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***Abstract*—The spectral window at L-band (1.413 GHz) is important for passive remote sensing of surface parameters such as soil moisture and sea surface salinity that are needed to understand the hydrological cycle and ocean circulation. Radiation from celestial sources (mostly galactic) is strong in this window, and an accurate accounting of this background radiation is often needed for calibration. This paper presents a comparison of the background radiation predicted by a model developed from modern radio astronomy measurements with measurements made with several modern L-band remote sensing radiometers. The comparison validates the model and illustrates the magnitude of the correction necessary in remote sensing applications.**

***Index Terms*—Galactic background, microwave radiometry, remote sensing.**

I. Introduction

THE spectral window at L-band (1.400–1.427 GHz) reserved for passive use only is important for measuring parameters such as soil moisture and ocean salinity that are needed for understanding the hydrological cycle, ocean circulation, and energy exchange between surface and atmosphere. At this frequency, radiation from celestial sources (mostly galactic) is strong and, unlike the constant cosmic background, is spatially variable across the sky. This radiation is sufficiently strong that it is necessary to take it into account during calibration (e.g., looking at cold sky) and necessary to make corrections for the down-welling radiation that is reflected from the surface and detected by the sensor. For example, this is the case in the remote sensing of sea surface salinity, which requires high radiometric accuracy (at L-band the sensitivity to salinity is on the order of 0.5 K/psu) [1], [2].

Recent radio astronomy measurements at 1.4 GHz [3]–[8] have made it possible to produce maps with sufficient spatial and radiometric accuracy to be relevant for remote sensing applications [9], [10]. In this paper, a comparison is presented of background radiation predicted using the model developed by Le Vine and Abraham [9] with the measurements of several modern remote sensing radiometers. Comparison is presented with the Passive/Active L/S-band (PALS) radiometer developed at NASA's Jet Propulsion Laboratory (JPL), the LEWIS radiometer developed by the French Aerospace Research Center (ONERA) for the Centre d'Etudes de la Biosphere (CESBIO), and the EMIRAD polarimetric radiometer developed at the Technical University of Denmark (DTU). The objective is to validate the database (e.g., the procedure for converting the radio astronomy measurements to equivalent brightness temperature) and to validate the procedure for locating the source of down-welling radiation in the celestial sky. The comparisons also illustrate the magnitude of the correction and its significance for Earth remote sensing at L-band.

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II. Background Radiation

The source of the background radiation in the window at 1.4 GHz is line emission from neutral hydrogen and broadband (continuum) emission primarily from thermal and synchrotron sources. Sources within our solar system, such as the sun, are not included. Radio astronomy measurements in this window were recently repeated with modern instruments, and these data were converted into an equivalent thermal source suitable for use in passive remote sensing applications [9]. The data are presented in the form of maps of the brightness temperature T_B of an equivalent thermal source with total power $P = \mathrm{k}T_\mathrm{B}\Delta_\mathrm{B}$. An example for a bandwidth, $\Delta_\mathrm{B} = 20$ MHz, is presented in Fig. 1 [9].

The cosmic background radiation is also significant at L-band (a thermal source with a temperature of 2.725 K). But this source is essentially constant across the sky and therefore easily taken into account. On the other hand as Fig. 1 illustrates, the sources of the emission from hydrogen and the broadband emission tend to be concentrated close to the plane of the galaxy [7], [9]. As a result, the background radiation can be quite variable spatially and care must be taken to identify the portion of the sky from which radiation reaches the radiometer.

The apparent brightness temperature actually seen in a remote sensing application can be significantly different from the peak values because the antenna smoothes the incident radiation. This is especially true in the vicinity of the galactic plane, which is relatively narrow compared to the resolution obtained with existing L-band radiometers. This is illustrated in Fig. 1, which shows (left) the equivalent brightness temperature of the sky with high spatial resolution (0.25° × 0.25°) and (right) the same map after smoothing by an antenna with a Gaussian beam and a half-power beam width [full-width at half-maximum (FWHM)] of 15°.

