Determining the Requirements for the Star Tracker on JEM-EUSO

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Abstract:

This work will focus on how the JEM-EUSO project, which orbits around Earth on the International Space Station and whose purpose is to detect air shower from the atmosphere caused by high energy particles from outer space, will be able to determine its positon once it detects such air shower. This is best done by adding a star tracker to it. The main purpose is to determine how accurate the star tracker has to be. To do this a few calculations were made, as well as looking for any star trackers that may fulfill the requirements. The report will start with an introduction that consists of the air shower phenomenon itself, followed by the objective, the calculations and the results of the calculations. This is then followed by a small discussion and a conclusion.

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1 Introduction

1.1 Background

One thing that has been bugging scientists is the high energy particles that come from space into the Earth atmosphere. These particles, with energies of 10^{18}-10^{20} eV, are many orders of magnitude higher than what have been achieved at LHC. The most famous one would be the “Oh My God-particle”, which was detected on 15 October 1991, with an energy of $3.2 \cdot 10^{20}$ eV. This means that if the particle is a proton, that it had a velocity so high that, if it were to race with a photon, it would over a year, only fall behind 46 nanometers. [1]

How do these particles achieve such velocities? That’s what the JEM-EUSO project is made to find out. By detecting the trace of such particles, it will be able to determine where these particles possibly could come from, thus maybe find out what kind of phenomena that can accelerate particles to such velocities.

1.2 Theory

1.2.1 Cosmic Radiation

Cosmic radiation can be seen as a collection of photons and various particles that are emitted from various sources from outer space, like a background noise from space. Cosmic rays were first discovered in August 1912 when Victor Hess conducted a balloon experiment with a purpose to determine how much the radiation from earth dropped as the altitude was increasing. Instead, he discovered that the radiation increased with altitude, which was surprising. He made the conclusion that this radiation had to come from outer space. [2][3]

Cosmic rays mainly consist of nuclei from the two most common elements in the universe, i.e. protons (90%) and alpha particles (9%), the rest could be heavier nuclei, beta particles or other particles. [4]

Cosmic rays have a very wide range of energies stretching over 13 orders of magnitude, from 10^8 eV to 10^{21} eV, though the upper can, however still be discussed since there may be particles with higher energies that could be extremely rare. Particles with energies below 10^8 eV are blocked by the Earth’s magnetic field and can therefore not be detected below the atmosphere. The intensity of these particles will of course drop as the energy is increased, from 200 counts per m^2 per second for the lowest energies to less than 1 count per km^2 per century for the highest energies.

Cosmic rays with energies above 10^{18} eV are called Ultra-High-Energy Cosmic Ray (UHECR), while Extreme-Energy Cosmic Rays (EECR) are cosmic rays with energies above $5 \cdot 10^{19}$ eV. It is this part of the energy spectra that is interesting for this project. [5]

1.2.2 Cosmic Ray Air Showers

When UHECRs reach the atmosphere, they will interact with atoms (most likely nitrogen or oxygen) in the atmosphere. Due to their high energies, the collision creates a large quantity and variety of subatomic particles; some of these particles will still have very high energies, and may interact with other atoms deeper in the atmosphere creating new collections of particles. This will go on as long as the created particles have high enough energy, ending up with a large swarm of various particles in the atmosphere. This is called an air shower, the size of an air shower will of course depend on the energy of the incident particle since there will be energy losses with each collision. An Extensive Air Shower (EAS) is created if the incident particle belongs to the EECR group.

The area where new collisions no longer will create new particles is called a shower maximum, since the concentration of particles will be highest there. [6][7]

Air showers were discovered by Bruno Rossi in 1934. Bruno recognized that the cosmic rays which come to detector place apart from each other. Air showers consist of pions, muons, protons, neutrons, electrons. Pions and muons are not stable and may decay into gamma photons or other particles, the figure below shows how an air shower is created in the atmosphere. [6]

