Advanced Scintillator-Based Compton Telescope for Solar Flare Gamma-Ray Measurements

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A major goal of future Solar and Heliospheric Physics missions is the understanding of the particle acceleration processes taking place on the Sun. Achieving this understanding will require detailed study of the gamma-ray emission lines generated by accelerated ions in solar flares. Specifically, it will be necessary to study gamma-ray line ratios over a wide range of flare intensities, down to small C-class flares. Making such measurements over such a wide dynamic range, however, is a serious challenge to gamma-ray instrumentation, which must deal with large backgrounds for faint flares and huge counting rates for bright flares. A fast scintillator-based Compton telescope is a promising solution to this instrumentation challenge. The sensitivity of Compton telescopes to solar flare gamma rays has already been demonstrated by COMPTEL, which was able to detect nuclear emission from a C4 flare, the faintest such detection to date. Modern fast scintillators, such as $LaBr_3$, and $CeBr_3$, are efficient at stopping MeV gamma rays, have sufficient energy resolution (4% or better above 0.5 MeV) to resolve nuclear lines, and are fast enough (~15 ns decay times) to record at very high rates. When configured as a Compton telescope in combination with a modern organic scintillator, such as stilbene, sub-nanosecond coincidence resolving time allows dramatic suppression of background via time-of-flight (ToF) measurements, allowing both faint and bright gamma-ray line flares to be measured. The use of modern light readout devices, such as silicon photomultipliers (SiPMs), eliminates passive mass and permits a more compact, efficient instrument. We have flown a prototype Compton telescope using modern fast scintillators with SiPM readouts on a balloon test flight, achieving good ToF and spectroscopy performance. A larger balloon-borne instrument is currently in development. We present our test results and discuss the potential of a possible full-scale instrument suitable for flight on a long-duration balloon or Explorer satellite platform.

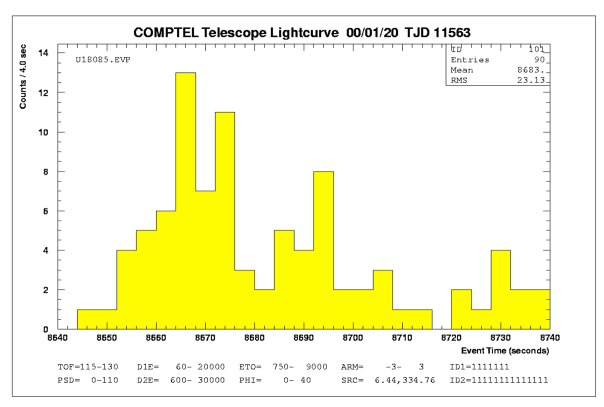
Ion Acceleration Problem

Compared to X-ray flares, γ-ray flares are poorly measured. Almost all those registered in any data base are M class and larger. This is the result of several factors.

- The γ-ray intensity is much weaker than that of hard X rays, requiring large instruments.
- The on-orbit background in the MeV band is very high, primarily from atmospheric neutrons and γ rays.
- Imaging is difficult because the photons are very penetrating.
- Lastly, there is a threshold ion energy for the production of γ rays. This threshold is of order 10 MeV/nucleon. Whether this threshold effect is important is difficult to ascertain, because of the above observation issues.

