Visualization of Earthquake Simulation Data

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Abstract – **We present various techniques to visualize time-varying, 3D earthquake modeling datasets. We use RIVA (Remote Interactive Visualization and Analysis) to visualize the surface deformation as a synthetic interferogram overlaid on top of a high resolution LandSAT image and digital terrain. We use ParVox (PARallel VOXel Renderer) to visualize the simulated normal stress and shear stress along the Northridge fault and the Landers faults after an earthquake. We use MSLT (Multi-Surface Light Table) to visualize the simulated stress and slip on the fault surfaces underneath the terrain. The data we visualized was generated from two earthquake models, GeoFEST and Virtual California. GeoFEST is a 3D finite element simulation modeling solid stress and strain. Virtual California is a Monte Carlo code that generates simulated earthquakes on an arbitrary fault surface mesh. Both models were developed under the QuakeSIM project sponsored by ESTO/CT.**

I. INTRODUCTION

The development of space-based instruments, such as the GPS Network and InSAR missions, has led to more precise, high fidelity, and real-time measurements. These NASA-developed space systems have facilitated and revolutionized our understanding of earthquake processes and fault interactions. JPL is developing a fully interoperable solid earth system science framework, called QuakeSim [1], to create an understanding of active tectonics and earthquake processes. The QuakeSim project develops tools to simulate earthquake processes, and manage and model the increasing quantities of space-based data now available. These tools include a research-oriented database system, a collaborative portal environment and three scalable parallel simulation codes, namely GeoFEST, PARK and Virtual California.

GeoFEST [2] is a 3D finite element model that uses stress-displacement finite elements to model stress and flow in a realistic model of the Earth's crust and upper mantle in a complex region such as the LA Basin. The model includes stress and strain caused by the elastic response to an earthquake event in the region of the slipping fault, the time-dependent visco-elastic relaxation, and the net effects from a series of earthquakes.

GeoFEST produces a time-sequence of 3D unstructured grid datasets. It generates displacement data on the nodes and stress tensor data on the elements. Scientists are interested in seeing the vertical displacements at the co-seismic and post-seismic time as well as the stress invariants around the fault segments.

Virtual California [3] is a program that utilizes the Monte Carlo method in order to generate simulated, realistic earthquakes on an arbitrary fault surface mesh. It uses topologically realistic networks of independent fault segments that are mediated by elastic interactions. These segments can be designed to represent fault systems spanning the region of California.

Virtual California models the stress accumulated on the fault segments and the slip caused by the simulated earthquakes. It also produces surface displacement in the modeled region. The simulation time is typically many thousands of years. Both GeoFEST and Virtual California produce massive amounts of data. The type of data they produce varies from 3D tensor data on a multi-resolution tetrahedral mesh (stress from GeoFEST), and scalar data (stress and slip from Virtual California) on arbitrary fault surfaces, to interpreted 2D surface data (displacement from both GeoFEST and Virtual California). Because of the diverse nature of the variables, it requires different visualization techniques to present the data effectively.

In this paper, we present three visualization software tools used to visualize the GeoFEST and Virtual California datasets. RIVA (Remote Interactive Visualization and Analysis System) [4,5], a parallel terrain renderer, is used to visualize the surface displacement data on top of high-resolution terrain images and realistic terrain. ParVox [5,6], a parallel volume rendering system, is used to visualize the stress on GeoFEST's unstructured mesh elements. MSLT (Multi-Surface Light Table) [7], an OpenGL based 3D terrain pan and zoom software tool, is used to visualize the slip and stress on the fault surfaces underneath the terrain.

II. SURFACE DISPLACEMENT VISUALIZATION

Interferometric Synthetic Aperture Radar (InSAR) provides a new way to measure, from the earth orbit, ground deformation caused by a major earthquake. About 10 years ago, the European Space Agency's ERS satellite produced a striking image of ground displacements caused by the magnitude 7.3 Landers earthquake, which struck about 150 km east of Los Angeles on 28 June 1992. Fig.1

is the interferogram generated by combining two InSAR images one taken by ERS-1 before and one after the Landers' earthquake. Each cycle of interference colors (from red to blue, also called color fringe) represents a 2.8 cm of ground motion in the direction of the satellite.

