Centre for Geo-Information

Thesis Report GIRS-2014-01

Incident light monitoring for UAV-acquired image correction

Jonas van Duijvenbode

28/01/14
Incident light monitoring for UAV-acquired image correction

Jonas van Duijvenbode

Registration number 88 10 09 206 090

Supervisors:

Dr. Ir. Lammert Kooistra
Dr. Juha Suomalainen

A thesis submitted in partial fulfilment of the degree of Master of Science
at Wageningen University and Research Centre,

The Netherlands.

28-1-2014
Wageningen, The Netherlands

Thesis code number: GRS-80436
Wageningen University and Research Centre
Laboratory of Geo-Information Science and Remote Sensing
Acknowledgement
The acknowledgements are in general the perfect place to tell the tale of all the hardships that were experienced during the whole process of writing a thesis. Unfortunately for the reader my mind draws a blank at this moment when I need to contemplate these hardships. Overall I have enjoyed the process of defining a problem and getting to a solution. For this I had the fortune to get aid of some people who I would like to thank. First of all I’d like to thank Lammert, who provided me with feedback in such detail that I still cannot comprehend. Second of all Juha, of whom I learned more about optics and sensors during the many field trips than in all courses combined. Of course Harm, who, although he was not even my supervisor, aided me with preparation of all equipment. Also I’d like to thank Gijs and Niene for proofreading it all one final time, proverbially dotting and crossing the last i’s and t’s. Lastly on a more personal note I’d like to thank Monique, who put up with me when I was physically at home while my mind was so often still in the thesis room.
Index
1 Introduction ........................................................................................................................................... 1
  1.1 Context ............................................................................................................................................... 1
    1.1.1 UAV’s ........................................................................................................................................... 1
    1.1.2 UAV’s and image acquisition ...................................................................................................... 2
    1.1.3 Incident light ............................................................................................................................... 2
  1.2 Problem definition ............................................................................................................................ 4
  1.3 Research objective ........................................................................................................................... 6
  1.4 Research questions ........................................................................................................................... 6
  1.5 Reading guide .................................................................................................................................... 6
2 Literature review ..................................................................................................................................... 7
  2.1 Atmospheric conditions .................................................................................................................... 7
    2.1.1 Constant changes ......................................................................................................................... 7
    2.1.2 Incidental changes ....................................................................................................................... 7
    2.1.3 Cloud types .................................................................................................................................. 8
  2.2 Image correction .................................................................................................................................. 10
  2.3 Incident light sensing ........................................................................................................................ 11
    2.3.1 Instruments .................................................................................................................................. 11
    2.3.2 ILS allocation ............................................................................................................................... 14
    2.3.3 Measurement time interval .......................................................................................................... 14
  2.4 Empirical line correction ................................................................................................................ 14
3 Methodology .......................................................................................................................................... 17
  3.1 General procedure ............................................................................................................................ 17
  3.2 Data acquisition .................................................................................................................................. 18
    3.2.1 Incident light measurements ....................................................................................................... 18
    3.2.2 Ground-based image acquisition .................................................................................................. 20
    3.2.3 Flight-based image acquisition ................................................................................................... 20
  3.3 Data preparation ................................................................................................................................... 22
  3.4 Data analysis ........................................................................................................................................ 24
    3.4.1 Instrument simulation ................................................................................................................... 24
    3.4.2 Vegetation indices ......................................................................................................................... 26
    3.4.3 Empirical line correction ............................................................................................................. 27
    3.4.4 Spatial ILS allocation .................................................................................................................... 28
    3.4.5 Time-lag analysis ......................................................................................................................... 29
    3.4.6 Ground- and flight-based image correction .................................................................................. 29
  3.5 Error estimation ................................................................................................................................... 29
Abstract
Image acquisition with UAV’s offer great possibilities for remote sensing problems like data gaps and can improve operational flexibility. The remote sensing community devotes major effort to the quality of image data. Unregistered irradiance changes during an UAV-based image acquisition flight can have a large negative effect on this quality. These changes are dependent on atmospheric conditions and need to be monitored and corrected for. Direct incident light sensing with irradiance measuring instruments and empirical line correction with reference reflectance panels offer this possibility. In this research, both methods have been evaluated for stratus, cumulus and cirrus cloud conditions and a clear sky atmosphere. Empirical line correction showed promising results for clear sky and complete overcast conditions. Direct incident light sensing is suitable for irradiance monitoring under most cloud conditions, besides cumulus conditions or other situations with abrupt and large irradiance changes. Incident light measurements need to be made as often and as close to the UAV as possible; spectral resolution is not an important factor. In this research irradiance monitoring and correction on UAV-acquired images has been applied in the field. The results showed that, although there are yet unknown factors that can negatively influence the quality of incident light correction, in general it can be stated that with simple methods UAV-acquired images can be much improved.

Keywords: remote sensing, UAV, irradiance monitoring, incident light sensing, empirical line correction
1 Introduction

1.1 Context

Unmanned Aerial Vehicles (UAV’s) provide a new, controllable platform for remote data acquisition. “In the past, the majority of remote sensing applications in agriculture were either satellite- or ground-based. Over the last few years we have seen a rapid increase in airborne remote sensing due to the proliferation of multispectral digital airborne sensors” (Nebiker et al., 2008). They provide potential for acquiring remote data more rapidly and at lower cost than from piloted aerial vehicles. They can monitor areas on a real-time basis at affordable costs at any moment that the researcher prefers (Everaerts, 2008). Furthermore, UAV-based remote sensing offers benefits in terms of frequency of coverage, spatial resolution, flexibility in spectral resolution and maintenance and calibration. They also have the advantage of being deployed during windows of good weather (Malthus & Mumby, 2003) and they offer the possibility to acquire images during cloudy weather conditions (even complete overcast), something a satellite cannot do (Sugiura et al., 2005).

The Laboratory of Geo-Information Science and Remote Sensing (GRS) of Wageningen University is currently working on a facility for Unmanned Airborne Remote Sensing. This facility has been operational since spring of 2013 and several experiments have been done during the summer of the same year. The main part of these experiments consists of image acquisition flights with sensing instruments mounted on an UAV, focusing on applications like precision agriculture and ecosystem classification.

1.1.1 UAV’s

Classification of Unmanned Aerial Systems (UAS) platforms for civil scientific uses has generally followed existing military descriptions of the platforms based upon characteristics such as size, flight endurance, and capabilities (Watts et al., 2012). There are basically two types of UAV’s, distinctive in their flying mechanisms. In the category of UAV’s with a fixed wing system -similar to the structure of an airplane-, there is a distinction between the smaller types that do not need a runway for take-off (a few kg’s), and the larger UAV’s with a high payload and/or long flight-time. A second type of UAV has the structure based on the same principle as a helicopter, using rotor blades for vertical lift and steering.

One of the UAV’s used by the Wageningen University is such a Vertical Take-off and Landing (VTOL) UAV. Aircrafts of this type operate at varying altitudes depending on their mission profile, but predominantly fly at low altitudes. High power requirements for hovering limit the flight durations for VTOLs (Watts et al., 2012). An advantage of VTOL UAV’s are the portability of the platforms for remote area operations without the necessity for a runway infrastructure (Watts et al., 2012). Another advantage is the fact that a VTOL-type can hover, and can maneuver in three dimensions. These maneuvering capabilities are also essential for successful operation in windy conditions when providing low-altitude coverage (Mullens et al., 2003). The UAV used in this study uses eight rotors for uplift and can move vertically and sideways by increasing or decreasing the spinning speed of its individual rotors.

There is a distinction between the term UAV and UAS. The UAS consist of the aircraft component, sensor payloads, and a ground control station (Watts et al., 2012). The UAV is solely the aircraft component. Further on only the term UAV will be used and it is assumed that this UAV has a mounted sensor and is controlled by a ground control station, either manually or based on GPS-points. When necessary the sensor type is stated.
1.1.2 UAV’s and image acquisition

The UAV can be mounted with a wide range of sensors and virtually the only limit is the payload of the UAV. The GRS Laboratory of Wageningen University currently uses three different sensors, namely an orthophoto sensor system measuring in the visual part of the spectrum, a three-band multispectral system (green, red and near-infrared) and a hyperspectral camera system measuring in the range of 400-1000 nm with 5nm spectral resolution (Juha Suomalainen, 2012a). Because of the low payload of the UAV and limited financial budget, commercially available, affordable, lightweight sensors have to be used for image acquisition. There is a relatively large budget but top-of-the-shelf equipment is not always in the affordable price range. However, “if enough attention is paid to the processing and calibration of the data, satisfying results can be achieved with these relatively cheap sensor systems” (Hakala et al., 2010). “The remote sensing community devotes major effort to calibration and validation of sensors, measurements, and derived products to quantify and reduce their uncertainties” (Schaepman-Strub et al., 2006). The calibration and validation needs are not only applicable to classical remote sensing systems like satellites and sensors mounted on airplanes but also for UAV image acquisition.

1.1.3 Incident light

The information of interest for which any image acquisition procedure is executed is the reflectance characteristics. This reflection, as depicted in Figure 1 is the result of the irradiance minus the absorbed radiance and transmitted radiance. These latter two radiance types are the link between irradiance and reflected radiance and are called the reflectance characteristics of an object. What is also clear from Figure 1 is that it is essential to not only measure the reflected radiance but also the irradiance. In general every passive sensor system uses as sole source of irradiance the radiance from the sun. Due to changes in the composition or length of the path that the photons have to pass through (the length from the source to the object and/or image acquisition sensor and the particles in that path, like the atmosphere) a change in the irradiance can occur. If the irradiance is not measured there is an uncertainty whether changes in the reflected radiance are due to the reflectance characteristics of the object of interest or due to the changing irradiance.

There are two methods to determine the level of irradiance and they can be found by looking at the equation that can be derived from Figure 1, as given in Equation 1.

\[
\text{irradiance} = \text{reflected radiance} + \text{absorbed radiance} + \text{transmitted radiance}
\]  

Equation 1

To monitor the irradiance it is both possible to measure the irradiance directly or measure the reflected radiance of an object with known reflectance characteristics. Both methods are used in remote sensing and multiple examples of these methods are given in the literature review. Not all of these methods are directly applicable to remote sensing with the use of an UAV. As already discussed, an UAV has a relatively low payload and is, compared to satellites and airplanes, very close
to the ground with a small operation area. These characteristics can have an influence on which method of irradiance measurement is suitable and/or optimal for the correction of UAV images. UAV’s are also generally below the cloud cover. This is of course one of the main advantages because it can take images at every moment, but on the other hand a different approach is needed for incident light correction than for satellite images. The suitability of these methods can also depend on the nature of irradiance changes. There are multiple types of influence on the irradiance, as can be seen in Figure 2. All objects depicted in this figure (clouds, common and uncommon particles in the atmosphere) can have an influence on the composition of the path of irradiance. The second kind of influence is a change in the solar zenith angle (visualized in Figure 3) which is a function of the time of day, year and global location. The solar zenith angle has an influence on the air mass the photons have to pass through (atmospheric path length). Both types of influence are discussed more extensively in the literature review.

Figure 2: Simplified scheme of the scattering effects of the atmosphere on the irradiance and reflected radiance from the sun (DLR-IMF, 2011)

Figure 3: Illustration of the atmospheric path as a function of the solar zenith angle. AM is the air mass (amount of air) that the irradiance has to pass through. (Newport, 2014)
1.2 Problem definition

The problem that is the inducement of this research is about the need for image correction for images taken with an UAV. Correcting images is necessary because calculated changes in the reflectance characteristics based on the reflected radiance as measured by the UAV sensor should not be dependent on changes in the irradiance from the sun (the incident light) but on changes in the object that is measured. These objects can be vegetation, soil, buildings or anything else worthwhile to measure. Haze or cloudiness can change the distribution of power over the spectrum of sunlight, and the passage of an object like a cloud across the sun can lead to serious error (Levinson et al., 2010). This error is the change in irradiance mistaken for changes in the reflected radiance of the measured object. For image analysis it is important to calculate the reflectance factor which allows the comparison of imagery in space and over time. A reflectance factor can be defined as the ratio of the flux reflected by a sample surface to that which would be reflected into the same beam geometry by a lossless, perfectly diffuse (Lambertian) surface that is identically irradiated (Nicodemus et al., 1977).

When changes in the atmosphere occur during flight they have an influence on the solar irradiance. A regularly used method to obtain an irradiance value is the following procedure: at the beginning of the image acquisition flight an image is taken of a reference panel. This panel has a known reflectance factor $R_{REF}$ and its use can be shown in the following formula (Equation 2):

$$R_{REF} = \frac{L_{REF}}{E_{REF}}$$  \hspace{1cm} \text{Equation 2}

Where $E_{REF}$ is the incoming irradiance hitting the reference panel and $L_{REF}$ the measured reflected radiance of the reference panels by the remote sensing device, in this case the UAV. The formula in Equation 3 can be used to calculate the reflectance factor of any target:

$$\frac{R_T}{R_{REF}} = \frac{L_T}{L_{REF}} \times \frac{E_{REF}}{E_T}$$  \hspace{1cm} \text{Equation 3}

Where $R_T$ and $R_{REF}$ are the reflectance of the target and reference reflectance, $L_T$ and $L_{REF}$ are the reflected measured value of the target and the reference reflectance object and $E_T$ and $E_{REF}$ are the irradiance at the target and reference reflectance object. Measured reflectance is saved and processed on a medium like a computer by a digital number (DN), a calibrated value representing the irradiance hitting the pixel of the sensor. This DN is till this part of the procedure not yet meaningful because only the total reflected radiance is known (Equation 1). What is needed is the reflectance as a ratio of reflected radiance to irradiance. The following formula (Equation 4) can thus be used to calculate the actual reflectance ratio of the target from the measured DN$_T$ (Ma et al., 2012):

$$R_T = \frac{DN_T}{DN_{REF}} \times R_{REF}$$  \hspace{1cm} \text{Equation 4}

Where $R_T$ and $R_{REF}$ and DN$_T$ and DN$_{REF}$ are the reflectance factors and DN’s of the target and the reference panel respectively.

This procedure makes it possible to compare images of different flights even when the irradiance changed between those flights. The problem with this simple method is that it uses one value per
spectral band, $R_{REF}$, to do an incident light correction for all DN values obtained during a flight. However, it does not take into account that the irradiance can change within one flight. It is without a doubt that these changes occur. As a matter of fact, these changes always occur since the irradiance path length is a function of the solar zenith angle, which is again a function of time, which changes constantly. The next question is whether the magnitude of these changes is relevant when the duration of an image acquisition flight is very short. Besides these constant changes there are more types of incidental changes, as depicted in Figure 2, that can influence the irradiance very abruptly regardless of the duration of the flight is, which are clouds. Irradiance changes caused by clouds can occur both in space and time, since they have a spatial location that can also change in time due to wind.

