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THE RATIONALE AND SUGGESTED APPROACHES FOR RESEARCH GEOSYNCHRONOUS SATELLITE MEASUREMENTS FOR SEVERE STORM AND MESOSCALE INVESTIGATIONS

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(AD HOC Severe Storms and Mesoscale
Requirements Committee)

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The Rationale and Suggested Approaches for Research Geosynchronous Satellite Measurements for Severe Storm and Mesoscale Investigations

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List of Acronyms

MCS	Mesoscale Convective System
VISSR	Visible, Infrared Spin-Scan Radiometer
VAS	VISSR Atmospheric Sounder
GOES	Geostationary Operational Environmental Satellite
GOES-Next	Next Generation GOES satellite
AVHRR	Advanced Very High Resolution Radiometer
EOS	Earth Observing System
TOMS	Total Ozone Mapping Spectrometer
MCR	Multi-Channel Cloud Radiometer
CTS	Cloud Top Scanner
MSU	Microwave Sounding Unit
MSS	Multi-Spectral Scanner

Preface

This document discusses the rationale for research geosynchronous satellite observations for the study of mesoscale meteorological phenomena. It describes the capabilities of current and planned systems and presents approaches by which new observations could make significant and critical contributions to research problems in mesoscale meteorology and severe storms.

The document is a product of an Ad Hoc Committee chaired by R. Adler (Code 612) and with L. Uccellini (Code 612), D. Chesters (Code 613), J. Susskind (Code 611), and W. Shenk (Code 610) as members. After committee discussions and agreement, W. Shenk drafted the document and each committee member reviewed and approved it. The result is a committee report on the need for new geosynchronous observations. The committee is indebted to W. Shenk for his major contribution in this effort.

R. Adler

Executive Summary

The required measurement of severe thunderstorms, tropical and extratropical cyclones, and other mesoscale phenomena is heavily dependent on the high spatial and temporal resolution information which can be acquired from geosynchronous satellites. The measurements from current and planned (e.g., GOES-NEXT) geosynchronous satellites (augmented by data from low orbiting missions) have provided or will provide quantitative estimates of temperature and moisture profiles, surface temperature, wind, cloud properties, and precipitation. However, there will still remain a number of significant observation characteristics yet to be achieved, including: 1) temperature and moisture profiles in cloudy areas; 2) high vertical profile resolution; 3) definitive precipitation area mapping and precipitation rate estimates on the convective cloud scale; 4) winds from low level cloud motions at night; 5) the determination of convective cloud structure; and 6) high resolution surface temperature determination.

Four major new observing capabilities are proposed to overcome these deficiencies. First, a microwave sounder/imager is proposed to provide the temperature and moisture profiles in cloudy areas and to be the principal measurement capability to map precipitation. A high resolution visible and infrared imager is added for sharp improvements in the determination of convective cloud structure, winds from cloud motions, and surface temperature. A high spectral resolution infrared sounder is proposed to improve temperature and moisture profile vertical resolution and to provide (in conjunction with the microwave sounder) more accurate profiles. Finally, a total ozone mapper is proposed to define the tropopause and

thereby substantially help temperature and moisture profiling near the tropopause, and delineate strong upper troposphere circulation features.

These four sensors should be flown together and some of the time could be used to support major mesoscale and short range forecasting field experiments. Also, it may be possible to move the satellite to view major meteorological systems around the world (e.g., monsoons, typhoons) and, therefore, to involve scientists from many other nations.

The Rationale and Suggested Approaches for Research Geosynchronous Satellite Measurements for Severe Storm and Mesoscale Investigations

A. INTRODUCTION

Geosynchronous satellites are capable of obtaining data over large areas with high spatial and temporal resolution. Therefore, they are the best satellites for determining meteorological parameters that are associated with events that are small scale and/or change rapidly. These events include severe thunderstorms, mesoscale convective systems, tropical and extratropical cyclones, frost and freeze situations, fog, and dust storms. Many of the measurements that are taken in association with these events can be used to detect and predict other localized phenomena, such as orographic effects and lake and sea breezes. The data can be used to initialize regional-scale and mesoscale models. Also, some of the measurement requirements for synoptic- and hemisphere-scale meteorological systems and climate systems (e.g., winds, diurnal cloud changes) are met by geosynchronous satellite data. These requirements (and other possibilities like earth resources) will not be addressed by this document.

There are several advantages (in addition to the high temporal resolution) that should be remembered in acquiring measurements from a geosynchronous satellite instead of from low orbit. First, there is a consistent viewing geometry to any given location--meaning that the spatial resolution and the atmospheric slant path do not vary, so excellent interpretations can be made of spatial and temporal gradients. It is possible to attain nearly synoptic coverage over a large area. Data are coming from a single sensor, which simplifies calibration corrections. There can nearly always be a nearly perfect pairing of data with measurements from other sources because geosynchronous data can be taken at frequent intervals. Time compositing may be used for effectively improving spatial resolution and coverage where clouds interfere, because clouds move and change between successive surveys.

