Validation of a “Universal” Particulate Scattering Phase Function with Measurements and Simulation of Upwelling Hemispherical Radiance Distributions

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Abstract

Predicting the angular variation of the water leaving radiance (BRDF) for ocean color remote sensing requires knowledge of the inherent optical properties of the water, in particular the absorption coefficient (*a*) and volume scattering function (VSF). Remote sensing can be used to estimate both *a* and the total backscattering coefficient, b_b. Variable particulate constituents leads to large variability in space and time of the VSF, especially in coastal (case 2) waters. Sullivan and Twardowski (2009), however, found remarkable consistency in the shape of the backward portion of VSFs measured in situ around the world. This is a promising development, because a “universal” particulate scattering phase function would simplify radiative transfer modeling in coastal waters. In particular combining this phase function with *a* and b_b from the remote sensing signal would enable the BRDF to be determined. The purpose of this work was to test the applicability of the Sullivan-Twardowski phase function over a range of inherent optical properties. We parameterized a monte carlo radiative transfer model with measured inherent optical properties (a_{pg} and b_{bp}) and the Sullivan- Twardowski phase function then compared the model output with measured hemispherical upwelling radiance distributions.

Initial tests used data collected in 2004 during the BIOSOPE cruise, which included both clear, oligotrophic water in the central South Pacific Gyre and moderately eutrophic conditions associated with upwelling off the Chilean coast. The BIOSOPE dataset spanned a range of a_{pg} from 0.01 to 0.16 m^{-1}, b_p from 0.07 to 0.38 m^{-1}, and solar zenith angles from 8 to 58 degrees. The average daily difference of upwelling radiance (normalized to the nadir value in each case) between model predictions and measured data was on the order of 3% using the Sullivan and Twardowski phase function, which is larger than the < 1% difference between the data and the Morel et al. (2002) bidirectional model (Voss et al. 2007) but still within the environmental noise of the measurements for most days.

The data presented here are from a cruise conducted in the Ligurian Sea during October 2008. In this dataset a_{pg} varied from 0.02 to 0.14 m^{-1}, b_p from 0.10 to 0.32 m^{-1}, and solar zenith angles from 54 to 79 degrees. The average daily difference of upwelling radiance (normalized to the nadir value in each case) between model predictions and measured data was larger than observed in the BIOSOPE dataset. In general, the Morel LUT performed best at low Chl levels, but the model using the Sullivan-Twardowski phase function matched the data as well or better than the Morel LUT at higher Chl levels. All of the models matched the data better in the blue (412, 436, 488 nm) than in the green (526 nm).

Method

The approach was to compare measured hemispherical upwelling radiance distributions with model simulations using three different volume scattering functions and two different radiative transfer codes (summarized as A-D in box to the right). Calculations using the Sullivan and Twardowski (2009) VSF and Petzold’s turbid water VSF were conducted using inherent water optical properties measured by ac-9 and ecobb-3 instruments. Measured values of total Chlorophyll (Chl) and solar zenith angle were used to interpolate the Morel et al. (2002) look up tables. The NuRADS instrument (Voss and Chapin, 2005) was used to acquire the measured hemispherical upwelling radiance distributions.

The IOPs and Chl were measured using vertical profiling casts and depth-weighted by $e^{-(a+b_b) * \text{depth}}$ in order to compute average values over the water column as input to the RTE. The NuRADS images were averaged both in time, by grouping 10 minute blocks (4 or 5 individual images), and in space, by exploiting the symmetry of the images about the principal plane.

Planar slices at different azimuths provide qualitative assessment of the agreement among the four datasets (see model-data slices, below). Quantitative comparison between the modeled and measured radiance distributions (see model-data summary, below) was performed by computing the model-data difference at every 5 degrees in nadir from 5 to 45 degrees and every 15 degrees in azimuth from 0 to 180 degrees. After omitting points within the instrument shadow, the average and standard deviation of the model-data difference for all NuRADS images at a given Chl value was computed.

Four Hemispherical Upwelling Radiance Distribution Datasets

A) Modeled with Sullivan - Twardowski VSF

IOP (*a* and b_b) + VSF (Sullivan and Twardowski, 2009) + RTE (Gordon) ⟶ Modeled Upwelling Radiance Distribution

B) Modeled with Petzold VSF

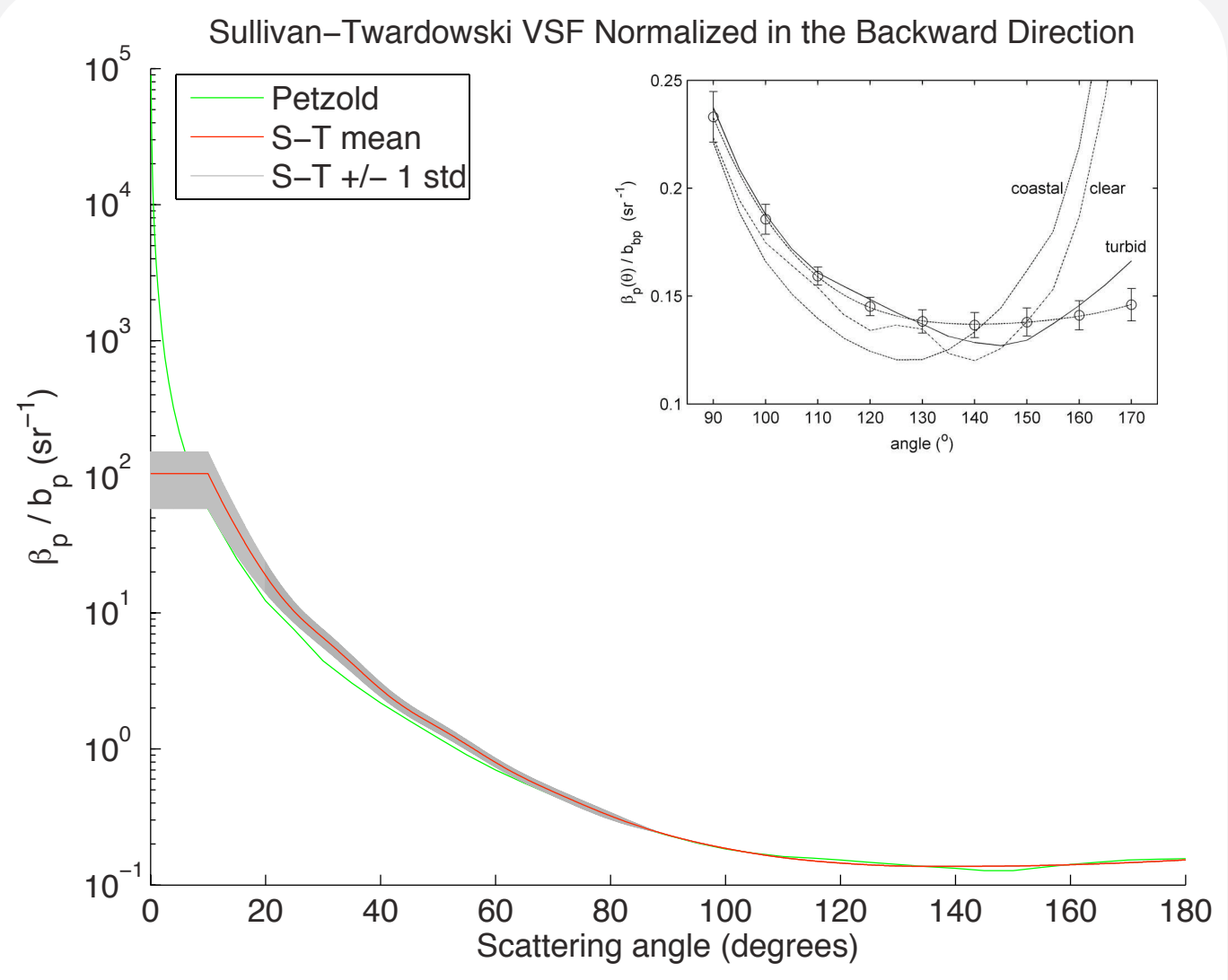
IOP (*a* and *b*) + VSF (Petzold) + RTE (Gordon) ⟶ Modeled Upwelling Radiance Distribution

C) Modeled with Morel VSF

Chl (measured) + VSF (Morel et al, 2002) + RTE (Morel) ⟶ Modeled Upwelling Radiance Distribution

D) Measured

NuRADS Instrument (Voss and Chapin, 2005) ⟶ Measured Upwelling Radiance Distribution



The S-T phase function is normalized to b_b, so integrates to 1 in the backward direction and some number > 1 in total. The key point is that b_b / b needs to be right, so the procedure here is:

1) load the saved S-T phase function (that integrates to 1 in backwards)
2) multiply this by b_b to get VSF that is correct in backward direction
3) integrate the whole function to find out the corresponding value of b
4) normalize by b to create a phase function integrating to 1 over all angles

The above plot shows the mean Sullivan-Twardowski phase function (red) and its variability in the forward direction (+/- one standard deviation in gray) compared with the Petzold turbid water phase function (green). All have been normalized to 1 over the angles 90-180 degrees.

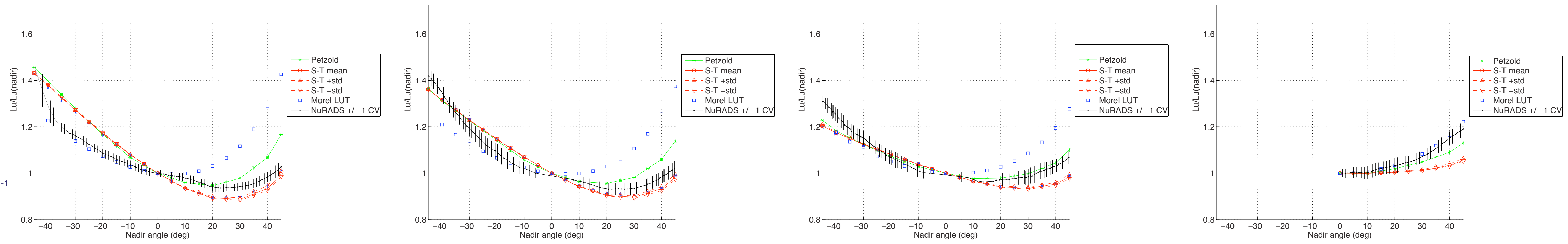
The inset shows a detailed version of this comparison for the backward direction only (reproduced from Sullivan and Twardowski, 2009). In the inset, the S-T phase function is plotted as open circles with +/- one standard deviation error bars. The Petzold turbid, coastal, and clear water phase functions are also plotted. All have been normalized to integrate to 1 over the angles 90-180 degrees.

Results

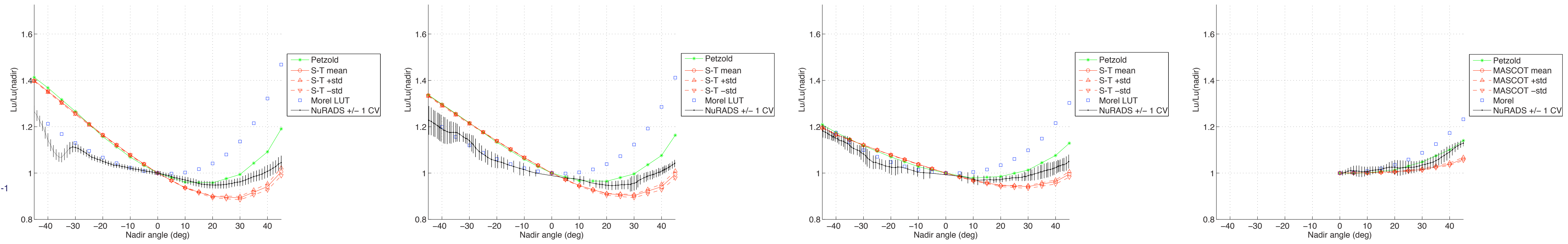
Model - Data Slices, Single Images from One Day

Principal Plane (Azimuth 0-180 degrees) | Azimuth 30-150 degrees | Azimuth 60-120 degrees | Perpendicular to Principal Plane (Azimuth = 90 degrees)

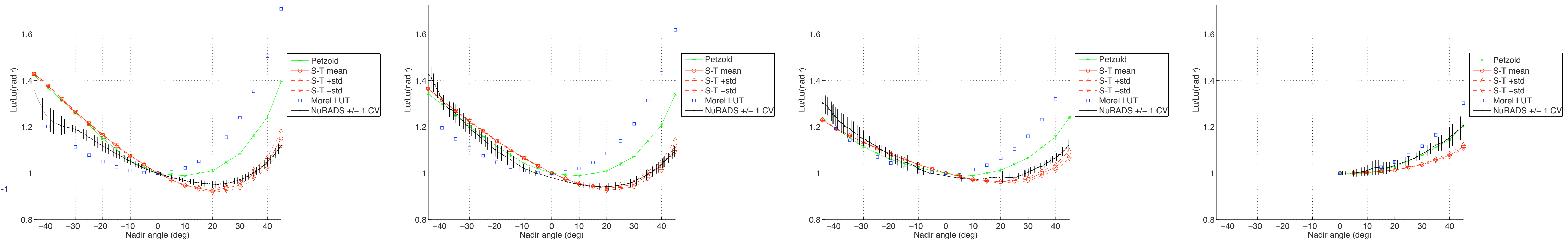
λ = 412 nm
θ_0 = 59.7 deg
a_p = 0.058 m^{-1}
a_w = 0.005 m^{-1}
b_p = 0.108 m^{-1}
b_w = 0.006 m^{-1}
ω_0 = 0.64
b_{bp} = 0.008
Chl = 1.21 μg l^{-1}



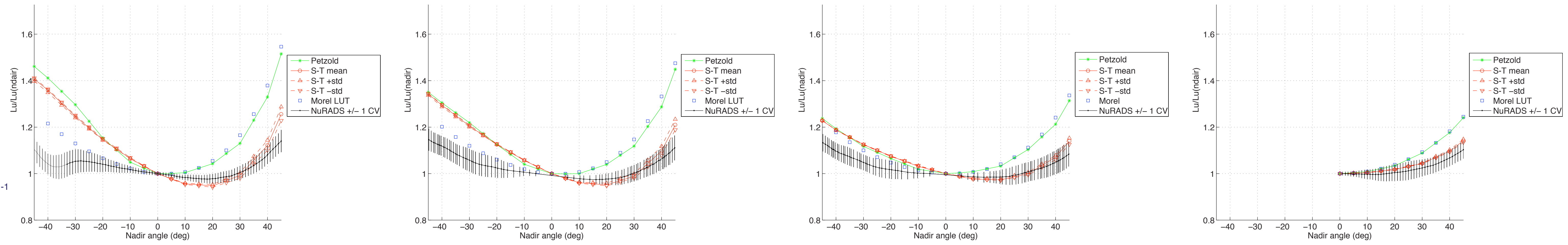
λ = 436 nm
θ_0 = 54.6 deg
a_p = 0.044 m^{-1}
a_w = 0.006 m^{-1}
b_p = 0.106 m^{-1}
b_w = 0.005 m^{-1}
ω_0 = 0.69
b_{bp} = 0.008
Chl = 1.19 μg l^{-1}



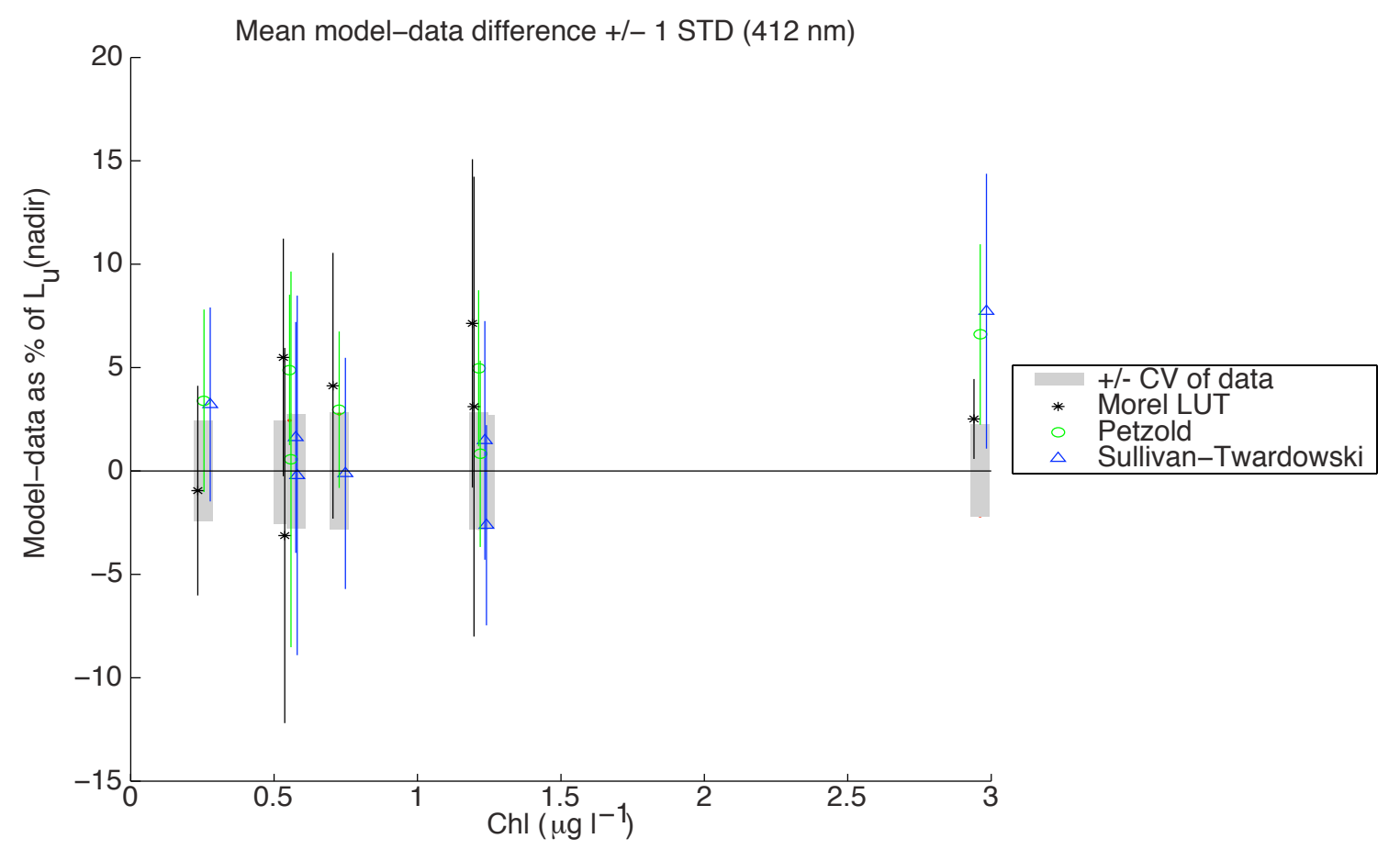
λ = 488 nm
θ_0 = 59.7 deg
a_p = 0.025 m^{-1}
a_w = 0.014 m^{-1}
b_p = 0.111 m^{-1}
b_w = 0.003 m^{-1}
ω_0 = 0.74
b_{bp} = 0.008
Chl = 1.22 μg l^{-1}

