

2025 SCEC Proposal

**Improvement and Harmonization of Optical Observations of the Coseismic
Fault Zone Deformation Towards an Enhanced Understanding of the Shallow
Fault Zone Behavior**

Final report

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SCEC Identifier: 22015

Proposal Category: Individual Research Project (Single Investigator / Institution)

SCEC Science Priorities: A1-2, B2-1, B3-3

SCEC Community Earth Models: Community Velocity (UCVM) and Community Rheology (CRM) models will be used to constrain the crustal rheological properties in the numerical modelling applications of the project. The Community Fault Model (CFM) will eventually be used to constrain the pre-existing faults across the study sites.

#1 Abstract: Describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

In line with the objective “*Improving observations and closing critical data gaps*” from the 2025 SCEC Science Plan, this project supported the development of new functionalities, documentation and tutorials for Cosi-Corr+ to become a complete, user-friendly, and open-source package for performing fast, optimized, and precise 3D satellite optical image cross-correlation. We used case studies to demonstrate the efficiency and accuracy of Cosi-Corr+, and explore the impact of these observations on the understanding of the processes. We applied the COSICorr+ method in particular to the case of the 2025 $M_w 7.7$ Mandalay, Myanmar earthquake. Our measurements revealed a 700-km long, straight and continuous surface rupture, making it the largest continental rupture ever observed (Antoine et al, PNAS, 2026). These measurements were combined with SAR measurements to produce 3D displacements. These 3D displacement data were inverted to infer the fault geometry at depth, and produce a finite-fault model representing the distribution of slip on the fault at depth. The surface offsets were next used to constrain a quasi-dynamic model of the Sagaing Fault earthquake cycle which reproduces sequences of earthquakes including events similar to the 2025 earthquake.

#2 Intellectual Merit: does the project contribute to the overall intellectual merit of SCEC? For example: *How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?* (Maximum 100 words.)

The COSI-Corr+ project has contributed to SCEC's intellectual merit by providing an open source software to measure ground deformation. The measurement of co-seismic deformation has advanced our understanding of earthquake sources by providing constraints on co-seismic slip distribution. These measurement have been be used to constrain the evolution of fault friction during seismic slip which is a central piece of physics needed to develop dynamic models of the earthquake cycle.

#3 Broader Impacts: How does the project contribute to the broader impacts of SCEC as a whole? (Maximum 100 words.)

The project has contributed to the broader impacts of SCEC by promoting educational opportunities, fostering mentoring and training at Caltech, encouraging cross-collaboration within the SCEC community, and reaching out to educate our local communities. Additionally, the project has strengthened research infrastructure through enhanced data-sharing networks and collaborators and provided valuable societal benefits by advancing efforts in earthquake preparedness.

Summary of results

Project motivation

High resolution satellite images with improved spatial and temporal resolution provide unprecedented opportunities to measure Earth Surface displacement in 2D and 3D. Optical image correlation is particularly used to image recent earthquakes, or revisit past earthquakes, and measure surface fault displacements, and so with unprecedented resolution and precision (*e.g.*, Antoine et al., 2026; Milliner et al., 2016). Optical displacement maps are now a common observable produced after continental earthquakes (*e.g.*, Milliner et al., 2024), and used to constrain finite-fault inversions and dynamic rupture models (*e.g.*, Antoine et al., 2025).

Supported by SCEC (2021: SCEC#21002; 2022: SCEC#22015), a new optimized image cross-correlation tool, named Cosi-Corr+, was developed to perform image correlation (Aati et al., 2022). In line with the objective “*Improving observations and closing critical data gaps*” from the 2025 SCEC Science Plan, this project has aimed at further developing functionalities, documentation and tutorials for Cosi-Corr+ to become a complete, user-friendly, and open-source package for performing fast, optimized, and precise 3D satellite optical image cross-correlation. We use case studies to demonstrate the efficiency and accuracy of Cosi-Corr+, and explore the impact of these observations on the understanding of the processes, both from an observational and modeling perspectives. We will also build tutorials as part of the final product package.

Primary case study

We applied the COSICorr+ method to the case of the 2025 M_w 7.7 Mandalay, Myanmar earthquake. Within a few days after the event, we downloaded pre- and post-event Sentinel2 satellite optical images that have a 10 m ground resolution. Two pre- and post-event pairs were cross-correlated, and the results mosaicked to produce horizontal displacement map over the full, rupture area (Figure 1a). Sensor-specific artefacts were removed by fitting spline functions to the artefact patterns outside of the earthquake displacement areas. Large-scale errors due to sensor model calibration were removed by fitting second order polynomials to the signal outside of the earthquake displacement areas. These measurements revealed a 700-km long, straight and continuous surface rupture, making it the largest continental rupture ever observed.