Following this introduction, specific scientific investigation areas are described that benefit substantially from geosynchronous satellite data, and the accompanying measurement and satellite observational requirements are discussed. Then, the current and planned low orbit and geosynchronous satellite observational capability is outlined and the areas are indicated where major deficiencies will still exist. A research geosynchronous satellite capability is proposed to substantially reduce these deficiencies. Finally, the spacecraft, mission timing, some possible areas of international cooperation, and specific studies are discussed.

B. SCIENTIFIC PROBLEMS

There are numerous significant scientific areas of investigation for small scale and/or rapidly changing phenomena where the geosynchronous satellite makes a contribution to the total observing system. These are listed below for several major phenomena.

1. Mesoscale Convective Systems (MCSs)[1]

- The determination of the relative importance of dynamic processes in the free atmosphere associated with synoptic- and subsynoptic-scale phenomena (e.g., upper tropospheric waves, jet streaks) in the organization of the preconvective environment and the subsequent initiation of MCSs.

- The determination of the relative importance of various boundary layer processes that depend on surface inhomogeneities in the organization of the preconvective environment and initiation of MCSs. These nonuniformities include soil moisture and vegetation distributions, skin temperature, and cloud cover differences.

- The determination of the means and how frequently specific mesoscale mechanisms (gravity waves, frontal circulations, outflow boundaries, circulations associated with boundary layer inhomogeneities, etc.) initiate the release of convective instability.

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[1] The objectives of the Storm-Central Development Plan were used as guidelines.

- The determination of the relationship between the environmental conditions and internal structure of the MCS which leads to their dissipation by observing the environment and MCS kinematic, thermodynamic, and cloud structures prior to and during MCS dissipation.

- The determination of the environmental factors (such as wind shear, buoyancy, and larger-scale forcing) and MCS internal structure that influence their motion and development in different modes (e.g., supercell thunderstorm, squall line or mesoscale convective complex) by observing the environmental kinematic and thermodynamic structure prior to, during, and following the onset of deep convection.

- The determination of how scale interactions between MCSs and their environment redistribute and generate momentum and redistribute heat and moisture during and after the system's active stages.

- The evaluation of the precipitation efficiency, mass, and moisture budgets of individual convective storms.

2. Tropical Cyclones

- The determination of the most significant processes (e.g., wind shear, upper tropospheric convergence, latent heat release) that contribute to all phases of cyclone development and maintenance.

- The determination of the role of scale interactions between different portions of the cyclone circulation and between the circulation and the surrounding environment on intensification and movement.

- o The determination of the nature of the transformation of a tropical cyclone into an extratropical cyclone under the influence of a strong baroclinic circulation.

- o The determination of the primary influential circulations and/or boundary conditions that control cyclone movement.

3. Extratropical Cyclones

- o The determination of the most significant atmospheric processes (e.g., upper troposphere circulation imbalances, boundary layer circulation, latent heat release) that contribute to cyclone development and maintenance.

- o The effects of orography on cyclone development, motion, and precipitation distribution and intensity.

- o The importance of mesoscale features in describing the circulation and morphology of extratropical cyclones and the scale interactions between these features and the larger scales.

C. OBSERVATIONAL GUIDELINES

The above general areas of investigation require the measurement of a set of atmospheric and surface parameters with certain resolutions, coverages, accuracies, etc. The measurement guidelines are based on horizontal, vertical, and temporal scales of the significant features of each of the phenomena along with the expected changes and their scales that are associated with the important processes during each phenomenon's life cycle. The most stringent of the guidelines are those connected with MCSs and tropical cyclones. These guidelines would also satisfy the needs of extratropical cyclone measurement and for many other mesoscale phenomena (e.g., fog, frost, and freeze conditions).

1. Observational Guidelines for MCSs

Two sets of guidelines were developed for MCSs (Tables 1 and 2) by the GOES-NEXT Concept Study Team, one for the antecedent stage and the other for storms once they form. These guidelines are also the ones needed for the scientific problems presented earlier. The parameters are almost the same in both sets, except that precipitation type (rain or hail) becomes part of the guidelines for storms in progress. The temperature and moisture profile guidelines are separated into two categories for storms in progress. One category is to continue to monitor the environment for further likely areas of storm development and the other (thunderstorm and immediate vicinity) is to assess the degree to which a thunderstorm is interacting with the environment. The guidelines for storms in progress are more stringent than in the antecedent stage.

