APPLICATION NOTE

Jet Engine Characterization

Abstract

Oil consumption for jet engines (Figure 1) and turbines and its adverse environmental and economic impacts can be mitigated through the application of more advanced technologies. In this paper, hyperspectral imaging coupled with novel data processing techniques were used to analyze the turbulent exhaust plume from a small turbojet engine. Spatial maps of brightness temperature and estimates of turbulence-induced temperature distribution are presented.

Hyperspectral infrared imagery coupled with digital image processing promise to substantially improve jet engines and turbines standoff and non-invasive measurements. This approach could help getting better jet engines and turbines designs resulting on a reduction of fuel consumption and a positive environmental impact.

Figure 1: Pratt & Whitney F100 turbofan

Introduction

Hyperspectral Imagery (HSI) using Fourier-Transform Spectroscopy (FTS) is a valuable tool for the characterization of various infrared sources. In particular, passive FTS has been extremely useful in the study of hydrocarbon combustion systems such as incinerators and smokestacks, laminar flames, detonation fireballs, and jet engines (Figure 2). It allows the determination of several constituents such as H_2O, CO_2, CO, NOx, SOx and numerous other gases produced from combustion.

Figure 2: AFIT SR-30 jet engine

Measuring the temperature field is key to understanding various elements of combustion including combustion efficiency, pollutant formation, and soot production. Combustion is often turbulent and the temperatures within the plume fluctuate stochastically. Most optical temperature diagnostics are based on interpretation of time-averaged spectra and ignore the influence of turbulent fluctuations. This can lead to highly-biased temperature estimates due to the non-linear relationship between radiant intensity and temperature.

The Telops Hyper-Cam enables simultaneous acquisition of spatial and spectral information at high resolutions in both domains. The ability to study combustion systems with high resolution, co-registered imagery and spectral data is highly desired.

While the benefits of hyperspectral imagery are well known, it is worth pointing out their utility in the context of studying combustion: (1) a narrow instantaneous field of-view (IFOV) minimizes spatial averaging and simplifies interpretation of spectra when temperature and density exhibit large variations throughout the combustion medium; (2) two-dimensional projection of combustion plume may reveal symmetry which could be used to reconstruct aspects of the three-dimensional structure; (3) rapid detection revealing plume dynamics such as turbulent vortex motion. For these and other reasons, hyperspectral imagery can enhance the understanding of combustion sources and would provide high value data for the calculations of fluid dynamics.

A novel statistical method of interpreting interferograms to begin understanding turbulence-induced temperature fluctuations was used to characterize jet engine exhaust plume and demonstrate that IFTS can, and should, be used to study turbulent combustion sources.

Figure 3: The Hyper-Cam

Experimental information

The Telops Hyper-Cam is a lightweight and compact hyperspectral imaging instrument using Fourier Transfer Infrared (FTIR) technology (Figure 3). The Hyper-Cam offers a unique combination of spatial, spectral and temporal resolution. The spectral resolution can reach up to several thousands of bands to fulfill the most demanding spectral characterizations. The Hyper-Cam features a focal-plane array (FPA) detector containing 320x256 pixels over a basic 6.4°x5.1° field-of-view. The spectral resolution of the Hyper-Cam is user-selectable between 0.25 and 150 cm^{-1} over the 3 to 5 µm (Mid-Wave) or 8 to 12 µm (Long-Wave) spectral range. The Hyper-Cam is also available with an extended Mid-Wave range (1.5 to 5.5 µm). The Hyper-Cam offers a high sensitivity for each pixel of the scene under observation, and its lightweight makes it ideal for field operation.

The Hyper-Cam was designed from the ground up so the control and the data acquisition are specifically optimized. The sensor is capable of generating calibrated data in real-time at the highest data rates. This real-time processing allows lossless compression by a factor of approximately 10-20, a welcomed factor for such a high-throughput instrument.

