

# Third Radiation Transfer Model Intercomparison (RAMI) exercise: Documenting progress in canopy reflectance models

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# <sup>1</sup> The third RAdiation transfer Model Intercomparison (RAMI)

# <sup>2</sup> exercise: Documenting progress in canopy reflectance models

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# 3 Abstract.

The RAdiation transfer Model Intercomparison (RAMI) initiative benchmarks canopy 4 reflectance models under well-controlled experimental conditions. Launched for the first 5 time in 1999 this triennial community exercise encourages the systematic evaluation of 6 canopy reflectance models on a voluntary basis. The first phase of RAMI focused on documenting the spread among radiative transfer (RT) simulations over a small set of pri-8 marily 1-D canopies. The second phase expanded the scope to include structurally comg plex 3-D plant architectures with and without background topography. Here sometimes 10 significant discrepancies were noted which effectively prevented the definition of a reli-11 able "surrogate truth" - over heterogeneous vegetation canopies - against which other 12 RT models could then be compared. The present paper documents the outcome of the 13 third phase of RAMI, highlighting both the significant progress that has been made in 14 terms of model agreement since RAMI-2, and the capability of/need for RT models to 15 accurately reproduce local estimates of radiative quantities under conditions that are rem-16 iniscent of in situ measurements. Our assessment of the self-consistency, the relative- and 17 absolute performance of 3-D Monte Carlo models in RAMI-3 supports their usage in the 18 generation of a "surrogate truth" for all RAMI test cases. This development then leads 19 1) to the presentation of the 'RAMI On-line Model Checker' (ROMC), an open-access 20 web-based interface to evaluate RT models automatically, and 2) to a reassessment of 21 the role, scope and opportunities of the RAMI project in the future. 22

# 1. Introduction

Space-borne observations constitute a highly appropri-23 ate source of information to quantify and monitor earth 24 surface processes. The quality/confidence that may be 25 associated with the outcome of interpretation and assim-26 ilation efforts of these data streams, however, relies heav-27 ily on the actual performance of the available modelling 28 tools. This understanding has led to a series of model 29 intercomparison projects (MIP) aiming either to docu-30 ment the spread of currently available simulation mod-31 els, or, else to assess and benchmark the quality of their 32 simulation results, e.g., Henderson-Sellers et al. [1995]; 33 Gates et al. [1998]; Dirmeyer et al. [1999]; Pinty et al. 34 [2001]; Latif et al. [2001]; Cahalan et al. [2005]; Ran-35 gasayi et al. [2005]. Among these MIPs the RAdiation 36 transfer Model Intercomparison (RAMI) activity focuses 37 on the proper representation of the radiative processes 38 occuring, in vegetated environments, in the optical do-39 main of the solar spectrum. The design and launch of 40 the first phase of RAMI occurred approximately in par-41 allel with that of the 'Intercomparison of 3-D Radiation 42 Codes' (I3RC) activity which deals with the correct rep-43 resentation of the radiative properties of 3-D cloud fields 44 (http://i3rc.gsfc.nasa.gov/). Both MIPs collaborate 45 actively and share their evaluation methodologies in or-46 der to overcome the difficulties associated with model 47

<sup>&</sup>lt;sup>1</sup>European Commission, DG Joint Research Centre,

48 benchmarking in the absence of absolute reference stan 49 dards.

50 The first phase of RAMI (RAMI-1) was launched in 51 1999. Its prime objective was to document the variabil-52 ity that existed between canopy reflectance models when 53 54 run under well controlled experimental conditions [Pinty et al., 2001]. The positive response of the various RAMI-55 1 participants and the subsequent improvements made 56 to a series of radiative transfer (RT) models promoted 57 the launching of the second phase of RAMI (RAMI-2) 58 in 2002. Here the number of test cases was expanded 59 to focus further on the performance of models dealing 60 with structurally complex 3-D plant environments. The 61 main outcomes of RAMI-2 included 1) an increase in the 62 number of participating models, 2) a better agreement 63 between the model simulations in the case of the struc-64 turally simple scenes inherited from RAMI-1, and 3) the 65 need to reduce the sometimes substantial differences be-66 tween some of the 3-D RT models over complex hetero-67 geneous scenes [Pinty et al., 2004b]. The latter issue 68 was noted as one of the challenges that future intercom-69 parison activities would have to face, since the reliable 70 derivation of some sort of "surrogate truth" data set will 71 not be possible in the absence of any agreement between 72 these RT models. This, in turn, would then imply that-73 except in some simple special cases—the evaluation of RT 74 model simulations can not proceed beyond their mutual 75 76 comparison due to the general lack of absolute reference standards. 77

This paper will describe the outcome of the third phase of RAMI (RAMI-3). Section 2 will provide an overview of the organisation and model evaluation protocol employed during RAMI-3. Section 3 documents how the performance of RT models—when applied to the various baseline scenarios inherited from RAMI-1—improved be-

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tween RAMI-2 and RAMI-3. Section 4 documents the 85 outcome of model simulations for the newly proposed ex-86 87 periments and measurement types in RAMI-3. Section 5 summarises the main achievements and issues observed 88 during RAMI-3 and introduces the "Rami On-line Model 89 Checker" (ROMC), a web-based tool intended to auto-90 91 mate the process of RT model benchmarking. Section 5 also describes possible roadmaps for the future develop-92 ment of the RAMI initiative. 93

## 2. The third phase of RAMI

The third phase of RAMI was officially launched at 94 the end of March 2005. Scientists from around the world 95 with an interest in canopy RT modelling were invited to 96 participate in this triennial benchmarking exercise. A 97 dedicated website (http://rami-benchmark.jrc.it/)<sup>1</sup> 98 99 provided detailed descriptions regarding the structural, spectral and illumination conditions of the test cases 100 proposed for RAMI-3. Prior to going public, each one 101 of these experiments and measurements had been ap-102 proved by the RAMI advisory body, a small group of well-103 known scientists in the field of radiative transfer mod-104 elling and/or model intercomparison activities. RAMI-105 3 included and built upon the various experiments and 106 measurements proposed during earlier phases of RAMI 107 (see Section 2.1 in *Pinty et al.* [2001] and Section 2 in 108 Pinty et al. [2004b]). Overall, the number of simulation 109 scenarios grew by 37% with respect to RAMI-2, which 110 led to two separate submission deadlines, namely, July 111  $30^{th}$  2005 for all RT simulations pertaining to struc-112 turally homogeneous vegetation canopies and December 113  $15^{th}$  2005 for all those simulations relating to structurally 114 heterogeneous test cases. As was the case during pre-115 116 vious phases of RAMI, the collection of the submitted RT model results and their detailed analysis were per-117 formed at the Joint Research Centre (JRC) of the Eu-118 ropean Commission in Ispra, Italy. Two public presen-119 tations describing the outcome of this community effort 120 were delivered, the first one-dealing with homogeneous 121 test cases only—was given during the  $9^{th}$  International 122 Symposium on Physical Measurements and Signatures in 123 Remote Sensing (ISPMSRS) in Beijing, China (October 124 2005), and the second one-including also the heteroge-125 neous test cases—at the  $4^{th}$  International workshop on 126 multi-angular measurements and models (IWMMM-4) in 127 Sydney, Australia (March 2006). 128

Table 1 lists the models that participated in RAMI-130 3, the main publications describing these models and 131 the names and affiliations of their operators. Also 132 indicated are the corresponding modelling approaches 133 that are used in order to simulate the radiation 134 These include Monte Carlo (MC) techtransfer. 135 niques associated with forward/reverse ray-tracing meth-136 ods (Drat, FLIGHT, frat, raytran, Rayspread and 137 Sprint3) or radiosity approaches (RGM and Hyemalis), 138 purely analytical formulations (2-Stream), as well 139 as, a large number of hybrid techniques, that com-140 bine one or more of the above with numerical, 141 stochastic and/or geometric optical approaches (ACRM, 142 143 DART, 1/2-discret, FRT, MAC, MBRF, Sail++, 4SAIL2, 5Scale). More detailed information on the participat-144 ing models can be found on the RAMI website under 145 http://rami-benchmark.jrc.it/HTML/RAMI3/MODELS/M 146 ODELS.php. Most of the participants received substantial 147 feedback on the performance of their model(s) both as 148 a result of phases 1 and 2, and in the case of obvious 149 errors/deviations also during phase 3 of RAMI. Conse-150

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quently, all results presented below refer to the latest and
most up-to-date version of these models. It is important
that prospective users of these models ensure that they
have access to the most recent version of these codes, as
the performance information provided here may not be
representative of, or applicable to, earlier versions.

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One of the traits of RAMI is to increase the number 158 159 of test cases by including a few new experiments (and measurements) from one phase to another. This strategy 160 serves a dual purpose, namely, a) to allow the evaluation 161 of RT models under an increasingly comprehensive set of 162 structural, spectral and also illumination conditions, and 163 164 b) to tailor new sets of RAMI experiments and measurements around scientific questions emerging in the context 165 of RT modelling and the quantitative interpretation of 166 remotely sensed data. Indeed, such an approach guar-167 antees that every phase will contain at least some test 168 cases for which the simulation results cannot be known 169 *a priori*. Within RAMI-3 the following new experiments 170 were proposed: 1) a conservative scattering scenario for 171 the heterogeneous "floating spheres" test cases originally 172 introduced during RAMI-1, 2) a "coniferous forest" scene 173 analogous to the Gaussian-hill canopy introduced during 174 RAMI-2 but without the topography, and 3) a "birch 175 stand" populated with trees of variable sizes and spec-176 tral properties - intended primarily to enhance the de-177 gree of structural realism amongst the RAMI test cases. 178 The new experiments complement those introduced dur-179 ing earlier phases of RAMI, which focused primarily on 180 structurally homogeneous vegetation canopies (both in 181 the solar domain and under conservative scattering con-182 ditions) but included also a small set of structurally het-183 erogeneous plant canopies (see Section 2.1 in Pinty et al. 184 [2001] and Section 2 in *Pinty et al.* [2004b]). Exhaustive 185 documentation on the spectral and structural properties 186 of the various plant canopies (including the exact posi-187 tion and orientation of individual leaves in the scenes with 188 discrete foliage representations, as well as the precise lo-189 190 cation of all tree-like objects in the scene) were accessible to the participants via the RAMI website. It was, how-191 ever, left to the participants themselves to choose what 192 level of detail their model required in order to represent 193 at best the proposed canopy scenes. 194

Similar to previous phases of RAMI, participants were 196 encouraged to generate a standard set of 11 measure-197 ments for every test case. These measurements in-198 clude the total spectral Bidirectional Reflectance Factor 199 (BRF), in both the principal and the cross plane, together 200 with the corresponding contributions due to the single-201 uncollided radiation scattered once by the soil only, the 202 single-collided radiation by the leaves or trees only, and 203 the radiation multiply collided by the leaves/trees/soil 204 system. Three flux quantities were also routinely asked 205 for, namely, the spectral albedo of the canopy (i.e., the206 directional hemispherical reflectance), the total transmis-207 208 sion down to the underlying background, and, the total absorption of radiation in the vegetation layer. In ad-209 dition to these standard measurements, RAMI-3 intro-210 duced two new measurement types, that applied, how-211 212 ever, only to selected test cases. The first of these was a local transmission transect measurement that was asked 213 for the "birch stand" experiment in order to assess the 214 ability of RT models to simulate *in-situ* measurement sit-215 uations. Similarly, a horizontal flux measurement was 216 proposed for the "real-zoom-in" scene, that was first 217 introduced during RAMI-2 (section 2.2 in Pinty et al. 218 [2004b]), in order to document the performance of RT 219

models when estimating the magnitude of horizontal photon transport at various spatial resolutions in a structurally heterogeneous canopy environment. Almost all the RAMI measurements, whether directional or hemispherical, had to be carried out with respect to a reference plane located at the top of canopy height level.

