A Synthetic Quadrature Phase Detector/Demodulator for Fourier Transform Spectrometers

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Abstract

A method is developed to demodulate (velocity correct) Fourier transform spectrometer (FTS) data that is taken with an analog to digital converter that digitizes equally spaced in time. This method makes it possible to use simple low cost, high resolution audio digitizers to record high quality data without the need for an event timer or quadrature laser hardware, and makes it possible to use a metrology laser of any wavelength. The reduced parts count and simplicity implementation makes it an attractive alternative in space based applications when compared to previous methods such as the Brault algorithm.

Introduction

Back in the 1999-2000 timeframe Nikita Pougatchev and the author [1] implemented the Brault algorithm [2] and data acquisition hardware that was designed by NIST and built by NASA Langley Research Center. A description of this data acquisition hardware can be found elsewhere [3]. This method originated in the early 1990s when Brault, motivated by the need to improve the performance of a balloon borne instrument, with a lack of funds, eventually developed what would later be known as the Brault algorithm [4]. Although he states in his paper he developed this to make near IR measurements [2], it is especially beneficial to UV spectroscopy [3]. In a continuous scan Michelson spectrometer, one method is to use a reference metrology source such as a laser to trigger the data acquisition hardware. Because one must sample at Nyquist, this reference laser must be at least twice the wavenumber of the spectral signal being sampled and also be stable in frequency. This presents a technical challenge in the case of UV spectroscopy because of the very short wavelengths required of the metrology source. One possible solution is to forego the reference laser altogether in the data acquisition system and control the slide to a high precision and sample the data evenly in time. If the velocity variations are very small, data sampled linearly in time will also be sampled linearly in space. The problem with this is it is also technically challenging and expensive to build a control system with the required precision. Brault's solution to this was very clever in that he found a method to use a sloppy control system by taking data sampled evenly in time, deriving what the velocity variations were using laser timing information, then using that and a deconvolution digital filter to help eliminate ghosts and interpolate the data so it is evenly sampled in space. The laser used in this situation could be of almost any wavelength, with the only requirement being that fringe times had to be sufficiently fine to Nyquist sample velocity variations. This made low cost UV spectroscopy a reality and lowered the cost of FT spectrometers in general by replacing elaborate hardware with a simple algorithm.

We felt that there were sufficient advantages to using the NIST/Brault hardware in the IR domain as well because one could take advantage of the then new low cost 24 bit audio digitizers that were then coming onto the market. In a lab environment this option is very attractive because of the wide dynamic range they offer, though such digitizers are not as yet space qualified. These digitizers required being triggered by a high precision clock so the Brault method was the only option at the time to take advantage of them. We also felt one had better control over data acquisition timing because one could precisely tune the data acquisition timing in software, which can result in more accuracy by tuning out delays from slow detectors, and special deconvolution filters could be applied to eliminates ghosts caused by imprecise control of the FTS slide in combination with amplifiers and detectors that are sensitive to fringe frequency variations. Indeed, this method has been shown to be generally superior in the reduction of such artifacts [6] for FTS spectroscopy in general. The main thrust behind this choice was to investigate this data acquisition system as a test bed for potential space applications since elaborate control systems are not easy to implement in space applications. Other types of FT spectrometers exist as well such as the step scan variety originally perfected in the group of Pierre Connes at the Laboratoire Aimé Cotton in Orsay, France. This is also one of the more popular FT spectrometer types known to produce high quality scans. One current project employing that technique at LaRC is the GIFTS satellite project [5].

