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14. ABSTRACT

The ability to rapidly calculate at-sensor radiance over a large number of lines of sight (LOSs) is critical for hyperspectral and multispectral scene simulations and look-up table generation, both of which are increasingly used for sensor design, performance evaluation, data analysis, and software and systems evaluations. We have demonstrated a new radiation transport (RT) capability that combines an efficient multiple-LOS (MLOS) multiple scattering (MS) algorithm with a broad-bandpass correlated-k methodology called kURT-MS, where kURT stands for correlated-k-based Ultra-fast Radiative Transfer. The MLOS capability is based on DISORT and exploits the existing MODTRAN-DISORT interface. kURT-MS is a new sensor-specific fast radiative transfer formalism for UV-visible to LWIR wavelengths that is derived from MODTRAN?s correlated-k parameters. Scattering parameters, blackbody and solar functions are cast as a few sensor-specific and bandpass-specific k-dependent source terms for radiance computations. Preliminary transmittance results are within 2% of MODTRAN with a two-orders-of-magnitude computational savings. Preliminary radiance computations in the visible spectrum are within a few percent of MODTRAN results but with orders of magnitude speed up over comparable MODTRAN runs. This new RT capability (embodied in two software packages: kURT-MS and MODTRAN-kURT) has potential applications for remote sensing applications such as hyperspectral scene simulation and look-up table generation for atmospheric compensation analysis as well as target acquisition algorithms for near earth scenarios.

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Correlated-*k* based fast, accurate bandpass radiance and transmittance calculations for hyperspectral and multispectral scenes

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ABSTRACT

The ability to rapidly calculate at-sensor radiance over a large number of lines of sight (LOSs) is critical for hyperspectral and multispectral scene simulations and look-up table generation, both of which are increasingly used for sensor design, performance evaluation, data analysis, and software and systems evaluations. We have demonstrated a new radiation transport (RT) capability that combines an efficient multiple-LOS (MLOS) multiple scattering (MS) algorithm with a broad-bandpass correlated-*k* methodology called *k*URT-MS, where *k*URT stands for correlated-***k***-based Ultra-fast Radiative Transfer. The MLOS capability is based on DISORT and exploits the existing MODTRAN-DISORT interface. *k*URT-MS is a new sensor-specific fast radiative transfer formalism for UV-visible to LWIR wavelengths that is derived from MODTRAN's correlated-*k* parameters. Scattering parameters, blackbody and solar functions are cast as a few sensor-specific and bandpass-specific *k*-dependent source terms for radiance computations. Preliminary transmittance results are within 2% of MODTRAN with a two-orders-of-magnitude computational savings. Preliminary radiance computations in the visible spectrum are within a few percent of MODTRAN results, but with orders of magnitude speed up over comparable MODTRAN runs. This new RT capability (embodied in two software packages: *k*URT-MS and MODTRAN-*k*URT) has potential applications for remote sensing applications such as hyperspectral scene simulation and look-up table generation for atmospheric compensation analysis as well as target acquisition algorithms for near earth scenarios.

Keywords: *k*URT, *k*URT-MS, Correlated-*k*, DISORT, Multiple Scattering, Look-up-tables, MODTRAN, MODTRAN-*k*URT, Hyperspectral and Multispectral Scene Simulation

1. INTRODUCTION

Look-up tables of radiative transfer (RT) quantities such as bandpass transmittance and radiance are used in a variety of remote sensing applications, including scene simulation and atmospheric compensation of spectral imagery. Since the calculations can be quite time-consuming if performed over a wide range of atmospheric conditions and viewing geometries, highly approximate methods are often used. For example, the Target Acquisition Weapons Software (TAWS) uses the 2-stream delta-Eddington plane-parallel atmosphere multiple scattering (MS) method.[1,2] This method can show errors of 30-50% with respect to the "exact" DISORT (DIscrete Ordinates Radiative Transfer) scattering algorithm[3,4] and displays singularities at line-of-sight (LOS) and solar zenith angles of 90º; *i.e.,* for horizontal paths (HLOS) and the sun near the horizon. For such broad bandpass applications, and other applications such as accurate hyperspectral and multispectral scene simulations, there is both the need and opportunity to develop new fast yet accurate RT methods that take advantage of both the low spectral resolution requirement and calculation redundancies inherent in multiple LOS views through the same or similar model atmospheres.

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In two previous SPIE papers[5, 6], we described a method, dubbed ***k*URT** (correlated-***k***-distribution based **U**ltra-fast **R**adiative **T**ransfer), which is a new fast and fairly accurate thermal radiance RT algorithm designed for scene generation, look-up table creation and target acquisition needs. Here, "fast" is defined as two or more orders of magnitude more rapid than 1 cm^{-1} MODTRAN calculations, and "accurate" is defined as an absolute transmission error no greater than 2% and typical radiance errors of 5-10% when compared to bandpass-averaged 1 cm^{-1}-resolution MODTRAN calculations. In addition, *k*URT automatically accounts for the sensor bandpass response function, thus eliminating post-processing of higher-resolution spectral information. The second SPIE paper[6] described expanding *k*URT ideas into computing multiple-scattered radiance by using DISORT within the *k*URT framework, dubbed *k*URT-MS. This paper serves as an update on both the previous two. Here we mainly present results, leaving out details of the *k*URT-MS formalism, for which the reader is referred to the aforementioned articles.

