HIRS-HYBRID - A HIGH RESOLUTION SOUNDER FOR THE NEAR TERM

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ABSTRACT

The accuracy of global weather forecasts is limited by the vertical resolution and accuracy of the HIRS. Higher spectral resolution sounders with 1000 - 1500 channels are under development but are unlikely to be operational until 2007. A concept has been developed by ITT A/CD and the Cooperative Institute for Meterological Satellite Studies at the University of Wisconsin/Madison that can provide high resolution sounding much earlier. This concept involves adding a longwave Fourier Transform Spectrometer to the current HIRS/3. This can be done in a low risk and low cost way that will provide advanced sounding data products without impacting the existing operational weather system capabilities.

1.0 INTRODUCTION

There is an urgent need for an advanced sounding instrument on operational polar satellites, yet all the current development programs do not permit an advanced sounder to be in orbit prior to the next century. The earliest opportunity for an operational advanced sounder[1] is the first DOD/NOAA Converged Spacecraft, C-1, with a launch readiness date of no earlier than 2006. With normal check-out, it would be 2007 before products would be available to the operational users for evaluation. As a consequence, it would be highly desirable to implement an interim advanced sounding capability which would provide both an opportunity to test, in space, critical hardware elements of the advanced sounder and, at the same time, provide advanced sounding products to Numerical Weather Prediction Centers. Such a system, by necessity, should not interfere with the current operational HIRS data flow and would remain relatively transparent to the existing operational system.

1.1 Why Advanced Sounding is Needed

Although the HIRS has been a very reliable instrument whose data has played a key role in improving global Numerical Weather Prediction (NWP) during the 1980s and 1990s, there is now an urgent need to replace it with a much higher spectral resolution instrument. This is because the vertical resolution of the current HIRS is much poorer than the resolution of contemporary NWP models. As a result, further improvements in the accuracy of global weather forecasts is now limited by the vertical resolution and accuracy of the HIRS. Because of the enormous economical benefits of accurate extended range forecasts and because of the life saving benefits of accurate shorter term forecasts of intense weather, mankind would greatly benefit from the implementation of this higher resolution vertical sounding capability.

[1] The EOS PM Platform AIRS instrument is recognized as one opportunity for achieving advanced sounder data prior to the C1. However, AIRS is an experiment without a commitment for its replacement in case of failure.

The advanced infrared sounder will also play an important role in the world's Climate and Global Change program. This is because the higher spectral resolution and more continuous spectral coverage will enable better monitoring of the elements which impact global climate including the radiative emissions from our planet's "Greenhouse" gases, sea and land surface temperatures, and the moisture budget of the atmosphere, including clouds. Thus, the implementation of a higher spectral resolution advanced sounder should also be considered useful for NOAA to optimize its climate monitoring capability for the global community.

1.2 Pathfinder Approach to an Advanced Sounding Capability

The HIRS-HYBRID design proposed here is a concept which provides a means for obtaining advanced sounding information from operational satellites with little impact on the current operational system. This concept, developed by ITT in conjunction with the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin/Madison, makes use of the current HIRS scanner and cryogenic radiant cooler assemblies. As such, it represents a minimum alteration of the HIRS to give an advanced sounding capability. Early implementation of the HIRS-HYBRID allows optimizing the ground systems required for producing and disseminating the advanced sounder data and products on an experimental basis without interference with the current operational system. At the same time, the experimental advanced sounder data would be made available in real time to operational centers who wish to use these data on an experimental or routine basis.

The HIRS-HYBRID plus associated AVHRR and AMSU data will be processed by CIMSS and meteorological products will be prepared on a routine quasi-operational basis. The radiance data and meterological products will be distributed to operational weather centers, e.g., National Meteorological Center (NMC), National Severe Storm Forecast Center (NSSFC), and National Hurricane Center (NHC), for their evaluation of the utility of these products in each of their analysis/forecast operations.

As part of an in-house activity, ITT A/CD has been working with Martin-Marietta Astro Space to insure that the required instrument modifications and experimental data could be accommodated by the current Advanced TIROS-N (ATN) spacecraft configuration with minimal impact.