In the NIST/Brault implementation, timing derived from zero crossings of a metrology laser is used to store timing information to be used for velocity correction. This was accomplished by using an event timer that was built into the NIST design. A quadrature signal from the laser was required for the event timer so hardware to generate this signal was required as well. Fringe timing information was stored in the form of a list of integers that represented the number 40 MHz time ticks from one zero crossing to the next. In another file is a list of digitized numbers representing the spectral data. That data was digitized with a Crystal CS5396 24 bit data acquisition board that was part of the NIST hardware. The two files are not in sync so one must do a calibration to discover the time delay. Once that is done one may use the laser timing data to interpolate/resample that spectral data evenly in space that was originally captured evenly in time. The author wrote a set of routines to do this that were somewhat different from what Brault had originally conceived. For instance, Brault implemented a third order interpolation routine in combination with a digital filter whereas we were using 5th order interpolation. Otherwise the implementation was very similar.

As time went on we started having problems with the data acquisition hardware, presumably due to a faulty part. It was very temperature sensitive. When it became too hot, the event timer failed and the laser timing data wouldn't record correctly. Since the data acquisition hardware had two channels, the author began recording the analog laser data along with the spectral channel, with the hope of being able to derive zero crossings if the event timer failed. When using interpolation between points, this worked very well. The author later discovered a different method based on frequency demodulation. This new method could derive the position at the time the spectral data points were recorded. Even better, an event timer was not required, nor was a quadrature laser signal. Although this concept was proven more than 8 years ago, it was never published until now. It has since been perfected over the years and used in many applications that go beyond the scope of this paper. It was thought that because it required less

than even the Brault method in terms of specialized hardware, it might have potential applications in space-based instrumentation.

The instrument

The spectrometer used was a Michelson type with 8x folding and was similar in concept to the Genzel interferometer [7] and at LaRC it is typically referred to as "The Web". By 8x folding we mean for every 1 cm of slide movement we have 8 cm of optical path length difference (OPD). This instrument was being investigated as a potential replacement for the Shuttle based Atmospheric Trace Molecule Spectroscopy (ATMOS) instrument and, because of its unique design, it resulted in an order of magnitude reduction in size and weight, which made it very attractive for use in space [8]. The control system was designed by the author and was based on a National LM628 PID motion controller chip that used an Intel 8751 microcontroller as a command interpreter. We have since developed a radiation hardened FPGA based motion controller for potential use in space. The drive system consisted of a simple voice coil and the optical layout of this instrument is shown in Figure 1.
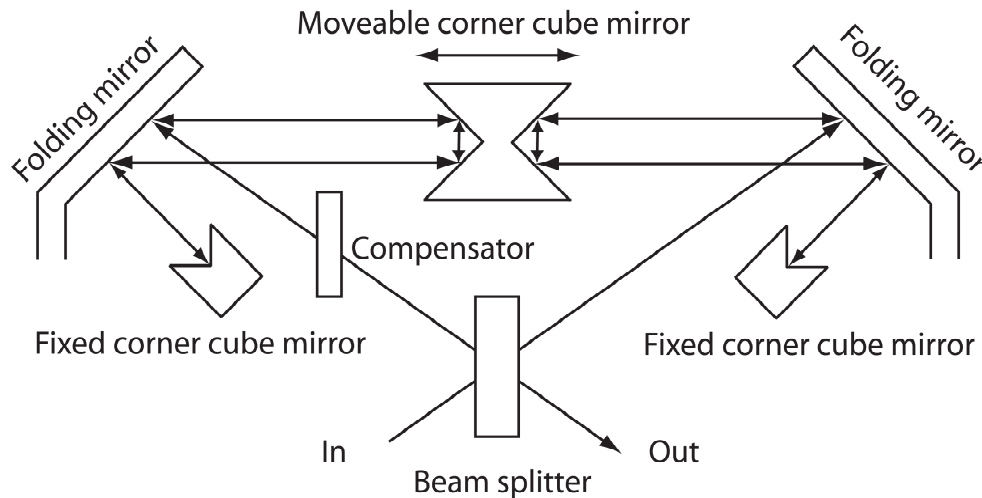

Figure 1. Optical layout of "The Web". This instrument has 8x folding and is similar in concept to the Genzel interferometer.

