Los Alamos
NATIONAL LABORATORY
EST. 1943

Variance Reduction at Scale

Improving IMC variance reduction methods for thermal transport problems

Scott Campbell

Gonzaga University
Physics & Math-Computer Science

LA-UR-19-28106

Introduction & Theory

Thermal Radiative Transport (TRT)

- $$\frac{1}{c}\frac{\partial I}{\partial t}(\vec{r},\vec{\Omega},\nu,t) + \vec{\Omega}\frac{\partial I}{\partial \vec{r}}(\vec{r},\vec{\Omega},\nu,t) + \sigma_a(\vec{r},\nu,T)I(\vec{r},\vec{\Omega},\nu,t) = 2\pi\sigma_a(\vec{r},\nu,T)B(\nu,T) + \frac{Q}{2}(\vec{r},\nu,t)$$
- $$c_v(\vec{r},T)\frac{\partial T}{\partial t}(\vec{r},t) = \int_0^\infty \int_{-1}^1 \sigma_a(\vec{r},\nu',T)\left[I(\vec{r},\vec{\Omega'},\nu',t) - 2\pi B(\nu',T)\right]d\vec{\Omega'}\,d\nu'$$

Implicit Monte Carlo (IMC)

- Developed by Fleck and Cummings in 1971 [1] to solve the TRT equations
- Uses 'effective scattering' events to model absorption/re-emission
- Two major approximations:
  1. Semi-implicit discretization of time
  2. Linearizes the TRT equations – not fully physical

Introduction & Theory Cont.

Standard Variance Reduction Methods

- IMC is stochastic – there is inherent uncertainty in the solution
- Variance reduction methods are implemented to improve simulation efficiency while producing equivalent unbiased results (e.g. implicit capture, splitting, Russian roulette, weight windows, etc.) [2]

Next Event Estimators (NXTEVT)

- Effective for limited particle histories, and large mean free paths [3] – i.e. few scattering events and few transported particles
- Method: 'points' particles toward region of interest and scores the tally accd. to

$$\phi(\mu) = w_0 \frac{e^{-\int_{\vec{r}}^{\vec{r'}} \Sigma_t(s)ds}}{S \bullet \mu}$$ where μ is angle between $\vec{\Omega}$ & $\vec{r'}$, the surface normal, Σ_t is the total cross-section in the material, and S is the tally surface area

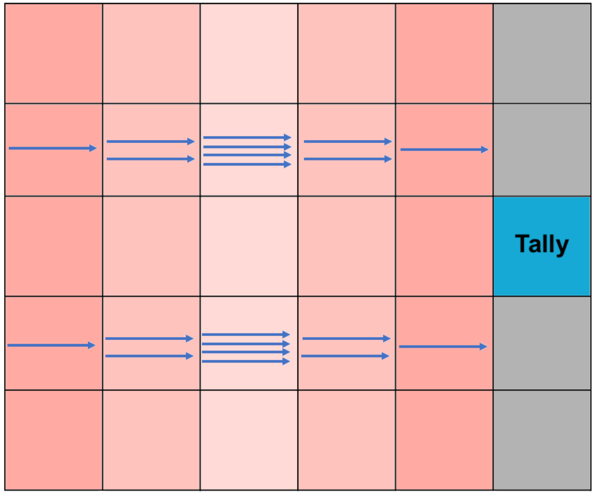


***Figure 1**:*

A visualization as to why splitting and Russian roulette are ineffective in cases of interest to NXTEVT. Particles not initially directed towards the tally won't likely reach it.

Research Objective & Motivation

Motivation

- We attempt to produce a light curve with Monte Carlo from a simplified model of a supernova (*SN2006gy*) interacting with its circumstellar medium [4]
- The opacities of the supernova ejecta and ejecta-CSM Shock do not lend itself well to standard VRMs or the NXTEVT estimator
- The multi-physics involved require a large number of particles for answer to converge – makes the simulation computationally expensive

Objective

- Investigate the advantages of a response function based VRM for problems modeling supernova-CSM interactions
- Provide high-quality simulation data to compare with physical observation

Method and Technical Approach

Response Function Method Overview

- Run two problems – an inverse and a forward problem:
- The inverse transport problem generates the response function value (σ_r) for each cell
- The forward transport problem is run, using the σ_r values to tally at a particle's birth and every subseq. scatter event

Inverse Transport

- Initialize the particle uniformly on the tally surface, and direct it towards the source via cosine-distribution
- Trace particle through the mesh, calculating σ_r based on:
  - Weighted σ_a value the particle encounters based on the distance it travels through each cell
  - Weighted σ_a value for each cell based on every particle that passes through $\rightarrow \sigma_r$

