The Millimeter Wave Atmospheric Sounder (MAS): A Shuttle-Based Remote Sensing Experiment

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Abstract—**The Millimeter Wave Atmospheric Sounder (MAS) will be launched by the Space Shuttle in the spring of 1992 as part of the ATLAS 1 (ATmospheric Laboratory for Application and Science) mission. Using passive limb-scanning millimeter wave radiometry, it will sense the thermal emission produced by ozone at 184 GHz, water vapor at 183 GHz, chlorine monoxide at 204 GHz, and oxygen (for retrieval of temperature and pressure) at 60 GHz. From these observations, concentration profiles of these gases throughout the middle atmosphere will be made. This paper describes the fundamentals of the measurements, the design of the radiometers, and the approaches used for the data analysis.**

I. Introduction

THE ATMOSPHERE is a thin gas cover that is essential to life on Earth. Studies indicate that changes in the chemical makeup of the atmosphere are taking place that may alter climate and weather and also affect the ability of the atmosphere to absorb the sun's harmful ultraviolet rays. Although we know how the atmosphere affects our life on Earth, we don't know enough about the way natural processes, human activities, and their interactions are affecting the atmosphere and its protective capabilities. We must develop a fundamental understanding of the atmosphere and assess the extent to which changes are taking place within it. In the process of its evolution, the chemical makeup of the atmosphere has changed considerably, with dramatic effects on life on the planet. The discovery of the large ozone depletions over Antarctica in austral spring (the Antarctic ozone hole) has demonstrated conclusively that the releases of chlorine and nitrogen compounds into the atmosphere, as a result of human activity, can cause catastrophic depletions of stratospheric ozone.

The process of ozone change in the stratosphere involves whole families of nitrogen, hydrogen, and chlorine atoms and compounds, as well as other chemically active trace species. The origin of these species, particularly their manmade sources, and their effects on the upper atmosphere have become the objects of intensive research in the last few years. The most effective means for gathering comprehensive long-term data on the upper atmosphere is the use of remote-sensing instruments located both on the ground and in space. Current technology can provide us with such instruments to measure, with high precision, ozone, other chemical species, solar radiation, the temperature, and the dynamics of the upper atmosphere on a global scale, continuously for several years.

The Millimeter Wave Atmospheric Sounder (MAS) is one such instrument. It uses the technique of passive radiometry to sense the mm-wave radiation originating from the atmospheric limb in the 20–90 km height range. This altitude range, consisting of the stratosphere and mesosphere, is also known as the middle atmosphere. The thermal emissions sensed are functions of the atmospheric composition, temperature, and pressure. The MAS will provide global information on temperature and ozone (O_3) and also on water vapor (H_2O) and chlorine monoxide (ClO), two trace molecules which play an important role in the photochemistry of ozone. The MAS is scheduled to fly as part of the ATLAS (ATmospheric Laboratory for Application and Science) missions that will contain many earth-sensing experiments, which will be located on the Space Lab pallet and operated from the cargo bay of the Space Shuttle. The MAS instrument is similar to the Microwave Limb Sounder (MLS) [1], which was launched in September, 1991 as part of the UARS satellite. The MLS will provide continuous global coverage of the same species that are observed by the MAS for the duration of the UARS mission, that is expected to be a minimum of 18 months. The MAS discussed here is one of the instruments of the ATLAS missions which are designed to monitor the sun and the earth-atmosphere system through

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periodic snapshots at approximately yearly intervals over a 11-year period (one solar cycle). These periodic observations of the earth's atmosphere will provide important continuity betwen the intensive measurement programs of UARS and the follow-on Earth Observing System satellites.

II. Experiment Goals

A. Middle Atmosphere Photochemistry

The MAS experiment is designed to observe the ozone-related photochemistry and composition of the middle atmosphere. Ozone is created by a 3-body reaction: $O + O_2 + M \rightarrow O_3 + M$. Trace constituents in the atmosphere, such as members of the chlorine, nitrogen, and hydrogen families, control the destruction of ozone via catalytic cycles. These trace radicals are produced by the photolysis of source molecules, which are themselves transported into the stratosphere and mesosphere. Improvement of current models is severely hampered by the lack of data specifying the amounts and distributions of these trace gases. The need for new measurements has been made more acute by the increasing realization that the chlorine molecules which catalytically destroy ozone are also important greenhouse gases. Global warming of the lower atmosphere, caused by the increasing amount of anthropogenic greenhouse gases in the atmosphere, is expected to be accompanied by cooling of the middle atmosphere. This temperature change will alter photochemical activity, perturbing the ozone distribution and the radiative balance, and result in changes in the middle atmosphere wind systems which may, in turn, impact upon climate at the surface. Thus, ozone and global warming are intimately linked through a network of intricate processes. There is strong theoretical evidence that the middle atmosphere is a sensitive detector of global warming and may provide early warnings of global change. In the following sections we summarize the observations made by the MAS and their implications on the photochemistry of the middle atmosphere.

