

Advanced Microwave Sensor Technology for Atmospheric Chemistry/Climate

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***Abstract* - This paper is a progress report on a NASA Earth Science Technology Office (ESTO) task to generate a ‘technology roadmap’ for developments that can substantially benefit future missions with microwave observations of atmospheric chemistry and climate. Although microwave techniques have reached high maturity for stratospheric chemistry observations and been applied to climate research, they have not yet been developed for tropospheric chemistry - an important emerging area of global change research. Technology developments are identified that can enable microwave techniques to be used for tropospheric chemistry. They include cooled radiometers that can provide ~100x improvement in sensitivity over current instruments and a novel antenna system that greatly improves microwave limb sounding spatial resolution. These developments will also greatly improve our capability for stratospheric chemistry and climate research measurements.**

I. Introduction

It is well recognized that ‘human activity is now powerful enough to begin to affect our planet’ [1]. A prime example is anthropogenic effects on stratospheric chemistry

that lead to global depletion of our protective ozone layer and the Antarctic ozone hole [e.g., 2]. Tropospheric ozone and related trace gases have also been perturbed significantly and are likely to have modified the atmospheric oxidizing capacity (affecting the ability of air to ‘cleanse itself’) and contributed to climate change [e.g., 3, 4]. Anthropogenic effects on climate due to greenhouse gas increases [e.g., 5] are also, of course, a very important - but very difficult to quantify - global change issue.

Microwave remote sensing of Earth’s atmosphere [e.g., 6, 7] is an important method of obtaining global observations needed for atmospheric chemistry and climate. Microwave measurements are obtained from observations of atmospheric spectral line thermal emission, allowing daily global coverage from a satellite-based instrument. Additional important features include the ability to (1) make chemical measurements in the presence of dense volcanic aerosol, smoke, and ice cloud, and (2) measure signals from weak spectral lines in the presence of nearby very strong ones. These features are due to (1) the relatively long wavelengths - compared to infrared, visible and ultraviolet spectral regions - and (2) the excellent spectral resolution available from heterodyne techniques.

These techniques have already been developed and applied to stratospheric chemistry measurements from space. The Microwave Limb Sounder (MLS) experiments [8] on the Upper Atmosphere Research Satellite (UARS), launched in 1991, and the EOS Aura mission to be launched in 2004, have stratospheric chemistry measurements as a primary goal - particularly measurements needed for understanding chemistry influencing delicate balances maintaining the

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ozone layer and the effect of anthropogenic chlorine on ozone depletion. Important results from UARS MLS include the first global mapping of ozone destroying ClO [9] (see Fig. 1), for which microwave techniques provide a unique capability. Upper tropospheric water vapor, which influences how greenhouse gas and sea surface temperature variations affect climate, has also been measured by UARS MLS [10] (see Fig. 3) which provides unique daily coverage and measurements in the presence of ice clouds. More than 200 peer-reviewed MLS-related scientific publications have been produced to date; a listing is available at <http://mls.jpl.nasa.gov>. The second-generation MLS on EOS Aura will measure many additional stratospheric chemicals that can be globally observed only by microwave techniques. EOS MLS is also designed to provide improved measurements of upper tropospheric water vapor and other parameters that are needed for climate research studies.

Although microwave techniques have reached a relatively high degree of maturity for application to stratospheric chemistry, and have been applied to climate research, they have not yet been developed for tropospheric chemistry. Recently, however, some microwave measurements relevant to tropospheric chemistry processes and pollution been obtained from UARS MLS data, and give an example of unique measurements that this technique can provide for tropospheric chemistry. Methyl cyanide (CH₃CN), a pollutant product of biomass burning, has been detected in the UARS MLS data, which have provided its first global stratospheric climatology [11]. A localized enhancement of methyl cyanide in the lower stratosphere has also been detected, as shown in Fig. 2, and traced to an Idaho forest fire [12]. An important thrust of the work whose progress is being reported here is to identify cost-effective technology developments that can enable the full potential of the microwave remote sensing technique to be applied to



Fig. 1. UARS MLS showed that ozone-destroying chlorine monoxide (ClO) - red and purple in the images above - can be as extensive in the Arctic winter as in the Antarctic ozone hole [9]. Red and purple colors correspond to ozone destruction rates of 1-4% per day. The enhanced abundances of Arctic ClO have not persisted as long each winter, resulting in less ozone loss than in the Antarctic. There is uncertainty concerning how climate change may affect chlorine depletion of ozone.