A Synthetic Quadrature Phase Detector

A phase detector is a device that multiplies/mixes a reference signal and generates a signal that is proportional to the phase difference between the signals. It is essentially an FM demodulator. However, it does have its limitations and one of those is that one is limited to a phase difference of ±90°. This is useful to decode small changes but is very limiting for our application. An alternative is to mix the signal with two references, with the second reference being 90° with the first. This is a quadrature phase detector. As we shall see this allows us to detect a phase difference of ±180°, which covers a full 360°. Similar ideas have been published in the past as a means of doing metrology. For instance, Fischer et al [9] describes a technique for using quadrature demodulation to measure distances using a phase locked loop. Although this

is a different type of implementation, the basic idea is the same. Other examples of FM demodulation in optics can also be found [10,11].

Using quadrature demodulation in combination with phase tracking we can extend phase difference measurements to any phase difference. Figure 2 illustrates how this is done.
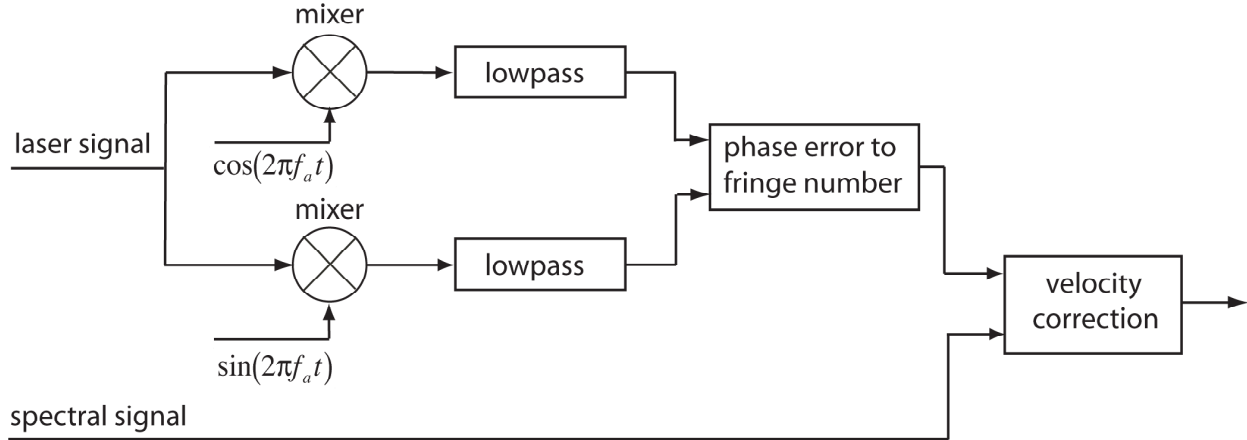

Figure 2. Synthetic quadrature phase detector uses synthetic reference derived from the average laser fringe frequency to demodulate the laser fringe signal and velocity correct the spectral signal by resampling the spectral signal evenly in space.

To see how this works we represent the laser signal in the time domain as,

$$S(t) = A(t)\sin\big(2\pi f(t)t + \phi\big). \tag{1}$$

where $A(t)$ is the amplitude which is assumed to be a slowly changing function. Any misalignment or vibration will cause the amplitude to change with time. The term $f(t)$ is the laser fringe frequency and is also a slowly changing function. Any variations in scan velocity will cause the laser fringe frequency to change with time. In order to demodulate this signal we need a reference. A convenient reference is a sine wave with a frequency equal to the average frequency of the laser fringe signal. This reference is created in software. The standard technique is to combine these two in a mixer and low pass filter the result. The result of this would be the sine of the phase error. In our case we also have amplitude modulation so something more is needed. Lets suppose we use two references. The first is $\sin(2\pi f_a t)$ and the second is $\cos(2\pi f_a t)$. The frequency lock, f_a, is determined by doing a weighted average about the maximum in Figure 5. The result of mixing is,

$$S_1(t) = A(t)\sin\big(2\pi f(t)t + \phi\big)\sin(2\pi f_a t),$$
$$S_2(t) = A(t)\sin\big(2\pi f(t)t + \phi\big)\cos(2\pi f_a t). \tag{2}$$