Overall a total of 464,816 (2,112) individual BRF 227 (flux) simulations were received at the JRC. In order 228 to pursue the analysis of these data beyond a mere vi-229 sual comparison a protocol is needed that permits the 230 quantitative evaluation of RT model simulations despite 231 the lack of absolute reference standards (i.e., in general 232 the true solution is not known). Oreskes et al. [1994]. 233 and many others since, maintain that-under these lat-234 235 ter conditions—the complete validation/verification of a model is quite impossible, and that any such endeavour 236 should focus instead on showing the opposite, that is, 237 the onset of flaws in a model's behaviour. RAMI thus 238 proposes a three-step procedure to identify incongruous 239 RT models: 1) by assessing the absence of inconsistencies 240 in the internal RT formulation of a model, 2) by verify-241 ing the accurate and reliable performance of a model in 242 the limited number of cases where analytical solutions 243 244 are available, and 3) by comparing the output of a model against a "surrogate truth" that is to be established from 245 credible candidates within the ensemble of available RT 246 simulations. Obviously the latter will only be meaning-247 248 ful if sufficient consensus exists among the simulation results of RT models, in particular those that are known to 249 minimise the number of simplifications/approximations 250 in their radiative transfer formulation. The objective of 251 252 this three-step procedure thus lies in identifying RT models that deviate from the norm rather than boosting the 253 credibility of those models that do not differ. In fact, 254 conformity with the anticipated outcome in each one of 255 the above steps is not proof of a model's physical cor-256 rectness. Hence any claims regarding the credibility of a 257 model's performance should be avoided, or-if they have 258 to be made—should always be limited to the set of pre-259 scribed conditions under which the models were actually 260 tested. 261

262 In general, RT simulation models are rarely completely 263 amiss, nor, totally correct for that matter, but tend to lie 264 somewhere in between these two extremes. The quality of 265 their simulations is often subject to the degree by which 266 a given set of experimental conditions satisfies the struc-267 tural, spectral and/or radiative premises on which the 268 models are based. In the context of RAMI, for example, 269 270 models often do not share the same internal representation or "image" of the prescribed canopy structure<sup>2</sup>. Such 271 architectural deviations may often form the basis for sub-272 sequent differences in simulation results – as will be seen 273 in sections 3 and 4. In addition to possible (structure and 274 illumination related) differences in the starting premises 275 of RT models, the precise manner in which certain RT 276 quantities are simulated may also vary, e.g., the width of 277 the solid angle over which BRFs are computed may vary. 278 The identification of suitable limits describing the thresh-279 old between valid and invalid models thus has to account 280 for these idiosyncrasies, and should preferably be formu-281 lated in conjunction with criteria relating to the usage of 282 these models. For example, by incorporating the abso-283 lute calibration accuracy of current space borne sensors 284 and/or the anticipated quality of state-of-the-art atmo-285 spheric correction schemes into the evaluation scheme. In 286 the next section the above three-step invalidation proce-287 dure will be applied to an ensemble of RAMI test cases for 288

which analytical solutions are available in a few isolated cases, and so-called "surrogate truths" may be derived for others, *e.g.*, *Pinty et al.* [2001, 2004b].

# 3. The RAMI baseline scenarios

All the forward-mode experiments that were proposed 292 during RAMI-1 have featured in subsequent phases of 293 the RAMI activity. These "baseline scenarios" can be 294 subdivided into two separate architectural classes: The 295 first one consists of structurally homogeneous canopies 296 that feature finite-sized (discrete) or point-like (turbid) 297 foliage elements that are randomly distributed within the 298 volume of a horizontally infinite vegetation layer bounded 299 by some top-of-canopy (TOC) level, as well as a lower 300 flat background surface. The second category relates 301 to structurally heterogeneous "floating spheres" environ-302 ments where the (discrete or turbid) foliage elements are 303 randomly distributed within a series of spherical volumes 304 that are themselves freely floating above an underlying 305 flat background surface (for a graphical depiction see the 306 inlaid pictures in Figure 1). In both categories the direc-307 308 tional scattering properties of the foliage and background are Lambertian, and the orientation of the foliage ele-309 ments follow predefined leaf normal distributions (LND), 310 i.e., Bunnik [1978] and Goel and Strebel [1984]. By vary-311 ing the illumination conditions, as well as the number, 312 313 size, orientation and spectral properties of the foliage elements in the canopy (*idem* for the background bright-314 ness) up to 52 structurally homogeneous and 8 "floating 315 spheres" baseline scenarios were defined. In the struc-316 turally homogeneous case, a "purist corner" was included 317 where the spectral leaf and soil properties are such as to 318 test model performance in the limit of conservative scat-319 tering conditions, *i.e.*, the soil brightness ( $\alpha = 1$ ) and 320 the single-scattering albedo  $(r_L + t_L = 1)$  are unity, and 321 the leaf reflectance  $(r_L)$  is equal to the leaf transmittance 322  $(t_L).$ 323

Figure 1 provides examples of the spread between 325 the various RT models that participated in the base-326 line scenarios during RAMI-3. Shown are bidirectional 327 reflectance factor (BRF) simulations along the princi-328 pal (top panels) and orthogonal (bottom panel) planes 329 for structurally homogeneous (left panels) and heteroge-330 neous "floating spheres" (right panels) canopies. The top 331 panels feature finite-sized disc-shaped foliage elements of 332 infinitesimal thickness (radius 0.1 m), whereas the bot-333 tom panels relate to turbid medium canopies, *i.e.*, having 334 infinitesimally small but oriented scatterers. The spectral 335 properties of the canopy constituents in the top (bottom) 336 panels are typical for vegetation and bare soils in the red 337 (NIR) spectral domain. The illumination zenith angle 338 339  $(\theta_i)$  was set to 20° in all these cases. The panels of Figure 1 exemplify the degree and variability of agreement 340 between the various participating models. In particular, 341 in the case of the structurally homogeneous test cases 342 it is only the BRF simulations of the MBRF model in the 343 turbid medium case (lower left panel), and, to a lesser ex-344 tent, the ACRM model in the discrete case (top left panel) 345 that are different. The deviations of the MBRF model 346 in the NIR may be largely explained by its usage of a 347 "two-stream" approximation when estimating the mutli-348 ple collided BRF component. At the same time the agree-349 ment between the FLIGHT, drat, Rayspread, raytran, 350 and Sprint3 Monte Carlo models is striking for both the 351 homogeneous and heterogeneous test cases. Somewhat 352 different from these 5 models—and each other—are the 353 simulation results for DART, MAC, FRT, 4SAIL2, and 5Scale 354

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 $_{355}$   $\,$  in the turbid and/or discrete "floating spheres" test cases.

356 Despite the visually noticeable dispersion of some of 357 the model contributions in Figure 1, one should—in 358 general—refrain from speculative guesses about potential 359 outliers without a careful examination of the exact con-360 ditions under which the various models were executed. 361 One of the first aspects to verify is the faithful repre-362 sentation of the prescribed architectural canopy char-363 acteristics. It is now well accepted that multi-angular 364 observations are sensitive to the structure of a given 365 canopy target, e.g., Gerard and North [1997]; Widlowski 366 et al. [2001]; Lovell and Graetz [2002]; Chopping et al. 367 [2003]; Chen et al. [2003]; Rautiainen et al. [2003]. By 368 the same token, deviations from the structural charac-369 teristics of a given RAMI scene may thus translate itself 370 into the model-simulated magnitude (and shape) of the 371 TOC BRF field. During RAMI-3 almost all of the par-372 373 ticipating models differed in their structural premiseseither systematically or occasionally-from those pre-374 scribed on the RAMI website. For example, the ACRM 375 and MBRF models both use elliptical equations [Campbell, 376 1990] rather than beta-functions or geometric formula-377 tions to describe the LNDs of the foliage elements; DART 378 approximates the "floating spheres" by a series of small 379 cubes; Hyemalis reduced the physical dimensions of the 380 proposed scenes to deal with internal computer memory 381 requirements; MAC, FRT and 5Scale assume a statistical-382 383 that is, random—spatial distribution of the objects in a scene rather than implementing the spatially explicit lo-384 cations prescribed on the RAMI website; MBRF uses rect-385 angular leaves rather than disc-shaped ones; RGM emulates 386 387 leaf shapes by aggregating small triangular primitives; and the Sprint3 model always uses statistical distribu-388 tions (rather than deterministic placements) of the foliage 389 elements. These structural deviations—which are often 390 motivated by the need for elegant and speedy solutions 391 to the RT equation—may, however, become relevant in 392 an intercomparison exercise like RAMI. 393

Widlowski et al. [2005] recently showed that vegeta-395 tion canopies with identical domain-averaged state vari-396 able values but different structural representations will, 397 in general, yield different multi-angular BRF patterns. 398 In the context of RAMI, one may thus expect differ-399 ences to occur between RT models featuring exact rep-400 resentations of the prescribed canopy structures and 1) 401 improved/expanded versions of essentially plane-parallel 402 RT models in simulations over structurally heterogeneous 403 canopy targets, or, 2) RT models that rely implicitly 404 405 on 3-D plant structures (*i.e.*, Geometric Optical models) when applied to structurally homogeneous test cases. For 406 these reasons the MAC (4SAIL2) model, which utilises a pa-407 rameterised formalism to distribute vegetation elements 408 (gaps) within each elevation of its (one or two layer) veg-409 410 etation canopy representation, may deviate from the RT quantities simulated using models that make use of the 411 actual location of vegetation elements in the heteroge-412 neous RAMI test cases. Similarly, the simulations of the 413 5Scale model in the context of 1-D canopies have not 414 been included in this manuscript. 415

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In order to obtain a comprehensive indication of the performance of a RT model in forward mode, it is essential to run it on as large an ensemble of structurally and spectrally different canopy scenarios as possible – without, however, compromising the structural premises on which its internal canopy representation is based. Thus, the greater the degree of realism and the larger the struc-

tural diversity of the available number of RAMI test cases 424 is, the more indicative the observed BRF deviations be-425 tween the various RT models and/or some "surrogate 426 truth" will become. Last but not least, one should also 427 note that the performance of many 1-D and 3-D RT mod-428 els could always be improved through the usage of more 429 precise numerical integration schemes, as well as, larger 430 numbers of ray trajectories in the case of some of the MC 431 models. Such a "tuning" of model performances would, 432 however, be of little interest to model users if 1) the pub-433 lically available versions of these computer codes cannot 434 deliver these accuracies, and 2) the computation times to 435 achieve such accuracies become prohibitive in the daily 436 usage of the models. 437

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When constrained to evaluate model simulations in the 439 absence of any absolute reference standard or "truth", as 440 is the case with RAMI, *Pinty et al.* [2001] argued that 441 RT model benchmarking on the basis of statistical mo-442 ments, derived from the entirety of participating models, 443 may be biased in the presence of outliers. Instead they 444 proposed a relative evaluation scheme where the simu-445 lations of individual models are compared against those 446 from all other participating models over as large as pos-447 448 sible a set of conditions. In this way, RT models that are consistently different from others can be identified 449 [Pinty et al., 2004b]. The same authors also note that 450 internal inconsistencies in one or more submodules of a 451 452 given RT model may compensate each other and lead to apparently correct overall BRF estimates. They thus 453 recommend the evaluation of BRF components as well as 454 the total BRFs generated by a model. In the following, 455 the three-step invalidation procedure from section 2 will 456 be applied to both the homogeneous and heterogeneous 457 baseline scenarios of RAMI-3. More specifically, subsec-458 tion 3.1 will investigate the internal self-consistency of 459 the models that participated in the baseline scenarios of 460 RAMI-3. Subsection 3.2 then looks at RT model per-461 formance in situations where exact analytical solutions 462 are available. Finally, subsection 3.3 documents various 463 aspects of relative model intercomparison with respect 464 to the discrete homogeneous and the "floating spheres" 465 baseline scenarios. 466

#### 3.1. Model self-consistency

It is difficult to offer meaningful interpretations as to
why the output of a given RT model may be different
from simulation results of other models without verification of the models' internal consistency. Energy conservation, for example, is one of the key principles to
ensure, and this both with respect to directional (BRFs)
and hemispherically integrated (fluxes) quantities.

## 475 3.1.1. Energy conservation

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The solar radiation entering a plant canopy is partitioned into an absorbed A, a reflected R and a transmitted T fraction such that all incident photons are accounted for. Energy conservation thus requires that  $A + R + (1 - \alpha)T = 1$ , where  $\alpha$  is the soil brightness. The capacity of a given model (m) to conserve energy can be described using:

$$\Delta_{\mathrm{F}}(m) = \frac{1}{N_{\mathrm{F}}(m)} \sum_{\lambda=1}^{N_{\lambda}^{m}} \sum_{\zeta=1}^{N_{\zeta}^{m}} \sum_{i=1}^{N_{\Omega_{i}}^{m}} \left[ A_{m}(\lambda,\zeta,i) + R_{m}(\lambda,\zeta,i) \right]$$

$$+[1-\alpha(\lambda)]T_m(\lambda,\zeta,i)\right] - 1$$

where  $N_{\rm F}(m) = N_{\lambda}^m + N_{\zeta}^m + N_{\Omega_i}^m$  is the total number of spectral  $\lambda$ , structural  $\zeta$ , and illumination  $\Omega_i$  condi-483 484 tions for which flux simulations were performed by model 485 m. Figure 2 shows the mean deviation from energy con-486 servation,  $\Delta_{\rm F}(m)$  for those models that simulated flux 487 quantities in the case of the structurally homogeneous 488 baseline scenarios. More specifically, the top panel dis-489 plays  $\Delta_{\rm F}(m)$  for canopies with discrete leaves in the solar 490 domain, and the bottom panel shows  $\Delta_{\rm F}(m)$  for turbid 491 medium canopies with conservative scattering properties 492 (purist corner). It should be noted that the MAC model 493 seems to generate an excess of energy  $(\Delta_{\rm F}(MAC) > 0)$ 494 that is equivalent to about 3% of the incident radiation 495 at the TOC in the solar domain. On the other hand, 496 the FLIGHT and raytran models both appear to lose en-497 ergy ( $\Delta_{\rm F} < 0$ ), equivalent to ~2% of the incident radia-498 tion at those wavelengths. Under conservative scattering 499 conditions, however, the latter two models comply very 500 well with energy conservation requirements ( $\Delta_{\rm F} \approx 0$ ), 501 a pattern that is observed for both discrete and tur-502 bid medium foliage representations in structurally ho-503 504 mogeneous, as well as heterogeneous environments (not shown). Since  $\alpha = 1$  under purist corner conditions it 505 must be the canopy transmission measurement that af-506 fects  $\Delta_{\rm F}$  for both FLIGHT and raytran. Indeed, in the 507 case of raytran it turned out that the diffuse transmis-508 sion component had been neglected in the submitted 509 simulations. By the same token the deviations of the 510 DART model under conservative scattering conditions are 511 512 likely to arise from its estimation of the canopy absorption and/or reflectance. Further analysis (not shown) 513 indicated that enhanced multiple scattering conditions 514 exacerbate the apparent deviations from energy conser-515 vation for all models with non-zero  $\Delta_{\rm F}$  values in Figure 2. 516 As to how much these apparent deviations from energy 517 conservation relate to model deficiencies rather than op-518 erator errors is, however, difficult to anticipate. By the 519 same token, RT models that utilise the principle of en-520 ergy conservation to close their radiation budget will ob-521 viously never be found deviating in such self-consistency 522 checks. This applies, for example, to the 1/2-discret, 523 Sail++ and 2-Stream models which derive their canopy 524 absorption estimate from simulations of the reflectance 525 and transmission properties of the vegetation layer. 526 527

