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"Instruments for Remote Sensing of Atmospheric Parameters "

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Instruments for Remote Sensing of Atmospheric Parameters

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Introduction

Remote sensing is defined as the acquisition of information about an object without being in phisical contact with it. Information is acquired by detecting and measuring changes that the object imposes on the surrounding field, be it an electromagnetic, acustic or potential field. The term "*remote sensing* " is most commonly used in connection with electromagnetic techniques of information acquisition. These techniques cover the whole electromagnetic spectrum from the low frequency radio waves through the microwave, far infrared, near infrared, visible, and so on. The advent of satellites is allowing the acquisition of global and synoptic detailed informaticn about the planets (including Earth) and their environments. Sensors on Earth-orbiting satellites provide information about global patterns and dynamics of clouds, surface vegetation coverand its seasonal variations, surface morphologic structures, ocean surface temperature and near–surface wind. The rapid wide coverage capability of satellite platforms allows monitoring of rapidly changing phenomena, particularly in the atmosphere.

Transmission Through The Earth And Planetary Atmospheres

The presence of an atmosphere puts limitation or the spectral regions that can be used to observe the underlying surface. This is a results of wave interactions with atmosperic and ionospheric constituents leading to absorption or scattering in specific spectral region (Fig. 1).

At radio frequencies below 10 MHz, the Earth's ionosphere blocks any transmission to or from surface. In the rest of the radio frequency region, up to the low microwave (10 GHz) the atmosphere is effectively transparent. In the rest of the microwave region there are a number of strong absorption bands, mainly associated with water vapor and oxygen. In the far infrared region the atmosphere is almost completely opaque and the surface is invisible. The opacity is mainly due to the presence of absorption spectral bands associated with the atmospheric constituents. This makes the spectral region most

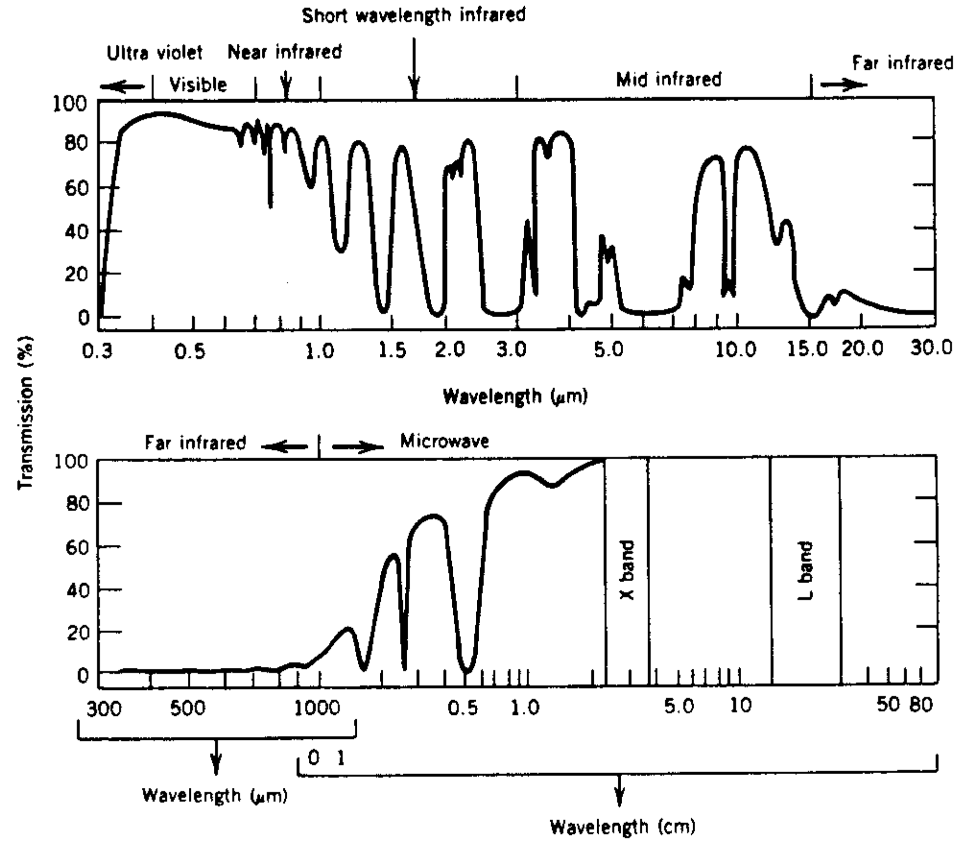

Figure 1. Generalized absorption spectrum of the earth's atmosphere at zenith. The curve shows the total atmospheric transmission.