TABLE 1

ANTECEDENT CONDITIONS FOR SEVERE LOCAL STORMS

OBSERVATIONAL GUIDELINES

PARAMETER	RESOLUTION REQUIREMENT			ABSOLUTE ACCURACY REQUIREMENT
	HORIZONTAL (KM)	VERTICAL (KM)	TEMPORAL (MIN)	
SURFACE TEMPERATURES	5-25	NA	10-60	±1-2°C**
TEMPERATURE PROFILES	20-100	1-5*	30-180	±1-2°C**
MOISTURE PROFILES	10-50	1-5*	30-180	±5-15%RH
LOWER TROPOSPHERIC MOISTURE GRADIENT, E.G., DRY LINE	3-15	NA	5-30	±10-25%RH
BOUNDARY LAYER WINDS	10-50	0.2-1	15-60	±1-3m/sec
WINDS ABOVE BOUNDARY LAYER	20-100	1-5	30-180	±1-3m/sec
PRECIPITATION RATE	5-50	NA	3-30	±20-50%
PRECIPITATION YES/NO	5-50	NA	6-60	NA
CLOUD TOP HEIGHT	0.5-10	0.25	1-15	±250-500m

* Need 0.5 km vertical resolution for inversions
**Relative accuracy is one-half these values

TABLE 2

SEVERE LOCAL STORM IN-PROGRESS OBSERVATIONAL GUIDELINES

PARAMETER	RESOLUTION			ABSOLUTE ACCURACY
	HORIZONTAL (KM)	VERTICAL (KM)	TEMPORAL (MIN)	
TEMPERATURE:				
o SURFACE	5-15	NA	10-30	±1-2°C**
o PROFILE, GENERAL	10-50	1-5*	30-120	±1-2°C**
o PROFILE, THUNDERSTORM AND IMMEDIATE VICINITY	5-25	1-5*	1-10	±1-2°C**
MOISTURE:				
o PROFILE, GENERAL	10-50	1-5*	30-120	±5-15%RH
o PROFILE, THUNDERSTORM AND IMMEDIATE VICINITY	5-25	1-5*	1-10	±5-15%RH
o LOWER TROPOSPHERIC MOISTURE GRADIENT (E.G., DRY LINE)	3-15	NA	5-30	±10-25%RH
WINDS:				
o BOUNDARY LAYER	5-20	0.2-1	5-30	±1-3m/sec
o ABOVE BOUNDARY LAYER	10-50	1-5	15-60	±1-3m/sec
PRECIPITATION:				
o RATE	3-50	NA	3-30	±20-50%
o TYPE	1-10	NA	1-10	RAIN/HAIL
o YES/NO	5-50	NA	6-60	NA
CLOUD TOP HEIGHT	0.5-10	0.25	0.5-15	±250-500m

* Need 0.5 km vertical resolution for inversions

**Relative accuracy is one-half these values

The ranges for the requirements in Tables 1 and 2 represent the intervals within which most of the improvements in prediction and understanding of MCSs would occur. Some useful information gain is still possible outside of the guideline limits, but the maximum information improvement is believed to be contained within the ranges shown.

2. Observational Guidelines for Tropical Cyclones

A set of observational guidelines for tropical cyclones (Table 3) has been generated by an Ad Hoc Working Group under the Interdepartmental Committee for Meteorological Services and Supporting Research (ICMSSR) and were accepted by the GOES-NEXT Concept Study Team. The ICMSSR report, published in January 1983[2], summarizes and makes recommendations on federal research and data collection programs for improving tropical cyclone forecasting. Table 3 was primarily generated from the perspective of what parameters (and their resolutions and accuracies) would be needed to adequately follow the key physical processes that govern cyclone genesis, movement, intensification, and dissipation. The same guidelines apply to the tropical cyclone problems indicated above and could serve the modeling community, with the temporal resolutions for some of the parameters reduced to the model initialization interval, which probably would be 6-12 hours. Most of the guidelines have ranges for the resolutions and accuracies.

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[2] Federal Coordinator for Meteorological Services and Supporting Research, 1983: "Review of Federal Research and Data Collection Programs for Improving Tropical Cyclone Forecasting," [illegible]-82, Washington, DC, January.

Table 3

Tropical Cyclone Observational Guidelines

Parameter	Resolution			
	Horizontal (km)	Vertical (km)	Temporal	Absolute Accuracy
Temperature:				
° Surface	20-100		6-24 hr	±1.0°C[a]
° Profiles				
1. Away from eye wall	40-200	1-5[b]	1-3 hr	±1-1.5°C[c]
2. Eye and eye wall	5-50	1-5	10-60 min	±1-3°C[c]
Moisture Profiles:				
1. Away from eye wall	20-100	1-5[b]	1-3 hr	±5-15%
2. Eye and eye wall	5-50	1-5	10-60 min	±5-15%
Surface Pressure:				
1. Away from eye wall	40-200		1-3 hr	±1-3 mb
2. Eye and eye wall	5-50		10-60 min	±1-3 mb
Winds:				
° Boundary layer	20-50	0.2-1	30-120 min	±1-3m/sec
° Above boundary layer	40-150	1-5	1-3 hr	±1-3m/sec
Precipitation:				
° Rate	10-50		15-120 min	±20-50%
° Yes/No	10-50		15-120 min	
Cloud Top Height	2-20	0.25	3-30 min	±500m[a]

[a] Relative accuracy should be one-half of these values.

[b] ≤.5 km through inversions.

[c] Relative accuracy ≤1.0 C.

