NO. 190 A REAL-TIME COMPUTER FOR MONITORING A RAPID-SCANNING FOURIER SPECTROMETER *

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ABSTRACT

A real-time Fourier computer has been designed and tested as part of the Lunar and Planetary Laboratory's program of airborne infrared astronomy using Fourier spectroscopy. The value and versatility of this device are demonstrated with specific examples of laboratory and in-flight applications.

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1. Introduction

A real-time computer for Fourier-transform spectroscopy has been developed at the Lunar and Planetary Laboratory for use as a monitoring device with a rapid-scanning interferometer. Its first application was in NASA's program of spectroscopic observations of Mars from the CV-990 aircraft in August 1971. We found real-time monitoring invaluable for checking on the quality of the data and for analyzing the behavior of the complex systems constituting our Fourier spectrometer that are particularly sensitive to the hostile environment encountered aboard aircraft. This ability to evaluate objectively our experiment while still in a position to modify its goals allowed us to record data superior to those previously acquired in airborne observations of Mars.

2. Computer Organization

The basic computer (Connes and Michel 1971) is of the type developed and used at Laboratoire Aimé Cotton (LAC), CNRS, Paris, France, with very-high-resolution stepping interferometers (Connes 1971). Its versatility and performance have been increased to handle interferograms generated by the commercially-produced, rapid-scanning interferometers used in LPL's programs. We will briefly recall its principles of operation and present the new features introduced in the LPL computer.

This special-purpose digital computer (Figs. 1 and 2) is hard-wired to perform a discrete Fourier transform. Each interferogram sample (10 bit + sign mantissa, 4 bit exponent) is multiplied by a sine function provided through an address generator and a read-only memory (ROM, 1024 10 bit words) in which is stored a quadrant of a sine table. The result of the multiplication is then scaled according to the exponent and fed into an adder connected to a circulating memory (1024 23 bit + sign words) storing the output spectrum points. The spectrum is displayed on an oscilloscope through a digital-to-analog converter.

The operation sequence is timed by a program generator. The number of modes or programs available for the transform calculation has been extended to three: sine transform, cosine transform, and both sine and cosine transforms with power spectrum display. This latter mode is especially useful with fast-scanning interferometers where the zero-path point cannot be predetermined, thereby precluding a simple sine or cosine transform. After selecting the transform mode, the operator dials the other initial settings: resolution in the spectrum, first point of the spectral window to be displayed.

To maximize the speed we used the same techniques developed at LAC for the first real-time computer, i.e., parallel computations and simultaneous operations; but thanks to a new technique of multiplication, this speed has been increased by a factor of two. The computation time expressed in terms of spectrum point per interferogram point is now 500 nsec. If we sample the interferogram at 1 KHz, the computer is able to produce 2048 spectrum points in the SIN or COS modes, and 1024 points in the SIN-COS mode. Technologically, the LPL computer is quite different from the original LAC model. Built two years apart, we have benefited from the fast-growing field of integrated circuits. The LPL computer is an all TTL-MSI device in place of ECL and TTL. The use of a single IC family greatly simplified the design. We introduced as an array multiplier a very interesting

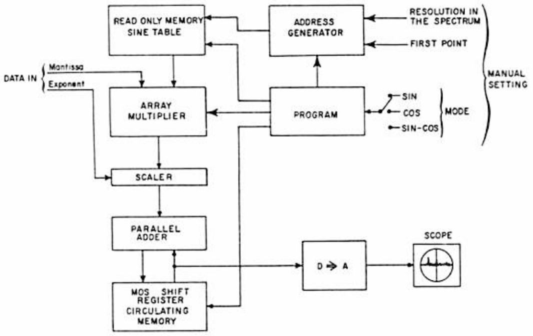

Figure 1 Block diagram of real-time computer

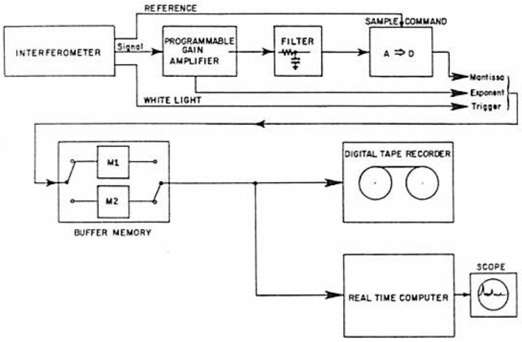

Figure 3 Connection of computer to Fourier spectrometer. This is a classical digitizing and recording system for Fourier spectroscopy. The sampling rate is always affected by flutter due to vibrations or residual solid friction in the moving mirror's slide. A buffer memory is added to drive the digital tape recorder at a constant data rate. The buffer memory includes two sections of 100 words each. When one section is accepting interferogram samples as input, the other is reading out at a clock rate determined by the tape recorder

