



FRM4DRONES
fiducial reference
measurements
for water using
drones

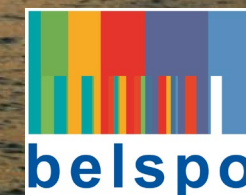


FRM4Drones-AQUA: Towards Fiducial Reference Measurements for UAV-Based Aquatic Reflectance – Community Insights and Roadmap Development

Sindy Sterckx, Liesbeth De Keukelaere (VITO)

Agnieszka Bialek, Morven Sinclair (NPL)

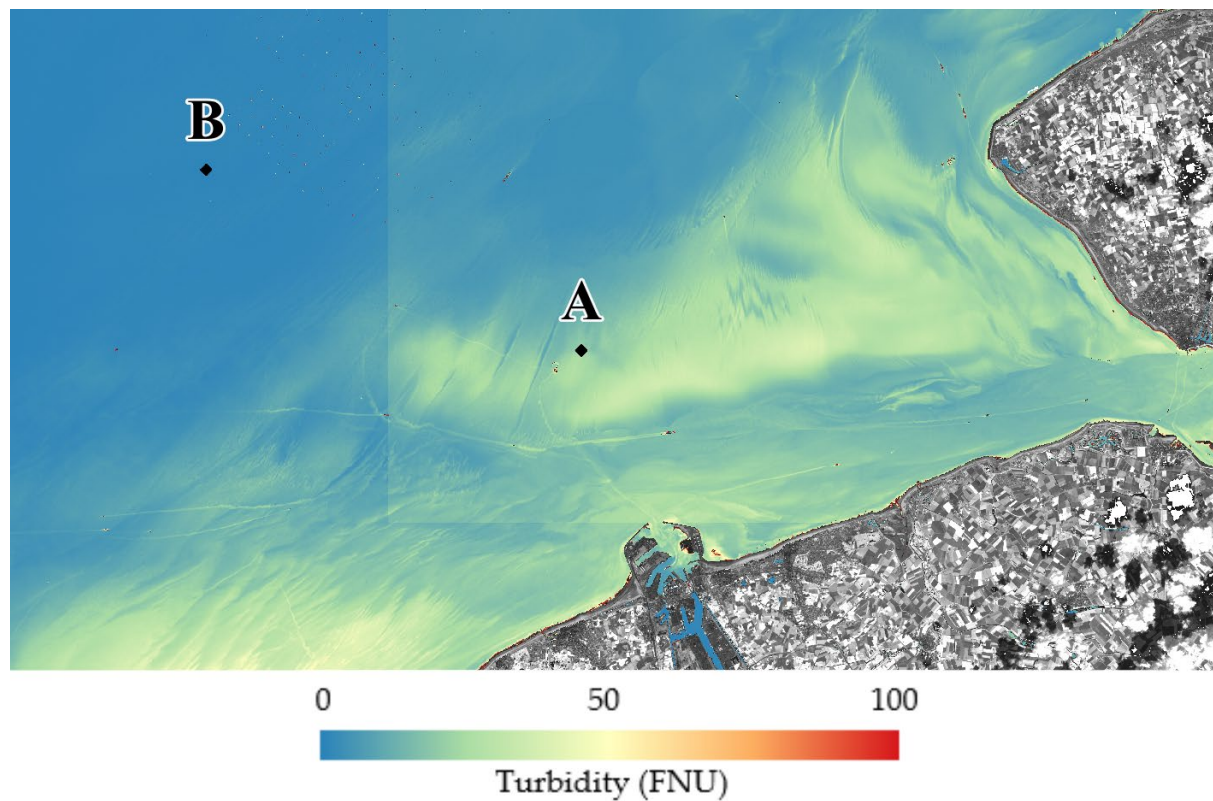
7th Sentinel-2 Validation Team meeting, 13-15 October 2025, ESA-ESRIN, Frascati





Why using drones for aquatic Cal/Val ?

Sentinel-2 10:59 UTC



“traditional” in-situ validation

	Tur (FNU) - A	Tur (FNU) - B
S2	19–21	1.5
In-situ	51.6 (40.7 – 58.6)	2.5



Article

Airborne Drones for Water Quality Mapping in Inland, Transitional and Coastal Waters—MapEO Water Data Processing and Validation

Liesbeth De Keukelaere ^{1,*}, Robrecht Moelans ¹, Els Knaeps ¹, Sindy Sterckx ¹, Ils Reusen ¹, Dominique De Munck ¹, Stefan G.H. Simis ², Adriana Maria Constantinescu ³, Albert Scricciu ³, Georgios Katsouras ⁴, Wim Mertens ⁵, Peter D. Hunter ⁶, Evangelos Spyarakos ⁶ and Andrew Tyler ⁶