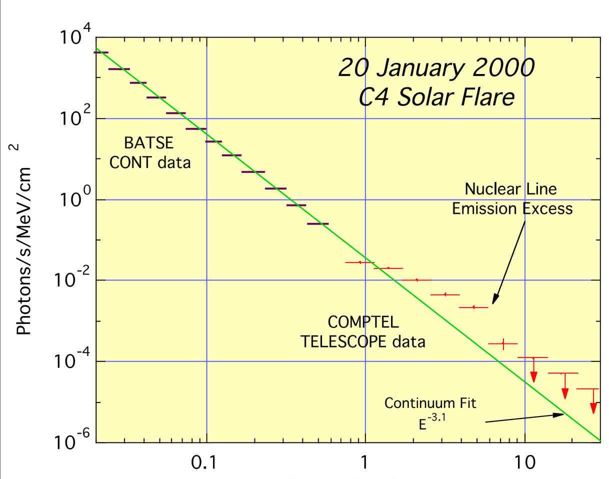
The consequence is that we are uncertain if ions are accelerated in all flares. If so, does the ion spectrum hold its shape as the flare becomes smaller or does the maximum ion energy decrease, so that the γ-ray emission vanishes from the nuclear reaction threshold effect? A subsequent question is how much flare energy is embodied in fast ions, much of it likely invisible, again because of the threshold effect. Naturally, some of the best flares to study are small, uncomplicated events. However, our knowledge of the role of ions in flares is entirely shaped by observations of much larger events, where the rules may be different.

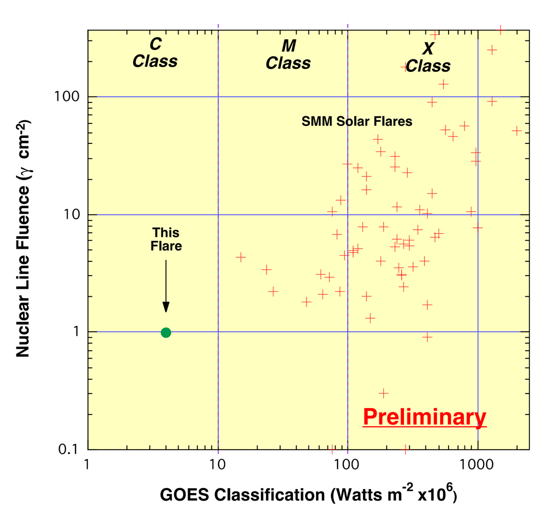
To make progress here, we need a large instrument with low background. This was demonstrated with the COMPTEL experiment on the Compton Observatory. Shown here is the light curve from the C4 flare that occurred on 2000 January 20, toward the end of the mission (Young et al. 2000).



COMPTEL, see below, was a Compton telescope—a double scatter instrument. The double-scatter requirement greatly reduced background. This, plus its size, allowed it to gather good statistics on this event (undetectable in the MeV range by the other instruments). The low background was further improved using its imaging properties, called by some *kinematic collimation*. By knowing the solar direction, one selects photons that conform to the proper scattering geometry, thereby also yielding a much improved energy measure per photon.

Shown below is the derived photon spectrum, X-ray and γ-ray, and the flare's position among the γ-ray flares measured by SMM. Using an unbiased de-convolution algorithm, the emerging photon spectrum exhibits the expected bump from 1-8 MeV, indicative of nuclear emission, continuum and lines. Sharp lines from excited ^{12}C, ^{16}O and other nuclei require greater statistics to resolve.



