TILT CORRECTION OF ONBOARD DRONE IRRADIANCE MEASUREMENTS – EVALUATION OF HYPERSPECTRAL METHODS

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ABSTRACT:

An accurate onboard irradiance measurement on drones is a requirement direct reflectance transformation of aerial images and remote sensing data without use of on-ground reference targets. One of the major error sources in onboard irradiance measurement is the effect of sensor tilt to the observed irradiances. In this paper/presentation, we will present an intercomparison of two methods: the FGI AIRS method and the Köppl method. Both methods require an irradiance sensor with good cosine response and IMU system providing accurate tilt angle for each irradiance measurement. Additionally to this, the AIRS method requires special hardware with multiple tilted irradiance sensors, which effectively allow interpolation of a virtual horizontal sensor. The Köppl method requires the irradiance sensor to be a spectral sensor, which allows the direct and diffuse fractions of irradiance spectrum to be deducted from shape of the measured spectrum using the spectral unmixing between direct and diffuse spectrum shapes. We present a field experiment where the AIRS sensor was flown in a typical mapping pattern flight and evaluate the tilt correction methods during it. During a fully sunny period of the flight, the standard deviations of the irradiances was ±6.4% for the uncorrected tilted irradiances, ±1.8% for the AIRS method, and ±2.0% for the Köppl method. The data shows that an accurate irradiance measurement onboard a drone is feasible using a well-calibrated irradiance sensor system and both methods are capable to produce quite similar results.

1. INTRODUCTION

Multi- and hyperspectral remote sensing on drones is gaining popularity, but the reflectance calibration of the images is still partially unsolved question. Fundamental requirement for the reflectance transformation is determination of the irradiance in the imaged area (Aasen et al. 2018). This can be done alternatively by either (1.) Simulation of irradiance using an atmospheric model (Zarco-Tejada et al., 2012). (2) Using reflectance reference targets on-site, imaging them with the remote sensing camera, and performing and empirical line method (ELM) transformation (Aasen et al. 2018). (3) Having an irradiance sensor installed on-site (Burkart et al., 2014);, or (4) Having an onboard irradiance sensor on the drone. Currently, the second method using reflectance reference panels and ELM is the most comment practice in small scale drone operations. However, both the panel and on-site irradiance sensors method are suitable only for local use and don't work in BVLOS operations. As the distance between the on-site reference and the imaged area increases, the representativeness of the reference measurement quickly deteriorates especially if cloud conditions are not ideal. The atmospheric modelling approach is commonly used in satellite applications and can also be used in BVLOS drone operations, but it is accurate only in ideal atmospheric conditions limiting its practical usability. This leaves the onboard irradiance measurement as only BVLOS suitable reflectance transformation method.

The standard method using Empirical Line Method (Aasen et al. 2018) is not practical on Beyond Visual-Line-of-Sight (BVLOS) flights and in real-time applications and is prone to failure under broken cloud conditions. An onboard irradiance measurement allows performing direct reflectance transformation in real-time onboard the drone, and is a method better suited for the long-lasting BVLOS flights.

The basic concept of irradiance measurement is to simply install a spectrometer or photodiode under diffuser optics. For accurate absolute irradiances at all solar angles and for good linearity in transitions between sunny and cloudy illumination, the cosine response of the optics must be followed with great precision. Unfortunately, this is often not the case as even the top-end optics of the major spectrometer manufacturers can often have 5–10% errors and unlinearities, and correction calibrations and modifications can be necessary (Suomalainen et al. 2021).

The irradiance measurements onboard drones have additional challenge of errors due to sensor tilting. Especially on low solar elevations, tilts towards or away from the sun can cause systematic errors of many percents per degree tilted (Suomalainen et al. 2018). The tilting problem could be eliminated by installing the irradiance sensor on a stabilized gimbal, but this is not commonly practiced. The tilting error can also be corrected/reduced mathematically, but usually this requires measurement of the sensor orientation and either additional irradiance measurements or advanced irradiance modelling.