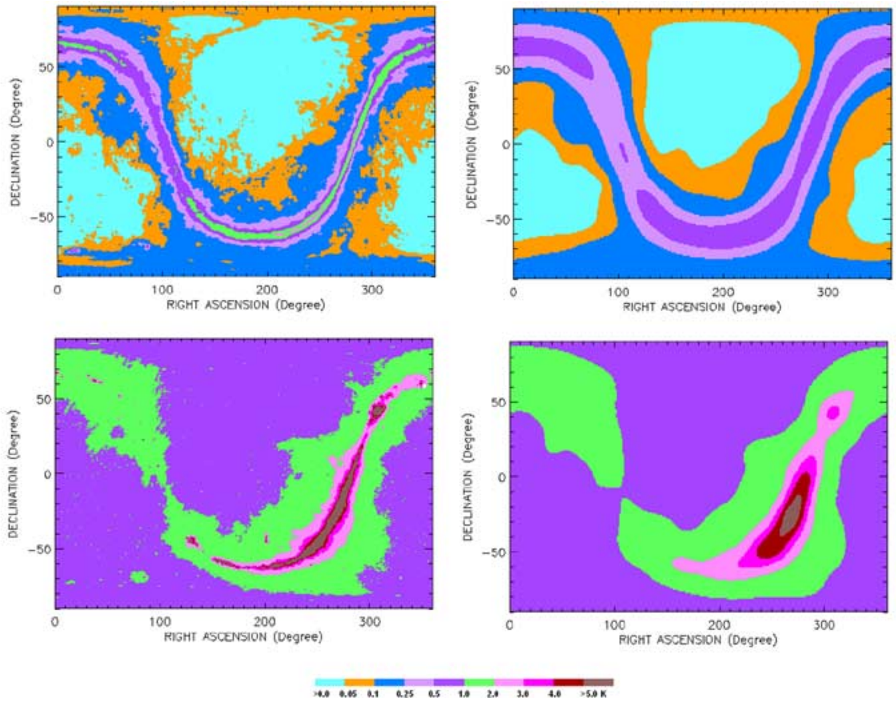

Fig. 1. (Top) Line emission and (bottom) continuum background in units of equivalent temperature in 20-MHz bandwidth. The cosmic background is not included. High-resolution data ($0.25^\circ \times 0.25^\circ$) are on the left, and the same data but smoothed with a 15° (FWHM) Gaussian antenna beam are on the right.

III. Comparison With Measurements

Measurements looking at the sky with modern radiometers provide data to validate the database [9] and the procedures for locating the source of radiation in the sky. Such measurements also provide insight into the signal level to be expected in practice from the background radiation. Comparisons are given below of data from three different radiometers with model predictions assuming a 20-MHz bandwidth and a Gaussian beam.

A. Comparison With PALS

PALS is a passive and active (radiometer and radar) instrument system that operates at two frequencies, L- and S-band [11]. One of the modes is a dual polarized (V- and H-polarization) radiometer operating in the radio astronomy window at L-band. The L-band instrument employs a large conical horn antenna with an aperture of 1 meter and an estimated half-power beam width of about 13.5° (the antenna pattern has not been measured). The radiometer bandwidth is 20 MHz. The PALS system is an aircraft instrument, which flies on a C-130 with the antennas looking toward the surface with the rear cargo door open. However, in September 2001, during stability testing on the ground, the radiometer was pointed at the sky (zenith) and allowed to collect data over night.

Fig. 2 shows the data recorded at L-band on the evenings of September 21–23 [12]. The top panel in Fig. 2 shows the average for the three days for each polarization plotted as a function of local time. Data was not collected during daylight because of possible contamination by radiation from the sun. The root mean square (RMS) value of the fluctuations about the mean was about 0.035 K and daily averages differed by less than 0.05 K [12]. During calibration of the radiometer, the bias was established by assuming a value of 5.5 K for the brightness temperature at the coldest point (about 0200 hours). This value is comprised of 2.7 K for the cosmic background, 1.9 K for the atmosphere and 0.9 K for the galactic background. The later value was chosen from the database in Fig. 1 and a different choice had been made before this data was available. (Because the antenna is in a fixed position relative to its surroundings, contributions from possible sidelobes are nearly constant and can be treated as part of the bias that is removed during calibration.)

