State of Atmospheric Sounding from Space - My Perspective on Past, Present, and Future, in the Infrared

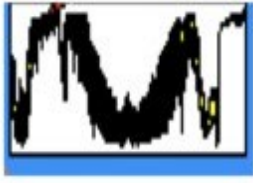
Nimbus 3/4 IRIS/SIRS (1969-1972)

First Satellite Sounders

Nimbus-5/6 ITOS ITPR/HIRS VTPR GOES-VAS & HIRS (1972-2011)

High Horizontal Resolution

NASA ER-2 Hires FTS Sounders (HIS/NAST-I/SHIS) (1972-)



Hyperspectral Resolution

ADEOS IMG (LEO) (1996-1997)

Aqua AIRS (LEO) (2002)

First Polar Hyperspectral Sounding (PHS) Spectrometers

Metop IASI (2006)

First Opnl PHS

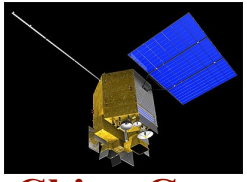
SNPP/JPSS CrIS (2011)

US Opnl PHS

Meteor IKFS (2014)

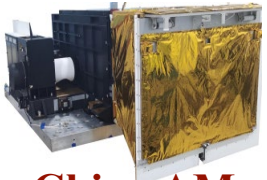
Russia Opnl PHS

FY-4 GIIRS (2017&2021)



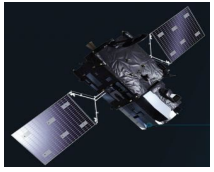
China Geo-Hypersectral

FY-3 HIRAS (2017&2021)



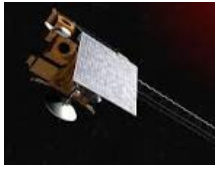
China AM PHS

MTG IRS(2024)



European GeoHyper

Geo-XO GXS(203?)

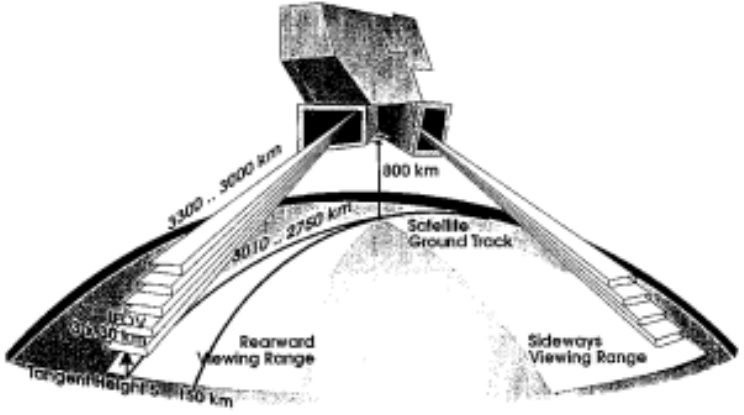


USA GeoHyper

Soon after the launch of Sputnik in 1957 there were two proposals as to how to sound the atmosphere from space.

1958: *Gene King proposed Vertical Profiling Through and Angle Scan:*

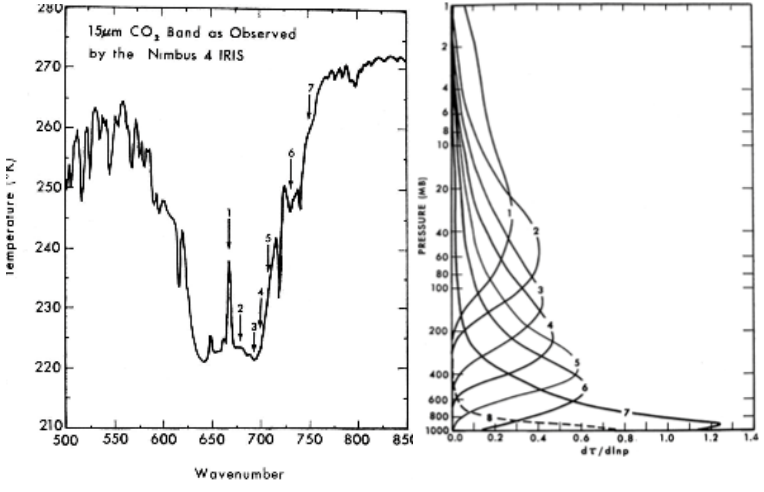
King, J.I.F., 1958: The radiative heat transfer of planet earth. Scientific uses of earth satellites, J.A.Van Allen, Ed., University of Michigan Press, 316 pp



Observation Geometry of MIPAS (Fischer)

1959: Lewis Kaplan proposed Vertical Profiling Through Spectral Scan:

Kaplan, L.D., 1959: Inferences of atmospheric structures from satellite remote radiation measurements. J. Opt. Soc. Amer., 49, 1004-1014.

