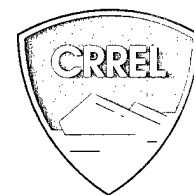


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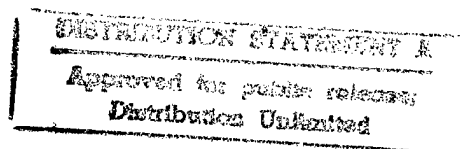
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The State of the Art of Modeling Millimeter-Wave Remote Sensing of the Environment

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October 1996



19961223 029

Abstract: A survey was undertaken of models for millimeter-wave (MMW) scattering and emission from environmental features, particularly in the vicinities of 35 and 94 GHz. The ultimate objective was to identify models suitable for current or near-future application in scene generation. The ideal model would be based on first principles, would be readily available in facilitated software, and would have reasonable requirements in terms of computational resources and input parameters. At MMW frequencies, these requirements push the frontiers of current science and technology. In most applications, one must accept as a first approximation the approaches currently under development in research settings. This report reviews the basic methods and approaches underlying all available models in terms of volume scattering, treatment of surfaces and transitions, and the development of statistical quantities from rational physics. Very rough surfaces, locally

steep surface slopes, and low-angle incidence can rarely be treated entirely successfully, but recent developments offer the prospect of significant progress. Volume and combined surface-volume scattering and emission models are reviewed for application to land, water, vegetation, snow, and ice environments. Most are essentially works in progress, with theory and validation currently building from earlier work at C and X bands. Very sound capabilities are available for treatment of common atmospheric features, with recent progress in modeling more complex meteorological events. Limiting consideration to truly available codes, a list is provided for each of the above areas of models and their sources. Because it is the most comprehensive and is currently facilitated in terms of software, the MIT EMSARS model is the foremost candidate to serve as a platform for future addition and development.

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PREFACE

This report was prepared by Dr. Kevin O'Neill, Research Civil Engineer, of the Civil and Geotechnical Engineering Research Division, Research and Engineering Directorate, U.S. Army Cold Regions Research and Engineering Laboratory. This project was funded by the Department of Defense as part of the Smart Weapons Operability Enhancement (SWOE) Program.

This report was technically reviewed by Dr. Robert Davis and Dr. Harold Boyne of CRREL.

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The State of the Art of Modeling Millimeter-Wave Remote Sensing of the Environment

KEVIN O'NEILL

INTRODUCTION

Recent improvements in technology and the prospect of superior performance have greatly increased interest in millimeter-wave (MMW) remote sensing. To assess the state of the art in the accompanying modeling capabilities, a study was undertaken with particular emphasis on implemented models, as opposed to disembodied theory. This report summarizes the results of that study. Its aim is to survey all available MMW modeling of scattering, emission, and propagation-absorption in the natural environment, particularly in the spectral vicinity of 35 and 94 GHz.

The models are evaluated equally in terms of validity and utility. In the context of this survey, *model* means a theoretical formulation that is derived from first principles, such as Maxwell's equations or conservation of energy, and that is incorporated in a tractable computational vehicle. Thus, some work that constitutes a model in the most general sense is recognized here for attention in the future, but it is not currently singled out as available through accessible software. The ultimate purpose for identifying, collecting, and integrating an ensemble of such models is to generate energy field distributions, i.e., scenes, that sensors might confront under the widest possible variety of conditions. To achieve this generality, models were sought based as much as possible on first principles, with minimal reliance on empirical or arbitrarily tunable parameterization.

Truly useful models should be sufficiently simple and accessible that users other than the originators can run them. This requirement tests the constraints of generality and first-principles validity. Due to the nature of the field, we may find in many instances that the most rigorous models, or perhaps the only rigorous models, are en-

sconced in sophisticated research structures. They may require advanced, specialized knowledge, extremely complex, difficult-to-obtain input data, and intolerably large computational resources. At least in extreme instances of this sort, such models cannot be pursued here for the purposes of ultimate scene generation. At the same time, the tension between generality and validity on the one hand and simplicity and accessibility on the other may force a degree of compromise in prioritizing models. The requirements may have to be relaxed in some cases; in others, utility may be achieved only by following an ongoing development or working with model originators over an extended period. While the field is developing, some applications may be best accomplished by combining the capabilities of theoretical models with organized, facilitated databases. In the latter connection, documentation and programs exist for extracting, manipulating, visualizing, and adding to the large amount of measured data that has evolved over recent decades—e.g., FINRACS (Borel et al. 1986) and material from Ulaby and his co-workers at the University of Michigan (Ulaby and Dobson 1989a, 1989b; Ulaby and Haddock 1990).

The specific information incorporated in this survey is derived from a variety of sources: the author's personal knowledge and information direct from the open literature, discussion and communication with various recognized modelers, the response of modelers to a questionnaire, and a workshop (held on 13–15 May 1992) for a general review and discussion of MMW modeling capabilities. (A list of workshop participants appears in Appendix A.) Beyond the specific topics for the workshop sessions, far-ranging discussions took place to establish the boundaries and content of the current state of the art. In soliciting

information and taking note of models for this report, emphasis was placed on the importance of successful model verification as a selection criterion. In this context, *verification* means all testing and validation, including comparison of computations to common-knowledge expectations or limits imposed by basic physics, comparison with "exact" numerical solutions, or qualitative and quantitative comparison with physical measurements.

The models of MMW propagation, scattering, and emission may be sorted according to three considerations:

1. Model type: physical process and basis, approach, methods and techniques used.
2. Applications: media considered and validation.
3. Computer codes: packages and their originators.

For the ultimate purpose of scene generation we must deal with computer codes, so we sought existing, facilitated, documented programs. Ideally these should be in integrated, modular packages, but single programs are also of interest if they pose no insurmountable problems to integration into larger ensembles in standard languages. The codes must be directly accessible, in the public domain or easily available for a modest cost, and should ideally have the prospect of continuing support. Thus, our ultimate constraints give a certain prominence to producers and active disseminators of finished software vehicles. At the same time, it is recognized that the physical problems we are addressing are extremely difficult. There is no well-established body of valid, recognized, elaborated computer packages as in some other areas, such as structural analysis or heat transfer. Typically, the models we desire are being generated at the frontiers of research as pursued at the most advanced research institutions. For the most part, these institutions have neither the resources nor the mandate to produce polished software for dissemination. We recognize also that when energy has been devoted substantially to software polish and dissemination, scientific rigor may have been left a bit behind. Therefore, if our ultimate demand is for generality and fidelity to nature, we must also devote attention to models that are in some intermediate or even early stage of development as far as computer code is concerned. In the very least, doing so provides valuable perspective on the more available packages.

Before considering the specific codes, our most

basic sorting category for review is applications. This is because we are asking *what* features we are able to model for inclusion in a generated scene: fallen and falling snow, fresh- and salt-water ice, bare soil, vegetated soil, vegetation canopy, clouds and rain ...? While the availability of codes may determine our options in the end, it is the need to model particular media and configurations that drives both our quest for codes as well as our drive to develop new methods. The bulk of the *Applications* section is therefore organized according to applications.

The model types provide the broadest and most far-reaching terms in which to consider the field. Various general approaches are applied in models of substantially different media. The same general types of models also appear in many different computer codes. Therefore, we begin what follows with a brief discussion of model types.

In summary: we converge on computer codes by passing through model types and applications. Some published models were eliminated at the outset because they fail in some serious way to meet one or more of these selection criteria. For reasons explained above, the *Applications* section and the next section of this report include items that have distinct value but fail in one or another way to meet our criteria ideally. Finally, in the *Available Computer Codes* section, a subset of the models considered first in terms of type and then application is presented in terms of specific, available computer programs or packages.

METHODS AND APPROACHES

Volume scattering

In essentially all applications of interest here, some type of randomness must be considered. For volumes, the randomness has been included by assuming that either

1. Dielectric properties vary continuously, with a zero mean fluctuating term added to the average permittivity, or
2. Dielectric properties have a discrete distribution, i.e., certain step changes in value occur across boundaries of discrete embedded elements.

Idealized representative elements are often assumed, such as dielectric disks, spheroids, or cylinders, possibly with statistical distributions of size, shape, or orientation. The simple sum of contributions from individual elements may suffice to compute the response when the medium is

diffuse, as in an aerosol, but the denser the media, the more interactions between the elements must be included. In the limit of very dense media, with a great deal of contact between elements or with continuous, tortuous intermixed phases, it may no longer be a promising approach to regard the medium in terms of contributions from discrete elements.

The distinction between continuous medium and discrete scatterer theory is somewhat misleading, in that the former can generally deal with discrete scattering elements as well. One merely specifies a discrete permittivity distribution and performs much the same computational motions as for a continuous distribution, ending up with essentially the same statistical descriptors for the medium as under the discrete scatterer approach. In either case, the statistical medium description must be integrated into a set of equations covering the medium as a whole. The principal approaches have been via analytical wave theory and radiative transport theory.

The perceived difficulty of applying wave theory (WT) to an extremely complex mixture has appalled some authors, to the extent that the WT approach is sometimes dismissed out of hand. Nevertheless, the brave beginnings of its recent incarnations in the early '80s have been followed by the undaunted into formulations of ever greater sophistication (e.g., Nghiem et al. 1990, Nghiem 1991). In principle, WT can include all multiple scattering, diffraction, and interference effects. In practice, it is limited by the difficulty of formulating the characteristics, behavior, and distribution of constituent elements and then solving equations incorporating their interactions. Green's function-based integral equations are generally used. Perhaps the simplest method for making the integral equations tractable is the Born approximation, which has been used for increasingly complex configurations in recent years, e.g., an isotropic-anisotropic three-layer system with rough surface (Borgeaud et al. 1986). The Rytov and Foldy approximations are also applied to extend the range of validity or tractability. The distorted Born approximation extends the WT density and fluctuation strength range further, particularly in conjunction with strong fluctuation theory. Recently, dense media formulations have been advanced for media with particle-size distributions, employing the quasi-crystalline approximation (QCA) and QCA with coherent potential (QCA-CP) and pair distribution functions (Ding and Tsang 1991, Tsang and Kong 1992).