B. Ozone

Ozone is important because of its effect of shielding the biosphere from harmful ultraviolet radiation. Its role in the absorption of solar radiation and the absorption and emission of infrared radiation is crucial in the determination of the stratospheric and mesospheric temperature structure. Ozone thus directly influences the stratospheric winds and wave motions. Furthermore, because of its relatively long chemical lifetime in the stratosphere, O_3 can also be used as a tracer of atmospheric motions. (Water vapor can also serve as such a tracer up through the mesosphere.) Work on the photochemistry of ozone [2] shows that, even though O_3 has been much studied, there remain many important uncertainties in the chemistry of the region.

C. Water Vapor

Current theories of ozone consider its interaction with a large number of other molecules. H_2O and its chemical products are among the more important of these. The lower stratospheric water vapor data base is quite large, extending back 25 years, and consists mainly of balloon-borne measurements. In addition, stratospheric water vapor was observed on a continuous basis from October 1978 until May 1979 as part of the LIMS (Limb Infrared Monitor of the Stratosphere) Nimbus 7 satellite experiment [3]. Generally, these stratospheric measurements are fairly consistent with the conventional wisdom regarding middle atmospheric water vapor.

However, the situation is somewhat different in the mesosphere. The data base is much more sparse and consists predominantly of microwave measurements [4], [5]. There are several aspects of these observations that are not completely understood in light of current photochemical theories. Perhaps the most significant of these is that the observations consistently indicate a far steeper water vapor mixing ratio gradient with height above 65 km than can be expected from the current understanding of vertical transport time scales and photodissociation rates. Also, the measurements occasionally show a water vapor mixing ratio increase with height of greater than 2 ppmv between 50 and 65 km that cannot be reproduced in photochemical model calculations. In addition, observed seasonal variations of H_2O mixing ratios in the upper mesosphere appear to be inconsistent with those of ozone [2]. If these features of the mesospheric water vapor profile are verified by subsequent systematic measurements, they would indicate fundamental flaws in our understanding of the processes important in controlling the distribution of water vapor in the middle atmosphere.

D. Chlorine Monoxide

The chlorofluoromethanes (CFM's) and related chemicals that produce chlorine radicals such as ClO in the stratosphere are deleterious to the ozone layer. The uncertainty both in understanding and in modelling these effects is such that prediction of the steady state depletion of ozone by CFM's may be unknown by a factor of two, due to the crude treatment of transport alone.

ClO has been measured *in situ* through chlorine atom fluorescence [6], [7] (and the references therein). Millimeter wave observations of ClO have been made from both balloon-borne packages [8], [9] and from the ground [10], [11]. To date these measurements sets have been obtained at only a few locations and seasons. Clearly, simultaneous global data sets of O_3 and ClO will be the key to finding an answer to this important question of anthropogenic influences on the ozone layer.

E. Temperature and Pressure

Temperature can also be measured by microwave remote sensing [12] and is important for many reasons.

From temperature and pressure data, the distribution of the geostrophic wind can be determined, which is a close approximation to the prevailing wind at stratospheric levels outside the tropics. Many important chemical reactions, such as ozone photochemistry, are highly temperature dependent, so the temperature must be known before chemical production and loss rates of several stratospheric constituents can be determined. The stratospheric temperature field is also important for determining the exchange of infrared radiation with the troposphere below, with the atmospheric regions above, and with space. Moreover, changes in stratospheric temperature have been linked to several aspects of global change.

One of the observed oxygen lines is used for the measurement of the temperature. Two additional observed oxygen lines are temperature insensitive and are used for retrieval of the pressure height. In addition, pressure information is contained within the line-broadening signatures of the ozone and water vapor lines that are observed.

F. Dynamics

Differential heating of the middle atmosphere occurs through solar UV absorption by ozone. Wind fields result that in turn may change the ozone distribution and consequently the temperature field. Such temperature changes again modify the ozone distribution, thus leading to feedback effects on the wind field, especially at heights where photochemistry dominates the ozone distribution. In the stratosphere, chemical composition depends critically on transport by winds and diffusion. Planetary and gravity waves greatly influence momentum transfer, sudden warmings, wave-mean flow interactions, and middle atmosphere circulation. Global data sets, as anticipated from the MAS, are useful in revealing the underlying atmospheric dynamics.

G. Global Coverage

Frequently in photochemical models of the stratosphere and mesosphere, the effects of atmospheric motions are parameterized by using a vertical eddy diffusion coefficient to effectively create a one-dimensional model. Reducing the complex three-dimensional interplay of motions and trace constituents to simple budget equations for vertical profiles of various constituents will in effect produce averages over both geographical and seasonal distributions.

Such averaging introduces considerable uncertainty both in the results themselves and in the predictions made with such models. In the absence of proper three-dimensional observations, there may be a tendency to over-interpret local vertical profiles in validation of one-dimensional models. Global observations are of paramount importance in establishing a data base for validating results from both one-dimensional and multi-dimensional photochemical models.

H. Periodic Calibration

Global measurements are most conveniently made from orbiting platforms. Intercomparison of separate ground-based measurement systems requires careful cross-calibrations of the instruments. Uncertainties are reduced if the same instrument is moved from location to location, but the time required to move a ground-based instrument from one location to another introduces the uncertainty of time variability in the global measurements. Space-based measurements provide global coverage by the same instrument over relatively short time intervals so that a truly global ''snapshot'' image of the atmospheric condition can be obtained.