The spectral range of *k*URT-MS is identical to that of MODTRAN; *i.e.*, from the infrared (IR) to the visible (VIS). Preliminary *k*URT-MS computations in the VIS-SWIR indicate that RT quantities, particularly radiance, which is dominated by MS solar radiance, will have sufficient accuracy for many applications. Of course, *k*URT-MS will not be accurate in all regions of the spectrum, especially in regions of low transmittance. Our computations in the visible region indicate that the *k*URT-MS method using DISORT predicts total radiance for HLOS paths with low solar elevation angles much more accurately (2-6% error) than the 2-stream scattering codes (+30% to –55% error).

In addition to *k*URT-MS, which can run independently of MODTRAN, we are also incorporating *k*URT concepts into MODTRAN. This code, which we call MODTRAN-*k*URT, will be fully compatible with MODTRAN and can run either in the *k*URT or the traditional MODTRAN mode. MODTRAN-*k*URT will take full advantage of MODTRAN infrastructure and machinery, including I/O and refractive geometry.

Concurrent with *k*URT development, we have also been working on the MODTRAN's DISORT interface to take advantage of DISORT's inherent multiple line-of-sight (MLOS) capability, namely, the capability to perform RT calculations for many lines of sight using a single call to DISORT from within MODTRAN. We have found that for a computation dominated by DISORT (which is typical for a calculation covering a large wavelength region), the MLOS method adds only 15% additional time for an additional LOS computation.

2. OVERVIEW OF THE *k*URT-MS METHOD

2.1 Methodology of *k*URT-MS

The *k*URT method is an adaptation of the traditional correlated-*k* method as implemented in MODTRAN[7, 8, 9], but for "large" bandpasses and with the instrument sensor relative response function (RSR) folded into the RT quantities. The *k*URT method uses pre-calculated bandpass specific absorption coefficient values (*k*-values) to efficiently compute bandpass transmittances. The bandpass specific *k*-values are created off-line and are the results of "compacting" a large number of MODTRAN-generated 1 cm^{-1} *k*-values (called fine-resolution *k*-data or, simply, *k*db for *k*-database, typically 17 per cm^{-1}) to a mere handful of *k*-values (typically 17 for the entire band). This compact-*k* database (c*k*db) approach (see the left side of Fig. 1) reduces the number of monochromatic calculations for a broad bandpass from thousands down to a handful. Note that MODTRAN had to be modified to output the *k*db.

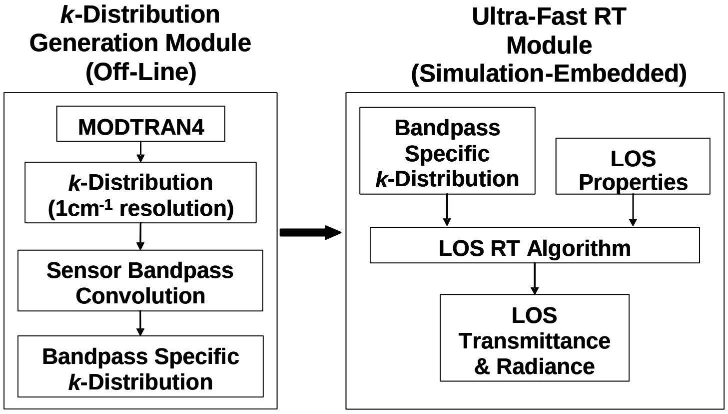

Fig. 1. Major Components of *k*URT-MS.

More on the *k*db and c*k*db, including their generation, use and dependence on atmospheric pressure and temperature is described in the earlier SPIE papers[5, 6]. There we also describe how blackbody, aerosol. Rayleigh and cloud scattering source terms (extinctions coefficients, phase functions, single scattering albedo) are correlated with c*k*db and with the effective transmittance of each layer.

As described in the aforementioned references, the *k*URT method divides the atmosphere into important absorbing species, whose concentrations change with altitude, and the rest of the atmosphere consisting of the uniformly-mixed species whose relative number densities do not change with altitude. The list of species are O_3, CO_2, H_2O and UMIX (uniformly mixed), the last of which includes CO, N_2 continuum, N_2O, CH_4, NO, O_2, SO_2, NO_2, NH_3 and HNO_3. Treatment of H_2O deals with H_2O self-continuum in a manner different from H_2O line-center, line-tail and foreign-continuum contributions. Whereas normally optical depth is proportional to absorber amount, for H_2O self-continuum the optical depth scales quadratically with concentration. Thus, we have five molecular "species" in *k*URT: O_3. CO_2, H_2O without self-continuum contributions, H_2O self-continuum and UMIX.