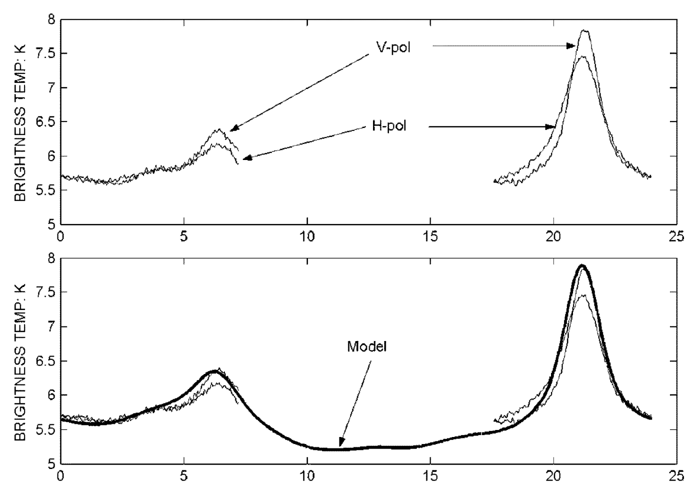

Fig. 2. Comparison of the PALS data with the predictions of the galactic background model. The figure at the top shows the average of PALS data collected on September 21–23, 2001. The figure at the bottom shows the comparison with the model prediction (bold line). Data were only collected during the nighttime hours.

The lower panel in Fig. 2 shows a comparison with the signal predicted by the model (bold line). The predicted signal is obtained in three steps. First, the data is smoothed by integrating with the antenna beam and normalized to the correct bandwidth (20 MHz). The result is a map such as shown on the right in Fig. 1. Then, using conventional astronomical time keeping the locus of points on the sky overhead in the direction of the bore-sight ray of the antenna is determined for the period of the measurements. This identifies the equivalent temperature of the down-welling radiation. The procedure is as outlined in [9, Appendices A-C]. Finally, 2.7 K is added to account for the cosmic background and 1.9 K to account for the down-welling emission from the atmosphere [13]. The contribution from the ionosphere (less than 0.05 K [14]) has been neglected. The net result for September 22, 2001 is the curve labeled "Model" in Fig. 2 (bold line).

Clearly the shape and dynamic range of the signal as the antenna bore-sight crosses the galactic plane (the peaks at 0600 and 2100 hours) of both the data and the model predictions are in agreement. In part, this is a consequence of the value assumed for the galactic background at the reference point (0200 hours) chosen for calibration of the radiometer. There are also some important differences between the measurements and model. In particular, notice the difference between the measurements at the two polarizations. This is most obvious near the peaks at 0600 and 2100 hours. The model assumes unpolarized radiation from the sky (the same signal for H and V polarization). However, the measurements indicate a difference, especially at the peaks that occur when the bore sight ray crosses the galactic plane. Although polarized radiation is possible [15], [16], the extent to which the difference is due to external sources or the antenna is still a subject of investigation [17]. For example, even though the main beam is identical for both polarizations, differences in the sidelobes could result in differences (from the relatively warm surroundings) at the two polarizations.

B. Comparison With LEWIS

The LEWIS radiometer is a dual polarized L-band radiometer designed for field work to study the effect of vegetation canopy, freeze-thaw cycle, incidence angle and other variables on the remote sensing of soil moisture [18]. It was developed for CESBIO by ONERA and is currently deployed at a research site near Toulouse. The radiometer antenna is a Potter horn about 1.1 m in diameter. It is 1.6 m long with a ring of corrugations at the aperture. The entire antenna assembly (horn plus transition and feed waveguide) is nearly 3 m long. The antenna beam has a FWHM of about 13.6° and the radiometer has an effective bandwidth of 20 MHz [19].

