A review on the ability of smartphones to detect ultraviolet (UV) radiation and their potential to be used in UV research and for public education purposes.

Abstract

The effects of ultraviolet (UV) radiation on life on Earth have continuously been the subject of research. Over-exposure to UV radiation is harmful, but small amounts of exposure are required for good health. It is, therefore, crucial for humans to optimise their own UV exposure and not exceed UV levels that are sufficient for essential biological functions. Exceeding those levels may increase risk of developing health problems including skin cancer and cataracts. Smartphones have been previously investigated for their ability to detect UV radiation with or without additional devices that monitor personal UV exposure, in order to maintain safe exposure times by individuals. This review presents a comprehensive overview of the current state of smartphones' use in UV radiation monitoring and prediction. There are four main methods for UV radiation detection or prediction involving the use smartphones, depending on the requirements of the user: devoted software applications developed for smartphones to predict UV Index (UVI), wearable and non-wearable devices that can be used with smartphones to provide real-time UVI, and the use of smartphone image sensors to detect UV radiation. The latter method has been a growing area of research over the last decade. Built-in smartphone image sensors have been investigated for UV radiation detection and the quantification of related atmospheric factors (including aerosols, ozone, clouds and volcanic plumes). The overall practicalities, limitations and challenges are reviewed, specifically in regard to public education. The ubiquitous nature of smartphones can provide an interactive tool when considering public education on the effects and individual monitoring of UV radiation exposure, although social and geographic areas with low socio-economic factors could challenge the usefulness of smartphones. Overall, the review shows that smartphones provide multiple opportunities in different forms to educate users on personal health with respect to UV radiation.

Keywords

Smartphone, ultraviolet, UV radiation, UV irradiance, CMOS, sensor, UVB, UVA

Section 1.0

Rationale/Introduction:

Research has long established that excessive exposure to ultraviolet (UV) radiation has detrimental effects on human health. Acute and prolonged UV exposures have been linked to erythema (sun burn), eye conditions such as cataracts, pterygiums and photokeratitis, photoaging and immune suppression, development of non-melanoma skin cancer and melanoma (Godar 2005). On the other hand, small UV exposures contribute to good health; UV radiation is essential for the synthesis of vitamin D which is required for bone health and general wellbeing, including contributing to maintaining healthy circadian rhythm (Matsui et al. 2016). Lack of vitamin D is directly related to diseases such as rickets (Holick 2006), while there are also links relating vitamin D deficiency to cancer of the breast, colon and prostate amongst other cancers (Garland et al. 2009). The global disease burden caused by UV radiation was estimated to be 0.1%, with an estimated 1.6 million disability-adjusted life years, due to diseases associated with UV radiation (Lucas et al. 2008), however it has been suggested that this burden could increase as other diseases are linked with UV radiation as a causative, or non-causative protective role. In comparison to other disease burdens, this may seem low in relative importance; however there is significant economic burden in related treatment costs.

The ability of humans to monitor and control their own UV exposure, whilst understanding the consequences of that exposure, is essential in maintaining good health. Studies have reported the need for deeper understanding by the public on UV radiation measurements and how to moderate an individual’s exposure (Carter & Donovan 2007; Hacker et al. 2018a; Nicholson et al. 2019). Continuous effort is required to provide interventions and education that influence the public’s understanding and knowledge of this important topic (Mahler et al. 2005; Rodrigues et al. 2017). Recent research has demonstrated that e-Health (electronic Health) focused solutions could play a role in reducing the disease burden caused by UV radiation (Hacker et al. 2018a; Hacker et al. 2018b; Hussain, Nicholson & Freyne 2017) by increasing education and public awareness of the effects of UV radiation. These e-Health methods for intervention and education purposes has involved the use of smartphones, by education through social media and self-instruction, and as a personal measurement device. Previous reviews (Grossi 2018; Li et al. 2016) have considered a wide range of applications of a large number of smartphone sensors. Other reviews are limited to specific types of UV sensing devices called dosimeters (Kanellis 2019). e-Health solutions are an emerging field which is associated with fast growing technology and measurement techniques (Burggraaff et al. 2019). The use of smartphones for health purposes is not new and a large number of health related applications (apps) are available (mostly free) for smartphones (Camacho et al. 2014; Grossi 2018). In a study conducted in 2012, Chang Brewer et al., (2013) reviewed almost all available health related smartphone apps. The study found that out of 229 studied apps, 8.3% (19) were devoted to offering advice on sunscreen application or about UV exposure. Another review (Patel et al. 2015) reported that the number of apps related to UV radiation or sunscreen application has increased from a total of 19 applications in 2013 to 34 applications in 2014. In the latter review, it was found that the most reviewed smartphone application by users was a UV Index with a sun exposure and sunscreen recommendation app.

Mobile phones have been proven to be an excellent means to conduct cognitive studies (Dufau et al. 2011). For instance, studies that use text messages as an intervention to raise UV exposure awareness or provoke sunscreen application showed increasing user awareness and adherence to sunscreen application (Armstrong et al. 2009). A broader trial conducted by Gold (2011) on the intervention of smartphones on both sexual health and UV exposure showed an increased awareness of sexual health, but the data did not show that awareness of UV exposure and preventative measures in decreasing UV exposure were improved. These studies, however, did not investigate the effect of self-motivated applications, such as those mentioned in some dermatological studies, on raising levels of awareness. Newer studies have provided some alternative results to consider. A study in Germany (Brinker et al. 2017) presented a sample of teenagers with a smartphone app capable of altering personal photos to visualise the photoaging effect of UV exposure. Although the study was not conclusive, it found some changes in perception around the importance of protection from solar exposure or tanning booths (Brinker et al. 2017). Other studies such as those conducted by Buller et al. (Buller et al. 2013; Buller et al. 2015a, 2015b), which also cannot be considered conclusive, found evidence that a smartphone app can provide useful mechanisms to change individuals' perceptions on sun protection. A more recent study by Hacker et al. (2018b) concluded that reduced UV exposures and enhanced UV protection can be achieved in young adults using smartphone apps and dosimeters, and suggested conducting further research in this field. Hacker et al. (2018a) showed that a smartphone app diary was a suitable replacement for other data collection methods in UV exposure research.

This review seeks to provide an overview on the current state of smartphone technology that is being investigated or employed to detect UV radiation. It will also discuss the use of this technology in public education to better communicate information about UV radiation and its effects. The review will start with an investigation into the use of smartphone applications used for UV radiation sensing. This is separated into using smartphones with and smartphones without devoted sensors. Then the review will explore the smartphone as a UV radiation sensor itself. The next section will explore how the smartphone as a sensor has been applied in research disciplines to measure UV radiation related factors. Finally the review proposes future directions for extending the use of this ubiquitous and accessible technology in UV related fields.

Literature for this review was obtained by focusing on searches in databases, using keywords such as "ultraviolet", "UV", "smartphone", and "apps" and other related search terms. However, as this is an emerging field, many resources were not found using this process. Many sources were identified from web searches. Another factor noted was that there appeared to be some disconnect between the literature in different research disciplines. For example, some published work in computing disciplines had little connection to those in published health disciplines (citing very few publications on the same topic in the health related areas). It is hoped this review will bridge the gap between these disciplines and provide better sharing within cross-disciplinary research.

Section 2.0 – Smartphones, applications and sensors.

This section describes and reviews the employment of smartphones in either predicting or detecting UV radiation; and describes some devices used with smartphones to satisfy this purpose. Given how quickly technology can change and new innovative applications are developed, it is likely that not all devices and measurement techniques and initiatives can be covered here by the time of publication. The following sections will elaborate on the most known applications and devices over the last decade. In addition, the first section will briefly review information about UV radiation and how it is influenced by the surrounding environment.