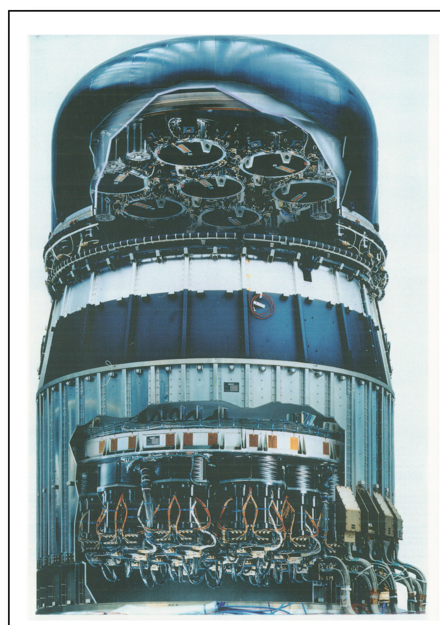


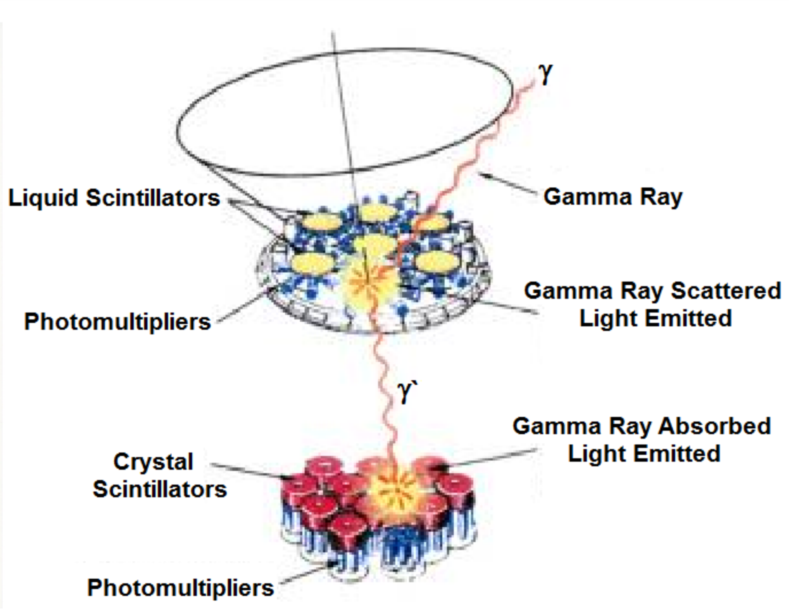
The success of COMPTEL is a stepping stone to instruments with even better background suppression and consequently improved sensitivity and resolving power. This is the objective of the SolCompT project, i.e., to test and evaluate techniques to further suppress background and improve resolving power, both for imaging and spectroscopy.

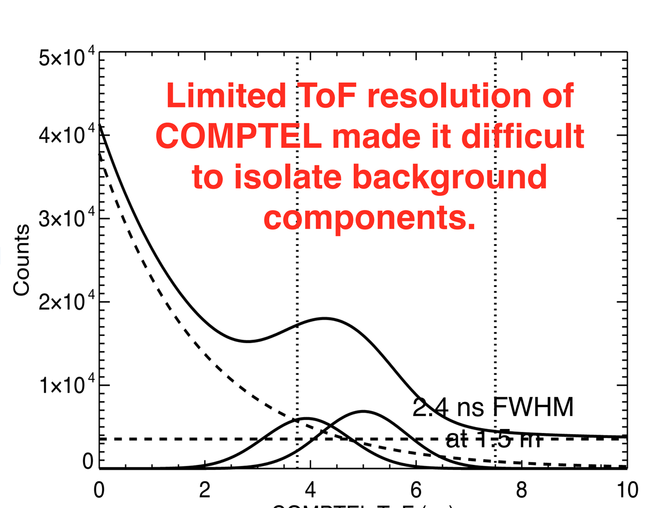
These steps include:

- Improving the Time-of-flight performance using smaller and brighter scintillators that will also improve energy resolution (and angular resolution).
- Replacing standard photomultiplier vacuum tubes with silicon photomultipliers (SiPM) to reduce passive mass.
- Using benign and radiologically quiet materials for structural components to minimize internal activation.

