IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 31, 2020, accepted September 23, 2020, date of publication October 12, 2020, date of current version October 22, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3030006

Improving the Results of Citizen Science Projects Through Reputation Systems: The Case of Wolf's Number Experiment

RAQUEL CEDAZO[1], ESTEBAN GONZALEZ[2], MIQUEL SERRA-RICART[3], AND ALBERTO BRUNETE[1], (Member, IEEE)

[1]Department of Electrical, Electronics and Automatic Control Engineering, and Applied Physics, Escuela Técnica Superior de Ingeniería y Diseño Industrial, Universidad Politécnica de Madrid, 28012 Madrid, Spain
[2]Ontology Engineering Group, Universidad Politécnica de Madrid, 28660 Madrid, Spain
[3]Canary Islands Institute of Astrophysics, 38200 La Laguna, Spain

Corresponding author: Raquel Cedazo (raquel.cedazo@upm.es)

This work was supported in part by the European Union Seventh Program (FP7/2007-2012) through the Project Global Robotic Telescopes Intelligent Array (GLORIA) for E-Science under Grant 283783.

ABSTRACT Collective intelligence projects based on citizen participation are gaining momentum in today's society. Citizen science applies crowdsourcing techniques to produce reliable data, quickly and easily. These projects allow getting new knowledge and help professional scientists to come to real conclusions. This paper proposes that the use of reputation systems improves the results obtained in citizen science projects. To prove this hypothesis, a reputation system is applied to a real experiment and the results are analyzed. The goal of the experiment is to calculate the real-time solar activity, known as the Wolf number, using the infrastructure and user community of the GLORIA project (a set of professional robotic telescopes running since 2013). The sample size of the study are 196 end-users and 2,108 executions of the experiment. The key findings presented in the paper are: 1) the online experiment with volunteers correctly reproduces the traditional method of the year 1848 performed by astronomers or advanced amateurs, 2) the model is contrasted and validated with the values published by the official organization, and 3) the reputation system reduces the error in calculations by more than half, discarding the contributions of the users with lowest karma.

INDEX TERMS Citizen science, collective intelligence, crowdsourcing, reputation system, solar activity.

I. INTRODUCTION

In 1848, the Swiss astronomer Rudolf Wolf introduced a method for registering solar activity by counting the number of visible sunspots, known as the *Wolf number*, also known worldwide as the *International Sunspot Index*. This method, updated in 2014 by several authors [1], has been used in the solar activity records for the last 400 years [2] and continues to be a rigorous method used in much research today [3], [4]. Since 1981, the Solar Influences Data Analysis Center (SIDC) is the world data center for the Wolf number. Its mission, as is indicated in its webpage,[1] is to advance knowledge about the Sun and its influence on the solar system, through research and observations.

The SIDC produces the longest running time-series of solar activity, under the SILSO (*Sunspot Index and Long-term Solar Observations*) project.[2] The data are freely available from their website, as shown in Fig. 1, where is represented the daily sunspot number (yellow), monthly mean sunspot number (blue), smoothed monthly sunspot number (red) for the last 13 years and 12-month ahead predictions. It serves as a reference input to multiple applications in a wide range of scientific disciplines, such as studies of the solar cycle mechanism and of the solar forcing on the Earth's climate. An important community is subscribed to its services, among them more than 500 for sunspot products; individuals (e.g. wider public, radio amateurs, space scientists, meteorologists and paleo-climatologists); and institutions (e.g. public organizations like the *International Astronomical Union* (IAU),

The associate editor coordinating the review of this manuscript and approving it for publication was Feng Xia.

[1]Website of the Solar Influences Data Analysis Center (SIDC): www.sidc.be

[2]SILSO, World Data Center - Sunspot Number and Long-term Solar Observations, Royal Observatory of Belgium, on-line Sunspot Number catalogue: http://www.sidc.be/SILSO/, 2020.

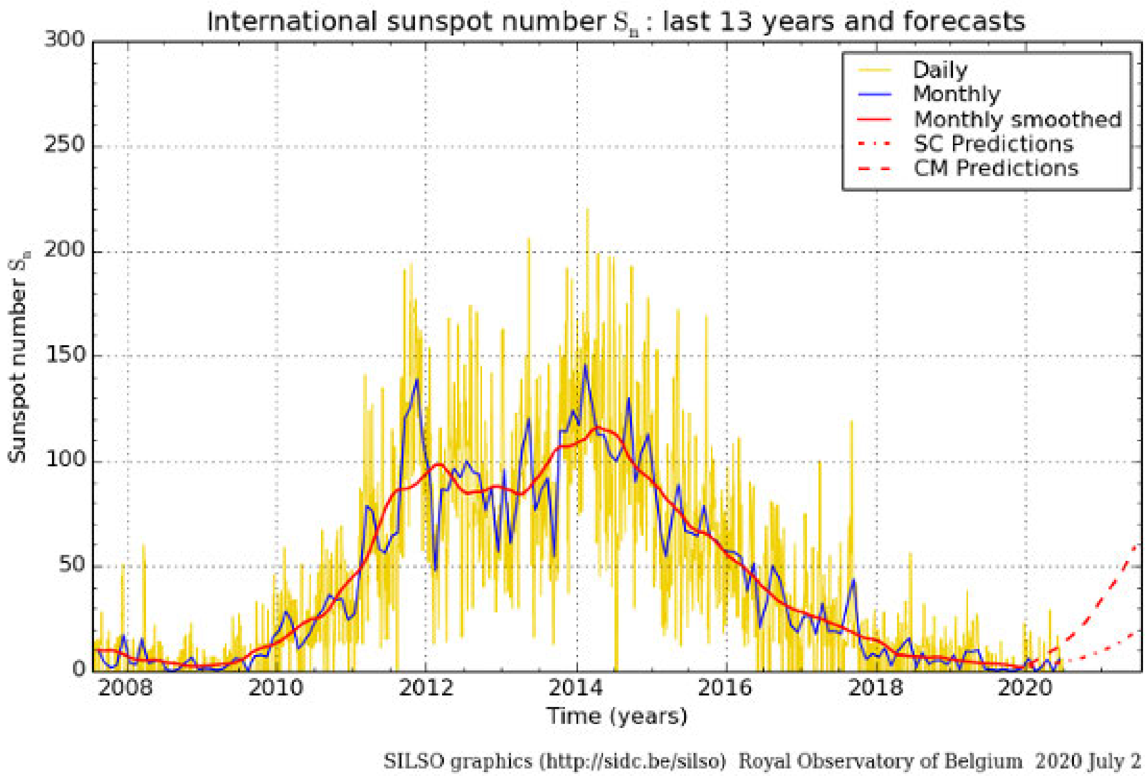


FIGURE 1. Last 13 years and forecast of the total sunspot number. Source: WDC-SILSO, Royal Observatory of Belgium, Brussels.

the *Illuminating Engineering Society* (IES), UNESCO, private companies, aviation, civilian and military).

Nowadays there are many sophisticated techniques for observing the Sun: CCD cameras, spectroscopy, space probes and radio astronomy, as well as automated methods to calculate the true area of the sunspot groups, and computer programs like S.C.A.T. (Solar Cycle Analyzer Tool) and Soonspot [5], [6] to study its evolution. However, by their simplicity and their cost savings, SILSO holds that visual observations keep key advantages for some time in the future: it is a fully sustainable method based on the extensive cross-validation and calibration among simultaneous observations from multiple stations. And this is product of the collective effort among observers, most of whom are advanced amateur or professional astronomers.

The experiment described in this paper is based on the GLORIA Solar Activity app, a crowdsourcing tool for measuring the solar activity under a groundbreaking method to calculate the Wolf number with the help of volunteers, experienced or not. This research presents the study case and the results of the execution during the first sixteen months. The contribution of this paper can be summarized as follows:

1) The study shows how it is possible to transform a traditional and relatively expensive method supported by astronomy professionals into a citizen science experiment conducted by the general public thanks to technology.
2) The empirical research is also focused on analyzing how a reputation system positively influences the results gathered.
3) Finally, the study shows how with the proposed method, the Wolf numbers calculated by volunteers are very close to those published by SIDC, the official body that is responsible for it.

