Sundroid: Solar Radiation Awareness with Smartphones*

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ABSTRACT
While the sun is important for our health, overexposure to sunlight carries significant health risks ranging from sunburn to skin cancer. Although people know about these risks, sunlight related skin damages have increased over the past decades. We have conducted a survey that sheds light on this phenomenon and suggests that the missing natural sense for UV radiation negatively influences people's sun related behavior. To address this issue, we have implemented *Sundroid*. Sundroid measures the incident UV radiation using a body-worn sensing unit that communicates wirelessly with the user's smartphone. The phone thereby acts as a user interface to present the measured data in an intuitive manner, and to notify the user once a critical amount of sunlight has been reached. Sundroid can also be applied in other contexts, such as behavioral research or medicine. We show that after calibration, errors are within 5% compared to a high-precision reference signal.

Author Keywords
Personal Health Monitoring, Wearable Sensor, Solar Radiation, UV Exposure, Dosimetry, Survey

ACM Classification Keywords
J.3 Life and Medical Sciences: Health.

General Terms
Design, Experimentation, Measurement, Reliability

INTRODUCTION
Sunlight is a driving force for life and, amongst others due to its role in the production of vitamin D, indispensable for our health. However, over the past decades an increasing number of studies warned against the risks of excessive sunlight exposure. A vast majority of people has already experienced the unpleasant feeling of sunburn after having stayed in the sun too long. Unfortunately, the harmful effects can go beyond unpleasant feelings. Long-term damage, such as premature skin aging and skin cancer are severe implications that can result from an overexposure to sunlight, even if no immediate signs of sunburn are visible [3].

Both, sunburn as well as the mentioned long-term damages are caused by the ultraviolet (UV) radiation contained in the sunlight. In fact, most of the non-melanoma skin cancers are associated with exposure to ultraviolet radiation [29]. A considerable fraction of people is aware of the risks originating from the sun. Nevertheless, the number of such skin cancer cases in the United States has constantly increased over the past years [30]. Even though most people know about appropriate protective measures, a large fraction of the population gets sunburned from time to time. A first contribution of this paper is a survey that sheds light on the reasons for this phenomenon. A relevant finding of our survey is that inattention and the inability to correctly assess the UV intensity are two major reasons for excessive UV exposure and therefore for people to get sunburned.

Contributions. Following these findings, the main contribution of this paper is a wearable prototype system that tracks the wearer's sunlight exposure in real-time. This is in contrast to existing wearable UV dosimeters, that are designed for offline analysis only. The proposed system is designed in a modular fashion and consists of two parts: (1) A small sensor unit that measures the UV radiation and is equipped with a Bluetooth module. (2) A smartphone application that collects and processes the sensor unit's measurements. The phone thereby acts as a generic processing platform, which makes the system adjustable to a wide range of applications. The application presents the measured solar radiation data in a user-friendly manner. Moreover, it is able to notify the user of the imminent danger due to UV radiation when appropriate, thereby taking into account critical factors such as the specific skin type of the user or sunscreen applied.

The modular design of our sensor system reduces the effort to address other usage scenarios, as basically only the smartphone application needs to be modified. In fact, we also envision applications that go beyond personal UV radiation monitoring. Discussions with a dermatologist have shown that our system could prove advantageous in several medical settings. Moreover, we see various usage scenarios in research and large-scale sensing.

For the discussed usage scenarios, it is essential that the sensor unit works reliably and provides accurate data. We

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have thus paid particular attention to the technical soundness of our system. By independently tracking UVA (400 nm - 315 nm) and UVB (315 nm - 280 nm) radiation, we can well approximate the action spectrum relevant to a given application. An example is the erythema action spectrum, which describes the radiation relevant to sunburn that is absorbed by the skin. The system has been calibrated using two six hours traces recorded at the World Radiation Center in Davos, Switzerland. The comparison with the reference measurements shows that our sensor module is able to accurately measure the radiation absorbed by the skin at the position of the sensor. In separate experiments we have investigated the effect of a diffuser to reduce angle dependencies. Furthermore, we have conducted two pilot studies in each of which we have recorded real-world data of a person wearing the system during a specific outdoor activity.

RELATED WORK

Existing research efforts have investigated various aspects relevant to our work both in medicine and in the field of ubiquitous computing. In the following, we will briefly review major achievements and results from these different areas and sketch how our work relates to or was influenced by these findings.

UV Dosimeters. A variety of wearable UV dosimeters based on different technologies have been proposed in the past. A rough categorization distinguishes between chemical, biological, and electronic methods to measure UV radiation [15]. While electronic measurements facilitate the post-processing of various sensor inputs to approximate a desired action spectrum, biological and chemical dosimeters are more restricted with respect to the spectral response. Biological dosimeters typically agree well with the DNA damage spectrum [15]. An example of the use of a biological dosimeter is a study on long-term UV exposure of mountain guides [24].

