

THE GEORGIA TECH HIGH SENSITIVITY MICROWAVE MEASUREMENT SYSTEM

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Abstract. As observations and models of the planets become increasingly more accurate and sophisticated, the need for highly accurate laboratory measurements of the microwave properties of the component gases present in their atmospheres become ever more critical. This paper describes the system that has been developed at Georgia Tech to make these measurements at wavelengths ranging from 13.3 cm to 1.38 cm with a sensitivity of 0.05 dB/km at the longest wavelength and 0.6 dB/km at the shortest wavelength.

1. Introduction

One of the greatest hindrances in modeling and fitting synthetic spectra of the planets is the lack of realistic models of the absorption profiles of the atmospheric components under planetary conditions (see e.g., de Pater and Mitchell, 1994). A program has been underway at the Georgia Institute of Technology to measure the absorptive and refractive properties of these components as a function of temperature, pressure, composition and frequency under conditions similar to those on Venus (Steffes, 1985; Fahd and Steffes, 1991; Fahd and Steffes, 1992) and the outer planets (Steffes and Jenkins, 1987; Jenkins and Steffes, 1988; Joiner *et al.*, 1989; DeBoer and Steffes, 1994). As the thermochemical and radiative transfer models of the planets become more sensitive and sophisticated the need for increasingly accurate measurements is apparent. This paper reviews the process of determining the refractive index and absorption coefficients of low-loss gases and describes the high sensitivity microwave measurement system used at Georgia Tech to measure these values, including a full discussion of the new computer interface and analysis system which greatly enhances the sensitivity and reliability of the results.

2. System Overview

2.1. DATA ANALYSIS

The Georgia Tech system (see Figure 1) uses the changes in the quality factor (Q) and center frequency of a resonator with a test gas present to measure absorptivity and refractivity. These changes are monitored using a swept signal source and a

spectrum analyzer whose output is read into a personal computer for display and analysis. The refractivity of the test gas is measured by noting the change in the center frequency of the resonance with the test gas present relative to the center frequency in the presence of a vacuum. The refractivity of the gas (defined as $N_R = 10^6(n - 1)$, where n is the refractive index of the gas) is given by

$$N_R = 10^6 \frac{f_v - f_g}{f_g} \quad (1)$$

where f_v and f_g are the center frequencies of the resonance with a vacuum and test gas present, respectively (see e.g., Tyler and Howard, 1969).

To determine the absorptivity of the test gas, the quality factor (Q) of the resonance is then measured a number of times with the test gas present to develop statistics of the measurement. The expression for the quality factor is given by

$$Q = \frac{f_g}{\Delta f} \quad (2)$$

where, again, f_g is the center frequency and Δf is the full-width half maximum power (FWHM) bandwidth of the resonance. The test gas is then vented and a reference, lossless gas is added such that the change in center frequency from a vacuum is the same for this reference gas as it was for the test gas. This is to compensate for the effects of dielectric loading; that is, when Equation 3 (to be introduced shortly) is not strictly valid due to changes in the real part of the refractive index (see e.g., DeBoer and Steffes, 1994 for a brief mathematical explanation and Spilker (1990) for a physical discussion of dielectric loading). The quality factor of the resonance is then measured with the reference gas and the absorptivity of the test gas is computed via

$$\alpha = 4.343 \frac{2\pi}{\lambda} \left(\frac{1 - \sqrt{t_g}}{Q_g} - \frac{1 - \sqrt{t_r}}{Q_r} \right) \text{ dB/m} \quad (3)$$

where λ is the wavelength in meters at the center of the resonance with the test gas present and Q and t refer to the measured quality factor and transmissivity (the portion of the power that is transmitted through the resonator at the resonance center) of the resonator with the test gas (subscript g) and reference gas (subscript r) present.

Errors in this calculation are due to the finite sensitivity and accuracy of the spectrum analyzer (which are minimized by proper selections of the spectrum analyzer parameters such as resolution bandwidth and analyzer span) and by electrical, stochastic noise (which is minimized by maximizing the signal-to-noise ratio and by taking and collecting many samples). For a more complete discussion of the techniques for data analysis, as well as a complete description of the measurement error and error determination, see DeBoer and Steffes (1994).