Whatever the current (evolving) limitations on density (volume fraction) and particle size relative to wavelength, we note that important links have been made between simulations based on dense media theory and Monte Carlo calculations, in effect verifying each. The latter have the advantage that true solutions of Maxwell's equations may be obtained, including coherent interactions, and no adjustable parameters are introduced. Dense media theory calculations have agreed well with Monte Carlo calculations of extinction rate for volume fractions up to 25% (Tsang et al. 1992b); they have also agreed well with laboratory data where input parameters were derived from measurement (Wen et al. 1990, Ishimaru and Kuga 1982).

In the radiative transport (RT) approach it is assumed that interacting field components are sufficiently uncorrelated so that addition of power, as opposed to addition of fields, holds. Thus, an energy balance equation is formulated in terms of specific intensity, in scalar form for completely unpolarized fields or in vector form in the sense that the (modified) Stokes vector is the dependent variable when polarization is important. Maxwellian underpinnings may reside in diffraction and interference effects expressed for the behavior of constituent elements in the medium. However, these are ultimately swallowed up through the phase and extinction functions (matrices) in the intensity-based governing equation. Comprehensive introductions to RT are provided by a number of recognized sources (Chandrasekhar 1960, Ishimaru 1978, Tsang et al. 1985, Ulaby et al. 1986). As in the WT approaches, researchers have built increasingly complex and diverse scattering elements into the medium formulations, treating increasingly complex shapes and distributions of scattering elements and media. Although complex media descriptions may be built into RT formulations more easily than for WT, numerical solution can still be daunting. Iterative methods are sometimes used, though they are suited primarily to sparse or weakly scattering media and are rarely carried beyond the second order. Kuga (1991) reports a system that provided third- and fourth-order iterations and compared well with "exact" numerical solutions obtained with the discrete ordinate method. While the method requires low density and spherical particles, it can deal with large particles. Rough surfaces have been included in WT approaches simply by incoherently adding the independently calculated volume and surface scatter (e.g.,

Borgeaud et al. 1986), though this does not take the volume-surface interactions fully into account. In RT, rough surface effects can be included completely consistently, at least in principle, by modifying the boundary conditions; in general, RT handles complicated configurations and media profiles more easily than does WT.

The deficiencies of conventional or "classical" RT are also to be noted. Its basis is less rigorous than WT. Phase information is generally absent, and coherent effects such as enhanced backscatter cannot be predicted. Other coherent effects associated with layer bottom boundary reflections are also not included. This may not be so important at MMW frequencies in instances when strong attenuation occurs such that lower boundaries may have little effect on measurements from above. In addition, the underlying lack of correlation assumed in RT for the interaction of fields associated with medium elements breaks down for sufficiently dense media. These shortcomings have given rise to recent formulations designed to include some coherent effects. Tsang and Ishimaru (1987) have introduced the radiative wave equation approach to RT, and the modified radiative transfer approach (MRT) has sought to include some coherent effects since the late 1970s (e.g., Tsang and Kong 1976, Zuniga and Kong 1980) with recent developments for more complicated media (Lee and Kong 1988, Lee and Mudaliar 1988, Mudaliar and Lee 1990). While the MRT equations are ultimately of the same form as traditional RT equations so that similar solution methods may be employed, the greater complexity of the MRT appears to limit its applicability at present. While the emphasis in these references has been on active remote sensing, this should not obscure the prominence of RT for addressing passive observations of the atmosphere. Numerous passive RT formulations applicable to terrain features have appeared as well (e.g., Kong et al. 1979; Shin and Kong 1982, 1989; Tsang 1991).

Scattering from surfaces and transitions

To date, our options in connection with surface scattering computation are relatively limited in the sense that usually only mild to moderate roughness of one kind or another can be treated. The by-now "classical" approaches are based on the assumption that physical optics or small-perturbation-method approximations are adequate. Lucid formulations of these methods are

presented in a variety of texts (Ishimaru 1978, Tsang et al. 1985, Kong 1986) and, together with their recent developments, are extensively reviewed (e.g., Ulaby et al. 1982, Fung et al. 1990). Multiscale roughness formulations have been developed, combining disparate ranges over which the approximate theories hold. Physical and numerical surfaces have been constructed and scattering behavior measured or obtained numerically to investigate the applicable ranges of validity (e.g., Chen and Fung 1988, Fung et al. 1990, Lou et al. 1991). Ishimaru et al. (1991) performed numerical, analytical, and experimental studies of very rough surfaces relative to the "classical" constraints. Their MMW experiments and numerical analyses of surfaces with known statistics illuminate enhanced backscattering from rough surfaces.

While significant questions remain as to the detailed limitations of these theories, a consensus emerges. This is reflected in the above references, in those discussed below, and is summarized succinctly by figures published in various locations by Ishimaru and his co-workers (e.g., Ishimaru and Chen 1990). Generally speaking, it is difficult to perform reliable calculations for rms surface height fluctuations approaching or greater than one wavelength or for rms slopes approaching unity. Perturbation methods are preferable at small correlation lengths, with physical-optics-based methods more successful for larger rms heights. The strength and appeal of these methods lie in their ability to provide information on expected coherent and incoherent scattered field properties based on the (statistical) spectral characteristics of the reflecting surfaces.

The Kirchhoff approximation (KA) constitutes a physical optics (PO) approach in that it uses the tangent plane approximation for surface fields to express sources in the diffraction integrals. It assumes that scattering of the incident field may be approximated locally as if reflection were from a flat surface with slope equal to the tangent to the actual curved surface. Alternatively, it may be stated that PO assumes induced surface currents equal locally to the corresponding geometrical optics plane wave fields. The diffraction integrals are very widely used in surface scattering formulation and computation in all the methods discussed here. As two-dimensional (surface coordinate) equivalents of their Green's function-based three-dimensional WT counterparts, they may be viewed as expressions of Huygen's principle or

simply as the results of various integrations and manipulations of the underlying electromagnetic wave equations. The integrands contain (usually) unknown tangential field or equivalent current values, which serve as sources of the general field to be calculated. Use of the tangent-plane KA approximations to obtain these surface sources implies a large radius of curvature on the scattering surface relative to the incident wavelength. This statement does not supply a very precise criterion for range of validity, and investigations have shown the importance of having a relatively large correlation length, even for rms heights that one might suppose corresponded to mild radii of curvature (Thorsos 1988). Except in some deterministic cases, additional assumptions must typically be made (including small slopes and constant Fresnel reflection coefficients), otherwise evaluation of the integrals cannot in general be carried out. With the stationary phase approximation applied in the high frequency limit, one obtains the geometrical optics approximation (GO). This implies essentially that only parts of the surface with local specular scatter toward the observer contribute to the integral. The Fresnel coefficients applied within conventional KA formulations have polarimetric content in the sense that they are different for horizontal and vertical polarizations. This inclusion of polarization effects is approximate at best, however, and one should not expect complete and accurate polarimetry based on classical KA formulations. Without the addition of special measures, such formulations also do not conserve energy in general, hence they do not provide reciprocal information, i.e., the use of active to infer passive behavior.

Over recent years the shortcomings of these approximations in terms of shadowing and multiple reflection have been attacked, and higher-order versions have been constructed (Chen and Ishimaru 1990, Ishimaru and Chen 1990). Successful application of these enhanced KA treatments is seen even at slopes on the order of unity, with rms heights and correlation lengths somewhat greater than one wavelength. Thus, these formulations may be capable of addressing the roughest surfaces without handling the smallest correlation length range. We note as an important advance that energy is conserved in these calculations. At the same time, the introduction of the shadowing and tapering functions is cumbersome and requires further study. For the most part,

simulation of two-dimensionally rough surfaces is still to come, awaiting the completion of more tractable numerical treatments of fully vectorial electromagnetic scattering.

In contrast to the PO-based approaches, the small perturbation method (SPM) proceeds by applying a correction factor to the field that would be present on a flat surface located at the mean of the actual surface. This factor is expanded in a perturbation series. Small rms surface heights and slopes are required. Relative at least to the more basic KA formulations, SPM has the advantage of being fully polarimetric in principle, although cumbersome higher-order calculations may be required for reasonably accurate and complete polarimetry. Recently the phase perturbation method (PPM) was introduced as an enhancement of SPM (Winebrenner and Ishimaru 1985). Exploration of the method by workers at the University of Washington and elsewhere has established a considerably wider range of application of PPM relative to the more traditional SPM formulations (see figure in Ishimaru and Chen 1990).

Fung et al. (1992) have extended earlier work for perfectly conducting surfaces (Fung and Pan 1987) so that computations for dielectric surfaces can be carried out in the same manner. The resulting integral equation method reduces to KA and SPM terms at the appropriate limits for both like and cross-polarized results. Good results are shown with the new method for rms surface heights on the order of the wavelength and slopes (i.e., correlation length divided by rms height) approaching 0.4.

The unified perturbation method (UPM) has been introduced and tested by Rodriguez, Kim, and their co-workers (Kim et al. 1992, Rodriguez and Kim 1992, Rodriguez et al. 1992a). A perturbation expansion is used that converges over a wider domain than SPM, and that converges in the appropriate limits to the KA, SPM, and two-scale results. In the last case, this is accomplished without the introduction of an artificial adjustable parameter for the spectral split. Recent 1-D roughness tests show success in addressing surfaces with rms height approaching one wavelength with rms slopes less than or equal to about 0.8, for both horizontal and vertical polarizations.