As opposed to biological and chemical dosimeters that exhibit an integral characteristic, electronic systems based on photodiodes can measure the UV intensity at a given point in time. They thus do not only provide higher flexibility with respect to post-processing, but are also well suited to creating plots of the UV intensity over time. Examples for such systems are [1], [6], and [12]. Like our sensor system, these devices are designed to be worn by humans. However, all of them measure UV intensity using a single sensor and thus fail to take advantage of the flexibility given by post-processing of individual UVA and UVB values. Moreover, they are primarily designed for the use in medical studies, and thus do neither provide a direct feedback to the user, nor do they support real-time monitoring. As a consequence the intensity data can only be retrieved after a measurement series has been completed, which is in contrast to our system that constantly transmits the sensor values to a mobile phone, and thus can directly take influence on the user's behavior. Beside these limitations, the system described in [12] was used in a medical study to record the exposure to UV radiation [36] of over 300 subjects. They found that sunburn is correlated with risk behavior.

Mobile phones. We have chosen the mobile phone as a processing platform as it provides high flexibility with respect to applications. Besides the powerful post-processing possibilities, the advantages of a phone are its communication capabilities that make it a perfect gateway to transmit sensor data to servers [37], the permanent reachability by the user [27] and the wide variety of sensors readily available [23]. For these reasons mobile phones have been said to be an ideal platform for context-driven reminders and alerts [34, 17], and for the use in large-scale sensing studies [23, 37].

Reminders. In a recent study, it was shown that the overall adherence to sunscreen use can be improved by daily text-message reminders [2]. As overly frequent reminders are likely to be disturbing over time, in this paper we propose to take the context into account to only issue reminders when required. Such context aware reminders have been proposed before, both, for medical scenarios [22, 20, 35, 28] and in everyday settings [34, 17, 18, 21, 8, 32, 13]. For everyday settings, location-based reminders have been examined particularly well, and have been found useful in several user studies [21, 17, 34]. These studies underline that people are interested in and amenable to context-aware reminders. We thus expect that the context dependent reminders issued by Sundroid can achieve a similar improvement of sunscreen adherence as reported by [2] in a much less obtrusive way.

Medical applications. Many of the usage scenarios we envision are related to health related contexts, such as sunburn warning or long-term behavioral training with respect to sunlight exposure. A variety of studies proposes remote and self-monitoring systems in medical contexts and/or investigates their success. Examples include diabetes self-care [10, 20, 35, 26], asthma management [28], context-aware pill reminders [22] and generic remote monitoring frameworks [5, 25]. User studies thereby on the one hand show that people are open to such systems [28, 35] and on the other hand indicate a positive effect on the patients' health and/or comfort [26, 22, 28, 10, 20]. Several authors highlight the advantages of mobile phones and PDAs as a platform and information hub [20, 10, 35, 28, 26, 25, 5] and the usefulness of context-driven reminders [20, 22, 26, 28, 35], for example triggered when the monitoring system detects low activity or the need to take medication. Moreover, visual feedback of the monitored data has said to be helpful by different studies [10, 26], in particular when it comes to train the user's awareness of, or behavior in a given context. A design evaluation of Logan et al. [20] further investigates relevant requirements as seen by the end users. In particular, they state that user intervention should be avoided for data-gathering, messages must be user understandable (i.e. in laymen terms), and that the system's user interface needs be intuitive. Moreover, Nachman et al. [26] conclude that a wearable sensor system should be unobtrusive, contain as few components as possible, and should not attract attention to the wearer in the public. When designing the prototype implementation of the Sundroid system, we have taken these different factors into account as far as possible given the hardware constraints.

SURVEY

As mentioned in the introduction, the number of skin cancer cases has constantly increased over the past years and most of the non-melanoma skin cancers are associated with exposure to ultraviolet radiation [29]. Moreover, a study in New Zealand showed that 17.8% of the skin cancer cases can directly be attributed to sunburn [33]. Despite the warnings of health departments from all around the world, most people have already experienced sunburn. In the following we present an online survey that investigates possible reasons for the mismatch between information and action, i.e. why people get burned even though they know about the severe health risks.

The online survey was conducted amongst 785 students (52% male, 48% female) from different departments at our university. We wanted to know how often people get burned, and why this happens. For this purpose we have also investigated how well people are informed about the risks of sunburn and protective measures. In addition, we wanted to know whether they believe that a warning system could prevent some of the sunburns they suffer, and whether they would be willing to use such a system. We first asked four control questions related to sunburn and its risks. As expected the participants are generally well informed. Roughly three quarter answered all questions correctly, and even 95% know that sunburn increases the risk of skin cancer.[1]

Despite this knowledge, roughly two thirds of the respondents experience sunburn at least once a year, and almost everybody (96%) has already been sunburned. For the rest of this section, the 4% of participants who never suffered sunburn are excluded. From the remaining participants almost all (96%) consider sunburn somewhat (38%) or very (58%) annoying. To understand why people are suffering sunburn despite the risks and the potential annoyance, we further asked for the reasons for getting sunburned. To get an unbiased picture, the question was formulated openly, i.e. replies were given in free form text. For evaluation, we manually grouped the answers into semantic categories. A single answer could have been assigned to more than one category. The most frequent answers are summarized in Table 1.

It seems that several of the issues mentioned in Table 1, such as the misjudgment of radiation intensity and staying in the sun too long, could be overcome if people were warned before the critical dose of UV radiation has been reached. To find out if people agree with this presumption we asked them whether they believe that a warning system would reduce the number of sunburns. More than two thirds of the respondents confirmed this. Those denying could state why such a warning would not help. People mainly said they knew when to react themselves, and/or could not take appropriate measures in the relevant situations anyways.

