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# Halogen Occultation Experiment (HALOE) Optical Filter Characterization

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# Halogen Occultation Experiment (HALOE) Optical Filter Characterization

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## Summary

The Halogen Occultation Experiment (HALOE) is a solar occultation instrument that will fly on the Upper Atmosphere Research Satellite (UARS) to measure mixing ratio profiles of $O_3$, HF, HCl, $CH_4$, NO, $H_2O$, and $NO_2$ in the stratosphere and lower mesosphere. The associated atmospheric pressure profile will be inferred from absorption measurements in a primary $CO_2$ band. The inversion of the HALOE data will be critically dependent on a detailed knowledge of the eight optical filters used in the HF, HCl, $CH_4$, and NO gas correlation channels and in the $O_3$, $H_2O$, $NO_2$, and $CO_2$ radiometer channels.

In order to meet the stringent HALOE requirements, a filter characterization program was undertaken to measure in-band transmissions, out-of-band transmissions, in-band transmission shifts with temperature, reflectivities, and in-band transmission stabilities with time of three sets (flight, environmental witness, and spectral witness) of the eight filters. The measurement results of this program are presented herein. The in-band transmissions of the corresponding filters of the three sets differ significantly. Five of the eight filters (NO, $O_3$, $H_2O$, $NO_2$, and $CO_2$) have measurable out-of-band leaks in the spectral range from 2 to 20 $\mu$m, but the leaks are not of consequence to HALOE; also, the spectral shift with temperature varies from 0.02 $cm^{-1}/°C$ for the $NO_2$ filter to 0.4 $cm^{-1}/°C$ for the HF filter. Much spectral structure is present in the reflection spectra, and no change with time has yet been measured in the in-band transmission.

The three unexpected results that are of possible significance to HALOE are (1) in-band transmissions of corresponding filters from different sets differ measurably; (2) out-of-band, Fabry-Perot induced transmissions are orders of magnitude larger than the conventional out-of-band transmissions of the two-element filters, and this could affect complex-precision optical experiments such as the Limb Infrared Monitor of the Stratosphere (LIMS); and (3) filter throughput changes by approximately 5 percent over the expected operating temperature range of HALOE.

## 1. Introduction

### 1.1. Purpose of HALOE

The Halogen Occultation Experiment (HALOE) is a solar occultation experiment that will fly on the Upper Atmosphere Research Satellite (UARS) and will measure, on a global basis, the concentration profiles of a number of trace gas constituents in the stratosphere (ref. 1). The species to be measured are $O_3$, HCl, HF, NO, $CH_4$, $NO_2$, and $H_2O$. (In order to correlate the data as a function of atmospheric pressure, the $CO_2$ transmittance profile is also measured.) These species were selected because they will permit the scientific community to study stratospheric ozone depletion resulting from chlorine in the stratosphere and to determine the relative amounts of chlorine from natural and man-made sources. The possibility of ozone depletion resulting from man-made chemical compounds entering the atmosphere has been a major concern for the past two decades (e.g., refs. 2 to 5). The concern over the particular effects of chlorine released from man-made chemical compounds (especially the fluorocarbons $CFCl_3$ and $CF_2Cl_2$) used as refrigerants, cleaning compounds, and foaming agents has surfaced more recently (refs. 6 and 7). It is this latter concern that HALOE will address directly. The data derived from HALOE will, however, permit extensive studies of stratospheric chemistry as a whole and, in particular, will permit studies of the interactions between the oxides of nitrogen ($NO_x$), chlorine ($ClO_x$), hydrogen ($HO_x$), and their overall effect on stratospheric ozone.

The HALOE optics are shown schematically in figure 1 and consist of 116 discrete elements, which include mirrors, lenses, beam combiners and splitters, windows, spectral filters, neutral-density filters, and detectors. All the optical components are attached to the optical bed with separate mounts that permit individual alignment. The majority of the optical elements are fabricated from germanium. The optical bed is fabricated from aluminum.

### 1.2. HALOE Measurement Technique

The HALOE instrument measures the atmospheric absorption of solar radiation in eight channels in the spectral range from 5000 to 1000 $cm^{-1}$ (2 to 10 $\mu$m) during both sunrise and sunset occultation events. (Values of the spectral range are given in two sets of units, or interchangeably, when considered useful.) By measuring the solar radiation with and without the intervening atmosphere during a solar occultation, the absorption of solar infrared radiation by the atmosphere can be determined and the concentration of specified atmospheric trace gases can be calculated. The HALOE instrument uses both conventional optical filter radiometers ($O_3$, $H_2O$, $NO_2$, and $CO_2$) and gas-filter correlation radiometers (HCl, HF, $CH_4$, and NO). Gas filters are used when a high degree of specificity is required (i.e., when the gas is of very low concentration and the spectral region is strongly contaminated with interfering gases). In the gas-filter concept, a specified quantity of the gas of interest, at a known pressure and temperature, is placed in a correlation gas cell in the optical path of the instrument. The correlation of the atmospheric absorption and the spectral signature of the gas in the cell in the band pass of the corresponding optical filter provides a signal that can be interpreted to obtain the atmospheric concentration of that gas (ref. 1).

The application of a gas-filter approach to satellite applications is relatively new. The technique was pioneered at the University of Oxford by the application of the Selective Chopper Radiometer (SCR) (ref. 8) and the Pressure Modulation Radiometer (PMR) (ref. 9) on the Nimbus satellites. The technique was also employed by the NASA Langley Research Center (LaRC) for the Measurement of Air Pollution from Satellites (MAPS) experiment which measured global tropospheric carbon monoxide during the second Space Shuttle mission (ref. 10). The PMR, MAPS, and HALOE approaches differ in that the PMR instrument modulates the pressure of the gas in the filter cell, whereas in MAPS and HALOE the total pressure of the gas in the filter cell is fixed and fluctuates only over a narrow range because of natural temperature variations. The PMR and MAPS measurement approaches both differ from that of HALOE in that PMR is a limb-viewing instrument and MAPS is a nadir-viewing instrument, whereas HALOE takes data during solar occultations.

Interpretation of the gas-filter channel signals, as well as those of the conventional filter radiometers, requires accurate characterization of the optical filters in order to retrieve good determinations of the atmospheric trace gases of interest. The design, fabrication, and characterization of 15-$\mu$m $CO_2$ filters for the Selective Chopper Radiometer is contained in reference 8.

The full range of signal change due to the gas of interest in the gas correlation channels will be of the order of 1 percent, but this 1 percent is amplified and digitized by a 12-bit analog-to-digital converter (ADC). Thus, the signal measurement resolution over the full band pass is of the order of $10^5$. This high measurement resolution leads to a $10^{-3}$ percent transmission-measurement requirement over 10-$cm^{-1}$ intervals for out-of-band spectral regions that can be seen by HALOE detectors. In order to meet the HALOE requirements for precise information of the eight optical filters, a filter characterization program was undertaken to measure the in-band transmissions, out-of-band transmissions, in-band transmission shifts with temperature, reflectivities, and in-band transmission stabilities of three sets of the eight filters.

An optical schematic showing the location of the filters is presented as figure 1. The measurement apparatus and techniques are described in the text.

## 2. Filter Descriptions

Of the eight filters, three sets (flight, spectral witness, and environmental witness) were used in the filter characterization program. (That is, a total number of 24 filters were used.) The flight filter set was mounted in flight filter holders and handled in accordance with clean room procedures. The spectral witness filters were similar to the flight filters but were mounted in 2.0-in-diameter brass filter holders. The environmental witness filters were similar to the spectral witness filters except that the radiometer filters had a 1.1-in. diameter rather than a 0.8-in. diameter.

The approximate center frequency, substrate material, and diameters of the HALOE optical filters are listed in table I. The germanium elements were the in-band transmission elements, and the $MgF_2$ and ZnS elements were long-wavelength blocking elements for the last three filters listed in table I.

All the optical filters, except the $NO_2$ channel filters, were obtained from Optical Coating Laboratory, Inc. (OCLI). The $NO_2$ channel filters were obtained from Balzers Optical Group. As will be shown later, the $NO_2$ filters have a different band pass shape and spectral shift with temperature behavior than the OCLI filters. All the filters for a given gas channel are believed to have been coated at the same time. The detectors for the four radiometer channels are bolometers sensitive to radiation greater than 10 $\mu$m, and separate elements were needed to block the high transmission of germanium from 400 to 800 $cm^{-1}$.

A photograph of a gas correlation-channel filter is presented as figure 2. The filters had a nominal wedge of 12 min of arc to minimize spectral channeling and a nominal thickness of 0.04 in. The two-element filters were separated by 0.15 in.

## 3. Measurement Program

The filter characterization program initially consisted of five types of measurements: in-band transmission, out-of-band transmission, spectral shift with temperature, reflectivity, and in-band transmission stability with time (the aging effect). Later in the program, filter throughput was also measured as a function of temperature. The optical filters in the HALOE instrument are all in parallel light beams; therefore, the ambient in-band transmission in a parallel beam was required. Accuracy and linearity were also important parameters for the in-band measurements. Repeatability was a primary parameter in the comparisons of filters of the same set.

The spectral region of principal interest for the in-band measurements was between the 1-percent transmission points. Transmission measurements in the $10^{-5}$ range were required for the out-of-band measurements. Dynamic range, transmission precision, and signal-to-noise ratio were primary parameters for these measurements. The initial requirement for out-of-band measurements was for the spectral interval from 0.5 to 50 $\mu$m. However, since germanium is the substrate of most of the optics in front of the filter (fore-optics), the shortwave limit became the germanium cutoff at 6300 $cm^{-1}$ (1.5 $\mu$m), as verified by the manufacturer's data and interferometer measurements. Similarly, the longwave limits became the substrate cutoff as verified by interferometer measurements of windows of the same substrate materials. Filter alignment and optics positions also became primary parameters in these measurements.

The philosophy for handling the filters was to perform as many of the measurements as possible on the spectral and environmental witness filters in order to minimize handling of the flight filters. The in-band transmission and temperature-effects data were written on magnetic tape for use in modeling the instrument and data retrieval purposes.

It is generally known that the in-band transmission of an interference filter can shift with change in temperature. The spectral shift was obtained from measurements at 60°F (the nominal operating temperature) and also at 20°F hotter and colder than 60°F. The filter throughput measurements were made at 45°F, 80°F, and 120°F. Temperature uniformity and stability were primary parameters for spectral shift and throughput measurements. The reflectivity of the filters was obtained by replacing a gold reference mirror in the parallel-beam accessory with the filter. Thus, the reflectivity measurements are all referenced to a gold mirror. These measurements covered the spectral range from 800 to 6300 $cm^{-1}$. The age stability of the filters is monitored by measuring the in-band transmission of spectral witness filters beginning in 1986. The measured transmission in a long-path interferometer is extremely sensitive to filter orientation at precision levels of tenths percent transmission, primarily from beam steering of the wedged filter. The optical alignment was a major parameter for the reflectivity and age-stability measurements.

## 4. Measurement Techniques and Instrumentation

The basic technique used to measure the transmission of the filters was to obtain the ratio of a single-beam spectrum from a Fourier transform infrared (FTIR) spectrometer, passed through the filter, to a single-beam spectrum obtained under the same conditions except that the filter was removed from the optical path. Two similar, moderate-resolution (16 to 0.06 $cm^{-1}$) FTIR spectrometers (Nicolet 7199 and Nicolet 170SX) were used for most of the filter measurements. A Nicolet 740 FTIR spectrometer was used for some of the measurements from 400 to 800 $cm^{-1}$. FTIR operating parameters (resolution, number of scans averaged, spectral interval, sample spacing, prefilters, aperture, electronic filters, and gain settings) were varied over wide ranges depending upon which HALOE filter and filter characteristic were being measured.

A 2-year filter-measurement feasibility study was conducted during the 1983–84 time period. Tests were performed on different spectrometers, including dispersive infrared (IR) spectrometers, using different measurement techniques, i.e., ratioing interferograms for out-of-band leaks. Since optical filter measurements of this scope had not previously been performed at LaRC, accessories and support equipment were acquired, designed, fabricated, and tested. A class 100 clean room air filter was installed over the 170SX spectrometer so that the filters could be handled in a lint-free environment.

### 4.1. FTIR Spectrometers and Thermal Housings

Two FTIR spectrometers were used: one for the spectral interval from 1800 to 6300 $cm^{-1}$ ($CaF_2$ beamsplitter and InSb detector), and one for the spectral interval from 800 to 2000 $cm^{-1}$ (KBr beamsplitter and MCTA detector). Each of the spectrometers was equipped with its own microprocessor and peripherals, including plotter and tape recorder. Each spectrometer optical table was fully enclosed with a hood and was purged with nitrogen obtained from the boiloff of liquid nitrogen. The gas bearings of the spectrometer moving-mirror carriage were also supplied with boiloff liquid nitrogen. The temperature of the spectrometer optical tables was monitored with digital readout temperature and humidity gauges. The spectrometers were located in a laboratory with dedicated temperature and humidity control. The FTIR optical bench from 1800 to 6300 $cm^{-1}$ rests on an air-bladder shock-absorbing system.

A special housing was obtained for the temperature characterization of the filters. The housing consisted of a 2- by 3-in. baseplate that could fit into the FTIR sample stand. The baseplate was drilled and fitted to allow fluid to flow through the baseplate. A cylinder with 1.5-in. inside diameter (I.D.) and 2.0-in. outside diameter (O.D.), internally wound with resistance-heating wire, was attached to the baseplate. A coverplate with a 0.75-in-diameter opening fitted over the cylinder opposite the baseplate. The housing was wrapped with closed-cell, polystyrene plastic foam for additional thermal insulation. For the colder-than-ambient filter measurements, the resistance-heating cylinder was later replaced with a brass cylinder of 1.7-in. I.D. Later, a small heater button fastened to the filter holder was used for the throughput measurements. Calibrated thermistors were potted to the filter holders and were read with 5½ digit multimeters.

