Gamma-Ray Burst Triangulation with a Near-Earth Network (NEN)*

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*Accepted for publication, Astrophysical Journal

- All-sky monitoring and localization of gamma-ray transients is an important component of multi-messenger astrophysics
- Detections of gravitational waves, neutrinos, very high energy gamma-rays, and optical transients, occur at a combined rate of at least several per month
- Inevitably the question of an associated gamma-ray burst arises
- GW-only localization areas are predicted to be up to 180 deg^2, with latencies of hours to days
- In other cases, precise localizations will become available almost in real time (e.g. ZTF20acozryr/AT2020yxz/GRB201103B)
- In all cases, however, it will be essential to have full-time all-sky coverage with localization, in the ~15 - 150 keV energy range

- A single spacecraft in low Earth orbit can’t provide the required coverage, due to duty cycle, Earth-blocking, and/or FoV considerations
- The current Interplanetary Network provides the coverage, and it is operating nominally, but its spacecraft are old, and new interplanetary opportunities do not arise frequently
- Here we explore the capabilities of a network of simple near-Earth detectors, using a novel method of data analysis
- The spacecraft could be 6U CubeSats or larger – the exact type of spacecraft isn’t too important

Three Simple Principles of Triangulation

1. When two spacecraft observe a GRB, triangulation produces an annulus of location; annulus width $\propto$ 1/spacecraft separation
2. When 3 spacecraft observe a GRB, two alternate positions can be obtained
3. A fourth, non-co-planar spacecraft observation can eliminate the ambiguity and produce a single error box

…and two more things to consider:

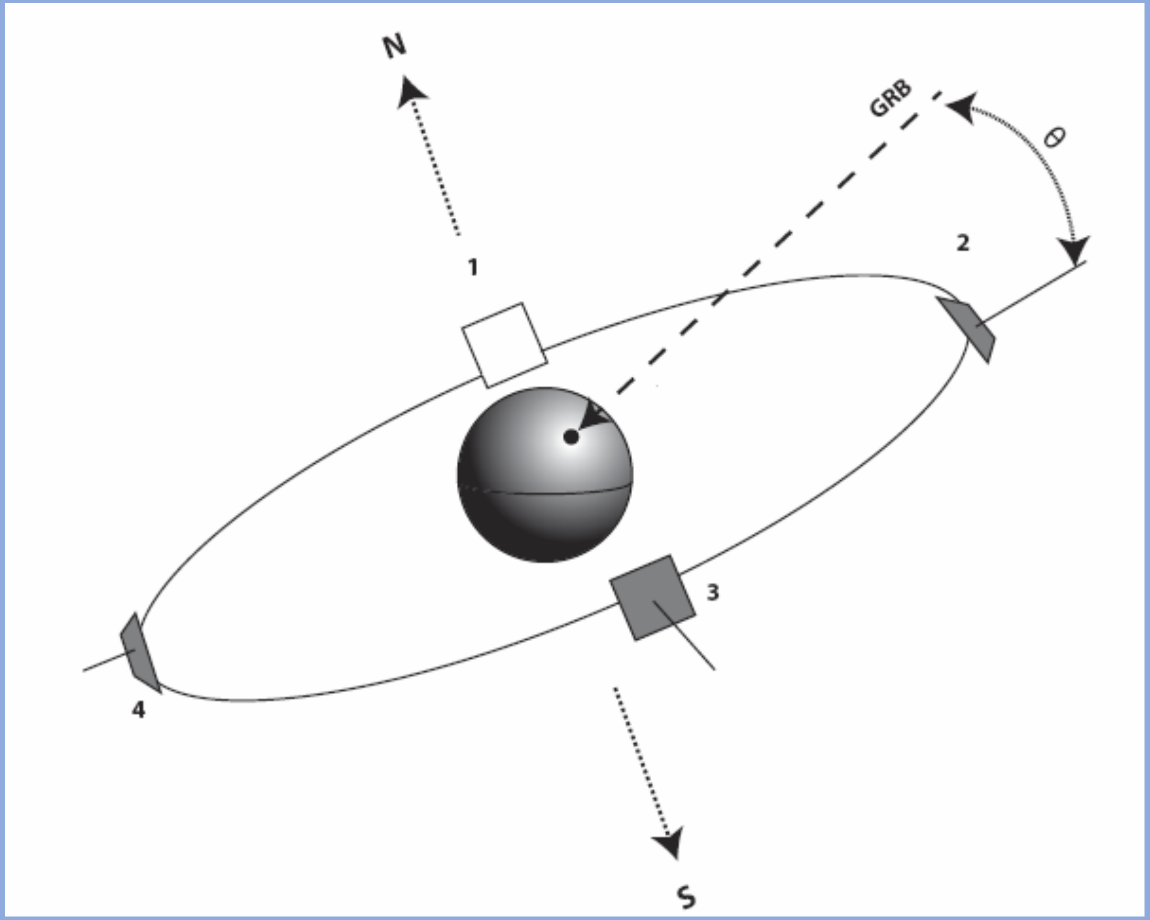
- The quality of a localization (i.e. size and shape of the error box) is determined by the *coverage* and the *total area*

