A benchmark for testing the accuracy and computational cost of shortwave top-of-atmosphere reflectance calculations in clear-sky aerosol-laden atmospheres

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Need of a SW benchmark

CAMS43 - WP3 aim : data assimilation of reflectance for aerosols

- Choose a model to perform 1D-Var reflectance assimilation in research mode
- Have to be **accurate** enough
- Have to be **fast** enough
- Performant under realistic aerosol-laden conditions

Requirements of RTM

- Short-wave
- Accuracy : close to model and observation accuracy
- Computing time : no larger than 10 times RTTOV infrared calculations (ie, about 1 ms per profile) in ECMWF/CAMS infrastructure
- Tangent linear and adjoint

CAMS: Copernicus Atmosphere Monitoring Service

Need of a SW benchmark

Benchmark design limitations

- Clear-sky
- Limited set of chosen surface and geometry
- Only direct mode (no adjoint, no tangent linear)
- No mixtures of aerosols
- One atmospheric vertical profile
- One aerosol vertical profile
- Plane-parallel
- Choice of reference model

Input data and definitions

Test with 4 models

Benchmark: 44080 cases

Wavelengths
470, 550, 660, 865, 1024 nm

Geometry
- Solar zenith angles :
  0, 20, 40 and 60 degrees
- Viewing zenith angles :
  0, 20, 40 and 60 degrees
- Azimuthal angles :
  0, 45, 90, 135, 180 degrees

Midlatitude summer atmospheric profile (49 layers)
- Molecular absorption and scattering optical depth
- Pressure, temperature, ...

Aerosol types Industrial scattering, Industrial absorbing, Dust, Sea salt
- Phase function (S_{11}, S_{12}, S_{33}, S_{34})
- Generalized spherical decomposition (Legendre moments)
- Single scattering albedo
- Extinction efficiency, size distribution parameters, refractive indexes ...

Aerosol optical depth (AOD,550 nm)
0,0.01, 0.05, 0.1, 0.2, 0.5, 1, 2
Aerosol profile exponential with 2 km height scale

Surface reflectance
- Lambertian reflectance : 0, 0.05, 0.1
- Cox-Munk BRDF (Mishchenko and Travis, 1997)

Models

DISORT (version 4)
* Discrete ordinary method
* Scalar
* Stamnes et al. (1988)
* 32 streams, TMS correction

6SV2 (version 2.1)
* Successive orders of scattering
* Vector
* Vermote et al. (1997); Kotchenova and Vermote (2007)
* Three elements approximation (I, Q, U)

VLIDORT (version 2.7)
* Discrete ordinary method
* *Scalar* and Vector
* Spurr (2008, 2014)
* 32 streams, TMS correction
* Output jacobians

FLOTSAM
* Forward-Lobe Two-Stream Radiance Model
* Two-stream + phase function decomposition
* Scalar
* Developed by Robin Hogan
* Output tangent linear and adjoint

Reference : VLIDORT - vector

Outputs and metrics

Reflectance

$$\rho_l = \frac{\pi \ I}{I_s \ \cos(\theta_s)}$$

CPU time (single-thread, exclude I/O)

- One call - one output
- One call - multiple output

Metrics

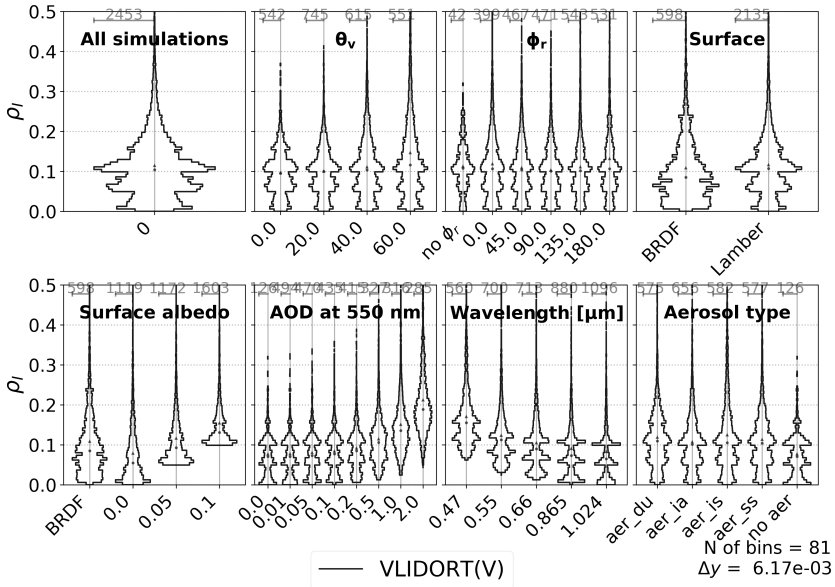
$$\text{Root Mean Square Error (RMSE)} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(m_i - r_i)^2}$$