Assuming a lack of spectral correlation among the species, the transmittance due to multiple species is equal to the product of the transmittances of the individual species. With 17 c*k*db terms per species, this leads to 17^5 terms for each layer transmittance. This would lead to 17^5 c-*k* terms for radiance calculations since each term in the c-*k* scheme is treated as a monochromatic radiance term. Thus there is a need to reduce the number of c-*k* terms in each layer transmittance. We have implemented a convolution-resampling (C-R) scheme to reduce the number of c-*k* terms for this purpose as described in references[5, 6]. The method, shown in Fig. 2, begins with sorting the 17^5 c-*k* terms and concludes with the resampling of 17^5 *k*-values to just 17; the process parallels the formation of c*k*db from the *k*db data shown in Fig. 1. In practice, instead of sorting 17^5 terms, we perform the C-R operation in a pair-wise fashion, which involves performing the *C-R* operation on 4×17^2 terms, a factor of 1228 smaller. For multiple layers, multiple species transmittance is calculated by assuming correlation across layers of the optical depth $K_{j,\,L\ C\text{-}R}$.

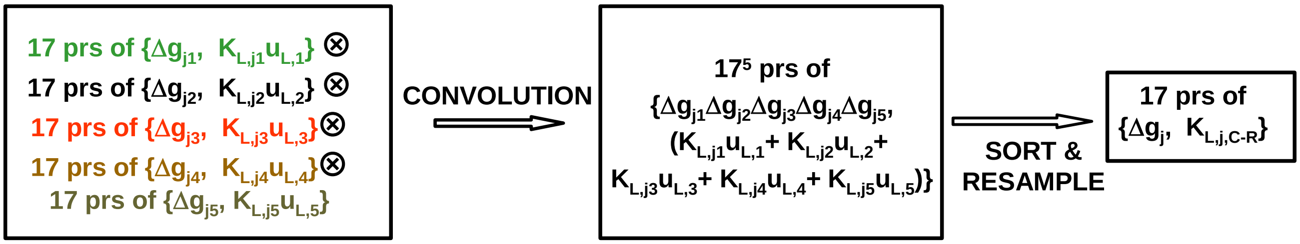

Fig. 2. The Convolution and Resampling (C-R) Scheme to Determine Layer Transmittance of the Entire Atmosphere. The reader is referred to references[5, 6] for further detail, including explanation of mathematical symbols.

2.2 Anticipated Use of *k*URT-MS software modules

An overview of the anticipated use of kURT modules is given in Fig. 3. Each "frame" corresponds to a calculation process, the results of which are stored for later use by the inner frame processes. An outer frame denotes a process that is less frequently performed. The innermost frame consists of the final LOS transmittance or radiance calculation that is performed repeatedly.

The outermost process is the one-time assembly of the full high spectral resolution *k*-distribution database, covering the entire spectral range of potential interest. The next process represents the calculation of the bandpass *k*-distribution for each atmospheric layer and each species. This process may be broken down into two steps, the bandpass convolution step on a grid of pressures and temperatures, and for the case of a specific atmosphere, interpolation of the results with respect to pressure and temperature. For a standard MODTRAN model atmosphere, pre-interpolations of the full high-resolution database may be created, avoiding the second step. The third process involves scaling the *k*-distributions according to the species concentration. In addition, for the calculation of radiance we implement the C-R scheme. In the innermost box, the correlated-*k* approach is used to compute path radiances and transmittances.

Once fully developed, the *k*URT-MS package will be a suite of RT routines that can be called from a variety of software programs such as TAWS as shown in Fig. 4. Although *k*URT-MS is being written in FORTRAN 77 and FORTRAN 90, wrappers can be written to call *k*URT-MS routines from programs in any language. Currently, we are developing IDL (Interactive Data Language) wrappers for *k*URT-MS.