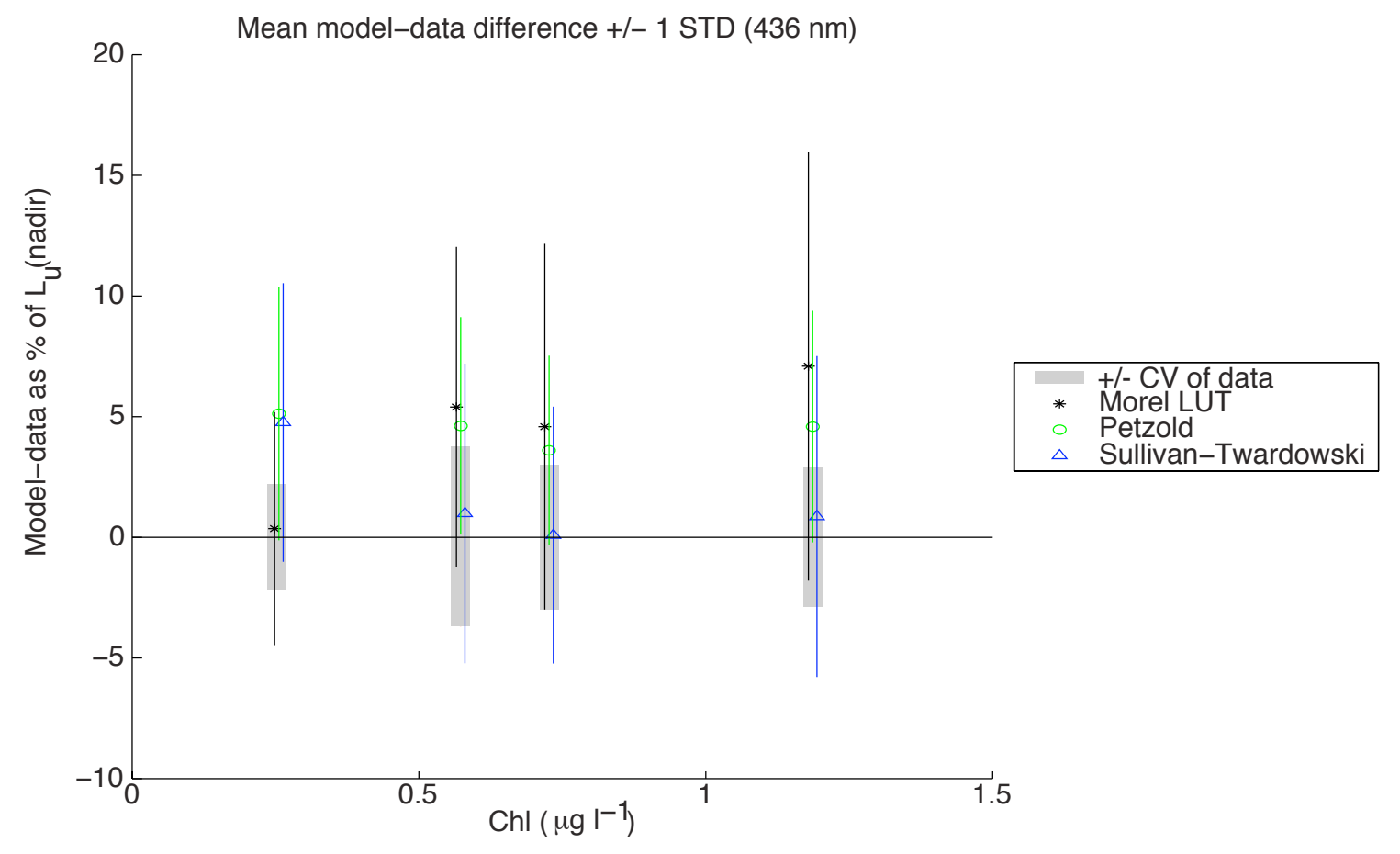


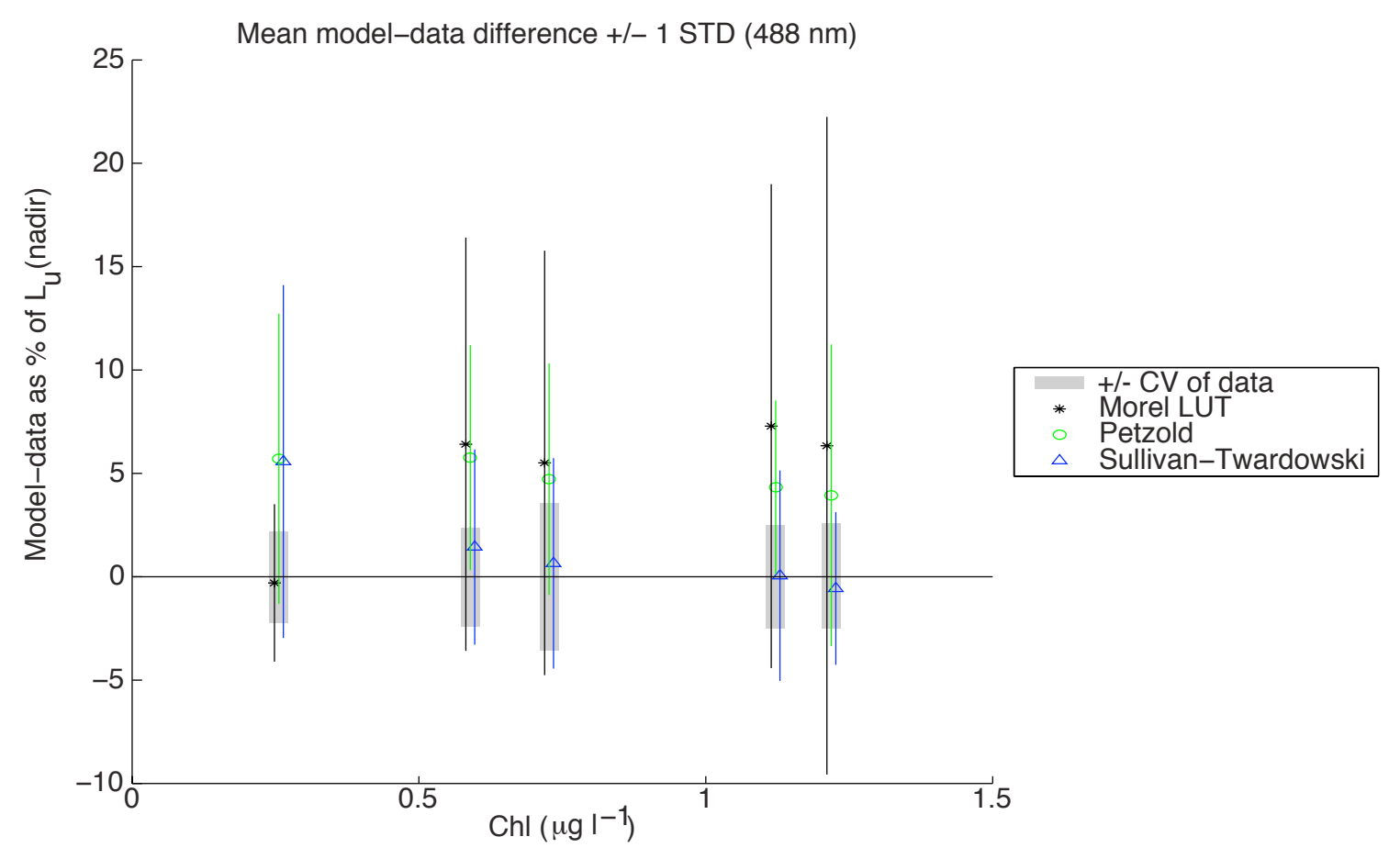
λ = 526 nm
θ_0 = 58.1 deg
a_p = 0.016 m^{-1}
a_w = 0.049 m^{-1}
b_p = 0.107 m^{-1}
b_w = 0.002 m^{-1}
ω_0 = 0.63
b_{bp} = 0.008
Chl = 1.22 μg l^{-1}