$$\text{Mean Fractional Bias (MFB)} = \frac{2}{N}\sum_{i=1}^{N}\frac{m_i - r_i}{m_i + r_i}$$

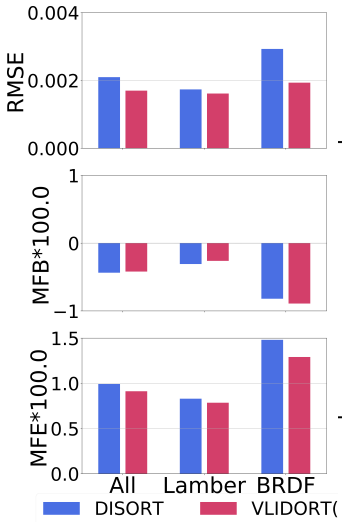
$$\text{Mean Fractional Error (MFE)} = \frac{2}{N}\sum_{i=1}^{N}\left|\frac{m_i - r_i}{m_i + r_i}\right|$$

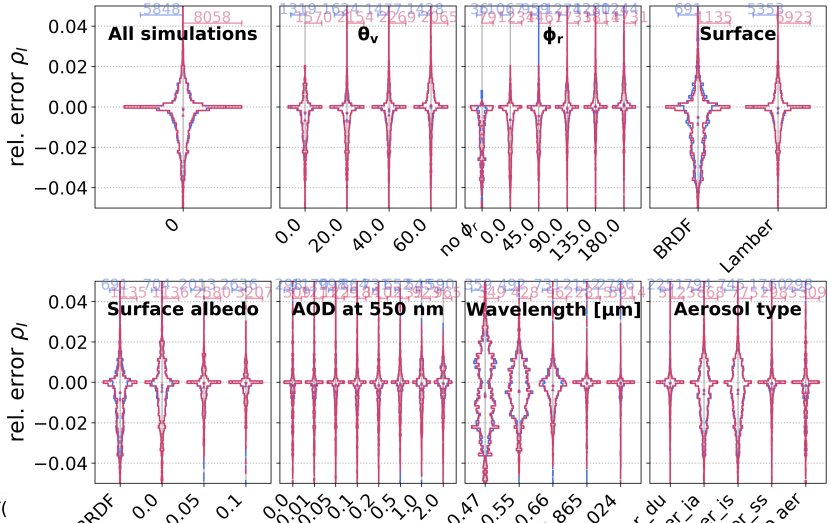
m_i : model ; r_i : model reference

Results : VLIDORT reflectances

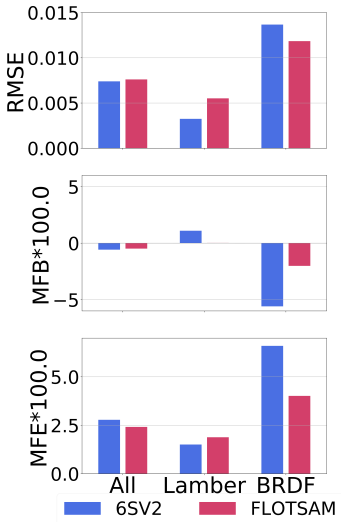


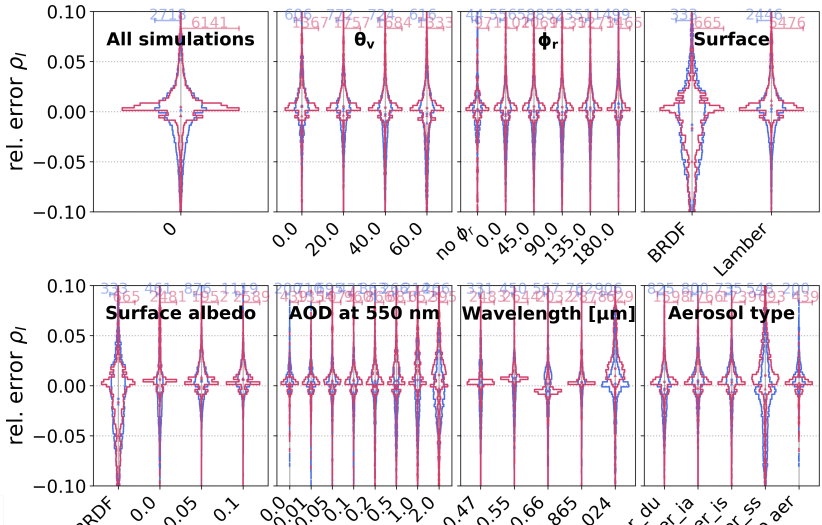
Results : Scalar VLIDORT and DISORT relative errors



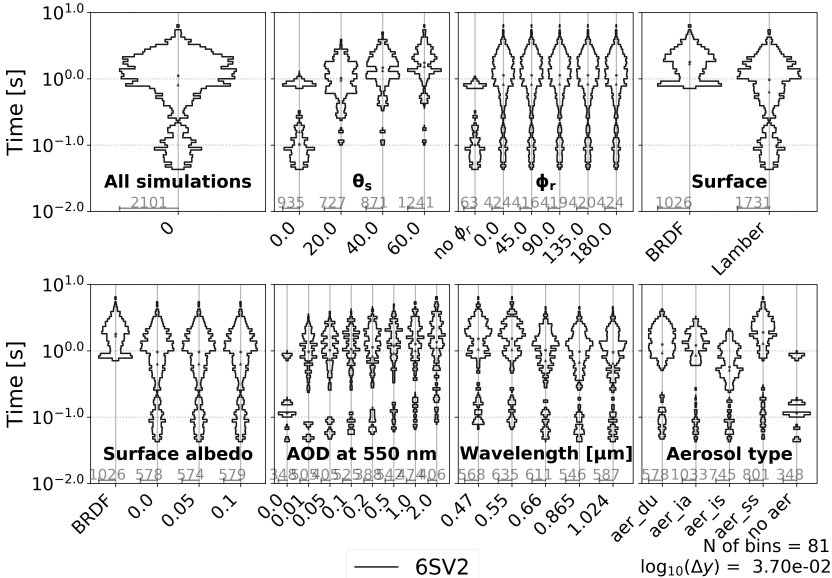


Results : FLOTSAM and 6SV2 relative errors





Results : 6SV timing



Results : Time comparison [s]

		FLOTSAM	6SV2	DISORT
one-off set-up	Lambertian	2.87×10^{-5} (1.99×10^{-6})		
	BRDF	2.76 (5.28×10^{-3})		
ind	Lambertian	3.05×10^{-4} (1.84×10^{-6})	1.06 (0.87)	0.22 (0.18)
	BRDF	3.70×10^{-4} (1.49×10^{-5})	1.90 (0.95)	0.99 (0.18)
mult	Lambertian	9.90×10^{-2} (6.23×10^{-4})		0.29 (0.16)
	BRDF	9.96×10^{-2} (5.63×10^{-4})		1.21 (0.16)

FLOTSAM *mult* = 640 profiles ($0.1/640 \approx 0.15$ [ms])
6SV2 *mult* = 1 profile
DISORT *mult* = 20 profiles ($0.5/20 \approx 25$ [ms])

Summary

- Benchmark has been designed for atmosphere with aerosols
- Target accuracy and computing time
- Tested with 4 models : VLIDORT, DISORT, FLOTSAM and 6SV2
- Errors in accuracy (against VLIDORT(V)) :
  - Lambertian MFE : 0.8, 1.5, 1.9 %
  - BRDF Cox-Munk MFE : 1.5, 6.6, 4 %
  - Spectral dependant (polarisation)
  - Aerosol optical depth dependant
  - Aerosol type dependant
- Computing time :
  - From seconds to less than milliseconds
  - Setup, single profile or multiple profile computations
  - Surface type dependence

Benchmark input data and VLIDORT(V) outputs are available at `https://doi.org/10.5194/gmd-12-805-2019`

Thank you!