The HIRS-HYBRID instrument implementation and science data handling is to be accomplished by a team of experts and organizations who have pioneered the development of the HIRS and the High resolution Interferometer Sounder (HIS) technology and their associated meteorological data processing systems. Specifically, the HIRS and HIS technology have been developed by ITT A/CD, BOMEM, and the University of Wisconsin (UW) Space Science and Engineering Center team, respectively. The first ground data processing systems for both the HIRS and the HIS instruments were developed by a team of UW and NOAA scientists at CIMSS. It is important to note that the CIMSS has previously conducted the type of pilot operational processing and data dissemination program proposed here as part of the "VAS Demonstration Program". During this program, CIMSS processed and disseminated GOES-VAS data to operational weather centers for trial operations prior to the VAS data processing becoming a fully operational function of NOAA-NESDIS.

2.0 HIRS-HYBRID SCIENCE CONSIDERATIONS

2.1 Spectral/Radiometric

The HIRS-HYBRID will possess the same spectral channels as the current HIRS/3 instrument with the addition of the Michelson Interferometer (MI) capability to measure the spectrum of radiation between 8.7 and 15 micron wavelength with a spectral resolution of about 1500:1 (i.e., about 0.6 cm^{-1}). Table 2.1-1 gives the spectral and radiometric characteristics of the HIRS-HYBRID together with the science application of each measurement region. Note that the MI component of the HIRS-HYBRID provides a spectral resolution improvement of nearly 25:1, with little loss of signal to noise, over the filter radiometer portion of the instrument.

Table 2.1-1 HIRS-HYBRID Nominal Radiance Measurement Specifications

Band	No. Chnls	Bandwidth (cm^{-1})	Resolution (cm^{-1})	NEΔN (mW/m^2 sr cm^{-1})	Purpose of Measurement
LW	12	669-1533	3-55	0.1-3.0	Temperature and water vapor profile, surface temperature, and total ozone
SW	7	2188-2660	23-100	0.001-0.006	Lower Tropospheric temperature profile, surface temperature
MI	800	650-1150	0.625	0.25-0.35	High vertical resolution temperature and water vapor profile, surface temperature and emissivity, ozone profile, cloud height and cloud micro physical properties

NOTE:
- LW and SW are the existing HIRS channels
- MI indicates the new channels provided by the Michelson Interferometer FTS

The improved meteorological sensing performance of the HIRS-HYBRID is demonstrated experimentally using spectral radiance measurements made with the HIS from the NASA ER-2 aircraft flying at an altitude of 20 km. Figure 2.1-1 shows the spectral positions and bandwidths of the HIRS filter channel superimposed upon a High resolution Interferometer Sounder (HIS) spectrum of upwelling radiance measured from the NASA ER-2 aircraft overflying Wallops Island, Virginia, on September 29, 1993. The spectrum observed in the 650-1050 cm^{-1} region is at the same spectral resolution as the unapodized spectral resolution to be observed with the HIRS-HYBRID FTS. It is immediately obvious that the FTS provides important detail in the 15 μm CO_2 absorption band (650-775 cm^{-1}), the 9.6 μm Ozone band (975-1075 cm^{-1}), and the 8-12 μm "window" region (800-1000 cm^{-1}) which remains unresolved by the filter channels of the HIRS/3 instrument. It is important to emphasize the fact that the ability of the FTS to resolve the radiance contribution from in between the 15 μm band CO_2 lines is what leads to a factor of two improvement in vertical resolution and accuracy of the temperature profiling capability of the HIRS (Figure 2.1-2). The Ozone spectral radiance information supplied by the FTS also makes it possible to derive vertical profile properties of the Ozone distribution as well as improved estimates of the total concentration of Ozone.

