Terahertz Pioneers

A Series of Interviews With Significant Contributors to Terahertz Science and Technology

AS A TRIBUTE to individuals who have contributed significantly, and over many years, to the Terahertz community, and as a guide and inspiration for those who are just beginning their professional association with this field of study, these transactions have included, on a regular basis, a series of biographical interviews with technical researchers who have appreciably impacted the THz community in a positive manner. In order to go beyond a strict technical review and to take better advantage of the information and commentary only available through a direct discussion, these articles take on a less formal style than the research articles that can be found within the remaining pages of the transactions. The Editor-in-Chief has taken some leeway in this regard, for the benefit of communicating more fully the character, experiences, and historic circumstances that have shaped our community and set the directions for our collective research. As a further means of assuring that the true flavor and circumstances of the contributions are expressed in the text, all of the articles are compiled after a face-to-face interview. The final text is shared with, and often helped considerably, by comments from the subject of the article. The Editor-in-Chief, with the support of the IEEE MTT Publications Committee, has chosen to incorporate these biographical articles within the more formal technical journal because of the diversity of disciplines that make up the THz community and the prior absence of a single unifying publication with sufficient outreach to extend across the whole of the RF and optical THz disciplines. The Editor-in-Chief hopes you have enjoyed the short diversion of reading these articles as much as he himself enjoyed the process of writing them.

This is the last planned THz Pioneer article that I will contribute to this journal. It is long past the time for me to step aside and give another enthusiastic supporter of our field a chance to shine. I would like to take this opportunity to thank all of the supporters of this series, especially those of you who have responded directly to me with comments. I hope you have enjoyed the articles and will recall a little something now and then, which helps you with your own goals or ideas.

To those individuals who have allowed me to come into their lives, and to record something of what they have accomplished and of what mettle they are forged, I cannot thank you enough for the privilege. You have taught me so much about yourselves, and by extension, about the process of doing science. More than that, you have instilled in me a profound faith in the value of hard work, devotion to a cause, and the absolute necessity of not allowing obstacles or setbacks to deter one from a goal. All of you have my most profound respect for what you have accomplished and for who you are as individuals. Thank you from all of us simple mortals, who must try to follow in your footsteps and learn from your teachings.

As this is the last planned article in this series, I want to make certain that the global impact of THz science and technology, the so called "killer application" many speak about and some still seek, receives the attention it has so rightly earned. This application comes when THz helps us with global problems, which have real consequences for all of us on planet Earth. Of course no field of science or technology holds all the answers or can provide all the tools to resolve questions of worldwide impact. However, when any field of science can play even a small part in helping us better understand or solve a problem with global consequences, it should bring enough satisfaction to gratify zealots and sponsors alike.

No individual, in my opinion, has done more to apply THz technology towards this most emphatic end—that of solving global problems—than Dr. Joe William Waters.[1] As you will read, Dr. Waters has been invoking THz science and techniques for his entire career of more than 40 years, and for the most altruistic of motives—serving the planet Earth, understanding our atmosphere, and elucidating the role humankind plays in tipping the balance of nature for or against our own best interests. As such, I have entitled this final Pioneer piece *"THz Meets Gaia"*. I hope you will appreciate the symbolism and the role that Joe Waters has played in applying THz techniques for the well-being of us all.

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[1] Joe W. Waters lives, works and hikes in Southern California. Coincidentally, when he is not out hiking the many wilderness trails of the west coast of the United States, or otherwise traveling, he resides a block away from my own residence in La Cañada. It was there that we spent the morning together this past Labor Day (September 7, 2015) reminiscing about a career spent in trying to better understand the processes that drive, or have driven, some of the most prominent of our global environmental policies—stratospheric ozone depletion, climate change, and air quality. At the same time I heard about the experiences of a dedicated scientist and naturalist and the challenges he faced in making a career out of trying to help the planet.

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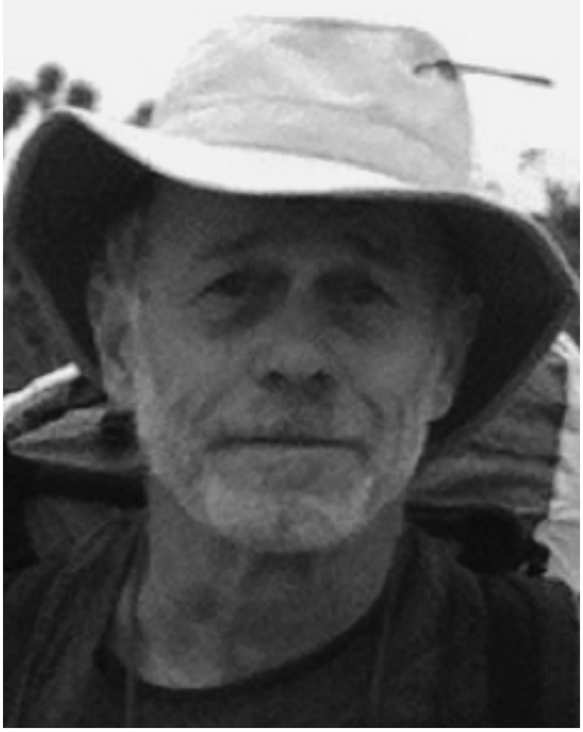
Terahertz Pioneer: Joe W. Waters

"THz Meets Gaia"

Peter H. Siegel, *Fellow, IEEE*

THE EARTH WE LIVE ON is the most precious gift the universe has granted to humankind. As we struggle to fully understand its frailties, and the impact we ourselves will have on its future as a habitable world, any science or technology that can shed some light on the condition of the planet as a whole, is of paramount value. Few individuals have recognized the special role that THz can play in understanding the processes that govern the stability of Earth's atmosphere, and in turn, all our futures, more than **Joe William Waters**.[1]



JOE W. WATERS

Joe Waters was born into a humble, and hard-working, farm family outside of Clarksville[2], Tennessee, in the southeastern United States. Joe's father Jamie, was late bringing back the midwife on a frigid winter morning in January 1944, and so Joe's mother, Sarah, a local school teacher, handled the delivery of her first born son on her own. That very strong tradition of individualism and self-sufficiency was passed on to Joe, who was not only the first in his father's family of five generations to leave farming, he was the first to attend university—a Northern one at that[3]. He chose his course after interacting with other high school students at a summer science school he attended in Nashville (TN, USA) at the urging of his local high school algebra teacher, Bannie Bowman. One of the Nashville students kept boasting about a school called MIT that he planned to attend—at the time Joe didn't even know what the initials meant. After learning more about MIT, Joe set his mind on going there, and like many things Joe set his mind to, he succeeded in following through. This decision to leave the farm he loved[4] was not an easy one, and Joe recalls the change in life direction with great emotion, and a true sense of abandoning an alternate path that he most certainly would have also enjoyed traveling.

When Joe decided he would like to apply to college, his family was more than supportive. Although his local schooling was not up to the standards of the larger cities, Joe made up for the lack of classes by learning trigonometry from his grandfather's surveying books and he taught himself calculus. He attended the larger Clarksville High School his senior year and won the prestigious Bausch and Lomb science medal.[5] Although he says it was a shock to all when MIT accepted him as a freshman student, it was Joe's father who made it a reality by posting the family farm as collateral for Joe to get a bank loan to cover expenses. Toting a single trunk of belongings, Joe

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[2] For those of you who have watched the popular Ken Burns documentary series about the US Civil War, you may notice that Clarksville is highlighted in several of the vignettes that describe small city life in the South during the conflict. The TV series first aired in Sept. 1990 on U.S. Public Television. https://en.wikipedia.org/wiki/The_Civil_War_(TV_series)

[3] Note that there was an animosity against the north that still lingered in the southern US during this time and it certainly extended to a distrust of "Yankee" institutions. To his family's great credit, they exhibited a liberalism that went well beyond the local community.

[4] Joe's best friend as a young boy of 7 was a Native American, Billy Burdette, of partial Creek Indian origin, whom he followed around constantly, learning how to survive in, and love, the wilderness.

[5] Since 1933—awarded to outstanding high school science students: http://www.bausch.com/our-company/community-relationships/science-award-and-scholarships#.VfBymxFVhBc

set off on his first trip north of Kentucky on board a Greyhound bus bound for Boston (MA, USA) in the fall of 1962.

Although he missed the country and was frequently homesick, Joe's strong farm-derived family work ethic allowed him to sail through freshman year and, starting his sophomore year, to earn a scholarship[6] that covered tuition ($1700 per year at the time!). His practical upbringing, and the desire to have strong job potential upon graduating, pushed Joe more into engineering, than the math and physics that were his first academic loves. While looking for part-time jobs at the beginning of his sophomore year, he stumbled on an advertisement for a technician in the MIT Radio Astronomy group working for Dave Staelin [7], a new assistant professor. When he got the job—assembling microwave radiometers (with no prior experience whatsoever), he felt it was going to be a game changer. Staelin ended up becoming a lifelong mentor and the single most important influence on Joe's career.

Staelin was an early Ph.D. student of MIT's Alan Barrett (founder of the MIT radio astronomy group, and himself a student of Nobel Laureate, Charles Townes). Barrett had led a key experiment on Mariner 2 that flew by Venus in December 1962, the first successful robotic probe of another planet (Mariner 1 was aborted and exploded shortly after takeoff in July 1962). The Jet Propulsion Laboratory, Pasadena, CA, USA, with a team led by a young microwave engineer just out of McGill University, Montréal, QC, Canada, Frank Barath (more on Frank a bit later), developed the two-channel (15.7 and 22 GHz) Dicke-switched microwave radiometer that definitively measured the Venusian temperature near the surface [1], [2]—more than 300 °C—convincing science fiction writers that it was not quite our "sister planet" after all![8] More importantly for our story, this initial collaboration between MIT and JPL involving space-based microwave radiometry, was to have an enormous impact on the subject of this article, as well as for atmospheric science.