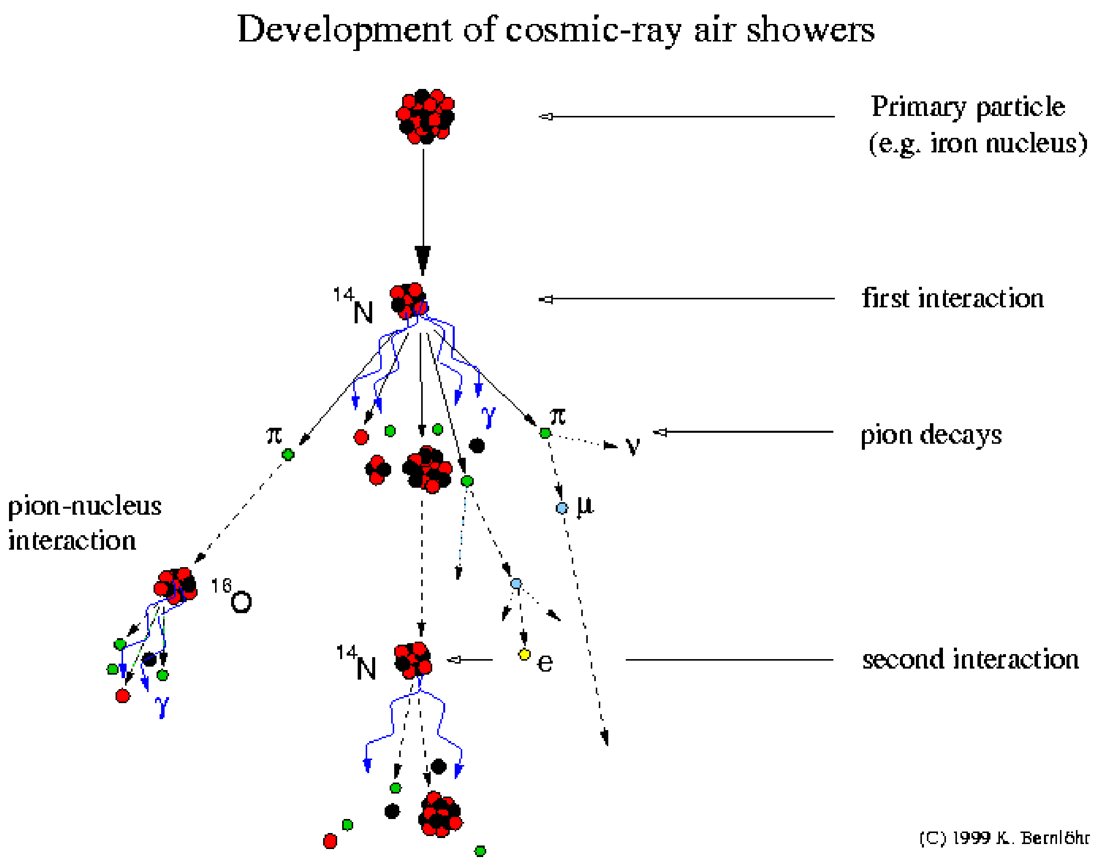

Figure 1, shows how air showers are created. [6]

1.2.3 JEM-EUSO

JEM-EUSO can be seen as a planned observatory on the Japanese Experiment Module (JEM) at the International Space Station (ISS). EUSO stands for Extreme Universe Space Observatory and its mission is to determine where EECRs come from by tracking the air showers, using the atmosphere as a detector. JEM-EUSO consists of a telescope with a 60^0 field of view, allowing it to observe a circle with a diameter of 400 km at a given time when looking straight down. [8]

