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A STUDY FOR A SATELLITE SYSTEM TO LOCATE GAMMA-RAY BURSTERS

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Abstract

We present a study on the feasibility of using a system of small, light, long lived and simple satellites in order to locate gamma-ray bursters. Each small satellite possesses only electronics to discriminate gamma-rays out of the large background of cosmic rays and to time the arrival of the front of a gamma-ray burst.

To locate the burster applying triangulation methods, we use the time of arrival of front of the gamma-ray burst and the position of the satellites at that very moment. We review an elementary version of the triangulation method to study the angular error in the determination of the burster position, since almost all non-pathological distances among satellites can determine the angular location of the source to better than one arc min. This precision allows us to find the visible counterpart of the burster, if it exists.

These simple satellites can be made modular in order to customize their sizes or weights in order to use spare space available during major launches.

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1. INTRODUCTION

Observation of the gamma ray sky was the last of the electromagnetic spectrum areas to be opened to astronomers. Since gamma-ray astronomy can only be carried out outside the atmosphere or at high altitudes, it had to wait until high altitude balloon flights, rockets and satellites were available to carry gamma-ray instruments. These instruments are based on techniques developed for High Energy Physics (HEP) for large particle accelerators, instruments that are large, heavy, complex and difficult to operate.

Several instruments flown until now show that the gamma-ray sky presents mainly a broad, stationary continuum of radiation with some identifiable emission lines. This continuum of radiation is dominated by the emission coming from the center of the galaxy, but the strangest phenomena, at the high energy photon range, are the gamma-ray bursters (e.g., Higdon and Lingelfelder 1990; Liang and Petrosian 1985; Lingelfelder et al.1982). As it often happens these gamma-ray bursters were discovered by accident. In the late 1960s, the Vela satellites were launched to detect atmospheric atomic tests by measuring the gamma-rays produced by atomic explosions. Even without the presence of thermonuclear explosions, the satellites detected bursts of gamma-radiation coming from some place in the sky. The Vela satellites could not locate the origin of the bursts since they had a very poor angular resolution. They could only ascertain that the bursts were not coming from the earth or the sun.

A gamma-ray burst can be detected at any time coming from virtually any place from the sky. As a matter of fact, they are not concentrated on the galaxy-center, but evenly distributed in the sky (e.g., Meegan, C. A. et al. 1992; Bloemen, H. 1989). Bursts last from milliseconds to several seconds and then disappear, never to be active again. The short duration of the pulses hinders the use of gamma-ray telescopes, because pointing them towards the probable area of the source takes longer than the duration of the pulse itself. A promising technique is to use triangulation (time-of-arrival analysis) using several contemporary gamma-ray space borne telescopes. But because telescopes of this kind are very expensive to develop and launch, only in 1978-80 and 1981-83 more than one such instruments were aloft. During these periods triangulation of the sources was possible and more than 100 bursters were roughly located.

The nature of the gamma-ray bursters is an important present problem for astrophysics. We know very little about bursters since, with some rare exception (e.g. Schaefer, B. E. 1981), they are not correlated to any visible counterpart. Their correlation is important because the intrinsic energy of the source cannot be determined without knowledge of the distance of the source. If bursters are closer than 1000 light years away, their outputs are modest and comparable with the output of most x-ray sources. If, instead, they are extra galactic in nature, their energy output challenges that of a super nova. If a correlation with a visible counterpart is found, the distance to the object can be calculated using standard astronomical techniques. This identification with a visible object is also essential to study the nature and behavior of the object.

Expensive gamma-ray telescopes such as EGRET have an angular resolution of 3-10 arc min., a low resolution by optical standards (e. g., Kanbach, G. et al. 1988; Kanbach G., et al. 1989). To determine the visible counterpart, resolutions below 1 arc min. are needed. Although at this very moment three such telescopes are flying at the same time, such lucky circumstance will not be easily repeated, since the high price tag of each telescope and the short useful lifetime of these instruments conspire against this likelihood.