During validation of this radiometer, data was collected while looking at the sun and at "cold sky." The latter was done at two incidence angles: 1) zenith (90° elevation); and 2) looking to the north (zero azimuth) at an elevation of 60°. The transit across the Sun indicated that the main beam was essentially identical for V- and H-polarization [19]. The data at 60° consisted of a continuous record from August 2–5, 2002 and the data at 90° elevation consisted of a continuous record from July 22–25, 2002. The data are shown in Fig. 3 (left) as a function of local time. There are several traces, one per day, and the curves have been shifted (4 min/day) to correct for the motion of the Earth around the sun.

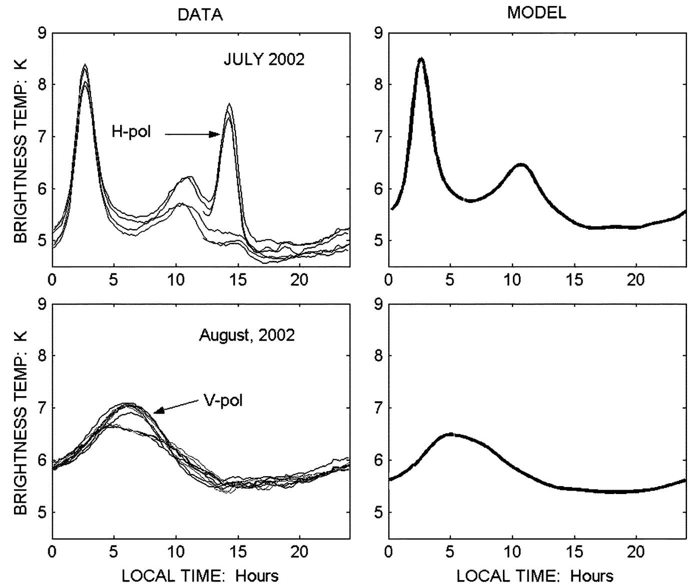

Fig. 3. (Left) Lewis radiometer data for (top) July 22–25, 2002 and for (bottom) August 2–5, 2002. (Right) Brightness temperature predicted by the model. The July measurements were made looking at the zenith (90°) and the August measurements looking to the north at 60°. In each figure on the left, there are two sets of curves, one for H-polarization and one for V-polarization. Only one set is labeled.

The predicted signal for each of these cases was computed using the procedures described above (PALS data). The only difference is that in this case, a factor $1.9/\cos(\theta)$ K was added to account for down-welling emission from the atmosphere and the calculations were done using a Gaussian beam with a 13.6° beam width. The results are plotted on the right in Fig. 3 (labeled "Model"). The value of 1.9 K for the emission from the atmosphere at zenith was calculated using temperature and pressure profiles representative of this location and date [20].

The shape of the measured brightness temperature (left) and the predictions (right) are in reasonable agreement. At the top (July), the two crossings of the galactic plane are clearly evident. At the bottom there is only one crossing as expected for the decreased elevation angle. However, there are some obvious differences. In particular, notice the large peak in the horizontally polarized signal for July (at about 1400 hours). This peak is neither in the model nor in the vertically polarized data. This peak is consistent with the passage of the sun through a sidelobe. At 1400 hours the sun comes within about 24° of the bore-sight ray of the main beam. The gain in this part of the pattern is on the order of −20 dB for horizontal polarization and −33 dB for vertical polarization, which accounts for the difference in response [19]. In the absence of the sun, the model and data are in close agreement. A numerical comparison has been made after slight adjustments in the offset: 0.66 K was added at vertical polarization and 0.32 K was added to the signal measured at horizontal polarization. The justification being that these biases are set during calibration. In the absence of the sun, the RMS fluctuation of the data about its mean is less than 0.05 K and the RMS fluctuation of the data about the model prediction (with the offsets) is about 0.1 K.