Using standard trigonometric identities we have,

$$S_1(t) = \frac{A(t)}{2}\cos\left(2\pi\left(f(t)-f_a\right)t+\phi\right) - \frac{A(t)}{2}\cos\left(2\pi\left(f(t)+f_a\right)t+\phi\right),$$

$$S_2(t) = \frac{A(t)}{2}\cos\left(2\pi\left(f(t)-f_a\right)t+\phi\right) - \frac{A(t)}{2}\cos\left(2\pi\left(f(t)+f_a\right)t+\phi\right). \tag{3}$$

Here we see each signal is comprised of an upper sideband and a lower sideband. The upper sideband may be filtered out using Fourier transform filters with the result,

$$S_1' = \frac{A(t)}{2}\cos\left(2\pi\left(f(t)-f_a\right)t+\phi\right)$$

$$S_2' = \frac{A(t)}{2}\sin\left(2\pi\left(f(t)-f_a\right)t+\phi\right) \tag{4}$$

By dividing the second equation by the first we have,

$$\tan\left(2\pi\left(f(t)-f_a\right)t+\phi\right) = \frac{S_2'}{S_1'} \tag{5}$$

This is completely independent of the amplitude so we have actually removed any (slow changing) amplitude modulation. The above equations uniquely determine the phase to within $-\pi$ to π. If the phase error is larger than π or less than $-\pi$ it is necessary to do phase tracking.

The distance in terms of fringes is

$$d_n = f_a t_n + \frac{1}{2\pi}\arctan\left(\frac{S_2'(t_n)}{S_1'(t_n)}\right) - \frac{\phi}{2\pi} \pm j \tag{6}$$

Due to the nature of the arctan function there will be sudden jumps of 2π. This problem can be solved using phase tracking. That is, we look for sudden changes in the phase from one point to the next and add or subtract one. The choice of addition or subtraction depends on which gives the smallest change. The correct choice produces the smoothest curve. We have then

$$d_{n+1} - d_n = f_a \Delta t + \frac{1}{2\pi}\arctan\left(\frac{S_2'(t_{n+1})}{S_1'(t_{n+1})}\right) - \frac{1}{2\pi}\arctan\left(\frac{S_2'(t_n)}{S_1'(t_n)}\right) \pm k \tag{7}$$

In this case k is either, 0, 1, or -1 – depending on whether or not there is a jump and in what direction. By evaluating this expression at the sample times we may form a table of amplitude as a function of distance in fringes. Since we know distance as a function of time and we have the laser and spectral signals as a function of time, we also know both the laser and spectral signals as a function of distance. By interpolating and resampling evenly in distance we effectively velocity correct the signal. One may also offset the interpolation by a small delta in time in order to "tune" in delays from slow detectors, and apply digital deconvolution filters to eliminate

ghosts [2,6], etc in order to obtain better accuracy just as with the Brault processing should that be desired.

Conversely, the amplitude modulation may be found by,

$$S_1'^2 + S_2'^2 = \frac{1}{4} A^2(t) \qquad (8)$$

This could possibly be used to take out amplitude variations in the interferogram or be used for optical alignment analysis, etc.