In addition to the obvious merits of the UPM system on the basis of this reported performance, we pause to take note of a particular application of the method to ocean backscatter simulation. Little or no work has been done on ocean simula-

tion in our frequency range, in any case not with meaningful tests against data. The ocean is attractive for analysis because it is a rare example of relatively pure surface scatter, despite sea spray and breaking waves. At the same time, there is usually a lack of "ground" (water) truth on which to base analyses. One must simulate both the water conditions and the consequent electromagnetic response as functions of other variables, most notably wind speed. Rodriguez et al. (1992b) have performed Ku-band altimetry-oriented simulations of scattering from the ocean surface, based on a simplified ocean spectral model driven by wind speed. While there are some discrepancies in results relative to observations or other studies, important agreements are achieved, particularly in connection with EM bias. This bias is caused by two modulating mechanisms, one due to small-scale waves and the other a result of tilt due to large waves. The 1-D surface roughness bias calculations show proper trends with respect to both frequency and wind speed, based on independent physical observations. Bias increases with wind speed, but ultimately saturates as wind continues to rise. The computed sign of the EM bias is correct relative to observations; the difference in magnitude by a factor of two may be due to use of the simple 1-D spectrum. UPM codes containing 2-D roughness are nearing completion and may offer more precise agreement. While the wavelength in these simulations is approximately half that at 35 GHz, it is close enough to encourage strong interest from the MMW point of view. Despite the limitations of this combined ocean-electromagnetic study, it deserves to be singled out as a source of simulations of some significance and validity.

While these newer approaches have pushed the bounds of application of surface roughness treatments, it is still difficult or impossible to address a great many realistically rough surfaces with rms roughness heights greater than the incident wavelength and especially with large slopes. These constraints can be severe at MMW frequencies for natural media such as soil, gravel, sand, moving water, or tree bark. In practice, most volume-scattering models that attempt to combine surface scattering adduce one of the "classical" formulations, such as KA with stationary phase. This can serve to provide an example of (interacting) surface and volume effects, but it rarely approaches the full physical reality to which one would like to apply these models, such as agricultural fields.

In practice, surface and volume scattering effects cannot be separated to the extent that the above discussion might suggest. Physical transitions are frequently encountered in the media being sensed that contain elements of both or that produce a kind of effect that cannot be accounted for by either or both in simple combination. For example, bare tilled or raked soil may be quite rough on the MM scale, with clumps and heterogeneous protrusions containing vertical slopes, large void inclusions, and the like. From one point of view, we confront a distinct (albeit complex) scattering interface between air and sharply contrasting soil media. From another view, we see a heterogeneous volume of scattering material over a transition zone, beginning with a low density at the highest point of soil protrusion and gradually increasing in density, homogeneity, and continuity with depth. This surface-volume scattering ambiguity is most likely to arise for very rough surfaces, which are not entirely uncommon in practice at MMW wavelengths. Certainly the traditional, mild roughness theories and their most recent improvements will ultimately fail for sufficiently rough transitions. It is also reported that surface scattering approaches must be modified in the face of dielectric heterogeneity, even when the bounding upper surface is geometrically smooth. Numerical simulations of an imaginably soil-like medium with voids and inclusions near the surface show behavior influenced significantly by the subsurface character, even in cases where penetration by the radiation should be slight.

Revelations provided by simulations may serve to indicate the best way (at present) to investigate medium configurations and effects such as these. Monte Carlo or other structured numerical experiments may guide us toward the best approaches at a more analytical or conceptual level. In any case, we do not yet have good methods for analyzing such cases with any real generality and do not have good guidelines as to how to proceed.

Statistical quantities and Monte Carlo calculations

Let us pause for some general observations on what we seek in any approach of the sort we are considering, on what sort of quantities are to be employed, and on what the nature of the methods is that allows us to obtain them. Basically, for natural media, *statistical* quantities must be generated for the application medium. Most commonly these consist of an rms variation of permit-

tivity for volumes and of surface height for an interface, or the equivalent, plus some measure of the spatial scale and geometry of this variation, most commonly through correlation length. Loosely speaking, the correlation length indicates the general size of a significant permittivity variation or of a discrete scatterer in a volume or the lateral extent of a contour variation on a surface. As such, correlation lengths may be anisotropic in the sense that different lengths may apply in different directions, as for elongated brine pockets in saline ice or narrow striations in a surface. The fact that directional information can reside in the correlation length underscores the significance of this quantity for polarimetric modeling. We also note that the correlation length does not entirely define the correlation function itself, given that the former is typically only defined as the distance over which the function decays by $1/e$. The entire function itself will depend on the case considered; a Gaussian function is often used. Note that the indication of a "Gaussian surface" usually means that the correlation function or, equivalently, the power spectrum of a surface has the form of a negative exponential of distance squared. This does not mean that the variation of surface height is assumed to follow a Gaussian *probability* distribution, though that is also often the case.

The appearance of statistical quantities both in remote sensing data and the modeling implies some particular kind of averaging procedure. In physical measurements this is performed, in effect, by the sensor. One footprint presumably spans many patches or subregions, in each of which a sufficient sample is present for statistical quantities to apply meaningfully. Thus, integration is performed over each subregion patch, and the ensemble of subregions is summed as well. Quite significant questions remain as to the correspondence between the kind of averaging implied in the theoretical bases of our models and that performed by any likely or conceivable sensor. Among other things, received data are likely to contain effects due to the variability of medium properties at a number of different scales, e.g., at both the subregion scale and at the scale of the ensemble of subregions.

In model formulations, the averaging process is typically carried out analytically, at a single scale, in the process of constructing governing relations. This means that the formulations are ultimately stated in terms of the statistical quantities themselves, such as expected or coherent field

and the diffuse incoherent field or average power. These theoretical average quantities presuppose a certain kind of averaging, typically averaging over an ensemble of surfaces, conceptually subjected to the same illumination regime and developed as realizations of the same statistical process. In this context, the correlation function, for example, means the correlation value of quantities (e.g., surface heights at a given separation) *averaged over the ensemble of surfaces*, not averaged spatially over a single domain. The latter sense of averaging, however, is often the one employed in practice when a limited domain is characterized experimentally to provide model input. While the two averaging processes bear some relation, questions remain in any given application as to the correspondences of the quantities obtained.

Lastly, we mention Monte Carlo techniques as an approach to calculation of responses of random media. Such techniques have received a great deal of attention as computing power has increased. The attraction of the non-Monte-Carlo techniques resides in their ability to proceed directly in relating statistical and spectral features of the modeled medium to the statistical properties of the received field or power. In such approaches, ensemble averaging is carried out analytically in the course of the formulation procedures; this is a result of the analytical simplicity of the expressions used and the introduction of limiting simplifications. By contrast, in Monte Carlo simulation one calculates the response of specific, geometrically defined (deterministic) medium samples, perhaps analogous to the "patches" mentioned above. This is typically done numerically. Each of the samples is constructed to be an individual realization of the hypothesized underlying statistical formation process. Once solutions have been obtained for a sizable number of such instances, they are added together to obtain effectively an ensemble average. Thus by "brute force" one mimics the supposed process by which a sensor might accomplish its averaging integration and also accomplishes a faithful rendering of the kind of averaging assumed in the more approximate analytical models.

Monte Carlo techniques have the attraction that many of the limiting assumptions needed to obtain results in the more analytical approaches can be avoided. In addition, because the details of the modeled media are known, there are no unknown tunable parameters, the estimation of which can render data-matching exercises suspect. In surface scattering, going beyond the constraints of

analytical approaches on scale of roughness or severity of slopes means that one can work with truly realistic surface profiles. This is accomplished, however, at impressive computational cost: two-dimensionally rough surfaces are rarely attempted, though we expect progress here in the near future. True Monte Carlo treatment of volume scattering as is done for surfaces is currently out of the question. The sheer detail required to describe the internal geometry of a *realistic* volume of environmental material is insurmountable; the computational requirements will also be invincible for the near future for solution of electromagnetic equations over a truly life-like variation of internal medium geometry.

Monte Carlo volume-scattering treatments in a certain limited sense have been carried out in the construction and analysis of collections of very simple shapes. For example, Ding et al. (1992) have used Monte Carlo procedures in achieving arrangements of spheres to determine the statistical pair distribution functions needed for their dense media volume-scattering calculations. Tsang et al. (1992b) have solved Maxwell's equations rigorously over similar dense media, for cases with as many as 4000 spheres, presumably with volume fraction limits imposed by the convergence of the iterative solution procedure. Good solutions were obtained at densities of 25% by volume. Alternatively, Chuah and Tan (1992a,b,c) have used Monte Carlo procedures to calculate a cascade of idealized contributing scattering events in vegetation. This statistical treatment of the contributing scattering events is fundamentally different from a rigorous deterministic analysis of events on a precisely realistic geometry for later ensemble averaging, i.e., for Monte Carlo treatment as meant here. In addition, because they proceed on the basis of a photon transport equation and not Maxwell's equation, coherent interactions as needed for dense media are absent; this may suffice for some vegetation applications. Tsang and his co-workers (1992b) are also evidently applying Monte Carlo WT analyses to obtain coherent and incoherent effects for vegetation that, though not dense, is clustered.

In summary, we should not look for volume-scattering progress in the near future from the ensemble averaging of numerical solutions of Maxwell's equations over truly realistic geometries in the same manner as is occurring for surfaces. Beyond this we note that pushing roughness limits using numerical solutions brings dangers with its opportunities. Even in the more

analytical approaches, more information on the distribution of the medium is generally required than just rms variation and correlation length. The specific character of the overall correlation function is needed or assumed; in volume scattering density information is needed, and other higher-order spectral or geometrical information may be required for complete analysis. This is particularly so when the limits of the approximate theories are exceeded.

It has been noted that a number of different models may produce reasonable agreement with observations even though they use contrasting versions of the underlying physics, even when the input data have been constrained by ground-truth measurements (Carsey 1992). Among other things, this serves to re-emphasize the fact that rms variation and correlation length do not uniquely define the system. For more extreme yet realistic media, we will have to recognize and implement additional parameters that catch the particular character of the variability, beyond what is incorporated in the traditional quantities. This makes sense and is even desirable: it says that we need to focus on the identification of new, specific, distinguishing medium characteristics that can be linked to some distinguishing statistical character in the received data. Only by doing this will we recognize realistically distinct media in our sensed data. While overall this is likely to mean that we must consider additional parameters, such as higher statistical moments, in some instances it may mean that we discard altogether one or more of the traditionally important medium quantities. One might even say that we require new physically based, probably case-dependent parameters and signal characterization specifically to simplify our task to the point of tractability.