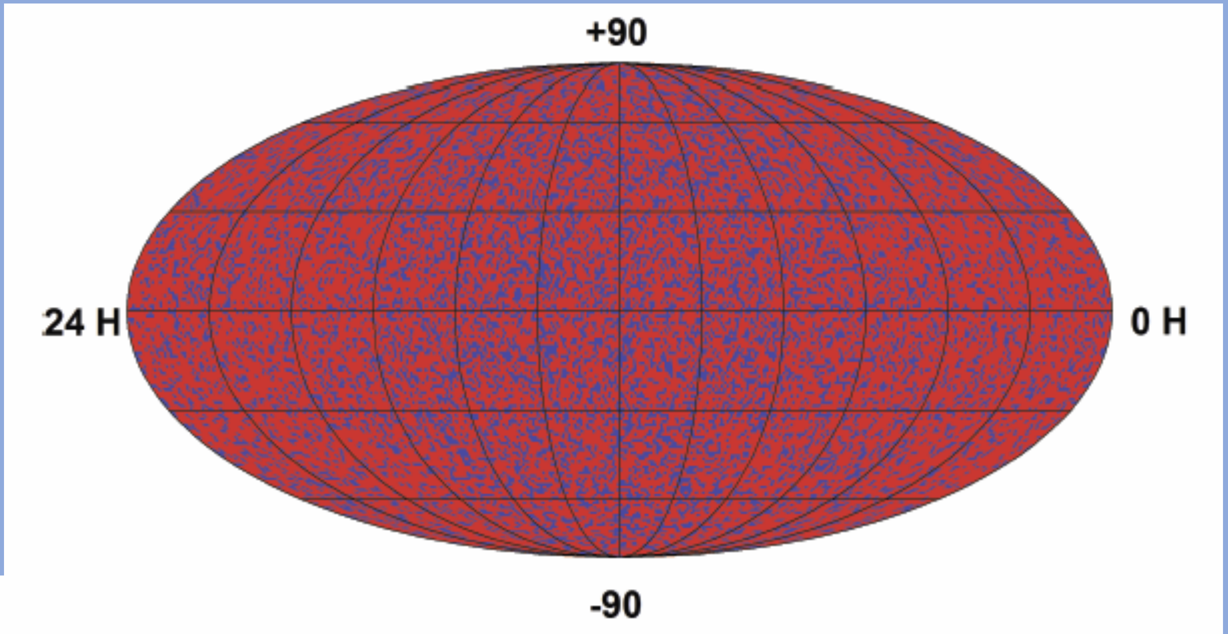
- Coverage: the number of spacecraft which observed the burst

- Total area: the total effective area of the detectors which observed the burst

Simple Example of a 4-Spacecraft Network

- Co-planar, equally spaced spacecraft, orbital inclination ~23°
- Each spacecraft has a planar detector viewing 2π sr, unit area
- Cosine law response
- Zenith-pointing
- Shielded on the Earth-facing side to eliminate albedo photons