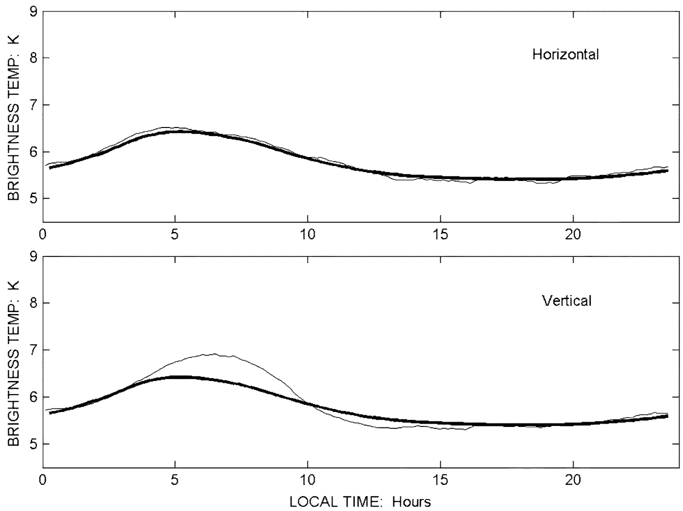

Fig. 4. Comparison of Lewis radiometer data for August 2, 2002 with the model (bold). (Top) Comparison for horizontal polarization. (Bottom) Comparison for vertical polarization. An offset of 0.15 K has been added to each polarization.

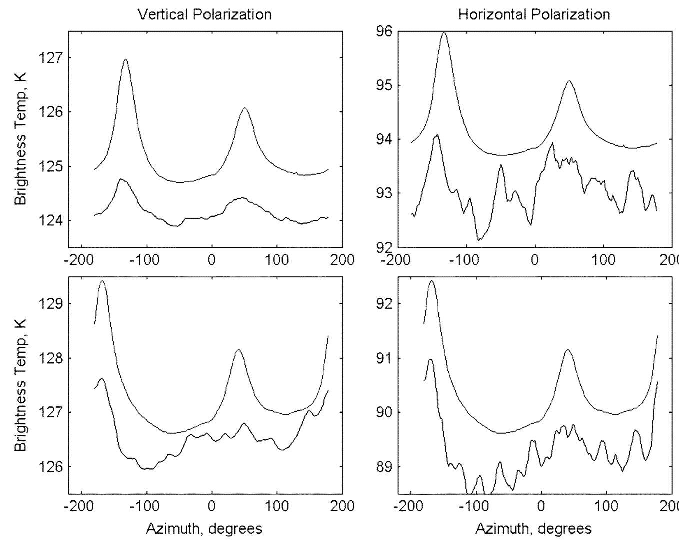

Fig. 5. Comparison of the EMIRAD measurements (lower curves in each panel) during the LOSAC experiments with predictions of the galactic background radiation (upper curves in each panel). The galactic background signal has been offset by an arbitrary amount to fit just above the measurements, but the amplitudes have not been changed.

There is no contribution from the sun in the August data because the elevation angle (60°) adds 30° more separation between the main beam and sun. Model and data for a single day (August 2) are shown in Fig. 4. An offset (0.15 K) has been added to each polarization. The agreement with the model is good in the case of horizontal polarization; however, there is a difference at vertical polarization between 0400 and 0900 hours. In this region the amplitude and shape differ from the predicted behavior and also from the data at horizontal polarization. A similar set of measurements in September 2002 showed the same behavior [19, Fig. 28]. This may be a source of interference (e.g., entering through a sidelobe) but evidence for this has not been found. With this exception, agreement with the model is good. The RMS fluctuation of the data about its mean for the three days in August is about 0.07 K and the RMS difference of data from the model is less than 0.1 K at H-polarization. At Vertical polarization, with the anomaly included, the RMS difference is about 0.2 K.

C. *EMIRAD L-Band Radiometer*

The EMIRAD L-Band radiometer is a polarimetric radiometer that employs A/D conversion at RF and digital processing [21]. The analog front end is reasonably conventional using noise injection for calibration and analog 90° hybrids to produce I and Q outputs at RF. However, at this point the signal is digitized using subharmonic sampling and the subsequent processing is digital. The effective bandwidth of the radiometer is about 27 MHz.