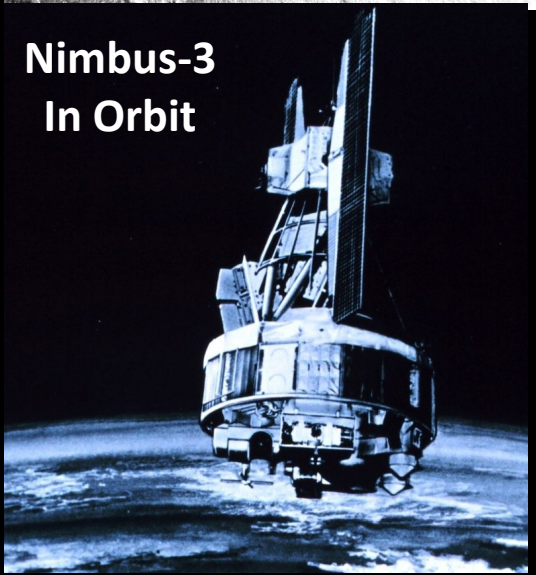


1968 Nimbus-B Launch Failure / 1969 Nimbus-3 Launch Success !

Nimbus-B on Pacific Ocean Floor

Nimbus B, meteorological satellite, launched on May 18, 1968, from the Vandenberg Airforce Base, Lompoc California. Nimbus B never achieved orbit because of a malfunction in the booster guidance system forced the destruction of the spacecraft and its payload during launch. The Radioisotope Thermoelectric Generator Nuclear Battery was salvaged from the water, refurbished, and later flown on Nimbus 3.

Nimbus-3 In Orbit

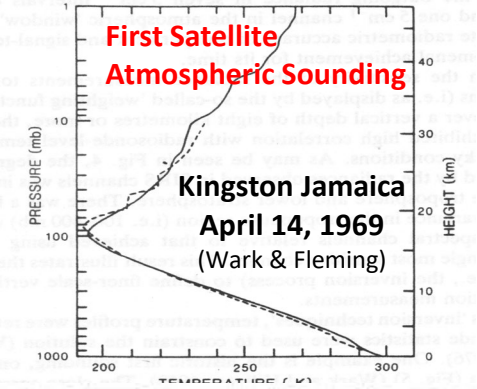


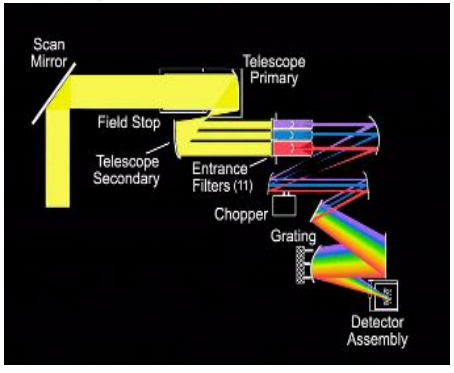
Nimbus 3 was launched 11 months later, on April 14, 1969, from Vandenberg Airforce Base, Lompoc California. The spacecraft functioned nominally until 22 January 1972. The satellite orbited the Earth once every 1 hour and 47 minutes, at an inclination of 99.9°. Its was 1,135 kilometers (705 mi).

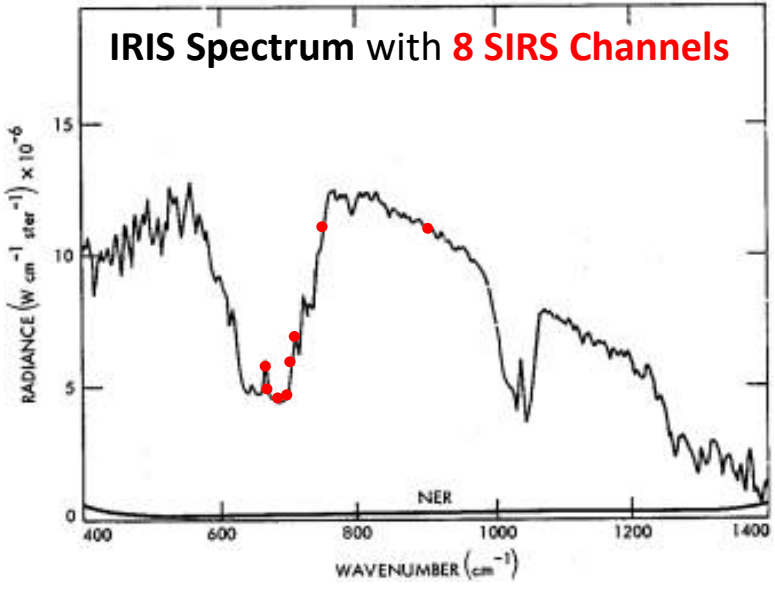
WIKIPEDIA

First Satellite Sounding Instruments

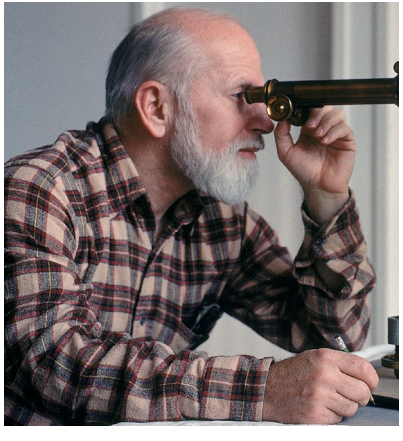
Dave Wark's Satellite Infrared Radiation Spectrometer (SIRS)

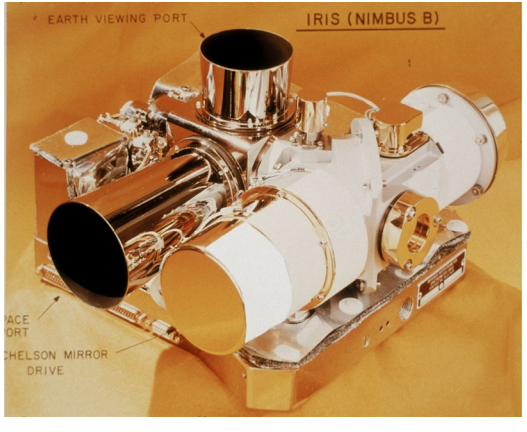






Rudy Hanel's Infrared Radiation Interferometer Spectrometer (IRIS)