2.1 Background Information about UV radiation

UV radiation comprises approximately 8 to 9% of the entire solar spectrum at the top of the Earth's atmosphere (Frederick, Snell & Haywood 1989), but it represents only about 5% of the solar spectrum at the Earth's surface, with the majority (95%) of that UV radiation being UVA radiation (320 nm-400 nm), while the rest is UVB radiation (280-320 nm). The divisions between the different wavebands of the UV spectrum are somewhat arbitrary and dependent on the research area (Diffey 2002) and may vary according to disciplines (315 nm was the original cut-off between UVB and UVA radiation, but environmental and dermatological photobiologists primarily use 320 nm as the industry cut-off). All UV radiation between 200 nm to 280 nm is classified as UVC; however, UVC and a proportion of UVB radiation are absorbed by ozone in the atmosphere before it can reach the Earth's surface. UV radiation is influenced by several factors that control the amount of UV exposure received by an individual at any time. Factors affecting UV exposure include: ozone, atmospheric components such as aerosols, solar zenith angle, latitude, altitude, cloud coverage and reflectance from surfaces and clouds. In addition, personal factors such as skin type can alter the potency of UV exposure. Overall, with the myriad of factors that can change the UV exposure of an individual, it becomes increasingly important to use a variety of methods to learn more about an individual's UV exposure. The approved method of communicating UV radiation exposure levels is through the use of the UV Index (UVI), this is a unitless measure that provides the rate of exposure from erythemally weighted UV irradiance (Gies et al. 2004; WHO et al. 2002). The erythemal weighting indicates the likelihood of sunburn. Most weather reporting outlets include UVI in their weather reports.

2.2 Current literature and published or commercial tools

This section provides information on a number of UV sensing devices. A summary of these devices discussed in sections 2.1.2 and 2.1.3 is provided in Table 1.

2.2.1 Smartphone Applications without devoted UV sensors

There has been considerable research in developing solar irradiance-based apps that rely on receiving external information and do not use any smartphone internal or added external sensors to detect UV radiation. These apps mostly access data provided freely on the web and use algorithms to present that data in a meaningful way to the user. A smartphone app, in general, is an interaction between external data sources, user input and in some cases, the computing power of the smartphone itself.

Most of the apps introduced for monitoring human health associated with sun exposure aim to improve attitudes and behaviours towards sun protection, monitor vitamin D levels, or raise awareness of other related UV exposure mechanisms such as tanning booths (Brinker et al. 2017; Buller et al. 2015a; Correia 2014; Dunstone & Conway 2014; Morelli et al. 2016b; Wakely et al. 2018). Two broad types of apps for human health without additional sensors are found in the literature, namely informational and visual, the latter using augmented reality features (Brinker et al. 2017; Wakely et al. 2018).

Informational based apps can access weather, cloud cover and UV Index (UVI) data from official sources (such as The National Oceanic and Atmospheric Administration or the Australian Bureau of Meteorology). These sources are generally networks of weather stations across states or countries. These apps apply user inputted data along with externally sourced atmospheric data and data from the smartphone's internal calendar and clock to provide users with details of safe levels of sun exposure, optimum UV levels for vitamin D production and also alerts to reapply sunscreen or to seek shade. Examples of these apps include Australia's *SunSmart* app (Dunstone & Conway 2014; Jenkins 2017; Wakely et al. 2018), *Solar Cell* from the United States (Buller et al. 2013; Buller et al. 2015a, 2015b), and the *HappySun* app from the United Kingdom. *HappySun* is slightly different, in that it interfaces satellite-based data with atmospheric radiative transfer modelling and user input (Morelli et al.

2016b). Satellite based information is used with personal data entered by the user, to calculate real time personal UV exposure measurements which are displayed on the smartphone's screen (Morelli et al. 2016a). Interestingly, it is promoted as a sensorless personal UV dosimeter (SIHealth 2018) rather than a smartphone application. Many apps are, by the nature of the information accessed, restricted to certain continents or locations, but there are a variety that aim to provide UVI predictions or measurements across the world, including *GlobalUV* (NIWA 2016), *UVIMate* (Unknown 2018) and *WorldUV* (British Association of Dermatologists no date).

Recent apps have sought to use the advent of augmented reality algorithms and the prevalence of people taking pictures of themselves, or 'selfies' to provide a visual representation of the effects of excessive sun exposure, such as the effects of skin cancer and photoaging. This is achieved by developing an overlay of known sun damage on to the user's image ('selfie'), although this technology is still developing methods to perfect the accuracy and realism of the overlay (Wakely et al. 2018). It has also been found that this visual approach is more appealing to younger users who are often at the critical age for developing good lifetime sun exposure habits (Brinker et al. 2017). Examples of this method include *seeUV* developed by *SunSmart* in Australia (Wakely et al. 2018), and *Sunface* from Germany (Brinker et al. 2017).

2.2.2 Smartphone applications with devoted wearable UV electronic sensors

Although there is no freely available technical specification data about the UV sensors used in smartphones and similar devices, it is reasonable to assume that the internal UV photodiode would follow similar operational principles as those used in external devices, such as *Sundroid*, where the incident irradiation on the UV photodiode is converted to a small electric current. The magnitude of the electric current is dependent on the intensity of the incident irradiation and the spectral sensitivity of the photodiode itself (Fahrni et al. 2011). This sensitivity to the UV is analogous to the inherent UV sensitivity of the smartphone complementary metal-oxide semi-conductors (CMOS) image sensor (Turner et al. 2017).

The period from 2009 to 2017 was prolific in the number of UV sensors developed. Fahrni et al., (2011) developed a wearable sensor *Sundroid* that incorporated the use of UV photodiodes (UVB and UVA photodiodes) with an embedded Bluetooth module. *UVsense wearable* was developed by a start-up company in New Zealand (Cheuk, Xu & McLean 2014), although it is unknown if this sensor has been commercially produced. It is unlikely that its production has continued, given that another device with the same name *UVsense* was being marketed in early 2018 by L'Oréal. This is the first non-battery electronic device that senses UV radiation in conjunction with a smartphone (L'Oreal 2018a) that is small enough to stick to a person's nail. However, since November 2018, the product has become known as *My Skin Track UV*, (L'Oreal 2018b). It is not quite clear if they are definitely the same product, as *UVsense* adheres to a fingernail while *My Skin Track UV* is a clip on device. One of the developers of this product previously developed a sensor that can monitor various health related features on the human body called the *Biostamp*. The *Biostamp* uses stretchable circuits supported by thin rubber that can be attached to the skin much like a temporary tattoo. This multifunctional sensor is composed of UV radiation sensors for UVB exposure, UVA exposure, UVB and UVA exposure as well as UVA and UVB intensity sensors along with body temperature sensors. The *Biostamp* can be connected with Android based devices, although the reports in 2015 suggested that these would soon be compatible with non-Android devices (Perry 2015). The UV radiation intensity measurement is achieved by taking a digital picture of the *BioStamp*. The colorimetric sensors are made up of photoactivators, colour changeable dyes and absorptive optical filters that make up the main components of the UV detection unit of the *BioStamp* (Araki et al. 2017). An algorithm then translates the information captured within the smartphone to provide data on the information collected by the *Biostamp*. A similar product (but without the electronics) is *My UV Patch* (La Roche-Posay), which requires image capture with a smartphone to measure colour changes due to UV exposure (Shi et al. 2018). This device is discussed in section 2.1.4.

Table 1 - Summary of UV sensing devices discussed in Section 2.0

Sensor	Form	Sensor Type/Data source	Data measured	Commercial availability	Cost
Non-wearable Sensors					
YOUVI	Plugs into smartphone headphone port/jack	Unknown	Unknown – output is UV Index	No	Not applicable
Integrated Environmental Monitoring System	Handheld device	UV photodiode: UVM-30A, Guangzhou Logoele Electronics Technology Co. Ltd	Broadband (200nm-370nm)	Unknown	Not applicable
Samsung Galaxy Note 4	Smartphone	Proprietary Information	Assumed: UV Index	No longer in production	Not applicable
Wearable Sensors					
Sundroid	Wearable sensing unit with Bluetooth module.	UVB and UVA photodiodes attached to custom made circuit board	Output: Accumulated dose in MED (minimum erythemal dose)	Unknown	Not applicable
UVsense wearable		AlGaN photodiode	Broadband UV	Unknown – undergraduate research project	Unknown
My Skin Track UV, L'Oreal (previously known as UVsense)	Adheres to skin surface Clips to clothing etc	Proprietary information www.laroche-posay.us	Output: Accumulated dose	https://www.laroche-posay.us/my-skin-track-uv-3606000530485.html	$59.95 US
Biostamp	Adheres to skin surface	Proprietary information www.mc10inc.com	Broadband UV	No – company assisted in development of My UV Patch	Not applicable
JUNE-by-Netatmo	Wristband – Bracelet design	Proprietary information	Unknown	No longer in production	Average price was $100 US.
Sunsprite	Magnetic Badge or suspended on necklace	Lux meter style sensor	Visible radiation (may include possible UV radiation)	www.sunsprite.com	Temporarily out of stock at time of review
Microsoft Band	Wristband – Fitness Tracker	Proprietary information	Unknown	No longer in production	Average price was $199.00 US
QSun	Clip to clothing	UV sensor (type not specified)	UVB/UVA +/- 0.5UVI (extracted from specs)	https://qsun.co/	$149.00 -$199.00 CAN
Huawei Honor Band A1	Fitness tracker	UV sensor: LTR 390	Unknown	www.amazon.com.au Associated app no longer available	$29.95 AUD
Shade	Magnet attachment to clothing	Proprietary information	Output: UV Index	www.wearshade.com	$299.00-$599.00 US
Samsung Gear S	Sports Watch	UV sensor (type not specified)	Unknown	No longer in production	Not applicable
SeaWatch - Sphere	Sports Watch	UV sensor (type not specified)	Output: UV Index	Shop.spheredrones.com.au	$59.95 AUD
My UV Patch	Adheres to skin surface temporarily	Colorimetric change (assumed)		Limited release with other La Roche-Posay products (sunscreen)	Not applicable
LogicInk	Temporary Tattoo	Colorimetric change (assumed)		Logicink.com	10 for $39.00 and other price ranges

