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A Conical-Scanning Microwave Limb Sounder for Atmospheric Measurements

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ABSTRACT We describe a novel scanning microwave limb sounder (SMLS) instrument that performs rapid and broad azimuth conical scans of Earth's limb while simultaneously scanning the limb in the vertical. This azimuthal scanning capability gives dramatic improvement in temporal and spatial coverage over that of previous limb sounding instruments. In a 1500-kilometer altitude, 52°-inclination Earth orbit, SMLS provides 6–8 vertical profile measurements separated by 1.9 hours every 24 hours everywhere between ±65° latitude, and 2–4 such measurements everywhere between ±(65–82°). Horizontal resolution is ∼50×50 km. Vertical resolution is ∼2 km for water vapor and cloud ice and ∼1–3 km for chemical species. In an equatorial orbit, emphasizing the tropics and subtropics, SMLS produces profile measurements every 1.9 hours everywhere between ±35° latitude. SMLS measurements address scientific issues of relevance to the upper troposphere, stratosphere, mesosphere, and lower thermosphere regions of the atmosphere (heights from ∼10 km to ∼100 km).

INDEX TERMS Microwave limb sounding, microwave remote sensing, ozone monitoring, temperature profiling, cloud ice measurements, pollution measurements, global climate variable, microwaves in climate change.

I. INTRODUCTION

The microwave limb sounding technique [1] obtains atmospheric vertical profile measurements by passively observing natural thermal radiation as the instrument antenna field-of-view (FOV) is vertically scanned through the atmospheric limb. The two Microwave Limb Sounder (MLS) instruments developed by the NASA Jet Propulsion Laboratory (JPL) have provided 32 years of daily near-global atmospheric measurements. The Upper Atmosphere Research Satellite (UARS) MLS [2] was launched 15 September 1991 and operated in orbit until 25 August 2001. The much-more-capable Earth Observing System Aura satellite Microwave Limb Sounder (EOS or Aura MLS) [3] was launched 15 July 2004 and, at the time of writing, continues operating in orbit. Atmospheric measurements are made at all times of day and night, including in the presence of ice clouds and dense volcanic aerosol.

Measurements from Aura MLS include:

1) **16 chemical species** in the upper troposphere, stratosphere and/or mesosphere [4],
2) **Temperature** in the stratosphere and mesosphere [4],
3) **Geopotential height** of pressure surfaces in the stratosphere and mesosphere [4],
4) **Water content of ice clouds** in the upper troposphere [4],

5) **Wind** in the mesosphere [5],
6) **Gravity (buoyancy) wave**s in the mesosphere [6],
7) **Geomagnetic field variations** in the mesosphere and lower thermosphere due to solar storms [7].
8) Information on **bulk alignment of cirrus particles** in the upper troposphere [8].

These measurements have helped improve our understanding of numerous atmospheric processes, especially stratospheric ozone depletion by chlorine. More than 1850 MLS-related peer-reviewed scientific publications have been produced to date; a continually updated publication list is publicly available online [9]. A summary of scientific results from UARS MLS, and from Aura MLS until 2015, is in [10].

A limitation of the MLS technique, as deployed on satellites to date, is that measurements are made only along the suborbital track (Aura MLS) or along a track offset from the suborbital (UARS MLS). The Scanning MLS (SMLS) concept described here overcomes these limitations and provides multiple measurements with no inter-orbit gaps every 24 hours over most of the globe.[1]

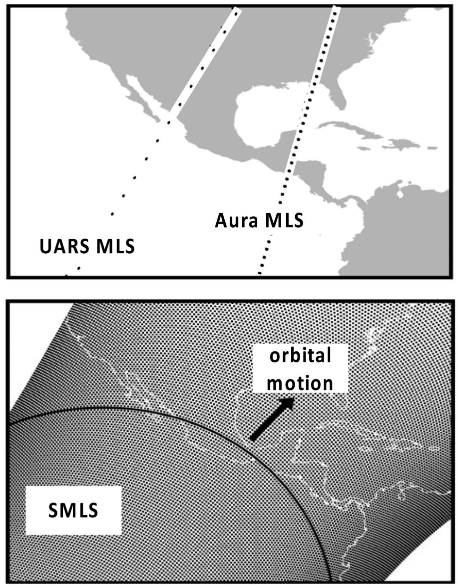

FIGURE 1. Comparing measurements of UARS and Aura MLS (top) and SMLS (bottom) for a small portion of an orbit. Each point shows the center location of a profile measurement.

II. TECHNIQUE

Novel features of the SMLS technique are:

1) broad and rapid azimuth conical scans of the instrument field-of-view that are performed simultaneously with the slower vertical scan, and
2) deployment in a higher orbit than previously used for microwave limb sounders.

The combination of these features provides atmospheric vertical profile measurements that overlap on many successive orbits, covering most of the globe.

Fig. 1 shows the dramatic improvement in measurement spatial coverage of SMLS over that of UARS and Aura MLS. Fig. 2 shows how overlapping SMLS scan swaths from successive orbits lead to multiple measurements at a given location and give the greatly improved temporal coverage.