### 4.2. Interferometer Operating Parameters

The two commercial FTIR spectrometers used in the filter characterization program are versatile instruments. The spectral resolution is determined primarily by the distance of travel of the moving mirror. Resolutions of 0.24 $cm^{-1}$ were used for most of the in-band transmission measurements, and 4 $cm^{-1}$ resolution was used for most of the out-of-band measurements. The number of interferograms that were averaged was typically 16 for in-band transmission measurements and 1024 for out-of-band measurements. Optical prefilters, typically 500 $cm^{-1}$ wide, were used for in-band measurements and to investigate some out-of-band leaks. Source apertures of 1.1 mm, 2.3 mm, and 6.4 mm were available, with 2.3 mm being used for the in-band measurements and 1.1 mm and 6.4 mm being used for the out-of-band measurements. Amplifier gains of 1 were generally used for in-band measurements and of 1 and 128 were used for out-of-band measurements. The sample spacing (nonoverlapping spectral interval) was typically eight for the in-band transmission and two for the out-of-band transmissions. The electronic (noise rejection) filters were chosen to optimize the signal-to-noise ratio for each measurement, as was the moving-mirror velocity. A number of software parameters were also chosen to optimize the results. Tests were conducted to verify the effects of the measurement parameters, i.e., aperture, gain, prefilters, electronic filters, mirror velocity, number of scans averaged, and interferometer temperature and temperature stability. The parameters that gave the greatest signal-to-noise ratio and the best linearity for each particular measurement were generally used.

## 5. Measurement Results

The optical filter measurement program provided detailed and specific information on the spectral transmissions of the HALOE optical filters. Certain optical characteristics such as angular deviation, homogeneity, and angle tuning (spectral tuning) were not measured. The in-band transmissions and the out-of-band filter leaks received the most attention and are believed to be state-of-the-art infrared filter measurements. Very precise measurements were also made of the change in filter throughput at several different filter temperatures.

### 5.1. In-Band Transmissions

The in-band transmissions of the HALOE optical filters are presented as figures 3 to 10. Each filter has been measured several times at ambient temperatures (approximately 25°C), and the precision of the measurements is indicated by the nearly overlapping curves for a given filter. However, very measurable differences in the transmission spectra of the individual filters of the same gas channel are clearly seen. These measurements were made with an $f/4$ IR beam. A six-mirror accessory was placed in the sample compartment of the interferometer in order to collimate the $f/4$ IR beam for flight-filter in-band measurements. Since the filters were wedged to prevent channeling, the absolute transmission, as measured by the interferometer, is a function of filter orientation when placed in a collimated beam because of the beam steering introduced by the wedge. Although the data were not shown here, the collimated beam transmissions are similar to the $f/4$ IR beam transmissions.

Precautions were taken with the collimated in-band transmission measurement to ensure that the IR beam was equally bounded for both sample and background spectra. This was particularly necessary for the $O_3$, $H_2O$, $NO_2$, and $CO_2$ filters with clear apertures of 0.7 in. The full aperture could not be filled because of vignetting by the accessory mirrors and mounts and the prefilter mount. A 0.4-in. beam aperture was used, and an empty filter holder was inserted in the filter position for the background spectrum for this purpose. Alignment was facilitated with the interferometer HeNe laser beam.

All the filters, except the $NO_2$ channel filters, were made by Optical Coating Laboratory, Inc. (OCLI). Figures 3, 4, and 6 to 10 show that the OCLI filters all tend to have flat tops and very steep sides. The $NO_2$ channel filters were made by Balzers Optical Group and have a Gaussian shape.

### 5.2. Spectral Shift and Throughput Versus Temperature

The HALOE filter characterization program initially required spectral shift measurements of the four flight radiometer filters and four spectral witness, correlation-channel filters at 40°F, 65°F, and 80°F (the nominal operating range of the instrument). Later, when significant differences were observed in in-band transmission between spectral witness and flight filters, temperature measurements were also made on the flight correlation-channel filters.

A spectral shift of the in-band transmission of the flight filters can be seen in figures 11 to 18. The average $(\Delta v/\Delta T)$ shifts of the filters for the eight HALOE channels are presented in table II, where $v$ represents the spectral frequency and $T$ represents the temperature. These spectral shifts were calculated by measuring the spectral frequency at 10-percent transmission intervals (normalized to peak transmission equal to 100-percent transmission). Thus, $\Delta v/\Delta T$ represents averages of 19 points over the bandwidth of the filter. It can be seen from table II that for six of the filters, the spectral shift is generally a function of the filter frequency and increases as the frequency increases. The $CO_2$ filter is an exception. However, for the $NO_2$ filters, which were supplied by a different manufacturer and have a different in-band shape than the other seven filter sets, the spectral shift is quite small.

The throughput of a filter can be defined as the integral of transmission over the filter bandwidth. During the spectral shift measurements and HALOE instrument testing, it was noted that the peak transmission and the bandwidth vary with temperature. The filters were heated to 50°C to increase the precision of the throughput measurement. The seven filter sets with measurable spectral shift have decreasing throughput with increasing temperature because both the peak transmission and the bandwidth decrease with increasing temperature. A typical case is a decrease of 5.9 percent in throughput when the $CO_2$ filter temperature is increased from 25°C to 54°C. The throughput of the NO filter decreased by 5.6 percent when the filter temperature was increased from 6°C to 51°C. Three transmission curves at each temperature are presented for each of the eight filters in figures 11 to 18.

### 5.3. Out-Of-Band Transmissions

The spectral witness filters were measured initially for possible out-of-band transmissions (leaks). Later, the flight filters were also measured. The spectral interval covered in the out-of-band measurements was determined by the germanium cutoff for higher wave numbers at 6300 $cm^{-1}$ and by the filter substrate transmission for the lower wave number limit. For example, the $CH_4$, HCl, $CO_2$, and HF filters were all on $SiO_2$ substrate, and the out-of-band measurements covered the interval from 1800 to 6300 $cm^{-1}$. Out-of-band measurements for the ZnS and Ge substrates of the $O_3$ and for the Ge substrates of the NO filter covered the interval from 400 to 6300 $cm^{-1}$. Out-of-band measurements for the MgF and Ge substrates of the $H_2O$ and $NO_2$ filters covered the spectral interval from 800 to 6300 $cm^{-1}$.

It was found that by orienting the two-element filters perpendicular to the IR beam, a Fabry-Perot leak could be induced in these filters if a flat optic window, i.e., a prefilter, was placed in front of the filter. Orientation of the filter was determined by reflecting the HeNe laser beam of the interferometer back upon itself. Figure 19 shows the leaks in the $O_3$ filter perpendicular to the IR beam, both with and without a flat optic window (NaCl) for the mid-IR region. These leaks increase in transmission and broaden when placed in a Fabry-Perot cavity. The strong Fabry-Perot enhancement of very small leaks in the spectral filters is a probable cause of the "side lobes" and the post-mission conclusion of a 1.5-percent leak in the $CO_2N$ filter of the Limb Infrared Monitor of the Stratosphere (LIMS) (ref. 11).

Figures 20 to 27 show out-of-band transmissions for representative regions of the other flight filters. All these measurements were made with the $f/4$ IR beam. The leak in the NO filter (fig. 23) at 600 $cm^{-1}$ is of no consequence to HALOE, because two $Al_2O_3$ windows (1500-$cm^{-1}$ cutoff) in the NO channel block this leak. Except for the $O_3$ and $H_2O$ filters, all the out-of-band data presented (figs. 22 to 27) are for "normal" leaks. The $H_2O$ filter was the most extensively studied (approximately 100 spectra).

The "normal" out-of-band transmission measurements can be summarized as follows:

1. The NO filter has a large leak (>10-percent transmission) below 1000 $cm^{-1}$.
2. The $CO_2$ filter has small leaks (<0.1-percent transmission) in the interval from 4000 to 6000 $cm^{-1}$.
3. The $NO_2$ filter has small leaks (approximately 0.001-percent transmission) in the interval from 2000 to 2500 $cm^{-1}$.
4. The $O_3$ filter has small leaks (<0.001-percent transmission) in the intervals from 2400 to 3900 $cm^{-1}$ and 4400 to 6000 $cm^{-1}$.

### 5.4. Reflectivity

The reflection measurements were made by placing the filters in the position of one of the plane mirrors in the six-mirror parallel-beam accessory. The interferograms are only about 25 percent as big when using this accessory as compared with the $f/4$ IR beam because of reflection losses and image degradation from the accessory. In addition, the interferograms and, hence, the measured reflectivity are extremely sensitive to the tilt of the plane mirrors (i.e., gold reference mirror and filter) since the angles of reflection are double the mirror tilt. The result is a lateral displacement of the interferometer IR source image on the detector between the reference spectrum and the filter-reflection spectrum when the mirrors are in a parallel beam. These aspects of the reflection measurements resulted in the accuracy, precision, and repeatability of the reflection measurements being much lower than for the in-band and temperature-effects measurements. Fortunately, the reflectivity of the optical filters is not used in the data retrieval of HALOE and, consequently, is of low priority. Nevertheless, all the spectral witness filters were measured over the spectral interval from 800 to 6300 $cm^{-1}$. A typical reflection spectrum (of the $H_2O$ filter) is presented as figure 28. As expected, the measured reflectivity of the filters is low (approximately 10-percent reflectivity) in the band pass regions. However, the filters also have numerous other spectral regions of low reflectivity. That is, there is a lot of spectral structure in the reflection spectrum. This structure is somewhat similar to the structure seen in the Fabry-Perot leaks and probably contributes to these leaks.

### 5.5. In-Band Time Stability

The initial filter stability-with-time measurements were performed on the spectral witness filters. The filter stability was by comparative measurements of the peak transmission of the filters in the $f/4$ IR beam. The measurements were initially scheduled to be made every 6 months, but conflicting data requirements of the interferometers precluded adherence to this schedule. Since the filters are wedged to minimize spectral channeling, the IR beam is deviated when passing through the filter. Even though the beam in the sample compartments is $f/4$ and is reduced to a diameter of about 6 mm at the center of the compartment, there is no image position where the filter-induced deviation of the IR beam is completely compensated for by the downstream optics with no translation of the source image on the detector. Consequently, the rotational alignment of the filter has an effect on the measured transmission at a 1-percent transmission level. The understanding of measurement repeatability in transmission was aided by a concurrent program of monitoring condensable-volatile-material contamination of optics at a 0.01-percent transmission level in the HALOE clean room using the Nicolet 170SX spectrometer (ref. 12). The transmission repeatability is also affected by interferometer alignment and filter location. Transmission of a $CH_4$ filter at two different times is presented as figure 29.

Although good baseline transmissions were not obtained early in the filter program, stability measurements with improved filter orientation and position indexing will be performed on a set of "instrument-build" filters on a periodic basis. There is no indication of change in transmission over a 2-year period within the estimated precision (5 percent) of the measurements. However, a similar CO spectral filter (fig. 30) from the MAPS program (ref. 10) shows extensive and continuing peeling and flaking even though maintained in an environmentally controlled and protected area. The half-width of the flaked area of the filter is about four times the half-width of the unflaked area.

## 6. Concluding Remarks

The Halogen Occultation Experiment (HALOE) is a solar occultation instrument that will fly on the Upper Atmosphere Research Satellite (UARS). The inversion of the HALOE data will be dependent on a detailed knowledge of the optical filters used in the HF, HCl, $CH_4$, and NO gas correlation channels and in the $CO_2$, $NO_2$, $H_2O$, and $O_3$ radiometer channels. A 2-year, measurement-feasibility study was conducted to define and determine the best way to perform the required filter characterization. The filter characterization was performed in-house using two moderate-resolution Fourier transform infrared spectrometers to perform various measurements over the spectral interval from 400 to 6300 $cm^{-1}$ (25 to 1.6 $\mu$m). The primary measurements were in-band transmission, throughput change with temperature, and out-of-band leaks. Measurements were also made of in-band stability with time and reflectivity. The in-band measurements are believed to have greater precision than any previously obtained and graphically show individual differences in filters from the same filter set and manufacturing run. The out-of-band measurements were generally made at the $10^{-4}$ percent transmission level and are believed to be of higher resolution than any similar out-of-band transmission measurements. These measurements have revealed a number of narrow leaks at the $10^{-2}$ percent transmission level and some greatly enhanced (several orders of magnitude) leaks of the two-element filters when placed in a Fabry-Perot cavity. The temporal stability and reflection measurements are strongly influenced by optical steering in the interferometer.

The optical filters procured and selected for the HALOE flight instrument are well-suited, in terms of in-band transmission and normal out-of-band rejection, for meeting the HALOE scientific objectives.