This citizen science project allows any registered user to visualize the sunspots of a solar image through a mobile device and, through a friendly and simple interface, interact with the application to calculate a solar activity index. The system gathers all the measurements and calculates the Wolf number, as will be detailed in the following sections. In this moment, the app uses digital images of the solar photosphere obtained with a solar telescope of the GLORIA[3] network, a set of professional robotic telescopes which emerged from an European project. However, the application is designed to operate with any images taken from other telescopes or gathered from open access databases.

GLORIA network works under a reputation system, as do other well-known websites, including the popular Amazon, eBay, Taboao, and others [7]–[9]. These reputation systems collect information on the past behavior of a user and then make it available, which affects the ability of users to act in

[3]Website of the GLORIA project, the first free access robotic telescope network of the world: http://gloria-project.eu

the future. GLORIA's reputation system produces an index for each user, which is called *karma*, based on their participation in the entire network. This index allows the network to distribute in a fairer way the observation time of GLORIA telescopes among users, basing the allocation of time on the amount and level of user contribution.

This paper is organized as follows. Section II provides an overview of the history, techniques and institutions related to the sunspots; and a review of citizen science and crowdfunding projects, with special interest in those in the Astronomy field, focused on measuring the solar activity. In Section III, a summary of the GLORIA project and a detailed description of the app and the case of study are presented, both technologically and theoretically. Section IV examines the results of the first version of the app in comparison with the official Wolf number extracted from the SILSO website. And, finally, Section V is devoted to the conclusions that can be extracted from the proposed work and possible future improvements of the application.

II. RELATED WORK

In this section, the literature review is presented in two parts. First, a brief introduction to the History of the Wolf Number is given, necessary for understanding the objective of the application presented in this paper. Secondly, a set of collective intelligent and citizen science projects are introduced, stressing those involved in Astronomy in general and Solar Activity.

A. HISTORY OF THE WOLF NUMBER

The Wolf number or solar index has been distributed since 1981 by the SIDC, the data are registered uninterrupted until today and it is still the most frequently used reference in long-term studies [10], [11].

The SIDC transformed the calculation and observation process from manual to automatic, getting coefficients monthly rather than yearly. Furthermore, it went from a system based on a single station method to one calculated with statistics over a set of observations, covering worldwide, rather than just Europe and Asia. In 2006, this observation network was composed by 34 professional observatories and 66 individual amateur astronomers.

Until 2005, most reports were received by e-mail, paper mail or telefax. Since then, a web application gathers the data through an electronic form into a database, reducing the error-checking workload. Data, however, vary enormously since the measure depends very much on observer interpretation and experience. Furthermore, the stability of the Earth's atmosphere is another factor to consider because the Sun rotates and the spot groups are distributed not uniformly across solar longitudes. To compensate for these conditions, the SIDC computes all data and sends the result sets to all subscribers and are public and freely downloadable from its website.

B. CROWDSOURCING AND CITIZEN SCIENCE

Crowdsourcing projects have grown rapidly in recent years [12], [13]. Although there is a certain discussion to set a proper definition [14], [15], the term refers to the *"type of participative online activity in which an individual or institution proposes to an heterogeneous group of people the voluntary undertaking of a task"*. Since the number of users is unlimited, the development of software tools for consensus decision making is necessary [16], [17]. This has driven into the development a new research field in Computer Science which has been called Collective Intelligence, which strongly contributes to the shift of knowledge and power from the individual to the collective. According to Raymond [18] and other authors [19], open source intelligence will eventually generate superior outcomes to knowledge generated by proprietary software developed within corporations.

Science has also profited from this tendency in crowdsourcing by creating the, so called, Citizen Science Projects, usually driven by professional researchers but with the participation of hundreds or thousands of inexperienced citizens. Citizen Science is a new term but an old practice [20]. Before the 20th century, science was carried out mainly by amateurs or self-funded researchers or was popular before it had been done by professionals. By the mid-20th century, however, science was outnumbered by researchers employed by public or private institutions.

These kinds of projects have also been growing rapidly in the last two decades, mainly due to the advance of the Internet and technology. They let volunteers easily contribute in active science programs. Most of today's citizen science initiatives are mainly focusing on providing support to professional scientists who want to involve citizen scientists in steps like data wrangling and/or result evaluation [21], [22]. Citizen science is a particular case of collective intelligence and a small set of crowdsourcing projects [23].

One the most ancient citizen science project is the Audubon Society's Christmas Bird Count [24], started in 1900, as an example of a long standing tradition which has persisted to the present day. The first Astronomy project which used citizen science was released in 1999, SETI@Home for the search of extraterrestrial intelligence [25]. In 2000 NASA started the Clickworkers project [26], where volunteers could help by identifying and classifying the age of craters on Mars analyzing images from Viking Orbiter. However the main goal of this project was to answer two meta-science questions:

1) Is the public ready, willing, and able to help science?
2) Does this new way of powering science analysis produce results that are just as good as the traditional way?

These questions were answered by Galaxy Zoo project, which in 2007 published a report [27], overwhelming the scientific community, claiming that 80.000 volunteers had classified more than 10 million images of galaxies [28]. Today this project has derived into Zooniverse, the largest platform for online citizen science, which host to over 120 projects with 1.7 million registered participants [29]. Nowadays there are a relevant number of citizen science projects around the world. References [30] and [31] perform a walkthrough of different projects to investigate its common features.

The list of citizen science projects in Astronomy keeps growing [32], with some examples of projects related with the solar activity:

- SILSO (Sunspot Index and Long-term Solar Observations) is a large network of telescopes and researchers who study the solar activity through the calculation of the Wolf number. The network is open to newcomers, they only need a telescope, dedication and some skills.
- Sunspotter is a citizen project of Zooniverse where users classify sunspots based on the complexity of them. Data come from an instrument aboard of the SOHO observatory. This instrument was switched off in 2011.
- Sun4All is a project funded by EU where users can execute a set of activities [33]. One of them consists of counting sunspots on various days from images taken over the last 80 years by the Astronomical Observatory of the University of Coimbra. Users access images via the Internet and write the results in a spreadsheet file.

III. THE GLORIA PROJECT

In this section the mobile app developed is described, but beforehand is an overview of the GLORIA architecture, its reputation system and the solar online experiment from which the solar images for the app are obtained; all of which is the framework of the case study. Then, the user interface and the functionalities of the mobile app are explained, including a brief introduction of how to calculate the Wolf number from a simple point of view and the basic concepts necessary to understand the presented experiment.

GLORIA stands for *GLObal Robotic Intelligent Array for e-science* and it is the first open access network of professional telescopes in the world. It started in October 2011 as a three-year European project and started operation opening the telescopes to the community in March 2013. Nowadays it offers to all citizens free access to teleoperate up to 14 telescopes on four different continents. It is just necessary to create an account and make a reservation in a free slot.

GLORIA innovation was driven to become the first citizen science project which involves users, not only in data analysis and wrangling, but also in data acquisition. Images can be taken by users teleoperating real telescopes placed in both hemispheres. GLORIA also allows any telescope owner to add new telescopes to the network and, therefore, share observing time with other owners in different locations. Citizens obtain a certain percentage of the observing time and images taken by them are used for the rest of the community. Therefore in GLORIA there are two kind of activities that can be performed:

- *Online experiments*, which allow users to acquire images from the telescopes and store them into the GLORIA database. The observation can be done real time teleoperating the telescope or batch mode [34]. The telescope owner can decide which mode to apply to their telescope, or a combination of both.
- *Offline experiments*, which allow users to perform data wrangling [35].

GLORIA offers solar telescopes which are tele-controlled by the users, who adjust themselves the parameters of the CCD camera and take the images of the Sun. These images are stored into the GLORIA database and then are used by the GLORIA Solar Activity app. From the beginning of the project, GLORIA has more than 12,000 active users who have acquired a total of more than 21,000 images of the Sun.