In this presentation, we will discuss the state-of-the-art in onboard irradiance measurement by recapping the onboard irradiance evaluation results published earlier in (Suomalainen et al. 2021) and present preliminary results on comparing the AIRS tilted-sensors method to the spectral-unmixing method proposed by Köppl et al. (2021)

2. MATERIALS AND METHODS

Figure 1. The FGI AIRS sensor system which is mounted on top of a drone. The center diffuser is the cosine collector of the main irradiance spectrometer. The three tilted diffusers house photodiodes used for tilt correction.

2.1 FGI AIRS

Our contribution to the tilt correction problem has been to develop the FGI AIRS (Aerial Image Reference System) sensor system, which consists of an irradiance spectrometer, three tilted irradiance RGB photodiode sensors, GNSS-IMU, and onboard processing solution. For the tilt correction, the AIRS uses the three photodiodes, tilted 10° to opposite direction, to sample the irradiance on different tilts, which basically allows interpolation of correction factors for the tilted spectrometer data. The spectrometer model is USB2000+ (Ocean Insight, Largo, FL, USA) with custom shadow ring diffuser optics with accurate cosine response and absolute radiometric calibration. The AIRS hardware and the method are described in more detail in Suomalainen et al. (2018), while the lengthy calibration procedure and evaluation of its accuracy is presented in Suomalainen et al. (2021).

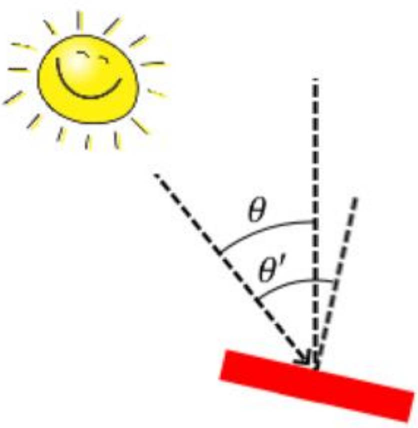

Figure 2. The solar zenith angle (θ) and solar apparent zenith angle (θ') on a surface of a tilted sensor.

2.2 Standard tilt correction

The AIRS method requires special hardware and cannot be directly applied to data of a simpler single irradiance sensor. However, for such data, it is possible to do a mathematical tilt correction using just tilt metadata and knowledge of the direct- and diffuse-fractions of the irradiance.

The basic tilt correction method is based on assumption that the irradiance (E) incident to a level surface can be split to ideal direct and diffuse components:

$$E = E_{DIR} + E_{DIF} \tag{1}$$

The direct component is assumed to be an unidirectional beam incident from the sun direction, while the diffuse component is assumed to be isotropic scattering incident uniformly from all angles. Following from the unidirectional beam assumption, the direct component on a level surface depends on the solar zenith angle (θ, Fig 2) following the equation:

$$E_{DIR} = \cos(\theta)\, E_{\perp} \tag{2}$$

where the $E_{\perp}$ is the direct component of the irradiance as measured on a plane perpendicular to the beam direction. If the sensor is tilted towards or away from the sun, the intensity of the direct component will vary while the diffuse component is assumed to remain constant. Thus an ideal tilted sensor will observe the tilted irradiance (E'):

$$E' = \cos(\theta')\, E_{\perp} + E_{DIF} \tag{3}$$

where θ' is the solar apparent zenith angle in relation to the sensor surface. By inserting Eqs 2 and 3 to Eq 1, we can form equation for irradiance sensor tilt correction.

$$E = \frac{\cos(\theta)}{\cos(\theta')}(E' - E_{DIF}) + E_{DIF} \tag{4}$$

This equation can be simplified slightly by introducing a direct- and diffuse-fractions (f_{DIR} and $f_{DIF} = 1 - f_{DIR}$) which describe the portion of each component in the observed tilted irradiance:

$$E = \frac{\cos(\theta)}{\cos(\theta')} f_{DIR} E' + f_{DIF} E' \tag{5}$$

These fractions are dependent on the wavelength of light as the diffuse light is typically bluish due to Rayleigh-scattering, while the direct component has flatter spectrum.