Errors in measuring the properties of the environment in which the absorptivity measurements took place (e.g., temperature, pressure . . .) do not affect the application or analysis of the above equation, i.e., the measured absorptivity is the value

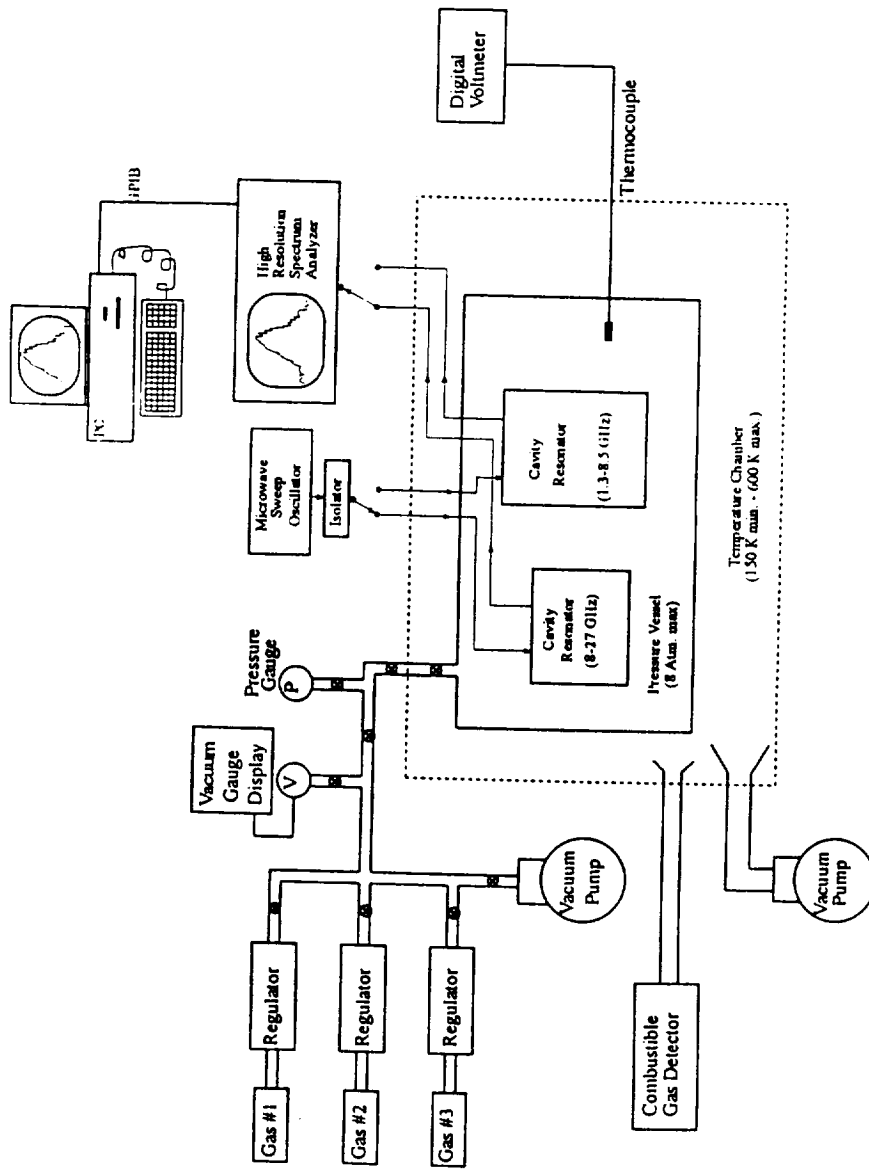


Figure 1. Block diagram of the Georgia Tech planetary atmospheric simulator and microwave measurement and data collection/analysis sub-systems.

for *that* environment. The environmental measurement errors manifest themselves when the measured absorption is fit to some sort of formalism to mathematically model the absorption.

Absorption is typically calculated by summing over the contributions from that molecule's set of absorption lines, unless the frequency of interest lies in the so-called continuum and a power law formalism can be fit. For a set of absorption lines, the absorption may be calculated via

$$\alpha = \sum_i n(P, T) S_i(T) F_i(\nu, \nu_i, P, T, \dots) \quad (4)$$

where $n(P, T)$ is the number density of the absorber, $S_i(T)$ is the line intensity, and $F_i(\nu, \nu_i, P, T, \dots)$ is the lineshape function as a function of frequency, line center, pressure, temperature, etc. See, for example, Townes and Schawlow (1955). Obviously, the temperature and pressure of the sample must be known to apply this equation. To first order (and assuming an ideal gas), variation in one term of this sum can be written