D. SATELLITE MEASUREMENT GUIDELINES

The next step is to take the observational guidelines that are associated with the scientific problems and translate them into satellite measurement requirements. These are often very different from the observational guidelines in Tables 1-3. A good example is the determination of winds from cloud motions. Tracking individual clouds requires very high spatial resolution (less than 1 kilometer) and the images must be taken frequently to insure that the same cloud is tracked throughout the entire series. The result can be wind fields that have measurements at cloud levels every half hour with a horizontal spacing of tens of kilometers which is the direct comparison with the requirements in Table 1. A detailed list of these requirements for many parameters is given in Volume 2 of the GOES-NEXT Study Report.[3] These published guidelines should be the basis for the sensor performance requirements.

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[3] Goddard Space Flight Center, 1981: "A Geostationary Operational Environmental Satellite (GOES) - Next Concept Study," Tech. Rpt. 1906, Greenbelt, MD, October.

E. CURRENT AND PLANNED OPERATIONAL GEOSYNCHRONOUS SATELLITE MEASUREMENTS

1. Current (VISSR/VAS)

Geosynchronous satellite data have been used for meteorological analysis for the past 17 years. During most of that period, the research community has used data from the operational satellites. Some of these data have been taken in special satellite operating modes in response to requests from researchers. For the GOES satellites, the special research data have included short interval (≤ 5 minutes) stereo imagery, VAS temperature, moisture profiles, and multispectral imagery. These products are not generally available operationally, since the NOAA/NESDIS ground processing and distribution system is not designed to accommodate them.

The current GOES satellites have the capability to satisfy some of the requirements in Tables 1-3. The parameter measurement capabilities of the VISSR Atmospheric Sounder (VAS) are summarized in Table 4. There are a number of important points that cannot be easily shown in Table 4 and these are described below.

The sea surface temperature horizontal and temporal resolutions and coverages are based on experience. Surface temperatures over land are more difficult to measure because of the high variability in surface emissivity and surface air-ground temperature difference. Areas of heavy persistent cloudiness will not allow any surface temperature estimates in those areas, although the high frequency data from a geosynchronous satellite should substantially help to overcome the cloud interference problem. The

Table 4

Parameter Measurement Capabilities of VAS

Parameter	Resolution			Accuracy		Coverage
	Horizontal (km)	Vertical	Temporal	Absolute	Relative	
Temperature						
°Sea Surface*	30		30 min	±1.0°C	±0.5°C	±50° of great circle arc from the subsatellite point
°Profiles*	30-90	5 km	1 hour	±2.0°C	±1.0°C	3500 x 10,000 km
Moisture Profiles*	30-90	5 km	1 hour	±25%RH		3500 x 10,000 km
Wind	20-100	Cumulus and Cirrus levels	10 min	2-5 m/sec		2500 x 12,000 km
Cloud Height	1-10	250 m**	3 min	±500 m**	±250 m	2500 x 12,000 km

*In clear and partly cloudy areas only

**Using stereoscopic technique (two satellites) accuracy estimates are based on those determined from multispectral techniques.

For the temperature and moisture profiles from the VAS, the 30 and 90 km horizontal resolutions are achievable from clear and partly cloudy (up to 60 percent cloud cover) conditions. The lower resolutions in partly cloudy conditions result from an additional profile retrieval step to determine the radiances that would have been present in clear conditions. The poor vertical resolution (5 km) prevents significant features, such as inversions or stable layers, from being diagnosed. The sounding technique using VAS measurements is complicated and involves both temporal and spatial averaging to acquire the necessary signal-to-noise ratios for each profile. The profile retrieval accuracies cited in Table 4 are for generally clear conditions. The accuracies degrade rapidly in borderline cloudy areas and no tropospheric information is available below even thin cirrus.

The coverage estimates (3,500 km north-south and 10,000 km east-west) are based on the nominal number of spacecraft spins to achieve the required signal-to-noise ratio (the time averaging portion of the profiling technique) and a judgement on how far from nadir that profiles can be retrieved within the accuracy estimated. Temperature profiles can be retrieved in the troposphere and up through the middle stratosphere while moisture profiles are possible only in the troposphere.

The loss of temperature and moisture retrieval information in cloudy areas (including cirrus-covered areas in the vicinity of convective systems) has been shown to be a critical limitation in the use of VAS sounding information, both for diagnosing the environment of evolving convective systems (mid-latitude convective systems, tropical cyclones) and for use of satellite-based temperature and moisture information in mesoscale forecast models. The strength of time continuous measurements from the geosynchronous satellite viewing of mesoscale phenomena is lost when clouds (even thin cirrus) interrupt the steady flow of sounding information from an infrared-based system.[4]

2. Planned (GOES-NEXT)

The next improvement in geosynchronous observations will be provided by the GOES-NEXT operational satellite. There will be a separate imager and sounder. This will allow long periods of continuous short interval imaging that will be interrupted only periodically for full disk imagery. Sounding and imaging will be limited to visible and infrared wavelengths. Therefore, limitations in sounding due to clouds remain. No microwave sounding instrument is planned for the GOES-NEXT series.