We further wanted to know what type of sunburn warning system people might use. The corresponding question was only given to those participants who previously confirmed that a warning system might help. More than half of the respondents could imagine to use a corresponding smartphone application. Roughly a third would feel comfortable to wear a dedicated sensor device and even more than half could imagine to use such a device if it was unobtrusively integrated into accessories or clothing.

[1]These numbers might be slightly biased as they reflect the answers of our participants that tend to be well educated people.

	Category of answer	Percentage
1.	Misjudgment the solar radiation	23%
2.	No sunscreen at hand	19%
3.	Staying in the sun for too long	18%
4.	Incorrect/insufficient application of sunscreen	13%
5.	Forgot to apply sunscreen	13%
6.	Did not pay attention	10%
7.	Sport activities	10%
8.	The skin was not yet accustomed to the sun (mostly in spring)	8%
9.	Did not apply sunscreen (reason unknown)	8%
10.	Sleeping in the sun	6%

Table 1. Most popular reasons for sunburn according to our survey. A single answer could have been assigned to more than one category. Therefore percentage numbers do not sum up to 100%.

The main findings of our survey can be summarized as follows:

- A significant fraction of the people (67%) suffer a sunburn regularly (at least once a year), despite their knowledge of the risks and countermeasures.
- A lot of the reasons for getting sunburned are related to inattention and misjudgment of the sun's intensity, and could be overcome by an adequate warning mechanism.
- Many people are willing to use such a warning system in form of a smartphone application and/or dedicated sensor device.

Following these findings, we propose *Sundroid*, a prototype system that is able to warn its user once a critical dose of sunlight has been absorbed, and can help to improve people's awareness of the incident radiation in different situations. It thereby acts as a replacement for a missing human sense for UV radiation that could naturally warn us, similarly as our sense of smell warns us of inappropriate food.

SYSTEM DESIGN

In this section, we describe the design and implementation of Sundroid, a wearable system to measure solar radiation. The current prototype system targets a broad range of application scenarios for solar radiation awareness. Sundroid consists of two separate components, as shown in Figure 1: A dedicated sensor unit to measure UV radiation, and a smartphone as a universal computing platform. To provide data relevant to its user, the sensor unit needs to be body wearable. Moreover, to find widespread acceptance, it is inevitable to make the corresponding device as unobtrusive as possible and available at low cost.

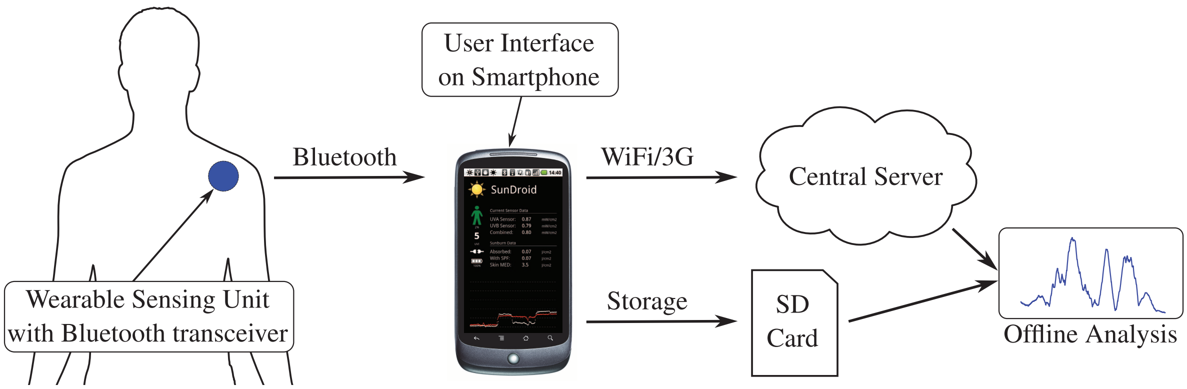


Figure 1. Schematic overview of the Sundroid system: A wearable sensing unit containing UV sensors is attached to a user's clothes or accessories. Sensor data is transferred using Bluetooth to a smartphone, which serves as a graphical user interface. Optionally, measurement data can be transferred to a central server or stored on a SD card for offline analysis by researchers or medical personnel.

Due to application specific action spectra, we decided to independently measure UVA and UVB intensities. This design provides maximal flexibility for the approximation of different spectra. An example is the erythema action spectrum in case of sunburn, which describes the wavelength dependent sensitivity of skin relevant to sunburn. Other examples include the action spectra for DNA damage [31] or skin cancer [7].

To further improve the flexibility with respect to possible applications, we rely on the user's smartphone as a generic information hub. The phone can on the one hand provide further context, such as location and activity patterns, and is on the other hand used for data processing, presentation and communication. Data exchange between the sensor unit and the smartphone is realized over a Bluetooth wireless link in real-time. An important requirement is that the system continually monitors the solar radiation to which the user is exposed, even when the user is temporarily not in the proximity of the phone. Depending on the application, the phone can either log the data and present it to the user, or forward it to a central infrastructure, e.g., for analysis by experts such as researchers or medical personnel.