Our claim is that it is worthwhile and cost effective to design and launch several small, light, long lived, inexpensive satellites, that use no consumables, and that are specifically built to locate gamma-ray bursters. These satellites could be launched into different orbits around the earth, dispersing them spatially.

The purpose of the study is to present an idea more than a finished detection system. The final detection system, hence the range of energy, weight, required electronics, etc., can only be known after deeper considerations, not all of them necessarily of a scientific nature.

2. THE SATELLITE SYSTEM

The principle of operation of the system of satellites is very simple. We use the fact that bursts have a typical duration of .01 to 100 sec and that the start of the gamma-ray burst is very abrupt, quite similar to the front edge of a shock wave. The satellites will see the arrival of the front of the gamma-ray burst at different times since they are at different points in space. Using triangulation we can locate with high precision the direction from which the burst came.

When a gamma-ray hits a satellite, the on-board instrumentation saves the number of ticks (the time) of the local clock. When passing over the controlling station, the satellite transmits to the ground-computer a token identifying the satellite, the time of arrival of every single gamma-ray stored in its memory, and the present tick count of its clock. The ID token determines a precise orbit, the hit times are used to place in space the satellite at the time of the impact of the gamma-ray, and the local time is used to compensate for the drift of the various clocks in the system. This transmission protocol can obviously be enriched to cover other functional parameters of the satellite environment, to add redundancy to the data, etc.

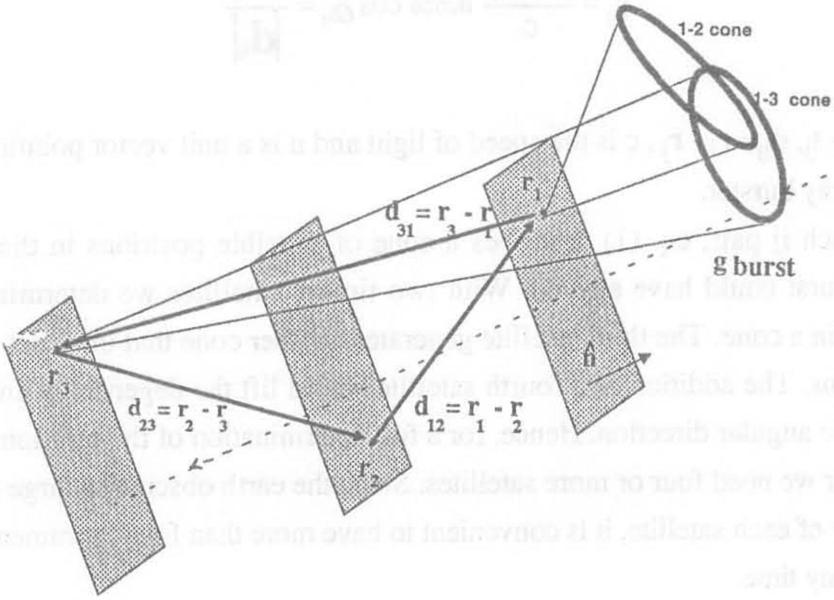

Figure 1: Three timing satellites are shown in positions r_1,r_2,r_3. The difference in arrival time between any pair of satellites determines that the burster is in a cone. A third satellite determines another cone that intersects the first one in only two directions. The addition of a fourth satellite lifts the degeneracy completely, locating the burster position in the sky.

If we do not design the satellite to measure the energy of the gamma-ray or the direction from which individual photons came, we can build small, inexpensive and electronically simple satellites that could be placed in orbit using spare space in major launches. The direction from which the burst came can be deduced from correlation of the arrival time of gamma-rays to several of the satellites at intervals compatible with the existence of a burst front. Only gamma-ray events separated by less than half a second need to be considered for a possible correlation, since half a second is the time required for light to traverse the base line presented by the system.

To have a feeling of the error with which we can calculate the position of a burster, let us consider three such gamma-ray instruments at positions r_1,r_2 and r_3. Figure 1 shows this case.

