Site Search for the Cherenkov Telescope Array (CTA) based on satellite data analysis

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***Abstract*. The CTA consortium aims to build a ground-based gamma-ray observatory that will do the best possible science in the domain of high energy astrophysics. The location of this astronomical facility should be selected following some basic requirements related to latitude, altitude, atmospheric conditions, ground quality and local infrastructure. Before performing in-situ characterization of the different possible locations we use the available global satellite data in order to have a first description of atmosphere behavior on these locations. We present here the approaches taken for this analysis with corresponding data selection and tools development.**

***Keywords*: Satellite data, site characterization, Cherenkov Telescopes.**

I. INTRODUCTION

Motivated by the success of the Imaging Atmospheric Cherenkov Technique (IACT) on the detection of VHE γ-rays in the last 10 years, part of the astrophysics community decided to invest big efforts on building the next generation of VHE γ-ray ground-based detectors. Some of these efforts are oriented to the conception of an array of Cherenkov Telescopes (CTA) which will work as an astronomical facility, open to the scientific community. This array would contain a large number of telescopes of different sizes and placed with different patterns in order to provide a wide and uniform energy coverage from $\sim$ 10 GeV to beyond 100 TeV with a better angular resolution. This observatory will consist of two arrays: a southern hemisphere array, which will cover the full energy range allowing a deep investigation of galactic sources; and a northern hemisphere array, consisting of low energy instrumentation (from $\sim$10 GeV to 1 TeV) which will be dedicated mainly to northern extragalactic objects. The observatory, with its two sites, will be operated by one single consortium[1]. This consortium is nowadays performing a Design Study for the optimization of the performance of the planned observatory and to study its implementation. Within these studies the search of possible sites for both arrays is one of the main tasks. In this paper we are presenting the analysis performed with the available satellite data for a first and worldwide site characterization. In Section II we present the basic requirements demanded for the sites based on the best environmental conditions for the atmospheric Cherenkov light detection. The next Section (III) is dedicated to a brief description of philosophy chosen for the site search task. In this section we also show how the satellite data can be used for this purpose. Section IV resume the compilation process followed in order to get the most valuable information from the current available data. Finally, we discuss our current possibilities and perspectives on section V.

II. SELECTION CRITERIA

The requirements on the sites for air Cherenkov telescopes are wide but he most important are: 1) Height: higher than the inversion layer of atmosphere; i. e. higher than 1500m. The upper limit is still unset but MC simulations [2] show that is not worthy going higher than 4000m. 2) Flat area : 3×3 km^2 is desirable for the installation of the telescope array. 3) Cloud coverage: as small as possible (good nights $>$ 70 %) to operate the telescope in high efficiency through the year. 4) Atmosphere: transparent, dry and quite in general (low aerosol content, reasonable relative humidity and wind speed). 5) Light pollution: $>$1.5 times the site of the currently working Cherenkov telescopes. 6) Latitude of two sites: around +30° north and -30° south to cover all sky by two facilities with some overlap.

There are many other (non-atmospheric) geophysical and geo-political important factors involved on site selection for Cherenkov Telescopes, such as soil and rock topologies, accessibility to infrastructure or nearby facilities, as well as many other cultural, sociological and political issues but these are not treated on this paper. Some of the points given above can be studied by means of satellite data analysis while others require some local measurements and monitoring. In principle, we can determine the behavior of parameters 1), 2), 3),4) and 5) through satellite data, climatological models and combined ground data.

III. SEARCH METHODOLOGY

It was decided to develop our search for sites in two different steps. The first one would consist on a

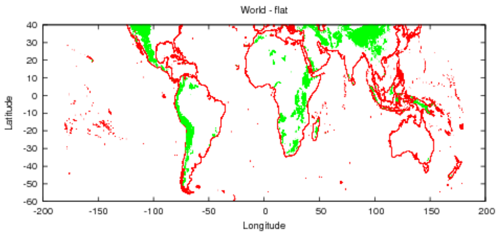

Fig. 1: World map showing the areas (in green) which fulfill two conditions: elevation higher than 1500m and flat area (difference in height between neighbors pixels < 50m) of about 1km^2. This map was produced using the Digital Elevation Model of the Earth given in [15] with a precision of 1km.