Irradiance changes caused by objects in the atmosphere or by a change in the solar zenith angle are not corrected for with the method shown in Equation 4. Every change in irradiance that occurs during the flight is in the current irradiance correction procedure contributed to a change in the reflectance characteristics of the object of interest on the ground. A different approach is needed to correct the measured reflectance during a flight for a change in solar irradiance (incident light) if these changes are significant. The significance of these changes needs to be reviewed in combination with the probability of these changes happening during the flight. This probability again depends on three aspects. The first is the duration of the flight, since a longer flight increases the probability of sudden changes occurring and extends the influence of the solar zenith angle on the irradiance level. The second aspect is the range of the image acquisition flight, because when a larger area is covered the probability increases of an object like a cloud being present in the atmosphere that is not measured at the location of the reference reflectance panel. The third aspect is the general condition of the atmosphere relating to heterogeneity and frequency of clouds. This aspect is also influenced by the wind-speed in the atmospheric layer where the clouds are present, which has a direct effect on the frequency of changes in irradiance on the ground.

At the moment there is no such classification of combinations of atmospheric conditions, flight duration and flight distance for which there are thresholds of error probability. This means that it is not known under which conditions the results of an image acquisition flight are useful and reliable or correctable for irradiance. In the current situation only a subjective classification by the UAV operator can be done and based on that the decision is made whether a UAV image acquisition flight is done.

In this research a method is proposed for monitoring and correcting the changes in irradiance for different atmospheric conditions, both constant and incidental changes. The basis for these atmospheric conditions is a basic atmospheric classification with the main distinct atmospheric conditions. Based on the results an advice is given for the actions necessary during these conditions to obtain better images through measurements of irradiance during an UAV image acquisition flight. A prediction is made about the errors that can occur during certain atmospheric conditions. To assess these steps the following research objective has been set up.
1.3 Research objective

The overall objective of this research is to develop a methodology and general protocol for solar irradiance measurement and correction of images taken with an UAV under different atmospheric conditions.

The following detailed research objectives elaborate on this general research objective:

- Develop a classification for atmospheric conditions influencing the choice of use of irradiance monitoring methods during an UAV image acquisition flight.
- Develop or obtain and test an instrument (system) most suitable for the irradiance measurements and test these instrument(s) in a controlled environment and in the field.
- Analyze the results of the correction of the acquired images with the obtained irradiance values that were monitored during a VTOL UAV image acquisition flight.
- Write a general protocol for the use of the incident light measuring methods under different atmospheric conditions

1.4 Research questions

The main research question that needs to be answered to reach these objectives is:

“Which combination of methods and instruments can be used to monitor the solar irradiance changes for the correction of images acquired during a VTOL UAV-flight?”

The following detailed research questions elaborate on this general research question:

- Which atmospheric conditions can be classified as influential on solar irradiance and how do they influence this irradiance?
- Which instruments are available to measure solar irradiance in which wavelengths?
- What is the best instrument (system) under different atmospheric conditions?
- How can measured changes in solar irradiance be incorporated in a procedure for UAV image correction?

1.5 Reading guide

In the next chapter there is a review on the current knowledge in this field. This is broadly split up in atmospheric conditions, image correction, incident light sensing and empirical line correction. Based on the findings in this literature review methods are proposed, in the methodology chapter to determine if and how well these findings can be applied to improve irradiance monitoring and correction of UAV-acquired images. The fourth chapter shows the results of the methods proposed in the methodology. In the discussion section unexpected results are discussed and based on an integrated summary of the results it is evaluated how the results can contribute to the current knowledge on irradiance monitoring and correction for UAV image acquisition. In the sixth chapter a concluding statement is made regarding the results and discussion. The last chapter gives recommendations for further research based on uncertainties and new ideas that arrived during this research.
2 Literature review
This section is a review about the methods that related research provide in the field of atmospheric classification, irradiance measurement and irradiance correction.

2.1 Atmospheric conditions
There is an influence of particles in the atmosphere on incident photons due to scattering and absorption characteristics of these particles. This influence depends on the type of particle the individual photons interact with—the composition of the atmosphere or the path composition—and the amount of particles that are interacted with—the path length—(Ritter, 2012) Both of these characteristics can be relatively homogeneous or heterogeneous in the atmosphere. Homogeneity and heterogeneity depend in this case on the area of the atmosphere relative to the area of interest (the area of which images are acquired by the UAV). When stated that the atmosphere is homogeneous, then this means that there are no temporal differences during the flight or spatial differences—lateral to the earth—within the atmosphere that influence the irradiance observed at ground-level. When there are spatial or temporal changes, for instance when clouds are present in the sky in the area of interest, then the atmosphere is heterogeneous. In the following paragraph the types of atmospheric influences are discussed. A distinction is made between constant changes and incidental changes.

2.1.1 Constant changes
It is possible to distinguish changes in path length (constant) or changes in path composition (mostly incidental). For this method it is necessary to distinguish between constant changes that occur because of a change in the path length of the irradiance and constant changes that seem to occur but are actually changes in the composition of the atmosphere that influence the irradiance for a relatively long time compared to the image acquisition flight. An object with that kind of influence could occur in a situation where there is a rapid accumulation of clouds, haze, fox or mist (Ritter, 2012). The distinction between constant changes due to a change in solar zenith angle and a change due to rapid accumulation is important because the former change does not have an impact on the atmospheric composition, while the latter does.

Since UAV image acquisition is at a low altitude the distance from the observer to the observed object is negligible in this case, leaving the atmospheric path length as a function of the solar zenith angle, as was shown in Figure 3. If all constant changes are due to changes in the solar zenith angle then it should be possible to correct for the change in atmospheric path length (air mass) with a function based on the solar zenith angle. This function is given in Equation 5 (Pickering, 2002):

\[ X = \frac{1}{\sin(h + \frac{244}{165 + 47h})} \]

Equation 5

Where X is the air mass and h is the altitude or angle above the geometric horizon (h is 90° minus solar zenith angle). The solar zenith angle or altitude can again be derived from the local time, date and latitude at the measurement with a solar position calculator (Cornwall et al., 2014).

2.1.2 Incidental changes
Incidental atmospheric changes are changes that can occur instantly and do not result in a linear increase or decrease over the duration of the UAV flight. The most regular cause of occurrence of incidental changes is the presence of clouds. Other aerosols can also influence the irradiance but no examples in literature were found that indicated large and frequent changes in the composition of the atmosphere caused by objects other than clouds. An occurrence of a change in air mass would
have an impact on the composition of the atmosphere, which would lead to changes in the irradiance that are not due to clouds. However, air masses tend to be very large (Kasten & Young, 1989) and the chances of rapid changes are very low since the area of interest for the UAV is so small in comparison. Therefore no changes in the composition of the entire atmosphere are expected during the relative short time span of an UAV image acquisition flight.

In the next sections, different kinds of clouds are discussed.

2.1.3 Cloud types
The interaction of photons with particles in the cloud is comparable to a homogeneous atmosphere-again a function of the composition of the cloud and the path length through the cloud, assuming that a cloud is a homogeneous object. When the atmosphere is not entirely covered it is necessary to add the diffuse irradiance at sea-level that has no path through the clouds. All possible radiance directions and interactions are shown in Figure 2. However, first it is necessary to find out if it is possible to estimate the spectral distribution of different cloud types. Figure 4 shows a summary of the different cloud types. For this research the thickness, homogeneity of thickness, size and spectral absorption distribution are important.

The optical thickness describes how much light passes through the cloud. This can be described by the extinction coefficient. The extinction coefficient is a product of the scattering and absorption coefficient (Hess et al., 1998). These coefficient variables are dependent on the density of these particles.

The homogeneity of the optical thickness is important for the spatial and temporal inter- and extrapolation of the field measurements for example in the case of complete overcast (e.g., stratus). When a cloud is fully homogeneous and there is a difference in irradiance between two irradiance measurement locations at the same time we can assume that at one location there is a cloud and at the location there is not.

The size of the clouds is a variable that influences the probability of differences in irradiance over the area that is observed by the UAV. To be more precise, the size of the clouds related to the size of the study area is the important variable. A larger cloud with equal wind speed will lead to a longer time-span with equal irradiance levels at ground level.

![Figure 4: Common cloud types occurring in the atmosphere and their relation with the height profile (NOAA, 2011)](image)
The spectral absorption distribution is the most important variable when a combination of incident light sensors (ILS) and image acquisition equipment is used where the spectral resolution of the image acquisition equipment is higher than that of the ILS. Different cloud types will show different spectral absorption distributions because of its composition. For instance, cirrus clouds mainly consist of ice crystals while cumulus and stratus clouds consist of water droplets (Hess et al., 1998). The absorption spectra of these particles can be different and therefore the irradiance spectra at ground-level.

A good solution for the classification of different clouds would be to model the influence on the spectral distribution of the irradiance for different clouds. However, there are still large anomalies between what this influence will be when derived from theoretical models and measurements in practice. This could be caused by the difficulty of obtaining empirical cloud absorption data in a controlled environment (Stephens & Tsay, 1990). There is still no conclusive explanation for the difference between actual and modeled cloud absorption characteristics (Schmidt et al., 2010).

2.1.3.1 Cirrus
Cirrus clouds are a genus of atmospheric clouds generally characterized by thin, wispy strands, giving them their name from the Latin word cirrus meaning a ringlet or curling lock of hair. Cirrus clouds generally appear white or light gray in color. Cirrus clouds range in thickness from 100 m to 8000 m, with an average thickness of 1500 m. There are, on average, 30 ice crystals per liter, but this ranges from one ice crystal per 10,000 liters to 10,000 ice crystals per liter, a difference of eight orders of magnitude. (Wikipedia.org, 2013a)

2.1.3.2 Cumulus
Cumulus clouds are a type of low-level cloud that can have noticeable vertical development and clearly defined edges. Cumulo- means "heap" or "pile" in Latin. They are often described as "puffy" or "cotton-like" in appearance, and generally have flat bases. Cumulus clouds, being low-stage clouds, are generally less than 2.000 m in altitude unless they are of the more vertical cumulus congestus form. Cumulus clouds may appear by themselves, in lines, or in clusters. (Wikipedia.org, 2013b)

2.1.3.3 Stratus
"A stratus cloud is a cloud belonging to a class characterized by horizontal layering with a uniform base, as opposed to convective clouds that are as tall or taller than wide (these are termed cumulus clouds). More specifically, the term stratus is used to describe flat, hazy, featureless clouds of low altitude varying in color from dark gray to nearly white. Stratus clouds may produce a light drizzle or snow. A "cloudy day" usually features a sky filled with stratus clouds obscuring the disk of the sun. These clouds are essentially above-ground fog formed either through the lifting of morning fog or when cold air moves at low altitudes over a region. Some call these clouds "High fog" for the fog like cloud." (Wikipedia.org, 2013c)

2.1.3.4 Nimbus
"A nimbus cloud is a cloud that produces precipitation. Usually the precipitation reaches the ground as rain, hail, snow, or sleet. Falling precipitation may evaporate before reaching the ground.

Since nimbus clouds are dense with water, they appear darker than other clouds. Additionally, nimbus clouds can be characterized by their great height. Nimbus clouds are formed at low altitudes and are typically spread uniformly across the sky. “(Wikipedia.org, 2013d). Nimbus clouds tend to produce rain, which could damage any equipment used in the field, being the UAV, the UAV sensor(s) and also the incident light sensor. Therefore it is not advisable to do a flight during these conditions and no further analysis of this type of cloud is discussed.
2.1.3.5 Combinations
Most cloud types mentioned above can be combined and there are numerous combinations possible (Wikipedia.org, 2013e). The list provided by Wikipedia is far too extensive for a visible classification in the field prior to an image acquisition flight. On the other hand, using only the four basic types - cirrus, cumulus, stratus and nimbus- might be too simplistic to predict the influence of the atmosphere on the spectral distribution. The balance in extensiveness of the classification of the clouds and atmosphere depends on the available instruments and the distinctiveness of the influence on the spectral distribution of different cloud types.

2.1.3.6 Cloud properties
As stated in the first part of this section on Atmospheric conditions (section 2.1) the influence of clouds on the spectral distribution depends on the length of the path of the photon through the cloud and the composition of the cloud in this path -the influence on individual wavelengths-. When the composition for a cloud is known then the irradiance spectrum can be calculated based on the total irradiance or a low number of spectral bands, regardless of the optical depth of the cloud.

The composition of clouds dictates the influence on different wavelengths of the incident light spectrum. Clouds consist mainly of water particles and these have their specific absorption bands, like water vapor at i.e. 1.4μm and 1.9μm (Cotton et al., 2010). Other particles besides water that are found in clouds are, among others, H$_2$O$_2$, Cl$^-$, NO$_3^-$, SO$_2^-$, NH$_4^+$ (Römer et al., 1985). Since different molecules have different absorption features, there are a multitude of absorption bands with different absorption levels for clouds. An atmospheric classification based on different cloud compositions would require knowing the probable composition of a cloud based on a visual observation by the UAV operator. This classification needs to include all cloud types that have a spectral distribution that differs significantly for individual wavelengths from other cloud types. When this results in a cloud classification set that is too complex for visual classification in the field then this method is not suitable and more spectral bands are needed in the ILS.

2.2 Image correction
The standard current method to calculate the reflectance values out of DN-values was already shown in Equation 4. In this section different methods to monitor the irradiance within a flight are discussed. As was explained in section 1.1.3 the irradiance can be measured by either measuring the irradiance directly, or measuring the reflectance factor of an object with known transmittance and absorption characteristics. This first method is called incident light sensing, the latter empirical line correction (Taylor et al., 2010).

Incident light sensing, the measuring of the irradiance directly with an instrument, is discussed in section 2.3. The technique of measuring reflected radiance of an object with known reflectance characteristics -empirical line correction- can be applied in two methods. With both methods a scan is made multiple times during a flight of an object that has absorption and transmittance characteristics that are invariant in time (Karpouzli & Malthus, 2003). The most suitable object in this case is a reference reflectance panel (Labsphere Inc., 2013). This panel is not only invariant in time, but also almost totally Lambertian and thus invariant regarding the viewing angle of the sensor that scans the panel. However, if the viewing angle is always virtually the same and if it can be said with certainty that the object used in the empirical line correction does not change in time then that object is suitable as well. More detail about the empirical line correction method is given in section 2.4.
2.3 Incident light sensing

With incident light sensing the irradiance is measured during a flight so that changes in the reflected radiance are only dependent on changes in the reflectance characteristics of an object and not due to irradiance. This incident light sensor (ILS) can be placed directly at the UAV sensor, turning it into an albedo meter (Schaepman-Strup et al., 2006), or it can be placed independently from the sensor mounted on the UAV. This latter method can produce errors due to differences in irradiance in space but it decreases the payload of the UAV and provides opportunities for better ILS instruments. This is elaborated upon in section 2.3.1 and 0. The formula to correct the reflectance of the target with irradiance measurements from an ILS is given in Equation 6:

\[ R_T = \left( \frac{D_{NT}}{D_{N_{REF}}} \times R_{REF} \right) \times \left( \frac{E_{REF}}{E_T} \right) \tag{Equation 6} \]

Where \( R_T \) and \( R_{REF} \) are the reflectance of the target and reference panel respectively, \( D_{NT} \) and \( D_{N_{REF}} \) the calibrated digital numbers of the target and reference panel, and \( E_T \) and \( E_{REF} \) the irradiance at the moment of measurement of the target and reference panel. The \( E_{REF} \) and \( E_T \) are measured by the ILS and should be measured at the same moment as the \( D_{N_{REF}} \) and \( D_{NT} \) respectively. These irradiance and reflected radiance values can later be combined based on the timing data that needs to be produced by the sensor, preferably GPS-timed (Lewandowski & Thomas, 1991).