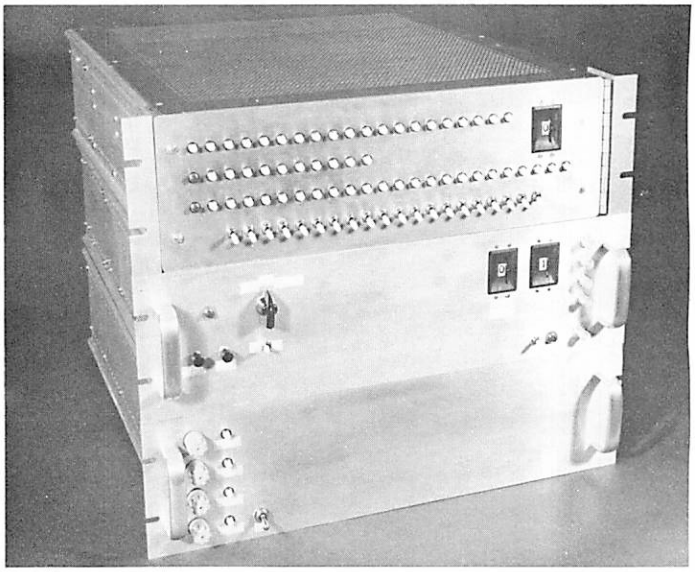

Figure 2 Complete computer system. Top chassis is the arithmetic unit and read-only memory. Middle chassis houses the output spectrum memory and function generators. Power supplies are contained in the bottom unit

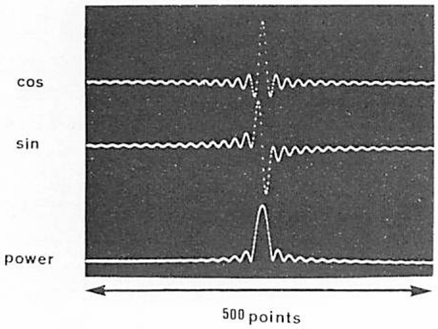

Figure 4 Transform of built-in test function showing the three modes of calculation available with the real-time computer

circuit for applications where speed is at a premium (Habibi and Wintz 1970; Kingsbury 1971). In this type of multiplier the multiplication time of two N-bit words is proportional to N instead of to N^2 with the classical technique of partial products and shifts. The price paid for the increase in speed is that the number of components is proportional to N^2. The actual multiplication time of two 10 bit + sign words is less than 200 nsec. The circulating memory was built with MOS dynamic-shift registers instead of magnetostrictive delay lines. Present memory size is 1024 words with provision for extension to 8192 words. An analog apodizing interpolator using the technique of tapped delay-line filters has been built but not yet incorporated into the system.

3. Real-time Computer Mode of Operation

Figure 3 shows the connection of the computer to an experiment including the rapid-scanning interferometer, a programmable gain amplifier to handle the dynamic range of the interferogram, an analog-to-digital converter and a buffer memory necessary to drive the digital tape recorder with a constant data rate. The computer is merely connected in parallel with the recorder input and computes at full resolution a slice of the spectral range covered by the spectrometer during each scan. The computer adds coherently the successive SINE and COSINE transforms. With faint sources we can see the improvement of the S/N in the spectrum versus the number of scans. With strong sources, where a single scan is sufficient, we get from the very start an estimate of the S/N and watch the improvement in resolution.

In our rapid-scanning interferometer no provision exists to locate the zero-path point. This is not a difficulty when the interferogram is transformed later with a general-purpose computer. One usually starts the interferogram far enough before the zero-path point to include the main lobes of the interferogram. Phase correction followed by a cosine transform is one of several possible treatments that can then be used with a large, general-purpose computer. With a real-time computer this is not practical, so we have to perform a power transform where the phasing of the sampled points with respect to zero path need not be explicitly known. A power transform theoretically requires recording the interferogram over the interval (-L, +L) with the disadvantage of having to double the path difference L and the number of points to be transformed for a given resolution. To avoid these complications, we checked by simulation on a general-purpose computer that we do get a correct power transform without noticeable phase distortion if we start the interferogram a few hundreds of samples before zero path. To do so, the white-light interferogram is optically phase-shifted and its main lobe is level-detected to produce a flag pulse used to trigger the computation sequence. The computer performs the sine and cosine transforms, and displays the POWER transform by taking the square root of the sum of the squares of both transforms with fast analog circuits.