How The First SIRS Soundings Got Into NWP

April 14, 1969

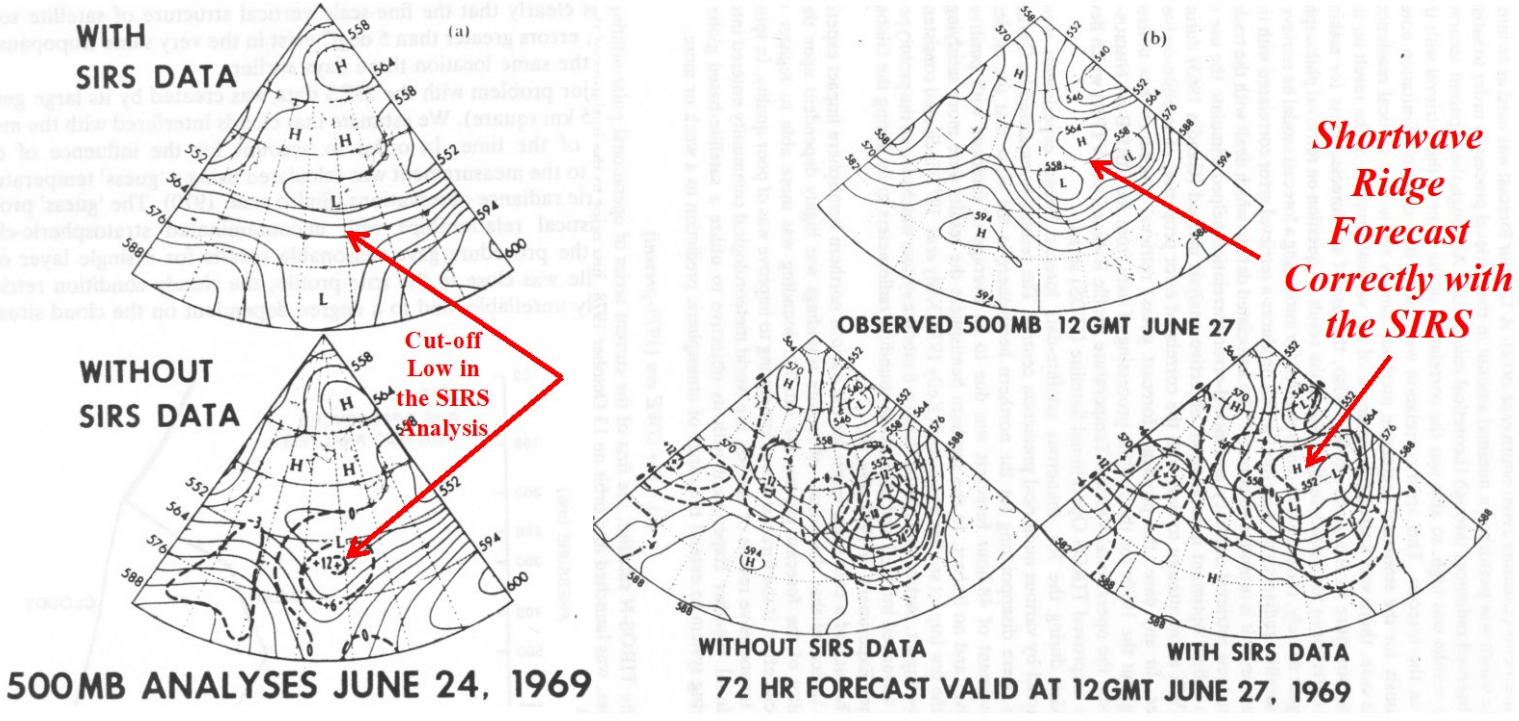
- A Magnetic Tape Containing 8-Orbits of SIRS-A Earth Located/Calibrated Data Carried from NASA/GSFC ground station to "NOAA"/Suitland
- Regression retrieval method[1] was used to produce global temperature and geopotential height vertical soundings from the first 8-orbits (12-hours) of SIRS-A data
- Hand Plotted and Analyzed Standard Level Geopotential Height Charts
- **April 15, 1969**
- Geopotential Height Analyses Shown to "NOAA" NMC Directors
- NMC Noted That SIRS Soundings Accurately Positioned the Jet Stream Head Winds Responsible for Fuel Stops Required for Commercial Air Flights. Airlines were complaining to the NWS for their poor aviation forecast.
- NMC Requests SIRS-A Data be Provided to NMC daily ASAP

May 22, 1969

- Using a Courier Ground Transport System, SIRS-A Soundings Were Processed on an Orbit-by-Orbit basis and provided to NMC for Experimental Assimilation of Satellite Sounding Data into "Final" Numerical Model Analysis/Forecast Operation.