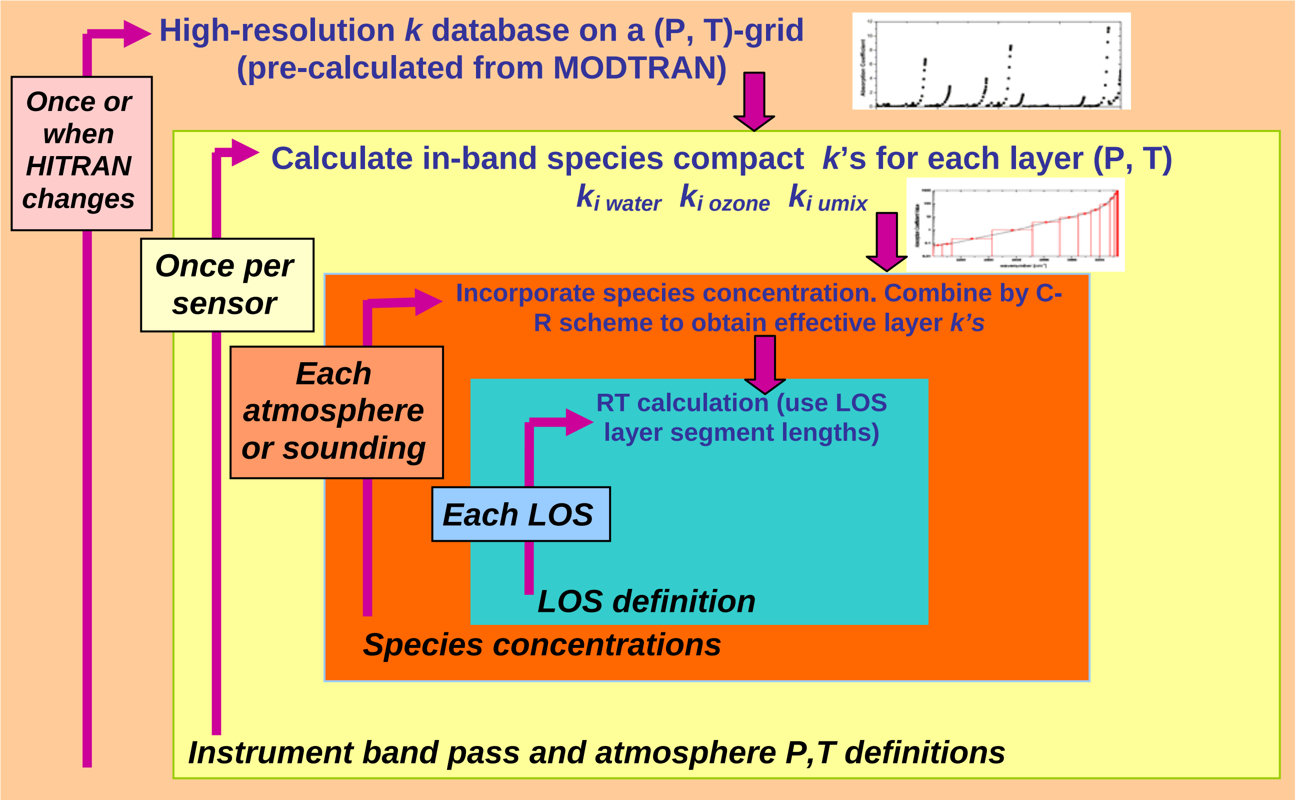

Fig. 3. Overview of the kURT calculation scheme.

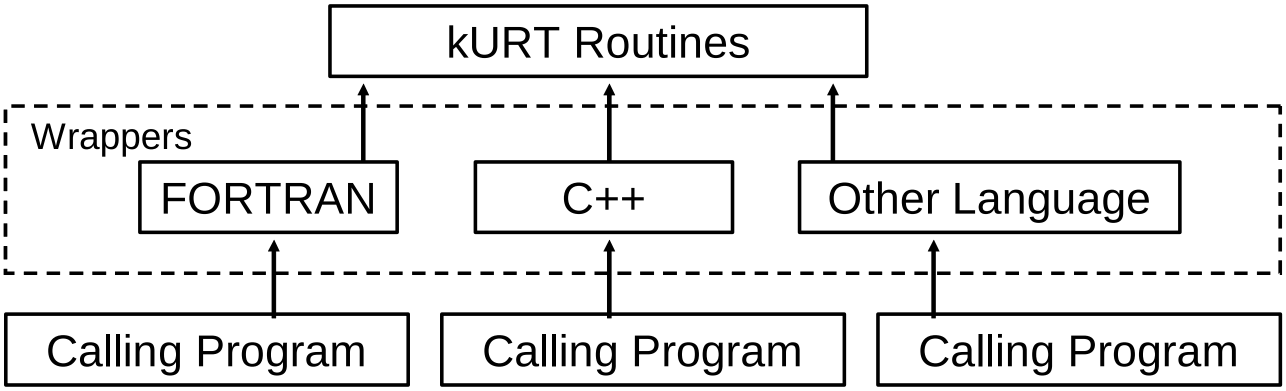

Fig. 4. Schematic of the *k*URT-MS interface architecture. The calling program will access the *k*URT–MS library through a collection of wrapper routines.

3. RADIANCE AND TRANSMITTANCE RESULTS

We have used the *k*URT method to compute transmittances and radiances in the 3-5 μm, 8-12 μm and visible wavelength regions for down-looking and horizontal paths. The 3-5 μm region has been the most difficult region to model because of the strong CO_2 absorption band from 4.2-4.5 μm and strong H_2O absorption from 4.5-5.2 μm. *k*URT-MS, at this point of development, gives poorest results when thermal radiance is both small and the dominant contributor to radiance (*e.g.*, in the 3-5 μm region) and when the transmittance is small but not negligible. The best results are when solar scattering dominates, as in the VIS-SWIR region. There is always excellent agreement with *k*URT and MODTRAN transmittance values.