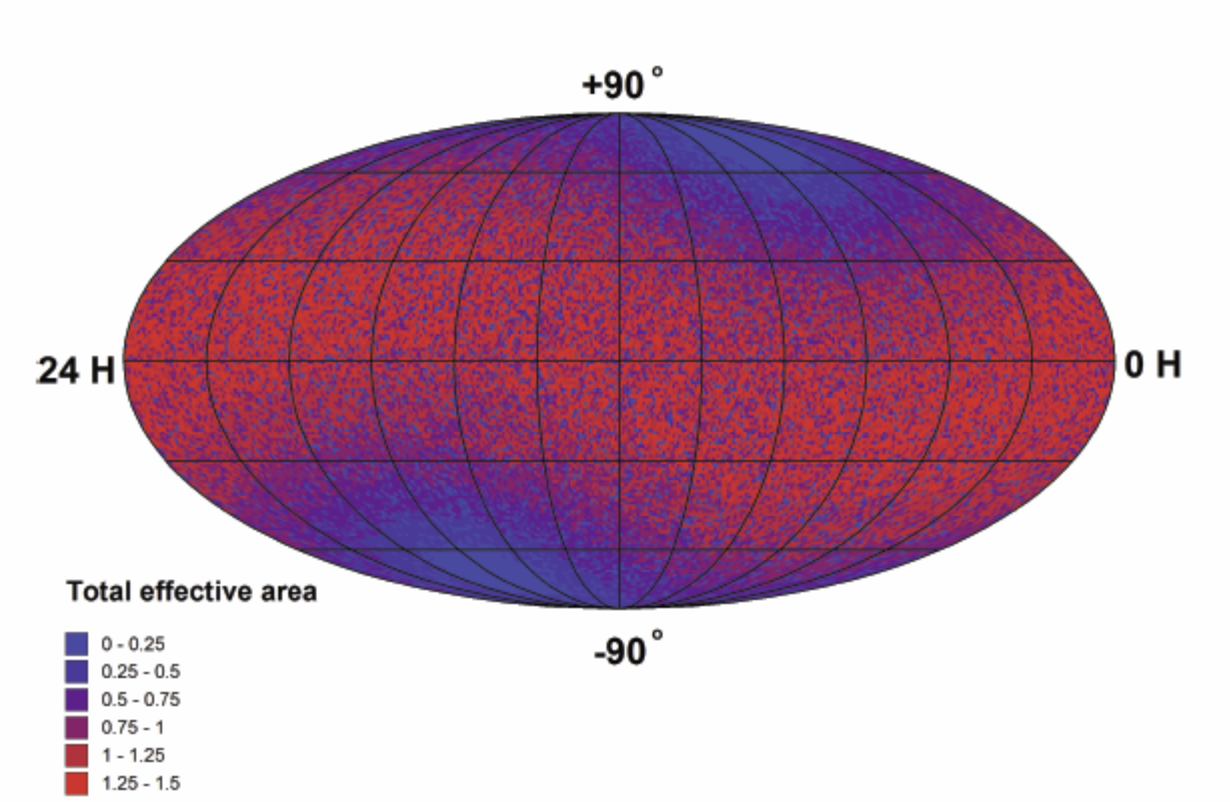


<u>Coverage</u>

Blue: 1 spacecraft

Red: 2 spacecraft

No point is observed by 3 or 4 spacecraft



<u>Effective area</u>

Goes to zero at the orbital poles, which are observed edge-on

- The 4-spacecraft network gives, at best, localization annuli, not error boxes (no point on the sky is observed by more than 2 spacecraft)

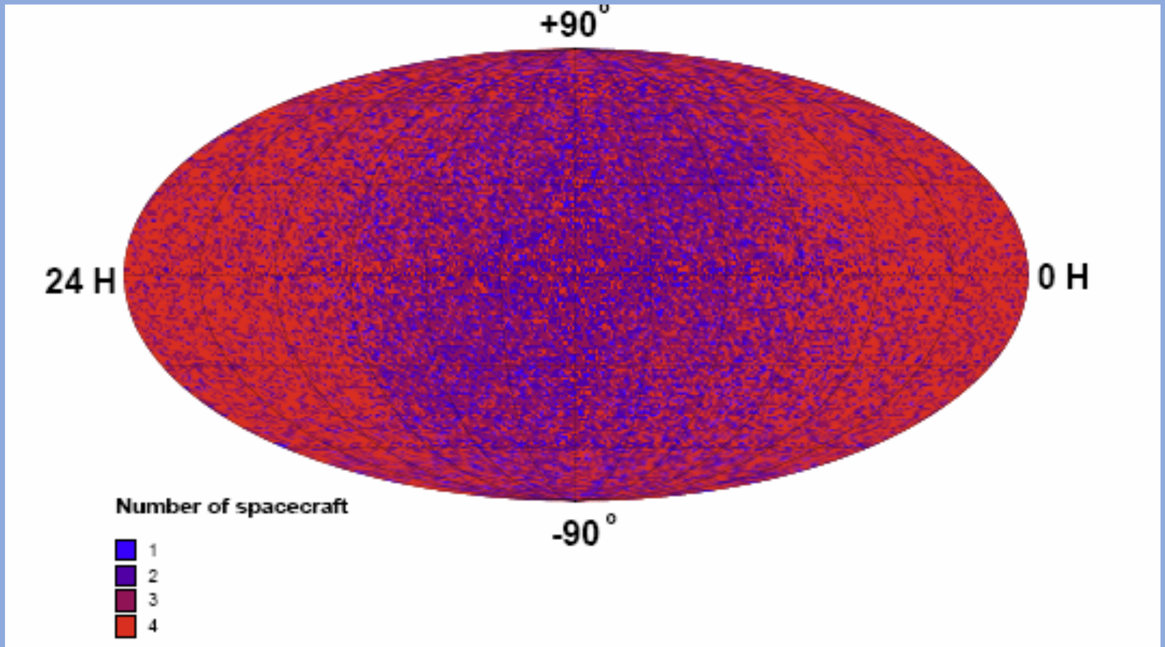
- The coverage is poor around the orbital poles (effective area→0)