However, it is also known that long-term drifts in the calibration of orbiting measurement systems can also introduce uncertainties in the measurements as well, although microwave measurements from space have shown very good long-term stability [13]. Even if long-term calibration drifts were to occur in the MAS, checks of the calibration of the instrument between flights will be possible. The possibility for ground-based checkout, calibration, and equipment upgrade is a particular advantage of the ATLAS series (of which the MAS is a part) and allows long-term (11-year) observation programs to be considered.

I. MAS Data Products

The MAS experiment science goals include 1) a survey of the ClO zonal average distribution in the stratosphere, including altitude profiles in the 20-40 km altitude range, to provide some understanding of the latitudinal and altitudinal distributions of this chemically active species; 2) a survey of global altitude profiles of O_3 and H_2O in the stratosphere; 3) a survey of global altitude profiles of O_3 and H_2O in the mesosphere; 4) a survey of global altitude temperature profile in the stratosphere and lower mesosphere; and 5) a search for evidence of gravity wave activity at altitudes 50–80 km. The exact altitude range and expected accuracy of each of the measurement goals depends upon the molecular species observed and the length of observation.

The intrinsic variance associated with any radiometric measurement performed over a finite length of observation time affects the accuracy of the retrieved profiles. While longer integration times reduce the variances, they also introduce temporal and/or spatial smoothing because of the moving observation platform. It is well known that the variance of a radiometric measurement also depends inversely on the square root of the observation bandwidth. Fine resolution spectral analysis must be made to obtain retrievals at the highest altitudes. Thus longer observation periods are needed for the topmost altitudes, while much shorter integration times are possible at the lowest altitudes. In Table I we have summarized each atmospheric constituent or parameter that the MAS will observe, along with a rough estimate of the accuracy of the measurement

TABLE I
EXPECTED DATA PRODUCTS FROM THE MAS

Constituent or Parameter	Frequency (GHz)	Height (km)	Estimated Accuracy	Integration Time (sec)
Kinetic temperature (O_2)	61.151	70	2 K	10
		25	2 K	2
Pressure (O_2)	62.998	55	1%	2
	63.568	25	1%	2
Water vapor H_2O	183.310	90	0.2 ppmV	100
		20	0.2 ppmV	2
Ozone (O_3)	184.370	90	0.2 ppmV	100
		20	0.2 ppmV	2
Chlorine monoxide ClO	204.352	45	0.2 ppbV	100
		30	0.1 ppbV	100

for the corresponding integration times. Between 20 and 70 km, the height resolution is expected to be about 3 km for H_2O and O_3 with a grid measurement size of about 1000 km by 1000 km. Because the ClO line is much weaker, longer integration times will be needed. As a result, only zonal averages at 10° latitude intervals and for 4 km height resolution may be obtained.

Since the longer integration times produce more spatial averaging, we expect that several types of gridded data will eventually become available from the MAS observations. Coarser grids will result in greater accuracy but have a larger "smeared" measurement volume. The error estimates shown in Table I reflect the information available from only the MAS. Intercomparison with other experiments aboard the ATLAS mission will strengthen the scientific results.

III. ORBITAL PARAMETERS

The MAS limb scanning observations may be made continuously during both daytime and nighttime, using the millimeter wave emission for the various gas constituents. However, observation times for the MAS are reduced somewhat by the need for MAS-incompatible flight attitudes of the Shuttle to accommodate the other experiments of the ATLAS mission.

The nominal altitude of the Shuttle during the ATLAS 1 mission is expected to be 300 km, although this may vary on future missions. The side-viewing design of the limb-scanning antenna of the MAS results in observations over a larger range of latitudes than would be expected from the 57° orbit inclination of ATLAS 1. While the exact latitude limits depend upon the tangent height altitude, the nominal measurement extends to either 70 N or 70 S, depending upon the Shuttle pointing attitude. The flight duration of each ATLAS mission will be either seven or nine days, depending upon the particular orbiter that is used. However, post-launch and pre-landing activities reduce the actual ATLAS observation period by about two days. Pre-launch mission planning determines the best compromises between the conflicting Shuttle attitude requirements. The MAS observation time is not a continuous block but will be broken up into many short time segments. The timeline analysis of the ATLAS flight activities has undergone several revisions, but we presently expect to obtain about 74 hours of limb-scanning observation time during the ATLAS 1 mission. Detailed plots of the antenna footprint during MAS observation times show that nearly complete global coverage will be obtained during a seven-day mission.

IV. MILLIMETER WAVE RADIOMETRY

The MAS instrument consists of a stable millimeter wave receiver and spectral analysis system which are used to measure the thermal emission of several gaseous constituents of the atmosphere. The molecular structure of these constituents results in frequency-dependent absorption and emission characteristics that can be used to uniquely identify each type. The rotational lines of ozone, water vapor, and chlorine monoxide are well separated from one another in the 180 to 204 GHz band. The incident emission intensity, I_ν, can be related to the noise power observed by the radiometer through the expression

$$\mathrm{BT} = (c^2/2k\nu^2)I_\nu \tag{1}$$

where c is the speed of light, k is Boltzmann's constant, and BT is the Rayleigh–Jeans temperature or brightness temperature. Profiles of the constituent as a function of altitude can be derived from the frequency dependence of this observed brightness temperature.