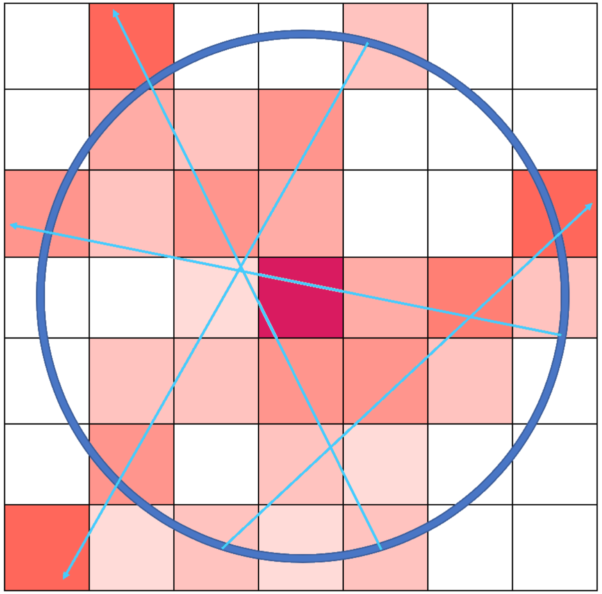


***Figure 2**:*

A visualization of the inverse transport method. The source is the purple cell, and a darker shade of red corresponds to a higher σ_r value.