Example

As an example, we take data from a simple interferometer using a black body source and a CO cell. The data was taken quite some time ago in another experiment and is useful as an example because the laser signal was also digitized. This means we may use demodulation techniques on the laser channel to decode the IR channel. The interferometer used is an in-house built unit based on an 8x folding Web design that has been previously discussed. The data acquisition was also in-house built and based on a NIST design as described earlier. The data acquisition hardware was originally designed for collecting two analog channels and a third channel for measuring laser fringe times in connection with the Brault technique. It has a data acquisition rate of 78.125 KHz and the laser used was an HeNe with a wavenumber of 15798 cm^{-1}. The scan speed was approximately 1.905 mm/sec, giving a laser fringe frequency of about 22 KHz at the detector. The scan distance was approximately 1.3 cm, giving a spectral resolution [12] of approximately 0.6/(8*1.3 cm) = .058 cm^{-1}, though spectral resolutions as high as 0.02 cm^{-1} are technically possible with this system [8]. We first decode the laser fringe signal by using the average fringe frequency as a frequency lock. Deviations from the phase of the lock determine the phase error and the distance can be found by adding the average frequency times the time to that. Both of those are shown in Figure 3. By differentiating the distance one may derive the number of fringles/sample, which is proportional to the velocity and is shown in Figure 4. To obtain the fringe rate we multiply by the sample rate and the true velocity may be obtained by multiplying by the sample rate, then dividing by the fringe density.

Figures 5 and 6 show how we may take advantage of this method to velocity correct any input signal regardless of the wavelength. Since we may resample at any reference even the metrology laser may be velocity corrected to give a single spectral line. The only restriction is the data acquisition unit must sample the signals at Nyquist or above.
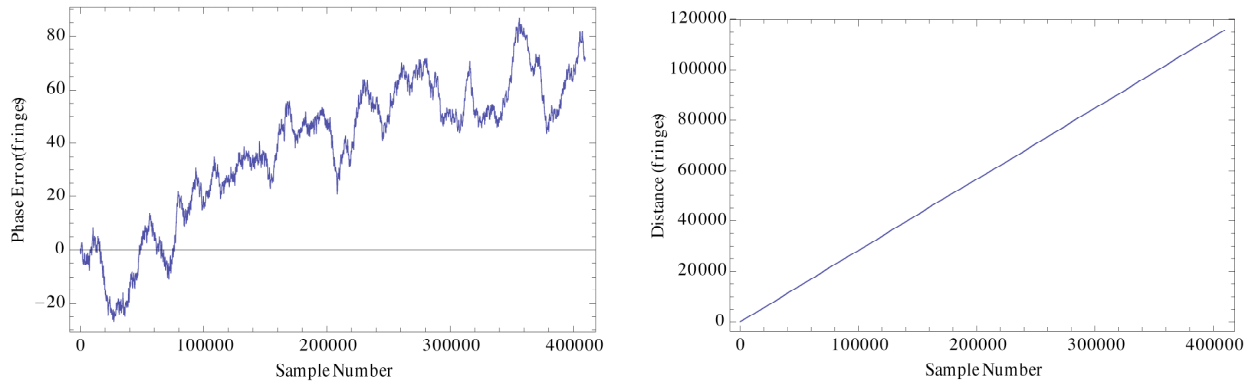
Figure 3. Derived phase error and displacement as a function of sample number. The phase error in the first graph is the deviation from the phase derived from the average frequency - $(f(t)-f_a)t$. The second graph is the phase error plus $f_a t$.
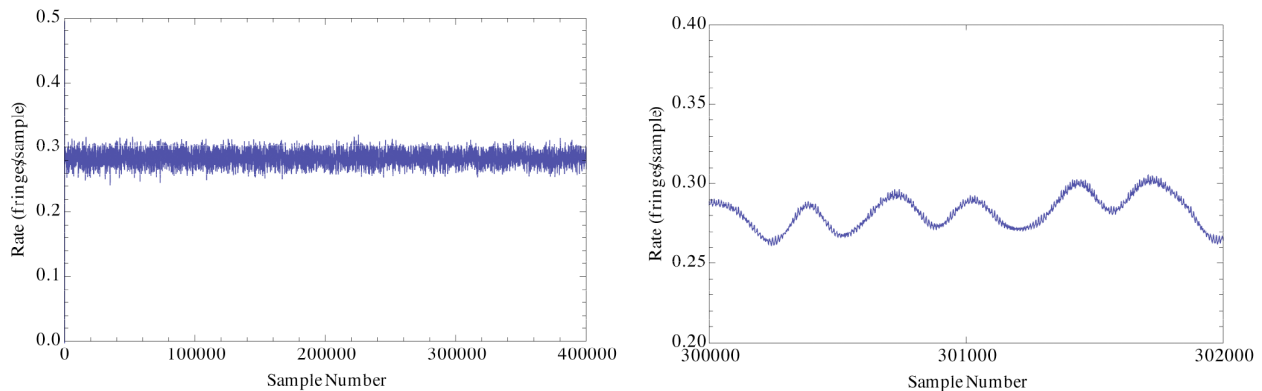