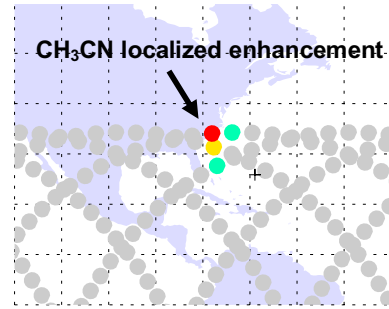


Fig. 2. Localized enhancement of methyl cyanide (CH₃CN) in the lower stratosphere detected by UARS MLS on 25 August 1992 [12, also see 11]. This enhancement has been traced to pollution from an Idaho forest fire that was injected into the stratosphere by a thunderstorm. The red color indicates CH₃CN abundance of ~1.5 parts per billion by volume (ppbv), which is a typical amount expected to be produced by biomass burning. Bullets give locations of MLS measurements on these two days; grey indicates <0.4 ppbv CH₃CN, and typical stratospheric abundances are <0.05 ppbv.

tropospheric chemistry. Because of absorption by water vapor, these techniques - at least from space - are expected to be limited to the middle and upper troposphere (above ~5 km) [7], important regions for understanding coupling between regional and global phenomena, coupling between chemistry and climate, and coupling between the troposphere and stratosphere

II. Approach and some general considerations

Our approach is to identify technical developments that likely can have the greatest impact on atmospheric measurements, especially those needed for tropospheric chemistry measurements, for NASA missions launching ~2010-2015. This launch time period is sufficiently near for meaningful planning, while sufficiently distant to provide time for developments that can have substantial benefits.

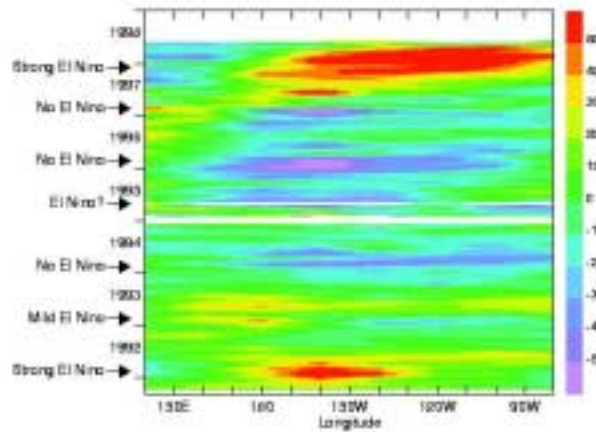


Fig. 3. UARS MLS data showing water vapor at ~10 km height being affected by El Nino sea surface temperature variations [8, also see 10]. These data show variations over the tropical Pacific for a period of 6 years, with El Nino events indicated along the left (temporal) axis. The color bar at right gives H₂O deviations from the average in units of parts per million by volume (ppmv).

General areas have been identified that (a) can provide substantial benefit for future chemistry/climate missions, (b) are timely for starting development, and (c) are likely to be affordable. These include:

- (1) significant improvements in radiometric sensitivity needed for tropospheric chemistry measurements,
- (2) significant improvements in microwave limb sounding spatial resolution needed for both chemistry and climate, and
- (3) programmable measurement capability needed for a cost-effective instrument with flexible measurements.

These areas involve developments, mainly, at the component or subsystem level. System-level considerations must also be addressed and in order for the benefits of these developments to be realized in practice. These include insuring (or having methods for ‘calibrating out’ deficiencies) adequate radiometric stability and overall linearity for allowing measurement of the weak tropospheric spectral line superimposed on a strong continuum.