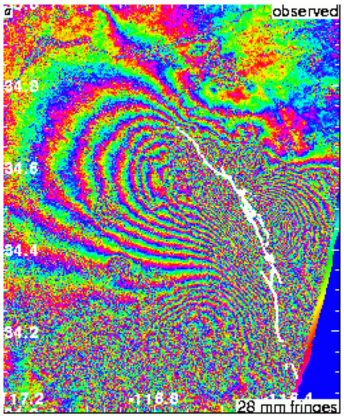


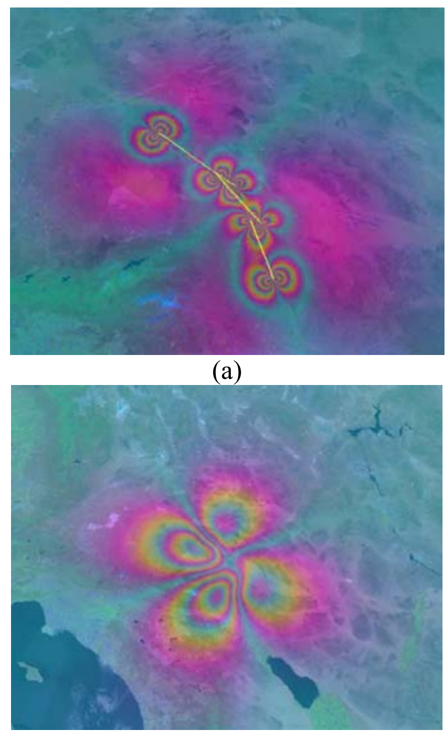
Fig. 1 InSAR Interferogram showing surface deformation from Landers Earthquake

A. GeoFEST

GeoFEST generates strain vectors, i.e., displacements, on tetrahedral nodes simulating the coseismic and post-seismic surface movement due to a major earthquake event. It is most effective in representing vertical displacement on the surface mesh as a synthesized interferogram. As such, we can compare and validate the simulation results with the InSAR observation data. In addition, we would like to overlay the interferogram on top of the real terrain image and digital elevation map. The following steps are required to convert the raw simulation data into such a visual representation:

1. Extract vertical displacement component from the nodes on the surface.
2. Calculate the difference between the displacement of the first simulation step and that of the following time steps. The difference represents the accumulated postseismic deformation.
3. Interpolate the displacement data on the triangle mesh into regular grid of a selected resolution.
4. Transfer the displacement data into a colored image mimicking the InSAR interferogram.
5. Extract the LandSAT image and digital elevation map for the problem domain and coregister the GeoFEST interferogram.
6. Render the LandSAT and GeoFEST surface displacement interferogram using RIVA.

Fig. 2(a) is a RIVA image of the simulated displacement interferogram from the Landers' earthquake. Fig. 2(b) is the postseismic deformation 500 years after the Landers' earthquake. Each color fringe represents 5.6 cm vertical displacements, equivalent to the wavelength of a C Band SAR. Note the two images were rendered at different viewpoints. The second image was rendered at a higher altitude because the postseismic deformation covers a much larger area than the coseismic deformation. The Landers simulation covers an area of 1000 km by 1000 km with a depth of 60km. There are 1.25 million tetrahedrons with most of them centered around the three fault segments that ruptured in the Lander's earthquake, namely, Camp Rock/Emerson Fault, Homestead Valley Fault, and Johnson Valley Fault (shown in yellow lines in Fig. 2(a)). The simulation runs for 500 years with 2 time steps per year. Fig. 3 shows the surface mesh of the Landers model. In order to preserve the resolution of the center mesh, the surface data was interpolated into a 250 meter square regular grid and overlaid on top of 30 meter LandSAT image and elevation map.