$$\begin{aligned} \delta\alpha = & \chi J(T) P \frac{\partial F}{\partial \nu} \delta\nu + \chi J(T) \left[F + P \frac{\partial F}{\partial P} \right] \delta P \\ & + \chi J(T) P \left[\frac{hcE}{kT^2} F - \frac{3}{T} F + \frac{\partial F}{\partial T} \right] \delta T + J(T) P F \delta\chi \end{aligned} \quad (5)$$

where

$$J(T) = \frac{A}{T_0} \left(\frac{T_0}{T} \right)^3 e^{-hcE/kt} \quad (6)$$

and A is a constant and χ is the mixing ratio of the absorbing gas. (Note, this equation also assumes that $\partial F / \partial \chi \approx 0$; i.e., the linear dependence of α on χ dominates).

The coefficients of the various terms show the magnitudes of the effects resulting from the uncertainty in measuring that term. Figure 2 plots those coefficients for a Van Vleck-Weisskopf lineshape assuming parameters similar to the 168 GHz absorption line of H₂S and an H₂S mixing ratio (χ) of 10%.

2.2. LABORATORY CONFIGURATION

The general characteristics of this type of measurement system have been described previously (DeBoer and Steffes, 1994). The objective of this laboratory system is to simulate the atmosphere of a given planet and measure the microwave properties of gases under these conditions. It consists of three sub-systems: (1) the planetary atmospheric simulator, (2) the microwave measurement sub-system and (3) the data collection and analysis sub-system. Figure 1 shows a block diagram of the laboratory configuration.