4. Preliminary Results

The following examples illustrate ways in which we have employed the computer in preparing and executing our airborne experiments. To check on its own internal functioning the computer has a built-in test generator producing the following sequence of samples: 0, +1, -1, 0, etc., which is merely the sampling of a sine wave. The transform of this function represents the theoretical instrument function for the resolution selected. Figure 4 shows the transforms of this test function in the three modes of computation.

Several experiments were conducted in the laboratory to evaluate the performance of our interferometer in the absence of vibrations. Real-time analysis eliminated the need to send interferograms to a large, general-purpose computer with consequent delays in reviewing the spectra. Figure 5 shows an absorption band of CO used to verify the resolution achieved by the interferometer. In this spectrum 10 scans,each of several seconds duration,were coadded.

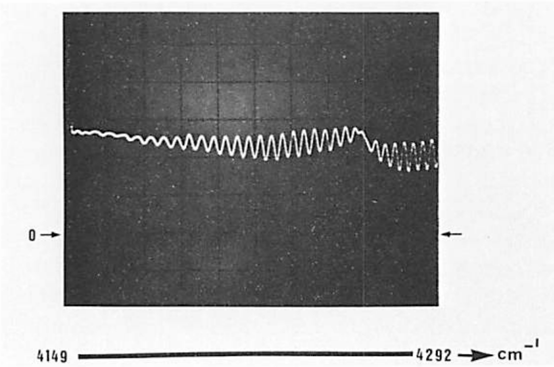

Figure 5 Laboratory test of spectrometer using CO band at 2.35 microns. Ten power spectra were coadded with resolution limit of 4.0 cm^{-1}

During the flights on the NASA CV-990 the computer was used in several ways to provide important documentation on *the performance of our interferometer in the presence of vibrations*. The first application concerned the problem of vibration isolation of the interferometer. We designed at LPL shock mounts to attenuate those vibration frequencies known to be severe on the aircraft. The computer provided a check on their effectiveness by serving as a real-time audio-frequency analyzer (Bially 1970). The signal from an accelerometer located above and below the shock mounts on our experiment was transformed, providing a real-time display of the aircraft vibration spectrum and the residual vibrations seen by the interferometer. Figure 6 shows such vibration spectra verifying the general attenuation of all aircraft frequencies and the absence of any resonant vibration in the interferometer's mount.

The sensitivity of the moving mirror to residual vibrations cast doubt on the ability of the interferometer to perform efficiently at maximum resolution aboard the aircraft. Again, the advantages of real-time analysis permitted us to study this problem in flight with subsequent modifications to the experiment that resulted in most effective use of our quite-limited and very-expensive observing time. By examining the reproducibility of high-resolution features of single scans of the Sun recorded in flight, we were able to select a resolution that guaranteed the best return from our Mars observations. Figure 7 shows a resolved CO_2 band at near maximum resolution (0.67 cm^{-1}), from a single scan of the Sun used for this purpose.

Finally, the computer was used in the actual observing runs providing a continual check on the acquisition of good data. Figure 8 contains portions of the spectrum of Mars seen by the real-time computer showing strong CO_2 bands in the

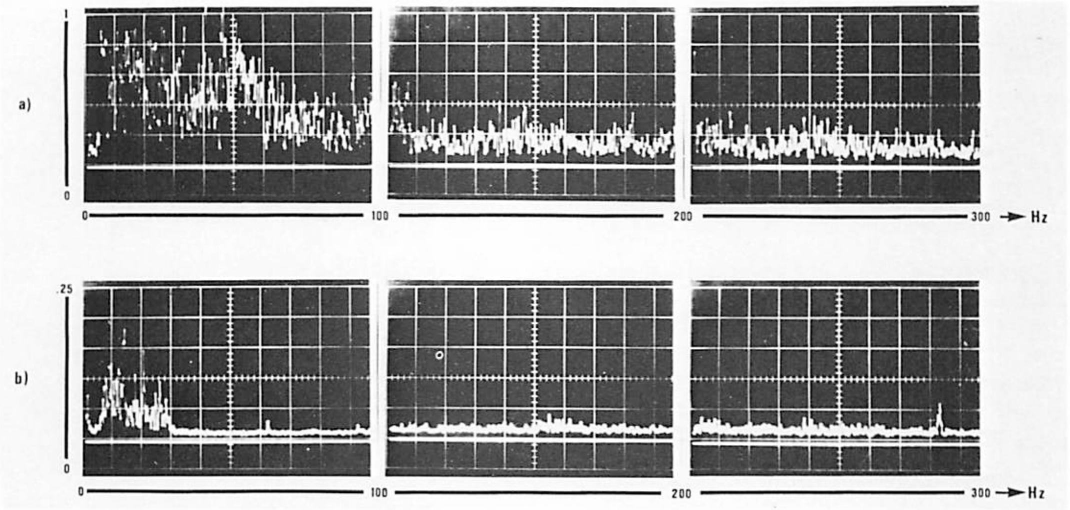

Figure 6 Aircraft vibration spectra produced by computer. The series of spectra in (*a*) and (*b*) were produced from an accelerometer located, respectively, before and after the shock mounts used to isolate the interferometer from the aircraft. The accelerometer axis was parallel to the main axis of the aircraft and to the translation axis of the moving mirror of the interferometer. Acceleration is in arbitrary units; note the change between series (*a*) and (*b*)