A. GLORIA ARCHITECTURE

Before tackling the functioning details of the app, it is necessary to understand the GLORIA architecture itself, described in detail in [36], where the Wolf number experiment is integrated. A three-layer architecture has been implemented, as is shown in Fig. 2.

The bottom layer, called Robotic Telescope Network, corresponds to the subset of software that is functionally and topologically located in each separate telescope. This software, through the Robotic Telescope Interface (RTI), offers the possibility of teleoperation of any telescope. The technology behind this interface is the Simple Object Access Protocol (SOAP).

The middle layer, corresponding to the GLORIA Services, brings together all the business logic of GLORIA network forming the core of the whole system. These services includes the authorization of users, experiments management (online, offline and scheduler), reputation system (karma) and images management. The technology used for these services has been designed according to the *Service Oriented Architecture* (SOA). In this way we achieve independence from any particular technology other than the web transport and give the system a scalable and distributed nature. This layer is wrapped by a GLORIA Application Programming Interface (API), developed with REST paradigm and JavaScript, which establish the entry point for all graphic interfaces. The main reason for applying this paradigm is to make GLORIA functionality independent from the various sources or interfaces used by the community. The functionalities of the GLORIA API are:

1) **Authentication**. This is responsible for capturing information from the user logged in to manage successive requests using a token.
2) **Telescope information**. This is a catalog containing the information of all telescopes, such as the owner, the location, the timetable, the terms and conditions of use, among others.
3) **Reservations**. This is responsible for observation time management where users reserve time to control real time telescopes (online experiment).
4) **Experiments**. This is responsible for the management of the experiment life cycle, that it includes the creation, customization, execution and publication of the results.

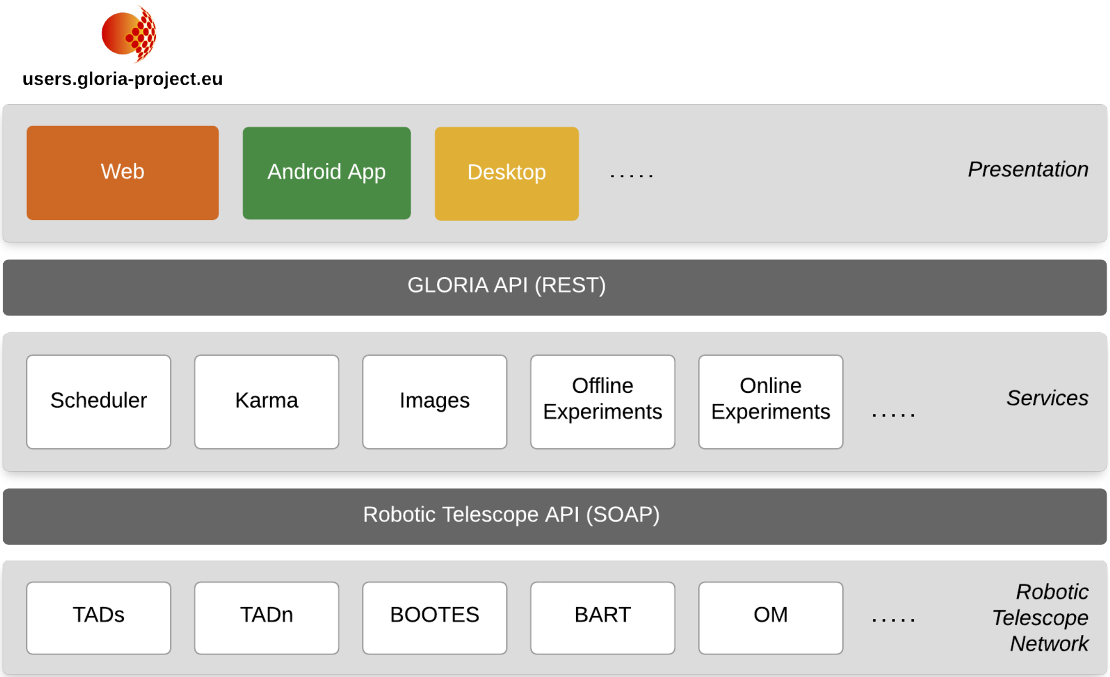


FIGURE 2. The GLORIA three-layer architecture.

5) **Image query**. This allows the access to all images taken by the GLORIA telescopes.

Finally, the top one corresponds to the Presentation layer, that is, the graphic user interfaces. These interfaces, whether web, a mobile or desktop application, consumes any operation offered by the GLORIA Services through the GLORIA API. At this moment, both the GLORIA users website[4] and the app presented in this paper are examples of use.

Furthermore, in order to facilitate the design, creation and integration of new content into GLORIA website, both the whole website and the experiments, an Authoring Tool has been developed. So anyone with average knowledge in HTML, CSS and JavaScript could create an interface integrated into GLORIA.

B. REPUTATION SYSTEM

GLORIA platform measures the activity of the users and generates an index for each one, called karma. At this time, as an initial version, the following three user actions are taken into account to calculate this karma:

- To take an image with a telescope through GLORIA users website.
- To analyze an image through the GLORIA Solar Activity app.
- To make a reservation on a robotic telescope.

The execution of these actions give points to the users, which establishes a **policy**. The present policy gives 5 points per reservation, 1 point per image taken and 1 point per image analyzed. The policy could be modified at any time, with public access at all times the way to calculate points.

After, the number of points is calculated and the karma is generated setting a ranking of users. The range of the karma is from 0 to 100 according to the following formula:

$$karma_i = 100 * log_{10}(points_i)/log_{10}(max)) \tag{1}$$

where:

- points_i is the amount of points of the user i, and
- max are the points generated by the best user.

When a new user is registered in the system, they automatically receive a karma of 40.

C. INTERACTION WITH THE SOLAR ONLINE EXPERIMENT

The images used by the Solar Activity app are those which have been taken by users of the **Solar Online Experiment** integrated into the GLORIA platform. This experiment lets users connect remotely in real time with a telescope and observe the Sun directly through a web browser, by means of a set of cameras connected to the telescopes. The project maintains a database of high resolution images of solar chromosphere.

This experiment has been developed with the Authoring Tool mentioned in Section III-A. For this, it was necessary to define a context composed of the operations and parameters needed to fulfill the experiment. To access the experiment, users have to make a reservation of a 15 minute duration. During that time, they are able to execute the following actions through an user interface as in Fig. 3:

[4] Website of the GLORIA Users: http://users.gloria-project.eu

FIGURE 3. Screenshot of the GLORIA Solar Online Experiment.

1) Open and close the dome.
2) Move the mount to the Sun. Also, additional precision movements are available in order to center the Sun in the visualization window.
3) Move the focuser to improve the quality of the image.
4) Select the exposure time of the CCD. Users are able to see the effects of changing these parameters. The limit of this parameter is 1 second to prevent any damage to the CCD.
5) Take images and download them in two formats: JPG and FITS.

Currently, there is only one solar telescope available, but the system is prepared for running with an unlimited number of telescopes. This solar telescope is the TADs (TAD means "Telescopio Abierto Divulgacion" in Spanish, "Outreach Open Telescope" in English, and the "s" means Solar). The telescope is located at the Observatorio del Teide (Institute of Astrophysics of the Canary Islands, in Tenerife), at a height of 2390 meters above sea level (see Fig. 4). The TADs has a main tube with a H-alpha filter and a color CCD camera model DBK 41AU02.AS, with a Sony CCD sensor and a resolution of 1280×960 pixels, which allows to observe in detail the solar photosphere.

D. GLORIA SOLAR ACTIVITY APP

The case study is based on a mobile application that reproduces the process to calculate and gather the values of the Wolf number. This app provides users with an attractive and easy-to-use interface to carry out the experiment from anywhere through their mobile phones. The authors chose Android versus iOS because the GLORIA network follows its same open source philosophy and, also, its operating system has dominated the market in the past years, according to data from the International Data Corporation (IDC) Worldwide Quarterly Mobile Phone Tracker. In 2018, 88.1 percent of all smartphones sold to end users were phones with the Android operating system.