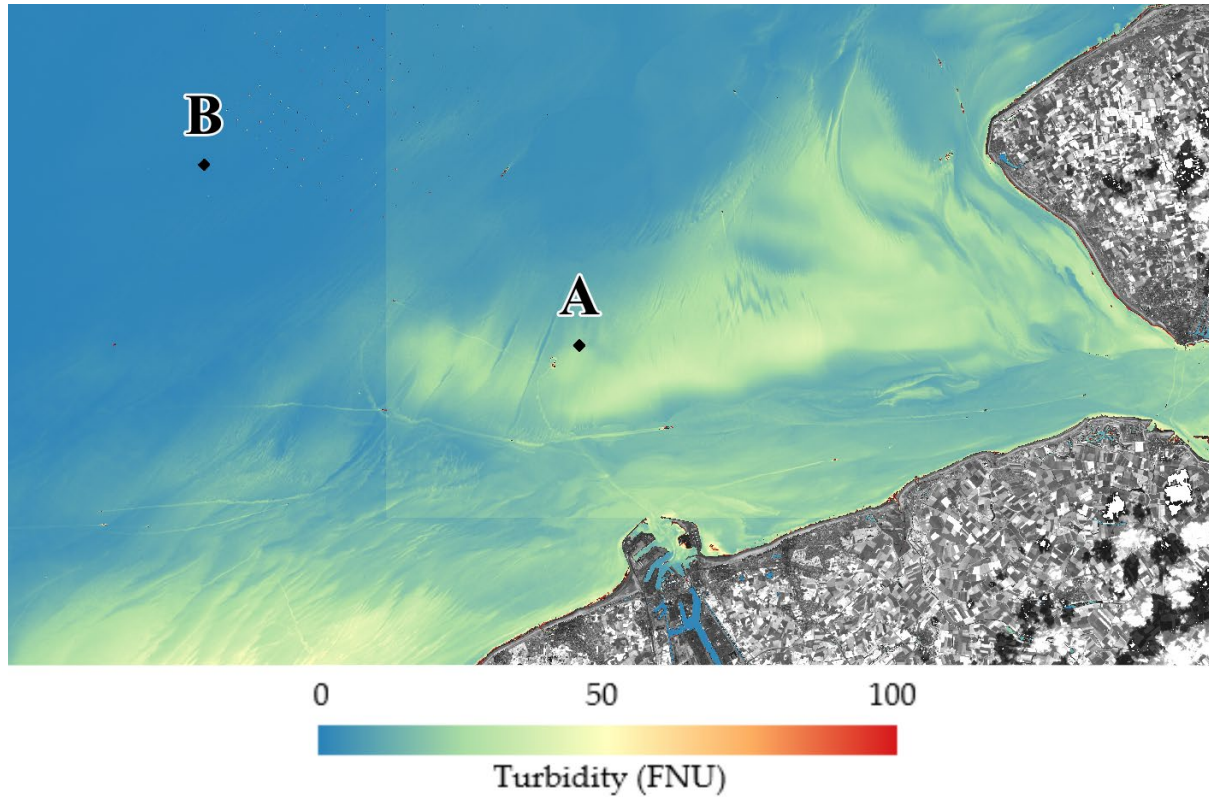
¹ Vlaamse Instelling Voor Technologisch Onderzoek (VITO), Boeretang 200, 2400 Mol, Belgium
² Plymouth Marine Laboratory (PML), Plymouth PL1 3DH, UK
³ Institutul National De Cercetare—Dezvoltare Pentru Geologie Si Geoecologie Marina (GeoEcoMar), 23–25 Dimitrie Onciul St., RO-024053 Bucharest, Romania
⁴ Athens Water Supply and Sewerage Company (EYDAP S.a.), Oropou 156, 11146 Athens, Greece
⁵ Instituut Natuur-En Bosonderzoek (INBO) Havenlaan 88 Bus 73, 1000 Brussel, Belgium
⁶ Earth and Planetary Observation Sciences (EPOS), Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling FK9 4LA, UK
 * Correspondence: liesbeth.dekeukelaere@vito.be



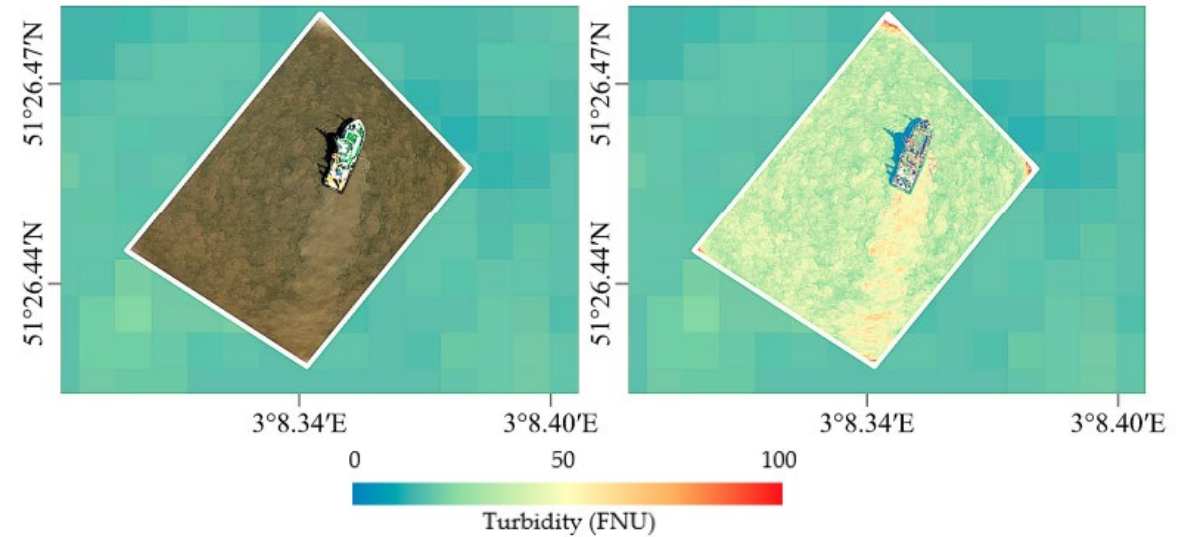


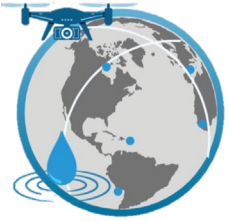
Why using drones for aquatic Cal/Val ?

