GEOSTATIONARY ATMOSPHERIC PROFILER (GAP)

PHASE A STUDY
FINAL REPORT

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MARSHAL SPACE FLIGHT CENTER

PREPARED UNDER
CONTRACT NO. NAS8-38499

PREPARED BY
UNIVERSITY OF WISCONSIN - MADISON
SPACE SCIENCE AND ENGINEERING CENTER

AND

HUGHES SANTA BARBARA RESEARCH CENTER

SUBMITTED
JUNE 15, 1990

FINAL REVISION
JANUARY 31, 1992
EXECUTIVE SUMMARY

This is the final report of a conceptual study (Phase A) for the Geostationary Atmospheric Profiler (GAP) by the Space Science and Engineering Center of the University of Wisconsin-Madison (UW) and the Santa Barbara Research Center (SBRC), a subsidiary of the Hughes Aircraft Company. The GAP is being designed as a facility instrument for the Earth Science Geostationary Platform (ESGP). The ESGP is the geostationary component of NASA's Earth Observing System for global change research.

The GAP will measure earth emitted radiances over a broad portion of the thermal emission spectrum (3.7 to 16.1 μm) at a spectral resolution of 0.33 cm⁻¹ with an accuracy of 1.0 K or better. In addition, the infrared emission of the radiatively important gases ozone, methane, carbon monoxide, and carbon dioxide will be measured at somewhat higher spectral resolution (0.1 cm⁻¹). This report defines a very capable baseline instrument design, and gives some of the tradeoff options for later system design considerations. The science requirements and performance analyses which form the basis of the design are also presented.

GAP Applications

The GAP is designed to be a versatile and flexible instrument, which will contribute to applications related to meteorology, atmospheric chemistry, radiation, and cloud physics. The physical parameters to be derived from the measurements include: atmospheric temperature profiles, atmospheric water vapor profiles, mixing ratio profiles of variable trace gases (CO, O₃, and CH₄), radiance impact of greenhouse gases (CO₂, H₂O, N₂O, CO, O₃, CH₄, CFC's, and CCl₄), moisture fluxes and wind profiles, surface temperature, boundary layer heat fluxes, and cloud properties (optical depth, height, phase, fractional coverage). Optimizing observations for the many different applications which can share the instrument will be possible using selectable spectral coverage and resolution, in addition to selectable targets, spatial sampling strategies, and coverage rates.

Advantages of Geostationary Orbit

Many of the GAP applications will take advantage of the special opportunities provided by a geostationary platform. Especially important observing capabilities, not available from low orbiting sun-synchronous orbits, are

(1) Selectable diurnal sampling with repeat times from minutes to hours,
(2) Sensitivity to near surface trace gas mixing ratios from the temporal variability of background surface temperature,
(3) Enhanced vertical resolution mixing ratio profiles from the use of clouds to shutter the lower atmospheric emission,
(4) Winds from time-lapse movies of retrieved gas fluxes,
(5) Optimized noise performance from variable dwell times, and
(6) All-weather coverage from time compositing, i.e. the ability to put together clear images from successive partly-cloudy images as winds translate the clear air interstices over the regions of interest.
Instrument Configuration

The GAP employs a single plane-mirror Michelson interferometer behind a 60 cm diameter telescope with a two-axis scan mirror to raster scan regions of the Earth. To increase coverage rates for some applications, the raster scan capability includes programmable step sizes for cluster sampling.

The Michelson interferometer mirror drive will have a programmable range to provide resolutions up to 0.1 cm\(^{-1}\) with a maximum mirror travel of \(\pm 2.5\) cm (\(\pm 5.0\) cm OPD). The scan rate will also be programmable to allow dwell time adjustment to give the desired noise performance and spatial coverage rates. Behind the interferometer, the beam is divided into five spectral bands and is focussed on 3x3 detector arrays. The detector arrays provide nine 10 km diameter circular fields of view in a square pattern with center-to-center spacings of 16.6 km. The use of 3x3 arrays increases the spatial coverage rate by a factor of nine over a single field of view instrument.

The baseline instrument has a weight of 195 kg, a power of 150 W, and a volume of 2.1 m\(^3\).

Performance

The specific spectral, spatial, and radiometric performance characteristics of the GAP are summarized along with some basic instrument information in Table i. The performance is given for two specific modes, currently envisioned to provide (1) broad spectral coverage at high spectral resolution (0.33 cm\(^{-1}\) unapodized) for temperature and water vapor sounding, trace gas survey information, and greenhouse gas radiances, and (2) narrow spectral band coverage at ultra high resolution (0.1 cm\(^{-1}\) unapodized) for trace gas profiling of ozone, methane, carbon monoxide, and water vapor. Either the broad or the narrow spectral coverage mode may be used during a dwell sounding, but not both simultaneously since they make use of the same set of detectors. Many other options are possible, including non-uniform spatial coverage, different coverage rates, and other spectral resolutions.

Conclusions

The GAP offers new capabilities for earth science studies. For meteorology, it goes far beyond the capabilities of the operational instrumentation planned for the same time frame, both in spatial coverage rates and noise performance at high spectral resolution. The derivation of atmospheric wind profiles using detailed water vapor profiles as a tracer offers an exciting possibility for more accurate measurements of wind as needed to define the transport of all atmospheric elements. For atmospheric chemistry, the GAP promises simultaneous trace gas profile measurements for multiple gases, coincident with temperature and water vapor profiles, when used with the important sampling advantages of the geostationary orbit.
Table i. GAP Instrument Design and Performance Summary

<table>
<thead>
<tr>
<th>Spectral range and resolution (cm(^{-1}))</th>
<th>Range, cm(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad Bands (nominal $\Delta \nu = 0.33$ cm(^{-1}))</td>
<td></td>
</tr>
<tr>
<td>Band 1</td>
<td>620-1000</td>
</tr>
<tr>
<td>Band 2</td>
<td>1000-1111</td>
</tr>
<tr>
<td>Band 3</td>
<td>1111-1700</td>
</tr>
<tr>
<td>Band 4</td>
<td>1700-2350</td>
</tr>
<tr>
<td>Band 5</td>
<td>2350-2700</td>
</tr>
<tr>
<td>Narrow Bands (nominal $\Delta \nu = 0.1$ cm(^{-1}))</td>
<td></td>
</tr>
<tr>
<td>15$\mu$m CO(_2)</td>
<td>620-1000</td>
</tr>
<tr>
<td>O(_3)</td>
<td>1000-1080</td>
</tr>
<tr>
<td>CH(_4/)H(_2)O</td>
<td>1240-1360</td>
</tr>
<tr>
<td>CO</td>
<td>2060-2220</td>
</tr>
<tr>
<td>4.2$\mu$m CO(_2)</td>
<td>2380-2393</td>
</tr>
</tbody>
</table>

| Field of view (FOV)                        |                      |
| Simultaneous array pattern                 | 3 x 3               |
| Single FOV diameter                        | 10 km, 280 $\mu$m    |
| Center-to-center spacing                   | 16.6 km, 465 $\mu$m  |

| Telescope                                  |                      |
| 60 cm diameter                             | Off-axis paraboloid   |

| Interferometer                             | 2" beam, Auto-aligned |
|                                           | Plane mirror Michelson|

| Detectors                                  | 3 x 3 arrays of       |
|                                           | PV or PC HgCdTe       |

| NE\(\Delta T\)/ 1 sec dwell (spectral mean) |                      |
| $\Delta \nu = 0.33$ cm\(^{-1}\)             | 0.2°C                 |
| $\Delta \nu = 0.10$ cm\(^{-1}\)           | 0.3°C                 |

| Calibration accuracy                       | 0.1°C reproducibility |
|                                           | 1.0°C absolute        |

| Spatial coverage rate for either the broad or the narrow band mode | 3000 x 3000 km/hour |

| Retrieved Parameters                      | Temperature           |
|                                           | Water Vapor           |
|                                           | Carbon Monoxide       |
|                                           | Methane               |
|                                           | Ozone                 |

| Derived Quantities                         | Vertical Profiles     |
|                                           | Column Amounts        |
|                                           | Motion Fields         |
TABLE OF CONTENTS

1.0 INTRODUCTION............................................................................................................ 1
2.0 SCIENTIFIC OBJECTIVES.......................................................................................... 2
   2.1 Enhanced Temperature and Water Vapor Profiling.............................................. 2
   2.2 Gas Concentration Information........................................................................... 3
   2.3 Measurement of the Radiative Effects of Greenhouse Gases............................. 7
3.0 RETRIEVAL PERFORMANCE TRADEOFFS .......................................................... 7
   3.1 Temperature and Water Vapor............................................................................ 7
   3.2 Trace Gases........................................................................................................ 9
       3.2.1 Signatures ................................................................................................ 9
       3.2.2 Weighting Functions................................................................................ 11
       3.2.3 Resolution Dependence.......................................................................... 14
       3.2.4 Expected Performance........................................................................... 17
4.0 GAP INSTRUMENT REQUIREMENTS .................................................................. 21
   4.1 Approach........................................................................................................... 21
   4.2 Specific Instrument Requirements ................................................................... 22
       4.2.1 Broad Spectral Coverage....................................................................... 22
       4.2.2 Specific Trace Gases............................................................................. 23
   4.3 Operating Mode Flexibility................................................................................ 24
5.0 BASELINE DESIGN................................................................................................. 26
   5.1 General Characteristics..................................................................................... 26
   5.2 Optical Conceptual Design............................................................................... 28
   5.3 Interferometer Concepts................................................................................... 31
   5.4 Configuration Concept..................................................................................... 31
   5.5 Technical Heritage........................................................................................... 33
   5.6 Mass, Size, and Power Estimates...................................................................... 34
6.0 BASELINE NOISE PERFORMANCE AND SYSTEM TRADE-OFFS....................... 34
   6.1 Baseline Performance....................................................................................... 34
   6.2 System Tradeoffs.............................................................................................. 35
7.0 CALIBRATION.......................................................................................................... 40
   7.1 Approach........................................................................................................... 40
   7.2 Implementation.................................................................................................. 41
8.0 SIGNAL PROCESSING ARCHITECTURE AND DATA RATES.......................... 41
   8.1 GAP Processing Overview.............................................................................. 41
   8.2 On-board Data Processing............................................................................... 42
   8.3 TMS320 Family Digital Signal Processors....................................................... 42
   8.4 Time and Power Budgets................................................................................ 42
9.0 GROUND SYSTEM.................................................................................................. 45
   9.1 GAP Data Processing Flow............................................................................... 45
   9.2 Processing Steps and Algorithms...................................................................... 46
   9.3 Ground System Data Rates............................................................................. 47
   9.4 Ancillary Data Requirements........................................................................... 49
10.0 OPERATIONAL RELIABILITY OF GAP INSTRUMENT........................................... 49
    10.1 Scan Mirror.................................................................................................. 49
    10.2 Interferometer Travelling Mirror................................................................... 49
    10.3 Dynamic Alignment Mirror.......................................................................... 50
    10.4 Laser Assembly............................................................................................. 50
1.0 INTRODUCTION

This is the final report for the Geostationary Atmospheric Profiler (GAP) initial Phase A Study by the University of Wisconsin-Madison (UW) Space Science and Engineering Center (SSEC) teamed with the Santa Barbara Research Center (SBRC), a subsidiary of the Hughes Aircraft Company. The GAP is designed as a facility instrument on the Earth Science Geostationary Platform (ESGP), the geostationary component of the NASA observing system for Earth System Science (Jedlovce, Wilson, and Dodge, 1989).

A high spectral resolution infrared interferometer was chosen as a high priority instrument for the ESGP by the Science Steering Committee which defined the science and mission requirements. In this role, the GAP will contribute toward understanding many of the processes, identified by the Science Steering Committee, that require geostationary measurements. Specifically, of those processes summarized by Jedlovce, et al. (1989), the GAP capability is important for mesoscale atmospheric circulations, the hydrologic cycle, atmospheric trace gas measurement, environmental pollution monitoring, cloud evolution, severe storms, and earth system radiation balance.

The High-resolution Interferometer Sounder (HIS) program at the University of Wisconsin-Madison, jointly funded by NOAA/NESDIS and NASA, has laid a strong foundation for the specific instrument approach and hardware implementation for GAP, as well as for many of the necessary performance simulations, analysis approaches, and processing techniques (Smith, et al., 1983, 1987a, 1987b, 1989, 1990b; SBRC, 1981; UW/SBRC/ITT, 1988). The instrument approach has been demonstrated by the HIS aircraft instrument which showed that highly accurate high-resolution radiances can be made using interferometry (Revercomb, et al., 1987/89, 1988a, 1988b, 1989a).

Retrievals of atmospheric state variables have demonstrated the improved vertical resolution provided by higher spectral resolution measurements (Smith, et al., 1987/89, 1988a, 1990c, 1990d). In addition, recent results demonstrate the applications of high spectral resolution to cloud studies (Smith, et al., 1988b; Ackerman, et al., 1990 a, b; Grund, et al., 1990 a,b), sounding through cirrus clouds (Smith, et al., 1990e), sounding from the ground (Smith, et al., 1990a), and spectroscopy (Clough, et al., 1988; Revercomb, et al., 1989b; 1990).

Given the constraints on the resources available to this study, we have emphasized the new opportunities of the GAP for atmospheric chemistry. The initial feasibility results, which define the requirements for the baseline instrument configuration presented here, will continue to be refined through a separately funded NASA project at UW. Therefore, one objective of the report is to define some of the performance and instrument tradeoffs to be further investigated as a part of more detailed follow-on design studies.

This report progresses from the statement of science objectives (Sect. 2) to performance tradeoffs (Sect. 3) and the resulting instrument requirements (Sect. 4); and from the requirements to a baseline design (Sect. 5) and its performance and tradeoff considerations (Sect. 6). In addition, it discusses calibration (Sect. 7), on-board signal processing plans and data rates (Sect. 8), ground processing considerations (Sect. 9), and
reliability (Sect. 10). The last section (11) gives future planning information by listing activities needed to advance all aspects of the program.

2.0 SCIENTIFIC OBJECTIVES

The general scientific objectives are to provide

(1) Enhanced temperature and water vapor profiling for both meteorological and atmospheric chemistry applications,
(2) Ozone, carbon monoxide, and methane mapping and profiling of the troposphere and the lower stratosphere, and
(3) Direct measurement of radiative effects of greenhouse gases (CO₂, H₂O, N₂O, CO, O₃, CH₄, CFC's, and CCl₄).