APPLICATIONS

The following is suggested as a general scheme of the media and physical features for which models are sought. In each case both active and passive polarimetric systems are ultimately desired.

Cultural features

- Buildings and transportation constructions, urban/suburban environments, edges or linear structures such as roads and wires.

Atmospheric applications

- Active propagation and emission horizon-

tally and up/down through profiles of clear air, turbulence, dust, clouds, and precipitation.

Vegetation

- Low: Grass, fields, agricultural plantings, shrubs, mostly single layer with diminished importance of branches, greater importance of leaves, blades, stalks.
- Tree canopy: Usually but not always two-layer, continuous/intermittent crown with branches and seasonal or evergreen leaves/needles, lower layer of trunks, horizontal and nonhorizontal propagation; as for low vegetation, possible significance of underlying ground/water surface.

Snow and ice

- Snow: Shallow/deep, uniform/layered, wet/dry, smooth/rough.
- Ice: Fresh/saltwater, smooth/jumbled, first-year/multiyear.

Exposed terrain and water bodies

- Rock: Rock-strewn terrains, or more monolithic formations that may be smooth except at MM scale, or may be steep, jagged outcroppings.
- Soil: Wet/dry, rough/smoothly undulating, multiscale roughness.
- Water: Smooth/rough, moving/still, expansive/narrow.
- Subpixel patches: Mud puddles, ice patches, thaw/wet patches in snow ...

This list is something of a litany of objectives, as context. What follows is a summary of what has been done toward addressing this list.

Cultural features

Clearly one can attempt to analyze specific constructed elements such as wires, stairs, or windows. Here, however, we seek more generic capabilities applicable in relatively indiscriminate remote sensing of a large-scale environment. Relatively little has been done to model lower-frequency microwave sensing of large-scale constructed or cultivated environments, and even less is available in the public domain at MMW frequencies. A few measurements have been reported (e.g., Violette et al. 1988), but without substantial attempts at modeling. Beyond the obvious (such as considering buildings or curbs as corner reflectors) we draw no inferences here for modeling purposes. We note that the constructed or controlled nature of cultural features offers greater regularity to the analyst on the one hand: swimming pools, walkways, and even lawns have rela-

tively distinct edges. On the other hand, the sheer variety of features and their distinctive forms is so great as to prevent much generalization.

For well-defined structures and their environments it may sometimes be possible to use various programs in the suite available from the Georgia Tech Research Institute (Peifer et al. 1988, Faust et al. 1989, Davis et al. 1992). This graphically facilitated package offers capabilities for defining structure geometry and then calculating returns in terms of combined PO responses of an assemblage of simple shapes (scattering centers). In less deterministic situations we may consider the possible presence of highly distinct structures at the subpixel level, that is, a terrain category of "patches," each of which may be relatively easy to model in itself but that must somehow be integrated statistically into an image effect. Rational, or at least rationalized, schemes exist for constructing "fading" (speckle) in images from this sort of process. Such schemes can be based on reasonable or at least specific physical assumptions and procedures (e.g., Ulaby et al. 1982, 1986; Yueh et al. 1991). While they come into play during the final steps of the scene generation sequence, we consider them to fall within the fringes of the domain of modeling that we are pursuing here. For this reason, no specific review of approaches and programs and no recommendations in this area are included in this report.

Some expansive cultural features such as lawns, bare tilled soil, or crop fields may be addressed under other headings below.

Atmosphere

Many of the radiative transfer approaches listed below can in principle be applied to atmospheric dust and precipitation. Ishimaru and his co-workers have developed models that are in principle applicable to rain or ice precipitation (Ishimaru and Cheung 1980; Ishimaru et al. 1984a,b), and others are directed at turbulence effects (Honig et al. 1977, Ishimaru and Painter 1980). McMillan et al. (1982) review applications of theory to measurement for MMW propagation. They conclude that while in most cases agreement is "plausible," data have been inadequate to determine the extent to which this is fortuitous. Weinman (1989) applies a Rayleigh-Gans model of MMW scattering from falling snow, with flakes considered to be a polydispersion of equivalent randomly oriented circular disks. Disk dielectric constants are obtained from the Bruggemann mixing rule with estimated ice fractions in the equivalent flakes.

Theoretical comparisons with measurements are good at 35 and 94 GHz, although Weinman emphasizes the need for access to more comprehensive data.

In general, efforts to model realistically complex meteorological events in a natural setting are hampered by our inability to characterize the medium (lack of "air" truth, as it were). Despite these difficulties we single out three sources of simulation that have seen some notable application: the work by Gasiewski at the Georgia Institute of Technology, the RADTRAN program, and the MPM program.

The most comprehensive and authoritative data measurement and modeling basis for atmospheric attenuation/delay is provided by the MPM model of Liebe and his colleagues (Liebe 1989, 1992; Liebe et al. 1989; Manabe et al. 1989). The MPM model is the generally acknowledged standard for predicting profiles of complex refractivity of the neutral atmosphere from 1 to 1000 GHz with contributions from dry air, water vapor, suspended water droplets, and rain. For clear air, the local line base (44 O₂ plus 30 H₂O lines) is complemented by an empirical water-vapor continuum. On the whole, the basis for the relationships in the MPM program and its testing lend it very high credibility. Possible shortcomings reside in missing trace gas spectra and the empirical water-vapor continuum. The physical origin of the latter is basically understood, but its empirical construction could lead to errors in predictions for some atmospheric window ranges. Even with these caveats, we note that the precision this model offers surpasses that of any other model considered here. The most approximate component may be the treatment of rain effects. No attempt is made to engage in elaborate calculations for individual drops, which would require drop shape and size distributions, variable permittivity of the water, and so on; similarly, no complicated RT-type computations are employed with an assumed or empirical phase matrix. Rather, the refractivity of the rain is expressed simply by a formula, with constituent terms and factors developed from a least-squares fit to Mie calculations based on a Marshall-Palmer drop-size distribution. Overall, this gratifyingly simple code is easily implemented and can feed into the more complex modeling vehicles discussed below.

Gasiewski has produced a program for calculating brightness temperature and associated statistics for planar stratified scattering atmospheres

over specularly reflecting surfaces for the 1–1000 GHz frequency range. Emphasis is more on the handling of complex precipitation events. The atmospheric portion of the model is described by Gasiewski and Staelin (1990); a wealth of details on the formulation, sensitivity, and exploratory runs and comparison with measurements is also provided by Gasiewski (1993). In general, this RT model assumes Rayleigh or Mie scattering from spheres. Given the expected sparse distribution of scatterers, models simpler than the Mie formulation are typically used to determine the form of the phase matrix, which is less influential than the other parameters. Both iterative and quadrature solutions are pursued, and both mono- and polydispersed hydrometeor scattering and extinction are considered. Isotropic, Sobolev (two-term), Rayleigh, Henyey–Greenstein, and two-stream phase function formulations are offered. Ground surface reflectivity is considered to be a minor influence in the applications considered and is typically assumed to be a convenient fixed value, e.g., 5%. Downward-looking brightness temperatures were calculated for flight paths over a relatively complex summertime convective cell couplet, with concomitant data from weather radar reflectivity used to determine hydrometeor size distribution and phase profiles (Gasiewski 1993). Agreement between observed and computed values is impressive. It appears that the model would benefit from the inclusion of some polarimetric effects under certain precipitation conditions. This may be accomplished to some degree by including more asymmetric particle geometry and scattering; more general polarimetric ground surface reflectivity is also planned.

The computational vehicle designated as RADTRAN has been developed from work originally done at the Air Force Geophysical Laboratory to model atmospheric transmission and emission in the 30–300 GHz range (Falcone et al. 1979, 1982). The package is oriented toward passive measurements and contains six each of clear atmosphere, cloud, and rain models as well as eight humidity models in an attempt to cover a worldwide variety of conditions. The original RT formulation has been upgraded more recently by Isaacs and his co-workers at Atmospheric and Environmental Research, Inc. (Isaacs et al. 1988, 1989a,b,c). The enhancements allow RT simulation of polarized multiple scattering for cases that involve various kinds of precipitation and surface emissivities. Jin and Isaacs (1987) show exploratory computations of hypothetical cases with

a polarimetric formulation in which the required scattering functions are based on Mie scattering. It appears that polarimetric effects enter essentially through the calculated terrestrial surface emissivities. In any case, it is not clear that this particular formulation has been built into the RADTRAN package. The other papers referenced above indicate that the package enhancements avoid an on-line computation of precise Mie scattering for each specific particle size, phase, temperature, and frequency combination. Rather, interpolations are performed on parameterized results of Mie scattering calculations for representative particle-size distribution functions under different conditions. The ultimate results appear to be accurate when compared with calculations based on full-fledged Mie scattering computations (Isaacs et al. 1988).

The enhanced RADTRAN is now designed to handle emission from a variety of user-specified types of surfaces. The surface or surface layer models used are quite simplistic: calm ocean is modeled as a dielectric slab; rough ocean, sea ice, and wet and dry snow are modeled using discrete random scatterer inclusions and WT; and vegetation and wet and dry soil are treated using RT and a continuous random medium model. These surface models enter significantly into calculations of polarized brightness temperatures that compare reasonably with SSM/I data over selected areas (Isaacs et al. 1989b), with further comparisons needed over snow, sea ice, and soil. It seems that essentially all of the specifically polarimetric content in the data comparisons enters through these surface factors, rather than through directional structure and scattering properties of precipitation particles. We note that the extremely approximate nature of these surface models makes it unlikely that they would stand up to the kind of testing applied elsewhere to more sophisticated models with mixed results at best. Most features of the original (1979) version of RADTRAN test well against laboratory data; parts of the package related to heavy precipitation and the most recent enhancements have seen only sketchy validation. Most recently (Pickle et al. 1993), the program was used to help quantify the uncertainty in DMSP SSMT/T-2 water vapor sounder brightness temperature measurements. Under precipitation-free conditions with clear or partly cloudy skies over land and sea, colocated radiosonde temperature and moisture profiles were used as input; outgoing radiance was calculated. In the context of both satellite and NASA ER-2 underflight

radiometer data, the model estimated sensitivities of the brightness temperature to variations of moisture content.

