A Case Study in Scientific Reproducibility from the Event Horizon Telescope (EHT)

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***Abstract*—This poster presents the first results of an interdisciplinary project aiming to develop and share sustainable knowledge necessary to analyze, understand, and use published scientific results to advance reproducibility in multi-messenger astrophysics. Specifically, the project targets breakthrough work associated with the First M87 Event Horizon Telescope (EHT) and delivers recommendations on how the published results of the first black hole can be effectively reproduced. The project has the potential to advance new discovery in multi-messenger astrophysics by providing guidance for generalizing methods and findings from use cases.**

***Index Terms*—Multi-messenger astrophysics, black hole image**

I. Motivation and Goal

Reproducing published results and incorporating the findings into their own work allow scientists to accomplish new research efforts more efficiently. However, obstacles such as the insufficient documentation describing codes' compilation and execution, the heterogeneous resources on which the experiments may run, and the complexity of data pre- and post-processing often hinder those efforts. This poster presents a case study for understanding, analyzing, and using published scientific results from a global multi-messenger astrophysics project. The case study targets recently published results from the Event Horizon Telescope (EHT) project (i.e., the generation of the images showing the shadow of the black hole in the center of the M87 galaxy observed by EHT) [1]. Several papers describe the data sets [2], [4] and workflows [3], and the EHT project codes [5] have been made available online. In this poster we present the first insights from our study on how the published results can be effectively reproduced.

II. M87 Event Horizon Telescope (EHT)

The EHT uses Very Long Baseline Interferometery (VLBI) to link eight radio telescopes around the world to study the immediate environment of a black hole with angular resolution comparable to the size of the black hole itself. In April 2019, the EHT collaboration published measurements of the properties of the central radio source in M87 [1], including the first direct image of a black hole. The collaboration's results garnered world-wide attention in the scientific community, revealing a bright ring formed as light bends in the intense gravity around a black hole in the galaxy M87 that is 6.5 billion times more massive than the Sun. To enable the reproduction and use of their work, the EHT collaboration provided links to their calibrated data [4] published in CyVerse Data Commons, a publication describing their data processing and calibration [2], a link to the software used in their imaging workflow [5], and a publication describing the imaging workflow [3]. The EHT data products and software are released by the EHT collaboration itself and are hosted by third-party repositories; this is a common model for many NSF-funded projects ranging in size from individual investigators to international collaborations.

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III. Data and Workflows

The data used in ETH is from eight telescopes, which work in concert, and consists of spatiotemporal data of visibility amplitudes over five days: April 5, 6, 7, 10, and 11, 2017. Each day contains data taken at high and low telescope frequencies, which is then fringe fitted, calibrated a priori, and network calibrated to reduce the size of the data set. This data reduction process is done in the EHT-HOPS Pipeline for Millimeter VLBI Data Reduction and the product of the process is stored in the First M87 EHT Results [4] data repository. It is formatted in a raw form that is filtered using Fourier transforms.

The data is injected in three different workflows, all processing the same input and generating similar images of a M87 black hole. They are: EHT-Imaging M87 Stokes I Imaging Pipeline for EHT (EHT-Imaging), Sparse Modeling Imaging Library for Interferometry (SMILI), and DIFMAP M87 Stokes I Imaging Pipeline for EHT (DIFMAP).

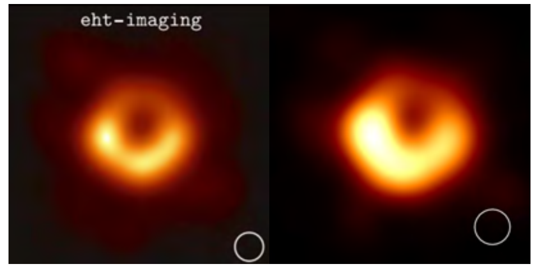
The EHT-Imaging workflow uses the Regularized Maximum Likelihood (RML) method of image reconstruction and relies heavily on the eht-imaging Python module (EHTIM) to complete its processes. The EHTIM module defines numerous classes to allow the loading, simulation, and manipulation of VLBI data. By leveraging the classes in this module, the EHT-Imaging workflow loads both the low and high band data files of a single day's observations into a data object and performs various data preparation and pre-calibration steps. The workflow then moves to an imaging cycle with four iterations. Each successive iteration relies directly on the image generated in the previous iteration. After four iterations, the final image is output. The workflow also allows for optional outputs including the final image and an image summary file containing various imaging parameters and data related to the imaging process.