Sounding will be possible every hour over 3000 x 3000 km areas with a small (approximately 1/4 degree C) temperature profile accuracy improvement in clear and partly cloudy areas (up to 60 percent) in the lower and middle troposphere. This, combined with better moisture measurements, should provide more useful stability estimates. The clear column sounding spatial resolution will be about the same as the VAS (30 km), but the partly cloudy resolution should be around 60 km (as compared with 90 km for VAS). As

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[4] Anthony, R. W., and G. S. Wade, 1983: VAS Operational Assessment Findings for Spring 1982/83. 13th Conference on Severe Local Storms, Tulsa, OK, American Meteorological Society, 323-328.

with the VAS, no profile information will be available below cloud top in cloudy areas. Vertical resolution of retrieved profiles will be approximately the same as for VAS.

The spatial resolution of the infrared channels will be improved to 4 km (from 7 km). The split window technique for measuring lower tropospheric water vapor and surface temperature determination both will benefit from the 4 km resolution (as compared to from 7 to 14 km on VAS), since cloud interference will be reduced. All scales of convection monitoring should be improved with the 4 km resolution of the 11 μm channel. The imager is designed for scan rates as high as once every 30 seconds (over areas of about 1000 x 1000 km), which will permit adequate surveillance continuity for the most violent convection.

The current and planned geosynchronous satellite measurements can be supplemented by data from the low orbiting satellites, most notably the operational NOAA series (with emphasis on microwave sounding and the 1 km resolution imaging from the AVHRR), and perhaps from the NASA research satellite called the Earth Observing System (EOS) by the early and middle 1990's. The latter satellite would carry active sensors (radars, lidars) for precipitation mapping and 1-2 km vertical resolution temperature, pressure, and moisture profiling, plus a wide range of improvements for passive imaging and sounding using the visible through the microwave. However, the lack of time resolution restricts the use of low-orbit data for studies of rapidly evolving mesoscale systems.

As useful as the previously described current and planned observing system is for severe storm and mesoscale research, there are still considerably more powerful capabilities that are required in geosynchronous orbit to meet the scientific observations guidelines shown in Tables 1-3, which are in support of the scientific problem areas. *The principal weaknesses in the current and planned observing system are: 1) the lack of measurement of temperature and moisture profiles in cloudy areas; 2) the inadequate vertical resolution of the profiles; 3) the insufficient horizontal and temporal imaging resolutions and spectral intervals involved in convection monitoring, winds derived from cloud motions, surface temperature, and low level moisture estimates; and 4) the lack of a precipitation mapping capability*. New sensors are required to alleviate these deficiencies. The combination of new sensors plus the optimum use of the GOES-NEXT operational instruments comprises a synergistic measurement system.

F. ADDITIONAL GEOSYNCHRONOUS OBSERVATIONAL CAPABILITY FOR RESEARCH

Temperature and moisture profiles in cloudy areas are very important to many of the scientific problems identified earlier, since many of the significant processes take place where clouds are almost always present. The experience with VAS has shown that infrared sounding alone provides inadequate coverage in numerous severe storm situations. An especially inhibiting cloud situation is where cirrus debris is produced from vigorous convection and covers large areas surrounding the active convection. The addition of microwave frequencies will allow complete areal coverage of profile information except in precipitating areas. Theoretical calculations and aircraft measurements also support the concept that temperature and moisture profiles derived from a combination of infrared channels and shortwave microwave frequencies (118 GHz for temperature profiles, 183 GHz for moisture profiles) will be significantly better in clear and partly cloudy areas than those derived from infrared frequencies alone. While the low orbiting microwave sounders can provide some information, the addition of a geosynchronous microwave sounder, with its high temporal frequency and consistent viewing geometry to a given location, will provide the proper observation frequency and relatively easy interpretation of the absolute temperature and moisture profiles and their gradients. With a 4.4 m antenna, nadir spatial resolutions of 30 and 20 km can be achieved for temperature and moisture profiles, respectively. These resolutions are expected to be adequate to define such important phenomena as the pre-thunderstorm environmental conditions, jet stream structure, scale interactions down to the large convective scale (e.g., squall lines), and most of the upper troposphere warm core inner structure of tropical cyclones (the eye itself will require still higher resolution). Areas of about 1000 x 1000 km can be scanned in less than 1 hour.

Aircraft data have also indicated that frequencies at 90, 140, and/or the more transparent portions of the 183 GHz water vapor absorption region can be used to map precipitation areas. With the above 4.4 m antenna, spatial resolutions of 20 km (183 GHz) up to 40 km (90 GHz) can be achieved. These data can be combined with higher spatial and temporal frequency visible and infrared data to estimate rain rates down to the scale of large convective cells.