Overall, the RADTRAN package has the substantial advantage that it is documented, facilitated, disseminated, and supported. It includes many accepted, state-of-the-art formulation features for atmospheric modeling. Gasiewski's model, which shows comparable care in formulation, currently eschews polarimetric effects and treats the terrestrial surface extremely simply. It shows good results against data for a complex precipitation event, with simulations backed by independent "air truth."

Vegetation

Perhaps the simplest MMW canopy model is the scalar RT formulation of Schwering et al. (1988), which utilizes a parameter extraction and solution system reported separately (Johnson and Schwering 1985, Schwering and Johnson 1986). Only horizontal propagation is considered, so that no layer boundaries are encountered. Three elevations at different parts of a tree canopy are treated, at seasons with and without leaves present. This model has both the attraction and the limitation that it was developed closely in tandem with relevant data acquisition and processing. One can see immediately what the model does in application to data from a two-layer canopy of "real" vegetation (a "regularly planted, well-groomed stand" of pecan trees), but it is not clear how widely it might be generalized. The formulation goes directly to the form of an assumed phase function, which is just the scalar function

$$p(\gamma) = \alpha(2/\Delta\gamma)^2 \exp[-(\gamma/\Delta\gamma)^2] + (1 - \alpha)$$

where γ is the angle between the incident and scattered directions of energy propagation, $\Delta\gamma$ is the beam width of the forward lobe, and α is the ratio of the forward-scattered power to the total scattered power. Thus, a strong forward lobe and an isotropic background are assumed. In addition to constituents of the scalar extinction coefficient, only the two parameters above are used, and these must be estimated from experience or with reference to some representative data. Still, with reasonable values of the parameters there is good qualitative agreement with the measured data. Different behaviors are notable at different levels in the canopy, with a strong coherent forward lobe at small optical depths. This compo-

nent broadens and decays rapidly with depth. The very rapid decay at shallow depths is due both to absorption and scattering, while beyond shallow depths the attenuation is due almost entirely to absorption alone, as scattering only reproduces the incoherent component. There is a fairly sharp transition to the much more slowly decaying, isotropic intensity that ultimately predominates.

We dwell on this model in part because of its attractive simplicity. It shows fidelity to the general character of the measured data without elaborate, costly, and perhaps unrealistic attempts to define scattering and extinction matrices, without significant CPU time, and without consideration of coherent effects. While much more sophisticated models exist, one can question the cost-benefit of pursuing them in light of inevitable uncertainties.

Test environments such as that used by Schwering et al. (1988) are desirable in that they are relatively uniform and controlled, but one may be wary of artificial effects due to their constructed regularity. Tavakoli et al. (1991) perform an exercise similar to that of Schwering and his colleagues, measuring and modeling propagation through a horizontal, planted vegetation canopy. The plants constitute only a single layer (corn), but as above their arrangement is quite orderly relative to untrammelled nature. An attempt is made to treat the medium as random within rows, with some deterministic interaction between rows. Thus it is a "semi-deterministic" field approach featuring notable coherent phenomena, agreeing impressively with the observed data. The point to be made here, however, is that this latter study was done at L band, so that individual leaves are much smaller than a wavelength and stalks might be considered smooth. In the azimuthal scanning data presented by Schwering et al. (1988), there is significant scintillation due to coherent effects not accounted for in the model. The variations of signal strength are extremely rapid, however; statistically the profiles are smooth or nearly flat, and clearly the correlation length of millimeter waves in a forest is extremely short. In addition, the field rapidly becomes thoroughly depolarized. Effects of the sort pointed out by Tavakoli and his colleagues were swallowed up in the MMW regime by the strong scattering of the vegetation elements, rapidly producing a predominantly incoherent field. Even structures viewed grossly as linear and distinctly oriented (e.g., tree

trunks) may easily have bark that is so rough on the MM scale that the linearity and orientation of the trunks and branches is largely irrelevant.

Some of the models admirably constructed from detailed analysis of idealized forest elements may apply in UHF and microwave regions where elements are often on the order of the incident wavelength or smaller. In those models, Schwering and his colleagues assert, only the forward-scattered incoherent component is likely to be important, together with the coherent component. They emphasize their conviction that at MMW frequencies the incoherent, multiscattered component is likely to be predominant and must be given corresponding importance in any modeling.

Ulaby et al. (1988) pursue the course set by Schwering et al. (1988) by developing an RT model at 35 GHz in conjunction with measurements. Noting the geometrical diversity of the target trees at MMW and expecting very weak polarization dependence, they adopt the general form of the scattering function in the equation above but with the forward lobe represented as

$$2(1 + \beta_s^{-2}) \exp[-|\gamma|/\beta_s],$$

in which β_s is a measure of the effective beam width of the forward lobe. The constituent parameters in this expression and extinction coefficients are derived from measurements on individual trees of a couple of types. While Schwering and Johnson (1986) present a solution formulation that accounts for all orders of multiple scattering, and Schwering et al. (1988) emphasize the advisability of accounting for extensive multiple scattering, Ulaby and his colleagues limit the formulation to first-order results. Calculated attenuation agrees well with observations.

Ulaby and his co-workers pursue this line of investigation further by polarimetric measurement and modeling of MMW scattering from a tree canopy (Ulaby et al. 1990). The essential focus is on the crown. Noting that "at millimeter wavelengths the penetration of foliage rarely exceeds 1 m," they treat both the upper and lower canopy boundaries as diffuse and nonreflecting. Despite very substantial small-scale morphological differences between the tree types investigated (*figus* vs. *arbor vitae*), the like-polarized (HH and VV) scattering patterns were approximately the same for each tree type, and those for the contrasting tree types also resembled one another. The same held true for the cross-polarized pat-

terns. Ulaby and his co-workers have pursued specific modeling and measurement of leaf-scattering patterns, with increasing morphological and constitutional complexity for the leaves and with increasing incident frequency (Senior et al. 1987, Sarabandi et al. 1988, 1990). Nevertheless, Ulaby et al. (1990) take the view that:

1. Truly realistic MMW phase functions for the variety of vegetation elements cannot currently be determined.

2. If they could be determined, realistically complex phase functions would be computationally intractable.

3. The observations above for different tree types warrant the use of a simple assumed scattering pattern and consequent phase function in any case.

Phase functions similar to the two displayed above are obtained from data for individual samples of the vegetation. Iterative first- and second-order and "exact" numerical solutions of the vector RT equations are obtained. While it is unclear why the second-order solutions should apply in an evidently inappropriate albedo range, computed backscatter solutions compare favorably with measured data.

While the result does not surpass these models in rigor, Borel and McIntosh (1990) construct a simple model for expressing backscatter from deciduous trees, including leaf orientation distributions. This can be seen as a step toward generality and rational basis inasmuch as it includes a basis for distinguishing the responses of different trees in terms of the physical characteristics of their constituents. Measurements at 35 and 94 GHz of individual leaves were used to justify the use of an average leaf radar cross section when computing the normalized radar cross section (NRCS). A simple system is used to superpose the individual leaf contributions, using orientation distribution and incidence (viewing) angle. Orientation dependence in the results is used to justify similar analysis of data from a variety of tree forms at 215 GHz. The modeling is quite approximate in that fine-scale leaf roughness, polarization, and shadowing effects are neglected, among other things. However, a noteworthy result of the combined analysis and data is the observation that one is able to distinguish returns from different (planophil, erectophil) morphology classes, despite substantial differences between individual members within each class, based on characteristic leaf orientation. This serves as a refinement of

the work by Ulaby and his colleagues, in that McIntosh's group shows differences in polarimetric returns distinctly as a function of tree type, or at least class of tree type.

These observations are intended to highlight the particular nature of MMW scattering from environmental features, to serve as a warning against the facile extension of lower-frequency modeling approaches to MMW and to suggest restraint on attempts to build sophisticated model structures based on gross features. Having said this, we proceed nevertheless, trusting that more aggressive analysis will eventually provide useful tools beyond the otherwise extremely simplistic devices currently at our disposal.

Lang and his co-workers at George Washington University (GWU) have developed primarily WT vegetation models for some time, attempting to include more specific analytical characterization of the canopy scattering elements. In early work, leaves are modeled as circular dielectric disks (Lang 1981), with the addition of a flat lossy ground surface and orientation statistics for lossy leaves (Lang and Sidhu 1983). The Foldy approximation was used, implying sparse media, and leaf sizes were assumed to be smaller than the incident wavelength. Some attempt has been made to include higher frequency effects in theory for individual leaf-scattering behavior (Levine et al. 1983).

Some more recent RT work by Lang and his colleagues approaches small wavelength limits (Lang and Yazici 1989). The culmination of the line of work by the GWU team in terms of an available model is WT-based, allowing for different classes of scatterers in two layers, each with a specific orientation distribution. Underlying surface roughness is treated by KA theory. Polarimetric backscatter coefficients are computed using the distorted Born approximation. The formulation implies contributions from direct volume-scattering, a direct-reflected or double bounce ground-vegetation term, a bottom reflection contribution, and a surface scatter term. Flat or curved disks with circular or elliptical shapes may be selected, as well as linear (cylindrical) members. For the most part the programs are oriented toward P, L, and C band; simulations have used ground truth input and have been compared where possible with measured backscatter for various canopy scales, including grass, soybeans, corn, and forest (e.g., Chauhan et al. 1991, Saatchi et al. 1991). Formulations for thicker disks,

needle arrays, and resonant size cylinders are being included so the system can be used at MMW wavelengths, with simulations performed at 10–50 GHz. Experimental validation at these frequencies is reported to be underway.