2.3.1 Instruments

For the monitoring of solar irradiance there is a large range of instruments available. These instruments can vary in radiometric, spectral and temporal resolution. In this section the range of instruments is discussed regarding the potential to irradiance monitoring during an UAV flight. The basis on the choice of instruments for different UAV-flight is to use the easiest and least expensive option that is suitable to obtain measurements that are reliable and usable for correction of UAV-acquired images. What is suitable and what is not may depend on the weather circumstances and the choice of instrument is therefore linked to the atmospheric conditions. One of the requirements of the instrument is that it measures in a dome of 180° of the sky so all illumination angles are considered when measuring the irradiance.

In general it can be said that instruments that have a higher temporal, radiometric and spectral resolution with better signal-to-noise ratios are heavier than instruments with lower resolution. This means that since UAV’s have such a small payload there is a consideration between the quality of the ILS and the option of placing the incident light sensor on the UAV. With a high-quality ILS less error can be expected due to rapid changes in time or changes in individual wavelengths of the irradiance. On the other hand, with a mounted low-quality instrument less error due to spatial differences in irradiance between the location of the ILS and the location of the object measured by the UAV can be expected.

The results of an experiment by Hakala et al. (2013) showed that a high-quality instrument placed on the ground, independent of the UAV, provided better results under varying illumination conditions than a low-quality sensor mounted on the UAV. They obtained a variation coefficient of 0.065-0.09 reflectance with a correction based on incident light sensing compared to a variation coefficient of reflectance of 0.14-0.18 with uncorrected data. In this experiment the high-quality instrument is a hyperspectral sensor, a Fieldspec 4 with cosine receptor (discussed in section 2.3.1.3) and the low-quality instrument is a panchromatic pyranometer (discussed in section 2.3.1.1). However they do state that the cause of the worse results from the mounted ILS compared to the ground-based ILS could be that the former was fitted on the UAV incorrectly. It was not discussed in this paper what
the exact atmospheric conditions were besides that the total irradiance changed up to 100% during the flights. It is also unknown what the spatial range of the UAV was. The UAV was a VTOL-type, the same as the one used further on in this research, and it can be assumed that the flight range was comparable to that discussed in the rest of this research.

2.3.1.1 Panchromatic

A panchromatic measurement instrument measures in one band. The instruments discussed in this category are the pyranometer and the photovoltaic cell. The pyranometer measures the direct and diffuse sun light over 180° with a single output in Wm⁻². The pyranometer is a flat surface with a dome. This dome filters all the light above 2800 nm and the rest is captured by a thermophile plate (Figure 5). The heat is then converted into an electric flux that can be registered by a storage device as a value. A potential problem with this system is the measurement lag during changes in irradiance due to the relatively slow heating and cooling of the instrument, which takes at least five seconds (Kipp & Zonen, 2013a). Because in this study the focus is on the wavelengths between 450 and 1000 nm it is assumed that a band filter is applied on the pyranometer simulated in this study to only allow the sunlight in these wavelengths.

Figure 5: Pyranometer models (Kipp & Zonen, 2013b)

A photovoltaic cell converts sun light to radiance in Wm⁻². It works in the same way as the pyranometer. However, the pyranometer is specially designed for measuring the solar irradiance, for instance with a coating to block the higher wavelengths and a structure that minimalizes heating of the measuring instrument. The advantage of a photovoltaic cell is that it is cheaper than the pyranometer. A photovoltaic cell has been successfully used as an irradiance measurement device by Salas et al. (2006) and Suomalainen et al. (2009). There is no time-lag for the measurements because it does not work with a thermophile measurement system like the pyranometer but registers the irradiance immediately (Knier, 2013).

2.3.1.2 Multispectral

A multispectral sensor measures in multiple bands. The most well-known multispectral instrument is the RGB-camera. Another well-known adaptation of this camera is a false color camera that makes images in the green, red and near-infrared (Resource Mapping, 2010). A standard RGB-camera can be fitted with a fish-eye lens, giving it a larger viewing angle than a normal camera. This system has been tested by (Gauchet et al., 2012)to take irradiance measurements and has given satisfactory results. These images could possibly also provide spatial data on the atmospheric conditions but this is not of interest to the current research. One of the problems with this camera system is the probability of over-saturation when exposed to direct sunlight, since this system is not build for irradiance measurements. Also, the camera does not take images of the whole sky, even with a fish-eye lens. For the simulations as described in the methodology it is assumed that it is possible to measure over the entire 180° atmospheric dome.

The photovoltaic cells as described above in section 2.3.1.1 can be adapted to only measure in a certain band when a band filter for a specific wavelength is applied. It is possible to measure
different wavelengths with the use of multiple photovoltaic cells and different band filters. This means that the irradiance could be measured in specifically tailored bands that would provide the most complete coverage of the variation in the irradiance spectra during a UAV flight. An example of an instrument with customized multispectral bands is the Cropscan (Cropscan Inc, 2013). The measurements of an instrument like the Cropscan have no spatial attributes since it measures in only one pixel. The manufacturer of this instrument supplies many possible combinations of bands, which is too extensive to analyze in this research. Therefore the RGB and false color camera are used for analysis further on. Also, it is calculated which combinations of bands or all weather types would be most suitable to incorporate in one instrument for incident light sensing.

2.3.1.3 Hyperspectral sensor

A hyperspectral radiometer measures the irradiance over multiple bands in the (shortwave) spectrum. The spectrometer can have multiple or only one pixels, meaning that there is a spatial indicator for the origin of the irradiance or not. The FieldSpec 4 (ASD, 2012) used as ILS (as shown on the left of Figure 9) in this research has no spatial unit so it cannot distinguish the irradiance for different parts of the atmosphere. The FieldSpec can measure the irradiance over a 180° dome when mounted with a cosine receptor (Figure 7). A cosine receptor measures cosine-corrected values from which measurement errors are eliminated that can arise when the light source has a zenith angle larger than 0° (Skye instruments, 2007). The instrument is presumably the best available on the market. A downside of this instrument is that it is heavy and relatively expensive.

<table>
<thead>
<tr>
<th>Instrument Type</th>
<th>Bands</th>
<th>Wavelength Range</th>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyranometer</td>
<td>1</td>
<td>400-2800 nm</td>
<td>Built for solar irradiance measurements</td>
<td>Long time-lag due to thermophile plate</td>
</tr>
<tr>
<td>Pyranometer with band filter</td>
<td>1</td>
<td>UD</td>
<td>Measure wavelength range that is necessary</td>
<td>Not readily available plus long time lag</td>
</tr>
<tr>
<td>Photovoltaic cell</td>
<td>1</td>
<td>400-2800 nm</td>
<td>Immediate irradiance change</td>
<td>Not readily available</td>
</tr>
<tr>
<td>Photovoltaic cell with band filter</td>
<td>UD</td>
<td>UD</td>
<td>Infinite combination of bands</td>
<td>Not readily available</td>
</tr>
<tr>
<td>RGB camera (+fish-eye lens)</td>
<td>3</td>
<td>400-750 nm</td>
<td>Readily available</td>
<td>Fish-eye lens not extensively tested</td>
</tr>
<tr>
<td>False color camera (+fish-eye lens)</td>
<td>3</td>
<td>500-1000 nm</td>
<td>Measures infrared and readily available</td>
<td>Produces lot of noise plus</td>
</tr>
<tr>
<td>Hyperspectral sensor</td>
<td>UD</td>
<td>UD</td>
<td>High accuracy, large number of bands</td>
<td>Expensive &amp; heavy</td>
</tr>
</tbody>
</table>
2.3.2 ILS allocation

The ILS should ideally be placed on the UAV, to minimize the distance between UAV sensor and ILS and the probability of spatial variation in irradiance. Due to the low payload of an UAV it may however not be a possible or best option. An increase in payload will limit the possible weight (and in most cases therefore quality) of other sensors and the maximum-flight-time. Also, if the ILS would be placed on the ground the weight of the ILS would not matter and a Fieldspec could be used as easily—with regard to weight-as a pyranometer (of course except for other operational constraints like the ease of carrying the instrument around). Also, when an ILS is mounted on the UAV and the UAV tilts away or towards the sun an error is produced due to an over-or underestimation of the irradiance. This was tested by Katsaros & Devault (1986) and it was estimated that a tilt of 10° produces an error of 10-20%.

As said this spatial difference between UAV and ILS could result in a measurement of the irradiance that is not representative for the irradiance level at the location of the UAV. Multiple measuring locations of the incident light could mitigate this problem, decreasing the average/maximum distance between an ILS and the UAV. There is a limit to the extent of how much an increasing number of measuring points can mitigate this problem. When weather conditions change too abruptly, virtually no images can be entirely corrected for the rapid change of atmospheric conditions. The need for more instruments increases the need for inexpensive and light ILS instruments.

Because the UAV is not directly on the ground but has a flying height of 10-80 meters (Juha Suomalainen, 2012b), there can be irradiance anomalies within the width of one scan line. This means that it is always possible that errors occur within one scan that cannot be registered by an ILS, even when it is mounted on the UAV.

2.3.3 Measurement time interval

The ILS takes measurements of the incident light in intervals. These intervals can be small or large and this has influence on the reliability of the correction of images that are not taken at the exact moment that a measurement with the ILS is done. The pyranometer discussed in section 2.3.1.1 had a time-lag minimum of five seconds because a thermophile plate was used. Other reasons for a delay can be a slow processing time of irradiance to digital values or a longer illumination time to increase the signal-to-noise ratio of the measurement. If changes in irradiance are rapid then it is important to have small time-lags. With high temporal resolution the error due to these rapid changes is smaller.

2.4 Empirical line correction

The current irradiance correction with one scan of the reference reflectance panel does not provide solutions for irradiance changes within one flight. When changes are linear, because there is no change in the composition of the atmosphere but only due to the solar zenith angle one extra scan at the end of the flight could be a solution to this problem. With even more scans of a reference reflectance panel also incidental changes could be tracked because a change in the DN value of a scan of a reference panel indicates a change in the irradiance. The method to calculate the actual reflectance of a target based on multiple scans of a reference reflectance panel during a flight is shown in Equation 7.

\[ R_T(t=t_2) = \frac{DNT(t=t_2)}{DNREF(t=t_1) + DNT(t=t_2)} \times R_{REF} \]

Equation 7
Where \( R_T \) and \( R_{\text{REF}} \) are the reflectance of the target and reference panel respectively, \( \text{DN}_T \) the digital number of the target, \( \text{DN}_{\text{REF}} \) the digital number of the scan of the reference panel, \( t_1 \) the time of the scan of the reference panel prior to the target, \( t_2 \) the time of the scan of the reference panel after to the target and \( t_2 \) the time of the scan of the target.

Hakala et al. (2013) have used a similar method where they used the difference in reflected radiance from objects that were scanned multiple times during a flight. This difference was then attributed to a change in the irradiance. Since only relative values are used no absolute reflectance characteristics need to be known about the object in the pixels that are used for this method. This method showed even better results than using an ILS (described in section 2.3.1), with a variation coefficient of 0.05-0.075 with a correction based on the relative offset between pixels combined with a bidirectional reflectance distribution function (BRDF) correction. The uncorrected variation coefficient was 0.14-0.18.

Since only relative reflectance values are used care needs to be taken with this method. “The effect of these methods on quantitative estimation of land surface properties is unknown” (Asmat et al., 2011). All changes in reflected radiance are attributed to a change in irradiance while this does not necessarily need to be the case. The reflectance characteristics could have changed between the scans of a pixel (e.g. due to a deformation of a flexible object (like crops) through wind or human interference). Also, when the anisotropic characteristics of the object in the pixel are not known the BRDF correction can introduce more errors when absolute reflectance characteristics are calculated later in the process.

Because of these uncertainties it is advisable to use a reference reflectance panel like a Spectralon panel (Labsphere Inc., 2013), which will minimize the effect of the BRDF and errors in irradiance correction due to changes in reflectance characteristics of the object that is used for empirical line correction. Downside of using a reference reflectance panel as the only source for the empirical line correction is that a lot of them need to be placed in the field or the UAV has to have a flight plan with which it passes over the panel several times if there are frequent changes in the irradiance.

This method of irradiance correction with the empirical line method with the use of a reference reflectance panel has been used in earlier studies (J. Clevers, 1986) with images taken from a plane. However, this method can be even more useful with UAV-based image acquisition. Since the UAV is relatively close to the ground (compared to planes) the size of the reference reflectance panel can be smaller. With a limited budget this means that the quality of the panel can be higher which leads to less uncertainty about the relation between irradiance and measured reflected radiance.
3 Methodology

3.1 General procedure

The general procedure consists of two parts, which both consist of four steps. These parts and steps are shown in Figure 6. The first part (starting with incident light measurements in the flowchart) simulates the effects of a range of methods to measure and correct the incident light. One large part of this range is the use of an ILS instrument or ILS instrument system. All instruments evaluated in section 2.3.1 are simulated as realistically as possible with data obtained with the Fieldspec. This includes the possible temporal resolution of such instruments and the spatial setup of these instruments. The other method for incident light sensing and correction was the empirical line correction method -as explained in section 2.4- with multiple scans of a reference reflectance panel.

![Figure 6: Flowchart of general methodology procedure](image_url)
The other part of the methodology (starting with flight- and ground-based image acquisition) is a validation and usability analysis of the whole procedure of incident light sensing and correction during an UAV image-acquisition flight. This is done in two ways. The first method is more controlled, with the UAV sensor at a fixed location and viewing angle. This is the procedure shown on the right side of the flowchart above, starting with ground-based image acquisition. The other method consists of a setup with the sensor mounted on the UAV doing a normal UAV image-acquisition flight. This is the middle part of the flowchart that starts with flight-based image acquisition.

The methodology consists of four steps after which the data has been analyzed. These steps are: 1) Data acquisition, 2) Data preparation, 3) Analysis and 4) Error estimation. These steps are discussed in the next four sections.

3.2 Data acquisition

3.2.1 Incident light measurements

Four datasets are used for the simulation of the effects of multiple incident light measurement and correction methods (Table 2). These datasets are all obtained during distinct weather/cloud conditions. All measurements are taken with a combination of the FieldSpec and a cosine receptor (Figure 7) which collects light with an 180° field of view using demountable diffusers with ~10% loss (ASD inc., 2013). The measurements of the FieldSpec are of relatively high quality and given the expected quality of other instruments like an RGB camera or pyranometer -that are now simulated-, it is used as the best instrument available. The cosine receptor was placed about 1.5 meters above the ground, at least 15 meters away from trees and no significant influence from other illumination sources than direct sunlight and diffuse sunlight are expected.