The greatly improved spectral resolution in the 8-12 μm "window" region, provided by the HIRS-HYBRID FTS component, will enable significant improvements in the sea and land surface temperature derivations. The FTS's spectral resolution and coverage minimizes the correction for atmospheric absorption, and enables surface emissivity/reflectivity effects, important for land surface

temperature estimation, to be taken into account from the variation of radiance across weak absorption lines which is dominated by the variation of the surface reflected radiance component

FIGURE 2.1-1 Spectral Positions of HIRS/3 Filter Radiometer Longwave & Ozone Channels Superimposed Upon an Aircraft HIS Observed Brightness Temperature Spectrum

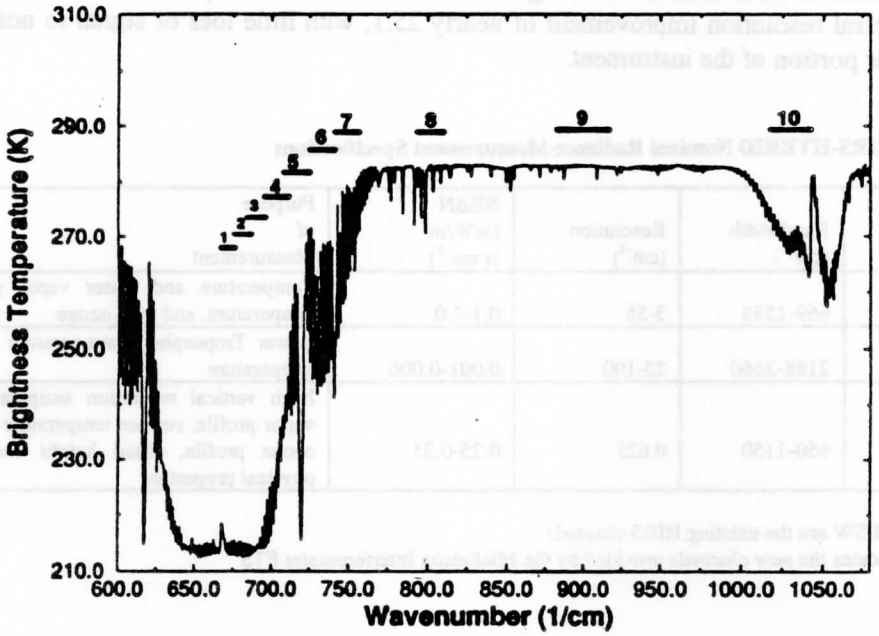
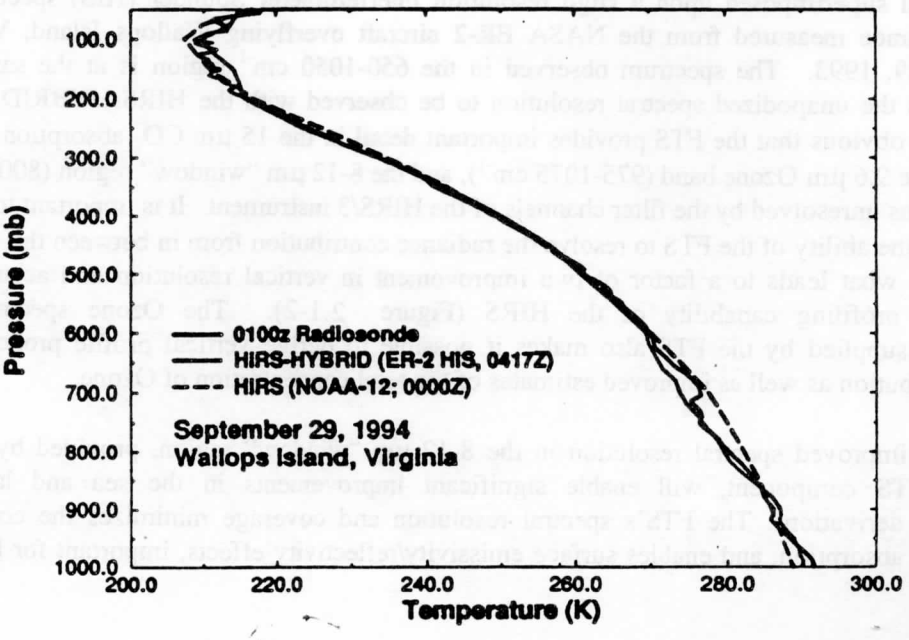