Method Cont. & Testing

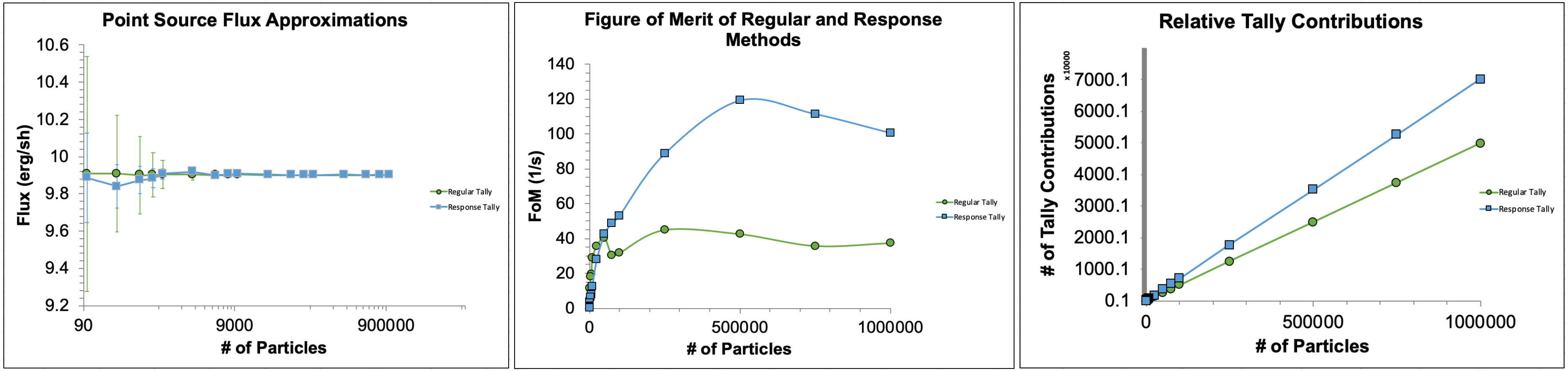
Forward Transport

1. Upon the particles creation, a contribution is added to the tally accd. to:

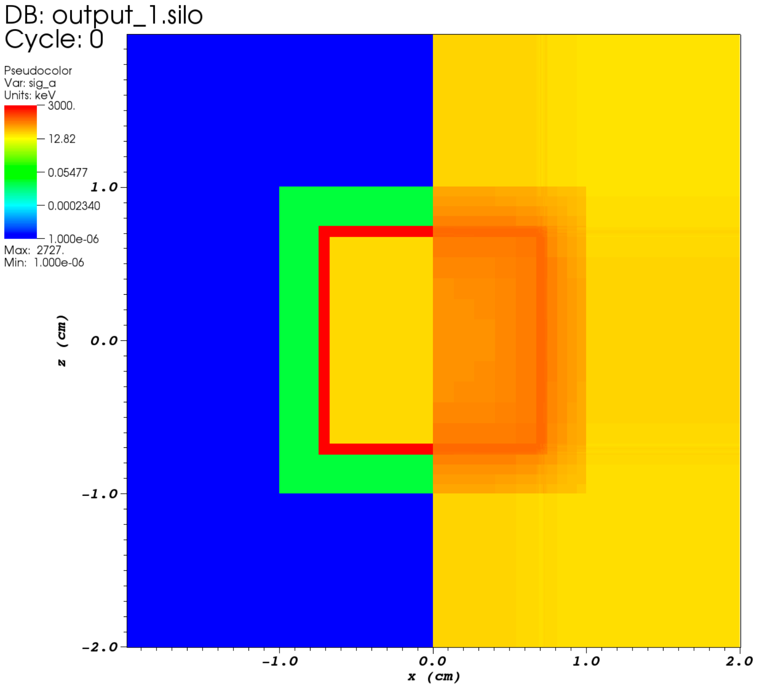
$$Contribution = E_{particle} e^{-\left(\sigma_r + \frac{1}{c\Delta t}\right) d_{tally}}$$

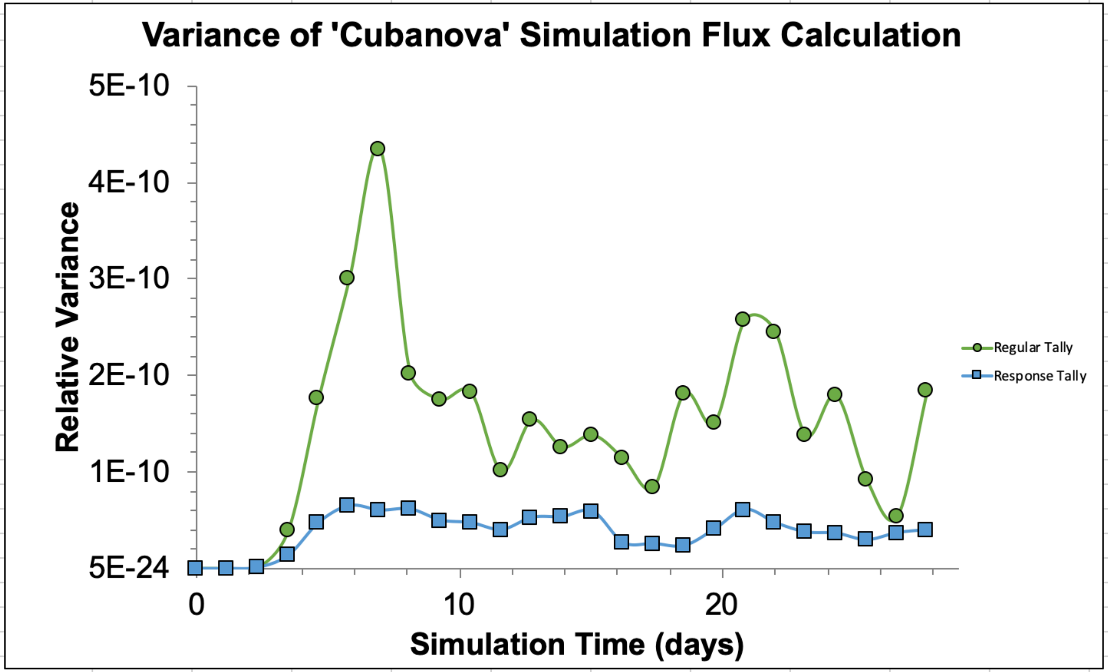
2. Transport the particle through the mesh. If the particle is scattered, add a contribution to the tally as above
3. Repeat 1 & 2 for the duration of the timestep or until absorbed. Repeat for all particles