Figure 4. Derived fringe/sample rate obtained from differencing the displacement with respect to sample number. This is directly proportional to the velocity. The left graph shows the profile over the entire scan and the right graph shows the fine detail.
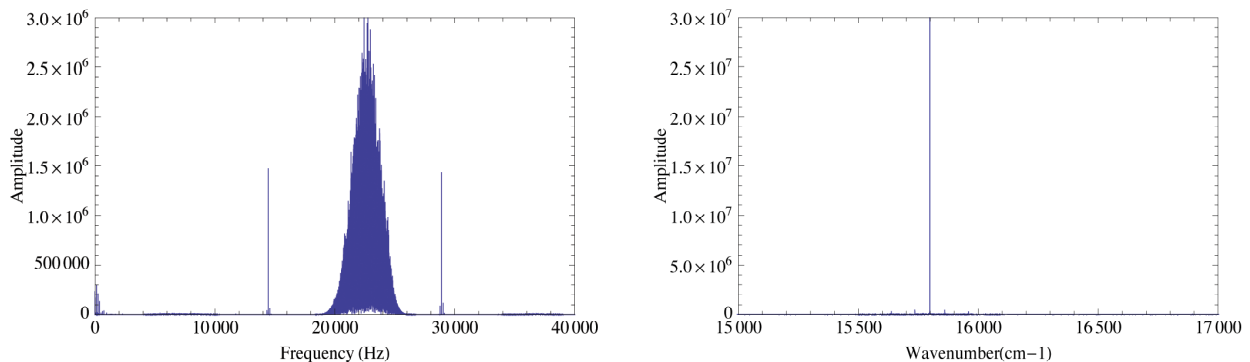

Figure 5. Fourier transform of laser interferogram before and after processing. Since we can resample at any rate we can even velocity correct the reference metrology laser. The above correction was done by resampling at 3 times per fringe, which is the approximate original data acquisition rate. Since the data is captured evenly spaced in time and corrected evenly space in distance, the units along the x axis must be different.
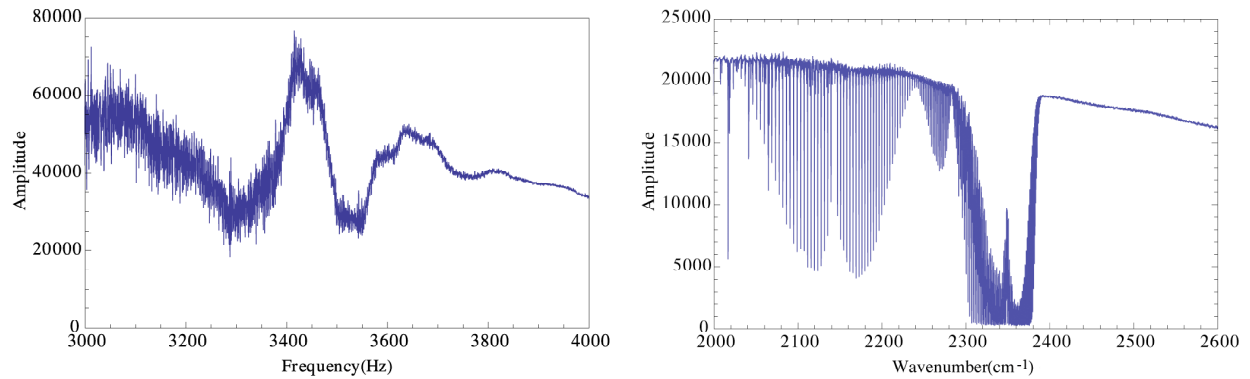
Figure 6. Fourier transform of spectral interferogram before and after processing. Before correction the absorption spectra is barely visible. After correction one can clearly see the characteristic CO absorption lines. Since the data is captured evenly spaced in time and corrected evenly space in distance the, units along the x axis must be different.