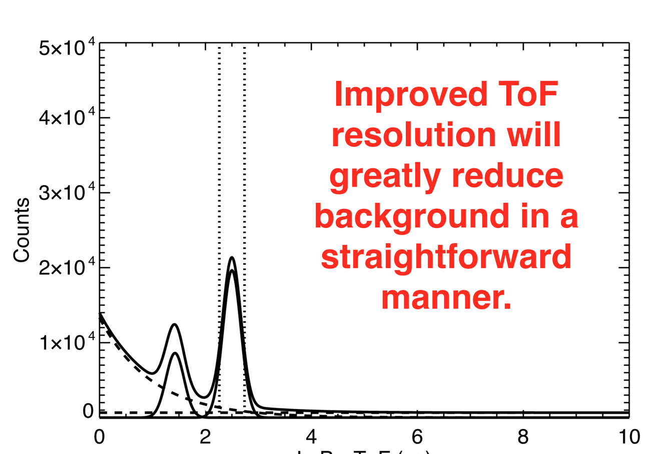
CGRO / COMPTEL and ToF







The COMPTEL instrument on CGRO was a double-scatter instrument (D1 - liquid scintillator D1 / D2 - NaI(Tl)) capable of imaging 0.75-30 MeV gamma rays. With a D1-D2 separation of 1.5 m, it relied on both pulse shape discrimination (PSD) and Time-of-Flight (ToF) to identify and reject various background components (e.g., neutrons and activation of passive materials). The ToF proved to be a crucial aspect of COMPTEL data analysis. We believe that ToF techniques utilizing the latest technologies offer a significant advantage for future Compton telescopes.

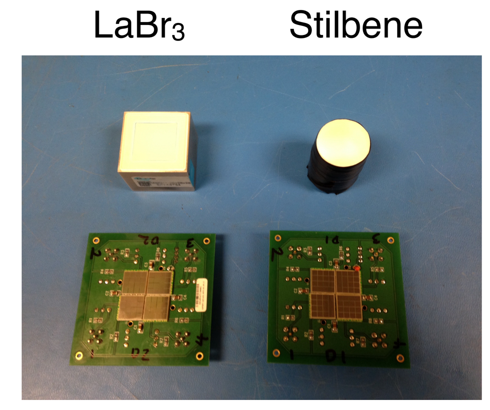


2014 Balloon Flight - SolCompT

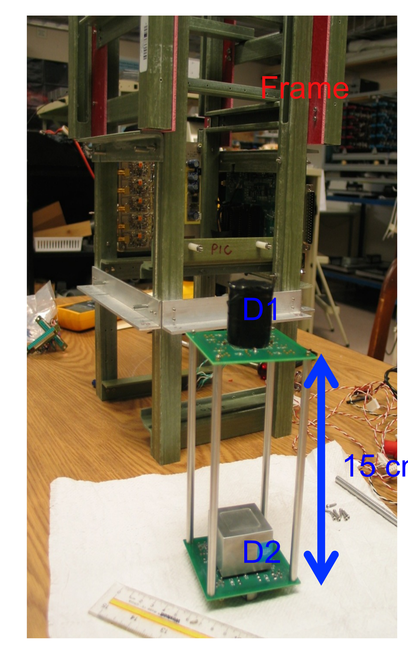
The Solar Compton Telescope (SolCompT) experiment was designed to demonstrate the stable operation of a prototype Compton telescope using advanced scintillators with silicon photomultiplier (SiPM) readout under balloon-flight conditions. Modern scintillators (stilbene in D1; $LaBr_3$ in D2) improve ToF performance, energy resolution, and efficiency compared to COMPTEL, while retaining PSD capability. SiPM readouts greatly reduce passive mass and volume while retaining the performance of PMTs.