III. Radiometric Sensitivity Improvements

Fig. 4 compares current satellite-based radiometric sensitivity at millimeter and submillimeter wavelengths, as available on EOS MLS for launch in 2004, with sensitivity that can be expected with advanced technology that could be deployed in future missions. Note that up to two orders of magnitude improvement is expected, which gives up to four orders of magnitude reduction in the required integration time. Fig. 5 shows the resulting measurement times with

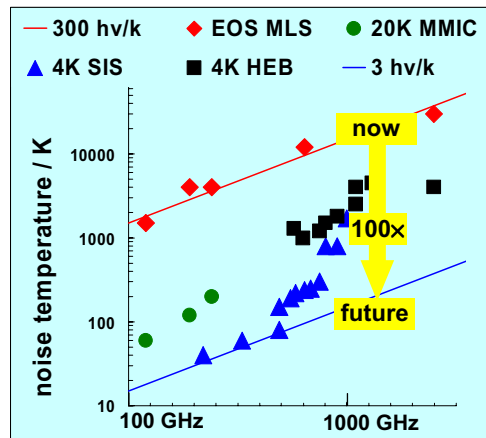


Fig. 4. Noise of a current mm/submm chemistry sensor operating at ambient temperature (EOS MLS, to be launched in 2004) compared with what now can be expected using advanced technology cooled components. Adapted from [13], with points added for EOS MLS and 20 K cooled MMIC projections. MMIC is “microwave monolithic integrated circuit,” SIS is “superconductor-insulator-superconductor,” and HEB is “hot electron bolometer.”

which, in principle, some important middle and upper tropospheric chemistry measurements can be made. Note that many measurements, at least for polluted situations (generally the situations of most interest) can be achieved - in principle - with measurement times of a small fraction of a second. The improvements in sensitivity that are now possible can thus enable the application of microwave remote sensing to the measurement of tropospheric chemistry. However, cooling is needed and - in addition to the required technology developments - the overall instrument into which

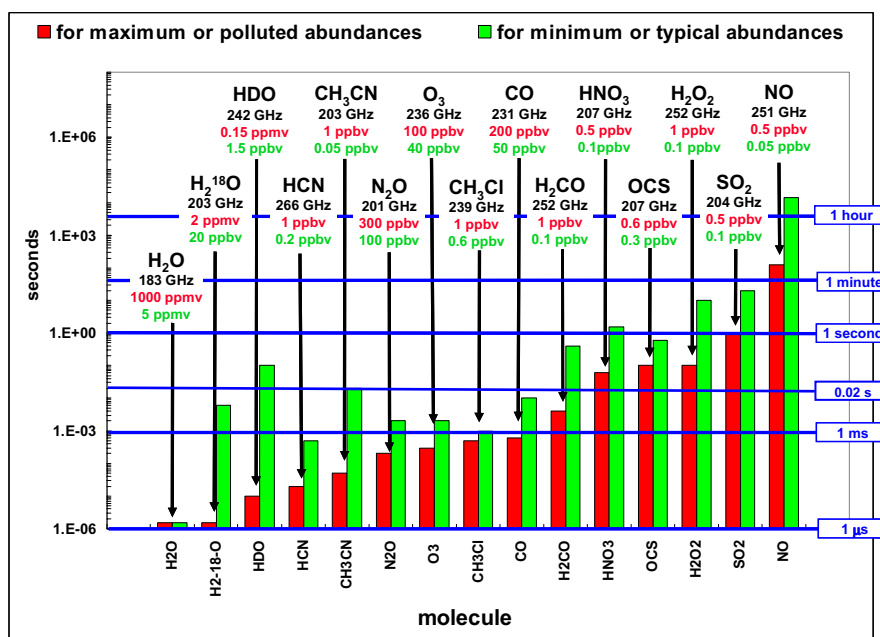


Fig. 5. Some candidate molecules and spectral lines for mid-upper tropospheric chemistry measurements by a future satellite-based sensor. The vertical axis gives the integration time required for measurements with spectral line signal to noise of 10 that, in principle, can be achieved with advanced technology feasible for satellite instruments within the next several years. These estimates include both the instrument and background atmospheric noise.