Next, the basic concepts to understand how astronomers calculate the Wolf number are explained, and following this, a description of the whole process carried out by volunteers through the app in order to calculate the values.

1) THE WOLF NUMBER FORMULA

The process of calculating the Wolf Number through the app is very simple. However, users must understand a set of concepts necessary to obtain the proper value. The app contains an introductory tutorial to teach users the following terms:

- **Groups of spots**: Set of spots (with penumbra) and pores, or individual pores, close together and jointly evolving. For its calculation is assumed the Zürich classification described below.
- **Foci**: This is the name for both spots and individual pores. For example, if in a spot two umbras are distinguished, then there are two foci.
- **Unipolar Group**: A spot or a compact group of spots with a maximum heliographic distance between the ends not exceeding three heliographic degrees.

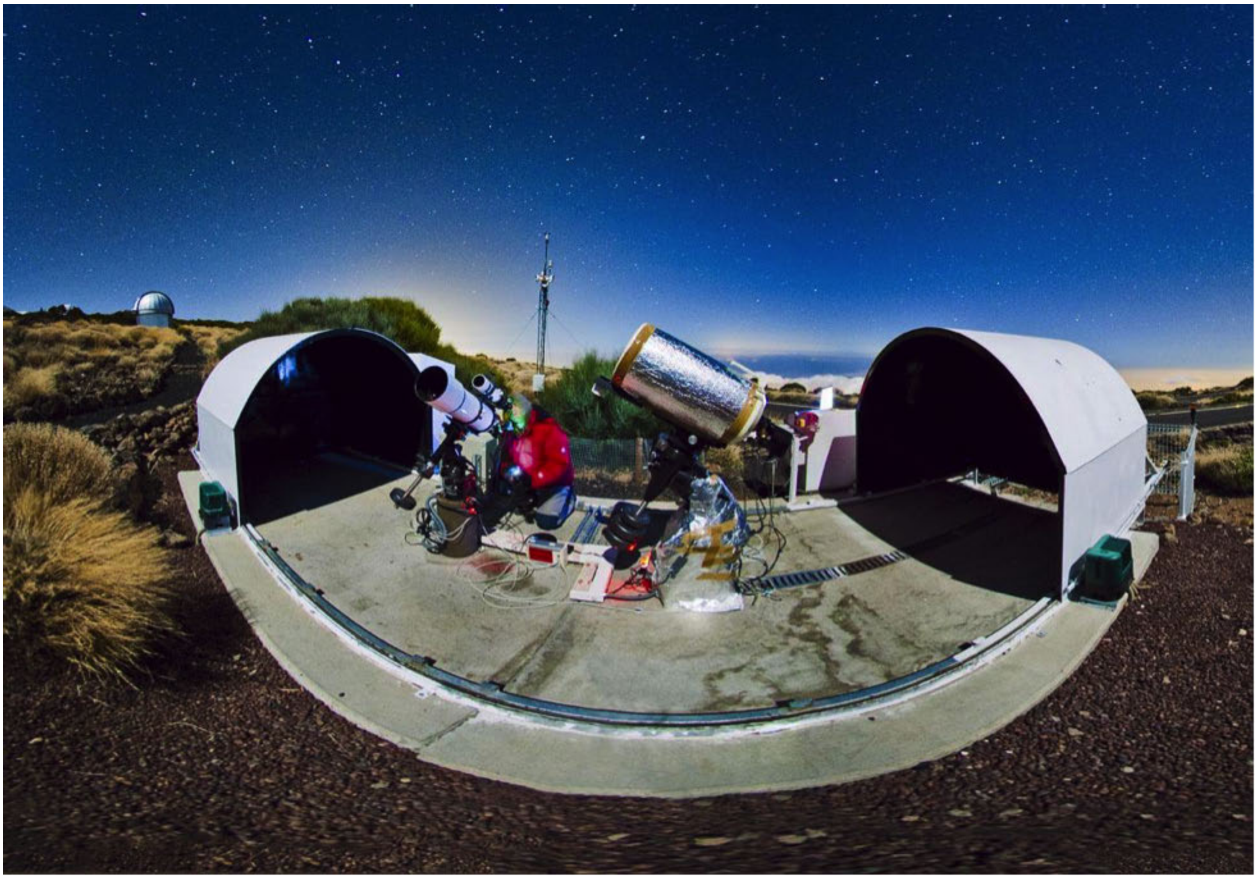


FIGURE 4. The two telescopes installed at the Observatorio del Teide (IAC, in Tenerife) and belonging to the GLORIA network: TADn is the night one (on the right) and TADs is the solar one (on the left).

- **Bipolar Group**: Two spots or a group of several spots extending east-west with a heliographic distance of three heliographic degrees.

The Wolf number (W or R) is obtained from the following equation:

$$R = k * (10 * G + s) \tag{2}$$

where:

- **k** is a statistical correction factor applied by SIDC which coordinates and analyses the observations. It takes into account the atmospheric conditions and the type of instrument used for the observation, i.e. telescope, binoculars, etc. It is usually lower than 1.
- **G** represents the number of visible groups. An isolated pore counts as a focus and as a group.
- **s** is the number of total foci of all the spots, as previously explained.

The minimum activity or smallest Wolf number is 0 (the solar surface should be completely clean), then going to 11 since one group on the solar disk with a single focus would be G = 1, s = 1, therefore, R = 11. From 11, it is possible to follow the consecutive values of natural numbers (12, 13, 14, etc.). And, the number of sunspots on the solar surface could be roughly calculated if the Wolf number or sunspot number is divided by 15.

A graphical example is shown in Fig. 5 with an image of the solar photosphere obtained by the GONG Telescope (NSO, USA) installed at the Observatorio del Teide (IAC). In the image, the number of groups of spots, that is G = 9 in this case, and the total of spots, that is s = 25 are marked. The resulting Wolf number, according to the previous equation, is 115, unlike the official value of 87 given by SIDC in that specific date. This shows a different of 28 between these two numbers. It should be remembered that the official number given by SIDC is the average of all measures, as explained at the beginning of Section I.

E. METHODOLOGY

The goal of the experiment is to analyse the user activity while they are using the app to calculate the Wolf number. The methodology is described below:

1) The user signs into the system with the GLORIA username and password. So, the first step that users have to do is to register into the GLORIA network.
2) The user selects a date and, then, an image taken of this day is randomly selected and shown on the screen.

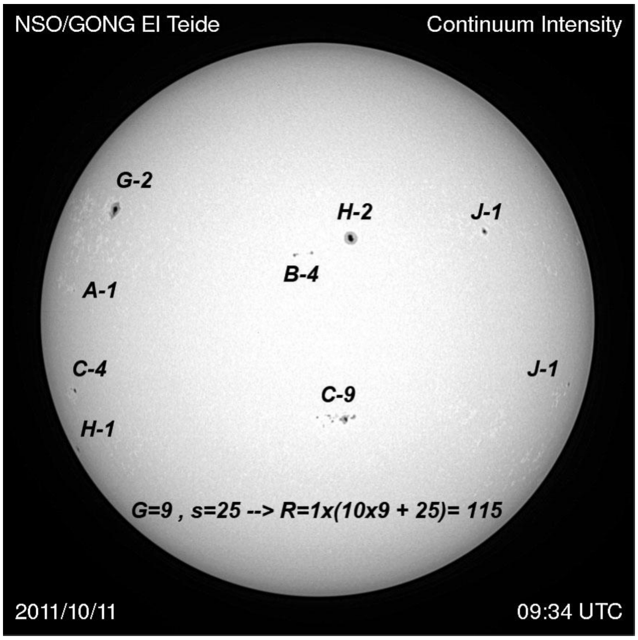


FIGURE 5. A graphical example of calculating the Wolf number for an image of the solar photosphere taken by the GONG Telescope (NSO, USA) installed at the Observatorio del Teide (IAC). The formula applied over the image gives 115, however the official number (Relative Sunspot Number) given by SIDC for the selected day was 87.