Questions?

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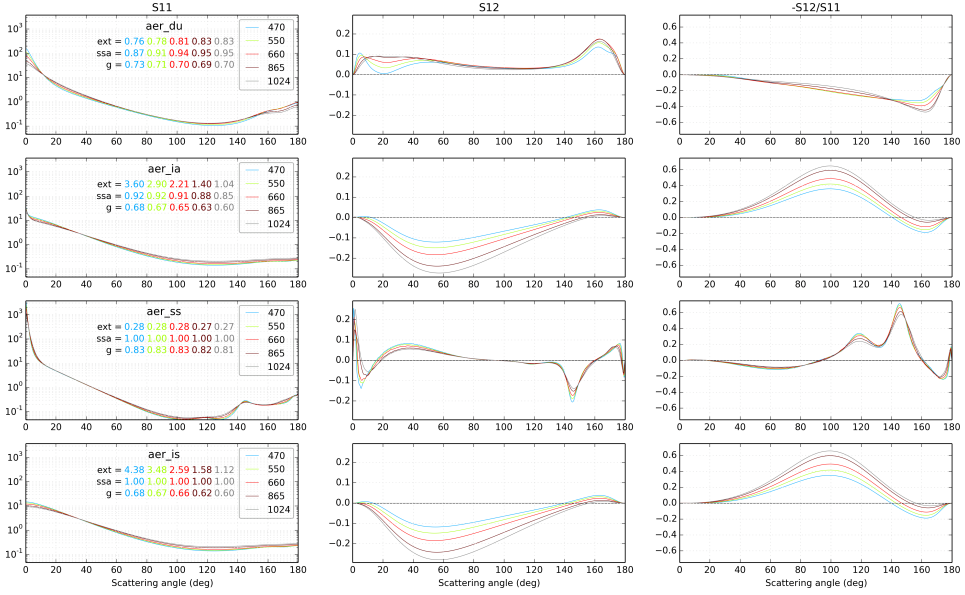
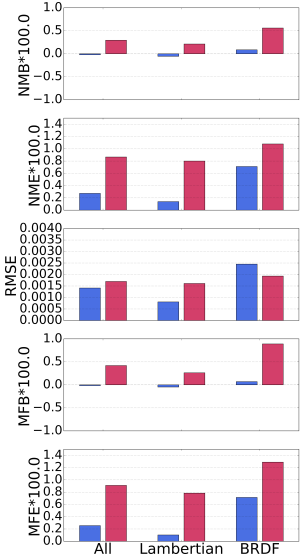
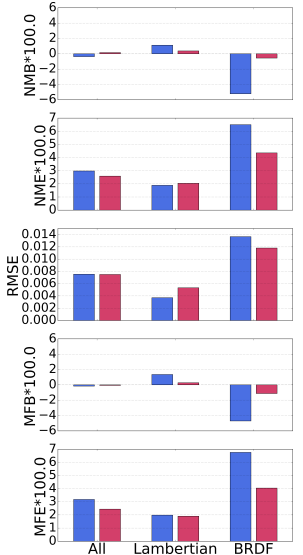
Extra slides

