

The double FFT method requires the fast fourier transform of the original spectrum (with a power of two number of points, N=2(n-1)) to the interferogram domain where additional zeros are added to the end of the interferogram ("zero padding"). For the GIFTS focal plane arrays used in this analysis, the number of points in the spectrum are taken to be n = 1025 (LW), and 2049 (SMW). Zeros are added to produce a symmetric interferogram containing M*N points where M*N is a power of two. Transforming this expanded interferogram back to the spectral domain provides an oversampled spectrum that can be used to interpolate to the desired spectral sampling. Equation 1 illustrates this method where the original radiance spectrum S is interpolated to the final resampled spectrum S'. In Eqn. 1, FFT and IFFT are the Fast Fourier Transform and its inverse, and L() is the linear interpolation operator from the oversampled wavenumber scale v'' to the desired final spectral scale v'. The double FFT method (with linear interpolation) is of order M'*N log (M'*N) + M*N floating point operations (FLOPs) where M' = M+1 to account for the original forward FFT. The FLOP estimate is valid only when a power of two is used in the inverse FFT. Powers of two are the most efficient use of FFTs, although prime factor algorithms are also an option.

$$
\begin{aligned}
&I = FFT(S, N) \\
&I'(i) = I(i), i = 1, n; \\
&I'(j) = 0, j = n+1, M*(n-1) \qquad (1) \\
&S'' = IFFT(I', M*N) \\
&S' = L(S'', v'', v')
\end{aligned}
$$

The sinc resampling (or F-matrix) method can also be used to transform the original spectrum S to the desired resampled spectrum S' defined in Eqn. 2 as the matrix multiplication (from CrIS ATBD; BOM-CrIS-0067)

$$S' = F \cdot S,$$
$$where \qquad (2)$$
$$F = \frac{dv}{dv'} \cdot \frac{\sin c((v - v')/dv')}{\sin c((v - v')/(Ndv'))}$$

In Eqn. 2, F is an nxn matrix, S and S' are 1xn column vectors, the sinc function is defined to be sin(x)/x, and N = 2(n-1). The generation of the F-matrix is computationally expensive, but it can be pre-computed and stored for later use as long as the GIFTS spectral calibration is stable over time. The application of the sinc resampling method is a simple matrix multiplication and has order n^2 floating point operations for a full rank matrix.

The GIFTS focal plane arrays contain 128x128 (16384) pixel elements each of which represents a complete GIFTS spectrum (one spectrum per spectral band). Due to the fact that the laser trigger is aligned with the interferometer optical axis, the spectral calibration of the GIFTS sensor varies as a function of off-axis pixel angle from near the center of the focal plane arrays. Correcting for this effect using the double FFT plus linear interpolation method requires only that the initial wavenumber sampling scale be known for each pixel element. Once this original scale is known the actual computational time required to perform the FFT method is independent of which pixel is being corrected. There is no preferred order of processing the pixel elements. In contrast, the F-matrix approach suggests that concentric “rings” of detector elements should be grouped together in the data processing to take advantage of pre-computed F-matrices. This is because the full F-Matrix is too expensive to generate for each of the individual 16384 pixel elements in each spectral band. Since the F-matrix approach will require a more sophisticated data management approach for efficient implementation, it is important to quantify the computational advantages (if any) of this approach over the double FFT method.

5. ACCURACY VERSUS EFFICIENCY

In order to compare the numerical performance of the two spectral resampling methods, we first investigate the theoretical number of floating point operations for each method. As stated previously, the number of operations of the FFT method with linear interpolation is proportional to M'*N log (M'*N) + M*N where M'=M+1, N=2(n-1), and n = 1025 (LW), 2049 (SMW). The expansion factor M is a parameter that can be adjusted to increase algorithm efficiency by reducing algorithm accuracy. Note that M*N must be a power of two for this estimate of FLOPs to be valid. Figures 2 and 3 illustrate the tradeoff between algorithm accuracy and number of zeros used in the inverse FFT transform for a c-language implementation of the double FFT method with linear interpolation (using FFTW for the FFT).

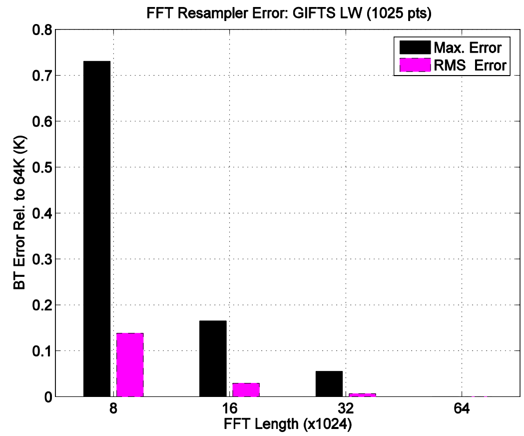

Figure 2. FFT resampler maximum and root mean square error for the GIFTS LW band where the 64K length is taken to be exact (zero error).