Sentinel-2 10:59 UTC



“Drone” based validation

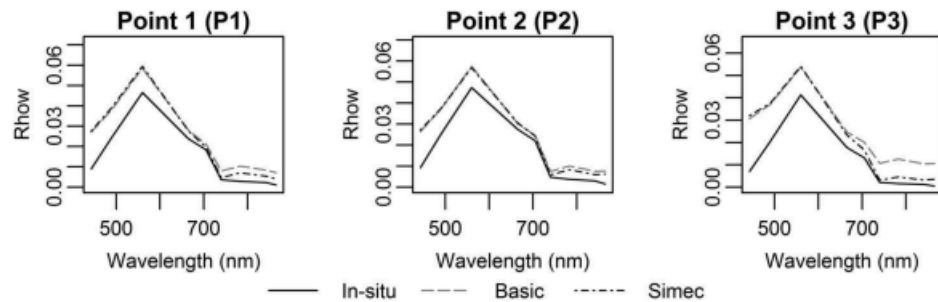
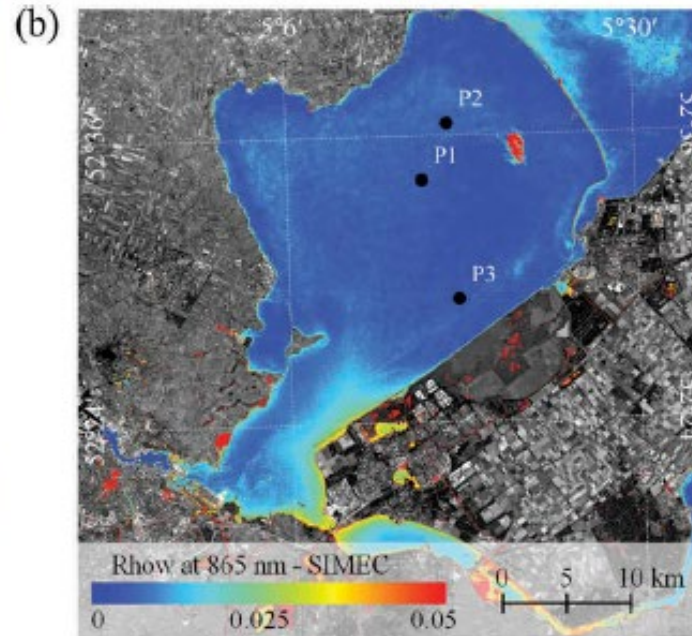
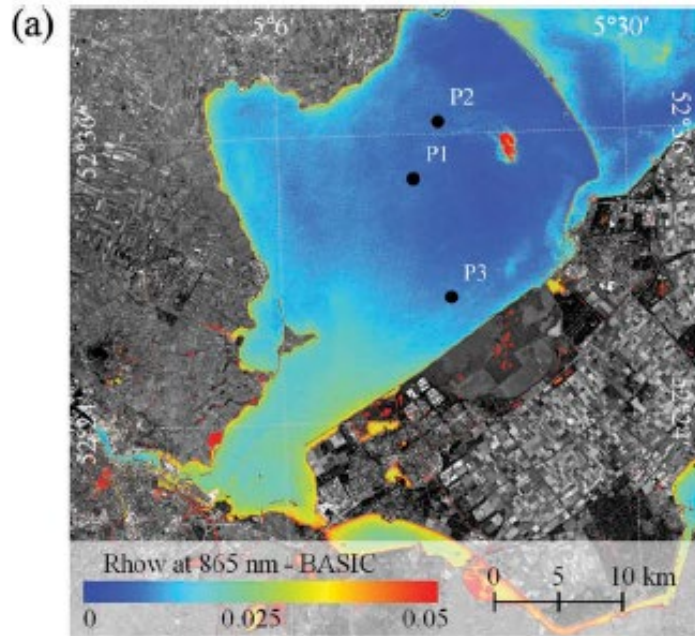




Why using drones for aquatic Cal/Val ?

Without adjacency correction

With adjacency correction
(SIMEC)



European Journal of Remote Sensing



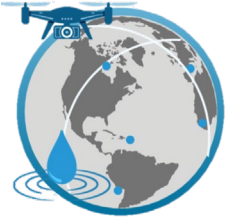
ISSN: (Print) 2279-7254 (Online) Journal homepage: <https://www.tandfonline.com/loi/tejr20>

Atmospheric correction of Landsat-8/OLI and Sentinel-2/MSI data using iCOR algorithm: validation for coastal and inland waters

L. De Keukelaere, S. Sterckx, S. Adriaensen, E. Knaeps, I. Reusen, C. Giardino, M. Bresciani, P. Hunter, C. Neil, D. Van der Zande & D. Vaiciute

To cite this article: L. De Keukelaere, S. Sterckx, S. Adriaensen, E. Knaeps, I. Reusen, C. Giardino, M. Bresciani, P. Hunter, C. Neil, D. Van der Zande & D. Vaiciute (2018) Atmospheric correction of Landsat-8/OLI and Sentinel-2/MSI data using iCOR algorithm: validation for coastal and inland waters, European Journal of Remote Sensing, 51:1, 525-542, DOI: 10.1080/22797254.2018.1457937

To link to this article: <https://doi.org/10.1080/22797254.2018.1457937>



Enhancing Satellite Cal/Val with Aerial Drones

Traditional in-situ Cal/Val

From ships, fixed stations (e.g., AERONET-OC, HYPERNET)

Limitations:

- Limited spatial coverage
- Representativeness issues for satellite pixel scale

Aerial Drones as a Complementary Solution:

- Assess the spatial & temporal variability surrounding fixed stations
 - ✓ Improves understanding of how representative point measurements are at satellite scale
- Aerial drones to conduct transects from the shoreline to the open sea
 - ✓ Supports validation of atmospheric correction algorithms (e.g., adjacency effects)



A holistic approach combining traditional in situ methods with drone observations improves the accuracy and reliability of satellite Cal/Val processes



Cal/Val reference data needs CEOS “FRM-label”

Cal/Val of satellite products requires high-quality in situ measurements, referred to as **Fiducial Reference Measurements (FRM)**.

Before a measurement can be labelled as FRM, it should:

- be accompanied by an **uncertainty** budget,
- adhere to openly available measurement **protocols and community-wide practices**
- have documented evidence of International **System of Units (SI) traceability**
- be **independent** of the satellite retrieval process.