If we assume that we have measured the differences of the arrival time t_{ij} between satellites i and j, with i,j=1,2,3, then for each pair we have that:

$$t_{ij} = \frac{\mathbf{n}\bullet\mathbf{d}_{ij}}{c} \text{ hence } \cos\alpha_{ij} = \frac{c\cdot t_{ij}}{\left|\mathbf{d}_{ij}\right|} \tag{1}$$

where $t_{ij}= t_i - t_j$, $\mathbf{d}_{ij}= \mathbf{r}_i - \mathbf{r}_j$, c is the speed of light and n is a unit vector pointing towards the gamma-ray burster.

For each ij pair, eq. (1) describes a cone of possible positions in the sky from which the burst could have arrived. With two timing satellites we determine that the burster lays in a cone. The third satellite generates another cone that intersect the first in two directions. The addition of a fourth satellite would lift the degeneracy and leave us with only one angular direction. Hence, for a full determination of the position in the sky of the burster we need four or more satellites. Since the earth obscures a large part of the angular view of each satellite, it is convenient to have more than four instruments circling the earth at any time.

Each cone has a "thickness" of uncertainty $\Delta\alpha$ for the direction of the burster. This uncertainty is created by errors in the knowledge of the time of arrival and of the position of the satellite when the gamma-ray is detected. Very important in determining the error is the orientation of the $\mathbf{d}_{ij}$ vector with respect to **n,** the vector that points in the direction of the burster. The expression for the error is:

$$\Delta\alpha = \frac{\partial\alpha}{\partial t}\cdot\Delta t + \frac{\partial\alpha}{\partial d}\cdot\Delta d = \frac{c}{d\,\mathrm{sen}\alpha}\Delta t + \frac{1}{d\tan\alpha}\Delta d \tag{2}$$

where we have not written the sub indexes for reasons of brevity.

There are two extreme cases for $\Delta\alpha$ as a function of the angle between the burster location and the distance $\mathbf{d}_{ij}$. If $\alpha=0$ then $\Delta\alpha=\times$; if $\alpha=\pi/2$ then $\Delta\alpha=c\Delta t/d$, the latter case gives us the best attainable precision for a given distance between satellites. It is the case for which **d** is perpendicular to the direction of the burster. It is reasonable to measure the time of arrival of the gamma-ray with a precision $\Delta t=200$ ns. Then, if to locate the visible counterpart of the burster we require a precision of 1 arc min., the distance between the satellites must be larger or equal than 206 km. In the best of cases, the satellites are separated by about 14.000 km. For maximum separation: $\Delta\alpha=1.47\times10^{-2}$ arc min. Figure 2 shows $\Delta\alpha$ for various other values of d and α.