FIGURE 2.1-2 Temperature Profile RAOM vs HIRS-HYBRID and HIRS Retrievals



of the signal (Smith et.al,1995). Finally, the spectral resolution and coverage of the FTS permit greatly improved cloud altitude (Smith and Frey, 1990), cloud phase (Smith, Ma, and Ackerman, 1989), and cloud micro-physical property information (i.e., effective radius and water content estimates, Smith et al, 1993) to be derived from the HIRS-HYBRID data. It is important to reemphasize that all the improved measurement capabilities described here have already been experimentally demonstrated, with the University of Wisconsin HIS instrument which has flown on more than one hundred missions of NASA's ER-2 aircraft.

2.2 Instantaneous Field of View (IFOV) and Sounding Resolution

The instantaneous resolution of the HIRS-HYBRID will be 10 km diameter circular as being implemented for the HIRS/3 to fly on the NOAA-N and its successors. Statistical studies of cloudiness (Smith and Huang, 1993) reveal that this resolution will provide clear air radiances for high vertical resolution sounding the earth's surface over 60 percent of the time for a 3 x 3 HIRS IFOV array covering a sounding area of 75 km linear resolution. The 3 x 3 HIRS IFOV array processing procedure is currently used to produce TOVS soundings with the International TOVS Processing Package (ITPP). In cloudy areas, the HIRS radiance data is also used to provide sounding information above clouds while the microwave component of the TOVS provides lower vertical resolution sounding information below cloud level. It is important to note that the improved vertical resolution of the FTS component of the HIRS-HYBRID will enable better detection of cloud effects and thereby better "cloud cleared" radiances in partly cloudy areas as well as more accurate soundings down to cloud level in cloud overcast regions.

3.0 HIRS-HYBRID DESIGN

The information in the following section describes the overall approach being taken in the design of the HIRS-HYBRID sounder.

3.1 Guidelines

- The system must demonstrate all of the functional elements of an operational Advanced Polar Sounder (APS).
- The HIRS-Hybrid will be a demonstration instrument and need not meet all of the spectral coverage requirements of an operational FTS.
- Both the HIRS and the FTS will have simultaneous, collocated footprints for cross verification and synergistic data processing. By viewing with the same scan mirror, both instruments will share both the space and on-board blackbody calibration targets. The existing HIRS internal blackbody calibration target area uniformity is adequate to provide superb comparative measurements.
- On-orbit operation of the FTS is to have no impact on HIRS/3 operation. The developed user community would continue to use the accustomed data link for HIRS data.
- Removal of FTS leaves the HIRS/3 fully operational.

3.2 Approach

- Employ the centrally-obscured area of the HIRS telescope for a fold mirror to a single cavity, single-band Michelson Interferometer. This requires a lengthened HIRS/3 baseplate.

- The FTS mounts on top of HIRS/3 with self-contained electronics and thermal control.
- The FTS output is folded into HIRS/3 cooler modified for a second longwave detector.
- The HIRS-HYBRID will provide multiple data modes for concept validation on orbit.
- The longwave (LW) spectral coverage spans 650-1150 cm^{-1}.
- Electronics will be added to operate and control the interferometer and to process the detected IR signal energy.

The development of the HIRS-HYBRID instrument involves two distinct areas:

1) Addition of a Michelson Interferometer and associated electronics.
2) Modification of the HIRS/3 instrument to accept the interferometer.

3.3 Modifications to HIRS/3

In order to adapt the HIRS to accept the addition of the FTS, the following areas will be modified:

1) The baseplate will be lengthened to accommodate the added fold mirror placed in back of the telescope secondary.
2) The radiant cooler will have the patch area expanded to provide room for the added detector. Also an optical port will be added to the cooler housing to allow entry of the energy from the interferometer. Sufficient cooler margin exists for the detectors to still operate at 92 K.
3) Some of the covers and shields will be modified to accommodate the addition of the interferometer to the HIRS structure.