Ruddick et al. (2019)
Goryl et al. (2023)



FRM4VEG



fiducial reference
measurements
for vegetation

FRM4Veg considerations



Transferable Concepts:

- Calibration transfer & traceability
- Uncertainty quantification (metrology-based)
- Flight planning & execution (to some extent)

Limitations:

- No reference panels on water
- Sun/sky glint requires new corrections
- No GCPs on water for georeferencing
- Water dynamics require precise timing with satellites

Good Practice Guidelines for UAV-based Surface Reflectance Validation

Authors: Origo, N., Kalacska, M., Arroyo-Mora, J.-P., Soffer, R., Smigaj, M., Brede, B., De Los Reyes, R., Koehler, C., Pflug, B., Niro, F., Sinclair, M., Ong, C., Lau, I., Byrne, G., Morris, H., Suomalainen, J., Kooistra, L., Brell, M., Randall, C., Latini, D., Wilk, J., Raqueno, N., Gerace, A., Dash, J., Camacho, F., Sanchez-Zapero, J., Martinez, E., Brown, L., Morrone, R., Mota, B., Gillespie, J., Memington, A., Van der Zee, J., Petracca, I., Thankappan, M., Ormane, R., Scholes, M., Honkavaara, E., Broomhall, M. & Boccia, V. – others to be included / order subject to change



Image credit: Johannes Wilk
Cover page design: Rasma Ormane





FRM4SOC



fiducial reference
measurements for
satellite ocean colour

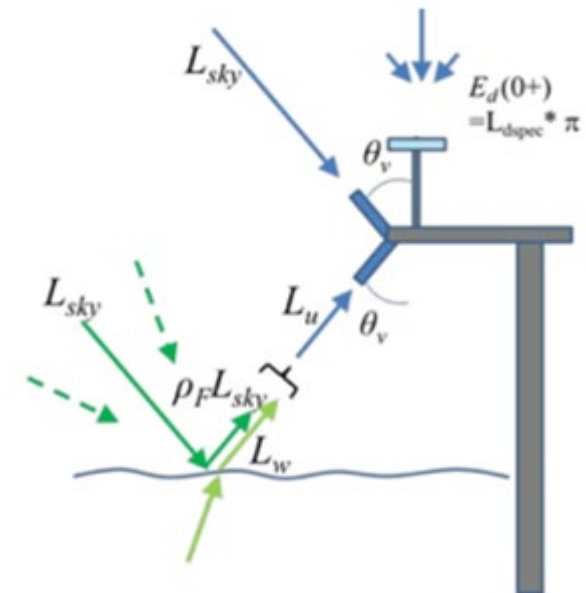
Transferable Concepts:

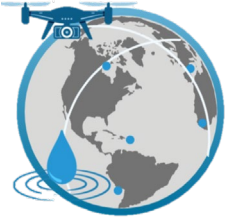
- Set of minimum requirements for qualifying ocean colour radiometers and their measurements as FRM

(Banks et al. 2020)

Limitations:

- Developed for field-based systems
- Assumes stable, fixed geometry and straightforward downwelling irradiance/sky radiance measurements
- Does not address UAV-specific challenges (e.g. dynamic platform, variable geometry, atmosphere)





FRM4drones - challenges



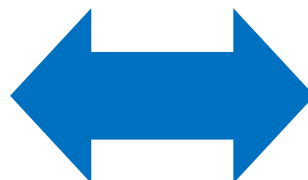


Aquatic reflectance

What we need :

The remote-sensing reflectance $R_{rs}(\theta, \phi, \lambda) = \frac{L_w(\theta, \phi, \lambda)}{E_d(\lambda)}$

The aquatic reflectance $R_w(\lambda) = \pi \cdot R_{rs}(\lambda) = \pi \cdot \frac{L_w(\lambda)}{E_d(\lambda)}$



What UAV measures :

$$L_T^{UAS}(\lambda) = L_{path}(\lambda) + t(\lambda)L_{SR}(\lambda) + t(\lambda)L_w(\lambda)$$

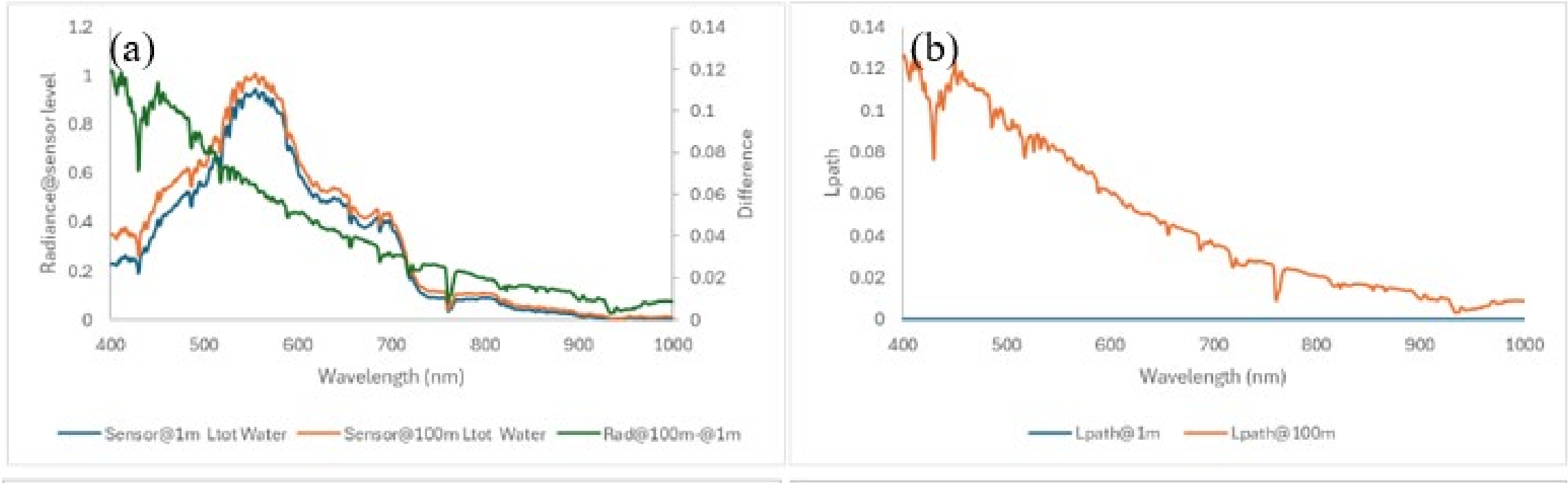
Atmosphere

Surface (sky glint, sun glint, white caps)

$$L_{SR}(\lambda) = L_{skyG}(\lambda) + L_{sunG}(\lambda) + L_{WF}(\lambda)$$



Atmospheric correction ?