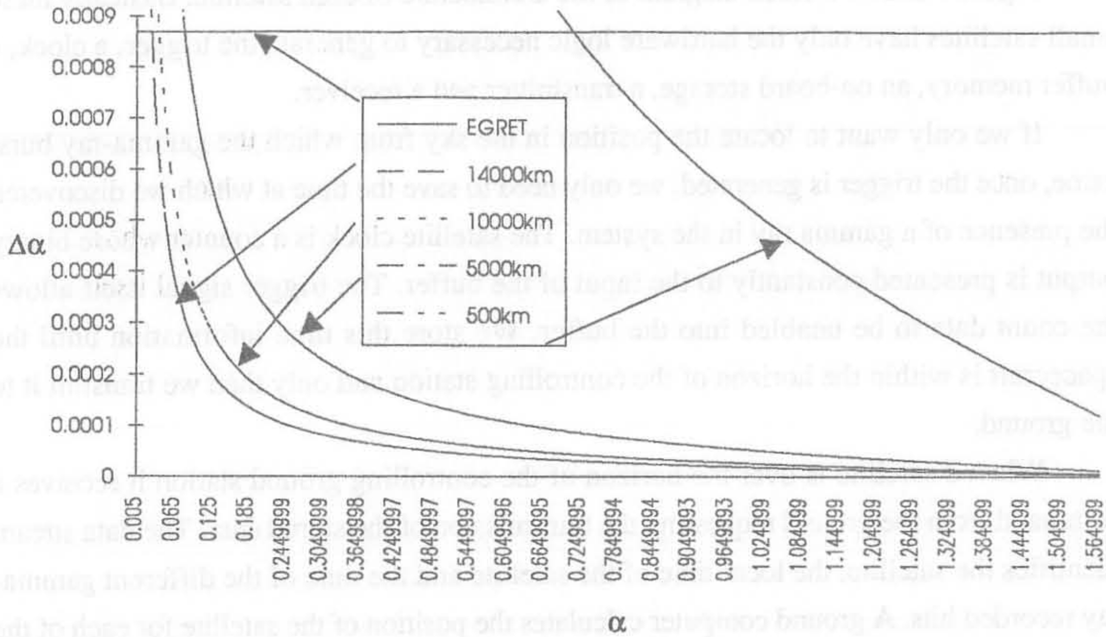

Figure 2: shows the angle error $\Delta\alpha$ as a function of α for various distances between satellites, fixing Δt=200 ns and Δd=300 m. The horizontal line, included only for comparison purposes, is the best angular accuracy attainable with EGRET.

3. INSTRUMENT

So far, we have only showed the obvious advantage of a large base line for triangulation purposes. The novelty is the simplicity of the instrument.

In all high energy photon telescopes, such as EGRET, or any HEP apparatus, there is a signal pulse called "trigger" (e. g. Leo, W. R. 1992), that announces the arrival of a gamma-ray to the instrument. This pulse "triggers" the data acquisition system into action. The trigger pulse is generated by some fast electronics capable to discriminate the signature of one gamma-ray out of the signals of approximately 10000 cosmic rays. More complex systems may have more than one temporal or logic level of triggering.

Only a few gamma-rays arrive every minute in one square meter detector, therefore it is a very unlikely event. The encountered fluxes are very low, typically in the range of 10^{-4}-10^{-6} photons cm^{-2} s^{-1}. But during a burst several photons arrive within a millisecond and they have to be recorded appropriately. Hence, the electronics has to be capable of handling high data rates for short times but of storing, on the average, a small amount of data.

Figure 3 shows a block diagram of the architecture of each satellite. Basically these small satellites have only the hardware logic necessary to generate the trigger, a clock, a buffer memory, an on-board storage, a transmitter and a receiver.

If we only want to locate the position in the sky from which the gamma-ray burst came, once the trigger is generated, we only need to save the time at which we discovered the presence of a gamma ray in the system. The satellite clock is a counter whose binary output is presented constantly to the input of the buffer. The trigger signal itself allows the count data to be unabled into the buffer. We store this time information until the spacecraft is within the horizon of the controlling station and only then we transmit it to the ground.

When a satellite is over the horizon of the controlling ground station it receives a command from the ground requesting the transmission of the stored data. The data stream identifies the satellite, the local time of the satellite and the time of the different gamma-ray recorded hits. A ground computer calculates the position of the satellite for each of the recorded arrival time of the hits and correlates this information with the information delivered by the other satellites of the system. If a burst is identified the computer calculates the angular position of the source, the error of this determination, as well as the temporal development of the burst. Since we do not measure the energy of each photon we can only express the intensity of the burst in photon counts.

3.1 The trigger and detector plane

The generation of the trigger (e. g. Leo, W. R. 1992) is of foremost importance since it allows to discriminate one gamma-ray out of a background of 10^4 hits of cosmic ray particles. We use an anti-coincidence technique using Cherenkov light generating materials to distinguish photons from charged particles.

The bulk of a layer of suitable plastic material, such as Lucite and Plexiglas, generates Cherenkov radiation when a charged particle traverses the layer at a speed higher than the speed of light in that particular material. Lucite or Plexiglas are suitable materials since the refractive indexes are around 1.5, allowing the detection of the passage of particles with velocities higher than 0.6c .

