SpaFLEX: Evaluation of Systematic and Random Uncertainties in Sun-Induced Chlorophyll Fluorescence and Reflected Radiance Retrievals in the Framework of the Spanish FLEX Cal/Val Campaigns

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FLEX Mission and SpaFLEX Project

ESA's FLEX (Fluorescence Explorer) mission will provide global data on vegetation photosynthetic activity by retrieving **sun-induced chlorophyll fluorescence (SIF)** and **surface reflectance** from space.

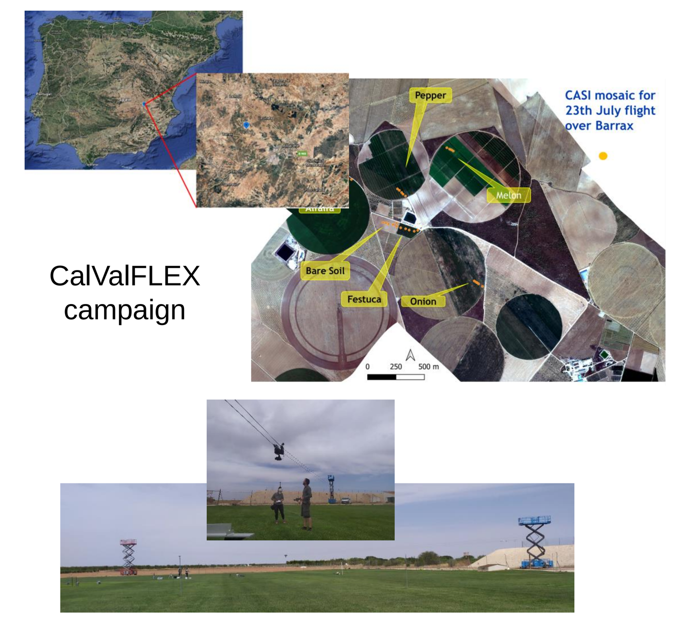
To ensure the reliability of these Level-2 products, the **SpaFLEX project** supports ESA's calibration and validation (Cal/Val) requirements through:

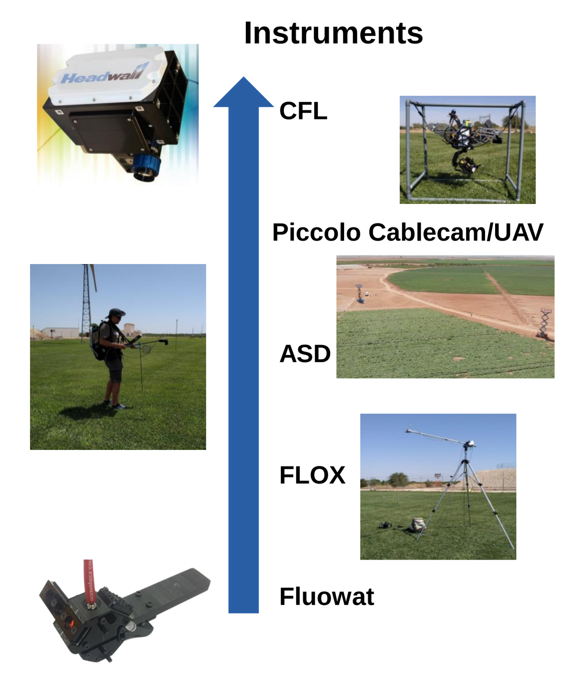
- The development of **test sites in Spain**
- Instrument characterization (ground, UAV, and airborne)
- Fiducial reference measurements
- Ground measurements and sampling protocols
- The estimation of **systematic and random uncertainties** in SIF and reflectance retrievals

Field Campaigns

As part of the Spanish FLEX calibration and validation (Cal/Val) activities, airborne, cable-suspended, and in-situ measurements, including those from the FLOX system, were collected during **field campaigns in Spain** to support the uncertainty analysis of SIF and surface reflectance under varying canopy conditions.

In particular, the **CalValFLEX campaign (2020)**, conducted at the **Las Tiesas agricultural site** (Barrax, Albacete), included measurements over multiple vegetation plots, among them a homogeneous Festuca grassland. Additional measurements were acquired during the **2024 Sarrión campaign** over a **Holm oak forest**, representing heterogeneous conditions.