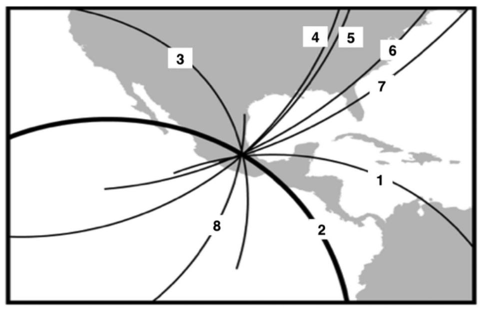

FIGURE 2. Example of individual SMLS scan swaths on successive orbits. In this example, the atmosphere over Mexico City is repeatedly observed on 8 successive orbits. The orbits are numbered sequentially, with orbit number 2 (shown with a thicker line) being the orbit shown in Fig. 1.

III. ILLUSTRATIVE MEASUREMENTS

We chose a 1500-km altitude, 52°-inclination, circular orbit as an illustration of SMLS measurement capability. This 1.9-hour-period orbit is a compromise between (1) higher orbits requiring a larger antenna to provide a given vertical resolution and (2) lower orbits having poorer global coverage. The inclination and right ascension of the orbit ascending node are chosen to (1) favor measurements in the summer hemisphere to better study global transport of air pollution lofted to the upper troposphere by deep convection, which peaks during the summer, (2) give measurements to ±82° latitude on each orbit, and (3) have a coverage pattern that repeats annually. The instrument concept, described later, scans ±65° in azimuth every 0.5 s. Fig. 3 shows, for this orbit, a sample of the SMLS measurement swaths for 8 consecutive orbits. Fig. 4 shows the number of measurements around the globe for a representative 24-hour period. Other orbits could be chosen to optimize specific science objectives. An equatorial orbit to emphasize the tropics and subtropics, for example, provides profile measurements every 1.9 hours everywhere between 35° N and 35° S. The SMLS scans and measurement coverage are in-orbit programmable.

[1]A large number of scanning microwave remote sensing instruments have been implemented to date, starting with the cross-track Scanning Microwave Atmospheric Sounder (SCAMS) for atmospheric measurements on the NASA Nimbus-6 satellite launched in 1975 [11], and the azimuth-conical-scanning Scanning Multichannel Microwave Sounder (SMMR) for, primarily, surface measurements on the NASA Nimbus-7 satellite launched in 1978 [12]. Since 1978, cross-track scanning microwave radiometers to measure atmospheric temperature profiles have been continuously deployed on U.S. operational meteorological satellites (see NOAA Satellite Information System, *The Joint Polar Satellite System (JPSS)*, https://www.noaasis.noaa.gov/POLAR/JPSS/jpss.html, and National Environmental Satellite, Data, and Information Service, *Advanced Technology Microwave Sounder (ATMS)*, https://www.nesdis.noaa.gov/our-satellites/currently-flying/joint-polar-satellite-system/advanced-technology-microwave-sounder-atms). The unique aspect of the SMLS scan system is that, for the first time, it combines conical azimuthal-scanning and vertical limb scanning to obtain unprecedented spatial and temporal coverage for limb sounding measurements.

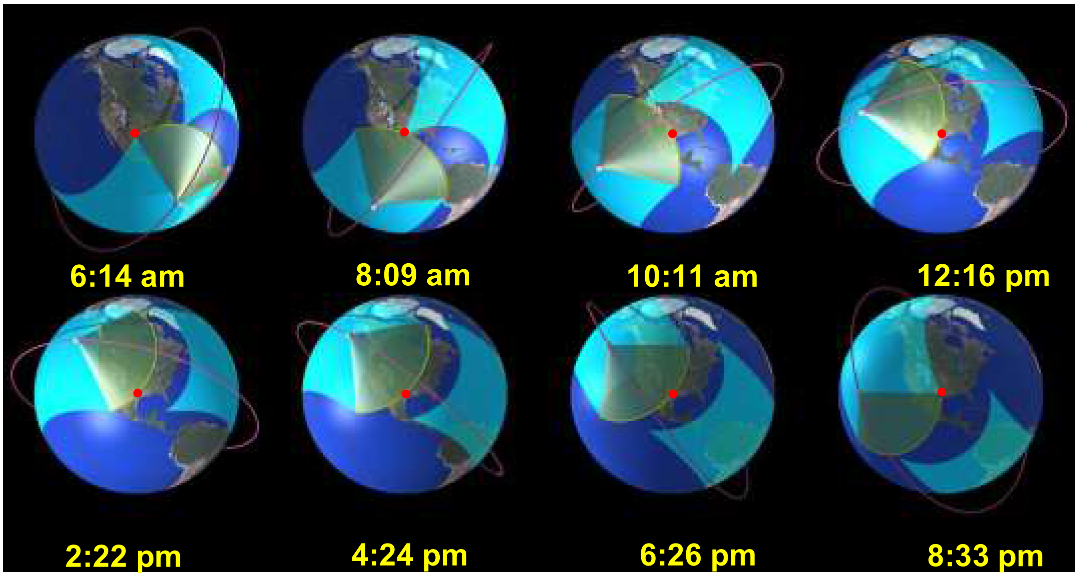

FIGURE 3. **Example of SMLS measurement coverage (turquoise color) on successive orbits. Labels under each image give local times for this example day's measurements over Houston, Texas (red dot).**

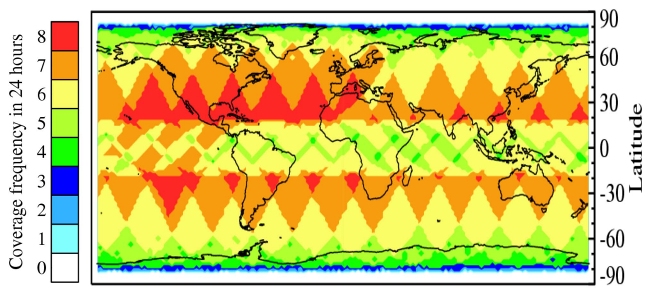

FIGURE 4. **Example SMLS measurement coverage for a typical day. Everywhere within a given color is measured the number of times per 24-hour period indicated by that color. Successive measurements are separated in time by 1.9 hour. The coverage drifts in longitude each day as the orbit plane precesses in response to Earth oblateness.**

Fig. 5 shows atmospheric measurement capability for the example SMLS instrument considered here, which measures in two spectral bands: 180–280 GHz and 550–780 GHz.