The low vertical profile resolution from current and planned sounding systems results in inadequate determination of strong atmospheric circulation features (e.g., jet streams) and inaccurate specification of thermodynamic quantities (e.g., instability). The largest errors in temperature profile retrievals are near the tropopause and near the ground, regions of large changes in lapse rate. These important features, which cannot be resolved due to the inherent width of radiance contribution functions, produce errors throughout a profile. The vertical resolution of infrared derived temperature sounding can be about 50 percent better than the planned GOES-NEXT sounder by increasing the spectral resolution significantly (to 0.5-2 cm^{-1} from about 10 cm^{-1}). It is anticipated that this better spectral resolution will improve tropospheric profiling accuracy in clear and partly cloudly areas by about 1/2 degree C, which is significant for circulation feature definition (e.g., jet streams, short wave troughs), dynamical model initialization, and the calculation of pre-storm stability indices. Two possible sensor approaches are being studied. Either would be able to provide <1.5 degree C temperature profile accuracy (and better moisture profiles than are expected with the GOES-NEXT sounder) with <20 km clear column sounding spatial resolution and be able to cover at least 1000 x 1000 km areas in an hour. In addition, land surface temperatures with 1°C accuracy will be obtainable from the advanced infrared sensors. One of the sensor approaches would be selected for the spacecraft.

Even greater improvements are possible if profile structural information, such as the height of the tropopause, is supplied from external sources. The total ozone amount is very closely related to tropopause height and can be used to specify that quantity if accurately estimated, such as is possible during the day with the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus low-orbiting satellite. The TOMS ozone measurements are valid under all weather conditions including cloud covered areas and therefore can be used to specify the tropopause height for both infrared and microwave soundings. The improvements, which are greatest in the upper troposphere and lower stratosphere, approach 1°C in the VAS spectral resolution infrared soundings and approximately 2°C for microwave soundings. A geostationary TOMS with a spatial resolution of 50 km and a temporal resolution of 30 minutes is feasible using existing technology. Selected channels on an advanced IR sounder could also be used to estimate total ozone, day and night, although with less accuracy.

It is well established that TOMS data help delineate the large-scale stratospheric temperature field and provide information on tropopause heights. But more recent evidence suggests that TOMS data are even more valuable in describing the high tropospheric wind field. With careful analysis and interpretation of the total ozone distribution, one can now isolate jet streaks and even specific quadrants of these streaks. Such knowledge implies that we can diagnose the vertical circulations above and below the jet streaks. Thus, the TOMS data, in conjunction with VAS and conventional data, can help specify areas of strong horizontal and vertical wind shears - both extremely vital in improving initialization of forecast and diagnostic models. In fact, the TOMS data are unique in providing wind information at the high levels of the troposphere where VAS and radiosondes have only limited usefulness. Wind information at jet levels is important because cyclogenesis, frontogenesis, and the outbreak of severe weather are intimately related to the position and intensity of the jet core.

The TOMS technique also has demonstrated capability for imaging volcanic eruption sulfur dioxide clouds. The time resolution provided by a geostationary TOMS would resolve questions about SO_2 lifetimes at the lower altitudes, enable accurate inventories of volcanic sulfur gases, and provide for the nearly immediate detection of daytime eruptions.

There is a strong requirement for ≤ 1 km thermal infrared (e.g., 11 μm) imaging to discern the important growth phases and small scale phenomena (e.g., updraft cores, arc cloud lines) associated with strong convection, to determine lower tropospheric nighttime winds from cloud motions, to derive accurate cloud top heights, and to obtain better coverage and accuracy of surface temperatures (e.g., important for frost and freeze measurements). This instrument would also be capable of high resolution (200 m) visible data, which would greatly improve daytime lower tropospheric winds from cloud motions. Several other channels are proposed that will further improve some of the above list and provide estimates of lower tropospheric water vapor. This sensor could also include channels for earth resources and ocean color measurements with 50-100 m resolution. It would be a large instrument and, therefore, would be proposed as an option to be evaluated once the others had been accommodated.

If the large imager could not be part of the mission, then the GOES-NEXT operational imager should be flown. The most significant improvement in using the operational imager in a research mode would be for routine temporal resolutions of ≤ 3 minutes for winds from cloud motions and 30 seconds for daytime convection monitoring. While these could be done by the operational imager, the current NOAA plan is for the routine temporal frequency to be 5 minutes to provide coverage over most of the United States.

If the high spectral resolution infrared sounder is not part of the mission, then a slightly modified version of the GOES-NEXT operational sounder should be included. Improvements in the operational sounder to at least the level of the NOAA HIRS sounders would come from additional higher resolution (20 cm^{-1}) 4.3 μm channels and split 3.7-4 μm window channels (not high cost items). These would improve the accuracy of lower atmospheric and surface temperatures. More significantly, the ability to account for cloud effects would be improved and more accurate soundings would be obtained in partly cloudy areas.

Therefore, the suggested sensor complement for a research geosynchronous spacecraft to support severe storm and mesoscale research is:

1. Microwave Sounder and Imager
2. High Spectral Resolution Infrared Sounder

3. High Spatial Resolution Imager
4. Total Ozone Mapping

The operational GOES-NEXT imager or sounder could be substituted for the proposed infrared sounder and/or imager in the list above.