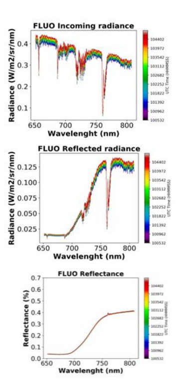
FLOX Processing Chain

FLOX System

FLOX is a dual-channel hyperspectral field spectroradiometer used to continuously measure upwelling (L↑) and downwelling radiance (E↓). It is designed for SIF and reflectance monitoring under natural sunlight conditions.

Parameter	FLUO MODULE	FULL MODULE
Wavelength range	~ 650–800 nm	~ 400–950 nm
Spectral sampling interval (SSI)	~ 0.17 nm	~ 0.65 nm
Spectral resolution (FWHM)	~ 0.3 nm	~ 1.5 nm
Signal to noise ratio (SNR)	~ 1000	~ 250
Field of View (FOV)	L↑ 25° E↓ 180°	L↑ 25° E↓ 180°

FLOX measurements over a Festuca homogeneous field in the CalValFLEX campaign

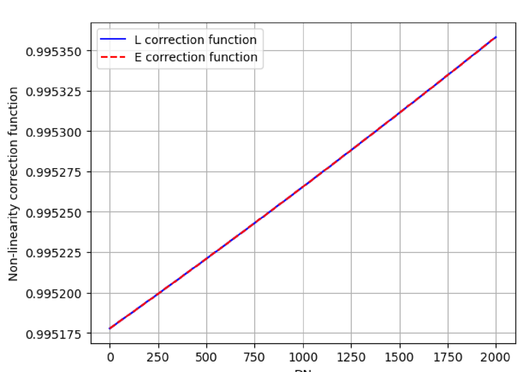


Non-linearity correction:

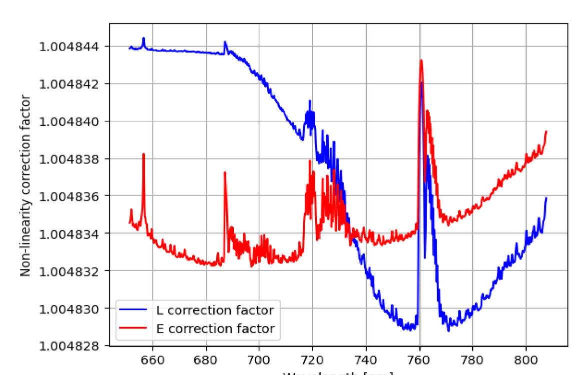
$$DN_{corr} = \sum_{i=0}^{7} a_i \cdot DN_{raw}^{i}$$

- DN_{raw}: raw digital number (uncorrected)
- DN_{corr}: corrected digital number, after applying non-linearity correction
- a_i: non-linearity correction coefficients derived from laboratory calibration

i	a_i
0	$9.95177822 \times 10^{-1}$
1	$8.47455122 \times 10^{-8}$
2	$2.95313508 \times 10^{-12}$
3	$-1.19966918 \times 10^{-16}$
4	$1.82129111 \times 10^{-21}$
5	$-1.46119140 \times 10^{-26}$
6	$5.96795747 \times 10^{-32}$
7	$-9.81466058 \times 10^{-38}$



FLOX non-linearity correction function



FLOX non-linearity correction factors (*CorNonlin*)

L0 to L1: radiometric calibration

The raw output of the FLOX system (L0) is converted into calibrated upwelling and downwelling radiance (L1):

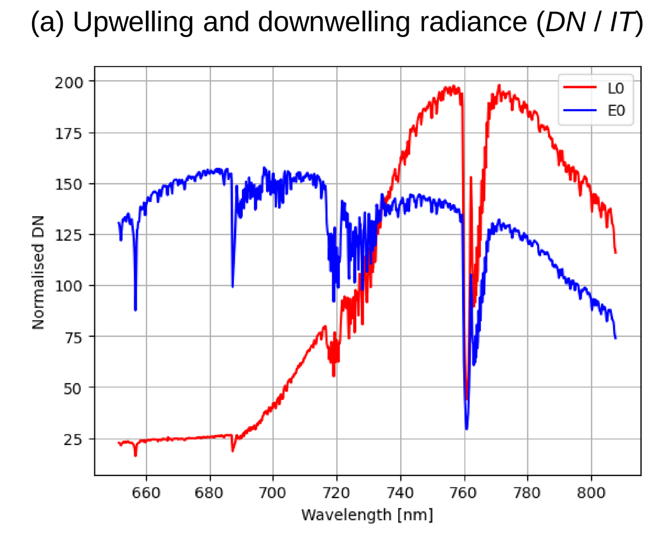
$$L_1 = \left(\frac{DN_{L0} - DN_{dark\_L0}}{IT}\right) \cdot cal\_coef_{L0\_nonlin} \cdot CorNonlin_{L0}$$

$$E_1 = \left(\frac{DN_{E0} - DN_{dark\_E0}}{IT}\right) \cdot cal\_coef_{E0\_nonlin} \cdot CorNonlin_{E0} \cdot CorCos$$