[1]William L. Smith, Harold M. Woolf, and Warren J. Jacob (1970): Monthly Weather Review, Vol 98, 582 - 603

First Numerical Weather Prediction Validation Using Satellite Infrared Sounding Data (SIRS-A)



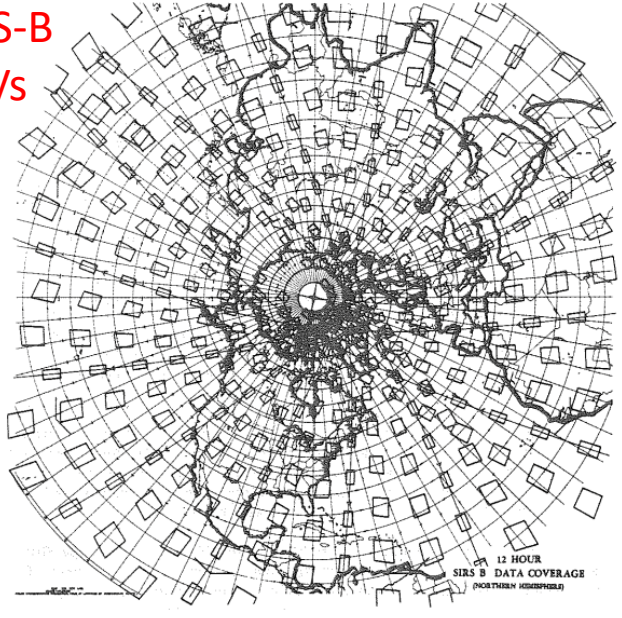
Satellite Sounding Improved Pacific Ocean Analysis Reduced Maximum 3-day Forecast Errors for the Central US by more than 50%

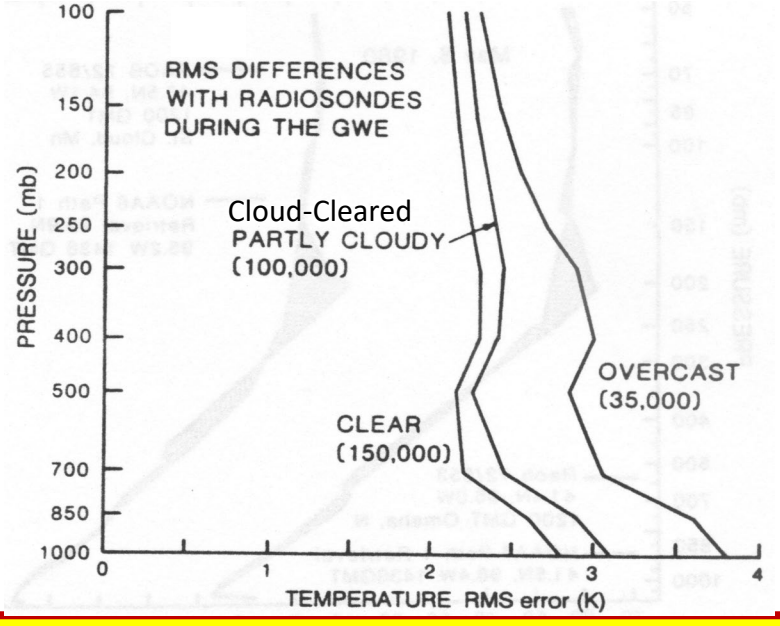
Nimbus-5 ITPR (1972), Nimbus-6 HIRS (1975)
TIROS-N/NOAA 6-19 TOVS/ATOVS (HIRS, MSU/AMSU(1978)

High Horizontal Resolution, Spatially Scanning, (20-km) Filter Radiometers

The major problem for atmospheric sounding with the SIRS and IRIS Instruments was posed by Clouds, which generally contaminated by their large (>150-km) Fields of View.

SIRS-B FOVs



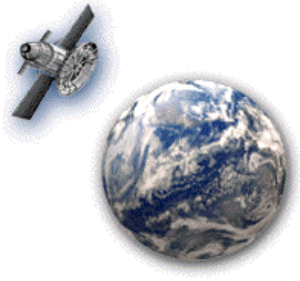


***Nimbus* -5 ITPR, Nimbus-6 HIRS, TIROS/NOAA TOVS/ATOVS (~20-km FOV) greatly increased the yield, and accuracy, of clear, and partly cloudy, observation**

The First Global GARP Experiment (FGGE)

- The vast Global Weather Experiment, first conceived by Jule Charney and Verner Suomi, was carried out by many nations in 1979 under the leadership of the World Meteorological Organization to demonstrate what high-quality global observations could do to improve forecasting by numerical prediction models.
- The TIROS-N and NOAA-6 TOVS (HIRS and MSU) provided the global vertical sounding data that was critical for initializing the numerical models used to achieve the FGGE objectives:
  - 1)To obtain a better understanding of atmospheric motion for the development of more realistic models for extended range forecasting, general circulation studies and climate;
  - 2)To assess the ultimate limit of predictability of weather systems;
  - 3)To develop more powerful methods for assimilation of meteorological observations, in particular, for using non-synchronous data as a basis for predicting the large-scale motion and,
  - 4)To design an optimum composite meteorological observing system for the numerical weather prediction of the larger-scale features of the general circulation

1981: The Role of International TOVS Working Group (ITWG)



The International TOVS Working Group (ITWG) was formed in 1981 hosting ITSC meetings to support the international meteorological community in the processing and applications of the direct readout TOVS digital sounding data being telemetered via the NOAA satellite Automatic Picture Transmission (APT) system.

UW-CIMSS created a software package called the "TOVS Export Package" to help weather services to use TOVS data for operational weather forecasting. This support continues, led by Allen Huang and Liam Gumley, with the system called the CSPP. It is noteworthy that the Export Package was distributed to participants of the first ITSC, held in IGLS Austria in 1983, a year ahead so that they could show results, and discuss problems, from using the TOVS Export Package in their country at this first meeting.