There are other sensor candidates that are being evaluated, which include a lightning mapper and those which are not severe storm related (e.g., two climate related solar monitoring instruments).

G. ADDITIONAL ADVANCED CONCEPTS

All of the recommended research sensors mentioned above have been studied and after more detailed and/or updated study (e.g., the microwave sounder-imager) would be ready for flight no later than the early or mid 1990's. There are more advanced concepts that require further fundamental investigation before they could be recommended for space flight. They are all concerned with improving the vertical resolution of infrared sounding and the horizontal resolution of microwave sounding and imaging. The horizontal resolution of microwave sensing needs to be as high as 1 km for precipitation convective core delineation and 5 km for sounding in the vicinity of convection and in the eye of tropical cyclones. With the current size of the Shuttle bay, these resolutions will require synthetic aperture techniques or a furlable antenna. The former method is already being investigated by Hughes Aircraft.

Infrared sounding vertical resolution can be improved by another 50 percent (to about 2 km) over the 0.5-2 cm^{-1} spectral resolution sounder proposed above by a further increase in spectral resolution. This increase would be to 0.2 cm^{-1} in the 4.3 micron CO_2 absorption region. Although it would take a relatively long time (say 0.5-1 minute) to obtain a single sounding, the sounding locations can be selected in clear areas. This concept deserves further study.

H. SUGGESTED IMPLEMENTATION APPROACHES

1. Spacecraft

One attractive approach would be for NASA to support a research geosynchronous satellite mission carrying all of the above sensors. The spacecraft could be a larger version of the GOES-NEXT spacecraft, thus procured through the same contractor who is awarded the GOES-NEXT mission. If only the normal operational GOES-NEXT spacecraft were available, then the highest priority sensors could be selected. The minimum complement should be the microwave sounder/imager, a high spectral resolution infrared sounder, and a GOES-NEXT operational imager.

There is another possible approach and this involves adding the research sensors onto commercial domestic communications satellites. A large number of these are planned in the late 1980's and 1990's and the research sensors would use whatever extra space is available or the space could be planned with the spacecraft builder. It may be necessary to have payloads on more than one spacecraft that are close together in order to have the right sensing combination in orbit simultaneously.

2. Mission Timing

Mission timing is important. If it is possible, it would be very beneficial to phase the mission with major meteorological experiments. There is a chance that a large mesoscale research/operational prototype experiment (STORM-Central) will occur in the early 1990's. It is currently scheduled for 1988, but it could slip to the early 1990's. We should phase our development to coincide with this experiment if the expected slip occurs. This would require substantial funding by FY86 and studies starting this fiscal year. STORM-Central will be followed by STORM-East and STORM-West within a few years and the same satellite system could be used to support them. If a research satellite were placed at 100 degrees W to support STORM-Central, extended periods of stereo would be possible with GOES-East or GOES-West and the potential stereo coverage would be almost twice as great as the current coverage.

3. International Cooperation

An important area of cooperation that should be explored is international. This could require a dedicated mission, since there is a strong likelihood that the spacecraft would be moved to support foreign programs away from viewing the United States. For example, there is currently a significant short range forecasting program in Great Britain that could benefit from the measurements we propose. In between supporting the major U.S. experiments mentioned above, the satellite could be moved to a favorable longitude for Europe. Although the latitude of Great Britain is between 50 degrees and 55 degrees N, there are many meteorological systems which approach from the southwest over the ocean and, therefore, these would be at better viewing angles. Even at 50-55 degress N, it should be possible to interpret spatial gradients and temporal changes accurately since the viewing angle to a given location does not change. Perhaps the British could supply a portion of an instrument, such as the 183 GHz portion of the microwave sounder/imager since they will be providing that part of the NOAA AMSU. By the 1990's, it is likely that other European countries would have programs similar to Great Britain's.

Other possibilities include Japan and India, since these countries have operational geosynchronous satellite systems. Japanese cooperation would be especially exciting since the greatest cyclone in the world, the Western Pacific typhoon, could be studied.

4. Studies

The realization of the new research capability will require further studies for refinement of the measuring concepts, greater understanding of the impact of these data, and sensor and spacecraft definition. The specific studies for each sensor are shown in Table 5, along with spectral regions for the microwave sounder/imager and the large research imager. Atmospheric models would make a large contribution to understanding the value of the new data. A combination of the aircraft flights and theoretical/empirical studies would help the refinement of the measuring concepts and the assessment of the impact of the new data. The list of specific theoretical/empirical studies for the larger imager is too long to list in Table 5, so just the discipline areas are shown with examples for meteorology and earth resources.