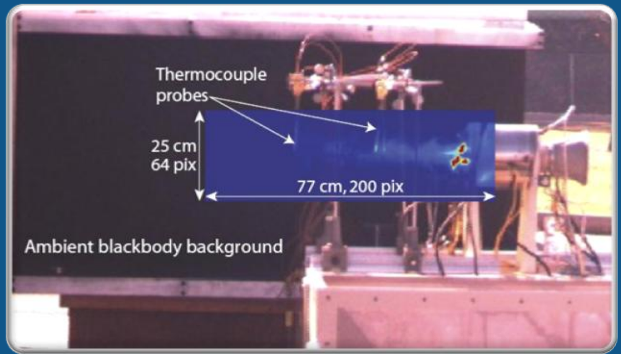

Figure 4: Sub-window on the SR-30 turbine viewed by the Hyper-Cam

Results & Discussion

Infrared hyperspectral imagery of the exhaust plume from a Turbine Technologies SR-30 turbojet was collected using a Telops Hyper-Cam Mid-Wave. The SR-30 is designed for educational laboratory work and features a single-stage compressor capable of producing approximately 180N of thrust with a nominal exhaust temperature between 500–700°C depending on engine configuration.

The Hyper-Cam measured the exhaust plume at $1cm^{-1}$ resolution on a 200×64 pixel sub-window as shown in Figure 4. Integration time on the focal-plane array was 50μs and an iris at the instrument's aperture stop was used to prevent saturation. Measurements were recorded with the engine operating at 70,000RPM burning diesel fuel at a flow rate of $225cm^3/s$. For this work, 189 individual interferogram cubes from the Hyper-Cam were processed.

Raw experimental data (Figure 5) shows a lot of sporadic, strong transient features. These transient flare-ups are the result of excess fuel occasionally exiting the engine and being ignited by the hot exhaust gases. This causes a bright, short-lived combustion fireball to travel down the plume. Performing a standard averaging of the interferograms when such impulses are present would undoubtedly result in erroneous averages. However using median interferograms has much less sensitivity to low-probability events such as these impulses, since the quantile estimations rely on data where the extreme values are simply pushed at the limit of the sorted vector, no matter how far they are from the others.

In order to demonstrate the information gained by this processing method, brightness temperature images were compared. For this purpose the brightness temperatures were processed at $2280cm^{-1}$. This corresponds mainly to the peak of the observed CO_2 emission. The resulting spatial map of brightness temperature is presented in Figure 6 and is computed from the spectra corresponding to the median interferogram. A similar brightness temperature map was generated using the mean spectrum and qualitatively the results appeared quite similar. Figure 7 shows the map resulting from the differences between the mean and median brightness temperatures. It can be seen that they differ significantly in several plume locations. Differences in temperature of up to 15K can be observed. Figure 8 brings meaningful information to interpret the shape of the observed bias. Estimate of the standard deviation of the brightness temperature has been performed to highlight the exhaust plume fluctuations. The lower quantile and upper quantile were used for the resulting map shown in Figure 8. It is seen that the fluctuations vanish, or are at least strongly reduced, for all regions not related to the plume, e.g. cold vertical posts, hot thermocouples, hot engine and background. Moreover it can be observed that the fluctuations are much stronger in the upper part of the plume than in its lower part. It is possible that mixing of descending cold air on the top of the plume creates more turbulence in this area. It also explains why smaller fluctuations are observed in the central part of the plume close to the engine. Turbulence is expected to be large in regions where hot exhaust gases interact with the much cooler atmospheric gases. This method of computing quantile interferograms associated with the Hyper-Cam is a novel way of extracting important information related to turbulent plume dynamics without suffering from its effects [1].

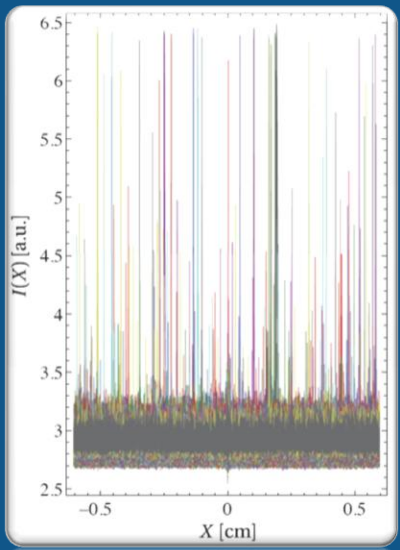

Figure 5: Raw data showing sporadic transients

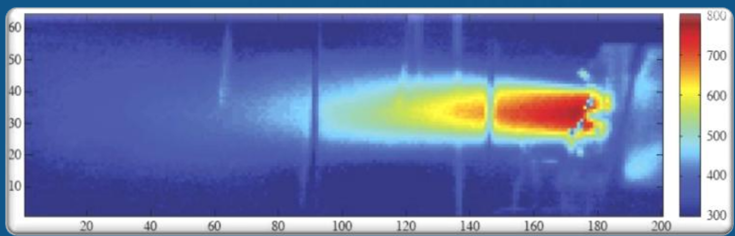

Figure 6: Brightness temperature near $2280cm^{-1}$ computed from the median interferogram