Wearable Sensing Unit

The wearable sensing unit consists of a custom made printed circuit board (see Figure 2) and a plastic enclosure. It features a TI MSP430 low-power microcontroller with 4 KBytes program flash and 512 Bytes of RAM, which is connected to a Roving Networks RN-42 low-power Bluetooth module. All components are standard parts available at low prices (tens of dollars). The sensing unit is supplied with power by a 3.7 V lithium-polymer rechargeable battery.

UV Sensors. We equipped the wearable sensing unit with a UVA photodiode (Genicom GUVA-S10GD) and a UVB photodiode (Genicom GUVB-S10GD). Each of the two photodiodes gives an estimation of the current sunlight intensity in their intrinsic spectrum. Depending on the use case we are interested in different spectra. Some medical applications, for example, require the measurement of UVA only. In the context of sunburn, we are interested in the erythema action spectrum, which can be approximated using a weighted linear combination of the values of the UVA and UVB sensors. We found that a combination of 9% UVA estimation and 91% UVB estimation can accurately approximate the erythema action spectrum in our setting, as shown in Figure 3.

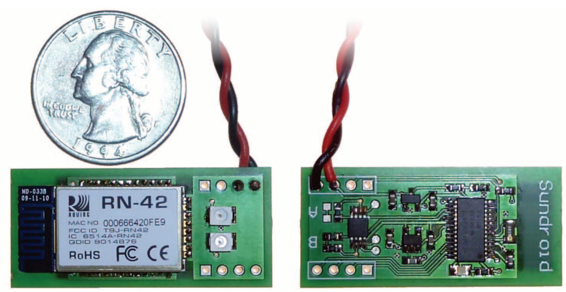


Figure 2. The wearable sensing unit consists of a double-sided printed circuit board. The Bluetooth module and the UV photodiodes are mounted on the top layer (left), while the microcontroller and the analog circuits are on the bottom layer (right).

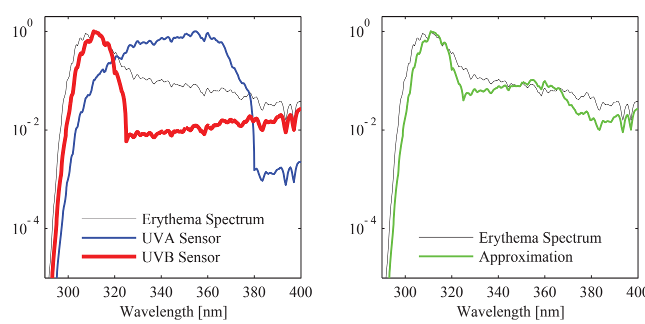


Figure 3. Normalized sensor responses for sunlight (left). The erythema action spectrum can be approximated by combining the values of the UVA and UVB sensors (right).

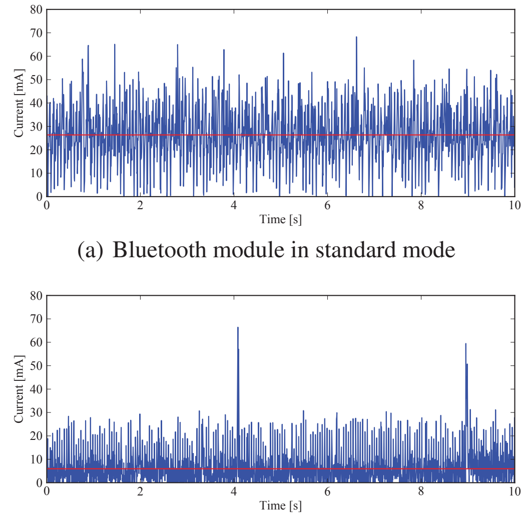
Data Acquisition and Buffering. Measurement of UV radiation using photodiodes can be accomplished with a simple analog circuit. The energy of the incoming light within the active area of the photodiode is converted into a small current. The magnitude of this current depends on the intensity of the light and the wavelength dependent sensitivity of the photodiode with respect to the incoming light's spectrum. Since the resulting currents are very small, we use a transimpedance amplifier circuit to convert the photocurrent into a corresponding voltage, which is continually sampled using the 10-bit analog-digital converter of the microcontroller. Both sensors can be sampled multiple times per second. Depending on the availability of a Bluetooth connection to the user's smartphone, measurement data is either transferred immediately to the phone or buffered locally in the memory of the microcontroller. This helps to avoid data loss when the user temporarily leaves the connection range of the phone. The storage capacity of the microcontroller allows to store several minutes of samples at the highest resolution using a circular buffer. Furthermore, we also accumulate the sum of the sensor readings which have not yet been transferred to the phone. This assures that we can track the total absorbed radiation even if no Bluetooth connection is available for longer periods. However, we might loose some of the individual sensor readings since they have been overwritten in the local buffer with new data.