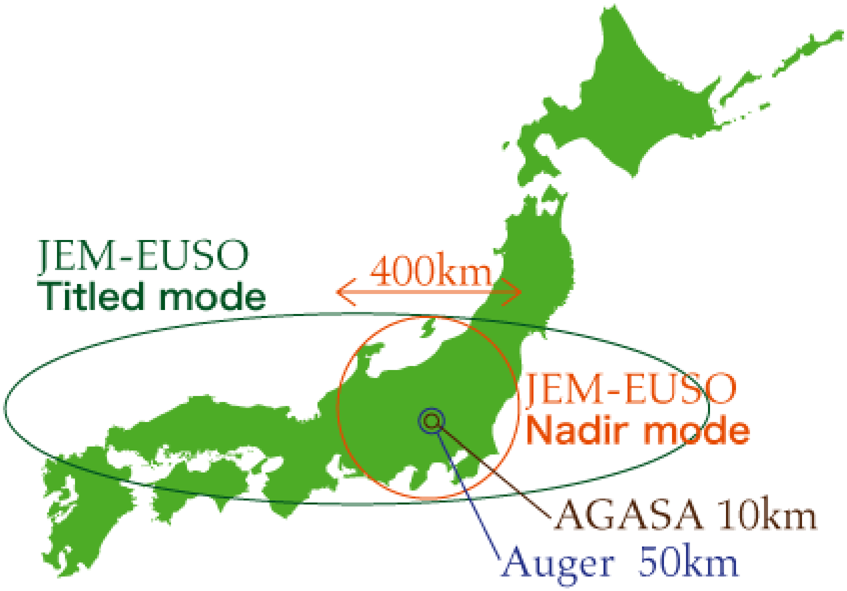

Figure 2, shows the observing area of JEM-EUSO in both modes, compared with current technologies. [8]

JEM-EUSO can also increase its effective area by inclining the telescope from nadir mode to titled mode as shown in the figures below.

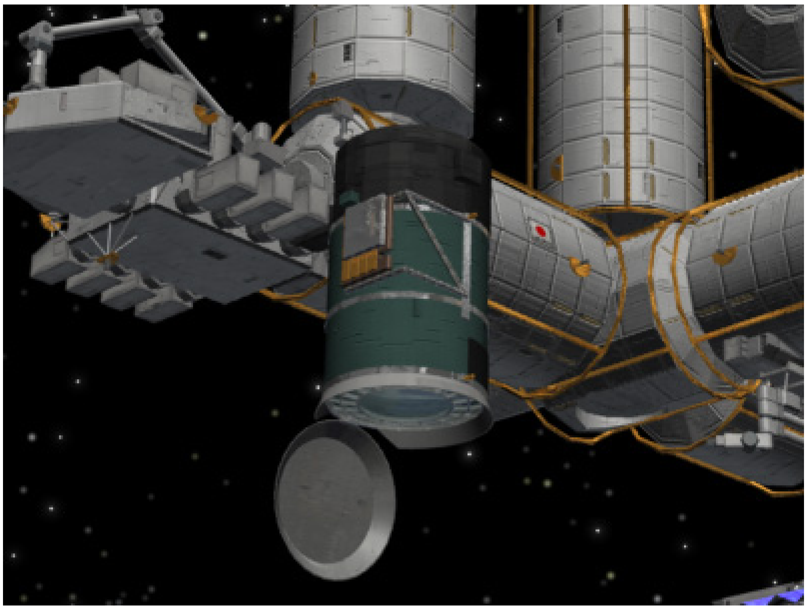

Figure 3, the telescope in nadir mode. [8]

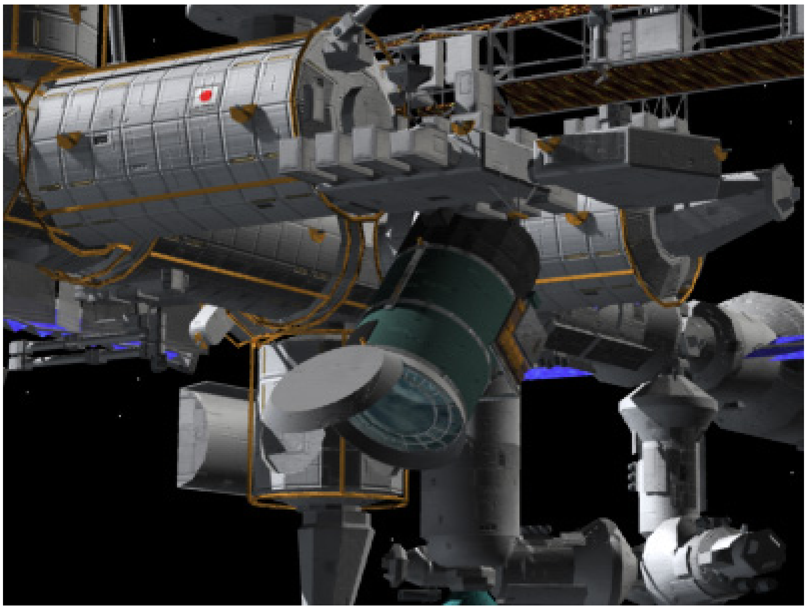

Figure 4, the telescope in tilted mode. [8]

The JEM-EUSO telescope detects high energy photons (UV and higher) that are emitted from an EAS. Using these data, JEM-EUSO will then be able to track the air shower back to where it came from. In order to do this, it first needs to be able to determine its position in relation to Earth once it detects such photons. This is done with the help of a star tracker.