Table 2: Datasets that were acquired during the data acquisition - incident light sensing step. The local time at the data acquisition is approximate for the starting time of the measurements. Cloud conditions were visually identical during the whole acquisition.

<table>
<thead>
<tr>
<th>atmospheric class</th>
<th>Number of measurements</th>
<th>Date and local time</th>
<th>Time between measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cirrus clouds</td>
<td>3223</td>
<td>03/10/2013 12:00</td>
<td>3 seconds</td>
</tr>
<tr>
<td>Clear sky</td>
<td>2499</td>
<td>30/09/2013 12:00</td>
<td>3 seconds</td>
</tr>
<tr>
<td>Cumulus clouds</td>
<td>1000</td>
<td>12/09/2013 15:15</td>
<td>3 seconds</td>
</tr>
<tr>
<td>Stratus clouds</td>
<td>719</td>
<td>13/09/2013 15:30</td>
<td>3 seconds</td>
</tr>
</tbody>
</table>

The measured atmospheric conditions (Table 2): are during clear sky, during heavy stratus cloud conditions, during heavy cirrus cloud conditions and during heavy cumulus cloud conditions. Images were taken during these conditions (Figure 8). It needs to be stated that spectral profiles obtained during visually identically classified weather conditions at other moments can be different than presented in this research since the possibilities of cloud combinations are virtually endless.

Figure 7: Cosine Receptors that can be mounted on the FieldSpec 4 (ASD inc., 2013) The upper-left instrument was used in the acquisition of the ILS datasets.
Figure 8: Four pictures taken during the data acquisition of the incident light data for four distinct weather types. From top-left to bottom-right: Cirrus dataset, clear-sky dataset, cumulus dataset, stratus dataset. The camera’s with which these images were taken had automatic adaptation to the illumination levels, so the brightness of the pictures is not representative for the irradiance levels in the ILS datasets.
3.2.2 Ground-based image acquisition

The result of the ground-based image acquisition consists of two datasets. The first is the ILS dataset. It was obtained with the cosine-receptor mounted on the Fieldspec 4. The instrument was placed at 1.5m above the ground, at least 15 meters from high objects. The dataset is equal to the last half hour of the cirrus dataset, which is described in Table 2 (the acquisition of the cirrus dataset and the ground-based image acquisition test was at the same moment, the Fieldspec data was used for both acquisitions). An impression of the cloud conditions during this image acquisition experiment is shown in the top-left of Figure 8.

The other dataset is from the hyperspectral UAV sensor (Suomalainen et al., 2013) which was mounted on a tripod about 50cm from the ground. The sensor is focused on a fixed point on a reference reflectance panel (Labsphere Inc., 2013) in a fixed viewing angle (setup in Figure 9). The sensor made a scan every ±0.05 seconds with a width of 255 pixels or approximately 30cm. The result is a hyperspectral data cube with DN-values of the reflected radiance of the reference reflectance panel. If the data cube is seen with xyz-coordinates then the x-axis is the scan-width of the scan line, 255 pixels, the y-axis is the time of the data acquisition and the z-axis the different spectral bands of the sensor.

Both sensors were equipped with a GPS-timer, which means that the timing of both instruments is off for a maximum of a few milliseconds. This is necessary to combine the data to later on correct the reflected radiance of the UAV-sensor with the irradiance measured by the ILS.

The advantage of this setup is that it is possible to minimize the effects of differences in illumination of both sensors. The viewing angle is fixed for both instruments and the instruments could be placed very close to each other, minimizing the possibility of a spatial difference in illumination. A downside is that it does not resemble a real UAV-based image acquisition procedure, because the sensor is not mounted on the UAV.

3.2.3 Flight-based image acquisition

The flight-based image acquisition experiment resembles an UAV-based image-acquisition flight as close as possible. The setup consists of the Fieldspec as ILS, one small and ten large reference...
reflectance panels, the UAV and the UAV-sensor. The hyperspectral UAV-sensor (Juha Suomalainen, 2012a) is placed underneath the UAV. The UAV is of the brand/type Altura PRO AT8 (AerialTronics, 2012)

The small reference panel is the same one as used in the ground-based image acquisition and has been used as the only source for calculation of the reference reflectance for irradiance correction during UAV image acquisition flights prior to this research, with a correction according to Equation 4.

The large reference reflectance panels were placed in a line, the panels with the same color overlapping slightly. The panels are 250 by 125 cm, combined about 250 by 250 cm. The panels have 5 shades and there are two panels per shade. The shades range from cream-white (color 1) through gray to black (color 5), as shown in Figure 10. These reference panels have been used by Clevers (1986). The reference panels have not been tested for homogeneity or to what extent they are Lambertian for many years.

The FieldSpec 4, mounted with a cosine receptor and a GPS-timer, is placed 1.5m above the ground and about two meters from the middle of the line of the panels.

The UAV has made three separate flights. At the beginning of every flight a scan is made of the small reference panel. This scan is later in the process used for irradiance correction for comparison between flights. Note that this is the correction method without regard for changes in irradiance within the flight. This method for correction is formulated in Equation 4. The flight is flown in two directions, as shown in Appendix A. This has an influence on the viewing angle, since the UAV is always slightly tilted towards its flight direction. The flying height is approximately 15 meters above the ground. The weather conditions during the flight are clear sky conditions with a slowly decreasing

Figure 10: The setup of the flight-based image acquisition. In the middle the FieldSpec as ILS. Just above it the UAV with UAV sensor. In the front the reference reflectance panels. From left to right; from black (colour 5) to cream-white (colour 1).
solar zenith angle between flights. The irradiance spectra are part of the clear-sky dataset as shown in Table 2 and an image was taken during the flight which shows the weather conditions, which is shown in the top-right of Figure 8. During the third flight some small cirrocumulus clouds (Figure 4) were observed. These measurements are not included in the dataset shown in section 3.2.1 of the clear sky ILS dataset.

3.3 Data preparation
The data obtained during the data acquisition phase needs to be converted to data that is readable and meaningful for analysis. The Fieldspec data consists of raw DN values. A calibration file, created according to the methods described by Hatchell (2013), is used to convert these DN’s to values in Watts per square meter per wavelength. One of the outputs of the Fieldspec measurement is a GPS-timing file. This file contains a GPS time for every measurement made with the Fieldspec. The GPS-timing is added to every measurement. The average spectra for all wavelengths are shown in Figure 11. In Figure 12 the total irradiance for wavelengths between 450 and 1000 nm is shown over time.

Figure 11: Average spectral profiles over all measurements for the four different datasets. Largest differences are observed in the cumulus dataset while no significant differences seem to occur in the stratus dataset. No dataset shows absorption dips that are not observed in other datasets, which means that no significant amount of atmospheric particles with distinct absorption features were present during one dataset acquisition that was not present during other acquisitions. This means also that even though the cirrus clouds consist of ice crystals, the absorption dips are the same as for stratus and cumulus clouds which consist of liquid water.
Figure 12: The total irradiance (sum of wavelengths 450-1000 nm) over time for the four datasets. Note the almost on-off values for the cumulus dataset, with a minimum of around 40 W/m². The clear sky dataset shows a steady increase, which is caused by a decrease in solar zenith angle. The cirrus dataset shows a lot of vibrations due to small clouds passing the direct solar radiance path continuously, with some larger dips due to larger clouds. The stratus dataset shows no abrupt changes, with a maximum of 26 Watt/m². Also note the large differences in length of datasets (0:40-2:50 hours) for a better comprehension of changes in irradiance over time.

The four datasets that are obtained during the data acquisition of section 3.2.1 and prepared in this step are the subject of the analysis as proposed in the sections 3.4.1 to 3.4.5.

The data cubes obtained with the UAV-sensor during the ground- and flight-based image acquisition are converted with the formula described in Equation 4. The reference reflectance \( R_{\text{ref}} \) is the average value of a hand-selected number of pixels from the first scan of the small reference panel used during both tests. For the ground-based test the first few scan lines were used as reference reflectance, for the other scan lines the reflectance was calculated based on this reference reflectance and DN values of both the reference reflectance and the other scan lines. A downside of this method in this case is that the data cannot be compared between flights because all flights use a different reference reflectance in the data preparation phase.

In the case of the ground-based image acquisition only the middle pixels of every scan line (between 100 and 200 of all 255 pixels) are selected. This is done because the pixels that are far off-nadir contain more noise due to a vignetting effect (Catrysse et al., 2000). The removal of the pixels with a far off-nadir viewing angle was not possible for the flight-based image acquisition, because the large reference reflectance panels are located at the edges (Appendix A).
For every line the average value of these 100 pixels is calculated. This is done because this will increase the signal-to-noise ratio even more and the only relevant variable in this test is the change in time (per scan-line). Every pixel on a scan line is taken on virtually the same moment so there is no loss of information if the average value is taken. The result is a non-spatial dataset with an average value per spectral band per scan line. These values are combined with the GPS-data obtained from the UAV-sensor to get timed spectral data.

For the flight-based image acquisition the pixels of the large reference reflectance panels are hand-selected. The pixels are loaded as a data cube in image processing software IDL ENVI and the pixels of these large reference reflectance panels are selected. The datacubes are shown in Appendix A. To these hand-selected reflectance values the timing of the GPS of the UAV-sensor is added to get a timed value for every pixel for every spectral band per large reference reflectance panel.

Only the wavelengths between 450 and 1000 nm are preserved for both flight-based and ground-based test because the wavelengths between 400 and 450 nm produce a lot of noise. Since the ILS measures less often than the UAV-sensor, the ILS data is linked to the UAV-sensor by taking the ILS irradiance value that is closest in time to the individual scan lines of the UAV-sensor.

3.4 Data analysis

In this step the simulations are prepared for different instruments (ILS correction method), different intervals between a scan of a reference reflectance panel (empirical line correction method), and the effects of different spatial ILS distributions and time-lag analysis for an ILS. These simulations are based on the ILS data gathered in the process as described in section 3.2.1 and are more thoroughly described in the sections 3.4.1-3.4.5

The data cubes obtained by the UAV sensor in the flight-based and ground-based test are corrected with the ILS data according to the procedure explained in section 3.4.6. All analysis was done with statistics- and data handling-program Rstudio (Rstudio inc., 2014). The scripts with which the calculations and simulations are done, together with the datasets used for this analysis, can be requested by sending an e-mail to jvduijvenbode@gmail.com.

3.4.1 Instrument simulation

The instrument simulation procedure focuses on the bands that are used by the devices mentioned in 2.3.1, namely the pyranometer, RGB-camera, false color camera and customized instruments that consist of photovoltaic cells with band-filters (Table 1). The bands of these band-filters are derived from the four irradiance datasets (Table 2). For every weather type individually, and all weather types combined, it is analyzed which possible combinations of bands would represent the irradiance for all wavelengths best. The algorithm to calculate the optimal bands per weather type is shown in Figure 13. This algorithm is applied to the individual four datasets and to the aggregation of all datasets. This aggregation is made by merging all datasets into one large dataset, spanning the datasets of the four different weather types.
Figure 13: Algorithm to determine bands of photovoltaic cells with customized band-pass filters. If the correlation value between wavelength n and the first wavelength of the current band is higher than the threshold given by the user, it is added to that band; otherwise it is stored in a new band and from there on every next wavelength is compared to the first wavelength in this new band, and so on.

The wavelengths for the different instruments, with the results of the above-mentioned procedure, are shown in Table 3. The wavelengths in the datasets (1nm bands between 450 and 1000) are averaged per band for every instrument and multiplied by the original number of wavelengths of the datasets (e.g. to simulate the green band of an RGB camera all values of the individual wavelengths between 501 and 600 nm of the Fieldspec are summed up and divided by the number of wavelengths (100 in this case)).

Table 3: The wavelength ranges that are used to calculate the bands of the instruments (sensor bands) and the wavelengths for which these simulated bands are used to again calculate the values of individual wavelengths (measure for). Differences between both columns are in the RGB-camera bands, where the red band of the camera is used to calculate for the wavelengths of the NIR. The same goes for the false color camera, which uses the green band to monitor the blue band. The photovoltaic sensor with bands optimal for all weather types uses a band of 828-930 nm to monitor the wavelengths of 820-1000 nm.

<table>
<thead>
<tr>
<th>instrument</th>
<th>sensor bands (nm):</th>
<th>measure for (nm):</th>
</tr>
</thead>
<tbody>
<tr>
<td>RGB camera</td>
<td>450 - 500</td>
<td>450 - 500</td>
</tr>
<tr>
<td>RGB camera</td>
<td>501 - 600</td>
<td>501 - 600</td>
</tr>
<tr>
<td>RGB camera</td>
<td>601 - 750</td>
<td>601 - 1000</td>
</tr>
<tr>
<td>false color camera</td>
<td>500 - 600</td>
<td>450 - 600</td>
</tr>
<tr>
<td>false color camera</td>
<td>601 - 750</td>
<td>601 - 750</td>
</tr>
<tr>
<td>false color camera</td>
<td>751 - 1000</td>
<td>751 - 1000</td>
</tr>
<tr>
<td>pyranometer</td>
<td>450 - 1000</td>
<td>450 - 1000</td>
</tr>
<tr>
<td>all weather types</td>
<td>450 - 717</td>
<td>450 - 717</td>
</tr>
<tr>
<td>all weather types</td>
<td>718 - 742</td>
<td>718 - 742</td>
</tr>
<tr>
<td>all weather types</td>
<td>743 - 827</td>
<td>743 - 827</td>
</tr>
<tr>
<td>all weather types</td>
<td>828 - 930</td>
<td>828 - 1000</td>
</tr>
<tr>
<td>stratusmeter</td>
<td>450 - 717</td>
<td>450 - 717</td>
</tr>
<tr>
<td>stratusmeter</td>
<td>718 - 764</td>
<td>718 - 764</td>
</tr>
<tr>
<td>stratusmeter</td>
<td>765 - 896</td>
<td>765 - 896</td>
</tr>
<tr>
<td>Instrument</td>
<td>Bands</td>
<td>Bands</td>
</tr>
<tr>
<td>------------------</td>
<td>----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>stratusmeter</td>
<td>897 - 1000</td>
<td>897 - 1000</td>
</tr>
<tr>
<td>cirrusmeter</td>
<td>450 - 757</td>
<td>450 - 757</td>
</tr>
<tr>
<td>cirrusmeter</td>
<td>758 - 772</td>
<td>758 - 772</td>
</tr>
<tr>
<td>cirrusmeter</td>
<td>773 - 1000</td>
<td>773 - 1000</td>
</tr>
<tr>
<td>clearskymeter</td>
<td>450 - 761</td>
<td>450 - 761</td>
</tr>
<tr>
<td>clearskymeter</td>
<td>762 - 930</td>
<td>762 - 930</td>
</tr>
<tr>
<td>clearskymeter</td>
<td>931 - 1000</td>
<td>931 - 1000</td>
</tr>
<tr>
<td>cumulusmeter</td>
<td>450 - 609</td>
<td>450 - 609</td>
</tr>
<tr>
<td>cumulusmeter</td>
<td>610 - 758</td>
<td>610 - 758</td>
</tr>
<tr>
<td>cumulusmeter</td>
<td>759 - 1000</td>
<td>759 - 1000</td>
</tr>
</tbody>
</table>

The spectral band is the only aspect that is covered in the analysis of the different instruments. Other factors, like time-lag between measurements or the viewing angle of the instruments are not taken into account in the analysis or error estimation of this part. The time-lag is covered in section 3.4.5 but independent to the type of instrument. For the viewing angle it is assumed that the simulated instruments measure in a 180° dome, either through a fish-eye lens or any other type of accessory that will produce cosine-corrected values. The results of this analysis are shown in section 4.1.

