CARVE-FTS Observations of Arctic CO$_2$, CH$_4$ and CO – Overview of the Instrument

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ABSTRACT

CARVE-FTS is a near-IR Fourier-Transform Spectrometer (FTS) used by the Jet Propulsion Laboratory (JPL) for the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE). CARVE is a 5-year mission of intensive aircraft campaigns in the Alaskan Arctic selected as part of NASA’s Earth Ventures program (EV-1). The CARVE-FTS has been designed, manufactured and tested by ABB Inc. The objective of this instrument is to provide integrated column measurements of carbon dioxide (CO$_2$), methane (CH$_4$), and carbon monoxide (CO). The system is inspired from the TSUKUBA-FTS built by ABB for the Japanese Aerospace Exploration Agency (JAXA). JAXA uses the instrument for preparation, calibration and validation within the GOSAT program.

The instrument is a Michelson based FTS with three spectral bands. The light modulator is a Michelson single pass type interferometer with large aperture and medium spectral resolution. It provides infrared spectra from 12,900 cm$^{-1}$ to 13,200 cm$^{-1}$, from 5,800 cm$^{-1}$ to 6,400 cm$^{-1}$, and from 4,200 cm$^{-1}$ to 4,900 cm$^{-1}$. This instrument is also able to measure the scene radiance with S and P polarization simultaneously using monopixel detectors. The instrument is mounted on a damping platform and is installed in an aircraft. It delivers continuous data for flight campaigns over the Alaskan Arctic. SNR higher than 100 is reached for each band and the measured ILS full width at half maximum is as low as 0.26 cm$^{-1}$. We present the instrument design, its specification and test results obtained at ABB.

Keywords: FTIR, Spectrometer, CO2 retrieval, methane retrieval, Fourier Transform Spectrometer

1. INTRODUCTION

The carbon budget of Arctic ecosystems is not known with confidence because fundamental elements of this complex system are poorly quantified. CARVE aims at collecting detailed measurements over the Alaskan Arctic on local and regional scales. These measurements along with modeling will help to better quantify carbon fluxes in order to improve our knowledge and understanding of the Arctic carbon cycle and climate processes. CARVE is a five year project part of NASA’s Earth Ventures program (EV-1).

The airborne observations are done from a C-23 Sherpa aircraft carrying three payloads: an In-Situ Gas Analyzer (ISGA) to measure atmospheric trace gas concentrations, a Passive-Active L-band System (PALS) to measure surface control variables and a nadir viewing FTS to measure CO$_2$, CH$_4$ and CO columns. They are complemented by ground-based measurements of well-instrumented calibration and validation ground sites, flux towers, and satellite data from the Greenhouse Gases Observing Satellite (GOSAT) and the upcoming Orbiting Carbon Observatory 2 (OCO-2).

The CARVE-FTS is similar to the TSUKUBA-FTS [1] with minor modifications. The instrument has a circular field of view of about nine degree; and three near infra-red channels with spectral ranges of 12,900-13,200 cm$^{-1}$ (O$_2$ A band), 5,800-6,400 cm$^{-1}$ (CH$_4$ and CO$_2$) and 4,200-4,900 cm$^{-1}$ (CH$_4$ and CO). It measures S and P polarizations simultaneously for all channels. The instrument has three spectral sampling intervals of 0.2, 0.5 and 1 cm$^{-1}$. It delivers one interferogram every 1 second at maximum scan speed. A passive damping platform reduces the effect of aircraft vibrations to acceptable levels. A thermal blanket keeps the instrument stable thermally and reduces acoustic vibration effects. Finally a visible camera is bore sighted and synchronized with the FTS.
ABB has designed, built and characterized the instrument for JPL. The instrument has been designed to operate in an aircraft without degradation of its performance. The FTS was delivered to JPL in January 2012. Flight tests were carried out at the NASA Flight Facility in Wallops, Virginia, in mid-May 2012, and the instrument has been deployed as part of the CARVE field campaign in Alaska since late May 2012. We present the instrument design, test results and preliminary spectra from the Wallops test flights.

2. INSTRUMENT DESIGN OVERVIEW

2.1 System Overview

The instrument is composed of a nadir looking input telescope, a light modulator, a detection module and an amplifier for each detector. It provides one interferogram per detector for each light modulator scan. The acquisition system is composed of the CARVE-FTS instrument, two electronic boxes, a power supply and an interface control computer. Data are processed externally for higher level products. Figure 1 shows the system.