#### 528 3.1.2. BRF consistency

The RAMI format specifications ask for all radiative 529 quantities to be provided with a precision of six decimal 530 places, *i.e.*, the implicit error associated with the mea-531 surements is thus of the order of  $10^{-6}$ . The average ab-532 solute difference  $\Delta \rho$  between the total BRF ( $\rho_{tot}$ ) and the 533 sum of the BRF contributions due to the single uncollided 534  $(\rho_{uc})$ , the single-collided  $(\rho_{co})$ , and the multiple-collided 535  $(\rho_{mlt})$  radiation components should thus be of a similar 536 537 magnitude when defined as follows:

$$\Delta \rho(m) = \frac{1}{N_{\rho}(m)} \sum_{\lambda=1}^{N_{\lambda}^{m}} \sum_{\zeta=1}^{N_{\zeta}^{m}} \sum_{v=1}^{N_{\Omega_{v}}^{m}} \sum_{i=1}^{M_{\Omega_{i}}} \left| \rho_{tot}^{m}(\lambda, \zeta, v, i) - \left[ \rho_{uc}^{m}(\lambda, \zeta, v, i) + \rho_{co}^{m}(\lambda, \zeta, v, i) + \rho_{mlt}^{m}(\lambda, \zeta, v, i) \right] \right|$$

where  $N_{\rho}(m) = N_{\lambda}^{m} + N_{\zeta}^{m} + N_{\Omega_{v}}^{m} + N_{\Omega_{i}}^{m}$  is the total number of BRFs that were generated with the model m

for different spectral  $\lambda$ , structural  $\zeta$ , viewing  $\Omega_v$ , and 540 illumination  $\Omega_i$  conditions. Apart from Hyemalis and 541 2-Stream, all models in Table 1 provided simulations of 542 the three BRF components for at least some of the test 543 cases of RAMI-3. In general, the average absolute devia-544 tion  $\Delta \rho$  was  $< 10^{-5}$ , with the exception of  $\Delta \rho$ (5Scale) = 545 0.0027 for the discrete homogeneous solar domain, as well 546 as  $\Delta \rho(\text{frat}) = 0.0013$  and  $\Delta \rho(\text{FLIGHT}) = 0.0002$  for the 547 homogeneous discrete purist corner. These deviations, 548 although small in terms of the magnitude of the total 549 BRF and often related to the configuration of the model 550 in its day to day usage, are nevertheless significant in the 551 context of a model intercomparison exercise like RAMI 552 since—by their statistical nature—they seem to indicate 553 that some of the models do not conserve energy when 554 partitioning the total BRF into its various subcompo-555 nents. 556

#### <sup>558</sup> 3.1.3. Spectral ratio of the single-uncollided BRF

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Model self-consistency can also be evaluated across 559 different wavelengths. The ratio  $\rho_{uc}(\lambda_1)/\rho_{uc}(\lambda_2)$  of the 560 single-uncollided BRF components in the red and NIR 561 spectral regimes, for example, relates to the differing 562 amounts of radiation that have been scattered once by 563 the underlying background (and never interacted with 564 the canopy foliage) at these two wavelengths ( $\lambda_1$  and  $\lambda_2$ ). 565 In the case of Lambertian soils, this spectral ratio must 566 be a directionally invariant constant equal to the ratio 567 of the soil albedos at the wavelengths of interest, *i.e.*, 568  $\alpha(\lambda_1)/\alpha(\lambda_2)$ . Ensemble-averaging over a variety of struc-569 ture  $\zeta$  and illumination  $\Omega_i$  conditions  $(N_S = N_{\zeta}^m + N_{\Omega_i}^m)$ 570 then provides an indication of the average deviation from 571 spectral consistency for any model m: 572

$$\Delta_S(m,\Omega_v) = \frac{\alpha(\lambda_1)}{\alpha(\lambda_2)} - \left[\frac{1}{N_S(m)}\sum_{\zeta=1}^{N_\zeta^m}\sum_{i=1}^{N_{\Omega_i}^m}\frac{\rho_{uc}^m(\lambda_1,\zeta,\Omega_v,i)}{\rho_{uc}^m(\lambda_2,\zeta,\Omega_v,i)}\right]$$

Figure 3 documents the angular variation of  $\Delta_S$ , obtained 573 from single-uncollided BRF simulations in the red and 574 NIR spectral domains, for homogeneous turbid medium 575 (left) and discrete floating-spheres canopies (right) hav-576 ing uniform LNDs. Not included in these graphs are 577 the forward MC ray-tracing models frat and raytran 578 due to the large noise levels associated with their sam-579 pling schemes. MC noise is also evident for the drat and 580 Rayspread models, although this decreases as more rays 581 582 are being used in the RT simulation and/or the fraction of the contributing background in the scene increases, 583 e.g., in the "floating spheres" scenarios. One will notice 584 that, with the exception of the Sprint3 model in the 585 "floating spheres" case, the spectral ratio of the single-586 uncollided BRF component remains relatively constant 587 for all models (including ACRM in the homogeneous dis-588 crete case – not shown) up to view zenith angles of about 589  $65 - 70^{\circ}$ . The Sprint3 model, and to a lesser extent 590 also the Rayspread model, utilise a variance reduction 591 technique known as "photon spreading" in order to re-592 duce the number of rays that sample the radiative trans-593 fer properties of the medium of interest. In Figure 3 594 the deviations in the magnitude but not in the shape 595 of the single-uncollided BRF components in the homo-596 geneous turbid case (left panel) may thus be solely due 597 to an insufficient sampling (LAI=3) of the lower bound-598 ary condition contributing to  $\rho_{uc}$ . On the other hand, 599 the variations of  $\Delta_S(\text{Sprint3})$  with view zenith angle in 600 the "floating spheres" case (LAI=2.36) may be due to 601

the spatially varying presence of foliage in the canopy to-602 gether with the statistical distribution of foliage-rather 603 than a deterministic placement of scatterers—within the 604 various spherical volumes. As such the actual number 605 of rays, that traverse the floating spheres (LAI=5) and 606 reach the ground or escape the scene unhindered, is never 607 the same in different directions if model runs at different 608 wavelengths do not use the same starting seeds to ini-609 tialise their random number generator. 610

#### 3.2. Absolute model performance

Exact analytical solutions to the radiative transfer 611 equation do not exist for the vast majority of conceiv-612 able vegetation canopies. In some cases, however, the 613 structural and spectral properties of vegetated surfaces 614 may be such that it becomes possible to predict at least 615 some of their radiative properties analytically. Within 616 the available set of RAMI test cases there are at least two 617 different types of absolute model evaluations that can be 618 performed: The first one relates to single-collided BRF 619 components of structurally homogeneous turbid medium 620 canopies with uniform LND, and the second to the re-621 flected and absorbed energy fluxes in the various conser-622 vative scattering (purist corner) scenarios. 623

#### 624 625

#### 3.2.1. Homogeneous turbid uniform canopy

Structurally homogeneous leaf canopies with az-626 imuthally invariant uniform LNDs are characterised by 627 a constant probability of foliage interception irrespective 628 of the direction of propagation in that medium [Ross,629 1981; Verstraete, 1987]. In addition, turbid media—with 630 their infinitesimally small scatterers—satisfy the far field 631 approximation and thus never yield a hot spot, *i.e.*, a 632 localised increase in the BRF around the retro-reflection 633 direction of the incident illumination, e.g., Gerstl [1988]; 634 Verstraete [1988]; Kuusk [1991]. The single-uncollided 635 BRF component of such a canopy can be written as: 636

$$\rho_{uc}(\Omega_i, \Omega_v) = \alpha \, \exp\left[\frac{-\text{LAI}\left(\mu_i + \mu_v\right)}{2\,\mu_i\,\mu_v}\right]$$

where  $\alpha$  is the albedo of the Lambertian soil,  $\mu = \cos \theta$ is the cosine of the illumination (i) or view (v) zenith angle  $0 \le \theta \le \pi/2$ , and LAI is the leaf area index of the canopy. Similarly the single-collided BRF component of such a canopy can be written as:

$$\rho_{co}(\Omega_i, \Omega_v) = \frac{2\Gamma(\Omega_i \to \Omega_v) \left[1 - \exp\frac{-\text{LAI}\left(\mu_i + \mu_v\right)}{2\mu_i \mu_v}\right]}{\mu_i + \mu_v}$$

where the canopy scattering phase function is given by[Shultis and Myneni, 1988]:

$$\Gamma(\Omega_i \to \Omega_v) = \frac{r_L + t_L}{3\pi} \left(\sin\beta - \beta\cos\beta\right) + \frac{t_L}{3}\cos\beta$$

and  $\beta$  is the phase angle between the illumination and viewing direction:

$$\cos\beta = \cos\theta_i \cos\theta_v + \sin\theta_i \sin\theta_v \cos|\phi_i - \phi_v|$$

and  $r_L$  ( $t_L$ ) is the reflectance (transmittance) of the foliage elements. Figure 4 shows the mean absolute error between RT model simulations and the above analytical formulations for the single-collided (left panel) and the single-uncollided (right panel) BRF components of

a turbid medium canopy with uniform LND and Lam-651 bertian scattering laws. The averaging was performed 652 over BRF simulations in the principal and orthogonal 653 planes, as well as, for illumination zenith angles of  $20^{\circ}$ 654 and  $50^{\circ}$ . With the exception of MBRF all RT models lie 655 within 0.0025 of the truth in the single-collided case. The 656 657 operator of the MBRF model conjectures, however, that the observed deviations may be due to a softare error 658 (bug) since the formulation of the single-collided BRF 659 component in Qin and Xiang [1997] is based on a proper 660 theoretical derivation. In the single-uncollided case the 661 agreement between the participating RT models and the 662 analytical solution is ten times better still than in the 663 single-collided case, *i.e.*, all models lie within  $2.5 \cdot 10^{-4}$ 664 of the analytical solutions. This is impressive since the 665 magnitude of  $\rho_{co}$  ( $\rho_{uc}$ ) along the orthogonal plane was 666 typically around 0.017 (0.003) in the red and 0.16 (0.005)667 in the NIR. Furthermore, it should be noted that none of 668 the participants had any *a priori* knowledge about these 669 absolute evaluation tests. In principle, the performance 670 of many of the participating RT models could thus still be 671 improved further, for example, by increasing the number 672 of integration steps (e.g., Gaussian quadrature points) 673 in numerical techniques, or, by adding further rays to 674 675 sample the characteristics of the canopy-leaving radiation field (in the case of MC ray-tracing models). 676 677