SolCompT Instrument and Balloon Payload

D2 LaBr₃ D1 Stilbene



SiPM array readouts

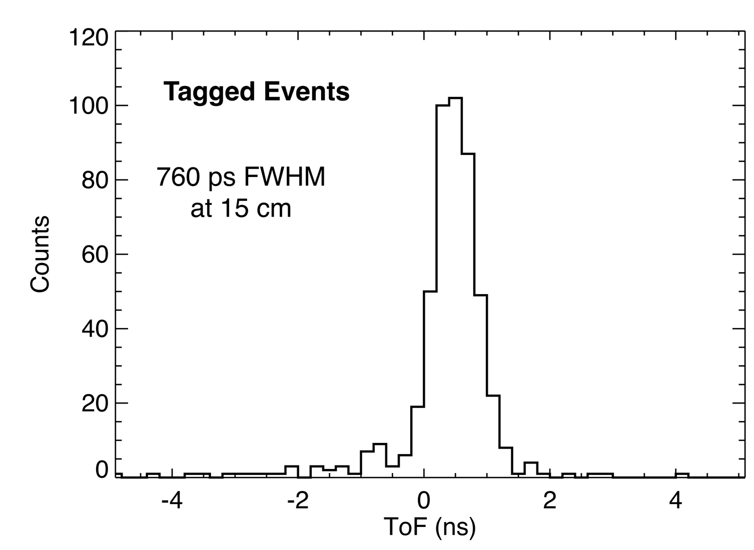


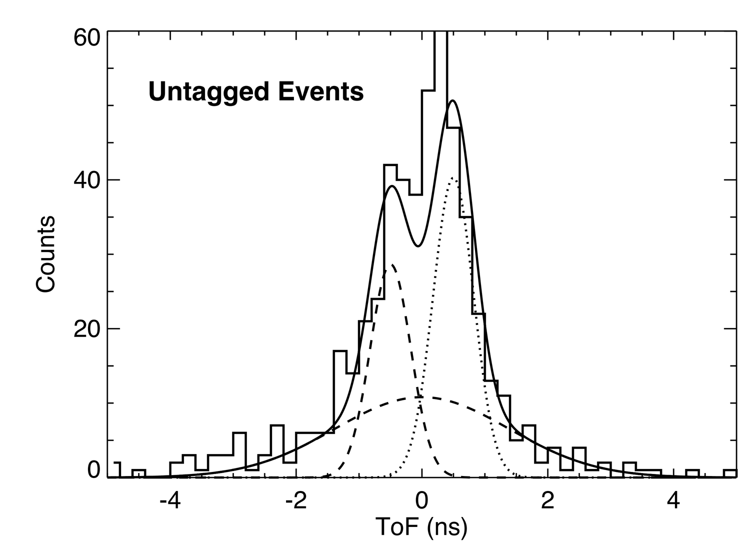
2-element Compton telescope

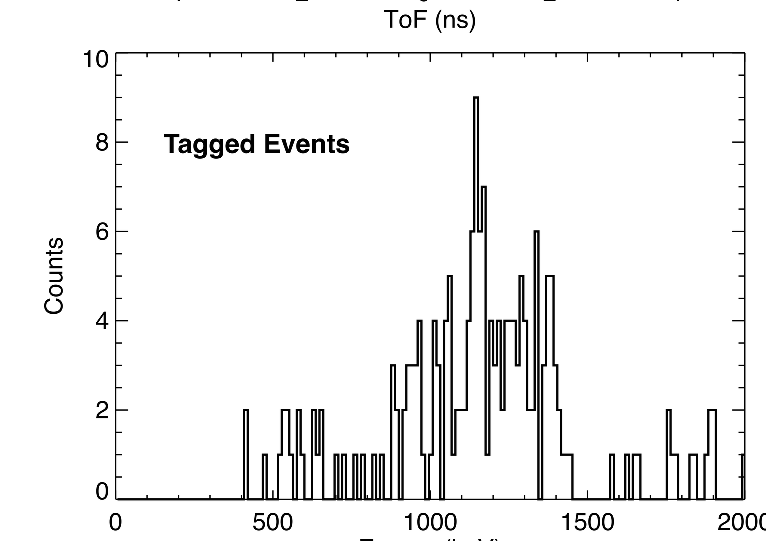
Balloon Payload

2014 Balloon Flight

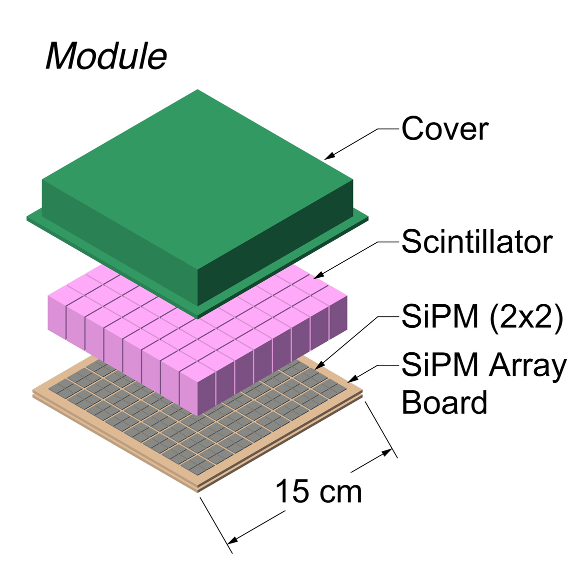
SolCompT flew on a test balloon flight in August 2014 from Ft. Sumner, NM. A tagged ^{60}Co source placed in the field of view gave the instrument a known source of gamma rays to measure. The ToF resolution for tagged events was ~760 ps (FWHM). Untagged background events are hard to interpret due to surrounding passive material in balloon gondola.