This radiometer has been developed to look for effects of wind/wave direction on the brightness temperature of the ocean at L-band. Several experiments have been conducted in which the radiometer was flown aboard a Danish Air Force C-130 in circles about a fixed point on the surface. The antenna used in these experiments is a horn with an aperture of 0.9 × 0.9 m and length of 2 m. It has a theoretical beam width (FWHM) of about 12°. The antenna looks to the side (out the parachute door) at fixed depression angles of 23° and 40° with respect to the axis of the aircraft, but the actual angle with respect to the surface depends on the aircraft attitude (e.g., pitch and roll) during the circles [22].

Fig. 5 shows data from circles flown in October 2003 with an incidence angle of 45°. Data for vertical polarization is shown on the left and the data at horizontal polarization for the same circle is shown on the right. The panels at the top and bottom represent two different surface conditions. The data at the top was collected over the North Sea at about 55.68 N latitude and 4.70 W longitude, a site chosen for its proximity to oil rigs with meteorological instruments to help with surface truth. The wind speed at the time of the measurements was about 10 m/s. The data shown in the lower panel were collected shortly afterward but some distance away and across a weather front where the winds were calm.

Each panel shows the EMIRAD data (lower curve) and also model prediction (upper curve). The data represent the average of 16 circles. During LOSAC the objective was to measure relative changes around the circles (signature in azimuth) and the absolute calibration (bias) is only accurate to within a few degrees Kelvin. The model calculations were done as described above except that in this case the antenna bore sight ray is reflected off the ocean surface. In these calculations the surface is assumed to be specular with a reflection coefficient of unity. The predicted signal has been arbitrarily shifted, by adding a constant, so as to fit on the same plot as the data. Corrections to match the predicted antenna beam width and bandwidth (27 MHz) have not been made (i.e., 15° and 20 MHz have been used). A better fit was not pursued because of uncertainty already inherent in the reflectivity of the actual ocean surface.

In the low wind case (bottom pair of figures) there is a clear correspondence between the data and the peaks in the predicted background radiation where the reflected bore-sight ray crosses the plane of the galaxy. This is what one would expect in the case of a specular surface. In the high wind case (top pair of figures) there is a good correspondence between the predicted background radiation and the data at vertical polarization, but the correspondence is less obvious at horizontal polarization (top, right). This is reasonable since at incidence angles in this range (40° to 50°), horizontal polarization is much more sensitive to wind speed than vertical polarization [23]–[25]. The purpose of the circle flights was to determine if there was an effect of wind direction at L-band. Clearly, a correction for the galactic background will have to be made before looking for such an effect.

IV. Conclusion

To first order the model [9] for the galactic background radiation derived from the recent radio astronomy surveys at L-band is consistent with measurements made with several modern remote sensing instruments. The agreement is particularly good (RMS differences of 0.05–0.10 K) if small changes in the level (bias) of the radiometer measurements are permitted. Without such adjustments, agreement is obtained to within 0.5 K even in the worst case.

The data suggest a slight difference between observations at horizontal and vertical polarization that is not included in the model (which assumes unpolarized background radiation). Sources of polarized radiation exist [15], [16]; however, the differences can also be reduced with slight shifts in the calibration bias and gain of the radiometer. Consequently, it would seem that the extent to which a polarized component of the background exists requires additional research [17].

The data reinforce the need to make accurate corrections at L-band for the background radiation. Changes in the background radiation of 1–3 K are observed when crossing the galactic plane. The actual value depends on the location of the crossing and even larger signals than this can be expected for antennas with better spatial resolution [9]. The EMIRAD circle flights (Fig. 5) illustrate a case in which a correction for the background radiation is needed before drawing conclusions.