These measurements were used directly to infer 1) the surface rupture location, geometry, and length, and 2) the surface fault displacements (called offsets) (Figure 1b). These measurements were used to constrain two types of numerical models. First, the 2D displacement maps were combined with SAR measurements to produce 3D displacement maps with optimum signal to noise ratio across the near-field, where optical is more accurate, and far-field, where SAR is more accurate. These new maps were inverted together with the surface offsets to infer the fault geometry at depth, and produce a finite-fault model representing the distribution of slip on the fault at depth (Figure 2). The surface offsets were later used to constrain a quasi-dynamic model of the Sagaing Fault earthquake cycle which reproduces sequences of earthquakes including events similar to the 2025 earthquake (Figure 3).

Based on the CosiCorr+ image analysis and subsequent modeling works, we proposed the following observations: - the surface rupture is longer than expected from typical earthquake

scaling laws, - the earthquake re-ruptured fault sections that experienced significant ($M > 6.8$ earthquake) over the last 50 years, - surface slip only partly fits with that expected from the slip-predictable model, and slip was larger than expected in several areas, especially those that already ruptured recently, - slip does not significantly penetrate deeper within the creeping transition zone as it is sometimes observed for large earthquakes, and – there is no significant shallow slip deficit for this event. The quasi-dynamic modeling of the earthquake cycle on the Sagaing Fault shows that fault geometry, especially its continuity in some places but also the presence of few geometrical complexities, largely controls the patterns of earthquake recurrence, including where earthquakes start and stop, and their magnitude.

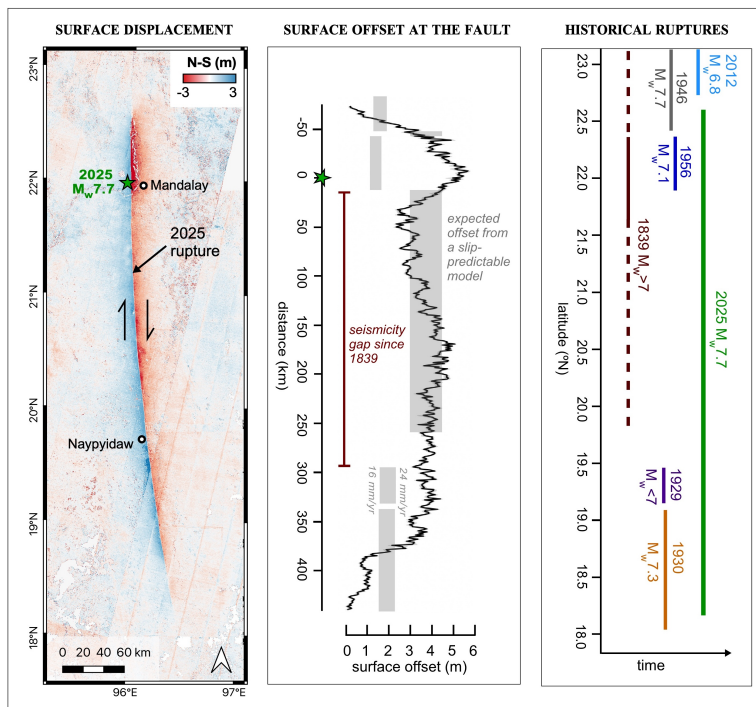


Figure 1. North-South (NS) surface displacement associated with the 2025 earthquake from the correlated Sentinel2 images. (b) Fault-parallel surface offsets extracted from the Sentinel2 displacement maps. Grey dashed polygons are the expected slip using a slip-predictable model, an interseismic loading of 16-24 mm/yr, and the rupture history from (c). No prediction is proposed in regions without known past ruptures. Seismicity gap identified in (Wang et al., 2014) is indicated with the brown horizontal line. (c) Horizontal extend of past ruptures documented by Wang et al., (2014) and of the 2025 rupture (this study). Horizontal distribution of the events reflects their relative chronology.

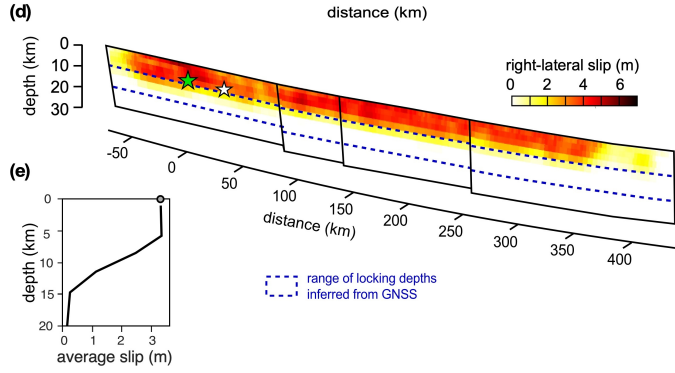


Figure 2. (a) Finite slip model for the 2025 Mandalay earthquake, including the M_w 6.7 aftershock and the M_w 7.7 mainshock. Hypocenters are projected onto the fault plane, and indicated with a green and white star for the mainshock and aftershock, respectively. Dashed blue box highlight the range of locking depths inferred from GNSS ¹⁷. (b) Integrated slip distribution along the depth of the model. The grey dot at 0 km is the average surface slip from the offset data.

