NOAA/NESDIS SOUNDING PRODUCTS

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1. INTRODUCTION

The Soundings Implementation Branch (SIB) of the Office of Research and Applications (ORA) provides science maintenance and development support for operational satellite sounding products distributed by NOAA. Currently five principal projects are supported by SIB:

* TIROS Operational Vertical Sounder (TOVS) operational sounding system,
* Defense Meteorological Satellite Program (DMSP) operational sounding system,
* NOAA-KLM series operational sounding system development,
* Geostationary Operational Environmental Satellite (GOES I/M) operational sounding system development, and
* Baseline Upper Air Network (BUAN) test, results and data archive activities.

The following sections present the status and discussion for each of the above activities.

2. TOVS SOUNDING PRODUCTS

a. Current Status

The status of TOVS operational sounding products is discussed in this section. Recently, four activities have been completed:

o a physical retrieval approach was installed on September 15, 1988,

- o the surface field algorithm was improved including the use of satellite based ice fields,
- o the NOAA-11 satellite was implemented in January, 1989, and
- o procedures to compute and distribute routine error statistics on sounding products were initiated during April, 1989.

a.1 Physical Retrieval Approach

A physical retrieval approach was installed into the TOVS operation on September 15, 1988 and replaced a statistical regression approach. This concluded several years of development and evaluation, including a Numerical Weather Prediction (NWP) forecast impact study (Dey, 1989) conducted by the National Meteorological Center (NMC) of NOAA for final approval. The physical retrieval approach uses an explicit knowledge of radiative transfer processes in the atmosphere to compute temperature and moisture soundings from the TOVS radiance profiles and replaces a purely statistical approach.

The procedures to compute sounding products are identical to the statistical regression method for the preprocessing, clear radiance computation and radiance consistency testing done to compute the clear column radiance profiles for each TOVS minibox (Reale, 1986). However, the steps of the subsequent retrieval sequence are quite different. The new method uses a "tuning" database of radiosonde and satellite sounding matched pairs to select the first guess temperature, moisture and radiance profiles (Goldberg, 1988) for a given minibox. The first guess temperature profile is then used to select the retrieval operator which is the Minimum Variance Simultaneous (MVS) solution (Fleming, 1988). Finally, the first guess profiles and retrieval operator are combined to compute the temperature and moisture soundings from the surface to .1 mb (Reale, 1989).

An important part of the TOVS physical retrieval system is the support system for tuning. Tuning refers to the collection and application of recent radiosonde and satellite sounding matched pairs to provide estimates of the first guess temperature, moisture and TOVS radiance profiles. Tuning avoids errors introduced through the computation of simulated radiances by providing collocated vectors of observed temperature, moisture and satellite radiance measurements (Fleming, 1986) for the retrieval step. Explicit computation of the atmospheric transmittances and weighting functions for each TOVS channel, and an estimate of the covariance matrix of the product vectors (Crosby, 1973) for use in the retrieval step are also provided through the routine tuning procedures (Reale, 1989).

The tuning database of radiosonde and satellite sounding matched pairs is also used to compute transmittance adjustment factors. The transmittance adjustments factors are applied to minimize the difference between simulated and observed radiances for each TOVS channel and are used in operational computations. These factors are global and updated for each satellite as need.

a.2 Improved Surface Fields

Several improvements to the TOVS surface field algorithm were installed into the operation during the fall of 1988. The first phase improved procedures to update the separate TOVS surface fields for day and night based on the NMC synoptic surface field data. Phase 2 improved procedures which append the TOVS surface field data to each satellite observation based on the observed solar zenith angle.

Phase 3 added two more changes to the TOVS surface field algorithm. First, the process of updating of the day and night TOVS surface fields was upgraded to consider the latitude and the time of year of the observation in addition to the solar zenith angle for the day/night designation. TOVS surface fields are routinely updated by both the latest

satellite and NMC surface observations. Secondly, operational satellite (AVHRR) based ice field data provided by the Joint Navy-Sea Ice Center were introduced to identify the polar ice boundary and procedures were installed to update the ice boundary each week. The introduction of the ice field boundary has led to improved cloud detection over polar ocean regions, particularly for low clouds.

a.3 Implementation of NOAA-11

TOVS sounding products from the NOAA-11 satellite became operational during January of 1989. This was the first satellite to be implemented using the new physical retrieval approach. The TOVS sounder onboard NOAA-11 featured a modified water vapor channel 10 at 795.7 cm^{-1} and a new sounding channel 17 at 2416.3 cm^{-1}.