3) The user tags the sunspot groups and selects the number of sunspots inside of them.
4) The user terminates the calculation clicking the arrow at the top right. Then, the measures are sent through the GLORIA API to the offline experiment service where they are stored and labeled.

Fig. 6 shows a screenshot of the interface of the experiment in an Android device. The date of the solar image is shown at the top of the screen, and the image is shown in the center panel. The user simply zooms in or out from the center of the image and clicks the position where they want to indicate a sunspot group. As the user marks the groups and the number of sunspots, the interface updates the total of the Wolf Number calculated, as shown in the box at the bottom right of the screen.

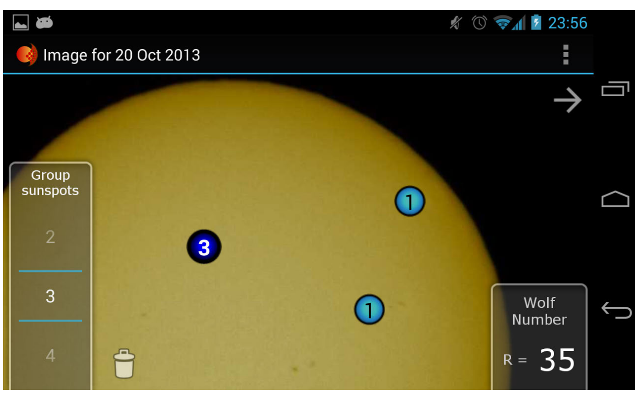


FIGURE 6. Interface of the Android app for the experiment of the GLORIA Solar Activity.

After gathering the user data for a period of time, it is processed offline in two steps. In a first step, the data obtained from the users app is validated with official data downloaded from the SILSO project website.[5] In a second step, the data obtained from the users app are filtered according to a threshold of 25%, as explained in the next section, retaining only the data of users with the highest reputation index. This means that contributions from the 25% of users with the lowest karma are discarded.

IV. RESULTS

This section presents the results gathered by the app from its starting point and corresponds to the first sixteen months of operation, which equals 480 days. Firstly, in the subsection IV-A, the method used to validate the case of study is presented, and a comparison with to the official data is carried out. In the following subsection IV-B, the user community is analyzed according to their reputation parameters, and a contrast is made with the method of IV-A with the same data but filtering out the less participative users.

In the period evaluated, as global figures, the number of experiment executions was 2,108, which corresponds to a total of 291 different days and 196 end-users. This sample covers 60% of the possible days of the analyzed period, as the same images are shown to different users to get the average value. With respect to users, 196 represent a scarce 2% of the total of about 10,000 users registered in the GLORIA portal, however it is interesting to know this information to realize the environment in which the experiment is carried out and because the parameters of the reputation of the users depend on their contribution within the community.

A. MODEL VALIDATION

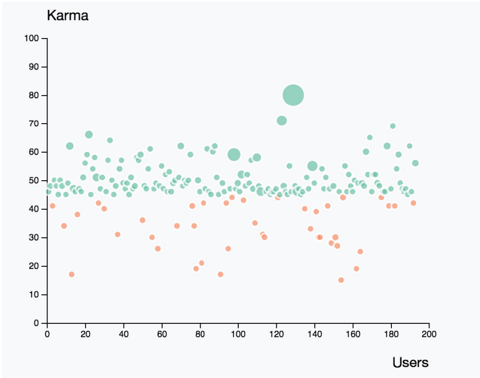
The validation of the model is carried out as follows: the comparison between the calculated values by the app users and the official data is done and the calculation of RMS-errors of the model results corresponding to each day. The official values have been downloaded freely from the SILSO project website.

In this first approach, the daily value of the Wolf Number corresponds to the mean of all contributions made by the users using the app for each specific day. The authors have processed the data discarding the days with a unique sample, which entails a total of 51 measures with an only one sample (17.5%). As a result, finally the comparison is made taking only 240 different days.

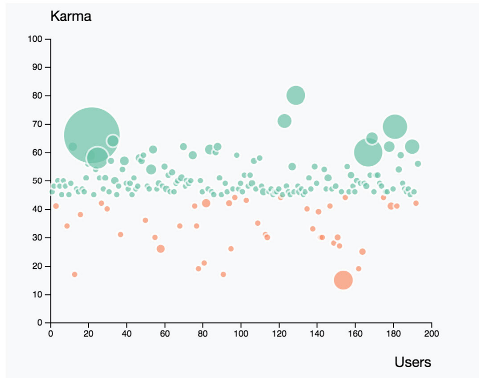
The root mean square (RMS) in this case reveals differences between official and calculated data, according to the following formula:

$$RMS = \sqrt{\frac{\sum_{i=0}^{n}(wolf_i - wolf_{real})^2}{\#executions}} \tag{3}$$

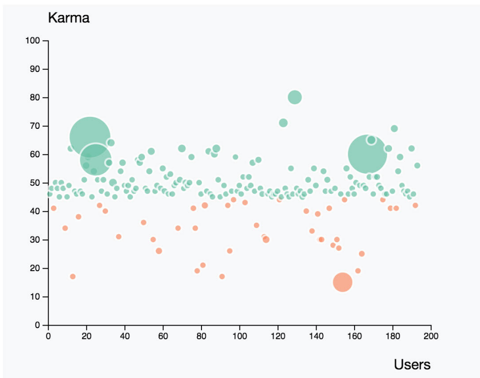
[5]SILSO, World Data Center - Sunspot Number and Long-term Solar Observations, Royal Observatory of Belgium, on-line Sunspot Number catalogue: http://www.sidc.be/SILSO/. URL: http://www.sidc.be/silso/datafiles



(a) shows the relationship between the karma and the number of executions of the Wolf number experiment.



(b) shows the relationship between the karma and the number of images taken in the Solar Online experiment.



(c) shows the relationship between the karma and the number of reservations carried out the Solar Online experiment.

FIGURE 7. Users distribution according to their karma. The dataset provides the karma, the number of executions of the Wolf number experiment, the number of images and the number of reservations carried out with the Solar Online experiment for the 196 users involved. The orange bubbles represent those users whose karma is below 25%.

where i represents the date; $wolf_i$ is the mean of the all measures of the Wolf number calculated by the users in that date; and $wolf_{real}$ is the official Wolf number.

Applying this formula, it turns out that the mean RMS-error of the calculated daily Wolf number with respect to the official values is 33.91.

The Fig. 8a shows this comparison by means of the time series. The measures vary depending on the factors such as the observer interpretation and experience, such as was explained in subsection II-A. Consequently, the results are not completely accurate. However, the same trend between the two series can be clearly appreciated.

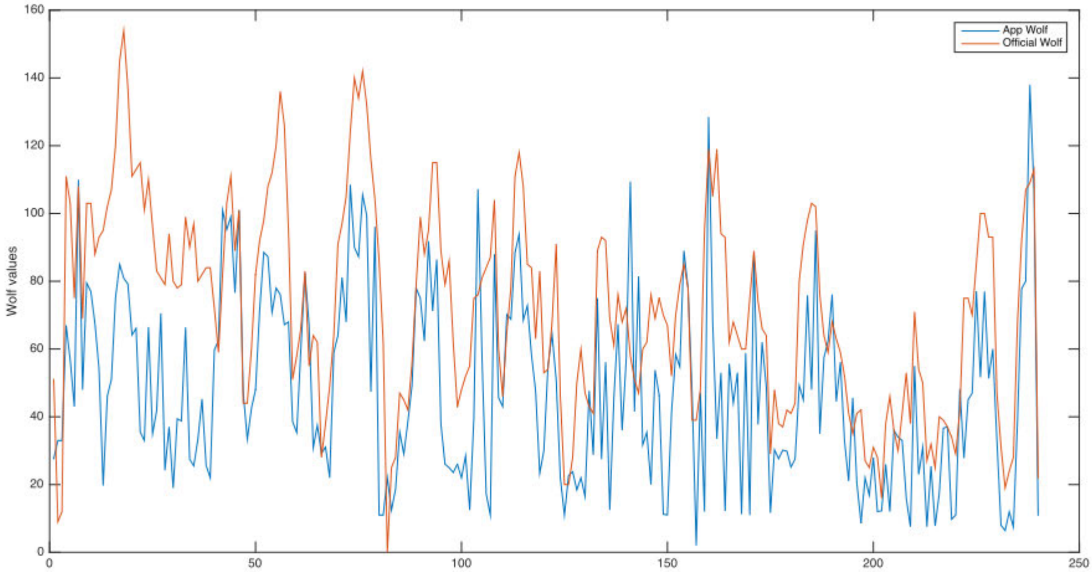
B. SECOND APPROACH: INTEGRATING A REPUTATION SYSTEM

This subsection aims to demonstrate the main objective of the case of study, that is, to take into account the underlying reputation system and discuss how the previous method is affected. However, first of all, it is convenient to analyze the behavior of users within the network.