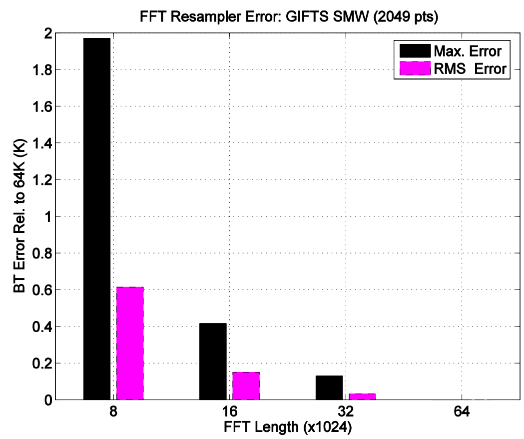

Figure 3. FFT resampler maximum and root mean square error for the GIFTS SMW band where the 64K length is taken to be exact (zero error).

The sinc resampler method has significant overhead associated with the generation of the full F-matrix for a given initial wavenumber scale. After the F-matrix is generated, application of the full matrix is of order n^2 floating point operations. A comparison of the theoretical number of floating point operations for the two methods is shown in Figure 4 for a range of M values in the double FFT method. Figure 4 was computed using n=1025 which is appropriate for the GIFTS LW band. Note that the double FFT method has an overall constant scale factor that is difficult to estimate theoretically. For that reason both methods have been implemented in c-language and test runs were performed as a function of pixel number. The results are shown in Figures 5 and 6 for the sinc resampler and double FFT methods respectively.

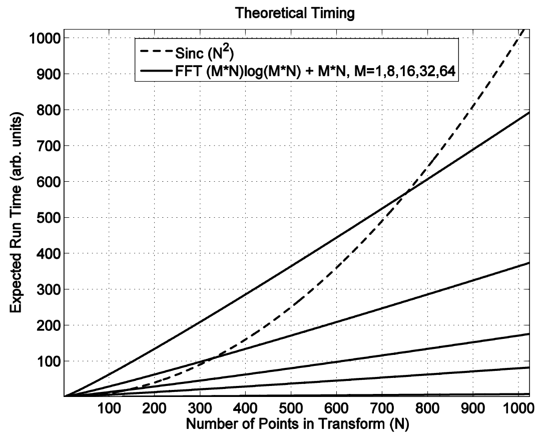

Figure 4. Theoretical execution time for Sinc resampler (N^2) versus FFT resampler (M*N log(M*N)+M*N. Note FFT estimate is valid only for powers of two.

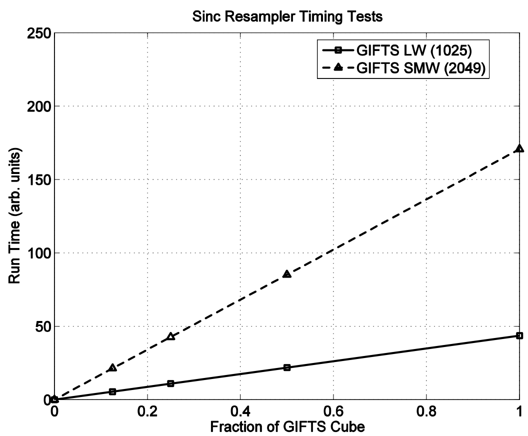

Figure 5. Sinc resampler execution time as a function of the number of spectra processed (full GIFTS cube has 128 x 128 pixel elements).

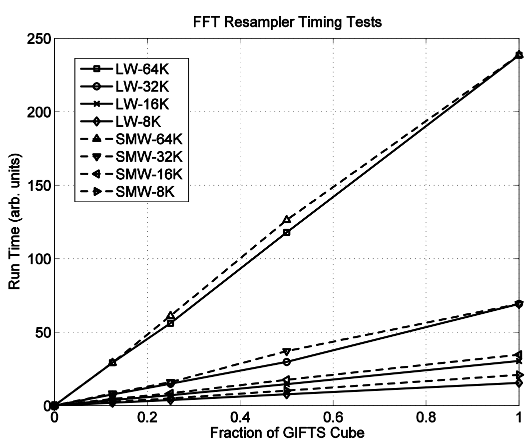

Figure 6. FFT resampler execution time as a function of the number of spectra processed (full GIFTS cube has 128 x 128 pixel elements).

4. CONCLUSIONS

The UW-SSEC has performed timing tests using prototype implementations of two competing algorithms for the task of resampling the GIFTS spectra in each band to a common wavenumber scale. The conclusions of this analysis are given below:

(1) The computational performance of the FFT resampling method using a 16K FFT is roughly comparable to the full F-matrix sinc resampler for the GIFTS LW band. However, in the GIFTS SMW band the FFT 32K FFT is about 3 times faster than the full F-matrix method with similar accuracy.