![Figure 1: CARVE-FTS system: (a) instrument, (b) control electronic boxes, (c) power supply and (d) interface control computer.](image)

2.2 Optical Design

The native interferometer Field Of View (FOV) of 15.8 mrad is magnified using a 10× input telescope to reach a total FOV of 9° in the scene domain. This wide FOV is much larger than the aircraft pointing errors, thus removing the need for the image motion compensator that is required for the TSUKUBA-FTS [1]. The input telescope is equipped with an internal shutter for reference data. A visible camera is bore sighted and synchronized with the FTS for data quality assessment.

The light modulator is a well proven ABB design and is a 2-port Michelson based interferometer with cube corner mirrors and double pendulum rotary scan mechanism. Scanning is performed using a voice coil rotary actuator. The Optical Path Difference (OPD) is monitored by a 1310 nm laser diode. The laser diode controller has heritage from previous projects and delivers highly stable wavelength within 0.5 ppm over one scan duration. This feature coupled to a thermally controlled optical bench ensures a very high spectral stability for the spectra. A redundant metrology system is available thus extending the light modulator lifetime. Laser fringes are sampled at zero crossing to trigger the science beam acquisition signal. Maximum OPD is 5 cm providing 0.2 cm⁻¹ spectral sampling interval. Spectral sampling interval is selectable from 0.2 cm⁻¹, 0.5 cm⁻¹ and 1 cm⁻¹. The interferometer speed is user-selectable and, depending on the settings, an interferogram can be generated every 1, 2 or 4 seconds at 0.2 cm⁻¹ spectral sampling interval.

At the output of the interferometer, the beam is folded and focused on the detection module. A first dichroic reflects high wavenumbers. The transmitted light is split using another dichroic that transmits lowest wavenumbers. This set of two
dichroics lead to three extended spectral bands. A set of lenses and a narrow optical bandpass filter are used in front of each detector. The first spectral band covers 12,900 cm\(^{-1}\) to 13,200 cm\(^{-1}\) for \(\text{O}_2\) A band. Band 2 covers 5,800 cm\(^{-1}\) to 6,400 cm\(^{-1}\) for \(\text{CH}_4\) and \(\text{CO}_2\) and Band 3 covers 4,200 cm\(^{-1}\) to 4,900 cm\(^{-1}\) for \(\text{CO}\) and \(\text{CH}_4\). Three polarizing cube beamsplitters are inserted in the optical path between the dichroic and each set of lenses to separate S and P polarization states for each extended spectral band. The transmitted light travels to the first set of detectors and the reflected light travels to a second set of detectors. The detection module thus has six detectors. If polarization is not needed, the polarizing cube beamsplitters can be easily removed from the optical path to illuminate only the first set of detectors.

### 2.3 Mechanical Design

The instrument outer box is an eight cubic foot machined aluminum block designed for higher stiffness. The input telescope is bolted to this block. Figure 2 shows a closer view of the instrument.

![Figure 2: CARVE-FTS instrument.](image)

The enclosure is nitrogen purged and equipped with dehumidifiers. The instrument rests on a passive damping platform, not represented here, to minimize transmission of aircraft vibrations to the light modulator. A thermal blanket, also not shown in Figure 2, keeps the instrument thermally stable and reduces acoustic vibration effects.

### 2.4 Electrical Design

Two electronic boxes are used to control the outer box temperature, the visible camera, the light modulator and to acquire digital data from the detection module. Silicon, InGaAs, and extended InGaAs commercial monopixel detectors are used respectively for Band 1, Band 2 and Band 3. Band 1 is almost shot noise limited while Band 2 and Band 3 are electronic noise limited. The signal chain is composed of a transimpedance amplifier, an Alternating Current (AC) or Direct Current (DC) switch, a pre-amplifier and an Analog to Digital Converter (ADC). Instrument performance is verified with the Signal to Noise Ratio (SNR) test. AC mode is used to remove dark current bias and to increase the dynamic range. Up to 10 different gains can be used independently for each detector analog signal. The signal is converted using a 16-bit ADC. Digital signals are sent to the outer electronic box. The interface control computer displays the interferogram in near-real time and records all the data on the instrument control computer. Typical settings are DC mode at lowest gain, polarization mode ON, providing six interferograms per scan.
2.5 Specifications

Table 1 summarizes the instrument specifications.