Uvision	Arduino system	Adafruit SI1145 UV/Visible/IR sensor	UV Index	Unknown – MIT Undergraduate project	Not applicable
UV Dosimeter	Wrist attachment	Semiconductor sensor	Broadband	scienterra.com/home/4567276434	$450.00 NZD

Similar to the *UVsense wearable*, which was designed by an undergraduate team, the *Uvision* was presented by MIT undergraduates, however the sensor used in this device detected visible and infrared radiation and predicts UV radiation from that information (Hoblos et al. 2015). It is unknown if this devise progressed any further. The *JUNE-by-Netatmo* (JUNE-by-netatmo 2015) was a device marketed as a jewellery and beauty product, enabling the user to monitor their UV exposure by wearing it like a watch or bracelet. The target market looks to be those who are able to afford luxury items, offered in the same price bracket as lower cost jewellery items. The *Sunsprite* is a similar jewellery-smartphone paired device, with more options on how it is worn, including as a necklace (SunSprite 2017). The *SunSprite* is similar to the *Microsoft Band* (Microsoft 2018) which was included in a study that reviewed the effectiveness of promoting awareness of UV exposure (Hussain et al. 2016; Hussain, Nicholson & Freyne 2017). It is also similar to the *QSun* UV exposure tracker (QSun 2018). Both the *Sunsprite* and the *QSun* focus on obtaining optimal daylight exposure, or vitamin D exposure, while the *Microsoft Band* is a fitness tracker similar to another fitness tracker by Huawei (GSMarena 2016). Work by Puente-Mansilla et al. (Puente-Mansilla et al. 2016) developed a wearable UV sensor with smartphone accessibility and auditory warning signals for people with visual impairments. Another wearable device was proposed by Dey et al.(2017). This UV device uses a lux meter and a correlation model between lux and UVI measurements to determine the UV exposure of the user. The process used in this device could be considered similar to that used by Mei et al., (Mei, Cheng & Cheng 2015a; Mei, Cheng & Cheng 2015b; Mei et al. 2017). Their work uses fog computing to capture visible images through the smartphone CMOS and compute the UV irradiance from global irradiance as presented by key characteristics of the visible image. Banarjee et al., (2017) reviewed an array of wearable devices that detect UV radiation and compared them to a calibrated radiometer. Their study concluded that their own designed wearable UV device *Shade*, (Shade 2019) was the most comparable to the calibrated radiometer. *Shade* also appears to be accessed by an accompanying smartphone application. Samsung developed “smart” watches and included a UV sensor within the Samsung Gear S, but not in the subsequent model S2 (Mei et al. 2017). The added feature of a UV sensor is not prolific amongst similar products. Sphere created a watch with a UV tracker (Sphere Drones) but it does not appear to be used in conjunction with a smartphone.

A small wearable electronic dosimeter that is solely devoted to UV radiation exposure measurement and suitable for research (Allen & McKenzie 2005; Seckmeyer et al. 2012) has previously only been accessible using devoted devices to extract data. Forthcoming work indicates that data collected by these dosimeters will soon be accessible via smartphone devices, with an array of new features (Sherman 2018).

2.2.3 Smartphone applications with devoted non-wearable UV electronic sensors

There is a wide range of devices that can be used with smartphones, however this section focuses specifically on devices employed in conjunction with a smartphone to detect UV radiation that are not designed to be worn by the user. Large numbers of commercial and non-commercial products for UV measurements are available online and widely used in research and are gaining traction in education and citizen science. The field of smartphone based UV measurements is rapidly expanding, therefore this summary is current at the time of writing.

A device using UV photodiodes was proposed in 2009 (Amini et al. 2009). Many UV devices are introduced in the numerous patents found online to be used with smartphones (ETH Zurich 2013; Sandhu, Alavi & Reshef 2014; Shi, Pielak & Balooch 2017). In 2011, DoCoMo conceived of a smartphone case or cover that would monitor the UV Index of the smartphone user (Ishida, Hayashi & Yoshikawa 2012), although there is little evidence on the success of this product. Interestingly, this smartphone cover was targeting females rather than males. In 2014, the release of the Samsung Galaxy Note 4, revealed that a UV sensor was included within the smartphone (Acharya 2014), however it appears that the sensor was removed from later models. Another UV device called *YOUVI,* designed to plug into the smartphone headphone jack port, was proposed for creation through a crowd-funding website (Indiegogo.com) by a commercial company but was subsequently not funded and therefore not mass marketed (Somalingam, Greuet & Gilliam 2014). A large hand-held device, known as the Integrated Environmental Monitoring System, developed by Wong, Yip & Mok (2014) can measure temperature and air quality as well as UV Index. This device is a portable low-cost sensor used in conjunction with smartphones. Notable amongst the smaller, bulkier devices is that they are rarely designed to detect only UV radiation. It seems that it is more desirable and cost-effective to have a device that monitors multiple factors, such as air quality and volcanic plumes (examples such as these will be discussed later), rather than a single device measuring only one quantity. Most of these multifunctional devices rely on UV sensitive photodiodes that are gathering broadband data and would not be considered effective for research based work that requires spectral information.

2.2.4 Smartphone applications with devoted UV non-electronic sensors

The *Biostamp* mentioned in an earlier section may be argued to be almost non-electronic in its overall design for UV detection, apart from the construction design that allows connection to the smartphone (Araki et al. 2017; Perry 2015). However, there are examples of devices that definitely are non-electronic in their construction. One example is the colorimetric analysis of UV radiation (which the *Biostamp* also uses). Meng et al. (2016) have used the colorimetric concepts to create a UVI indication card that uses digital image capture and an associated smartphone algorithm to calculate the UVI. However, this method requires an externally held reference card to always be available, rather than being inbuilt into the device, like the *Biostamp*. Most non-electronic based devices used with smartphones, require some reference due to the possible changes in light during the image capture. This reference allows the digital image analysis to correctly calculate the observed colorimetric changes in the device. This method was also used by the more recent epidermal sensor *My UV Patch,* which was developed by L'Oreal, and distributed jointly by La Roche-Posay and L'Oreal (Shi et al. 2018). The patch is a heart shaped patch with multiple squares of colour in shades of blue. The different squares show a reference colour and a reversible or irreversible UV variable ink. The smartphone uses digital capture and a devoted algorithm to determine UV exposure. In a similar way with the *Biostamp*, the *My UV Patch* can stay affixed to the skin for several days and therefore can be used with sunscreen applied over the top of the patch to measure its sun protection factor. A recent Kickstarter introduced by a company called LogicInk has also created a temporary tattoo that provides information about UV dose. The introduced dosimeter does not require the use of a smartphone to measure UV exposure. Instead, the colour of an indicator bar on the tattoo changes gradually throughout UV exposure, until a maximum is reached. A separate indicator shows the UV intensity with a reversible variable section. The tattoo is single use, and it is not clear from the company's site (Logic.Ink.com 2019) whether it uses dyes that change colour under UV, or some other mechanism.

2.2.5 Proposed smartphone devices with UV sensors - patents

The concept of developing UV sensors built in existing systems is not new. There is a patent that proposes a mobile device (such as a smartphone) with embedded UV sensors or alternatively uses devoted camera capture of UV radiation to detect UV irradiance on an added embedded sensor (Sandhu, Alavi & Reshef 2014). Another patent proposes to use multiple mobile devices that can be connected to networks and rely on "crowd sourcing" UV data as input (Reshef et al. 2015). An alternative patent suggests using real time reflectance imaging from a generated video (Feldman 2016). This might be considered somewhat similar to the UV imaging systems that can be used to show users of sunscreen how sunscreen application works within the UV spectrum. An example of a similar device is the Nurugo Smart UV device, that attaches to a smartphone to capture reflected UV radiation for reviewing sunscreen application (nurugo 2019).

Section 3.0 Detection of UV irradiance using Smartphones or devices connected with Smartphones

Nowadays most people carry a smartphone, which is an ideal mechanism to incorporate UV measurement. The camera image sensors used in digital cameras and smartphones are silicon-based CMOS. The multiple advantages of the CMOS sensor (Bigas et al. 2006; Daponte et al. 2013; Theuwissen 2008) makes it an ideal sensor not only for compact smartphones, but also for scientific measurements and research. Luo, Yang & Yan (2010) pointed out that CMOS sensors are capable of detecting UV radiation. Unfortunately, extra mechanisms put in place to protect the CMOS from UV radiation so that visible imaging is prioritised by the sensor, means that the usefulness of the CMOS sensor in the smartphone is reduced unless modified or calibrated. Extending outside the UV spectrum, recent studies showed that a smartphone CMOS sensor has the potential to detect high energy radiation used for medical applications (X-rays and gamma rays) (Kang et al. 2016). Some details of the historical aspects of smartphone usage for UV detection and measurements were recently outlined by Grossi (2018).

This section summarises the requirements for using smartphones in a self-contained manner to measure UV radiation, primarily with the focus on radiation detection via the camera CMOS image sensor hardware held within the smartphone device. The main stages that have been performed in the research to date to characterise the smartphone camera response to UV irradiation will be reviewed, from laboratory settings and when observing the sun.

3.1 Characterisation of Smartphones for measurement purposes

The use of a smartphone sensor for measurement purposes requires the characterisation or calibration of the camera sensor response, this is done in the form of the pixel digital values to the magnitude of the irradiation source being measured. Any measurement of the incident irradiance by an opto-electronic sensor requires a calibration between the input and the resulting pixel values (Wu et al. 2010). The camera sensor response is provided by the pixel values of the respective red (R), green (G) and blue (B) channels, with each respective 8-bit value ranging from 0 to 255 in the default JPEG, and more recently: RAW format images provided as standard by a smartphone camera. The size of the respective RGB pixel values will vary depending on the energy per photon of the irradiation source being measured.

This relationship can be determined by irradiating the sensor with narrow band radiation of known spectral irradiances at a series of wavelengths from an irradiation monochromator or determined by narrow passband filters (Igoe 2013; Turner et al. 2017). For all cases, a preliminary investigation of the maximum expected irradiance needs to be undertaken to establish if any of the R, G or B pixel values will be saturated (Igoe 2013; Turner et al. 2017). If any saturation is anticipated, the relevant neutral density filters have to be employed over the camera sensor. Prior to use as a measurement device to measure a variable, all smartphones need to be characterised in the manner described above due to image sensor manufacturing differences. Recently, initial research has been made to standardise image sensor responses (Burggraaff et al. 2019), this important research is progressing.

3.1.1 Dark response characterisation

Associated with the calibration of the camera sensor response is the influence of temperature on sensor response, particularly influencing dark noise and dark current, for the purposes of this review, these are referred to as dark response (Igoe & Parisi 2014; Igoe et al. 2018a; Kim et al. 2017), the sensor spectral response and the response of the sensor to the source being measured (Igoe 2013; Igoe, Parisi & Carter 2013b, 2013a, 2014). Dark noise characterisation is a critical step for any low-illuminance observation and measurement (Kim et al. 2017).

The influence of dark noise can be evaluated by ensuring no signal reaches the camera, recording a number of images and determining the average pixel value for the three colour channels (Igoe, Parisi & Carter 2014; Igoe et al. 2018c; Igoe et al. 2018a). The response of the camera sensor to variations in temperature is determined by varying the ambient temperature and recording and analysing a series of dark noise images (Igoe, Parisi & Carter 2014). Investigations of the temperature response have indicated that the smartphone camera sensors are sufficiently shielded from the temperature changes attributable to normal daily fluctuations, thus causing negligible variations (Burggraaff et al. 2019; Igoe, Parisi & Carter 2014; Turner et al. 2017). Knowledge of the spectral response of the camera sensor is required to ensure that the sensor is responsive to the required wavelengths.

3.2 Laboratory characterisation of smartphone camera responses

Methods for laboratory characterisation of an unmodified smartphone camera image sensor response to UVA narrowband wavelengths (340 nm, 360 nm, 380 nm) were initially developed to determine overall grayscale response (Igoe 2013). This research was further extended to narrowband filters with a centre wavelength of 400 nm where the red, green and blue colour channel alongside the grayscale response to irradiance on the image sensor was measured (Xu et al. 2015). The observations made by Xu et al. (Xu et al. 2015) and Igoe et al. (Igoe 2013) identified that the smartphone image sensor response was approximately logarithmic to incident irradiance, the laboratory response to varying wavelength was modelled according to the algorithm developed by Debevec and Malik (Debevec & Malik 2008). This relationship was described by Turner et al. (2017) as a Hurter-Driffield modelled relationship.

$$f(Z) = ln\, I_\lambda + ln\, \Delta t$$

Where:

- I_λ is the incident irradiance from the irradiation monochromator.
- Δt is the camera exposure time and is generally constant for smartphone cameras, and so can be removed from further analysis
- $f(Z)$ is a function of the pixel intensity values (Igoe 2013; Turner et al. 2017).

The function $f(Z)$ is based on the individual R, G and B pixel values or combinations of these respective pixel values. Various combinations of the pixel values have been employed. Examples are:

- Chromaticity values, $\frac{\{R,G,B\}}{\sum R,G,B}$ (Igoe 2013; Malacara 2011; Turner et al. 2017),
- Grayscale values provided by Y = 0.30 R + 0.59 G + 0.11 B (Alala, Mwangi & Okeyo 2014; Ruderman & Bialek 1994) or other combinations to provide the grayscale values (Xu et al. 2015)

Investigations and observations have been extended into the UVB bandwidths. Laboratory observations were made of the response of a de-lensed (outer lens excised) image sensor to discrete UVB irradiation from a monochromator (Turner et al. 2017), in a similar manner to earlier UVA characterisation (Igoe, Parisi & Carter 2013b). The outer lens of certain smartphone models did not have any significant transmission in the UVB in laboratory settings.

3.3 Solar irradiance characterisation

3.3.1 UVA measurements

Laboratory observations were then tested in the field, to measure and quantify the smartphone image sensor response to direct solar UVA irradiances at 340 nm and 380 nm, calibrated against measurements recorded by a Microtops II sunphotometer (model E540, Solar Light) (Igoe 2013; Igoe & Parisi 2015a; Igoe, Parisi & Carter 2013a). An example of the setup is shown in Figure 1. The observational method was simplified with the development of an app that calculated the average grayscale response of the image sensor (Igoe 2013; Igoe, Parisi & Carter 2014), and systems that send data via the 'cloud' (Mei, Cheng & Cheng 2015a). Due to differences in manufacturing, each image sensor was found to have its own response to irradiances, but all image sensor responses in the UVA were found to follow a general logarithmic relationship similar to laboratory observations (Igoe 2013; Igoe, Parisi & Carter 2013a, 2014):

$$ln\, I_\lambda = f[ln(\{Y, R, G, B\}D^2\, cos^4\, \theta_{SZA})]$$

Where:

- I_λ is either the direct UV irradiance measured with a sun photometer or the global UV measured with a radiometer.
- $\{Y,R,G,B\}$ is the appropriate average of grayscale (Y), red (R), green (G) or blue (B) pixel values averaged after an adaptive threshold is applied to separate it from background noise (Igoe et al. 2017; Igoe et al. 2018c; Igoe et al. 2018b).
- D^2 is the Earth-sun distance factor (Porter et al. 2001).
- θ_{SZA} is the solar zenith angle.
- f is the calibration regression function.

Figure 2 shows an example of the conversion of the captured image to digital number.

In further observations made in Hong Kong, the equation was modified to account for different configurations of instruments and narrowband filters being used, providing a similar accuracy (Fung & Wong 2016).

$$\ln I_{\lambda} = m \ln(Y^{1.5} \cos\theta_{SZA}) + c$$

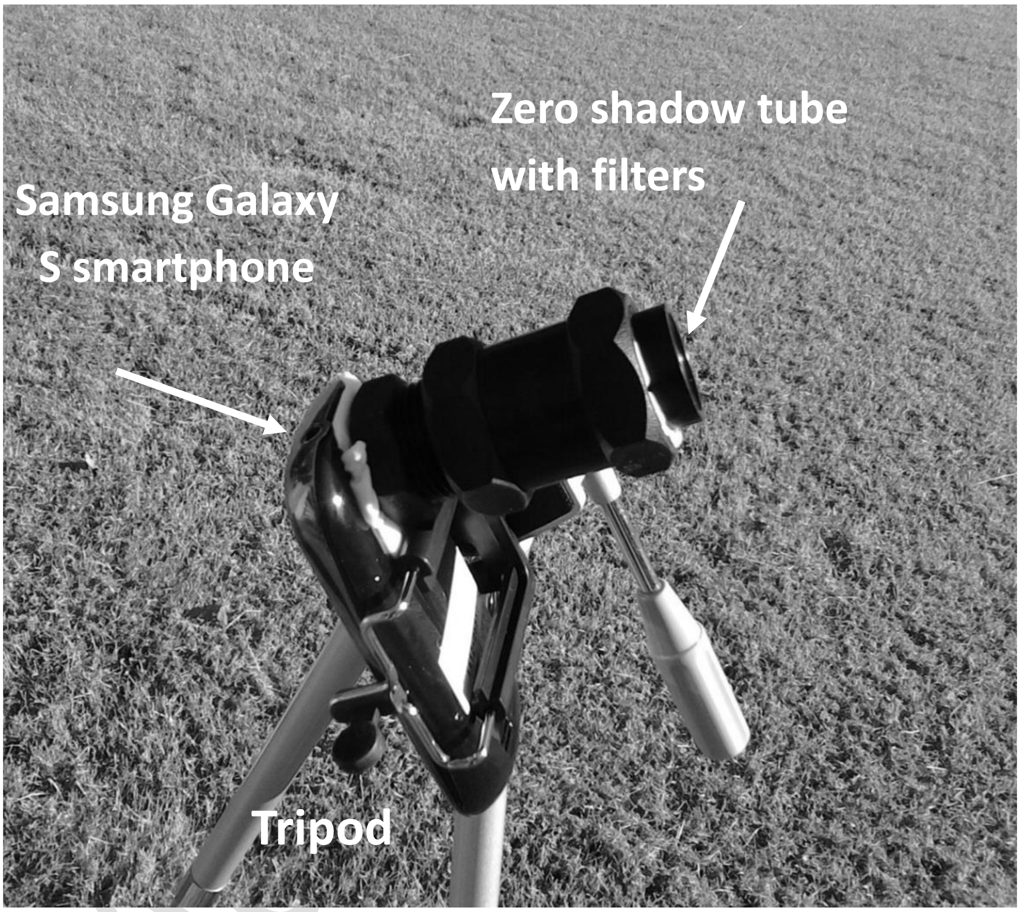

Figure 1 – Example of Setup, using a second-hand Samsung Galaxy S. The 340 nm filter was held in place using plumbing supplies (tube), and held together with blutak and electrical tape. Photo courtesy D. Igoe.

Research into narrowband observation of solar UVA radiation was extended to establish broadband UVA models using an unmodified smartphone image sensor, this was achieved by using narrowband UVA responses as a basis to develop broadband models, calibrating strongly against a UVA Meter (model 3D, Solar Light) (Igoe & Parisi 2015c, 2015b). The modelled image sensor responses were found to achieve similar accuracy as for narrowband observations (Igoe & Parisi 2015b).

Development of wearable sensors linked to smartphone sensors (discussed in Section 2.0), such as the use of *Arduino* have been developed, where inexpensive small UV sensors are used to measure solar ultraviolet radiation, such as used in the *UVision* system (Hoblos et al. 2015). Using a diffuser over the lens and a prewritten pyranometer app, after calibration, reasonably accurate measurements of broadband UVA can be achieved (Al-Taani & Arabasi 2018). Aggregate broadband data from several devices with an *UV Meter* app have been employed to determine broadband UV levels (Mei et al. 2017).

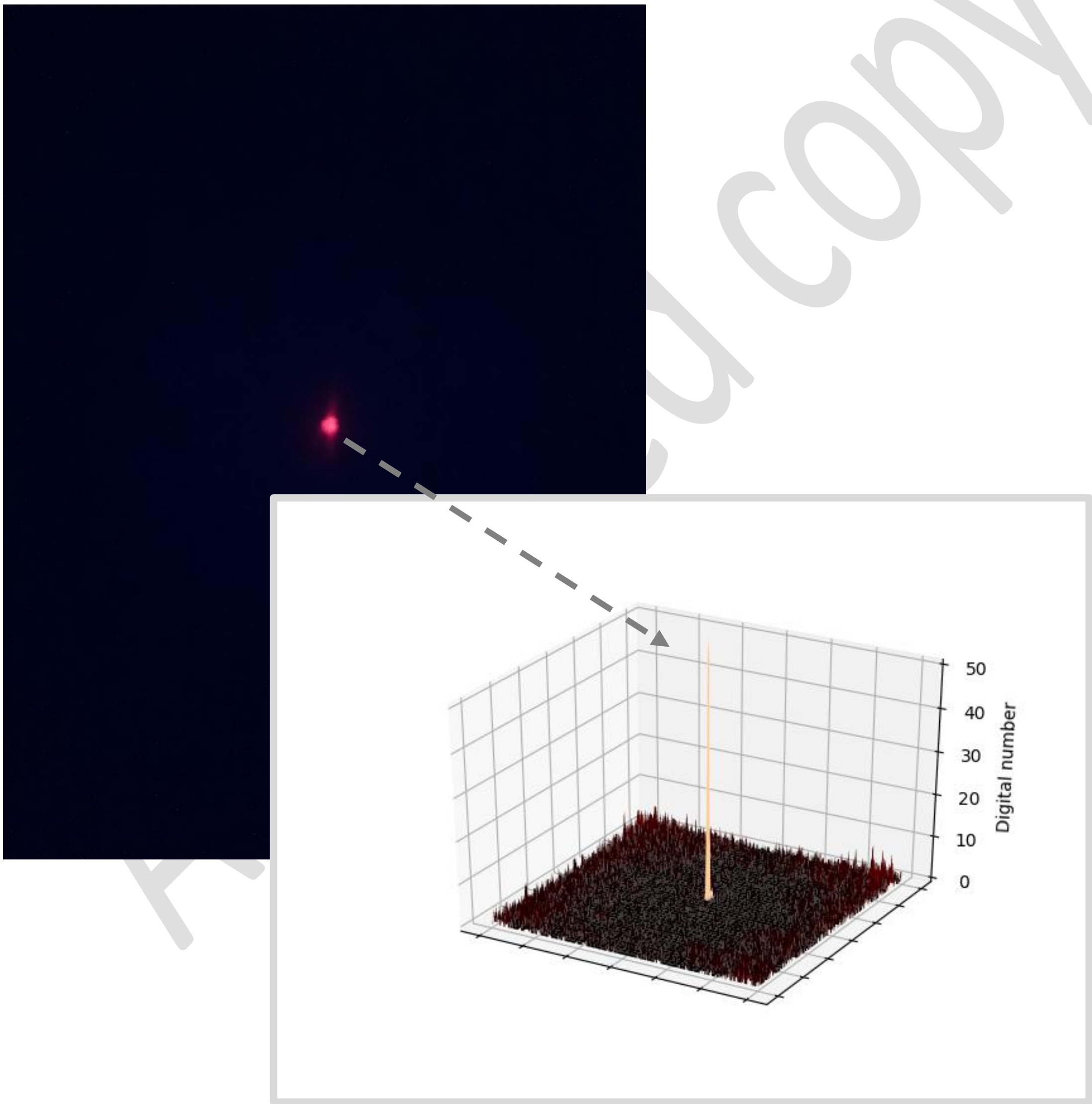

Figure 2- 340 nm image of the sun taken using a Sony Xperia Z1 with a 340nm filter, with the relative scale of the red channel shown. Photo by A. Amar, 3D rendering by D. Igoe.

3.3.2 UVB measurements

The observations indicated that smartphone image sensors were sensitive to the entire UVB bandwidth (Turner et al. 2017). External sensors were used to detect solar UVB irradiances to 310 nm (Wilkes et al. 2016). It was found that the smartphone image sensor was able to detect solar UVB radiation to 305 nm with the outer lens kept intact, even at high air masses (Igoe et al. 2017). This was possible even though the lens transmission was low in the UVB due to the sun having a greater irradiance than the laboratory monochromator. Observations were made at 305 nm (Igoe et al. 2017) and at 312 nm (Igoe et al. 2017; Igoe et al. 2018c), using the same narrow bandpass filters with a 2 nm FWHM as used in the Microtops II sunphotometer (Igoe et al. 2018c). The use of the specialised filters represents a cost limitation of this method. An example of this data collection setup is shown in Figure 3.

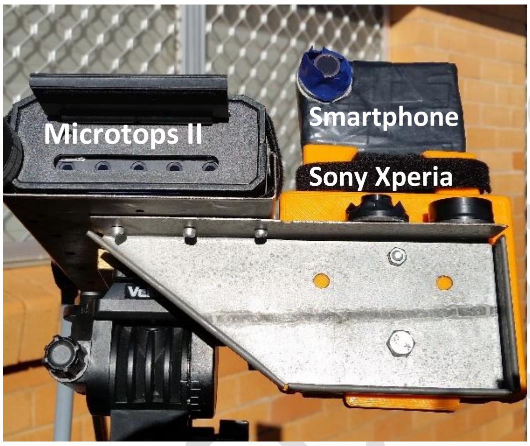

Figure 3 – Example set up of use of narrowband filters with smartphone and Microtops II. Filter is attached in image. Image courtesy J.Turner

The calibration exhibited the same relationship as for the UVA, except it was found that the green channel was indistinguishable from background noise for several smartphone models such as the Sony Xperia Z1 (Igoe et al. 2017; Igoe et al. 2018c; Igoe et al. 2018b). In the images taken in the UVB, the solar disk appears magenta (Igoe et al. 2017), the red channel was found to be the most prominent component with the highest signal to noise ratio (Igoe et al. 2018b). A proportional blue-red (PBR) model based on an image's signal to noise ratio (SNR) was developed PBR = xR + yB (Igoe et al. 2018b), this method has been mainly used for solar irradiances. Unlike the UVA responses, the calibration formed broad quadratic curves, becoming more linear as wavelength increased (Turner et al. 2018), suggesting a greater influence of ozone optical depth on image sensor responses (Igoe et al. 2018c).

Section 4.0 - Measurement of UV radiation to quantify atmospheric factors

Whether the focus is to measure UV radiation, or some subsidiary measurement that uses UV evaluations to measure some other factor, it is apparent that smartphones could fill sensing gaps in technology or be an accessible technology to supplement existing techniques. Likewise, it is equally important to measure factors that influence UV radiation to help understand the patterns, trends and anomalies in UV irradiance observations. In this section we review factors influencing UV radiation, as well as factors that use UV radiation in the measurement process.

4.1 Aerosols

Aerosols in the atmosphere contribute to the total optical depth of the atmosphere and so influence the solar radiation reaching the Earth’s surface. The amount of aerosols is defined as the aerosol optical depth (AOD) - also known as aerosol optical thickness (AOT). The influence on UV irradiances increases with increasing aerosol optical depth (Wenny, Saxena & Frederick 2001). There have been numerous studies in the use of smartphones for the detection of aerosols and the measurement of AOD. The focus of this research has varied from attachable devices, using the processing power of the smartphone to record, analyse and sometimes, transmit collected data; to systems where the smartphone internal camera is used with accompanying processing power. There have been a few very comprehensive reviews of mobile and portable devices for detection of particulate matter and air quality, examples are given by Gozzi (2016), Thompson (2016) and Grossi (2018) respectively. Often reviews are focused on other sensors available, not strictly on smartphone usage (Morawska et al. 2018). A recent review by (Grossi 2018) briefly summarised some aspects of this smartphone application.

Much of the research involving the use of smartphones has been to detect and measure aerosols in the visible wavelengths using attachments that interface with the smartphone (McGonigle et al. 2018; Wilkes et al. 2016; Wilkes et al. 2017a; Wilkes et al. 2017b). Many of these studies took advantage of the crowdsourcing potential that smartphones provide, given their ubiquity (Athanasopoulou et al. 2017; Cartwright 2016; Hasenfratz et al. 2012; Pierce et al. 2017; Rietjens et al. 2013; Snik et al. 2014). A prominent example of a crowdsourcing project using a smartphone attachment was the *iSPEX* add-on that made air quality measurements available to many participants, allowing a greater resolution of aerosol measurements (Athanasopoulou et al. 2017; Cartwright 2016; Hasenfratz et al. 2012; Snik et al. 2014). Optical scattering detected using a camera flash, available as an attachment or inbuilt with some smartphone models, was used to develop a particulate matter dosimeter (Budde et al. 2013).

Similar research was completed using related technologies such as digital cameras that employ similar image sensing technology (Igoe 2011; Tetley & Young 2008; Williams & Williams 1993). UV-capable digital cameras were also developed to measure aerosol SO_2 (Bluth et al. 2007). The smartphone camera colour response to aerosols was the subject of a NASA ‘Space Apps’ challenge: *My Sky Color*, when compared with GLOBE data (Bujosa & Pippin 2016). Yellow, green and blue colour filters were employed to directly measure attenuation due to aerosols as detected by an iPhone (Cao & Thompson 2014). Chemical analysis attachments to smartphones have been developed to sense the presence of aerosol species with the data processed in the smartphone (Cao & Thompson 2014; Thompson 2016). These attachments include mobile gas sensors (Hasenfratz et al. 2012) and aerosol filter samplers to measure and quantify aerosol black carbon (‘soot’) (Ramanathan et al. 2011).

Recently, there have been considerable efforts in employing similar techniques for the detection and measurement of UV attenuating aerosols, both using external attachments and using the solar UV sensitivity of the smartphone image sensor itself. It has been found that the same technique used to detect and quantify UVA irradiances could be applied to measure AOD without making any significant physical modification to the smartphone itself (Fung & Wong 2016; Igoe 2013; Igoe, Parisi & Carter 2013a), and that a relatively simple *Android* app could be written and used to simplify data collection (Cao & Thompson 2014; Igoe 2013; Igoe, Parisi & Carter 2014), achieving very high accuracy when the observations were compared with a Microtops II sunphotometer. Raspberry Pi attachments have been used to visualise SO_2 aerosols in the UV (to 310 nm) (McGonigle et al. 2018; Wilkes et al. 2016; Wilkes et al. 2017a; Wilkes et al. 2017b).

4.2 Ozone

There is now evidence, because of the Montreal Protocol, of the beginning of a recovery of stratospheric ozone over Antarctica (Bais et al. 2018). However, statistically significant increases are yet to be detected at other latitudes. The ground based measurement of atmospheric ozone is undertaken by employing the ratio of direct irradiances in narrow wavebands at UVB wavelengths (Balis et al. 2007). Once it was shown that solar narrowband UVB wavelengths at 305 nm can be quantified using specific smartphone image sensor colour channels (Igoe et al. 2017), observations were made at 312 nm and of the total ozone column (TOC) with the same degree of accuracy when compared with readings from the Microtops; however, the necessity of a lower full-width at half-maximum (FWHM) for these measurements have required very expensive filters to be used (Igoe et al. 2018c). One of the authors (A. McGonigle), with his team, has made significant progress towards refining and improving the accuracy of ozone measurements using much more inexpensive and accessible Raspberry Pi systems similar to those used for volcanic plume observations (McGonigle et al. 2018; Wilkes et al. 2016; Wilkes et al. 2017b).

4.3 Clouds

For a given solar zenith angle, cloud is a significant influencing factor on the solar UV irradiances and the global solar irradiances (Alados-Arboledas et al. 2003). Cloud type, amount and distribution modify the solar irradiances that reach the Earth’s surface, with the influence of cloud either attenuating the solar irradiances or at times depending on the type and distribution of cloud, enhancing the irradiances above that of a clear day (Calbo & Sabburg 2008; Sabburg & Long 2004a).

As a result, information on the amount and properties of cloud is necessary in any attempts to predict solar UV irradiances for public health and global solar irradiances for solar energy generation (Tapakis & Charalambides 2013). The prediction of the solar UV radiation on a daily basis through the UVI (WMO 1994) is based on the modelled clear sky UV that does not consider the cloud cover. Providing UVI that takes into account the effect of clouds improves the accuracy and usability of the information delivered to the public (Sabburg & Long 2004b).

The fraction of the sky covered in cloud has originally been determined by trained observers at set intervals during the day (Long, Slater & Tooman 2001). The introduction of whole sky cameras for the imaging of the whole sky: examples are mentioned in (Long, Slater & Tooman 2001; Pfister et al. 2003; Shields et al. 2013), and sun tracking cameras (Sabburg & Wong 1999): along with associated image analysis has enabled the automation of the determination of the fractional cloud cover of the sky, along with various properties of the cloud (Calbo & Sabburg 2008; Long et al. 2006). The prediction of global solar radiation for solar energy generation has also been investigated with fish eye lens cameras and concurrent solar radiation measurements (Chu et al. 2014).

The widespread uptake of smartphones has provided an opportunity for the application of this technology in the provision of cloud information. An app provided by NASA allows Citizen Scientists to provide cloud information either by visual cloud observations or taking and uploading images of clouds with a smartphone camera (GLOBE Observer 2018). Recently, a smartphone camera fitted with an inexpensive fish eye lens has been employed in whole sky imaging (Parisi et al. 2016), along with the analysis of the images on a personal computer for the determination of the cloud fraction, proportion of thin and thick cloud and the amount of cloud in proximity to the sun. The further development of this approach has the potential for uptake by Citizen Scientists, as well as input of local cloud data into determination of the UVI and improved information of local cloud trends for forecasting solar energy production.

4.4 Volcanic Plumes

Notwithstanding the significant progress reported in this review, unmodified smartphones are fundamentally limited in their capacity to sense the UV spectral region. The reasons for this are twofold: firstly, the lenses used to form images on the sensor plane are usually composed of UV absorbing media, and secondly, the fore of the sensors themselves are typically coated with colour filter arrays, which serve not only to generate RGB mosaics from the sensors, but also block most ultraviolet light transmission.

Whilst disassembly of smartphones in attempts to remove/replace these elements in order to enhance UV sensitivity has been achieved (McGonigle et al. 2018; Sabburg & Wong 1999; Turner et al. 2017; Wilkes et al. 2017a; Wilkes et al. 2017b), there is a significant risk of destroying the possibly rather expensive, entire smartphone assembly. For this reason, focus has been placed on modification of the considerably cheaper hobbyist electronics Raspberry Pi camera modules, which are based on sensors developed for the smartphone market. Recently there have been reports of successful removal of colour filter arrays from these devices, with reassembly of the camera modules, using UV transmissive quartz lenses, and 3D printed lens mounts (Wilkes et al. 2016). Given the back illuminated CMOS architecture of these sensors, they have been demonstrated to have useable UV sensitivity down to at least 300 nm, following this procedure.

The principle application area of these units has been remote sensing of sulphur dioxide (SO_2) fluxes from volcanoes (Wilkes et al. 2017b), based on the significant UVB absorption by this gas, which is typically the third most abundant molecule, behind water vapour and carbon dioxide, in volcanic gas plumes. Various remote sensing protocols have been applied to measuring these emissions over the last decades, with a view to constraining gas outputs from volcanoes, in order to better understand subterranean volcanic dynamics and forecast impending eruptions. These approaches are normally based on discriminating the absorption due to this gas species, from the broadband extinction caused by aerosols across the UV. This is achieved either using differential optical absorption spectroscopy, whereby the absorption spectrum is high pass filtered, to resolve the rapidly varying structure, in the spectral domain, caused by the SO_2 absorption (McGonigle et al. 2002) and to eliminate broadband aerosol effects. Alternatively, imaging using a pair of ultraviolet cameras can be applied, using bandpass filters in front of each one, such that the units capture radiation at 310 nm and 330 nm, respectively, where SO_2 does and does not absorb, enabling removal of the aerosol effects which are common to both wavelengths.

Ultraviolet radiation is also subject to multiple scattering issues within volcanic plumes. In this respect the radiative transfer can become very complicated, particularly where there is significant condensation, in which case it become very challenging to retrieve usable SO_2 gas emission rate data. Furthermore there are light scattering issues in the atmosphere between the remote sensing instrumentation and the gas plumes, which, at significant distances from the source can act to reduce the retrieved gas emissions from the volcano; for this reason, observations are typically made not more than a few kilometers from the gases in order to try and minimise this effect (McGonigle et al. 2017).

In the case of the Raspberry Pi smartphone sensor based volcanic measurement configuration, dual camera systems (310 nm and 330 nm, as detailed above) have been developed, which resolve SO_2 concentration profiles in the plumes rising from volcanoes. By contrasting these images, and applying Beer's law, the gas column amounts across the instrumental field of view can be established. The resulting images are then processed in order to determine emission rates from the source. This modality has been applied to measure gas emission rates from power station sources, as well as from volcanoes in Italy, Hawaii, Peru, Chile, Nicaragua, Papua New Guinea, Vanuatu and Ecuador. Given the low cost of the developed devices (build cost per unit of hundreds of dollars), a particular emphasis has been on dissemination of the unit to resource limited regions, where volcanic risk is high.

The modified Raspberry Pi units have also been implemented in spectral UV sensing modes, by housing the sensor within a low cost 3D printed spectrometer architecture (Wilkes et al. 2017a). The unit is based on a Czerny Turner design, using off the shelf optical components, in order to yield a linewidth of ≈1 nm at 300 nm. This unit has been utilised in measurements of SO_2 from volcanoes, with fair performance reported in comparison with rather more expensive commercially available units (Figure 4).

Figure 4- Raspberry Pi based spectrometer being used to measure gas release from fissure 8, Kilauea volcano, Hawaii – August 2018. At this point in time, this vent was one of the most prodigious point sources on the planet of sulphur dioxide to the atmosphere.

Section 5.0 Discussion

5.1 Practicalities, limitations and challenges of smartphone UV observation techniques.

The utility of smartphones as a tool for a greater accessibility, low cost UV observation and measurement is very clear from the myriad of examples reported in this review. Overall, this review has shown that there are four main utility methods that have been used for UV observations and measurement, authored by multiple authors, companies and research groups:

1. Smartphone apps without UV sensors, where the smartphone processor calculates quantities, usually for public health concerns, based on online and accessible databases accessed by the internet.
2. Smartphone apps with UV sensors, where the smartphone processor analyses data from an external UV detecting sensor, usually a photodiode. This method has been used for both public health concerns and atmospheric observations.

3. Smartphone apps with non-electronic UV sensors, where the smartphone processor analyses data from sources that are often in direct contact with a person, such as tattoos. These are almost exclusively used for public health concerns.
4. The use of smartphone image sensors directly, where the camera response is calibrated against standard equipment. This method has been primarily used for measuring atmospheric phenomena.

Each have their own practicalities, limitations and challenges, these are summarised in a non-exhaustive list in Table 2. All methods listed present potential limitations and challenges common with smartphone applications – compatibility, support and version control, as well as automation. In particular, a great challenge for methods 2-4 in particular is the cost and accessibility of devices needed for calibration and validation (e.g. monochromator, sunphotometer etc). This situation is expected to improve as technology and methodologies develop, capabilities expand and more data is collected and cross referenced, potentially leading to standard measures used for comparison and calibration.

Not included in the list and the tabulated summary are:

1. Augmented reality, primarily as this is a new development with the most recent applications involved with simulations of the health effects of UV radiation (e.g. photoaging).
2. Smartphones with built-in UV sensors, this is due to the lack of applicable UV radiation measurement research using these devices. Also, given the rarity of models having this feature, it is unlikely to be used in anything other than small scale dedicated research.
3. Drones, specifically with interfaces with smartphones, once again there has been very little applicable use of this technology.