Our detector consists of a layered structure of Cherenkov material and high-Z absorbing material like tungsten. The two outermost layers produce Cherenkov radiation and they will be used for anti-coincidence triggering. Since the light yield is low, the plastic layers are covered with a very thin reflecting layer of aluminum in order to deliver as many photons as possible to the photo multipliers. Also, the aluminum coating prevents light from the outside from entering the plastic and activating the photo multiplier tubes. Gamma-ray photons do not produce Cherenkov radiation in the plastic layers, only charged particles do.

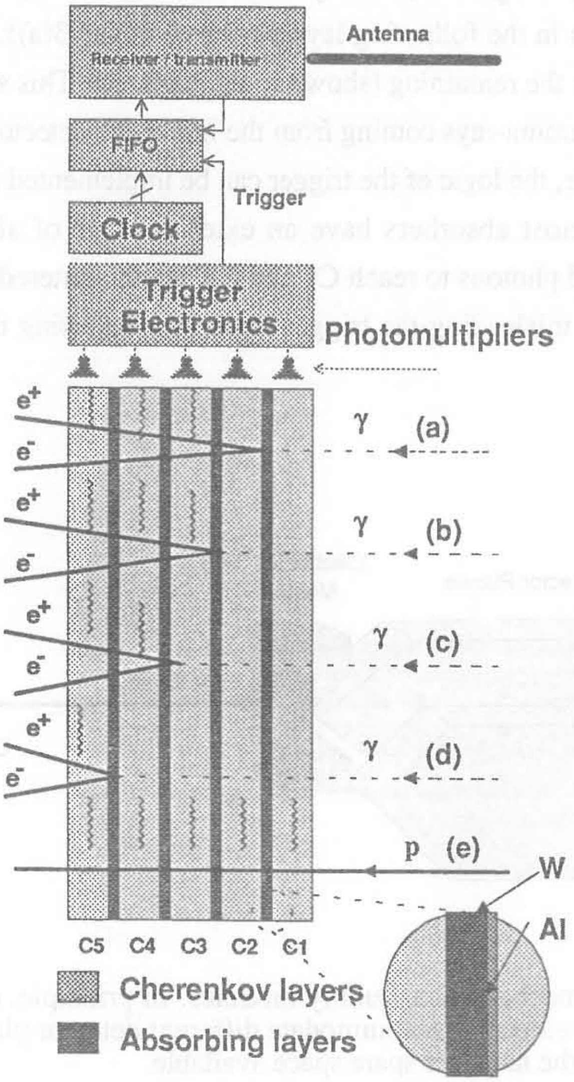

Figure 3: shows the block structure of the on-board electronics and the layered structure of the detector plane. The detector is made of layers of Cherenkov light producing materials and absorbers made with high-Z materials such as tungsten. The two outermost absorber layers have an exterior layer of Al in order to reduce back-scattered particles from more centrally located layers into the outermost scintillators.

Figure 3(e) shows a proton coming from the right of the detector sandwich. The **p** will produce Cherenkov light in all plastic layers, but particularly in C1. The trigger logic must reject such an event, since it indicates the passage of a charged particle. Also shown are four possible gamma-ray events. The gamma-ray in fig. 3(a) traverses the first plastic layer leaving no signal. Afterwards, it can produce a positron-electron pair in any of the high-Z material layers producing photons in all following Cherenkov layers. Hence, a good gamma-ray trigger is generated every time that the photo multipliers see no photon in C1 and see photons in the following layers (shown in fig. 3(a)), or no photons in C1 and C2 and photons in the remaining (shown in fig 3(b)), etc. This argument is also valid for cosmic-rays and gamma-rays coming from the left of the detector since the detector is symmetric. In principle, the logic of the trigger can be implemented using an ASIC.

The two outermost absorbers have an exterior layer of aluminum in order to prevent back-scattered photons to reach C1 and C5. Back-scattered particles would give Cherenkov radiation, misleading the trigger logic into believing that a cosmic ray has struck the detector.