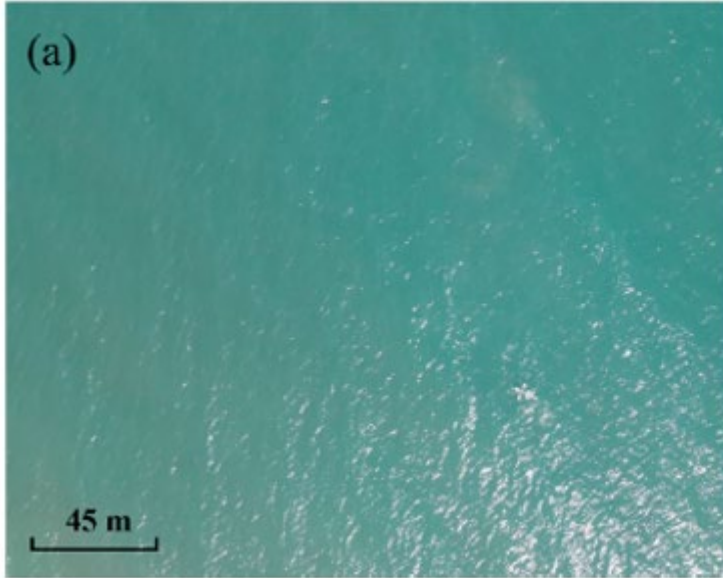


For moving toward FRM-level, the residual atmospheric effects—though small—should not be disregarded, and the associated uncertainty should be explicitly quantified and incorporated into the overall uncertainty budget of UAS-based reflectance measurements.

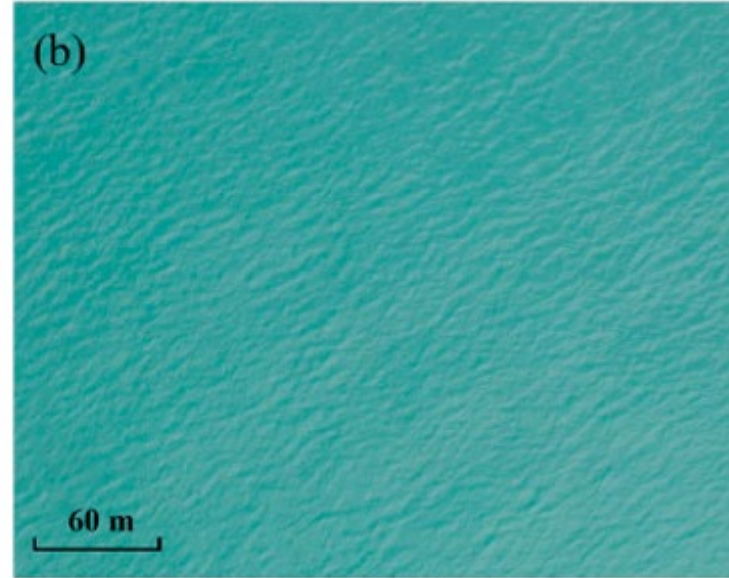


Sky & Sun glint corrections

$$L_{SR}(\lambda) = L_{skyG}(\lambda) + L_{sunG}(\lambda) + L_{WF}(\lambda)$$



Sun glint



Sky glint

(source: Lee et al., 2025)

- Sun glint:
 - Caused by direct sunlight reflecting off the water surface toward the sensor.
 - Highly dependent on sun-sensor geometry and water surface conditions.
 - Often appears as localized bright spots in images.
- Sky glint:
 - Originates from diffuse sky radiation reflecting off the sea surface.
 - Affects every pixel due to the hemispherical nature of skylight reflection.
 - Sky glint is unavoidable, while sun glint can be minimized by adjusting viewing geometry.



Sky glint corrections

The reflected diffuse sky radiance on individual wave facets may therefore be approximated as the product of the diffuse sky reflectance ρ_{sky} and the sky radiance $L_{sky}(\lambda)$:

$$L_{skyG}(\lambda) = \rho_{sky} L_{sky}(\lambda)$$

Above water measurements

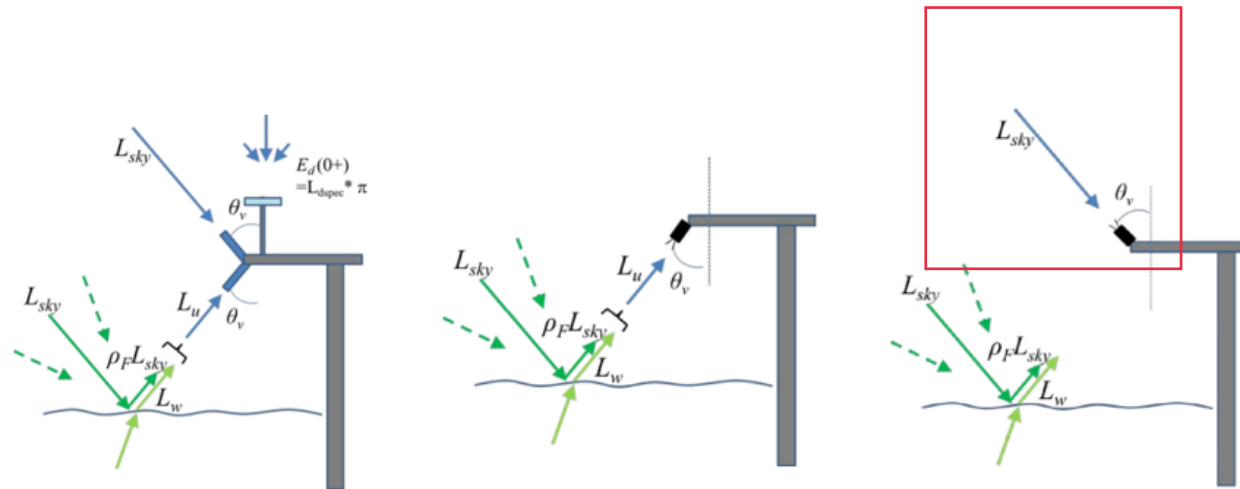


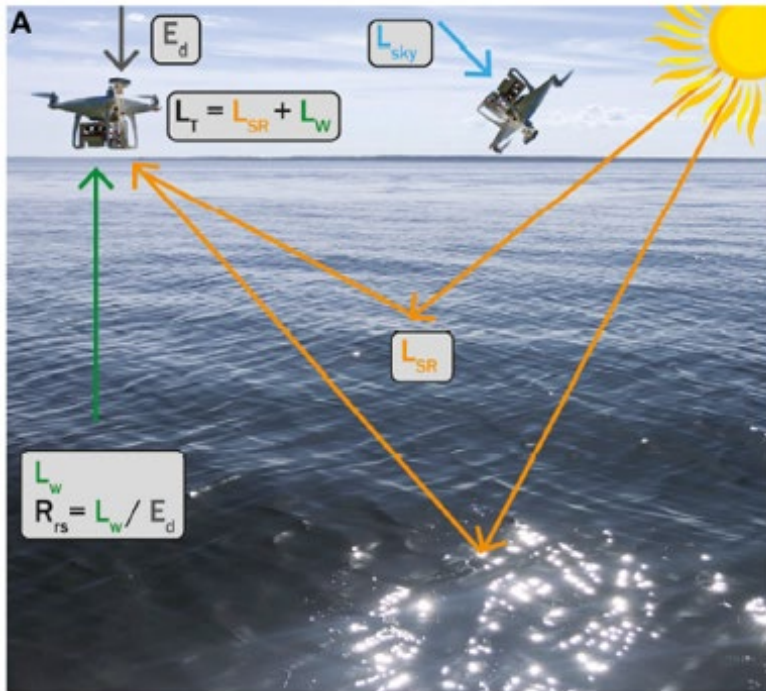
Figure 11 Above water measurements: E_d (left), L_T (center), L_{sky} (right) (Source: Knaeps et al., 2018 [66])



Sky glint corrections

$$L_{skyG}(\lambda) = \rho_{sky} L_{sky}(\lambda)$$

Measurement



Source: Windle and Silbse (2021)

Radiative Transfer modelling

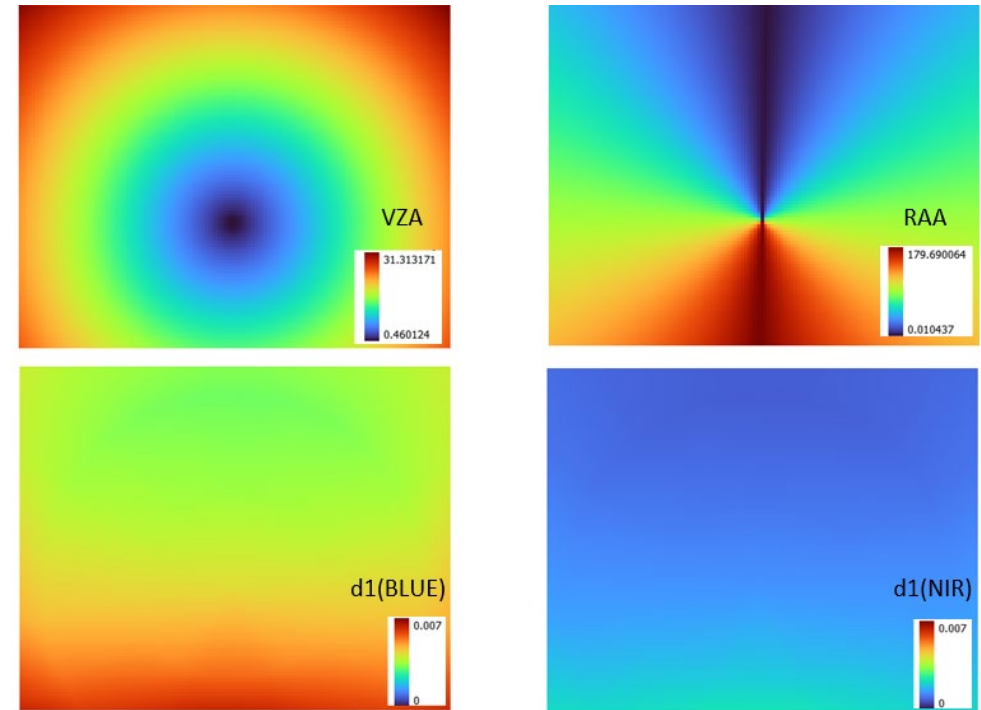


Figure 14. Sky glint correction with MAPEO-Water: View Zenith Angle (VZA); Relative Azimuth Angle (RAA); d1 for BLUE band with $d1 = \frac{\rho_{sky} L_{sky}(\lambda)}{F_s(\lambda)}$; d1 for NIR

MAPEO-Water (VITO)



Irradiance

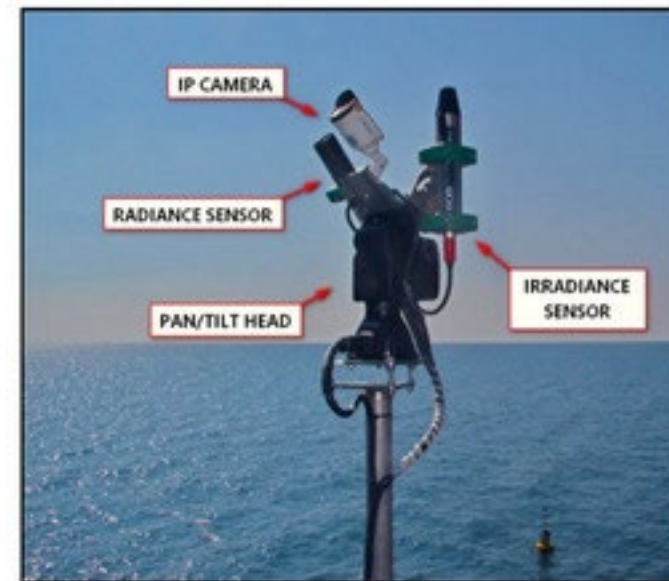
$$R_{rs}(\theta, \phi, \lambda) = \frac{L_w(\theta, \phi, \lambda)}{E_d(\lambda)}$$