JEM-EUSO is planned to be attached to JEM of ISS and it will be launched in 2016 or 2017. During its mission, JEM-EUSO is expected to detect >1000 EAS. [8]

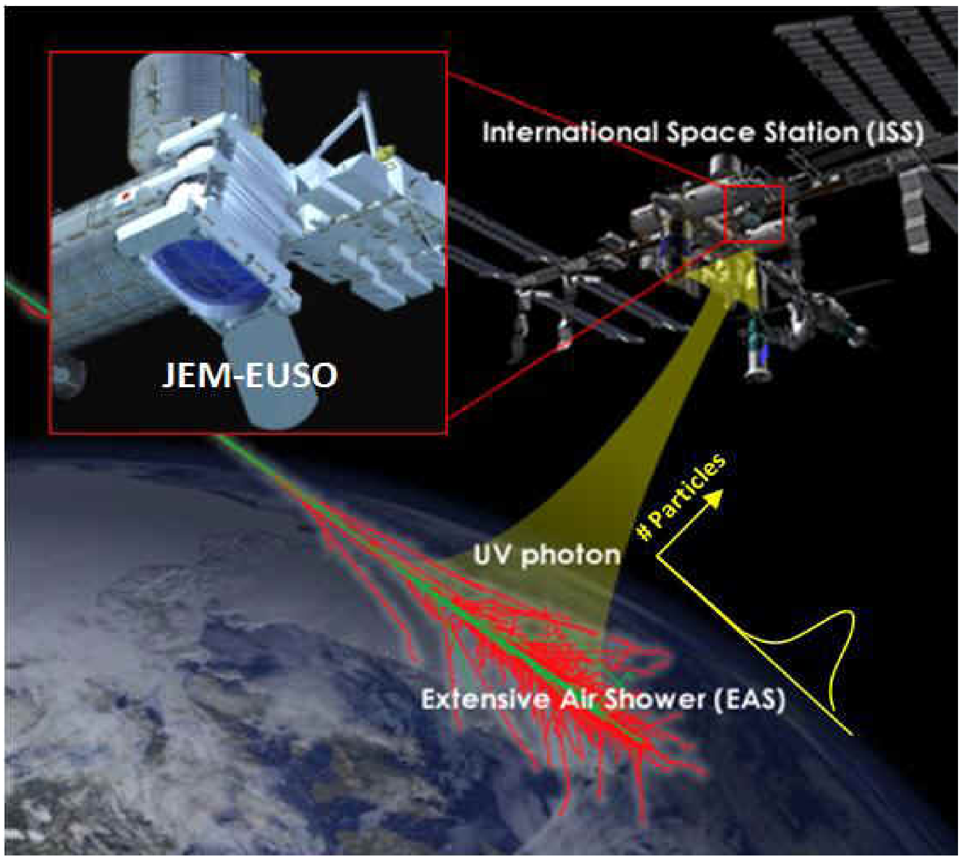

Figure 5, shows the principles behind JEM-EUSO. [9]

1.2.4 Star Tracker

Star trackers are one of the most accurate instruments for determining positions. The way a star tracker works is that it continuously takes pictures of the stars in space with a specific frequency and then compares these images to a star catalog. A star tracker is, in other words, an optical instrument used to measure the position of stars, allowing it to determine its own position in its trajectory around the earth.

A star tracker is basically a digital camera with a sensor at the focal plane made of a CCD or a CMOS. CMOS sensors are more resistant to radiation and can also read different pixels independent of each other, while a CCD sensor have much lower noise.

The first star tracker was developed in the 1970s and differs significantly from star trackers today. Star trackers are categorized in two groups, the first generation and the second generation.

First generation star teachers were only able to give the position of a few stars in a coordinate system that they referenced to the sensor, meaning external processing was needed to determine its position. They can detect two to six stars at a time and after that they outputted the CCD coordinates of the stars.