Power Consumption

Prolonging battery lifetime is a crucial aspect for wearable applications. Therefore, we carefully designed the sensor unit for low-power operation. The analog sensor circuit and the microcontroller can be put into low-power mode most of the time to reduce the overall power consumption. As a result, the biggest part of the power budget is assigned to the Bluetooth module. By duty-cycling the Bluetooth module when connected (sniff-mode), the total current drawn of the sensor unit can be reduced significantly from 27 to 6 mA, as shown in Figure 4. However, the Bluetooth low-power mode has to be supported by both master (phone) and client (sensor). Given the nominal battery capacity of 110 mAh, the sensor unit can be operated up to 18 hours before it has to be recharged. To prevent a sudden power failure, the battery voltage is measured continuously and displayed on the smartphone. While the current hardware design supports operation of the wearable sensing unit during an interval which is in the order of a typical recharge cycle of a modern smartphone, next generation hardware supporting the upcoming Bluetooth 4.0 low energy standard will allow to tremendously prolong the operation time of the sensor unit using even smaller batteries.

SMARTPHONE APPLICATION

Measurement data from the wearable sensor unit is transferred over Bluetooth to a smartphone running the Google Android operating system. The phone runs a background service, which handles the Bluetooth communication with the sensor device. The wearable sensing unit is polled periodically for new sensor measurements. All sensor readings from the UVA and UVB photodiodes are stored together with the corresponding timestamp and location information provided by the phone. These measurements are made available to the user via the phone in real-time. This is in contrast to existing UV dosimeters which only allow for offline analysis (see section on related work). Furthermore, data is written to the phone's SD card for further analysis. If needed, sensor readings can also be sent to a web server, if the phone provides Wifi or 3G connectivity.



(a) Bluetooth module in standard mode

(b) Bluetooth module in low-power mode

Figure 4. Current consumption of the sensing unit with an active Bluetooth connection for the standard (a) and low-power operation mode (b). The horizontal line indicates the average power consumption measured for the normal operation mode (27 mA) or the low-power mode (6 mA).

Data Processing and Visualization

A considerable difference between stand-alone sensors and smartphone based sensors systems is that the data processing and displaying can be easily adapted to the needs of the use case on smartphone based systems. In the case of Sundroid, this allows us to adapt the system to various applications. In the following we shortly describe two user interfaces we have implemented for Sundroid.

Simple View. The first use case is the one of a person that has an outdoor job or likes to do outdoor sports and wants to avoid skin damage by UV radiation. This user is mainly interested in not being sunburned and avoiding long term skin damage. In order to asses the danger of the accumulated UV radiation to a person, we refer to the commonly used method of Fitzpatrick's skin typing [16]. It classifies a persons skin, based on external features, such as pigmentation, tanning history, and eye color to estimate a minimal erythema dose (MED) for that skin type. The minimal erythema dose is defined as the minimal solar radiation energy that results in a reddening of the skin, that is not induced by heat (i.e. sunburn) [16].

On top of the screen, a simple diagram informs the user about the incident UV radiation he was exposed to that day (see Figure 5). The plain energy value of the accumulated incident UV radiation in J/cm^2 would not be a valuable information for most users. Therefore we display aggregated radiation energy in terms of the percentage of the user's minimal erythema dose. As the minimal UV dose a person can

Skin type	Description	MED in $\frac{mJ}{cm^2}$
1	White, very fair skin	20 - 35
2	White, fair skin	30 - 45
3	Beige skin	40 - 55
4	Beige to brown skin	50 - 80
5	Dark brown skin	70 - 100
6	Black skin	100

Table 2. The skin type and the corresponding minimal erythema doses based on Fitzpatrick's skin typing.

be exposed to without getting a sunburn depends mainly on the skin type and the sun protection factor of the applied sunscreen, these parameters can be set in the application and are taken into account to asses the correct moment to issue a warning. When the accumulated radiation intensity exceeds 80% of the MED (multiplied with the sun protection factor of the applied sunscreen) the users is warned about the acute danger of a sunburn through a notification on the phone (see Figure 6).

To inform the user about the current radiation intensity in an easily understandable manner, the values of the UVA and the UVB radiation are not displayed directly, but are combined to match the erythema action spectrum. The resulting radiation intensity is transformed into the according UV-index[2] and displayed on the center of the screen (see Figure 5, left). On the bottom of the screen the user can see the radiation history of the day, which can serve as an educational component, to learn in which situations the skin was exposed to the highest radiation intensities. Beside processing the data of the external sensors, the use of a smartphone allows to gather more context information. For example, Sundroid fetches the UV-index forecast of the day from the Internet. The predicted UV-index can be used to inform the user on time about necessary precautions, such as to take along appropriate sunscreen or clothing.

Advanced View. The second user interface shows a more technical view, which can be seen in Figure 5 on the right. This view is mainly intended to be used by technical experts (e.g. physicians, researchers or medical staff). It displays the exact values of the incident UVA, UVB and accumulated radiation. The graph on the bottom of the screen displays the UVA and UVB radiation intensities separately. The live feedback on the screen and the possibility to send the sensor data to a central server in real time make it a useful tool for UV-radiation related research (see Application Scenarios).

Data Fusion

The advantages of smartphones as a generic processing platform are manifold. On the one hand, they are personal devices that are almost always with their user. On the other hand, they exhibit a variety of readily available sensors, such as 3D compass, accelerometers, GPS, light sensor, camera,

[2]The UV-index is a common measure to communicate UV radiation intensity to the general public. It is defined to be the incident UV radiation irradiance in the erythema action spectrum, divided by $25\frac{W}{cm^2}$.