The modified channel 10 is more sensitive to atmospheric water vapor and has resulted in an improved water vapor correction of the HIRS window channel 8. The modified HIRS channel 10 is preprocessed in the same manner as the old channel 10, that is, it serves as a predictor for correcting the HIRS channels 8, 18 and 19 for water vapor attenuation. For previous satellites, an average 1.5 K cold bias was observed between the corrected HIRS channel 8 brightness temperatures and ground truth (i.e., the sea surface temperature) for clear and partly cloudy soundings in the tropics. A cold bias is not observed for corrected HIRS channel 8 brightness temperatures from NOAA-11. Biases observed for previous satellites in the HIRS channels 18 and 19 are also removed for NOAA-11.

NOAA-11 also has a new HIRS channel 17. This sounding channel measures the lower troposphere and can be described as a "dry" HIRS channel 13. Preliminary evaluations using the new HIRS 17 in the retrieval sequence indicate a nominal improvement between 1000 and 700 mb for clear and partly cloudy soundings in the tropics over land. The new channel 17 is used in the preprocessing (i.e., as a predictor for limb correction) and is cloud cleared, unlike for previous satellites.

a.4 Sounding Error Statistics

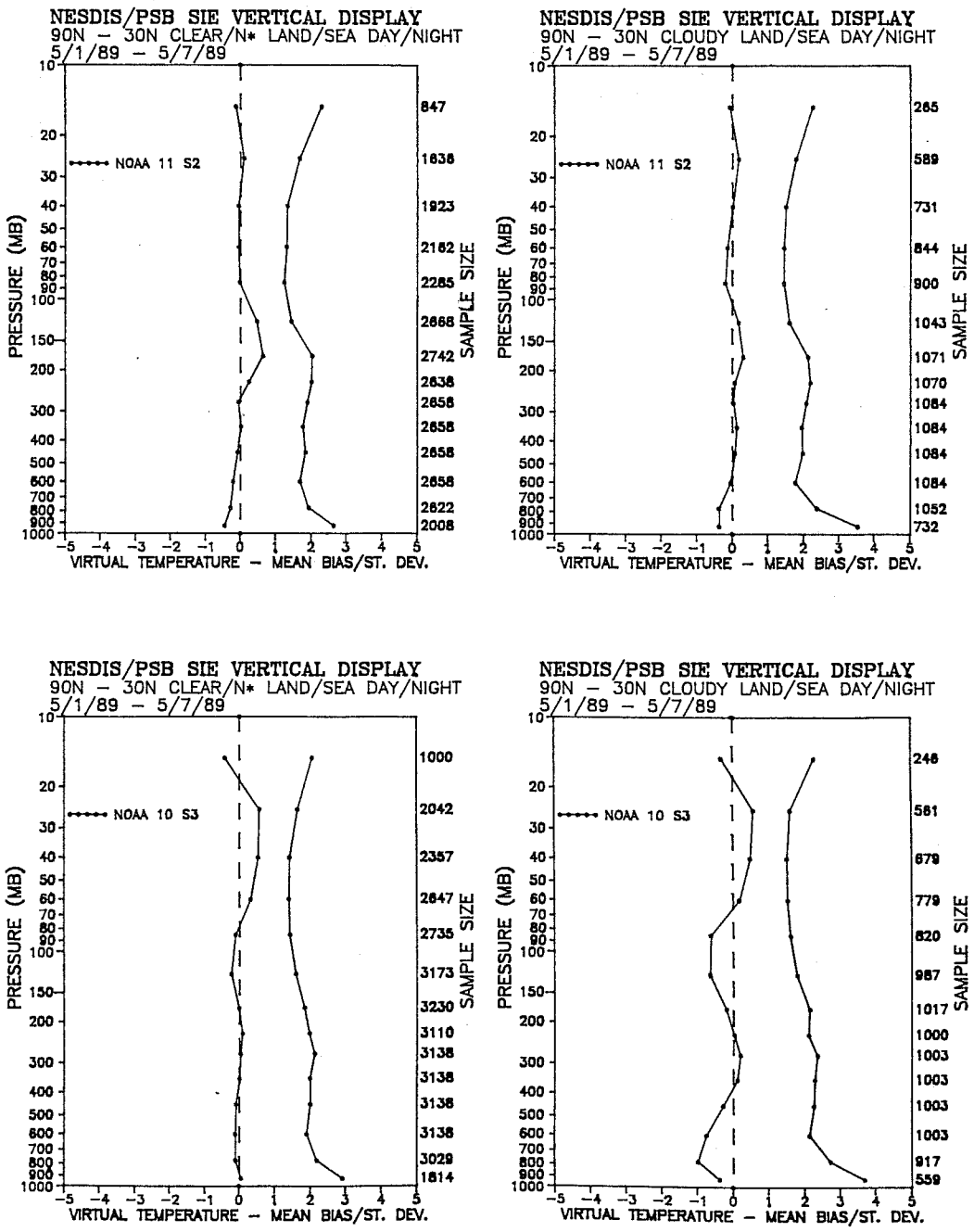
NMC and NESDIS have collaborated to develop procedures for computing vertical error statistics for satellite sounding products. This effort was completed during March of 1989 and vertical error statistics (similar to those computed by the ECMWF) are now computed and distributed by NESDIS. These statistics are included in the routine monitoring of sounding products and the evaluation of science upgrades. NWP impact studies are also important for evaluating satellite product upgrades and are conducted by NMC when changes are significant.