The geostationary platform is important for all of these measurements because it provides diurnal sampling of both the state variables and the radiation fields. The diurnal variation of the spectral radiance signals provides an effective absorption measurement of gas concentrations as needed to provide accurate chemistry measurements near to the earth's surface.

2.1 Enhanced Temperature and Water Vapor Profiling

Current capabilities for temperature and water vapor profiling from satellite can be enhanced greatly by using high spectral resolution, broad band measurements. The resultant vertical resolution improvement will provide better observations for atmospheric research and will allow improvement in extended weather forecasting. (Smith, 1990d).

Quantitatively, the goal is to achieve vertical resolutions of better than 2 km for both temperature and water vapor in the troposphere, with RMS temperature errors of less than 1°C and RMS mixing ratio errors of less than 10-15%. In addition, this performance is to be achieved more rapidly than is currently possible with operational instruments, thus allowing a more versatile schedule of observations.

An important role is expected for the ESGP, even though other steps are currently being taken in the direction of improving sounding capabilities. An advanced high resolution temperature and water vapor sounder will probably be implemented on the NOAA operational polar orbiting satellites by the time of the ESGP. The Atmospheric InfraRed Sounder (AIRS) will make high spectral resolution, broad band measurements on the low orbit complement of EOS. We believe these capabilities are even more important from a geostationary platform. The GAP should provide temperature and moisture sounding capabilities that exceed those available operationally from geostationary orbit when the first ESGP is launched. The best foreseeable operational capability at the turn of the century is represented by the options under consideration for NOAA's current GOES-N Phase A study. The GAP should enhance the noise performance and the coverage rates by substantial factors from those of the present interferometer option for GOES-N, which is represented by the design of the UW/SBRC/ITT September 1988
report to NOAA/NESDIS entitled "High-resolution Interferometer Modification of the GOES L/M Sounder: Feasibility Study." Meteorological applications will benefit significantly from the 5 to 10 fold increase in the spatial coverage rates at high resolution and in the factor of two increase in noise performance.

Advanced temperature sounding is crucial for the atmospheric chemistry applications as well as for the meteorological applications of GAP. An important ingredient of the retrieval process for all trace gases is accurate knowledge of the atmospheric temperature (see Section 3).

Enhanced water vapor profiling is fundamentally important. Improvements are needed for better observations of the hydrological cycle, for understanding the important role of water in atmospheric chemistry, and for defining the circulation of trace gases as mentioned above. Because of the overlap of the spectral features of water vapor with those of other gases, an advanced profiling capability also is needed for the accurate retrieval of other trace gases. Methane is an example of a species for which knowledge of water vapor is especially important because its strongest spectral features are imbedded in the 6.3 micron water vapor band.

One of the most exciting new possibilities for the enhanced capabilities of the GAP is the derivation of winds from tracking features in the retrieved water vapor distributions. Winds over a wide range of known heights could be derived from this technique. Winds need to be measured simultaneously with the concentrations of important chemical elements in order to define the transport of these gases. We believe it is important that future needs of the meteorological community be anticipated and tested on the ESGP research satellite. The combination of advanced instrumentation and freedom from operational constraints will provide important new research opportunities.

2.2 Gas Concentration Information

Emission spectra measurements offer an attractive opportunity to simultaneously monitor mixing ratio profiles or column abundances for several gases along with atmospheric state parameters. The upwelling emission spectra of Figure 1 show the signatures of the optically active trace species which are readily identifiable in the IR emission spectra from the HIS. The large brightness temperature signatures of tens of degrees for some of the species (H$_2$O, O$_3$, and N$_2$O) are very apparent. As will be shown later (Section 3.2), the signatures of the other species which are less apparent (methane, carbon monoxide, and CFC 11 and 12) are also quite strong. Coupled with the large radiative impact of these gases, the excellent quantitative agreement of the observed spectra with calculated spectra (from the AFGL FASCOD line-by-line code using temperature and moisture profiles observed with radiosondes) suggest that, as demonstrated in Section 3.2, vertical profiles can be derived for significant portions of the atmosphere.

Special emphasis in trace gas retrieval will be placed on species, those with sizeable radiance signatures, which undergo substantial spatial and temporal variations in concentration. In addition to water vapor, the primary gases in this category are ozone, carbon monoxide, and methane. For these gases, which are important to atmospheric
Figure 1. Upwelling emission spectra at 20km altitude shown as equivalent blackbody temperature as measured by the High-resolution Interferometer Sounder on 14 April, 1986. The spectral regions of interest to trace gas retrieval have been indicated. Also shown is a radiative transfer calculation using the line-by-line program FASCODE2 based upon a coincident raob. The spectral resolution shown in this figure is 0.35 cm\(^{-1}\) (unapodized) in the 600-1100 cm\(^{-1}\) region and 0.63 cm\(^{-1}\) in the region 1100-2600 cm\(^{-1}\).
chemistry, vertical profiles are of interest in addition to total burden. For ozone, it is important to separate the tropospheric and stratospheric concentrations.

The quantitative objectives for trace gas profiling are given in Table 1. These objectives were arrived at through consultations with representatives of the ESGP Science Steering Committee (Professors Michael Rodgers and Derek Cunnold of Georgia Institute of Technology). The specified accuracy and sampling are based on the characteristics of the individual gases. The large difference between the sounding accuracy and temporal sampling interval for methane from that for the other gases is due to its long chemical lifetime in the atmosphere (10 years compared to 2-4 months for CO, for example). Methane soundings can be averaged over the indicated time and space scales to arrive at the desired accuracy.

Table 1. Trace Gas Profiling Objectives

<table>
<thead>
<tr>
<th>GAS</th>
<th>SOUNDING ACCURACY (Δq/q)</th>
<th># VERTICAL LEVELS</th>
<th>TEMPORAL SAMPLING INTERVAL</th>
<th>SPATIAL SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>10-20%</td>
<td>3-4</td>
<td>HOURS</td>
<td>10's of km SOURCE REGIONS</td>
</tr>
<tr>
<td>O3</td>
<td>10-20%</td>
<td>2 TROP +2-3 STRAT.</td>
<td>HOURS</td>
<td>10's of km SOURCE REGIONS</td>
</tr>
<tr>
<td>H2O</td>
<td>10-15%</td>
<td>6-8</td>
<td>HOURS</td>
<td>10's of km</td>
</tr>
<tr>
<td>CH4</td>
<td>FEW% *</td>
<td>3-4</td>
<td>DAYS</td>
<td>100's of km SOURCE REGIONS</td>
</tr>
</tbody>
</table>

*AVERAGE OVER LARGE SPACE AND TIME SCALES

The vertical resolving power of trace gas retrievals from geostationary observations can be optimized by making use of the time domain. Two sampling strategies to enhance vertical resolving power are illustrated in Figure 2. The use of clouds as shutters is illustrated in Figure 2a. In the crudest sense, solid cloud cover drifting over a
Using cloud drift to enhance vertical resolution

(a) Above cloud

(b) Clear air

Below cloud

Mixing ratio sensitivity

\[ R_{\text{below}} = R_{\text{total}} - R_{\text{above}} \]

Optimizing boundary layer sensitivity through diurnal radiance signal

Figure 2. Illustration of the enhanced vertical resolving capability of a geostationary sounder when used with two time sampling strategies; a) the use of clouds as a shutter to discriminate between above cloud and below cloud gas concentrations, and b) the use of diurnal surface heating to provide increased sensitivity to boundary layer gas concentrations.
target provides a natural separation of the trace gas radiance contribution originating above the cloud level from the total radiance contribution. As illustrated, additional vertical discrimination arises from the narrowing of weighting functions near the cloud boundary, thereby also narrowing the effective weighting functions below the clouds obtained by subtraction from clear observations.

Figure 2b illustrates the advantage of being able to sample radiance changes over short time periods when surface heating is large. Basically, these measurements provide trace gas transmittances directly by absorption. The mixing ratio vertical weighting functions corresponding to the change in surface radiance with time are strongly peaked at the surface.

2.3 Measurement of the Radiative Effects of Greenhouse Gases

Because the direct influence of greenhouse gases on the earth emitted radiance is important for detecting and evaluating global change, a spectral survey mode with nearly continuous coverage of a broad portion of the emission spectrum is desirable.

The measurement of the radiance impact of greenhouse gases is compatible with the broad-based needs for temperature and water vapor retrieval, which include surface property and cloud parameter retrievals from window channel radiances. The HIS program has shown that retrievals benefit from the added information and noise reduction offered by broad spectral coverage. Also, the noise and calibration performance needed for temperature and water vapor sounding is quite adequate for the survey mode.

Broad spectral coverage will also provide further trace gas information and may help to identify any new gases with substantial greenhouse contributions. Chlorofluorocarbons, CFC 11 and 12, and carbon tetrachloride are examples of man-made trace gases that have significant absorption features in the infrared spectrum.

3.0 RETRIEVAL PERFORMANCE TRADEOFFS

The main measurement parameters which determine retrieval performance are instrument noise and spectral resolution. This section summarizes the results of our theoretical studies of the dependence of retrieval performance on these parameters. The results have been used to convert science requirements (Section 2) into instrument requirements (Section 4).

3.1 Temperature and Water Vapor

Many simulation studies have been conducted to show how the RMS error and the vertical resolution of temperature and water vapor soundings depend on measurement noise and spectral resolution (Smith, et al., 1990b). An example is shown in Figure 3. The
Figure 3. Retrieval simulation analysis showing the dependence on the two instrument parameters most important to retrieval performance; instrument noise (left-hand panels) and spectral resolution (right-hand panels). In (a) the expected RMS temperature error of a retrieved vertical temperature profile is shown, in (b) the expected vertical resolution of the retrieved temperature is shown, and in (c) the expected fractional error in the retrieved precipitable water content of the atmospheric water vapor is shown.
plots on the left show the dependence on instrument noise of RMS temperature errors, vertical resolution of temperature, and fractional water vapor errors (from top to bottom). The noise parameter is the noise equivalent brightness temperature at 260 K and all results are for a spectral resolving power ($\nu/\Delta\nu$) of about 1000. The plots on the right show the dependence on spectral resolution for a brightness temperature noise of 0.25°C. The resolutions referred to as high, medium, and low correspond to resolving powers of approximately 2000, 1000, and 300 respectively.

The results of Figure 3 show how sounding performance improves as the noise is reduced and as the spectral resolution is increased. While the improvements grow as the noise and resolution performance improve, they tend to diminish near the lowest noise levels and highest resolutions considered here. The instrument resources required to do substantially better become prohibitive, and even the meaning of the simulations becomes questionable. In the real atmosphere, detector noises smaller than 0.1°C at long wavelengths where the signal-to-noise ratio is about 1000 will be dominated by other effective noise sources related to atmospheric and spectroscopic uncertainties.

To approach the ultimate in passive temperature and water vapor sounding for GAP, a single sample NEAT of 0.2°C and a resolution similar to that defined to be "high" in Figure 3 was chosen. An average of four spectra for clear fields of view will yield an NEAT of 0.1°C. In order to improve the near-surface retrievals important to trace gas profiling, the specified resolution for the GAP shortwave temperature sounding region is actually about three times higher than that simulated in Figure 3.

3.2 Trace Gases

Our ongoing research into trace gas profiling accuracy shows that the science objectives summarized in Section 2 are achievable. However, these studies are not yet complete and refinements which will be important for instrument design optimization are continuing under another NASA funded project at UW-Madison. Results available at the time of this report range from the determination of the amplitudes of trace gas radiance signatures based on both observations and calculations, to detailed studies of atmospheric weighting functions. The results from weighting function studies make use of analogies to temperature and water vapor retrieval characteristics. They demonstrate the vertical coverage and profile errors to be expected for a given spectral resolution. Refined results will ultimately be obtained from retrieval simulations of the type that have been used for temperature and water vapor studies.

3.2.1 Signatures

The sizes of the infrared spectral signatures for the highest priority trace gases are all much larger than the noise level specified for temperature sounding. This is illustrated in Figure 4a, b, and c for ozone, methane, and carbon monoxide. For each gas, a brightness temperature spectrum measured by the HIS aircraft instrument on 14 April 1986 is shown on top. On the bottom, two very similar difference spectra show the brightness temperature contribution of the particular gas. The respective peak amplitudes are about 30°C for ozone, 20-40°C for methane, and 5°C for carbon monoxide.
Figure 4. Infrared spectral signatures of (a) ozone (at 0.36 cm⁻¹ resolution), (b) methane (0.63 cm⁻¹), and (c) carbon monoxide (0.63 cm⁻¹) as identified in the HIS observations of upwelling radiance at 20 km altitude on 14 April, 1986. For each gas the upper curve labeled HIS is the blackbody equivalent temperature of the observed radiance spectrum for the wavelength region shown. The lower curve labeled HIS (thick) is the signature of the gas obtained by subtracting from the observed spectrum a calculated spectrum where the absorption due to that gas has been left out. The overlaid curve labeled FASCODE (thin) is the spectral signature predicted by theory in the U.S. Standard Atmosphere.
In addition to showing that a large signal-to-noise ratio exists for trace gas detection, Figure 4 shows excellent agreement between measured and calculated spectra. This indicates that the transmittances needed for retrieval are reasonably well known. Next the sensitivity to small changes in mixing ratio for each gas is considered.

3.2.2 Weighting Functions

The sensitivity of the measured top-of-the-atmosphere radiance to changes in trace gas mixing ratio can be represented by weighting functions, \( W \), defined by the equations of Table 2, where \( P \) and \( T \) are atmospheric pressure and temperature, respectively, and "s" refers to the surface values of these quantities. In words, a fraction times \( W \) represents the change in radiance which results from a fractional change in mixing ratio over about one scale height. It is defined in an analogous way to the temperature weight, \( W_T \), also defined in Table 2. The temperature weight represents the change in radiance which results from a one degree change in temperature over about one scale height.

**Table 2. Weighting Function Definitions**

**Linearized Radiative Transfer Equation:**

\[
\delta N_0 = \int_{\ln P_{\text{top}}}^{\ln P_S} \delta T(P) \ W_T(P, T^o, q^o) \ d\ln P \\
- \int_{\ln P_{\text{top}}}^{\ln P_S} (\delta q/q^o) \ W_q(P, T^o, q^o) \ d\ln P
\]

for one gas, neglecting surface temp changes.