The MAS will sense the 184.37 GHz line of ozone, the 183.31 GHz line of water vapor, and the 204.35 GHz multiplet line of chlorine monoxide, all of which have been previously observed [8], [14]. The spectral lines are broadened by both pressure and temperature, with the pressure effects predominating below about 70 km. Collisional or pressure broadening within each emitting or absorbing layer contributes pressure altitude information to the received atmospheric radiance. The radiative transfer equation [15] for the MAS limb scanning geometry can be expressed as follows:

$$\mathrm{BT}_{AP} = \mathrm{BT}_{\mathrm{BACK}} \times e^{-\tau(-\infty,\infty,\nu)} + \int_{-\infty}^{+\infty} \mathrm{BT}(s) \times e^{-\tau(-\infty,s,\nu)} \times K(s,\nu)ds \tag{2}$$

where $\mathrm{BT}_{\mathrm{back}}$ is the apparent brightness temperature from the interstellar cosmic background and $\mathrm{BT}(s)$ is the brightness temperature due to the gas at position s. Often at atmospheric temperatures and lower microwave frequencies, the brightness temperature can be replaced by the physical temperature. $K(s, \nu)$ is the frequency-dependent species absorption coefficient, which is defined below and depends upon the molecular concentration at position s, the temperature, and the absorption cross-section for the gas; s is the position along the tangent path.

The radiation emitted by each species at each position s is attenuated by the intervening atmosphere between s

and the radiometer, which is located external to the atmosphere. This attenuation is included in the radiative transfer expression by the $\tau(-\infty, s, \nu)$ term. The attenuation in the atmosphere occurs not only from the self-absorption of the particular gas constituent but also from the absorption of the radiation by the other gases present in the path.

$$\tau(-\infty, s, \nu) = \int_{-\infty}^{s} K(s', \nu)\, ds' \tag{3}$$

and

$$K(s', \nu) = \sum_i n_i(s') \times \sigma_i(s', \nu) \tag{4}$$

where $n_i(s)$ is the molecular concentration for each gas species that has an appreciable cross section at the frequency of interest and $\sigma_i(s, \nu)$ is its absorption cross section.

The MAS experiment also measures a band of spin rotational lines near 60 GHz from molecular oxygen. Since oxygen is well mixed throughout the middle atmosphere, observation of several of the oxygen fine structure lines (61.151 GHz, 62.998 GHz, and 63.568 GHz) provides a means of measuring the atmospheric temperature and pressure.

V. HARDWARE DESCRIPTION

A. *Limb Scanning*

Limb scanning is a technique by which the atmospheric limb is observed at many different tangent heights, producing separate multiple ray paths. It is used by the MAS to obtain a finer altitude resolution than would be possible if only a single ray path through the atmosphere were used [16]. The MAS uses a one-meter, offset Cassegrain antenna for all three frequency measurement bands [17]. Several different pointing modes can be commanded from the ground-support equipment. Most of the data will be acquired in a scanning mode, which lasts 12.8 sec. The scan cycle begins with a cold space calibration at a tangent height of 130 km. The antenna is then rapidly slewed to a tangent altitude of 82 km. The limb scan then proceeds linearly down to a nominal tangent height altitude of 10 km. A hot-load calibration is performed for 1.6 seconds in this position by moving a small mirror into the antenna beam and thereby looking into a microwave blackbody with an accurately monitored temperature. The scan then retraces to the 82 km tangent height followed by a fast slew to the cold calibration position at 130 km position, which is then held for 1.6 sec before the limb scan repeats. This scan range requires an antenna movement of about 4 degrees (depending on the orbit altitude). The total slewing range is 13 degrees, allowing an adjustment of up to 4.5 degrees on either side for the actual scan range to compensate for roll attitude deviations.

During the flight, Guidance, and Navigation Control (G&NC) information and Horizon Sensor data is passed from the Shuttle to the onboard computer of the MAS (discussed below). This information is used to determine the exact scan angles. A resolver located at the rotary bearing points (Fig. 1) determines the relative antenna position to a resolution of 0.0013°. The overall positioning accuracy of the antenna beam relative to the cargo bay is affected by thermal distortion of the cargo bay and initial misalignment. The Horizon Sensor of the Shuttle has an error of about 0.1° in its fine range, which would result in a vertical uncertainty of 2.5–3.0 km. Of course the MAS observations themselves contain the actual pressure altitude information of each measurement through the pressure broadening of the emission lines. Also, observations of both temperature-sensitive and temperature-insensitive oxygen lines allow temperature and pressure to be measured and, thereby, the determination of pointing altitudes (to vertical precision of the order of 0.5 km), independent of the Shuttle pointing information.