the technology is to be infused must be affordable. Cooling by stored cryogen is not feasible because of the large mass of cryogen required and the desired operational lifetime for Earth observation missions. The Cryogenic Limb Array Etalon Spectrometer CLAES [14] flown on UARS, for example, needed ~1000 kg of neon/CO₂ cryogen for cooling to 10 K with an operational lifetime of only 1.5 years. A 4 K mechanical refrigerator being developed by Japan (for the 600 GHz SubMillimeter wave Limb Emission Sounder (SMILES) to be deployed on the Japanese Experimental Module of the International Space Station) is estimated to require ~250 W for cooling to ~4 K, with an overall SMILES power consumption of ~900 W [15]. A goal of our work is to identify methods/technology by which the power required for cooling is only ~100 W or less, with an overall instrument power consumption of only a few hundred Watts.

IV. A ‘Strawman’ Instrument Concept

In order to determine overall drivers on an advanced mm/submm atmospheric sensor, and how - overall - to make such an instrument affordable, we have developed a ‘strawman’ instrument concept that is providing a framework for understanding how new technologies and capabilities might best be deployed in a practical instrument. This approach is needed in order to identify the technologies that can have a ‘home’ in an overall instrument that is feasible.

The ~3 km or better vertical resolution needed for measurements, and the need to measure very weak signals from trace gases, requires limb observations. Fig. 6 shows the ‘strawman’ instrument signal flow block diagram. We have selected the following, as optimum spectral bands and technology, to provide the needed measurements:

- 200-280 GHz (‘240 GHz’) SIS radiometer with programmable measurement capability, primarily for tropospheric chemistry observations,
- 240 GHz MMIC radiometer, primarily for temperature and pressure (from 234 GHz O¹⁸O line) that have strong signals and need to be measured continuously,
- 190-GHz MMIC radiometer, primarily for H₂O with a strong signal that needs to be measured continuously
- 600-680 GHz (‘640 GHz’) SIS radiometer with programmable measurement capability, primarily for stratospheric chemistry,
- 2.0-2.5 THz (‘2 THz’) HEB radiometer for programmable stratospheric chemistry measurements that cannot be obtained at the lower frequencies.

All spectral bands contribute to measurement of ice cloud parameters important for climate research. The design is modular so that decisions on each band can be made at appropriate times in mission formulation and development.

An overall cooler concept combining passive radiators and active cooling for cost-effectively producing the needed temperature stages is being investigated. The different stages