**for which the Weighting Functions are:**

**FOR TEMPERATURE**

\[
W_T = -(dT/d\ln P)^o \beta^o \beta^o \beta^o = (q^o/g) \ P \ k^o \ \tau^o \ \beta^o
\]

**FOR MIXING RATIO FRACTION**

\[
W_q = (q^o/g) \ P \ k^o \ * \\
\int_{\ln P}^{\ln P_S} [ (dT/d\ln P)^o \tau^o \beta^o \ d\ln P \ + \tau^o \beta^o \Delta T_s]
\]

where \( q = \) mixing ratio \( k^o = \) absorption coef \( \beta^o = (dB/dT)^o \)
\( \tau^o = \) transmittance \( g = \) gravitational const \( B^o(T)=\) Planck Distribution \( N_0=\) top of atm. radiance \( \Delta T_s = \) surface skin/atmosphere temp. difference
Mathematically, the weights, $W$ and $W^T$, are the kernels of the integral equation which result from linearizing the radiative transfer equation about a guess atmospheric state. It is this linearized equation which can be solved simultaneously for the deviation of the temperature and mixing ratios from a guess state (Smith, Woolf, and Revercomb, 1990). In general, the weighting functions are peaked functions of pressure. The range of pressures over which the set of available weighting functions have peaks roughly indicates the range of pressures which can be profiled. The narrower the peaks, the more detailed the altitude structure that can be derived from radiance measurements.

Representative weighting functions for trace gas retrieval, including water vapor, are shown in Figure 5 for a spectral resolution of 0.1 cm$^{-1}$ (unapodized). The atmospheric state was defined by the U.S. Standard Atmosphere pressure and temperature profiles as well as the U.S. Standard mixing ratio profiles for water vapor, carbon dioxide, methane, nitrous oxide, and carbon monoxide. The U.S. Standard ozone mixing ratio profile was used everywhere with the exception of the lowest 2 km where a 150 ppbv ozone concentration was used to simulate a polluted boundary layer. A 10°C surface skin/atmosphere temperature difference has been used throughout to illustrate the increased sensitivity to near-surface concentrations from diurnal surface heating. As indicated in the equations of Table 2, the envelope of the weighting functions for a given gas is determined by both the mixing ratio profile of the gas and the temperature lapse rate of the atmosphere. This dependence on mixing ratio explains why the envelope of the water vapor weights peaks more strongly near the surface (the mixing ratio of water decreases exponentially with increasing altitude from the surface), and the envelope for ozone peaks high in the atmosphere (ozone mixing ratio peaks at about 10 mb) with a secondary peak near the surface due to the polluted boundary layer. In contrast, the carbon monoxide mixing ratio decreases slowly with increasing altitude, and methane is nearly uniformly mixed below 100 mb. The effect of the lapse rate, $dT/dlnP$, which is positive for altitudes below the 200 mb level and negative for altitudes above the 65 mb level, is responsible for the fall-off of the ozone envelope in the middle and upper stratosphere.

To give a rough feeling for the amplitudes of the weighting functions, note that the peak values of the ensemble of weighting functions correspond to a brightness temperature of order 10°C for all of the gases. Although a more quantitative interpretation will be given later in this section, it is worth pointing out that this suggests that a temperature retrieval uncertainty of 1°C will yield a mixing ratio retrieval accuracy on the order of 10% (assuming similar brightness temperature uncertainties for trace gas and temperature retrievals).

The ensemble of weights for methane and carbon monoxide suggest that profiling should be possible over roughly the same altitude range as that for water vapor. The situation for ozone is markedly different. The ozone weights indicate a strong sensitivity near the surface for a polluted boundary layer, and in the upper troposphere and the lower stratosphere. This offers a good complement to current stratospheric ozone detection techniques.
Figure 5. Constituent weighting functions as defined in Table 2 representing the change in observed radiance for a 100% change in gas concentration. For example, a doubling of the carbon monoxide concentration at the 800 millibar level would cause up to a 0.8 mW/m² cm⁻¹ sr change in the radiance spectrum in certain indicated spectral channels. Note the change in vertical scale between water vapor, methane/carbon monoxide, and ozone.
The difference of temperature between the surface skin and the atmosphere near the surface is a crucial parameter for trace gas retrieval. The contribution of the mixing ratio weights from the surface is proportional to the surface skin/atmosphere temperature difference (See Table 2). The sensitivity to this temperature difference is illustrated in Figure 6, which shows the contribution to the weights of a 10°C surface skin/atmosphere temperature difference. This is the same temperature difference included in the weights of Figure 5. As pointed out in Section 2, the ability to observe the effects of surface skin temperature changes from geostationary orbit is an important asset of the ESGP for trace gas retrieval.

3.2.3 Resolution Dependence

The spectral resolution necessary for trace gas retrieval is an important driver for this instrument. For a fixed instrument throughput, the dwell time required to attain a given noise performance is inversely proportional to the square of the resolution. Put another way, for a fixed dwell time, the linear dimension of the primary telescope varies inversely with the spectral resolution.

It is important to understand the tradeoffs related to spectral resolution and trace gas retrieval. We have initial results based on weighting function shapes, but more quantitative results will be necessary before the resolution chosen for the baseline requirements (0.1 cm⁻¹, unapodized, or 5 cm maximum OPD) can be solidly justified.

The effects of spectral resolution on carbon monoxide weights are illustrated in Figure 7. The weights at a fixed wavenumber are shown for several different spectral resolutions. The most apparent characteristic of the resolution dependence is that the peak altitude decreases as the resolution decreases. This occurs because the spectral lines are narrow compared to their spacing, meaning that the portion of the spectrum which produces weights peaking high in the atmosphere is relatively small. Therefore, as the resolution is decreased, lower altitudes are weighted more heavily.

The other characteristic of interest is the peak value of the weights. The weights in Figure 7 have been normalized, such that the integral over lnP is unity for each of the weights shown. This means that the narrowest weights have the largest peak amplitudes. Note that there are two competing effects controlling the widths of the weighting functions. At the highest altitudes, the weighting functions for the highest spectral resolution have a larger amplitude and are narrower than the lower resolution functions which peak somewhat lower. The monochromatic weight represents the highest possible weighting for wavelengths near line centers. This is the effect of spectral resolution at some distance from the surface. However, the effect of the surface reverses this trend at lower altitudes. Because the weight is zero at the surface if the surface skin/atmosphere temperature difference is zero, lower resolution weights which peak lower become somewhat narrower. Of course, there is no real advantage to these narrower functions, because there are also high resolution weights which peak at similar altitudes. Thus we see that, near the ground, proximity to the surface makes the widths of the lower resolution weights very similar to the widths of the higher resolution weights.
Figure 6. Surface contributions to the constituent weighting functions shown in figure 5. The surface term is that defined in Table 2 for a ten degree surface skin/atmosphere temperature difference.
Figure 7. Illustration of the effect of spectral resolution on carbon monoxide constituent weights as defined in Table 2. A single wavelength (2111.567 cm$^{-1}$) is shown here at different spectral resolutions (1 cm OPD = 0.5 cm$^{-1}$ unapodized; 5 cm OPD = 0.1 cm$^{-1}$ unapodized). Each weight has been normalized such that the integral over lnP equals unity so that the magnitude of the function peaks are a measure of their width.

The resolution issue is somewhat complicated. It is not always true that higher spectral resolution gives significantly higher vertical resolution. However, higher resolution does extend the coverage to higher altitudes, and it appears to give a better immunity to uncertainties in surface temperature. The effect of reducing spectral resolution is to cause the weighting functions to peak at lower altitudes which can cause either a broadening or a narrowing of the functions depending on proximity to the surface.

Figure 8 shows the effects of resolution on the weights for ozone. The weights for 0.1 cm$^{-1}$ resolution, shown in Figure 8a, show substantially more vertical independence in the upper troposphere than those for 0.33 cm$^{-1}$ shown in Figure 8b. In addition, the 0.1 cm$^{-1}$ resolution has substantially greater ability to distinguish between boundary layer ozone concentrations and the main ozone concentrations in the middle atmosphere. It seems probable that among the greenhouse gases the higher resolution option will be most important for ozone.
Figure 8. Comparison of resolution dependence of the constituent weights for ozone (U.S. Standard Atmosphere with polluted boundary layer, and a 10°C degree surface skin/atmosphere temperature difference) at (a) 0.1 cm\(^{-1}\) resolution and (b) 0.33 cm\(^{-1}\) resolution. The weights shown, a small selection of all those available, have been chosen to indicate the improved ability at 0.1 cm\(^{-1}\) resolution to discriminate between upper tropospheric and stratospheric ozone.

3.2.4 Expected Performance

Expected performance estimates can be obtained from the mixing ratio weights in conjunction with the temperature weights (Figure 9), using temperature sounding results showing an RMS retrieval accuracy of about 1°C. The basis of these performance estimates is the similarity of the mathematical inversion problems and the weighting function characteristics for temperature and mixing ratio retrieval. These results should be considered preliminary; to be followed up with a complete retrieval accuracy estimate based on the formalism developed for temperature retrieval (see Section 3.1).
Figure 9. Weighting functions for temperature as defined in Table 2 for the same wavelength channels shown in figures 5 and 6. The temperature weights give the change in the observed spectra radiance for a 1°C change in atmospheric temperature.
The basic assumption of the current estimate is that the uncertainties for trace gas retrieval can be scaled from those associated with temperature uncertainty by using the ratios of the temperature and mixing ratio weighting functions as scaling factors. This assumption would be exact for the situation of retrieving the mixing ratio profile with a known temperature profile, if the weighting for mixing ratio retrieval and for temperature retrieval had exactly the same shapes and the radiance noise levels were the same. If the amplitudes of the mixing ratio weights were 10 times those of the temperature weights, a 1°C uncertainty in temperature would convert to a 0.10 fractional error, i.e. a 10% error in mixing ratio (see form of the linearized equation in Table 2). This assumption is approximately true for uniformly mixed gases, for which the weighting functions are very similar to those for CO2. The biggest uncertainty of this procedure occurs for ozone, for which the weighting functions are very different from those for temperature sounding.

Application of the above scaling argument (in which the integrands of the radiative transfer equation can be used to scale the uncertainties from the known retrieval characteristic of temperature and water vapor) to trace gas retrieval allows each component of the fractional mixing ratio uncertainty to be estimated from the ratios of weighting functions. That is, the uncertainty related to temperature uncertainties of 1°C is given by \((W^T/W) \cdot 1°C\). Likewise, the uncertainty due to overlapping water vapor features is given by \((W^W/W) \cdot 0.10\) assuming that the water vapor mixing ratio can be retrieved to 10% near the surface (see Section 3.1). Finally, the uncertainty from the trace gas retrieval itself (assuming perfect knowledge of temperature and water vapor) is approximated by a factor close to one times \((W^T/W) \cdot 1°C\). The factor used to scale the retrieval for methane and carbon monoxide is 1.0 because of the similarity of their weights (and mixing ratio profiles) to those for CO2; the factor for water vapor is 0.7 because of the weighting function narrowing caused by the rapidly varying mixing ratio profile of water; and the factor used for ozone was 1.5 to provide a margin to account for the unusual nature of the weighting functions caused by the mixing ratio peaked in the upper stratosphere. The total error estimate is given by the root sum square of these components.

Figure 10 summarizes the results of these mixing ratio uncertainty analyses. The plotted points are the minimum uncertainties selected from the set of weighting functions peaking at the indicated levels and having amplitudes of at least 10 times the expected noise. The surface point is the only exception, in that it was always included even if no weighting function peaked there. This is to account for the weights for surface temperature changes, which will always peak at the surface. Note that the uncertainty profile for water vapor compares reasonably well with the profile of Figure 3 derived from a retrieval analysis, and thereby, provides some corroboration for the procedure used here. The uncertainties for the mid-troposphere for methane, carbon monoxide, and ozone seem very small (≤5%) and need to be corroborated with more rigorous retrieval uncertainty estimates. This estimate is especially suspect for ozone near the tropopause. The dashed line on the ozone plot in Figure 10 shows the \(W^T/W\) ratio for a single wavelength channel at 0.1 cm\(^{-1}\) resolution. It is included to show the trend of the uncertainty due to temperature in an altitude range where there are no peaks in the ozone mixing ratio weights.
Although the uncertainty estimates increase substantially as the surface is approached, the desired uncertainty goals are met there. The increase near the surface emphasizes the importance of making use of the near surface sensitivity arising from the surface skin/atmosphere temperature difference.

Figure 10. Retrieval error estimates at 0.1 cm\(^{-1}\) resolution for the gases ozone, methane, carbon monoxide, and water vapor. Each symbol point of the curves labeled "E(T)" is the minimum value of W/T over all mixing ratio weights of the indicated gas which peak at that level in the atmosphere. The curves "E(T)" represent the component of the retrieval uncertainty related to temperature uncertainty. The curves labeled "TOTAL" are an estimate of the total expected retrieval uncertainty at this resolution.
4.0 GAP INSTRUMENT REQUIREMENTS

This section presents the requirements for the GAP facility instrument based on the scientific objectives stated in Section 2 and the retrieval performance information given in the previous section. The requirements stated here are for a Michelson interferometer instrument design consistent with the baseline instrument design (the GAP) presented in the next section.

4.1 Approach

Some of the specific measurement requirements for the GAP are very well defined at this stage, and others are still evolving. While the temperature and moisture sounding performance from this type of instrument has been simulated for over a decade and has been proven from aircraft flights, the specific radiometric performance needed for optimum trace gas retrieval is still being studied as indicated in Section 3.2.

The use of an interferometric approach from a geostationary platform makes it possible to proceed with a flexible instrument design without a complete specification of optimum spectral resolution, spectral coverage and noise levels. Even after more specific measurement specifications have been developed, it is expected that designing for maximum flexibility in operating modes will enhance the value of this research instrument.

The value of enhanced measurement capabilities specifically for trace gas monitoring can be anticipated. Current studies indicate that vertical profiling of gaseous concentrations will benefit from a higher spectral resolution than that needed for temperature sounding, especially for ozone. Therefore we divide the requirements into two sets which we expect to correspond to two distinct implementations behind a single telescope. The first set is for applications needing broad spectral coverage at a moderate spectral resolution. These requirements are for temperature and humidity sounding, greenhouse radiative effects, and trace gas survey applications. The second set applies to concentration measurements of specific gaseous absorbers for which narrower spectral coverage requirements allow higher resolutions to be measured with low noise.