The SMLS azimuth scanning capability should be especially valuable for improving our understanding of regional-scale processes in the upper troposphere. These include convective processes that play prominent roles both in climate feedback mechanisms and in depositing boundary layer pollution into the upper troposphere, where it is transported globally. The combination of fine temporal resolution and full global coverage of vertically resolved measurements of water vapor and cloud ice should be valuable for testing and improving the representation of clouds in climate models. The SMLS regional-scale composition measurements are also critical for stratosphere-troposphere exchange and upper-troposphere and lower-stratosphere transport in the subtropics and midlatitudes [15], [16]. These are needed for quantifying the distribution of radiatively active trace gases where they have largest radiative impact.

The SMLS FOV width at the tangent point is 30 km in the horizontal, normal to the line of sight, and 0.5–1 km in the vertical. Special 'limb-tracking' observations of Aura MLS (whereby the limb tangent point is maintained at a fixed altitude with respect to Earth's surface for extended periods) have shown that 50-km horizontal resolution (or better) along the line-of-sight can be achieved with SMLS.

Measurement precision depends upon the specific measurement (including spectral line width, which varies significantly with atmospheric pressure, as well as line strength) and on the time used to make it. Furthermore, precision and resolution can be traded for each other, both through choice of scan rate/range and through choices of smoothing parameters in ground data processing algorithms. A 'global coverage' scan mode, with individual radiance measurements at 20 points in the vertical and every ~50 km along the ±65° azimuth scan arc, provides useful measurements of upper tropospheric water vapor, cloud ice, and temperature. Measurement times required for other upper tropospheric measurements are shown in Fig. 6. Typical values for enhanced abundances of boundary-layer pollution injected into the upper troposphere (the injections of most interest) should be measurable with the 'global coverage' scan mode for CO, HCN, CH_3CN, CH_3OH, H_2CO, SO_2, and NO. A 'regional targeted' scan mode (described in the caption of Fig. 6) should allow additional measurements of upper tropospheric O_3, HNO_3, and NO_2.

Upper tropospheric composition measurements are made from observations of spectral line emission in the 180–280 GHz region. This spectral region also provides stratospheric information. Stratospheric, mesospheric, and lower thermospheric measurements are made from observations in

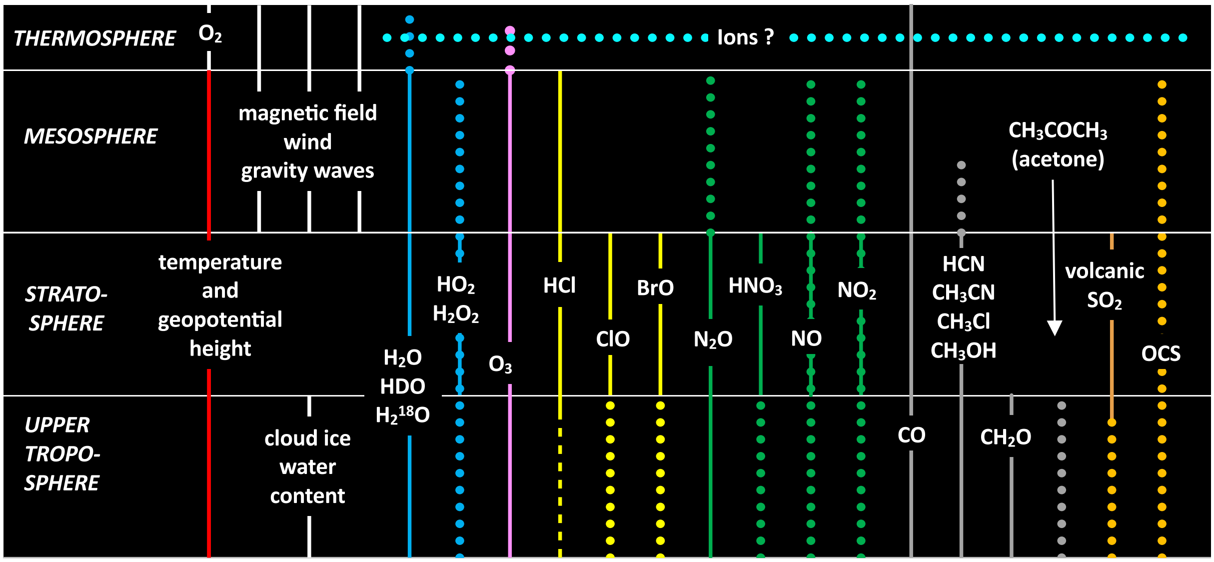

FIGURE 5. Atmospheric measurement capability for the example SMLS instrument considered here. Dotted lines are goals. Geomagnetic field measurements observe solar storm disturbances. The 'gravity waves' indicated here are what atmospheric scientists usually call 'buoyancy waves' (they are not Einstein's gravitational waves!). Fig. 2 of [13] shows 25 ions, in decreasing order of detectability (on a per-ion basis), whose millimeter and submillimeter spectra are in the JPL Spectral line Catalog [14].