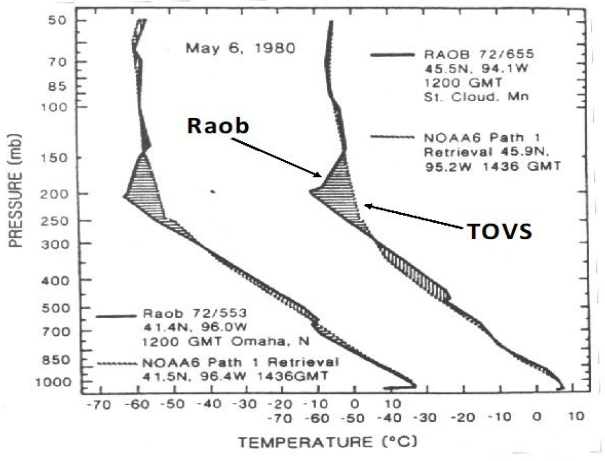
I believe that a most important part of the ITSC meetings are the working groups that leads to important recommendations to satellite agencies and users of satellite data.

Example: In mid-1990, the ITWG recommended that the next ATOVS HIRS FOV requirement be changed from 20-km to 10-km in order to increase the yield of clear-air soundings. The HIRS-4 with it's 10-km FOV was launched on NOAA-15 in 2005. This change increased the number of clear-sky IR soundings by >80%.

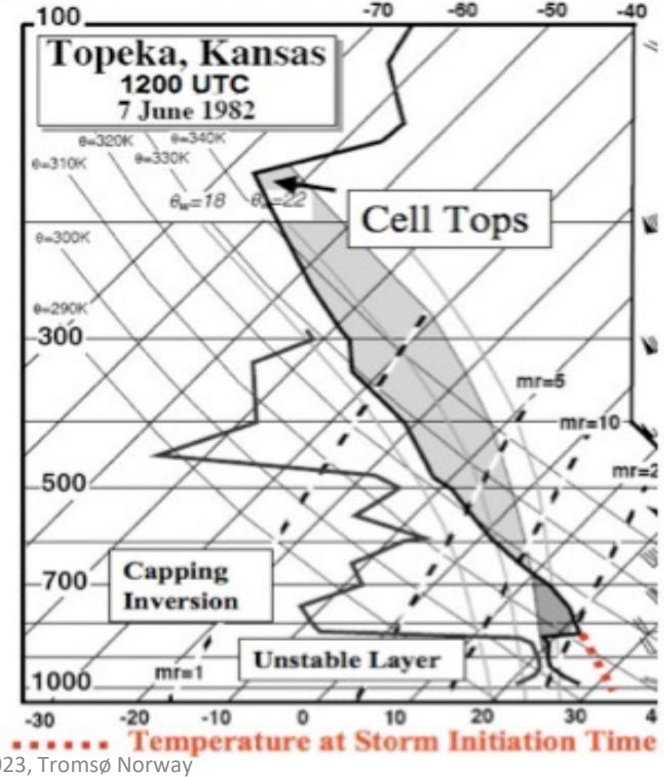
How Hyperspectral IR Sounding Originated and Became an International Operational Reality

- ***In the 1970s, UW-Madison Prof. V. E. Suomi, the Father of Satellite Meteorology, proposed the first geostationary satellite sounder, the GOES VISSR Atmospheric Sounder (VAS). VAS was a filter radiometer designed to measure the multispectral radiance to space needed for atmospheric sounding.***
- ***The VAS objective was to provide atmospheric atmospheric T & H_2O soundings with high time frequency to improve forecasts of severe storms and tornadoes.***
- ***However, it was realized that while VAS provided high horizontal and temporal resolution, the spectral resolution was too limited to achieve the high vertical sounding resolution needed for the severe storm forecast applications.***
- ***Thus, in the late 1970s, the development of the hyperspectral radiance sensing capability was initiated at the UW–Madison to increase the vertical resolution of the satellite sounders to follow the VAS.***

The Multi-spectral TOVS/VAS Sounding Problem – Lack of Vertical Resolution



Significant temperature & moisture structure could not be resolved from low spectral resolution radiances



1977: Theoretical Studies Indicated:

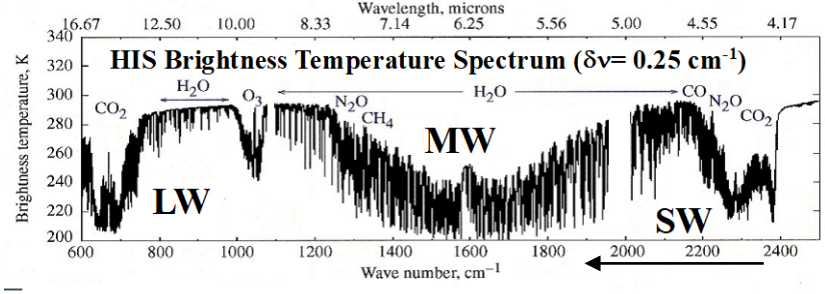
- Multispectral Radiometer measurements of thermal radiance to space arises from deep layers of atmosphere.
- Fourier Transform Spectrometer (FTS) interferogram radiance signals (i.e., the radiance derivative with respect to spectral resolution) result from the vertical structure within atmospheric layers.
- An FTS resolves the radiance emission line structure with the high spectral fidelity required to achieve high vertical resolution.
- **Profile retrieval studies showed that a factor of 2- to 3-improvement in vertical resolution and atmospheric sounding accuracy results from using an IR FTS instrument, rather than a Multispectral Radiometer.**