3.4.2 Vegetation indices

Often derived products from remote sensing images are vegetation indices. These indices are either a ratio (ratio vegetation indices) or a difference (differentiated vegetation indices) between wavelengths or a combination of ratios and absolute differences.

3.4.2.1 Ratio vegetation indices

A ratio or normalized vegetation index, like the RVI (ratio vegetation index) (Thenkabail et al., 2000) is an index that looks at the ratio between two spectral bands. If there is a perfect correlation according to the formula in Equation 8 between the individual bands used in this index then errors observed in these individual bands due to changes in incident light might be mitigated because no absolute values are calculated.

\[
\frac{\text{Band } A}{\text{Band } B} = \text{Constant}
\]

Equation 8

3.4.2.2 Differentiated vegetation indices

A differentiated vegetation index, like the WDVI (weighted difference vegetation index) (Clevers, 1991), is an index based on the absolute difference between reflectance of objects. If there is a high correlation between the individual bands according to the formula in equation 9 used in the index then errors observed in these individual bands due to changes are mitigated because only the difference in reflectance is observed.

\[
\text{Band } A - \text{Band } B = \text{Constant}
\]

Equation 9
Table 4: Vegetation indices used for the analysis of the robustness of vegetation indices under changing irradiance conditions. The C in the WDVI is a constant that consists of the ratio between the near-infrared and red reflection of bare soil in the study area. In this case the value 1 is used, since the reflection of the soil is not known and also not of importance.

<table>
<thead>
<tr>
<th>Index</th>
<th>Name</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>RVI</td>
<td>Ratio vegetation index</td>
<td>$RVI = \frac{NIR}{RED}$</td>
</tr>
<tr>
<td>WDVI</td>
<td>Weighted difference vegetation index</td>
<td>$WDVI = NIR - C \cdot RED$</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalized differentiated vegetation index</td>
<td>$NDVI = \frac{NIR - RED}{NIR + RED}$</td>
</tr>
</tbody>
</table>

The NDVI uses both a ratio and a difference and it is interesting to investigate how such an index behaves when corrected with different ILS or interpolated over different time spans. For this particular study the chosen wavelengths for the near infrared and red bands are respectively 780 and 670 nanometers, based on research by Stone et al. (1996). There are different wavelengths that can be used as red or NIR (Thenkabail et al., 2000) but as was already illustrated in Figure 11 the wavelengths seem to correlate well so not much difference is to be expected when a slightly different wavelength would be used.

To see what indices work best under different atmospheric conditions the regression coefficient between is calculated. This coefficient is based on a simple linear regression. If the two bands show high dependency between the two wavelengths then a vegetation index based on a ratio will be more “robust” than a differentiated index. If the residual of the linear regression formula is relatively large then a differentiated index is more robust. For the calculations three vegetation indices are used, as given in Table 4. The results of this analysis are shown in section 4.2.

3.4.3 Empirical line correction

For the empirical line correction based on repeated reference reflectance panel scan simulation, 1-22 evenly spaced out measurements (as many as the number of panel scans in a simulated flight) are preserved, while all other measurements for all wavelengths in between are interpolated as a function of the values and distance to the two nearest panel scans, according to the formula in Equation 7, illustrated in Figure 14.

![Figure 14: Visualization of the effect of an interpolated value of irradiance with the repeated panel-scan method.](image)
All datasets are made the same length (700 measurements or approximately 2100 seconds) so that differences in the error estimation later on are not caused by longer time-lags which would lead to a distorted comparison. Since this simulation is evaluated for 1-22 panels, this means a time-lag of 95 (2100/22) to 2100 (2100/1) seconds between a scan of a reference panel. The results of this analysis are shown in section 4.3.

3.4.4 Spatial ILS allocation
The spatial ILS allocation considers the placement of one or more ILS in the area that is scanned by the sensor on the UAV. If the expected spatial variance in irradiance is large, then the ILS needs to be close to the UAV-sensor to give a meaningful indication of the irradiance at the location of the UAV sensor. A difference in irradiance can be created not only when the ILS is not mounted on the UAV but also when it is mounted. This is because the scan line of the UAV sensor has a swath width where the lateral difference between the UAV and the largest view angles at the ground are significant, in the order of 10-30 meters depending on the height of the UAV. In this section the expected variance over multiple distances for the four different weather types is evaluated.

Since no irradiance data with spatial attributes –only temporal- is available this spatial factor needs to be simulated. Objects like clouds in the atmosphere move in one direction at any moment due to wind. Because of this it can to some extent be assumed that a change in irradiance over time at one location equals a difference in space on one moment. The ratio between change in space and change in time can of course be derived from the wind-speed, since speed is time multiplied by distance. For the simulation of these spatial attributes the ILS data as discussed in section 3.2.1 is used.

The wind-speed at the altitude of the objects in the atmosphere (the clouds) was not registered during these acquisitions. It is therefore assumed that the wind-speed at that moment is 2.2 m/s, based on an annual national average in the Netherlands (Wikipedia.org, 2013f). The consequences of such an assumption are quite large but unfortunately no data is available on the wind speed at cloud height. The possible effect of the assumption is that the assumed distance based on the timing of the Fieldspec is off, which will give a distorted result of how far an ILS should be located from the UAV to get good results. However the speed of the clouds is always different, which is also discussed in the discussion section, so the results of the analysis in this section is an approximation of what distance would give what results.

Semivariance diagrams are drawn to see how a distance from a point correlates with the possible value of that point. A semivariogram is a plot of the semivariance as a function of the distance between observations. The semivariance is half the variance of the differences between all possible points spaced a constant distance apart. The formula for semivariance is given in Equation 10 (Burrough & McDonnell, 1998).

\[ \hat{\gamma}(h) = \frac{1}{2} \cdot \frac{1}{n(h)} \sum_{i=1}^{n(h)} (z(x_i + h) - z(x_i))^2 \]

where \( \gamma \) is the semivariance of a point pair, \( x \) is a point value, \( z \) is the (irradiance) value at a particular location, \( h \) is the distance between ordered data, and \( n(h) \) is the number of paired data at a distance of \( h \).

The semivariance is calculated over multiple spatial lags. Out of the semivariance the coefficient of variation is calculated by taking square root of double the semivariance as a fraction of the mean irradiance. The results of this analysis are shown in section 4.4.
3.4.5 Time-lag analysis
To see how an instrument with different time-intervals between measurements would behave the difference between measurements over a certain time is calculated. These time-intervals, or time-lags, range from 3 seconds to 15 minutes. This latter long time-interval is based on instruments that would need a manual scan to measure the irradiance, instead of automatic measurements. Since the FieldSpec has a minimal time-lag of three seconds it is not possible to see the changes within this timespan. The results of the time-lag analysis are shown in section 4.5.

3.4.6 Ground- and flight-based image correction
The correction for the data cube of the ground- and flight-based acquired images is done according to the formula given in Equation 6. In the case of the ground-based acquired images the correction is also made with ILS data that would have been obtained by other instruments, simulated according to the methods discussed in section 3.2.1. The results of the analysis are shown in sections 4.6 and 4.7.

3.5 Error estimation
For the error estimation of the different incident light correction methods the relative root mean square error (RRMSE), as given in Equation 11, is used. The RRMSE is a derivative of the root mean square error, given in Equation 12. The RRMSE is a relative absolute error of the original values. An RRMSE of 0.05 equals an expected error of 5% of the average for that kind of atmospheric conditions. In this case, it is an indication for the expected error when a certain method is used.

\[
RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (o_i - s_i)^2}
\]

\[
RRMSE = \frac{RMSE}{\sum_{i=1}^{N} o_i}
\]

Where N is the number of observations, o are the original values and s are the simulated values.

For the expected error related to the spatial allocation of the ILS the coefficient of variation (CV) is calculated, which is the standard deviation as a fraction of the mean irradiance.

As error estimation for the ground-based image acquisition test, the standard deviation of both the corrected values (with the ILS values as the same wavelengths of the UAV sensor or as simulated by instruments) and uncorrected values is compared. Since the reference reflectance panel is always scanned at the same location, it can safely be assumed that any deviation in the reflectance is due to a change in irradiance.

For the flight-based image acquisition test the error is a deviation in reflectance between panels of the same color during the same flight. All pixel values of one panel are aggregated to one average value per spectral band per panel. It is not possible to compare panels of different flights, since they have both been corrected with a different hand-picked reflectance value of the reference reflectance panel (Equation 4). It is also not possible to compare panels of a different color, since they have different absorption characteristics. When only one scan of a panel was made during a flight the results are omitted, since one value cannot be compared to anything. When more than two scans are made of a large reference reflectance panel of a certain color, then the deviation values are combined to one value for that panel color for that flight.
A threshold is needed to evaluate if an instrument, spatial allocation, number of panel-scans or time lag is acceptable under different atmospheric conditions. For every research there is a difference in what is an acceptable expected error and what is not. However, to provide an evaluation in this research, the following thresholds have been set up. For the empirical line correction and ILS simulation an RRMSE of less than 0.01 (1%) is optimal, an error of 0.05 (5%) is acceptable and an error of 0.10 (10%) only acceptable when the option of not doing an image acquisition flight would provide unacceptable gaps in time-series. For the spatial ILS distribution the standard deviation over different time lags is calculated. In an optimal situation the standard deviation is at max 1% of the total irradiance, acceptable is 5% and only acceptable to prevent unacceptable data gaps is 10%. For the time lag analysis the optimal maximum change within a time-lag is 1%, acceptable is 5% and again only acceptable for the prevention of unacceptable data gaps is 10%.

To evaluate if the ground- and flight-acquired image correction works a lower standard deviation for corrected values than for uncorrected values is the benchmark. If this latter criterion is met then this means that the method works and that the use of incident light sensing instruments or repeated panel scans as executed in this research is justifiable under any atmospheric correction method, regardless of whether it is advisable to do an UAV image acquisition flight under those atmospheric conditions.

The above chosen thresholds are chosen only to clarify the results. There are no set thresholds, like ISO-standards, to determine what accuracy for reflectance values is necessary. A researcher must determine for himself what is acceptable and what is not.

The results of both the empirical line and incident light sensing method are compared to the results obtained by Hakala et al. (2013). As already mentioned, they have also used ILS instruments and empirical line correction to correct data obtained by a VTOL UAV. The atmospheric conditions during their acquisition flights had irradiance increases of up to 100%, which is about equal to the cirrus dataset in this research (Figure 12). The duration of the flight is not given in their research. The coefficient of variation of their results for different atmospheric correction methods is shown in Table 5.

Table 5: Absolute coefficient of variation (CV) and relative improvement of different irradiance correction methods compared to uncorrected CV from the research of Hakala et al. (2013). Corrected ILS (1) is based on data from a pyranometer fitted on the UAV; ILS (2) is a hyperspectral ILS located on the ground independently from the UAV. Empirical line correction (1) is based on radiometric block adjustment with multiplicative correction term, empirical line correction (2) is a correction based on relative offset and BRDF correction.

<table>
<thead>
<tr>
<th>correction method</th>
<th>coefficient of variation</th>
<th>improvement compared to uncorrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>no correction</td>
<td>0.14-0.18</td>
<td></td>
</tr>
<tr>
<td>corrected ILS(1)</td>
<td>0.10-0.12</td>
<td>30.95%</td>
</tr>
<tr>
<td>corrected ILS(2)</td>
<td>0.065-0.09</td>
<td>51.79%</td>
</tr>
<tr>
<td>corrected empirical line (1)</td>
<td>0.05-0.075</td>
<td>61.31%</td>
</tr>
<tr>
<td>corrected empirical line (2)</td>
<td>0.02-0.04</td>
<td>45.24%</td>
</tr>
</tbody>
</table>
The right-side of Table 5 can be compared to the results from this study, either to an expected RRMSE of a simulated correction method (as described in section 3.4.1 and 3.4.3) or compared to the correction of the images acquired in the field (as described in section 3.4.6). Note that the results of Hakala et al. were derived from empirical data that was obtained under less controlled conditions (or less documented) than the acquisitions in this research. It seems from their methods that their UAV was further away from the ground-based ILS and weather conditions have not been extensively reported. Also, uncorrectable variation in their results due to an error in calibration of the sensor mounted on the UAV is one of their worries in their studies, which could contribute to the variation as presented in Table 5.

The RRMSE of the uncorrected values for the simulations with the ILS datasets is based on the simulation with one panel scan. This means that the images are corrected based on one scan at the beginning of the flight (see section 3.4.3 and Equation 4). This is the method as it is used at this moment in the field by the Laboratory of Geo-Information Science in Wageningen. The RRMSE for these datasets with this method is 0.056 for Cirrus, 0.029 for clear sky, 0.791 for cumulus and 0.116 for stratus conditions.
4 Results

The results are based on the methods described in the methodology. The datasets for which the results are presented in sections 4.1 through 4.5 are acquired through the procedure as explained in section 3.2.1. The results of the ground-based image and irradiance acquisition as explained in section 3.2.2 are presented in section 4.6. The analysis of the flight-based image acquisition, as explained in section 3.2.3, is presented in section 4.7.

4.1 Incident light sensing instruments

Figure 15 shows the results for the simulation of different instruments. There are no large differences between instruments, except for the high RRMSE with a pyranometer during cumulus cloud conditions. The reason for these small differences can be observed in Figure 16. Most wavelengths in the visual and near infrared spectrum correlate almost perfectly. Therefore no large errors are to be expected when individual wavelengths are aggregated into one panchromatic band with such small differences between bands.

All instruments produce an error that is acceptable (within 5%). The instruments with bands especially designed for their particular weather types (cirrus-, clearsky-, stratus- and cumulusmeter, as calculated by the method described in section 3.4.1) do not perform significantly better for that particular weather type. The instrument trained for all weather types produces larger errors than a normal RGB-camera.

![Figure 15: RRMSE for measurements with different instruments under varying atmospheric conditions. The RRMSE is a result of the comparison of simulated values based on the method of incident light sensing and the original ILS data. All instruments perform acceptable for all weather types and optimal under clear sky or cirrus conditions. A reason for the high error for stratus cloud atmospheric conditions can be the low signal-to-noise ratio due to low irradiance levels.](image)
This could have been caused by the fact that the instrument for all weather types has many bands in the (noisy) part of the spectra around 900 nm and only one band for the visual spectrum. The stratus dataset shows large errors with all instruments. This could be due to a low signal-to-noise ratio since the spectra showed no distinct differences with the other spectra of the other datasets, as observed in Figure 11. On average, regardless of the instrument that is used, the simulated corrected values show a possible error of only about 2% compared to the uncorrected values for cirrus clouds (section 3.5), 6% for clear sky conditions, 2.5-5% for cumulus conditions and 10% for stratus conditions.