A low-accuracy tilt correction can be performed by simply assuming some plausible fractions, and is likely to give better results than using uncorrected irradiances. However for better accuracy especially on low solar elevations, the actual fractions should be determined. Direct measurement of the fractions requires specialized sensors with shadowers, etc, which can be impractical onboard drones.

Recently, Köppl et al. (2021) proposed a spectral-unmixing method and full workflow to solve these fractions directly from the raw irradiance spectra. The spectral unmixing method requires knowledge of the spectral shapes of the direct and diffuse components. To extract these direct and diffuse spectral endmembers, the Köppl-workflow requires selection of two time periods – one with high and one with low irradiance level - where diffuse and direct fractions remains nearly constant while the sensor experiences tilting motion. The spectral endmembers are then solved for both periods by least squares minimization of the

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variance in tilt corrected irradiance. These spectral endmembers are then used in spectral unmixing of the tilted irradiance spectra producing the direct and diffuse fractions for each. This allows tilt correction of the tilt spectra using the standard tilt correction method.

Figure 3. The drone and the sensor payloads used in the flight experiment.

2.3 Field Experiment

To evaluate the accuracy of the AIRS irradiances and to test its usage in direct reflectance workflow, a flight experiment was performed. The dataset is the same that has been earlier published and analysed in (Suomalainen et al. 2021). The AIRS and a hyperspectral camera (Senop Rikola HSI, model 2018) were installed on a drone (Fig. 3) flying repeatedly a small mapping flight pattern consisting of parallel flight lines in north-south direction. The experiment was performed at Sjökulla radiometric test field, in southern Finland (60.242 N, 24.383 E) on 2019-08-20 between 13:30 and 14:30 local time (UTC + 3 h). The solar zenith angle was ~49°. Due to light wind from south, the drone had systematically small tilt towards the sun. During the experiment the sky was mostly blue with approximately 1/8th of the sky covered by fast-moving low-altitude cumulus clouds. During the flight of interest, the sun was in the beginning behind the clouds, but rest of the flight was in full sunshine. When applying the Köppl-method, the stable part of the cloudy section was used as the low-irradiance sample and the fully sunny section right after it as the high-irradiance section. In-situ reference irradiances were measured on ground using ASD FieldSpec with improved RCR irradiance optics.

3. RESULTS AND DISCUSSION

The data from the flight experiment (Fig. 4) was processed using both the AIRS method and using the Köppl spectral unmixing and tilt correction workflow. The processed data has a gap because the drone was landed for a moment between different sections of the flight. In the test dataset, for the Köppl "low irradiance" period we used a cloudy section at t=610650s and for the "high" a sunny section at t=720-760s (Figure 3, Top). Using the spectra between 400–900 nm on these periods, the direct and diffuse spectral endmembers (Fig. 5) were solved. The direct and diffuse fractions were then solved for each tilted spectrum. The figure 6 shows the time series of the irradiance direct fraction on three wavelengths regions.

Next, the irradiances were tilt-corrected using both methods and their accuracies were evaluated. The figure 7 shows the time series of the irradiances during the whole flight. The accuracy of tilt correction was evaluated using the stable illumination period at the latter half of the flight (t=1200–1600 s). The figure 8 shows the tilt-corrected irradiances during this period normalized with the mean irradiance. In figures 7 and 8, both the AIRS method and the Köppl method are visibly able to correct most of the systematic tilt errors. In the stable period, the standard deviations of the irradiances was ±6.4% for the uncorrected irradiances, ±1.8% for the AIRS method, and ±2.0% for the spectral-unmixing method. The average unsigned disagreement between methods is 1.7%. These values were calculated from single spectra and the noise can be further reduced using temporal averaging and filtering. In the data the errors show up similarly in both tilt correction methods. Most of these errors coincide with the changes in drone attitude, which neither of the methods is able to fix and these may be due to e.g. inaccuracies in IMU orientations or slight asymmetries is the diffuser optics. However at certain times, e.g. at t=1300s and at t=1440, the two tilt correction methods disagree by more than 3%, these may be due to inaccuracies in the relative calibration of the photodiodes that that AIRS uses, but based on this data alone it is impossible state for certain.