the 550–780 GHz region (chosen to cover both the strong line of H_2O at 557 GHz and of O_2 at 774 GHz). The spectral lines chosen here for SMLS measurements were selected from considerations of (1) line strength, (2) freedom from interference, and (3) instrument simplification. This is the method used for selection of spectral lines measured by Aura MLS. Spectroscopic data used in selecting the targeted species lines are from the JPL Spectral Line Catalog [14]. Pressure height reference for measurements is obtained from the 233.946 GHz $O^{18}O$ line for the low-frequency radiometer and from the 773.838 GHz O_2 line for the high-frequency radiometer.

Aura MLS upper tropospheric measurements include water vapor, cloud ice water content, O_3, and CO [4]. These species would also be measured by SMLS in the upper troposphere, along with others. Fig. 7 illustrates the value of the improved SMLS temporal and spatial coverage in the upper troposphere by showing an example result from the GEOS-CHEM atmospheric model [17] with the same horizontal and temporal resolution as SMLS. This example is enhanced formaldehyde (CH_2O) being convectively injected into the upper troposphere over the southeastern U.S. CH_2O is a proxy for volatile organic compound (VOC) emissions. Quantifying biogenic emissions of VOCs is important for improving our understanding of tropospheric radical chemistry that affects air quality. Strong biogenic emissions of the VOC isoprene (C_5H_8) cause enhanced abundances of CH_2O to form. During summer, when VOC emissions peak, there is also frequent deep convection that deposits enhanced CH_2O directly into the upper troposphere, as shown in Fig. 7. This CH_2O can be the primary source of HO_x, which regulates upper tropospheric O_3 production, especially in the tropics and subtropics. SMLS could measure the temporal and spatial evolution of injections of CH_2O and other boundary-layer gases into the upper troposphere. These measurements would be valuable for both directly quantifying the injections and improving the models. They also should be valuable for identifying the specific source locations and global transport pathways for pollution injected into the upper troposphere. Such information could be essential for supporting any future international regulations curtailing emissions of pollution.

Aura MLS observations include volcanic injections of SO_2 [18] and HCl [19] into the stratosphere. The 2022 eruption of the undersea Hunga volcano is notable in that, in addition to injecting a large (though not exceptional) amount of SO_2 into the stratosphere, it lofted an unprecedented amount of water vapor [20]. Many studies of the consequences of this stratospheric moistening [21], [22] have relied heavily on Aura MLS observations. Aura MLS measurements have also been central to studies of pyro-convective injections of enhanced HCN, CH_3CN, CH_3Cl, CH_3OH, and, in some cases, H_2O, from the troposphere to the stratosphere [e.g., 23]. Aura MLS tracked plumes of polluted air deposited in the stratosphere by the 2019/2020 Australian New Year's fires for $\sim$110 days [24]. The subsequent widespread conversion of stratospheric chlorine from reservoir to active forms was unprecedented and not explicable by then state-of-the-art atmospheric chemistry models [25]. The SMLS described here measures all these species and more with dramatically improved spatial and temporal coverage, which would greatly aid tracking of such plumes and better quantification of their dynamical and chemical impacts in the stratosphere. The improved SMLS spatial and temporal coverage would also greatly benefit studies of the vertical transport of polluted air into the Asian summer monsoon anticyclone in the upper troposphere and