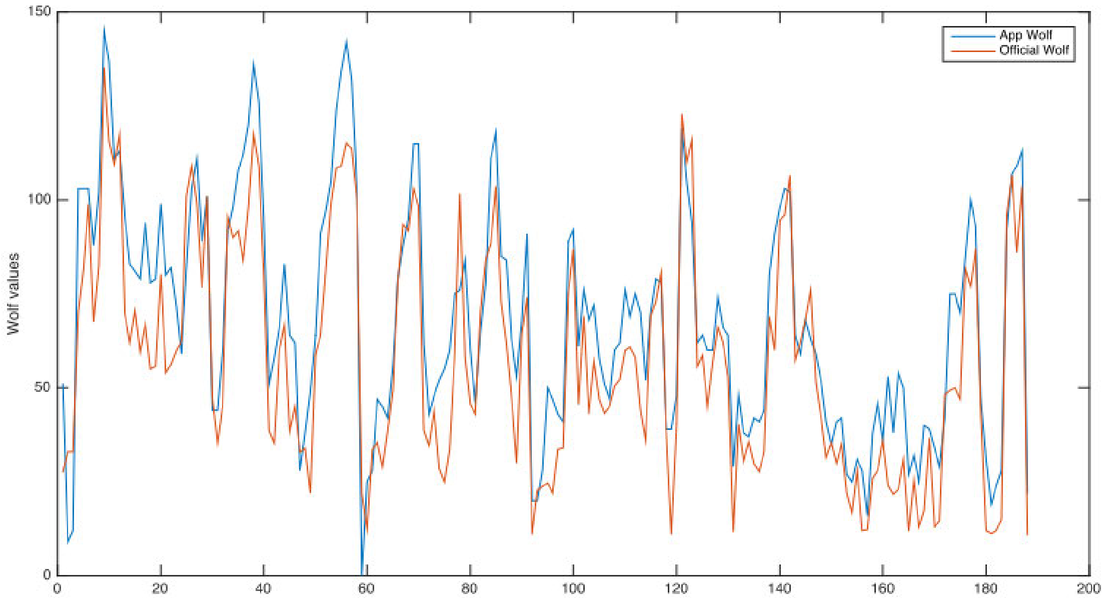
The authors have classified the users in 10 groups, depending on the number of executions of the experiment carried out by each user. This means that the users of the group 0 executed the experiment between 1 and 9 times, those of group 1 executed it between 10 and 19 times, and so on. Table 1 summarizes the parameters of community participation during this period. In Table 1, it can be observed that more than 80% of users belong to the first group and also covered a total of 1,492 of the images analyzed, which represents 70% of the total. These indicators reflect, although it is not relevant in the validation of the method, that most users leave the experiment promptly, after few executions, mainly because the experiment needs to be improved to be more attractive to users, through gamification techniques that motivate or reward them, as proposed by [37], [38].

From the point of view of the users reputation, the authors have analyzed a dataset with the karma, the number of executions of the Wolf number experiment, the number of images and the number of reservations carried out with the Solar Online experiment for the 196 users mentioned.

The distribution of those users who have executed the experiment is shown in the three graphs or bubble pots in Fig. 7. In these graphs, the X-axis represents the users, and the Y-axis corresponds to the value of karma that ranges between 0 and 100. As can be seen, most users have a



(a) samples of 240 different days, taking into account those with at least two values. The RMS-error of the calculated daily Wolf number with respect to the official values is 33.91.



(b) the same dataset as Fig. 8a but filtering out users 25% with the lowest karma. The RMS-error is 15.58, which reflects a reduction in error by more than half.

FIGURE 8. Time series of daily Wolf number during the first sixteen months. The official Wolf number extracted from the SILSO website (orange line) is compared to the calculated Wolf number through the app (blue line).

karma in the range included between the values 45 and 50, the average being 45 and only 26.7% of them are greater than 50. On the other hand, the different size of each bubble or dot represents a third variable: in Fig. 7a is the number of executions of the Wolf number experiment, in Fig. 7b is the number of images taken in the Solar Online experiment, and in Fig. 7c is the number of slots booked. This information represents a similar idea to Table 1 but allowing the study of individual contributions. These data allow the extraction of the following analysis:

1) The karma average of 45 reflects that they are users who have maintained a constant contribution over time with respect to the participation of the rest of the community since, as mentioned in section III-B, this value is greater than the initial value of 40. This means that most users have participated in one way or another in the GLOBAL network, so they are regular and constant users.
2) As can be seen in Fig. 7a, there is an obvious relationship between karma and number of executions.

TABLE 1. Statistics for user participation in the Wolf Number experiment.

Group	Number of executions	Number of users	Number of images analysed
0	[1 - 9]	157	1,492
1	[10 - 19]	20	107
2	[20 - 29]	6	76
3	[30 - 39]	1	32
4	[40 - 49]	3	56
5	[50 - 59]	3	430
6	[60 - 69]	2	3
7	[70 - 79]	0	0
8	[80 - 89]	0	0
9	[90 - ∞]	4	270

While most users have run the experiment a few times, between 1 and 9 (group 0), and correspond to the smallest bubbles, it is clear that they are only a few who have contributed a large number of executions, being users whose karma is above average. In fact, approximately 61% of executions correspond to users with a karma higher than 50. This means that the most experienced users with the app (greater number of executions) are also users with greater karma, always above average.

3) There is also a relationship between karma and the interaction with the Solar Online experiment, both for the number of images obtained and for the number of reservations made, as can be seen in Fig. 7b and 7c, respectively. In both cases, the distribution is more homogeneous but it is obvious that the most interactive are also those of a greater karma. This means that most users were familiar with the solar experiment and showed prior interest.

This study allows to establish the hypothesis that karma is a determining factor in the quality of the results. In fact, it is the basis for launching the second approach based on the assumption that a user with more karma can better carry out the proposed experiment. Thanks to the reputation model, it is possible to know which users participate more and better in the system, as previously explained.

The authors have repeated the same method as in the previous subsection but using the karma values in order to prune the samples. In this way, contributions of the users with different karma values have been discarded, allowing to find out the karma for which the RMS-error is reduced. The results show that the lowest RMS-error is obtained by discarding the 25% users with the lowest karma. In this way, it turns out that the mean RMS-error is 15.58. That means the error is reduced by more than 50% from the first approach detailed in subsection IV-A.

As can be seen in Fig. 8, the chart reduces the differences. However, if the contributions of users with 25% less karma are discarded, the negative effect is obvious since there are 30% contributions less. That is, the number of days analyzed is reduced with respect to the first approach, dropping from 240 to 188 days, that is, a 21.7% less. However, the calculation of the Wolf Number is more accurate in spite of having a lower number of days analyzed, as can be seen in Fig. 8 which shows the comparison by means of the time series.

V. CONCLUSION

The present study has allowed the validation of the underlying scientific method developed under a mobile app and focused as a citizen science experiment. The dataset, registered by the experiment during the first sixteen months running, showed a moderate participation of volunteer citizens and allowed the validation of the model. The user contributions showed an acceptable error margin with respect to the official Wolf number obtained by professionals and compiled by the Solar Influences Data Analysis Center.