As Joe began working on radiometers with Staelin, he became more and more excited by the potential applications of microwave systems. For his Master's thesis (under Staelin), Joe developed and experimented with microwave holograms [3], while working as an MIT engineering co-op student at General Electric's Advanced Technology Laboratory in Schenectady, NY, USA. After completing his Masters in 1967, Joe decided to stay on at MIT for a PhD, and to work with Staelin on applications of radio astronomy techniques for Earth atmospheric studies. He also applied for, and received a slot in the summer student program at the National Radio Astronomy Observatory (NRAO) in Greenbank, WV, USA, where he met Sandy Weinreb, Robert Mattauch [4], and Tony Kerr—three microwave engineers who would have a great impact on his future. His work with NRAO, under Sandy, involved analyzing balloon data to help in the site selection for what was to become the Very Large Array radio astronomy facility in Socorro, NM, USA, and the development of a technique using 22 GHz water vapor emission measurements to correct for atmospheric phase effects in interferometer data [5], [6].

Back at MIT, Joe started on his Ph.D. course by taking Alan Barrett's class on "Fundamentals of Radio Astronomy" where he learned about radiative transfer, microwave spectroscopy and calculating radiometric signatures for molecules from their spectral data. He claims it was the best class he ever took. Waters also participated in microwave astronomical observations from Haystack radio observatory and at NRAO. In particular, the measurement of water vapor [7], which was to become a later theme, and methyl alcohol [8]. Dave Staelin was now focusing on developing microwave techniques for use in atmospheric studies. Haystack's Marion Littleton Meeks had earlier, as a student of A. E. Lilley at Harvard, made the first calculations of atmospheric absorption and emission by the 60 GHz spin-rotational spectral band of molecular oxygen, O_2 [9]. Staelin was convinced that satellite measurements in the 60 GHz band could provide global atmospheric temperature profiles with the accuracy needed for weather forecasting and—very importantly and uniquely—they could also be made in the presence of clouds that limit infrared and shorter-wavelength measurements. He was developing such an experiment for the Nimbus satellite program, and would soon become the leading proponent and pioneer of microwave remote sensing of the Earth [10]. Also, Alan Barrett, with his student Tom Wilheit, had a stratospheric balloon program at the National Scientific Balloon Facility in Palestine, Texas, for testing the O_2 theory. Joe's involvement with this program would later serve him in good stead when he developed his own ballooning program for microwave limb sounding—more on this later.

Staelin and Barrett were interested in stratospheric water vapor, which had become a political issue due to a proposed fleet of commercial supersonic aircraft (SSTs) whose exhausts were calculated to release large quantities of water vapor into the stratosphere—doubling the then accepted stratospheric concentrations (as measured by some aircraft and balloon sensors) and thus potentially affecting global climate [11]. However, there was a controversy over how much water vapor was actually in the stratosphere. Some balloon in situ measurements had indicated the concentrations were 100× greater than the accepted values, which—if correct—would mean the proposed SST fleet would not likely pose an environmental problem. In what is likely the earliest publication on applying radio astronomy techniques to study Earth's atmosphere, Barrett and his student, Victor Chung, calculated that if the stratospheric water vapor concentration were as high as some balloon data indicated, the emission signatures could easily be detected from the ground by observations of the 22 GHz spectral line [12]. When Staelin and Barrett offered this as a challenge to Joe for a Ph.D. thesis topic, he enthusiastically signed on.

Joe had to build the instrumentation from scratch (receiver, spectrometer, data processing equipment and data reduction

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[6] Joe won MIT's Science Scholarship endowed by Harry and Betty Morss of Boston and Marblehead, MA, USA, who took a personal interest in Joe, and would treat him to dinner, sailing and an occasional concert, greatly broadening his social skillset. They remained lifelong friends.

[7] In addition to his many achievements in the development of the field of microwave atmospheric spectroscopy, Dave Staelin is also notable for the discovery in 1969 of two pulsars in the Crab Nebula which provided the first evidence linking supernovae and rotating neutron stars to these stellar objects.

[8] The radiometers flew three different swaths across the planet and were able to measure the average temperature through what turned out to be an optically thick atmosphere at the chosen wavelengths (13.5 and 19 mm). The 320 °C–420 °C thermal signatures were two times higher than those measured by the Mariner 2 infrared radiometers (that did not penetrate as far), and somewhat lower than the actual surface temperature which is closer to 460 °C as first measured by the Soviet Union's Venera 4 lander in October 1967.

software). He used components left over from MIT's involvement in the development of radar, for the radiometer front end, and was able to put an upper limit on the amount of stratospheric water vapor [13]. This confirmed that the balloon measurements of large amounts of stratospheric water vapor clearly overestimated the concentration,[9] and supported the case for restrictions on the SST emissions.[10] The same technique is still being used today—with much more sensitive 22 GHz radiometers—in the Ground-Based Network for the Detection of Stratospheric Change, providing continuous measurements of upper stratospheric and mesospheric water vapor, e.g., [14]. In the end, the political issue was settled by an economic reality—stratospheric SST's were just too costly to operate in large commercial fleets!

During this period, Joe also was able to use the Haystack telescope to try absorption measurements at 22 GHz using the Sun as a hot background. Joe's observation time at Haystack was Sunday morning, so he would have to leave Boston for the 30 mile drive to Haystack at 2AM in order to arrive and get set up for sunrise. It put a real damper on his weekend partying!

At Haystack, Joe became friendly with M. L. Meeks (the Haystack astronomer in residence), who suggested that he (Joe) might also be able to measure upper stratospheric O_2 emission [9] from the ground, and that this would make a good extension of his thesis. Joe took up the challenge, and put together a 53 GHz ground-based radiometer to record several high spin-rotational state O_2 transition lines with the goal of being able to measure stratospheric and mesospheric temperature profiles [15]. The O_2 lines are split into several Zeeman components that are affected by the Earth's magnetic field (presenting a polarized emission signature, which becomes noticeable in the upper stratosphere and above). Analyzing the full radiative transfer process of the polarized O_2 signal proved to be a challenge, but prior work by one of Barrett's former students, Bill Lenoir, who had just left MIT to join the NASA scientist-astronaut program, had developed the necessary theory [16]. Joe's calculations, using Lenoir's theory and done as part of his PhD dissertation, would provide valuable experience for later supervising more involved calculations for satellite measurements. Around this time Joe also starting writing a chapter on atmospheric absorption and emission for the *Methods of Experimental Physics* volume on *Astrophysics: Part B, Radio Telescopes* that Meeks was editing [17].

The results of the O_2 experiments were successful and well received [18], and Joe afterwards—while helping Alan Barrett with some astronomical observations—took his instrument to Arecibo Radio Observatory in Puerto Rico to make the first measurements of predicted changes in O_2 signals due to differences in the Earth's magnetic field between Massachusetts and Puerto Rico [19]. He also flew the instrument on NASA's Convair (CV)-990 Galileo Flying Laboratory[11] for temperature profile measurements up to high altitudes [20].

Joe received his doctoral degree in Electrical Engineering from MIT in 1970. He decided to stay on as a staff member to work with Staelin on the microwave spectrometer that was to be carried aboard Nimbus-5. The Nimbus satellite series started with Nimbus-1 in August 1964 and extended to October 1978, with Nimbus-7. Nimbus satellites were responsible for developing advanced measurement systems for weather forecasting, and for various Earth observation research activities such as sea ice measurements, solar radiance balance, global observations of stratospheric ozone, and later for communications links for search and rescue operations. Nimbus-5 launched on December 11, 1972, with a passive microwave radiometric instrument spanning five bands between 22 and 59 GHz. Staelin was the Principal Investigator. Frank Barath led development of the instrument at the Jet Propulsion Laboratory, and Joe was responsible for the data retrieval algorithm and validation of the atmospheric temperature profile measurements. The instrument proved to be a resounding success, and not only measured temperature and water vapor distribution in the presence of cloud cover (something IR systems could not do), but also parameters impacting surface emissivity (sea roughness, snow cover and ice type) [21]–[23]. This first-of-its-kind radiometric instrument cemented the value of microwave remote sensing measurements of the Earth's atmosphere into the bulwarks of numerous satellite programs to come. Nimbus-6 was launched in June 1975 with a scanning version of the radiometers [24]. The success of the Nimbus-5 and 6 microwave spectrometers led to use of similar instruments on operational weather satellites, starting with TIROS-N in 1978 [25], and the US Air Force Defense Meteorological Satellite program's (DMSP), Block 5D-2 Special Sensor Microwave Imager (SSM/I) series [26].

The many achievements of the Nimbus-5 passive microwave sounder were not lost on management at the Jet Propulsion Laboratory, who realized that having a strong science presence on site in Pasadena, would enhance their already well-developed instrument capability. With strong support from Frank Barath, JPL offered Joe a position "carte-blanche" to set up a science capability for microwave remote sensing of the atmosphere at JPL, emphasizing whatever areas he felt were important—and for which he could secure funding!

Leaving Boston was a difficult decision for Joe, since his whole career had been formed and nurtured by his friends and colleagues at MIT. Also, Joe's impression of Los Angeles was typical of residents of US northeastern cities at the time—smog, traffic and movie stars, not at all the bastion of technology and innovation that JPL and Caltech supposedly represented! Nevertheless, Dave Staelin recommended the move, advising Joe that it would benefit his career, and allow him to develop his own programs. Joe finally accepted the position at JPL, which was to begin in late November 1973, but before transferring his career to California, he decided to accept an invitation to attend a COSPAR (Committee on Space Research) meeting in Baku, Russia, to present a paper on the Nimbus-5 results.