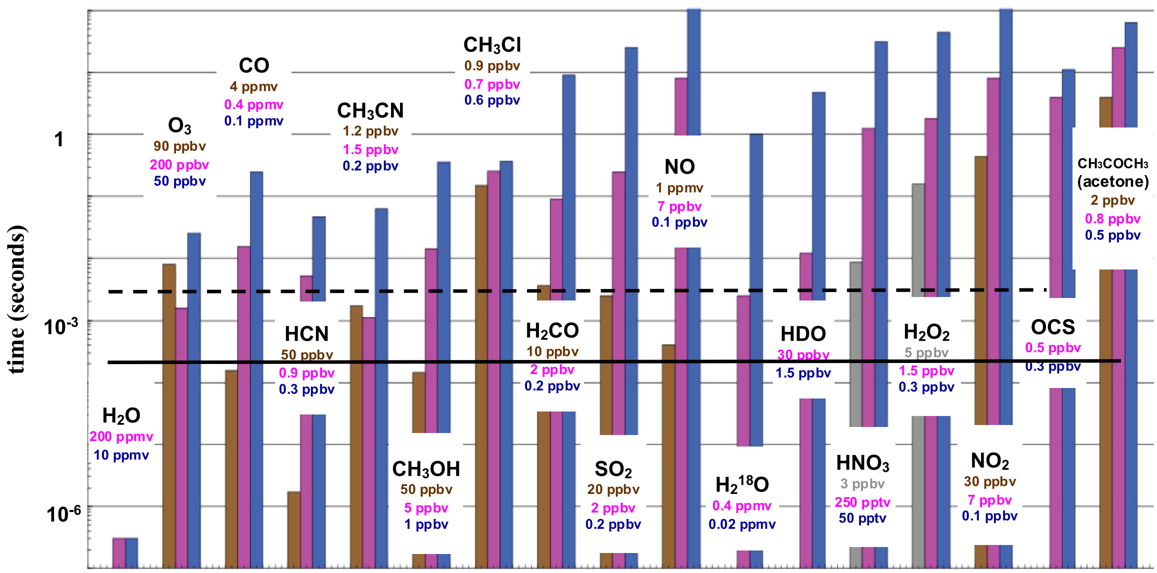

FIGURE 6. **Vertical bars show the SMLS measurement time needed for an upper tropospheric spectral line radiance signal-to-noise of 10 for various species (taller bars indicate greater integration times needed for some species due to a combination of low abundance and intensity of the spectral lines required for upper tropospheric measurements[2]). Colors of the bars give representative abundances of upper tropospheric species for different situations. Blue is for typical or minimum abundances; pink for enhanced abundances that have been observed or inferred; brown for enhanced boundary layer abundances that can be convectively transported to the upper troposphere; grey for soluble species that may reach the upper troposphere less easily. This plot is for a tropical 'background' atmosphere and 9 km altitude; it includes 2–3× attenuation of the target molecule signals by water vapor continuum, as well as spectral line wings of 'interfering' gases. For the tropical troposphere above 12 km, a region of considerable interest, SMLS signals are typically 2–3× stronger than indicated here. Horizontal lines give SMLS individual measurement times. The thick solid line is for the SMLS 'global coverage' scan mode described in the text, with 3 ms individual measurement time. The dashed horizontal line is for an SMLS 'regional targeted' scan mode with, for example, 2000 km cross-track width and measurements at 5 points in the vertical every 50×50 km in the horizontal, giving 50 ms individual measurement time. A measurement has greater than 10× signal-to-noise if its bar is below the horizontal line. There is a continuum of scan modes available, easily implemented by in-orbit programming of the scan. A 'local targeted' scan mode with measurements at 3 points in the vertical and every 50×50 km in the horizontal over a 200 km cross-track width allows 1 s for each measurement. Because of the large dynamic range in the abundance of many species, useful measurements can be obtained with a signal-to-noise of 3, which reduces the required measurement time 9× from that shown here. The precision and spatial resolution of retrieved geophysical profiles ultimately depends on a range of factors, including instrument noise temperature, scan range and rate, atmospheric molecular line strengths, and choices made in the geophysical product "retrieval" calculations. Summary quantities shown here result from consideration of the degree to which molecular abundances contribute to observed radiances (the "weighting function") combined with radiance signal-to-noise, informed by experience with Aura MLS. Cloud ice measurements from 'continuum' emission, and temperature from $O^{18}O$, are obtained in milliseconds.**

lower stratosphere [26] and of the chemical and transport processes affecting the air confined within that region during northern summer.

The SMLS temporal and spatial resolution, and its global coverage with no inter-orbit gaps, can test and improve our understanding of other stratospheric processes such as (1) the formation of polar stratospheric clouds, which cause enhanced ozone destruction in polar regions, (2) the dispersion of depleted ozone from the stratospheric polar vortex to mid-latitudes via narrow filaments, and (3) rapid transport and anomalous mixing of trace gases (including O_3, N_2O, H_2O, CO, HCl, HNO_3, others) during vortex disruptions caused by sudden stratospheric warmings. SMLS – because of its ability to make composition measurements in the presence of aerosol – would be an invaluable component of observing systems intended to track the impacts (intentional and inadvertent) of intervention strategies to mitigate climate change through injection of aerosols into the stratosphere. (See [13] for a new instrument system concept whose primary objective is detecting threats to the ozone layer.) The SMLS measurements also could improve our understanding of mesospheric and lower thermospheric processes such as (1) the breaking of gravity waves and (2) the effects of solar storms on atmospheric composition [27]. A 'mini-SMLS', using an appropriate high-frequency radiometer and in a 1500-km polar orbit, gives complete polar coverage (no inter-orbit measurement gaps) every 1.9 hours.[3] This would provide new information on the dynamics and electrodynamics of the mesosphere and

[2] All the species in Fig. 6 have much stronger lines at higher frequencies, which – due to increased water vapor attenuation at higher frequencies – are not suitable for the SMLS upper tropospheric measurements. Active microwave limb sounding, described in Appendices 4 and 5 of [13], has the potential for upper tropospheric species measurements with much better precision. Fig. 8 of [13] shows that active measurements with 2 m antenna (half the size of the SMLS antenna described in this paper) has ∼15,000 times better signal-to-noise than passive for 180–280 GHz upper tropospheric measurements such as those indicated in Fig. 6. Active microwave sounding, however, has the disadvantage (for a minimum two-satellite active system) of having much poorer vertical resolution and global coverage than SMLS.

[3] Size of the SMLS instrument described in this paper is driven by upper tropospheric measurements. An instrument devoted to the mesosphere and lower thermosphere could be one-tenth the size.