Test Problem

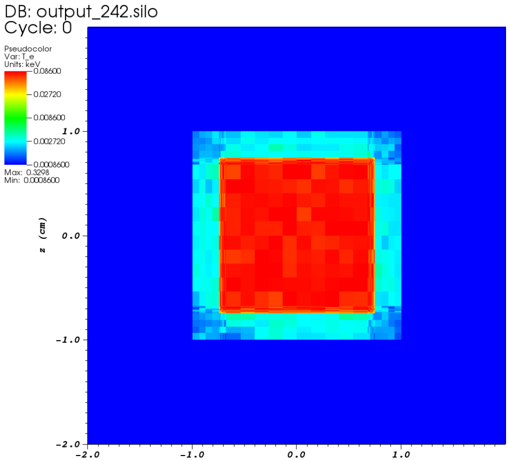


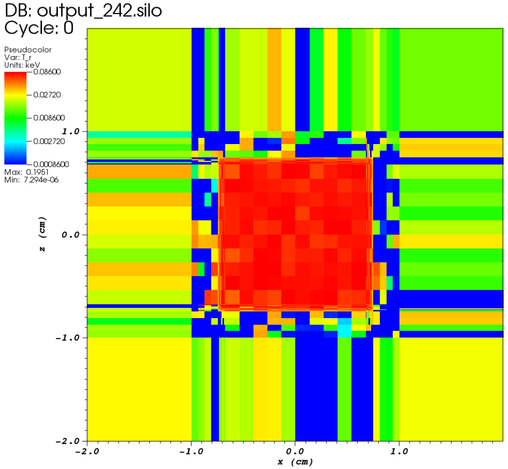
Supernova Applications

