An Interference Spectrometer for the Remote Sensing of Pollutants

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Introduction

A SMALL, high-resolution interference spectrometer for sensing environmental pollutants from spacecraft or aircraft has been developed. The instrument takes less than 3 min to generate an interferogram of the electromagnetic radiation in the 1.2–5.5 μ wavelength interval (8000–1800 cm^{-1}) which can be transformed into a spectrum displaying a resolution of 0.2 cm^{-1}. The high speed with which the interferogram can be recorded is sufficient to make the instrument usable in a 1000-km altitude polar orbiting satellite for a global survey of pollutants. The resolution capability and wavelength coverage is such that unequivocable identifications and concentration measurements can be made of many molecules such as CO, NO_2 and O_3 by the methods of high-resolution IR spectroscopy.

There are two reasons for using a Fourier interference spectrometer instead of a grating instrument. The first is for the "multiplex advantage," which means that a single IR detector can look at all wavelengths simultaneously instead of one resolution element at a time. The second is the "through put advantage," which refers to the fact that an interferometer has more light-gathering power than a grating spectrometer.

Interferometer Optics

The optical configuration is a modification of the basic Michelson interferometer and is shown in Fig. 1. Instead of using plane mirrors, cat's-eye retroreflectors are used. Optically, these act similarly to a cube corner; a light ray comes back parallel to the incident ray, but it is displaced. Light coming through either arm of the instrument is reflected by the mirrored surface on the beamsplitter cube, and passes through the instrument again before going to the IR detector. Use of the cat's-eyes makes the interferometer insensitive to tilting of the moving element. In the original plane mirror Michelson configuration, the normal to the mirror surface must be kept parallel to the axis of motion within a few seconds of arc. Double-passing the light through the instrument makes the instrument insensitive to lateral displacements of the cat's-eye. The instrument is, thus, inherently insensitive to both angular and lateral motions of the moving element. The original beam splitter was assembled from two quartz 90° × 45° × 45° prisms, one with a 1/4 wave silicon coating on the hypotenuse which is wrung together to make optical contact. No particular problem was encountered in its procurement, in spite of the severe requirement that the difference in the measure of the two angles defined by the reflecting surfaces and the hypotenuse be less than two seconds of arc. For the long wavelength version, however, another material had to be used—namely, calcium fluoride, which is more difficult to grind to the required optical flatness and angular tolerances, and which cannot be wrung together. Two satisfactory prisms were fabricated and assembled, using an optical contacting oil displaying no absorption in the region of interest.

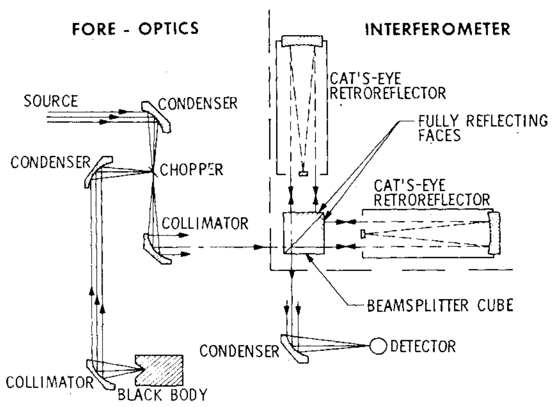

Fig. 1 Optical diagram.

Foreoptics

Incoming radiation is chopped before entering the interferometer in order to have the IR detector operate at a frequency sufficiently high for low-noise performance. A tuning fork chopper, operating at 830 Hz, is used in order to avoid the problems of a rapidly rotating chopper wheel in a space environment. This requires that the incoming radiation be condensed to a small enough diameter to be chopped by the tuning fork and then be recollimated. The chopper's blade is made of calcium flouride. Half of its area is covered with a reflective gold coating so that it can alternately transmit the source energy or reflect energy from a constant temperature reference blackbody. The 830 Hz tuning fork frequency was chosen so that the instrument could step at a sufficiently fast rate because the interferometer must be synchronized to the chopper, and yet have enough displacement at the end of the fork's tine to completely chop a 1-mm beam diameter. The minimum beam diameter is determined by the smallest obtainable *f*/number of the optics. Because of this *f*/number requirement, and in order to reduce the number of optical elements required, off-axis paraboloids were used in the instrument.

A second detector called the total power detector has been used to correct the interferogram for source intensity fluctuations. This detector receives radiation from the source or the reference blackbody, but in the opposite phase with respect to the interferometer. Recently, it has been determined that a low-pass filtering of the IR data during the data reduction process can accomplish the task originally assigned to the total power detector. This will result in a significant weight reduction and a much less complicated foreoptics design in future instruments. It might be noted that compensation for variations in total power are essential to successful reduction of interferometric data.

Interferometer

The cat's-eye moves in steps under servo control using a He-Ne laser source operating at 6328 Å as a positional reference, remaining stationary during the data-taking period. Each step is equal in length and is an integral multiple of the reference wavelength. This step-length multiple can be changed upon command to greatly reduce the interferogram taking time if the wavelength interval to be sampled can be reduced by optical filtering. Thus, one can reduce the time from 2 min 45 sec to 77 sec using a multiple of 6, while maintaining the chopping frequency at the optimum value for the IR detector performance, and still maintaining optimum spectral resolution.