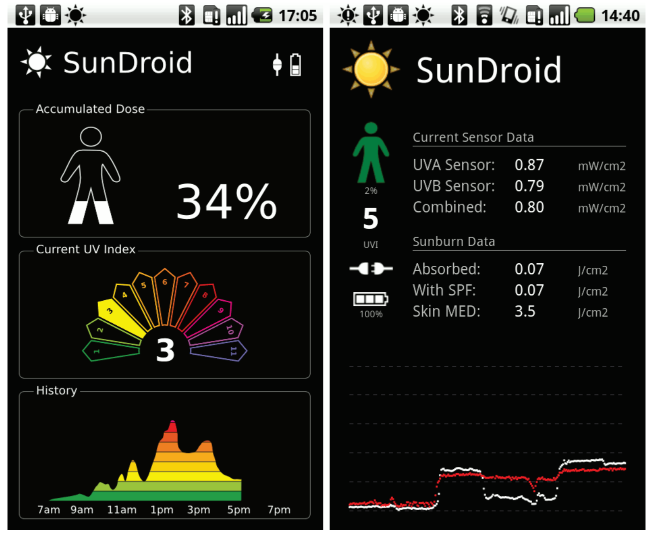


Figure 5. Sundroid activity screens on the smartphone: The *Simple View* displays the accumulated UV dose, the current UV index, and the time line of UV exposure (left). The *Advanced View* shows more detailed information about the current and accumulated UV radiation (right).

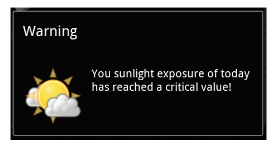


Figure 6. A notification window is shown when the absorbed UV radiation exceeds a critical value for the specified skin type and sunscreen.

and microphone, from which the user's context can be inferred. In addition, state-of-the-art smartphones feature enormous computing and communication capabilities, which provides a flexible way to process and distribute the gathered sensor data. Currently, we assign the current timestamp and location of the user as provided by the GPS to each sensor reading, which provides valuable context information for the analysis of the measurement data.

EVALUATION

In this section, we evaluate several aspects of the Sundroid system. First, we compare the accuracy of UV measurements against reference values. Second, we investigate the sensitivity of the sensors with different incident angles of sunlight.

Sensor Calibration

To ensure high accuracy of UV measurements, we have calibrated the sensor units against the erythema specific reference signal of the World Radiation Center (WRC) in Davos, Switzerland. For the measurements, our sensor devices were horizontally mounted on the roof of the WRC building, next to the reference probes. Figure 7 compares the erythema specific responses measured by the high-precision reference equipment with those of our sensor devices during two days. The first measurement was conducted during a partly cloudy day in autumn with some rain around 2.30 pm, and the second measurement took place during a sunny day in winter.

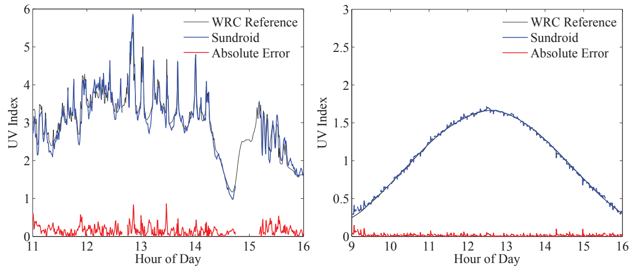


Figure 7. Sensor calibration: The sensors have been calibrated against the reference measurement for the erythema action spectrum at the World Radiation Center (WRC). The calibration measurements were conducted on a partly cloudy day in autumn (left) and on a sunny day in winter (right).

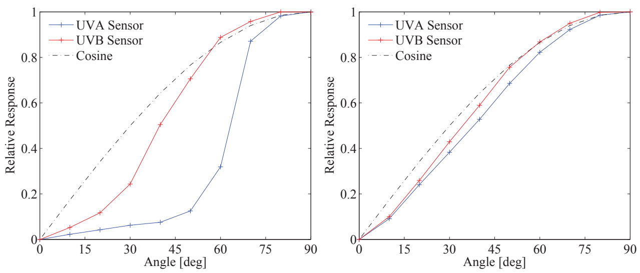


Figure 8. Relative response of the UVA/B photodiodes when exposed to sunlight at different incident angles (left). Placing a PTFE diffuser foil on top of the sensors results in a response which approaches the ideal cosine curve (right).

Due to a bug in the recording software, a small number of sensor readings have been lost during the first measurement day. Nevertheless, the good match of our sensor data with the reference curve after calibration shows that our sensor unit is able to accurately measure the UV radiation relevant to erythema. In fact, the resulting relative error after calibration is less than 5%. The linear correction factor used for calibration needs to be known by the Sundroid application to convert the raw UV measurements into the human readable UV index scale.

