The Aristarchus Campaigns: Collaboratively measuring the Solar System

Jorge I. Zuluaga
FACom-Instituto de Física-FCEN, Universidad de Antioquia & Sociedad Antioqueña de Astronomía Colombia
jorge.zuluaga@udea.edu.co

Juan C. Figueroa
FACom-Instituto de Física-FCEN, Universidad de Antioquia & Sociedad Antioqueña de Astronomía Colombia

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Summary

Citizen astronomy has proven to be one of the most effective ways to actively involve amateur astronomers in real scientific endeavours. We present here the Aristarchus Campaigns, a citizen astronomy project intended to collaboratively reproduce historical astronomical observations. During the campaign amateur astronomers were invited to use simple optical instruments to gather data about some common astronomical phenomena. This data was used to calculate the value of well-known physical and astronomical quantities such as the speed of light and the distance to, and size of the Moon. We describe the project and the results of the first two Aristarchus Campaigns. We argue that this type of simple campaign may help to engage the public with astronomy in developing counties and prepare their astronomical communities to participate in high-impact observational campaigns.

Introduction

Ancient astronomers devised inventive methods to measure the Solar System. Using these methods, which are in principle very simple, we can measure the sizes of the Sun, the Moon and the planets, and their distances from us. One of the best known of these ancient methods was originally proposed by Aristarchus of Samos (*ca.* 310–230 BCE) who devised procedures that used lunar phases and eclipses to estimate the relative sizes and distances of the Moon and the Sun (Van Helden, 2010; Heath, 2013).

More recently, physical constants have attracted the attention of astronomers. Using the huge spatial and temporal scales natural to astronomy, astronomers have devised ingenious ways to measure the values of these physical constants. Take for example the method devised by Ole Rømer (1644–1710) who measured the speed of light in vacuum by observing the periodic occultation of the moon Io by its host planet, Jupiter (Cohen, 1940).

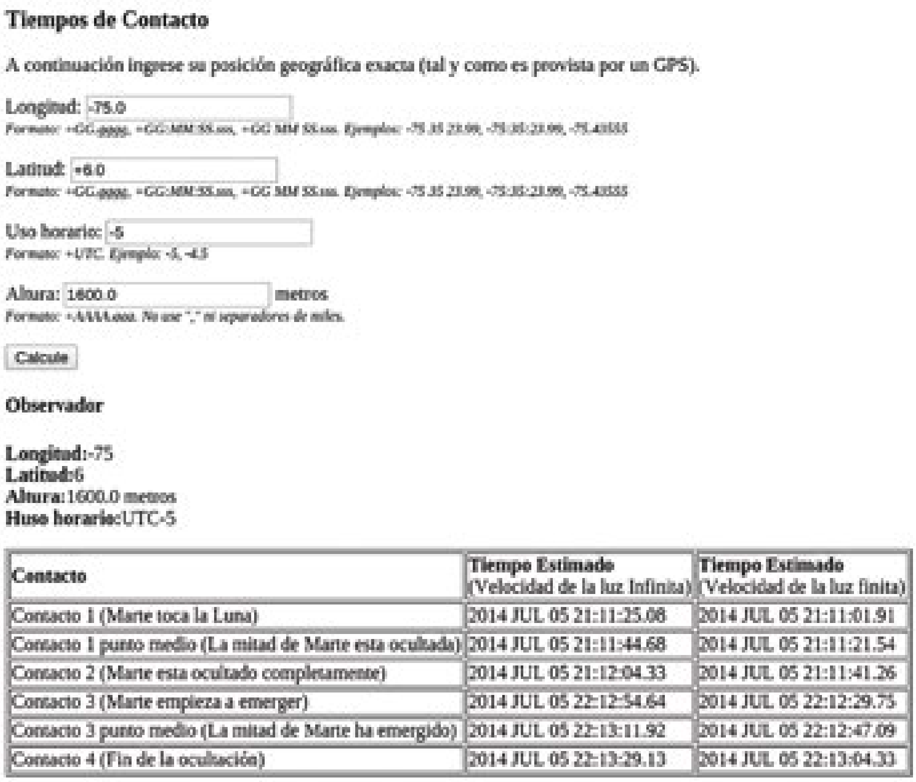
Now, many centuries after the invention of these historical methods, astronomers and physicists have measured these quantities with exquisite precision using vastly more elaborate tools and methods. The distance to the Moon can be determined using powerful lasers and retro-reflecting arrays of mirrors placed on the lunar surface by the Apollo astronauts, so that the distance is now known to within just a few centimetres (Tapley, 2004; Dickey, 1994). The diameter of and distance to the Sun have been determined to one part in a billion and one part in a 100 billion respectively (Schou, 1997; Muhleman, 1969) and the speed of light, which until a few decades ago had only been constrained using astronomical methods, is now regularly measured in the laboratory so precisely that it is known to roughly one part in a billion (Sullivan, 2001).