On his way to Baku, Joe had arranged a stopover in the U.K. to visit John Houghton, Head of the Oxford University Department of Atmospheric Physics (later co-chair of the IPCC Inter-governmental Panel on Climate Change, and now Sir John Houghton), who had been very successfully developing atmospheric remote sensing techniques in the infrared. The visit was

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[9] As it turned out, the balloon observations were contaminated by water vapor being carried aloft on the balloons themselves.

[10] Satellite infrared measurements also confirmed the low stratospheric water vapor concentration by this time.

[11] A few weeks after his flights, a US Navy patrol plane and the NASA Convair 990 collided on approach to Moffett Field near San Francisco killing all aboard—many of whom Joe had flown with.

a great success and led to many years of collaborative work with individuals from Oxford, nearby Rutherford Appleton Laboratory, and Heriot-Watt University in Edinburgh, Scotland, U.K. (which Joe visited on the same trip).

On arriving in Baku, and after presenting his paper at the COSPAR conference, Joe was surprised to find that he had risen to the level of local celebrity. Kirill Kondratyev (notable head of the Department of Atmospheric Physics at Leningrad—now St. Petersburg—University) called him up impromptu from the audience (Joe was actually in the anteroom having coffee when he was immediately ushered into the large auditorium at Kondratyev's beckoning) to participate on a discussion panel that included a Soviet cosmonaut, a U.N. representative, and heads of several Soviet Institutes. After this honor, Joe found himself invited to Moscow and Leningrad—where he was even featured on local television! In one of his many adventures on that trip in the Soviet Union he was asked by a well-known professor to smuggle out several science papers and publicize them in the West. It should be noted that the Russian space-science program had included 22 and 37 GHz radiometers that had flown on Cosmos 243 and 384 as early as 1968 and a 300 GHz instrument that was used on Cosmos 669 in 1974 [27].

After returning to Boston from Russia, Joe loaded up his little VW square-back, and went by Tennessee to visit his family and pick up his brother Paul, who joined Joe on his long drive out to Pasadena, CA. On the way, the two brothers decided to take a short detour into Mexico to visit the Sea of Cortez. Coming back across the border into the U.S., their car was stopped and searched (for those of you who know Joe, you can easily guess why he might have been profiled for this!). Amongst his other belongings, the border guards noticed a pile of Russian literature, Russian artifacts and even some Russian currency. It took many hours to convince the authorities that Joe (and Paul) were not Russian agents, but that Joe had merely returned from a visit to Russia, albeit by way of Tennessee, and that the items in the car were just souvenirs. They eventually did make it to Pasadena, where Joe began work at JPL on November 19, 1973.

Joe's first responsibility at JPL was to take over the SIMS (Shuttle Imaging Microwave System) proposal concept from Frank Barath, who was on his way to Washington, DC for a three-year stint (officially known in government circles as a Detailee position) at NASA Headquarters. SIMS was being developed for lower atmospheric studies and surface imaging using passive radiometry between 1 and 100 GHz. A major challenge was the antenna system, which had to perform rapid scanning simultaneously over a very wide frequency range. Joe consulted several antenna engineers but found only one who managed to come up with a viable concept [28]. This was Jack Gustincic, a local JPL consultant, and soon to become Joe's "right-hand" person for microwave instrument development.

The SIMS concept proposal [29] was well received, but like the overwhelming majority of space mission proposals, it was never implemented. SIMS did provide funding for Joe to hire as a post-doc, Eni Njoku (a fellow student from MIT), who did some of the first remote sensing experiments (in support of SIMS), to develop and demonstrate the capabilities for passive microwave measurements of soil moisture. Eni used multi-frequency radiometers to measure soil samples using a giant "sandbox" built at JPL, with controlled water content. His work through the years eventually led to the SMAP (Soil Moisture Active Passive) satellite for measuring soil moisture that was launched by NASA in January 2015 [30]. Also, as part of the SIMS development to demonstrate microwave measurements of ice thickness, Joe had installed a portable swimming pool at nearby Big Bear Solar Observatory in the San Bernardino Mountains (where it got cold enough in winter to freeze water). He added a multi-frequency microwave system to record radiometric signatures while the ice was being melted by hot air jets at the bottom of the pool. On the first run, the plastic pool caught fire, much to the chagrin of the Big Bear Fire Department who were not pleased with the crazy scientists from JPL that were disturbing their peaceful resort community! Undaunted, Joe continued with the experiments, and demonstrated that ice thickness could be measured by this technique. Later, Joe, Eni, and post-doc Roland Hofer (from the University of Berne, Switzerland), analyzed data from the SEASAT satellite microwave radiometer and produced the first global maps of sea surface temperature using microwaves [31]. Assisting them with analyses of the antenna patterns was Rick Cofield. Rick had graduated from Caltech in 1974, started working with Joe in 1975, and went on to design the antenna optics for all of Joe's later satellite instruments.

Soon after starting work on SIMS, Joe realized that the antenna size that could be accommodated on the space shuttle could, for the first time, enable microwave limb sounding of the stratosphere from orbit. This observation technique records emission signatures from gases in the atmosphere by aiming the receiving antenna at the atmospheric limb, in order to obtain the longest-possible path for detecting weak signals. The incoming emission signal (which fills the beam) is measured against the cold backdrop of space, and the antenna beam width (set by the antenna size and the observation wavelength) and distance to the limb, determine the vertical and horizontal resolution. Limb scanning was then being developed in the infrared for Nimbus-6, which was to launch in 1975. Joe concluded that a 1.6 m antenna operating with a heterodyne receiver centered at 183 GHz [32] (water vapor line, with nearby ozone spectral lines as well) would enable H_2O and O_3 stratospheric measurements with the needed vertical resolution of 3 km from a satellite about 3000 km from the limb (typical for low-Earth orbits). The antenna would vertically scan the atmospheric limb in order to measure the altitude profile of the gases, and the orbital motion would provide global coverage. Joe calculated the signal strengths that could be expected from a number of potential molecules, and was quickly convinced that microwave (millimeter-wave) limb scanning was a potentially breakthrough technology for stratospheric research and monitoring.

The first microwave limb sounding (MLS) proposal was submitted to NASA in May 1974 [33], to build an aircraft instrument that would serve as development for a possible later space shuttle mission. Tony Kerr, then at NASA Goddard Institute for Space Studies, New York City, NY, USA, was a co-investigator, to supply the 183 GHz heterodyne front-end mixer and IF amplifier. The proposal was successful, and an aircraft instrument was built (more on this later)—but it would be another 17 years before the first microwave limb sounding satellite instrument was actually launched into space!

While Joe was investigating MLS signal strengths for upper atmospheric gases, he came across a paper [34], that predicted large amounts of carbon monoxide in the mesosphere (the atmospheric layer above the stratosphere) caused by photo-dissociation of CO_2. He calculated that the predicted amount of CO would have a very strong ground state rotational transition $(J = 1 - 0)$ signature at 115 GHz and should be observable from the ground (like the oxygen lines near 60 GHz). CO $J = 1 - 0$ had just recently been measured in the Orion Nebula [35], starting a spectral-line measurement revolution in the millimeter-wave radio astronomy community [36]. Joe contacted a former fellow "Alan Barrett" MIT student, Bill Wilson, who was then at Aerospace Corporation in nearby El Segundo, CA, USA, and proposed using one of the first large diameter millimeter-wave telescopes (a 4.6 m diameter dish on the roof of one of the Aerospace buildings) to make the mesospheric CO measurement in absorption against the Sun. Working with Aerospace's Fred Shimabukuro, Joe and Bill in May 1975 easily detected the 115 GHz CO signal and measured the amount of CO in the mesosphere for the first time [37]. Both Bill Wilson and Fred Shimabukuro would later move to JPL.

Following this measurement of CO in Earth's upper atmosphere, Ramesh Kakar[12], who had been a National Academy of Science post-doctoral research associate in the JPL radio astronomy group and had just become the first permanent JPL employee hired by Joe, suggested that a large CO signature should similarly occur around Venus and Mars whose atmospheres are mostly CO_2. Kakar, Waters and Wilson then quickly detected the first resolved millimeter wave spectral lines from the atmospheres of other planets: CO on Venus [38] in August 1975 using the Aerospace radio telescope, and CO on Mars [39] in November 1975 using the 36 foot telescope on Kitt Peak, AZ, USA, that had been operating since 1968 as part of the National Radio Astronomy Observatory.

In 1974, the science focus for upper atmospheric research took a sea change, when Sherwood Rowland and Mario Molina at UC Irvine, California published their groundbreaking paper on the threat to stratospheric ozone from chlorofluorocarbons (CFCs) [40]. The long lived CFCs were, over time, carried up into the stratosphere whereupon dis-association by UV photons released free chlorine Cl: e.g., $CFCl_3 + UV \rightarrow Cl + \text{other products}$. The released free chlorine quickly reacts with stratospheric ozone to form $ClO : Cl + O_3 \rightarrow ClO + O_2$. The ClO then quickly reacts with stratospheric atomic oxygen to release back the free chlorine: $ClO + O \rightarrow Cl + O_2$. This produces a catalytic cycle that destroys ozone without using up the free chlorine: the net reaction is simply $O_3 + O \rightarrow 2O_2$. Rowland, Molina and Dutch atmospheric chemist Paul Crutzen (who pointed out the potential deleterious effect of industrial N_2O–and SST NO exhaust—on ozone), shared the 1995 Nobel Prize in Chemistry for their discoveries.