appropriate for atmospheric remote sensing. The opacity of the atmosphere in the visible and near infrared region is high in selected bands where the high absorption coefficients are due to a variety of electronic and vibrational processes mainly related to the water vapor and carbon dioxide molecules. In the ultraviolet, the opacity is mainly due to the ozone layer in the upper atmosphere. The presence of clouds leads to additional opacity due to absorption and scattering by clouds drops. This limits the observation capabilities in the visible and infrared regions. In the microwave and radic frequency regions, clouds are basically transparent.

Principles of Instrument Design

The important quantities which determine the quality of a given set of instruments are the vertical resolution and the accuracy of the measurements. To be adequate for meteorological purposes, measurements of the mean temperature over layer 200 mbar thick need to be made with a probable error of less than 1 K. For radiance measurements in the 15 micron CO_2 band, an error of 1 K in temperature roughly corresponds to 1 % in radiance. Since metereologist are more interested in spatial and temperal gradients of temperature than in absolute values, relative accuracy between similar instruments on the same spacecraft or between different channels of the same instruments is more important than absolute accuracy. The requirement for absolute accuracy is that there should be compatibility with the radiosonde network. To realize compatibility between remote measurements and radiosondes, empirical adjustments can be made on the basis of detailed comparisons. The basic components of a radiometer for temperature sounding in a clear atmosphere are an optical system for defining the field of view and gathering the energy, a monocromator to define the spectral band pass and a detector. An instrument possessing a performance close to the theoretical limit would have a spectral resolution small compared with the width of an individual spectral line and an error of measurement equivalent to a temperarture error of much less than 1 K, the time for a measurement for an instrument based on a satellite in fairly low polar orbit being much less than one second if adequate horizontal resolution is to be obtained. The number of independent spectral channels required to cover the lowest 50km of a clear atmosphere is about 6. However, because of the need to identify surface characteristics, clouds and water vapor distribution as well, something more like twice this number of channels are required in practice. For radiometers operating in the infrared part of the spectrum the required precision of measurement is possible although not easy to achieve. A further class of instrument is the Fourier transform interferometric spectrometer, an example of which is the Michelson interferometer. In this instrument the spectrum is observed all the time. As the path difference between the two beams within the instrument is changed, an interferogram results from which the spectrum is obtained by numerical transformation. A number of instruments have been developed for flight on the Nimbus series of satellites. In the following sections instruments which have been flown or are being developed are described.

The NIMBUS Satellite Series.

The Nimbus satellite program was initiated by the National Aeronautics and Space Administration in the early 1960s to develop an observational system capable of meeting the research and development needs of atmospheric and earth scientists. The general objectives of the program were:

- to develop advanced passive radiometric and spectrometric sensor for daily global surveillance of the atmosphere of the earth and thereby provide a data base for long-range weather forcasting;
- to develop and evaluate new active and passive sensor for sounding the atmosphere of the earth and mapping surface characteristics;
- to develope advanced space technology and ground techniques for meteorological and other earth–observational spacecraft;
- to develop new techniques and knowledge useful for the exploration of other planetary atmospheres;
- to partecipate in global observation programs (World Weather Watch) by expanding daily global weather observation capability (National Research Council, 1978).

The Nimbus System was designed to be the test-bed for advanced instruments for the future operational TIROS polar orbiting satellites and the research system for remote sensing and data collection . A total of seven Nimbus spacecraft were successfully placed into orbit from 1964 through 1978. The final spacecraft, Nimbus 7, was launched in November 1978. This spacecraft was instrumented with sensor to monitor the atmospheric pullulants, oceanography, and weather and climate (Fig. 2).