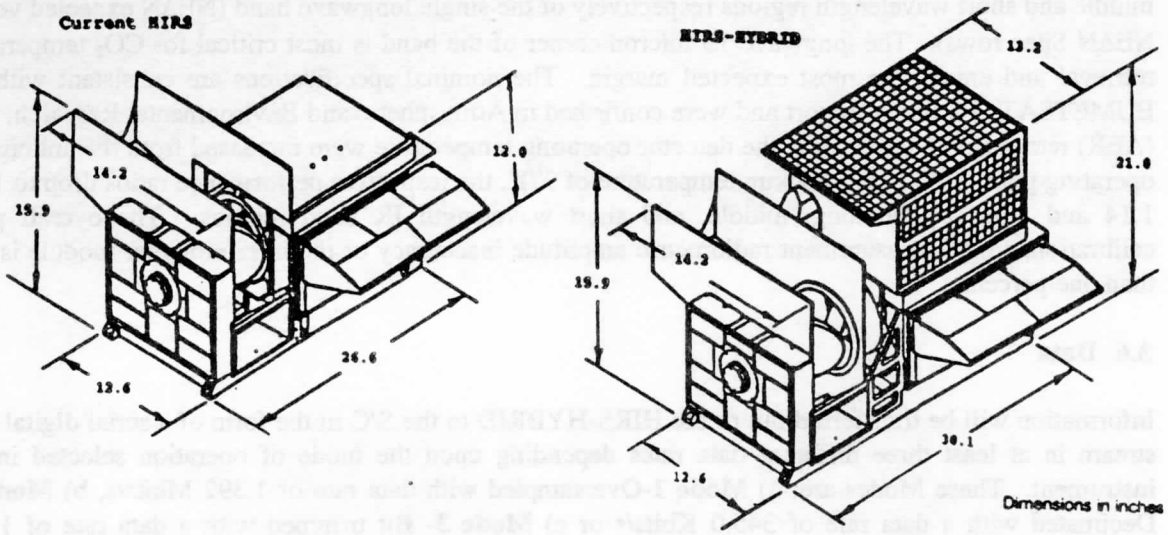
The electronics to drive and control the interferometer and process the data are mounted on the redesigned earth panel. Six Circuit Card Assemblies (CCAs) will be required. An earth-facing radiator which uses Optical Solar Reflector (OSR) tiles for cooling is provided. The OSR thermal panel permits the electronics to be thermally isolated from the existing structure. All new connectors are included in this assembly which results in a completely independent wiring interface.

A summary of the weight increase for the added hardware is shown in Table 3.3-1. The weight of the enhanced instrument increases from 33.6 kg (74 lb) to 46.6 kg (102.5 lb). A side-by-side comparison of the existing HIRS instrument and the modified HIRS-HYBRID is shown in Figure 3.3-1

Table 3.3-1 Comparison of Instrument Parameters

INSTRUMENT	SIZE	WEIGHT	POWER	NUMBER OF DETECTORS (IR)	COMMENTS
HIRS/3	12"X12.6"X 25.6" (LESS SHIELDS)	74lbs	22 watts	2	PASSIVE COOLER
HIRS-HYBRID	21"X12.6"X 30.1" (LESS SHIELDS)	102.5 lbs	54 watts	3	PASSIVE COOLER

Figure 3.3-1 Side-by-side Comparison of HIRS and HIRS-HYBRID Instruments



3.4 Spectral Considerations

The hybrid portion of the HIRS-HYBRID Sounder is designed to operate in the same wavelength region as the Long Wave Band of the HIRS/3 instrument. The FTIR operating band for this design will be from 650 to 1150 cm^{-1}, depending upon the results of further investigation during the Phase B study, at spectral resolution of 0.625 cm^{-1}. The band edges are driven by considerations of detector sensitivity and data bandwidth versus penetration into the CO_2 absorption lines.