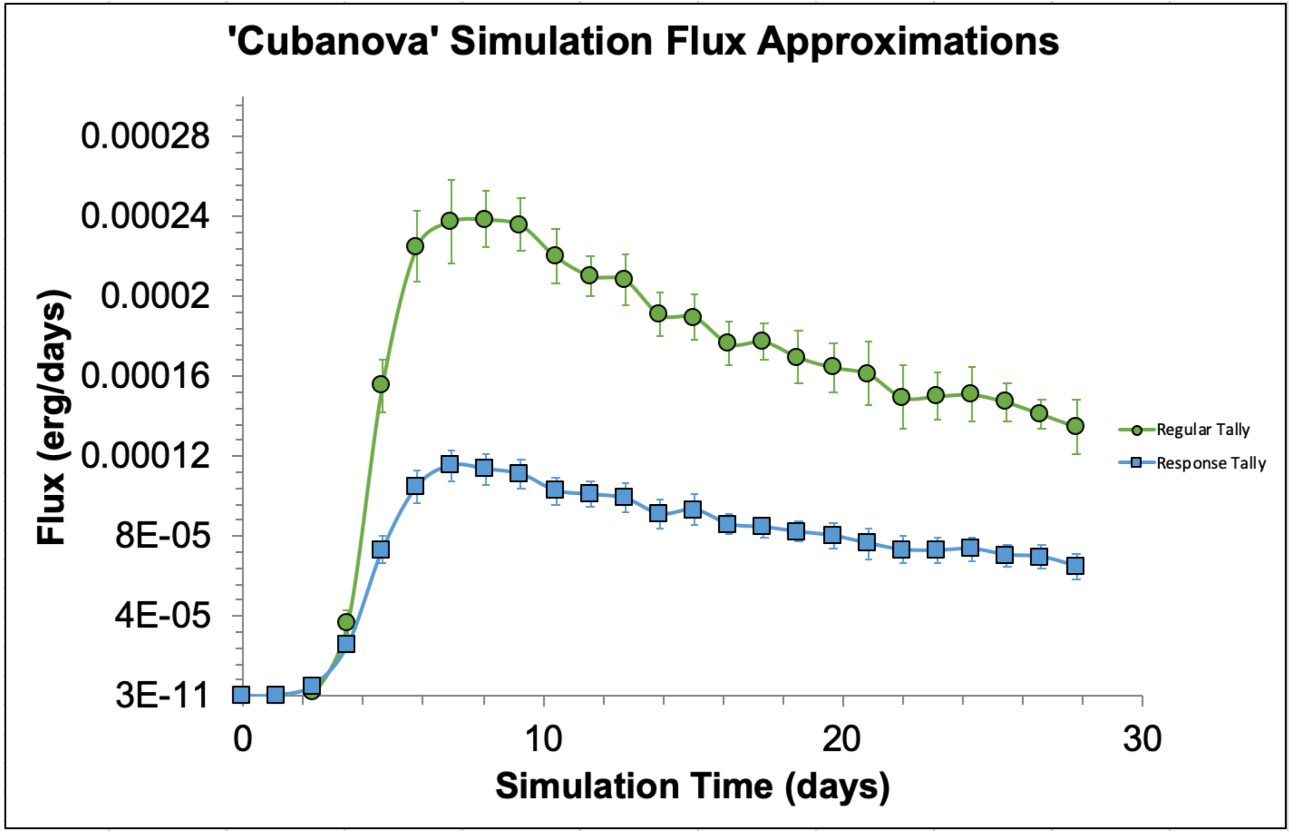




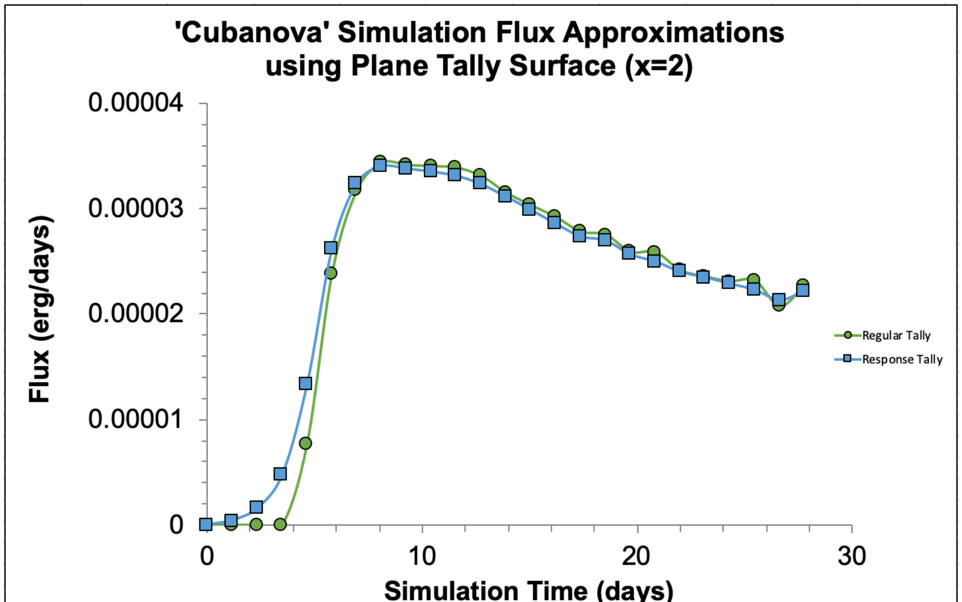
Supernova Applications Cont.