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Table I. HALOE Optical Filter Characteristics

| Filter | In-band frequency, $cm^{-1}$ | Substrate | Diameter, in. |
|---|---|---|---|
| HF | 4100 | $SiO_2$ | 1.1 |
| $CO_2$ | 3600 | $SiO_2$ | .8 |
| HCl | 2900 | $SiO_2$ | 1.1 |
| $CH_4$ | 2900 | $SiO_2$ | 1.1 |
| NO | 1900 | Ge | 1.1 |
| $NO_2$ | 1600 | Ge + $MgF_2$ | .8 |
| $H_2O$ | 1500 | Ge + $MgF_2$ | .8 |
| $O_3$ | 1000 | Ge + ZnS | .8 |

Table II. Spectral Shift of Filters

| Filter | Frequency, $cm^{-1}$ | $\Delta v/\Delta T$, $cm^{-1}/°C$ |
|---|---|---|
| $O_3$ | 1000 | 0.11 |
| $H_2O$ | 1500 | .19 |
| $NO_2$ | 1600 | .02 |
| NO | 1900 | .23 |
| $CH_4$ | 2900 | .36 |
| HCl | 2950 | .39 |
| $CO_2$ | 3600 | .23 |
| HF | 4100 | .40 |

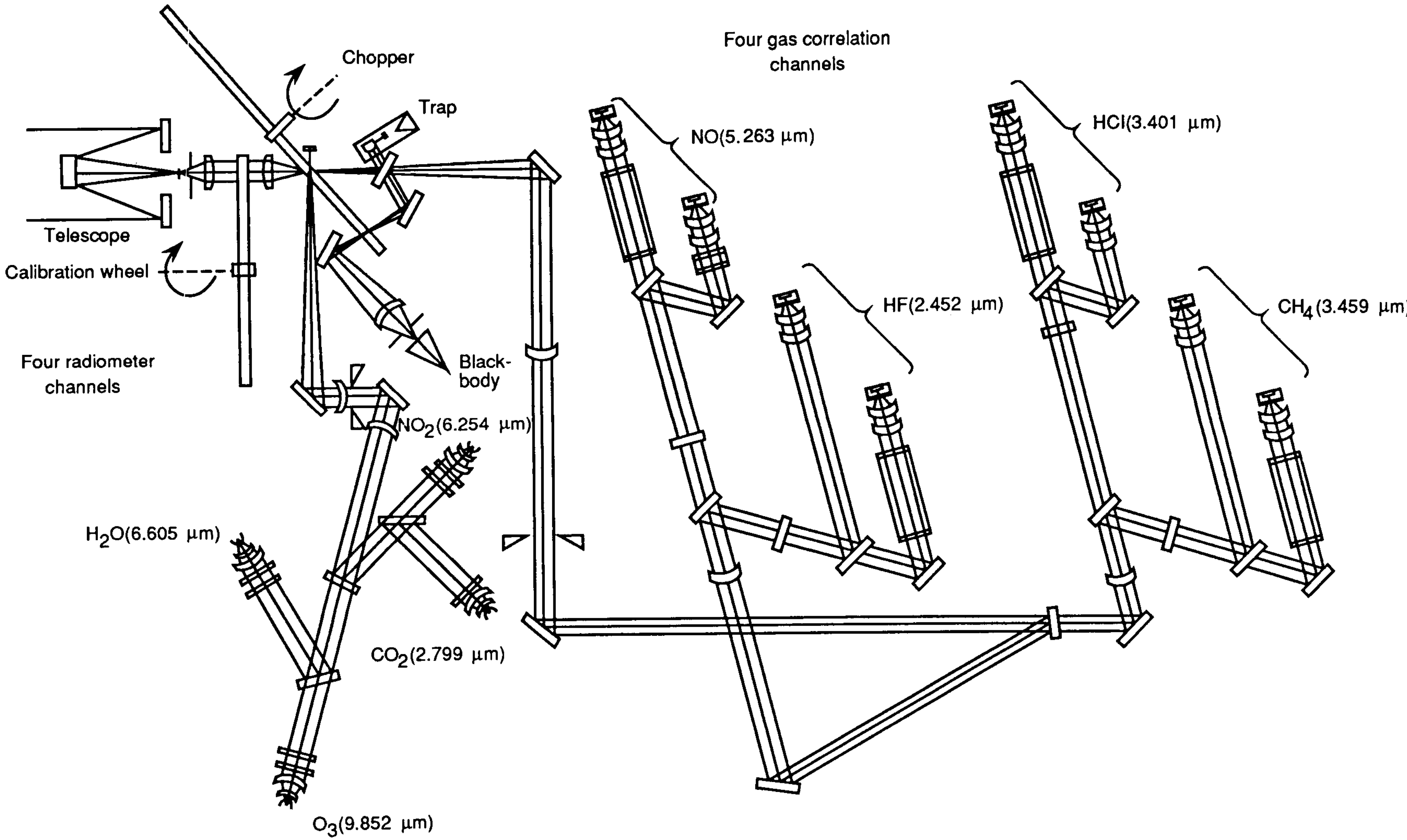


Figure 1. HALOE optical schematic.

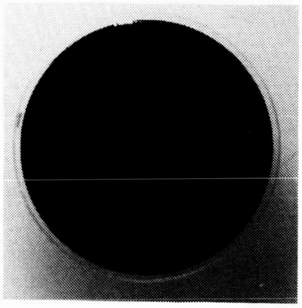

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Figure 2. Photograph of a gas correlation-channel filter.

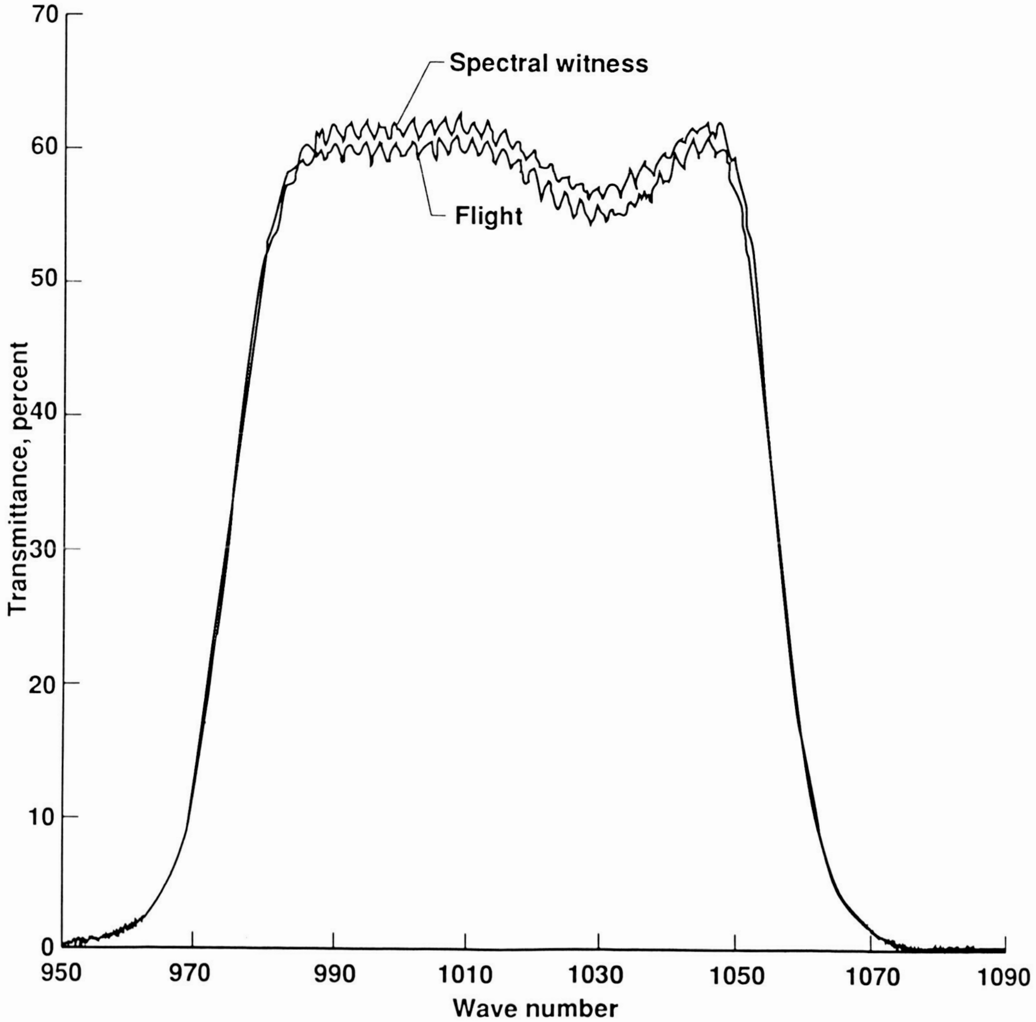


Figure 3. Transmissions of two $O_3$ filters.

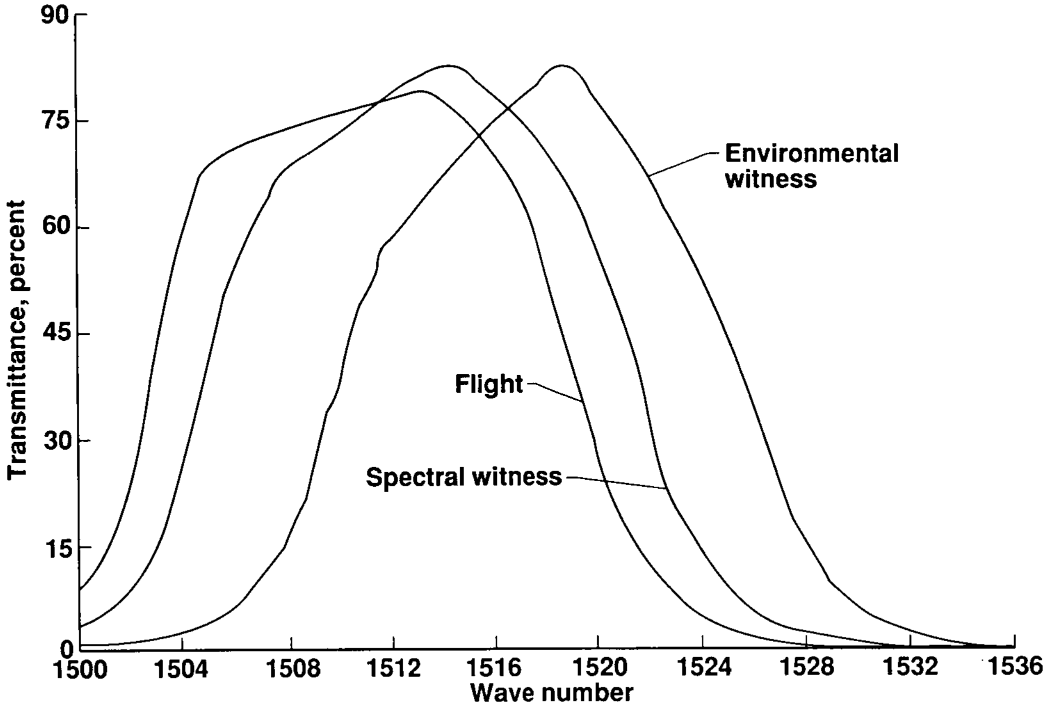


Figure 4. Transmissions of three $H_2O$ filters.

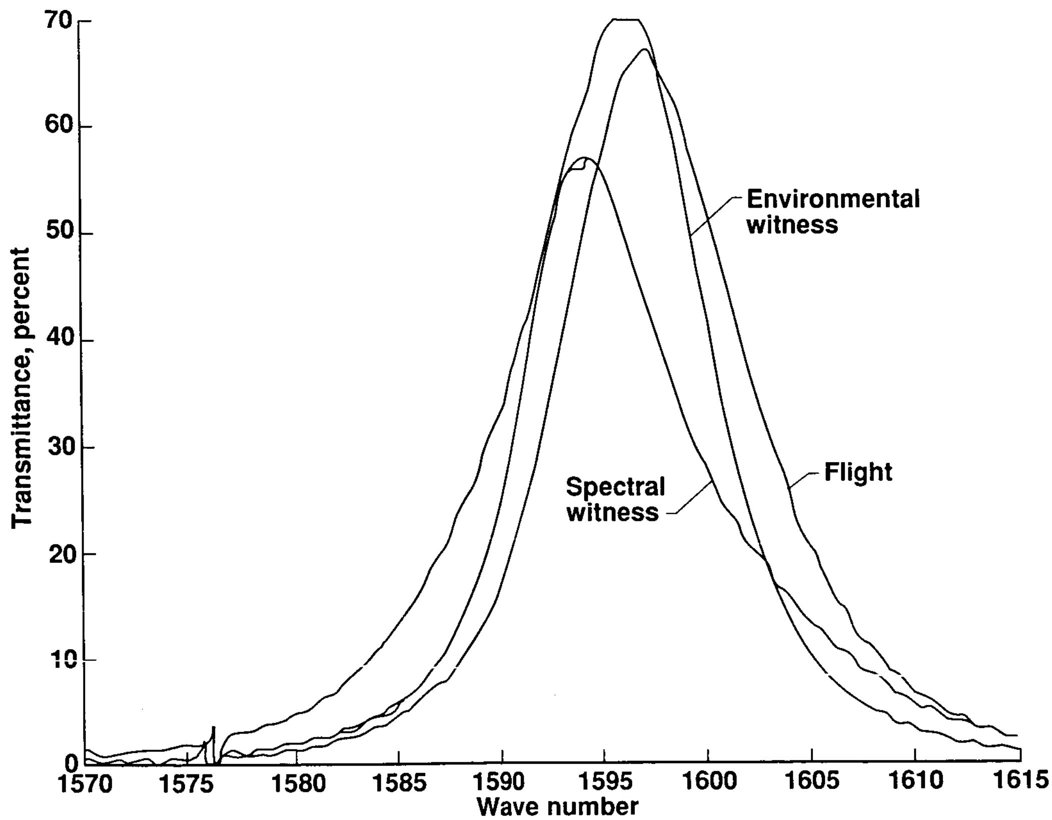


Figure 5. Transmissions of three $NO_2$ filters.