The vertical error statistics are based on collocated pairs of radiosonde and satellite soundings. The collocated pairs are screened and unacceptable pairs are removed. Examples of the vertical error statistics generated by NESDIS are shown in Figures 1a-1d. Statistics are computed weekly, for each of three 60 degree latitude belts, for clear/partly cloudy and cloudy sounding types and for each satellite. The statistics displayed are the mean and standard deviation of the satellite sounding minus radiosonde layer mean virtual temperature. The pressure scale and sample sizes are also shown on each plot.

The matched pair datasets are also routinely stored, condensed and made available to NMC. A cooperative effort between NMC and NESDIS is underway to study their use to compute horizontal and vertical error correlations of sounding products for use in NWP forecast models.

b. Planned Upgrades

Timely feedback on the impact of TOVS sounding products on NWP models was received from the ECMWF this past winter which indicated significant errors particularly for cloudy soundings. It was reported that the cloudy soundings had large errors in the vicinity of frontal boundaries and also in regions of cold air over warm ocean surfaces. The errors were found to be largest in the surface layer and also compensating



Figures 1a - 1d: NOAA vertical accuracy statistics for TOVS soundings from 90N to 30N for NOAA-11 (top) and NOAA-10 (bottom) and for clear/partly cloudy (left) and cloudy (right) sounding types from May 1 to May 7, 1989.

in nature, that is, warm biases near the surface with cold biases aloft. Errors were also observed for clear and partly cloudy soundings near the center of sub-tropical high pressure systems, these errors were smaller than for the cloudy soundings.

Regional case studies of TOVS sounding products during the past winter are currently being conducted by NESDIS to document these problems. Preliminary indications are that poor meteorological representation in the "tuning" dataset of radiosonde and satellite sounding matched pairs used to compute the first guess may be an important aspect of the problems. It is not certain whether this can be corrected in the current operational system.

b.1 Short Term

NESDIS is currently studying four short term actions to reduce the problems observed during the 88/89 winter, these are:

- o introduce matched pairs of radiosonde and "cloudy" satellite soundings into tuning procedures,
- o introduce matched pairs containing 6Z and 18Z radiosondes into tuning datasets for improved meteorological representation,
- o introduce procedures to maintain the meteorological representation of the tuning dataset during all seasons, and
- o improve cloud clearing procedures to remove noisy partly cloudy soundings.

Currently, only matched pairs of radiosonde and clear/partly cloudy soundings are used in the tuning procedures. The introduction of matched pairs of radiosonde and cloudy satellite soundings for tuning the cloudy soundings may reduce the errors in cloudy sounding products. For example, winter radiosondes matched to cloudy TOVS soundings near Taiwain were found to be significantly colder near the surface than those

matched to clear soundings. However, it is uncertain whether improvements can occur given the limited sounding channels available for TOVS cloudy soundings.

The addition of the 6Z and 18Z radiosondes to the 0Z and 12Z radiosondes which are used for tuning potentially improves the global representation of the matched pairs used to tune each satellite. Unfortunately ,the proportional number of 6Z and 18Z radiosondes is small.

Procedures are also being developed so that the tuning dataset (in particular the first guess library) for a given region is never significantly depleted especially in radiosonde sparse regions. It appears that this may have contributed to the increased errors in tropical soundings (both clear and cloudy) during this past northern hemisphere winter.