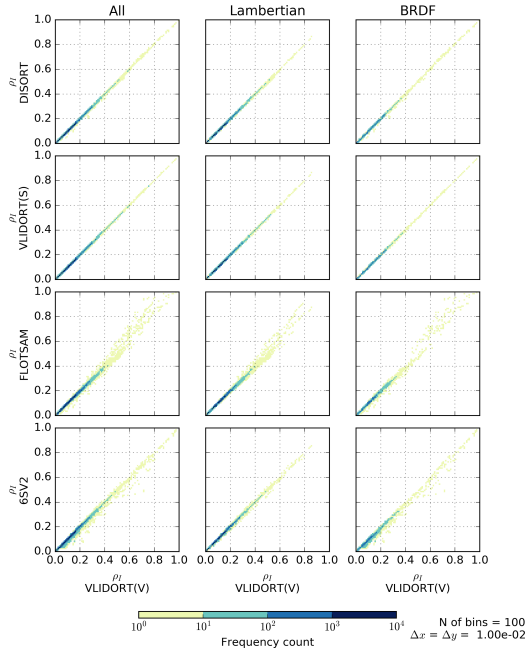
Aerosol types



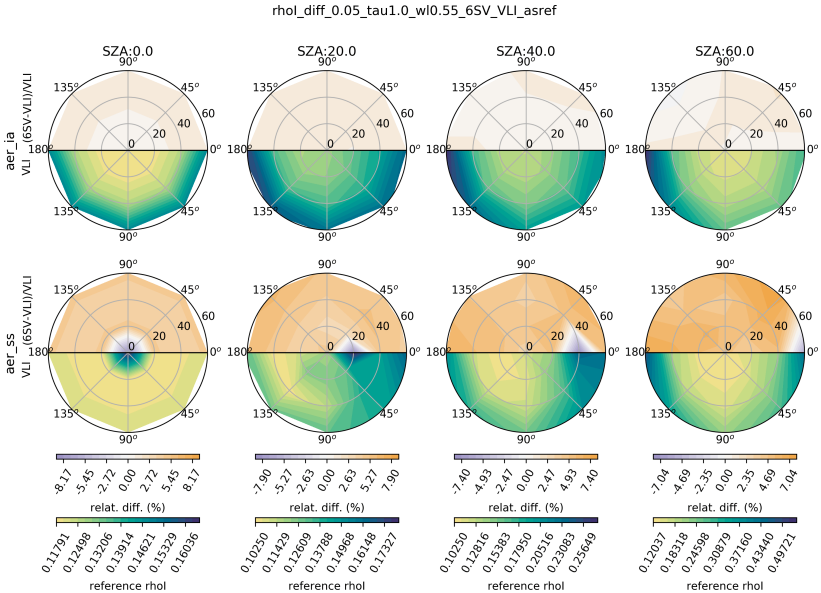
Metrics against VLIDORT(S)



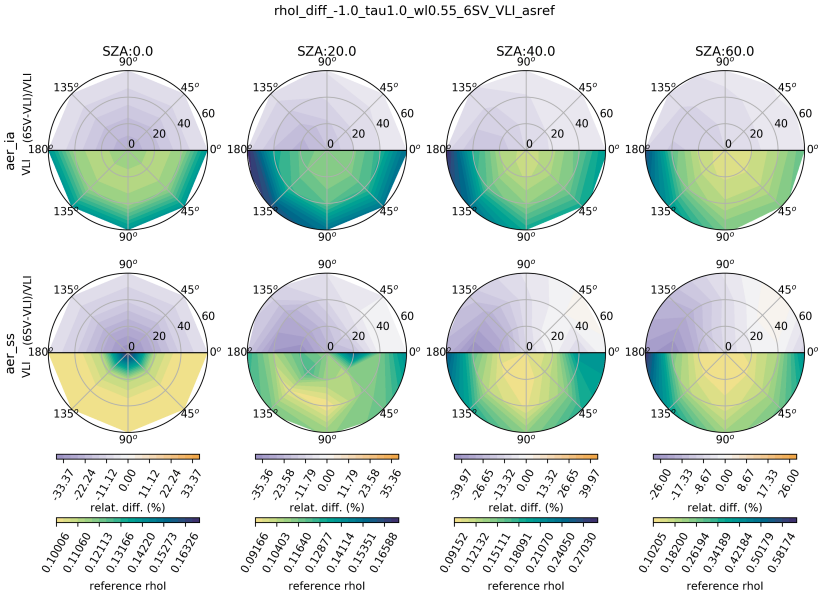



All
Lambertian
BRDF
ρ_l DISORT
ρ_l VLIDORT(S)
ρ_l FLOTSAM
ρ_l 6SV2
ρ_l VLIDORT(V)
ρ_l VLIDORT(V)
ρ_l VLIDORT(V)
0.0 0.2 0.4 0.6 0.8 1.0
10^0 10^1 10^2 10^3 10^4
Frequency count
N of bins = 100
$\Delta x = \Delta y =$ 1.00e-02