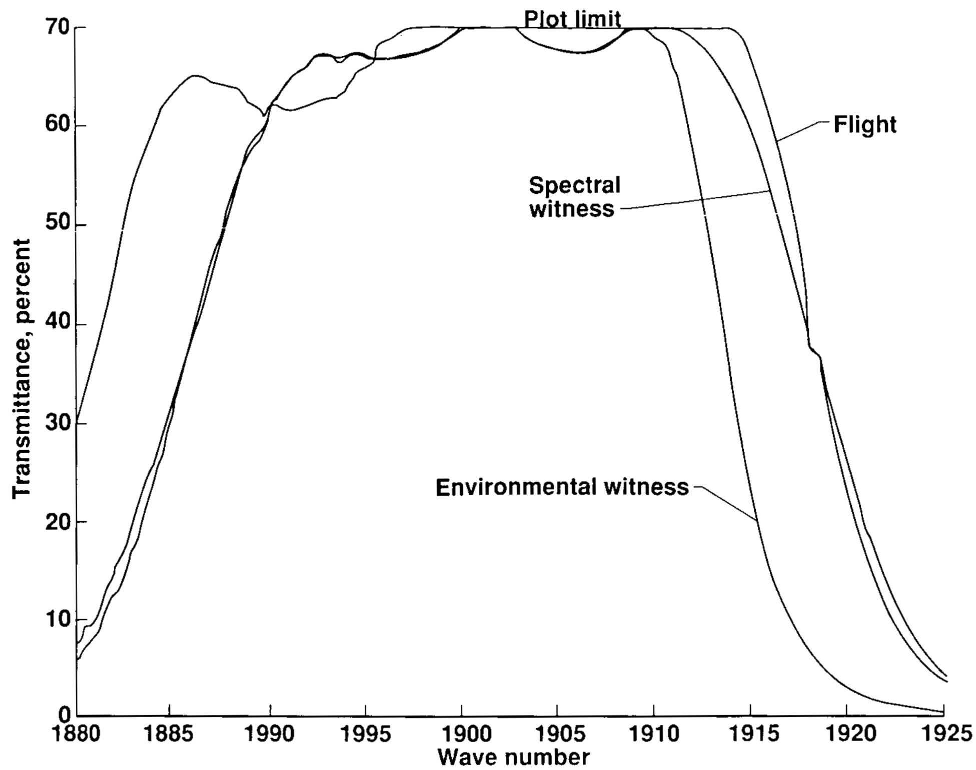


Figure 6. Transmissions of three NO filters.

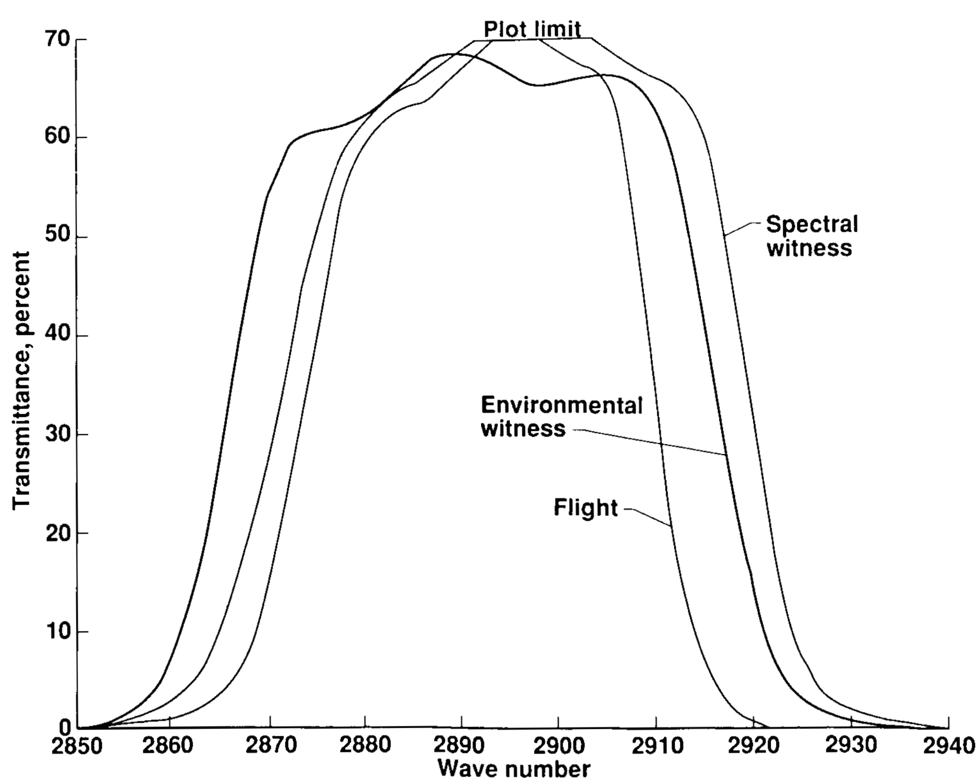


Figure 7. Transmissions of three $CH_4$ filters.

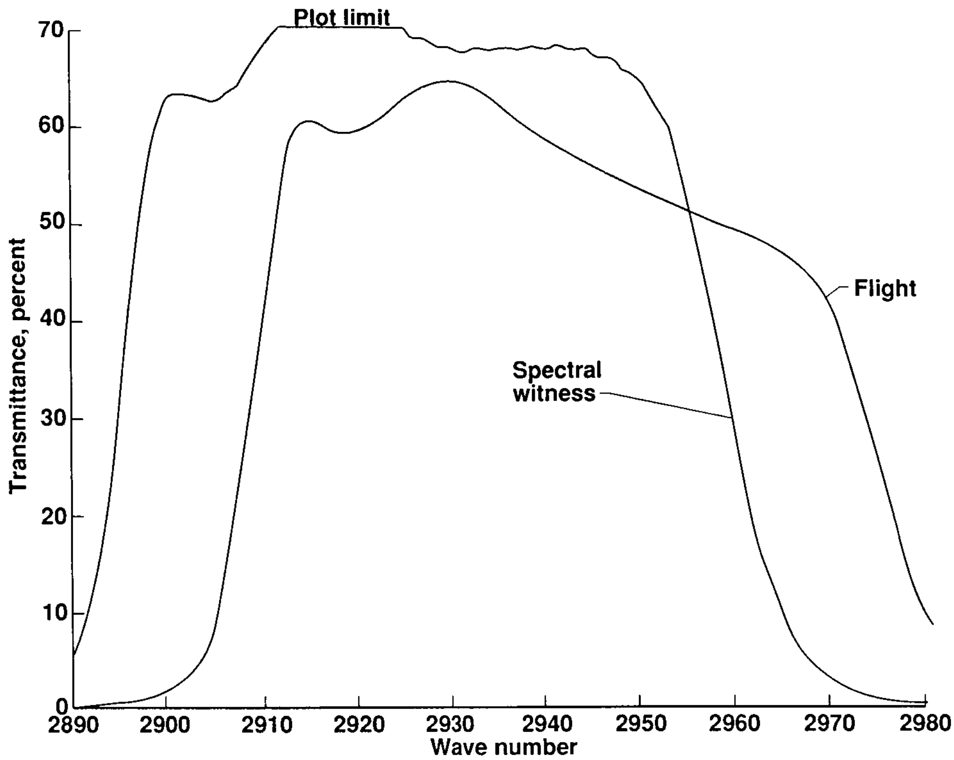


Figure 8. Transmissions of two HCl filters.

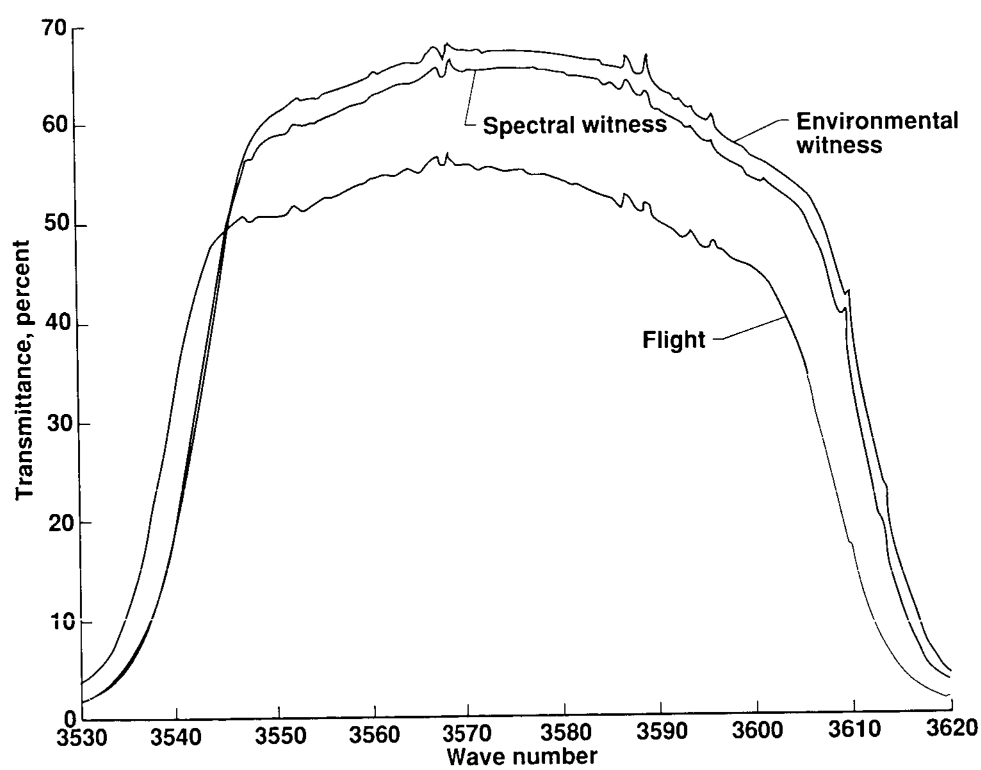


Figure 9. Transmissions of three $CO_2$ filters.

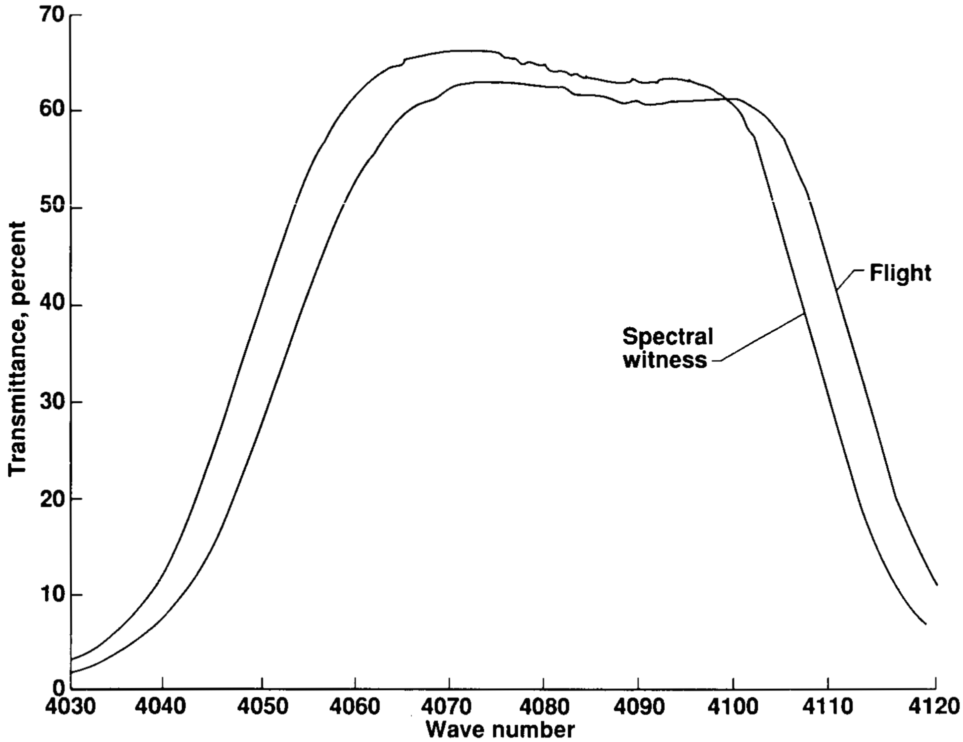


Figure 10. Transmissions of two HF filters.

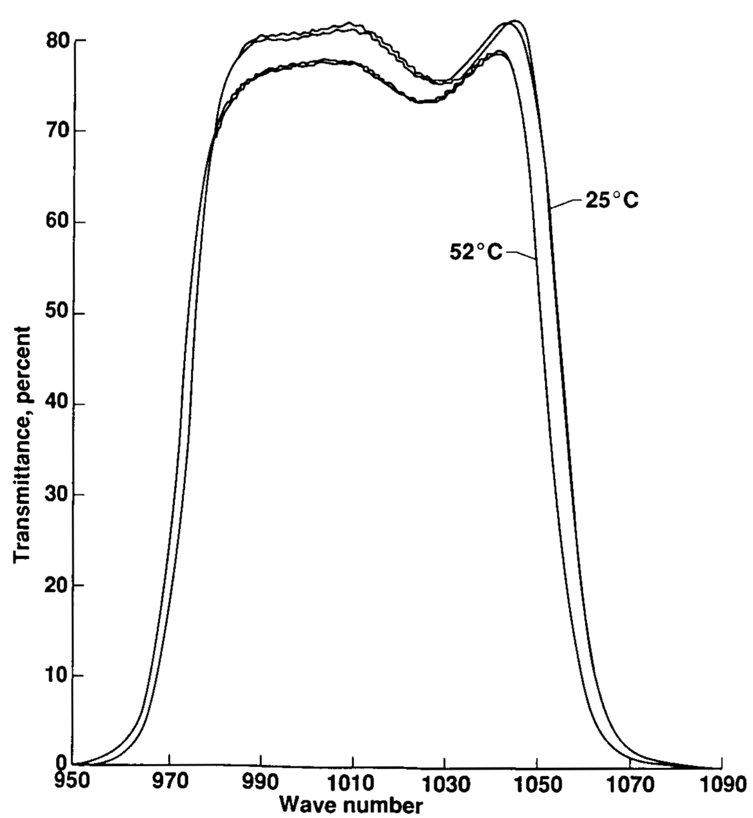


Figure 11. Throughput of $O_3$ flight filter.