Finally, an improvement of the "nstar" cloud clearing algorithm (McMillin, 1982) which reduces the noise in partly cloudy soundings has been developed and verified. NESDIS hopes to implement all the above upgrades prior to the onset of the 1989-90 winter season.

b.2 Long Term

NESDIS is also conducting long term research projects to improve soundings products accuracy. Two major areas of research to improve the accuracy of the first guess are the:

- o radiance classification approach, and
- o "interactive" approach.

The radiance classification approach uses the observed TOVS radiances to determine a radiance profile class which is based on a pre-computed set of classes generated from historical atmospheric data (McMillin, 1986). The interactive approach uses the NMC 6-hour forecast to determine the first guess temperature and moisture and to calculate the first guess radiances (Fleming, 1989). The development of sounding

processing systems which use these approaches is underway and the initial testing of each in an operational scenario is expected to begin by the end of 1990.

b.3 Other

Resources permitting, NESDIS will study other upgrades to the operational sounding systems, including:

- o use of the NMC 6-hour forecast to quality control sounding products,
- o use of the TOVS moisture channels to compute moisture products,
- o upgrade of the limb correction procedure, and
- o removal of radiosonde and radiance bias errors.

The use of the NMC 6-hour forecast to quality control the sounding products would be based on a stability departure parameter (similar to that used by the ECMWF). The sounding products would be verified prior to distribution with a quality indicator appended to the sounding data record.

The TOVS moisture channels (HIRS 10, 11, and 12) are currently not used to generate moisture products. Previous results based on statistics from collocated radiosondes and satellite soundings indicated that satellite moisture products were degraded when the HIRS moisture channels were used. These results are now being questioned.

The limb correction upgrade would replace the existing TOVS limb correction procedure which is based on simulated radiances from a marginally representative database of atmospheres. The new method (Wark, 1989) is based on observed satellite measurements with the option for seasonal updating if necessary.

Finally, bias errors between different radiosonde types and between simulated and observed radiances degrades the accuracy of sounding products when incorporated in the soundings

generation process. Procedures to remove bias errors during the generation of coefficients and prior to the retrieval sequence are currently being studied.