The payload consisted of eight instruments :

1. Scanning Multichannel Microwave Radiometer (SMMR). Measures radiances in five wavelengths and ten channels to extract information on sea surface roughness and winds, sea surface temperature, cloud liquid-water content total water–vapor content, precipitation (mean droplet size), soil moisture, snow cover and sea ice.
2. Stratospheric and Mesopheric Sounder (SAMS); measures vertical concentrations of H_2O, N_2O, CH_4, CO and NO; measures temperature of stratosphere to 90km and trace constituents.
3. Solar-Backscattered Ultraviolet/Total Ozone Mapping System (SBUV/TOMS); mea-

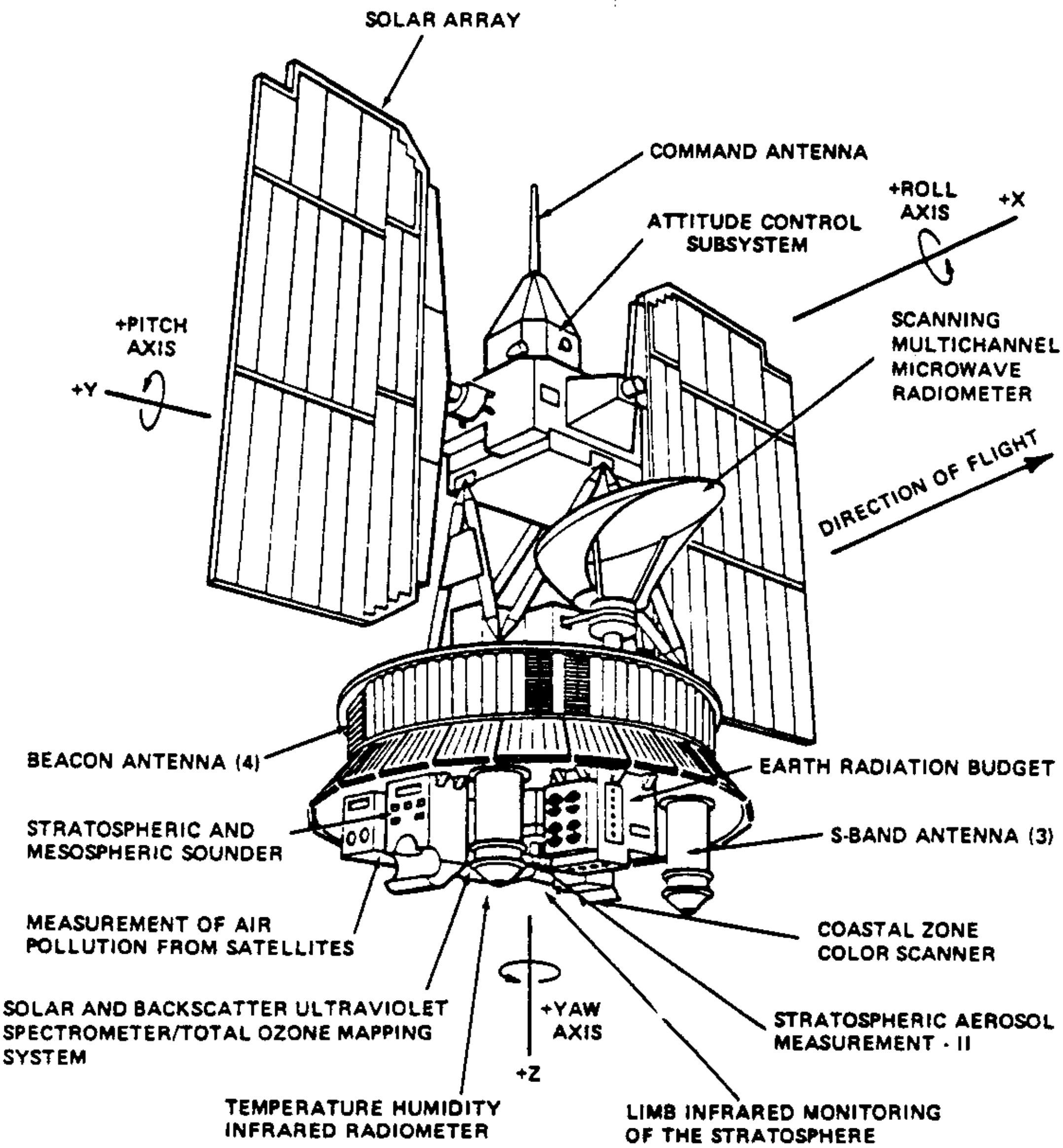

Figure 2. Schematic view of NIMBUS-7 Spacecraft.

sures direct and backscattered solar UV to extract information on variations of solar radiance, vertical distribution of ozone and total ozone on a global basis.