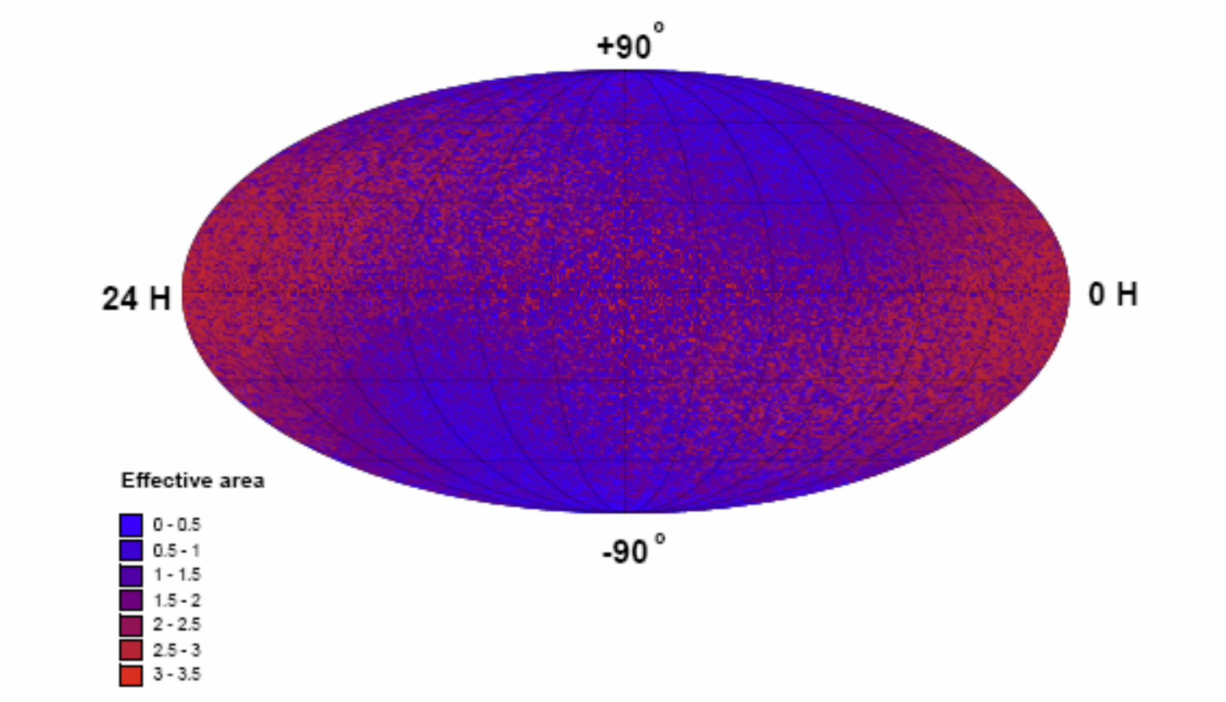
- The network can be improved by adding more spacecraft, and placing them in orbits with different inclinations (placing them in the same orbit won't produce single error boxes)

- Consider a 9-spacecraft network, with 4 spacecraft in an orbit with inclination i=0°, and 5 spacecraft in an orbit with i=56°

Coverage

77% of the sky is covered by ≥3 detectors





Effective Area

The effective area decreases towards the two orbital poles, but does not go to zero anywhere

A New Localization Method

- For 40 years, GRB triangulation has been done by cross-correlating time-binned light curves to obtain annuli, and calculating the intersection points of the annuli to obtain error boxes
- This is because detectors had trigger systems that produced high time-resolution light curves with binning, for a short time after trigger
- The detectors were usually very different from one spacecraft to the next, leading to large systematic uncertainties
- But if the NEN detectors are identical, and downlink continuous time- and energy-tagged photon data, a better method can be used