Table 3.4-1 compares the spectral coverage of the HIRS-HYBRID (the HIRS with the MI longwave FTS channel) and the full Advanced Polar Sounder baseline design, defined here as ITS(APS). Note that the proposed HIRS-HYBRID FTS /LW channel is the same as the longwave channel of the ITS (APS). Thus, the use of the HIRS-HYBRID will provide the same spectral information in the longwave band as the longwave band of an ITS(APS) instrument.

Table 3.4-1 Comparison of HIRS-HYBRID to Advanced Sounder Requirements - ITS(APS)

INSTRUMENT		SPECTRAL COVERAGE		SPECTRAL RESOLUTION			
TYPE	BANDS	(microns)	(1/cm)	(1/cm) nominal	Relative	Number of channels	Sensitivity (NEdN) (mw/m^2 str cm^{-1})
HIRS-HYBRID	HIRS/LW	14.95 - 6.52	669-1533	18	50	12	0.1 - 3.0
	HIRS/SW	4.57 - 3.76	2188-2660	23	100	7	0.001- 0.006
	FTS/LW	15,38 - 8.70	650-1150	.0625	1360	800	.025 to 0.35
						TOTAL # 819	
ITS(APS)	ITS/LW	15.38-8.7	650-1150	.0625	1360	800	0.25-0.35
	ITS/MW	8.26-5.71	1210-1750	1.25	680	432	.005
	ITS/SW	4.65-3.68	2150-2720	2.5	340	228	0.01
						TOTAL# 1460	

3.5 HIRS-HYBRID Radiometric Considerations

The NEΔN predictions indicate a performance to specification ratio of 1.8, 1.5, and 1.3 for the long, middle and short wavelength regions respectively of the single longwave band (NEΔN expected versus NEΔN Spec rows). The longwave 15 micron corner of the band is most critical for CO_2 temperature retrieval and enjoys the most expected margin. The nominal specifications are consistent with the EUMETSAT ITS Study Report and were confirmed in Atmospheric and Environmental Research, Inc., (AER) retrieval simulations. If the detector operating temperature were increased from the anticipated operating point of 92K to a backup temperature of 97K, the respective performance ratios drop to 1.35, 1.14 and 1.01 for the long, middle, and short wavelength IR band regions. The overall post-calibration, single-measurement radiometric amplitude inaccuracy of the interferometer module is less than one percent.

3.6 Data

Information will be transferred out of the HIRS-HYBRID to the S/C in the form of a serial digital data stream in at least three different data rates depending upon the mode of operation selected in the instrument. These Modes are; a) **Mode 1**-Oversampled with data rate of 1.392 Mbits/s, b) **Mode 2**-Decimated with a data rate of 345.0 Kbits/s or c) **Mode 3**- Bit trimmed with a data rate of 172.5 Kbits/s.

Martin Marietta indicates that there are 10 tape transports on the S/C. All are used for GAC data, TIP data, and "snapshots" of high-resolution LAC data. The LAC snapshots support various users (i.e., Air Force, etc.). As a result, additional storage will have to be provided on the spacecraft for the FTS data. Current thinking is that a 1.9 Gbit solid state recorder would be added to the storage capability of the S/C. The new solid-state recorder capacity is the maximum currently available in a flight-qualified unit configuration. At 1.9 Gbits, its capacity is equivalent to 11.9 minutes playback time at the LAC and GAC playback rate of 2.6616 Mbits/s. This means that data from a full orbit of the HIRS-HYBRID operating in mode 3 or the majority of an orbit in Mode 2 could be stored on the solid state recorder and then played back to the ground though the down link on the non-blind orbits. This allows nearly full earth coverage by the instrument. Operation of the HIRS-HYBRID in Mode 1, which provides direct unprocessed data from the interferometer, would be considered as a backup or debug mode and would provide limited earth coverage (i.e., ~20-25 minutes per orbit using S/C storage or 10-12 minutes of direct readout). This mode would not be used normally.