4. Earth Radiation Budget (ERB); measures short and longwave upwelling radiances and fluxes and diret solar irradiance to extract information on the solar constant, earth albedo, emitted longwave radiation, and the anisotropy of the outgoing radiation.
5. Costal Zone Color Scanner (CZCS); measures chlorophyl concentration, sediment distribution, gelbstoff (yellow substance) concentration as a salinity indicator, and temperature of coastal water and open ocean.
6. Stratospheric Aerosol Measurement II Experiment (SAM II); measures the concentration and optical proprieties of stratospheric aerosols as a function of altitude, latitude, and longitude. Tropospheric aerosols can be mapped also if no clouds are present in the IFOV.
7. Temperature Humidity Infrared Radiometer Experiment (THIR); measures the infrared radiation from the earth in two spectral bands (11 and 6.7 micron) both day and night to provide pictures of cloud cover; three-dimensional maps of clouds cover; temperature maps of cloud, land, and ocean-surface and atmospheric moisture.
8. Limb Infrared Monitoring of the Stratospheric Experiment (LIMS); makes a global survey of selected gases from the upper troposphere to the lower mesosphere. Inversion techniques are used to derive gas concentrations and temperature profiles.

TIROS-N

The third generation operational polar orbiting environmental satellite system, designated TIROS-N, completed development and was placed into operational service in 1978. Eight spacecraft in this series provide global observational service. This new series has a new complement of data-gathering instruments. One of this instruments, AVHRR (Advanced Very High Resolution Radiometer), increases the amount of radiometric information for more accurate sea-surface temperature mapping and identification of snow and sea ice, in addition to day and night imaging in the visible and infrared bands. Other instruments, contained in a subsystem known as TOVS (TIROS Operational Vertical Sounder), provide improved vertical sounding of the atmosphere. These instruments are the HIRS/2 (High Resolution Infrared Radiation Sounder), the SSU (Stratospheric Sounding Unit), and the MSU (Microwave Sounding Unit). A Data Collection System (DCS) receives environmental data from fixed or moving platforms such as buoys or balloons and retains them for transmission to ground station.

The AVHRR for TIROS-N and four follow-on satellites is a four-channel scan- ning radiometers, sensitive to visible/near IR and infrared (IR) radiation. The channels (Table 1.) have been chosen to permit multispectral analyses which provide estimates of hydrologic, oceanographic, and meteorological parameters.

Table 1.AVHRR Channels characteristics.

Protoflight Instrument (1)
1.* 0.55 – 0.90 μm
2. 0.725– 1.10 μm
3. 3.55 – 3.93 μm
4. 10.5 –11.5 μm
5. Channel 4 data repeated

Four-Channel Flight Instruments (4)
1. 0.55 – 0.68 μm
2. 0.725– 1.10 μm
3. 3.55 – 3.93 μm
4. 10.5 –11.5 μm
5. Channel 4 data repeated

AVHRR/2—Five Channel Instruments (3)
1. 0.58 – 0.68 μm
2. 0.725– 1.10 μm
3. 3.55 – 3.93 μm
4. 10.3 –11.3 μm
5. 11.5 –12.5 μm

Characteristics	Channels 1	2	3	4	5
Spectral Range (μm)	0.58–0.68	0.725–1.1	3.55–3.93	10.3–11.3	11.5–12.5
Detector	Silicon	Silicon	InSb	HgCdTe	HgCdTe
Resolution (km)	1.1	1.1	1.1	1.1	1.1
IFOV (mrad)	1.3	1.3	1.3	1.3	1.3
NETD @ 300 K	—	—	0.12	0.12	0.12
S/N 0.5% albedo	>3:1	>3:1	—	—	—
MTF (IFOV/single bar)	0.3	0.3	0.3	0.3	0.3

Optics: 8-inch diameter a focal cassegrainian telescope
Scanner: 360-rpm hysteresis synchronous motor
Cooler: 2-stage passive

* In-orbit data obtained after completion of the protoflight instrument has shown the necessity of eliminating spectral overlap with channel 2 if snow-cover areal extent is to be accurately measured.