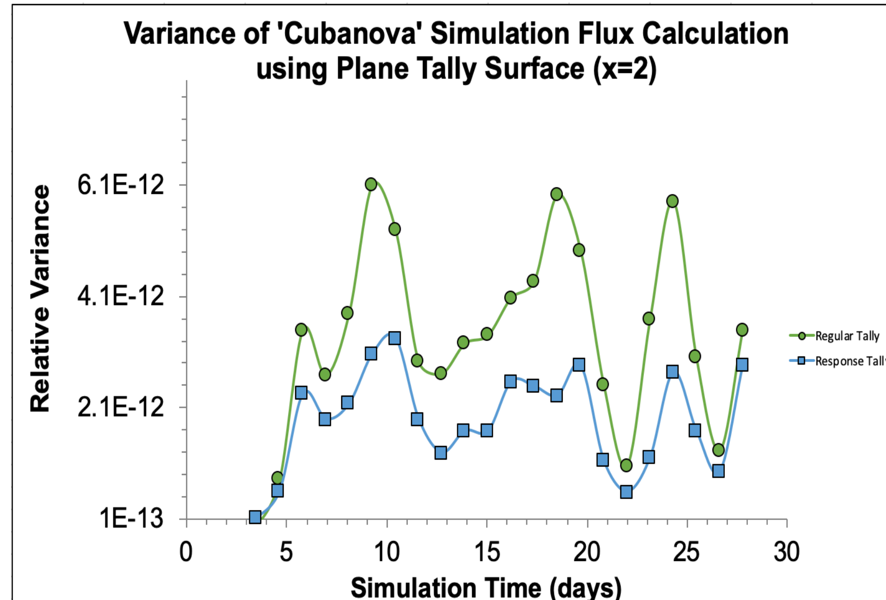




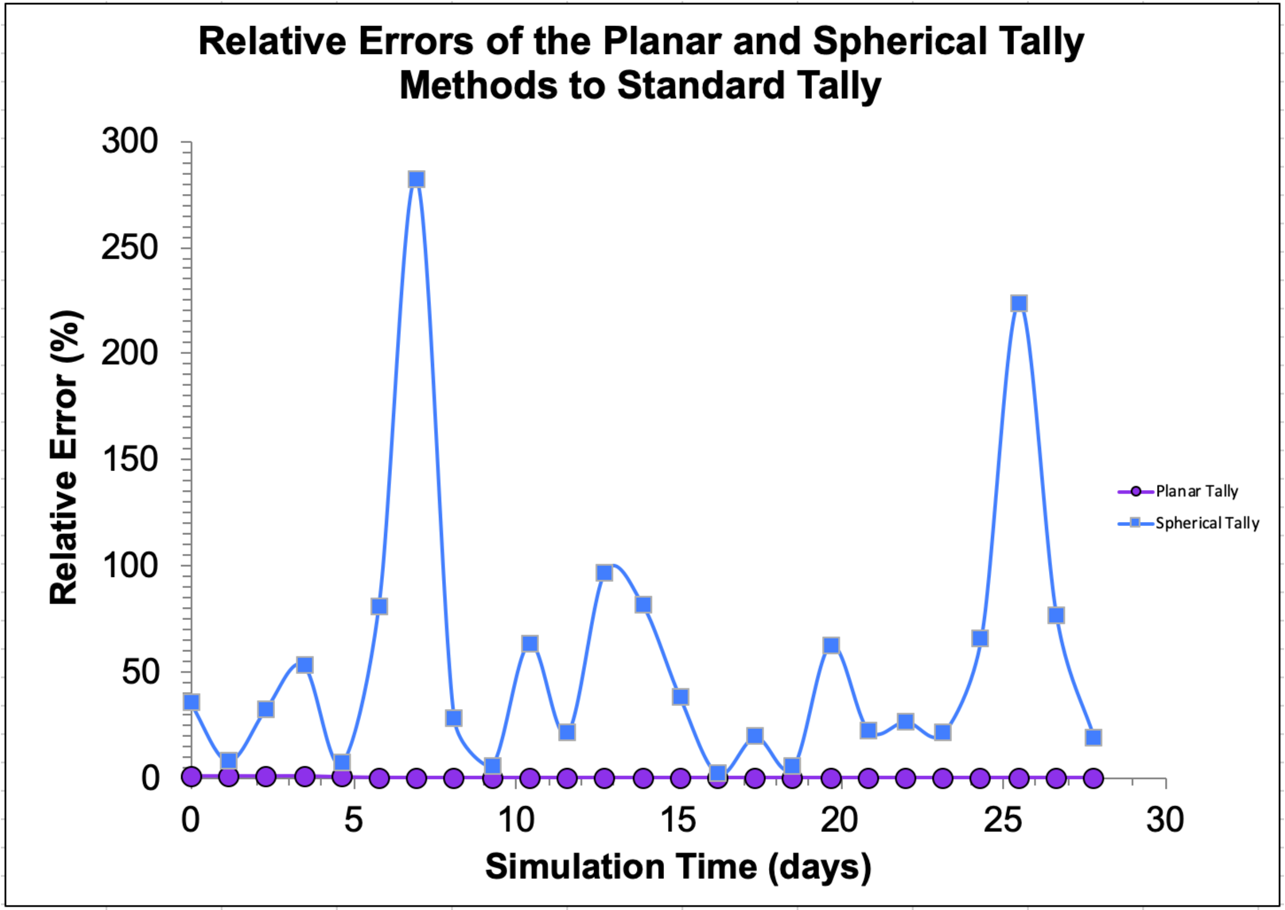


Supernova Applications Cont.





Supernova Applications Cont.



Conclusions & Future Work

- Our investigation into the use of a response function-based variance reduction method has shown a notable improvement in variance over standard methods.
- Our method can be applied to astrophysical events such as supernova interactions with its CSM
- There is a strong link between problem and tally geometry in determining how effective our method will perform
- Future work will be looking at potentially improving the directionality of the response function and its performance for other tally geometries.

Acknowledgements & References

Acknowledgements

- We would like to thank the XCP Summer Computational Physics Workshop, its directors, and its mentors for the opportunity, time, and mentorship.
- I would like to personally thank Mat Cleveland, Kendra Long, and Ryan Wollaeger for their mentorship and expertise.

References

[1] J.A. Fleck, Jr. and J.D. Cummings, Jr., “An implicit Monte Carlo scheme for calculating time and frequency dependent nonlinear radiation transport,” *J. Comp. Phys.* 8, pp. 313–342, (1971).

[2] J.T. Landman, “Variance reduction strategies for implicit Monte Carlo simulations,” PhD thesis, Texas A&M University, *Texas A&M University*, (2016).

[3] W.T. Dailey, “Ray next-event estimator transport of primary and secondary gamma rays,” PhD thesis, Air Force Institute of Technology, *Air Force Institute of Technology*, 2011.

[4] T.J. Moriya, S.I. Blinnikov, N. Tominaga et al., “Light-curve modelling of superluminous supernova 2006gy: collision between supernova ejecta and a dense circumstellar medium,” *MNRAS* 428, pp. 1020–1035, (2013).