1980: NASA & NOAA Fund Experimental Demonstration of High-resolution Interferometer Sounder (HIS)

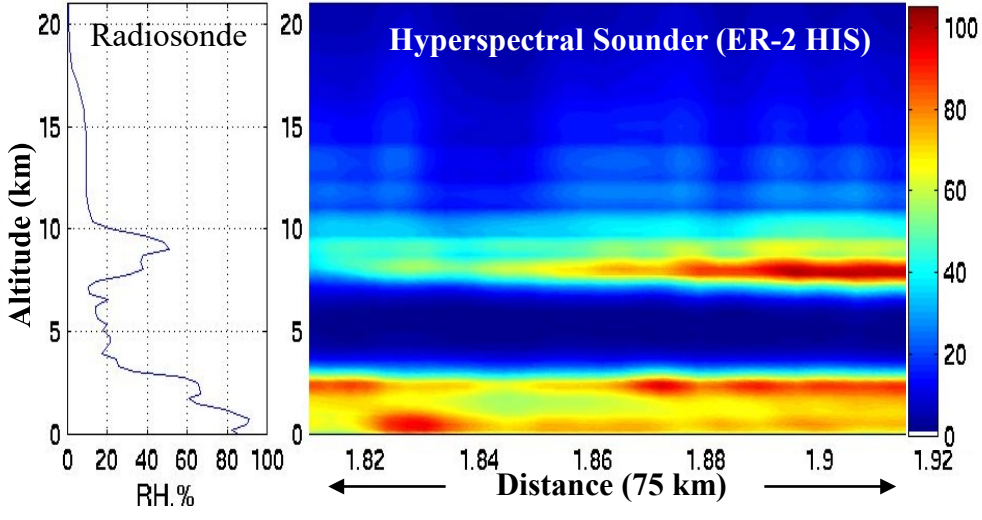
HIS Aircraft Instrument Shadowed by NASA ER-2 Aircraft in 1995

Three spectral bands, covering most of the region from 3.8 to 16 microns, with a spectral resolution ~ 0.25cm^{-1}

H. E. Revercomb et al., "Radiometric calibration of IR Fourier transform spectrometers: solution to a problem with the High-Resolution Interferometer Sounder (HIS)," Appl. Opt. 27, 3210-3218 (1988).