Fung and his co-workers have also attempted to build specific leaf and branch character into vegetation models for frequencies higher than those considered in previous models. Using the Rayleigh–Gans approximation, a first-order RT formulation is presented that should be valid for leaf dimensions up to the size of the incident wavelength (Karam and Fung 1989). Size variations are included through elliptic disk leaves and needles for conifers. On the basis of simulations it is suggested that both like and cross polarizations may be needed to distinguish leaf type effects on scattering behavior. As frequency increases, near-field effects enter increasingly in leaf-to-leaf field interactions. Fung et al. (1987) allow leaves to be in the Fresnel zone of one another for both disc and needle-shaped leaves. VV and VH measurements are matched to calculated X-band scatter for soybean plants. Liu and Fung (1988) use an empirical parameterization of vegetation material with a rough underlying ground surface to perform polarimetric scattering computations for $k \cdot a$ values approaching 4, where a is a characteristic leaf dimension. Comparisons of the computations with data are good. Karam and Fung (1988) use a first-order RT formulation for randomly oriented dielectric cylinders to link surface scattering with that from a defoliated vegetative volume. While comparisons with data are best for lower $k \cdot a$ (a = cylinder radius) values, favorable comparisons are seen as high as $k \cdot a = 2$. While MMW frequencies strain these $k \cdot a$ limits, leaf sizes and branch radii up to some significant fraction of a centimeter could possibly be accommodated at 35 GHz.

Tsang and his co-workers at UW, MIT, and GE have developed vector RT models that may be applicable to vegetation over rough-surfaced soil (Tsang et al. 1990, Tsang 1991, Tsang and Ding 1991, Tsang et al. 1992a). First-order, second-order, and full-multiple scattering solutions are obtained. Extinction and phase matrices are calculated in such a way that energy is conserved and reciprocity preserved. Application of the models to measured data is awaited.

In an interesting new approach pursued separately by investigators at MIT and GWU, models are designed to include the effects of vegetation architecture. The needles on an evergreen, for ex-

ample, are distributed with a randomness that is structured by the basic tree morphology; they cluster with predisposed alignment along twigs and larger branch elements. Thus, the needles may effectively form a random distribution of arrays. Drawing on such observations of underlying architecture also allows incorporation of the multiscale nature of vegetation systems. Yueh et al. (1992) employ two scale branching models with idealized independent scattering behavior of individual elements. Calculated responses for simple structures as a function of frequency and incidence angle show an importance of coherent or phase relations between constituent elements. In application, including ground surface effects and a hole-correction pair distribution function, good agreement is obtained in comparisons with polarimetric C-band data from soybean fields. While greater small-scale coherence effects might be anticipated at frequencies below C band, it remains to be seen whether the approach produces significant revelations in the higher-frequency domain we are interested in.

Lang and Kavaklioglu (1991) pursue a related modeling exercise in which they contrast the behavior of randomly oriented elementary needles with that of randomly oriented arrays of such needles. It is assumed that the radius of each cylindrical needle is small compared with the wavelength, which is a reasonable assumption at 35 GHz, if not at 94 GHz. While comparisons with data are not indicated, the modeling evidently showed differences in response between the random needles and random arrays of needles when the wavelength was comparable to the array size. We cannot yet say that the concepts used in these studies have been shown to be of great relevance for MMW simulation. However, these first results as well as the appealing rationale of the basic concepts suggest strongly that this is an area to watch.

We close this section with a brief mention of Monte Carlo modeling. Chuah and Tan (1992a) have proposed a model for backscatter from forest stands. Their approach is “Monte Carlo” in that individual contributing scattering events within the canopy are treated probabilistically and then looked at in their intensity sum. As noted above, this and any other such treatment based on a cascade of statistical events differs fundamentally from the Monte Carlo treatments of surface scattering that have appeared recently. In the surface scattering case, investigators calculate the scattering deterministically from an entire, spe-

cifically described, generally realistic geometry. This procedure is repeated many times for different example surfaces, and the ensemble of results is summed coherently. In Chuah and Tan's model, the top layer consists of randomly oriented leaves and branches, the next layer is a random distribution of trunks, and a randomly rough soil surface forms the bottom boundary. The medium model differs from that of Karam and Fung (1988) in that Chuah and Tan assume a multilayer model with a mixture of different classes of scatterers in the top layer. Leaves are modeled as randomly oriented dielectric circular disks or small needles; branches and trunks scatter as infinite cylinders, and the ground is treated using a GO-type limit to the KA. The primary distinguishing feature of the approach here is the use of a Monte Carlo method to track photon transport through multiple scattering interactions in the media. Characterization of the interactions at each collision are used to build up an overall transport picture in terms of intensity, not field value as for a WT approach. Using parameters considered to be justified by ground truth, the authors produce calculated backscatter from trees that compares well with measurements at S and X bands.

A closely related approach is applied to the computation of emission (Chuah and Tan 1992b,c). Given its fundamental basis, we assume that Chuah and Tan's overall approach should produce results equivalent to an RT approach. For this reason, together with the uncertain availability of code and support, we do not pursue it here. However, it is an innovative approach that merits continued attention, as it may eventually produce physical results or computational facilitation not obtainable otherwise.

Snow and ice

Hallikainen et al. (1987) use a simplified strong fluctuation theory following Ishimaru (1978) to model the extinction behavior of snow in the 18–90 GHz range. Eighteen types of snow were considered, from newly fallen to refrozen. Agreement between computed and observed values is good if the single free parameter of grain size is tuned to a value somewhat less than the observed. A very interesting observation emerges from the study by Hallikainen et al. in connection with surface scattering. Especially for the dry snow considered, surface scattering is often considered to be negligible at MMW frequencies. By implication, this is explained by the prominence of particle-scale scattering, assumed to be as domi-

nant near the edge of the medium as within its interior. Hallikainen and his co-workers measured extinction ranging from only a small number of dB/m to about 500 dB/m. The latter occurred in cases combining the highest frequencies and largest grain sizes. To be emphasized here are the additional surface scattering losses that were inferred, ranging from a small effect to tens of dBs. The larger surface effects were seen in cases including the highest frequencies, largest grain sizes, and roughest surfaces in undisturbed samples. We note particularly that the roughest surface had rms height variations that were only on the order of a couple of grain diameters. In other words, the grains themselves appear to offer an effectively roughened surface. At the highest frequencies, where this was most significant, penetration depth in the snow is effectively only some tens of centimeters. This means that the surface losses constituted an effect comparable in order of magnitude to volume scattering over the depth sensed. The significance of all this lies in the implication that one may have to model rough surface scattering to account accurately for all scattered energy, and the surface roughness treatment may have to include particle scale effects as well as more macroscopic surface considerations.

The version of strong fluctuation theory employed by Hallikainen et al. (1987) includes some coherent effects associated with particle proximity. In a broader and more rigorous treatment (see below), Tsang and Kong (1992) perform calculations for a dense medium with correlated scattering by particles near one another. The assumed spherical particles are characterized by a size distribution, with sizes comparable to a wavelength. Including these features in the model produces quite good agreement with the same data. Full calculation of the incoherent scattering is limited by the use of the distorted Born approximation.

Others at the University of Michigan constructed and tested an RT model for scattering from snow (Kuga et al. 1991, Ulaby et al. 1991). MMW-scale scattering from assumed spherical ice particles is treated by Mie scattering expressions to obtain the phase function; nonuniform liquid-ice contact to be expected in small inclusions is modeled by assuming an equivalent "wet air" background medium; the density of the medium is dealt with by the QCA in a manner less complete than that of Wen et al. (1990); and the equations are solved using the discrete ordinate technique with Fourier decomposition of azimuthal components. The effect of upper snow

surface roughness is accounted for in an extremely simple KA stationary-phase approximation. Copolar volume contributions are added incoherently to the direct backscatter calculated from the surface. With the addition of a hybrid first-order numerical solution in Ulaby et al. (1991) to address the refrozen case, overall good agreement is shown between experimental observations and theoretical calculations. Having gained confidence in the numerical model, Ulaby et al. (1995) run it for a matrix of cases to generate broader information on the dependencies of the backscattering cross section of snow at 35 and 94 GHz. From these results a semi-empirical model is constructed in the form of a single equation. This equation may represent the simplest model of snow backscatter from the point of utilization. It offers the great advantage that, for example, a large number of scene pixels can be generated extremely rapidly for changing conditions. While the ultimate equation rests on both data and theory, it requires faith that the numerical model extended the original data with sufficient fidelity.

Narayanan and McIntosh (1990) study high-frequency polarimetric backscatter from multilayered snow. Their model treats multilayered snow in terms of a cascade of scattering from a number of homogeneous layers with distinct boundaries. The approach uses inputs from ground truth measurements, which in their entirety have included surface roughness, moisture content, density, hardness, particle size, and grain type. Total back-scattered power is the incoherent sum of surface reflection at the interfaces and a very simply computed volume scatter. An effort is made to include bistatic scattering effects and shadowing on the rough surface. Multiple scattering between layers and ice particles is ignored. Transmission between layers is considered to be simple Fresnel transmission of fields as for incidence on a solid slab. Slab dielectric constants are obtained from the Polder-van Santen mixing formula for ice spheres and water, and volume scattering is computed as the simple summation of Mie scattering from individual grains with a Rayleigh distribution of diameters. Weak surface scattering is computed using the stationary-phase KA approximation. Reported co-polar NRCS values computed from the model compare favorably with measurements.

Another generation of empirically based models has come from a group at the University of Massachusetts, beginning with Mead et al. (1993). Fully polarimetric measurements of snow back-

scatter showed different rates of decline of σ_{VV} and σ_{HH} with increasing incidence angle. Encouraged by observations of approximately spherical grains in the snow surveyed, the authors constructed input-output relations of the polarimetric quantities based on a modified Mueller matrix for orientation-independent scatterers, modified by transmissivity factors. The latter assume Fresnel-type interface effects and provide much of the polarimetric behavior sought; the whole is tuned using the original measurements. While admittedly empirical, this model provides a structure consistent with basic physical mechanisms and common forms of their description, and it catches some basic polarimetric behavior. We note that the inclusion of the surface effects is essential. Subsequently, Chang and his colleagues (Chang et al. 1996) report and analyze snow backscatter measurements at 35, 95, and 225 GHz. Newly fallen snow in which grains still exhibit flattened, platelet-like geometry shows distinctive polarimetric effects, with decrease in magnitude and increase in phase in the correlation of horizontal and vertical copolar components. Together with information from the scattering measurements, this particle geometry is taken into account in a simple way in the construction of a phase matrix. The resulting RT formulation avoids both the rigor and complexity of the dense-medium treatments outlined below; calculations using it reflect the distinctive polarimetric observations.