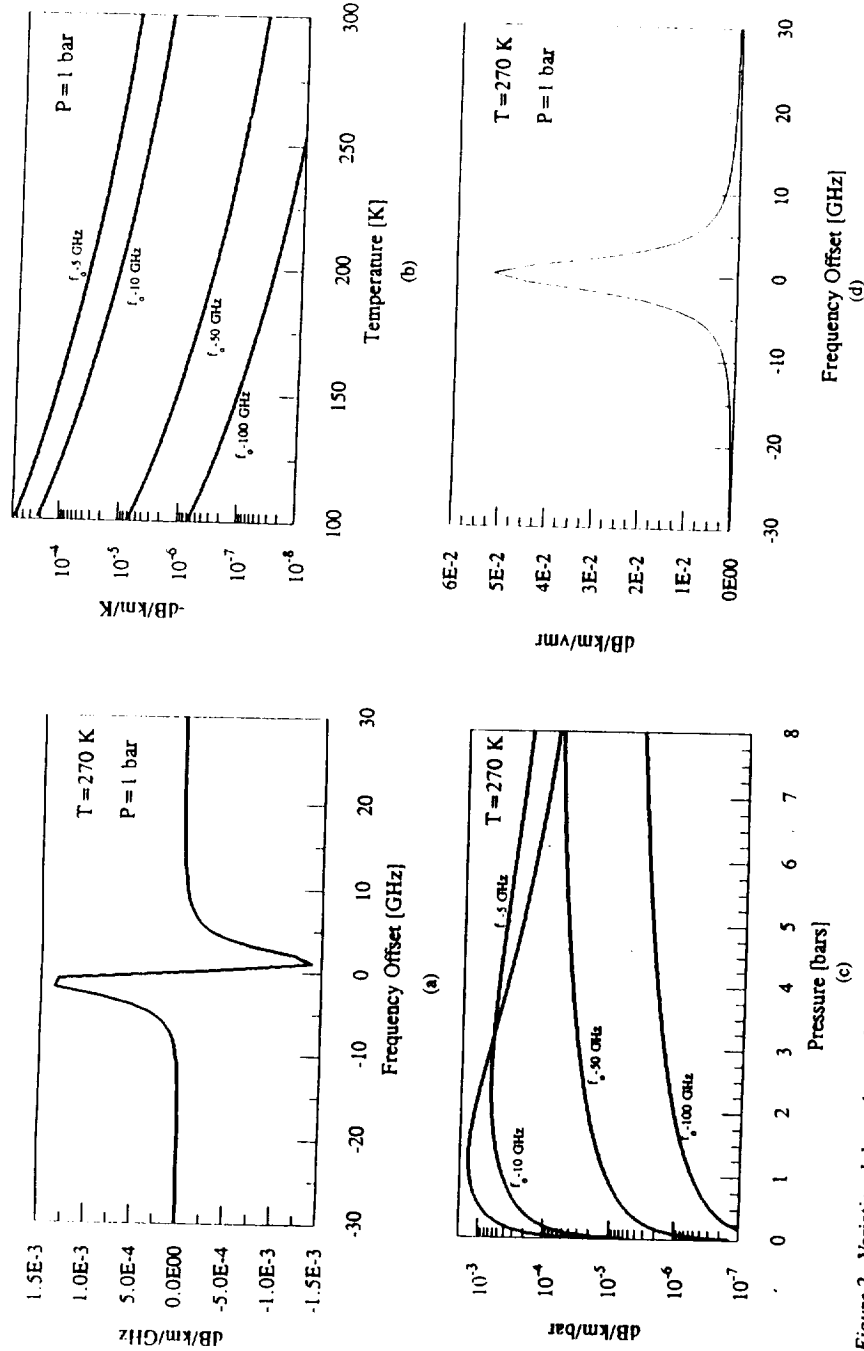


Figure 2. Variational dependence of the environmental parameters (frequency, temperature, pressure, and mixing ratio) of one term of the mathematical formalism expression (Equation 4) for a 10% mixing ratio and typical line parameters of the 168 GHz H₂S line.

The planetary atmospheric simulator consists of a hermetically sealed stainless steel pressure vessel which in turn is placed inside a temperature chamber capable of reaching temperatures as low as 150 K or as high as 600 K. The pressure vessel is connected to three gas cylinders via stainless steel tubing with sufficient stop valves such that every piece of the network may be isolated to aid in the detection of leaks, as well as for safety considerations. A combustible gas detector and a water bubble technique were used to detect and locate leaks within the system. When properly sealed, the system can safely contain pressures exceeding 7 bars and sustain this pressure with no discernible leaks over a period of many hours. A roughing vacuum pump was also connected to the vessel to evacuate the chamber and is capable of producing a vacuum of 3 torr. For pressure measurements between 1 and 800 torr, a digital thermocouple vacuum gauge was used, while for higher pressures an analog gauge was used with an accuracy of 0.2 atm throughout its usable range.

The microwave sub-system consists of two cylindrical silver-plated cavity resonators which both reside within the pressure vessel. The larger of the two resonators has been used for S band (2.25 GHz or 13.3 cm) and X band (8.5 GHz or 3.5 cm) measurements which correspond to TE_{013} and TE_{067} modes respectively. The small resonator has been used for K band (21.7 GHz or 1.38 cm) measurements which corresponds to the TE_{034} mode. Many other resonances are available for use at other wavelengths (see Figure 3). The three bands discussed above were used due to their relatively large quality factors. Mode suppression slots are incorporated in each resonator to block the degenerate TM modes which have lower quality factors as well as to let the gas flow freely into the resonators. Two HP (Hewlett-Packard) 8690 microwave sweep oscillators are used to generate the input signal in the three bands and a high resolution HP 8562B spectrum analyzer is used to measure the output signal. Initially a 10 dB attenuator was used on the output of the sweepers to provide 20 dB of return-loss isolation for the sweeper as it swept through the resonance. Later, a 40 dB return-loss ferrite isolator was used at S and X bands which greatly improved the isolation allowing the use of greater output power from the microwave sweeper as well as providing 10 dB extra throughout. This results in an approximate 15 dB increase in the signal-to-noise ratio for these bands. At K band, the 10 dB attenuator is still used.

The final sub-system (the data collection and analysis sub-system) consists of a personal computer and software package which reads the data in and allows data processing and resonance line-fitting to be performed (see appendix). This interface greatly improves the sensitivity and reliability of the experimental system from previous configurations, when the operator was required to eye-fit the half-power and center frequency points on the spectrum analyzer display. Full control of the spectrum analyzer is possible and batch file input gives speed and flexibility to this control. The following section describes in more detail this sub-system and other issues of the data processing.