Mounted on drone

Panels on land

Ground-based

Example Altum + DLS 2 Integration



Source: Van Steenwegen et al., 2019





FRM4DRONES

**fiducial reference
measurements
for water using
drones**



Online Workshop:

**Uncertainty, Fiducial
reference measurements
(FRM), and Traceability**

25 September 2025, 15:00-17:00 CET



Workshop objectives

- Share expertise on drone-based aquatic reflectance and Cal/Val
- Discuss best practices for measurement, calibration, processing, and uncertainty quantification.
- Identify Challenges and Key Needs
- Shape the roadmap towards Fiducial Reference Measurements (FRM) from drones for aquatic Cal/Val



Invited Experts and Their Talks



Carmen Cillero (Estonian University of Life Sciences)

Experimental setup and first results of drone-based radiometry; comparison to standard instruments



Anna Windle (SSAI / NASA GSFC)

Evaluation of Unoccupied Aircraft System (UAS) Remote Sensing Reflectance Retrievals for Water Quality Monitoring in Coastal Waters



Alejandro Román (Marine Sciences & Technologies)

Direct georeferencing-based mosaicking of UAV multispectral imagery over water



Giuseppe Zibordi (EO Science-JRC)

Optical radiometry requirements for drone systems supporting ocean-colour validation



Robbie Ramsay (NERC)

Current calibration activities involving UAV imagers and underwater optics



Andreas Baumgartner (DLR)

DLR'S Calibration Home Base for imaging spectrometers



Stefan Plattner (DLR)

LimnoVIS, a new platform for optimized in-situ validation measurements at inland water bodies

Presentations available at :

<https://remotesensing.vito.be/services/frm4drones-aquatic>



Where are you located? - Pin on the map



144 registrations

~ 65 attendees

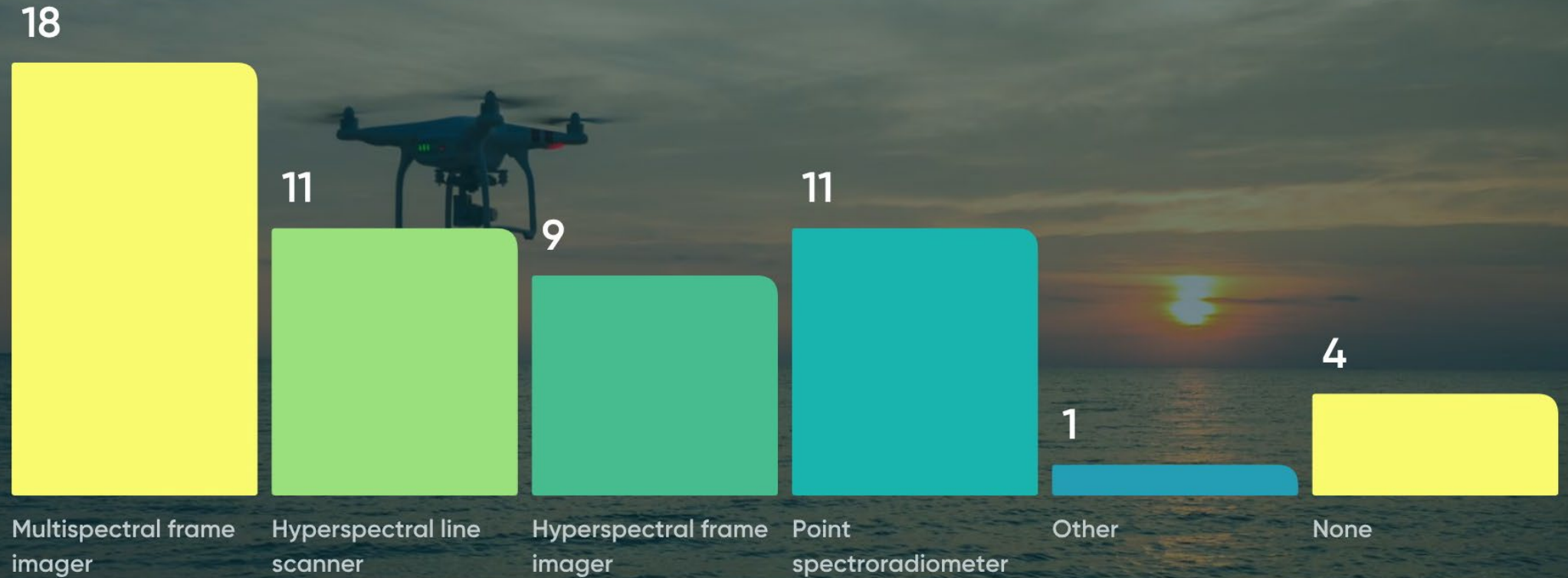
FRM4DRONES-Aquatic Second Workshop, where are you joining us from?