The work by Chang et al. also shows instances in which the backscatter behavior is dominated by a thin refrozen crust on the snow. Together with the evident effect of nonspherical particle geometry, the importance of the crust poses a considerable challenge for modelers. A layer only a few wavelengths or grains thick (0.5–2.0 cm) may throw into question the applicability of an RT volume-scattering analysis. In addition, one must confront an essential scattering volume with rough surface excursions that could be greater than the thickness of the volume (layer) itself. In any case, we note that reliance on the measured results in the construction of the recent U. Mass. models limits their predictive value and places them largely outside of the type of model sought here.

Fung and Eom (1985) investigate the scattering and emission behavior of snow. The medium is modeled as a densely packed matrix of ice spheres; distance-dependent terms are kept in the development of expressions for particle scattering as input to the phase matrix. Limiting the

formulation to far-field interparticle interaction resulted in underestimation of computed backscatter and overestimation of brightness temperatures. Computations with near-(intermediate-) field effects between particles produce superior agreement to backscatter data shown for about 8 GHz. Tjuatja et al. (1992) build on this with their multilayer model that includes volume scattering, surface scattering, and volume-surface interaction. With the volume component treated by RT, the surface scattering may be computed using Fung's integral equation method (e.g., Fung and Pan 1987, Fung et al. 1992, Fung 1994) and then added incoherently as a boundary condition on the volume. Although all volume scatterers are treated as spheres, the model is applied successfully to sea ice. Snow-covered ice is only treated at 5 GHz, but frequencies as high as about 14 GHz are considered for ice alone. While this still remains somewhat below our desired frequency range, it does entail a treatment of scattering elements that are large relative to the wavelength, with dense media, in the sense that non-far-field interaction of particles is included. Most recent investigations in the same frequency range with active sensing are reported by Fung et al. (1995). Passive sensing of snow-covered sea ice (Tjuatja et al. 1995) up to 90 GHz treats dense-medium effects by calculating a P matrix including near-field and coherent interactions of elements in a randomized 3-D grid. Simulated behavior parallels that seen in measurements elsewhere.

Substantial groundbreaking work on volume scattering has come from researchers working at MIT. Using an RT approach, Shin and Kong (1989) calculate bistatic scattering coefficients for a two-layer random medium using all four Stokes parameters (vector RT). In general, RT calculates energy balances, and most phase effects are lost. However, vector RT offers a partial compensation in that general elliptically polarized incidence and response states are included. The numerical approach provides valid solutions for both small and large albedos; azimuthal Fourier decomposition is used, with Gaussian quadrature and eigen analysis. Combined volume and rough surface scattering effects are included by modification of the boundary conditions. KA-GO surface conditions are assumed. While measured data are not treated, illustrative computer runs show dominance of rough surface effects for incidence near nadir with volume scattering predominant for large angles. Applications to media and fre-

quencies of interest here are limited by, among other things, the assumption of small permittivity variations.

Investigators in collaboration with MIT researchers and others, at the University of Washington (UW), have developed a number of models that may be applicable to snow and ice. Concentration has been on generic dense non-tenuous granular media and size distribution effects (Tsang and Ishimaru 1987; Ding and Tsang 1989, 1991; Wen et al. 1990; Tsang and Kong 1992). A rigorous basis for dense-medium RT is provided by Tsang et al. (1985) and Tsang (1992) based on multiple-scattering-field theory. The paper by West et al. (1993) actively incorporates most of the developments leading up to it, and it is a good display of the revelations made possible by the method. With variations and departures in each of the works cited, correlated scattering is incorporated via the QCA and QCA-CP for the first moment of the field and the correlated ladder approximation for the second moment, such that an intensity operator may be obtained that conserves energy. A size distribution is employed for constituent particles with pair distribution functions calculated under the Percus-Yevick approximations. Near-, intermediate-, and far-field particle interactions are taken into account such that coherent effects are expressed in the near- and intermediate-field ranges. Many interesting features emerge from the numerical simulations, such as less scattering from a dense correlated medium than from an equivalent independent scattering medium; much greater scattering from a medium with distribution of particle sizes compared with a monodispersed mixture of the same average radius; and the importance of multiple scattering.

In treating the correlated scattering in dense media, these DMRT approaches require the definition and computational treatment of a particle pair distribution function (PDF). This function expresses the conditional probability of finding a particle at a given distance from another, and it is directly related to the correlation function for the medium. Its computational implementation is made tractable for spherical particles through employment of the Percus-Yevick approximation. Once PDF and other dense-medium considerations are accounted for in determining the constituents of the basic energy balance equation, the form of that equation is essentially the same as for CRT, hence the same numerical considerations apply to its solution. We note that multiple scat-

tering should normally be significant in dense media. Thus, computational maneuvers that rely on weak or insignificant multiple scattering are unlikely to apply. Using the DMRT approach, Wen et al. (1990) show the convex relation between extinction and particle density that has been observed in measurements (e.g., Ishimaru and Kuga 1982, Gibbs and Fung 1990).

DMRT simulations show a relation between interparticle correlation and size distribution effects. While Wen et al. (1990) show reasonable agreement with snow backscatter measurements, they assume a uniform grain size. More reasonable physical parameters produce good agreement when a grain size distribution is employed (West et al. 1993). Most simulations up through the work of West et al. assume Rayleigh scattering, i.e., $ka \leq 1$, which limit applicability to the bottom of the MMW frequency range. (This limitation is not inherent in the basis of DMRT.) In this regime, for independent scattering, the scattering cross section increases as the sixth power of particle radius a . Thus, it should not be surprising that DMRT calculations based on a Rayleigh distribution of sizes produces backscatter on the order of 15 dB greater than that from a uniform distribution, with size equal to the mode radius in the distribution. A relatively small number of larger particles can produce a disproportionately great effect. At the same time, the increase in scattering by the larger particles in a nonuniform distribution is not nearly as great as one would expect from the sixth-power law. The point is that the close proximity of the smaller particles to the larger particles reduces the overall correlation length of the medium, which is expressed through the PDF.

These results suggest that both dense-medium and particle-size-distribution effects must be treated, and must be treated together, for high-fidelity simulations. For a particular application, i.e., to snow, one might hope that it could be possible to develop an "equivalent" uniform particle size. That is, if snow tends to come in various particular micromorphologies with particular attendant particle distributions, it might be possible to develop systematically a corresponding fictional uniform particle size that would give the correct results in simulations. This particle size would in general be different from the average particle size. It is questionable that such a quantity could be implemented so as to portray accurately all effects of interest, e.g., polarization ef-

fects. Hopes are even more dim for development of an "equivalent" CRT formulation that lacks detailed realism in the mechanisms incorporated but that also somehow reliably produces correct behavior.

In principle, there is no problem in including different species as well as different sizes of particles in DMRT formulations. This suggests that water inclusions might be modeled as small ring-shaped or otherwise nonspherical inclusions at points of particle contact. However nonspherical particles interfere with the established strategies for the necessary PDF-related computations. Because the liquid water inclusions are small, their shape may not be so important and they might be modeled as many very small spheres concentrated somehow in the smaller crevices of the medium. Ding et al. (1993) have produced "sticky" particle formulations, by which specified degrees of particle clustering can be achieved in the numerical construction of the medium. Beyond its possible relevance for the inclusion of liquid water, this sort of formulation has shown promise in producing more realistic morphology and scattering behavior (Shih et al. 1995). Extreme degrees of anisotropic "stickiness" might successfully treat some of the anisotropic particle effects mentioned above. In any case, ongoing work at MIT seeks ways to generate dense distributions of spheroidal particles, together with their correlation/PDF functions. As in nature, some degree of average particle orientation is forced by the density of the medium.

The particle basis for DMRT formulations heretofore imposes considerable computational burden as the particles become large relative to the wavelength. Restricting particles to a spherical shape facilitates both PDF and scattering determination as dimensions increase, inasmuch as Mie scattering schemes may be employed. However, to date most formulations and computations have been performed assuming particles that are small enough to warrant the assumption of simpler Rayleigh scattering. When nonspherical grains are treated, however, the Mie scattering formulations are inapplicable. When particles are relatively large, the details of their shape have more effect on overall scattering behavior and one has less liberty to just assume a somehow equivalent sphere. In response to this, work at MIT has also been directed into correlation functions for "bicontinuous" nongranular geometries. In the end, this may be both simpler and more

successful than the particle-based approaches, which in any case are somewhat artificial for most applications to snow.

While ice and snow are logically considered together, one must distinguish the particular problems associated with each. Until recently, few MMW sea-ice studies could be found with comparisons of simulations to data, exceptions being the work of Lee and Mudaliar (1988) and Mudaliar and Lee (1990). At present, one does well to begin with the wealth of detail on sea-ice phenomenology and sensing, measurement and modeling, and theory and evaluation as presented in the volume edited by Carsey (1992). A chapter by Winebrenner and others on theoretical modeling of sea-ice microwave/MMW behavior recounts the testing of various contrasting models on three reasonably well-characterized saline ice samples over a frequency range that includes some of our span of interest. Any applicable model must somehow include the effects of elongated, oriented brine pockets or bubbles in the ice. Alternatively, it can concentrate on the complementary shape of the individual crystals defining the boundaries of those pockets. Models tested (and their originators) were designated to include independent Rayleigh scattering layers (Drinkwater); dense media RT (Tsang and West); dense-medium theory with integral equation method for rough surface (DMT-IEM, by Fung and his co-workers); many-layer strong fluctuation theory (SFT by Stogryn/Grenfell); polarimetric SFT (Nghiem and the MIT team); and MRT (Lee and Mudaliar). The reader is referred to the above reference for the details of these studies. Particularly in certain aspects and certain frequency domains, successes are shown, although many questions remain. Among other things, models based on rather different physical mechanisms sometimes still manage to provide more or less the same (correct) answers. This raises the question of how much seemingly good results derive from modeling technique and manipulation, as opposed to incorporation of mechanisms that truly correspond to the dominant physical processes. Most of the work reported in Carsey's (1992) volume was part of a large ongoing effort, with some additional results reported elsewhere. The reader is referred to IGARSS'94 (1994), with somewhat fewer sea-ice papers in IGARSS'95 (1995) showing MMW content.