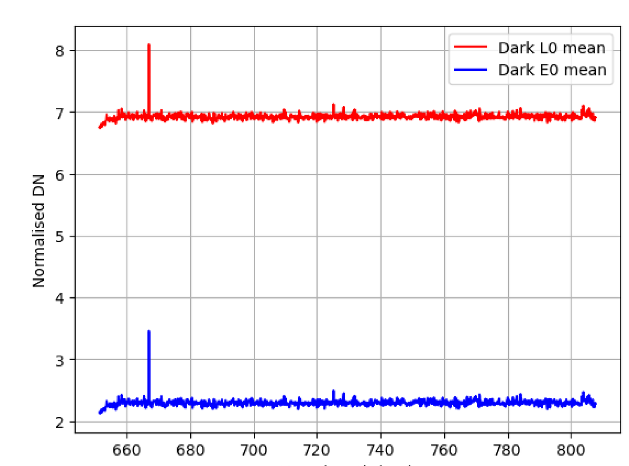
- DN_{L0}, DN_{E0}: raw digital number (counts) from radiance and irradiance
- DN_{dark_L0}, DN_{dark_E0}: dark signal (counts)
- *IT*: integration time (ms)
- $cal\_coef_{L0\_nonlin}$, $cal\_coef_{E0\_nonlin}$: radiometric calibration coefficients (W·m⁻²·sr⁻¹·nm⁻¹·ms⁻¹)
- $CorNonlin_{L0}$, $CorNonlin_{E0}$: non-linearity correction factors (dimensionless)
- $CorCos$: cosine correction factor for downwelling radiance (dimensionless)
- L_1, E_1: calibrated upwelling/downwelling radiance (W·m⁻²·sr⁻¹·nm⁻¹)

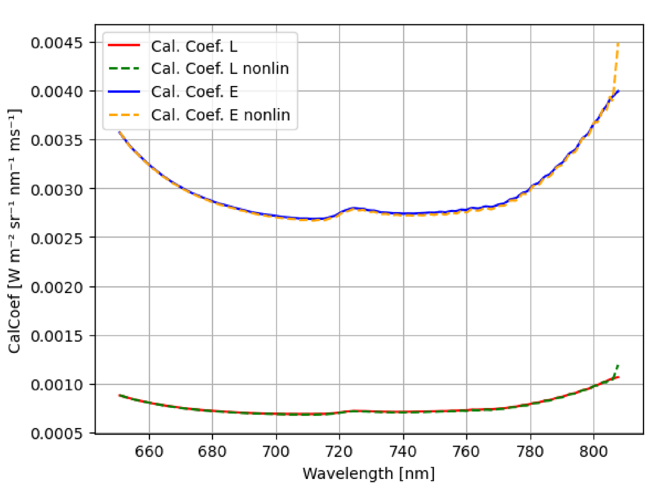
FLOX measurements over the homogeneous *Festuca* plot at Las Tiesas, Barrax, on 21 July 2020 at 11:00 UTC:

(a) Upwelling and downwelling radiance (*DN / IT*)

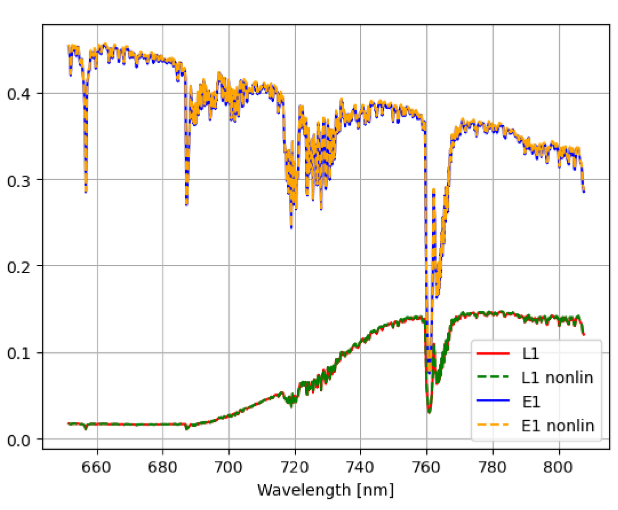


(b) Corresponding dark signals (*DN / IT*)