In the 200 GHz band the one-meter diameter of the main reflector produces a beamwidth of about 0.1° [18]. Because of the longer wavelength at 60 GHz, the antenna beamwidth would be expected to broaden to about 0.32°. Through careful simulation studies, we have determined that the 60 GHz resolution can be improved in the scan mode by a factor of three through use of the known antenna directivity and a deconvolution algorithm [19], [20]. After processing the data through the inversion of the radiative transfer equation, we expect to obtain a vertical data resolution of 3 km. As successive scans are made, a data sampling footprint of about 50 km by 200 km is obtained [21]. The line strength of chlorine monoxide is so weak that longer integration times will be required at each altitude than can be obtained through limb scanning. Thus for part of the flight, a "pointing mode" will be used that sacrifices spatial resolution for longer integration times. In this pointing mode, the antenna slews rapidly to a fixed tangent height (for example, 30 km). After 9.6 sec it returns to the cold calibration position for 3.2 sec, completing the 12.8-sec cycle.

The reflector is moved from one position to another by a linear actuator that uses an electronically commutated brushless dc motor. The maximum slew rate of the reflector position is 5.5°/sec. The linear actuator also includes a device to lock the antenna in a fixed position during lift-off and landing. As can be seen in Fig. 1, the MAS receiving electronics are also included in the moving portion of the scanning assembly. A quasi-optics arrangement for three feed-horn antennas are used [17]. The 60 GHz band antenna is placed directly at the antenna focus. A polarizing grid located in front of this horn reflects a portion of the incoming radiation to the two higher-frequency (184 GHz and 204 GHz) feed horns, which are placed side by side (and thus slightly off the focus position). The feed horns are balanced with equal E- and H-plane patterns. The incoming radiation is down converted in the following mixer stages, which are also part of the MAS receiving electronics.

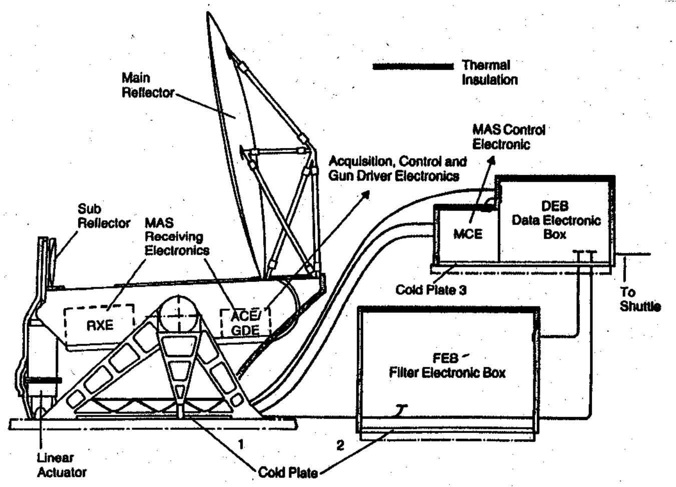

Fig. 1. Configuration of the Millimeter Wave Atmospheric Sounder (MAS).

B. Frontend Electronics

Three separate electronic packages are included in the receiver electronics unit. The first package contains the balanced Schottky diode mixers and frequency diplexers that produce five different IF signals that are in the 1.0-GHz to 5.5-GHz range (Fig. 2). The noise temperatures are about 1000°K for the 60 GHz receiver and 2000°K (double sideband) for the two higher-frequency bands. A second package contains the phase-locked Gunn oscillators that drive each mixer. These local oscillator signals sub-harmonically drive the corresponding mixer at a frequency of one half the final operating frequency. The third receiving electronics package is the acquisition and control electronics unit that controls the functions of the Gunn oscillator phase-lock loops, the amplifiers, and the hot target mirror. The five output IF signals from the mixers are carried by flexible couplings from the movable sensor package to the Filter Electronics Box, where spectral analysis is performed.

C. Filter Electronics Box

Each of the five IF signals is amplified in the Filter Electronics Box and directed through programmable attenuators that can be adjusted by ground commands during the flight. Six separate frequency synthesizers drive mixer stages for additional down-conversion to lower IF frequencies. The exact synthesizer frequencies are setable through ground-based commands. This frequency adjustment permits compensation for Doppler shifts in the apparent molecular line center frequency. The amount of the frequency shift depends upon the motion (7.5 km/sec) of the orbiter relative to the Earth's atmosphere, the rotation of the earth, and the Shuttle's flight attitude.

The down-converted signals are next directed to six separate filter bank assemblies, each centered at 250 MHz with a 400 MHz total analysis bandwidth (Fig. 3). In each filter bank, ten wide filters (40 MHz bandwidth) each determine the wing structure of each line. Additionally, located in each bank are twenty filters of 2 MHz bandwidth that are clustered around the line center. The temperature, water vapor, and ozone filter banks each have an additional 20 filters of 0.2 MHz located near the line centers.