The measurement of stratospheric ClO became the most critical issue for confirming the Rowland–Molina prediction of the chlorine threat to ozone. Ramesh Kakar pointed out to Joe that ClO should have a strong dipole moment, and therefore have a microwave rotational spectrum (undetermined at that time) that might be measurable by MLS. Howard Roscoe, from John Houghton's group at Oxford, who had recently joined Joe at JPL as a post-doc, went to UC Irvine to learn from Molina, how to make ClO for an absorption cell experiment. Kakar, with JPL spectroscopists, Ed Cohen[13] and Murray Geller,[14] then made laboratory measurements and worked out the ClO rotational spectrum for the first time [41]. Armed with this new spectroscopic data, Joe calculated that the aircraft MLS instrument then being developed, would have a good chance at measuring the ClO line at 167 GHz, to which the instrument could be tuned. He also was convinced that MLS on a satellite (providing a much longer limb path) should certainly be able to measure ClO, e.g., [42].

Joe and his team submitted a proposal, in collaboration with Oxford University, for a combined infrared/microwave limb scanning experiment on the NASA Space Shuttle's first Spacelab mission, which would include the measurement of stratospheric ClO [43]. This proposal was not funded, even though ClO was an extremely high-priority measurement. At that time there were only Joe's calculations (checked by Kakar) that ClO could be measured by MLS—and NASA was not about to spend millions of dollars on an unproved instrument whose ClO measurement was solely based on the calculations of some scientists whose credentials had not yet been established.

As part of Joe's MLS development program [33], he, Jack Gustincic, and colleagues had been flying the aircraft MLS on the NASA CV-990 out of Ames Research Center since November 1975—a replacement of the original aircraft (see footnote 11), that Joe had used during his days with Dave Staelin. They looked out through a passenger window of the CV-990, whose glass had been replaced with TPX, and, using a state-of-the-art mixer from Tony Kerr [32] and a klystron local oscillator, easily made the first measurements of the 183 GHz stratospheric H_2O line and a 184 GHz O_3 line [44] while on an interhemispheric survey on the CV-990 in October and November 1976. The plane flew from as far north as it could fly (from a base in Fairbanks, Alaska) to as far south as it could fly (from a base in Christchurch, New Zealand) [45].

In October 1976, just before leaving for the aforementioned CV-990 interhemispheric survey, Joe and his team, this time including millimeter-wave astronomy pioneers, Pat Thaddeus at Goddard Institute for Space Studies (who had hired and worked with Tony Kerr), and Tom Kuiper at JPL, attached the MLS 183 GHz receiver to the telescope on NASA's C-141 Kuiper Airborne Observatory (KAO), that had become operational in 1974 for conducting astronomical observations. The KAO boasted a 36-inch diameter Cassegrain telescope with a surface accuracy that allowed observations out to 1 micron, and that was mounted so as to peer out a large transparent window

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[12] Kakar would later head up a large atmospheric dynamics program at NASA Headquarters in Washington, DC, and lead development of the NASA TRMM (Tropical Rainfall Measuring Mission) satellite.

[13] Edward A. Cohen is a spectroscopist and quantum chemist who worked at JPL for more than 35 years. He contributed substantially to the JPL molecular line catalog and to the theory and microwave spectral measurement of many space-based radicals and atomic species. He co-edited a book, "Spectroscopy from Space," with Jean Demaison and Kamil Sarka which is available from Springer Science and Business Media, c. 2001.

[14] Murray Geller worked at JPL for more than 35 years as a well-respected quantum chemist and spectroscopist. He passed away in 2013 at age 79.

in the front fuselage. Waters *et al.* detected 183 GHz emission from the Orion Nebula [46], the first successful spectral line radio astronomy observations done from an aircraft!

Despite the early successes at measuring water and ozone, the stratospheric ClO measurement from aircraft, as expected, proved more elusive. Initial results at 167 GHz provided a tentative, but not definitive detection, so Joe and the team decided to try and measure stronger ClO lines at higher frequencies. Gustincic had developed a quasi-optical mixer mount that in principle could be tuned well into the submillimeter [47], [48]. Gustincic's quasi-optical radiometer front end was used in conjunction with a carcinotron local oscillator provided by Thijs de Graauw [49], who collaborated with Joe's team on board the CV-990, to search for the 241 GHz ClO spectral line. This again provided a tentative, but not definitive, ClO detection. Finally, Joe convinced Tom Phillips [50] to collaborate and use his much more sensitive hot-electron bolometer receiver [51] to search for the even stronger ClO line at 278 GHz. Tom's receiver used a tripled klystron for the LO, and had a very limited output bandwidth (1 MHz), because of the slow response of the superconducting bolometer, so measurements had to be made in a frequency-swept mode. The measurements with Tom Phillips were made 'piggyback' to astronomical observations on the KAO, with Tom's receiver mounted on the rear emergency door whose glass window was replaced with TPX. Again, a tentative—but not definitive—measurement of ClO was obtained. Overall the three aircraft ClO measurement campaigns provided a strong suggestion of the presence of ClO in the stratosphere and a useful upper limit [52]–both valuable in those early days of measurements related to stratospheric chlorine chemistry.

Anyone who has worked with these very finicky radiometer instruments will realize what a tremendous effort the aircraft campaigns involved. Operating on either of these two aircraft platforms was much worse than taking a commercial flight—even with today's budget conscious aircraft accommodations. Participants had to suffer extremely uncomfortable working conditions for themselves and their equipment (oxygen masks were required on the KAO for much of the flight), rigid safety guidelines, and long long days and nights of flying, and fatigue without the benefit of a tropical resort hotel to relax in after the ordeal! On one flight in particular, Joe remembers the rear emergency door of the KAO C-141 aircraft falling into the cargo area at the back of the plane (where he and Tom Phillips were doing their measurements) when the plane had descended to 3000 feet for landing. One of the ground crew had forgotten to engage the emergency safety pins before takeoff! Tom and Joe were sitting right next to the door (fortunately buckled in), having just removed the instrument from it, and were left staring out the gaping hole in the side of the plane! The positive cabin pressure had kept the door in place during the flight, as designed, until the approach for landing when the cabin pressure was no longer positive relative to the outside. A different, but equally frightening accident occurred on one of Tom Phillips later flights aboard the KAO (see [50, p. 480, col. 2]). Along with the risks, the comradery and teamwork that accompanied this type of research cannot be undervalued. Joe had no trouble attracting such notables as Tom Phillips, Thijs de Graauw, and many others to his cause, and the experiences they shared on these expeditions are deeply forged into all their psyches. In a horrible turn of events, Jack Gustincic was killed in a commercial plane collision over San Diego, CA, USA, in September 1978[15] just a year after the completion of Joe's aircraft campaigns described here.

Before the aircraft campaigns had started, Joe and Jack in 1975 had convinced JPL and NASA's Office of Aeronautics and Space Technology (OAST), to put a submillimeter technology development program in place at JPL in support of MLS. Its goals included, for example, development of receiver technology that could extend to 600 GHz for the first rotational lines of HCl (the major reservoir of chlorine in the stratosphere), and even up to 2 THz to measure OH (a critical radical in determining the relative importance of different chemical cycles of ozone destruction). That program supported technology development for Jack Gustinsic's quasi-optical receiver [47], [48] used in the aircraft MLS and, between 1979 and 1985, it supported 2 THz receiver technology by Tom Phillips and Herb Pickett (more on Herb later) with the goal of enabling OH measurements for both atmospheric and astrophysics applications. OAST, at Joe's urging, would later (1990's) contribute additional funding, by expanding its submillimeter-wave astrophysics receiver development program to include THz radiometer technology for Earth atmospheric science in support of EOS MLS (and by good fortune, the author of this article).

At this time, the early 1980's, Joe also realized that there needed to be much more emphasis on the spectroscopy of molecules that might be in the stratosphere. Only a limited number of laboratory measurements had been made in the THz range, and the large numbers of rotational and vibrational line signatures from all the molecules present in the atmosphere could cause undesirable overlap and screening of targeted weak spectral signatures—for example from ClO, BrO, and HO_2. Joe devised, e.g., [53] a simple "figure of merit", $M = f\mu^2/Q$, for prioritizing the spectroscopy needed for stratospheric molecules: f is the stratospheric abundance of the molecule, μ is its dipole (or higher order) moment, and Q is its partition function (number of available states)–all of which could be estimated without detailed knowledge of the molecule's spectrum. He then prioritized working out the microwave spectrum, including laboratory measurements if needed, of any molecule that had M more than 10× below that of a targeted molecule. As an example, ozone-destroying BrO was known to have a quite weak spectral line signature due to its very low abundance. In order to target BrO for a measurement on MLS for example, Joe needed to know whether the BrO lines would be obscured by lines from molecules such as sulfuric acid, vibrationally excited states of isotopic ozone and nitric acid, and many more—all of which had M more than 10× times below that for BrO. This meant lots of spectroscopy work, which the JPL (and other) spectroscopy groups enthusiastically jumped at.

In 1978, Ramesh Kakar left JPL for NASA Headquarters and Joe looked around frantically for a replacement. Fortunately several leaders in the field referred Joe to Herb Pickett (then at

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[15] Jacob Joseph Gustincic and all 144 people onboard Pacific Southwest Airways flight 182 were killed when a Cessna 172 flew into the commercial airliner over San Diego, CA, USA, on September 25, 1978. The data that formed the basis of the paper [52] was collected in 1977.

University of Texas). After a few telephone conversations and a short visit to JPL, Joe offered Herb the position, and Herb accepted. In September 1978, Pickett took up leadership for the spectroscopy work for MLS. He soon created the JPL Submillimeter, Millimeter, and Microwave Spectral Line Catalog[16] [54], [55] along with Ed Cohen and others, and he led the development of the technology for measuring stratospheric OH in the THz range. Pickett started his own successful stratospheric balloon instrument campaign using far infrared techniques for this purpose, and would later lead the 2.5 THz flight module development and OH measurement that would be carried on the second MLS satellite platform, EOS Aura MLS, in 2004—the first THz heterodyne spectrometer in space. Herb was also the "go to" person for almost every science or technology question or new idea that would come up in Joe's group (as well as many others at JPL) over the next 30 years. He was a master of quantum chemistry, radiometry, electronics, antenna theory and practically any other science and technology subject, and he remained a critical resource at JPL throughout his tenure.