The step-scanning method also solves two major problems inherent with the constant-speed scanning method used in most Fourier spectrometers. It eliminates errors resulting

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from driving speed fluctuations because the optical path difference between the two beams is known, and constant, at every instant in time. With a constant-speed system, sampling occurs only once; thus, the true position is only known once per monochromatic reference fringe. The other problem it solves is to eliminate phase-shift errors resulting from the IR detectors and to electrical filtering, which is important at high-data rates. The signal integration periods between position steps are equal in length, and are an integral multiple of the tuning fork chopper's period. This multiple can also be varied upon command from 1 to 32 chopper cycles, equivalent to 1.2–38.4 msec, in case a longer signal integration time is desired.

Detector and Signal Handling Electronics

Various infrared detectors have been used with the instrument, depending upon the application. These include lead sulfide, lead selenide and indium antimonide detectors, optimized for the particular wavelength and sensitivity requirement of the experiment.

The detector is followed by a preamplifier whose gain can be changed by ground command, further amplification, a phase-sensitive demodulator, signal integrator and, finally, an analog-digital converter. The analog signal processing can be described as an integrate-and-dump system; the chopped IR signal is amplified, phase-sensitively demodulated, and integrated for a fixed period of time which is one or a multiple of an integral number of chopper cycles as described earlier. After signal integration is completed, the integrator input is opened and the output digitized, then it is rezeroed to prepare for the next data point. The analog-digital converter is a 14-bit successive approximation type.

Data Handling and Processing

A pulse-code-modulation (PCM) data handling system incorporated into the instrument, formats the data into a serial stream which is either telemetered or tape-recorded on board the vehicle. It can be remotely commanded to start taking data and to change its mode of operation. The telemetered or recorded data is then decommutated and formatted into computer compatible digital tape, which is then processed by a Univac 1108 Fourier transform program. The computer generates another tape which then is played back off-line on a Cal-Comp digital plotter to produce a spectral plot which is then analyzed for the various constituents.

Summary

The "breadboard" version of this instrument has already been used to measure pollutants in several studies including airborne as well as ground-based measurements. One of these experiments was to measure the concentration of various pollutants on a Los Angeles Freeway, using a Globar infrared source.

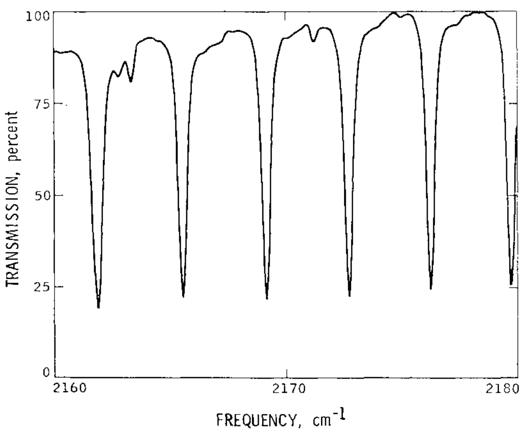

Fig. 2 Portion of 4.7-μ CO absorption band.

Figure 2 shows a portion of the 4.7-μ carbon monoxide absorption spectrum, made in this experiment. The airborne experiment was performed aboard a Goodyear blimp cruising above the Los Angeles area, using solar reflection and ground-emission to demonstrate the feasibility of doing experiments of this type from a space-platform, as well as demonstrating the capability of the instrument to operate in an aircraft type environment.

Plume Impingement Force during Tandem Stage Separation at High Altitudes

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Nomenclature

A = area
D = diameter of the lower stage
F = axial plume impingement force on lower stage
K = $\gamma_n(\gamma_n - 1)M_n^2$
M = Mach number
MM = momentum of the exhaust jet, $\gamma_n M_n^2 P_n A_n$
P, P_t = static, total pressure
r = radial distance from centerline
R = radius of the lower stage
T = thrust of the exhaust jet, $(1 + \gamma_n M_n^2) P_n A_n$
V = velocity
X = distance between nozzle exit and lower stage
ρ = gas density
θ = azimuthal angle, $\tan^{-1}(r/x)$
γ = ratio of specific heats

Subscripts

1, 2 = before and behind a bow shock wave, respectively
3 = on dome of the lower stage
n = nozzle exit
x = axial direction
* = sonic conditions

Introduction

STAGE separation is one of the critical operations during the flight of a multistage launch vehicle. The prediction of the separation trajectory must include the impingement force from the continuing stage propulsion system, and this force is especially large if the propulsion system fires in close proximity to the spent stage.

Pindzola and Hensel[1] have derived an empirical equation relating impingement force and separation distance of tandem-mounted vehicles. However, the correlation is limited to the particular model test conditions, and cannot be generally applied. The model data of Binion[2] show that reversed flow

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