3.1 Down-looking, 10-0 km path, radiance and transmittance results in the 3-5 µm region

Tables 1 and 2 present RT results for 10 km down-looking paths for the six MODTRAN model atmospheres. The model atmospheres range from the wettest tropical to the driest Sub-Arctic Winter. The vertical H_2O amounts are: Tropical (model 1) 5120 atm-cm, Mid-Latitude Summer (model 2) 3636 atm-cm, Sub-Arctic Summer (model 4) 2590 atm-cm, US Standard (model 6) 1762 atm-cm, Mid-Latitude Winter (model 3) 1060 atm-cm, and Sub-Arctic Winter (model 5) 518 atm-cm. The results are fairly good for the CO_2 absorption band (Table 2). For unknown reasons the radiance results tend to get worse in terms of percentage error as the H_2O amount in the atmosphere decreases (Table 1).

Table 1. 5.2-4.5 µm Bandpass (1925-2220 cm^{-1}) Thermal Radiances and Transmittances for the 10-0 km Vertical Paths for the Six MODTRAN Model Atmospheres. For all LOSs, CO_2 concentration is 365 ppmv.

10-0 km 5.2-4.5 µm	**TROP Model 1**	**MLS Model 2**	**SAS Model 4**	**USS Model 6**	**MLW Model 3**	**SAW Model 5**
MOD Rad (w/sr/cm^2), T	6.227E–05 0.257	5.110E–05 0.317	3.376E–05 0.387	2.909E–05 0.444	1.658E–05 0.522	8.122E–06 0.613
***k*URT T**	0.274	0.349	0.426	0.489	0.566	0.645
T Error	0.017	0.032	0.039	0.045	0.044	0.032
***k*URT R**	5.79E–05	4.56E–05	2.93E–05	2.45E–05	1.34E–05	6.33E–06
R Error (%)	−6.97	−10.84	−13.36	−15.94	−19.43	−22.02

Table 2. 4.5-4.2 µm (2220-2380 cm^{-1}) Bandpass Thermal Radiances and Transmittances.

10-0 km 4.5-4.2 µm	**TROP Model 1**	**MLS Model 2**	**SAS Model 4**	**USS Model 6**	**MLW Model 3**	**SAW Model 5**
MOD Rad (w/sr/cm^2), T	4.027E–06 0.009	3.586E–06 0.010	2.320E–06 0.012	2.005E–06 0.011	1.485E–06 0.012	9.874E–07 0.013
***k*URT T**	0.024	0.026	0.028	0.029	0.030	0.032
T Error	0.015	0.016	0.016	0.018	0.018	0.019
***k*URT R**	4.24E–06	3.74E–06	2.36E–06	2.08E–06	1.51E–06	9.61E–07
R Error (%)	5.28	4.22	1.77	3.86	1.68	–2.68

3.2 Down-looking, 10-0 km path, radiance and transmittance results in the 8-12 µm region

Tables 3 and 4 present RT results for 10 km down-looking paths for the six MODTRAN model atmospheres. Here the both transmittance and radiance results are satisfactory, although, again, the percentage radiance errors increase as the H_2O content of the atmosphere decreases.

Table 3. 10.664-8 µm (940-1250 cm^{-1}) Bandpass Thermal Radiances for the 10-0 km Vertical Paths for the Six MODTRAN Model Atmospheres.

10-0 km 10.664-8 µm	**TROP Model 1**	**MLS Model 2**	**SAS Model 4**	**USS Model 6**	**MLW Model 3**	**SAW Model 5**
MOD Rad (w/sr/cm^2), T	9.138E–04 0.544	6.258E–04 0.649	3.792E–04 0.736	2.677E–04 0.803	1.549E–04 0.847	7.931E–05 0.892
***k*URT T**	0.551	0.659	0.745	0.808	0.854	0.897
T Error	0.007	0.010	0.009	0.005	0.007	0.005
***k*URT R**	9.02E–04	6.11E–04	3.68E–04	2.62E–04	1.49E–04	7.61E–05
R Error (%)	–1.25	–2.42	–2.88	–2.02	–4.00	–4.06

Table 4. 8-7.377 μm (1250-1355 cm^{-1}) Bandpass Thermal Radiances and Transmittances for the 10-0 Vertical Paths for the Six MODTRAN Model Atmospheres.