The visible (0.6 micron) and near IR (0.9 micron) channels are used to discern clouds, land-water boundaries and snow and ice extent. The IR window channels are used to measure cloud distribution and to determine temperature of the radiating surface (cloud or surface). Starting with NOAA-7 and on later spacecraft in the series, a third IR channel is added to provide the capability for removing radiant contributions from water vapor when determining surface temperature. Prior to inclusion of this third channel, corrections for water vapor contributions were based on statistical means using climatological estimates of water vapor content.

The TOVS system has been designed to determine temperature profiles from the surface to 10mb, water vapor content at three levels of the atmosphere, and the total ozone content. HIRS/2 is an adaptation of the HIRS/1 instrument designed for and flown on the NIMBUS 6 satellite. The instrument measures incident radiation in 20 spectral regions of the IR spectrum, including both longwave (15 micron) and shortwave (4.3 micron) regions (Table 2a).

The HIRS/2 utilizes a 15-cm diameter optical system to gather emitted energy from the atmosphere of the earth. The instantaneous field of view (IFOV) of all the channels is stepped across the satellite track by use of rotating mirror. This across-track scan, combined with the motion in orbit of the satel- lite, provides coverage of a major portion of the surface of the earth. The energy recieved by the telescope is separated by a dicrhroic beam–splitter into longwave (above 6.4 micron) energy and shortwave (below 6.4 micron) energy controlled by field stops and passed through bandpass filters and relay optics to the detector. Essential parameters of the instrument are shown in Table 2b.

Table 2b.HIRS/2 System Parameters.

Parameter	*Value*
Calibration	Stable Blackbodies (2) and Space Background
Cross-Track Scan	±49.5° (±1120 km)
Scan Time	6.4 Seconds
Number of Channels	20
Number of Steps	56
Optical FOV	1.25°
Step Angle	1.8°
Step Time	100 Milliseconds
Ground IFOV (Nadir)	17.4 km Diameter
Ground IFOV (End of Scan)	58.5 km Cross-Track by 29.9 km Along-Track
Distance Between IFOV's	42 km Along-Track
Data Rate	2880 Bits/Second
Dectors: Long Wave	HgCdTe
Short Wave	InSb
Visible	Silicon

SSU is supplied by the United Kingdom Meteorological Office. It employs a selective absorption technique to make measurements in three channels. The principles of operation are based on the selective chopper radiometer flown on Nimbus 4 and 5, and a Pressure Modulator Radiometer (PMR) flown on Nimbus 6. Basic characteristics are shown in Table 3.

Table 2a. HIRS/2 Channels characteristics.

Channel number	Channel central wave-number	Central wavelength (μm)	Principal absorbing constitu-ents	Level of peak energy contri-bution	Purpose of the radiance observation
1	668	15.0	CO_2	30 mb	Temperature sounding. The 15 μm band channels provide better sensitivity to the temperature of relatively cold regions of the at-mosphere than can be achieved with the 4.3 μm band channels. Radiances in Channels 5, 6, and 7 are also used to calculate the heights and amounts of cloud within the HIRS field of view.
2	680	14.7	CO_2	60 mb	
3	690	14.4	CO_2	100 mb	
4	703	14.2	CO_2	250 mb	
5	716	14.0	CO_2	500 mb	
6	733	13.6	CO_2/H_2O	750 mb	
7	749	13.4	CO_2/H_2O	900 mb	
8	900	11.0	Window	Surface	Surface temperature and cloud detection.
9	1030	9.7	Window	Surface	
10	1225	8.2	H_2O	900 mb	Water vapour sounding. Provide water vapour corrections for CO_2 and window channels. The 6.7 μm channel is also used to detect thin cirrus cloud.
11	1365	7.3	H_2O	600 mb	
12	1488	6.7	H_2O	400 mb	
13	2190	4.57	N_2O	950 mb	Temperature sounding. The 4.3 μm band channels provide better sensitivity to the temperature of relatively warm regions of the atmosphere than can be achieved with the 15 μm band channels. Also, the short-wavelength radi-ances are less sensitive to clouds than those for the 15 μm region.
14	2210	4.52	N_2O	850 mb	
15	2240	4.46	CO_2/N_2O	700 mb	
16	2270	4.40	CO_2/N_2O	600 mb	
17	2360	4.24	CO_2	5 mb	
18	2515	3.98	Window	Surface	Surface temperature. Much less sensitive to clouds and H_2O than 11 μm window. Used with 11 μm channel to detect cloud contami-nation and derive surface tem-perature under partly cloudy sky conditions.
19	2660	3.76	Window	Surface	
20	14 500	0.69	Window	Cloud	Cloud detection. Used during the day with window channels to define clear fields of view and to specify any reflected solar contri-butions to the 3.7 μm channel.