After obtaining only a tentative detection of ClO from the aircraft measurements, Joe redoubled his efforts to remotely measure ClO, but from a stratospheric balloon platform. Measurements from balloon would provide a longer path length through the atmosphere, thus increasing the signal strength. The balloon platform also—very importantly—would not require observations through a window, which introduces baseline artifacts that were a major source of uncertainty in the aircraft measurements. Note that Jim Anderson, then at the University of Michigan but who joined Harvard in 1978, and who was later to make crucial in-situ aircraft measurements correlating ClO to ozone depletion in the Antarctic [56], made the first definitive stratospheric ClO measurements in 1976 with an *in-situ* resonance fluorescence instrument dropped on parachute from balloon [57].

The Balloon MLS program was funded in 1977 and targeted the 205 GHz spectral line of ClO. Joe's early experience at the Palestine, Texas National Balloon Scientific Facility, and the arrival of Bob Jarnot, another Oxford student from John Houghton's group, supplied critical expertise. Bob went on to become the overall lead for 'instrument science' for MLS satellite instruments, and was crucial to the overall success of the MLS program. Herb Pickett and super-technician Jack Hardy, also got involved in the balloon work around this time.

The first flight was on February 20, 1981 from Palestine, Texas, USA. A definitive detection of ClO and the simultaneous measurement of ozone were the result [58]. There was also a tentative detection of hydrogen peroxide and a measurement of the predicted ClO decrease at sunset. The BMLS receiver, was developed at JPL by Peter Zimmermann (a notable millimeter- and submillimeter wave instrument pioneer, and later founder of RPG Radiometer Physics GmbH, Meckenheim, Germany) using whisker contacted Schottky diodes from Bob Mattauch's lab [4] at University of Virginia, Charlottesville. A second flight in May 1981 [58] confirmed the decrease in ClO at night—predicted due to ClO binding with NO_2 after sunset to form $ClONO_2$, which is photo dissociated during daytime.

The BMLS instrument had many more successful flights tracking ozone and ClO at 205 GHz, e.g., [59], [60], in parallel with other activities to which Joe had now turned his attention. In 1988, NASA funded a BMLS upgrade to allow development of a 640 GHz radiometer channel that could capture the first rotational line of HCl at 626 GHz as well as ozone, HO_2, and the strongest ClO line. Robert Stachnik, who had joined Joe's team in 1983 from a post-doc position with Mario Molina—then at JPL—took over the higher frequency balloon program and later rechristened it SLS (Submillimeter Limb Sounder). University of Massachusetts' Neal Erickson from the University of Massachusetts, Amherst, MA, USA, supplied the first BMLS 640 GHz receiver [61], and the first of many successful flights began in 1991 [62]. Since then, SLS has been upgraded with a much more sensitive SIS (superconducting) radiometer, and is still operational under Stachnik's guidance, providing—for example—valuable measurements of stratospheric BrO [63].

With the microwave measurement of ClO now demonstrated on a balloon platform, Joe turned his full attention to a satellite mission. He had already submitted a proposal in response to a call for instruments on the NASA Upper Atmospheric Research Satellite (UARS) for which he had participated in developing the scientific objectives and satellite requirements [64]. UARS was a response to a Congressional mandate to NASA to develop a comprehensive program that would improve our understanding of the upper atmosphere. Joe's proposed UARS instrument—Microwave Limb Sounder (MLS) [65]–contained a suite of 5 radiometers at 63, 119, 183, 205 and 231 GHz for measuring ClO, O_3, H_2O, H_2O_2, CO, O_2, pressure, temperature, wind, and magnetic field. The receiver technology followed prior work by Staelin and Barath for Nimbus-5 [21] and Tony Kerr [32], but the latter technology (utilizing open whisker contact Schottky diode circuitry) required spaceflight verification and substantial reliability qualification.

The MLS instrument proposal was selected for definition phase in December 1980 and for implementation in November 1981 (soon after the appearance in October 1981, of the *Science* paper on the BMLS measurement of ClO [58]). However, the instrument had to be descoped due to cost constraints to only 3 critical channels: 205 GHz for ClO and ozone, 183 GHz for water, and 63 GHz for pressure (the pressure measurement was required in order to obtain a height reference for the other measurements). The funding of UARS MLS allowed Joe to add JPL's Rick Cofield, Lucien Froidevaux, Vince Perun, and Bill Read to the science team. Quoting Joe, "All of these folks would become, in their areas of expertise, pillars in the development, implementation, and operation of UARS MLS, and later, in the planning, development, launch and operation of EOS MLS."

A serious blow came in 1982, when due to cost overruns and scheduling problems at JPL, the 183 GHz channel was descoped by NASA program management. Water measurements would be available from two other infrared instruments on the UARS platform. Joe was extremely disappointed in the cutback and searched for ways to restore the lost measurement. John Houghton happened to visit JPL in January of 1983 and Joe invited him to dinner, where he relayed his regret on losing the water vapor measurement on MLS. John suggested that perhaps the UK might be able to provide the radiometer channel to NASA. On his return to UK, John confirmed the offer, and NASA accepted the contribution! Bob Harwood of Edinburgh

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[16] This was a greatly expanded version of an earlier JPL spectral line catalogue established for astronomical applications by Bob Poynter.

University led the UK science team, Gordon Peckham of Heriot-Watt University was the UK Principal Investigator for the instrument, and Peter Curtis managed the UK program. An excellent engineering team at Rutherford Appleton Laboratory, in Didcot near Oxford (a UK sister organization to JPL) developed the 183 GHz radiometer and delivered it to JPL for integration into MLS. At this point Frank Barath had returned from NASA HQ and, at Joe's urging, took over as project manager for MLS.

In 1985, the field of atmospheric science (and the world) was hit with a '*bombshell*' to quote Joe, when Joe Farman, released his findings from the British Antarctic Survey (BAS) instruments showing that total ozone levels (as measured from the ground) over Antarctica had dropped by as much as 70% in the austral spring [66]. Although the effects of chlorine on stratospheric ozone had been studied by leading atmospheric scientists for a decade, no one had predicted the ozone hole. Its cause turned out to be reactions that occur on Polar Stratospheric Cloud (PSC) particles, composed of mixtures of water and nitric acid, which form in the extremely cold Antarctic winter. These reactions convert the 'safe' forms of stratospheric chlorine, HCl and $ClONO_2$, into Cl_2 gas that is released into the stratosphere during the dark winter and then—upon return of the sun in spring—photolyzed into free chlorine, Cl, that rapidly destroys ozone.

Joe Waters later met Joe Farman, who told Waters that for years before announcing their discovery, the ground-based BAS instruments had shown that the Antarctic ozone was continually decreasing to unprecedented low abundances during the austral spring. Farman said he was somewhat worried about sending their paper in for publication, because he knew NASA had a satellite that was continuously monitoring ozone on a global scale, and that they had reported no unusual findings over the Antarctic. Farman trusted his measurements however, and submitted his findings to *Nature*, and the rest is history. As it turned out, the team responsible for the NASA satellite data had programmed their processing software to ignore such small ozone abundances, thinking they would be instrument anomalies, since it was 'known' that such low values could never occur. Once Farman's data became public, the NASA team reprocessed their data and produced the important ozone hole maps that are now so familiar. Waters made a pledge to himself that an oversight like this would never happen with any experiment while he was responsible for it. He even bet the UARS program manager a dinner that MLS would produce useful data within one month of launch—an unprecedented pledge for a new instrument on its first satellite platform. No dinner was ever so satisfying!

The Challenger tragedy in January 1986 was to have a big impact on UARS—which was so large that it required the shuttle for launch. The delay was to end up being two full years. During this time the MLS team had some necessary breathing room that helped them complete the more difficult parts of the instrument, including the front end radiometers at 183 and 205 GHz containing whisker contacted Schottky barrier diode mixers and frequency multipliers, which had never been flown in space. Joe had some time to complete a very well referenced book chapter on microwave limb sounding [67] and an equally popular contribution to the first PROCEEDINGS OF THE IEEE issue devoted solely to THz technology and science [53].

On Friday the 13th (Joe is not superstitious) in September 1989, the MLS instrument left JPL by truck for the cross country drive to General Electric's Astro Space facility in Valley Forge, NJ, USA, where it would integrated with nine other instruments onto the UARS satellite platform. UARS was launched at 23:11:04 GMT on September 15, 1991, by the Space Shuttle Discovery (STS-48). It was one of the largest Earth science spacecraft ever launched and was 35 feet long, 15 feet in diameter, and weighed 13,000 pounds. It was a major news story when it was launched, and also when it finally fell back to Earth in an uncontrolled descent on September 24, 2011. The platform carried 10 scientific instruments all devoted to upper atmosphere studies. The orbit was at an altitude of 375 miles with an inclination of 57 deg giving it near global day/night coverage of the Earth by instruments looking towards the limb. UARS performed an 180° 'yaw' maneuver each month to alternate high-latitude observations between the northern and southern hemispheres. Although I had the great privilege to be present at the launch from Cape Canaveral (I had spent some serious time working on the 3 radiometer package optical alignment and beam patterns), Joe was so nervous about the launch and so exhausted—a bit later we'll see what he was also doing with EOS MLS during this very time—that he chose to stay in Pasadena and watch it on NASA TV at JPL. It was a spectacular daytime launch, only 14 minutes behind scheduled countdown, and just as Joe had promised, MLS was producing useful data within two weeks! This was just in time to capture the austral spring and the Antarctic ozone hole.