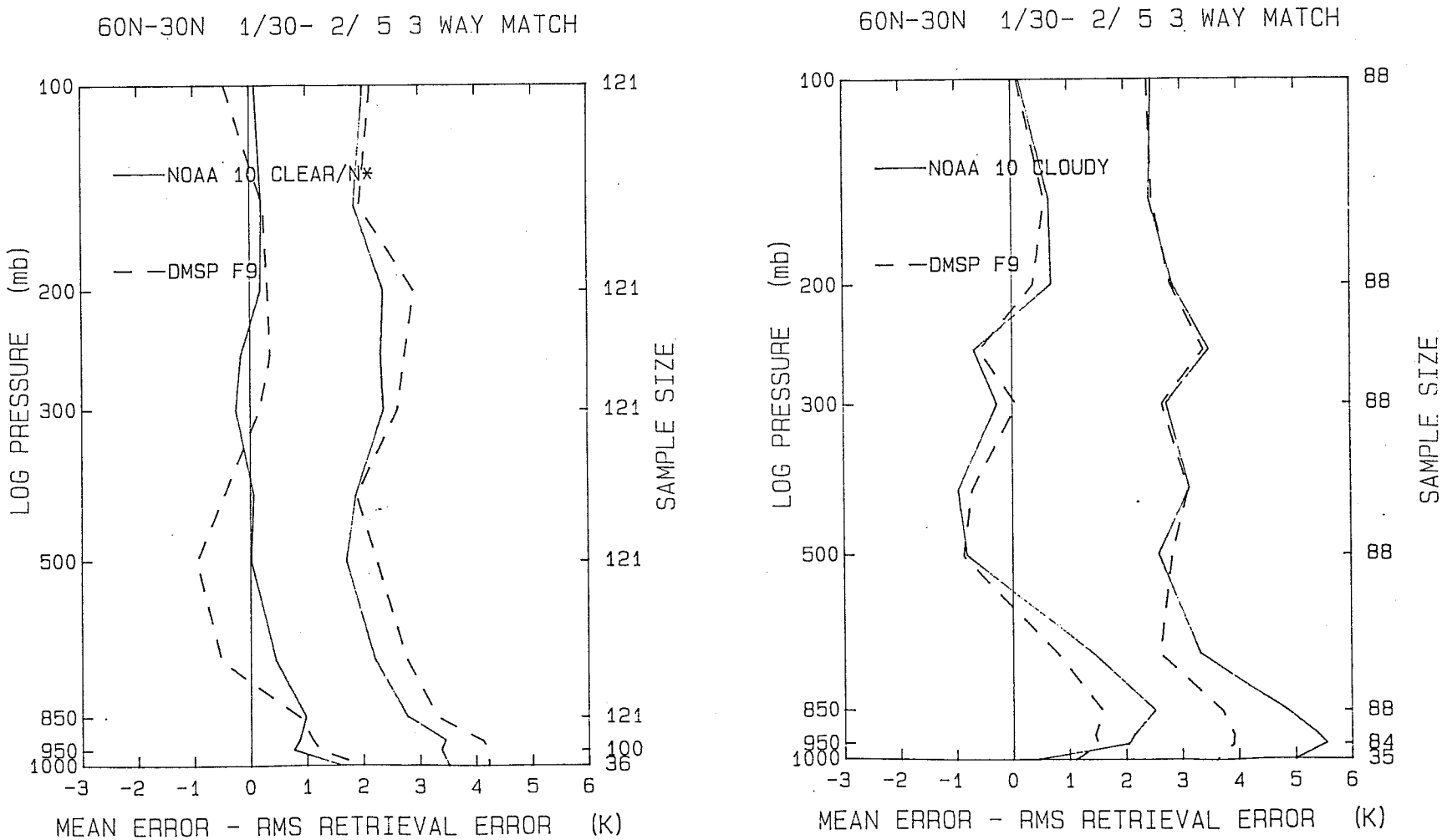
3. DMSP SOUNDING PRODUCTS

a. Current Status

As part of the Shared Processing Agreement between NESDIS and the U.S. Navy and the Air Force, NESDIS is currently processing and distributing atmospheric soundings from the 7-channel Special Sensor Microwave/Temperature (SSM/T) sounder onboard the DMSP F8 and F9 satellites. SSM/T data are transmitted to the NESDIS central computer facility in real time from Offutt Air Force Base in Nebraska. The data are transmitted over the dedicated Shared Processing Network link, and the transmission of sounding products computed by NESDIS is scheduled to begin this fall. In addition, NESDIS also routinely distributes DMSP soundings to NMC and the ECMWF.

The DMSP soundings of temperature, water mixing ratio and the layer mean virtual temperature are computed using a linear statistical retrieval algorithm. The SSM/T data are not limb corrected and surface and terrain height corrections are applied to the surface channels prior to the retrieval step. The surface and terrain height correction coefficients and the retrieval coefficients are updated weekly based on radiosonde and satellite sounding matched pairs from the previous 4 to 8 weeks. Ninety-six separate sets of coefficients are computed covering 12 latitude zones, land and sea categories and 4 symmetric scan angles (including nadir). The matched pairs of radiosonde and satellite soundings are collected and stored daily and are also used to provide routine monitoring of the DMSP sounding products.

Figures 2a and 2b show typical error characteristics of the DMSP sounding products in the northern hemisphere during the winter of 1988. The figures show vertical error statistics for three-way matches of collocated DMSP and TOVS sounding



Figures 2a and 2b: Vertical accuracy statistics for 3-way matched pairs of DMSP and TOVS clear soundings versus radiosondes (left) and DMSP and TOVS cloudy soundings versus radiosondes (right) from 60N to 30N for the period January 30 to February 5, 1989.

products versus radiosondes. A three-way match means that the radiosonde and soundings were all collocated within 300 km and 3 hours (this results in predominantly regional statistics centered about eastern Asia, Australia and the eastern U.S. coast). Figures 2a and 2b show statistics for soundings in clear and cloudy atmospheres respectively, based on the TOVS sounding type. The DMSP soundings appear more accurate than the TOVS cloudy soundings and less accurate than the TOVS clear and partly cloudy soundings. This is typically observed and is not surprising given the number of sounding channels available.

During February of 1989, a new algorithm to identify SSM/T data over ocean which is contaminated by precipitation by computing the cloud liquid water content was implemented into the DMSP operation. Precipitation detection is done as part of the preprocessing and quality control to prevent errors in sounding products. The equation used to compute the cloud liquid water content is:

$$Q = C_0 + C_1(TB_1) + C_2(TB_2)$$

where Q is the cloud liquid water content, TB_1 and TB_2 are the brightness temperatures for SSM/T channels 1 and 2 and C_i are regression coefficients based on simulated data (Grody, 1979) for each scan angle. At this time the "Q" values are computed for each SSM/T field-of-view (fov) and are compared to threshold values in order to identify contaminated fov's. The liquid water content is currently being evaluated for possible use as a new operational product.

b. Planned Upgrades

Feedback from the ECMWF and NMC have indicated interest in using DMSP soundings products in NWP forecast models. At this time, the primary interest is to use them either as a backup if one of the NOAA satellites fails, as a possible replacement for TOVS cloudy soundings, or as a quality control dataset to verify the TOVS soundings.