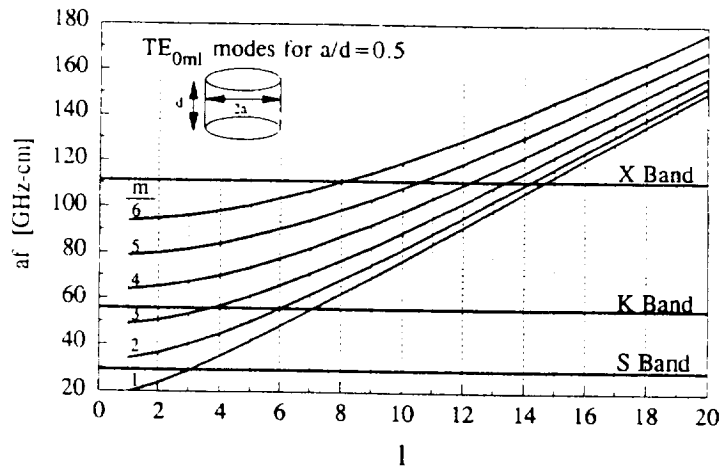


Figure 3. TE modes for the cylindrical resonators. Modes exist at the intersections of the curves and the vertical lines.

3. The Data Collection and Analysis Subsystem

As mentioned previously, in the past, data collection of the resonance parameters (i.e., bandwidth, center frequency and level) were eye-fit and read from the spectrum analyzer display. The disadvantages of this technique are manifold, not the least of which is operator fatigue near the end of a long series of data collection which degrades the quality of the results. The obvious solution is to read the data into a personal computer for analysis. A General Purpose Interface Bus (GPIB) was used to interface the spectrum analyzer and computer.

Data is read from the spectrum analyzer into a data buffer on the computer. A user-selectable Hamming window (typically a 50-point window) is convolved with the 600 data points read from the Hewlett-Packard 8562B spectrum analyzer to smooth the data and a simple peak searching routine then finds the center frequency and amplitude. The half power points are then found and the bandwidth computed. The spectrum, along with the smoothed fit, are displayed and the operator is queried as to whether this data point is to be used or not. (Occasionally, incomplete spectra are recorded which must be discarded.) If complete, the resonator measurement values are written to a data file. These values are:

- center frequency
- amplitude at the resonance center
- half power bandwidth
- quality factor
- an asymmetry figure of merit.

Date of run: 03/28/1994 Time of run: 14:40:05

X band at vacuum (3 torr)
3.95 mV, -60 C

<<Spectrum Analyzer Parameters>>			
center frequency:	8541.81 MHz	span:	50.00 kHz
RBW:	1.00 kHz	VBW:	1.00 kHz
sweep time:	20.0000 sec	ref level:	-76.00 dBm

Filter: 50 point Hamming

BW (kHz)	peak (MHz)	Q	level (dBm)	asymmetry (%)
73.190	8541.8032	116707	-76.94	5.05050
74.712	8541.8022	114330	-76.98	10.23102
74.965	8541.8052	113944	-77.01	0.65789
71.414	8541.8029	119609	-76.87	5.51724
73.697	8541.8007	115904	-76.87	12.37458
74.712	8541.8019	114330	-76.95	8.91089

6 data points.

<BW (kHz)> = 73.7817 ± 1.34866

<peak (Mhz)> = 8541.8 ± 0.00190367

<Q> = 115804 ± 2149.81

<level (dBm)> = -76.9367 ± 0.0571544

<asymmetry> = 7.12369 ± 4.22154

<|asymmetry|> = 7.12369 ± 4.22154

Date of run: 03/28/1994

Time of run: 14:44:20

Figure 4. Sample LAB mode data file for X band (see appendix). Note the output format: Date and time stamp; Comments; Spectrum analyzer parameters; Filter used; Data points for particular lab sequence; and Mean and standard deviation of the data.

The asymmetry figure of merit, af , is defined as

$$af = 100 \frac{(f_r - f_c) - (f_c - f_l)}{f_r - f_l} \% \quad (7)$$

where f_r , f_l and f_c are the higher frequency half-power (-3 dB) point, lower frequency half-power (-3 dB) point and center of the resonance, respectively. It varies from $\pm 100\%$, with 0% being perfectly symmetrical. Typical asymmetry factors range between $\pm 10\%$. (Excessive asymmetry may suggest contamination of the data from the effects of adjacent resonances, and the results may be unreliable. If it persists for more than one scan, the system must be dismantled and thoroughly checked.) When all data have been taken and recorded, the program computes the averages and variance of all quantities, including the absolute value of the asymmetry as well as the asymmetry itself. These values are written to a data file and used in the computation of the absorptivity and its associated error. Typically,