#### <sup>678</sup> **3.2.2.** Purist corner fluxes

Under conservative scattering conditions all of the en-679 ergy that enters a canopy system has to leave it, *i.e.*, 680 R = 1 and A = 0. The RAMI purist corner thus pro-681 vides another opportunity to assess the performance of 682 RT models against a known absolute reference. Figure 5 683 shows (on a log-log scale) the average absolute deviation  $\varepsilon$ 684 from the true canopy absorption (y-axis) and reflectance 685 (x-axis) for homogeneous canopies with finite-sized (left 686 panel), as well as turbid medium (right panel) foliage rep-687 resentations under conservative scattering properties. In 688 each case the averaging was performed over (N = 18) test 689 cases with different LAI, LND and  $\theta_i$ . With the excep-690 tion of MBRF, which did not provide absorption estimates, 691 all models featuring  $\varepsilon = 10^{-7}$  (or -7 in Figure 5) sub-692 mitted the theoretical values. In the homogeneous turbid 693 case, for example, both the raytran, and Sprint3 models 694 compute the canopy absorption and reflectance to within 695 computer-precision uncertainties. The 1/2-discret and 696 2-Stream models, on the other hand, showed an aver-697 age absolute deviation of 0.0015 and 0.0245, respectively, 698 for both  $\varepsilon_{\text{Absorption}}$  and  $\varepsilon_{\text{Reflectance}}$ . Models that fall on 699 the 1:1 line in Figure 5 estimate their canopy absorp-700 701 tion by closing the energy budget. In the case of the 1/2-discret model the (negative) canopy absorption de-702 viations arose from overestimated albedos under the fully 703 scattering purist corner conditions. These in turn, are a 704 consequence of the fixed number (16) of Gaussian quadra-705 ture points used in the numerical integration scheme of 706 the azimuthally averaged multiple-scattering component. 707 The DART model, on the other hand, which computes 708 canopy absorption on a ray-by-ray basis, features a re-709 spectable  $\varepsilon_{\text{Absorption}} = 0.0006$  and  $\varepsilon_{\text{Reflectance}} = 0.0125$ . 710 In the discrete homogeneous case (right panel), the av-711 erage absolute deviation of the 1/2-discret model from 712 the correct absorption and reflectance values increases to 713 0.0204, presumably due to highly variable BRFs in the 714 vicinity of the retro-reflection direction (hot spot) that af-715 fected the accuracy of the numerical integration scheme. 716 At this point, one should recall that the lack of deviations 717 from the "truth" is not a proof of the physical correctness 718

of a model since, for example, hard-encoded program-719 ming statements may be contained inside the computer 720 721 code that do account for the eventuality of situations for which the exact solution is known. In this way, the ac-722 tual model would not be executed—to compute canopy 723 reflectance and absorption here—but sidestepped to gen-724 725 erate the anticipated results. The primary interest here (and in all other parts of section 3) thus lies in under-726 standing the observed *deviations* from the correct solu-727 tion. 728

#### 3.3. Relative model performance

Without access to absolute reference standards the 729 evaluation of RT models has to rely on relative model 730 intercomparison. The goal being to identify systematic 731 trends in the behaviour of one (or more) models with 732 respect to others, over ensembles of test cases. Three 733 different types of relative intercomparison metrics will 734 be proposed here: model-to-model deviations, model-to-735 ensemble deviations, and deviations from model-derived 736 surrogate truths. 737

#### 738 739 **3.3.1.** Model-to-model deviations

The differences in the BRF simulations between two models (c and m), when averaged over a variety of spectral ( $\lambda$ ), structural ( $\zeta$ ), viewing ( $\Omega_v$ ) and illumination ( $\Omega_i$ ) conditions, can be defined as:

$$\delta_{m\leftrightarrow c} = \frac{200}{N} \sum_{\lambda=1}^{N_{\lambda}} \sum_{\zeta=1}^{N_{\zeta}} \sum_{v=1}^{N_{\Omega_{v}}} \sum_{i=1}^{N_{\Omega_{i}}} \left| \frac{\rho_{m}(\lambda,\zeta,v,i) - \rho_{c}(\lambda,\zeta,v,i)}{\rho_{m}(\lambda,\zeta,v,i) + \rho_{c}(\lambda,\zeta,v,i)} \right|$$

<sup>744</sup> where  $N = N_{\lambda} + N_{\zeta} + N_{\Omega_v} + N_{\Omega_i}$  is the total number <sup>745</sup> of BRF simulations that have been performed by both <sup>746</sup> models *c* and *m*, and  $\delta_{m \leftrightarrow c}$  is expressed in percent.

Figure 6 depicts a series of two-dimensional grids con-747 taining information on the various model-to-model BRF 748 differences (blue-red colour scheme in the lower right half 749 of each panel), as well as, the percentage of the total 750 number of BRFs over which the  $\delta_{m\leftrightarrow c}$  values were de-751 rived (black-green colour scheme in upper left half of each 752 panel). More specifically,  $\delta_{m\leftrightarrow c}$  is shown for those models 753 having submitted the total (top row), single-uncollided 754 (second row), single-collided (third row) and multiple-755 collided (bottom row) BRF data for structurally homo-756 geneous canopies with finite-sized (leftmost column) and 757 turbid medium (middle-left column) foliage representa-758 tions, as well as, for "floating spheres" scenarios with 759 finite-sized (middle-right column) and turbid medium 760 (rightmost column) foliage representations in the solar 761 domain. The blue colour scale increments in steps of 762 2%, the green colour scale in steps of 10%, and the red 763 also in steps of 10% with the bright red colour indicat-764 ing values larger than 50%. The maximum number of 765 BRF simulations included in the computation of  $\delta_{m\leftrightarrow c}$ 766 was 1216 for the structurally homogeneous and 608 for 767 the "floating spheres" canopies. To illustrate the reading 768 of the various panels in Figure 6 let's consider, for exam-769 ple, the total BRFs of the Hyemalis and Sprint3 models 770 in the discrete homogeneous case (top left panel): Their 771 model-to-model difference value, which lies between 10 772 and 20% (light red colour), has been obtained from less 773 than 10% of the total number of BRF simulations (dark 774 green colour) and thus may not be too representative. 775 On the other hand, the  $\delta_{m\leftrightarrow c}$  of the ACRM and Sprint3 776 models (same top left panel) lies somewhere between 6 777 and 8% and has been established using 100% of the pos-778

sible BRFs. In general, the majority of models in the 779 discrete and turbid homogeneous cases agree rather well 780 with each other ( $\delta_{m \leftrightarrow c} < 10\%$ ). This behaviour is also 781 present for the various BRF components with the ex-782 ception of the single-uncollided BRF component  $(\rho_{uc})$  in 783 the discrete homogeneous case where the various imple-784 mentations/approximations of the hot spot phenomenon 785 have increased the differences amid the simulated BRFs. 786 In the case of turbid homogeneous canopies the DART 787 model features somewhat elevated  $\delta_{m\leftrightarrow c}$  values for the 788  $\rho_{uc}$  component which may, however, be partly due to 789 the inter/extrapolation procedure that had to be sys-790 tematically applied to all BRF simulations of this model 791 in order to map its submitted 32 (18) viewing condi-792 tions in the principal (orthogonal) plane to the full set 793 of 76 as specified by RAMI. The FLIGHT model—which 794 did not update its baseline scenario simulations during 795 RAMI-3—shows slightly diverging multiple-collided BRF 796 components in both the discrete and turbid medium ho-797 mogeneous cases. These are caused by a Lambertian 798 assumption governing the angular distribution of higher 799 orders of scattered radiation in simulation results origi-800 nally submitted during RAMI-1. This effect is no longer 801 visible in the "floating spheres" case due to subsequent 802 803 model improvements in phase 2 (right panels in Figure 6). Unlike in the discrete homogeneous cases, the 804 "floating spheres"  $\rho_{uc}$  shows the smallest  $\delta_{m\leftrightarrow c}$  values 805 presumably because the hotspot here is dominated by 806 807 the geometry of the spheres themselves. In the "floating spheres" cases it is thus the multiple scattering and 808 to a lesser extent also the single-collided BRF compo-809 nents that show the largest differences between BRF sim-810 ulations of 3-D Monte Carlo models-featuring explicit 811 scene representations-and those of somewhat more ap-812 proximate models. 813

#### 815 3.3.2. Model-to-ensemble deviations

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In the absence of any absolute reference truth, the out-816 put from individual RT models may also be compared 817 to ensemble averages computed from simulation results 818 of other RT models, as first proposed by Pinty et al. 819 820 [2001, 2004b]. In this way, RT models that are very different from all other models can be identified and-although 821 not wrong in any absolute sense—they may then be ex-822 cluded from further iterations of the ensemble averaging 823 process, if this is deemed appropriate. For any spectral 824  $(\lambda)$ , structural  $(\zeta)$ , viewing (v), and illumination (i) con-825 dition one can compute: 826

$$\delta_m(\lambda,\zeta,v,i) = \frac{200}{N_c} \sum_{c=1;c\neq m}^{N_c} \left| \frac{\rho_m(\lambda,\zeta,v,i) - \rho_c(\lambda,\zeta,v,i)}{\rho_m(\lambda,\zeta,v,i) + \rho_c(\lambda,\zeta,v,i)} \right|$$

where  $N_c$  is the number of models with which the output 827 of model m is to be compared. One way to analyse such 828  $\delta_m$  statistics is to bin them over a variety of conditions 829 in order to yield a histogram of model-to-ensemble de-830 viations. The inlaid graphs in Figure 7 show a variety 831 of  $\delta_m$  histograms generated from total BRF simulations 832 of the 1/2-discret, drat, FLIGHT, frat, Rayspread, 833 raytran, RGM, Sail++, Sprint3, and 4SAIL2 models in the 834 case of the discrete structurally homogeneous canopies 835 (left panel), and the drat, FLIGHT, Rayspread, raytran, 836 and Sprint3 models in the case of the discrete "float-837 ing spheres" canopies (right panel). The main graphs 838 of Figure 7 show the outer envelope of these  $\delta_m$  his-839 tograms both for the discrete structurally homogeneous 840 canopies (left panel) and the discrete "floating spheres" 841

canopies (right panel). One will notice that the agree-842 ment between the RT models in RAMI-3 (red line) is 843 844 better than the corresponding agreement of models during the previous phase of RAMI three years ago (black 845 line). In the homogeneous baseline scenarios, where more 846 models are included than during RAMI-2, the first peak 847 848 of the histogram envelope ( $0 \leq \delta_m \leq 2.5\%$ ) can be attributed primarily to the models 1/2-discret, drat, 849 FLIGHT, Rayspread and raytran. The second half of the 850 histogram envelope ( $\delta_m > 2.5\%$ ), on the other hand, 851 arises from BRF simulations due to the models frat, 852 MAC, RGM. The models Sail++ and Sprint3-with their 853 broader distributions of  $\delta_m$ —contribute to both parts of 854 the histogram envelope. 855

Alternatively one may define an overall indicator of model-to-ensemble differences,  $\bar{\delta}_m$  [%] by averaging the above  $\delta_m(\lambda, \zeta, v, i)$  over appropriate sets  $(\bar{N})$  of spectral  $\lambda$ , structural  $\zeta$ , viewing v and illumination i conditions:

$$\bar{\delta}_m = \frac{1}{\bar{N}} \sum_{\lambda=1}^{N_{\lambda}} \sum_{\zeta=1}^{N_{\zeta}} \sum_{v=1}^{N_{\Omega_v}} \sum_{i=1}^{N_{\Omega_i}} \delta_m(\lambda, \zeta, v, i)$$

Table 2 shows the values of the overall model disper-861 sion indicator  $\bar{\delta}_m$  [%] obtained from an ensemble of six 862 3-D Monte Carlo models, namely: DART, drat, FLIGHT, 863 Rayspread, raytran and Sprint3. For each one of these 864 models  $\delta_m$  is provided for the total BRF ( $\rho_{tot}$ ) as well as 865 the single-collided  $(\rho_{co})$ , the multiple-collided  $(\rho_{mlt})$ , and 866 the single-uncollided  $(\rho_{uc})$  BRF components using sub-867 868 mitted simulation results from either RAMI-2 or RAMI-3. With the exception of the total BRF simulations of 869 **DART** all other  $\overline{\delta}_m$  values improved between RAMI-2 and 870 RAMI-3, meaning that a smaller dispersion exists be-871 tween the BRF values of the latest version of these mod-872 els. The average dispersion between the total BRF sim-873 ulations of the six 3-D MC models was found to have 874 almost halved from RAMI-2 (1.37 %) to RAMI-3 (0.72 875 %) in the discrete case, and in the turbid medium case 876 it improved by a factor of  $\sim 7$  from RAMI-2 (6.36 %) to 877 RAMI-3 (0.91 %). 878

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#### 880 3.3.3. Model-to-surrogate-truth deviations

Monte Carlo RT models allow for explicit 3-D repre-881 sentations of complex canopy architectures by describing 882 these environments with (sometimes Boolean combina-883 tions of) sufficiently small geometric building blocks of 884 885 known radiative properties. Solving the radiative transfer equation for such 3-D environments is then achieved 886 through a stochastic sampling of the surface-leaving ra-887 diation field [Disney et al., 2000]. Since this is a time 888 consuming undertaking—in particular for complex 3-D 889 scenes—the current generation of 3-D MC models dif-890 fer primarily in the amount of deterministic detail that is 891 used when constructing a scene, and, in the approach and 892 extent to which ray trajectories are sampled within the 893 3-D media. Both Figure 6 and Table 2 indicate that the 894 3-D Monte Carlo models, DART, drat, FLIGHT, Rayspread, 895 raytran and Sprint3 are generally in very close agree-896 ment with each other. In particular the numbers in Ta-897 ble 2 support their usage in attempts to provide a "sur-898 rogate truth" estimate against which further RT model 899 comparisons may then be carried out. One simple way to 900 obtain a "surrogate truth" estimate is by averaging the 901 BRFs obtained from a set of  $N_{3D}^{credible}$  credible 3-D MC 902 models, that is: 903

$$\bar{\rho}_{3D}(\lambda,\zeta,v,i) = \frac{1}{N_{3D}^{credible}} \sum_{n=1}^{N_{3D}^{credible}} \rho_{3D}(\lambda,\zeta,v,i;n)$$

where the precise number and names of the 3-D MC models that feature within  $N_{3D}^{credible}$  is selected from among the following models: DART, drat, FLIGHT, Rayspread, raytran and Sprint3. The selection procedure is applied to every RAMI experiment and measurement type individually and adheres to the following list of criteria:

• For every RAMI BRF (flux) measurement, identify at least two (one) 3-D Monte Carlo models that do not belong to the same RT modelling school/family,

• If two models from the same RT modelling school/family are available, *e.g.*, **Rayspread** and **raytran**, choose the one with the least amount of apparent MC noise,

• Remove all those 3-D Monte Carlo models from the reference set that are noticeably different from the main cluster of 3-D MC simulations,

• If sufficient models are contained in the main cluster of 3-D MC simulations then remove those models that would introduce noticeable levels of "MC noise" into the reference set,

If there are two distinct clusters of 3-D Monte Carlo
 models, or, no obvious cluster at all, then use all avail able 3-D RT models to define a reference solution.