Table 1: Instrument Specifications

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light modulator type</td>
<td>Michelson, 2 ports</td>
</tr>
<tr>
<td>Light modulator reflectors</td>
<td>Cube corners</td>
</tr>
<tr>
<td>Maximum optical path difference</td>
<td>± 5 cm</td>
</tr>
<tr>
<td>Metrology laser</td>
<td>DFB 1310 nm (7 633 cm⁻¹)</td>
</tr>
<tr>
<td>Metrology sampling</td>
<td>Zero crossing, selectable from 10 kHz, 25 kHz or 40 kHz fringe rate</td>
</tr>
<tr>
<td>Light modulator aperture</td>
<td>64 mm</td>
</tr>
<tr>
<td>Light modulator field of view</td>
<td>15.8 mrad (0.9°)</td>
</tr>
<tr>
<td>Instrument field of view</td>
<td>9°</td>
</tr>
<tr>
<td>Spectral Sampling Interval (cm⁻¹)</td>
<td>Selectable from 0.2 cm⁻¹, 0.5 cm⁻¹ or 1 cm⁻¹</td>
</tr>
<tr>
<td>Polarization</td>
<td>Detection of S and P</td>
</tr>
<tr>
<td>Spectral coverage and detector type</td>
<td>Band 1: 12,900 to 13,200 cm⁻¹ (757 nm to 775 nm), Silicon detector</td>
</tr>
<tr>
<td></td>
<td>Band 2: 5,800 to 6,400 cm⁻¹ (1 562 nm to 1 741 nm), InGaAs detector</td>
</tr>
<tr>
<td></td>
<td>Band 3: 4,200 to 4,900 cm⁻¹ (2 041 nm to 2 381 nm), Extended InGaAs detector</td>
</tr>
<tr>
<td>Filter mount design</td>
<td>Removable mount for each detector</td>
</tr>
<tr>
<td>Analog to Digital Converter</td>
<td>16 bit, AC sampling or DC sampling via a software command</td>
</tr>
</tbody>
</table>

Instrument operations can take advantage of the high optical throughput and adjustable spectral bands: S and P polarization components can be detected separately in each of the three spectral bands, providing up to six separate spectra simultaneously, or data acquisition can be performed without polarization sensitivity for higher SNR.

3. TEST RESULTS

3.1 Signal to Noise Ratio (SNR)

SNR is characterized at 40 kHz fringe rate, 0.2 cm⁻¹ spectral sampling interval, polarization OFF mode, averaging on 30 successive measurements of single scan. The source of the signal is a blackbody, its temperature is 924 °C for Band 1, 394 °C for Band 2 and 235 °C for Band 3. It corresponds to typical expected fluxes from Alaska land surfaces converted to the equivalent blackbody temperature. The wide input telescope field of view is focused on the 1 inch diameter cavity...
blackbody using a parabolic mirror (shown on Figure 4). The SNR is the ratio between the average spectrum value divided by the RMS value for each wavenumber. Figure 3 shows SNR for bands 1, 2, and 3.

![Figure 3: Signal-to-noise ratios for (a) Band1, (b) Band2, and (c) Band3.](image)

The maximum SNR for Band 1 (from 12,900 to 13,200 cm\(^{-1}\) spectral range) is about 120. The maximum SNR is found at 12,850 cm\(^{-1}\) due to the last optical filter cut-off. The SNR trend mainly relies on the Planck’s law and no absorption line is found here since the optical path is about 1 meter. The maximum SNR for Band 2 (5800 to 6400 cm\(^{-1}\) spectral range) is about 270. The main noise contributor is the electronic noise. A careful adjustment on the detector reverse voltage bias was done to maximize SNR. The result is above the science team requirement of 240 at 5800 cm\(^{-1}\). The maximum SNR for Band 3 (4200 to 4900 cm\(^{-1}\) spectral range) is about 250. The SNR trend follows the Planck’s distribution. SNR result is well above the requirement due to a different reverse voltage bias applied to the detector and the detector performance above the typical manufacturer specification.

### 3.2 Instrument Line Shape (ILS)

The ILS is measured at 0.2 cm\(^{-1}\) spectral sampling interval, 40 kHz fringe rate and polarization OFF mode. 20 interferograms in forward direction and 20 interferograms in reverse direction are acquired. A helium neon (He-Ne) laser coupled to an integrating sphere is used to characterize the ILS. This method is easier to implement compared to a blackbody and a gas cell. The selected He-Ne laser emitted at both wavelengths of 632.8 nm (15,8902.8 cm\(^{-1}\)) and 1,523 nm (6,566 cm\(^{-1}\)). The FTS polarizing mode is OFF. Figure 4 shows the setup.