2 micron region. After coadding just 10 scans, each of 9 seconds duration, the continuum level has been established although only a suggestion of the CO_2 absorptions exists. After 600 scans the S/N has increased, as expected, and the CO_2 triad at 2 microns is now quite evident. In addition, the H_2O band at 1.9 microns has emerged from the noise. By watching the real-time development of the Mars spectrum during our first flight, we were able to predict with accuracy the averaged result of all four scheduled flights. We decided that following the flight schedule as planned would lead to useful spectra, a conclusion later verified by complete data reduction at LPL.

5. Conclusions

The effectiveness of the real-time analysis offered by this small, special-purpose computer has been demonstrated through actual use in an airborne spectroscopy program. The experience acquired in these first experiments will result in improvements to both the computer and the interferometer, creating an even more effective combination. In addition, this computer will be attached to another spectrometer, the first high-resolution stepping interferometer built by Dr. Pierre Connes (Connes and Connes 1966) and now in use by LPL staff at the Steward Observatory 90-inch telescope on Kitt Peak. The availability and versatility of this computer effectively eliminates a frequently-voiced criticism of Fourier spectroscopy, the inability to see the spectra until some time, often days, after recording the interferograms.

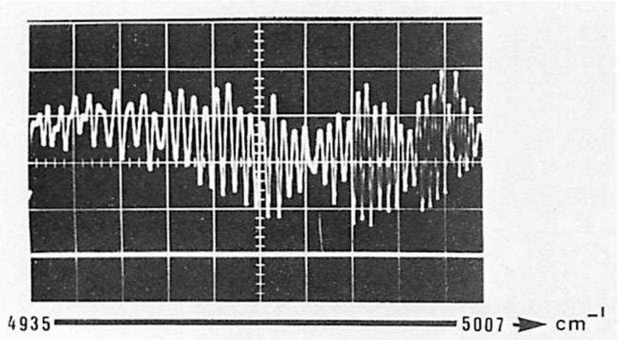

Figure 7 High-resolution test of spectrometer in flight. Single scan (24.5 sec) of the Sun showing CO_2 band at 2 microns with a resolution limit of 0.67 cm-1

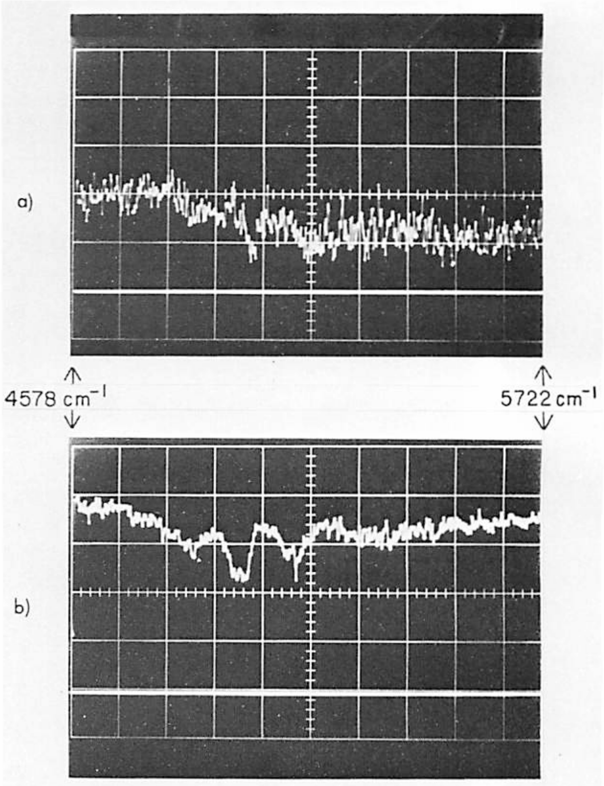

Figure 8 (right) Real-time monitoring of spectrum of Mars. The window selected includes the strong CO_2 absorptions at 2 microns and the water-vapor band at 1.9 microns. Upper trace is coadded result of just 10 scans (80 secs of observing). Lower trace includes 600 scans and exhibits the expected improvement in S/N

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