Scale Constraint

Before proceeding to the specific requirements, we impose an important constraint on the overall scale of the instrument. To provide an explicit closure to the overall instrument design problem in a way that available resources are used as efficiently (and cleverly) as possible, we set size, mass, and power targets of about 2 m$^3$, 200 kg, and 150 W. These constraints are consistent with previous spacecraft instruments of this type.
4.2 Specific Instrument Requirements

4.2.1 Broad Spectral Coverage

The specifications for the broad spectral bands significantly exceed those specified for previous studies of geostationary temperature and moisture sounding instruments, both to provide improved temperature and water vapor sounding (including water vapor winds) and new trace gas applications (GHIS, Smith et al., 1990b).

While the resolution specified here is not higher than that of previous studies, the coverage rates and noise performance at that resolution are much improved. Two important differences are also required for trace gas work. To improve trace gas survey capabilities, the spectral coverage is extended to be essentially continuous and the resolution is improved for the short wavelength bands. This enhanced performance should be feasible through the use of a larger telescope and larger detector arrays.

The specific requirements are enumerated below.

4.2.1.1 Field of View

The instantaneous field of view should be ≤ 10 km (side of square or diameter) at nadir, and all bands should be registered as well as possible. This requirement is designed to allow the instrument to sound through clear air interstices in clouds while ensuring consistency of the measurements from band to band.

4.2.1.2 Spatial Coverage

Selectable spatial coverage densities should be provided with the maximum spatial density providing samples with center-to-center separations of no more than 15 to 20 km. The lower density coverage could be provided by sampling the field with small but dense clusters with a selectable spacing between the clusters.

4.2.1.3 Spectral Coverage and Unapodized Resolution

Nearly continuous coverage is required from 620 cm\(^{-1}\) to 2700 cm\(^{-1}\) with a resolution of 0.33 cm\(^{-1}\) (maximum optical delay = 1.5 cm). The number of bands and specific band limits should be chosen to optimize noise performance.

4.2.1.4 Noise performance

With a dwell time of 1 second, the noise equivalent temperature difference for each FOV should be ≤ 0.2°C (at 260 K for wavenumbers smaller than 2000 cm\(^{-1}\) and at 280 K for larger wavenumbers). This requirement is meant to apply in an average sense over the spectrum. For each spectral band the requirement should be met near the middle of the band, whereby it is understood that the level will be exceeded on the shortwave side of the band.

4.2.1.5 Calibration Accuracy

The reproducibility of the calibration should be ≤ 0.1°C brightness temperature, and the absolute accuracy should be ≤ 1°C (at 260 K for wavenumbers smaller than 2000 cm\(^{-1}\) and at 280 K for larger wavenumbers).
4.2.1.6 Spatial Coverage Rate

The instrument will cover an area of 3000 x 3000 km in one hour with the specified noise performance. Faster coverage rates should also be possible, though with reduced performance.

To put these requirements in perspective, the noise performance at this resolution is about 2 times better than that of the design for the 1988 UW/SBRC/ITT GOES L/M Interferometer Modification Study for NOAA/NESDIS and the spatial coverage rate is about 6 times more rapid also.

4.2.2 Specific Trace Gases

To enhance capabilities for profiling gaseous concentrations, it should be possible to measure selected spectral regions at higher resolution. Possible implementations range from using a single interferometer with programmable mirror travel modes to configurations designed to multiplex the broadband and the specific gas applications. For example, the use of a second aperture-sharing interferometer with larger Michelson mirror travel, or the use of a stepped interferometer mirror to allow the maximum optical path difference to be doubled by single-sided scanning could be considered. The specific requirements are enumerated below.

4.2.2.1 Spectral Coverage and Unapodized Resolution

The requirements for spectral coverage and resolution are given in Table 3.

<table>
<thead>
<tr>
<th>Gas/Band Name</th>
<th>Range (cm⁻¹)</th>
<th>Max Delay (cm)</th>
<th>Resolution (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15μm CO₂</td>
<td>620-1000</td>
<td>1.5</td>
<td>0.33</td>
</tr>
<tr>
<td>O₃</td>
<td>1000-1080</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>CO/N₂O</td>
<td>2060-2220</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>CH₄/H₂O</td>
<td>1240-1360</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>4.2μm CO₂</td>
<td>2380-2393</td>
<td>5</td>
<td>0.1</td>
</tr>
</tbody>
</table>

CO₂ temperature sounding bands are included with the trace gas bands because of the importance of accurate temperatures for trace gas mixing ratio sounding. The broad 15μm CO₂ band is identical to Band 1 and is included to provide temperature sounding information. The 4.2μm CO₂ band will provide enhanced temperature sounding.
information near the surface. Information on water vapor concentration is obtainable both from the 15\textmu m CO₂ band and the CH₄/H₂O band.

4.2.2.2 Noise performance

The noise equivalent temperature difference for each FOV at a dwell time of one second should be ≤ 0.3°C, defined the same way as the ≤ 0.2°C was for the broadband, lower resolution measurements. Meeting this requirement will actually make the noise on the interferogram slightly smaller for the narrow band measurements than for the broadband measurements, despite the 3.3 times more rapid interferogram scan rate required to keep the field of view sample time the same for both modes.

The field of view, spatial coverage, calibration accuracy, and spatial coverage rates should be the same as for the broad spectral bands.

4.3 Operating Mode Flexibility

The final category of requirements relates to operational flexibility. The instrument is to be a versatile research instrument, and as such, should be programmable to operate in many different modes. Examples of the options desired are given in Table 4. It is expected that the optimum combination of modes will be arrived at through use in orbit.

The instrument should have selectable options for setting the extent of the interferometer moving mirror travel up to some maximum limit. It should also have selectable interferogram scan rates through selection of interferometer moving mirror velocities up to some maximum allowable limit. The combination of these two selections will determine the dwell time for any single sounding. In fact, it would be possible to trade off resolution and noise performance in this manner.

The instrument should have several spatial resolution modes so as be able to raster scan the entire globe at lower sampling density in about an hour and still be able to provide the high spatial resolution sampling necessary for study of severe storm outbreaks and local pollution episodes. By shifting a 3x3 array of fields of view by multiples of the array width it should be possible to accomplish this goal.

The geographical coverage times shown in Table 4 are an example of how the GAP might be used to meet the variety of scientific objectives intended for it. Assuming a fixed interferometer moving mirror velocity and a basic coverage rate of 3,000 x 3,000 km in 60 minutes, the same area could be raster scanned in half an hour at one-half the previous spectral resolution. This might be desirable if a rapid repeat image of a region was needed and the lower spectral resolution was deemed adequate. Alternatively, if the higher resolution measurements are necessary, then coverage requirements can be met using non-contiguous spatial sampling, e.g. the entire earth disk can be sampled with a spacing of 150 km between clusters in just 74 minutes.
Table 4. GAP Operating Mode Flexibility

- **Spectral Modes**
  MANY SELECTABLE OPTIONS FOR RESOLUTION
  AND INTERFEROGRAM SCAN RATE

- **Spatial Sampling and Resolution Modes**
  \[ DENSE = \text{UNIFORM COVERAGE OF 10 KM FOV'S} \]
  \[ \text{SPACED BY 16.6 KM} \]
  \[ \text{[50 KM CLUSTERS FROM 3X3 ARRAY]} \]
  \[ \text{REGIONAL = 100 KM SPACING OF 50 KM CLUSTERS} \]
  \[ \text{GLOBAL = 150 KM SPACING OF 50 KM CLUSTERS} \]

- **Dwell Time Modes**
  1 SECOND PER CLUSTER
  1/2 SECOND PER CLUSTER
  1/4 SECOND PER CLUSTER

- **Geographical Coverage Times**

<table>
<thead>
<tr>
<th>Dwell Times</th>
<th>1 Sec</th>
<th>1/2 Sec</th>
<th>1/4 Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>DENSE</td>
<td>60 min</td>
<td>30 min</td>
<td>15 min</td>
</tr>
<tr>
<td>3,000x3,000 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>REGIONAL</td>
<td>15 min</td>
<td>7.5 min</td>
<td>4 min</td>
</tr>
<tr>
<td>3,000x3,000 km</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLOBAL</td>
<td>74 min</td>
<td>37 min</td>
<td>19 min</td>
</tr>
<tr>
<td>10,000x10,000 km</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.0 BASELINE DESIGN

The baseline design concept for the GAP is presented in this section. Its performance and tradeoff considerations are given in the next section.

5.1 General Characteristics

The baseline was chosen to be a simple, flexible design which can meet the science objectives. It is not necessarily meant to be the final design, but is a reasonable approach to which optimization tradeoffs can be compared. The important parameters of the design are summarized in Table 5 for easy reference.

The GAP design employs a single plane-mirror Michelson interferometer behind a telescope with a two-axis scan mirror to raster scan regions of the Earth. The raster scan capability includes programmable step sizes for cluster sampling to increase coverage rates for some applications. The scan mirror periodically scans off the earth to establish the radiative offset from instrument emission and less frequently can be rotated 90° to view a full-aperture blackbody for tracking slowly varying responsivity changes. As for all modern interferometers, the wavelength calibration is established very accurately by the same laser which controls sampling.

The interferometer scan drive will have a programmable range to provide resolutions up to 0.1 cm⁻¹ with a maximum mirror travel of ±2.5 cm (±5.0 cm OPD). The scan rate will also be programmable to allow the dwell time to be adjusted to give the desired noise performance and spatial coverage rates.

Behind the interferometer, the beam is divided into five spectral bands and is focussed on five 3x3 detector arrays. The spectral bands are chosen to optimize the detector noise performance by reducing the photon flux with cold filters. To offset the natural noise performance degradation with increasing resolution, narrow band filters will be provided for the ultra-high resolution modes in those spectral regions which benefit substantially from reduced photon fluxes. The detector arrays, in conjunction with a 3x3 array of field stops, provide nine 10 km diameter circular fields of view in a 50 km square pattern with center-to-center spacings of 16.6 km. The use of arrays increases the spatial coverage rate, which is essentially proportional to the number of elements, for this application.

The spectral coverage options are illustrated in Figure 11. The broad, contiguous bands numbered 1 to 5 give complete coverage from 620 cm⁻¹ in the 15 μm CO₂ band to 2700 cm⁻¹ in the shortwave window beyond the 4.2 μm CO₂ band. It is anticipated that this complete coverage will be used with a resolution of 0.3 cm⁻¹, although both higher and lower resolution options will be available. The narrow bands labeled by the gases of interest provide trace gas profiling. Band 1, which includes the 15 μm CO₂ band, is used for temperature sounding in both trace gas and broad-band modes. The narrow version of band 5 covers the CO₂ band head near 4.2 μm to provide enhanced near-surface temperatures for more accurate trace gas retrievals.
Table 5. Characteristics of the GAP Instrument Design

<table>
<thead>
<tr>
<th>Spectral range (cm(^{-1})), IR bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broad Bands (nominal (\Delta \nu = 0.33) cm(^{-1}))</td>
</tr>
<tr>
<td>Band 1</td>
</tr>
<tr>
<td>Band 2</td>
</tr>
<tr>
<td>Band 3</td>
</tr>
<tr>
<td>Band 4</td>
</tr>
<tr>
<td>Band 5</td>
</tr>
<tr>
<td>Narrow Bands (nominal (\Delta \nu = 0.1) cm(^{-1}))</td>
</tr>
<tr>
<td>15(\mu)m CO(_2)</td>
</tr>
<tr>
<td>O(_3)</td>
</tr>
<tr>
<td>CH(_4)/H(_2)O</td>
</tr>
<tr>
<td>CO</td>
</tr>
<tr>
<td>4.2(\mu)m CO(_2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Field of view (FOV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simultaneous array pattern</td>
</tr>
<tr>
<td>Single FOV diameter</td>
</tr>
<tr>
<td>Center-to-center spacing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Telescope/Collimator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope type</td>
</tr>
<tr>
<td>Telescope diameter</td>
</tr>
<tr>
<td>Telescope f/#</td>
</tr>
<tr>
<td>Telescope/collimator afocal ratio</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area-solid angle product/FOV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.75 (\times) 10(^{-4}) cm(^{2})-sr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interferometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type:</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Mirror Scan length and rate</td>
</tr>
<tr>
<td>Nominal Broadband</td>
</tr>
<tr>
<td>Laser</td>
</tr>
<tr>
<td>Beam splitter:</td>
</tr>
<tr>
<td>Substrate</td>
</tr>
<tr>
<td>Coatings (1/4 (\lambda) at 3.3 (\mu)m)</td>
</tr>
<tr>
<td>Beam diameter</td>
</tr>
<tr>
<td>FOV (Max. dimension of array)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IR Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Band 1 &amp; 15(\mu)m CO(_2)</td>
</tr>
<tr>
<td>All Other Bands</td>
</tr>
<tr>
<td>Size (side of square)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Telescope</td>
</tr>
<tr>
<td>Interferometer</td>
</tr>
<tr>
<td>Detectors</td>
</tr>
</tbody>
</table>
Figure 11. GAP spectral band coverage.

5.2 Optical Conceptual Design

Two options for the optical conceptual design are illustrated in Figure 12. Optically, the options are essentially identical, but option 2 uses an extra element to move the radiative cooler to the opposite end of the instrument for flexibility in spacecraft design. The telescope uses a 60 cm off-axis paraboloid primary mirror. This form (off-axis afocal Gregorian) is selected for two reasons. First, there is no secondary mirror to be thermally stressed from the exposure to sunlight. This consideration is especially important to geostationary orbit applications, for which solar heating of the secondary mirror spider can lead to an unstable optical design. Second, there is no diffraction contribution from a secondary-mirror central obscuration. The current design is based on an f/1.1 parent paraboloid which gives excellent image quality and is reasonable to fabricate. A dichroic beamsplitter will be used to pull off broadband visible channels by reflection in the region before the prime focus (not shown).

After the prime focus the energy is collimated and passed through the interferometer. There is a 12:1 size reduction in the beam, yielding a 2-inch diameter collimated bundle. Thus, the interferometer optics are the size of many commercial laboratory interferometers. In fact, the required interferometer optics are the same size as those of the HIS aircraft instrument, which is based on a BOMEM DA2 (2 for 2 inch) interferometer. Also, the total field of view of the interferometer of 18 mr is actually smaller than the 30 mr of the HIS, even though a 3 x 3 array is used instead of a single detector. This occurs because of the small angular fields of view from geostationary altitude and means that the degree of self apodization will be quite small.
OPTION 1

OPTION 2

Figure 12. Two GAP optical layout options.
The collimated beam exiting the interferometer passes through a series of dichroic beam splitters to the detector arrays. The band splitting concept is illustrated in Figure 13. The aperture stop is focussed on the detectors to eliminate sensitivity to non-uniform detector response. The physical position of the field stop will be a subject of detailed design studies at a later stage. Location at the prime focus would simplify band-to-band alignment requirements, but imposes more stringent requirements on optical stability.