In contrast to the classical methods devised by such pioneers as Aristarchus or Rømer, most of these modern techniques are far from the reach and technological capacity of most amateur astronomers. Therefore, measuring distances in the Solar System, and constraining the physical constants that govern it, today seems to be a matter of sophisticated instrumentation and advanced scientific capabilities. But, these classical methods have a great deal left to offer and still find a privileged place in astronomy and physics textbooks. They are used today as educational tools, not only for teaching science history, but also for teaching the methods of astronomy and physics and inspiring new ways of thinking about the results (Salvador, 2009).

Today, the advent of advanced and accessible technological devices such as smartphones is opening new doors for do-it-yourself astronomy. Many personal electronic devices such as smartphones come with a GPS receiver, fast internet connections and precise clocks. This gives us, the science communicators, an incredible opportunity to involve astronomy enthusiasts, and the wider public, in astronomy projects. They allow for *in situ* measurements that would otherwise be prohibitively expensive and available only to professional scientific teams.

This scientific and sociological phenomenon is called citizen astronomy, or more generally, citizen science (Raddick, 2010).

Our citizen astronomy campaigns aimed to reproduce historical astronomical observations and measurements that helped to determine the size of the local Universe. Here, we will give a background to the project and the role that citizen astronomy plays in science outreach; we describe the project and the specific campaigns that we have run with the participation of individuals and communities in Colombia and abroad; summarise some the most important scientific results of the campaigns; and discuss the challenges involved when organising and running this kind of initiative.



Contacto	Tiempo Estimado (Velocidad de la luz Infinita)	Tiempo Estimado (Velocidad de la luz finita)
Contacto 1 (Marte toca la Luna)	2014 JUL 05 21:11:25.08	2014 JUL 05 21:11:01.91
Contacto 1 punto medio (La mitad de Marte esta ocultada)	2014 JUL 05 21:11:44.68	2014 JUL 05 21:11:21.54
Contacto 2 (Marte esta ocultado completamente)	2014 JUL 05 21:12:04.33	2014 JUL 05 21:11:41.26
Contacto 3 (Marte empieza a emerger)	2014 JUL 05 22:12:54.64	2014 JUL 05 22:12:29.75
Contacto 3 punto medio (La mitad de Marte ha emergido)	2014 JUL 05 22:13:11.92	2014 JUL 05 22:12:47.09
Contacto 4 (Fin de la ocultación)	2014 JUL 05 22:13:29.13	2014 JUL 05 22:13:04.33

Figure 1. *Screenshot of the iContact web-based application developed for the 5 July 2014 Aristarchus Campaign[1].*

The rise of citizen astronomy

A recent, inadvertent example of the power of citizen astronomy took place on 15 February 2013. On a cold morning in Siberia, hundreds of thousands of citizens of several large cities around the Chelyabinsk region in Russia witnessed only the second large asteroid impact ever recorded. Hundreds of pictures and videos were taken that day by random observers and shared almost instantaneously via social networks. The data collected by these *de facto* citizen scientists allowed professional astronomers around the world to study the phenomenon in unprecedented detail (Brown, 2013; Zuluaga, 2013).

Another well-known citizen astronomy project is the Globe at Night project, a successful initiative intended to measure light pollution around the world (Barringer, 2011).