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A synoptic table featuring the names of the various 3-D MC models that contribute toward the computation of  $\bar{\rho}_{3D}$  for all the RAMI-3 experiments and measurement types individually, can be found on the following internet page: http://romc.jrc.it/WWW/PAGES/ 934 ROMC\_Home/RAMIREF.html<sup>3</sup>.

Once the "surrogate truth" is available for the various RAMI baseline scenarios, the deviations of individual RT models from this norm may be quantified with the following metric [*Pinty et al.*, 2004b]:

$$\chi_m^2(\lambda) = \frac{1}{N-1} \sum_{\zeta=1}^{N_{\zeta}} \sum_{v=1}^{N_{\theta_v}} \sum_{i=1}^{N_{\theta_i}} \frac{\left[\rho_m(\lambda,\zeta,v,i) - \bar{\rho}_{3D}(\lambda,\zeta,v,i)\right]^2}{\sigma^2(\lambda,\zeta,v,i)}$$

<sup>940</sup> where  $\sigma(\lambda, \zeta, v, i) = f \cdot \bar{\rho}_{3D}(\lambda, \zeta, v, i)$  corresponds to a <sup>941</sup> fraction f of the average BRF obtained from the credible <sup>942</sup> 3-D Monte Carlo models.

Figure 8 displays the  $\chi^2$  values in the red and NIR 943 wavelengths for the structurally homogeneous (left panel) 944 and the "floating spheres" (right panel) baseline scenarios 945 having finite-sized scatterers. Arrows indicate changes 946 in the  $\chi^2$  values when comparing the performance of a 947 model in RAMI-2 (base of arrow) with that in RAMI-948 949 3 (tip of arrow) using the latter  $\bar{\rho}_{3D}$  as reference. The uncertainty in both the model and surrogate truth was 950 set to 3% of the latter, *i.e.*, f = 0.03. This estimate 951 is in line with the absolute calibration accuracy of cur-952 rent space borne instruments like MISR [Bruegge et al., 953 2002] and MERIS [Kneubühler et al., 2002], among oth-954 ers. Obviously there is a tendency for those 3-D MC mod-955 els that have participated in the computation of  $\bar{\rho}_{3D}$  to have smaller  $\chi^2$  values in RAMI-3 than in RAMI-2. This 956 957 is particularly so for the heterogeneous BRF simulations, 958 where drat, FLIGHT, Rayspread and sprint-3 served as 959 credible models for all the "floating spheres" test cases. 960

In the homogeneous case, however, both the number and 961 names of the credible 3-D MC models changed from one 962 test case to another. RT models that did not update 963 their BRF simulations in any significant manner during 964 RAMI-3, e.g., 1/2-discret and FLIGHT, do not show any 965 dynamics in their  $\chi^2$  values in the depicted graphs. Oth-966 967 ers, like the Sail++ and RGM models in the homogeneous case, for example, have reduced the distance between 968 their BRF simulations and  $\bar{\rho}_{3D}$  in RAMI-3 which translates into smaller  $\chi^2$ (red) and  $\chi^2$ (NIR) values when com-969 970 pared to those of RAMI-2. FRT was the only non Monte 971 Carlo model to participate in the "floating spheres" test 972 cases during both RAMI-2 and RAMI-3. Here one notices 973 a substantial improvement in its  $\chi^2(\text{NIR})$  value together 974 with a slight increase in  $\chi^2$  (red). 975

# 4. New test cases in RAMI-3

A series of additional experiments and measurements 976 were proposed for RAMI-3 that address new issues or 977 complement others raised during RAMI-2. In the follow-978 ing, the results obtained for the "birch stand" canopy will 979 980 be presented first. Next the "true zoom-in" scene, with its additional measurements, will be revisited before com-981 paring the BRF simulation results for the "conifer forest" 982 scene with and without topography. Last but not least, 983 results for the "floating spheres" purist corner will also 984 985 be displayed.

#### 4.1. The birch stand

This set of experiments was suggested to simulate the 986 radiative transfer regime in the red and near-infrared 987 spectral bands for spatially heterogeneous scenes resem-988 bling boreal birch stands (see Figure 9). The  $100 \times 100$  m<sup>2</sup> 989 scene is composed of a large number of non-overlapping 990 tree-like entities of different sizes and spectral proper-991 ties that are randomly located across (and only partially 992 covering) a planar surface representing the underlying 993 background. Individual tree objects were represented 994 by an ellipsoidal crown located just above a cylindrical 995 trunk. The finite sized foliage was randomly distributed 996 within the ellipsoidal volumes that represented the tree 997 crowns, and was characterized by radiative properties (re-998 flectance, transmittance) that are typical for birch trees. 999 Table 3 provides an overview of the structural and spec-1000 tral properties associated with the 5 tree classes of the 1001 "birch stand" scene. 1002

1003

#### 1004 4.1.1. Canopy-level BRF simulations

Figure 10 presents model generated total BRFs in the 1005 red (left column) and NIR (right column) spectral do-1006 main corresponding to observations of the "birch stand" 1007 along the principal (upper panels) and orthogonal (lower 1008 panels) planes for illumination conditions of  $\theta_i = 20^\circ$  and 1009  $\theta_i = 50^{\circ}$ . It can be seen that most models generate rela-1010 tively similar BRF patterns with the exception of 5Scale. 1011 This systematic difference may be partly explained by 1012 the fact that **5Scale** implemented a "birch stand" scene 1013 composed of only one single tree class having structural 1014 and spectral properties that corresponded to the aver-1015 age characteristics of the 5 tree classes described on the 1016 RAMI website. Moreover, 5Scale's multiple scattering 1017 scheme was designed for denser forests than the "birch 1018 stand" scene with a mean LAI of 0.398. The drat model 1019 generates BRFs that, in particular in the red spectral do-1020 main, have a tendency to be somewhat higher than those 1021 1022 of Dart, Rayspread, raytran and Sprint3. Further anal-1023 ysis revealed that these differences arise primarily due

to the single-collided foliage BRF component. One pos-1024 sible explanation may be found in the exact spatial ar-1025 1026 rangement of the various discrete leaf elements that make up the crown foliage in the drat simulations. The com-1027 monly used procedure of "cloning" individual tree objects 1028 when generating a larger canopy scene, may imply that 1029 small differences in the leaf orientations and positions-1030 especially along the rim of the crown volume—translate 1031 into noticeable differences in the simulated BRF values 1032 at the level of the whole scene. These differences are, 1033 however, only detectable due to the increasing agree-1034 ment that now exists between the various RT models that 1035 have contributed to RAMI-3. The histograms of model-1036 to-ensemble BRF differences,  $\delta_m$  in the "birch stand" 1037 scene (central panels in Figure 10), for example, show 1038 that the BRFs simulated by any one of the models Dart, 1039 drat, frt, Rayspread, raytran and Sprint3 typically fall 1040 within 2% of the ensemble average—and this irrespective 1041 of the plane of observation. 1042 1043

#### 1044 4.1.2. Local transmission transects

1045 Since the x, y location of every individual tree in the "birch stand" scene was specified on the RAMI website 1046 a new measurement type—asking for local transmission 1047 measurements along a transect of 21 adjacent  $1 \times 1$  m<sup>2</sup> 1048 patches—had been proposed. Models were asked to pro-1049 vide simulation results quantifying the total (*i.e.*, direct 1050 plus diffuse) transmission of radiation at the level of the 1051 background for two transects located at the center of the 1052 birch stand scene with orientations that were parallel and 1053 perpendicular to the azimuthal direction of the incident 1054 radiation,  $\phi_i$ , respectively. This setup, which aimed at 1055 reproducing conditions resembling those encountered in 1056 actual field measurements, was rather demanding on the 1057 capabilities of most RT models. The entire birch stand 1058 scene had to be illuminated but the transmission mea-1059 surements were restricted to small adjacent areas in the 1060 center of the scene. This lead to only two RT mod-1061 els contributing to this measurement type (raytran and 1062 Sprint3). Figure 11 shows their local transmission sim-1063 ulations for transects oriented parallel (left panels) and 1064 perpendicular (right panels) to the direction of the il-1065 lumination azimuth  $(\phi_i)$  in both the red (top panels) 1066 and NIR (bottom panels) spectral domain. Although the 1067 simulation results are somewhat different, both models 1068 capture obvious features in the spatial pattern of the lo-1069 cal canopy transmission. The various pink arrows indi-1070 cate obvious correlations with predominantly shadowed 1071 1072 and illuminated patches occurring along the transects depicted (in a perspective-free manner) at the top or bot-1073 tom of each of the four graphs. One should also note that 1074 both models occasionally simulate local transmission val-1075 ues that are larger than unity (i.e., they fall within the1076 grey shaded area at the top of each graph) which is an 1077 unambiguous signature of the presence of horizontal radi-1078 ation fluxes. The occurrence of T > 1 is somewhat more 1079 frequent in the NIR due to the larger single-scattering 1080 1081 albedo ( $\omega_L = r_L + t_L$ ) of the foliage there, as well as for transect orientations that are perpendicular to  $\phi_i$ , which 1082 are the ones least affected by shadows from adjacent tree 1083 crowns. 1084

#### 4.2. The true zoom-in experiment

The "true zoom-in" experiment was first proposed during RAMI-2 (section 2.2 in *Pinty et al.* [2004b]) and consists of a  $270 \times 270$  m<sup>2</sup> scene featuring a number of spherical and cylindrical volumes—having precisely defined locations—that are filled with disc-shaped scatterers hav-

ing different spectral properties (Table 5 and Figure 2 in 1090 Pinty et al. [2004b]). The scene itself is illuminated over 1091 1092 its entire length whilst RT simulations are to be extracted over a set of progressively smaller target areas located at 1093 the center of the scene. The spatial resolutions of these 1094 target areas are 270, 90 and 30 m, respectively. Such true 1095 zoom-ins are useful when 1) the nature of local horizon-1096 tal fluxes—arising from the deterministic occurrence of 1097 gaps and shadows in and immediately around the sam-1098 pling area—are to be studied/accounted for, and 2) the 1099 creation of artificial "order", due to cyclic boundary con-1100 ditions that reproduce the scene *ad infinitum*, has to be 1101 avoided. The latter may arise when RT models have to 1102 be executed on 3-D canopy representations at very high 1103 spatial resolutions since the complexity of the scene is 1104 such that spatially extensive representations cannot be 1105 generated due to computer memory limitations. 1106

Within RAMI-3 the number of local patches in the 1107 "true zoom-in" experiment was extended to nine, such 1108 that the BRF simulations at 90 (30) m spatial resolu-1109 tion, when averaged over all nine patches equal that of 1110 the (central) patch at the coarser 270 (90) m spatial 1111 resolution since the TOC reference level remained the 1112 same throughout the scene. The necessity for determin-1113 1114 istic canopy representations and the complexity of the RT simulation setup was, however, such that only drat, 1115 Sprint-3, raytran and Rayspread performed all of these 1116 simulations. Figure 12 thus restricts itself to total BRF 1117 simulations in the principal (top panels) and orthogonal 1118 (bottom panels) viewing planes for the 270 m (left), 90 1119 m (middle) and 30 m (right) patches located at the cen-1120 ter of the scene (for which also simulations from DART 1121 were available). The illumination zenith angle was set 1122 to  $20^{\circ}$  and the spectral properties of the environment 1123 feature typical NIR conditions. Going from coarse to 1124 fine spatial resolutions (left to right panels in Figure 12) 1125 one notices that the discrepancies between the various 1126 model simulations increase both in the principal and or-1127 thogonal planes. In particular, it is the DART and the 1128 Sprint3 models that differ from the BRF simulations 1129 of drat, Rayspread and raytran. Possible reasons for 1130 these BRF differences include 1) a magnification of the 1131 impact of small structural differences in the determin-1132 istic scene setup as the spatial resolution becomes finer, 1133 and/or, 2) the occurrence of different patterns of shadow-1134 ing/illumination due to erroneously specified illumination 1135 azimuth angles. 1136