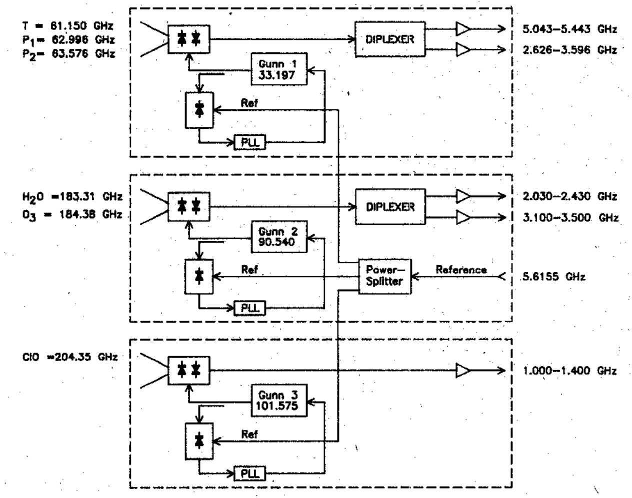

Fig. 2. Front-end receiver electronics of the MAS.

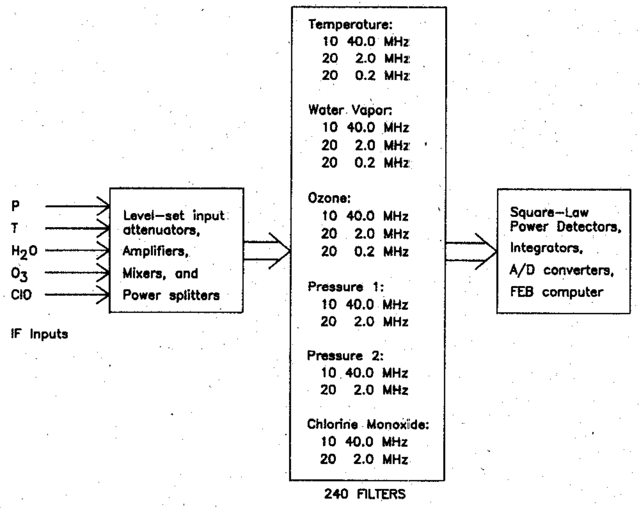

Fig. 3. Filter Electronics Box (FEB) of the MAS.

Each of the 240 filters isolates a portion of the emission spectrum, which is then measured by a square-law power detector. Short-time integration of the analog signal is provided by a lowpass filter that has an 8 millisecond time constant. Analog multiplexers are used to route subgroups of the analog signals to one of nine separate 12-bit analog-to-digital converters. Six conversions of each analog signal are performed in a 40 msec interval. A computer located within the Filter Electronics Box successively averages the six data values from each channel and assembles the resulting data words and housekeeping information into a serial data stream. An RS-422 data link transfers this information to the Data Electronics Box. Commands to adjust the input attenuators and synthesizers are also transferred by an RS-422 data link to the Filter Electronics Box from the Data Electronics Box.

D. Data Electronics Box

The Data Electronics Box contains several subassemblies that condition the data and control the experiment. One subassembly drives the linear actuator that moves the reflector and interfaces with the resolver. Another subassembly converts the incoming power from the Shuttle to the various voltages that are required by the other electronics within the MAS. A third box contains the master reference oscillator for the phase-locking of the Gunn diode oscillators.

The Data Electronics Box also includes the 16-bit CMOS microprocessor that controls all the MAS functions. It receives G&NC and Horizon sensor messages and commands from the ground support equipment through the Shuttle's Remote Acquisition Unit. This information is used by the onboard computer of the MAS to continuously calculate the required angular position of the steerable reflector so that the proper tangent heights are obtained. These position commands are then passed on to the linear actuator. The Shuttle's Remote Acquisition Unit also receives several thermistor signals so that the physical temperature of the MAS can be observed even when the MAS is powered down. The data from the Filter Electronics Box is combined with housekeeping and timing information and passed to the High Rate Multiplexer of the Shuttle at a data rate of 86.4 kbit/s.

The data streams from all the ATLAS experiments are transmitted to one of the TDRS satellites, which in turn relays them to the White Sands Missile Range ground-tracking station. The data is then relayed via DOMSAT to NASA-Marshall Space Flight Center in Huntsville, Alabama, for real-time display in the Payload Operations Control Center (POCC). If a TDRS satellite link is not available, the ATLAS data streams are recorded aboard the Shuttle for later downlink playback once a TDRS satellite becomes available again. Electrical ground-support equipment located in the POCC permits real-time display of the data from the MAS and the uploading of control commands to it.

E. Ground-Support Equipment

During the flight, ground-based support equipment located at the POCC supports the mission. Standard POCC displays can be programmed to show subassembly temperatures and currents. The MAS team will also bring to the POCC a PC-based quick-look data system whose displays can be used to observe the various housekeeping data channels as well as to monitor each filter channel's output on a bar graph display. This information can be used to adjust the attenuator settings in the Filter Electronics Box. The Doppler offset corrections for the synthesizers and the commands to change the reflector scanning mode can also be implemented from the POCC. The incoming data stream is recorded on write-once-read-many (WORM) and magneto-optic disks by the quick-look system for later off-line processing.