Collaborative astronomical observations that involve many amateur and professional astronomers are not new (Meech, 2005). These campaigns have been run in the past to study the evolution of comets, measure the position of near-Earth asteroids or observe the occultation of stars by Solar System objects (Ortiz, 2011). Projects like these have led to new discoveries and breakthroughs but, in most cases, the people enrolled in these campaigns are experienced observers, whether professional or amateur. More simple astronomical campaigns, such as those described here, aim instead to measure or to observe common astronomical phenomena such as lunar and solar eclipses and occultations, which use simpler and more readily available instrumentation and methods. These may serve as initial experiences for those who might then go on to participate in more advanced projects. Mass participation in these simple campaigns from communities in developing countries may prepare them for more interesting and challenging collaborative projects.

In 2014, with all of this in mind, we designed and launched a new set of citizen astronomy projects in Colombia called the Aristarchus Campaigns. The projects involved amateur astronomers distributed over a geographic area covering not only Colombia but several neighbouring countries.

The Aristarchus Campaigns

On 15 April 2014 a total lunar eclipse was visible from most of the Americas and the Caribbean. Lunar eclipses are very common phenomena that are spotted, photographed, and even measured by hundreds of millions of observers. They provide well-known opportunities to measure the size of, and distance to, the Moon and the Sun, as recognised over two thousand years ago by Aristarchus of Samos (Heath, 2013).

In 2014, a group of professional astronomers and astronomy undergraduate students at the University of Antioquia in Medellín, Colombia teamed up with the Sociedad Antioqueña de Astronomía — a regional astronomical association — and launched the Aristarchus Campaign. The campaign was intended to make the experience of observing the total lunar eclipse not only an enjoyable recreational activity, but also an opportunity to perform simple measurements using readily available astronomical equipment — such as binoculars, small telescopes and cameras — and personal electronic devices — like mobile phones and tablets.

The initiative was promoted by local astronomy clubs and through social networks. An observing guide was written to observe and measure the lunar eclipse and the public in Medellin were encouraged to submit their measurements and pictures for potential scientific use.

The weather in Colombia on the date of the eclipse made it very difficult for many committed enthusiasts to perform most of the measurements. However, despite this slow start we were motivated by the enthusiastic response on social networks and proposed, in the same year, several similar campaigns.

We now call these observational initiatives, collectively, the Aristarchus Campaigns. At the time of writing, there have been three Aristarchus Campaigns:

Campaign 1:
The 15 April 2014 campaign centred on the total lunar eclipse.

Campaign 2:
The 23 May 2014 campaign associated with the meteor storm of the 209P/Linear comet.

Campaign 3:
The 5 July 2014 campaign corresponding to an occultation of Mars by the Moon visible in most parts of South America.

Campaign design and preparation

Preparing observations of a simple astronomical phenomenon, such as a lunar eclipse, an occultation or a meteor shower, is a relatively simple task. Finding the most interesting things to observe and measure and devising ways to achieve these measurements with simple and readily available instrumentation, is much more challenging.

The campaign preparations began by selecting a phenomenon that could be observed from a wide geographic area. Lunar and solar eclipses, lunar occultations and meteor showers make ideal targets.

Once the phenomenon was identified, details of where in the sky the phenomenon would be visible for the specific geographic area covered by the campaign had to be prepared. In the case of an eclipse this meant calculating the contact times of the Moon with the shadow of the Earth and the magnitude of the eclipse, and for meteor showers the position of the radiant — the point in the sky where the meteors appear to originate for a ground-based observer — and an estimate of the meteor-sighting rate had to be calculated.

Occultations are far more challenging as contact times depend much more strongly on geographic position. In this case it is important to provide access to astronomical tools giving the occultation information for specific locations. These tools should be user-friendly and be accessible without any advanced astronomical or computational skills.

For our occultation campaign we developed a simple web-based application that was to provide contact times for a given location inside the occultation area[1]. A snapshot of the website we designed and created for this campaign is shown and described in Figure 1.

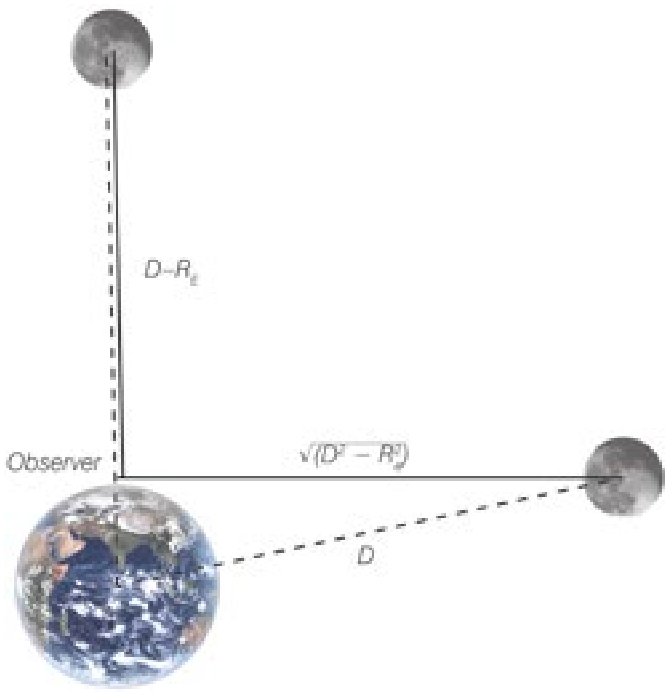


Figure 2. *As the Moon rises its distance to an observer on the Earth's surface of is reduced. Objects are not shown to scale.*

The selection of specific quantities to be measured or objects to be photographed is the next step in the preparation process. Since the campaigns are intended to reproduce historic astronomical measurements, it is good to start from the methods and quantities that were selected by astronomers in the past.

We prepared and distributed a short observing guide featuring information on the campaign and the observations. A guide of this type should be engaging, short and very easy to read and follow. It should also include a clear description of the goals and scope of the campaign and more importantly, a statement about the precise usage of the data provided by participants. For the purpose of the call for participants it is very important that the guide is easily downloadable.

Depending on the complexity of the observations, we additionally prepared and distributed detailed guides containing further technical instructions, intended for more advanced observers.

The guides from all the campaigns can be downloaded from the official website of the project[2].

Call for participation

It is important that the local institutions and groups that normally act as sources of astronomy information for the public be fully involved in the marketing of the campaign. For the first Aristarchus Campaign we were supported by Medellin's planetarium and the local science museum, as well as by the astronomy clubs.

Social networks, Facebook, Twitter, email lists, blogs and other astronomy-related websites allowed us to reach communities in other regions of Colombia and other countries.

Gathering the campaign measurements

For gathering the data and images obtained by the participants in the campaigns we use three basic methods:

Social networks

Social networks such as Facebook and Twitter are the simplest method for gathering the data. Social media is especially suitable for providing information that can be summarised in a few words, for example, contact times of occultations or equipment specifications.

Email

When the information to be provided is more complex, we ask participants to send emails to the campaign organiser with their images or data files attached.

Upload repository

If the amount of data to be provided is very large and cannot be sent using the two previous methods, participants may upload pictures and files to a public repository especially prepared for this purpose.

We have not yet designed a specific web interface to gather the campaign data, as has been done in other citizen science projects, as there are significant differences between the data requirements for each campaign, making it harder to design a universally applicable platform. For one campaign we may primarily need pictures or videos, whilst for another we may just need positions and times.

One of the biggest challenges when dealing with information provided by a large community of observers, is the diversity of data formats that has to be dealt with. Differences in equipment, time zones, observational experience and even operating systems, can make the analysis of this information potpourri a very challenging task.

Our second and larger campaign taught us that it is very important to instruct observers in advance on how to deal with the data they are gathering. For instance, it is important to warn participants that pictures should not be modified after being digitally extracted from the cameras as it is important to preserve the EXIF data stored by the devices as this contains key information needed for analysis. These data manipulation tips are the kinds of best practices that astronomy or science citizen campaigns can use to improve the skills of the community before they participate in advanced or global projects.