These technologies have considerable scope to be used in research, but as of writing this review, very few applications have been developed, so their practicalities, limitations and challenges cannot be fully analysed. Considerable challenges that can be predicted for these technologies include their cost and accessibility.

5.2 Alternatives to sensing UV radiation in smartphones

It may seem counter-intuitive to present information about the alternatives to sensing UV radiation in smartphones, however this area of interest is drawn from the possibility of extracting UV radiation information from different sectors of the solar spectrum. Examples include the study by Downs et al. (2017) which uses an infrared photodiode to track sun exposure, for a more effective sun diary for solar exposure studies. Lack of infrared radiation detection indicates the device is inside as opposed to outside, and is able to keep track of solar exposure for participants who may not recall their solar exposure over the day accurately. Devices like this could be correlated to UV exposure and UV doses could be extrapolated. Similarly, existing studies show that UV irradiance can be extracted from existing global solar irradiance measurements or calculated from knowing the near infrared and visible irradiance measurements (Escobedo et al. 2009, 2011). A not yet published study has proposed the extraction of health related UV doses from PAR (photosynthetically active radiation) using a relatively simple 2nd degree regression equation (Corrêa et al. 2019). Extraction of UV irradiance data indirectly from other radiation that is more straightforward to detect, may provide a means to collect UV exposure data to smartphone users. Neural networking has been used to predict PAR (Deo et al. 2019), therefore it is conceivable that UV radiation could similarly be predicted using similar methods. This may be considered somewhat similar to the fog computing processes previously discussed (Mei, Cheng & Cheng 2015a; Mei et al. 2017).

Table 2- Summary of the practicalities, limitations and challenges for each of the most widespread methods of smartphone UV observation.

	Method Type			
	1. Without devoted UV sensors	**2. With devoted UV sensors**	**3. With non-electronic UV sensors**	**4. Use of the image sensor**
Practicalities	• No additional device needed. • Use of validated official data. • No additional cost.	• Uncomplicated devices used based on educational kits (e.g. Raspberry Pi). • Accurate real time observations. • Relatively low cost.	• Real time observations of personal health information. • Reasonable accuracy. • Relatively low cost.	• Accurate real time observations. • Minimal amount of additional equipment and no internet needed. • Potential to work on all models with cameras.
Limitations	• Most likely not real time data, or delayed data. • Not every location has coverage. • Internet connection not always available.	• Accessing standard equipment for calibration • Assessing the accuracy over a range of conditions. • Potential external device connectivity issues.	• Calibration of the data with the individual person's physiology – assessing the accuracy over a range of conditions. • Potential medical and ethical concerns. • Reference card typically required.	• Accessibility and cost of filters, particularly for UVB measurements. • Accessing standard equipment for calibration. • Calibration currently required for each smartphone model.
Challenges	• Access to multiple sources of real-time data on demand. • Universal coverage and acceptable data resolution. • Utility to efficiently cross-reference and validate multiple data sources.	• Increasing accuracy and precision of measurements without significant cost increases. • Maintaining unobtrusive device utility. • Developing low cost and accessible calibration techniques.	• Developing the devices to be non-intrusive. • Prevention of harmful health side effects. • Increasing accuracy and precision of measurements without significant cost increases.	• Low cost filter alternatives. • Standardising image sensor responses across smartphone models. • Using all sensors to increase accuracy.

Another possibility within the alternative options to sensing within the UV radiation spectrum with smartphones, is the use of augmented reality. Brinker (2017) uses simulations within the app used in their study, however there is only one app to date that appears to truly use augmented reality (Wakely et al. 2018) specifically within the scope of UV radiation effects. Online searches show that many patents are reviewing this type of technology. However, at this stage, the augmented reality app is not technically sensing UV radiation, rather it is relying on other information collected to inform the user, while the augmentation provides a visual simulation to which the user can respond.

5.3 Implications for Public Education

Common among the articles reviewed for this discussion, is the key feature surrounding the development of the sensor, the app, or both, being driven by the need to promote more effective engagement with the public on the understanding of the implications and effects of UV radiation exposure. The work by Buller et al. (2013); Buller et al. (2015a, 2015b); Gold et al. (2011); Hacker et al. (2018a); Hacker et al. (2018b), while not conclusively demonstrating quantitative results that people are more aware and engaged: provided qualitative analysis suggesting that participants can potentially feel more motivated to learn about and monitor their own UV exposure, and that the participants may suggest their perspective is changed regarding UV exposure. It is essential that the work continues to engage the public about UV radiation exposure, as it has been previously posited that education is the best way to reduce deleterious effects of UV radiation to humans. The smartphone, an everyday item, can encourage engagement due to its ease of use and its ubiquitous nature in modern society. Similarly, the electronic components used as external sensors in conjunction with smartphones are often included in inexpensive educational kits (e.g. Raspberry Pi) and are usually available in retail electronics stores or online.

While smartphones and associated technologies used with smartphones allow the ability to engage with the public further on UV radiation understanding and knowledge, there are still challenges that can be an issue. Use of apps without devoted sensors can be a good general provider of information, but it does not satisfy the need for individualised information. These types of information sources may confuse users particularly in countries like Australia, where the UVI is consistently at the level of "extreme" throughout the year.

An individual sensor used in conjunction with the smartphone is the next step to individualising a user's understanding of personal UV exposure. However, amongst the challenges already noted in Table 2, other hindrances include the ability to lose or forget the device, incorrect use of the device, or damage to the device. The additional costs of these devices can shut out lower socio-economic groups, as it is an additional cost compared to the multi-faceted use of a smartphone (which can range in price significantly). Additional UV sensing devices that are non-electronic can substantially reduce these costs, as well as barriers to access. However, the sensing mechanism may not be as consistent or as comfortable to use as an electronic device, and unless the user is undertaking purposeful outside activities, the user may not consistently use the device. Some of these devices are also for single or short-term use, hence limiting their availability over time, potentially incurring additional expense with their replacement.

The last option, in using the smartphone image sensor, has cost issues with requiring filters to isolate the UV radiation for sensing purposes. At this stage the authors are unaware of any opportunities that could reduce this cost. However, there are opportunities for manufacturing low cost lenses (Lee et al. 2014). Developing low cost substrates capable of filtering out visible and infrared radiation will provide UV lenses that can be embedded into low cost smartphone cases. Possible configurations could allow the filter to be placed across the image sensor (for example by smartphone case), without impacting the construction of the smartphone itself. This of course adds additional cost of the item to be obtained, which suggests there will be many more considerations required to solve the issues facing sensing UV radiation with smartphone sensors.

Overall, the key implications surrounding the use of smartphones in educating people about UV radiation is that the delivery process should be consistent with the current health messages regarding UV exposure, and provide systems that are easy to use and understand.

Section 6.0 - Future Directions for UV detection with smartphones

This review has considered all aspects of sensing UV radiation in conjunction with smartphones, including inbuilt sensors already existing within the smartphone; directly connected devices to smartphones; wireless devices that can be used in conjunction with smartphones, or indirectly through correlation with other solar irradiance detection methods.

In furthering the research that focuses on employing inbuilt smartphone sensors to measure UV exposure, one of the key issues that should be addressed is the ability to calibrate each smartphone CMOS sensor to UV radiation detection. Not only does each model of smartphone require calibration, but equally every individual smartphone requires calibration. Using a standardised method such as that used by Burggraaff et al., (2019) could provide a solution. However, it is still unavailable to be delivered to smartphone users in a low cost and easy to access way. A possible application of this calibration method could be the development of a device that can calibrate smartphone camera sensors based on standardised principles. This in turn could provide a wider scale system of calibration for multiple devices. Such a device could be made available in pharmacies or through other health care providers. Consumers could plug their smartphone into the device for calibration purposes, to be used with a specially designed smartphone application that can control the smartphone sensors for UV radiation detection and hence UV exposure measurement.

Other issues that need to be overcome, in regard to using inbuilt sensors of smartphones for UV detection, includes the current need for narrow bandpass filters to ensure CMOS sensors are not saturated by UV wavelengths particularly when measuring for solar irradiances. A more straightforward and less expensive option needs to be available for these narrow bandpass filters which are currently relatively expensive.

Section 7.0 - References

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