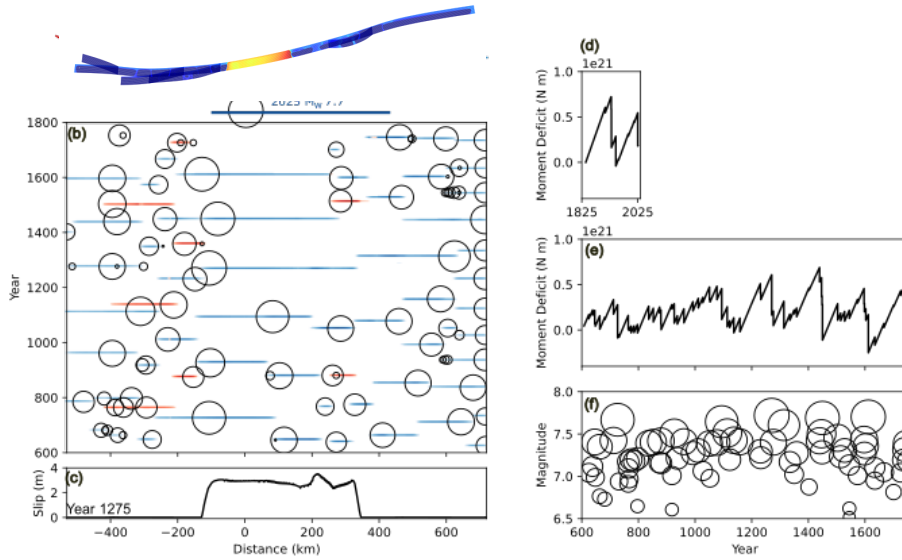


Figure 3. Quasi-dynamic seismic cycle simulations of the Sagaing fault. (a) 3-D view of the model. The snapshot is taken at a time of the propagation of a M_w 7.7 event on the central section of the fault, similar to the case of the 2025 event. The color represents the slip rate, with warm colors representing values up to $>1\text{m/s}$. (b) Time series of ruptures once a steady-regime is reached.

Ruptures of the main fault are shown in blue and on secondary faults in red. Circles show epicentral locations with a size proportional to magnitude. (c) Slip (averaged along dip) for a simulated event that occurred in 1933 with rupture similar to that observed in 2025. (d) Known moment deficit as a function time calculated using a locking depth of 13 km, a slip rate of 20 mm/yr and the magnitudes reported in the ISC-GMS catalog. The left panel in (d) has the same time scale as the panels below. (e) Simulated moment deficit and (f) Earthquake magnitudes from Quake-DFN. For computational efficiency the characteristic distance of the friction law is set to 3cm. This value results in a relatively large nucleation size so that the model produces events with magnitude generally larger than 6.5.

Products

The open-source software COSI-Corr+ is available on [GitHub](https://github.com/gnssguo/Geospatial-COSICorr3D.git) (<https://github.com/gnssguo/Geospatial-COSICorr3D.git>). The software include all the tools previously available in the COSI-Corr+ version as well as the new tools developed for batch data processing and time series analysis. Application to the 2025 Mw7.8 Mandalay, Myanmar, earthquake was published at the [Proceedings of the National Academy of Sciences](#) (Antoine et al., 2025), and cited 40 times at the date of the writing of this report. This work attracted the attention of the non-scientific community, and was highlighted in a [first-page article at the Los Angeles Times](#) in July 2025 (<https://www.latimes.com/california/story/2025-08-11/what-would-a-future-san-andreas-earthquake-in-california-look-like-this-study-offers-clues>), and other news medias. Another associated publication that uses the results from this study was just accepted at Science Advances (Chen et al., accepted).

Commented [AS1]: <https://github.com/gnssguo/Geospatial-COSICorr3D.git>

Conclusions, and ongoing work

The current project demonstrated the potential of CosiCorr+ for measuring surface displacements. Especially, in the aftermath of the event, is demonstrated how fast and accurate the measurements can be, and how they can be used to constrain different types of numerical models. The subsequent publications and communications in seminars, conferences, but also in non-scientific medias enhanced the interest from the community in these methods. To facilitate the use of the software by a wider community, documentation was produced and given individually when asked. A public documentation is currently in creation, and will be added to the GitHub page. Video tutorials on “How to get the data and generate optical displacement maps” are also in production. Ongoing work also include time-series analysis of the image correlation products for applications to, for example glaciers and debris flows in across Nepal.

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