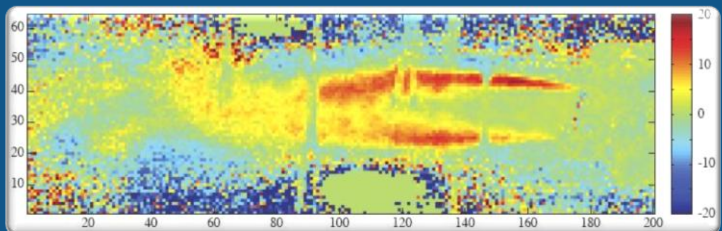

Figure 7: Differences in brightness temperature computed from the mean and median interferograms

Coupled with this method and using a tool developed by Telops to simultaneously look at images corresponding to a given wave number as well as the spectrum observed for a given pixel, precise jet engine's exhaust plume identification of gases could be performed. Furthermore, level of each component spectra allows determining each gases concentration present in the plume.

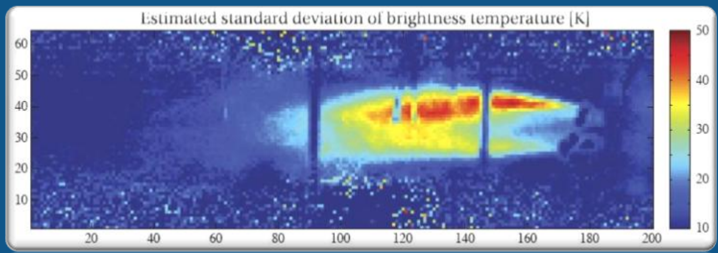

Figure 8: Estimated standard deviation of brightness temperature (K)

Conclusion

It has been shown that Infrared Hyperspectral Imaging coupled with novel data processing techniques can be used to improve the characterization of jet engines and turbines exhaust plumes as shown on Figure 9. Instead of suffering from scene fluctuations, the Hyper-Cam coupled with data processing techniques permitted the extraction of information related to the fluid dynamics. The results were derived from the quantiles of the spectral radiance distribution for each wavenumber. They offer a substantial advantage to enable correct interpretation of the spectral measurements by providing an unbiased estimate of the mean temperature of the source. They also allow precise identification and quantification of gases from rotary engines with non invasive measurement techniques. The Hyper-Cam offers a great potential for designing superior jet engines and turbines by providing a better visualization and understanding of combustion phenomenology.

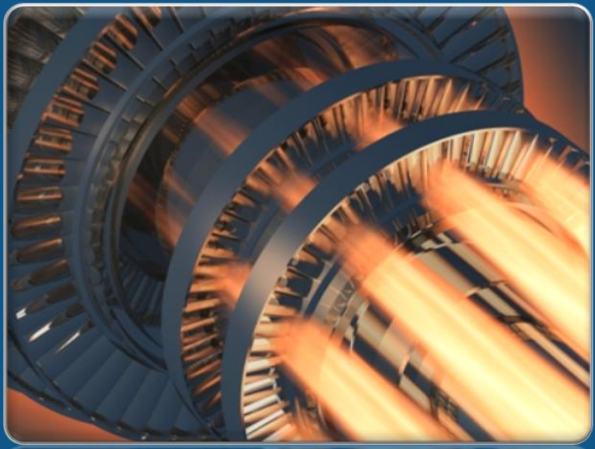

Figure 9: Gas Turbine Engine

We acknowledge our collaborators from US Air Force Institute of Technology.

[1] "Understanding and Overcoming Scene-Change Artifacts in Imaging Fourier-TransformSpectroscopy of Turbulent Jet Engine Exhaust". Pierre Tremblay*, Kevin Gross**, Vincent Farley*, Martin Chamberland*, André Villemaire*, and Glen P. Perram**. Proceeding of SPIE Imaging Spectrometry XIV, Vol. 7457 74570F-11.
*Telops inc., **Air Force Institute of Technology.

www.telops.com

100-2600 St-Jean-Baptiste avenue Quebec, QC, G2E 6J5 | Tel: 418.864.7808 | Fax: 418.864.7843 | sales@telops.com