Second generation star trackers have an internal star catalog which consist of more than 20 000 stars. They can detect lots of stars and have very high accuracy compared to first generation STs. They can utilize 25 to 60 stars in their FOV (field of view). These star trackers are autonomous and their integration with the space craft is simplified which it leads to lower cost and higher reliability. [10]

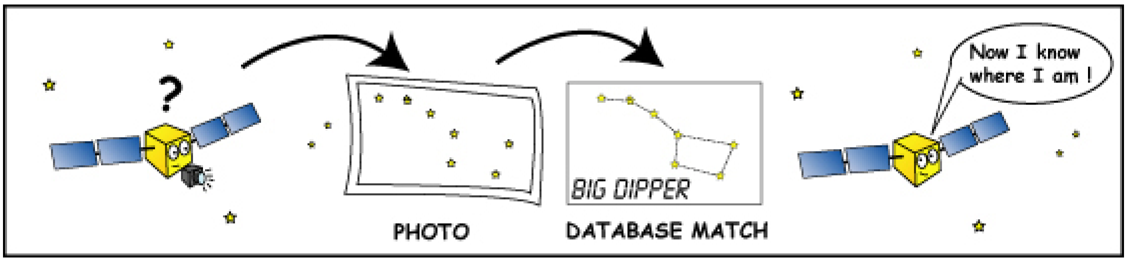

Figure 6, shows how a second generation star tracker basically works. [11]

1.2.4.1 The Field of View and the Camera Resolution

Field of view and resolution are two important parameters which are commonly used to asses star tracker performance. A star tracker with high resolution is able to determine the position of stars more accurately but the accuracy of this determination also depends on the resolution of the star tracker's sensor and its size, the size of FOV and the accuracy of centroiding. In fact, the resolution can be improved by using a large number of sensors with small sizes.

The tracker's software has effect to resolution grade of star tracker which it may use a couple of star pattern and determine the attitude with each of them. Then it can evaluate the attitude for the different star and choose the accurate one. [10]

1.2.4.2 The Update Rate

Typical star tracker have an update rate in a range of between 0.5 to 10 Hz and accuracy of about a few arc seconds in bore sight direction and also mass about 3 kg with 10 w power requirement.

Star tracker use stars as reference points because the position of the stars in relation to Earth does not change over time, meaning stars can be considered as fix points from Earth. STs choose the brightest stars and compares their fluxes. The difference between magnitudes of two stars is 2.5 times the base 10 logarithm of their flux which it can be calculated with this formula:

$$m_2 - m_1 = 2.5.\log\left(\frac{F_2}{F_1}\right) \quad (1)$$

Where m is the magnitude of the star and F is its flux. [9]

1.3 Objective

Since the star tracker uses incoming data and compares it with a catalogue with already known data for different objects in space, it can be used to approximately determine the position of the current EAS.

The main objective of this project is to determine how accurate the star tracker itself has to be given the telescope parameters in order for this experiment to work as efficient as possible. This means determining the three parameters of a star tracker, which are the field of view, the resolution and the update rate. This will be done through a series of calculations using a few assumptions to simplify the cases. This will be followed by suggestions on STs from the market that can be used on JEM-EUSO.

2 Calculations

2.1 The Update Rate

The update rate of the star tracker is directly linked to the exposure time of the camera. In order to get an accurate measurement from the star tracker, the exposure time needs to be as long as possible. This is because the light flux from the stars to the ST are not constant, meaning that if two stars have a magnitude relatively close to each other, the dark star might appear to shine brighter than the bright star during a short time, meaning that if the exposure time is low, this will give a false reading to the ST. However, since the ST is constantly moving with ISS, having a too long exposure time will induce too large uncertainties when it comes to the “area of event”.

To determine the update rate, two assumptions were made; the main one is that it is assumed that ISS orbital around Earth is circular, which is not the case in reality; this is done to give it a constant velocity. The second assumption is that each pixel on the telescope covers a square area. This is to prevent any overlaps between the viewing areas of two adjacent pixels.