Joe recalled that one of the most exciting moments in his career was shortly after the UARS launch when he was working alone in the lab late one night running the software to produce the MLS maps, and the first maps of ClO in the Antarctic vortex came through. He said his heart almost stopped. Although large amounts of ClO in the ozone hole had been expected from the aircraft measurements by Anderson in 1989 [56], Joe was shocked to see—for the very first time—the ClO completely filling the Antarctic vortex. The official NASA UARS project web page lists the number one significant science achievement of UARS as[17]

> "A few months after launch, MLS was able to map ClO (chlorine monoxide—an ozone destroying radical) within the Arctic vortex showing the extent of ClO formation and its close association with polar stratospheric cloud formation temperatures. Not only was this was an important confirmation of earlier aircraft results, but it also showed the extent of the zone of elevated ClO. Since these initial observations UARS has continued to monitor both the Arctic and Antarctic late winter-spring ozone depletions. The northern hemisphere depletion in January–March 1996 was the largest ever."

The same source lists the 8 most significant science achievements of the 10 UARS instruments. MLS plays a significant role in 6 of the 8.

The MLS measurements of ClO and ozone led to the first publication from UARS where MLS maps of enhanced ClO in both the Antarctic and Arctic vortices appeared on the cover of *Na-*

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[17] Quote from: http://umpgal.gsfc.nasa.gov/uars-science/science_highlights1.html

ture [68]. The instrument is fully described in [69], its calibration in [70], and the data processing algorithms and validation in [71]. Joe was told that NASA took the MLS maps of ClO and O_3 to the White House, and that they were a significant factor in convincing (the first) President Bush to support regulation of the levels of production and consumption of CFCs that had been spelled out in the Montreal Protocol on Substances that Deplete the Ozone Layer[18] in 1987, and were to be in full force by 1992.

UARS MLS provided daily measurements from September 29, 1991 (two weeks after launch), through March 1994 (although stratospheric water vapor measurements ceased in April 1993 after a failure in the 183 GHz radiometer front-end). After March 1994 the measurements became increasingly sparse in order to conserve lifetime of the MLS antenna scan mechanism and UARS power. The last data set was obtained on August 25, 2001. The UARS satellite was decommissioned on Dec. 14, 2005. The original mission lifetime goal was 36 months.

To date, there have been more than 275 peer-reviewed scientific publications related to UARS MLS (a full list is available at http://mls.jpl.nasa.gov). Almost 25 years after launch, UARS MLS data are still being used in scientific publications, e.g., [72]. The most important findings from the MLS instrument and their associated references are listed below in Joe's own words[19]:

- MLS quantified the amount of ClO and chlorine destruction of ozone in the Antarctic and Arctic lower stratosphere, e.g., [68], [73]–[87].
- The MLS H_2O measurements provided new information on how polar dehydration affects ozone loss, e.g., [88]–[90].
- As the MLS spectra became better understood, nitric acid (HNO_3), a critical player in polar ozone loss, was obtained from the data. This provided a wealth of new information on how differences in ozone loss between the Arctic and Antarctic, e.g., [91] are affected by denitrification e.g., [92]–[98]. The distribution and variations of HNO_3 throughout the globe were also quantified, e.g., [99], [100].
- MLS quantified the global content of ClO in the upper stratosphere, providing tests of chlorine chemistry in this higher region of the atmosphere, e.g., [101]–[104] that was initially thought to be most important for stratospheric ozone depletion.
- MLS measured the amount of SO_2 injected into the stratosphere by the Pinatubo volcano (erupted June 15, 1991 in the Philippines), and its effects on stratospheric ozone and temperature, e.g., [72], [105]–[107]. This information was obtained from the unplanned MLS measurement of SO_2 spectral lines.
- A wealth of new data was obtained on the distribution and variations in global stratospheric O_3, e.g., [108]–[113], H_2O, e.g., [114]–[122], and the general circulation and transport processes of the stratosphere, e.g., [123]–[132].
- A new measurement obtained from MLS was the observations of gravity waves e.g., [133]–[136]. These are atmospheric 'buoyancy' waves, (not—of course—the gravity waves of Einstein!) which had never before been observed on a global scale, but are important for parameterizing high-altitude wave-breaking affects in atmospheric circulation models.
- The UARS MLS stratospheric O_3 measurements, in conjunction with other satellite instruments that measure total vertical column ozone, have also been used to infer the amount of ozone in the troposphere, e.g., [137], [138], important for global air quality studies.
- MLS mapped the global distribution and variation of methyl cyanide (CH_3CN) in the stratosphere for the first time [139] and observed an injection of forest-fire CH_3CN into the stratosphere by a strong thunderstorm [140]. Although not planned, these measurements were obtained from careful analyses of the observed spectra.
- Last, but certainly not least, MLS provided the first height-resolved global measurements of upper tropospheric water vapor and cloud ice, e.g., [141]–[149]. They have provided unique and important new information on key processes affecting climate change, e.g., [150]–[156], tests of existing climate change models, e.g., [157]–[159], and insights into processes in the Tropical Tropopause Layer and exchange between the troposphere and stratosphere, e.g., [160], [161].

As a testament to the scientific value of UARS MLS data, *Science Watch* (November/December 2001) listed Joe Waters as the 16th most-cited author in geoscience worldwide for the decade 1991–2001.

While all of the UARS MLS development was going on, NASA in 1988 announced an enormously ambitious international (NASA, ESA, Japan) Earth applications program known as the Earth Observing System, e.g., [162]. EOS was originally planned as a multiple launch (6 enormous 12,000 kg satellite platforms—twice the mass of UARS), 50+ separate science and monitoring instruments, a complete ground based data handling facility, and a 30 billion dollar price tag. The response to the original Announcement of Opportunity for instruments was due in July 1988, and Joe and his team enthusiastically responded [163], despite the overwhelming workload of preparing for UARS. The EOS platform represented a chance to implement technology that had not been flight ready when UARS MLS was proposed, but was now within reach. The 626 GHz HCl line was added as well as 557 GHz water, and ClO at 268 GHz along with 205 GHz ClO and ozone, and 118 GHz oxygen, water and CO, amongst many other molecular species (more than 25 primary measurements in all). The five radiometer bands were designed to operate continuously and simultaneously along the same optical beam path.

MLS made the EOS baseline selected instrument list, and was planned for launch on the second NASA Polar Platform, then

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[18] The Montreal Protocol (spurred by Farman's measurements of the ozone hole) is one of the most successful international treaties ever conceived. It was ratified by 196 countries and the EU—the first universally ratified treaties in UN history—in 1987, and has since undergone eight revisions. CFC production and use was mandated to 150% of 1986 levels by 1992 and to zero by 1996. Despite the treaty, the predicted healing of the ozone layer (return to pre-1980 levels) is not expected to occur until after 2050. Ref: https://en.wikipedia.org/wiki/Montreal_Protocol.

[19] Joe gave me a selected set of references that he requested be listed in categories that present an up to date list of the scientific accomplishments of MLS in these categories. Since MLS played such a major role in upper atmospheric chemistry and was such a major influence and motivation for the deployment and use of THz technology in space the references are listed here as Joe presented them with summary descriptions in his own words.

designated as NPOP-2 [162]. However, congress had other ideas for EOS. Baulking at the cost and scope, they allocated only ten billion dollars for the program and an immediate 3× descope ensued. On August 29th, 1991, Joe received the news that MLS was cut from the EOS program payload.

NASA's reasoning was not unfounded. UARS had not been launched, MLS had not yet demonstrated that it could really make its advertised measurements, the infrared measurements community was much stronger than the microwave measurements community in regards to atmospheric science, and work on the ozone problem had indicated that measurements in the lower stratosphere would be much more important than the upper stratosphere where the UARS MLS design was targeted.

The next week was extremely critical. Joe felt so sure about the quality and importance of the measurements MLS would be able to make under the EOS program, and he was so passionate about the role of microwave limb sounding for atmospheric science, that—despite his other overwhelming responsibilities getting ready for the UARS MLS launch that would take place in less than two weeks—he worked around the clock and through the Labor Day holiday, consulting many people on the MLS team, to come up with a strategy and response to the NASA program office regarding the descope of EOS MLS.

Joe quickly and boldly responded to NASA. In a September 9th, 1991 letter to the NASA Director for Earth Science and Applications, Shelby Tilford, he argued that the MLS capability was crucial to the goals of EOS, and that in particular, ClO and upper tropospheric H_2O could not adequately be measured by any other technique. He told Tilford, that MLS would readily target the lower stratosphere, now considered so important, and that it could uniquely make composition measurements in the presence of aerosols and clouds that limit other techniques. Joe even proposed that MLS should be enhanced with an additional measurement channel at 2.5 THz to map OH—critical to models for many chemical cycles in the stratosphere. In effect—at the time when the EOS budget had been reduced to one third, and MLS had just been removed from the payload—Joe not only argued that MLS should be reinstated, but also asked NASA for more money and to take on more technical risk, by adding a completely new and untested OH measurement capability! In fairness, Joe reduced the power consumption and data rate by deleting some less-important measurements (mostly isotropic species), and changed from the originally proposed forty 1000-channel acousto-optic spectrometers, to a smaller number of filter bank and auto correlator spectrometers with many fewer channels.