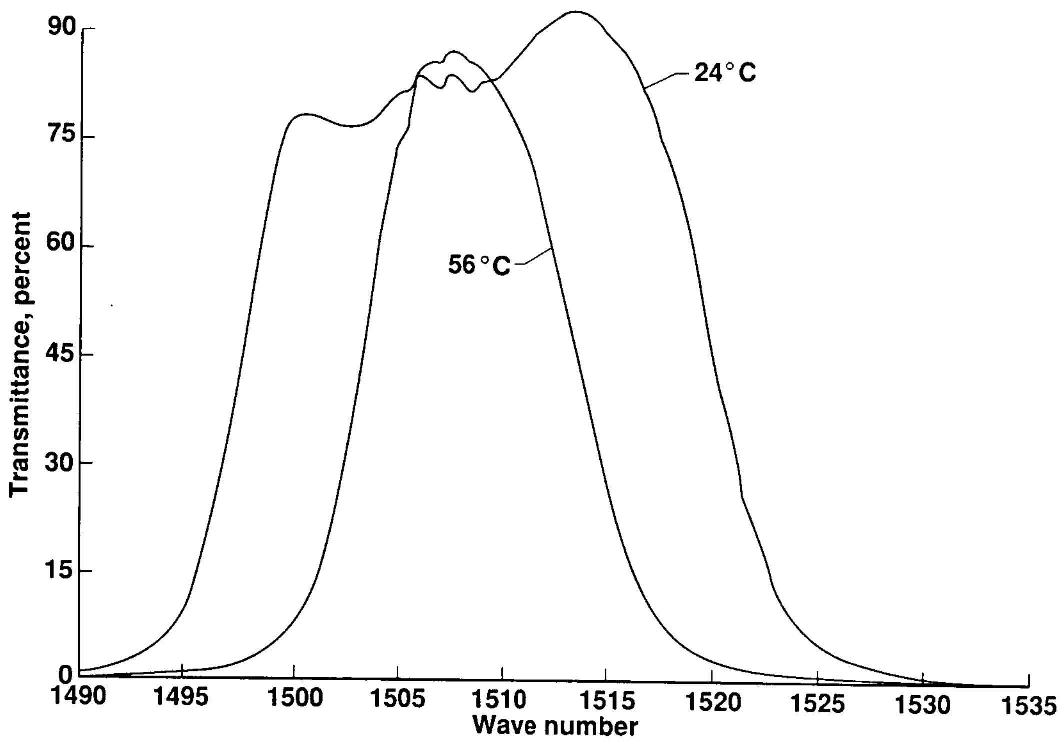


Figure 12. Throughput of $H_2O$ flight filter.

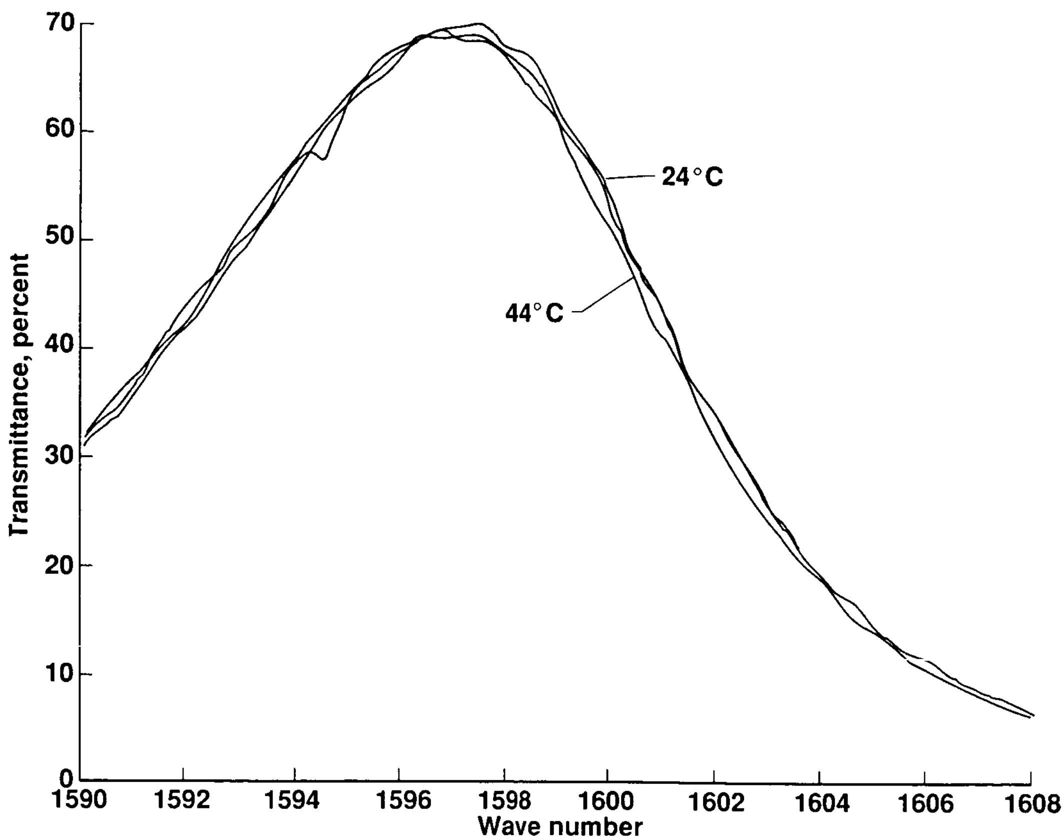


Figure 13. Throughput of $NO_2$ flight filter.

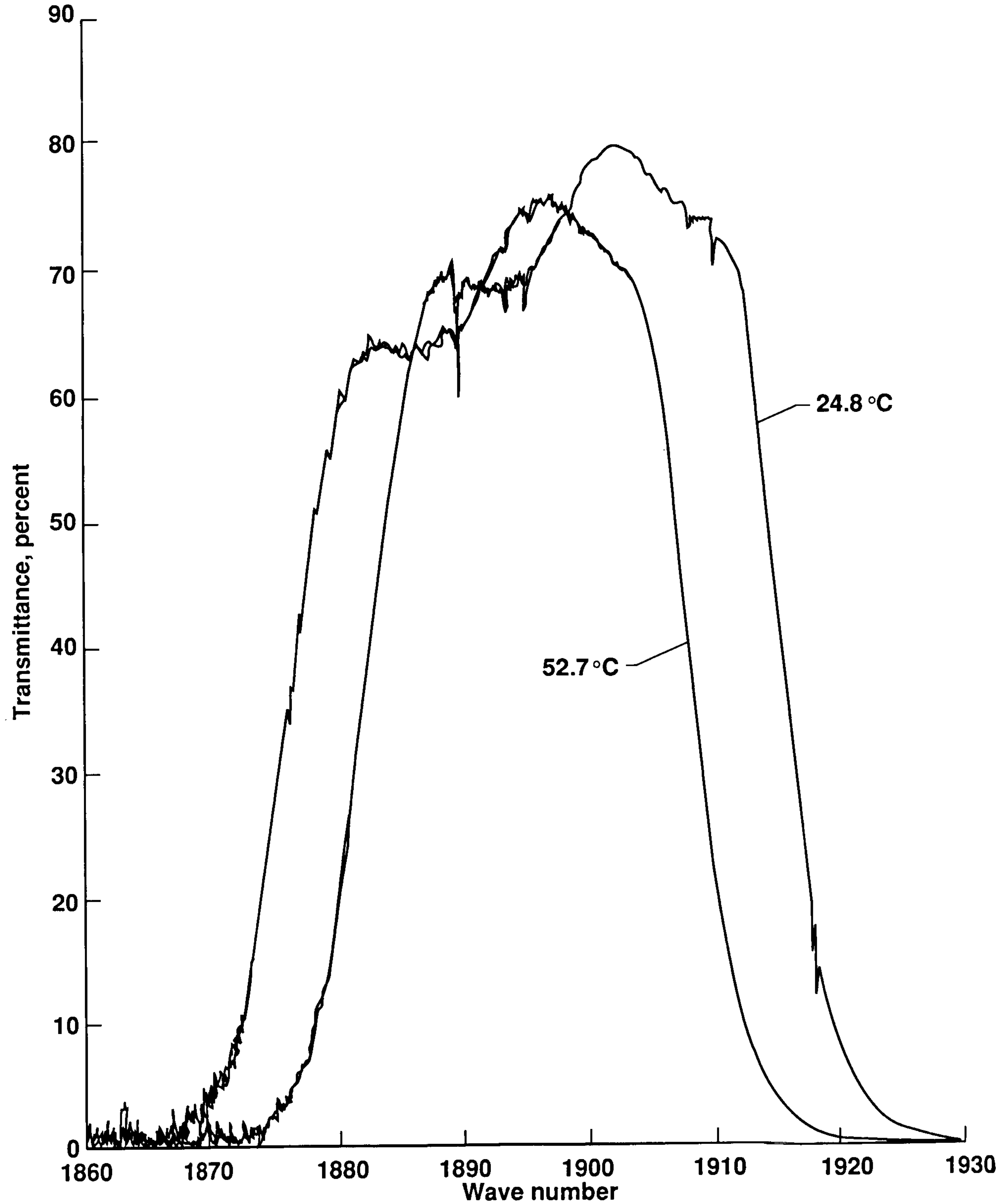


Figure 14. Throughput of NO flight filter.

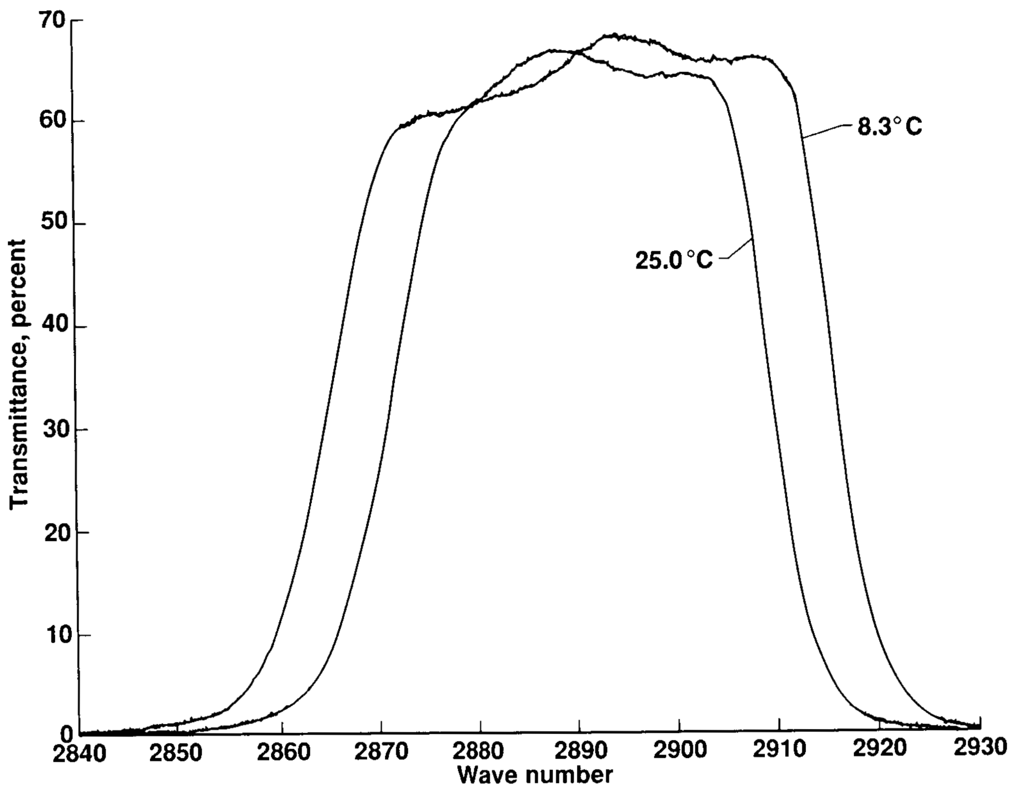


Figure 15. Throughput of $CH_4$ flight filter.