(a)

(b)

Fig. 2 Surface deformation generated by GeoFEST Simulation: (a) vertical displacement after Landers Earthquake, (b) postseismic deformation 500 years after

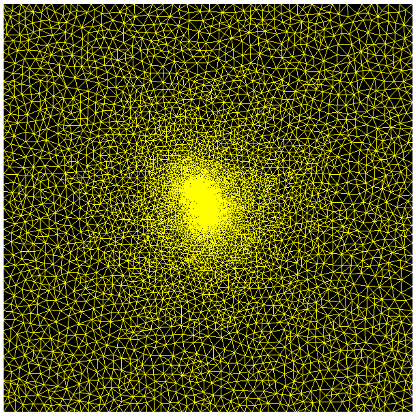


Fig. 3 Surface mesh of the Landers model

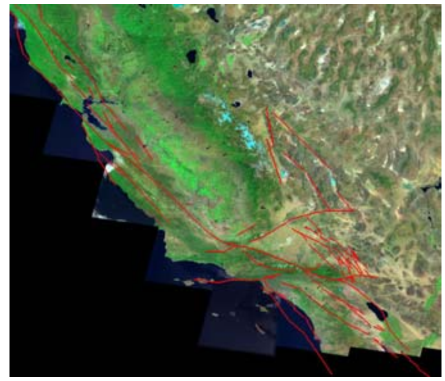


Fig. 4 Fault segments modeled in Virtual California

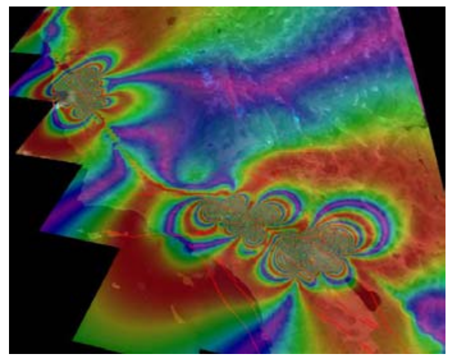


Fig. 5 Surface Deformation interferogram caused by the simulated earthquakes in Virtual California

B. Virtual California

Virtual California models the fault elastic interaction in the California region. The red lines in Fig.4 represent about 60 major slip-strike faults in California. They are broken into 650 fault segments, each 10km wide. Virtual California generates slips and stress on those fault segments over thousands of simulation years. The slips on the fault segments can be interpolated into horizontal surface displacement. Fig. 5 is a synthetic interferogram representing the surface deformation in a five year window caused by simulated earthquakes using Virtual California. Each color fringe represents 5.6cm of horizontal deformation along a 45 degree northeast direction. Several small scale earthquakes can be observed along the San Andreas Fault. Just north of Salton Sea, several faults in the vicinity rupture at the same time showing the interaction between faults.

The process to produce a visual representation for the Virtual California data is similar to the one described for the GeoFEST data. First, calculate the surface deformation by accumulating the slips on the fault segments. Secondly, calculate the deformation difference for a 5 year moving window. Next, interpolate the data into a regular grid of 800 meter resolution and convert the data into InSAR color fringes. Finally, overlay the interferogram on top of LandSAT image and digital elevation map and render them using RIVA. The resolution of the surface deformation is coarser for Virtual California because the simulation covers a much bigger domain with a lower resolution, i.e., 10 km.

We have generated animations of a 500 year simulation of the Northridge earthquake model and a 500 year simulation of the Landers earthquake model using GeoFEST. The animations can be found at http://pat.jpl.nasa.gov/RIVA/images.html. On the same site, there are also two Virtual California animations, one covers a dozen faults in Southern California and the other covers all of California. Both simulations run for 1000 years.

C. RIVA as a Visualization Tool for QuakeSim

RIVA is a parallel terrain rendering system designed for both interactive exploration of large datasets and batch generation of animations. It is capable of rendering multiple surfaces with different resolutions and covering different areas. The surfaces – global maps in spherical projections, high resolution terrain images, or time varying simulation datasets like the simulated interferograms generated by the earthquake models - can be overlaid with adjustable opacity. RIVA's GUI consists of a key frame editor to help create an animation. The key frames can be planned, edited and previewed interactively. Once they are selected, the flight path is calculated using a cubic spline algorithm. The renderer then renders the flight path in the batch mode and saves the animation frames onto disk.

RIVA has been integrated into the QuakeSim portal [8] (http://complexity.ucs.indiana.edu:8080) to produce the visual output for the GeoFEST simulation. The QuakeSim portal is a three-tiered web portal containing a web-based user interface that allow users to start a client component, monitor its progress, and view the results when it is done, a service tier that provides general services such as job submission, file transfer, database accesses on multiple host computers, and a backend resource including databases, modeling codes and visualization tools.