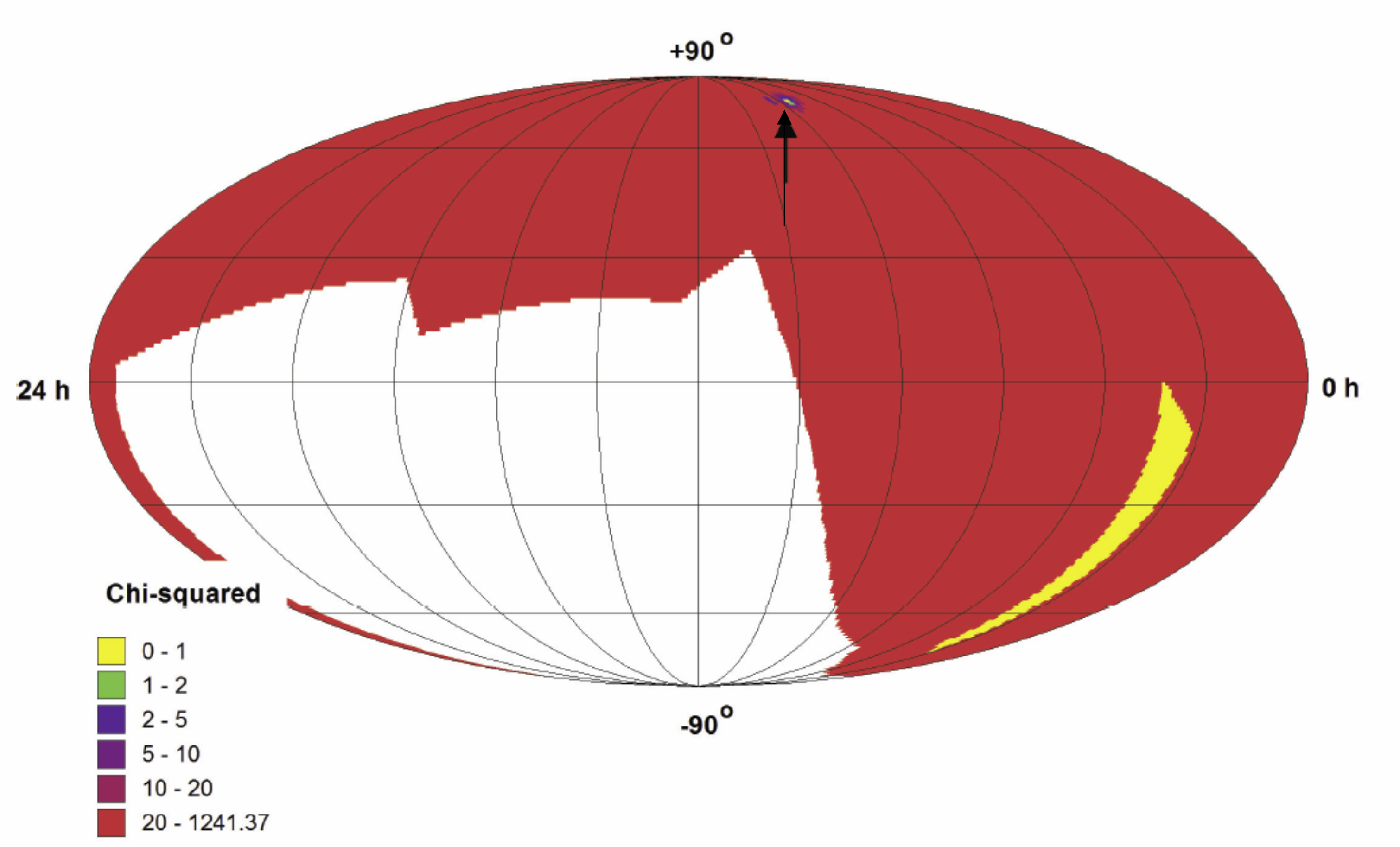
It’s complicated, but briefly…

1. Divide the celestial sphere into ~1° cells
2. For each cell, calculate the crossing time of a hypothetical GRB at each detector in the NEN
3. Sum the counts at each detector over various time intervals
4. Compare the results with the background
5. Calculate a χ^2 for that sky cell
6. Derive the probability that a GRB originated from that cell at that time
7. If the probability is high, explore the region around the cell in detail to derive a localization contour
8. If it is low, go to step 2 and repeat the calculations after some time has elapsed