#### 1138 4.2.1. Local horizontal flux measurements

1137

In the visible part of the solar spectrum the divergence 1139 of horizontal radiation in vegetation canopies is largely 1140 controlled by the occurrence of mutual shadowing be-1141 tween individual canopy elements and photon channel-1142 ing through the gaps between them. As the canopy tar-1143 get becomes smaller the likelihood of non-zero horizontal 1144 radiation balances increases, resulting in local radiative 1145 regimes that are highly variable across the overall domain 1146 1147 of the canopy [Widlowski et al., 2006b]. The interpretation, spatial distribution and up-scaling of in situ mea-1148 surements thus could benefit from a quantitative analysis 1149 of the magnitude (and directionality) of horizontal radi-1150 ation transport, not only because this may contribute 1151 toward the design of optimal sampling schemes for fu-1152 ture field validation campaigns, but also, because it may 1153 allow the identification of site-specific spatial resolution 1154 thresholds below which the pixel-based interpretation of 1155 1156 remotely sensed data may no longer be adequate (without explicit accounting of horizontal radiation transport). 1157

RAMI-3 therefore introduced a horizontal flux measure-1158 ment for the "true zoom-in" canopy scene, where par-1159 1160 ticipants were asked to simulate the total flux [W] that entered and exited through the various sides of a vir-1161 tual voxel (box) encompassing the canopy at different 1162 spatial resolutions. These voxels—which coincide both 1163 in size and location with the local areas used for the 1164 "true zoom-in" BRF simulations—extend to a height of 1165 15 m and have their lateral sides either parallel (constant 1166 x coordinate) or perpendicular (constant y coordinate) 1167 with the azimuth of the incident radiation,  $\phi_i$  (see Fig-1168 ure 13). As was the case for the local transmission tran-1169 sect measurement, only a couple of models (Sprint-3 1170 and ravtran) submitted results for the local horizontal 1171 flux experiment. Figure 14 displays the results of these 1172 simulations for voxel locations corresponding to the BRF 1173 simulations depicted in Figure 12. More specifically, the 1174 various entering (solid) and exiting (dashed) total hor-1175 izontal fluxes, normalised by the total incident flux at 1176 the top of the canopy, are shown for voxels with spa-1177 tial dimensions equal to 270 m (left), 90 m (middle) and 1178 30 m (right) in the NIR spectral domain. The illumina-1179 tion azimuth,  $\phi_i$  is parallel (perpendicular) to the voxel 1180 sides labeled Y<sub>LOW</sub> and Y<sub>HIGH</sub> (X<sub>LOW</sub> and X<sub>HIGH</sub>), and 1181 1182  $\theta_i = 20^\circ$ . 1183

The direct illumination component entering through 1184 the sunward side of a voxel  $(X_{HIGH})$  and exiting through 1185 its opposite side  $(X_{LOW})$  will naturally increase the mag-1186 nitude of the corresponding normalised fluxes with re-1187 spect to fluxes occurring in other directions and through 1188 other lateral sides of the voxel. These latter fluxes, in 1189 turn, can only arise from radiation that has been scat-1190 tered by the canopy/soil system, and tend to remain 1191 directionally invariant in canopies with randomly dis-1192 tributed Lambertian scatterers [Widlowski et al., 2006b]. 1193 By going from left to right in Figure 14, that is, from 1194 relatively large voxels to smaller ones, it can be seen that 1195 1) the differences between entering and exiting fluxes in-1196 crease, due to the increasingly non-random (and highly 1197 deterministic) location of shadows and gaps, and 2) the 1198 magnitude of the various horizontal fluxes increases, since 1199 the ratio of the lateral and upper voxel sides increases 1200 also. The total net horizontal flux of these voxels (*i.e.*, 1201 the sum of all 4 laterally entering radiation streams mi-1202 nus the sum of the 4 laterally exiting radiation streams). 1203 when normalised by the incident total flux at the TOC 1204 level, was found to be of the order of  $-0.010 \ (-10^{-4})$ 1205 at a spatial resolution of 270 m. -0.099 (-0.002) at 90 1206 m, and 0.038 (0.007) at 30 m by the model Sprint3 1207 (raytran). One should note that Sprint3 deviates by  $\sim 1$ 1208 % from the zero net horizontal radiation transport that 1209 energy conservation dictates at a spatial resolution of 270 1210 m - since here the entire scene is contained within the 1211 voxel. The increasing magnitude of the net lateral radi-1212 1213 ation exchanges as function of spatial resolution is, however, confirmed by both models. This behaviour has to 1214 be accounted for when deriving domain-averaged canopy 1215 transmission, absorption or reflectance estimates on the 1216 basis of a series of local point measurements, e.g., Tian 1217 et al. [2002]; Gobron et al. [2006]. 1218

#### 4.3. The conifer forest

The "conifer forest" scene was originally proposed during RAMI-2 with the aim of simulating the radiative transfer regime in structurally heterogeneous scenes of rather large spatial extent  $(500 \times 500 \text{ m}^2)$  that featured tree architectures and spectral properties reflecting those of typical coniferous forests (overlying a snow back-

ground). The RAMI-2 specifications of the "conifer for-1225 est" included conical tree crown representations (of fixed 1226 1227 dimensions) that were distributed uniformly over a Gaussian shaped hill surface. In RAMI-3 a non-topography 1228 version of the same coniferous forest was added in order 1229 to investigate whether the deviations in the RT simula-1230 tions in the Gaussian hill scenario were solely due to the 1231 topography itself. Both implementations of the "conifer 1232 forest" feature identical numbers and sizes of trees. Fig-1233 ure 15 displays the model simulated BRFs in the princi-1234 pal (top 2 rows) and orthogonal (bottom 2 rows) viewing 1235 planes for the "conifer forest" scene with topography (left 1236 panels), without topography (middle panels), and the dif-1237 ference between these two (right panels). Simulations 1238 pertain to the red (top and third row) and near-infrared 1239 (second and bottom row) spectral regimes of the canopy, 1240 and  $\theta_i = 40^\circ$ . 1241

One notices the close agreement between the BRF sim-1242 ulations of the models drat, Rayspread, raytran, and 1243 Sprint3 in all of the test cases. The MAC model provided 1244 identical simulations for both the flat background and the 1245 Gaussian hill scenarios. Both of these tend to be higher 1246 than the BRF values from most other models, however. 1247 The **5Scale** model, which utilises a cylinder and a cone to 1248 1249 represent the shape of the tree crowns, generates somewhat higher BRF values in the red spectral domain and 1250 somewhat lower BRF values in the NIR spectral domain. 1251 Accounting for the reduced number of models participat-1252 ing in the Gaussian hill case, one may say that, overall, 1253 the envelope of all the BRF simulations in the Gaussian 1254 hill scenario is very similar to that in the flat background 1255 case. The impact of topography becomes, however, no-1256 ticeable when subtracting the BRF simulations in the flat 1257 background case from those of the corresponding Gaus-1258 sian hill scenario (right column) – in particular at large 1259 view zenith angles. For observations close to nadir, on 1260 the other hand, few topography-induced differences can 1261 be observed since both "conifer forest" representations 1262 feature identical canopy statistics (e.g., LAI, tree num-1263 ber, fractional cover, etc.). In the principal plane the 1264 presence of a hill shaped background thus leads to en-1265 hanced BRFs in the backward scattering direction (*i.e.*, 1266 a large amount of radiation is reflected back from the illu-1267 minated slopes of the hill), and reduced BRFs in the for-1268 ward scattering direction (*i.e.*, little reflection from that 1269 part of the scene that lies in the shadow of the hill). In the 1270 orthogonal plane, the Gaussian hill BRFs exceed those of 1271 the flat background case at large view zenith angles be-1272 cause of the larger contribution from the snowy slopes of 1273 the Gaussian hill (*i.e.*, the single-uncollided BRF com-1274 1275 ponent). In the NIR, this effect is somewhat dampened by the single-collided and multiple-collided BRF compo-1276 nents, which tend to be larger in the flat background case. 1277 The absolute impact that the Gaussian hill exerts on the 1278 simulated BRFs thus tends to be more noticeable in the 1279 red than the NIR spectral regime. 1280

#### 4.4. The "floating spheres" purist corner

Adding conservative scattering conditions in heteroge-1281 neous canopy environments allows to push the RT formu-1282 1283 lations of 3-D models to their limits, in particular with 1284 respect to the multiple scattered radiation component. RAMI-3 thus proposed to run the "floating spheres" test 1285 cases under purist corner conditions, *i.e.*, with  $r_l = t_l =$ 1286 0.5 and  $\alpha = 1$ . Seven RT models participated in these 1287 test cases and their simulation results are shown in Fig-1288 ure 16. More specifically, the total BRFs in the princi-1289 pal (left columns) and orthogonal (right columns) planes 1290 for discrete (top row) and turbid medium (bottom row) 1291

"floating spheres" representations at two different illu-1292 mination zenith angles ( $\theta_i = 20^\circ$  and  $50^\circ$ ) under purist 1293 corner conditions are shown. The structure of the scenes 1294 is indicated in the inlaid images. One can see that, simi-1295 lar to the solar domain simulations, the 3-D Monte Carlo 1296 models drat, Rayspread, raytran, and Sprint3 gener-1297 ated very similar results, with both DART and FRT being 1298 somewhat different in the turbid and discrete cases. The 1299 4SAIL2 model, on the other hand, generates significantly 1300 higher BRFs than the other models. 1301

#### 4.5. Overall model performances in RAMI-3

There is an expectation that the RAMI activity should 1302 provide an overall indication of the performance of a 1303 given model. This is, however, not a trivial task, 1304 since there is a need to account for the reliability of 1305 the model simulations, the number of experiments per-1306 formed, and the computer processing time that was re-1307 quired to do these simulations. Instead, Figure 17 pro-1308 vides an overview of the participation and model-to-1309 ensemble performance of the various models that con-1310 tributed toward RAMI-3. Statistics are provided for to-1311 tal BRF simulations over structurally homogeneous (top 1312 table) and heterogeneous (bottom table) discrete canopy 1313 representations. The various model names are listed on 1314 the top of each table (one per column). The experiment 1315 identifier is provided to the left, whereas the spectral 1316 regime is indicated to the right of each table column. 1317 Light (dark) grey fields indicate incomplete (no) data 1318 submission. The green-yellow-red colour scheme repre-1319 sents the overall model-to-ensemble difference,  $\delta_m$  quan-1320 tifying the dispersion that exists between a given model 1321 m and all other models that have performed the complete 1322 set of prescribed total BRF simulations for the experi-1323 1324 ment/spectral regime combination of interest. One will note that almost all models—whether analytic, stochas-1325 tic, hybrid, or Monte Carlo—agree to within 2–4 % with 1326 the ensemble of all other models in the homogeneous 1327 cases. The MBRF model stands out as being somewhat 1328 different from the other RAMI-3 participants. In the 1329 heterogeneous case, the 3-D MC models tend to be in 1330 good agreement with the ensemble of model simulations, 1331 whereas models with structural and radiative approxima-1332 1333 tions/parameterisation deviate somewhat more - as was discussed and documented in the various previous sub-1334 sections. One should note that the predominant hue in 1335 the  $\bar{\delta}_m$  colours of any given row in Figure 17 depends 1336 both on the degree and manner in which the models are 1337 dispersed around the main cluster of simulation results. 1338 The mostly red colours characterising  $\bar{\delta}_m$  for the discrete 1339 "floating spheres" canopies in the NIR spectral domain 1340 (second last row in lower panel), for example, are due 1341 to the consistently large deviations of the 5Scale and 1342 4SAIL2 simulations with respect to each other and to the 1343 cluster of 3D Monte Carlo models. Finally, the large, 1344 noticeable, amount of (light and dark) grey patches in 1345 Figure 17 indicate that a significant number of experi-1346 ments were not completed or submitted. 1347

# 5. Concluding remarks

The third phase of the RAdiation transfer Model Intercomparison (RAMI) activity with its record participation, its extensive set of new experiments and measurements, and its substantially improved agreement between 3-D MC models sets a milestone in the evolution of the RT modelling community. It is now estimated that about 60 - 65% of all currently existing canopy reflectance mod-

els have voluntarily participated at some time or other in 1355 the RAMI initiative. Through its continuing support and 1356 1357 active encouragement of RAMI the RT modelling community has demonstrated maturity 1) by acknowledging 1358 the necessity for quality assured RT models if these are 1359 to be applied to the interpretation of remotely sensed 1360 data, 2) by voluntarily contributing to the establishment 1361 of benchmarking scenarios against which future develop-1362 ments of RT models may be evaluated, and 3) by agree-1363 ing to publish their model simulations in the refereed 1364 scientific literature prior to knowing the results of the 1365 intercomparison exercise. Since its first phase in 1999, 1366 RAMI has served as a vehicle to document the perfor-1367 mance of the latest generation of RT models by charting 1368 both their capabilities and weaknesses under a variety 1369 of spectral and structural conditions. During RAMI-3 it 1370 has been possible to actually demonstrate, for the first 1371 time, a general convergence of the ensemble of submitted 1372 RT simulations (with respect to RAMI-2), and to doc-1373 ument the unprecedented level of agreement that now 1374 exists between the participating 3-D Monte Carlo mod-1375 els. These positive developments do not only further the 1376 confidence that may be placed in the quality of canopy 1377 reflectance models, but they also pave the way for ad-1378 1379 dressing new and challenging issues, most notably, in the context of supporting field validation efforts of remotely 1380 sensed products. The latter is of prime importance given 1381 the abundance of global surface products from the cur-1382 rent fleet of instruments, like MISR, MODIS, MERIS. 1383 etc. The usage of quality-assured RT models in detailed 1384 simulations of *in situ* field measurements at very high 1385 spatial resolutions is thus only a first step toward propos-1386 ing optimal sampling/up-scaling schemes that guarantee 1387 accurate domain-averaged absorption, transmission, etc. 1388 estimates. RAMI-3 has, however, also shown that only a 1389 few models are currently able to perform such kinds of RT 1390 simulations. The challenge thus lies with the modelling 1391 community as a whole to provide the scientists involved 1392 in field validation campaigns of satellite derived surface 1393 products with optimal sampling practices that are rooted 1394 in a proper understanding of the radiative transfer in ar-1395 chitecturally complex 3-D media. 1396 1397