10-0 km 8-7.377 μm	**TROP Model 1**	**MLS Model 2**	**SAS Model 4**	**USS Model 6**	**MLW Model 3**	**SAW Model 5**
MOD Rad (w/sr/cm^2), T	2.628E–04 0.029	2.436E–04 0.049	1.953E–04 0.079	1.797E–04 0.110	1.388E–04 0.167	9.360E–05 0.257
***k*URT T**	0.029	0.055	0.093	0.135	0.204	0.298
T Error	0.000	0.006	0.014	0.025	0.037	0.041
***k*URT R**	2.75E–04	2.52E–04	1.99E–04	1.81E–04	1.35E–04	8.92E–05
R Error (%)	4.62	3.28	1.65	0.60	–2.73	–4.75

3.3 10 km near-HLOS path RT results in the 0.4-0.9 μm (VIS-SWIR) bandpass

Table 5 shows transmittance RT results for a 10 km near-HLOS path (from 0.1 km to 0.1 km) using the US Standard MODTRAN atmosphere and two aerosols models. The *k*URT results for the wavelength region 0.4-0.9 μm are excellent. The two regions correspond to 11,000-15,000 cm^{-1} and 15000-25,005 cm^{-1}.

Table 5. Single- and Two-Region Transmittance Values for a 10 km near HLOS path using the US Standard MODTRAN model atmosphere and two aerosol models.

Aerosol, PATH LENGTH and O.D.	**2-region, *k*URT**	**1-region, *k*URT**	**MODTRAN**
Rural, 10 km, OD=2	0.1388 (+0.003)	0.1447 (+0.008)	0.1359
Rural, 10 km, OD=3	0.0597	0.0625 (+0.003)	0.0588
Urban, 10 km, OD=2	0.1364	0.1420 (+0.008)	0.1336
Urban, 10 km, OD=3	0.0576	0.0603 (+0.003)	0.0567

As with the transmittance calculations, we performed *k*URT radiance calculations using single-region and two-region methods. The two-region results are significantly better than the one-region results. A typical set of 2-region results is presented in Fig. 5. Here the solar zenith angle is 80º. There are 12 pairs of calculations. Each pair consists of a 2-stream MODTRAN[10,11] calculation (purple and negative bars) and *k*URT DISORT calculation (dark red and errors are all positive). The first six pairs correspond to rural aerosol, optical depth of 2 and 3, and the next six pairs correspond to urban aerosols of optical depth 2 and 3. Each grouping of three pairs corresponds to azimuths of 180º (staring away from the sun), 90º and 0º (staring at the sun). As expected, when looking towards the sun 2-stream errors are at their peak. In general *k*URT-DISORT errors versus MODTRAN with 8-stream DISORT are less than 6%, whereas 2-stream errors are as high as 55%.

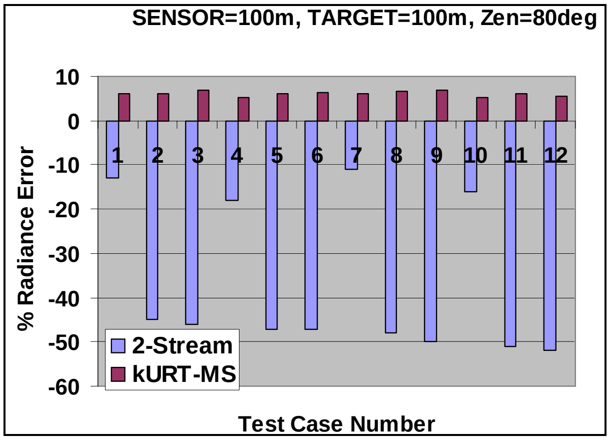

Fig. 5. Isaacs 2-stream and kURT-MS 0.4-0.9 μm radiance comparisons to MODTRAN DISORT ("ground truth") for the ARL scenario. Results are shown for rural (cases 1-6) and urban (7-12) aerosols of optical depth 2 (cases 1-3, 7-9) and 3 (4-6, 10-12). Each triple compares results for backward, broadside and forward scattering. The solar zenith angle is 80°.

3.4 Down-looking visible-MWIR radiance

We carried out several off-nadir VIS-MWIR RT calculations (Table 6) using the mid-lat summer MODTRAN atmosphere with H_2O scaled to a fairly high value (2.5 cm, Scenario 1) and the winter atmosphere with H_2O scaled to a fairly low value (0.4 cm, Scenario 2). The aerosol was rural with visibilities of 23 and 5 km. Ground reflectance was 10% and the CO_2 was 365 ppmv. The solar and observer elevation angles are both 45º above the horizon, and the sun is located in front of the observer (MODTRAN azimuth is 0º). We considered several generic (not top-hat) response functions. Results from 8-stream MODTRAN-*k*URT calculations are shown below. Only the highest errors are shown within parenthesis, and are omitted when they are negligible**.** The highest radiance error is +4%, but typically, much lower. For these wavelengths and scenarios, it is the solar scattering that constitutes almost all of the total radiance.

We also performed timing analyses on these types of calculations. We found that for a 4000 cm^{-1} *k*URT calculation, *k*URT was faster by a factor 15 over 15 cm^{-1} MODTRAN band model calculation and about 200 times faster than 1 cm^{-1} MODTRAN band model computations. These timing ratios are consistent with the number of spectral calculations performed by the respective methods.

Table 6. VIS-MWIR Nadir Calculations.