75 registrations
~ 50 attendees



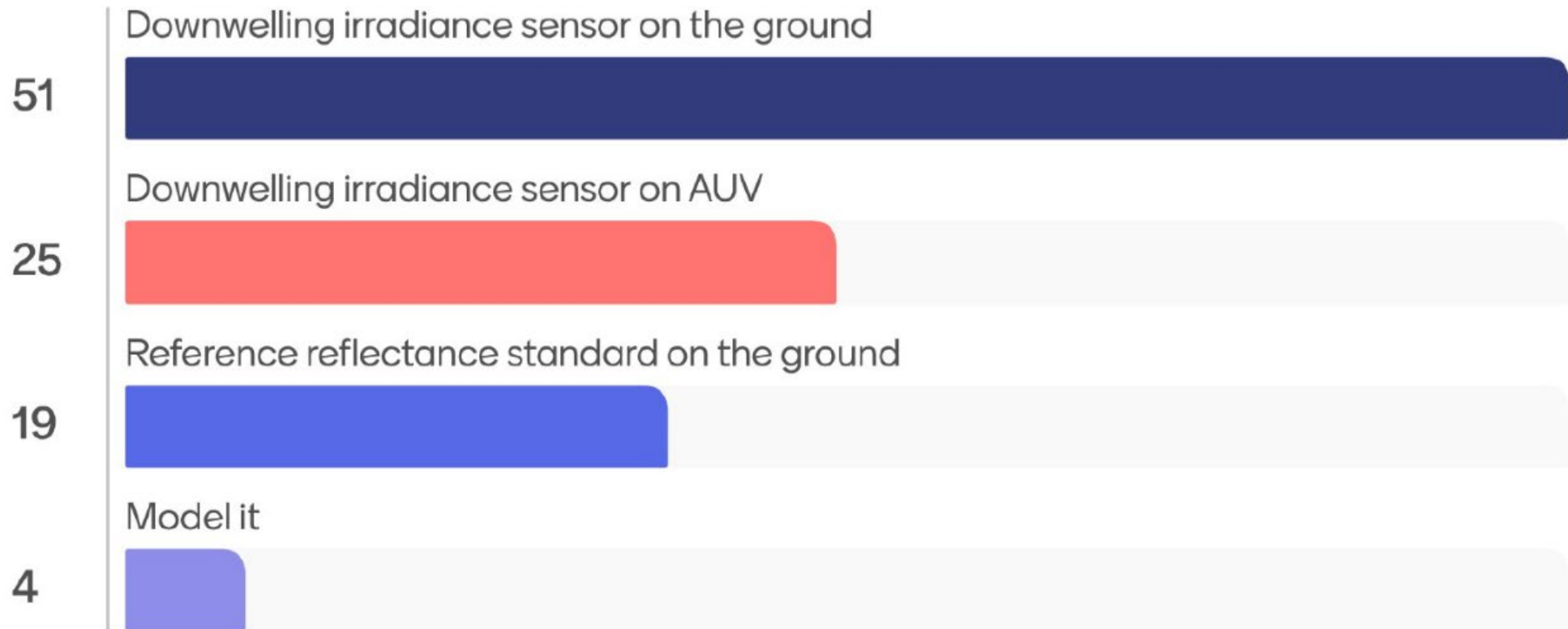


What sensors are you using or considering for aquatic reflectance on drones?



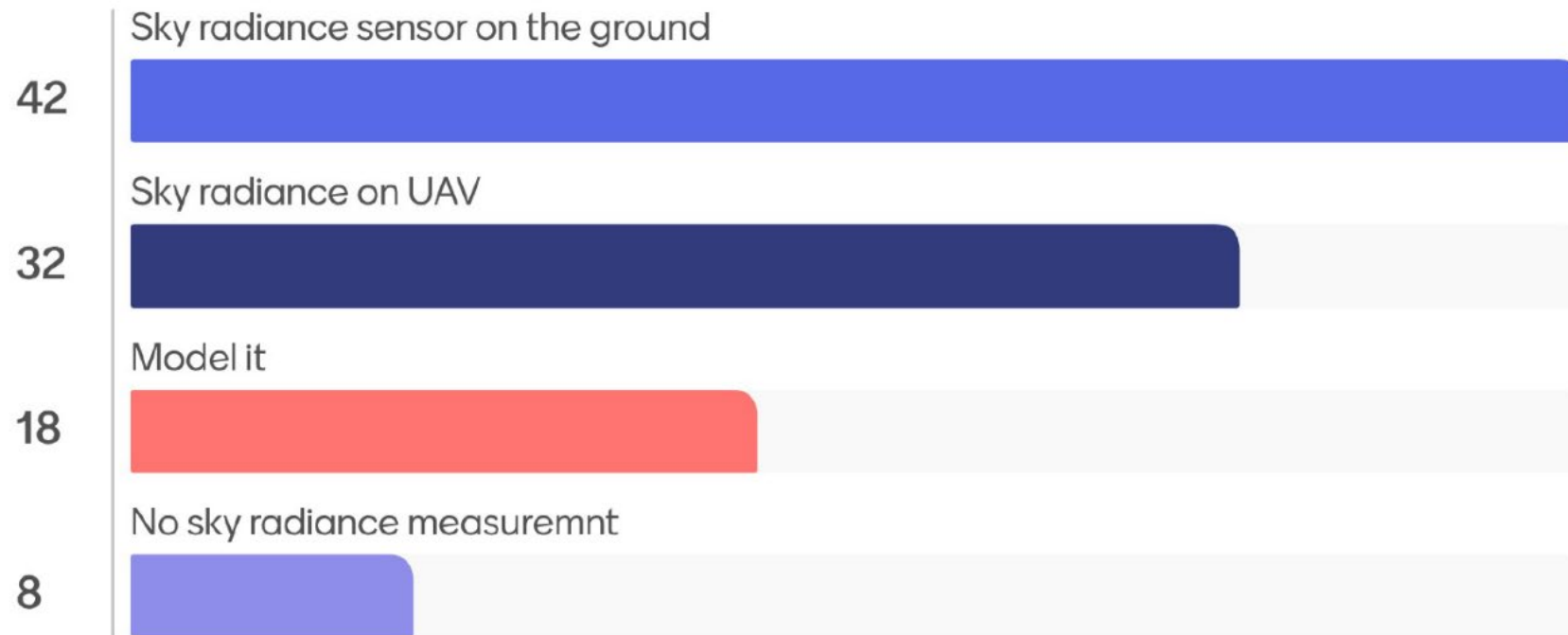


How do you measure downwelling irradiance in situ?





How do you measure sky radiance in situ?





Community Feedback Highlights

- Strong consensus: drones are essential to bridge in-situ Cal/Val and satellite observations.
- Top priorities:
 - Practical guidance needed for measurement and processing
 - Modular uncertainty frameworks adaptable to different UAV sensors
 - Intercomparison campaigns for verifying protocol robustness, evaluating cross-sensor consistency, and benchmarking uncertainty estimates
- The community shows readiness to support protocol development and intercomparison exercises
 - 16 participants want to join working groups
 - 20 participants indicated active willingness to contribute to UAV-aquatic intercomparison efforts (data acquisition, processing, calibration).



FRM4DRONES
fiducial reference
measurements
for water using
drones



The FRM4Drones-Aqua project received funding from
ESA (No. 4000147111/24/I-LR-cl) &
BELSP0 (NR SR/67/426)



Thank you