![Diagram of band separation schematic.](image)

Figure 13. Band separation schematic.

The detector cooler in the baseline is a passive radiative cooler. The cooler shown in Figure 12 is similar in design to the VISSR/IAS cooler, but is substantially larger. A detailed cooler design has not been performed, but it is clear that a passive radiative design is feasible. However, in the time frame of the ESGP, a mechanical cooler should be considered, especially considering the development effort on cooler reliability already underway for EOS. Colder temperatures would benefit the performance of both the 15\(\mu\)m and the 4.2\(\mu\)m CO\(_2\) bands, and fewer constraints would be placed on the spacecraft configuration.

The optical construction techniques would employ graphite epoxy structures and low expansion glass optical elements. This material combination has proven very stable in a wide range of thermal environments. The optical elements, except for the scene scan mirror which is not alignment critical, would be supported on an internal optical bench rather than using the box for support.
5.3 Interferometer Concepts

The interferometer design uses the same basic principles as the HIS aircraft interferometer, and in fact has optical elements of nearly the same size. The approach has been shown to be extremely rugged, as proven by continued successful operation mounted in a pod directly under the jet engine of the ER-2 high altitude aircraft. Also, the performance has been shown to yield very accurate radiometry, free of any significant radiometric artifacts.

Sampling is controlled from zero detection of the signal of a laser passed through the same interferometer optics as the IR beam. The area of the beamsplitter used by the laser uses a different coating than the rest of the beamsplitter to give efficiency at its wavelength. The beamsplitter will be a KCl substrate, with the portion used by the IR beam coated with 1/4 wavelength (at 3.3 $\mu$m) of germanium and the same thickness of antimony trisulfide. Only the antimony trisulfide coating is used for the laser path.

The laser will be a solid-state diode pumped YAG laser, which offers a much higher reliability than the HeNe gas discharge-tube laser used on the HIS aircraft instrument. It consists of several redundant 1.06 $\mu$m laser diodes used to pump Nd:YAG rods. Space qualified diodes with projected lifetimes of 80 years when operated at 15°C are already available. The existing YAG lasers will need some modification to ensure true single frequency operation, but no new technology is involved. This approach, with its long-lived and redundant laser diodes, should eliminate concerns over laser reliability.

The length of travel of the Michelson scan mirror for the current baseline design (up to ±2.5 cm) exceeds the capability of the flex-pivot designs used in previous HIS studies. We believe that a new design using magnetic bearings would be the best approach for GAP. Detailed design of such a drive mechanism should be the subject of follow-on Phase A and B studies.

Finally, a dynamically aligned "fixed" Michelson mirror will be employed to guard against any alignment changes which might be encountered during launch or in orbit from the daily heating cycles. This system can be similar in principle to the BOMEM design on the HIS aircraft instrument. A design for space application using linear magnetic drivers and flex pivots was presented in the first HIS feasibility study (SBRC, 1981: "A Design Feasibility Study for the HIS").

5.4 Configuration Concept

Two options for the overall GAP configuration are illustrated in Figure 14. Option 2 is most consistent with the current spacecraft concept. For both options, a single enclosure includes all components, electrical and optical, and mounts to a spacecraft shelf in the X-Y plane. The protrusions are sun shades, one around the earth viewing port and one shading the radiative cooler. As drawn, the earth viewing sun shade totally shields the primary mirror for sun angles from the viewing direction of greater than 17°. The best length will be the subject of further study.
Figure 14. Two GAP instrument envelope options.
The appropriate positions and sizes of thermal control louvers have not been evaluated, and none are shown.

The current concepts are preliminary and are expected to be modified as more becomes known about spacecraft constraints. Many changes are possible. For example, option 1 could be mirror-symmetric about the Y-Z plane. Also, the option 1 enclosure could be turned over with a 180° rotation about the Z-axis. This would be consistent with the need for the cooler to point either north or south. Another reasonably simple change to option 1 would be to move the radiative cooler to the smallest end of the enclosure (pointing in the negative X direction in Figure 14) and rotating the enclosure by ±90° about the Z-axis.

A possible, more extensive change involves the optics design. The optical design could be more compact with a folded Cassegrain approach, and this option will be reevaluated when more detailed design tradeoff studies are performed. It is not clear at this time what premium will be placed on size and weight.

Other tradeoffs which are related to the basic requirements and performance of the instrument are discussed in Section 6.2.

5.5 Technical Heritage

There is a strong heritage for all of the fundamental technology required for the GAP design. This heritage is summarized in Table 6.

Table 6. GAP Heritage

<table>
<thead>
<tr>
<th>Interferometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Demonstrated in the HIS ER2 aircraft flight program.</td>
</tr>
<tr>
<td>• Design concepts and performance models validated by the aircraft program and the Mars Observer's Thermal Emission Spectrometer development.</td>
</tr>
<tr>
<td>• Derived from the Bomem, Inc. line of very successful aircraft, balloon and laboratory instruments.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>• VAS and Thematic Mapper (TM) programs provide &quot;real&quot; detector data.</td>
</tr>
<tr>
<td>• No difficult detector requirements.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Cooler scaled directly from VAS.</td>
</tr>
<tr>
<td>• Cooler requirements well within the cooler capabilities.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scene Scan Mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Mirror drive and control system derived from the VAS and TM programs.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Structure Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Graphite/Epoxy material technology derived from the TM project.</td>
</tr>
</tbody>
</table>
The HIS aircraft model and BOMEM heritage for the interferometry has already been described, but the Thermal Emission Spectrometer (TES) has not yet been mentioned. The TES is a low resolution (5 cm\(^{-1}\)) Michelson interferometer being built by SBRC for the Mars Observer mission. In addition to the basic interferometric and design experience, the TES offers experience with onboard processing of interferometric data, very similar in principle to that needed for GAP (see Section 8).

The detector and radiative cooler technology needed for the GAP does not pose new or difficult requirements. SBRC has a long history of building these types of detector/cooler assemblies and of implementing them in spacecraft.

### 5.6 Mass, Size, and Power Estimates

The following estimates of the basic spacecraft resources needed for GAP are based on scaling arguments performed by SBRC, using the parameters of other instruments which they have built or studied:

**Mass:** 195 kg

**Size (see Figure 14):**
- X-dimension: 240 cm
- Y-dimension: 80 cm
- Z-dimension: 110 cm
- Volume: 2.1 m\(^3\)

**Nominal Operating Power:** 150 W

Note that these instrument dimensions do not include the local protrusions of the deployable sunshade (40 cm in the Z direction, 6 cm in the negative X direction) and the radiative cooler (8 cm in the Y direction).

### 6.0 BASELINE NOISE PERFORMANCE AND SYSTEM TRADE-OFFS

The purpose of this section is to show that the baseline design can meet the requirements laid out for GAP in Section 4, and to give some tradeoff considerations for use in optimization studies of the ESGP payload.

### 6.1 Baseline Performance

The fundamental issues in the performance of this type of instrument are the noise performance and the calibration. As discussed in the next section, the interferometer approach handles the new aspects of calibration for high spectral resolution because of its accurate wavelength calibration. Therefore, the noise performance is the main design consideration.
The RMS noise equivalent radiance (NEN) for an apodized interferometer spectrum is given by the following relationship (the NEN for an unapodized spectrum is \(1/2\) larger):

\[
NEN = \left[\frac{A_d}{(2t)}\right]^{1/2} \times 10^7 / \left[\frac{(A\tilde{\nu}) \tau D^*}{\text{mW/m}^2 \text{ sr cm}^{-1}}\right]
\]

where

- \(A_d\) = Detector area (cm\(^2\))
- \(t\) = Total dwell time (s)
- \(X\) = Maximum optical path difference (cm)
- \(A\) = Telescope area (cm\(^2\))
- \(\tilde{\nu}\) = Solid angle field of view (sr)
- \(\tau\) = Optical transmission
- \(D^*\) = Detector specific detectivity (cm \(\sqrt{\text{Hz/W}}\))

The results of applying this relation to the baseline design are shown in Figures 15 and 16 in terms of NEDT at 260K or 280 K. The numerical results, the detailed assumptions and the specific parameter values not already given in Table 5 are listed in Tables 7 and 8. The requirements, which are stated as mid-band requirements, are adequately met by all bands of both the broad-band, 0.33 cm\(^{-1}\) resolution set (Figure 15) and the narrow-band, highest resolution set (Figure 16).

It is interesting that the performance relative to the requirements is similar for both groups. As currently formulated, the needs for enhanced temperature and water vapor sounding and trace gas sounding are quite compatible.

One notable feature, which suggests that the number of bands could possibly be reduced from 5 to 4, is that the bands from about 1000 to 1750 cm\(^{-1}\) considerably exceed requirements. Originally, the separate ozone band was included because the trace gas performance is inadequate if it is included in Band 1 and another narrow band was needed in Band 3 to handle methane. However, given the good performance of the longwave end of Band 3, the possibility of eliminating the separate ozone band and including both it and methane in a new band which could go from 1000 to 1750 cm\(^{-1}\) should be reevaluated.

6.2 System Tradeoffs

A few rough comparisons with the GOES L/M Modified sounder (UW/SBRC/ITT, 1988) are useful to understand the extra resources required by this instrument, and to explain some of the basic system tradeoffs. There are two fundamental differences between the GAP and the GOES Mod design which have large impacts on the performance: (1) the GAP 60 cm telescope diameter is twice as large as that for GOES and yields a factor of two reduction in noise or a factor of 4 reduction in spatial coverage times (see noise equation in Section 6.1), and (2) the use of 3x3 detector arrays in place of 2x2 arrays speeds up the spatial coverage by another factor of 2.25.
Figure 15. Broadband instrument noise performance.

Figure 16. Narrowband instrument noise performance.
Table 7. Expected noise performance for broad bands (X=1.5 cm, t=0.975 s).

<table>
<thead>
<tr>
<th>Band Name</th>
<th>Band 1</th>
<th>Band 2</th>
<th>Band 3</th>
<th>Band 4</th>
<th>Band 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum ν, cm⁻¹</td>
<td>620</td>
<td>1000</td>
<td>1111</td>
<td>1700</td>
<td>2350</td>
</tr>
<tr>
<td>Maximum ν, cm⁻¹</td>
<td>1000</td>
<td>1111</td>
<td>1700</td>
<td>2350</td>
<td>2700</td>
</tr>
<tr>
<td>NEN, mW/m²sr cm⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Minimum ν</td>
<td>0.17</td>
<td>0.059</td>
<td>0.028</td>
<td>0.0067</td>
<td>0.0042</td>
</tr>
<tr>
<td>@ Mid-band</td>
<td>0.22</td>
<td>0.063</td>
<td>0.035</td>
<td>0.0079</td>
<td>0.0045</td>
</tr>
<tr>
<td>@ Maximum ν</td>
<td>0.27</td>
<td>0.066</td>
<td>0.043</td>
<td>0.0092</td>
<td>0.0048</td>
</tr>
<tr>
<td>NEΔT, °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>@ Minimum ν</td>
<td>0.13</td>
<td>0.06</td>
<td>0.03</td>
<td>0.04</td>
<td>0.11</td>
</tr>
<tr>
<td>@ Mid-band</td>
<td>0.17</td>
<td>0.07</td>
<td>0.09</td>
<td>0.14</td>
<td>0.22</td>
</tr>
<tr>
<td>@ Maximum ν</td>
<td>0.27</td>
<td>0.08</td>
<td>0.25</td>
<td>0.53</td>
<td>0.44</td>
</tr>
<tr>
<td>Transmission, τ</td>
<td>0.117</td>
<td>0.122</td>
<td>0.157</td>
<td>0.138</td>
<td>0.155</td>
</tr>
<tr>
<td>D*peak, cm/Hz/W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>4.4+10¹⁰</td>
<td>1.2+10¹¹</td>
<td>2.8+10¹¹</td>
<td>4.2+10¹²</td>
<td>4.2+10¹²</td>
</tr>
<tr>
<td>BLIP</td>
<td>1.5+10¹¹</td>
<td>3.4+10¹¹</td>
<td>2.6+10¹¹</td>
<td>9.2+10¹¹</td>
<td>1.3+10¹²</td>
</tr>
<tr>
<td>Combined</td>
<td>4.2+10¹⁰</td>
<td>1.2+10¹¹</td>
<td>1.9+10¹¹</td>
<td>9.0+10¹¹</td>
<td>1.3+10¹²</td>
</tr>
</tbody>
</table>

* NEΔT evaluated at 280 K (all others at 260 K)

Table 8. Expected noise performance for trace gas bands (X=5.0 cm, t=0.975 s**).

<table>
<thead>
<tr>
<th>Band Name</th>
<th>15μm CO₂</th>
<th>O₃</th>
<th>CH₄/H₂O</th>
<th>CO</th>
<th>4.2μm CO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum ν, cm⁻¹</td>
<td>620</td>
<td>1000</td>
<td>1240</td>
<td>2060</td>
<td>2380</td>
</tr>
<tr>
<td>Maximum ν, cm⁻¹</td>
<td>1000</td>
<td>1080</td>
<td>1360</td>
<td>2220</td>
<td>2393</td>
</tr>
<tr>
<td>NEN, mW/m²sr cm⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Minimum ν</td>
<td>0.30</td>
<td>0.21</td>
<td>0.055</td>
<td>0.0020</td>
<td>0.0092</td>
</tr>
<tr>
<td>@ Mid-band</td>
<td>0.39</td>
<td>0.22</td>
<td>0.058</td>
<td>0.0021</td>
<td>0.0092</td>
</tr>
<tr>
<td>@ Maximum ν</td>
<td>0.48</td>
<td>0.23</td>
<td>0.061</td>
<td>0.0022</td>
<td>0.0092</td>
</tr>
<tr>
<td>NEΔT, °C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>@ Minimum ν</td>
<td>0.23</td>
<td>0.21</td>
<td>0.09</td>
<td>0.20</td>
<td>0.27</td>
</tr>
<tr>
<td>@ Mid-band</td>
<td>0.31</td>
<td>0.23</td>
<td>0.11</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>@ Maximum ν</td>
<td>0.47</td>
<td>0.26</td>
<td>0.13</td>
<td>0.37</td>
<td>0.28</td>
</tr>
<tr>
<td>Transmission, τ</td>
<td>0.117</td>
<td>0.113</td>
<td>0.133</td>
<td>0.138</td>
<td>0.155</td>
</tr>
<tr>
<td>D*peak, cm/Hz/W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td>4.5+10¹⁰</td>
<td>1.2+10¹¹</td>
<td>7.0+10¹¹</td>
<td>2.3+10¹²</td>
<td>2.2+10¹²</td>
</tr>
<tr>
<td>BLIP</td>
<td>1.5+10¹¹</td>
<td>3.9+10¹¹</td>
<td>4.4+10¹¹</td>
<td>1.1+10¹²</td>
<td>3.9+10¹²</td>
</tr>
<tr>
<td>Combined</td>
<td>4.3+10¹⁰</td>
<td>1.2+10¹¹</td>
<td>3.8+10¹¹</td>
<td>1.0+10¹²</td>
<td>1.9+10¹²</td>
</tr>
</tbody>
</table>

* NEΔT evaluated at 280 K (all others at 260 K)

** 15μm CO₂ is for X= 1.5 cm, t=0.3 s
Another change, which has little impact on resources, but which also makes the coverage of the GAP another 2.8 times faster, is the larger center-to-center spacing of the detectors for GAP. The spacing for the baseline is to be 16.6 km, instead of the 10 km for GOES. This spacing gives 9 fields of view in each 50 km square region and was judged to be adequate sampling density for handling cloud clearing. Spatial sampling strategy can have a big impact on instrument performance and must be evaluated carefully.