It could be that because the wavelengths between 450-1000 nm correlate so well that this is also the case for other wavelengths like the ultraviolet (UV) and the short-wave infrared (SWIR). This hypothesis was tested and visualized in Figure 17. It turns out that the UV (350-400 nm) and first part of the blue spectrum, which was not taken into account in this study due to the high level of noise in the UAV sensor (400-450), do correlate well with the visual and NIR spectra. The far part of the SWIR does not correlate with the visual and NIR but it does also not correlate with neighboring wavelengths. This could be caused by a low signal-to-noise ratio, which seems plausible because the irradiance is low at these wavelengths. This is confirmed by the fact that the correlation is especially high in the water absorption bands (around 1425 and 1900 nm). The SWIR wavelengths that are not affected by water absorption do correlate well with the visual and NIR spectra and an instrument like the pyranometer or any other instrument mentioned in this section can be used to monitor these parts of the SWIR without large errors.

![Correlation matrix of spectral wavelengths from the ILS data of the four ILS datasets. For every wavelength there are 7441 measurements (sum of all measurements as given in Table 2). The smallest correlation coefficients can be found around 970 nm, where a water absorption dip is present that fluctuates more than other wavelengths when clouds are in front of the sun. Overall correlation is very high.](image_url)
Figure 17: Correlation matrix based on 1000 measurements of the cumulus ILS dataset for all wavelengths measured by the FieldSpec 4. The bands that have been used in this research (450-1000 nm) do correlate highly with the ultraviolet and some parts of the short-wave infrared (SWIR). The bands that do not correlate or correlate negatively are found in the water absorption bands. The low correlation is caused by the low signal-to-noise ratio, which means that the main component of the calculated irradiance in the water absorption bands is caused by noise.

It is interesting to see is that the blue band correlates strongly with the rest of the visual and NIR spectrum (not below a 0.99 correlation coefficient). It would seem that because photons with lower wavelengths are scattered more in the atmosphere, more blue light would still reach the ILS as diffuse irradiance, but this effect is not visible in the data, because it would result in lower correlation coefficients in the spectrum around 350-450 nm.

4.2 Vegetation indices
In Figure 18, a scatterplot is displayed of 800 randomly selected irradiance measurements from the four ILS datasets (200 per dataset) of the NIR and red band. The correlation is almost perfect ($R^2=0.994$) with an almost negligible offset of 0.0075 (<1%) and there are no significant differences between atmospheric conditions. This means that only one band at most needs to be measured (either red or NIR) to calculate any vegetation index that uses these two bands. Since there is a linear correlation between the two bands a vegetation index that uses a ratio between the two bands rather than the absolute difference will be more “robust”.

35
Figure 18: Scatterplot of 200 sample measurements from the four ILS datasets. The red-band (650nm) and NIR-band (780) nm correlate almost perfectly and measuring only one of the two bands would give enough information to calculate the vegetation index.

This is clearly shown in detail in Table 6. Although the results are not optimal for stratus and cumulus conditions when the irradiance is not measured the ratio index gives much better results under unmonitored changes in irradiance. It is important to note that vegetation indices are not developed to monitor irradiance but to monitor vegetation. If plants always absorb, transmit and reflect the same fraction of the irradiance, regardless of the intensity of the irradiance, then the results above are as valid for irradiance as for reflected irradiance.

Table 6: Coefficient of variation of the calculated indices as plotted in Figure 18. The results do show that a ratio vegetation index will give the best results under varying atmospheric conditions. During cirrus and clear sky conditions optimal results can be obtained even without irradiance monitoring with the RVI. The WDVI and NDVI produce mostly unacceptable errors when no irradiance is monitored.

<table>
<thead>
<tr>
<th>dataset (200 samples)</th>
<th>coefficient of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RVI</td>
</tr>
<tr>
<td>cirrus</td>
<td>0.009859954</td>
</tr>
<tr>
<td>clear sky</td>
<td>0.006569766</td>
</tr>
<tr>
<td>cumulus</td>
<td>0.041059567</td>
</tr>
<tr>
<td>stratus</td>
<td>0.012572961</td>
</tr>
</tbody>
</table>
4.3 Empirical line correction

In Figure 19 the RRMSE is shown of a simulated empirical line correction method with multiple scans of reference reflectance panels during a UAV flight. It is clear that an increase in scans does not automatically mean a lower RRMSE; this is best visible in the cumulus and cirrus cloud conditions. A distinctively high error can be caused by a scan of a reference panel at a moment that is not representative for the largest part of the measurements during that time. This can also happen in the field. For instance, if a panel scan is made at a moment when a small cloud is blocking the sun while the rest of the atmosphere consists of clear sky then that panel scan is not expected to be representative for the average irradiance level of the flight.

The clear sky dataset shows only significant improvements between one scan and two scans (in Figure 19 shown at the 1050 and 2100 second intervals). This is because with one scan the constant irradiance due to a change in solar zenith angle are not corrected (based on Equation 4), while with two scans a linear change can be corrected for (Equation 7).

The largest improvements with multiple panel-scans are observed in the cumulus dataset. The reason for this is the large irradiance changes compared to the other datasets. The smallest improvements are observed in the cirrus dataset. The fluctuations in irradiance are very frequent (Figure 12) and at least more frequent than the number of panel scans. With such frequent fluctuations in irradiance caused by a heterogeneous atmosphere it is not useful to interpolate the irradiance between panel scans. The actual irradiance changes are not constant but fluctuate, even within a time span between panel-scans that is very short.

In this simulation the panels were scanned at regular time intervals. However, changes in irradiance do not occur in regular time intervals (as was shown in Figure 12). Therefore it would be wise for the UAV pilot to make a scan of a reference panel right before and/or after sudden changes in irradiance due to clouds. A disregard for the actual changes in the atmosphere while making the panel scans can even lead to a worse correction, which can be observed from the fact that a decrease of the time between scans is not automatically a decrease in error.
Figure 19: RRMSE of interpolated irradiance for different time lags between measurements of a reference reflectance panel (as explained in Figure 14). The RRMSE is a result of the comparison of simulated values based on the method of repeated panel scans and the original ILS data. The graphs do not show a steady increase over time in all circumstances, since there can be large differences in error with a little change in timing between a large change in irradiance and a scan of a reference reflectance panel.

4.4 Spatial ILS allocation
In Figure 20 the results for the spatial ILS allocation is shown. The results are shown in more detail in Appendix B as a table for the first 1000 meters. As is immediately clear the cumulus dataset has the absolute largest variation coefficient. The coefficient of variation is 0.89 at one kilometer, meaning that the standard deviation is almost equal to the mean at such distance. For cumulus cloud conditions no acceptable measurements can be made under any circumstances.

Another case is an atmosphere with cirrus clouds. For the cirrus dataset the maximum distance at which acceptable results can be obtained is 36 meters, for acceptable results only to prevent data gaps the maximum distance is about 200 meters. The former distance can be achieved by mounting an ILS on the UAV and flying at a relatively low height. The latter option allows the flight in a normal sized area for VTOL UAV’s, about 200 meters from the ILS (Juha Suomalainen, 2012b). No optimal results can be obtained under heavy cirrus cloud conditions.
Figure 20: Coefficient of variation for different lags in space for the four different weather types. The distance in meters is based on an assumed wind speed of 2.2m/s. Part of the deviation can be part of a constant change due to changes in solar zenith angle, especially in the clear sky dataset. Note different y-scales for graphs.

Optimal results can without much difficulty be obtained during stratus cloud conditions. An ILS mounted on a UAV would always provide optimal results and an ILS system with two evenly spaced out sensors in a 200 by 200 meter field would provide sufficient coverage to also achieve optimal conditions. For the clear sky dataset it does not matter how large the distance is between ILS and UAV. The variance over distance shown in Figure 20 can be contributed to constant changes due to a change in the solar zenith angle, which is homogeneous over small areas.

4.5 Time-lag analysis

In Figure 21 the change in irradiance in percentages is shown over 900 and 60 seconds respectively, based on the ILS datasets (section 3.2.1). This is an average value for the entire dataset. Maximum values can vary greatly, as could be observed in Figure 12. From the left figure it is clear that, when the time between irradiance samples increases, the impact of (average) change does not increase much with long time-lags, except for cumulus cloud conditions. When a non-automated ILS instrument is used –in other words, an instrument that needs someone to measure the irradiance- it is important to realize that when an ILS-measurement is not often made, the error due to irradiance changes can become quite significant. When an automated ILS instrument is used a measurement is made every few seconds. The expected deviation at such time lags is shown on the right of Figure 21.
Both cumulus and cirrus dataset show that the minimum time lag of an instrument like the FieldSpec does not produce results within the optimal threshold of 1%. The pyranometer with a time-lag of 5 seconds will produce optimal results under stratus and clear sky atmospheric conditions. This can be quite significant when all other factors during an UAV flight are very well controlled and within 20 seconds the average change for the cumulus dataset even increased to 10%. This is especially interesting to note for the thermophile pyranometer, which needs some time to adjust to sudden changes in irradiance levels (Kipp & Zonen, 2013a).

4.6 Ground-acquired image correction

In Figure 22 the uncorrected and corrected values of the ground-based image acquisition are shown. The correction has been done with the values from the FieldSpec (same as sensor), and as simulated with different instruments based on the FieldSpec data. There are no large differences to be seen between the corrections with different instruments, which confirms the results of section 4.1. The fact that the instrument with the highest resolution, the corrected values with the same wavelengths as the sensor, do not result in the best correction for all wavelengths is due to noise in the FieldSpec, since with small spectral bands the signal-to-noise ratio is lower.

The standard deviation of the corrected values, regardless of the (simulated) instruments, is about 45% of the uncorrected values. This is about the same as the results as Hakala et al. (2013)(Table 5) have obtained with their ground-based ILS. Their correction method based on empirical line correction showed better results. This could potentially mean that in practice the empirical line correction method would have worked better for the correction of the ground-based image acquisition in this research, but this has not been tested.
Figure 22: Top: the standard deviation of the average spectra per wavelength acquired during the ground-based image acquisition, both corrected and uncorrected. The correction decreased the standard deviation by a factor four, whatever the instrument. Bottom: a close-up of the corrected values for the different simulated instruments. No large differences are visible in the correction with different instruments.

4.7 Flight-acquired image correction

The flight test values were obtained by taking the average for every spectral band of every panel of every scan. During most flights, three scans were made of every panel (during the third flight, which was longer, five scans were made of most panels). The uncorrected values are calculated according to Equation 4, while the corrected values are calculated according to Equation 6.

What is most clear from Figure 23 and Figure 25 is that an incident light correction is not useful when the incident light changes little and other factors have a large influence on the measured reflected radiance. This means that changes in the reflected radiance of the large reference reflectance panel are caused by differences in reflectance characteristics of the panels. The changes in the reflected radiance and irradiance are shown in Figure 24.
Figure 23: Deviation of reflectance from first scan of every panel (Appendix A). Every panel scan from every flight is compared to the first scan of the same panel during that flight. With multiple scans the average value is taken. The values are the mean value of all wavelengths between 450-1000nm. In 11 of 15 cases the correction increased the error which leads to the assumption that deviation in panel reflectance is due to changes in reflectance characteristics and not irradiance changes.

If it would have been possible to compare scans of the panels between the first flight and the third flight, there might have been more clear improvements in the correction. In that case there would have been large differences in irradiance because of changes in the solar zenith angle during the flights (as observed in the clear sky dataset of Figure 12). However, due to the processing chain, this was not possible. Since the reference reflectance panel correction is integrated in the processing of raw data to reflectance data through the method as described in Equation 3 and the result is already a level 2 product (Juha Suomalainen, 2012a).

Figure 24: The change in irradiance as measured by the Fieldspec and the change in reflected radiance from the large reference reflectance panels as measured by the UAV sensor. The magnitude of change and in some cases the direction of this change do not correspond.
When the flight based image acquisition test would have been done during cumulus or optically thick cirrus cloud conditions the changes might have correlated more, since the irradiance change would have had a larger impact on the reflected radiance. Reasons for why changes in reflected radiance do not relate to changes in irradiance are discussed in the discussion section.

A factor besides a difference in sensors that would lead to such results as shown in Figure 25 could be that the reference reflectance panels do not have spatially homogeneous reflectance spectra, but this was a necessary risk when this experiment was set up. A reason for this can be that the panels haven’t been used in a long time and have been weatherworn in time or through use. Another reason can be that the panels were not homogeneous in the first place. This is why the results of the ground-acquired image acquisition showed much better results, since the panel was of higher quality than the large reference reflectance panels used in the flight-acquired image acquisition correction.

![Figure 25](image)

**Figure 25:** The average deviation of reflectance of the 2nd (and 3rd) scan from the first scan of every panel per flight and per panel of the flight tests. The green lines are the uncorrected average reflectance values per panel per flight, the orange line the corrected reflectance values. All plots have the same scale on x- and y-axis. No individual wavelengths tend to benefit from the correction. The deviation in reflectance for the uncorrected values shows a lot of fluctuations, which leads to the conclusion that the panels are not spectrally homogeneous. The darkest panels (color 5) show the highest deviation, both corrected and uncorrected for every flight.
5 Discussion

5.1 Summary of results

In Table 7 a summary is shown of all the results regarding the irradiance measurement and correction methods of incident light measurement and empirical line correction with a reference reflectance panel. The results in this table can be used to estimate the quality of the images obtained during a UAV flight, based on the number of panel scans or a combination of the temporal resolution, the spectral resolution and average distance to UAV of an ILS. For instance, a RGB camera could measure irradiance with a temporal resolution between measurements of 12 seconds, while being at a maximum distance from the UAV of 150 meters during atmospheric conditions with stratus cloud conditions. According to the results shown in Table 7, this setup would have optimal spectral resolution, optimal temporal resolution and acceptable maximum distance from sensor. A more detailed estimation of the expected error can be found by combining the results as presented in sections 4.1, 4.4, 4.5.

Overall it can be stated that all measurement methods can be used during clear sky conditions (Table 7). In that case a spectral reference scan before and after the flight to correct for constant changes (due to the change in solar zenith angle) would be the simplest solution for operational reasons, although the ILS method would give equally optimal results. With empirical line correction only one extra scan is required compared to the regular method at the moment, based on one scan at the beginning. For short flights of a few minutes it is not even necessary to adapt the irradiance correction procedure as it is currently. The current method, shown in Equation 4, suffices with such conditions since the effects of a change in solar zenith angle are negligible, as is clear from the fact that a panel scan every 1050 seconds for clear sky conditions will still give optimal results (Figure 19).