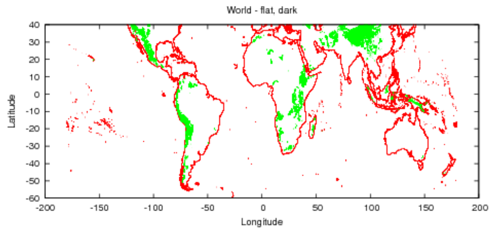

Fig. 2: World map showing the areas (in green)which fulfill the two same conditions as Figure 1 with the additional condition of low light pollution in the area. The light contamination information was taken from [6].

general determination of the possible sites based on the most basic selection criteria, as it would be the latitude, altitude and extension of the flat area needed (see Figure 1 and Figure 2). For the world portions passing these criteria, we intend to make a compilation of the satellite data available together with the existing studies developed by other observatories site survey. In this part of the work we look for high quality satellite data which should meet some requirements detailed together with long term re-analyzed data and precise climatological evolution models. The combination of the satellite data with simultaneous ground measurements, when available, will give another security check to our task.

The second part will consist on the development of ground measurements campaigns on the reduced site list coming from the first stage. We intend to monitor the chosen sites for about 6 months before having the final decision. The organization of this second stage is out of the scope of this paper.

A. Satellite's Data: basic requirements

There are several satellite monitoring the terrestrial atmosphere with much or less precision for different time periods. The data from these satellites have also different degrees of accessibility depending on the instrument ownership and purpose. For us, the important information is related to cloud coverage, relative humidity, temperature, wind speed and aerosol content. We need climatological databases actualized and covering the bigger time interval possible. Nowadays there are also available some long-term ($\sim$40 years) global climatological data sets known as "re-analyses". Re-analyses are reconstructions of past weather conditions using the state-of-the-art data assimilation and numerical weather prediction models of today. These models can also predict the climatological changes in the next 40 years together with the geographical changes expected.

There are hundreds of satellite watching the Earth with different sensors but only some of them can produce data useful for the sites characterization. The basic requirements demanded for the data compilation in our case can be summarized in four: 1) Spatial Resolution: this is defined as the capacity to distinguish between two very near objets in one image. It depends essentially on the Field of View (FoV) of the instrument, the orbit height and the sensor viewing angle. 2) Spectral Resolution: the wavelength bands of the electromagnetic spectrum covered by the sensors installed on the satellite should be compatible with the future detector sensibility range. 3) Temporal Resolution: is given by how many times the data is retrieved for the same area. This could vary from some hours to several days. 4) Radiometric Resolution: is the sensitivity the sensor has for recording variations in the electromagnetic spectrum. Higher values mean that more subtle changes in the image can be detected.

IV. Data Compilation and analysis

In this section we show the result of our compilation of data and analysis tools already available. We intend to use this material for the future determination of few candidates sites for CTA. For the moment we only present our first approach to this data. Even though we're developing our own search methodology, we study the limitations and advantages of the tools already developed through some concrete applications. Our attention is focus, in this stage, on cloud fraction, aerosol content, humidity, wind speed and weather fluctuations.

A. MODIS (Moderate Resolution Imaging Spectroradiometer)

The first set of data chosen, especially for the cloud coverage analysis, is from MODIS instrument [3]. This choice was based on its spatial and time resolution and its accessibility. The MODIS instrument is operating on both the Terra and Aqua spacecrafts. It has a viewing swath width of 2,330km and views the entire surface of the Earth every one to two days with a $\pm 55°$ scanning pattern with an orbit of 705km. Its detectors measure 36 spectral bands and acquire data at three spatial resolutions: 250m, 500m, and 1,000m. Different levels of data are provided in [3], but the useful level for us is the second which content the "raw" scientific data related to aerosols, water vapor, cloud fraction and atmosphere parameters. Analyzing a given period of time and a given location is possible in this context. Different kind

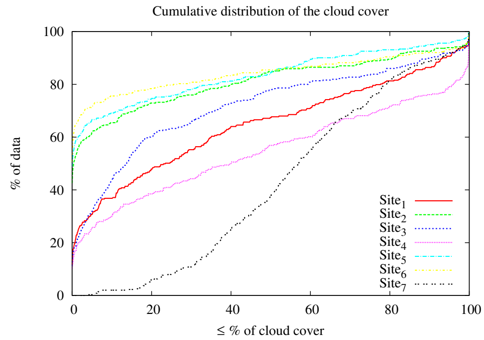

Fig. 3: Cumulative distribution of the night cloud coverage in different places over the world. This represents the percentage of nights with a given percentage of clouds.

of analysis can be performed, as regarding the time variation of a given variable or its standard deviation. We can also calculate the number of nights with a given percentage of clouds. An example of this type of analysis can be seen on Figure 3. For this figure we selected one year of MODIS only-night cloud coverage data for seven different places and we calculated the cumulative distribution of the cloud coverage for each. The origin ordinate gives us the percentage of clear nights per year for a given location.

B. ISCCP (The International Satellite Cloud Climatology Project)

Another available resource on cloud coverage analysis of the sites is The International Satellite Cloud Climatology Project(ISCCP). This was established (as part of the World Climate Research Program (WCRP) [5]) to collect weather satellite radiance measurements and to analyze them to infer the global distribution of clouds, their properties, and their diurnal, seasonal and inter-annual variations. Data are collected from the suite of weather satellites operated by several nations and processed by several groups in government agencies, laboratories, and universities. The cloud data provided by ISCCP has a spatial resolution of 30km, with a 3hrs time resolution and it corresponds to single satellites.

C. ERA-40 and ERA-Interim database

ERA-40 is a reanalysis of the global atmosphere and surface conditions for 45 years, from September 1957 through August 2002 by ECMWF [7],[8]. Many sources of meteorological observations were used, including radiosondes, balloons, aircraft, buoyes, satellites, scatterometers. This data was run through the ECMWF computer model at a 40km resolution. The new reanalysis project ERA-Interim is un update of ERA-40 in which the 1989-2007 period data was included with a spatial resolution of 1.5°. It contains almost the same information as ERA-40 and it follows the same reanalysis philosophy with only few improvements. For more information see [9]. We can ask for daily, monthly means and and monthly means of daily means data. It is also possible to have the information at different vertical levels.

D. Global 30 Arc-Second Elevation (GTOPO30), USGS

Global 30 Arc-Second Elevation Data Set (GTOPO30) is a global raster Digital Elevation Model (DEM) with a horizontal grid spacing of 30 arc seconds (∼1km)[15]. GTOPO30 was derived from a variety of raster and vector sources. The data is expressed in geographic coordinates (lat./long.) and is referenced to the World Geodetic Survey (WGS) system of 1984 (WGS84). The files are available in generic binary format and are distributed in the net. This database is used to select sites by its altitude and its flatness.

E. TOMS

The TOMS sensor was operational on three different satellites between 1979 and 2005 (NIMBUS-7, ADEOS and EARTH-PROBE). Since 2005, the new Ozone Monitoring Instrument (OMI) has replaced the TOMS record for aerosol, total ozone and other atmospheric chemistry measurements. While the TOMS spectrometer was not initially designed to measure aerosols, the capability of the instrument to detect desert dust and carbonaceous aerosols, as a by-product of the TOMS ozone algorithm, has been shown by [16]. The Aerosol Index (AI) is a measure of how much backscattered UV light from an atmosphere containing aerosols (resulting from a combination of Mie and Rayleigh scattering and absorption) differs from that of an atmosphere consisting of pure Rayleigh scattering. The Aerosol Index is available from TOMS for all latitudes between -60°S and 60°N.

F. FriOWL

FriOWL is a site-selection tool for large telescope projects developed jointly by the European Southern Observatory (ESO; Garching, Germany) and the University of Fribourg (Switzerland) [11]. This tool is a combination of a large database of global long-term climate data and a graphical user interface application software. The climatological database is composed largely of mean monthly ERA-40 and NCEP-NCAR re-analyses data [10]. The software has the ability to interact with the database in the style of a Geographical Information System (GIS), by using a range of overlaying, re-sampling, reclassifying, weighting, adding and other data-layer manipulation functions. It's also possible to create time series of the monthly means of different parameters and achieve the minimum, maximum and standard deviation of the variable in study. This give the possibility of making weighted composite global maps showing all locations which would meet a set of criteria defined by the user. Finally, this tool has also the flexibility of accepting new entries to its database adapting them to its format. In Figure 4 we present the time evolution of the monthly average Total Column of Precipitable Water Vapor calculated with FriOWL for 2006 and 4 different places.

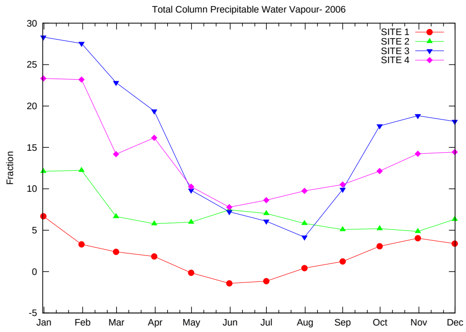

Fig. 4: Time evolution of monthly average Total Column of Precipitable Water Vapor for different locations for 2006. This figure was made using the ERA-40 re-analyses database and the software FriOWL with a pixel size of 2.5° × 2.5°.

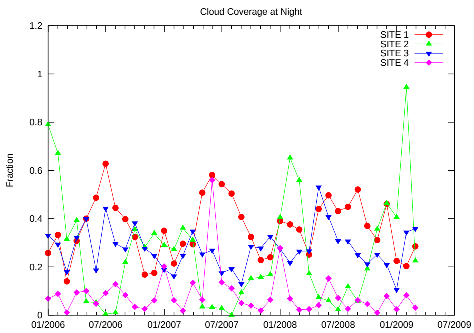

Fig. 5: Time evolution of monthly mean cloud coverage (at night) for different locations, from 2006 to 2009. This figure was made using Giovanni tool and MODIS data level 3 with a pixel size of 1° × 1°.

G. Giovanni

Giovanni is a Web-based application developed by the GES-DISC(Goddard Earth Sciences Data and Information Services Center) that provides a simple and intuitive way to visualize, analyze, and access vast amounts of Earth science remote sensing data without having to download the data [14]. Giovanni is an acronym for the GES-DISC Interactive Online Visualization ANd aNalysis Infrastructure. It is comprised of a number of interfaces, each tailored to meet the needs of specific fields of Earth science research. Each interface provides functions and parameters applicable to that specific area of Earth science. We can generate plots or ASCII outputs for Lat/Lon maps, time series, Hovmoller diagrams, scatter plots, and Correlation maps. Only level 3 MODIS data can be visualize with Giovanni with a spatial resolution is of 1°.

H. HDFLook

HDFLook-MODIS is a multi functional data processing and visualization tool for land, ocean and atmosphere MODIS data [12], [13]. This tool allows the access and visualization of all swath (levels 1-2) and gridded (levels 3-4) MODIS radiometric and geo-location, atmosphere, land, and ocean products. Its other capabilities are: re-mapping of swath data to world map, geo-projection conversion, re-projection of the initial projection into several pre defined selection, production of enhanced false and true color (RGB) images with map grid overlays, data conversion from scaled quantities to physical units and format conversion (HDF-EOS to ASCII, Binary, JPEG).

V. Discussion and Perspectives

We presented here a summary of the data search and analysis tool development for a preliminary site characterization for CTA. Tons of data are available and our goal is to get the most useful one to have a global view of the possible sites. There are also several web-based tools available for visualization and data-management. We consider that temporal evolution of averaged variables in different sites is one key-point for this search, together with the study of their short and long term fluctuations. At the other hand, the results obtained by the analysis of satellite data should be compatible with on-situ measurements in order to be used confidently for a world wide search. That's why the next step in our study will be the comparison between ground and satellite data, beginning with astronomical sites which are extensively monitored. With MODIS data we have a spatial resolution compatible with CTA size and two values per night per site, covering a time period long enough for the long-term studies. With the re-analysis data and the climatological models is possible to have also predictions for the next years. The final goal of our work is to have a precise, trustable and flexible set of tools which will allow to systematize the search of sites for Cherenkov Telescopes.

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