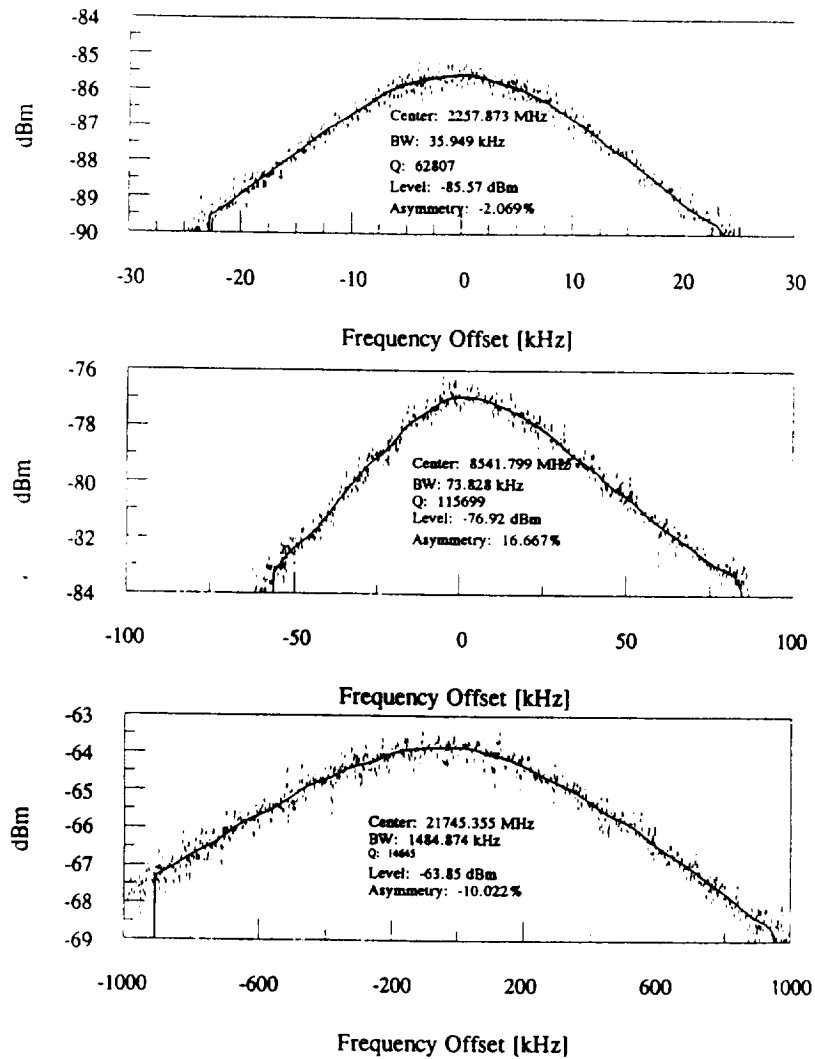


Figure 5. Representative spectra at the three bands used.

20 data points are taken per temperature, pressure and frequency to develop the error statistics.

The above sequence, beginning from reading a spectrum into the data buffer to computing the variances of a set of measurements and writing to an output data file, describes what is known as the "LAB mode" of the computer software PCSA, which is discussed in the appendix. Figure 4 shows the output data file for

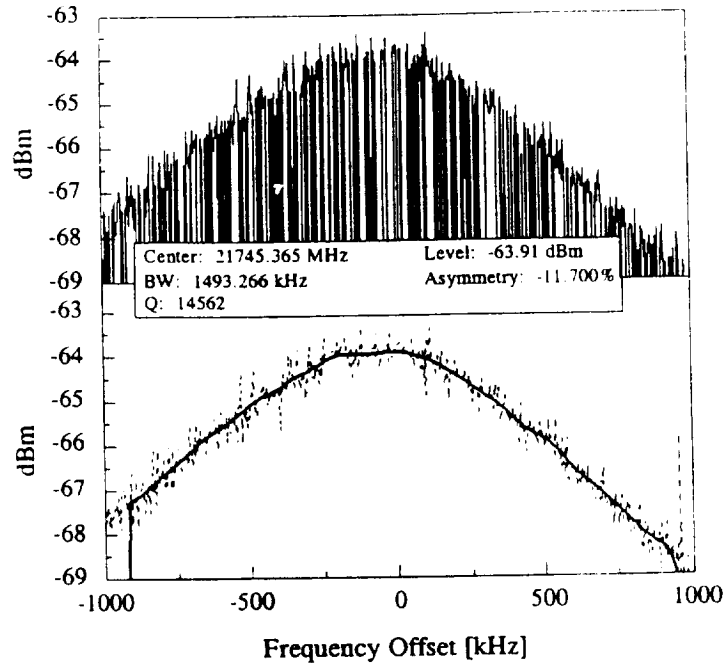


Figure 6. Same K-band spectrum as in the previously figure with artificially generated sweep-on-scans nulls along with the FIXed spectrum and new resonance fit.

six individual measurements at X band (8.5 GHz). Figure 5 shows representative spectra at the three bands, as well as the associated parameter fits for the smoothed data.