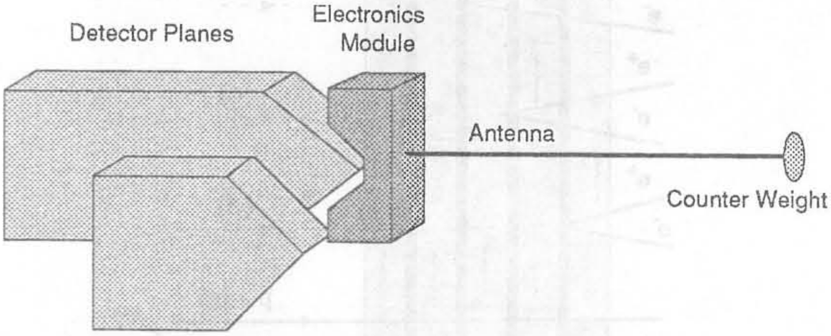

Figure 4: shows the mechanical assembly modules. In principle, only one electronics-antenna module is developed to accommodate different detector plane sizes. This planes are sized according to the launcher spare space available.

To convert gamma-rays into electron-positron pairs is enough if the sum of the absorbing layers is one radiation length. X_0 (e.g. Longair, M. S. 1992). The radiation length X_0, is the mean distance in which a particle loses 1/e of its energy. If the layers are made out of tungsten, we need X_0=3.5 mm. Hence, the total tungsten weight for a one m^2 detector is 67.55 kg. The weight of the tungsten, or any other absorbing material dominates the overall weight of each satellite.

In principle, as shown in fig. 4, we can develop one electronics-antenna assembly to accommodate a variety of detector plane sizes. These detector sizes are determined by the available spare space during major launches. If we divide the satellite into electronics and detector plane, a new "satellite" could be built at very short notice.

Since a gamma-ray burst comes from anywhere in the sky, a good attitude control system is not needed. We propose to keep the electronics side of the satellite looking towards the earth. This can be achieved by adding a weight to the tip of the antenna. Once in orbit, the antenna is extended producing passive gravity gradient stabilization. In this way we achieve: zero power consumption for stabilizing the satellite, the antenna will be always facing the earth surface, no consumable gasses are needed to stabilize the spacecraft, and we point the dead angle of the detector towards the ground, from where no gamma-rays are expected.

The power consumption of the whole should be extremely low, since the only electronics working all the time are the clock, the receiver and the trigger logic. The memory could be powered up only while writing into the memory, and the transmitter is activated only for a short time during data transfers to the ground.

4. SUMMARY

We present a study on the feasibility and usefulness of building and using a system of small, light, long lived, low price tag, simple satellites to locate gamma-ray bursters. Each small satellite possesses only electronics to discriminate gamma-rays out of the large background of cosmic rays and to time the arrival of the front of a gamma-ray burst.

To locate the burster applying triangulation methods, we use the time of arrival of the front of the gamma-ray burst and the position of the satellites at that very moment. More than four satellites must be aloft at any given time to allow triangulation to be used. We reviewed an elementary version of the triangulation method in order to study the angular error on the burster position. For almost all non-pathological distances among satellites we can determine the angular location of the source to much better than one arc min. This precision allows us to find the visible counterpart, if it exists.

We proposed an electronic and mechanical structure for the detector and trigger. The final satellite consists of two separate modules. The electronics can be made suitable for different sizes of detector planes. Building these modular satellites we are allowed to customize their sizes and weights to use spare space available during major launches.

The power consumption of the whole should be of a few watts. In the case of a satellite with a 1 m^2 detector, its weight should be around 80 kg.

We are well aware that the system as presented here is effective for very energetic gamma-rays and that it is rudimentary in nature. If we require a lower energy threshold scintillating plastics can replace the Cherenkov materials with great advantage. We can also include a larger number of thinner absorbing layers to be sure that, at low gamma-ray energies, the pair is not re absorbed within the layer itself. The positioning of the satellites could in principle be performed using the global positioning satellite system. This last change complicates the electronics but decreases drammatically Δd. Fortunately, many other possible improvements come easily to mind.

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