III. GEOFEST STRESS TENSOR VISUALIZATION

A. Normal Stress and Shear Stress

In addition to the displacement vectors on the node, GeoFEST also generates stress tensors at the tetrahedron elements. The stress variable is a 6 dimensional tensor: (σ_{xx} σ_{yy} σ_{zz} σ_{xy} σ_{xz} σ_{yz}), where the first three components represent normal stress and the second three components represent shear stress. Visualization of multi-dimensional data itself is a challenge. After several discussions with the model designer, we decided to visualize the stress as three scalar values as shown in equations (1), (2) and (3).

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz} \tag{1}$$

$$I_2 = \sigma_{xx}\,\sigma_{yy} + \sigma_{xx}\,\sigma_{zz} + \sigma_{yy}\,\sigma_{zz} - \sigma^2_{xy} - \sigma^2_{xz} - \sigma^2_{yz} \tag{2}$$

$$I_3 = 0.0277 \times ((\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{xx} - \sigma_{zz})^2 + (\sigma_{yy} - \sigma_{zz})^2 + \sigma^2_{xy} + \sigma^2_{xz} + \sigma^2_{yz}) \tag{3}$$

I_1 and I_2 represent the first invariant and the second invariant of the stress tensor, where I_1 is the mean normal stress. I_3 is a positive value used to represent the magnitude of the shear stress. Fig. 6 shows these three variables from the Landers' model. All of them are rendered using ParVox, a parallel volume renderer for structured and unstructured grid 3D datasets.

GeoFEST Landers' model consists of 1.25 million tetrahedrons; most of which are concentrated on the three fault segments at the center of the model domain (Fig. 3) The majority of the stress tensors are zero except for those around the edges and at the both ends of the faults. In addition, the stress values change very little over the simulation time. Since the three faults overlap each other, scientists are very interested in the effect caused by the interaction between adjacent faults. The images in Fig. 6 are rendered at a vantage point inside the volume in order to get a close up view of the three faults. The opacity of the volume is set to make the zero stress transparent. The color map is displayed next to the image.

B. Unstructured Grid Volume Rendering & ParVox

The GeoFEST tensor data is rendered using a parallel unstructured grid volume renderer based on a cell-projection volume rendering algorithm proposed by Ma [8]. The algorithm is enhanced to do perspective rendering with clipping planes along the line of sight in order to support viewpoints within the volume. Since the renderer only renders data on the nodes, the stress data on the elements have to be interpolated and mapped onto the node before it can be visualized.