Past evaluations and feedback from the two centers have also indicated problems with the DMSP soundings. In particular, inconsistencies between neighboring soundings in frontal regions, across polar latitudinal boundaries and for adjacent scan angle positions in the southern hemisphere have been reported. These problems, and observed differences between collocated DMSP and TOVS cloudy soundings make combining the TOVS and DMSP soundings in the same NWP model difficult, whether as a model parameter or a quality control tool.

NESDIS is dedicated to improving the DMSP sounding products and in response to user feedback plans the following upgrades which are listed in priority order:

- o limb correct the SSM/T data,
- o apply an air mass classification approach to determine the first guess,
- o replace the statistical regression with a physical retrieval approach,
- o use Special Sensor Microwave/Imager (SSM/I) data for precipitation detection and surface and terrain height correction of SSM/T data, and
- o use NMC 6-hour forecast for quality control

Much research has occurred to finalize a limb correction algorithm for the SSM/T data (Wark, 1989) during the past year. Work is currently underway to develop operational procedures in order to install the limb correction algorithm into the DMSP operation. These procedures are expected to remove the inconsistencies across the scan angles and latitude boundaries caused by the different coefficients for neighboring soundings, particularly in radiosonde scarce regions. Recent upgrades in precipitation detection using the "Q" values are expected to reduce the inconsistencies between soundings in frontal regions.

An air mass classification approach to determine the first guess and a physical retrieval approach based on the TOVS method are currently being studied. The unification of

sounding algorithms for all polar orbiting satellites is a long term goal of NESDIS and appears to be the best way of insuring agreement between the products from these systems.

The use of the SSM/I data to help identify precipitation contamination in the SSM/T channels and to provide improved surface emissivity and terrain height correction has been planned since the beginning of the DMSP operation in 1985. Software to generate mapped fields of SSM/I data that are compatible for correcting the SSM/T data have been completed. However, scientific algorithms and software to use the SSM/I mapped fields to correct the SSM/T data have neither been defined nor developed. Given the recent progress in the routine transmission of SSM/I data from Offutt Air Force Base to NESDIS in Suitland, it is hoped that this activity can be accelerated.

Finally, the use of the NMC 6-hour forecast to quality control the DMSP sounding products is an important task for data validation. Resources are currently not available to begin this task but support for this task is planned as other tasks are completed.

4) NOAA-KLM SOUNDING SYSTEM DEVELOPMENT

A series of three next generation polar orbiting satellites, NOAA-KLM, are scheduled for launch by NESDIS in the 1990's. The launch of NOAA-K is currently scheduled for late 1993 at which time a sounding instrument configuration of the 20 channel High resolution InfraRed Sounder (HIRS), the 20 channel Advanced Microwave Sounding Unit (AMSU) and the five channel Advanced Very High Resolution Radiometer (AVHRR) will be used to compute NOAA sounding products.

The development of upgraded systems software and scientific algorithms to process data for NOAA-K is currently underway. A preliminary version of this upgraded system, known as System'90, is scheduled to become operational in late 1991. System'90 is expected to process data from the TOVS/AVHRR

instrument configuration onboard NOAA D and J. The package of scientific upgrades to be implemented in System'90 is scheduled to be those which were independent of the sounder configuration (SMSRC, July 1987). However, given the recent limitations in resources for sounding algorithm development, the science package for System'90 is again under review.

System'92, which represents the complete system and scientific capability to process the data from the AMSU/HIRS/AVHRR instrument configuration is scheduled for operational implementation 6 months after the launch of NOAA-K. A block diagram summarizing the scientific processing steps planned for System'92 (SMSRC, Aug. 1987) is shown in Figure 3. The level 1-b data are the raw satellite data for each fov with earth location and calibration coefficients appended. Antenna pattern and calibration algorithms are first applied to generate the raw radiance data. The HIRS and AVHRR are then used to perform preliminary cloud tests. The AMSU are used to estimate surface emissivity and precipitation contamination with the former used to correct the AMSU surface channels. The AMSU, HIRS and AVHRR data are then combined for the final cloud testing and cloud clearing. The clear column HIRS and AMSU-B data are interpolated to the AMSU-A fov's, global limb correction is applied, and the resulting radiance profiles undergo objective analysis with outlier fov's identified. The radiance profiles for each AMSU-A gridpoint are then input to the retrieval sequence to compute the temperature and moisture soundings. The retrieval sequence includes any adjustment to the radiances (if not applied previously), a classification approach to determine the first guess, and the MVS physical retrieval solution. The final step is to use the NMC 6-hour forecast for quality control prior to soundings distribution.