FLOX radiometric calibration coefficients (*cal_coef*)



Calibrated upwelling/downwelling radiance

L1 to L2: apparent reflectance, SIF and true reflectance

$$R_{app} = \frac{L_1}{E_1}$$

R_{app}: apparent reflectance (dimensionless)

SpecFit (Cogliati *et al*., 2019) models upwelling radiance as the sum of reflected downwelling radiance and a fluorescence emission term. **Reflectance** $R(\lambda)$ is parameterized using a **cubic spline**, while the **SIF**(λ) is represented as a **linear combination of two Lorentzian functions**. The retrieval is performed by minimizing the residuals between the measured and modeled radiance:

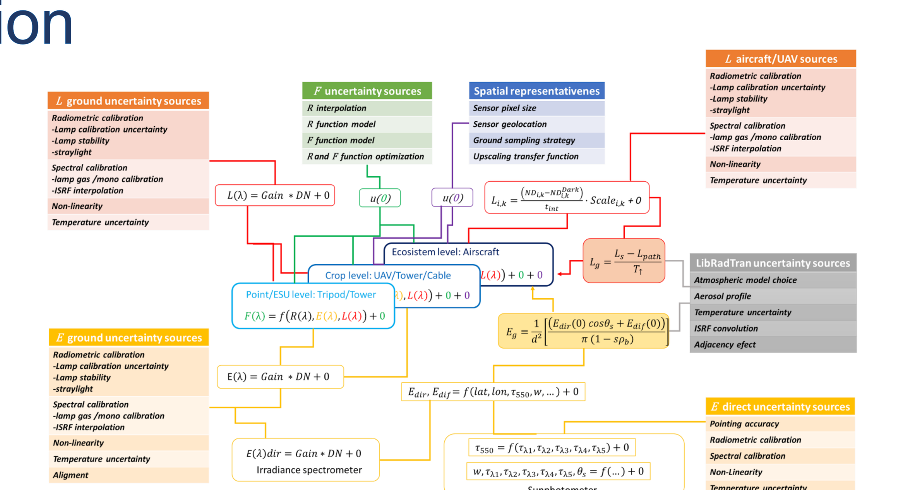
$$L_{mod}^{\uparrow}(\lambda) = R(\lambda) \cdot L^{\downarrow}(\lambda) + SIF(\lambda)$$

Uncertainty Estimation and Propagation

A metrological approach based on the Guide to the Expression of Uncertainty in Measurement (GUM; JCGM, 2008) was adopted to assess both systematic and random uncertainty components. Uncertainty contributions were organized in an **uncertainty tree diagram**, covering all sources from instrument calibration to field sampling. This approach ensures full traceability of uncertainties across instruments and retrieval levels.

Uncertainty propagation from Level-0 to Level-2 products (SIF and surface reflectance) was performed using **Monte Carlo methods**, implemented through the **CoMet-Punpy tool** (Community Metrology Toolkit - Propagation of UNcertainties in Python). The total uncertainty was assessed by combining systematic and random components:

$$u_{total} = \sqrt{u_{systematic}^2 + u_{random}^2}$$



Sources of uncertainty

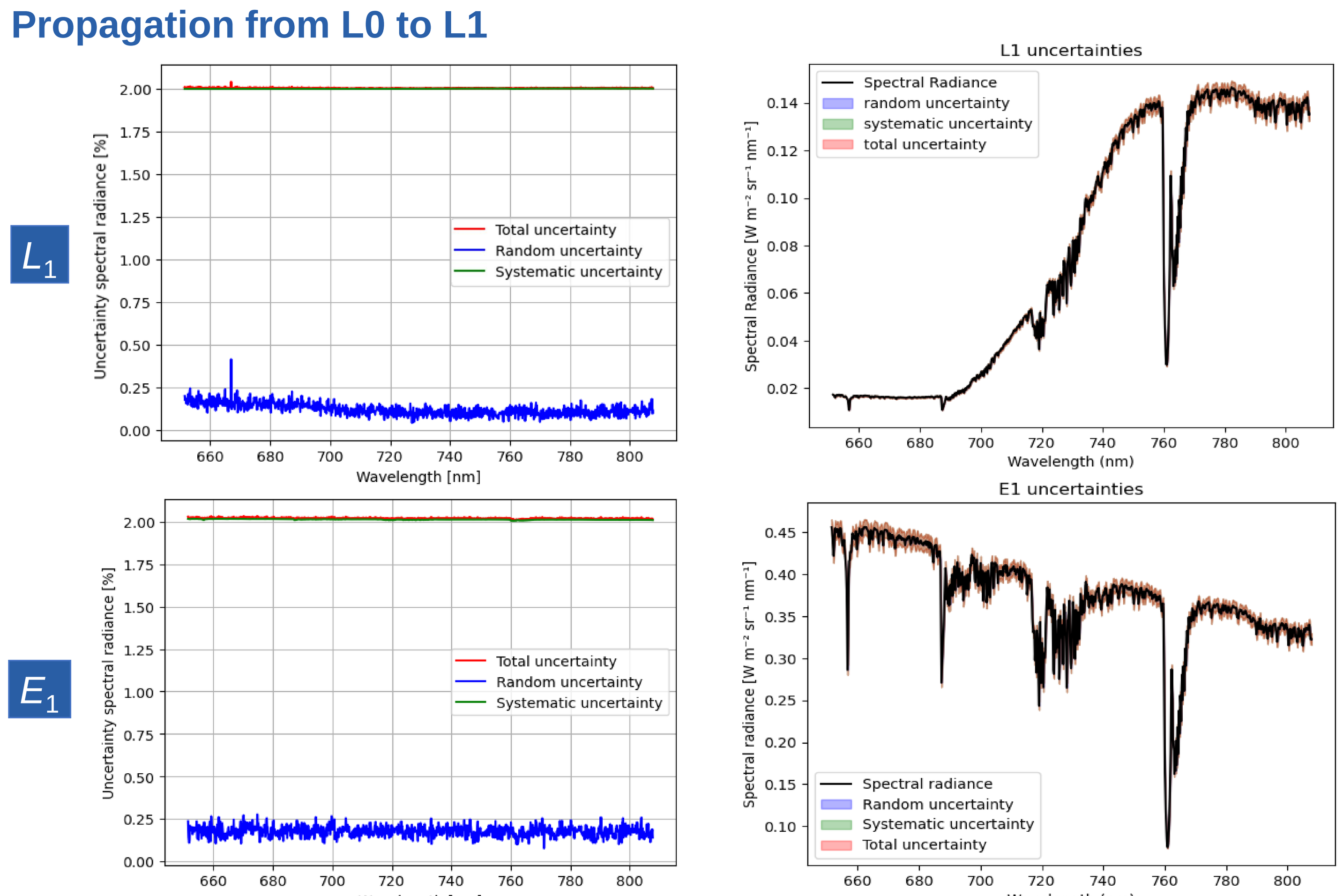
1. Systematic uncertainties

- **Instrument calibration:** estimated as 2% of the calibration coefficients for both radiance and irradiance sensors.
- **Non-linearity:** the effect of correcting the detector's non-linearity was evaluated as the difference between radiance values with and without the correction.
- **Cosine receptor**: assumed to have negligible uncertainty due to ideal cosine response or correction of the effect.