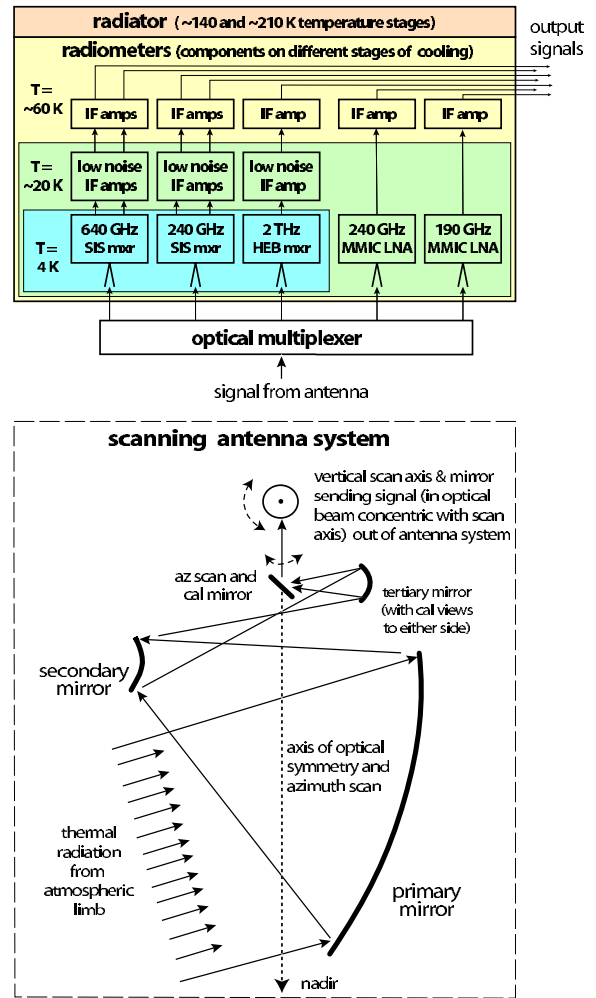


Fig. 6. Signal flow block diagram of a ‘strawman’ instrument concept. The different colors in the top portion refer to different stages of cooling for various components of the radiometer systems. The scanning antenna system collects radiation from the atmospheric limb and measures a vertical profile by vertically-scanning the entire antenna system over ~1° angular range - covering the altitude range of interest. A small (few cm diameter) ‘azimuth scanning and calibration’ mirror, located near a focal point, performs azimuth scanning for complete orbit-to-orbit coverage, as shown in Fig. 7, and radiometric calibration. A complete vertical scan is done in ~25 s, each azimuth scan and calibration in ~0.5 s, and individual measurements in ~0.02 s. The ‘output signals’ indicated here go to further amplifiers, band splitters, spectrometers and data collection system.

are used for optimum placement of components to reduce overall power consumption.

A novel, and relatively simple, antenna concept has been generated that provides simultaneous vertical and ‘azimuth’ scanning. This concept, an outgrowth of a rotating radiometer/feed antenna developed many years ago [16] for another application, gives simultaneous scanning and calibration of all spectral bands. It also greatly reduces the overall power consumption of a previous instrument concept that gave azimuth coverage by an array of MMIC-based radiometers (which could not be used at higher frequencies

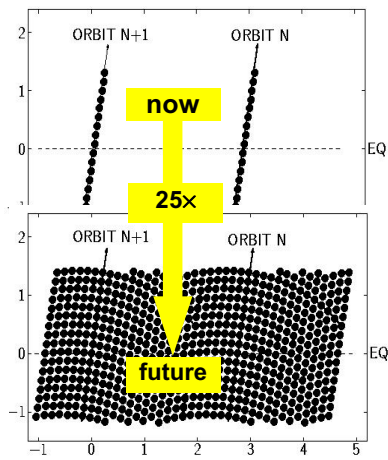


Fig. 7. The improvement in microwave limb sounding cross-track resolution enabled by the new scanning antenna concept combined with the sensitivity of cooled radiometers. This improvement in resolution will help understand regional-global couplings in the atmosphere and upper tropospheric processes important to climate variability. Each bullet gives the location of a vertical profile measurement. Coverage near the equator (EQ) from two adjacent orbits is shown here. Distances are in 1000 km units.

of interest). The azimuth scanning is conical about the limb, so that each azimuth scan covers - approximately - the same tangent point height. Fig. 7 shows the great improvement in cross-track resolution enabled by this capability.

Fig. 8 shows an initial overall concept for the advanced instrument. This concept accommodates cooled radiometers, a hybrid active-passing cooling system to reduce power consumption, and azimuth scanning for complete orbit-to-orbit coverage. Vertical resolution is set by the size of the primary mirror. A primary mirror 'vertical' dimension of ~1.6 m (seen from the direction of the atmospheric limb) as flown on UARS and EOS MLS provides 2-3 km vertical resolution for most measurements. Improving the vertical resolution to 1-2 km is desirable, but requires a larger primary mirror. Fig. 9 shows a concept by which a larger