5. GOES I/M SOUNDING SYSTEM DEVELOPMENT

A series of five new geostationary satellites (GOES-I/M) are planned for operation by NOAA during the 1990's and early 2000's. These spacecraft will differ from the current GOES satellites in that they are three-axis stabilized, allowing

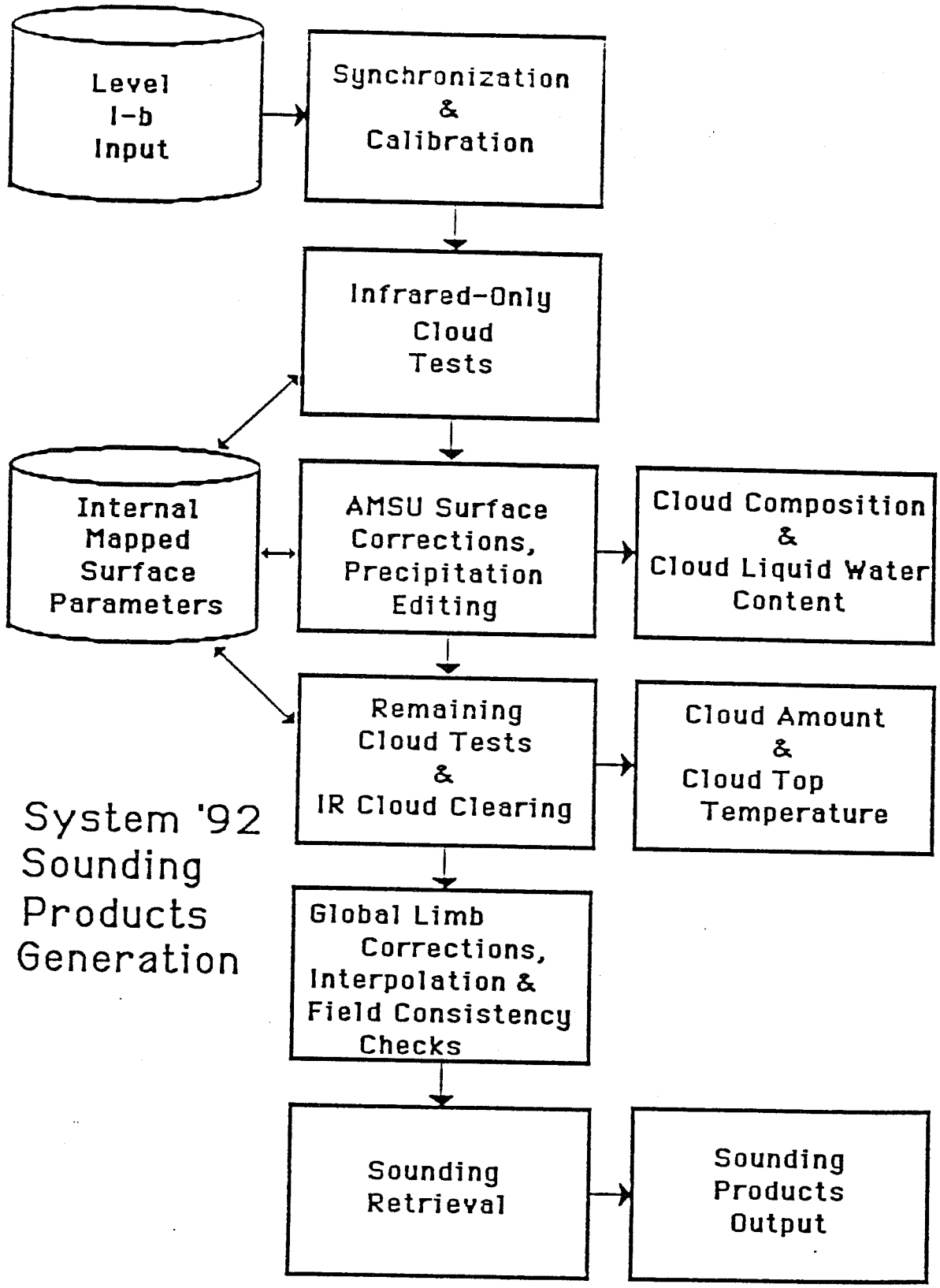


Figure 3: Block Flow Diagram for NOAA-KLM, System '92.

for more effective sounding of the atmosphere and generation of temperature and moisture profiles. A 19-channel infrared sounder (similar to the HIRS/2 on the NOAA polar orbiters) will be flown on these spacecraft. The first in the series, GOES-I, is planned for launch in late 1990.