Given these assumptions, the update rate can be determined if the angular resolution for each pixel in the telescope is known. This will allow determination of the area coverage for each pixel, using following equation:

$$\tan\left(\frac{\theta}{2}\right) = \frac{l}{2h} \qquad (2)$$

Where θ is the angular resolution, l is the length of the square and h is the height of ISS. When the length is known, the next step is to determine how long time that is needed for ISS to move the distance that corresponds to that length on earth. This is easiest done by determining its angular velocity ω. This is done by:

$$\frac{v_{ISS}}{O} \cdot 360^0 = \omega \qquad (3)$$

Where v_{ISS} is the velocity of ISS, and O is the orbital length. The orbital length is given by:

$$O = 2 \cdot (r_e + h) \cdot \pi \qquad (4)$$

Here, r_e is the Earth radius.

Once ω is known, the final piece is to determine what angle φ the length l creates with respect to the center of Earth, using following equation.

$$\frac{l}{2 \cdot \pi \cdot r_e} \cdot 360^0 = \varphi \qquad (5)$$

The maximum exposure time can then be determined by dividing φ with ω, giving the update frequency as its inverse. The following picture explains all the parameters more clearly:

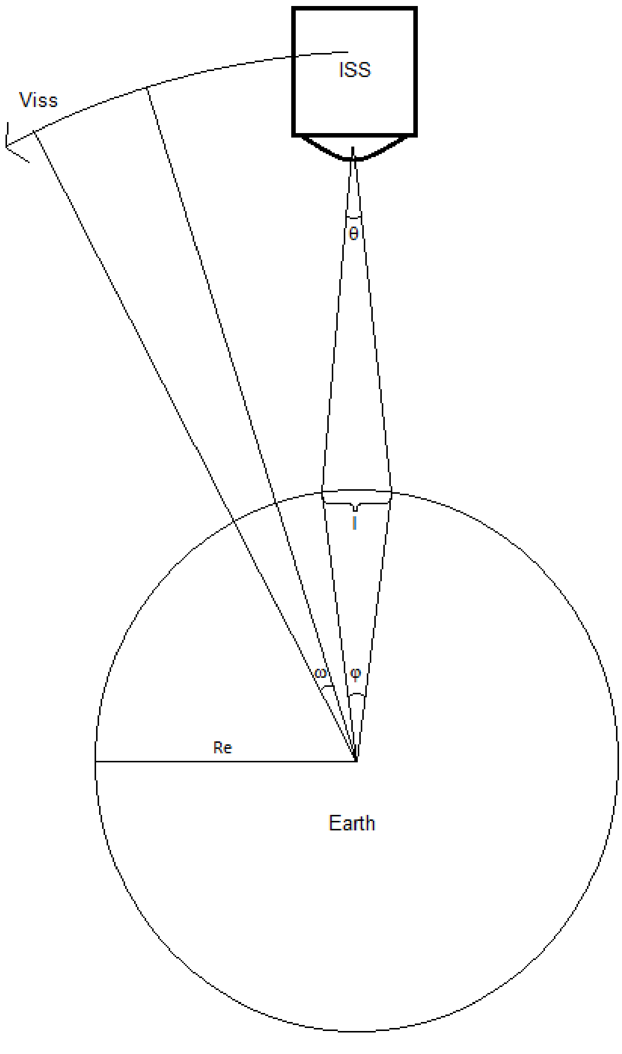

Figure 7, a basic sketch explaining all parameters.

2.2 The Field of View and the Camera Resolution

The FoV and the camera resolution are linked to each other and require a third parameter in order to be determined. This third parameter is the angular resolution of the camera itself. Assuming the pixels of the camera are oriented as a circle, the field of view and the camera resolution are related as following:

Assuming the FoV is known, using the angular resolution β, a pixel diameter d can be determined.

$$\frac{FoV}{\beta} = d \qquad (6)$$

This pixel diameter is a measurement of how many pixels with angular resolution β that can be put on a line to get the desired FoV. The camera resolution R can then be determined using:

$$\frac{d^2}{4} \cdot \pi = R \qquad (7)$$

Combining these equations gives the following relationship:

$$\frac{(FoV)^2}{4\beta^2} \cdot \pi = R \qquad (8)$$

The angular resolution of the camera will also induce uncertainties to the angular resolution of the telescope as following:

$$\theta + 2\beta \qquad (9)$$

This means that in order to get an as accurate reading as possible, β has to be as small as possible, which limits the FoV because there is a limit to how high the camera resolution can be.