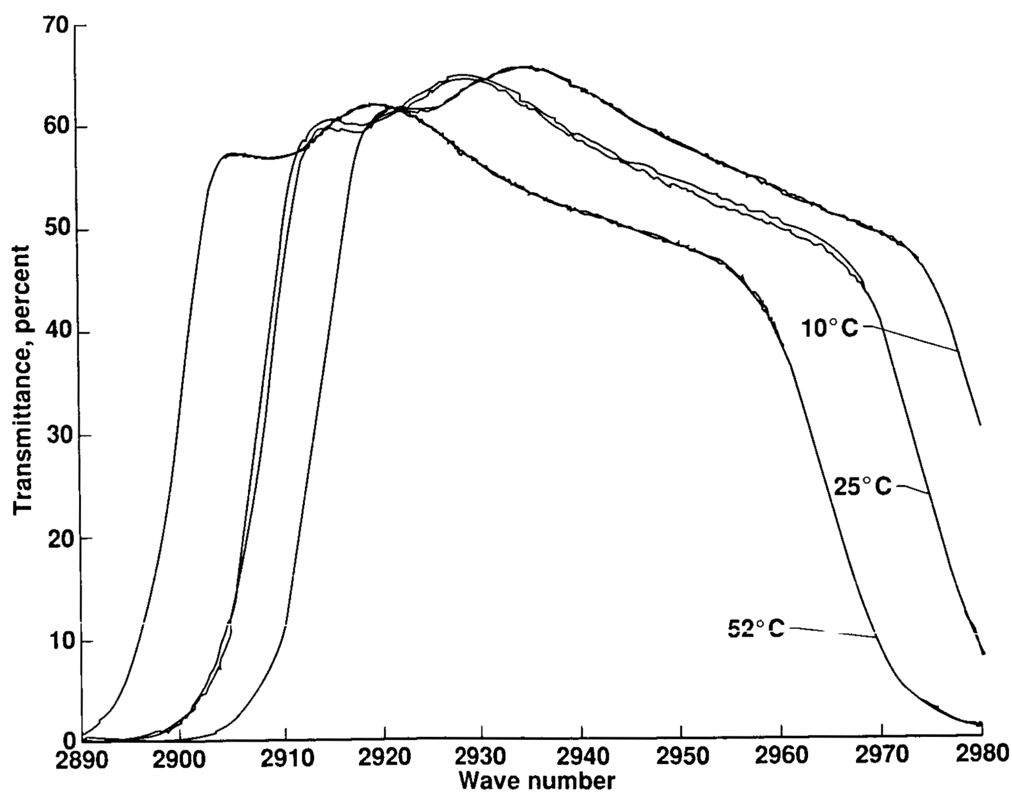


Figure 16. Throughput of HCl flight filter.

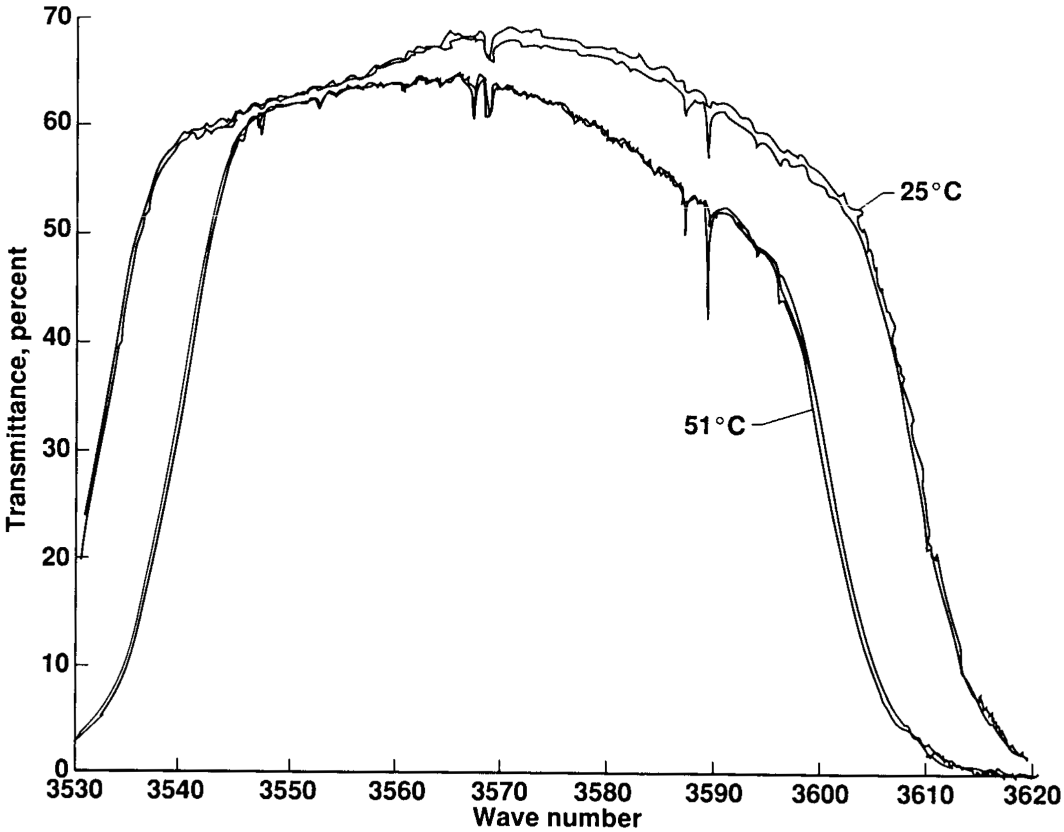


Figure 17. Throughput of $CO_2$ flight filter.

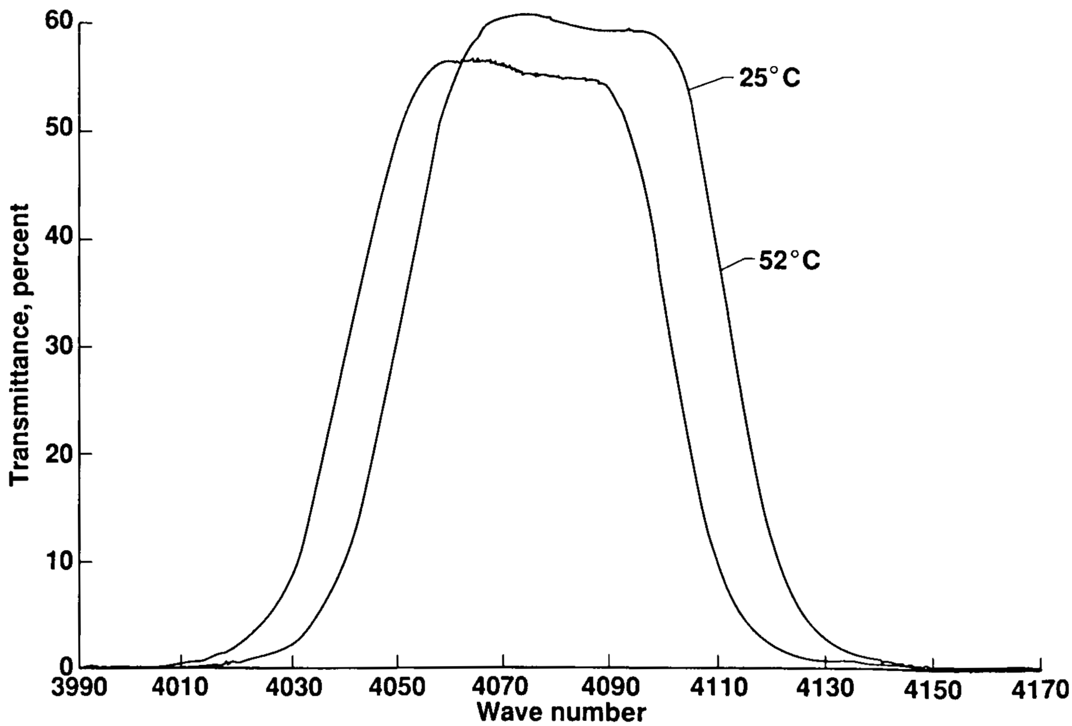


Figure 18. Throughput of HF flight filter.

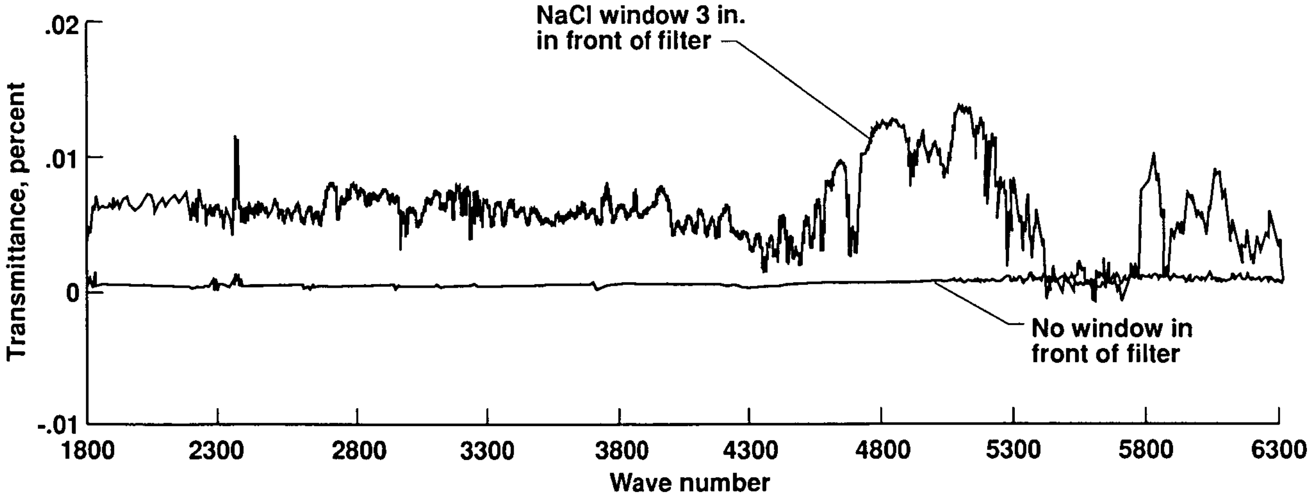


Figure 19. Out-of-band transmissions of $O_3$ flight filter.

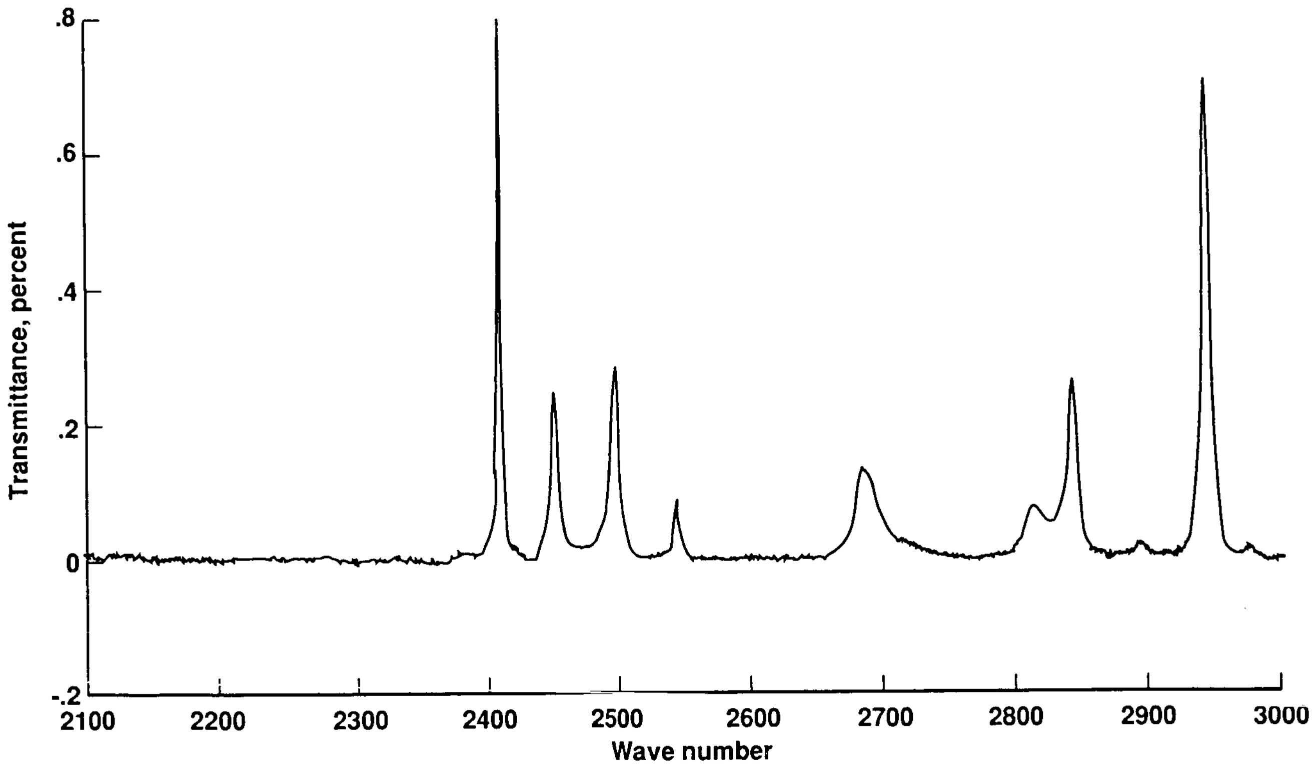


Figure 20. Out-of-band Fabry-Perot transmission of $H_2O$ flight filter.