Next best weather conditions for UAV image acquisitions are atmospheric conditions with stratus clouds. The UAV can be relatively far away from the sensor (150-500 meter) without much error caused by spatial irradiance differences (Figure 20). Also, when a correction is done with the empirical line method then a scan needs to be made every 150-300 seconds, which means an average of three panel-scans during a normal flight of 6-8 minutes. A downside of stratus cloud conditions is that the irradiance level is low. This leads to a low signal-to-noise ratio, which is the cause of the high RRMSE for different simulated instruments compared to the other weather types (Figure 15). This low signal-to-noise ratio can have a negative effect on the quality of both ILS and UAV sensor data. Besides clear sky atmospheric conditions, stratus –overcast- cloud conditions are the only conditions in which optimal results can be obtained while measuring the irradiance at a distance from the UAV.

With atmospheric conditions with cirrus clouds acceptable results can be obtained as long as the sensor is close to the UAV, favorably mounted on it. Also, with regard to the swath width of the UAV sensor the UAV needs to fly low so no anomalies are present in the swath line itself. This is due to the fact that cirrus clouds vary in optical depth on small spatial distances. Cirrus clouds are optically thin, which leads to relatively low errors when the irradiance is not measured at the exact same spot as the reflected radiance compared to cumulus clouds. This can be observed from the small vibrations in the cirrus dataset as shown in Figure 12. The empirical line correction method is not suitable for cirrus cloud conditions since changes in irradiance are more frequent than any number of panel scans that can be made in a practical UAV image acquisition setup (Figure 19). Incident light sensing is a more suitable method (Figure 15), provided that the ILS is very close or mounted on the UAV (Figure 20).
Table 7: An overview of all results for irradiance measurements with both the incident light sensing method and the empirical line correction method. UC acceptable is acceptable under circumstances when a measurement is absolutely necessary. Classification is based on theory explained in section 3.5. The temporal resolution for the instruments has not been taken into account with the evaluation of the instruments, only the spectral resolution.

<table>
<thead>
<tr>
<th>Monitoring and correction method characteristics</th>
<th>clear sky</th>
<th>stratus</th>
<th>cirrus</th>
<th>cumulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrument types</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RGB camera</td>
<td>optimal</td>
<td>acceptable</td>
<td>optimal</td>
<td>acceptable</td>
</tr>
<tr>
<td>False color camera</td>
<td>optimal</td>
<td>acceptable</td>
<td>optimal</td>
<td>acceptable</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>optimal</td>
<td>acceptable</td>
<td>optimal</td>
<td>acceptable</td>
</tr>
<tr>
<td>Photovoltaic cell (all weather types)</td>
<td>optimal</td>
<td>acceptable</td>
<td>optimal</td>
<td>acceptable</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 seconds</td>
<td>optimal</td>
<td>optimal</td>
<td>optimal</td>
<td>acceptable</td>
</tr>
<tr>
<td>6 seconds</td>
<td>optimal</td>
<td>optimal</td>
<td>acceptable</td>
<td>acceptable</td>
</tr>
<tr>
<td>12 seconds</td>
<td>optimal</td>
<td>optimal</td>
<td>acceptable</td>
<td>UC acceptable</td>
</tr>
<tr>
<td>30 seconds</td>
<td>optimal</td>
<td>optimal</td>
<td>acceptable</td>
<td>acceptable</td>
</tr>
<tr>
<td>5 minutes</td>
<td>optimal</td>
<td>acceptable</td>
<td>UC acceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>15 minutes</td>
<td>acceptable</td>
<td>UC acceptable</td>
<td>unacceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>Maximum distance from sensor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 meter</td>
<td>optimal</td>
<td>optimal</td>
<td>acceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>50 meter</td>
<td>optimal</td>
<td>optimal</td>
<td>UC acceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>150 meter</td>
<td>optimal</td>
<td>acceptable</td>
<td>UC acceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>500 meter</td>
<td>optimal</td>
<td>UC acceptable</td>
<td>unacceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>1000 meter</td>
<td>optimal</td>
<td>UC acceptable</td>
<td>unacceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>Empirical line method</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multiple reference panel scans</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Every 100 seconds</td>
<td>optimal</td>
<td>optimal</td>
<td>acceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>Every 150 seconds</td>
<td>optimal</td>
<td>optimal</td>
<td>acceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>Every 300 seconds</td>
<td>optimal</td>
<td>UC acceptable</td>
<td>UC acceptable</td>
<td>unacceptable</td>
</tr>
<tr>
<td>Every 1050 seconds</td>
<td>optimal</td>
<td>unacceptable</td>
<td>UC acceptable</td>
<td>unacceptable</td>
</tr>
</tbody>
</table>

During cumulus cloud conditions it is not possible to achieve acceptable results with any distance from the sensor, since changes can occur so rapidly and within such a short time span. It would be possible to do an UAV image acquisition flight only when an UAV operator can say with a certainty that there will be no change in irradiance. This is possible with very large cumulus clouds or with large patches of clear sky. The resulting long periods with unchanging irradiance were also observed during the acquisition of the cumulus dataset (Figure 12), where no significant changes in irradiance occurred for over 10-15 minutes. If such a homogeneous atmosphere is present then the errors that can be expected will be either relatable to clear-sky conditions or stratus-cloud conditions (depends on whether clouds are absent or continuously blocking the sun during the flight).

The irradiance does not need to be monitored if a vegetation index is used based on a ratio during cirrus or clear sky cloud conditions. If the irradiance is not measured under cumulus or stratus conditions the results are acceptable but not optimal. For indices that use the absolute difference
between multiple bands the irradiance does need to be monitored for at least one (panchromatic) band. It is not necessary to monitor the irradiance for all bands used in a vegetation index since the correlation between individual wavelengths is so high (as shown in Figure 16 & Figure 18).

In the previous paragraphs the expected quality of images acquired during different atmospheric conditions were discussed and an advise was given on the instruments to use during these conditions. What was not taken into account is the wind speed. It was assumed that the wind speed during the acquisition of the ILS data was average (2.2 m/s) but this was not specifically measured during the acquisition of the data. Besides, the wind speed does not need to be equal at ground level and at cloud level. Especially high cirrus clouds can have a very different speed, since they can be found not only in the troposphere but also in the stratosphere atmospheric layer. In the stratosphere the clouds can go through jet streams, which can travel from 100 km/h up to 400 km/h (Wikipedia.org, 2014).

Because of these varying wind speeds the results for the temporal resolution, frequency of panel scans for empirical line correction and distance to the UAV of an ILS are not representative for all weather and wind conditions. If the clouds tend to move much faster or slower than what can be called ‘average’, then the methods used need to be adapted accordingly. This means with higher wind speeds that the ILS needs to be closer to the UAV and the temporal resolution needs to be higher for incident light sensing, or the frequency of panel scans for empirical line correction higher.

An even briefer summary of the results is given as a protocol for UAV operators in Appendix C. This protocol can be used during a flight to determine what irradiance monitoring method to use under what atmospheric conditions and some other recommendations based on the conclusions of the rest of the discussion (sections 5.2 through 5.7).

5.2 Causes for differences in expected and measured irradiance
The correction of the flight-acquired images did not improve the quality of the reflected radiance. This is not caused by the processing phase of the image correction since the results of the better controlled ground-based image acquisition did show significant improvement. Therefore the causes have to be found in the data acquisition step. A change in measured reflectance of the same object can be influenced by several aspects that are not due to a change in irradiance. The reasons for why the incident light correction did not work for the flight-based image acquisition could also be reasons for errors in future UAV flights that use incident light sensing for image correction. Therefore the possible causes for a difference in reflected radiance regardless of irradiance are discussed in the next three sections.

5.2.1 Differences in sensor calibration and accuracy
When the ILS and UAV-sensor are differently calibrated, errors are produced when the DN values of both instruments are headlong compared. When the difference in calibration is known then these differences can be corrected later on in the incident light correction processing chain. When one of the two sensors produces a significant amount of noise or has a low radiometric resolution then this correction is not possible, which results in an error in the irradiance correction. This noise can potentially be found in all viewing angles of the UAV sensor but especially at the largest off-nadir viewing angles of the sensor, caused by a vignetting effect (Catrysse et al., 2000). Since the large reference reflectance panels that were measured during the flight-based image acquisition were at the border of the image the vignetting effect could have had a particularly large effect on the quality of the images and it may have been one of the reasons of the large differences in measured reflected radiance that were not due to changes in irradiance. Errors due to a vignetting effect can also occur in irradiance measurements if the instrument used for cosine correction is not perfect. This can lead
to an under- or overestimation of the irradiance at large observation zenith angles. Errors due to noise or vignetting were not of interest to this study but could have been of influence on the results.

The UAV sensor used in this research had a relatively low signal-to-noise ratio in the lower and higher wavelengths. This could be observed from the results of the correction of the ground-based acquired images, presented in Figure 22. The spikes at the beginning and end of the spectrum (450 and 1000 nm respectively) are caused by noise. Both instruments have an output in Watts per square meter per wavelength and for the correction only relative values have been used. It is assumed that the conversion from DN-values to reflectance or irradiance values is correct. This means that no significant errors could have been produced in the correction of the flight-based acquired images due to a difference in calibration. The empirical line correction method proposed in this research based on a repeated panel-scan is very suitable when differences in sensor calibration or accuracy are unwanted because only one sensor is needed that measures reflected radiance.

5.2.2 Differences in spectral characteristics of the sensors

When the UAV-sensor and the ILS do not measure in bands of the same wavelengths or do not have the same spectral resolution then the values obtained by the ILS may not be useful as correction values for the reflected radiance measured by the UAV sensor. The only setting where a difference in spectral characteristics does not definitely influence the quality of the processed images is when the ILS has the same (or more) bands as the UAV sensor but has a higher spectral resolution, since spectral values can be aggregated. With the use of the FieldSpec there is the guarantee that there are no problematic differences in spectral characteristics since it has a higher spectral range and resolution than the hyperspectral scanner on the UAV.

As was observed in Figure 15 and Figure 16 it does not greatly influence the correction if an ILS instrument has lower spectral resolution, since all wavelengths of the irradiance correlate very strongly. This was at least the case for the ILS datasets used in this research, but as already explained in section 2.1 this does not necessarily need to be the case for all weather conditions. Different aerosols that were absent in this research can be present during other moments or at other locations and can have a significant impact on the irradiance spectra due to specific absorption dips. Therefore it is always better to use an instrument with higher spectral resolution if available, even if it is only used to make sure that no unexpected presence of different aerosols will influence the correction of the UAV images.

5.2.3 Differences in illumination

The ILS and the object of interest are never at exactly the same location and the ILS and UAV sensor cannot measure at exactly the same moment. This means that a difference in illumination in time or space could produce a significant error in the correction phase. The difference in space does not only depend on the location of the object of interest and the ILS itself. Since the object is measured from a distance, there can be an impact on the measured radiance due to a change in the solar irradiance angle and/or a change in the view angle of the UAV sensor. The effects of changes in irradiance or observation angle have not been taken into account in this research. These effects could have caused the changes in reflected radiance that were not correctable with irradiance correction of the flight-based acquired images (Figure 25). The effects of a change in reflectance due to anisotropic reflectance of an object have also been described by Laliberte et al. (2011) and Hakala et al. (2013). In both studies, it has been tried to correct for these effects by applying a BRDF correction on their measurements. However, the produced BRDF model did not fit the anisotropic characteristics of the objects in the field and the results were therefore not satisfactory (Table 5).
The effects of differences in illumination due to differences in location or time of the irradiance and/or reflected radiance measurements were discussed in sections 3.4.4 and 3.4.5. When these illumination differences were not of interest, like in the validation and usability analysis part, the causes were mitigated as well as possible. This was done by placing the ILS as closely as possible to where the UAV-sensor was mounted (Figure 9) in the ground-based image acquisition or as close to the flying path of the UAV (Figure 10) during the flight-based image acquisition. Also, the highest possible temporal resolution was set for the Fieldspec during all measurements. The angle of the UAV sensor during the ground-based image acquisition was fixed so the angle would not change. Tilting of the UAV during the flight-based acquisition was limited as well as possible but it could not be avoided to have some level of tilt, since the UAV needs this to go in any direction.

5.3 Empirical line correction
In this research an empirical line correction method has been proposed and analyzed based on repeated scans by the UAV-sensor during the flight to correct the changes in irradiance throughout the flight. This method has shown promising results for the correction of constant changes in the atmosphere (the clear sky dataset results of Figure 19) but not for cloud conditions with very frequent changes (cirrus dataset of Figure 19).

The analysis of section 4.3 was based on a scan in regular time intervals. If it is possible to do a scan right before or after a change in irradiance then an interpolation in time would give much better results. This is especially the case for cumulus cloud conditions, which shows almost no gradual but only abrupt changes. This method is however not very implementable. One of the reasons for empirical line correction was that it does not require an ILS on the UAV, which would increase the payload and thus decrease the duration of the flight. This advantage would be nullified if an UAV would need to fly to a reference reflectance panel every time a change in irradiance occurs.

The empirical line correction method has not been tested in the field in this research so it is not known how well the empirical line correction method with multiple reflectance reference panels works in practice. The results from the flight-acquired image acquisition (Figure 25) show that a non-Lambertian or inhomogeneous panel can have a potentially large negative effect on the usefulness of empirical line correction. For the results of this research it has been assumed that it is possible to get at least one perfect pixel at any flying height of the UAV of a perfectly Lambertian and homogeneous reference reflectance panel.

Hakala et al. (2013) have obtained empirical line correction results that were better than a correction based on incident light sensing (Table 5). The results of the current research do not ratify this conclusion, which can be observed from the results in sections 4.1 and 4.3, where the RRMSE is much lower with incident light measurement correction than empirical line correction. This anomaly could have been caused by different atmospheric conditions, different spatial allocation of the ground-based ILS on the side of irradiance correction through direct incident light sensing. Also, the measurements of reflected radiance of objects with unknown reflectance characteristics could have been made more often in their research than as was simulated in this research. As was discussed in section 2.4 there are some side notes to be made about the methods used by Hakala et al. (2013). It would be interesting to compare a correction based on ILS and the empirical line method with one or multiple reference reflectance panels (instead of their block adjustment method with pixels with unknown reflectance characteristics). This will both evaluate the results of the simulations in this research and the methods of the research of Hakala et al. (2013).
5.4 Combination of mounted and ground-based ILS

The main problem with fitting an UAV with a high spectral resolution ILS (like the FieldSpec) is the weight of such an instrument. On the other hand the main problem with placing such an instrument on the ground is that the spatial difference between ILS and UAV-sensor in that case can lead to unregistered irradiance changes at the location of the UAV. The advantage of an ILS with low spectral resolution (like a pyranometer), is that it is light, which makes it easier to mount it on the UAV. The disadvantage is that it has a long time-lag and less spectral resolution than a FieldSpec and also a lower expected signal-to-noise ratio. The results of sections 4.1 and 4.4 show that it is more important to have the ILS as close to the UAV as possible, than to have an ILS with high resolution.