Figure 17. Broadband noise performance versus telescope aperture tradeoff.

Figure 18. Narrowband noise performance versus telescope aperture tradeoff.
Figure 19. Instrument mass versus telescope aperture tradeoff, where MSS is the Multi-Spectral Scanner, VISSR is the Visible Infrared Spin Scan Radiometer, and TM is the Thematic Mapper.

The telescope size is the parameter in this instrument with the major impact on overall size and weight. The noise performance dependence on telescope aperture diameter is illustrated in Figures 17 and 18. The need for a 60 cm diameter telescope with the current assumptions is clearly shown. However, depending on the available resources and the importance of the science, many tradeoffs are possible. The importance of these tradeoffs to minimizing weight is illustrated in Figure 19, which shows a parameterization of instrument weight in terms of aperture diameter based on experience at SBRC.

One technical possibility which should be traded off against reliability is the mechanical cooler. Extra cooling capacity would mainly improve the performance in the longest wavelength band. In this band, the detector performance is temperature limited and could be improved by about a factor of two by added cooling (see Tables 7 and 8). The shortest wavelength bands, which are the other performance drivers, will only be helped marginally by extra cooling, since their performance is already largely set by photon noise from the scene.

Other tradeoffs which can have major impact are related to the science requirements. While it seems clear that there would be a scientific benefit to flying a large telescope, there are many ways in which the performance of this instrument could be reduced and still offer significant improvements over any other measurements of its type. The factors of improvement for meteorology over GOES-N are large. A smaller improvement in meteorological measurements could be tolerated if continuing studies of trace gas retrieval show that useful information can be returned with somewhat reduced performance.

Some other tradeoff considerations related to the basic instrument configuration are discussed in Section 5.4 and will not be repeated here.
7.0 CALIBRATION

Discussion of calibration will concentrate first on the general approach and then on its implementation on the spacecraft.

7.1 Approach

Experience with the High-resolution Interferometer Sounder (HIS) aircraft instrument has demonstrated that Fourier Transform - Infrared (FTIR) instruments are especially well suited to absolute emission measurements of broad spectral bands at high resolution (Revercomb, et al., 1987/89; 1988b; 1989a,b; 1990).

The fundamental advantage of FTIR instruments for accurate calibration of emission measurements is their wavelength integrity, the same property which has made them the standard for very high resolution absorption measurements. The interferometer approach, coupled with laser triggered sampling, yields an instrument for which accurate central wavelengths and spectral weightings are mathematically defined from a few design parameters or a single adjustable parameter (Brault, 1985). Because the large slopes on the sides of lines can create large effective radiance errors for very small wavelength errors, the importance of the extremely accurate wavelength calibration possible with FTIR increases with increasing spectral resolution.

Radiometric calibration of the HIS is accomplished with the same basic technique used in low resolution radiometry. Periodic viewing of two high emissivity, uniform temperature blackbody references provides the responsivity and offset parameters needed to convert measured spectra to radiances. Two blackbodies are adequate for the HIS because of the linearity of its detectors. One property which must be handled properly for accurate calibration of an interferometer is the phase. This topic is discussed in detail in Revercomb, et al., 1988b.

Laboratory verification of the HIS calibration consisted of the use of the instrument's 300 K blackbody and a liquid nitrogen blackbody to calibrate the spectrum of the instrument's second blackbody set for 260 or 280 K. It was consistently possible to retrieve the unknown blackbody temperature to within a few tenths of a degree across the whole spectral band except in regions of strong spectral absorption (about 1 m air path is included between the interferometer and the detector dewar assembly).

Atmospheric observations have verified that the HIS calibration is sufficiently accurate to serve as a standard for comparison with calculated radiances (Revercomb, et al., 1989a,b; 1990). The general agreement between HIS spectra and calculations from radiosonde temperature and water vapor profiles using the AFGL FASCOD2 program is remarkably good, this is a tribute to the current state of line-by-line codes. However, spectroscopic deficiencies of several degrees Celsius are indicated by differences in many regions which are reproduced for very different atmospheres and observing conditions. Our comparisons with FASCOD2 have revealed other substantial differences resulting
from trace gas absorption, CO₂ and H₂O line strength and/or line shape uncertainties, and from uncertainties in the strength of the H₂O foreign broadened continuum.

In summary, it has been demonstrated that Fourier transform instrumentation of the type proposed here is especially well suited to making highly accurate radiance measurements. Both laboratory and atmospheric verification of the calibration of the HIS instrument show that the measurement objectives of the GAP can be achieved.

7.2 Implementation

The GAP design incorporates an external blackbody source as indicated in Figure 12. This source, of high emissivity and known temperature distribution, will fill the instrument aperture with radiation of a known intensity during a calibration view. The blackbody is external, i.e. viewed by the same scene scan mirror optics used to view the earth, in order to be able to remove the effect of emission from each optical element in the calibration process. A view to cold space will provide the other calibration point. Space and the external blackbody will be viewed as often as necessary to compensate for internal instrument temperature drift. The frequency of this calibration will depend on the time rate of change of temperature of the emitting surfaces within the instrument which will be closely monitored. Typically, a space view will be taken at the end of an earth raster scan so as not to unnecessarily disrupt the mirror scan sequence. During periods of nominal instrument operation, external blackbody views will be made less frequently than views to space.

8.0 SIGNAL PROCESSING ARCHITECTURE AND DATA RATES

The signal processing architecture described here is a very conservative approach based upon existing technology and using proven designs. In fact, the timing and power estimates given below were derived from a breadboard processing module put together at the UW to demonstrate the signal processing concepts. These estimates show that the signal processing job can be done with relatively little power and at low risk using current technology. However, given the expected launch date near the turn of the century, and considering the rapid advances in microchip technology, the design advocated here should be continually revised in order to further reduce the chip count and the power requirements.

8.1 GAP Processing Overview

The output of the interferometer portion of the GAP instrument is an analog signal representing an interferogram sampled at intervals fixed by the optical delay of the reference laser. The signal processing system digitizes this signal and filters the data to reduce data volume, while preserving the full information content of the signal. This data
can be brought to the ground as an interferogram, or optionally, on-board digital signal processors could perform the Fourier transform to the spectral domain where channel selection can be used to further reduce the data volume (and data rate). The ground processing to perform the calibration and subsequent data analysis is discussed in section 9.

8.2 On-board Data Processing

The block diagram representing the on-board data flow for the GAP is shown in Figure 20 with internal data rates shown at each step in the processing. The downlink data rate is 2.5 Mbs for interferometric data and 0.80 Mbs if the option to perform on-board processing to spectra is chosen.

Each detector output from bands 1 to 5 is passed through an analog prefilter to reduce the effect of Johnson noise. After analog-to-digital (A/D) conversion, the output of the 45 detectors (five 3x3 detector arrays) is directed to a set of digital signal processor (DSP) modules to perform input scaling, and digital prefiltering. The selected DSP module using current space qualified technology is based on the TI 320C25 processor and contains a total of about 25 microchips.

8.3 TMS320 Family Digital Signal Processors

The TMS320C25 is a digital signal processor well suited for use in space. It is:

1. Capable of performing 10-million instructions per second.
2. Uses only 725 mW (average) power at the highest clock rate.
3. Fabricated using CMOS technology so power consumption is clock-rate dependent.
4. Manufactured by Texas Instruments, a well-recognized name in the electronics industry, ensuring continued part availability and support.

The TMS320C25 has been commercially available since June 1987, and is in use on the Thermal Emission Spectrometer instrument for the Mars Observer Mission. The military-qualified part is designated SMJ320C25 and has been available since November 1987. The SMJ prefix indicates routine part screening to MIL-STD-883, Rev. C, Class B.

8.4 Time and Power Budgets

Figure 21 shows a typical spectrum for which a full breadboard simulation has been conducted to obtain time and power estimates. The total time available for processing the data from each dwell period is assumed to be one second. Table 9 shows the time required for each of the DSP functions for a single DSP module.
Figure 20. GAP data processing flow (MBPS is Megabits/Sec).

Figure 21. Spectrum used in breadboard circuit to verify signal processing time estimates.
Table 9. DSP Timing Budget

<table>
<thead>
<tr>
<th>FUNCTION</th>
<th>TIME (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input/Scale Data</td>
<td>2.2</td>
</tr>
<tr>
<td>21 Point Prefilter</td>
<td>17.2</td>
</tr>
<tr>
<td>4096 Point Radix 8 FFT</td>
<td>71.1</td>
</tr>
<tr>
<td>Format for Output</td>
<td>6.2</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>96.7</strong></td>
</tr>
</tbody>
</table>

Table 10 gives a power budget for the DSP module under consideration. The power requirements for onboard processing are relatively small because of the use of CMOS memories which require very little power when not being accessed.

Table 10. DSP Module Power Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
<td>TMS320C25 @ 10 MHz</td>
</tr>
<tr>
<td>Memories</td>
<td></td>
</tr>
<tr>
<td>Honeywell 8k x 8</td>
<td></td>
</tr>
<tr>
<td>Data Banks 4 x 16k x 16 (16 used)</td>
<td></td>
</tr>
<tr>
<td>Program Memory 16k x 16 (4 used)</td>
<td></td>
</tr>
<tr>
<td>Active Memories</td>
<td></td>
</tr>
<tr>
<td>Active Program Bank</td>
<td>414 mW</td>
</tr>
<tr>
<td>Processor Side Data Bank</td>
<td>120 mW</td>
</tr>
<tr>
<td>A/D Side Data Banks (2 used)</td>
<td>22 mW</td>
</tr>
<tr>
<td>Miscellaneous Control Logic</td>
<td>345 mW</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>1.40 W</strong></td>
</tr>
<tr>
<td><strong>Total Power for 15 DSP Modules</strong></td>
<td><strong>21.0 W</strong></td>
</tr>
</tbody>
</table>

The time estimates shown here have been used to determine the number of DSP modules required to process the interferogram samples at the rates generated by the baseline interferometer design. The signal processing power requirements have been included in the total instrument power of 150 W.
9.0 GROUND SYSTEM

The role of the ground system of the GAP is to convert the signals received from the instrument into physical units corresponding to infrared upwelling radiation at the satellite orbit and to apply to this data a standardized algorithm for the retrieval of atmospheric state parameters. The retrieved parameters are to include altitude profiles of temperature, water vapor, and trace gas concentration over a variety of geographical areas with a particular emphasis on the troposphere.

9.1 GAP Data Processing Flow

A diagram showing the flow of data through the GAP ground system is given in figure 22. This figure shows two input streams, the raw satellite data and ancillary supporting data, and two output streams, calibrated radiance spectra (level 1B) and atmospheric profiles (level 2). The flow of data will be described from the satellite down.

![Diagram of data processing flow]

Figure 22. Block diagram of ground system data flow.

The downlinked data packets received by the ground system are decoded and the level 0 data and engineering data are ordered in sequence by the time of the beginning of each interferometer OPD scan. With five 3x3 detector arrays, there will be 45
simultaneous measurements to accommodate. If the downlinked data consists of interferometric data, then a fast Fourier transform is done on each interferogram to generate a spectrum. If the Fourier transform is performed on-board the spacecraft, then the downlinked spectra can be used directly. A spectrum would be combined with navigation information, a time stamp, and quality control flags and stored in short term storage. When enough calibration data has accumulated, the time series of raw spectra would be passed through a linear calibration algorithm to generate a time series of calibrated earth spectra. This invertible calibration process would be monitored off-line to assess instrument performance and perform trend analysis of the data quality.

The time series of calibrated earth radiances makes up the Level 1B data and is a principle level 1 product of the GAP instrument. This data can be used directly for earth radiation budget investigations as well as providing the basic data for further scientific analysis.

The level 2 products generated in the GAP ground system consist of atmospheric state parameters derived from the calibrated earth radiances. There are two classes of data generated by the GAP instrument. Broad band data at moderate resolution will provide vertical profiles of temperature and water vapor as well as total concentrations of individual trace gases. Narrow band trace gas data at high resolution will be used to obtain vertical profiles of the gases ozone, carbon monoxide, and methane as well as coincident temperature and water vapor. In each case, the algorithms will depend only on the availability of GAP radiance data. The form of the level 2 products will be three dimensional gridded data representing a limited area surface region with up to about 40 levels of vertical information (fewer levels for trace gases). At this product level, each 3-D grid will consist of profile information corresponding to one raster scan sequence of the instrument. If the same surface region is scanned repeatedly, the time sequence of these grids will then comprise a four dimensional view of the atmospheric state, otherwise the sequence of gridded data will represent a time series of views of different regions of the earth, the details of which will depend on the programmed operating schedule for that day.

It is anticipated that some higher level products, such as contour maps of trace gas concentration and water vapor winds, will be generated routinely by the ground processing system, but that most level 3+ products will be generated by scientific investigators at their home institutions.