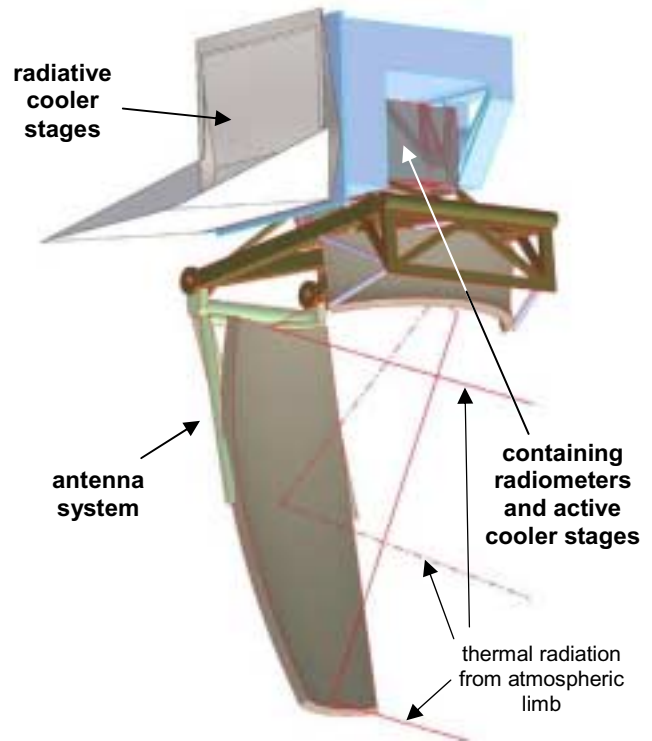


Fig. 8. An advanced microwave instrument concept for atmospheric chemistry and climate measurements.

primary mirror could be accommodated in a reasonably-sized launch vehicle, and then deployed for operation. This deployment concept, a pivot of the primary mirror, minimizes the impact to the overall optics design and utilizes new technology such as the precision rotary joint and latching mechanism developed by the NASA Langley Research Center for the Next Generation Space Telescope (NGST). It allows the primary mirror to be 'folded' for launch in a direction along the axis of the launch vehicle, the direction in which most space is likely to be available.

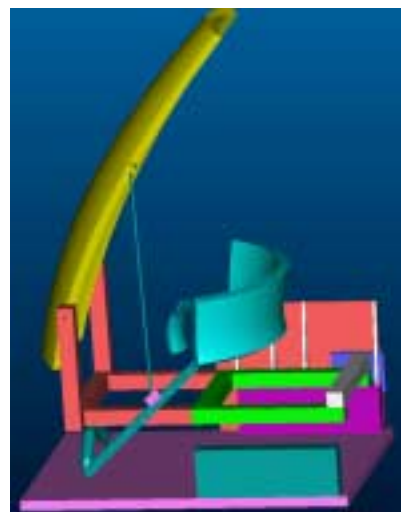
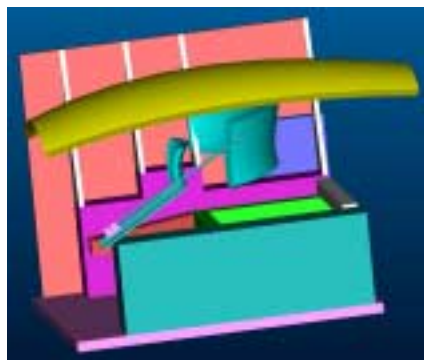


Fig. 9. A concept by which the primary mirror can be stowed (left) to fit in a smaller launch vehicle, and then deployed (right) for operation.

V. Areas for further study and development

The following have been identified as key areas for further study and/or development. Progress in these areas can have large benefits for an advanced microwave instrument for atmospheric chemistry and climate that could be operational in the ~2010-2015 time period.

A. Cooling system

Essential for microwave tropospheric chemistry measurements is a cooling system with low power consumption that can be used on Earth-orbiting satellites. This system should provide cooling to 4 K with additional stages at higher temperatures. The most cost-effective way to minimize power consumption for a cooler with these requirements is by combining active and passive (radiative) cooling, and by minimizing heat loads on the actively-cooled stages. Our studies to date indicate that actively-cooled stages at 4 K, ~20 K and ~60 K - with passively-cooled stages at ~140 K and ~210 K - are optimum. Each 1 mW of heat load at the 4 K stage is estimated to require ~5 W drive power, at 20 K require ~0.5 W, and at 60 K require ~0.05 W. Our current goals are to keep the 4 K load down to ~5 mW, the 20 K load to ~50 mW, and the 60 K load to ~500 mW. Concepts are being studied for accomplishing this. Developments of advanced active coolers, recently started by the NASA Space Science Enterprise, can possibly benefit our application.