One problem encountered in fitting the spectrum is the presence of sweep-on-scan nulls. These occur when a sweeping source is used along with a sweeping bandpass filter on a spectrum analyzer so that at a given time energy from the signal may not be present in the given small frequency range received instantaneously by the spectrum analyzer. One solution is to slow the sweep time on the spectrum analyzer. In some cases, however, totally eliminating these nulls requires unacceptably long sweep times. Another is to utilize a feature of the data processing software called "FIX". FIX is a multi-pass averaging scheme whereby "null" data points are set to an average of its ten nearest neighbors until the change of all points to be FIXed is less than a one percent threshold.

Figure 6 is the same spectrum as the K-band spectrum in the previous figure with artificially generated sweep-on-scan nulls. The spectrum was then FIXed and new fits were computed. Note that the values of the original and manipulated data agree very well, as summarized below in percent differences:

- center frequency: 0.00005%

system at the Georgia Institute of Technology. Calculating the standard deviation for 10 measurements of the FWHM bandwidth before and after the inclusion of the computer interface shows marked improvement. For example, the standard deviation of 10 measurements of H₂S opacity at 6 bars in an H₂/He atmosphere at 213 K showed improvements of 34%, 41% and 16% at S, X and K bands respectively. It is probable that the improvement in reliability is greater than represented by this since an inherent viewer bias is present whenever eye-fit measurements are made on a noisy display. Another factor added by the computer-aided system is that more sample points can be easily taken to further increase the sensitivity. Table I shows the square root of the mean measurement variance of the system (the "standard deviation") at the three bands for all temperatures and pressures before and after the inclusion of the computer interface. For comparison, a resonator-based system similar to the K band resonator but operating between the frequencies 9.18 and 17.44 GHz (Spilker, 1990) had root mean variances of 1.02 and 2.46 dB/km, at frequencies corresponding to the two end-points.

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Appendix: The Computer Software – PCSA

The computer interface software consists of one stand-alone program called PCSA (Personal Computer-Spectrum Analyzer) written in the C programming language. PCSA is a case insensitive command-line driven system of which many commands have optional arguments, denoted below in square brackets []. Most commands can be abbreviated to the shortest possible number of unique characters. General PCSA commands are:

!

FILTER

DOS command sub-processor.

Set smoothing filter. Any filter can supplied by the user. Currently supported are 10, 20, 30, 40 and 50 point Hamming windows (out of 600 points comprising a spectrum from the HP 8562).

<u>FIT [SPECTRUM]</u>	Fit the bandwidth etc. to a smoothed spectrum [take new spectrum]. If there is no data in the buffer, a new spectrum will automatically be taken.
<u>FIX [PLOT]</u>	FIX raw data buffer [and plot].
<u>HELP, ?</u>	On-line help facility.
<u>LAB [nn]</u>	Enter PLANETARY lab mode [and auto-take nn samples with no check]. <u>LOAD 'file'</u>
Read batch processing commands from 'file'.	
<u>PARAMETERS ['file']</u>	Write spectrum analyzer parameters to screen/'file'.
<u>PLOT</u>	Plot spectrum in buffer.
<u>QUERY 'xxx'?</u>	Ask spectrum analyzer for data 'xxx'. E.g. 'query cf?' for center frequency data for the 8562.
<u>QUIT, Q</u>	Exit this program.
<u>READ 'file'</u>	Read 'file' into data buffer.
<u>SAVE 'file'</u>	Save buffer to 'file'.
<u>SET FIX</u>	Toggles between FIX being ON and OFF for lab mode.
<u>SMOOTH [SAVE]</u>	Smooth and plot spectrum in buffer, [and write to file (current directory)]. If there is no data in the buffer, a new spectrum will automatically be taken.
<u>SPECTRUM [SAVE]</u>	Write spectrum to raw data buffer and plot [and write to file (current directory)].
<u>TRANSFORM [SAVE]</u>	Take, view [and save (current directory)] the Fourier transform of the buffer.
<u>All commands supported by the resident device.</u>	

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