#### 5.1. Structurally divergent model premises

More models than ever participated in the third phase 1398 of RAMI, and the agreement between them, in particu-1399 lar for the various baseline scenarios, has noticeably in-1400 creased with respect to previous phases of RAMI (Fig-1401 ure 7). The continuation of the strategy adopted during 1402 RAMI-2, *i.e.*, to provide detailed descriptions of the posi-1403 tion and orientation of every single leaf in scenes with dis-1404 1405 crete foliage representations, as well as indications of all tree/crown locations in the relevant scenes on the RAMI 1406 website, has-among other factors-contributed to im-1407 proving the agreement among the various 3-D MC RT 1408 models (Figures 6, 8, 10, 16 and Table 2). This devel-1409 opment provides further weight to using these models in 1410 defining a "surrogate truth" that may then be used—even 1411 for structurally heterogeneous canopy architectures—to 1412 1413 obtain an indication of the performance of other RT mod-1414 els. It may be argued, however, that such an approach is only meaningful if all the models implement identical 1415 canopy representations in their RT simulations. Both 1416 the deviations in the structural premises of a RT model 1417 and the approximations and/or errors in the implementa-1418 tion of the model's radiative transfer formulation may be 1419 held responsible for the observed BRF/flux differences. 1420 If the purpose of RAMI were solely to identify RT re-1421

lated differences in canopy reflectance models, then the 1422 current flexibility in the implementation of RAMI test 1423 1424 cases would have to be replaced by rigorously specified canopy architectures that were specifically tailored to the 1425 scene description formalism of each and every partici-1426 pating RT model. Alternatively, the derivation and use 1427 of "effective" state variables may be proposed to poten-1428 tial RAMI participants, since recent findings, e.g., Cairns 1429 et al. [2000]; Pinty et al. [2006]; Widlowski et al. [2005], 1430 have suggested that diverging target structures may still 1431 yield identical radiative properties provided that "effec-1432 tive" instead of actual state variable values are avail-1433 able for RT simulations (one possible approach to derive 1434 such effective state variables is described in *Pintu et al.* 1435 [2004a]). 1436

1437 Ultimately, however, it is the accuracy of the retrieved 1438 state variable values that counts in RT model applica-1439 tions. The logical consequence of this line of reasoning 1440 thus would be to address the inversion of RT models 1441 in the context of RAMI against predefined sets of spec-1442 tral and angular observations, similar to those provided 1443 by the current fleet of space borne sensors, e.g., ATSR-1444 2/AATSR [Stricker et al., 1995], CHRIS-Proba [Barnsley] 1445 et al., 2004], MISR [Diner et al., 2002], and POLDER 1446 [Deschamps et al., 1994]. In this way, the impact that 1447 the various structural and radiative formalisms in the 1448 RT models may have with respect to the values of the re-1449 1450 trieved state variables could then be assessed in the light of the known uncertainties in the available surface BRFs. 1451 Indeed, during RAMI-1 a set of "inverse mode" scenar-1452 ios had been proposed but this had been abandoned in 1453 subsequent phases due to a lack of participants. Given 1454 the close agreement of the various participating models in 1455 RAMI-3, it may become appropriate to revisit this issue 1456 in the future. 1457

#### 5.2. The RAMI On-line model checker (ROMC)

One of the positive outcome of RAMI-3 is the consis-1458 tently good agreement (see Table 2) between simulation 1459 results of a small set of 3-D MC models – and this both 1460 over homogeneous as well as heterogeneous vegetation 1461 canopies. It thus is feasible to derive a "surrogate truth" 1462 for almost all of the measurements and experiments fea-1463 tured within RAMI (current exceptions are the "local 1464 transmission transects", the "local horizontal fluxes" and 1465 some of the BRF simulations relating to the 30 m spa-1466 tial resolution patches in the "true zoom-in" experiment). 1467 With this valuable dataset at hand, it becomes possible 1468 to allow model owners, developers and customers to eval-1469 uate the performance of a given RT model even outside 1470 the frame of a RAMI phase. To facilitate such an under-1471 taking the RAMI On-line Model Checker (ROMC) was 1472 developed at the Joint Research Centre of the European 1473 Commission in Ispra, Italy. The ROMC is a web-based 1474 interface allowing for the on-line evaluation of RT mod-1475 els using as reference the "surrogate truth" derived from 1476 among the 6 Monte Carlo models DART, drat, FLIGHT, 1477 Rayspread, raytran and Sprint3 using an appropriate 1478 set of selection criteria (see section 3.3.3). Access to 1479 the ROMC can be obtained either via the RAMI web-1480 1481 site or directly using the URL http://romc.jrc.it/<sup>4</sup>. After providing a username and valid email address, the 1482 ROMC can be utilised in two different ways: 1) in **debug** 1483 mode, which allows to *repeatedly* compare the output of 1484 a RT model to that of one or more experiments and/or 1485 measurements from RAMI, *i.e.*, the simulation results 1486 are available on the RAMI website, and 2) in validate 1487 mode, which enables the *once-only* testing of the RT 1488

model against a continuously changing set of test cases 1489 that are similar but not quite equivalent to those from 1490 1491 RAMI, *i.e.*, the solutions are not known *a priori* and the experiments cannot be repeated. 1492

• In debug mode users may choose to execute one 1494 particular experiment and/or measurement from the set 1495 of RAMI-3 test cases ad infinitum, or, at least until they 1496 are satisfied with the performance of their model. De-1497 tailed descriptions of the structural, spectral, illumina-1498 tion and measurement conditions are available. Once the 1499 model simulation results are generated, they can be up-1500 loaded via the web-interface, and-provided they adhere 1501 to the RAMI filenaming and formatting conventions-1502 this process will result in a series of graphical results files 1503 being made available for all test cases. In debug mode 1504 users may not only download their ROMC results but 1505 also an ASCII file containing the actual "surrogate truth" 1506 data 1507

• In validate mode users may choose between 1508 1509 structurally homogeneous and/or heterogeneous "floating spheres" canopies to verify the performance of their 1510 model. The actual set of test cases will, however, be 1511 drawn randomly from a large list of possible ones, such 1512 that it is unlikely to obtain the same test case twice, 1513 *i.e.*, in all likelihood one will not "know" the solution 1514 a priori. Again, the "surrogate truth" was derived from 1515 simulations generated by models belonging to the same 1516 set of 3-D MC models as was the case for the debug 1517 mode. In validate mode the reference data will, however, 1518 not be available for downloading. The procedure for data 1519 submission, on the other hand, is identical to that of the 1520 debug mode, and—provided that all RAMI formatting 1521 and filenaming requirements were applied-will also lead 1522 to a results page featuring a variety of intercomparison 1523 graphics. 1524

Users may download their ROMC results either as jpeg 1526 1527 formatted images from the ROMC website, or else, opt for receiving them via email in postscript form. Both 1528 the debug and validate mode ROMC results files feature 1529 a reference number and a watermark. Available graphs 1530 include: Plots of both the model and reference BRFs 1531 in the principal or orthogonal plane, 1 to 1 plots of the 1532 model and reference BRFs, histograms of the deviations 1533 between model and reference BRFs,  $\chi^2$  graphs for all sub-1534 1535 mitted measurements using an f value of 3% as well as, graphs depicting the deviation of the model and reference 1536 fluxes using barcharts. Users of ROMC are encouraged 1537 to utilise only ROMC results that were obtained in val-1538 idate mode for publications. Those obtained in debug 1539 mode, obviously, do not qualify as proof regarding the 1540 performance of a RT model since all simulation results 1541 may readily be viewed on the RAMI website. Last but 1542 not least, a large ensemble of FAQs should help to guide 1543 the user through the ROMC applications. It is hoped 1544 that the ROMC will prove useful for the RT modelling 1545 community, not only by providing a convenient means to 1546 evaluate RT models outside the triennial phases of RAMI 1547 (something that was rather tedious in the past if authors 1548 wished to rely on the experiences gained from RAMI, 1549 e.g., Gastellu-Etchegorry et al. [2004]) but also to attract 1550 participation in future RAMI activities. 1551 1552

## 5.3. Future perspectives for RAMI

RAMI was conceived as an open-access community ex-1553 ercise and will continue to pursue that direction. As such 1554

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it's goal is to move forward in a manner that addresses 1555 the needs of the majority of RT model (developers and 1556 1557 users). For example, relatively simple RT modelling approaches designed only to simulate integrated fluxes, like 1558 the 2-Stream model, should not be neglected in future 1559 developments of RAMI due the large communities in-1560 1561 volved with soil-vegetation-atmosphere transfer (SVAT) models, as well as general circulation models. Whereas 1562 such two stream approaches remove all dependencies on 1563 vegetation structure beyond leaf quantity and orienta-1564 tion, the various findings of RAMI-3, and in particular 1565 the above discussion, have highlighted the relevance of 1566 canopy structure in forward mode RT simulations. With 1567 every model having its own implementation of "reality" it 1568 may be appropriate to provide as detailed descriptions as 1569 possible of highly realistic canopy architectures in future 1570 phases of RAMI (see for example Disney et al. [2006]). 1571 Various techniques are currently available for the genera-1572 tion of realistic 3-D trees, the most well known one being 1573 probably the L-systems approach, e.g., Prusinkiewicz and 1574 Lindenmayer [1990]; Weber and Penn [1995]; De Reffye 1575 and Houllier [1997]. Using these methodologies to gen-1576 erate a detailed depiction of the architectural character-1577 istics of (part of) well documented sites—like BOREAS 1578 1579 [Sellers et al., 1997] and/or the Kalahari transect (SA-FARI 2000) [Scholes et al., 2004], for example—would 1580 allow to 1) study the variability in the radiative surface 1581 properties predicted by a whole suite of participating RT 1582 models, as well as their possible impact on the hydro-1583 logical and carbon cycles, 2) investigate by how much 1584 RT model simulations vary when carried out on the basis 1585 of canopy representations with a progressively increasing 1586 1587 degree of structural abstractions (all state variable values remain constant, or are converted to "effective" val-1588 ues), e.g., Smolander and Stenberg [2005]; Rochdi et al. 1589 [2006], 3) compare such surface BRF simulations with 1590 atmospherically-corrected observations from space borne 1591 instruments, 4) investigate the potential of RT models 1592 to reproduce in situ measurements of transmitted light, 1593 e.q., Tracing Radiation and Architecture of Canopies 1594 (TRAC) instrument [Chen and Cihlar, 1995; Leblanc, 1595 2002], and/or hemispherical photographs [Leblanc et al., 1596 2005; Jonckheere et al., 2005], and 5) assess the accuracy 1597 of up-scaling methodologies currently used in validation 1598 efforts of satellite derived products like FAPAR and LAI, 1599 e.g., Morisette et al. [2006]. In this way RAMI can ac-1600 tively contribute towards systematic validation efforts of 1601 RT models, operational algorithms, and field instruments 1602 - as promoted by the Committee on Earth Observation 1603 Satellites (CEOS). 1604

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### Notes

1. Due to the renaming of all European Commission websites this URL is likely to change in the near future to http://rami-benchmark.jrc.ec.europa.eu/

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- 2. Canopy structure is defined here as the (statistical or deterministic) description of locations and orientations of foliage and woody constituents within the three-dimensional space of a RAMI scene.
- 3. Due to the renaming of all European Commission websites this URL is likely to change in the near future to http://romc.jrc.ec.europa.eu/ .
- 4. See footnote 3.