3.7 Ground System Requirements

3.7.1 Command and Data Acquisition

The additional requirements imposed on the command and data acquisition facilities by the HIRS-HYBRID will be minimal. There will be additional commands and telemetry required for the instrument; however, these are similar in nature to those that are already used for HIRS and, therefore, should only result in a slight modification to the daily command schedule.

The acquisition of the additional data from the HIRS-HYBRID will be handled by existing equipment at the ground station. The data will be in the LAC format and will be transmitted to the ground as just additional data from the on-board recorders or through the backup Air Force transmitter/CDA receiver combination.

3.7.2 Science Data Processing Center

The HIRS-HYBRID, plus associated AVHRR and AMSU, data will be received at the University of Wisconsin, Cooperative Institute for Meteorological Satellite Studies, which will be the Science Data Processing Center. The CIMSS consists of a joint NOAA/NESDIS and University scientific team experienced in the real-time processing of new satellite sounding data and the distribution of experimental products of these data to weather forecast centers for evaluation of their operational utility. Examples of prior CIMSS roles as an experimental satellite data processing center include the TIROS-N TOVS beginning in 1978, the GOES-VAS beginning in 1980, and the GOES-I beginning in 1994. In each of these previous examples, the CIMSS developed the data processing software, prepared meteorological products on a routine quasi-operational basis, and distributed the products to operational weather centers (e.g., the National Meteorological Center, NMC, the National Severe Storms Forecast Center, NSSFC, and the National Hurricane Center, NHC) for evaluation of the product's utility for each of the center's analysis/forecast operations.

The Space Science and Engineering Center (SSEC) which houses the CIMSS has the satellite receiving system and the computer and communication facilities required to carry out this program. The data will be ingested at SSEC through its DOMSAT receiving station which is capable of obtaining all the direct readout and on-board recorded data retransmitted through a domestic communications satellite (DOMSAT) from the Wallops Island, Virginia, and Gilmore Creek, Alaska, Command and Data Acquisition (CDA) stations. The SSEC receiving system is identical to the operational NOAA/NESDIS system in Suitland, Maryland. Thus, global HIRS-HYBRID plus associated TOVS and AVHRR data will be ingested, processed, and archived at the SSEC.

The HIRS-HYBRID interferometric data plus filter wheel observations will be processed with associated AMSU and AVHRR data using high performance work stations available at CIMSS. Currently CIMSS possesses six RISC-6000 series and one Silicon Graphics work station, each capable of performing the science data processing in real-time. The raw data will be accessed from the McIDAS data base manager which will ingest the data through the SSEC receiving system. The HIRS-HYBRID, plus associated AMSU and AVHRR data, will be ingested, calibrated, and earth-located using preprocessor software already in place at the SSEC. The science data processing, including the handling of clouds and profile retrieval, will be based on software already used at CIMSS for processing TOVS plus AVHRR data and the High resolution Interferometer Sounder (HIS) aircraft data.

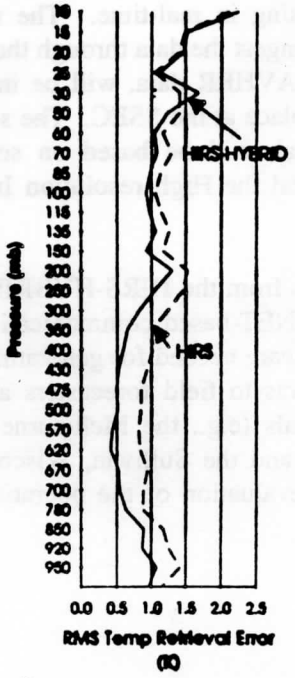
The delivery of Meteorological products from the HIRS-HYBRID will be performed using the SSEC McIDAS system and associated INTERNET-based communications system. McIDAS possesses the meteorological analysis and display software needed for generating forecast-sensitive products and the meaningful presentation of these products to field forecasters at NSSFC, NHC, and other regional centers which possess McIDAS terminals (e.g., the Melbourne, Australia, Bureau of Meteorology (BOM) and its associated field offices and the Sullivan, Wisconsin, NWS office). Many of these forecast centers will participate in the evaluation of the operational utility of these HIRS-HYBRID advanced sounding products.