The SSU makes use of pressure modulation tecnique to measure radiation emitted from carbon dioxide at the top of the atmosphere of the earth. A cell of CO_2 gas in

Table 3.SSU channel characteristics.

Channel Number	Central Wave No. (cm^{-1})	Cell Pressure (mb)	Pressure of Weighting Function Peak mb	km
1	668	100	15	29
2	668	35	5	37
3	668	10	1.5	45
Calibration			Stable Blackbody and Space	
Angular Field-of-View			10°	
Ground IFOV—Nadir			147.3 km	
Number of Earth Views/Line			8	
Time Interval Between Steps			4 Seconds	
Total Scan Angle			±40° from Nadir	
Scan Time			32 Seconds	
Data Rate			480 Bits/Second	
Detector			TGS Pyroelectric	

the optical path of the instrument has its pressure changed (at about 40-Hz rate) in a cyclic manner. The spectral caracteristics of the channels and, therefore, the height of the weighting function is then determined by the pressures in the cell during the period of integration. By using three celles filled at different pressures, weighting functions peaking at three different heights can be obtained. The primary objective of the instrument is to obtain data from which stratospheric (25-50 km) temperature profiles can be determined. This instrument will be used in conjunction with the HIRS/2 and MSU to determine the temperature profiles from the surface to the 50-km level.

MSU is an adaptation of Scanning Microwave Spectrometer (SCAMS) experiment flown on the Nimbus 6 satellite. The instrument, which is built by Jet Propulsion Laboratory of the California Institute of Technology, is a four-channel Dicke radiometer making passive measurements in four regions of the 5.5 mm oxygen region. The frequencies are shown in Table 4. which lists the instrument parameters.

The instrument has two scanning reflector antenna system, orthomode trasducers, four Dicke superheterodyne recievers, a data programmer, and power supplies. The antenna scan +/-47.7 either side of nadir in 11 steps. The beamwidth of the antennas is 7.5 (half-power point), resulting in a ground resolution at the subpoint of 109 km.

The High Resolution Interferometr Sounder (HIS)

The Michelson interferometer has long played an important role in the measurement of

Table 4.MSU Instrument Parameters.

Characteristics	Value CH 1	CH 2	CH 3	CH 4	Tolerance
Frequency (GHz)	50.3	53.74	54.96	57.05	±20 MHz
RF Bandwidth (MHz)	220	220	220	220	Maximum
NEΔT K	0.3	0.3	0.3	0.3	Maximum
Antenna Beam* Efficiency	>90%	>90%	>90%	>90%	
Dynamic Range K	0–350	0–350	0–350	0–350	
Calibration	Hot Reference Body and Space Background Each Scan Cycle				
Cross-Track Scan Angle	±47.35°				
Scan Time	25.6 sec				
Number of Steps	11				
Step Angle	9.47°				
Step Time	1.84 sec				
Angular Resolution	7.5° (3dB)				
Ground IFOV (Nadir)	109 km				
Data Rate	320 bps				

* >95% Obtained.

infrared spectra. This is partly a result of its inherent spectral accuracy and the theoretical understanding of its instrumental response functions. Under continuous evolution within NASA since the early 1960s, Michelson interferometers have been used for remote sensing of the surface and the atmosphere of the earth from the Nimbus III and IV Mars from Mariner-9, and Jupiter, Saturn and Uranus from Voyager spacercraft.

Errors in the retrieved temperature are mainly due to the coarse vertical resolution and residual cloud and minor constituent contamination effects. Some minor improvements in temperature accuracy has been achieved by the application of first order corrections for clouds contamination and surface emissivity effects, utilizing a multispectral retrieval approach. The current generation of sounders has shown that microwave and infrared information is an effective combination in the elimination of cloud contamination. However, much more is required to achieve 1 degree accuracy and 1 km vertical resolution. A number of approaches have been suggested which require new instrumentation. The only passive radiometric means of achieving the combined accuracy and vertical resolution requirements is through measuring a large portion of the infrared spectrum (4.0 - 15 micron) with a spectral resolution $\Delta\lambda/\lambda$ greater than 1000.