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Table 1. List of the participating models, their RT implementation type, scene construction approach and main scientific reference, as well as the names of their operators during RAMI-3

Model name	RT formalism	Scene Setup	Reference	Participant
1-D models				
ACRM MBRF Sail++ 1/2-discret 2-Stream	analytic + MKC analytic + hotspot kernel N+2 stream analytic + DOM analytic	2-layer PP, SD PP, SD PP, SD PP, SD PP, SD PP, SD	Kuusk [2001] Qin and Xiang [1997] Verhoef [1998, 2002] Gobron et al. [1997] Pinty et al. [2006]	Kuusk A. <sup>1</sup> Qin W. <sup>11</sup> Verhoef W. <sup>2</sup> Gobron N. <sup>3</sup> Lavergne T. <sup>3</sup>
3-D models				
5Scale FLIGHT 4SAIL2 frat FRT DART Drat Hyemalis MAC Rayspread raytran RGM Sprint3	hybrid (GO) MC,RT (forward/reverse) hybrid (4 stream + GO) MC,RT (forward) hybrid (GO) RT (forward) + DOM MC,RT (reverse) radiosity approach hybrid (GO) MC,RT (forward + VR) MC,RT (forward) radiosity MC,RT (forward + VR)	GP, SD GP, DL or SD 2-layer PG,FC GP, DL GP, SD voxels, SD GP, DL GP, OP, DL GP, SD, FC GP, DL or SD GP, DL or SD GP, DL GP, SD	Leblanc and Chen [2001] North [1996] Verhoef and Bach [2003] unpublished Kuusk and Nilson [2000] Gastellu-Etchegorry et al. [1996, 2004] Lewis [1999]; Saich et al. [2001] Soler and Sillion [2000], and Helbert et al. [2003] Fernandes et al. [2003] Widlowski et al. [2006a] Govaerts and Verstraete [1998] Qin and Gerstl [2000] Thompson and Goel [1998]	Rochdi N. <sup>9</sup> and Leblanc S. <sup>12</sup> North P. <sup>10</sup> Verhoef W. <sup>2</sup> Lewis P. <sup>8</sup> and Disney M. <sup>8</sup> Mõttus M. <sup>1</sup> and Kuusk A. <sup>1</sup> Martin E. <sup>5</sup> and Gastellu J-P. <sup>5</sup> Lewis P. <sup>8</sup> and Disney M. <sup>8</sup> Ruiloba R. <sup>7</sup> , Soler, C. <sup>13</sup> , and Bruniquel-Pinel V. <sup>7</sup> Fernandes R. <sup>9</sup> and Rochdi N. <sup>9</sup> Lavergne T. <sup>3</sup> Lavergne T. <sup>3</sup> Lavergne T. <sup>3</sup> Xie D. <sup>4</sup> Thompson R. <sup>6</sup>

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 $\mathrm{DL}$ deterministic location of scatterer

DOM discrete ordinate method

 $\mathbf{FC}$ statistical description of foliage clumping

- GOgeometric optics
- $\operatorname{GP}$ geometric primitives
- MCMonte Carlo approach
- MKC Markov chain
- OPOptic primitive
- $\mathbf{PP}$ plane parallel canopy
- $\mathbf{PG}$ parametric description of canopy gaps
- $\mathbf{RT}$ ray-tracing scheme
- SDstatistical distribution of scatterer
- VR variance reduction technique

model	BRF	discrete scenes		turbid scenes	
name	$\mathbf{type}$	RAMI-2	RAMI-3	RAMI-2	RAMI-3
DART	$\rho_{tot}$	-	-	1.42	1.46
	$\rho_{co}$	-	-	1.80	0.81
	$\rho_{mlt}$	-	-	21.44	2.72
	$ ho_{uc}$	-	-	29.02	2.40
drat	$ ho_{tot}$	1.92	0.55	-	-
	$ ho_{co}$	15.98	1.43	-	-
	$\rho_{mlt}$	3.49	1.14	-	-
	$\rho_{uc}$	72.93	7.47	-	-
FLIGHT	$\rho_{tot}$	1.26	0.97	9.63	1.06
	$\rho_{co}$	19.92	3.08	12.72	1.66
	$\rho_{mlt}$	3.33	2.79	15.40	3.10
	$\rho_{uc}$	32.99	10.80	14.29	4.48
Rayspread	$\rho_{tot}$	-	0.55	-	0.64
	$\rho_{co}$	-	1.42	-	0.69
	$\rho_{mlt}$	-	1.18	-	1.48
	$\rho_{uc}$	-	5.88	-	2.62
raytran	$\rho_{tot}$	1.31	0.60	1.06	0.69
	$\rho_{co}$	10.24	1.38	1.47	0.78
	$\rho_{mlt}$	2.73	1.32	10.29	1.81
	$\rho_{uc}$	32.62	7.20	12.83	3.61
Sprint3	$\rho_{tot}$	1.29	1.01	9.66	0.69
-	$\rho_{co}$	9.11	2.12	12.67	0.94
	$\rho_{mlt}$	2.44	1.61	15.27	1.61
	$\rho_{uc}$	31.53	7.94	15.72	3.44

**Table 2.** Model-to-ensemble dispersion statistics,  $\bar{\delta}_m$  [%] forsix 3-D Monte Carlo models in RAMI-2 and RAMI-3

In each case, the averaging was performed over all available structural, spectral, illumination and viewing conditions.

Table 3. Major variables defining the structural and spectral properties associated to the 100  $\times 100~{\rm m^2}$  "birch stand" scene.

parameter [units]		tree	class		
	Α	в	$\mathbf{C}$	D	$\mathbf{E}$
tree height [m]	2.5	5.5	8.5	11.5	14.5
$LAI/tree [m^2m^{-2}]$	0.751	1.081	1.340	1.575	1.805
crown height [m]	1.237	2.952	4.919	7.137	9.606
crown width [m]	0.611	0.995	1.430	1.937	2.538
trunk height [m]	1.263	2.548	3.581	4.363	4.894
trunk width [m]	0.014	0.033	0.054	0.078	0.107
tree density [stem/ha]	38	507	981	261	13
red leaf reflectance	0.10	0.09	0.08	0.07	0.06
red leaf transmittance	0.06	0.05	0.04	0.03	0.03
red trunk reflectance	0.32	0.31	0.30	0.29	0.28
NIR leaf reflectance	0.49	0.48	0.47	0.46	0.45
NIR leaf transmittance	0.50	0.49	0.48	0.47	0.46
NIR trunk reflectance	0.40	0.39	0.38	0.37	0.36

The reflectance of the Lambertian soil was 0.127 (0.159) in the red (NIR) spectral band. The scattering properties of both leaves and trunks were Lambertian.



Figure 1. Sample BRF results for structurally homogeneous (left panels) and "floating spheres" (right panels) canopies. Model simulations along the principal plane (top panels) relate to test cases with finite-sized scatterers and spectral properties that are typical of the red spectral band. Those along the orthogonal plane (bottom panels) relate to turbid medium foliage representations with spectral properties that are typical of the near-infrared (NIR). The illumination zenith angle was  $20^{\circ}$ in all cases. Also shown are graphical representations of the various canopy structures.



Figure 2. The average deviation from energy conservation  $(\Delta_F)$  for RT models performing 1) the discrete homogeneous baseline scenarios in the solar domain (top panel), and 2) the turbid medium homogeneous test cases under conservative scattering conditions (bottom panel).



Figure 3. Average deviation from the true spectral ratio of the single-uncollided BRF components in the red and NIR spectral domains,  $\Delta_S$ , as a function of view zenith angle for homogeneous turbid medium canopies (left) and discrete floating-spheres canopies (right) with uniform LNDs.



Figure 4. The mean absolute error between model simulations and the analytical formulation of the single-collided,  $\rho_{co}$  (left panel) and the single-uncollided,  $\rho_{uc}$  (right panel) BRF components of a homogeneous turbid medium canopy with uniform LND and Lambertian scattering laws. For any view zenith angle the averaging was performed over the principal and orthogonal plane, as well as, for illumination zenith angles of 20° and 50°.



**Figure 5.** The average absolute deviation,  $\varepsilon_q$  between RT model estimates and the true canopy absorption,  $q^{\rm truth} = A = 0$  (y-axis) or reflectance  $q^{\rm truth} = R = 1$  (x-axis), on a logarithmic scale, for structurally homogeneous canopies with finite-sized (left panel) and turbid medium (right panel) foliage representations under conservative scattering conditions. The averaging was performed over (N = 18) test cases with varying LAI, LND and  $\theta_i$ . Note that—with the exception of MBRF which did not provide absorption estimates—all exact A and R values are plotted at log  $\varepsilon_q = -7$ .



**Figure 6.** Model-to-model differences  $\delta_{m\leftrightarrow c}$  of the total (top row), single-uncollided (second row), single-collided (third row) and multiple-collided (last row) BRF data of models performing the required simulations for structurally homogeneous canopies with finite-sized (leftmost column) and turbid medium (middle-left column) foliage representations, as well as, for "floating spheres" scenarios with finite-sized (middle-right column) and turbid medium (rightmost column) foliage representations in the solar domain. The lower right half of every panel indicates  $\delta_{m\leftrightarrow c}$  in [%] (blue-red colour scheme), whereas the top left half indicates the percentage of available test cases that pairs of models performed together (blackgreen colour scheme). The green colour scale increments in steps of 10%, the blue in steps of 2% (up to  $\delta_{m\leftrightarrow c} = 10\%$ ), and the red in steps of 10% (with a bright red colour indicating  $\delta_{m\leftrightarrow c} > 50\%$ ).



Figure 7. The inlaid panels show histograms of modelto-ensemble differences,  $\delta_m$  [%] for selected models participating in the discrete homogeneous (left panel) and discrete "floating spheres" (right panel) test cases. Included in the generation of these histograms are BRF simulations in the principal and orthogonal planes using illumination zenith angles of 20° and 50° in both the red and NIR spectral domain. The main panels show the envelope encompassing the various RAMI-3 (red colour) histograms—shown in the inlaid graphs—in relation to that obtained during RAMI-2 (black line) for the same set of test cases.



**Figure 8.**  $\chi^2$  statistics in the red (X-axis) and NIR (Y-axis) wavelengths for the structurally homogeneous (left panel) and the "floating spheres" (right panel) baseline scenarios with finite sized scatterers. Arrows indicate changes in the  $\chi^2$  values of models performing both in RAMI-2 (base of arrow) and in RAMI-3 (tip of arrow) using the latter  $\bar{\rho}_{3D}$  as reference.



**Figure 9.** Graphical representation of a portion of the RAMI-3 "birch stand" scene when looking from its southern edge in an northward direction towards the centre of the scene. The sun is assumed to be located behind the viewer, *i.e.*, "south" of the scene.



Figure 10. Model simulated BRFs in the red (left column) and NIR (right column) spectral domain of the "birch stand" along the principal (upper panels) and orthogonal (lower panels) planes under illumination conditions of  $\theta_i = 20^\circ$  and  $\theta_i = 50^\circ$ . Histograms of model-toensemble deviations  $\delta_m$  are provided for (all models but 5Scale in) both observational planes (central panels).



Figure 11. Model simulated local transmissions along transects composed of 21 adjacent  $1 \times 1 \text{ m}^2$  patches oriented parallel (left panels) and perpendicular (right panels) to the direction of the illumination azimuth ( $\phi_i$ ) in the red (top panels) and NIR (bottom panels) spectral domain. Pink arrows indicate obvious correlations with predominantly shadowed and illuminated patches in the various graphical representations of the transects (inlaid images featuring the transect as a sequence of white squares). Transmission values that are larger than unity fall within the grey shaded area.



Figure 12. Model simulated BRFs along the principal (top panels) and orthogonal (bottom panels) planes of the "true zoom-in" scene at spatial resolutions of 270 m (left), 90 m (middle) and 30 m (right). The illumination zenith angle was set to  $20^{\circ}$  and the spectral properties are typical for the NIR spectral domain.

Horizontal fluxes wrt. coordinate system



Total horizontal fluxes across voxel sides that are perpendicular to the X-axis



Total incident flux across the top of voxel



Total horizontal fluxes across voxel sides that are perpendicular to the Y-axis



Figure 13. Schematics of the various horizontal (and incident) total fluxes entering and exiting a voxel—here of  $30 \times 30 \times 15$  m lateral dimensions—via its lateral (and top) sides. Note that the X-axis is aligned with the azimuthal direction of the incident light.



Figure 14. Normalised horizontal fluxes entering (solid) and exiting (dashed) the lateral sides of voxels with spatial dimensions equal to 270 m (left), 90 m (middle) and 30 m (right) in the NIR spectral domain. The voxels are centered at the origin of the local coordinate system and have a height of 15 m. The illumination azimuth,  $\phi_i$  is parallel (perpendicular) to the voxel sides labeled Y<sub>LOW</sub> and Y<sub>HIGH</sub> (X<sub>LOW</sub> and X<sub>HIGH</sub>), and  $\theta_i = 20^\circ$ .



Figure 15. Model simulated BRFs in the principal (top 2 rows) and orthogonal (bottom 2 rows) viewing planes for the "conifer forest" scene with topography (left panels), without topography (middle panels), as well as, the difference between these two, respectively (right panels). Simulations pertain to the red (top and third row) and near-infrared (second and bottom row) spectral regimes at  $\theta_i = 40^{\circ}$ .



Figure 16. Model simulated BRFs for the "floating spheres" scene under conservative scattering conditions (purist corner). Results are shown in the principal (left columns) and orthogonal (right columns) observation planes for discrete (top row) and turbid medium (bottom row) foliage representations and two different illumination zenith angles ( $\theta_i$ ). The structure of the scenes is indicated in the inlaid images.



Figure 17. Model performance and participation during RAMI-3 for structurally homogeneous (top table) and heterogeneous (bottom table) discrete canopy representation. Model names are listed on the top of each table (one per column). The experiment identifier is provided to the left, the spectral regime to the right, of each table column. Light (dark) grey fields indicate incomplete (no) data submission. The green-yellow-red colour scheme represent the integrated model-to-ensemble difference,  $\bar{\delta}$  [%] obtained with respect to all models that have performed the complete set of prescribed total BRF simulations for any given experiment/spectral regime combination.