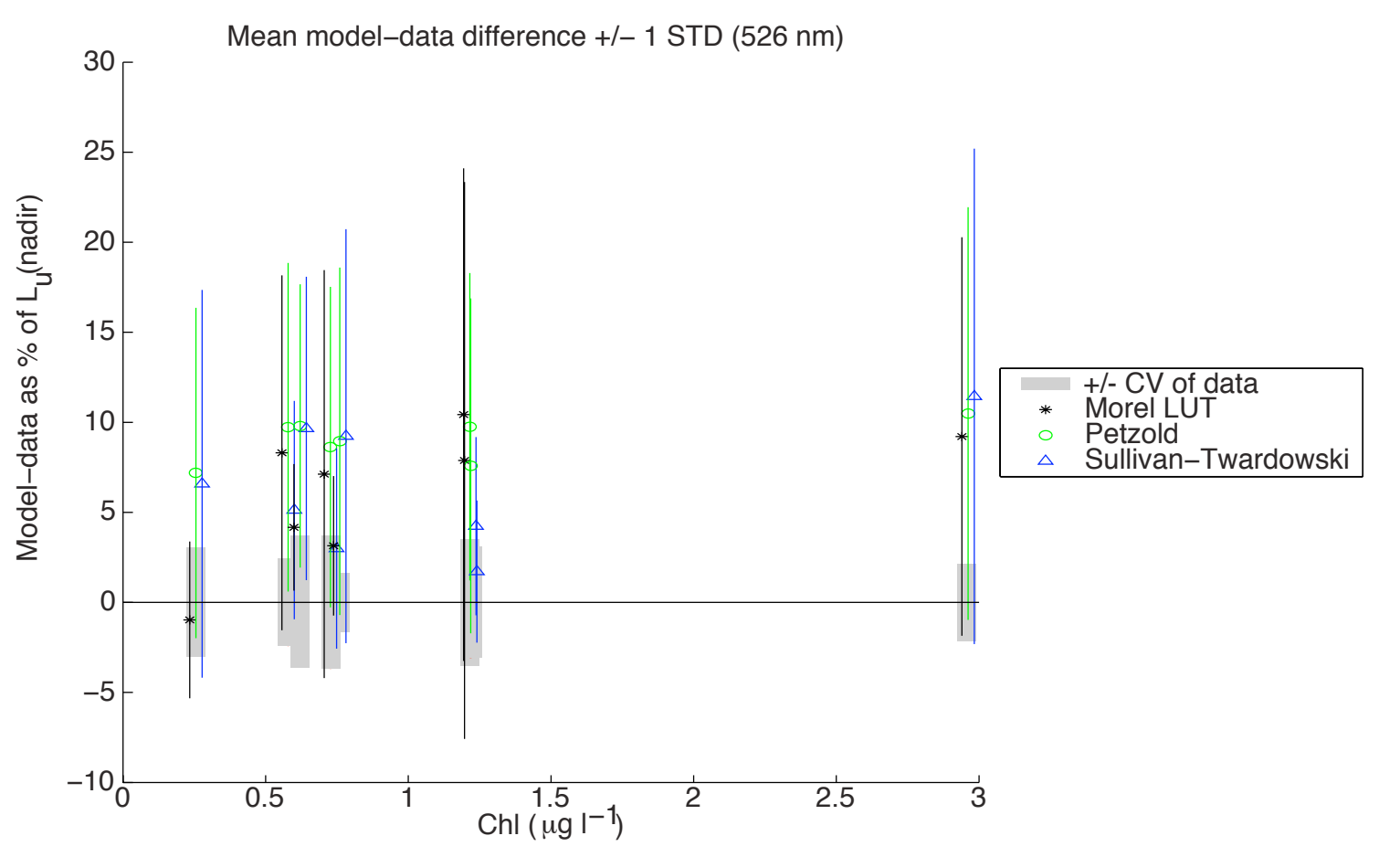


Model - Data Summary









Note: At any given Chl value, results with the Morel, Petzold, and Sullivan-Twardowski VSFs are offset slightly in the above plots to make the symbols easier to read. In reality, each set of those three symbols corresponds with one grey bar indicating the average coefficient of variation in the NuRADS data for a single Chl value.

References

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