9.2 Processing Steps and Algorithms

As discussed in the previous section, the main processing steps that need to be accomplished are navigation, calibration, quality monitoring, and sounding profile retrieval. A summary of the processing steps is given in figure 23 along with estimates of the expected processing load. The lines of code in this figure represent only the core routines where the bulk of the processing is performed. The total number of lines of code that need to be written to create a reliable and maintainable software environment is of course many times greater than this number. Note that the sounding retrieval computation, which involves considerable matrix and vector multiplication, is only about half of the processing load with an equal load generated by the preprocessing algorithms necessary for the proper
treatment of clouds and other effects. Because of this division it may be desirable to consider a two stage retrieval process with the sounding radiance preprocessing handled by a machine optimized for input/output operations and with data pipelined to a second machine optimized for vector operations, thus effectively creating an efficient parallel processing system.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Lines of Code</th>
<th>CPU Load (MFLOPS)</th>
<th>Heritage</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAVIGATION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Image/Earth Coordinate Transformation</td>
<td>1K</td>
<td>&lt;1</td>
<td>GOES</td>
</tr>
<tr>
<td>CALIBRATION</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calculate and Apply Coefficients</td>
<td>1K</td>
<td>&lt;1</td>
<td>HIS</td>
</tr>
<tr>
<td>QUALITY MONITOR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Quality Checks</td>
<td>2K</td>
<td>&lt;1</td>
<td></td>
</tr>
<tr>
<td>SOUN DA RANCE RADIANCE PREPROCESSING</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ Slicing for Cloud Determination</td>
<td>5K</td>
<td>38</td>
<td>VAS, HIRS -- experience at higher spatial resolutions pending</td>
</tr>
<tr>
<td>N* Technique</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOUN DA RANCE RETRIEVALS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simultaneous Physical / Statistical Retrievals</td>
<td>7K</td>
<td>43</td>
<td>HIS -- evolving higher spectral resolution algorithms</td>
</tr>
</tbody>
</table>

NOTE: Rates assume 9 retrievals per second.

Figure 23. Processing steps and algorithms.

9.3 Ground System Data Rates

A diagram showing the estimated rate of data product generation by the GAP ground system is given in figure 24. The downlink data rate depends on the option chosen for the on-board data system. If interferometric data is downlinked then the incoming data rate to the ground system is about 2.5 Mbps. After Fourier transform and restriction to the specified spectral ranges the data rate drops to
about 0.8 Mbps. This is also the incoming data rate to the ground system if Fourier transforms are done on the spacecraft rather than on the ground. Since the Fourier transform is as easily done on the ground as on the spacecraft, the issue is one of downlink bandwidth and archival storage costs versus increased onboard signal processing cost and risk. This is an area that requires further study.

The calibration procedure does not change the data rate in any significant manner. Each raw spectrum is replaced by a calibrated spectrum of the same size, and a small amount of instrument temperature and engineering data is included in the data stream. Thus the level 1B data is generated (and must be archived) at a rate of about 0.8 Mbps. Since this is a sequence of physical earth-emitted radiance spectra each marked by latitude, longitude, and time of observation, the data stream can be readily subdivided to facilitate distribution to scientific and instrument investigators.

The retrieval process is an information extraction process which significantly reduces the data rate by replacing the somewhat redundant spectral measurements with a small set of physical parameters that characterize the atmospheric state. The expected data rate for level 2 retrieval products is about 25 Kbps for 40 altitude levels of temperature (fewer levels for the constituent profiles).
9.4 Ancillary Data Requirements

The GAP ground system does not place a requirement on real time access to data from other instruments, with the exception of platform position and orientation as required to successfully navigate the GAP data to an earth based coordinate system.

The GAP level 2 products would benefit however from near real time access to two proposed ESGP instruments; the Geostationary Microwave Precipitation Radiometer (GMPR), and the Geostationary Earth Processes Spectrometer (GEPS). Non-ESGP data of interest are conventional forecast model analyses and balloon profile/surface station data. The main use for this data is to improve the knowledge of cloud cover in the sounding field of view and for use in surface temperature determination. It should be emphasized, however, that these ancillary data will only enhance the level 2 products and are not necessary for level 2 product generation, which can be based solely on GAP data.

10.0 OPERATIONAL RELIABILITY OF GAP INSTRUMENT

The GAP instrument conceptual design incorporates several elements that might be considered potential life-limiting subsystems. Proper design of the following will ensure that the lifetime goal of 10 years will be met: 1) Scan Mirror, 2) Interferometer Moving Mirror, 3) Dynamic Alignment Mirror, and 4) Laser Assembly.

10.1 Scan Mirror

The scan mirror for the GAP instrument must rotate ±5° during Earth viewing, and it must be capable of rotating 360° for instrument calibrations. A system that will reliably provide support and accommodate these mirror motions can be obtained by using a flexpivot configuration (for the ±5° motions), in series with two duplex pairs of ceramic ball bearings (for the 360° motion).

Flex pivots have a long history of spaceflight application. SBRC has used commercially available flex pivots in several of their instruments, including the Thematic Mappers on Landsats 4 and 5. Flex pivot components have completed over 1 billion cycles on Landsat 4.

10.2 Interferometer Travelling Mirror

The interferometer travelling mirror must translate 5 cm in the high resolution mode. The most suitable and reliable method for supporting this mirror is to use active magnetic bearings. Magnetic bearings avoid rubbing parts which need lubrication.

SBRC has been investigating scan drive mechanism improvements for several years and recently opted to use active magnetic bearings to support these mirrors. Magnetic Bearings, Inc. (a joint venture of Kollmorgen Corp. and S2M of France) is a manufacturer
of such subsystems and have successfully replaced standard bearings in such applications as turbomolecular vacuum pumps, cryogenic helium compressors, and ultra-high-precision grinding spindles. Since the magnetic bearing has no physical contact with the device, the reliability question centers on the electronics, rather than mechanics. This technology is now being used to solve the general problem of oscillating or slow-moving scanning mirrors that must operate for long durations.

10.3 Dynamic Alignment Mirror

The purpose of the dynamic alignment mirror in the GAP interferometer is to maintain optical parallelism between the optical path difference travelling mirror and the fixed (but tiltable) mirror. The dynamic alignment mirror system is mechanically simple. It consists of a central flexural column and four active coils, selectively driven by a closed loop system that provides corrective rotations about each orthogonal tilt axis. The central flexural column is basically a cantilever beam spring that can easily be designed to provide the necessary deflections at stress levels that will ensure an infinite life.

10.4 Laser Assembly

The GAP interferometer uses a laser for sample control and for the dynamic alignment system. The laser assembly to be used in the interferometer is a laser-diode-pumped Nd:YAG laser that operates at a single frequency (1.06 μm) and has a lifetime of greater than 10 years. Previous interferometer systems used HeNe gas discharge-tube lasers that required high-voltage power supplies. Both the high voltage power supplies and the discharge tubes have been reliability issues in the past. The solid-state laser-diode-pumped YAG laser system proposed for the GAP interferometer is far superior to the HeNe gas-discharge-tube lasers.

Laser diodes are used to pump the Nd:YAG rods, enabling use of low-voltage power supplies. Space-qualified diodes are available with lifetimes greatly exceeding the desired system life of 10 years. To avoid the possibility of a single-point failure, the YAG gain medium is designed to have several redundant pump diodes.

The Nd:YAG rod is a commonly used laser gain medium and represents off-the-shelf technology. Also, YAG lasers have been operated successfully in very high radiation dose environments and are mechanically stable. They will also be easier to package to survive the launch environment than gas discharge tube lasers, which require a seal between the end mirrors and the laser tube. No new technology is needed to develop the laser system.
11.0 AREAS FOR FURTHER STUDY

As a result of the work that has been done to date on the GAP Phase A study, several areas have been identified for further study as a follow-on to the work that has already been completed. These tasks are listed in outline form below:

11.1 Trace Gas Soundings Performance

(1) Collect and process atmospheric data from the HIS aircraft instrument with trace gas validation to demonstrate retrieval capabilities with real data.

(2) Perform more extensive trace gas sounding simulations to refine estimates of expected performance.

(3) Breadboard signal processing software.

11.2 Operating Modes

(1) Prioritize the science objectives.
   a. Define the percentage of time allocated to ozone, methane, and carbon monoxide sounding versus pure temperature and water vapor sounding.
   b. Define observational scenarios for use of global, regional and sub-regional coverage in various vertical resolution modes.

(2) Simulate satellite data and retrieval products for the proposed operational modes.
   a. Perform regional (and sub-regional) simulations of what the GAP instrument would observe in different spectral resolution modes. [This could be done for example, using a three day period for which VAS data, NWS gridded temperature/water vapor data, and urban air pollution data are available (August 1988)].
   b. Perform a GAP instrument simulation of daily global observations using several operation modes.

(3) Simulate retrieval products for several proposed observing strategies.
   [The emphasis is to understand the best combination of operation modes to satisfy the largest number of science objectives within the constraints of coverage time and the vertical resolution inherent in each operating mode.]

11.3 Instrument Design

(1) Review, in depth, the potential interferometer options and from them define a configuration that meets the scientific, technical and mission objectives in an optimum fashion.

(2) Study and participate in the development of the interfaces between the instrument and the spacecraft.
(3) Advance the design of the following GAP instrument subsystems:
   a. optics
   b. focal plane
   c. electronics
   d. cryogenic cooler
   e. spectral separation techniques
   f. on-board and ground calibration systems
   g. sensor structure an associated mechanisms
   h. scan system and bearings
   i. thermal control system
   j. on-board signal processing
   k. sun shade

(4) Studies are needed in the following areas to develop:
   a. methods for implementing high absolute and relative radiometric
      calibration accuracy for the final design.
   b. methods for implementing band-to-band registration.
   c. methods for implementing specified dynamic range and sensitivity.
   d. a highly credible cost estimate for a follow-on phase B and C/D
      flight hardware development program.

(5) Signal processing architecture
   a. Conduct an ongoing survey of state of the art digital processor
      technology. Of particular interest are the reliability and screening
      data and the radiation hardening data.
   b. Consider system redundancy and fail-safe options.

11.4 Ground Data Processing System

(1) Generate a systems requirements document using the Phase A
    requirements summary and other inputs as directed by the ESGP program.
    This document will serve as the baseline for Phase B designs.

(2) Develop the system design and prepare subsystem specifications for
    software, algorithms and communications interfaces.

(3) Prepare ground systems test plan.

(4) Support the ESGP DIS definition and development.

(5) Study and develop the interfaces between the ground system and the
    spacecraft and the instrument and the spacecraft.

(6) Study high reliability ground processing options.
REFERENCES


APPENDIX A

EARTH SCIENCE GEOPLATFORM INFORMATION
EARTH SCIENCE GEOPLATFORM INSTRUMENT INFORMATION

INSTRUMENT NAME:
Geostationary Atmospheric Profiler (GAP)

- Latest Update: June 15, 1990

- Summary of changes since (date): April 17, 1989
  1. Instrument weight increased from 150 to 195 Kg.
  2. Instrument dimensions increase from (1.5, 1.0, 0.9) to (2.4, 0.8, 1.1) m.

- Development Status:
  Phase A Study complete.

CONTACT:
Fred A. Best
University of Wisconsin
Space Science and Engineering Center
1225 W. Dayton Street
Madison, WI 53706
(608) 263-6777

MEASUREMENT OBJECTIVE(S)
Temperature, moisture, and trace gas sounding, greenhouse gas radiative impact and wind profiling from moisture tracking.

INSTRUMENT DESCRIPTION:
Michelson interferometer with variable spectral coverage and resolution.

DRAWINGS / PHOTOS:
See attachment.

PHYSICAL
 MASS (KG): 195

DIMENSION (M): X=2.4, Y=0.8, Z=1.1
Note: These instrument dimensions do not include the local protrusions of the deployable Sun Shade (0.4 m in the Z axis, and 0.06 m in the X axis) and the Radiative Cooler (0.08 m in the Y axis).

- Any motion that affects the physical envelope?
  Deployable sun shade.

LOCAL CENTER OF GRAVITY: TBD
ELECTRICAL

VOLTAGE: Can design to spacecraft plans.

POWER:
- Nominal operating (Watts): 150W
- Peak (W): TBD
- Standby (W): TBD
- Safe Mode (W): TBD
- Requirements during launch & deployment: TBD
- Duty cycle (%): 100%

THERMAL

<table>
<thead>
<tr>
<th>Heat Rejection (Watts)</th>
<th>Launch</th>
<th>Operating</th>
<th>Standby</th>
<th>Safe Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature Limits (°C) (MAX/MIN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor:</td>
</tr>
<tr>
<td>Antenna:</td>
</tr>
<tr>
<td>Electronics:</td>
</tr>
<tr>
<td>Detectors: 95/85K (radiative cooler)</td>
</tr>
</tbody>
</table>

DATA/COMMUNICATION

DATA RATE (KBPS)
- Scientific: 1400 Kbps
- Engineering: 100 Kbps (includes calibration)

DUTY CYCLE (%)
- Scientific: 93%
- Engineering: 7%

DATA REQUIREMENTS

<table>
<thead>
<tr>
<th>Launch</th>
<th>Operating</th>
<th>Standby</th>
<th>Safe Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0/0</td>
<td>0/1.5M bps</td>
<td>0/TBD</td>
<td>0/TBD</td>
</tr>
</tbody>
</table>

- Analog/Digital
- Uplink characteristics:
- Downlink characteristics:
- Acceptable bit error rates:

POINT AND CONTROL

VIEW DIRECTION: Earth plus periodic space and blackbody views.

SCANNING/NON-SCANNING: Scanning, using single two axis internal mirror.

UNOBSSTRUCTED FIELD OF VIEW (FOV)
- Instrument: 20° full angle
- Thermal Radiator (Detector): 130°
POINTING REQUIREMENTS (angle, rate, short & long term, N-S & E-W)
- Target(s): Geographic regions and meteorological/atmospheric chemistry events.
- Accuracy (with respect to?): Earth coordinates.
- Knowledge (real time or post flight?): 10 km real time
  2 km post flight
- Stability: 1 km/s
- Integration time: selectable
- Instantaneous field of view (IFOV): 10 km diameter / detector; 3 x 3 detector array with center-to-center separation of 16.6 km

POINTING CONSIDERATIONS
- Moving masses (mirrors, antennas, ...): Earth scanning mirror and small Michelson moving mirror
- Accelerations/Dimensions of moment arm: TBD; Note, momentum compensation will be provided.
- Moments of Inertia (I_x, I_y, I_z): TBD

CONTAMINATION ENVIRONMENT
No special considerations. No source of contamination or radiation from GPHIS.