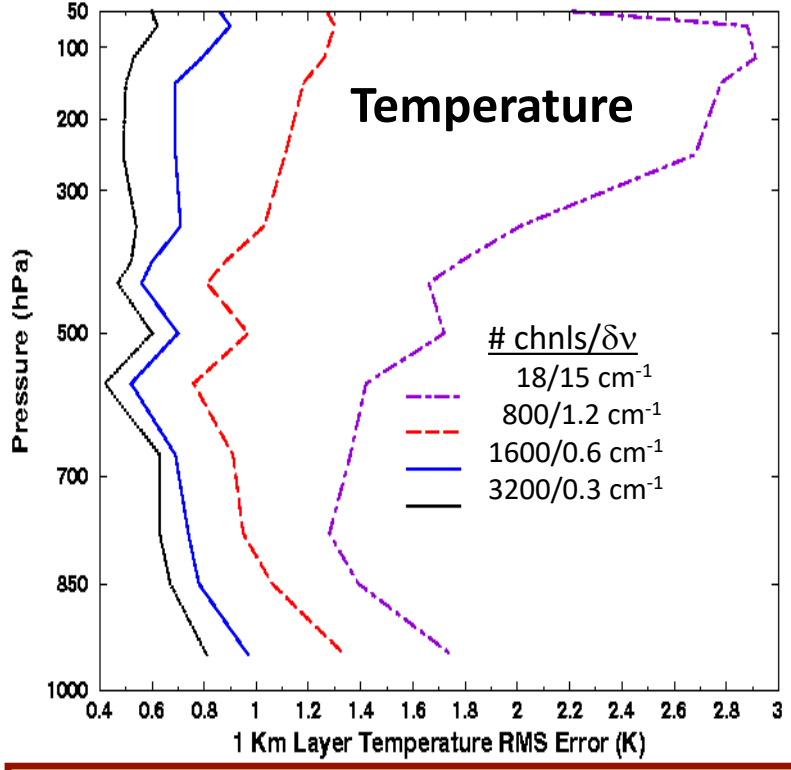


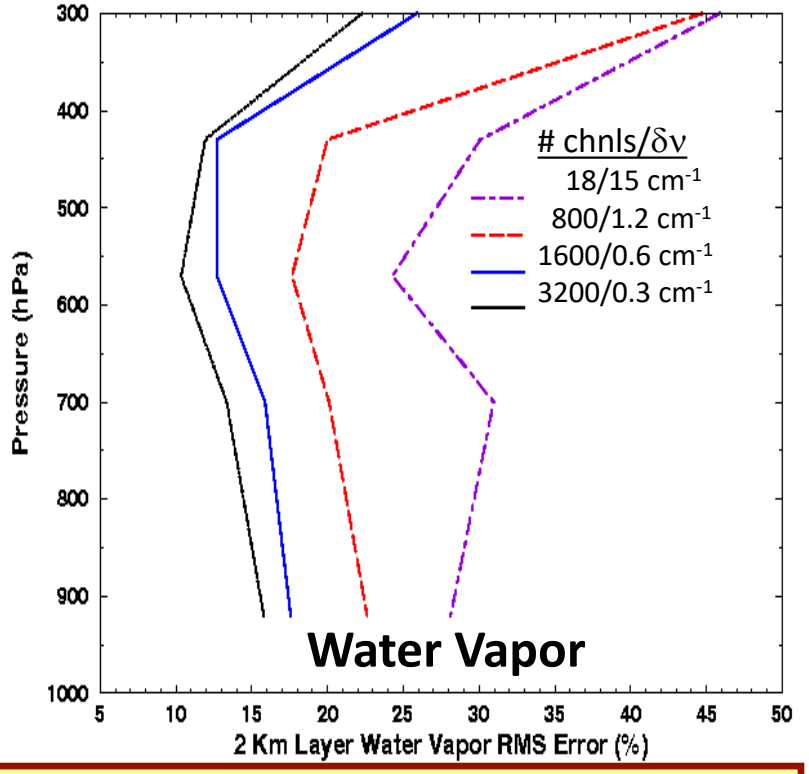
Hyperspectral High Vertical Resolution Sounding Concept Demonstrated in 1986



Small Vertical Scale Variations in Humidity Observed by a Radiosonde Resolved by HIS

Retrieval Accuracy Vs Spectral Resolution & Number of Spectral Radiance Observations

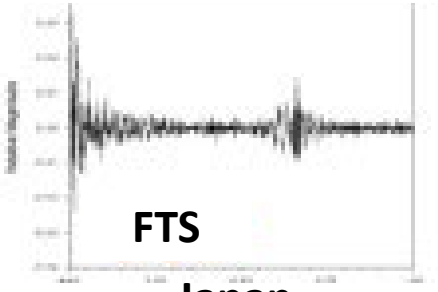




Shannon Sampling Explains the Vertical Resolution and Accuracy Improvement With Channel Number

Polar Hyperspectral Sounder History

ADEOS
IMG (1996)



Japan

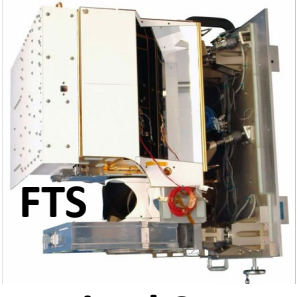
Aqua
AIRS (2002)

United States

Metop
IASI (2006/12/18)

Europe

SNPP/JPSS
CrIS (2011/17/22)

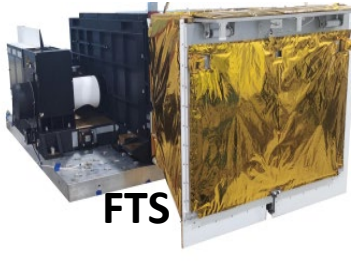


United States

Meteor
IKFS (2014)

Russia

FY-3
HIRAS (2017/21)



China

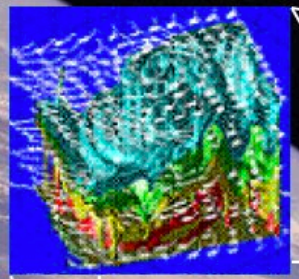
1999: Geostationary Imaging Fourier Transform Spectrometer

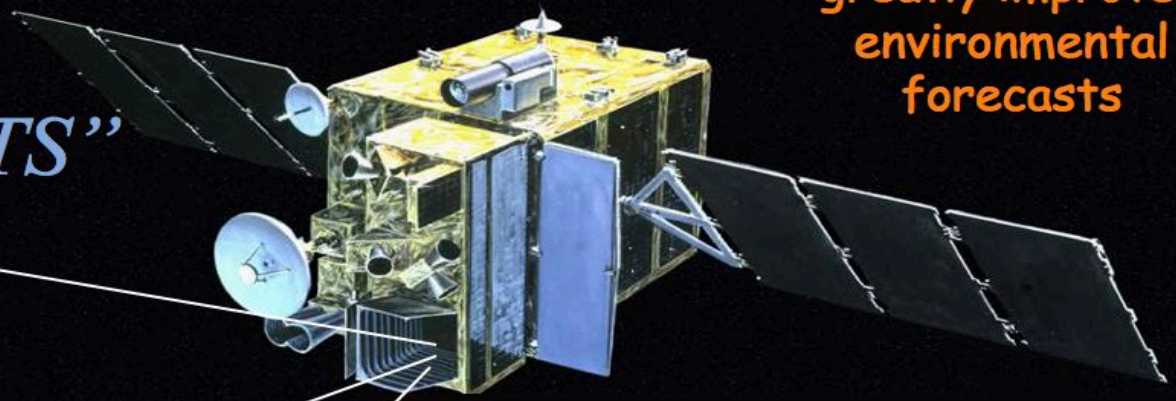
Hyperspectral Instrument for Atmospheric Temperature, Moisture, Chemistry, & *Winds*

The opportunity for greatly improved environmental forecasts

Provides more than 80,000 atmospheric soundings every minute

"GIFTS"





4-d Digital Camera:

Horizontal: Large area format Focal Plane detector Arrays

Vertical: Fourier Transform Spectrometer

Time: Geostationary Satellite

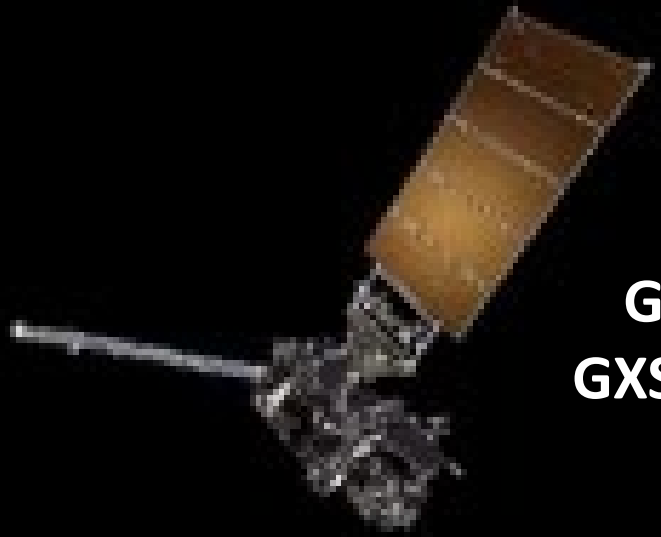
Geo-Hyperspectral Sounder History

FY-4A
GIIRS(2017)

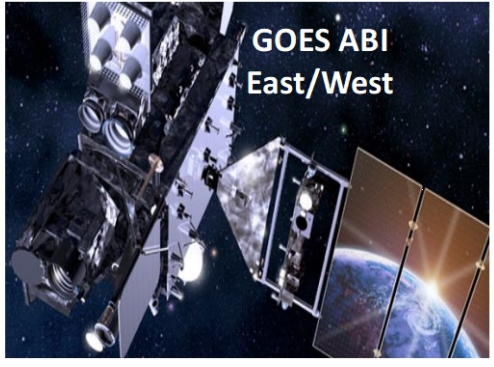
FY-4B/C
GIIRS(2021/2?)

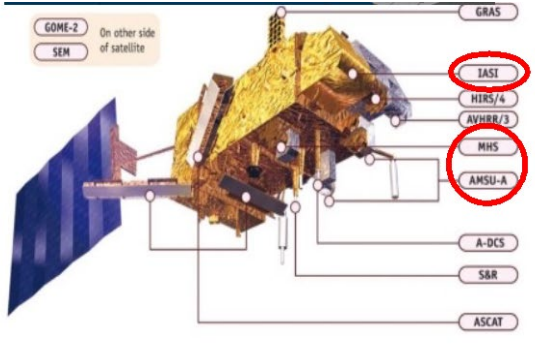
MTG
IRS (2024)

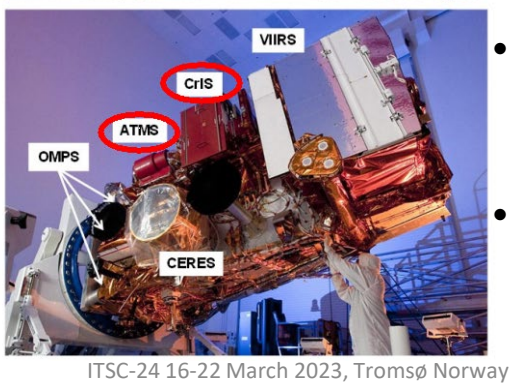
GeoXO
GXS (203?)



Not having Global Geo-hyperspectral satellite Data, 2-3 km horizontal and 30-minute temporal (30-min) resolution "Proxy Geo-hyperspectral" soundings are being created by the fusion of polar sounder and geostationary imager radiances







Data Characteristics

- Full Spectral Resolution
- Full Spatial Resolution
- Polar Hyperspectral clear soundings and above cloud
- MW soundings used below cloud
- 3-km Res. NWP Model
- 30 to 60-minute continuous Humidity data assimilation used to diagnose winds and dynamics
- 0-to-12-hour forecast cycle conducted every hour

Next-Gen Satellite System Sounding Proxy– The fusion of Current Generation Geostationary and Polar Satellite Soundings

Lessons Learned From 3-years of High-resolution Proxy Sounding NWP Model Data Assimilations ?

- **High Spatial Resolution:**
  - **Improves Density of Lower Troposphere Clear-air Sounding**
  - **Improves Detection of Convective Storm Initiation**
- **Hourly High-resolution Sounding Data Assimilation:**
  - **Improves Forecasts of Atmospheric Parameters**
  - **Improves Model Diagnosis of 3-D Winds and Vertical Motion**
  - **Improves Severe Precipitation Forecasts**
  - **Improves Severe Storm/Tornado Forecasts**
  - **Improves Nowcasting Severe Weather**

My Perspective

- **Satellite sounding has evolved over 60 years to enable significant improvements in the understanding and prediction of weather, chemistry, and climate processes.**
- **However, I believe that the best is yet to come! Why ?**

  - Advances in NWP have been generally restricted by using relatively small subsets of the full spectrum of satellite radiance observations available, limiting the use of their full vertical structure information content. (Dave Tobin to discuss next Tuesday and in the 'Advance Sounding Working Group' meeting.

  - Spatial resolution of IR instruments and spatial thinning of the satellite moisture data limits the impact of their assimilation into convection resolving NWP models.

  - Hourly 2 to 3-km proxy next-generation sounding data show that significant improvements in atmospheric analyses and predictions can be expected once the full vertical and horizontal resolution information content is utilized.

  - Future satellite products for NWP assimilation should be based on the fusion of all available LEO/GEO, IR/MW, Imager/Sounder radiances to achieve the highest Spatial/Temporal resolution provided by the complete set of satellite observations.

Thank You for Your Attention

Questions or Comments ?