After theoretical demonstration of the greatly improved vertical temperature and water vapor sounding performance possible with a high spectral resolution interferometer, NASA and NOAA supported University of Winsconsin to develop an High spectral resolution Interferometer Sounder (HIS). The HIS has flown reliably on over 40 flights including two major NASA field experiment. The HIS experiment has demonstrated that radiometrically precise high spectral resolution measurements can be achieved with a Michelson interferometer as required to meet the sounding requirements for the weather analisys and forecast application. The instrument can resolve the spectral structure associated with the fine scale details of atmospheric temperature, water vapor clouds, ozone, methane, nitrons oxide and other trace gases. It measures the upwelling radiation (3.5 - 16.6 micron) with a spectral resolution of 0.3 cm^{-1} or 0.03 %. The spectra can be used to infer the infrared transmittance and emittance proprieties of clouds and optically active constituents (gases and aerosols). The HIS instrument consist of three arsenic–doped germanium detectors immersed in a liquid helium filled dewar, a BOMEM laser controlled autoaligned interferometer and a 3-M high density data recording system. Three detector/filter system are used to optimize the signal to noise ratio of the observations throughout the brood spectral region of measurement.

High radiometric precision is required because radiometric noise and time–dependent and wavelength–dependent calibration errors are magnified in the inversion process to derive atmospheric parameters. To obtain temperature profiles with rms errors of less than 1 K from high resolution measurements requires noise equivalent temperature errors and calibration reproducibilities of the order of 0.1 K and absolute errors of less than about 1 K.

Fig. 4 shows one of the first spectra observed by HIS over Pacific Ocean near Oakland, California. The major features are : the 15 micron CO_2 band near 660 cm^{-1}; the strong CO_2 absorption lines between 684 and 772 cm^{-1}; the weak H_2O lines within the 11 micron window region; the 9.6 micron O_3 band (1040 cm^{-1}); the strong and randomly spaced H_2O lines in the 6.3 micron band. Band 3 which includes the 4.3 micron CO_2 and N_2O absorption bands and the 4 micron window region. These spectra were obtained from a single six second scan with 0.5 1/cm resolution for band 1, while band 2 and band 3 spectra are at spectral resolutions of 1.5 1/cm and 3.0 1/cm respecti- vely.

Atmospheric temperature and moisture profiles can be derived from complete HIS

Table 5. Characteristics of the HIS aircraft instrument.

Spectral range (cm^{-1})[a]	
Band I	590–1070
Band II	1040–1930
Band III	2070–2750
Field of view diameter (mrad)	
Telescope	100
Interferometer	30
Blackbody reference sources	
Emissivity	>0.998
Aperture diameter (cm)	1.5
Temperature stability (K)	±0.1
Temperatures (K)	240, 300
Autoaligned interferometer:	Modified BOMEM BBDA2.1
Beam splitter	
Substrate	KCl
Coatings (¼ λ at 3.3 μm)	Ge + Sb_2S_3
Maximum delay (double-sided current configuration (cm)	
Band I (hardware limit is ±2.0)	±1.8
Bands II and III (limited by data system)	+1.2, −0.8
Michelson mirror optical scan rate (cm/s)	0.6–1.0
Aperture stop (at interferometer exit window)	
Diameter (cm)	4.1
Central obscuration area fraction	0.17
Area (cm^2)	10.8
Area-solid angle product (cm^2 sr)	0.0076
Detectors	
Type	Ar-doped Si
Diameter (cm)	0.16
Temperature (K)	6
Nominal instrument temperature (K)	260

[a] The ranges shown are design ranges. The current bandpass filters were chosen from available stock filters and will be changed as new filters are acquired.

spectra using the ' Simultaneous Retrival Algorithm ' (Smith, 1984). The algorithm permits full physical interpretation of spectra and yields high spectral resolution soundings as a result of several thousand high spectral resolution radiance observations. Fig. 5 shows the vertical resolution of temperature profile retrievals for the HIS as compared to that of the current infrared profilers (HIRS and VAS) aboard the NOAA and GOES-6 satellites, and the Advanced Microwave Sounding Unit (AMSU) to fly on the next generation Polar Orbiting Satellite System.

The improved resolving power of HIS is easely seen. Because of the exponential decay of water vapor with altitude, HIS water vapor retrievals possess an even higher resolution than that shown for atmospheric temperature.