![Figure 4: Instrument Line Shape Setup.](image)

Table 1 summarizes the results.

<table>
<thead>
<tr>
<th>Integrating Sphere</th>
<th>He-Ne Laser</th>
</tr>
</thead>
</table>

Table 1
Table 1 – Instrument Line Shape Results

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavenumber (cm(^{-1}))</th>
<th>Measured ILS (full width at half maximum)</th>
<th>Fitting Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15,802.8</td>
<td>0.43</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>6,566.0</td>
<td>0.26</td>
<td>15.5 mrad</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>0.825 mrad</td>
</tr>
</tbody>
</table>

Figure 5 shows the measured (+) and theoretical (continuous line) curves for the instrument line shape of Band 1 and Band 2. Band3 ILS is not represented here since it is very similar to Band2 result. The ILS shows a very good fitting to the simulation for all the three bands. The ratio of ILS for the two wavelengths is typical for this kind of instrument. This result confirms that optical alignment is optimized.

3.3 Polarization Sensitivity

The polarization sensitivity is measured at 0.2 cm\(^{-1}\) spectral sampling interval and 40 kHz fringe rate. 30 interferograms in forward direction and 30 interferograms in reverse direction are acquired. A blackbody and a linear polarizer are used to characterize the polarization sensitivity. Figure 6 shows the setup.
The polarizing cube beamsplitter extinction dictates the polarization sensitivity value for each detector. A perfect polarizing cube beamsplitter would split S from P optical signals. In fact, some S-polarized radiance travels through the P optical path. We assess the polarization sensitivity with the amplitude of interferogram signal in AC mode at Zero Path Difference. We measure the voltage for a linear polarizer orientation $\theta_0$ that maximizes the signal for P and for a $90^\circ$ rotation. Polarization sensitivity is 100% for P if no light goes through the P optical path when the polarizer is rotated by $90^\circ$. Polarization sensitivity is 33% for P if half the light goes through the P optical path when the linear polarizer is rotated by $90^\circ$. Table 2 summarizes results.

Table 2 – Polarization Sensitivity Results

<table>
<thead>
<tr>
<th>Angle</th>
<th>Amplitude of Signal (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Band 1</td>
</tr>
<tr>
<td>$\theta = \theta_0$</td>
<td>S 0.05  P 1.57</td>
</tr>
<tr>
<td>$\theta = \theta_0 + 90^\circ$</td>
<td>S 1.87  P 0.17</td>
</tr>
<tr>
<td>Polarization Sensitivity</td>
<td>S-P 0.95</td>
</tr>
</tbody>
</table>

Polarization sensitivity mainly corresponds to the polarizing cube beamsplitter specification. Discrepancies between maximum signal for S and P detectors in Band 3 are due to a combination of a variation in their electrical properties and a variation in bandpass filter transmission. Nevertheless, the SNR is very similar for S and P in Band 3.

### 3.4 Spectral Stability

Spectral stability is critical for accurate FTS data retrieval. A water vapor line near 4100 cm$^{-1}$ is tracked to characterize the spectral stability. The optical path was about three meters, laboratory temperature was 22°C and the relative humidity was 50%. 4,000 spectra were acquired at 0.2 cm$^{-1}$ spectral sampling interval and 25 kHz fringe rate. A retrieval algorithm was used to track a water vapor line for each of the 4,000 spectra. The fitted line is compared to the theoretical line and the ratio between them is reported. It corresponds to a spectral stretch between the expected line wavenumber compared to the measurement. The ratio is illustrated in Figure 7.
The average ratio is 0.9983 at 4,100 cm\(^{-1}\), which corresponds to an offset of 7 cm\(^{-1}\) for this wavenumber. This originates from an offset in the 7,633 cm\(^{-1}\) metrology laser of 13 cm\(^{-1}\) between the real value and the one used for post-processing. The subsequent spectral calibration corrected this offset to provide an accurately calibrated wavenumber scale. The fitting RMS error is 2.5 ppm, which includes contributions from noise and reflects the ability of the retrieval software to obtain a good fit on only one water vapor line without co-adding. A basic fitting indicates a slope of 3\(\times\)10\(^{-4}\) ppm/min. It corresponds to a calculated drift of 7\(\times\)10\(^{-5}\) cm\(^{-1}\)/hour. We can conclude that a moving average shows a negligible drift. It confirms the excellent behavior of the instrument with respect to spectral stability.