Angle Dependencies

Clearly, the sensor sensitivity is dependent on the direction of the incident radiation. Ideally, the response follows a cosine curve, similarly as the response of the human skin. Unfortunately, this curve is not well matched by the raw photodiodes, as shown in Figure 8 (left). To overcome this problem, we integrated a diffuser made from Polytetrafluoroethylene (PTFE). PTFE, also known as Teflon, has been used as a material for UV diffusers in similar contexts before [6, 1]. After applying a diffuser, the dependency on the angle closely follows the ideal cosine curve as shown in Figure 8 (right). The figure shows that the use of a diffuser mitigates angle dependencies, such that the (ideal) cosine response is closely approximated. For these plots, we assumed that at 0 degrees (perpendicular to the incident sunlight) there is only diffuse radiation. The corresponding intensity value has been subtracted from the entire measurement series to account for directed light only.

APPLICATION SCENARIOS

The modular design of the Sundroid system facilitates the use not only as a personal assistant to track absorbed UV radiation in everyday life, such as in personal informatics systems [19], but also opens possibilities in a variety of other settings. This section describes how Sundoid can be used in a variety of contexts.

Behavioral Research. We believe that the real-time reporting capabilities, together with the possibility to grasp the context of a given user, can considerably improve our understanding of the impact of UV radiation throughout different activities. Using time and GPS information, for example, we can precisely match the detected solar irradiation to a person's location. Using the phone's 3D compass, the sun's incident angle becomes known, under the assumption that the user keeps the phone in the same place on the body most of the time. Furthermore, acceleration data, microphone, etc. help to infer the user's current activity. This additional information might help to answer previously unanswered questions. Holman et al. [14], for example, speculate that some of the differences they found compared to a manikin based study [9] originate from the fact that people tend to turn away from the sun. The additional sensor data (GPS, compass) provided by the Sundroid system could help to prove or disprove this conjecture.

Participatory Sensing. Our survey suggests a general interest in using Sundroid as a personal assistant and warning device, in particular when the sensor part is unobtrusively integrated into clothing and/or accessories. If such a system indeed happens to find widespread use, information about UV radiation can enter the domain of participatory sensing [4]. Participatory sensing aims at collecting and sharing sensor data gathered by the everyday use of mobile devices. In the context of UV radiation, large scale UV maps could be drawn at a much finer resolution than currently possible, thereby for example taking time, shadow, and reflection effects into account.

Applications in Therapy. In discussions with a dermatologist, we were pointed to a variety of medical application scenarios. Examples include the different use cases in the context of photodynamic therapy, UV induced immunosuppression, and the treatment of light allergies. Moreover, it could be used to research the positive effects of sunlight, for example in the production of vitamin D, circadian rhythm regulation, or seasonal affective disorder. In particular, a wearable UV sensing device could help both, physicians as well as patients to monitor the irradiation and user activity over a longer period of time, thereby facilitating a more precise treatment at lower cost, as part of the monitoring task is shifted from the physician to the patient. Via the mobile network infrastructure the sensor data can be transmitted to a physician in real-time, who can directly take adequate actions if required. Long-term irradiation traces can further be used to improve people's awareness of sunlight intensity in different situations and are thus well suited for health related behavior training.

Figure 9. Positioning of the three wearable sensor units during the field experiments: Unit 1 is attached on the helmet, Unit 2 is attached on the shoulder, and Unit 3 is attached near the chest. The sensor units are enclosed within a plastic housing to protect them from snow.

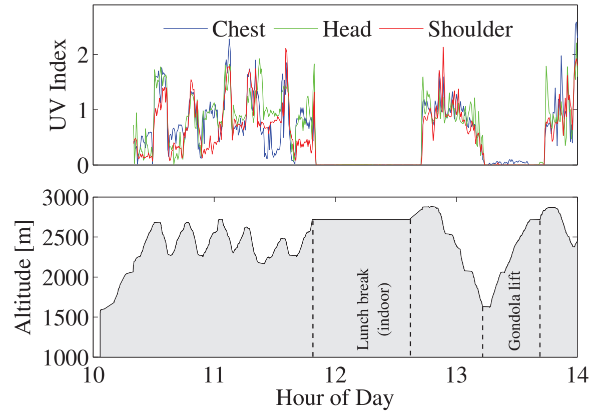


Figure 10. The elevation profile of the test subject during one day of snowboarding in a ski resort (bottom) and the measured UV intensity of the different Sundroid sensors (top).

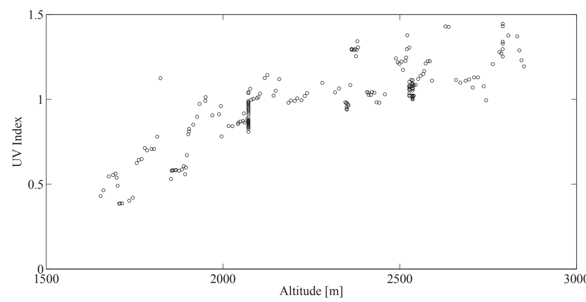


Figure 11. UV intensity versus altitude of the test subject during the ride on the longest ski slope. The correlation of altitude over mean sea level and UV radiation is clearly visible.

PILOT STUDY

In order to demonstrate the practical usability of the system and to investigate the effects of sensor placement in a real-world setting, we have conducted a small scale pilot study. The study encompassed two different outdoor sport activies: snowboarding and climbing. In both experiments the incident UV radiation on a single test subject was measured over several hours.