Analysis of the observations and publication of the results

The last part of the campaign was the compilation and analysis of the observations. In most citizen astronomy projects this process is performed by researchers, but in the Aristarchus Campaigns we have always tried to actively involve some of the participants. Additionally, all the analytical tools, such as numerical methods, formulae and computer codes, have been made publicly available to allow other experts, and amateur astronomers, to reproduce the results.

For each campaign we prepare a technical report describing the campaign itself, its scientific goals, the data provided by the citizen astronomers and the full results of the data analysis. Two technical reports have been written so far, the first on the 15 April 2014 lunar eclipse (Zuluaga, 2014) and the second on the 5 July 2014 occultation of Mars by the Moon[3].

Results of the campaigns

In the following paragraphs we summarise the two successful Aristarchus Campaigns we have already concluded.

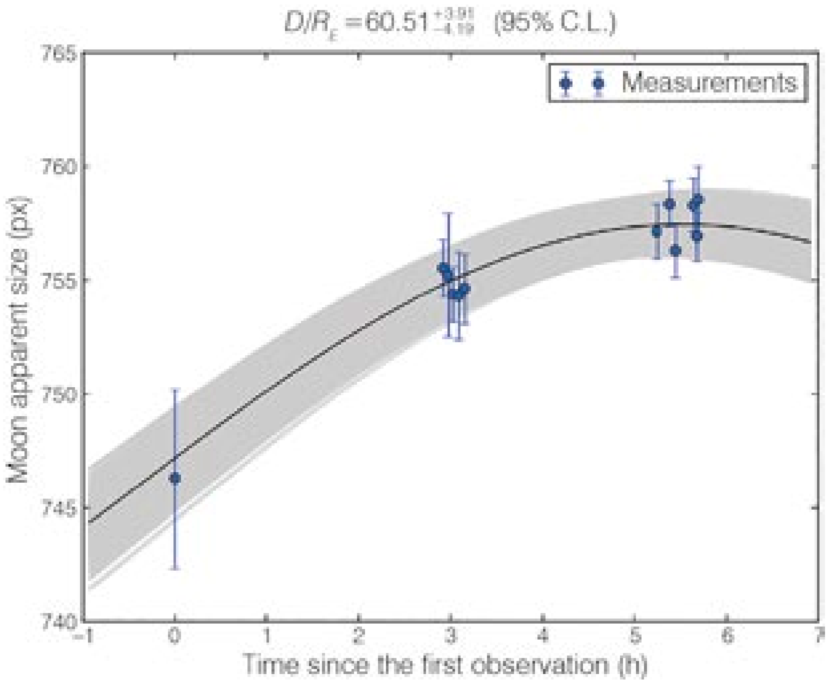


Figure 3. Best fit of the measured apparent sizes (data points) of the Moon compared to the theoretical model (continuous line). The shaded region corresponds to solutions statistically compatible with the observed apparent sizes at a 95% confidence level.

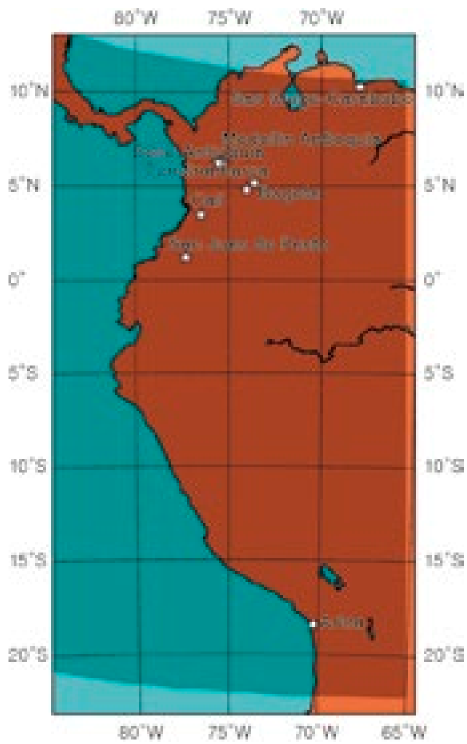


Figure 4. Locations of the observers who contributed to the 5 July 2014 Aristarchus Campaign for the occultation of Mars by the Moon. The shaded areas correspond to the region where the occultation was visible.

A simple method to measure the distance to the Moon

Although our perception seems to indicate that the Moon is larger, and thus closer, when it is just above the horizon, the reality is actually the opposite. The distance from the Moon to any observer on the surface of the Earth decreases as the Moon rises in the sky, although the distance from the Moon to the centre of the Earth remains approximately constant. In Figure 2 we show the cause of this nightly observer-Moon distance variation. Measuring the angular size of the Moon as a function of elevation provides an estimate of the lunar distance to the centre of the Earth.

Five specific observations and measurements were proposed for this campaign, to be executed during the lunar eclipse. The first — actually unrelated to the eclipse itself — invited people to take pictures of the full Moon from rising to culmination, when the Moon reaches its highest altitude in the sky. The aim of these measurements was to detect the subtle variation in the lunar disc size due to changes in the lunar distance that result from observations taken from different locations on the Earth's surface as the Moon rises, rather than at the centre of the Earth.

The second task involved taking pictures of the Moon before it entered the Earth's shadow and after it was completely eclipsed. The aim of this measurement was to evaluate the properties of the light refracted through the Earth's atmosphere.

The third task was to measure, as precisely as possible, the times of the eclipse contacts and the fourth was to photograph the partial eclipse with the shape and size of the Earth's shadow clearly visible.

The fifth and last task was to take a picture of the Moon and include in the same field of view as the star Spica and the planet Mars.

From the pictures that were taken and the measurements that were made we were able to determine the distance to the Moon with a fractional precision of 3% (ie to three parts in a hundred; see Figure 3), finding a value of 386 000 kilometres, fairly accurate when compared to the accepted value of 384 400 kilometres. (Zuluaga, 2014)

We discovered that the only information required to achieve this precision is the angular size of the lunar disc and the precise time when the disc size is measured. This constitutes the most simple and affordable way to measure the lunar distance and radius devised so far. The only instrument required to achieve this is a good camera.

Measuring the speed of light with an occultation of Mars by the Moon

On 5 July 2014 we had an occultation of Mars by the Moon that was visible from the northern part of South America (see Figure 4). This phenomenon provided a perfect opportunity for setting up an Aristarchus Campaign.

It is well known that when we observe an object in the sky, we see the object as it was in the past as light takes a finite amount of time to reach us. For bodies with a substantial apparent motion, like Solar System objects, whose position on the sky changes from day to day, the effect of this light travel time is a detectable difference between the position predicted without taking the light travel time into account and the observed position of the object in the sky.

During the occultation on 5 July 2014, light took approximately 8.5 minutes to reach us from Mars. On the same date the apparent motion of Mars was one arcsecond per minute and the apparent motion of the Moon was approximately 21 arcseconds per minute. To put the arcsecond unit into context, the Moon has an angular size of about 1800 arcseconds, or, in other words, it extends up 1800 arcseconds across the sky. Due to the time taken for the light from Mars to arrive at the Earth, its apparent position on the sky was almost 8.5 arcseconds off from the position calculated assuming that the light had arrived instantaneously (as shown in Figure 5) and the occultation took place 24 seconds later than expected. Using simple mathematics this meant that, by working out the difference between when we could expect the occultation to take place if the light travel time were zero, and when it was actually observed to take place, the speed of light could be calculated. For the Aristarchus Campaign we exploited this effect to measure the speed of light in a vacuum. Although this is a novel method it was inspired by the original method devised by Ole Rømer to measure the speed of light by looking at variations in the predicted times for the transits of Jupiter's moon Io.

For the campaign we asked participants to measure visually or photographically the contact times of the occultations in different locations across a wide geographic area. We gathered results from at least nine groups and individuals from Colombia, Venezuela and the north of Chile (see Figure 4). The joint analysis of the data provided by these groups, allowed us to determine the speed of light in vacuum as 320 180 kilometres per second, a value that, although inaccurate, is just 7% different from the value measured with more sophisticated methods. We show in Figure 6 the contact time delays measured by the participants and the theoretical delay expected for different values of the speed of light.

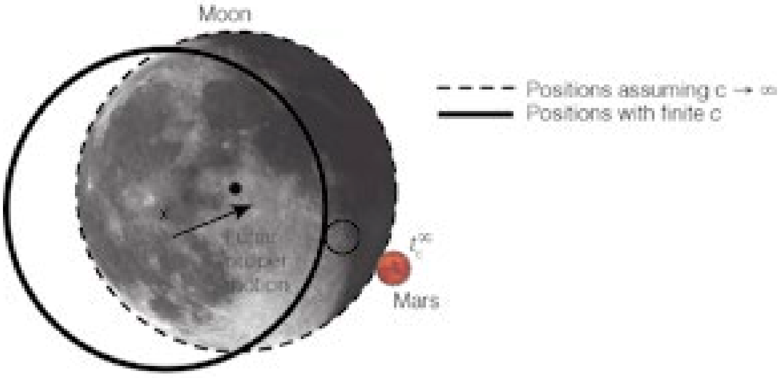


Figure 5. *Illustration comparing the positions of Mars and the Moon in the sky assuming an infinite speed of light (c) (dashed lines and photographic representations) and a finite speed of light (solid lines). The contact times for an infinite or finite speed of light are different. The solid lines show what we would observe. Sizes and apparent motion were exaggerated for illustration purposes.*

Acknowledgements

We want to thank all the friends and colleagues who supported the Aristarchus Campaigns by sharing information about the project via social networks and by encouraging people to participate in the observational campaign. We also thank our co-authors in the technical reports for sharing some of the results and figures presented in this paper. The Campaign is a project of the Sociedad Antioqueña de Astronomía (SAA) and the University of Antioquia. We thank both organisations for promoting and supporting these public initiatives. Jorge I. Zuluaga is funded by El Programa de Sostenibilidad de la Vicerrectoría de Docencia de la Universidad de Antioquia 2014-2015 and El Comité para el Desarrollo de la Investigación de la Universidad de Antioquia.

References

Barringer, D. et al. 2011, Earth and Space Science: Making Connections in Education and Public Outreach, 443, 373

Brown, P. G. et al. 2013, Nature, 503, 238

Cohen, B. 1940, Isis, 31, 327

Dickey, J. et al. 1994, Science 265, 482

Heath, T. 2013, *Aristarchus of Samos, the Ancient Copernicus: A History of Greek Astronomy to Aristarchus.* (Cambridge: Cambridge University Press)

Meech, K. J. et al. 2005, Science, 310, 265

Muhleman, Duane O. 1969, Monthly Notices of the Royal Astronomical Society 144, 151

Ortiz, J. L. et al. 2011, *The stellar occultation by Make on 2011 April 23*, EPSC-DPS Joint Meeting 2011, held 2–7 October 2011 in Nantes, France, 704. (Available online from: http://meetings.copernicus.org/epsc-dps2011)

Raddick, M. Jordan et al. 2010, *AGB Stars and Related Phenomenastro 2010: The Astronomy and Astrophysics Decadal Survey, 46P*, (Available online from: https://www.zotero.org/groups/creative_action_lab/items/itemKey/3MBC8ZXQ?fullsite=1

Salvador G. et al. 2009, Latin-American Journal of Physics Education, 3, 2, 329

Schou, J. et al. 1997, The Astrophysical Journal Letters 489, 2, 197

Sullivan, D. B. 2001, *A Century of Excellence in Measurements, Standards, and Technology,* (Florida: CRC Press) 191–193

Tapley, B. D. et al. 2004, Science 305, 503

Van Helden, A. 2010, *Measuring the universe: cosmic dimensions from Aristarchus to to Halley,* (Chicago: University of Chicago Press)

Zuluaga, Jorge I. et al. 2013, Submitted to Earth and Planetary Science Letters (EPSL) (arXiv:1303.1796)

Zuluaga, Jorge I. et al. 2014, submitted to American Journal of Physics (arXiv:1405.4580)