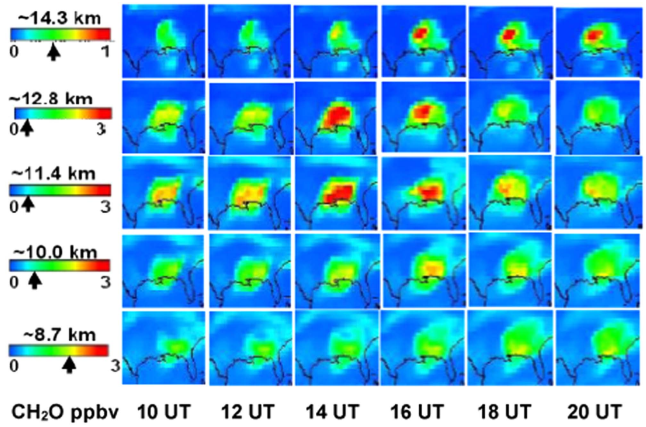

FIGURE 7. GEOS-CHEM atmospheric model results for CH_2O over the southern U.S. on 11 July 2000. Colors give the abundance of CH_2O in parts per billion by volume (ppbv) with each row representing a different altitude as indicated at the left. Each column is for the time at the bottom of that column. Convective deposition into the upper troposphere (above 10 km) is seen at 14 UT. SMLS has approximately the same spatial and temporal resolution as this model. SMLS precisions are indicated by arrows on the color bars.

lower thermosphere and the impacts of solar storms on those processes and regions. In addition to neutral chemical species, many ions might be measurable (See Fig. 2 of [13]).

The various science issues mentioned above demand measurements with varying degrees of precision and resolution. Nevertheless, we are confident that the 50×50 km SMLS spatial resolution represents a needed improvement in measurement capability for these and other topics. Further studies, including end-to-end simulations based on 3D model output, can more fully quantify the degree to which SMLS observations provide new insights into front-line questions in atmospheric science.

IV. INSTRUMENT

Fig. 8 shows a generic SMLS signal flow block diagram. Limb radiation, for the example instrument described in this paper, is collected by an antenna system with a 4×2 m primary reflector. The primary reflector surface, and that of following secondary and tertiary reflectors, are circularly symmetric about the azimuth scan axis [28]. A complete azimuth scan is performed every 0.5 s by ±65° back-and-forth rotation of a 10-cm mirror located at a beam waist following the tertiary reflector. The vertical limb scan is accomplished by articulating the complete antenna and azimuth scan mirror system, totaling ∼200 kg (of which ∼100 kg is the primary antenna), by ∼1°. A complete vertical scan is performed every 10 s to give along-track sampling every 50 km (the orbital movement of the field-of-view tangent point in 10 s).

The primary reflector has a 3.2 m high aperture as projected in the vertical plane normal to the boresight direction (4 m total length) with a 2 m focal length. The equivalent focal length for the complete optical path to the radiometer feed horns is 12 m. The FOV has the same size and shape for all elevation and azimuth view angles, with a 25:1 aspect ratio at the limb (cross-track:vertical). The ±65° azimuth scan range gives a 7700-km cross-track swath width for a 1500-km orbit. An individual radiance measurement is made every 3 ms, giving 50 km cross-track sampling to match the along-track sampling. Overscan in the vertical accounts for Earth's oblateness and changes in vertical scan range with azimuth. Calibration is performed by viewing cold space and a calibration target through a polarization grid. In-orbit programmable rotation of this grid provides multi-point calibration.

Our example SMLS instrument has radiometers in two spectral bands to produce the measurements shown in Fig. 5: (1) 180–280 GHz mainly for the upper troposphere, and (2) 550–780 GHz for the stratosphere, mesosphere and lower thermosphere. Local oscillator frequencies are programmable in orbit to allow coverage of selected spectral regions within these bands. State-of-the-art receiver noise temperatures for SIS receivers for our 2005 study (see next paragraph) were ∼100 K for the 200 GHz band, and ∼200 K for the 600 GHz band (Fig. 15 of [29]. These values were used — with an added 100 K to account for the noise introduced by the thermal signal itself — in calculations of the signal-to-noise estimates leading to the results shown in Fig. 6 and 7. Current technology gives SIS receiver noise temperatures of ∼40K for the 180–280 GHz band [30] and ∼100 K for the 570–780 GHz band [31].

An unpublished conceptual design of SMLS was done as part of a JPL mission study for NASA in 2005, when the authors were together at JPL. It used superconductor-insulator-superconductor (SIS) radiometers to allow useful radiance measurements in milliseconds of measurement time. Its estimated power consumption, including 180 W for the SIS radiometer cooler, was 400 W (150 W less than that of Aura MLS). The estimated mass was 450 kg (same as that of Aura MLS) and data rate was 5 Mb/s (50× larger than for Aura MLS, but reducible with data compression techniques).

Other work at JPL has addressed the design and performance of the SMLS antenna. Given that the observing frequencies cover essentially the same range as that employed for Aura MLS, the same optical surface precision requirements are expected to be sufficient for SMLS. As with Aura MLS, thermal gradients across the reflector surface are a concern. Studies of these gradients have included fabrication of a full-size primary reflector that was then subjected to thermal testing and near-field-range calibration. Thermal deformations were found to be less than a tenth of a wavelength at 280 GHz (0.24 wavelengths at 660 GHz), meeting requirements for rigidity. Measured and modeled distortions agreed to within 14% [32]. A comparably large (3.5 m diameter) antenna system operating at frequencies from 500 GHz into the far infrared has already been demonstrated on the orbiting Herschel Space Observatory [33]. The SMLS antenna system is simpler than that used for Herschel, as the latter mission required a cooled antenna, whereas for SMLS, only the SIS receiver components need to be cooled.