To the great delight (and, perhaps, amazement) of all of us on the MLS team at JPL, in particular Joe himself, this strategy ultimately worked! Over the next year, the NASA program office conducted a series of formal reviews to vet the MLS Principal Investigator's proposed claims, and to determine the feasibility of actually building and delivering a working 2.5 THz heterodyne radiometer (particularly the proposed local oscillator—a never before flown CO_2 pumped far IR laser system). I can personally attest to the seriousness, the hard work, and the stress of this process (being largely responsible for proving technically that we could deliver both the 2.5 THz as well as the other submillimeter-wave radiometer channels with the specified performance in flight), and to the passion that Joe showed throughout in support of the revised MLS instrument. The outcome was by no means certain, and there were competing infrared instrument measurement teams that tried to argue alternative schemes for producing similar data, but in Dec 1992, Joe received a much anticipated letter from Shelby Tilford, re-instating EOS MLS with the OH measurement included! By this time UARS MLS had been producing spectacular data for more than a year - making it easier for Tilford to decide in favor of EOS MLS.

Herb Pickett, who had been developing his own far-infrared interferometric based instrument for measuring OH [164], came back onto the MLS team and took overall responsibility for the OH measurements. Unfortunately, proposed U.K. support for providing a 557 GHz radiometer did not come through (although U.K. participation on the EOS MLS science team continued) and the five lower frequency bands were reconfigured to include: 1) 118 GHz for both polarizations of O_2 emission, temperature, pressure and wind; 2) 190 GHz for continuity with UARS MLS: ClO, O_3, H_2O, and HNO_3—and for N_2O, HCN, CH_3CN and volcanic SO_2; 3) 240 GHz primarily for upper tropospheric O_3 and CO, but also providing HNO_3 and volcanic SO_2; 4) 640 GHz primarily for HCl, ClO, BrO, and HO_2, but also providing HOCl, HNO_3, N_2O, and CH_3CN; and 5) 2.5 THz (both polarizations for improving signal-to-noise) to measure OH (also water and ozone).

State-of-the-art planar diode mixers and multipliers were used in all the radiometers [165] and newly developed InP based low noise MMIC amplifier technology [166] was employed for the 118 GHz radiometer channel. Subharmonically pumped mixers (LO at half the signal frequency) were used in the 118, 190, 240 and 640 GHz receivers and a fundamental mixer employing a new GaAs membrane Schottky diode concept [167] was employed at 2.5 THz. Local oscillator systems were all solid state, except at 2.5 THz where a specially developed all autonomous low DC power flight-qualified CO_2-pumped methanol gas laser was used [168], as no solid state source at that frequency was then available. The 2.5 THz radiometer [169] was in a separate module [170], with separate optics from the other MLS radiometers. In addition to much broader spectral coverage than UARS MLS, EOS MLS had much wider-bandwidth IF amplifiers and spectrometers for measurements at lower altitudes and new high-resolution digital autocorrelator-based spectrometers for measurements at higher altitudes. Note that the EOS MLS design and development (without the OH module) had started well before UARS MLS had left the ground!

In order to make sure EOS MLS could make the claimed lower altitude measurements more accurate knowledge of the continuum absorption from water and oxygen in the upper troposphere was needed. Joe enlisted noted microwave spectroscopist Frank De Lucia [171] at Ohio State who was able to develop the needed theoretical models and perform the supporting laboratory measurements [172].

Despite the stress, and oppressive work load and juggling between two flight programs as well as all his regular supervisory duties and professional functions, Joe remembers the early days of EOS MLS with great excitement and enthusiasm. He was in constant flux and claims it was not unusual for him to wake up at 2 in the morning, go into his office and do some necessary calculations or prep work for the coming days challenges. In the end, he was satisfied that he had done the best job possible in choosing the spectral bands and the measurements that would end up on the instrument that would not fly until 16 years after the initial proposal.

EOS MLS was launched on the EOS Aura spacecraft on July 15, 2004, from Vandenberg Air Force base, Lompoc, CA, USA, on board a Delta rocket (Joe went and watched this launch!), and like UARS MLS the instrument went fully operational within two weeks, and began producing useful results [173]. A complete and detailed overview of the experiment is available for download on the MLS home page [174].

As with UARS MLS, a tremendous amount of effort was put into the instrument calibration, e.g., [175], [176], the radiative transfer or 'forward models' required for data processing, e.g., [177]–[179], the algorithms for extracting atmospheric profiles from the data, e.g., [180], and the validation of the resulting data products, e.g., [181], [182].

As in the case of UARS MLS, Joe supplied me specific statements, and selected references, for what he felt to be the major science accomplishments of EOS MLS in various categories, included accomplishments made after he retired in October 2007. Since these stem from the very first comprehensive submillimeter-wave satellite measurements of the Earth and the first THz heterodyne radiometer in space, and therefore should be of great interest to the THz community at large, I have reproduced Joe's inputs in his own words below and included all his selected references in the extensive bibliography at the end of this article:

- A major new feature of EOS MLS was its capability to provide global height-resolved measurements of the pollutants CO and O_3 in the upper troposphere. These have provided unique new information on the intercontinental transport of pollution, e.g., [183]–[194], and how pollution may affect climate change by altering the formation and radiative properties of clouds, e.g., [195]–[199].
- The improved measurements of upper tropospheric water and cloud ice, e.g., [200]–[207] have provided new insights on processes affecting global warming, e.g., [208]–[213] and for improving models for weather prediction and climate change, e.g., [214]–[223]. These, and other, MLS measurements have also provided new information on exchange pathways between the troposphere and stratosphere, e.g., [224]–[234], important for both climate change and ozone depletion.
- EOS MLS has continued, with an improved suite of measurements, the UARS MLS quantification of polar ozone loss and the processes affecting it, e.g., [235]–[243]. Chemical ozone destruction over the Arctic in early 2011 was—*for the first time in the observational record*—comparable to that in the Antarctic ozone hole [240]! New insights have been provided on processes affecting polar ozone loss, including dehydration, e.g., [244], [245], and de-nitrification, e.g., [246]–[248]. These—for example—have placed the chemical processing in, and dispersal of processed air from, the winter polar vortex, into a global context [249].
- The measurements of HCl, the dominant form of chlorine in the upper stratosphere, allowed EOS MLS to quantify the decrease in stratospheric chlorine as expected, following the regulated phase-out of industrial chlorocarbons [250], [251]. (There are, however, indications of a recent anomalous stratospheric HCl increase that is attributed to a slowdown in the northern hemisphere atmospheric circulation [252].)
- The EOS MLS measurements have provided additional insights and constraints on stratospheric chlorine chemistry, e.g., [253]–[257], and the first global climatology and variability of methyl chloride in the stratosphere and upper troposphere [258].
- The EOS MLS first global measurements of stratospheric BrO, the dominant molecule in the bromine destruction of ozone, have allowed inference of the total bromine content of the stratosphere [259]. Recent analyses of the data [260] imply a contribution from short-lived bromine substances.
- The OH and HO_2 global measurements, also the first ever, have provided constraints needed to resolve problems with model calculations of O_3 in the upper stratosphere and the so-called "HO_x dilemma", e.g., [261], [262], and quantified the diurnal variation of OH in the stratosphere and mesosphere, e.g., [263], [264]. They have also given new information on solar and energetic particle effects on mesospheric OH, e.g., [265]–[270] and on nitric acid in the stratosphere and mesosphere [271], [272].
- The first global measurements of HCN, e.g., [273]–[276], have given yet another avenue of insight into atmospheric processes.
- The EOS MLS measurements have provided much new information on the overall global distribution and variations of O_3, e.g., [277]–[283], H_2O, e.g., [284]–[289], stratospheric and mesospheric CO, e.g., [290]–[293], temperature, e.g., [294]–[297], mesospheric clouds, e.g., [298]–[300], mesospheric wind, e.g., [301], [302], gravity waves, e.g., [303]–[306], and the overall circulation and transport of the upper atmosphere, e.g., [307]–[317].
- EOS MLS detected water vapor ejected into the high atmosphere from Space Shuttle exhausts (each launch deposits some 700 tons of water vapor into the atmosphere) [318], with approximately 50%–65% of the Shuttle launches detected, [318]. SO_2 injected into the stratosphere by a number of volcanic eruptions was also measured [319]
- In a very novel use of EOS MLS data, Pumphrey *et al.* [320] used the routine above-atmosphere views of MLS to detect 230 GHz emission from galactic CO and perform a survey covering a larger area of the sky than any other 230 GHz survey to date. No previously unknown galactic sources of CO were observed.
- The EOS MLS O_3 data have also been used extensively in conjunction with other satellite measurements of total column O_3 to infer the total amount of O_3 in the troposphere, e.g., [321]–[328], valuable for improving our knowledge of the global distribution and variation of this important contributor to the lowering of our air quality.

After more than 10 years in orbit, EOS MLS is still operational and producing its scientific data products, (with some measurements now made intermittently to conserve instrument lifetime, most notably OH since the THz module design was based on a requirement to have only a one year lifetime—but which operated essentially continually for the first five years in orbit). Since launch there have been more than 550 peer-reviewed publications related to EOS MLS (an up-to-date list is available at http://mls.jpl.nasa.gov).

As if there could be time for anything else during the period of UARS MLS in-orbit operation and EOS MLS development, Joe Waters began thinking about a "next generation" MLS well before EOS MLS had launched. He reasoned that the whole THz region soon would be completely available to high resolution spectroscopy (still not quite true, but we are getting there! *voc. ed.*). The current MLS technique, using vertical scanning to get high vertical resolution, provides limited horizontal coverage as it was not feasible to simultaneously scan the antenna in both the vertical and horizontal planes, and vertical resolution was a higher priority. Better horizontal resolution was needed, however for adequately studying important atmospheric phenomena such as transport of pollutants in the upper troposphere, convective processes in the troposphere that affect climate change, and transport processes impacting ozone loss in polar regions.