CALIBRATION REQUIREMENTS
Full aperture blackbody and space views.

SPECIAL CONSIDERATIONS/COMMENTS
- Location/mounting constraints: Free view for passive radiation cooler.
- Field of view restrictions: None
- How data should be handled (onboard processing, storage, downlink):
- Scan pattern/footprint (gimbal range): Variable with full Earth capability.
- Other comments: None
GAP INSTRUMENT ENVELOPE AND OPTICAL LAYOUT: OPTION 1
GAP INSTRUMENT ENVELOPE AND OPTICAL LAYOUT: OPTION 2
APPENDIX B

GAP RESPONSES TO GEO INSTRUMENT QUESTIONS
GAP RESPONSES TO GEO INSTRUMENT QUESTIONS
(Reference: Ron Koczor memo of 10/26/89)

1.1 What is the minimum size & volume allowable for each instrument? What is the minimum radiant area for the sensor cooler and thermal control louver?

The dimensions of the current baseline instrument are \((X, Y, Z) = (2.4, 0.8, 1.1)\) m. Note: These instrument dimensions do not include the local protrusions of the deployable Sun Shade (0.4 m in the Z axis, and 0.06 m in the X axis) and the Radiative Cooler (0.08 m in the Y axis). The volume is 2.1 m\(^3\). The radiation area for the detector cooler is 0.3 m\(^2\) (the field of view of the radiation cooler is 150\(^\circ\)). The area required for the thermal control louver is TBD.

1.2 Can the sensor radiant cooler, the thermal control louver and the viewing optics port be located on any surface of the instrument envelope?

The radiant cooler must have an unobstructed view to deep space in the North or South direction (along the spacecraft Y axis). The thermal control louver can be mounted on any face of the instrument (other than the mounting surface). The viewing optics port must face toward the Earth (the normal to the port is the spacecraft Z axis).

1.3 What are the instrument mounting requirements such as footprint, mounting points, etc.?

It is envisioned that the instrument plane opposite the Earth viewing plane will interface to the spacecraft. Discrete mounting feet will be provided to accommodate the spacecraft mechanical mounting interface. The instrument plane that will mount the spacecraft has the dimensions \((X, Y) = (2.4, 0.8)\) m.

1.4 What is the minimum weight and estimated CG location of each instrument?

The current weight estimate of the GAP is 195 kg. The instrument CG is TBD.

2.1 What are key "Breakpoints of Performance" as a function of other key parameters such as instrument power, weight, cost, physical size, etc? Provide parametric data where available.

Discussions of the parametric analyses that were performed on the GAP instrument are provided in the body of the Final Report.
2.2 Will the following gas products from the propellant cause contamination problems with any instrument: H2, N2, NH3, H2O, CO, CO2?

NH3, H2O, CO, and CO2 have infrared signatures that are within the sensing range of the GAP. In order to present a problem to the GAP, these gases would have to: 1) be present in such large quantities that they would reduce instrument throughput (thus reducing the signal to noise ratio); or, their quantities would have to change rapidly with respect to the period of time between instrument calibrations (one hour maximum). It is envisioned that neither of these conditions will exist and that the GAP sensitivity to all the gases listed above will be totally negligible.

2.3 Give a brief description and performance range of Image Motion Compensation, if any, including the worst allowable pointing performance from the platform.

The GAP will not use Image Motion Compensation. The maximum acceptable motion of the spacecraft is 27 μ radians/s.

2.4 Indicate occurrences of internal or external equipment motion (movement of equipment at the focal plane, slewing of antennas, etc.)

The GAP instrument will have a fully momentum compensated, two axis scan mirror at the instrument entrance aperture. There is also a Michelson interferometer travelling mirror which has a relatively small mass and velocity. This mirror will be momentum compensated if it is found to be necessary.

3.1 Show typical instrument viewing sequences/timelines? Need vernier and/or coarse scales (e.g., one typical viewing cycle and one typical orbit,, may be even one year).

Because of the great range of operational flexibility designed into the GAP (see section 4.3) there are no "typical" instrument viewing sequences that can be constructed at this time. Table 4 defines GAP coverage times that might be used to meet a variety of scientific objectives intended for it.

3.2 Show the duration and frequency of calibration, image buildup, data readout,, etc.?

The on-orbit calibration scheme is described in section 7.2. The on-orbit data processing flow (with timing budget) is described in section 8.2 and 8.4.

3.3 Show periods when instruments are inoperable (e.g. on the dark side of the Earth).

The GAP will be operating at all times.
4.1 What are the life-critical or reliability-critical elements of the instrument?

The body of the Phase A Final Report contains a detailed discussion of what are traditionally considered the life-critical or reliability-critical elements of the GAP instrument. At this time we envision no life-critical elements for the GAP instrument.

4.2 Can you power-manage your instruments to avoid the requirement of continuous power?

The GAP will be operating at all times in the same power mode; thus, it will essentially require a constant level of power.

4.3 What is the present status of key technologies related to the instrument? What are estimated development times and costs before flight readiness of key technologies?

With the exception of magnetic bearings for the interferometer traveling mirror, no new technologies are required for the GAP instrument. All of the technologies required (except for magnetic bearings) have been adequately demonstrated in spaceflight programs (or, in soon to be launched spaceflight programs).

To date, magnetic bearings have been applied to robots, multidegree-of-freedom fine positioners, high speed rotors, turbo-molecular pumps, satellite attitude control flywheels and to many other demanding applications. Recent work at Santa Barbara Research Center and at the University of California at Santa Barbara has concentrated on magnetic bearing designs suitable for space based sensor mechanisms. Their work yielded a magnetic bearing design with low power and weight. It is described in a soon to be published paper titled "Magnetic Bearing Experiment System Model and Control" by Daryl Schmidt and Brad Paden.

4.4 What on-board data compression or processing can be done? What type and how much data is needed real time vs. later, and at what location(s)?

The on-board Numerical Filtering and Fourier Transformation provide data compression yielding the data rates given in section 8. Further compression of the spectral data is possible if future spacecraft designs require significantly lower rates. The scheduling requirements for GAP data will depend on the overall objectives of the ESGP mission as defined by the science team. If desired, it is possible to provide all of the GAP data in real time.
APPENDIX C

UW RESPONSE TO QUESTIONS ON THE
DRAFT VERSION OF THE GAP FINAL REPORT
Questions from Vernon Keller:

1. The discussion on the use of clouds to enhance vertical resolution, Figure 2 (pg. 6), seems to assume a "thin" cloud layer. How does one accurately determine the height and thickness of the clouds (or is this necessary)?

The use of clouds to enhance vertical resolution assumes only knowledge of cloud opacity and cloud top altitude. Techniques for obtaining estimates of these quantities have been developed at the University of Wisconsin-Madison using high spectral resolution data ["On Cloud Altitude Determinations from High Resolution Interferometer Sounder (HIS) Observations" by W. L. Smith and R. Frey; Journal of Applied Meteorology, Vol. 29, No. 7, July 1990].

2. This report appears incorrectly to use geostationary and geosynchronous interchangeably (pgs. i [3 times], ii, 2 [3 times], 5, 6, 14, 21 [2 times], 28 [2 times]).

In the final report, the term geosynchronous (which occurs several times as specified in the question) is replaced with the term geostationary.

3. What is OPD? (pg. 26)

OPD is an acronym for Optical Path Difference. This is the difference in length between the two optical paths that light travels in the two legs of a Michelson interferometer.

4. What is the optimum detector temperature? i.e., 85 °K (pg. 27) or colder? What temperature can reasonably be achieved with passive radiators? (See pgs. 37 and 39)

It is felt that scaling-up the size of the standard VAS type passive radiative cooler could provide detector temperatures of 85 K. Detectors at this temperature will insure that the GAP scientific objectives will be met. Extra cooling capacity (from an active Stirling cooler, for example) would mainly improve the performance in the longest wavelength band where detector performance could be improved because the NEN is temperature limited.
5. "The optical elements would be supported on an internal optical bench rather than using the box for support." (pg. 30) Does this imply some internal three point mount?

Yes, the GAP optical bench would have to be kinematically mounted in order prevent thermal distortions from coupling into the optical bench.

6. What are the requirements (power, single frequency stability, size, ...) for the laser? (pg. 27 and 31)

The key laser requirements are listed below. Several candidate Diode-Pumped Solid-State Laser systems that meet these requirements are currently available (or are in the process of being developed).

- Laser Power: 2mW average power (continuous wave operation). (Input electrical power including the servo system less than 250 mW.)
- Optical Wavelength: 1.06μ
- Single Frequency Stability: 0.3gHz over a period of 2 hours.
- Intensity Variation: Less than 5%.
- Weight: less than 0.4 lb (excluding power supply)

7. As presently configured (Fig. 14, pg. 32) this instrument would be very difficult to accommodate on the MSFC inhouse geoplatform concept. Could the optics be modified to move the detector radiative cooler to the +X end of the box and the thermal louvers to the -X end of the box? (This option does not seem to appear in the discussion - pg. 33.)

The current version of the Final Report contains instrument configuration options that are compatible with the MSFC in-house geoplatform concept.

8. Pg. 42 says the downlink data rate is 2.5 Mbps for interferometric data and 0.80 Mbps if the option to perform on-board processing to spectra is chosen. (Also see pg. 48). Pg. A2 says data rate is 1.5 Mbps. Why the discrepancy?

The essential difference between 0.8 and 1.5 mbps is whether complex spectra (1.5) or magnitude spectra (0.8) comprise the downlink data stream.

9. What are the two most critical areas requiring further study?

The most important next step in the GAP study is to proceed with a more detailed design of all the major subsystems of the instrument. This will result in a better definition of the following subsystems: optics, detectors, interferometer, mechanisms, electronics, signal processing, radiative cooler, and sunshade. As part of the design process there will be several science/engineering trade-offs considered. Advancing the GAP design will allow more refined weight and power estimates.
10 The pointing requirements as we understand them are:

- **accuracy:** \( N/A \)
- **knowledge:**
  - \( 10 \text{ km (58 arcsec) real time} \)
  - \( 2 \text{ km (12 arcsec) post flight} \)
- **pointing stability:**
  - \( 1 \text{ km/sec (5.8 arcsec/sec) (pg. A3)} \)
  - \( 27 \mu\text{radians/sec (5.5 arcsec/sec) (pg. B2)} \)

Is our understanding correct?

In general, yes. For consistency the 27 \( \mu\text{radians} \) should be 28 \( \mu\text{radians} \).

**Questions from Travis E. Dawson, Jr.**

1. **Provide "time-line" of accelerations/velocities/positions of moving parts.**

Because the GAP instrument design is very preliminary, this type of detailed quantitative information is not currently available. However, the GAP instrument plans to use momentum compensation for all of its moving parts. The level of compensation provided can be tailored to the needs of the spacecraft. In other words, the GAP moving parts can be "tuned" to whatever degree necessary to insure that the level of uncompensated momentum is below virtually any desired spacecraft threshold.

2. **Provide mass, moments of inertia, and kinematics for moving parts.**

Same answer as number 1 above.

3. **What is the pointing accuracy requirement?**

The GAP instrument pointing requirements are defined in Appendix A. Pointing accuracy is not critical given that there is knowledge of pointing to within 10 km (58 arcsec).

4. **Is pointing stability requirement based on a 1 sec time period, or is this number "normalized" to one second? Prefer numerical accuracy over numerical time period. Example: 20 \( \mu\text{rad}/40 \text{ sec}, \) NOT 0.5 \( \mu\text{rad/sec}. \)**

The nominal dwell time is 1 second, thus the specified rate is "un-normalized."
Question from Dale Strider:

1. Figure 12, page 29 (also Figure 14, page 32). Does the GAP have a radiative cooler on the side of the experiment box? This is not compatible with our present configuration. This issue is also addressed at the top of page 33. Need to be coordinated with Gene Comer.

See response to Vernon Keller's question (7).

Questions from Gene Comer:

1. The configuration as shown on F16, 14, page 32, is not compatible with our platform. However, the proposed change on pg. 33 to move the radiative cooler to the small end and rotate the instrument +/-90 deg. about the Z-axis would be compatible with our platform.

See response to Vernon Keller's question (7).

2. On pg. 31, the louvers have not been defined. When the radiators are defined, they should be on the small end of the instrument enclosure to be compatible with our platform.

We understand this constraint.

Questions from Mike Davis:

1. A stupid question. What is the relationship between wavelength (in microns) and wavenumber (given as cm⁻¹)?

[1 micron] = 10,000/[cm⁻¹]. One over the wavenumber is the wavelength in centimeters.

2. Page 30 states a preference for colder temperatures than the 85K for 15 and 4.2 micron studies. How much colder or is it better said that the colder you get the better the data?

See response to Vernon Keller's question (4).

3. LMSC also may find it difficult for many SIs with the GAP configuration of long axis oriented along the X-axis. What is the impact on GAP design if the instrument is mounted to the platform such that the instrument X-axis is pointed to the Earth?

See response to Vernon Keller's question (7).
4. On page 41 mention is made in Section 7.2 of the mirror scan sequence. What is the operational sequence for GAP as a function of time? The operational sequence for the instrument as a function of time will be determined in follow-up studies.

5. Given the overall downward trend in total platform instrument data rates, there will probably be no major impact on the platform data system if GAP data rate is 2.5 mbps or 0.8 mbps. Good.

6. What are the electrical power and mass properties budgets of the GAP? Because the GAP instrument design is very preliminary, this type of detailed quantitative information in not currently available. The total power and mass estimates that appear in Appendix A, were scaled on the instrument level from past experience. These estimates were not built up from the subcomponent level.

7. Section 10.0 on page 49 discusses lifetime goal of 10 years. Given that MSFC stated in the kickoff a platform design life of 7 to 10 years, are there any impacts on GAP mass, power or size if GAP life is reduced from 10 to 7 years?

A three year reduction from 10 to 7 year lifetime would not fundamentally change the technology required for the GAP instrument. Also the GAP instrument uses no consumables. Therefore, the reduction in lifetime would have little if any impact on mass, power, or size.

8. Note that on page 49 section 9.4 that MIMS is now GMPR and GMODIS is now GEPS. These changes are so noted.

9. Does GAP impose any pointing accuracy requirements on the platform? None are given.

Same answer as for question (3) by Travis Dawson.

10. If GAP integration time is selectable, then what drives the stability requirement of 1 km/sec? Is one second the longest integration time? Stability is required during the period of interferometer scans. The longest integration time is one second.