6SV2 - VLIDORT (V) , AOD=1 , 550 nm , Lambertian 0.05 , ind. abs. and sea salt



6SV2 - VLIDORT (V) , AOD=1 , 550 nm , CM BRDF, ind. abs. and sea salt



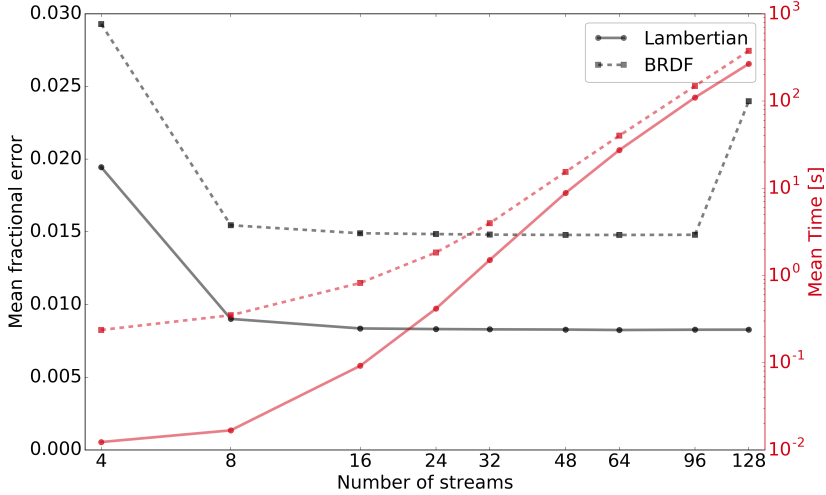
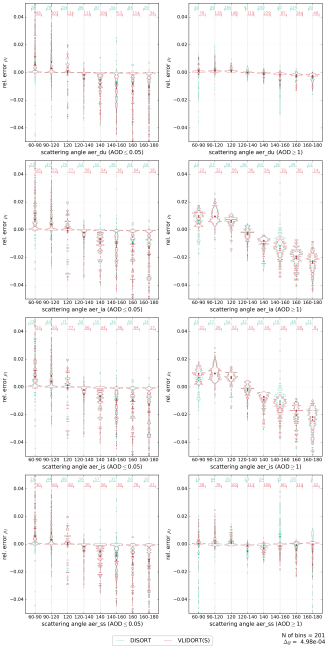
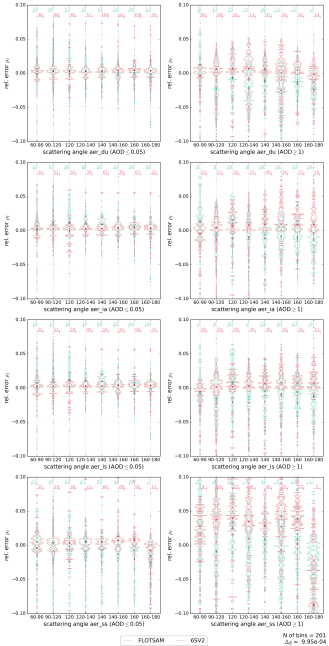


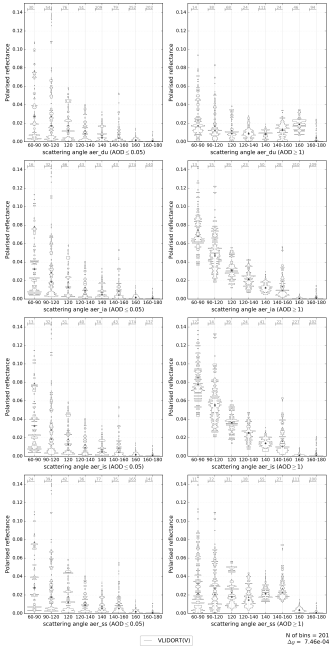
Figure: Accuracy (in black) and computing times (in red) for the DISORT model as a function of the number of streams used. The Lambertian and oceanic BRDF surface cases are shown with solid and dashed lines, respectively. The accuracy is shown in terms of Mean Fractional Error against VLIDORT (vector). The computing times are an average for 20 geometries and were estimated on a processor AMD Opteron 6378, 2.4 GHz.