3 Results

3.1 The Update Rate

Both the angular resolution and the height are known parameters with the values 0.074⁰ and 400 km respectively, giving the length as:

$$\tan\left(\frac{\theta}{2}\right) = \frac{l}{2h} \;=>\; l = 2 \cdot 400 \cdot 10^3 \cdot \tan(0.037^0) \approx 516.6\, m$$

And with the Earth radius being 6371 km and the velocity of ISS being 7.66 km/s, the angular velocity is calculated as:

$$O = 2 \cdot (r_e + h) \cdot \pi = \; 2 \cdot (6371 + 400) \cdot 10^3 \cdot \pi \approx 4.254 \cdot 10^7\; m$$

$$\omega = \frac{v_{ISS}}{O} \cdot 360^0 = \frac{7660}{4.254 \cdot 10^7} \cdot 360^0 = 0.06482^0/s$$

The known parameters also give φ as:

$\frac{l}{2 \cdot \pi \cdot r_e} \cdot 360^0 = \varphi = \frac{516.6}{2 \cdot \pi \cdot 6371 \cdot 10^3} \cdot 360^0 \approx 0.004646^0$

Giving the maximum exposure time as:

$t = \frac{\varphi}{\omega} = \frac{0.004646^0}{0.06482^0/s} \approx 0.07168s = 71.68\, ms$

This gives an update frequency of 13.95 Hz.

3.2 The Field of View and the Camera Resolution

This part was solved by looking for STs that have an update frequency of at least 14-15 Hz and that also have an angular resolution that is as low as possible. While most star trackers seem to be used for hobby purposes, one interesting ST is the HYDRA CMOS Star Tracker from Sodern. [12]

HYDRA has an adjustable update frequency that can go up to 30 Hz and an angular resolution of less than 2.8 arc sec. 1 Arc sec corresponds to 1/3600 of a degree, giving:

$\beta = 7.778 \cdot 10^{-4 0}$

This means that the error will be at around 2.1% of θ.

4 Discussion

The calculations here were using on simplified models and assumptions, like that ISS is moving in a circular orbit and that the Earth is a perfect sphere, this is of course not the case in reality, where ISS is moving in an elliptical orbit, which creates variations in the velocity, and therefore the angular velocity. Meaning the update frequency of the ST will vary periodically around the calculated value.

It was also assumed that ISS has a stable movement around Earth; this isn't the case of course, because there will be small vibrations and such and this may cause a few errors due to the small angular resolutions of the instruments on JEM-EUSO.

5 Conclusions

There have been works on both the JEM-EUSO project and on STs. By combining these two areas, it will be possible to determine the position of JEM-EUSO telescope in real time as it detects an air shower in the atmosphere.

As this experiment goes for a while, patterns may be discovered that allows the determination of the origin of these high energy particles and as a result understand how they are accelerated to such energies.

6 References

[1] John Walker; *The Oh-My-God Particle*; 4 January 1994; Cited 29 April 2015; (https://www.fourmilab.ch/documents/OhMyGodParticle/)

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[3] *Cosmic Rays: Particles from Outer Space*; CERN; Taken 15 March 2015; (http://home.web.cern.ch/about/physics/cosmic-rays-particles-outer-space).

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[5] G. Sáez Cano; *Discrimination of Ultra High Energy Cosmic Rays with the Extreme Universe Space Observatory (EUSO)*; Universidad Complutense de Madrid; Facultad de CC. Físicas; Published December 2014.

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[7] *Detecting UHE Cosmic Rays*; Telescope Array Project at the University of Utah; Cited 5 March 2015; (http://www.telescopearray.org/index.php/about/detecting-uhe-cosmic-rays).

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[9] Picture from: http://www1.na.infn.it/wsubnucl/cosm/JemEuso/; Taken 26 April 2015.

[10] Nikola Shterev; *Design and Testing of the Start Trackers for the SEAM Nanosatellite*; Luleå University of Technology; Department of Computer Science, Electrical and Space Engineering; Published 2015.

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[12] *CMOS Star Trackers: HYDRA family*; Sodern; Cited 28 April 2015; (http://www.sodern.com/sites/en/ref/Star-Trackers-HYDRA_51.html)