Another major component of electrical ground-support equipment was used during the flight hardware development and checkout before turning over the MAS to Kennedy Space Flight Center. This test equipment provided simulation signals for each subsection of the MAS, enabling verification of proper operation at each stage of processing. Also provided were simulated signals from the Shuttle's data interface. Another part of the ground-support equipment provided simulations of the Shuttle's power supply bus to verify proper MAS operation under all expected conditions.

F. Off-line Data Processing

One of the first steps in the off-line data processing is to format the data from quick-look WORM data disks (the conventional data product tapes supplied by NASA could also be used). This preprocessing will flag potentially bad data and add appropriate header records. The preprocessing will be done at the Max Planck Institute for Aeronomie in Lindau, Germany. Data reduction and interpretation of the MAS results are expected to be a group effort. A series of ongoing science data meetings has been held on both continents to coordinate the development of the instrument and to develop the data processing algorithms that will be used. Data simulations have been used to generate expected data products and explore various data inversion methods.

VI. DATA RETRIEVAL

Comparison of data simulations from the various institutions involved has helped the MAS team to refine its inversion techniques and develop a common strategy for the data reduction. Forward calculations are first performed for the ideal situation, when there is little data degradation due to equipment errors. Fig. 4 shows the line spectrum for ozone at several representative tangent heights calculated by using a climatological mean mid-latitude ozone profile. The actual observed spectra will have departures from the true value because of not only systematic effects but also the variances resulting from the short length of observation of the thermal emission. Because of this intrinsic measurement noise, inversion of the radiative transfer equation (Equation 2) is not well behaved. Several mathematical approaches have been used on such data sets in the past. The primary methods have been "onion peeling" [22], the Twomey-modified Chahine inversion technique [23], and the Twomey-Phillips constrained matrix inversion [24]. More recently the Rodgers optimal estimation technique [25] has been used quite extensively. In an effort to develop the MAS operational retrieval algorithm, we have applied all of these techniques to the MAS measurement problem. In order to evaluate their performance, we are conducting an extensive data simulation study in which the MAS forward model is used to generate synthetic spectra with various constituent profiles. Various sources of error, such as ran-

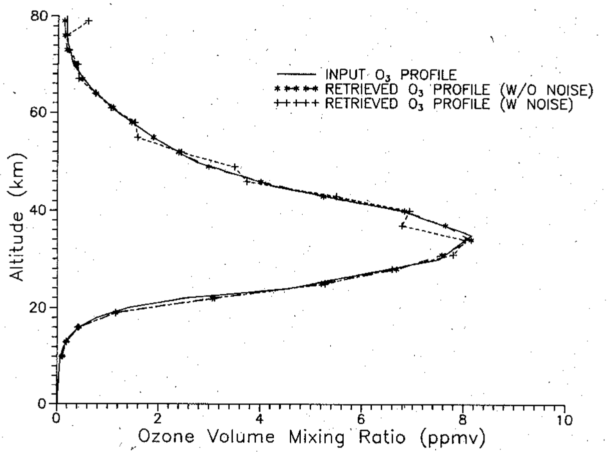

Fig. 4. Synthetic spectra for ozone at representative tangent height altitudes.

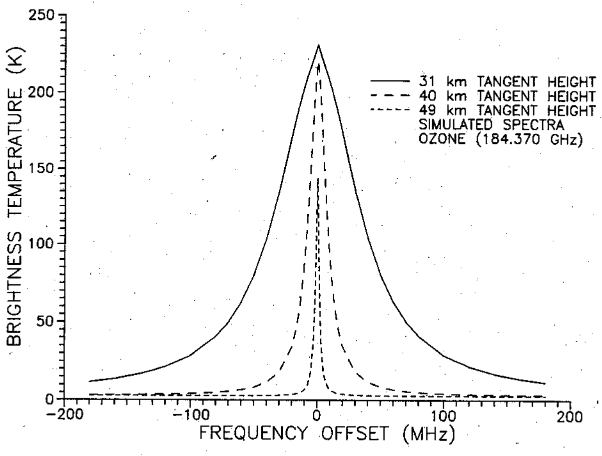

Fig. 5. Input and retrieved ozone profiles (noiseless and noisy case, integration times as indicated in Table I).

dom noise, and systematic effects, such as non-linearities in the square-law detectors and VSWR-produced baseline ripple, are then added to the synthetic spectra. The resulting spectra are then inverted with each of the candidate retrieval algorithms and the results compared with the "true" spectra. Fig. 5 shows a Chahine-based retrieval of an ozone concentration profile for both a noiseless and noisy case, along with the original profile that was used to generate the noiseless synthetic spectra. Simulation studies show that a similar inversion process for ClO will be possible between 35 and 45 km with the longer integration times shown in Table I. Even with the longer integration times and resulting larger spatial averaging, the data retrievals for ClO are expected to be about 20% worse than those attainable for water vapor or ozone. In addition to the data simulation study, we are also in the process of applying the formal error analysis of Rodgers [26] to each of our candidate retrieval algorithms which allows us to objectively characterize the inversion techniques and quantify the retrieval errors.