Simulations

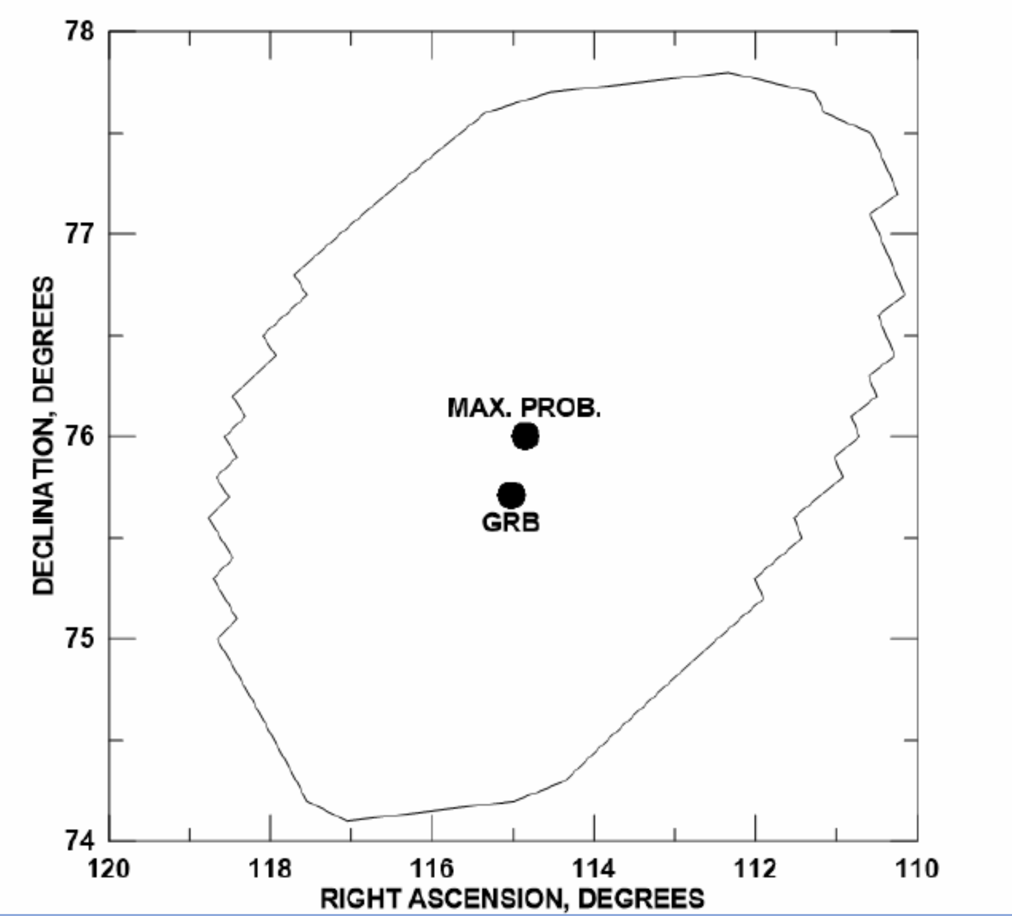
- Number of detectors
- Detector areas
- Detector energy resolution
- Photon timing accuracy
- Burst intensity
- Random GRB arrival directions

One simulation of the sky in χ^2 space



White: areas with no net counts above background
Red, yellow: high χ^2, low probability
Arrow: points to the simulated GRB location

The simulated GRB position, the position where the probability reaches a maximum, and the 3σ localization contour (dimensions ~5°)



After many simulations…

- For a network of 9 100 cm^2 detectors, a 10^{-6} erg cm^{-2} burst produces error boxes roughly equivalent to the *Fermi* GBM

- Possible improvements to reduce size and area of error boxes, and increase sensitivity:

1. Increase the detector areas
2. Add more detectors in the same orbits to increase duty cycle (but spacing decreases)
3. Increase the orbital altitude to increase spacing between detectors and reduce error box dimensions (but background increases)
4. Increase the number of detectors, placing them in a third orbit with a higher inclination (but lower duty cycle)

Spacecraft Requirements for a NEN

- Stabilization (zenith-pointing, several degree accuracy)

- Continuous downlink of time- and energy-tagged photons (energy-tagging could possibly be eliminated if there is active gain control)

- 0.1 ms timing accuracy

- Careful control of systematics:

-Good energy resolution (CZT resolution is adequate)

-Eliminate Earth albedo, which distorts detector responses from cosine law

- All appear to be within current capabilities

- For more details, see ApJ (in press) or https://arxiv.org/abs/2010.04229

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