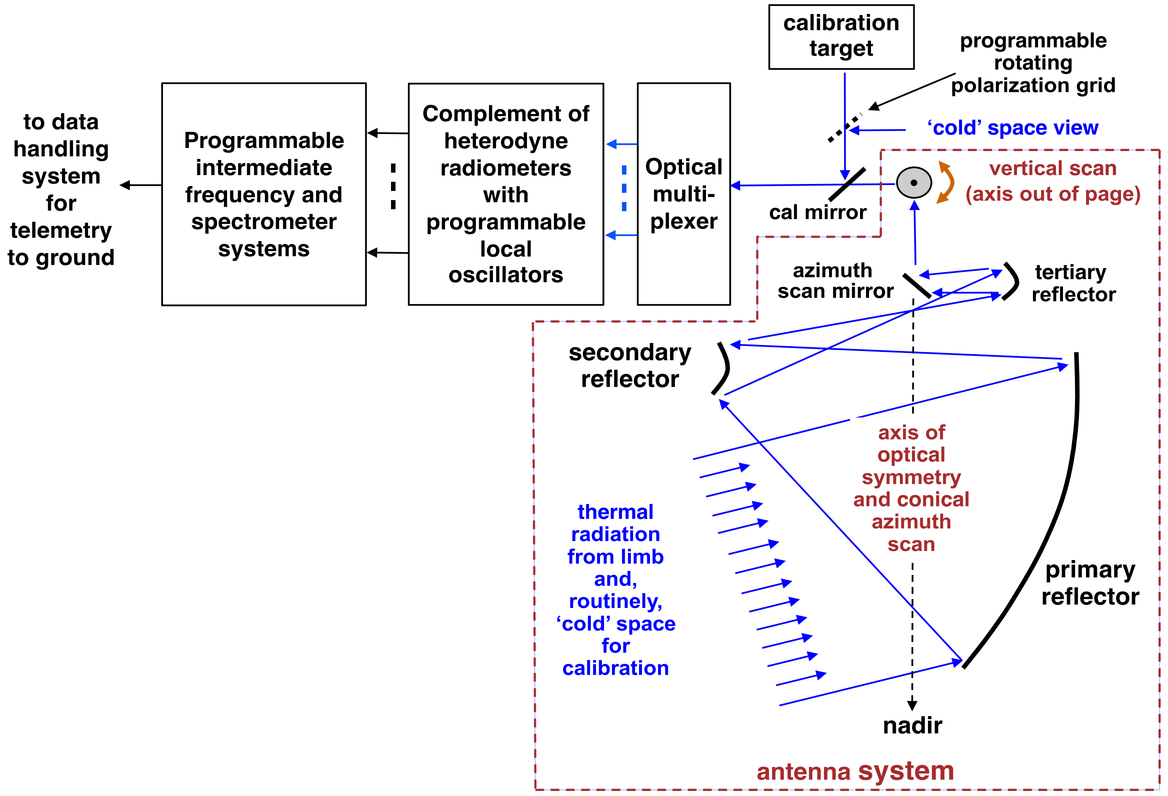

FIGURE 8. Generic SMLS signal path block diagram. The broad and rapid conical azimuth scan is performed by a small back-and-forth rapidly rotating mirror placed at a beam waist. The azimuth scan mirror rotation axis coincides with the axis of symmetry of the overall antenna system, which is in the nadir direction. Vertical scanning, slowly over a small angular range, is by up-and-down rotation of the entire antenna system about an axis that is perpendicular to nadir and to the direction of orbital motion. The signal path between the antenna system and the calibration (cal) mirror is, for clarity, shown here in the plane of the page, but it actually coincides with the vertical scan axis, which is orthogonal to the page. Routine calibration, using the cal mirror, is done by views of a calibration target and 'cold' space through a programmable rotating polarization grid that selects the amount of each. A 'zero-point' calibration through the entire antenna is occasionally performed by vertically scanning the field-of-view tangent point to be well above the atmosphere for views of cold space.

Since the 2005 study, significant improvements in millimeter-wave solid-state source technology (amplifiers and frequency multipliers) have made it possible to cover broader spectral bandwidths and use fewer radiometers. For example, a single amplifier module coupled with a Schottky diode frequency tripler, now commercially available from Virginia Diodes, Inc. [34], can drive the SMLS 550–780 GHz radiometer. Radiometer performance has also improved since the launch of Aura MLS. Space-ready room-temperature receiver noise temperatures (T_R) in the 500–700 GHz frequency range are now in the 1000–2000 K (double-sideband) range [35] and drop by almost a factor of two if passively cooled to 150 K [36], perhaps alleviating the need for more complex and costly helium-cooled superconducting detectors used in the 2005 study.

Fig. 9 shows an illustration of SMLS stowed for launch in the payload module of a Delta-II launch vehicle and operating in orbit. A study was made to ensure that the radiation environment of the 1500-km orbit does not stress the instrument or mission designs. A companion instrument can be accommodated by the launch vehicle, as studied in 2005. An ultraviolet/visible instrument measuring pollution in the lower troposphere, such as a follow-on to TROPOMI [37], would be an excellent complement to SMLS. Their combined measurement suite would provide tracking of pollution from its surface sources to its spread around the globe and to the upper troposphere and lower stratosphere.