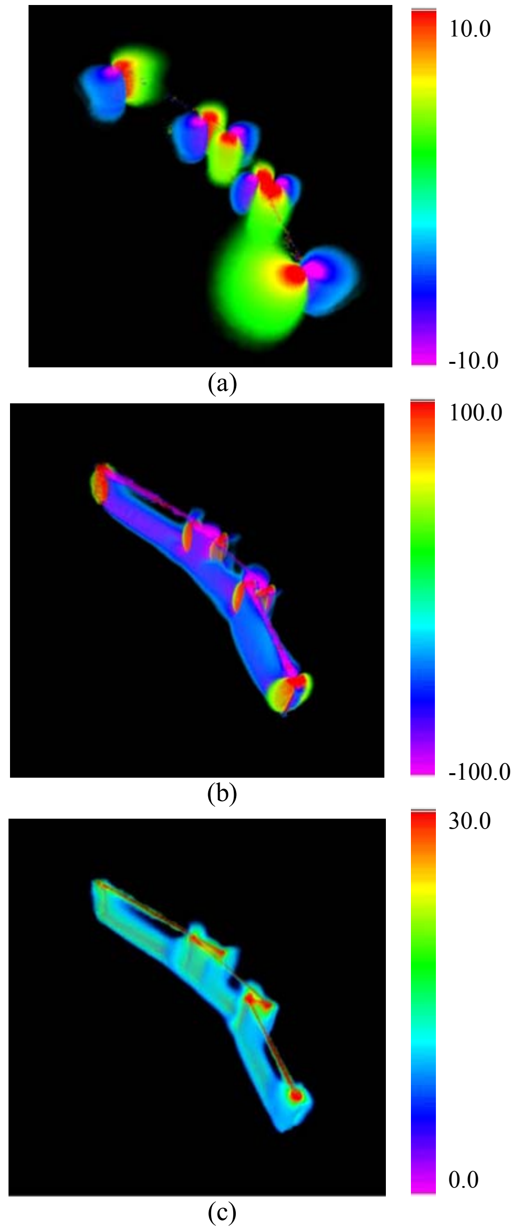


Fig. 6 Three ways to look at the stress data from Landers Model (1) first invariance- the volume stress (2) second invariance, (3) magnitude of the sheer stress

The unstructured grid volume renderer is one of the two parallel rendering programs supported in the ParVox visualization system. ParVox is a parallel volume rendering system for interactive distributed visualization. It is equipped with an X window based GUI program for display and viewing control, two input modules that read structured and unstructured 4D datasets in NetCDF format, respectively, two core renderers, one for structured grid datasets and one for unstructured grid datasets, and an output module that supports multiple output formats, including a wavelet image compression format for both loseless and lossy compressions. The input, the renderer, and the output modules form a functional pipeline using MPI for inter-module communication.

ParVox has been integrated into the QuakeSim portal [8] (http://complexity.ucs.indiana.edu:8080) as an interactive tool to visualize the GeoFEST stress volume. To do that, a user has to download the ParVox GUI on his/her workstation first. Then, he/she can launch a GeoFEST simulation from the QuakeSim portal starting with selection of the problem domain, mesh generation and refinement, and model configuration. Once the initialization is done, the input data is sent to an SGI Altix machine at JPL and a PBS job request is submitted to run the model. Once the model is complete, the model output will be converted into the NetCDF files for ParVox to render and the ParVox rendering engine will be started on the Altix machine. When the data is ready to be viewed, a message will be sent to the user with instructions to launch the GUI program. The user can then interactively explore the dataset on his local workstation.

IV. VISUALIZATION OF STRESS AND SLIP ON THE FAULT SEGMENTS

A. Multiple Surface Light Table (MSLT)

Multiple Surface Light Table (MSLT) is a high-resolution 3D visualization tool for large terrain and imagery datasets with additional surfaces representing the earthquake fault segments. It can pan and zoom over a very large multi-channel image dataset in real-time as well as in 3D perspective with digital terrain. The images are partitioned into tiles and constructed in multiple resolution levels. Only the portions of the images visible on the screen will be loaded on the fly.

As depicted in Fig. 7, the fault surfaces, represented as semi-opaque rectangles, are co-registered with the terrain and a high-resolution LandSat image. MSLT views the fault database as catalog data in a text window as well as fault polygons underneath the image and terrain. The catalog data and the fault overlay are linked together and are selectable by mouse click from both the text window and the image overlay. The fault polygons can be viewed in 3D perspective from any vantage point including underneath the terrain while still maintaining the context of its surrounding terrain. The color of the faults represents the dip angle relative to the surface of the terrain.

MSLT can also be used to view the time-varying simulation data on the fault polygons such as stresses and slips generated by Virtual California. In Fig. 8, the stress is represented by color and the slips are represented by red triangles on the surface. The color on the fault segment changes from blue to yellow when the stress is building up. Once the stress accumulates over a certain threshold, an earthquake occurs and the fault slips in lateral direction. The earthquake releases the accumulated stress (energy) on the fault and the color of the fault segment changes back to blue. The points of the triangles indicate the direction of the slips whereas the brightness and the duration of the triangles represent the magnitude of the slips. Fig. 8 is a snapshot of four parallel faults rupturing at the same time, an indication of the interaction among adjacent fault movements.

MSLT is an interactive visualization software tool implemented with OpenGL and X/Motif. It runs on UNIX, Linux, and Mac OS X systems. There are three types of interactive controls in MSLT:

- **Viewing control** -- A control panel to select the camera position and the viewing angel and a virtual trackball to pan, zoom and rotate the image.
- **Fault surface display control** – bi-directional selection and de-selection of the fault group and fault segments by clicking the fault entry in the text window or the fault segment in the image window; options to change the opacity of the faults.
- **Animation control** – control buttons to start, stop, pause, and resume the animation, change the play back speed and display the current time step.