Furthermore, the authors have applied a novel approach to improve the results, which consists of introducing a reputation system based on an indicator which measures the quality of a user within the global system, known as karma in the case of the GLORIA network. The analysis showed interesting results regarding the behavior of the end-users and the calculations provide the conclusion that excluding the contributions of the users with the karma below 25%, the RMS-error was reduced by more than 50% with respect to the original method.

In the short term, the aim will be to vary the different karma formulas and policies by introducing some temporal variable, comparing the results and checking if there are improvements. Another very interesting study will be to analyze user behavior over time and its variations to build user profiles and detect possible anomalies.

In the longer term, gamification techniques and artificial intelligence algorithms for the selection of the images shown to users will be considered to engage and optimize the efforts made by citizens, getting results faster.

ACKNOWLEDGMENT

The authors thank to the WDC-SILSO (http://sidc.be/silso/) for publishing in open-access its database of solar observations.

REFERENCES

[1] F. Clette, L. Svalgaard, J. M. Vaquero, and E. W. Cliver, "Revisiting the sunspot number: A 400-year perspective on the solar cycle," *Space Sci. Rev.*, vol. 186, nos. 1–4, pp. 35–103, Dec. 2014.

[2] F. Clette, J. M. Vaquero, M. C. Gallego, and L. Lefèvre, "Sunspot and group number: Recent advances from historical data," *Proc. Int. Astronomical Union*, vol. 14, pp. 156–159, Aug. 2018, doi: 10.1017/S174392131900396X.

[3] B. Kakad, R. Kumar, and A. Kakad, "Randomness in sunspot number: A clue to predict solar cycle 25," *Sol. Phys.*, vol. 295, no. 6, Jun. 2020, Art. no. 88, doi: 10.1007/s11207-020-01655-7.

[4] L. H. Deng, X. J. Zhang, H. Deng, Y. Mei, and F. Wang, "Systematic regularity of solar coronal rotation during the time interval 1939–2019," *Monthly Notices Roy. Astronomical Soc.*, vol. 491, no. 1, pp. 848–857, Jan. 2020.

[5] H. Çakmak, "A semi-automated method to reveal the evolution of each sunspot group in a solar cycle," *Astrophys. Space Sci.*, vol. 363, no. 12, p. 263, Dec. 2018, doi: 10.1007/s10509-018-3485-9.

[6] P. Galaviz, V. M. S. Carrasco, F. Sánchez-Bajo, M. C. Gallego, and J. M. Vaquero, "Soonspot: Software to determine areas and sunspot positions," *Sol. Phys.*, vol. 295, no. 2, Feb. 2020, Art. no. 17, doi: 10.1007/s11207-020-1587-3.

[7] M. Wang, G. Wang, Y. Zhang, and Z. Li, "A high-reliability multi-faceted reputation evaluation mechanism for online services," *IEEE Trans. Services Comput.*, vol. 12, no. 6, pp. 836–850, Nov. 2019, doi: 10.1109/TSC.2016.2638812.

[8] A. Benlahbib and E. H. Nfaoui, "Aggregating customer review attributes for online reputation generation," *IEEE Access*, vol. 8, pp. 96550–96564, 2020, doi: 10.1109/ACCESS.2020.2996805.

[9] M. Hesse and T. Teubner, "Reputation portability-quo vadis?" *Electron. Markets*, vol. 30, pp. 1–19, Sep. 2019.

[10] J. M. Vaquero, L. Svalgaard, V. M. S. Carrasco, F. Clette, L. Lefèvre, M. C. Gallego, R. Arlt, A. J. P. Aparicio, J.-G. Richard, and R. Howe, "A revised collection of sunspot group numbers," *Sol. Phys.*, vol. 291, nos. 9–10, pp. 3061–3074, Nov. 2016, doi: 10.1007/s11207-016-0982-2.

[11] T. K. Friedli, "Recalculation of the wolf series from 1877 to 1893," *Sol. Phys.*, vol. 295, no. 6, p. 72, Jun. 2020.

[12] K. Wazny, "Crowdsourcing ten years in: A review," *J. Global Health*, vol. 7, no. 2, 2017, Art. no. 020602, doi: 10.7189/jogh.07.020602.

[13] L. A. Shanley, A. Parker, S. Schade, and A. Bonn, "Policy perspectives on citizen science and crowdsourcing," *Citizen Sci., Theory Pract.*, vol. 4, no. 1, p. 30, Dec. 2019, doi: 10.5334/cstp.293.

[14] E. Estellés-Arolas and F. González-Ladrón-de-Guevara, "Towards an integrated crowdsourcing definition," *J. Inf. Sci.*, vol. 38, no. 2, pp. 189–200, Apr. 2012, doi: 10.1177/0165551512437638.

[15] C. L. Tucci, A. Afuah, and G. Viscusi, *Creating and Capturing Value Through Crowdsourcing*. London, U.K.: Oxford Univ. Press, 2018.

[16] M. Jiménez, I. Triguero, and R. John, "Handling uncertainty in citizen science data: Towards an improved amateur-based large-scale classification," *Inf. Sci.*, vol. 479, pp. 301–320, Apr. 2019, doi: 10.1016/j.ins.2018.12.011.

[17] F. Daniel, P. Kucherbaev, C. Cappiello, B. Benatallah, and M. Allahbakhsh, "Quality control in crowdsourcing: A survey of quality attributes, assessment techniques, and assurance actions," *ACM Comput. Surv.*, vol. 51, no. 1, Apr. 2018, Art. no. 7, doi: 10.1145/3148148.

[18] E. Raymond, "The cathedral and the bazaar," *Knowl., Technol. Policy*, vol. 12, no. 3, pp. 23–49, Sep. 1999.

[19] E. L. Uhlmann, C. R. Ebersole, C. R. Chartier, T. M. Errington, M. C. Kidwell, C. K. Lai, and B. A. Nosek, "Scientific utopia III: Crowdsourcing Science," *Perspectives Psychol. Sci.*, vol. 14, no. 5, pp. 711–733, 2019, doi: 10.1177/1745691619850561.

[20] M. V. Eitzel, J. L. Cappadonna, C. Santos-Lang, R. E. Duerr, A. Virapongse, S. E. West, and Q. Jiang, "Citizen science terminology matters: Exploring key terms," *Citizen Sci., Theory Pract.*, vol. 2, no. 1, p. 1, 2017, doi: 10.5334/cstp.96.

[21] R. Follett and V. Strezov, "An analysis of citizen science based research: Usage and publication patterns," *PLoS ONE*, vol. 10, no. 11, Nov. 2015, Art. no. e0143687.

[22] C. Kullenberg and D. Kasperowski, "What is citizen science?—A scientometric meta-analysis," *PLoS ONE*, vol. 11, no. 1, Jan. 2016, Art. no. e0147152.

[23] K. Crowston, E. Mitchell, and C. Østerlund, "Coordinating advanced crowd work: Extending citizen science," *Citizen Sci., Theory Pract.*, vol. 4, no. 1, p. 16, Apr. 2019, doi: 10.5334/cstp.166.

[24] G. S. Butcher, M. R. Fuller, L. S. McAllister, and P. H. Geissler, "An evaluation of the christmas bird count for monitoring population trends of selected species," *Wildlife Soc. Bull.*, vol. 18, no. 2, pp. 129–134, 1990.

[25] E. Korpela, D. Werthimer, D. Anderson, J. Cobb, and M. Leboisky, "SETI@home-massively distributed computing for SETI," *Comput. Sci. Eng.*, vol. 3, no. 1, pp. 78–83, 2001, doi: 10.1109/5992.895191.

[26] S. T. Ishikawa and V. C. Gulick, "Clickworkers interactive: Towards a robust crowdsourcing tool for collecting scientific data," in *Proc. LPI*, vol. 1659, 2012, p. 2917.