AVAILABLE COMPUTER CODES

In this section we provide information on specific models and their sources. The entries are listed by source and are grouped more or less by area of application. For each model or package, information is given on applications, model features and approach, and source contact. Comments on each include information such as location of reference discussion in the body of the report, limitations and advantages, and status of code testing and facilitation. In some instances considerations of code documentation, availability, ease of use, and support are subsumed in the category "code usability."

Many notable models discussed in this report are not mentioned below because they failed in some way to meet our general criteria for inclusion (e.g., insufficient information from originators, complexity or resource requirements beyond the feasibility limits, unavailability of code, reliance on empirical quantities, lack of application/testing against geophysical media, unlikely future support for the code, etc.). This should not be interpreted as a negative judgment on the scientific validity or research value of such models.

MPM

Features

Computes complex refractivity profiles together with power attenuation and propagation delay rates as functions of frequency, humidity, or pressure for air, with possible inclusion of water vapor, haze, fog/cloud, and rain.

Comments

Refer to the discussion under *Atmosphere*, in the *Applications* section.

Input factors may be frequency, barometric pressure, RH, temperature, haze type, suspended water-droplet concentration, and rain rate. In different versions of the model, the user inputs a range for one of the first three variables and fixed values for some or all of the remaining ones. Rain treatment is very simple. The code is easy to use, with plentiful comments and references embedded.

Source/contact

Dr. Hans J. Liebe
NTIA/ITS.S1

325 Broadway
Boulder, CO 80303
Phone: (303) 497-3310

Enhanced RADTRAN

Features

Computes atmospheric attenuation and brightness temperature for typical atmospheric paths, including effects of clear air, fog, cloud, and rain, with polarized surface emissivities.

Comments

Refer to the discussion under *Atmosphere*, in the *Applications* section.

Improvements by Atmospheric and Environmental Research, Inc., of the 1979 Air Force Geophysics Laboratory program; core treatment of gas and aerosol effects is solid; newer RT algorithm treats multiple scattering from precipitation; the formulations of terrestrial surface effects are very approximate; limited validation of recent enhancements; code documented, disseminated, and supported; more extensive validation is underway.

Contact/source

Dr. Vincent J. Falcone
Geophysics Laboratory
Air Force Systems Command
United States Air Force
Hanscom AFB, MA 01731-5000
Phone: (617) 377-4029

Dr. Ronald G. Isaacs
Atmospheric & Environmental
Research, Inc.
840 Memorial Drive
Cambridge, MA 02139
Phone: (617) 547-6207

Gasiewski radiative transfer model

Features

Computes brightness temperature and associated statistics for planar stratified scattering atmospheres over specularly reflecting surfaces.

Comments

Refer to the discussion under *Atmosphere*, in the *Applications* section.

An RT solution for absorbing atmosphere and Mie scattering from precipitation; very simple surface emissivity factors, with general user-specified (constant) bistatic scattering coefficient inclusion under development; as with RADTRAN, polarimetric effects from precipitation are generally lacking; aspherical hydrometeor formulation is under development; code usability: "Undergraduate students at Georgia Tech have been able to obtain useful results from the model within a few hours."

Source/contact

Professor Al Gasiewski
Department of Electrical Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0250
Phone: (404) 894-2934

Fung surface model

Features

Integrated and facilitated surface scattering model based on SPM, KA, or the integral equation approach.

Comments

Refer to the discussion under *Scattering from Surfaces and Transitions*, in *Methods and Approaches* section.

PC-oriented, user-friendly software and documentation under development; user inputs choices of rms height, correlation length, and possibly correlation function, program displays results compared with user input data; subject to parameter field limits of each technique; integral equation approach most permissive, requiring primarily rms slope less than about 0.4.

Source/contact

Professor Adrian Fung
University of Texas at Arlington
Arlington, TX 76019
Phone: (817) 273-3422

UPM surface model

Features

Unified perturbation method producing complete bistatic cross sections for E and H polarization; Gaussian and power law surface spectra are included so far, others are possible.

Comments

Refer to the discussion under *Scattering from Surfaces and Transitions*, in the *Methods and Approaches* section.

The formulation reduces where appropriate to KA, SPM, and two-scale theories, with greater overall range of convergence but similar input requirements; 1-D roughness code is available, 2-D reported nearing completion; possible inclusion of 1-D roughness finite element and method of moments codes for Monte Carlo simulation; bistatic results allow inference of reciprocal passive behavior; upcoming 2-D roughness treatment would allow fully polarimetric treatments and possible integration with specific ocean modeling capability.

Source/contact

Dr. Ernesto Rodriguez and Dr. Yunjin Kim
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA 91109
Phone: (818) 354-9500

GWU vegetation model

Features

WT-based approach to sparse layer over half space with classes of scatterers having orientation distributions.

Comments

Refer to the discussion under *Vegetation*, in the *Applications* section.

Some ground-vegetation multibounce paths are included, but overall the model treats two-layer single scattering theory with attenuation; KA treatment of rough ground surface; polarimetric backscatter coefficients are calculated. Previous formulation and especially validation at frequencies no higher than C band, with recent developments oriented toward at least X-band and higher; documentation status is unknown.

Source/contact

Professor Roger Lang
Department of Electrical Engineering
and Computer Science
George Washington University
Washington, DC 20052
Phone: (202) 994-6083

Schwering and Johnson vegetation model

Features

Scalar RT treatment of vegetation field with surface but no deep boundary; computes propagation from which backscatter can be obtained.

Comments

Refer to the discussion under *Vegetation*, in the *Applications* section.

Very simple model that relies on measured or estimated two-parameter phase function; satisfactory simulation of data on which phase function was based; limited generality; program could be made available and documentation developed at small to moderate cost.

Source/contact

Dr. Robert Johnson
Textron Defense Systems, MS 3106
201 Lowell St
Wilmington, MA 01887
Phone: (508) 657-1721

UW snow model

Features

Computes polarimetric surface and volume scatter and emission from snowpacks under different moisture conditions.

Comments

Refer to the discussion under *Snow and Ice*, in the *Applications* section.

Assumed spherical particles allow calculation of pair distribution function and consequent dense medium approach; formulation includes particle-size distribution with the presence of moisture; developments are anticipated in connection with MIT personnel and Shi from UCSB. The validation is encouraging, and the code usability has potential. Documentation status is unknown. Continuing developments are currently underway.

Source/contact

Professor Leung Tsang
Electromagnetics of Remote Sensing Laboratory
Department of Electrical Engineering
University of Washington
Seattle, WA 98195
Phone: (206) 685-7537

EMSARS

Features

EMSARS, or Electromagnetic Model for Scattering Applied to Remote Sensing, is a general active and passive polarimetric computational package for generic anisotropic volume and surface scattering with layered media.

Comments

Surface scattering modules can treat perturbed quasi-periodic surface, reducing to classical two-scale random rough surface, or "classical" KA, GO, SPM. Rough surface effect added incoherently to WT and RT volume scattering; treatment of vegetation layers and individual trees; integrated code and documentation exist with ongoing debugging; prospective union with UW dense medium/snow model; importantly, integrated capability has been developed from GIS/map data through simulation to scene generation.

Source/contact

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and Application
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE October 1996		3. REPORT TYPE AND DATES COVERED	
4. TITLE AND SUBTITLE The State of the Art of Modeling Millimeter-Wave Remote Sensing of the Environment				5. FUNDING NUMBERS	
6. AUTHORS Kevin O'Neill					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Cold Regions Research and Engineering Laboratory 72 Lyme Road Hanover, New Hampshire 03755-1290				8. PERFORMING ORGANIZATION REPORT NUMBER Special Report 96-25	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of the Chief of Engineers Washington, D.C. 20314-1000				10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES For conversion of SI units to non-SI units of measurement consult ASTM Standard E380-93, <i>Standard Practice for Use of the International System of Units</i> , published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.					
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited. Available from NTIS, Springfield, Virginia 22161				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A survey was undertaken of models for millimeter-wave (MMW) scattering and emission from environmental features, particularly in the vicinities of 35 and 94 GHz. The ultimate objective was to identify models suitable for current or near-future application in scene generation. The ideal model would be based on first principles, would be readily available in facilitated software, and would have reasonable requirements in terms of computational resources and input parameters. At MMW frequencies, these requirements push the frontiers of current science and technology. In most applications, one must accept as a first approximation the approaches currently under development in research settings. This report reviews the basic methods and approaches underlying all available models in terms of volume scattering, treatment of surfaces and transitions, and the development of statistical quantities from rational physics. Very rough surfaces, locally steep surface slopes, and low-angle incidence can rarely be treated entirely successfully, but recent developments offer the prospect of significant progress. Volume and combined surface-volume scattering and emission models are reviewed for application to land, water, vegetation, snow, and ice environments. Most are essentially works in progress, with theory and validation currently building from earlier work at C and X bands. Very sound capabilities are available for treatment of common atmospheric features, with recent progress in modeling more complex meteorological events. Limiting consideration to truly available codes, a list is provided for each of the above areas of models and their sources. Because it is the most comprehensive and is currently facilitated in terms of software, the MIT EMSARS model is the foremost candidate to serve as a platform for future addition and development.					
14. SUBJECT TERMS Algorithms Emission Millimeter-wave (MMW)			Modeling Remote sensing Software	Surface scattering Volume scattering	15. NUMBER OF PAGES 33
					16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL		