Characterization of Potential U.S. Sites for the Cherenkov Telescope Array

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Abstract: The Cherenkov Telescope Array (CTA) is a major ground-based observatory proposed for gamma-ray astronomy. CTA is envisioned to consist of two large arrays of atmospheric Cherenkov telescopes for the study of sources of high-energy gamma rays in the energy range of a few tens of GeV to beyond 100 TeV. One array would be located in the southern hemisphere and one in the northern hemisphere. After a detailed search, we have identified two potential sites in the USA for the northern array. Both sites are located in northern Arizona. Here we describe the two sites and the deployment of instrumentation to characterize them. The characteristics of the sites, in terms of their atmospheric and climatic properties, are described. We show recent data from the automated monitoring equipment at the sites and compare these data to a commercial simulation. Details regarding the facilities and infrastructure required for the sites are also presented.

Keywords: CTA, sites, atmospheric Cherenkov telescopes, VHE gamma-ray astronomy

1 Introduction

The Cherenkov Telescope Array (CTA) is an international consortium of 27 countries and approximately 1,000 scientists working to build the next generation gamma-ray observatory using the atmospheric Cherenkov technique and improving by a factor of ten the sensitivity of ground-based facilities for very high energy (VHE) gamma-ray astronomy. CTA will comprise two arrays, one in each hemisphere. Essential physical characteristics of the sites include 1 km\textsuperscript{2} of relatively flat land (with < 8% grade across the entire area) and elevation > 1500 m. The standard CTA atmospheric monitoring station, the ATMOSCOPE, has been installed at each site since June, 2012.

The US team of CTA has identified two sites in Arizona as candidates for the northern hemisphere array. Land in Arizona has a variety of ownership types (private, State, US national forest, and Native American reservation). The proposed CTA sites are both on 1.6 km x 1.6 km square sections of privately owned land, which allows maximum ease and promptness of leasing and permitting. Figure 1 shows maps of the sites, illustrating the checkerboard pattern of land ownership prevalent in Arizona. White sections are privately owned.

2 The Arizona Sites

The Arizona East site is located 3 km from Meteor Crater and 65 km from the city of Flagstaff (pop. 65,500). The site is almost completely flat and treeless, and it lies at an elevation of 1,677 m. One of the US four-lane national highways, Interstate 40, is 6 km north and the main line of the Burlington Northern Santa Fe railroad is 1 km farther north of the proposed site.

The Arizona West site is located on the Yavapai Ranch, 25 km south of the town of Seligman, AZ (pop. 400), at an elevation of 1,670 m. Vegetation at the site is the low juniper pine and pinyon pine characteristic of this elevation in Arizona. This site is less flat than Arizona east but remains well within the CTA requirements.

Figure 1: Maps of the sites. Left: Arizona East, near Meteor Crater. The four-lane Interstate 40 is the blue line, 6 km north of the site (red square). Right: Arizona West, 25 km south of the small town of Seligman, AZ, on Interstate 40. Green sections of land are the Prescott National Forest. The US team investigated sites 1 and 11 as indicated by the red squares. Site 11 (upper square) is the proposed one for CTA.

The sites are reasonably close to Flagstaff, requiring either a 50-minute (Arizona East) or a 1 hour 45 minute (Arizona West) drive to reach. Lowell Observatory, which could serve as the local managing and scientific partner for the CTA, is sited in Flagstaff and permanent CTA employees would likely be based there.

3 Meteorological and Atmospheric Characteristics of the Sites

3.1 General Characteristics

Both sites have decades to over 100 years of meteorological records in place. All significant variables (temperature, humidity, wind, and natural hazards) in the historical record are within the CTA survivability requirements and within the operating requirements for a high fraction of the time. Data from the CTA ATMOSCOPEs also show no episodes of weather outside the requirements as well.
Figure 2: Photographs of the sites. Left: Arizona East, with the lip of Meteor Crater in the distance. Right: Arizona West. The CTA ATMOSCOPEs are visible in each fenced enclosure, as are the 30-m (left) and 12-m (right) anemometer towers.

Table 1: Long-term average climate values for the proposed Arizona sites. The duration of climatic records for the Arizona E(W) site is 118(20) years.

| Quantity       | Arizona E | Arizona W |
|----------------|-----------|-----------|
| Ave max temp   | -34.2 °C (Jul) | 33.3 °C (Jul) |
| Ave min temp   | -6.8 °C (Jan)  | -7.5 °C (Dec)  |
| Ave precipitation | 19.3 cm/yr   | 33.2 cm/yr   |
| Ave snowfall   | 28.2 cm/yr  | 13.0 cm/yr  |

3.2 Night Sky Background

In addition to the ATMOSCOPE measurements, we commissioned sky brightness measurements from the US National Park Service. An example of the results is given in Figure 3, showing the all-sky image for the Meteor Crater site. This is a V-band image of the entire sky taken at the Arizona East site in September 2012. The light domes from nearby communities are on the horizon and none encroach on the CTA operational field of view > 30 degrees above the horizon.

3.3 Studies using the CTA ATMOSCOPEs

To precisely characterize the meteorological and observational conditions at the CTA candidate sites, self-contained devices, dubbed ATMOSCOPEs, were installed at both the Meteor Crater and Yavapai Ranch locations in northern Arizona. The ATMOSCOPEs consist of a number of instruments that measure wind speed, wind direction, temperature, relative humidity, atmospheric pressure, night sky background light, and cloud cover. The ATMOSCOPEs were installed at both sites at the end of June, 2012 and have been operating nearly continuously since that time. Additional instrumentation for each ATMOSCOPE (the all-sky camera and Sky Quality Monitor) were installed in September 2012. At that same time, two mirrors of the VERITAS design were installed at the Arizona East site to study the effects of weathering at the site. These mirrors were placed on the tower, 8 m above the ground and oriented facing north and south. Some details about the ATMOSCOPEs and the various instruments can be found in [1].

During the nearly full year of ATMOSCOPE operation at the Arizona sites, detailed information on the environmental conditions (wind, temperature, humidity) have been acquired and analyzed. Of particular interest are the wind speeds. It was found that average wind speeds have a strong correlation with the time of day, being significantly higher during the day than at night. Figure 4 shows the average wind speed versus hour of the day for both CTA candidate sites in Arizona.

While the ATMOSCOPEs have provided very detailed information since their installation, estimating the suitability of the sites for the 10+ years of the CTA experiment’s presumed lifetime calls for an understanding of the longer-term trends. In addition to the long-term weather records mentioned previously, retrodictions of environmental conditions at the CTA candidate sites have been obtained from weather simulations carried out by a private company (SENES) (see [1]). Correlation studies with simultaneous ATMOSCOPE and weather simulation data have been performed and the results from these studies give us a picture of the long-term weather patterns.

As an example, Figure 5 shows the correlation between the temperature as recorded by the ATMOSCOPE and the prediction of the simulation for the Arizona East site. The data are essentially simultaneous (i.e. within one hour overlap, the time resolution for the SENES study). As can be seen, the correlation is relatively good with a moderate amount of spread. On the other hand, Figure 6 shows the comparison for the wind speed at the same site. Here it is clear that the observation overestimates the wind speed. Thus a correction factor (that varies with wind speed) is needed in order to correctly use the simulation to estimate, for example, the fraction of time when the wind speed is expected to be above the CTA operational requirement.

To quantify the darkness of the night sky at the candidate CTA sites, two devices are employed in the ATMOSCOPE [2]. One is the Sky Quality Monitor (SQM) which
Figure 5: Comparison of the temperature as measured by the ATMOSCOPE and the temperature predicted by the simulation (SENES) at the Arizona East site. The red line (and associated inset) gives a linear fit to these data. These data come from the period between late June 2012 and early March 2013.

is a commercial device produced by Unihedron. It utilizes a TSL237 photodiode and a temperature sensor to provide a measure of the night sky brightness in mag/arcsec². It has a claimed precision of ±10% (±0.10 mag/arcsec²). The spectral responsivity of photodiode is quite broad, extending from 300 nm to 1100 nm with the peak responsivity at ~ 700 nm. This broad spectral response makes it a less-than-ideal instrument for measuring the night sky background relevant for atmospheric Cherenkov telescopes. The second device on the ATMOSCOPE used to measure the night sky background is the Light of Night Sky (LoNS) device. The key elements of the LoNS are a Hamamatsu 3584 PIN-photodiode and a filter wheel which includes a V-band filter and a custom "B" filter made from a combination of Schott BG25 and BG39 filters - meant to emulate the response of a photomultiplier tube. The data from the LoNS is the current measured from the photodiode (in pA).

In order to validate the night sky background measurements and to try to establish a conversion between LoNS photodiode current (in pA) and night sky background light (in mag/arcsec²), the correlation between the LoNS "B"-filter photodiode current and the SQM measurement was investigated. This procedure was also used for the LoNS V-band filter. The correlation scatter plot (LoNS "B" vs. SQM) and unbinned fit are shown in Figure 7. Based on the definition of magnitude, one expects the correlation to follow the function $\text{SQM} = a \log(10(\text{LoNS})) + b$ where $a = -2.5$. Due to the difference in spectral response and fields of view (SQM FWHM ~ 20⁰, LoNS FWHM ~ 40⁰), the theoretical correlation is not seen in either the "B" or V-band LoNS filters. However, the relatively tight correlation does allow for a conversion from narrow-band LoNS current measurements to broadband measure of the night sky background in mag/arcsec². We find that the ATMOSCOPE estimates for the night sky background levels at both sites agree with those determined by photometric techniques and carried out by the US National Park Service (see, e.g., Figure 3).

4 Facilities and Infrastructure

Both sites offer easy access and convenient infrastructure development. A modern, four-lane highway runs to within 7 km of AZ East and 25 km of AZ West, with either paved or good dirt roads coming to within a few kilometers of the sites. Electric substations operated by Arizona Public Service (APS) are nearby (within about 8 km for the East site). Wells are available at both sites for water, and internet connectivity up to 1 Gbps is available with high-speed microwave connections using either direct or 1-hop lines of sight to mountaintop towers near Flagstaff.

Nearby support facilities are excellent. Flagstaff has a modern airport with a 2,700 m runway and instrument landing system, and both Phoenix Sky Harbor International Airport and Las Vegas McCarran International Airport are 3-4 hour drives from the sites. Flagstaff Medical Center is a 267-bed, Level 1 Trauma Center facility equipped to handle any medical emergency and it is served by an air transport service that can reach the hospital from Arizona East in 15 minutes and from Arizona West in 35 minutes. Most permanent CTA personnel would likely be based in Flagstaff.

5 Conclusions

After a search of possible locations in the United States for the northern site of the Cherenkov Telescope Array, we have identify two sites in northern Arizona that fully satisfy all CTA requirements. Here we provide some of
Figure 7: Comparison of the night sky light conditions as measured by the SQM device (Sky Quality Monitor, see text for details) and the LoNS device (Light of Night Sky, see text for details), both incorporated into the CTA ATMOSCOPE. The fit to the data, shown by the black curve, is described in the text.

the general characteristics for the sites, including typical meteorological conditions, night sky background levels, and available facilities and infrastructure. Results from the CTA ATMOSCOPE monitoring stations are shown, including initial comparisons between weather conditions measured by the ATMOSCOPE and those predicted by a commercial simulation. These comparisons give us some confidence in the ability of the simulation to estimate the weather conditions over a longer period of time.

Acknowledgment: We gratefully acknowledge support from the agencies and organizations listed in this page: http://www.cta-observatory.org/?q=node/22. This work was carried out, in part, with support from the US National Science Foundation, from the University of California and from the Economic Collaborative of Northern Arizona (ECoNA). We are grateful for the assistance of Judy Prosser and Fred Ruskin.

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