VII. Flight Schedule

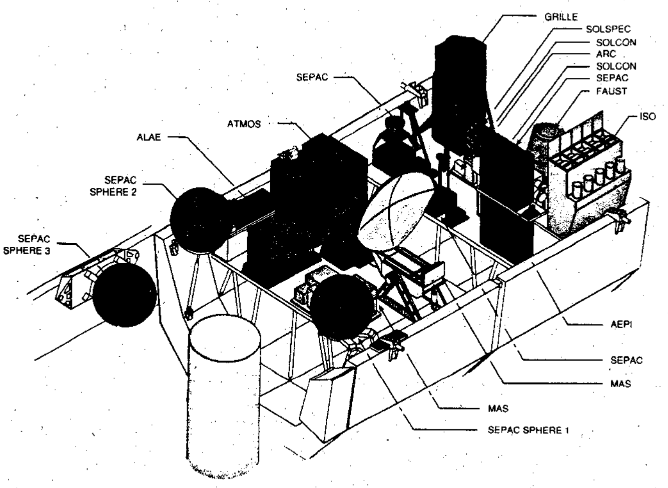

Fig. 6. ATLAS 1 experiment configuration (Courtesy of NASA).

At the time of this writing, the first ATLAS mission is now scheduled for launch in March 1992. Several of the other instruments on board the ATLAS mission will also be observing the middle atmosphere (Fig. 6). The ATmospheric Trace Molecule Spectroscopy (ATMOS) instrument uses high-resolution interferometry of infrared absorption during solar occultation to observe many different trace species of the chlorine, fluorine, and nitrogen families. In addition, it will observe water vapor and ozone in the same altitude regions observed by the MAS. The GRILLE infrared spectrometer also makes similar measurements. Photodissociation of water vapor in the upper regions of the middle atmosphere is one of the major sources of hydrogen to the region. The Atmospheric Lyman Alpha Emissions (ALAE) experiment will sense the Lyman alpha ultraviolet emissions produced by hydrogen. These measurements, combined with the MAS water vapor profiles, contain important information about the hydrogen budget of the earth. Another instrument, the Imaging Spectrometric Observatory (ISO), will observe ultraviolet, visible, and near-infrared airglow emissions to help determine atmosphere composition and chemistry.

Because the composition of the middle atmosphere is, to a large extent, solar driven, the solar physics measurements of the ATLAS mission will also be important for our understanding of the MAS observations. The Active Cavity Radiometer (ACR) will measure the solar irradiance, as will the SOLar CONstant (SOLCON) and the SOLar SPECtrum measurement (SOLSPEC).

The wide range of atmospheric measurements made at the same time during the ATLAS missions makes possible many correlative studies. Correlative studies will also be possible with the data from the UARS satellite, which was launched in September 1991. Of the many measurements performed by the UARS experiments, those of the Microwave Limb Sounder (MLS) are the most directly comparable to data from the MAS. The MLS uses limb sounding in the same frequency bands as the MAS to observe water vapor, ozone, and chlorine monoxide [1], [27]. Comparisons of both the MLS and MAS data sets with ground-based measurements such as those obtained in the UARS Correlative Measurements Program will also be very useful.

The MAS is also expected to be part of the ATLAS 2 and ATLAS 3 follow-on missions on a yearly basis. The ATLAS series of flights is envisioned to last more than a decade, so that solar cycle dependencies can be determined. Comparisons of the MAS results with data from the Earth Observing System satellites in the latter half of the 1990's should thus be possible.

VIII. SUMMARY

The Millimeter Wave Atmospheric Sounder, located in the cargo bay of the Space Shuttle, will use limb-scanning microwave radiometry techniques to determine ozone, water vapor, chlorine monoxide, temperature, and pressure profiles throughout the middle atmosphere. Rotational emission lines in the 60 GHz, 184 GHz, and 204 GHz regions are used for the observations. Vertical volume mixing ratio profiles are determined by the limb-scanning technique and the pressure dependence of the spectral line shapes of these emissions. Scanning of the Earth's limb is performed by a one-meter diameter dish. The incoming radiation is split into three receiver bands. Phase-locked Gunn diode oscillators subharmonicaly pump the Schottky diode mixers to produce IF frequencies in the 1 to 5.5 GHz range. Five separate IF frequency signals are spectrally analyzed by 240 different frequency ranges. The received power in each range is measured, digitized, and transmitted to the ground through the high-rate multiplexer system of the Shuttle. A quick-look data system located on the ground records the incoming data on magneto-optic disks. The ground support equipment also permits control of the experiment during the flight. Post-flight analysis will invert the data to altitude concentration profiles on a global basis. Since the experiment will be repetitively flown as part of the ATLAS missions over many years, possible long-term trends will be observable. Experiment recalibration and refurbishment between flights will ensure the integrity of the measurements. The global data sets of ozone, water vapor, and chlorine monoxide concentrations and temperature and pressure fields of the middle atmosphere will greatly increase our understanding of the complex interactions of the region.

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The front-end receiver electronics were developed by the Institute for Applied Physics. The experiment control electronics were developed at the Max Planck Institute for Aeronomy. The Filter Electronics Box was developed by the Naval Research Laboratory and the Pennsylvania State University.

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