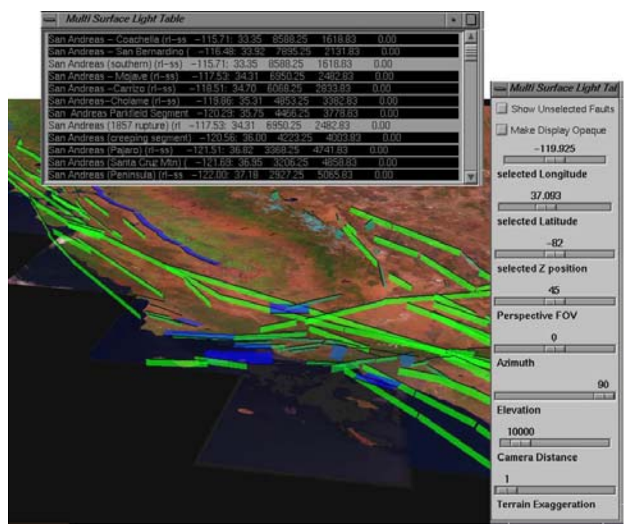


Fig. 7 Visualization of the QuakeSim fault database using MSLT

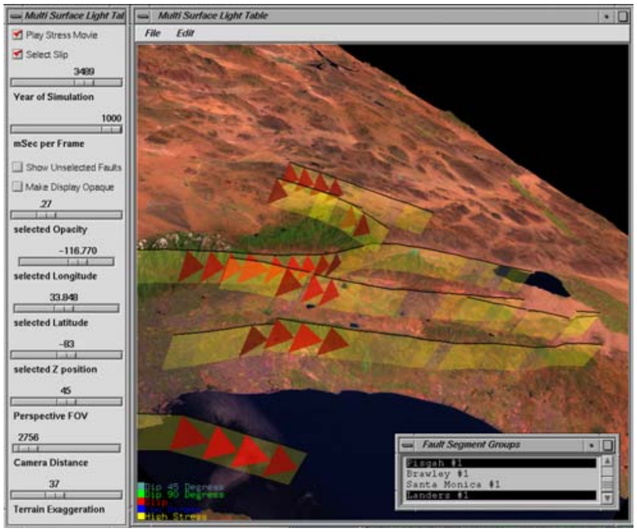


Fig. 8 Visualization of stress and slips from Virtual California

V. CONCLUSION

In this paper, we describe three different softwares for the visualization of earthquake simulation data. We created animations using a parallel terrain rendering system, RIVA, to overlay the surface displacement interferogram generated by GeoFEST and Virtual California on top of LandSAT images and digital terrain. We visualized the normal stress and the shear stress on the fault segments produced by GeoFEST interactively using a parallel unstructured grid volume renderer, ParVox. We used an interactive image pan-and-zoom system, MSLT, to visualize the fault surfaces and the simulated stress and slips on the fault surfaces underneath a realistic terrain image.

Scientific visualization is an effective method for understanding scientific results extracted from a massive volume of scientific data. It is also an essential tool for the presentation of results to the general public. Visualization of a large time-varying, multi-dimensional dataset requires extensive computing resources, storage, network bandwidth, and programming effort, which are not available to most scientists. Integration of visualization tools and model programs through a web portal can hide the computation complexity from the end users and thus improve the usability of the software and supercomputing resources.

ACKNOWLEDGMENT

The work presented in this paper was sponsored by NASA Earth Science Technology Office (ESTO), Computational Technologies Project (CT). The GeoFEST data set was provide by Jay Parker and Greg Lyzenga of JPL and the Virtual California dataset was provided by John Rundle of UC Davis. Jay, Greg and John have provided us numerous valuable suggestions on the effective presentation of their datasets. We also like to thank Andrea Donnellan of JPL, the PI for the QuakeSim project , for her feedback and technical review of the visualization software, Marlon Pierce of Indiana University for integrating RIVA and ParVox into the QuakeSim portal as a visualization tool. Finally, we would like to thank Robert Ferraro, our project manager, for his trust and his technical guidance.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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