		Scenario 1		**Scenario 2**	
FILTER (μm) Effective Width Visibility		**Transmittance**	**Total Rad (μW cm^{-2} sr^{-1})**	**Transmittance**	**Total Rad (μW cm^{-2} sr^{-1})**
A 0.438 – 0.536 2092 cm^{-1} 23 km	***k*URT**	**0.4643 (+0.0013)**	**406**	**0.4865**	**393**
	M5	**0.4630**	**403**	**0.4853**	**390**
5 km	***k*URT**	**0.1191**	**572**	**0.1249**	**564 (+0.9%)**
	M5	**0.1187**	**567**	**0.1246**	**559**
F 0.895 – 0.985 611.6 cm^{-1} 23 km	***k*URT**	**0.3653**	**38.8 (+0.5%)**	**0.6265 (+0.0069)**	**69.6 (+2.4%)**
	M5	**0.3647**	**39.0**	**0.6196**	**68.0**
5 km	***k*URT**	**0.2021**	**56.0 (+2.0%)**	**0.3435 (+0.0053)**	**104 (+4.0%)**
	M5	**0.1994**	**54.9**	**0.3382**	**100**
D 0.730-0.889 1101 cm^{-1} 23 km	***k***	**0.6747 (+0.0022)**	**184 (+0.5%)**	**0.7209 (+0.0005)**	**189**
	M 5	**0.6725**	**183**	**0.7204**	**189**
5 km	***k***	**0.3199 (+0.0023)**	**282 (+0.7%)**	**0.3401 (+0.0006)**	**298**
	M 5	**0.3176**	**280**	**0.3395**	**297**
H 1.352-1.416 139.5 cm^{-1} 23 km	***k*URT**	**0.0000**	**0.274 (–2.5%)**	**0.0427(+0.0012)**	**0.540 (–3.0%)**
	M 5	**0.0000**	**0.281**	**0.0415**	**0.557**
5 km	***k*URT**	**0.0000**	**0.274 (–2.5%)**	**0.0303 (–0.0013)**	**0.681 (–2.1%)**
	M 5	**0.0000**	**0.281**	**0.0316**	**0.696**
J 3.30-4.26 381.9 cm^{-1} 23 km	***k*URT**	**0.7490 (+0.0097)**	**23.8 (+0.8%)**	**0.8279(+0.0003)**	**13.9 (+3.0%)**
	M 5	**0.7393**	**23.6**	**0.8282**	**13.5**
5 km	***k*URT**	**0.6603 (+0.0082)**	**24.2 (+1.7%)**	**0.7272 (+0.0002)**	**14.5**
	M 5	**0.6521**	**23.8**	**0.7270**	**14.5**

4. MODTRAN SPEED-UP USING DISORT MLOS STRATEGY

The DISORT code outputs information that can be used to compute radiances for multiple lines-of-sights (MLOSs) with a single subroutine call. The one caveat is that either the sun and sensor latitudes and longitudes or the sun and target latitudes and longitudes must be fixed for the entire set of calculations. However, the MODTRAN-DISORT interface has not until now been programmed to take advantage of this capability. The basic concept within DISORT is reasonably straightforward. Given a stratified plane-parallel atmosphere and a fixed solar geometry, the discrete ordinate MS algorithm DISORT solves the monochromatic radiation transport equation (RTE). Output includes m^{th} azimuth moment radiant intensities, $I^{m}(\tau, \pm\mu)$, at user-specified nadir optical depths, τ, within the atmosphere and at user-specified up-look ($+\mu$) and/or down-look ($-\mu$) view angles ($\mu > 0$ is the cosine of the zenith or nadir view angle, respectively). The final azimuth (ϕ)-dependent radiant intensities are computed from a truncated Fourier cosine series:

$$I^{m}(\tau,\mu,\phi)=\sum_{m=0}^{2M-1} I^{m}(\tau,\mu)\cos m(\phi_0-\phi) \tag{1}$$

where ϕ_0 is the solar azimuth angle and $2M$ is the number of azimuth moments.

The MODTRAN-DISORT MLOS option, when fully implemented, will greatly accelerate the generation of MLOS look-up tables by exploiting the full set of results acquired from a single run of DISORT. For single-LOS MODTRAN runs that include DISORT MS and a large number of spectral grid points, the DISORT module execution time completely dominates (>99%) the overall run time. However, the DISORT MS results for an additional view angle can be obtained with about a 15% increase in the baseline execution time. Thus, the MLOS option enables the users to run ~8 view angles in the same time that the single LOS MODTRAN would perform 2 view angle calculations. Furthermore, varying path azimuth angle, sensor altitude and/or target altitude adds less than 1% to the baseline execution time. Thus, a grid of 8 view angles, 8 path azimuth angles, 8 sensor altitudes and 8 target altitudes, a total of more than 4000 LOSs, will run in about the same time as 3 single-LOS MODTRAN runs.