	All		BRDF		Lambertian	
	DISORT	VLIDORT (scalar)	DISORT	VLIDORT (scalar)	DISORT	VLIDORT (scalar)
Reference (VLIDORT vector) Mean	0.114		0.108		0.116	
Model Mean	0.114	0.114	0.108	0.108	0.116	0.116
RMSE	0.002	0.002	0.003	0.002	0.002	0.002
Mean Fractional Bias (%)	–0.44	–0.42	–0.82	–0.89	–0.31	–0.26
Mean Fractional Error (%)	0.99	0.91	1.48	1.29	0.83	0.78
N	44,080	44,080	11,020	11,020	33,060	33,060
% of exps. with errors $> 0.5\%$	55.09	51.34	68.43	61.79	50.64	47.86
% of exps. with errors $> 1\%$	35.27	34.47	48.97	47.71	30.70	30.05
% of exps. with errors $> 2\%$	14.63	14.71	25.95	27.04	10.85	10.60
% of exps. with errors $> 2.5\%$	9.09	9.08	17.18	18.12	6.39	6.07
% of exps. with errors $> 5\%$	0.77	0.28	2.18	0.60	0.30	0.17
% of exps. with errors $> 7.5\%$	0.29	0.00	0.97	0.00	0.07	0.00
% of exps. with errors $> 10\%$	0.18	0.00	0.68	0.00	0.02	0.00

	All		BRDF		Lambertian	
	6SV2	FLOTSAM	6SV2	FLOTSAM	6SV2	FLOTSAM
Reference (VLIDORT vector) Mean	0.114		0.108		0.116	
Model Mean	0.114	0.114	0.102	0.107	0.117	0.116
RMSE	0.007	0.008	0.014	0.012	0.003	0.006
Mean Fractional Bias (%)	–0.58	–0.49	–5.60	–2.01	1.09	0.02
Mean Fractional Error (%)	2.78	2.41	6.60	4.01	1.51	1.88
N	44,080	44,080	11,020	11,020	33,060	33,060
% of exps. with errors $> 0.5\%$	71.30	80.21	82.56	89.86	67.54	77.00
% of exps. with errors $> 1\%$	45.84	63.70	71.08	79.76	37.42	58.35
% of exps. with errors $> 2\%$	30.04	39.91	54.44	61.91	21.91	32.58
% of exps. with errors $> 2.5\%$	25.04	32.02	48.57	53.80	17.20	24.76
% of exps. with errors $> 5\%$	14.01	11.89	34.50	26.05	7.18	7.17
% of exps. with errors $> 7.5\%$	8.25	4.70	26.00	11.59	2.34	2.40
% of exps. with errors $> 10\%$	5.63	1.97	20.20	5.56	0.77	0.77


rel. error ρ_1
scattering angle aer_du (AOD ≤ 0.05)
rel. error ρ_1
scattering angle aer_du (AOD ≥ 1)
rel. error ρ_1
scattering angle aer_la (AOD ≤ 0.05)
rel. error ρ_1
scattering angle aer_la (AOD ≥ 1)
rel. error ρ_1
scattering angle aer_ss (AOD ≤ 0.05)
rel. error ρ_1
scattering angle aer_ss (AOD ≥ 1)
rel. error ρ_1
scattering angle aer_ss (AOD ≤ 0.05)
rel. error ρ_1
scattering angle aer_ss (AOD ≥ 1)
DISORT
VLIDORT(S)
N of bins = 201
$\Delta\mu$ = 4.98e-04


rel. error ρ_c
scattering angle aer_du (AOD ≤ 0.05)
scattering angle aer_du (AOD > 1)
rel. error ρ_f
scattering angle aer_la (AOD ≤ 0.05)
scattering angle aer_la (AOD > 1)
rel. error ρ_s
scattering angle aer_ss (AOD ≤ 0.05)
scattering angle aer_ss (AOD > 1)
FLOTSAM
6SV2
N of bins = 201
Δρ = 9.95e-04


Polarised reflectance
scattering angle aer_du (AOD ≤ 0.05)
scattering angle aer_du (AOD ≥ 1)
scattering angle aer_ia (AOD ≤ 0.05)
scattering angle aer_ia (AOD ≥ 1)
scattering angle aer_is (AOD ≤ 0.05)
scattering angle aer_is (AOD ≥ 1)
scattering angle aer_ss (AOD ≤ 0.05)
scattering angle aer_ss (AOD ≥ 1)
VLIDORT(V)
N of bins = 201
Δy = 7.46e-04