Notes

1. The simple web-based application developed to provide contact times for a given location inside the Mars occultation area is now publicly available at: http://github.com/facom/iContact
2. The official website of the project: http://saastronomia.org/campana-aristarco
3. Further details about the campaigns and the analysis or their results can be found in the technical reports available in the arXiv e-print repository: http://arxiv.org/abs/1405.4580 and: http://arxiv.org/abs/1506.00346

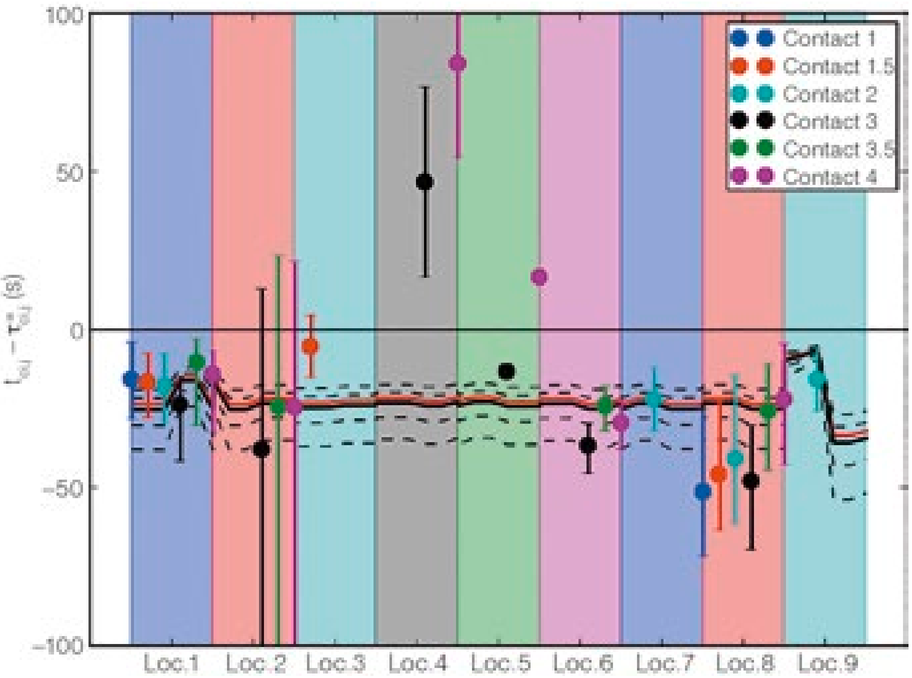


Figure 6. *The difference between the contact times measured at each location and the value expected if the speed of light was infinite. Dashed lines correspond to the expected contact time difference if the speed of light was (from bottom to top) 200 000; 250 000; 350 000 and 400 000 kilometres per second. The solid black line corresponds to the actual speed of light; 300 000 kilometres per second. The solid red line is the best-fit value obtained after excluding the most problematic measurements.*

Biography

Jorge I. Zuluaga is an associate professor at the Institute of Physics at the University of Antioquia, Colombia and a collaborator of the Harvard–Smithsonian Centre for Astrophysics. He is the founder of the undergraduate programme in astronomy at the University of Antioquia, the first of its kind in Colombia and the Andean region. Jorge has more than fifteen years of experience as a university lecturer in physics and astronomy and as a science communicator. His public talks have appeared on local television networks and his contributions to the development of astronomy in Colombia was recently recognised by the International Astronomical Union by naming asteroid 347940 with his name.

Juan C. Figueroa is a computer scientist with a bachelor's degree in Engineering from the Universidad EAFIT (jointly, the Escuela de Administración y Finanzas [School of Administration and Finance], or EAF and the Instituto Tecnológico [Institute of Technology] or IT) and is currently an undergraduate student of astronomy at the University of Antioquia. He recently completed the Diploma Course in Astronomy, a three-semester programme offered by the same University. Juan has fifteen years of experience as a software developer and ten years as a teacher of programming languages. His passion for astrophotography led him to participate actively as a contributor to the Aristarchus Campaigns and design of some of its experiments.