This capability is also ideally suited for 3D radiance scene simulations, which typically involve radiance and/or contrast signature imagery over a short time duration. Thus, sun location relative to the Earth is essentially constant, and radiation transport solutions may be required for thousands of LOSs. In the past, accurate incorporation of the MS signal has been thought to be computationally prohibitive. However, if the myriad of views are extracted from a single MS calculation, the computation of high-fidelity background scattered radiances for each imaged pixel is an achievable goal.

5. CONCLUSION

An instrument response function-specific correlated-*k* approach, dubbed *k*URT-MS, is being developed to rapidly compute bandpass LOS transmittances and radiances from the visible to the IR. In its full implementation, *k*URT-MS will be a complete RT code that includes scattering due to aerosols and clouds. *k*URT-MS software will be a complete library of RT routines that includes all significant radiance components; and the individual routines of the library can be called on an a-la-carte basis for a variety of applications that require forward RT modeling. The goal is a hundred- to thousand-fold speed-up with 2% accuracy in transmittance and 10% accuracy in radiance compared to a 1 cm^{-1} MODRTRAN run. Preliminary results on several wide bandpasses and narrower visible-MWIR instrument response functions indicate that both accuracy and speed goals are within reach. We are also incorporating the *k*URT methodology into a version of MODTRAN, called MODTRAN-*k*URT, which will run from a MODTRAN interface either in the *k*URT mode or in the usual MODTRAN mode.

Additionally, MODTRAN's DISORT interface is being upgraded to take advantage of DISORT's inherent multiple line-of-sight (MLOS) capability, namely, the capability to perform RT calculations for many lines of sight using a single call to DISORT from within MODTRAN. This will result in very substantial savings in computation time for scene modeling and radiance look-up table generation.

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REFERENCES

1. R. Shirkey, and M. Gouveia, "Weather Impact Decision Aids: Software Engineered to Help the War fighter Plan for Optimal Sensor and System Performance," Crosstalk, the Journal of Defense Software Engineering, pp 17-21 (December 2002).
2. S. O'Brien, and R.C. Shirkey, "Determination of Atmospheric Path Radiance: Sky-to-Ground Ratio for War gamers," Army Research Laboratory Technical Report ARL-TR-3285 (September 2004).
3. K. Stamnes, S. -C. Tsay, W. Wiscombe and K. Jayaweera, "Numerically S0 Algorithm for Discrete-Ordinate-Method Radiative Transfer in Multiple Scattering and Emitting Layered Media," Applied Optics 27, 2502-2509 (1988).
4. P.K. Acharya, A. Berk, G.P. Anderson, N.F. Larsen, S-Chee Tsay and K.H. Stamnes, "MODTRAN4: Multiple Scattering and Bi-Directional Distribution Function (BRDF) Upgrades to MODTRAN," Proceedings of SPIE: Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research III, Vol. 3756, Paper No. 37, pp. 354-362 (July 1999).
5. P.K. Acharya, R. Panfili, A. Berk, S. M. Adler-Golden, M. Fox and A. Wetmore, "A Correlated-*k* Based Ultra-Fast Radiative Transfer (*k*URT) Method," SPIE Europe Symposium on Remote Sensing, Bruges, Paper No. 5982-44, Belgium (19-22 September, 2005).
6. P.K. Acharya, A. Berk, R. Panfili, S. M. Adler-Golden, A. Wetmore and R. Shirkey, "Correlated-*k*-Based Method for Fast Generation of Bandpass Radiance and Transmittance Look-up Tables," Proceedings of SPIE: Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XIII, Volume 6565, pp. 65651R-1 to 65651R-11 (Orlando, FL, USA; April 2007).
7. L.S. Bernstein, A. Berk, D.C. Robertson, P.K. Acharya, G.P. Anderson and J.H. Chetwynd, "Addition of a Correlated-*k* Capability to MODTRAN," Proceedings of the 1996 IRIS Targets, Backgrounds, & Discrimination Mtg. (1996).
8. A. Lacis, and V. Oinas, "A Description of Correlated-*k* Distribution Method for Modeling Nongray Gaseous Absorption, Thermal Emission and Multiple Scattering in Vertically Inhomogeneous Atmospheres," J. Geophys. Res. 96, 9027 (1991).
9. R.M. Goody, R. West, L. Chen and D. Crisp, "The Correlated-*k* Method for Radiation Calculations in Nonhomogeneous Atmospheres," J. Quant. Spectrosc. Radiat. Transfer, 42, 539-550 (1989).
10. R.G. Isaacs, W.C. Wang, R.D. Warsham and S. Goldenberg, "Multiple Scattering Treatment for Use in LOWTRAN and FASCODE Models," Report No. AFGL-TR-86-0073, Air Force Geophys. Lab, Hanscom AFB (1986).
11. R.G. Isaacs, W.C. Wang, R.D. Warsham and S. Goldenberg, "Multiple Scattering in LOWTRAN and FASCODE Models," Applied Optics, Volume 26, 1272-1281 (1987).