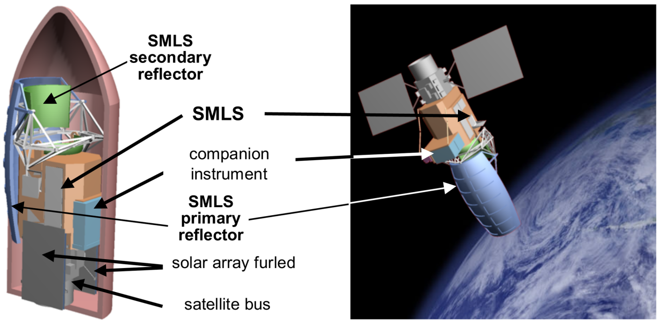

FIGURE 9. Artist renditions of (left) SMLS stowed in the payload faring of a Delta-II rocket and (right) deployed in orbit with SMLS looking into the page. The SMLS primary reflector is stowed and deployed using a precision hinge/latching mechanism.

V. FUTURE POSSIBILITIES

Much better horizontal resolution than the ∼50×50 km of the SMLS described here is needed to resolve convective-scale processes in the upper troposphere. Such improvement in resolution potentially could be obtained with a 180–280 GHz conical-scanning antenna system having ∼1 km field-of view width in both the vertical and horizontal planes at the limb tangent point. Two SMLS-type instruments with such antennae could be placed in adjacent orbits to nearly simultaneously observe the same parcel of atmosphere with their respective line-of-sights crossing at an angle of, say, 45° or more. Such a system could, in principle, provide measurements with ∼1 km resolution in all three spatial dimensions. Over the last several years, designs and several important radiometer components have been demonstrated for two-dimensional planar integrated fly's eye heterodyne array receivers [38]. Individually optimized beam forming lenses to mitigate wide scan angle antenna gain loss and phase distortion have also been demonstrated [39]. Further improvements are likely to be forthcoming and may allow an electronically scanned phased array receiver. Additional studies are needed to determine the feasibility of such an instrument.

ACKNOWLEDGMENT

J. W. Waters thanks his former colleague and dear friend, J. J. Gustincic, for developing in 1975 a rapidly-rotating-feed offset-fed scanning antenna [40] for an early project [41]. That antenna system inspired R. E. Cofield's design of the SMLS antenna described in this paper. Very sadly, we lost Dr. Gustincic in the 25 September 1978 crash of Southwest Airways flight 182 on its approach to San Diego. Waters would like to dedicate this paper to his memory.

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JOE WILLIAM WATERS was born in 1944 in Montgomery County, TN, USA. He was admitted to the Massachusetts Institute of Technology (MIT), Cambridge, MA, USA, in 1962. His career in microwave radiometric measurements began in 1964 through a part time job with Professor David Staelin in the MIT Radio Astronomy Group who then was first applying radio astronomy techniques to measurements of Earth's atmosphere. He received the B.S. and M.S. degrees from MIT in 1967, and the Ph.D. degree in 1971 with Professor Staelin as an advisor. His Ph.D. thesis, ground-based microwave remote sensing of Earth's upper atmosphere – done jointly in the MIT Departments of Electrical Engineering, Physics, and Meteorology – first demonstrated the use of microwave spectral line shapes for remotely sensing vertical profiles of stratospheric gases. That technique now is used operationally by instruments deployed worldwide in the Network for Detection of Atmospheric Composition Change.

From 1971 to 1973 he was a member of the MIT Research Laboratory of Electronics research staff and responsible for atmospheric temperature profile retrievals from the MIT-led microwave spectrometer on the NASA Nimbus-5 satellite launched in 1972. This work provided the first demonstration that passive microwave remote sensing from satellite could measure atmospheric temperature profiles with the accuracy required for operational weather forecasting. It led to microwave temperature sounders, which can "see" through clouds, being continuously deployed on operational meteorological satellites since 1978. In 1973 the California Institute of Technology Jet Propulsion Laboratory (JPL), where the Nimbus-5 microwave spectrometer instrument was developed, lured Waters from MIT to start a JPL science capability for developing passive microwave measurement techniques for Earth observations. Within a few months he conceived and initiated development of the Microwave Limb Sounder (MLS) experiments, which he led for the next 34 years. These progressed through aircraft, balloon, and instruments launched 1991 on the NASA UARS satellite and launched 2004 on the NASA Aura satellite. To date there have been ∼2000 MLS-related peer-reviewed scientific publications. In 1975 – when the high-frequency limit of instruments that could be put on satellites was around 200 GHz – he started a JPL program in submillimeter-wavelength technology to initiate development of the technology needed for measurements of stratospheric molecules having spectral lines at higher frequencies. Initial goals of the program, realized 30 years later by Aura MLS incorporating technology developments from follow-on programs, included measurements of stratospheric HCl at 626 GHz and OH at 2.5 THz. In 2007 he conceived and documented a differential absorption cloud radar technique for measuring temperature and composition inside clouds. That technique now is being developed for measuring water vapor inside clouds.

He has more than 200 peer-reviewed scientific publications, two book chapters, and numerous conference proceedings papers and technical reports. *Science Watch* 2001 listed him as the 16th most-cited author in geoscience worldwide for the decade 1991–2001. His honors include many NASA Group Achievement Awards, NASA's Exceptional Scientific Achievement Medal (awarded twice, between 1985 and 1993), the JPL Chief Scientist's Award of Recognition in 2007, and NASA's Exceptional Achievement Medal in 2008. The International Science Council's Committee on Space Research (COSPAR) in 2008 honored him with its William Nordberg Medal. Waters retired in 2007.

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