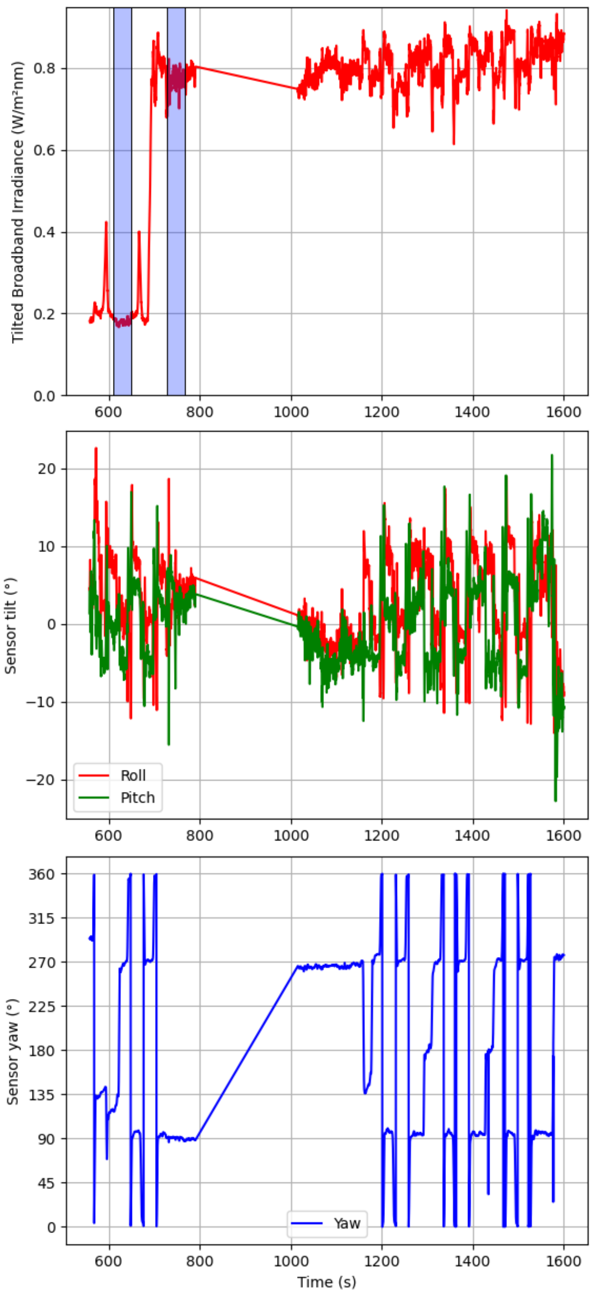

Figure 4. **(Top)** Time series of not-tilt-corrected irradiances as measured by the AIRS spectrometer during the flight experiment. The blue boxes highlight the low and high irradiance periods used in solving the direct and diffuse spectral endmembers. **(Middle)** Irradiance sensor roll and pitch angles as measured by the AIRS IMU. **(Bottom)** Irradiance sensor yaw angle.

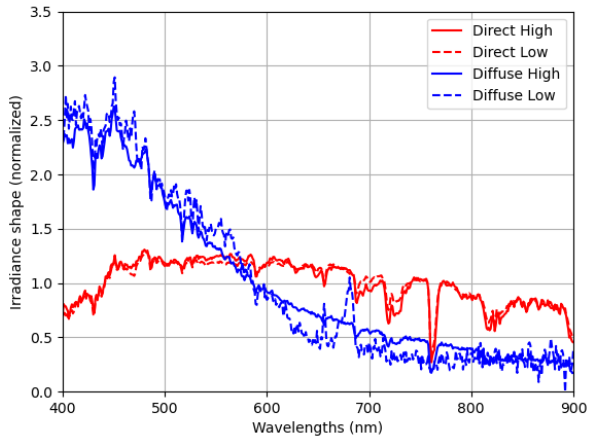

Figure 5. Diffuse and direct irradiance spectrum endmembers extracted using the Köppl method at the full sunshine (“High”) and under shadow of a cloud (“Low”)