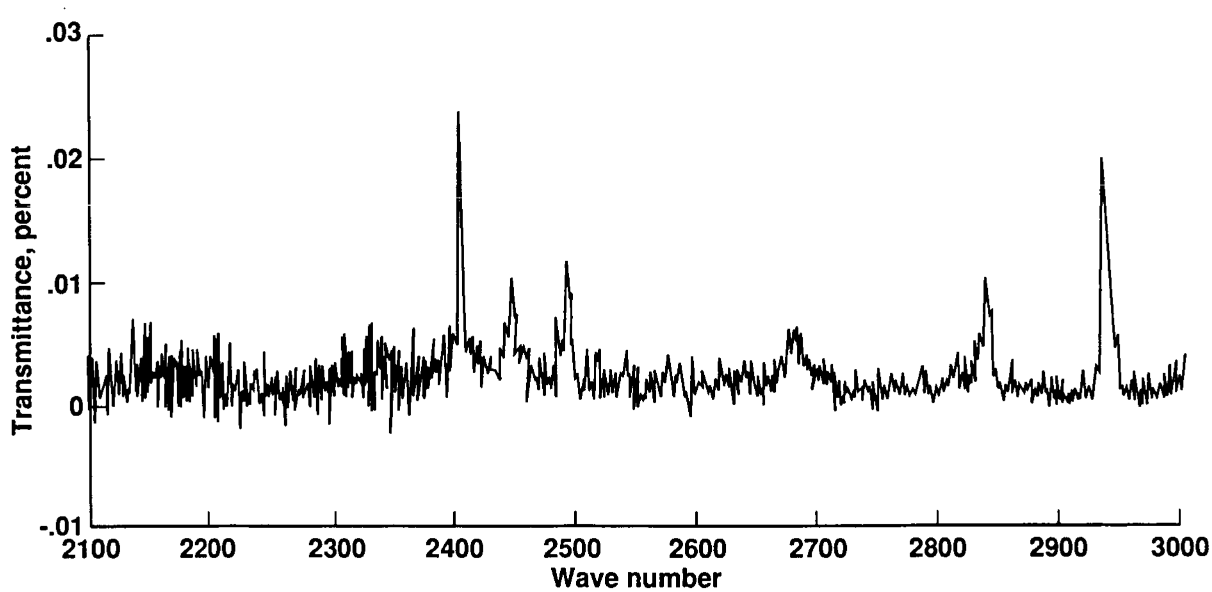


Figure 21. Out-of-band transmission of $H_2O$ flight filter.

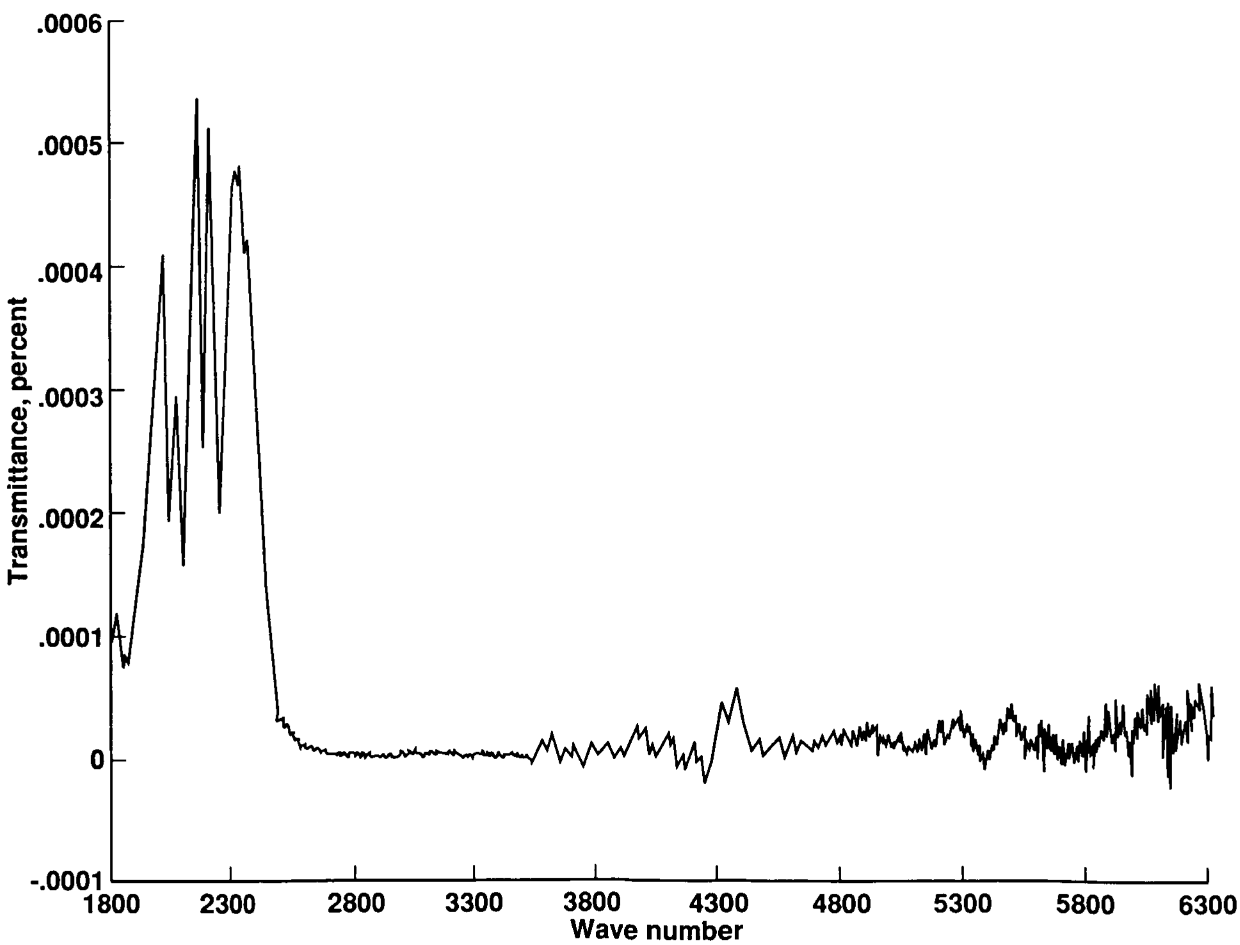


Figure 22. Out-of-band transmission of $NO_2$ flight filter.

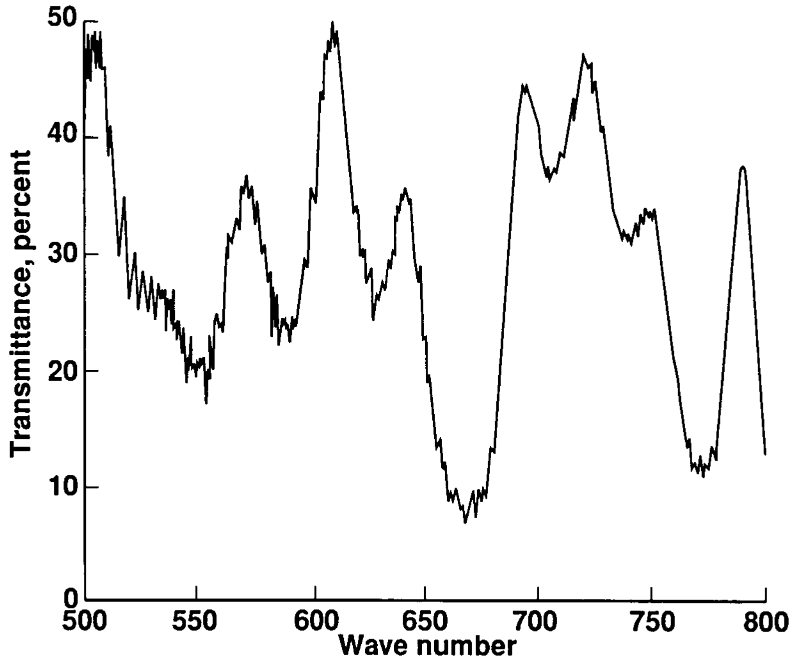


Figure 23. Long wavelength out-of-band transmission of NO flight filter.

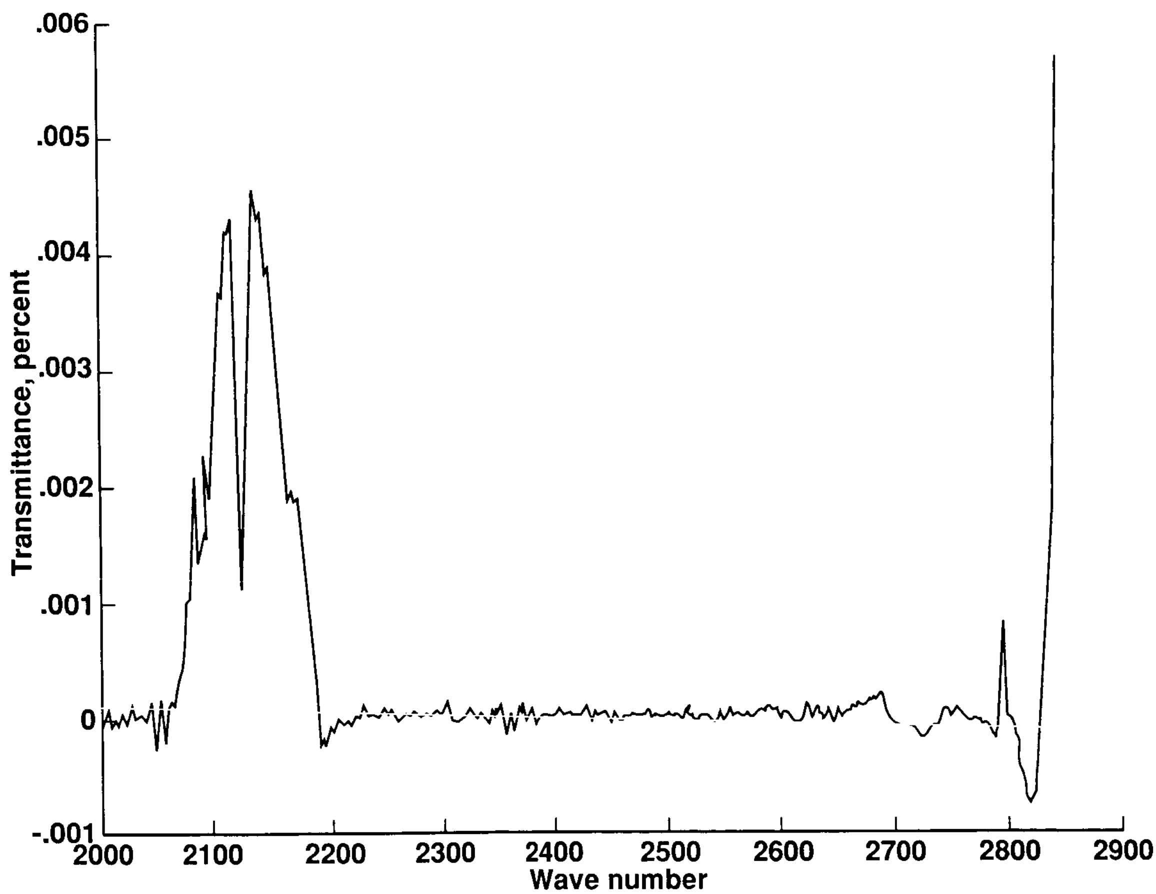


Figure 24. Mid-IR out-of-band transmission of $CH_4$ flight filter.

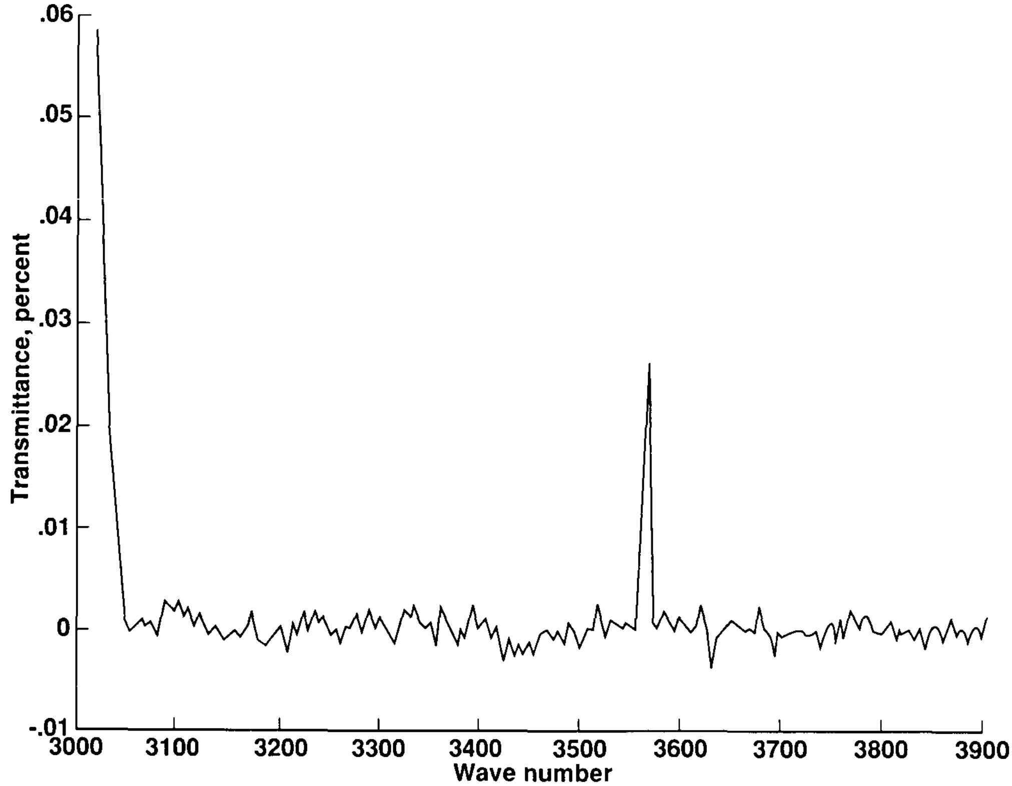


Figure 25. Mid-IR out-of-band transmission of HCl flight filter.