Scenario 1: Snowboarding

The snowboarding experiment was conducted in a large ski resort. We have attached three Sundroid sensor units to the test subject: One on the helmet, facing upwards, one on the shoulder, facing upwards, and one on the chest, facing frontwards, as shown in Figure 9. The test subject's task was to use all the ski lifts and slopes freely. Beside the UV intensity values we tracked the location of the person using GPS. The location and the UV data was logged on the Android mobile phone carried by the person. From the location, an elevation profile was derived that can be seen in Figure 10 along with the plot of the measured UV radiation of the three sensor units. In the plot, one can clearly see two periods of zero UV radiation; the first of them, around 12 pm, was caused by a lunch break in a restaurant. The second one, around 1.30 pm, was caused by a trip in a closed cabin gondola lift.

This day trace provides a good example of how the Sundroid system can be used in scientific experiments. One can gain different insights by analyzing the UV radiation traces.

For instance the role of the sensor placement (i.e. where a user is wearing the sensing unit) can be studied. Prior research using a rotating manikin has shown that the weather conditions (i.e. amount of clouds) affect the overall UV intensity, but play a minor role for the proportions of sunlight absorbed by different sites of the body [9]. Further studies on living subjects have shown high and relatively stable values for measurements on the shoulder for different outdoor occupations, namely gardener, roof carpenter, bricklayer [14]. The reported values show that roughly 70% of the total radiation, as measured by a horizontally placed dosimeter, is received at the shoulder, which is slightly less than the doses measured at the vertex of the head. Moreover, under lightly cloudy weather conditions, the incident radiation at the chest is stated to be about two thirds of the radiation measured at the shoulder.

However in the case of the snowboard trip, the measured intensity ratios of the three sensors (on the head, shoulder and chest), differ significantly from the values reported in [14]: In particular, the sensor mounted on the chest absorbed about 10% more energy than the sensor mounted on the head. These differences can, presumably, be explained by the low position of the sun during winter days and the substantial amount of UV reflection by the snow. Such factors have shown to have a relevant impact by Gröbner et al. [11].

Another interesting observation discussed in [11] is the dependency between UV radiation and the altitude above sea level. The data of the longest downhill drive (around 1 pm) confirms such a dependency. Figure 11 shows the measured intensities versus the current altitude of the test subject. It is important to note that the measured decrease of UV intensity at lower altitudes cannot be explained by the elevation level alone. Other effects, such as an increased amount of shadow in lower areas, or the direction of the slope are also likely to have an influence.

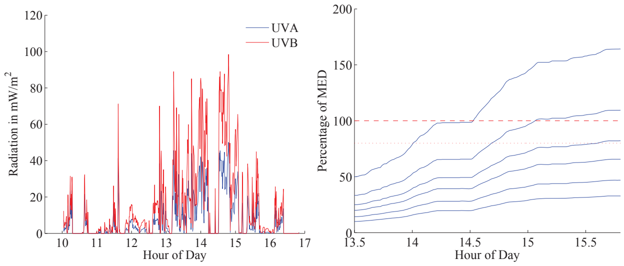


Figure 12. The left plot shows the incident radiation during one day of climbing on a sunny spring day. On the right, one can see the accumulated radiation energy, expressed as percentage of the MED for the different skin types. The blue line on top is skin type 1, whereas the blue line on the bottom is skin type 6.

This experiment demonstrates that the Sundroid system can be used to gain insights into the effects of sensor placement in different environments and to improve the understanding of the surface albedo in various settings. Moreover, the relatively cheap hardware allows to realize studies with a large number of participants.

Scenario 2: Climbing

Another measurement series were conducted during one day of climbing on a sunny spring day. We attached one Sundroid sensor at the climber's harness, which measured the incident sun radiation on the back of the test person. Plots of the recorded UVA and UVB radiation can be seen in Figure 12 (left). Figure 12 (right) plots the accumulated energy in the erythema action spectrum as percentage of the minimal erythema dose for the skin types 1 to 6. The lowest blue line corresponds to the percentage of the MED, a person with skin type 6 would have been exposed to, whereas the highest blue line corresponds to the percentage of the MED of a person with skin type 1.

The UV forecast of the national meteorological institute for that day was UV index 5. As one can see, the radiation was high enough to exceed the minimal erythema dose for skin type 1 and skin type 2. However, a person with skin type 1 would have been warned around 2 pm about the high radiation energy (80% of the MED), which would have allowed the person to apply sunscreen, or seek shadow in time. Similarly, a person with skin type 2 would have been warned around 40 minutes later, which again would have been early enough to take precautions.

CONCLUSIONS AND OUTLOOK

We have presented Sundroid, a wearable prototype system designed to increase the awareness of solar radiation by means of body worn sensors. Our experiments show that despite the use of low cost components, the accuracy reached by our sensor unit is comparable with the one of high-precision infrastructure. In a survey we could further show that a relevant fraction of people could imagine using such a system to reduce sun-related health problems. Our prototype demonstrates the potential of combining wearable sensors with a smartphone. If the Sundroid sensor is worn during everyday activities, it can notify people in time about the imminent risk of a sunburn. The modular design featuring a smartphone as a versatile platform facilitates the use in several other settings, such as medical therapies and research. We are convinced that technological advances will empower the seamless integration of a variety of sensors in clothing and accessories, making systems such as Sundroid a ubiquitous part of our daily life.

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