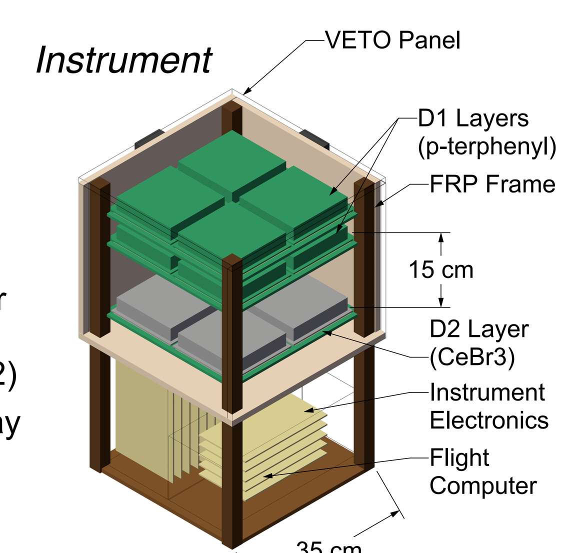


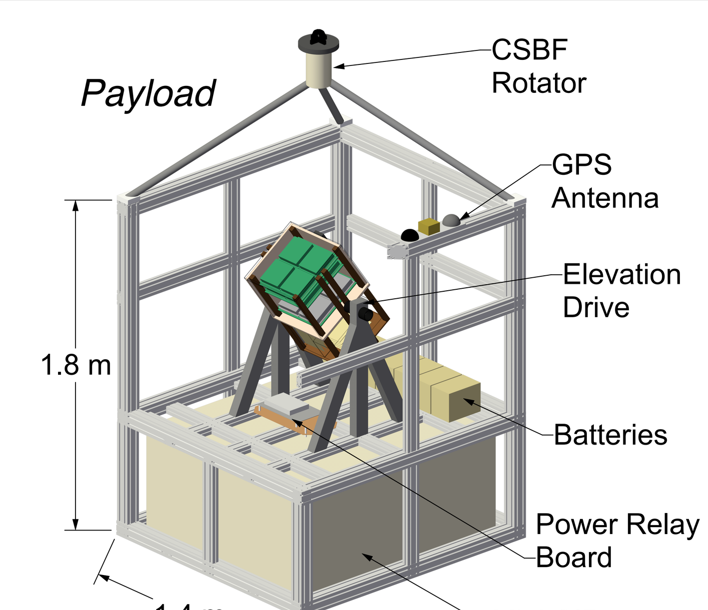




ASCOT Balloon Instrument (2017)







Larger balloon payload (to be launched in 2017) will be capable of measuring the Crab in a 1-day flight. Compton telescope consisting of two D1 layers (organic p-terphenyl crystal with 3 ns decay time) and one D2 layer ($CeBr_3$ with 16 ns decay time) separated by 15 cm. $CeBr_3$ chosen because it is more easily obtained and has lower intrinsic background than $LaBr_3$. Smaller separation increases both the effective area and the FoV. Estimated Crab sensitivity for a 1-day flight is about 4σ.

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