TABLE 5

STUDY AREAS

SENSOR	ATMOSPHERIC DYNAMICAL MODELING		AIRCRAFT FLIGHTS (FIELD EXPERIMENTS)	SENSOR DEFINITION STUDIES	THEORETICAL/EMPIRICAL STUDIES	OTHER COMMENTS
	SIMULATIONS	ACTUAL DATA				
MICROWAVE SOUNDER/IMAGER	o TROPICAL CYCLONES o TEMPERATURE PROFILES-MOTION EFFECT o LATENT HEAT INTENSITY o SEVERE LOCAL STORMS o ANTECEDENT CONDITIONS o STORM MAINTENANCE	o TROPICAL CYCLONES o MSU DATA MOTION EFFECT o SEVERE LOCAL STORMS-ANTECEDENT CONDITIONS (MSU)	o 94/118/183 GHz ON U-2 (OR CV-990 FOR THUNDERSTORM ANTECEDENT CONDITIONS) o TROPICAL CYCLONES-INTENSITY o SVR-LOCAL STORMS-STABILITY AND STORM-ENVIRONMENT INTERACTIONS	o REVIEW STATUS OF MICROWAVE TECHNOLOGY (ALSO REEXAMINE MASR CONCEPT) o LOOK AT LARGER ANTENNAS/HIGHER FREQUENCY	o RAIN RATE ESTIMATES WITH 94 AND 183 GHz WINDOWS o CIRRUS EFFECTS ON ALL HIGH FREQUENCY MICROWAVE o DEVELOP TEMPERATURE RETRIEVAL ALGORITHM FOR 94/118 GHz	o SENSOR CHARACTERISTICS (SPECTRAL REGIONS) o TEMPERATURE PROFILES-118 GHz o MOISTURE PROFILES-90, 140, OR 183 GHz
VISIBLE AND IR MULTISPECTRAL IMAGER	o EFFECTS OF IMPROVED WINDS, SURFACE TEMPERATURE AND DIABATIC HEATING ON MESOSCALE FORECASTING AND STORM STRUCTURE DEFINITION	o CONTINUED DEMONSTRATION OF THE MESOSCALE WIND FIELDS FROM CLOUD MOTIONS	o CLOUD PROPERTIES WITH CTS/MCR COMBINATION ON U-2 (ALSO USE MICROWAVE DOPPLER) o SURFACE TEMPERATURE WITH CTS (AND IR SOUNDER) o EARTH RESOURCES—ESPECIALLY DIURNAL AND ANISOTROPIC PROPERTIES o CLOUD MOTION—WIND RELATIONSHIPS	o UPDATE PRIOR SEOS STUDIES	o METEOROLOGY (E.G., THUNDERSTORM SEVERITY STUDIES) o EARTH RESOURCES (E.G., ANISOTROPIC PROPERTIES) o OCEAN COLOR	o SENSOR CHARACTERISTICS (SPECTRAL REGIONS) o 0.5-0.7 μm o 0.95-1.25 μm o CLOUD HEIGHT CHANNELS (FROM MCR) o MSS CHANNELS o OCEAN COLOR CHANNELS o 1.5-1.7 μm o THERMAL IR o 3.7-4.0 μm o 6.5-7.0 μm o 10.2-11.2 μm o 11.5-12.5 μm o 3 14 μm CHANNELS

TABLE 5, CONTINUED

STUDY AREAS

	ATMOSPHERIC DYNAMICAL MODELING					
SENSOR	SIMULATIONS	ACTUAL DATA	AIRCRAFT FLIGHTS (FIELD EXPERIMENTS)	SENSOR DEFINITION STUDIES	THEORETICAL/EMPIRICAL STUDIES	OTHER COMMENTS
HIGH SPECTRAL RESOLUTION IR SOUNDING	o CAPABILITY TO DEFINE STABILITY AND MOISTURE FIELDS o JET STREAM STRUCTURE o BOUNDARY LAYER STRUCTURE o TOTAL OZONE o GROUND TEMPERATURE	o HIRS/MSU COMBINATION	o 1984 HIS FLIGHTS--EMPHASIZE SEVERE LOCAL STORM ANTECEDENT CONDITIONS AND STORM-ENVIRONMENT INTERACTIONS (U-2) o SIMILAR AMTS FLIGHTS o COMBINE WITH MICROWAVE SOUNDERS	o AMTS VERSUS HIS APPROACHES	o LOOK AT EVEN HIGHER SPECTRAL RESOLUTION THAN AMTS OR HIS	
TOTAL OZONE MAPPING SPECTROMETER (TOMS)	o DETAILED JET STREAM STRUCTURE o POTENTIAL VORTICITY FIELD o SEVERE STORM INITIATION THROUGH DESTABILIZATION		o GALE EXPERIMENT TROPOPAUSE STRUCTURE AND FOLDING DURING DESTABILIZATION	o HIGH RESOLUTION GEOSYNCHRONOUS TOMS o HIGH ALTITUDE OZONE MAPPING FEASIBILITY WITH ADDITIONAL CHANNELS	o REFINEMENT OF TROPOPAUSE HEIGHT ESTIMATES o TROPICAL CYCLONE SIGNATURE ANALYSIS o TROPOSPHERE CHEMISTRY STUDIES	