Cosmic ray shadowing

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Abstract

Cherenkov Telescope Array (CTA) is an initiative to build the next generation imaging atmospheric Cherenkov telescope (IACT) observatory. The CTA instrument will be capable to to detect electromagnetic air showers of high energies and it will provide additional capabilities to study the Cosmos. CTA will be able to study the composition of positrons and electrons of cosmic origin by measuring their spectra when they are deflected by the Moon due to the geomagnetic field. This work presents a summary of the concept of using IACTs to study electrons and positrons by measuring the shadow of the Moon, and the work to adapt a CTA telescope prototype to be capable of tracking that shadow. A Python module, which uses standard astronomical packages, has been written and provides the capability of determining the proper observation window as well as the implementation of the tracking of the Moon.

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1 Introduction

The Cherenkov Telescope Array or CTA is an international project to build a new generation ground-based gamma-ray instrument in the energy range extending from some tens of GeV to about 300 TeV. It is proposed as an open observatory and will consist of two arrays of Imaging Atmospheric Cherenkov telescopes (IACTs), a first array at the Northern Hemisphere (La Palma, Canary Islands, Spain) with emphasis on the study of extragalactic objects at the lowest possible energies, and a second array at the Southern Hemisphere (Atacama desert, Chile), which is to cover the full energy range and concentrate on galactic sources. The physics program of CTA goes beyond high energy astrophysics into cosmology and fundamental physics. A picture of the array is shown in Figure 1.

Figure 1: CTA array representation. The Large Size Telescopes are shown in this picture

An IACT records the picture of the short Cherenkov radiation flash produced by an extense air shower, which is, in turn, generated by a high energy gamma ray. This particle shower starts at a height of 10-20 km. The original gamma ray generates a pair electron-positron next to an air molecule. Each particle of this pair has a very high energy and they produce more gamma rays via a Bremsstrahlung process. Then, more pairs electron-positron are created, and so on, ending with a huge atmospheric shower. We will take a closer look at the Cherenkov emission in Chapter 2.

1.1 MST Prototype

The sensitivity in the core energy range of CTA will be dominated by up to 40 Medium-Sized Telescopes (MSTs). The MSTs are currently in the prototype phase. The telescope optics is based on a modified Davies-Cotton layout with a reflector diameter of 12 m, mirror focal length of 16 m and dish radius of curvature of 19.2 m. A full-size mechanical telescope structure has been assembled in Adlershof, Berlin, in order to test a design of the mechanical structure and drive system. The telescope is partially equipped with different mirror prototypes, which are currently being tested and evaluated for performances characteristics. This prototype doesn't have any PMT cameras. The main components of the telescope are shown in Figure 2.

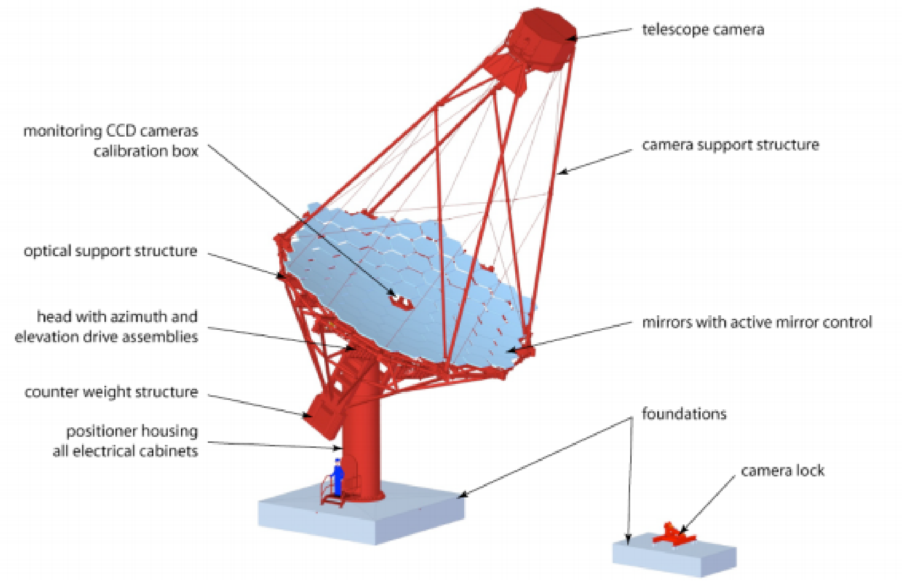

Figure 2: Components of the MST design

The tower of the MST has a cylindrical shape with a diameter of 1.8 m and a wall thickness of 20 mm. The azimuth bearing, installed on top of the tower, acts as the interface to the head and allows rotation along the horizontal axis. The elevation drive sub-assembly connects the head with the yokes and provides the rotation of the optical support structure in the vertical direction.

2 Cherenkov emission

The particle cascades in the atmosphere are produced by the high-energy cosmic radiation, which can consist e.g. of electrons, protons, atomic nuclei or gamma-rays. Propagation through the atmosphere of these particles can result under certain conditions in the Cherenkov radiation, which can be detected by telescopes at the ground, while the actual shower develops in the upper atmosphere. By collecting the Cherenkov radiation, one can reconstruct from shower events the information on the primary particle, such as energy and direction [6].

Most of the charged particles in an air shower emit Cherenkov radiation when they travel though the atmosphere. This light is emitted in a narrow cone around the direction of the particle. The angle θ between the particle track and the emission direction depends on the velocity $v = \beta c$ of the particle and the velocity of light $c' = c/n$ in the medium:

$$cos\theta = \frac{c'}{v} = \frac{1}{\beta n} \tag{1}$$

This implies that light emission can only take place if $\beta \geq 1/n$. This leads to a minimum energy of the particle needed to emit Cherenkov light:

$$E_{min} = \frac{mc^2}{\sqrt{1-\beta^2}} = \frac{mc^2}{\sqrt{1-n^{-2}}} \tag{2}$$

The mass dependence of E_{min} indicates that light particles like electrons dominate the Cherenkov light emission in air showers.

2.1 Frank-Tamm formula

The Frank-Tamm Formula gives the number of Cherenkov photons from a charged particle produced per wavelength interval and per travelled distance (above the energy threshold). If β is the speed of the particle in units of c and the medium's refractive index is n, we have:

$$\frac{dN}{dx} = 2\pi\alpha Z^2 \int_{\lambda_1}^{\lambda_2} \mathrm{d}\lambda \left(1 - \frac{1}{n(\lambda)^2\beta^2}\right) \lambda^{-2} \tag{3}$$

where $\alpha \simeq 1/137$ is the fine structure constant, Z is the charge of the (charged) particle, and λ is the wavelength.

As the density of air, and hence the refractive index, is not constant within the atmosphere, the energy threshold and the Cherenkov angle depend on the atmospheric altitude h. If one assume the atmosphere is isothermal, the barometric formula can be used:

$$n = n(h) = 1 + \eta_0 \cdot e^{-h/h_0} \tag{4}$$

with $\eta_0 = 2.9 \cdot 10^{-4}$ and $h_0 = 7.1\ km$.

2.2 Results

Using ROOT and atmospheric data[1] that are important for shower simulations, one can have some plots, which are shown in Figure 3.

[1] These parameters have been provided from a file and they depict the atmospheric conditions of HESS location in Namibia.

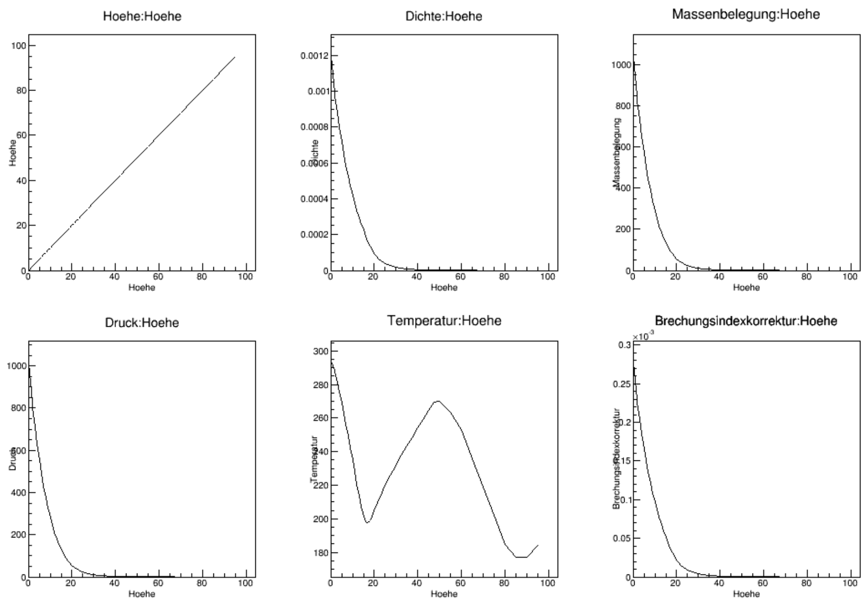

Figure 3: Diagrams representing the atmospheric data included in the model of the atmosphere used in this work: height (Hoehe), density (Dichte), column density (Massenbelegung), temperature (Temperatur), pressure (Druck) and refractive index correction (Brechungsindexkorrektur)

Then, one can do a simulation of the Cherenkov emission due to the propagation of a muon through the atmosphere, assuming that the azimuthal angle is random uniformly distributed. The results of this simulation are presented in Figure 4.

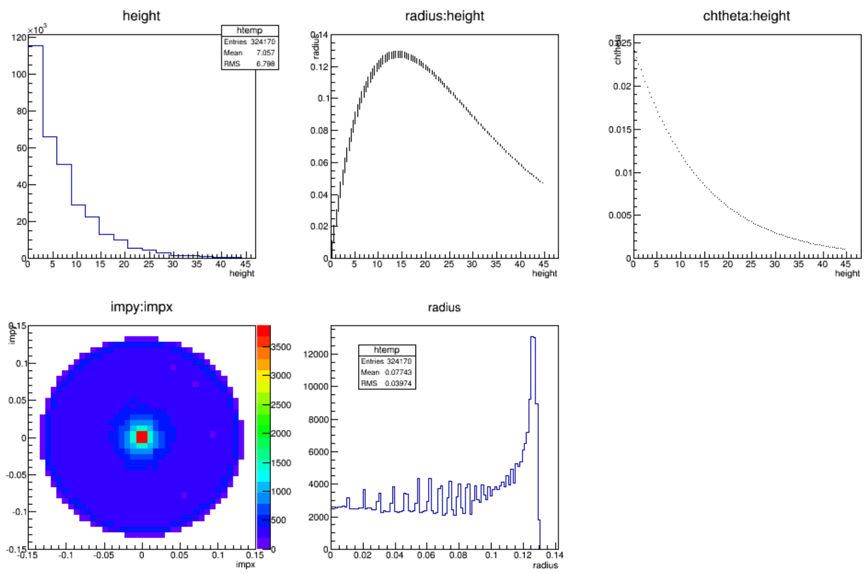

Figure 4: Muon shower simulation: Number of photons per height, radius on the ground, Cherenkov angle, radial distribution and photons per radius

3 Cosmic ray shadowing

3.1 Justification

The excess of positrons in cosmic rays above 10 GeV has been a puzzle since it was discovered. Possible interpretations of the excess have been suggested, including acceleration in a local supernova remnant or annihilation of dark matter particles. To discriminate between these scenarios, the positron fraction must be measured at higher energies. One technique to perform this measurement is using a technique called Earth-Moon spectrometer: observing the deflection of positron and electron Moon shadows by the Earth's magnetic field. The measurement has been attempted by previous imaging atmospheric Cherenkov telescopes without success. We can see the positron deficits in Figure 5.

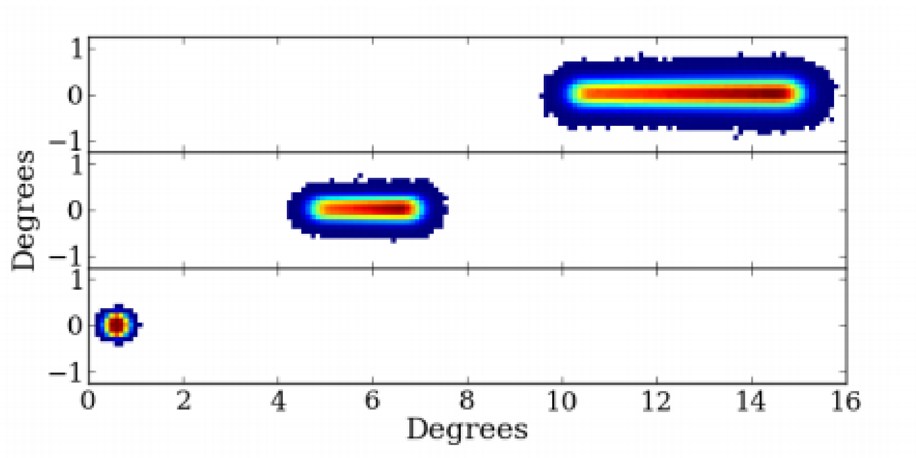

Figure 5: Position of the positron shadow for three different energy bins: 100-147 GeV on the top, 215-316 GeV in the middle and 2-3 TeV on the bottom. The origin is placed at the actual Moon location, and the axes indicate the angular distance

The Earth-Moon system forms a spectrometer where the Earth magnetosphere deflects the trajectory of any incoming particle depending on its charge and momentum (equivalent to its energy for an ultra-relativist particle) and the Moon creates a hole in the isotropic CR (cosmic ray) flux corresponding to the CRs which would go through the Moon to reach an observer on Earth.

The position of the CR-flux hole (Moon shadow) depends on the charge and energy of the particles. For neutral CRs (like diffuse γ rays), it lies at the actual Moon position. For charged CRs, the Moon shadow is shifted perpendicularly to the geomagnetic field along an axis close to an east-west orientation. Negative and positive CRs are shifted respectively eastward and westward. As most of the CRs are positive particles (atom nuclei), the all-CR Moon shadow is asymmetric with a larger deficit at the west side of the Moon.

3.2 Attempts

The first try to observe the Moon-shadow effect with IACT was performed in the 90's with the ARTEMIS experiment, which was using UV–filter (200−300 nm) to suppress most of the moonlight [4]. Unfortunately, the Cherenkov light of the air showers was strongly suppressed too, and the Moon shadow could not be detected.

Another attempt was made by the MAGIC collaboration [2]. MAGIC observed the shadow of the Moon in the 2010-2011 campaign, but because of bad weather, they were only able to collect less than 10 h per shadow, and no detection was possible. Actually, in realistic scenarios, MAGIC would need about 50 h to detect the e^- shadow and at least 100 h for the e^+ shadow [4]. This is longer than the available time per year (15 or 20 h for each shadow). With this observation strategy, MAGIC would need then several years for a significant detection.

Finally, VERITAS made its attempt too, but as in the case of MAGIC they did not managed to detect the shadow. This is something to be expected as to take tens of hours to detect either shadow (potentially hundreds for the positron shadow) and it would require a multiyear investment as a maximum of $15 - 20$ hours of observing time can be expected in any one year (even less with bad weather) [3].

3.3 Perspectives for CTA

CTA will have such an unprecedented sensitivity and background rejection that the expected e^- shadow detection time would decrease dramatically (< 5 h). In addition, the possibility of using silicon photomultipliers in some of the CTA telescopes could greatly increase the feasibility of making observations near the Moon [5]. Summing this up, the perspectives for CTA making these measurements successful for the first time are very promising.

4 Implementing Moon shadow observations for CTA

4.1 Coordinates transformation libraries

SOFA, Standards of Fundamental Astronomy, provides algorithms and software for use in astronomical computing [7]. The International Astronomical Union's SOFA service has the task of establishing and maintaining an accessible and authoritative set of algorithms and procedures that implement standard models used in fundamental astronomy.

ERFA, Essential Routines for Fundamental Astronomy, is a library derived and 'freed' from SOFA [8]. ERFA is a copy of the ANSI C version of the SOFA library but with "iau" removed from all function names and re-licensed to be compatible with typical Free/Open Source Software licenses (it is no longer read-only and therefore changes may be made by anyone). It has been produced by the AstroPy group.

4.2 Python libraries

The AstroPy package contains functions useful for professional astronomers and astrophysicists, as well as anyone developing astronomy software, and draws upon ERFA scripts [9]. The AstroPy Project is a community effort to develop a single core package for Astronomy in Python and foster interoperability between Python astronomy packages.

PyEphem [11] provides basic astronomical computations for the Python programming language. Given a date and location on the Earth's surface, it can compute the positions of the Sun and the Moon, of the planets and their moons, and of any asteroids, comets, or earth satellites whose orbital elements the user can provide. Additional functions are provided to compute the angular separation between two objects in the sky, to determine the constellation in which an object lies, and to find the times at which an object rises, transits, and sets on a particular day.

Currently, the MST prototype is working with the SLALIB library [12], CTA will likely setup ERFA as the standard library for coordinate transformations. One of the possibilities under study is using only AstroPy, but PyEphem might be also necessary, up to a point. At the moment and after comparing the functions used in AstroPy and SLALIB, we conclude that AstroPy is enough for the needs in the project. Table 1 shows the different arguments that SLALIB (`sla_AOP`) and AstroPy (`AltAz` and other classes and functions) need and their impact in the coordinate transformation calculations.

In AstroPy, the longitude, latitude and height of the observation place are given in the `EarthLocation` class. Besides, the function `transform_to` takes the right ascension and declination and the arguments from `AltAz` to give the altitude and azimuth.

Once given the parameters in AstroPy, changing them a little doesn't affect the result significantly. See below the impact of small changes of the parameters.

Original parameters
Temperature = 15.0 ^oC
Pressure = 1015.0 hPa
Relative humidity = 0.7
Observed wavelength = 0.5 μm

Temperature
Shift of 10 ^oC: Moon altitude changes in 0.0029 deg when the elevation is small (10 deg) and less at higher altitudes. Altitude is lower for larger temperature.

Pressure
Shift of 10 hPa: Moon altitude changes in 0.00080 deg when the elevation is small (10 deg) and less at higher altitudes. Altitude is larger for larger pressure.

Argument	AstroPy	Argument	SLALIB
obstime	time of observation	DATE	modified Julian date[5]
loc	`EarthLocation`	ELONGM PHIM	mean long, lat
pres	pressure	PMB	local atmospheric pressure
temp	ground-level	TDK	local ambient temperature
wl	average wavelength	WL	effective wavelength
$\star^1$ $\star^3$	-	DUT	ΔUT: UT1 - UTC
rel hum	relative_humidity	RH	local relative humidity
$\star^2$	-	TLR	tropospheric lapse rate rate at which atmospheric temperature decreases with an increase in altitude
height	`EarthLocation`	HM	height above sea level
$\star^1$ $\star^4$	-	XP, YP	polar motion (rad)[6]
-	`transform_to`	RAP, DAP	geocentric apparent ra, dec

Table 1: Analogies between SLALIB and AstroPy parameters needed to calculate the altitude and azimuth of the Moon

[1] Some coordinate frames such as `AltAz` require Earth rotation information (UT1-UTC offset and/or polar motion) when transforming to/from other frames. These Earth rotation values are automatically downloaded from the International Earth Rotation and Reference Systems (IERS) service when required. See IERS data access (astropy.utils.iers) for details of this process [10].

[2] The tropospheric lapse rate is not included as argument in ERFA, but AstroPy uses some default values because the authors have checked that the difference is negligible.

[3] The scale argument specifies the time scale for the values, e.g. UTC or TT or UT1. The scale argument is optional and defaults to UTC except for Time from epoch formats. In normal usage, UT1-UTC differences are calculated automatically on the first instance ut1 is needed. Besides, in all these scripts UTC is used so as not to be worried about timezones.

[4] The polar motion xp, yp can be obtained from IERS bulletins. The values are the coordinates (in radians) of the Celestial Intermediate Pole with respect to the International Terrestrial Reference System [13], measured along the meridians 0 and 90 deg west, respectively. For many applications, xp and yp can be set to zero. Internally, the polar motion is stored in a form rotated onto the local meridian.

[5] Slalib DATE - The DATE argument is a UTC instant expressed as an MJD. This is, strictly speaking, wrong, because of leap seconds. However, as long as the ΔUT and the UTC are consistent there are no difficulties, except during a leap second. In this case, the start of the 61st second of the final minute should begin a new MJD day and the old pre-leap ΔUT should continue to be used. As the 61st second completes, the MJD should revert to the start of the day as, simultaneously, the ΔUT changes by one second to its post-leap new value.

[6] Motion of the Earth's rotational axis relative to its crust. This is measured with respect to a reference frame in which the solid Earth is fixed (a so-called Earth-centered, Earth-fixed or ECEF reference frame). This variation is only a few meters.

Relative humidity
Shift of 0.3: Moon altitude changes in 0.000058 *deg* when the elevation is small (10 *deg*), which is completely negligible, and less at higher altitudes. Altitude is larger for lower humidity.

Observed wavelength
Shift of 0.1 μm: Moon altitude changes in 0.00058 *deg* when the elevation is small (10 *deg*) and less at higher altitudes.

4.3 Project and results

The project consisted of creating a Python module using the AstroPy library in order to track the Moon with the Cherenkov prototype located in Berlin and, when CTA be built, with the respective arrays, since this telescope is not able to track the Moon right now. The Python code can be used to decide which nights are the best to observe the Moon. Besides, it calculates the starting time and the ending time each proper night. It also retrieves the illumination of the Moon, its altitude and the altitude of the Sun, too. If the Moon is too bright, we aren't able to see the shadowing effect. Besides, it is easier to see it at higher altitudes.

The accuracy is very important because the maximum amount of time that the measurements can fail is two minutes per night. That's why the starting and ending time of observing calculated by the script have to be as much exact as possible. Moreover, the program allows the MST to track the Moon in real time operations, by giving the altitude and azimuth of the latter at each moment (and also the illumination if it is needed). Finally, we will insert and test the module in the real time control of the telescope (this scripts are already made) and see how it reacts to them, in order to make sure that no issue concerning delays and corrections on the position arise in the live operations.

The code is organized in three different classes and a set of scripts that use them. The classes are the following:

- `MoonPlan` can be used to create objects with the information of the Sun and the Moon. One needs to give some parameters at the beginning: place of observation and height above sea level, starting time, number of points in the interval, number of days (or minutes) in the interval, the average wavelength, and atmospheric parameters such as the pressure, the temperature and the relative humidity. The last ones can be fixed (small changes don't affect significantly the result, as we have shown when comparing ERFA and Slalib) or taken from a database. This class returns the altitude of the Sun and the altitude, azimuth and illumination of the Moon in each point of the interval, as well as the time interval itself.

- `MoonInterpolate` uses a small amount of data of the Moon position and illumination to interpolate and get more accurate values, and can show them in a text file.

- `MoonGraph` takes the Sun and Moon results and plots the scattered points and the interpolation lines. It can distinguish between days and nights, as shown in the Figures 6 and 7.

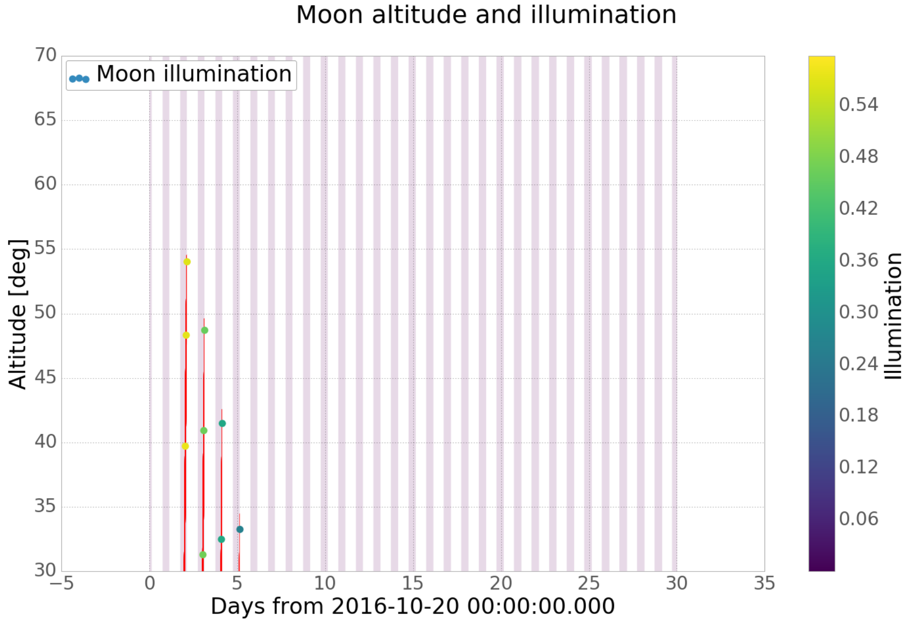

Figure 6: A plot of 30 days to plan the observations. The astronomical nights are indicated by the pink shadow; the colour of the scattered points indicates the illumination of the Moon

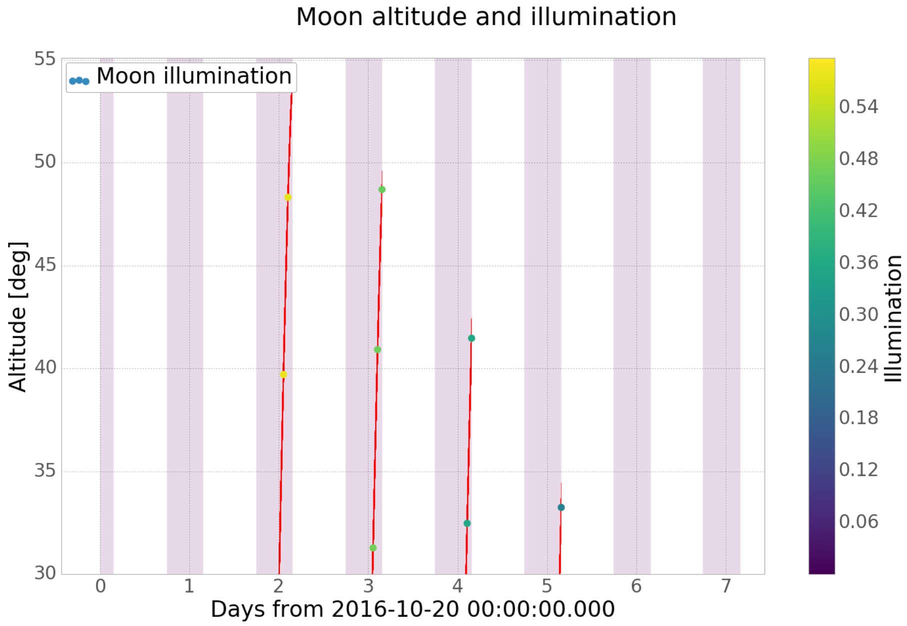

Figure 7: Zoom of the plot shown in Figure 6

This is a little example of what one gets when the text mode is chosen:

```
Date and time:  2016-10-22 00:07:08.114
Altitude:  30.0 deg
Illumination:  0.58
Date and time:  2016-10-22 03:49:30.971
Altitude:  54.4 deg
Illumination:  0.57
```

So, if the conditions are well defined, the user can determine with accuracy the time of starting and ending the observations if the night and Moon conditions are good enough.

Eclipses are not included yet in the module but it would be convenient to know if there is going to be one because in those cases one has the optimal conditions to observe.

5 Conclusions

This project enables a CTA telescope to track the shadow of the Moon and thus to study the spectra of cosmic positrons and electrons of cosmic origin when they are deflected by the Moon due to the Earth magnetosphere.

Since the observing nights can be fully planned and we can track the Moon with CTA, the next step would be trying to use the telescope to actually point the Moon and see how it works and how accurate it is so as to make the necessary changes. In the course of this study, we have realized that changing the atmospherical conditions a little bit doesn't affect the accuracy obtained in the coordinate transformation significantly.

This study has been used to give feedback to the Software Standards group of CTA. These scripts are also suitable to be used, with minimal modification, to track other objects of the Solar System such as the planets.

As stated before, it would be optimal to perform such a kind of study when a eclipse is going to occur, because these are the most favorable moments to observe.

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Besides, I want to thank the people who supported me from the distance.

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[7] http://www.iausofa.org/

[8] https://github.com/liberfa/erfa

[9] http://www.astropy.org/

[10] http://docs.astropy.org/en/stable/coordinates/

[11] http://rhodesmill.org/pyephem/

[12] http://star-www.rl.ac.uk/docs/sun67.htx/sun67.html (SLALIB)

[13] IERS Conventions (2003)