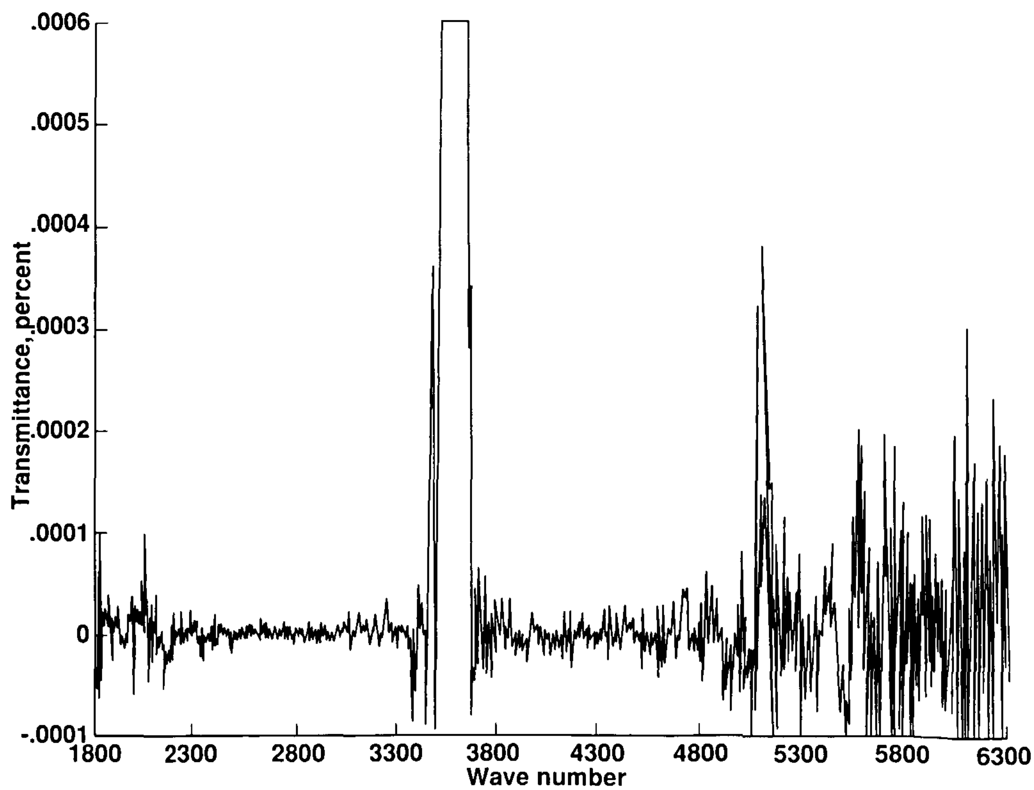


Figure 26. Out-of-band transmission of $CO_2$ flight filter.

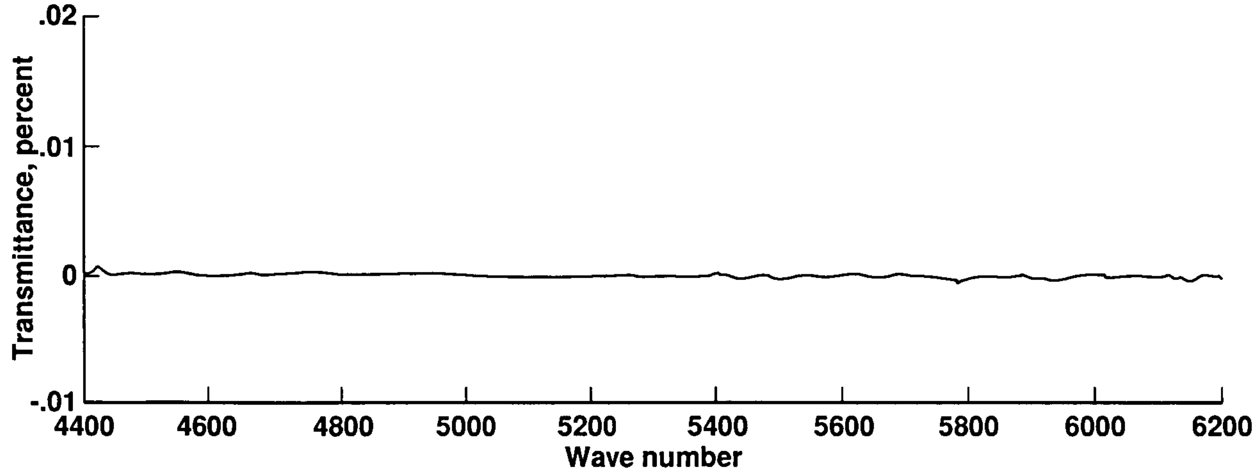


Figure 27. Out-of-band transmission of HF flight filter.

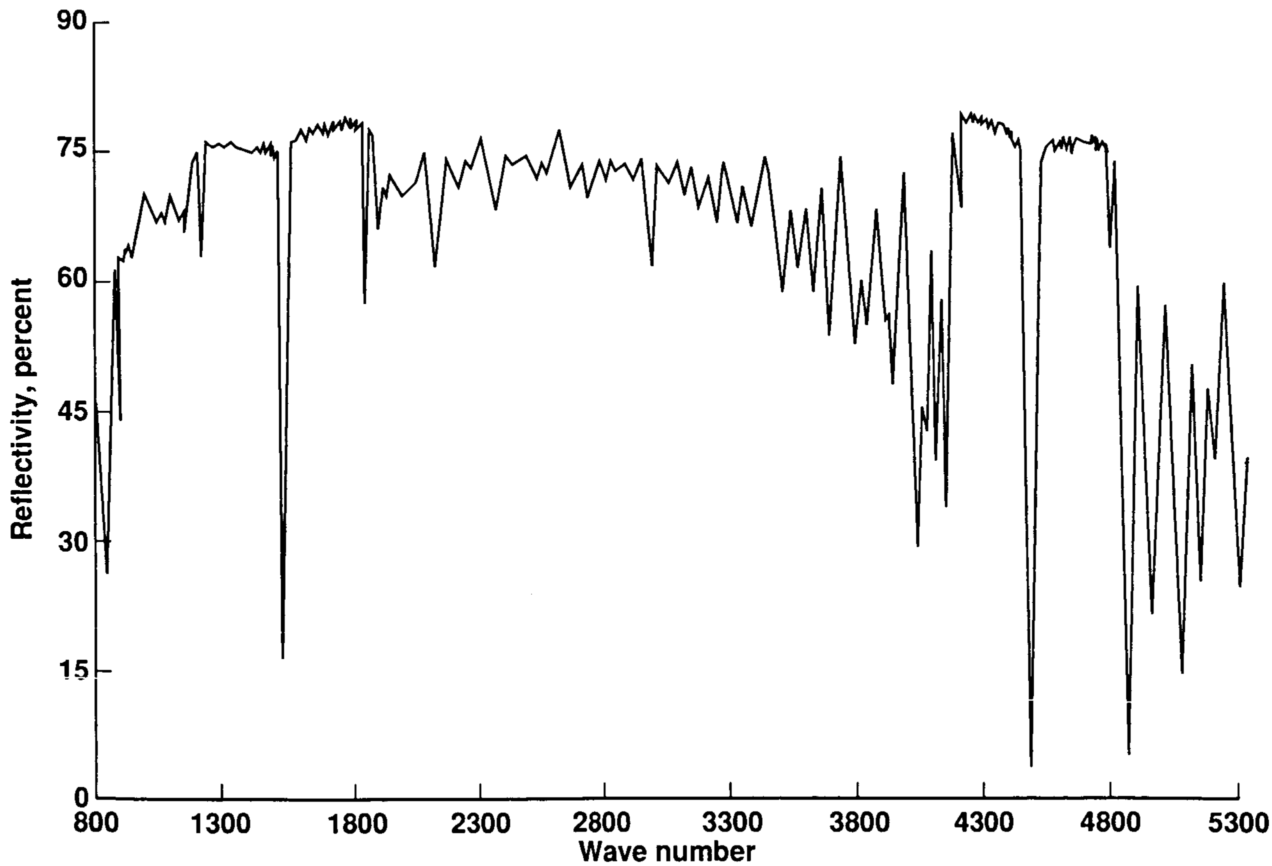


Figure 28. Reflectivity of $H_2O$ flight filter.

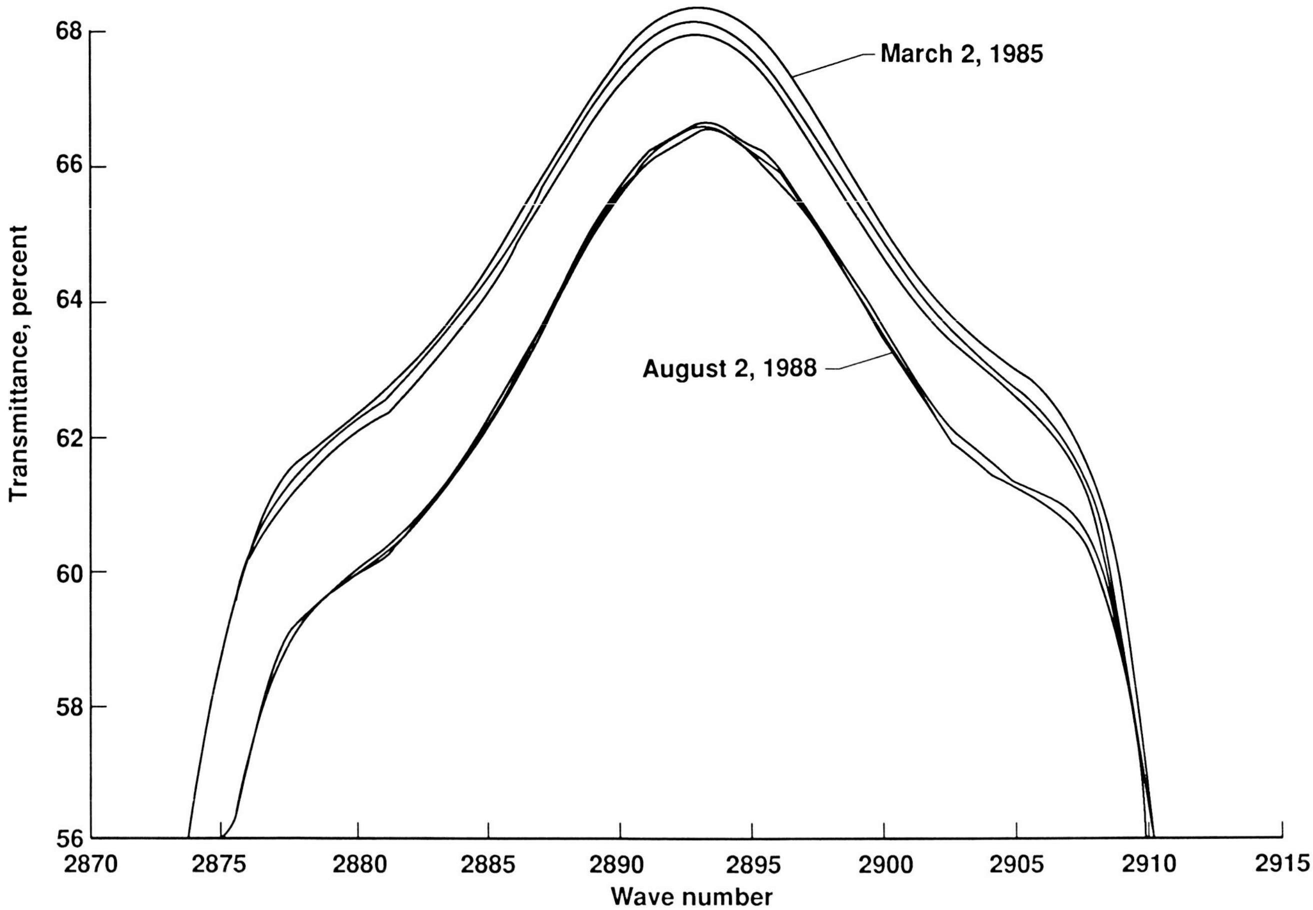


Figure 29. $CH_4$ filter-measured transmission at two epochs.

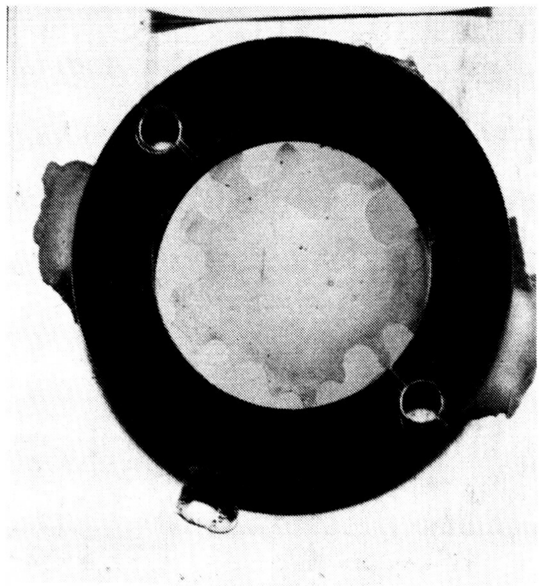

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Figure 30. Photograph of deteriorated MAPS filter.

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15. Supplementary Notes

16. Abstract

The Halogen Occultation Experiment (HALOE) is a solar occultation instrument that will fly on the Upper Atmosphere Research Satellite to measure mixing ratio profiles of $O_3$, $H_2O$, $NO_2$, NO, $CH_4$, HCl, and HF. The inversion of the HALOE data will be critically dependent on a detailed knowledge of eight optical filters. A filter characterization program was undertaken to measure in-band transmissions, out-of-band transmissions, in-band transmission shifts with temperature, reflectivities, and age stability. Fourier transform infrared spectrometers were used to perform measurements over the spectral interval from 400 to 6300 cm$^{-1}$ (25 to 1.6 $\mu$m). Very high precision ($10^{-1}$ percent transmission) in-band measurements and very high resolution ($10^{-4}$ percent transmission) out-of-band measurements were made. The measurements revealed several conventional leaks at $10^{-2}$ percent transmission and greatly enhanced ($10^3$) leaks of the two-element filters when placed in a Fabry-Perot cavity. Filter throughput changes by 5 percent for a 25°C change in filter temperature.

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