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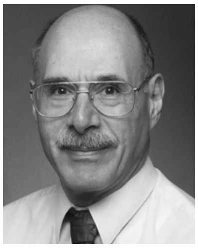

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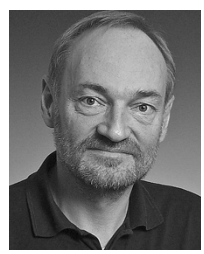
From 1980 to 1985, he was with the Centre National d'Etudes Spatiales, Toulouse. In 1985, he joined the Laboratoire d'Etudes et de Recherches en Télédétection Spatiale, Toulouse, as a Research Scientist. From May 1987 to December 1988, he was on leave of absence to work at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena. He is currently with the Centre d'Etudes Spatiales de la Biosphère, Toulouse. His fields of interest are in the theory and techniques for microwave and thermal infrared remote sensing of the Earth, with emphasis on hydrology and vegetation monitoring. He is currently the Lead Investigator of the ESA/CNES/CDTI Earth Explorer Opportunity Soil Moisture and Ocean Salinity mission, which is currently in phase C/D, and is a Co-Investigator on the NASA ESSP HYDROS mission.

William J. Wilson (S'59–M'64–SM'86–F'98) received the B.S.E.E. degree from the University of Washington, Seattle, in 1961, and the M.S.E.E., E.E., and Ph.D. degrees in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in 1963, 1964, and 1970, respectively.

He is currently a Senior Research Scientist at NASA's Jet Propulsion Laboratory (JPL), Pasadena, CA. In 1964, he served in the U.S. Air Force, working on military communication satellites. In 1970, he joined the Aerospace Corporation, Los Angeles, CA, and was involved in the design and construction of the millimeterwave receivers and radio astronomy observations. In 1976–1977, he was an Assistant Professor in the Electrical Engineering Department, University of Texas, Austin. He returned to Aerospace Corporation in 1977, where he was involved with research in millimeterwave radiometers and low-noise receivers. In 1980, he joined the staff of JPL, and is the Supervisor of the Microwave Advanced Systems Group. At JPL, he has been working on low-noise microwave and millimeterwave radiometers and radar systems for aircraft and spacecraft for Earth remote sensing applications. He is currently working on the Aquarius ocean salinity mission, development of ultrastable microwave radiometers, and the GeoStar Geosynchronous microwave-sounding instrument. He has published more than 160 technical papers and reports.



Niels Skou (S'78–M'79–SM'96–F'03) received the M.Sc., Ph.D., and D.Sc. degrees from the Technical University of Denmark (DTU), Lyngby, in 1972, 1981, and 1990, respectively.

He is currently a Professor with DTU. His research has been directed toward microwave remote sensing systems. After working for three years with the development of radar systems for measuring the ice sheets in Greenland and Antarctica, his interest turned toward microwave radiometry. He developed a scanning, multifrequency, airborne radiometer system. After that, his subjects were radiometer measurements of sea ice and oil pollution on the sea, spaceborne radiometer systems, and development of new systems for specific purposes. In the mid-1980s, his interest turned back to active instruments, and he became engaged in the development of an airborne, multifrequency, polarimetric, and interferometric synthetic aperture radar system—with special emphasis on calibration fidelity. However, activity within microwave radiometry has continued, mainly within the areas of synthetic aperture radiometry and polarimetric radiometry. The work on synthetic aperture radiometry has led to the Soil Moisture and Ocean Salinity (SMOS) mission, one of ESA's Earth Explorer Opportunity Missions, and he is currently heavily involved in this project, e.g., as a member of the SMOS Science Advisory Group.

Sten Schmidl Søbjærg (M'99) received the M.Sc.E.E. and Ph.D. degrees from the Technical University of Denmark (DTU), Lyngby, Denmark, in 1996 and 2003.

He is currently an Assistant Professor in the Section for Electromagnetic Systems, Ørsted-DTU Department. His research has concentrated on microwave radiometers and their applications. From 1996 to 1999, he participated in the development of an airborne fully polarimetric dual-frequency scanning radiometer system for 16 and 34 GHz, operated on a C-130 platform in order to determine wind direction over the ocean. From 1999 to 2001, he developed the EMIRAD L-band polarimetric radiometer with subharmonic sampling, and he has been involved in land measurements as well as the ESA L-band Ocean Salinity Airborne Campaign (LOSAC), preparing for the SMOS (Soil Moisture and Ocean Salinity) mission.