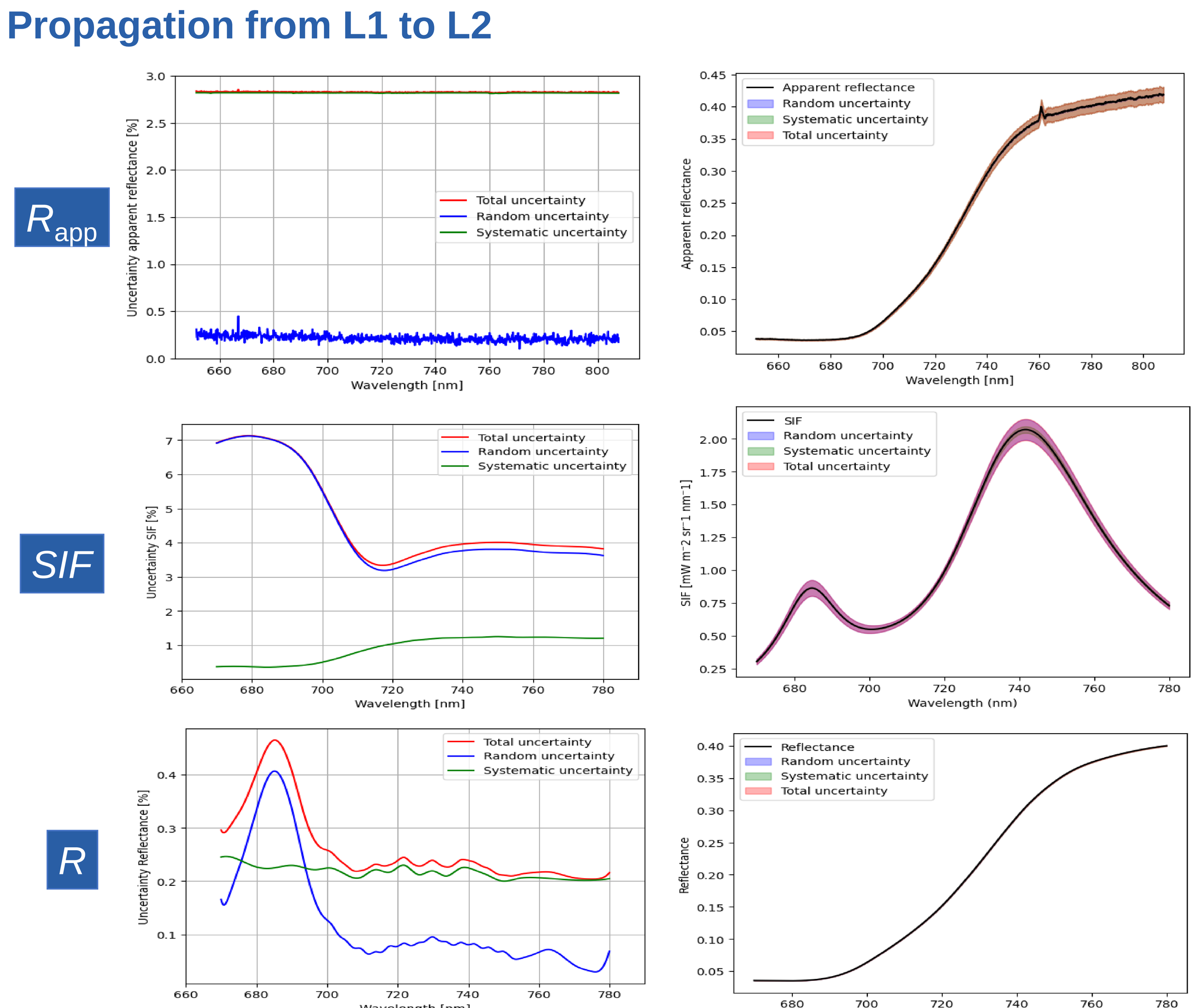
2. Random Uncertainties

These represent **instrumental noise**, computed as the standard deviation of repeated measurements in a calibration sphere.

Propagation from L0 to L1



Propagation from L1 to L2



The uncertainty obtained with the FLOX system (u_{SIF} ≈ 4% at O_2A and ≈ 7% at O_2B) complies with the FLEX mission requirements for SIF (≈10%). However, a large discrepancy is observed between the uncertainty of the true surface reflectance obtained with SpecFit (<0.5 %) and the uncertainty estimated for apparent reflectance (≈ 2.8%), which exceeds the mission requirement of ≈1%.

Conclusions

The FLOX system plays a key role in providing high-quality point-level SIF and reflectance measurements, which are essential for **characterizing the uncertainty of integrated observations over a 300 × 300 m FLEX-S3 pixel**. While the **random uncertainty component**, estimated here for a single measurement, meets the FLEX mission requirements, it can be further reduced by increasing the number of repetitions. **Systematic uncertainty sources**, in turn, can be reduced by improving correction procedures, such as those related to radiometric calibration. An accurate estimation of SIF and apparent reflectance (R_{app}) uncertainties is crucial to support the validation of FLEX products at the pixel scale.

References

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- JCGM, **2008**. Evaluation of measurement data — Supplement 1 to the "Guide to the expression of uncertainty in measurement" — Propagation of distributions using a Monte Carlo method.

Acknowledgments

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