B. SIS Technology

SIS-based receivers provide the lowest noise available in the 200-300 GHz region (see Fig. 4) that is optimum for tropospheric chemistry measurements (see Fig. 5). Key SIS component developments needed for tropospheric chemistry are increasing the spectral bandwidth and generating separate outputs for the mixer upper and lower sidebands. A proposal for these developments has been submitted [17].

C. MMIC Technology

MMIC-based receivers can provide excellent measurements of stronger tropospheric signals (such as temperature, pressure, water vapor and certain other chemicals such as ozone and carbon monoxide) with cooling to temperatures substantially above the 4K required for SIS-based receivers. These MMIC-based receivers provide an excellent complement (for the stronger tropospheric signals) to the SIS-based receivers (for the weaker tropospheric signals). The key MMIC development needed for this application is a 240 GHz low-noise amplifier to operate at temperatures down to ~20 K. The most appropriate temperature for operation of the MMIC amplifier will be determined after further system-level trade-offs have been

made. A proposal has been submitted for development of a 240 GHz cryogenic MMIC low noise amplifier [18].

D. High Dynamic Range Spectrometer

Tropospheric chemistry observations require measurement of ~0.01 K brightness temperature spectral line signals, up to 1-2 GHz wide, that are superimposed on a continuum background of ~100 K brightness. This requires broadband spectrometers that operate well, with good differential linearity, over 10^4 dynamic range. A robust method of implementing such a spectrometer is with high-speed digital techniques, for which the technology is now emerging. The key component that needs to be developed is a low power (< ~1 W) high speed (~5 GHz or faster sampling, ~20 GHz or greater bandwidth) digitizer with ~2 bit resolution. Spectral resolution needed for the tropospheric measurements is ~100 MHz.

E. Scanning Antenna System

The novel scanning antenna system described here has been studied mathematically with both geometrical and physical optics models. Development and testing of a breadboard is needed to validate the mathematical models.

F. Programmable Measurement Capability

Programmable measurement capability appears best implemented by programmably-tunable oscillators in the ~15 GHz range. Signals from these oscillators can be frequency-multiplied to generate the (very low power) local oscillators needed for the SIS, MMIC and HEB radiometers. Studies are underway to determine whether any technology developments are needed in this area.

G. Balloon Demonstration

Balloon demonstration of tropospheric chemistry measurements can improve confidence for proceeding with development of a satellite-based instrument. The necessary balloon demonstrations can be performed using stored cryogen for cooling, and thus not require an expensive active cooler. Development of such an instrument has been proposed [19].

H. HEB technology

HEB technology provides best noise performance for microwave measurements at frequencies above ~1000 GHz (see Fig. 4), and measurement of several important stratospheric chemicals (e.g., atomic oxygen and hydroxyl radical) can only be done in this range. HEB-based radiometers require sufficiently-small local oscillator (LO) power, like SIS devices, that the LO can be generated by solid state technology - which is both more reliable and

consumes less power than the 2.5 THz gas laser local oscillator used for the OH measurement on EOS MLS. HEB technology, especially in the 2.0-2.5 THz region (both the HEB devices and the solid state technology for tunable LO generation) should be developed to a sufficient level of maturity for deployment in an advanced satellite instrument for stratospheric chemistry measurements.

I. Schottky technology

Schottky-based radiometer systems have - to date - been the 'workhorse' for atmospheric chemistry measurements with microwave techniques. Advances in this technology, at least at frequencies above ~300 GHz where development of low noise MMICs is not yet feasible, should continue to be supported for applications in which cooling to the lower temperatures required for SIS and HEB is not available or needed. We are not yet at a stage in development of an advanced chemistry instrument that we can rule out the need for Schottky technology being most cost-effectively used in a portion of the instrument.

VI. Summary

Microwave techniques have already been developed and applied with great benefit to stratospheric chemistry measurements, and are also being used for climate research. Technology developments are now possible that can allow these techniques - with their unique ability to measure through ice clouds, dense aerosol and smoke - to be applied to the important area of tropospheric chemistry. The developments for tropospheric chemistry will also greatly improve stratospheric chemistry and climate research measurements by this technique.

Acknowledgements

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