Joe felt that a future instrument was needed that could fill in the horizontal gaps between orbits while simultaneously measuring vertical profiles. On a visit to Sandy Weinreb's MMIC facility at Martin Marietta, Baltimore, MD, USA, in 1995 (Sandy was at Martin Marietta for a few years after leaving NRAO and University of Virginia in Charlottesville, and before going to University of Massachusetts, Amherst, MA, USA, and finally JPL and Caltech) he found a potential way to realize such an instrument. Sandy was developing close-packed millimeter-wavelength monolithic integrated circuit (MMIC) radiometer modules which could enable large focal plane millimeter-wavelength arrays of radiometers operating up to 200 GHz, and urged Joe to consider using them as an array in a future instrument.

Joe became very excited about the array concept and started up a program for development of an Array MLS instrument. NASA was supportive and over the next several years detailed concept proposals were generated and submitted, but major program funding did not materialize. A side benefit of the work was the replacement of the traditional mixer front-end on the EOS MLS 118 GHz radiometer channel with a more innovative and better performing MMIC amplifier front-end based on the developments Sandy Weinreb had shown Joe.

As superconducting radiometer technology, and low-power cryogenic cooler technology, advanced under the THz Astrophysics spectroscopy programs (e.g., Herschel Space Telescope [49], Joe realized that the complex focal plane array geometry envisioned for Array MLS could be replaced by a simpler superconductor receiver system—having detection sensitivity sufficient for individual measurements to be made in such a short time that they would allow simultaneous vertical and horizontal scanning. He reckoned that an antenna system, somewhat similar to that conceived 30 years earlier for SIMS by Jack Gustincic [28], but with the SIMS rotating feed replaced by a small properly-shaped horizontally-scanning subreflector placed at a radiometer beam waist located at the focal point of the main antenna would do the trick—with the overall antenna system simultaneously being scanned more slowly in the vertical plane. Rick Cofield quickly did an optical design and analyses that showed this could be done. Joe then revamped the Array MLS concept to a Scanning MLS (SMLS) using the superconductor-based detectors. In Joe's vision, SMLS would be an appropriate step forward for a next generation MLS, which could uniquely provide many crucial measurement needs for better understanding climate change, the intercontinental transport of pollution affecting global air quality, and continue measurements needed for monitoring upper atmospheric chemistry. A very important feature of this concept is that in the correct orbit, it can perform vertically and horizontally resolved measurements 8 times per 24-hour diurnal cycle over much of the globe (to date, most global vertically-resolved measurements have been made at only two local times, thus missing a wide range of diurnally-varying phenomena whose measurement and understanding are crucial for many important atmospheric processes).

The SMLS concept, along with a companion UV Tropospheric Pollution Imager instrument from the Royal Netherlands Meteorological Institute was presented to NASA in 2005 [329] as the CAMEO (Composition of the Atmosphere from Mid-Earth Orbit) mission. Although an SMLS-type instrument has not yet been selected for a mission, NASA is funding work at JPL that supports developments for it. Rick Cofield and colleagues have fabricated and tested a 4 m prototype of the light-weight antenna. Nathaniel Livesey (another product of John Houghton's former Oxford group, who joined Joe in 1996) and colleagues are now planning flights on NASA's ER-2 of an aircraft version of SMLS that has already flown on NASA's WB-57, and have funding to enhance that instrument with new technology (which also simplifies it). For the satellite version of SMLS, Livesey and team at JPL are incorporating much new technology—developed since Joe first presented the concept to NASA—that both simplifies and improves the instrument.

In his last project before retiring from JPL, Joe developed and documented [330] the fundamentals for a new concept to obtain very high vertical resolution measurements of water vapor within clouds using a cloud radar to measure differential absorption near 183 GHz. NASA is also funding further development of this concept under Nathaniel Livesey's leadership.

Joe retired from JPL in 2007 and turned his MLS Principal Investigator position over to Nathaniel, his science group supervisor position over to Michelle Santee, and his engineering group supervisor position over to Paul Stek. Retiring was a difficult decision, as Joe very much loved his work and colleagues, and had a secure position at JPL. EOS MLS, on which he had worked so hard, was producing exciting new and valuable data that was keeping his entire team occupied and satisfied, and he felt there was already in place a robust concept for a next-generation MLS instrument, which would keep things going for years to come. However, Joe had many other interests, which he wanted to pursue while still in good health and thought it was time to give younger people a chance to determine the future of MLS.

Since retiring, Joe has made good on his promise to himself to do the things he most missed while working. He has hiked the Pacific Crest Trail that runs 2650 miles from Mexico to Canada, completing all except 50 miles in southern California—mostly solo (at the time of this interview Joe had just returned from re-hiking a 270 mile portion of the PCT that he especially loves in northern Washington). He has also done a lot of world traveling with his wife, Jill (a long time high school physics teacher—now also retired—and a favorite teacher of my son, Alex who had Jill as a teacher at La Cañada High School).

As you can tell from reading this article, Joe Waters loves nature and loves the Earth. It was the motivation for his work of 40 years, and it is his constant source of wonder, as well as concern that we are not doing enough to make sure we do not damage it beyond repair. One man can do only so much in one lifetime. Certainly Joe Waters has fulfilled that mantra. However much he has already accomplished, it is very much in character that his last words to me in this interview were: "*We've seen only the very start of what THz technology can do for atmospheric science*."

Special Acknowledgements from Joe Waters:

Knowing Joe for many years, it was no surprise to me when he asked if I might devote a small section of this article for him to thank the individuals who have most helped him throughout his career. How could I refuse such an altruistic request? Here is Joe, in his own words:

"There are so many people to thank, but space to name only those who most crucially affected the course of my life and whatever success my career had. First I thank my parents, Jamie and Sara Waters, for their love and inspiration that honesty and hard work for a good cause are virtues worth pursuing—and for encouraging my education. I thank my high school algebra teacher, Bannie Bowman, for convincing me to attend a science summer school—without which I would not have applied to MIT. I thank my MIT professors and mentors, Dave Staelin and Alan Barrett, for guiding me into a wonderful career. Becoming associated with Dave was—second only to attending MIT itself—the best thing that ever happened to me professionally.

I thank Tony Kerr for developing 200 GHz low-noise mixer-preamps just (coincidentally) at the critical time needed for starting MLS; Bob Mattauch for his great UVa diodes and especially for developing the deep-well diodes used in UARS MLS; Jack Gustincic for so many contributions in the critical early days of MLS and his passion for submillimeter technology development; Thijs de Graauw and Tom Phillips for collaborating with me on the pioneering aircraft measurements; Jack Hardy for learning to contact the UVa diodes and teaching UARS MLS flight technicians; Peter Zimmermann for developing the BMLS radiometer; Peg Frerking and Brian Maddison for leading development of the UARS MLS radiometers; Peter Siegel for leading development of planar diode technology and the EOS MLS radiometers, and—especially—his inspirational enthusiasm for THz science and technology; Mike Gaidis and Herb Pickett for leading development of the EOS MLS 2.5 THz module; Eric Mueller for leading development of the 2.5 THz laser at Coherent Corporation. I thank Frank Barath and Gary Lau for managing the MLS flight projects, and JPL Director Charles Elachi for his sustained support of my activities. I thank Shelby Tilford, formerly NASA Director of Earth Science and Applications, for having faith in our work to make the decisions to fly MLS on the UARS and EOS satellites.

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Finally, I thank my wife Jill for being a major part of my life's adventure, for her love and support especially while our careers occupied us so much, and additionally—now in retirement—for broadening my horizons with the world travels she organizes for us."

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Joe William Waters received the B.S. and M.S. degrees from the Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, in 1967, and the Ph.D. degree from Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, in 1970—all in electrical engineering, and under the supervision of Professor David Staelin. His Ph.D. dissertation was on microwave remote sensing of Earth's upper atmosphere, done jointly through the MIT departments of electrical engineering, physics, and meteorology.

From 1971 to 1973, he was a member of the MIT Research Laboratory of Electronics research staff, with primary responsibility for atmospheric temperature profile retrievals from the recently-launched MIT/JPL microwave spectrometer on the NASA Nimbus-5 satellite. This was the first demonstration that microwave sensing could produce global temperature profiles with the accuracy needed for weather forecasting, and led to the microwave temperature sounders on operational weather satellites. In November 1973, he joined the Jet Propulsion Laboratory to lead development of microwave experiments for Earth applications, and within a few months started the Microwave Limb Sounder (MLS) experiments, which he led for the next 33 years. These progressed through aircraft, balloon, and satellite instruments launched 1991 (on the UARS satellite) and 2004 (on EOS Aura). 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 in order to get developed the technology needed for measurements of important stratospheric molecules having spectral lines at higher frequencies. Initial goals of the program, realized 30 years later with the launch of MLS on Aura, by incorporating technology developments from follow-on programs, included the measurements of stratospheric HCl at 626 GHz and OH at 2.5 THz. Numerous additional molecules have been measured. The MLS experiments have produced unique global information on stratospheric ozone depletion, climate change, and intercontinental transport of pollution. To date, there are over 900 peer-reviewed scientific publications related to MLS (listed at http://mls.jpl.nasa.gov).

Dr Waters' honors include NASA's Exceptional Scientific Achievement Medal (awarded twice, in 1985 and 1993), the JPL Chief Scientist's Award of Recognition for "profound contributions to Atmospheric Science" (2007), NASA's Exceptional Achievement Medal (2008), and COSPAR's William Nordberg Medal (2008). *Science Watch* (November/December 2001) listed him as the 16th most-cited author in geoscience worldwide for the decade 1991–2001. He has over 200 peer-reviewed scientific publications, 2 book chapters, and numerous conference proceedings papers and technical reports.

Dr. Waters retired in 2007. Since then his major passions have been long-distance backpacking and traveling the world with his wife Jill. Other activities/interests include wooden ship modeling, woodworking, miniature machining, neuroscience, reading (mostly non-fiction), dabbling with playing guitar, and camping around the western US with Jill in their camper van. When not traveling he and Jill divide their time between homes in La Cañada, CA, USA, and Cambria, CA, USA.