A solution to both disadvantages is to use a combination of an ILS with low spectral resolution mounted on the UAV and an ILS with high spectral resolution on the ground. A condition of such a setup is that the ILS is horizontally stabilized, since a tilt of the UAV will lead to an error in the irradiance measurement (as discussed in section 2.3.2). If the total irradiance of both instruments is equal and doesn’t change, then with some certainty the data of the ILS on the ground can be used for correction. If the total irradiance is not equal then there is a large chance that there is a difference in irradiance in space, in which case the data from the ILS on the UAV is used for image correction. This would be most useful in the case of cumulus clouds, which irradiance levels show two almost discrete values (Figure 12). In that case if the levels of irradiance are equal the high-resolution ILS on the ground is used, if not the ILS mounted on the UAV is used. This method was also recommended by Hakala et al. (2013).

5.5 Quality flags

The products of satellite images often get quality flags, like MODIS data (Daac et al., 2012). Quality flags are an indication of the quality of image data as retrieved from a sensor. With MODIS data these quality flags are automatically generated based on an estimation of the cloud cover, or missing, interpolated and out-of-bounds data (Daac et al., 2012). This could also be done with UAV images. In that case any researcher can determine for himself if an image dataset is accurate enough given the quality indication value that the dataset has for his or her research.

The methods to obtain the values for these quality flags can be deductive or inductive. The deductive method is based on the knowledge that was gained from this research. The UAV operator can give a qualitative evaluation of the atmospheric conditions during the entire flight or during a part of the flight. This requires some knowledge of atmospheric conditions by the UAV operator. The protocol in Appendix C can aid with this evaluation.

The other method is inductive, based on the data that was gathered. If the incident light monitoring is based on a setup with an ILS, rapid changes in irradiance mean that the quality of the dataset can be expected to be low around the time that these changes occur. The size of the part of the image dataset that is not reliable around such a rapid change depends of course on the scale of the clouds in the atmosphere and on the speed of the clouds passing over. With the empirical line correction method with multiple reference panel scans a large change in the DN-value of these panels indicates changes in the irradiance as well. Any images taken between the panel scans between which a large change in irradiance is measured are labeled as qualitatively low.

In the post-processing phase, when the images acquired are evaluated, it is easier still to observe which parts of the dataset are not reliable. An evaluation based on the gray DN’s as discussed by Hakala et al. (2013) can be used to see what areas (that are scanned multiple times), show large irradiance changes over time even after irradiance correction. The quality of the images taken of these areas can be expected to be low.
5.6 Representativeness of atmospheric classes
The number of ILS datasets that were used to produce the results of sections 4.1 to 4.5 is relatively low compared to all possible atmospheric/cloud conditions that can be measured. All datasets were obtained in the Netherlands about 100 km out of the coast, during the summer in a relatively rural area. A change in any of these characteristics can have an influence on the cloud or atmospheric composition and with that on the absorption spectrum of the irradiance path. As was observed in Figure 16 the bands in the visual and NIR spectrum correlate well and a panchromatic instrument suffices for incident light sensing for the atmospheric conditions as measured during the acquisition of the ILS datasets. However, during other flight campaigns the atmosphere or clouds can be polluted - i.e. a different atmospheric composition- which would result in a different spectral distribution of the irradiance. For instance,

- closer to the sea there could be an impact of salt water damp on the absorption spectrum (Boyce, 1951)
- Closer to urban areas there can be an impact of any number of air pollution particles due to car exhausts or industrial activities. A number of these particles with their absorption dips has been discussed by Bergstrom (2007).

If UAV image acquisition tests are flown where any of the above mentioned characteristics differ greatly from the characteristics of the weather conditions of the training data it would be wise to monitor the atmosphere with an ILS instrument with the same spectral bands and resolution as the UAV sensor. This way, it is easy to recognize bands that behave differently than other bands during changes in the atmosphere. If these bands behave in a predictable way and correlate linearly or exponentially with other bands then these bands do not necessarily need to be included in the bands of the ILS for further flights in the same area. However, if the bands do not correlate to other bands and they are important for the purposes of the research then it is advisable to acquire an instrument that can measure these bands/wavelengths.

The clouds in the atmosphere can differ not only spectrally but also in their dispersion or the speed with which they are coming over due to wind. If the dispersion of the clouds is more diverse or the wind speed is higher than average then the temporal resolution of the ILS should be higher and the ILS should be placed closer to the UAV with image correction through incident light sensing. With the empirical line method a scan of a reference reflectance panel needs to be made more often under such atmospheric conditions.

5.7 Testing of ILS instruments
One aspect that was not taken into account is the quality of the possible instruments that were categorized and simulated in this research. This was because it was not of interest for this project and unevaluated noise or other causes for errors in sensors could give a skewed result in the evaluation of the simulation, as discussed in section 5.2.1. The expected error of measurements (due to noise, radiometric resolution, and oversaturation) of the instruments is nevertheless one of the most important aspects of an instrument and if any of the instruments as described in section 2.3.1 is used, or any other instrument for that matter, then it needs to be tested first.
6 Conclusion
Changes in irradiance have a large effect on reflected radiance and thus on the measured reflectance characteristics of objects of interest to remote sensing through UAV image acquisition. UAV’s are close to the ground, below cloud height, which leads to different problems with changes in irradiance compared to traditional remote sensing methods, but it also offers new opportunities for the measurement of these irradiance changes. Empirically measured irradiance levels in this research varied from 20 to 130 W/m² for 450-1000 nm which can lead to large errors when such variations are not measured and corrected. Especially clouds, but also a change in the solar zenith angle, can cause changes in irradiance. Monitoring changes in irradiance can mitigate these errors by using these irradiance values to correct the reflected radiance of objects imaged during an UAV. Either direct incident light sensing methods or the measurement of reflected radiance of objects with known reflectance characteristics can be used to monitor this irradiance. This latter method, empirical line correction, is most useful during atmospheric conditions with only constant changes in irradiance (e.g., clear sky conditions) or during weather conditions without frequent changes. The incident light sensing method uses an incident light sensing instrument to directly monitor the irradiance. A simple panchromatic instrument suffices as incident light sensor, since the wavelengths of the irradiance show an almost perfect correlation in the visible and NIR and for most wavelengths in the SWIR. Most important about incident light measurement is to have the instrument placed as closely to the UAV as possible and to measure the irradiance often. The importance of the frequency of measurements both with empirical line correction and incident light sensing is highly dependent on the wind speed and the heterogeneity of the atmosphere. The method of empirical line correction and incident light sensing can be incorporated in the current atmospheric correction procedure by correcting the measured reflected radiance with a (interpolated) normalized irradiance value. In general it can be said that with an addition of simple techniques and instruments to the current UAV image acquisition and atmospheric correction procedure great improvements can be made in the mitigation of the effects of changes in irradiance on the quality of UAV-acquired images.
7 Recommendations

7.1 Evaluation of more atmospheric classes
In this research four main types of atmospheric conditions were classified and used as simulation data, namely a clear sky atmosphere and atmospheric conditions with cirrus, cumulus and stratus clouds. As was shown in Figure 4, there are much more cloud types and combinations of these clouds. Any combination of these three main cloud types can occur with varying densities.

It is not possible to classify and evaluate all possible combinations. But, if some cloud types or atmospheric conditions show distinct differences in absorption spectra that have an effect on the irradiance spectrum, then it is important to distinguish them and determine what irradiance monitoring and correction method would be most suitable.

7.2 Empirical line correction tests
In this research the empirical line correction method was only evaluated through simulation. However, simulations and reality do not necessarily have to be the same. This became very clear in the incident light correction method, which showed no improvements for UAV-acquired images although simulations indicated that the method would always improve the quality of the reflected radiance. Therefore it would be wise to evaluate the empirical line correction method with scans of spectral reflectance panels in an actual field test. This will give a better indication of the practical aspects of this irradiance correction method. Also, aspects that were not considered, like errors due to the measurement of diffuse scattering by the UAV sensor, can be evaluated in such an experiment.

The empirical line correction test can also be repeated with the block adjustment method as proposed by Hakala et al. (2013). To validate their method the reflected radiance can be corrected with the change in DN's of objects in the field, which are not reference reflectance panels. To validate this method multiple reference reflectance panels need to be placed in the field. If the correction based on objects that are not these panels result in a uniform reflectance of the reference reflectance panels over time, then the method is valid. As was clear from their research the BRDF model did not fit the anisotropic characteristics of the object in the field. Therefore a BRDF model is needed that is calibrated to apply to the objects used in such an experiment. Favorably the objects in the field with which the correction is done are as close to objects of interest for remote sensing, for example crops in an agricultural field.

7.3 Measuring incident light with spatial attribute
In section 2.3.1.2 the possibility of using an RGB camera with fish-eye lens was proposed. Such an instrument can be used as ILS by combining all pixel values, which would lead to one irradiance value with three bands. However, with the spatial attribute (the location of the pixels on the image), it could be possible to give an approximation of the spatial location of objects (clouds) in the atmosphere, based on the angle off-nadir on the image and the distance to these clouds. Gauchet (2012) describes this method as very promising and it would provide a solution to the errors in difference in irradiance that could occur because of the distance between ILS and objects on the ground, as described in section 4.4. Such a sensor is place at one position but can identify the objects in the atmosphere at multiple locations, from which the expected irradiance levels at ground level at these locations might be derived.
7.4 Calculating constant changes
In section 2.1.1 a method was proposed to correct for constant changes in the atmosphere, as were observed in the clear sky dataset. These constant changes are dependent on the air mass, which is dependent on the solar zenith angle, which is dependent on the local time, date and latitude. It would be interesting to find out how well an irradiance correction with only time, date and latitude data would work in practice. At closer inspection of Figure 12 the clear sky dataset does not show an entirely linear increase but more logarithmic. This has an effect on the quality of the correction with two panel scans, even though it is a minor effect. A calculated approximation of the air mass for all measurements could further improve the quality of UAV-acquired images during clear sky conditions.

7.5 Gyroscopically stabilized mounted ILS
One of the main findings of this research was that the most important factor for obtaining usable irradiance measurements is the distance from the UAV. A solution to this method is mounting the ILS on the UAV, assuring that the irradiance is as representable as possible for the reflected radiance measured by the UAV sensor. There are however still two limitations to this solution: first of all the limited payload of a UAV and second of all the error due to over- or underestimation of the irradiance when there is a tilt of the UAV. This error can be as large as 10-20% with a tilt of 10° (Katsaros et al., 1986). The payload limitation can be an absolute limitation, in that the UAV cannot get enough lift to become airborne, or a relative limitation in that the UAV operator favors a longer flying time. A solution to the error of tilt is a gyroscopic stabilizer. Such an instrument can either support the ILS, in which case the angle of the ILS can remain fixed with tilt of the UAV. A second method is using a gyroscopic measurement instrument to measure the tilt of the UAV and correcting the irradiance based on the angular offset as measured by this instrument (Bird & Riordan, 1986). Gyroscopic stabilizers on which instruments can be mounted can be as light as 350 gram (gyroscope.com, 2013). Gyroscopic measurement instruments can be as light as 20 gram (Bluelight Technologies, 2013) and may already have been integrated in the UAV (Chatys & Koruba, 2005).
8 References


Everaerts, J. (2008). The use of unmanned aerial vehicles (UAVs) for remote sensing and mapping. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 37, 1187–1192.


Suomalainen, Juha. (2012b). *Altura PRO AT8 characteristics, personal communications.*


9 Appendices

9.1 Appendix A: image acquisition flights of reference reflectance panels

<table>
<thead>
<tr>
<th>Flight 1; two (and a bit) scans per panel</th>
<th>Flight 2; three scans per panel</th>
<th>Flight 3: five scans per panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>The arrows point to the north. The image shows the scan-lines made by the UAV sensor, starting from the top of the image and finishing the flight at the bottom of the image. The images have been processed so only the lines with the reference reflectance panels on them have been preserved.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Appendix B: Semivariance over Distance

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Coefficient of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulus (0.16)</td>
</tr>
<tr>
<td>13.19</td>
<td></td>
</tr>
<tr>
<td>214.49</td>
<td></td>
</tr>
<tr>
<td>287.09</td>
<td></td>
</tr>
<tr>
<td>36.29</td>
<td></td>
</tr>
<tr>
<td>339.89</td>
<td></td>
</tr>
<tr>
<td>421.49</td>
<td></td>
</tr>
<tr>
<td>112.19</td>
<td></td>
</tr>
<tr>
<td>438.89</td>
<td></td>
</tr>
<tr>
<td>203.59</td>
<td></td>
</tr>
<tr>
<td>135.29</td>
<td></td>
</tr>
<tr>
<td>313.49</td>
<td></td>
</tr>
<tr>
<td>386.09</td>
<td></td>
</tr>
<tr>
<td>412.49</td>
<td></td>
</tr>
<tr>
<td>260.69</td>
<td></td>
</tr>
<tr>
<td>451.49</td>
<td></td>
</tr>
<tr>
<td>511.49</td>
<td></td>
</tr>
<tr>
<td>537.89</td>
<td></td>
</tr>
<tr>
<td>610.49</td>
<td></td>
</tr>
<tr>
<td>663.29</td>
<td></td>
</tr>
<tr>
<td>689.69</td>
<td></td>
</tr>
<tr>
<td>712.79</td>
<td></td>
</tr>
<tr>
<td>735.89</td>
<td></td>
</tr>
<tr>
<td>762.29</td>
<td></td>
</tr>
<tr>
<td>814.96</td>
<td></td>
</tr>
<tr>
<td>837.97</td>
<td></td>
</tr>
<tr>
<td>861.29</td>
<td></td>
</tr>
<tr>
<td>887.69</td>
<td></td>
</tr>
<tr>
<td>914.09</td>
<td></td>
</tr>
<tr>
<td>937.19</td>
<td></td>
</tr>
<tr>
<td>960.29</td>
<td></td>
</tr>
<tr>
<td>986.69</td>
<td></td>
</tr>
<tr>
<td>1013.08</td>
<td></td>
</tr>
</tbody>
</table>
9.3 Appendix C: General protocol for irradiance monitoring during an UAV image acquisition flight.

During clear sky conditions optimal results can be obtained with two scans of a reference reflectance panel, at the start and end of a flight. During stratus conditions (completely overcast) both multiple panel scans (more than two, as often as possible) or a simple incident light sensor can be used for irradiance monitoring. This ILS does not need to be very close to the UAV, so it can be placed on the ground and can still produce acceptable results. During cirrus cloud conditions the irradiance can be very volatile and with both the ILS method and empirical line with multiple scans method optimal results can be expected. However an ILS mounted on the UAV will produce acceptable results. In that case the UAV should fly as low as possible to mitigate irradiance anomalies within the scan line.

During cumulus conditions only a flight can be done when the UAV operator is absolutely sure that there will be no change in irradiance due to a cloud blocking the irradiance path. If that is the case an incident light sensor suffices.

With a very diverse atmosphere (many small, optically thick clouds), or high wind speeds the errors will increase and flights are less advisable in such conditions.

The incident light sensor can measure in one panchromatic band, although more spectral bands will always improve the results slightly, as long as the noise is not significant. Temporal resolution is more important than spectral resolution and the sensor should be as close to the UAV as possible, favorably mounted on it.

Apply quality flags to the products of a UAV based on the experience of the researcher during the flight or based on the irradiance data. Use an instrument with high spectral resolution in a situation with an atmospheric composition that greatly differs from the situations as described in this research.