[27] C. Lintott, K. Schawinski, S. Bamford, A. Slosar, K. Land, D. Thomas, E. Edmondson, K. Masters, R. C. Nichol, M. J. Raddick, A. Szalay, D. Andreescu, P. Murray, and J. Vandenberg, "Galaxy zoo 1: Data release of morphological classifications for nearly 900 000 galaxies: Galaxy zoo," *Monthly Notices Roy. Astronomical Soc.*, vol. 410, no. 1, pp. 166–178, Jan. 2011.

[28] A. J. Holincheck, J. F. Wallin, K. Borne, L. Fortson, C. Lintott, A. M. Smith, S. Bamford, W. C. Keel, and M. Parrish, "Galaxy zoo: Mergers—Dynamical models of interacting galaxies," *Monthly Notices Roy. Astronomical Soc.*, vol. 459, no. 1, pp. 720–745, Jun. 2016, doi: 10.1093/mnras/stw649.

[29] L. Trouille, C. J. Lintott, and L. F. Fortson, "Citizen science frontiers: Efficiency, engagement, and serendipitous discovery with human–machine systems," *Proc. Nat. Acad. Sci. USA*, vol. 116, no. 6, pp. 1902–1909, Feb. 2019, doi: 10.1073/pnas.1807190116.

[30] N. Reeves, R. Tinati, S. Zerr, M. G. Van Kleek, and E. Simperl, "From crowd to community: A survey of online community features in citizen science projects," in *Proc. ACM Conf. Comput. Supported Cooperat. Work Social Comput.*, Feb. 2017, pp. 2137–2152, doi: 10.1145/2998181.2998302.

[31] C. Jennett, L. Kloetzer, D. Schneider, I. Iacovides, A. Cox, M. Gold, B. Fuchs, A. Eveleigh, K. Mathieu, Z. Ajani, and Y. Talsi, "Motivations, learning and creativity in online citizen science," *J. Sci. Commun.*, vol. 15, no. 3, pp. 1–23, Apr. 2016.

[32] S. Odenwald, "A citation study of citizen science projects in space science and astronomy," *Citizen Sci., Theory Pract.*, vol. 3, no. 2, p. 5, Oct. 2018, doi: 10.5334/cstp.152.

[33] C. Silva, "SOCIENTIZE participatory experiments, dissemination and networking activities in perspective," *Hum. Comput.*, vol. 1, no. 2, pp. 1–17, Dec. 2014.

[34] M. C. Lopez-Casado, C. J. P. Del Pulgar, J. Cabello-Castillo, V. F. Munoz, O. Lara, A. Castro-Tirado, J. Strobl, E. Maureira, F. M. Sanchez, and E. Gonzalez, "A fuzzy logic based decision algorithm for a heterogeneous telescope network," in *Proc. IEEE Int. Conf. Ind. Technol. (ICIT)*, Seville, Spain, Mar. 2015, pp. 1814–1819, doi: 10.1109/ICIT.2015.7125360.

[35] A. Majcher, A. Ćwiek, M. Ćwiok, L. Mankiewicz, M. Zaremba, and A. F. Żarnecki, "The GLORIA demonstrator experiment," *Proc. SPIE*, vol. 8903, Oct. 2013, Art. no. 890328, doi: 10.1117/12.2035442.

[36] C. J. Pérez-del-Pulgar, C. Jesús, R. Cedazo, J. Cabello, E. González, V. F. Muñoz, F. Serena, M. C. López, F. Ibáñez, F. M. Sánchez, A. Castro, and R. Cunniffe, "GLORIA: The first free access e-infrastructure of robotic telescopes for citizen science," in *Advances in Information Systems and Technologies* (Advances in Intelligent Systems and Computing), vol. 206, Á. Rocha, A. Correia, T. Wilson, K. Stroetmann, Eds. Berlin, Germany: Springer, 2013, doi: 10.1007/978-3-642-36981-0_28.

[37] E. Simperl, N. Reeves, C. Phethean, T. Lynes, and R. Tinati, "Is virtual citizen science a game?" *ACM Trans. Social Comput.*, vol. 1, no. 2, pp. 1–39, Jun. 2018, doi: 10.1145/3209960.

[38] M. Ponti, T. Hillman, C. Kullenberg, and D. Kasperowski, "Getting it right or being top rank: Games in citizen science," *Citizen Sci., Theory Pract.*, vol. 3, no. 1, p. 1, Jan. 2018, doi: 10.5334/cstp.101.

RAQUEL CEDAZO was born in Madrid, Spain, in 1981. She received the B.S. degree in computer science, in 2005, and the Ph.D. degree in computer science from the Universidad Politécnica of Madrid (UPM), Spain, in 2009.

Since 2010, she has been an Associate Professor with the Electrical Engineering, Electronics, Automatic, and Applied Physics Department, UPM. She is currently an Assistant to the Director of continuous improvement and communications with the Senior Technical School of Engineering and Industrial Design, UPM. She has been an Administrator with the Francisco Sánchez Astronomical Observatory, she has also been a Researcher with COLDEX and GLORIA European projects and with AstroMadrid and Astrocam National Consortiums. She is a Main Researcher with three citizen science projects funded by the Spanish Foundation for Science and Technology: the Asteroid Hunters, the Star Counters, and the Sky Sounds. Since 2014, she is also an In Charge in UPM with the MEGARA Project, a multispectrograph of high-resolution for Astronomy, funded by the Gran Telescopio de Canarias. Her research interests include collaborative e-learning, educational web laboratories, online reputation systems, and citizen science.

ESTEBAN GONZALEZ was born in Madrid, in 1979. He received the B.S. degree in computer science, in 2011, and the master's degree in artificial intelligence from the Universidad Politécnica de Madrid, in 2014.

From 2001 to 2007, he was an Intern with EADS-CASA and a Software Developer with DEIMOS Space. From 2009 to 2015, he was a Software Developer and a Researcher with the GLORIA European Project and MEGARA, a multispectrograph of high-resolution for astronomy, funded by the Gran Telescopio de Canarias. Since 2016, he has been with the Ontology Engineering Group, UPM, as a Software Developer. He was a Software/Data Manager with the STARS4ALL European Project. He is currently with the ACTION Project and collaborates with the Francisco Sánchez Astronomical Observatory, UPM. He is a Co-Creator with the Asteroid Hunters, the Star Counters, and the Sky Sounds National Projects. His research interests include open science, online reputation systems, and citizen science.

MIQUEL SERRA-RICART was born in Barcelona, Spain, in 1966. He received the B.S. degree in physical sciences from the University of Barcelona, in 1989, and the Ph.D. degree in astrophysics from the University of La Laguna, La Laguna, Spain, in 1993.

Since 1994, he has been an Administrator with the Teide Observatory, Canary Islands Institute of Astrophysics (IAC). He has dedicated to the dissemination of astronomy. He is currently the Founder with the Shelios Association, the StarryEarth Photographic Project, the Astroaula Educational Portal, the Star Route Project, and the Sky-Live Tv Astronomical Events Broadcasting Channel. He is also responsible with the GLORIA and STARS4ALL European Projects and a Co-Creator with the Asteroid Hunters, the Star Counters, and the Sky Sounds National Projects. He is the author of more than 100 articles and more than 30 astronomical expeditions. His main research interests include minor bodies of solar systems (comets and asteroids) and gravitational lenses.

ALBERTO BRUNETE (Member, IEEE) received the M.S. degree in telecommunication engineering and the Ph.D. degree in robotics and automation from the Universidad Politécnica de Madrid (UPM), in 2000 and 2010, respectively. He was a Technical Manager with the Research Center for Smart Buildings and Energy Efficiency (CeDInt), UPM, and a Visiting Professor with the University Carlos III of Madrid. He is currently an Associate Professor with UPM and a Researcher with the Centre for Automation and Robotics. His main research interests include service robots and smart environments (the IoT and ambient intelligence). He received the Spanish Prize ABC Solidario for Fall Detector Project for Elderly People in 2016.