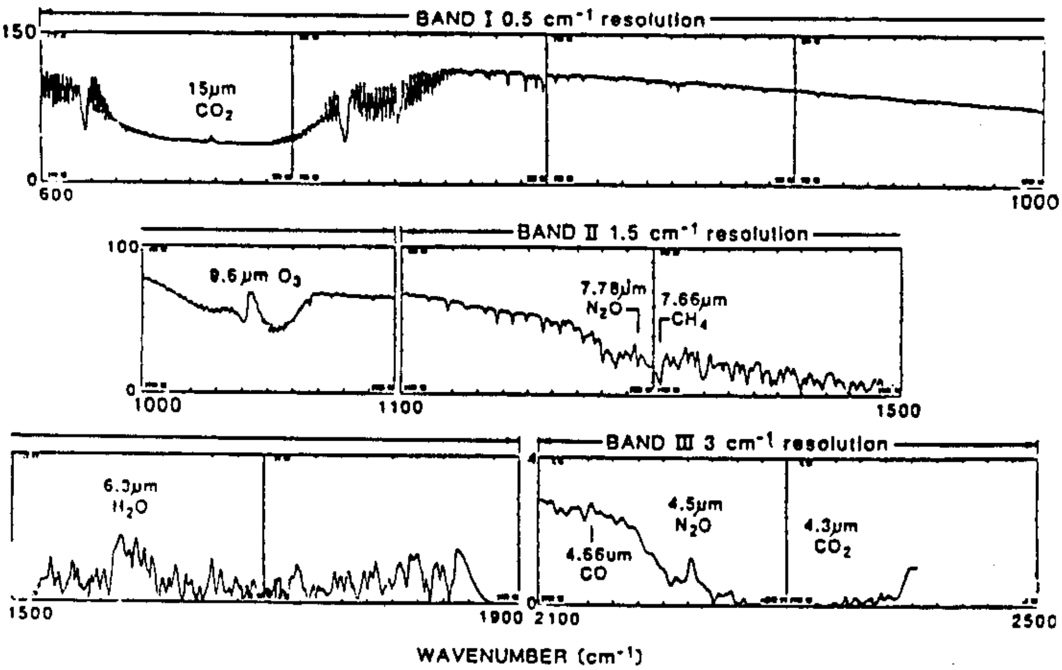

Figure 4. An example of radiance spectra measured by HIS

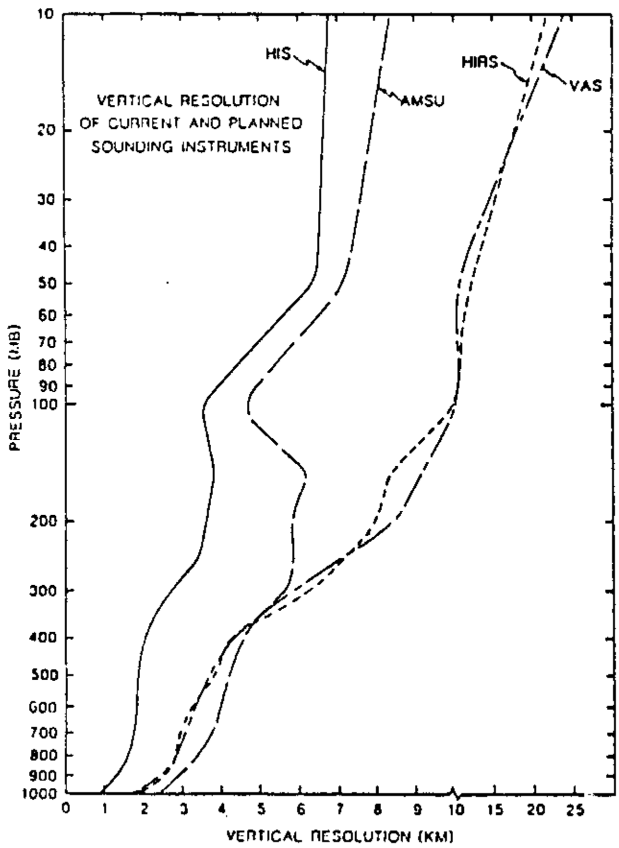

Figure 5. Vertical resolution of temperature retrievals for HIS, AMSU, HIRS/2 and VAS instruments.