Similar to the EHT-Imaging workflow, SMILI uses the Regularized Maximum Likelihood (RML) algorithm method of image reconstruction. Prior to imaging, SMILI also uses the EHTIM module in order to use data sets pre-calibrated consistently with the other workflows. After the pre-calibration stage, the software generates data tables that are used for the final imaging process. Reconstruction of an image begins with a circular Gaussian with successive iterations relying on the image generated from the previous iteration. There are four stages of iterations with each stage performing three imaging cycles. Once completed, the software outputs the final image and packages the input, pre-calibrated, and self-calibrated data files for traceability.

In contrast to EHT-Imaging and SMILI, DIFMAP uses the CLEAN algorithm, a more established method of imaging involving iterative deconvolution, paired with a technique called "difference mapping." EHT's DIFMAP script takes a file containing observation data, a mask (set of cleaning windows) file that defines areas of interest for the algorithm to iterate upon, and five command-line arguments, which have been provided in the EHT repository [5]. After loading this file, the script initializes values, reads the file specifying the mask, and begins the pre-calibration phase, which involves its first cleaning and phase self-calibration. Afterwards, the image undergoes twenty rounds of amplitude self-calibrations and cleanings, and this is when image reconstruction occurs. Following this stage, several files are output and saved, most importantly the two files containing the resulting image with and without its residual map. In both EHT's and our results, the residual map is excluded.

IV. Methods and Results

Compiling the workflows' code across different platforms resulted in some errors. For example, on a Power9 system we experienced some workflow dependencies and had to remove optimization compilation flags from the installation script to generate the executable code successfully. The codes do not include a list of required dependencies or the library versions used for each workflow. We solved dependencies manually by editing problematic scripts; we used Spack, Conda, and pip to install the latest stable version of each necessary library. Once the compilation was successfully completed, we experienced run-time errors with EHT-Imaging and SMILI that we solved by correcting syntax issues in part of the Python code. Furthermore, the lack of post-processing documentation on how to combine images from each workflow to generate a single image like that released by the EHT team added to the difficulty of replicating EHT released images across the three workflows. We solved this issue by utilizing a EHTIM module for post-processing of grayscale output. Once all these challenges were addressed, we were able to run the three workflows on both commodity hardware and a Power9 supercomputer (i.e., the Tellico Power9+V100 cluster at the University of Tennessee, Knoxville).



(a) Original (b) Reproduced

Fig. 1: Comparison of the EHT-released image (a) with our reproduced image output (b) using the EHT-Imaging workflow from observations on April 11, 2017.

Figure 1 shows an example of our results: Figure 1a shows the EHT-released image output of EHT-Imaging workflow using both low and high band input files from observation day April 11, 2017 [3] and Figure 1b shows our reproduced image output of EHT-Imaging workflow using the same input data. The images present some differences that are currently under investigation, starting from the comparison of the data input used for the generation of the two black holes.

V. Conclusions and Relevance for eScience

Efforts like the one presented in this poster provide new guidance for generalizing findings from use cases and thereby indicate potential avenues for building sustainable reproducibility efforts in a uniform fashion across scientific domains. Enabling reproducible research opens new research opportunities to a much larger audience. Postdocs, graduate and undergraduate students, and even high school students can benefit from accessing the code, data, and workflow information for being able to reproduce findings, learn about the work, and get engaged in STEM research. This is already happening in gravitational-wave physics, and such practices can be incorporated more broadly by adding the new workflows targeted in this poster (i.e., the case of the results from the EHT project). Disseminating our findings through eScience will facilitate connections between astrophysicists and computer scientists, ultimately resulting in greater scientific discovery.

References

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