A project to develop and implement an operational data processing system for the generation and distribution of sounding products is currently underway. The Systems Design and Applications Branch of NESDIS (located in Madison, Wisconsin) is responsible for developing the software subsystems to ingest GOES-I/M raw data, and process this data into atmospheric sounding products. These products consist of both quantitative and qualitative parameters. The quantitative products are planned for use in the NMC regional numerical weather forecast models, and the qualitative products will support the National Severe Storm Forecast Center and the National Hurricane Center. The soundings will be generated only in clear regions using the NMC regional forecast as the first guess and an iterative/simultaneous method (Hayden, 1989) to generate soundings. The SIB is responsible for developing and the support sub-systems for soundings generation and for the integration and operational implementation of the entire sounding system. The support sub-systems will provide the capability of routinely collocating the sounding products with a variety of ground truth measurements (radiosondes, profilers, forecasts, etc.) for the purpose of routine products monitoring and and to support research and development activities. An offline parallel system will be created which will provide the means for routinely processing upgrades to the operational system while maintaining the integrity of the operational products.

The implementation of the final operational capability is scheduled to coincide with the launch of GOES-I and the development of the Regional Data Assimilation System (RDAS) at NMC. The RDAS is being designed to receive the maximum benefit from non-traditional measurements, such as hourly GOES soundings and profiler measurements.

6. BUAN FEASIBILITY TEST SUPPORT

At the Extraordinary Session of the World Meteorological Organization (WMO) Commission for Basic Systems held in 1985, it was recommended that an experiment be undertaken to test the hypothesis that improvements in the accuracy of satellite soundings would result through the implementation of a BUAN. The BUAN were a special set of globally distributed radiosondes to be launched coincident with satellite overpass. The WMO, with cooperation from NMC and NESDIS, coordinated the planning of this activity (NWS, 1987) and the BUAN experiment was conducted from January 15 to July 18, 1988.

NESDIS was responsible for the generation and distribution of BUAN launch schedules and the collection and archive of matched pairs of BUAN radiosonde and satellite sounding data. NESDIS also operated a sounding products generation system which was "tuned" using only the BUAN matched pairs in order to test the BUAN hypothesis.

An important by-product of the BUAN experiment is the archive of BUAN radiosonde and satellite sounding matched pairs. The archive contains the special BUAN radiosondes which were received by NMC and for which at least one collocated satellite sounding was observed by NESDIS. Since the dataset is global and contains nearly coincident radiosonde and satellite sounding observations, it is expected to be useful in research studies to validate radiative physics models of the atmosphere. The BUAN archive is also important for studies on biases due to radiosonde type and for longwave and shortwave radiation corrections applied to radiosonde data.

The BUAN archive will be available on 5 standard label magnetic tapes (6250 bpi) and is separated into three parts. Part 1 contains the matched pairs of radiosonde and satellite soundings which include the TOVS clear column brightness temperatures used to generate the sounding products. Part 2 contains matched pairs of radiosonde and the adjusted (i.e., calibrated, limb corrected, etc) TOVS brightness temperatures

for the 99 HIRS fov measurements contained in the sounding "box" (Reale, 1986) with the MSU data interpolated to the HIRS fov. Part 3 contains the matched pairs of radiosonde and the un-adjusted (i.e., calibrated only) TOVS brightness temperatures for the 99 HIRS fov's contained in the sounding "box" with the MSU data interpolated to the HIRS fov. Parts 1 and 2 are available for the complete experiment whereas Part 3 is only available from May 22 to July 15. Rocketsonde data reported during the BUAN exercise are also stored at the end of each tape. An archive directory is compiled and will be available.

An added feature of the BUAN archive concerns the radiosonde report data. Two values for the radiosonde report data are stored, both the "as received" and "as adjusted" values. The adjustments refer to the radiation corrections applied to each radiosonde by NMC and which vary by height, solar zenith angle and radiosonde type.

The archive of BUAN radiosonde and satellite data is scheduled to be completed and ready for distribution by NESDIS at the end of 1989. The BUAN Evaluation Preliminary Report (WMO, 1988) is completed and the final report is scheduled for completion during the early part of 1990.

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