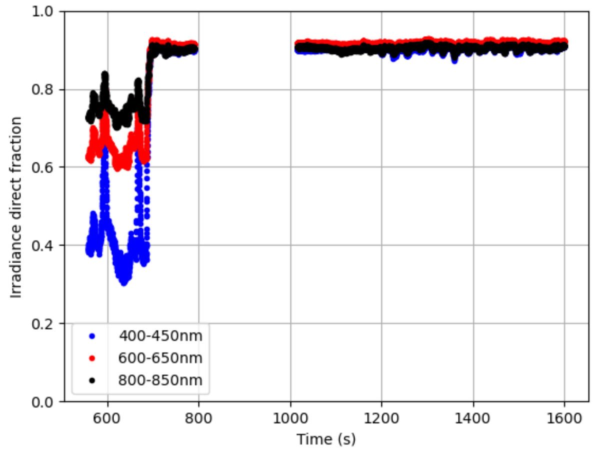

Figure 6. Time series of the direct fraction as solved by spectral unmixing using the Köppl-method.

When the same dataset was analysed in (Suomalainen et al. 2021) the absolute accuracy of irradiances produced with AIRS method were evaluated. When evaluating the average irradiance of the stable sunny period during, using the ASD FieldSpec values as reference, the irradiances using the AIRS method had normalized root mean square error (NRMSE) of 1.26%, while the uncorrected irradiances overestimated the irradiance on average by 12%. In the laboratory calibrations of the AIRS cosine response showed that the systematic errors in AIRS cosine response are in direct sunshine between -1.9% and +0.2% at zenith angles up to 70° and -1.3% in diffuse illumination.