The largest impact of the advanced sounding data to be provided by the HIRS-HYBRID is expected to occur in Global and Regional Numerical Weather Prediction (NWP). For this purpose, the data will be made available in terms of spectral radiances (for their direct assimilation into model analyses) as well as vertical profiles of temperature, water vapor, and ozone at a horizontal spatial resolution of 75 km. These data would be accessed through the INTERNET by NWP centers (e.g., the United States NMC, the European Center for Medium Range Weather Forecasts (ECMWF), and Australia's BOM). All these NWP centers possess McIDAS terminals which can be used for evaluation of the profile products and their resulting impact on their NWP operation. The CIMSS will also operate its own NWP system (the CIMSS Regional Assimilation System, CRAS), both with and without the HIRS-HYBRID interferometeric sounding products in order to evaluate the impact of these advanced soundings on regional NWP.

3.8 Expected Errors Based on Synthetic Radiances (AER Results)

Retrieval performance simulations were performed by Atmospheric and Environmental Research, Inc. (AER) on a global system level, as well as from an instrument maker's viewpoint (Figure 3.8-1). The atmosphere was described with forty levels of temperature extending from the surface (Level #1) to o.1 millibar (Level # 40), fifteen water levels up to 300 millibars, and the surface temperature. Ozone was not retrieved, although the HIRS-HYBRID long wave band will cover the 9 micron ozone spectral region. The first guess was derived from AMSU radiances, appropriately degraded by expected instrument and "atmospheric" (i.e., forward model) noise.

Figure 3.8-1 Expected Retrieval Errors for HIRS and HIRS-HYBRID



The HIRS-HYBRID improvement of about 0.5 degree less rms Temperature Retrieval Error than the HIRS, is quite significant when equated to increased forecasting ability. Forecast error growth is about 0.5 degree C per day so that this sounding accuracy improvement equates to a one-day extension of predictability (i.e., a two-day forecast can be made with the same skill as today's one-day forecast!!).

4.0 PROGRAM IMPLEMENTATION

The program plan to implement the HIRS-HYBRID consists of five stages; these are 1) Phase B i.e. a system development and preliminary design phase, 2) Engineering Model Modification and Test, 3) Flight Model Modification and Test, 4) High Resolution Sounder Algorithm Development and Implementation and 5) Spacecraft Accommodation/Modification Task. Programmatic studies show that HIRS-HYBRID could be implemented for flight on NOAA-N (nominal launch date of 2000) if a Phase B study is initiated in early 1995.

5.0 SUMMARY/CONCLUSIONS

Although there are many advantages to implementing the HIRS-HYBRID concept at this time, two major ones stand out worthy of further comment:

1. The HIRS-HYBRID provides a pathfinder operation at low cost to pave the way for a full-up, operational advanced sounder. The developmental problems along with the additional capabilities of ground processing required for a fully operational system without disruption to the current weather service. Because of this pathfinder effort, at such time that an advanced sounder becomes operational, the majority of the problems associated with a new program will have been solved and the transition to the advanced sounder capabilities should be smooth and seamless.

2. The HIRS-HYBRID will provide a valuable enhancement to the existing satellite sounding system. The higher resolution data obtained will allow improved global numerical weather forecast capabilities much earlier and at a much lower cost than would be otherwise possible. The improved vertical resolution and accuracy is expected to significantly improve the accuracy and extend the useful range of global forecasts.

In summary, an approach for achieving a high vertical resolution satellite sounding capability at the turn of the century and at low cost has been developed. The approach involves the addition of a small Michelson Interferometer unit to the operational HIRS/3 instrument, making use of most of the HIRS optical and mechanical assemblies without interference with the existing HIRS operational measurement capability. The major advantage of this approach is that it enables valuable ground system experience to be gained with a high vertical resolution satellite sounder on an operational spacecraft. Trial weather service applications of the data takes place several years in advance of the implementation of the next generation IR sounding system on the converged spacecraft, C-1, with a nominal launch date of 2006.

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