4. FIELD CAMPAIGN PRELIMINARY RESULTS

The CARVE-FTS was delivered to JPL in January 2012. After integration of all instruments on the CARVE C-23 aircraft, test flights were conducted during 10-13 May 2012 at the NASA Wallops Flight Facility, VA [2]. For flight operations, the CARVE FTS is mounted on a passive damping platform. The nominal mode of operations is to take one interferogram every second at 0.2 cm\(^{-1}\) spectral sampling, in AC mode, polarization ON, and with high-gain settings for all three bands. During the data evaluation process, multiple spectra (typically 10) are co-added for improved SNR.

Pre-flight tests of the dampening platform using a dummy mass showed no perceptible impact of aircraft vibrations on the light modulator. This was confirmed by the first in-flight spectra obtained during subsequent test flights, which showed no obvious contamination from aircraft vibration frequencies.

Figure 8 shows sample composite spectra from the test flight on 13 May 2012. One composite spectrum is shown for each of the three bands and the two polarization components, and each of the composites was derived from co-adding 10 consecutive spectra taken with 1 s integration time. At typical aircraft speeds, the effective 10 s integration time corresponds to roughly 1 km spatial displacement along the direction of travel.

The spectra shown in Figure 8 are radiometrically uncalibrated and therefore are displayed in arbitrary units (y-axis). Radiance levels between bands cannot be compared directly, but within the same band the relative signal levels between S and P polarization is accurate. Looking closely at the spectral envelopes, differences between S and P spectra are apparent, particularly in Band 2. The difference in radiance levels and spectral shapes between the polarization components is a combination of the bandpass filters and the optical signature of the atmosphere and underlying surface that has been observed. Spectral features introduced by the bandpass filters can largely be removed using blackbody measurements for radiometric calibration.
Figure 8: Sample composite spectra from the test flight on 13 May 2012.
First results from running a retrieval algorithm for O$_2$, CO$_2$, CO, and CH$_4$, including spectral calibration, on CARVE spectra from all three bands has shown that the FTS is spectrally very stable. As is typical for a FTS, spectral offsets tend to be uniform between different spectra, hence little to no error is introduced by first co-adding multiple spectra and subsequently spectrally calibrating the composite. This has been confirmed by retrieval tests that compared the results from spectral calibration of individual spectra with the corresponding multi-spectrum composites.

Both CARVE-FTS Wallops test flight and Alaska field campaign observations are currently being evaluated for the main CARVE target gases CO$_2$, CO, and CH$_4$. The lower than expected radiance levels during deployment in Alaska have made it necessary to reevaluate the currently employed observation and co-adding strategies. More than the originally envisaged 10 spectra may have to be co-added to reach sufficient SNR for high-quality retrievals. For the 2013 Alaska campaign, the instrument may be operated in polarization OFF mode for increased signal levels.

5. CONCLUSION

ABB has designed, built and characterized the near-IR Fourier-Transform Spectrometer for the CARVE mission led by JPL. The system has heritage from previous ABB projects delivered to the JAXA. The SNR was optimized to allow high-quality retrievals of CO$_2$, CO, and CH$_4$. The ILS is very well behaved, which confirms very good optical alignment. The spectral stability is also outstanding. Any of the instrument’s spectral bands can be tuned to any wavelength from visible to long wave infrared providing a retrofit of the detector and the detector optical bandpass filter. The spectral range of the interferometer, as delivered to the CARVE team, is about 0.75 µm to 20 µm. Scanning speed, maximum OPD, and signal voltage gain are user-selectable to optimize the performance to a given measurement scenario. The FTS was completed in December 2011 and delivered to JPL in January 2012. It was integrated to the aircraft and had a first test flight in May 2012 over Wallops, Virginia. It is currently being deployed in the 2012 Alaska field campaign, which lasts from May through October. Preliminary results from test flights and field operations are extremely encouraging, particularly with respect to vibration damping [2] and spectral stability. This high spectral stability provides the option to co-add individual spectra for improving the low SNR that can result from low radiance levels observed in Alaska.

6. AKNOWLEDGMENT

The authors would like to thank the CARVE team from Jet Propulsion Laboratory/California Institute of Technology for providing data from their measurement campaigns and for their participation in this paper. CARVE Principal Investigator is Charles E. Miller and CARVE Project Manager is Steven J. Dinardo.

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