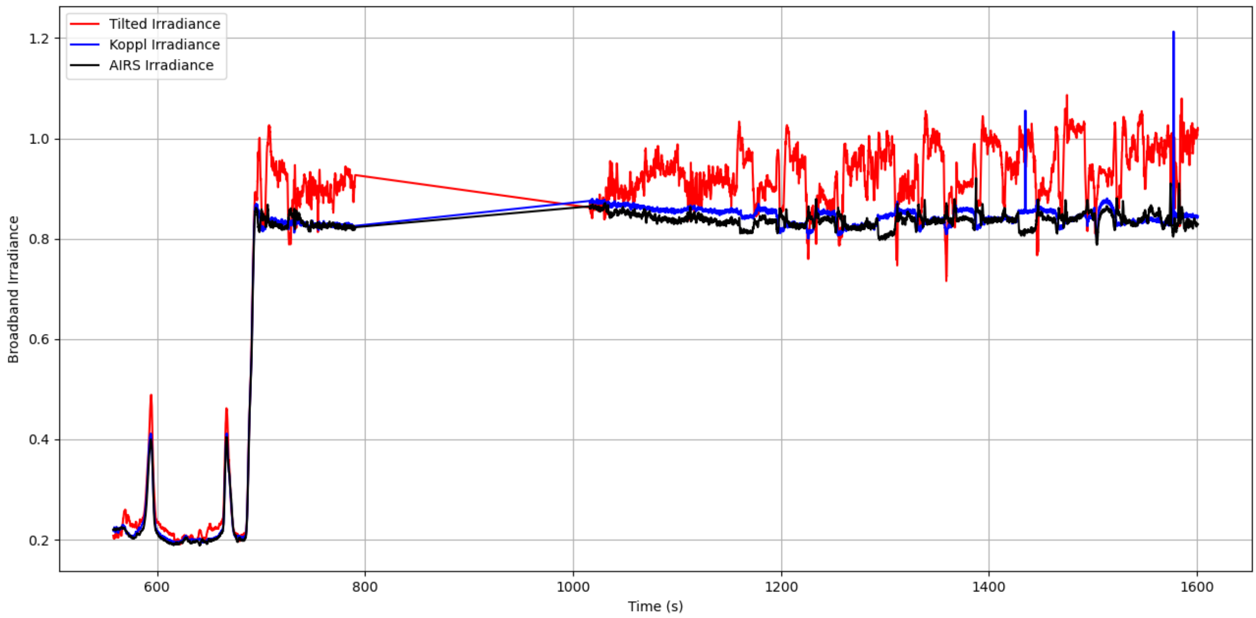

Figure 7. Time series of tilted and tilt-corrected irradiances

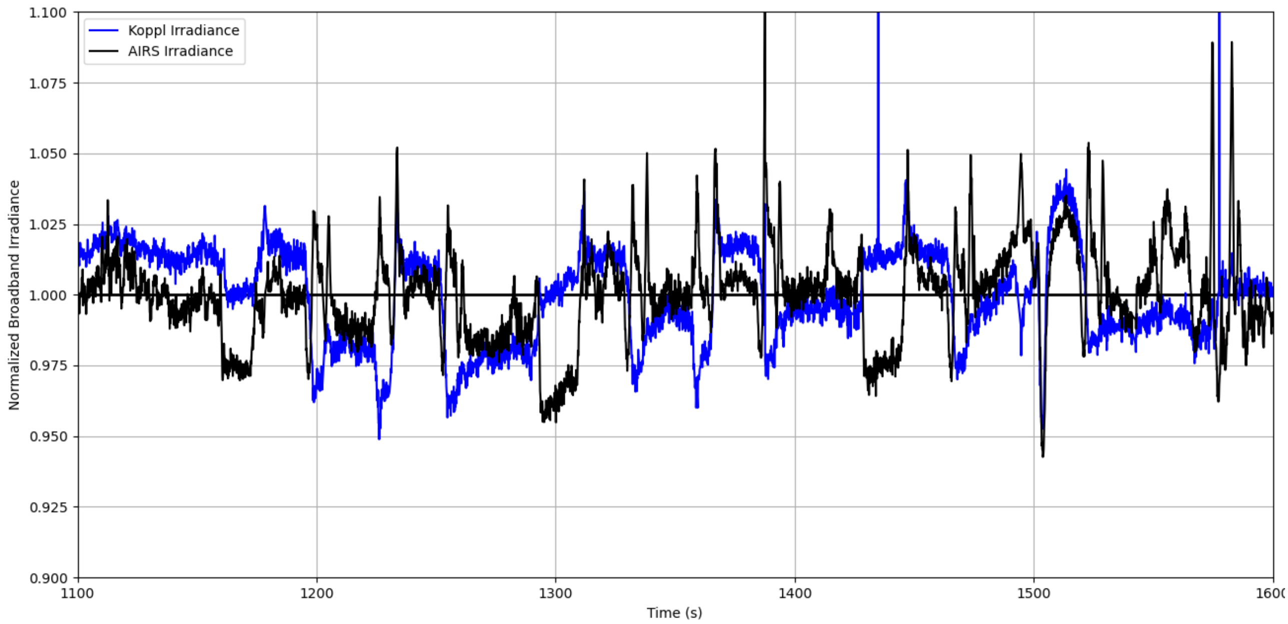

Figure 8. Relative tilt correction errors during the latter half of the flight with stable illumination. The irradiance data is same as in the previous figure, but normalized with mean irradiance value between t=1200–1600s.

4. CONCLUSIONS

An accurate irradiance measurement onboard a drone is feasible using a well-calibrated irradiance sensor system. For accurate absolute irradiances and good linearity between sunny and clouded transitions, it is mandatory to use diffuser optics with calibrated cosine response. The FGI AIRS method was shown to be able to produce onboard irradiances with accuracy better than ±1.9% relative to a ground reference measurement. The Köppl-method, was shown to be effective in reducing the tilt effects to approximately the same level as the AIRS method and produce similar irradiances as the AIRS method, with average disagreement of 1.7%. The AIRS and Köppl methods are both valid approaches to tilt correction with different technical requirements. Both methods require irradiance data to be accurately paired with an IMU. The AIRS method requires additional tilted irradiance photodiodes, while the Köppl method requires the irradiance sensor to be a full spectrometer.

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