(2) When the complications of the data management of the large F-matrices is taken in to account and the need to precompute the F-matrices, it would be hard to justify the use of sinc resampling using the full F-matrix approach for the GIFTS task.

(3) However, there is still the possibility that the F-matrix can be reduced in one dimension by zeroing out off-diagonal matrix elements while still meeting the accuracy requirements. Investigation of this “near diagonal” F-matrix approach is under evaluation.

ACKNOWLEDGEMENTS

This work was supported by NOAA federal grant NAO7EC0676.

REFERENCES

Best, F. A., H. E. Revercomb, G. E. Bingham, R. O. Knuteson, D. C. Tobin, D. D. LaPorte, and W. L. Smith, 2000: Calibration of the Geostationary Imaging Fourier Transform Spectrometer (GIFTS), presented at SPIE's Second International Asia-Pacific Symposium on Remote Sensing of the Atmosphere, Environment, and Space, Sendai, Japan, 9–12 October 2000.

Best, F. A., H. E. Revercomb, R. O. Knuteson, D. C. Tobin, S. D. Ellington, M. W. Werner, D. P. Adler, R. K. Garcia, J. K. Taylor, N. N. Ciganovich, W. L. Smith, G. E. Bingham, J. D. Elwell, and D. K. Scott, 2004: The Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) On-board Blackbody Calibration System. In: Proceedings of the SPIE, Fourth International Asia-Pacific Environmental Remote Sensing Symposium, 8 November 2004, Honolulu, Hawaii.

Bingham, G. E., R. J. Huppi, H. E. Revercomb, W. L. Smith, F. W. Harrison, 2000: A Geostationary Imaging Fourier Transform Spectrometer (GIFTS) for hyperspectral atmospheric remote sensing, presented at SPIE's Second International Asia-Pacific Symposium on Remote Sensing of the Atmosphere, Environment, and Space, Sendai, Japan, 9–12 October 2000.

Dittberner, G. J., James J. Gurka, and Roger W. Heymann, 2003: NOAA's GOES satellite program—status and plans, 19th Conference on IIPS, 83rd Annual Meeting, 8–13 February 2003, Long Beach, CA. Published by the American Meteorological Society, Boston, Mass.

Gurka, J. J., Gerald J. Dittberner, Pamela Taylor, and Timothy J. Schmit, 2003: Specifying the requirements for imaging and sounding capabilities on the GOES-R series, 12th Conference on Satellite Meteorology and Oceanography, 83rd Annual Meeting, 8-13 February 2003, Long Beach, CA. Published by the American Meteorological Society, Boston, Mass.

Huang, H-L., J. Li, E. Weisz, K. Baggett, J. E. Davies, J. R. Mecikalski, B. Huang, C. S. Velden, R. Dengel, S. A. Ackerman, E. R. Olson, R. O. Knuteson, D. Tobin, L. Moy, D. J. Posselt, H. E. Revercomb, and W. L. Smith, 2004: Infrared hyperspectral sounding modeling and processing, 20th Conference on IIPS, 84th AMS Annual Meeting, 11-15 January 2004, Seattle, WA. Published by the American Meteorological Society, Boston, Mass.

Knuteson, R., Best, F., Dedecker, R., Garcia, R., Limaye, S., Olson, E., Revercomb, H., and Tobin D., 2004a: LEVEL 0-1 Algorithm Description For The Geosynchronous Imaging Fourier Transform Spectrometer, AMS annual meeting, Seattle, WA, 12-16 January 2004, American Meteorological Society.

Knuteson, R. O., F. A. Best, G. E. Bingham, J. D. Elwell, H. E. Revercomb, D. K. Scott, J. K. Taylor, D. C. Tobin, W. L. Smith, 2004b: On-orbit calibration of the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS). In: Proceedings of the SPIE, Fourth International Asia-Pacific Environmental Remote Sensing Symposium, 8 November 2004, Honolulu, Hawaii.

Limaye, S. S., T. Smith, R. O. Knuteson, H. E. Revercomb, 2004: Geolocation of the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) data, 20th Conference on IIPS, 84th AMS Annual Meeting, 11-15 January 2004, Seattle, WA. Published by the American Meteorological Society, Boston, Mass.

Smith, W. L., D. K. Zhou, F. W. Harrison, H. E. Revercomb, A. M. Larar, A. H. Huang, B. Huang, 2000: Hyperspectral remote sensing of atmospheric profiles from satellites and aircraft, presented at SPIE's Second International Asia-Pacific Symposium on Remote Sensing of the Atmosphere, Environment, and Space, Sendai, Japan, 9–12 October 2000.

Tobin, D. C., H. E. Revercomb, R. O. Knuteson, 2003: On-orbit Spectral Calibration of the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS), in Proceedings of CALCON 2003, Characterization and Radiometric Calibration for Remote Sensing, Space Dynamics Laboratory / Utah State University, Logan, Utah, 15-18 September 2003.