Discussion:

We have demonstrated an application of a FM demodulation technique using a synthetic reference to velocity correct FTS spectrometers that is unique and has the potential of being used to build a lower cost FTS spectrometer than that envisioned by Brault because we have eliminated the need for specialized hardware such as an event timer and hardware required to generate a quadrature laser signal. All one needs is a slide, a cheap drive system, optics and a low-cost data acquisition system such as a 24 bit audio digitizer. Thus, the ultimate low cost FTS spectrometer is realizable. This also makes it attractive for use in space because the parts count is less, which decreases hardware complexity and therefore increases reliability. Although the processing required using this method is greater than that required by the Brault method, this is not an issue because it is not necessary to do this in real time, though one could if one wished using today's high speed processors.

References

1. N.S. Pougatchev, J.F. Campbell, C.R. Regan, M.C. Abrams, J.W. Brault, C.B. Farmer, D.E. Hinton, Advanced technologies high resolution Fourier transform spectrometer for atmospheric studies, 237-243 Vol. 3, Aerospace Conference Proceedings, 2000 IEEE

2. James W. Brault, New approach to high-precision Fourier transform spectrometer design, Applied Optics, Vol. 35, No. 16, June, 1996

3. Ulf Griesmann, Rainer Kling, John H. Burnett, and Lukasz Bratasz, The NIST FT700 Vacuum Ultraviolet Fourier Transform Spectrometer: Applications in Ultraviolet Spectrometry and Radiometry. Proc. SPIE, Vol. 3818, 180 1999.

4. Sumner P. Davis, Mark C. Abrams, and James W. Brault, Fourier Transform Spectrometry, Academic Press; 1st edition, 2001, p 181

5. John J. Murray, The GIFTS satellite project - enabling the NAS of the future with high resolution soundings and imagery, 41st Aerospace Sciences Meeting and Exhibit, AIAA 2003-385, January 2003

6. Luca Palchetti and Davide Lastrucci, Spectral noise due to sampling errors in Fourier-transform spectroscopy, Applied Optics, Vol. 40, No. 19 , July 2001

7. L. Genzel and J. Kuhl , Tilt-compensated Michelson interferometer for Fourier transform spectroscopy, Applied Optics , Vol. 17, No. 20 , October, 1978

8. Dwayne E. Hinton, Ira G. Nolt, Jae H. Park, William L. Smith, and Mark C. Abrams, Applications of Advanced Technologies to Spacebased Fourier Transform Spectrometers for Atmospheric Remote Sensing, 499-504 Vol. 2, Aerospace Conference Proceedings, 1998 IEEE

9. Edgar Fischer, Ernst Dalhoff, Silke Heim, Ulrich Hofbauer, and Hans J. Tiziani, Absolute interferometric distance measurement using a FM-demodulation technique, Applied Optics, Vol. 35, No. 25, September 1995.

10. Yogesh C. Agrawal, Quadrature demodulation in laser Doppler velocimetry , Applied Optics, Vol. 23, No. 11, June 1984

11. Munther A. Gdeisat, David R. Burton, and Michael J. Lalor, Fringe pattern demodulation with a two-dimensional digital phase-locked loop algorithm, Applied Optics, Vol. 41, No. 26, Septmber, 2002

12. Reinhard Beer, Remote Sensing by Fourier Transform Spectroscopy, John Wiley & Sons, 1992, p 20.