9. The Vision Machine and Computer Simulation
Exploring New Horizons in Virtual Photography

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It took a century of astronomical research to photograph the compact radio source, first identified by Heber Curtis in 1918.[1] This source, spanning approximately 2,005 x 10^{12} kilometers and estimated to be 40 million years old, emitted such kinetic power that it suggested the possible presence of a supermassive black hole in the center of the giant elliptical galaxy M87.

The evidence supporting the existence of this astronomical object, in line with Albert Einstein's theory of general relativity (1915), comes primarily from X-ray[2] and gravitational wave measurements.[3] However, until recently, obtaining event-horizon-scale images of the supermassive black hole candidate was impossible.

Although the "calculated photographs" by Jean-Pierre Luminet[4] significantly contributed to the understanding and visualization of supermassive black holes, it was the observation campaign conducted in April 2017 by the Event Horizon Telescope (EHT) that demonstrated the possibility of detecting the shadow of the event horizon of M87*, transforming a mathematical concept into a physical entity, now accessible and analyzable through repeated observations (Fig. 9.1).

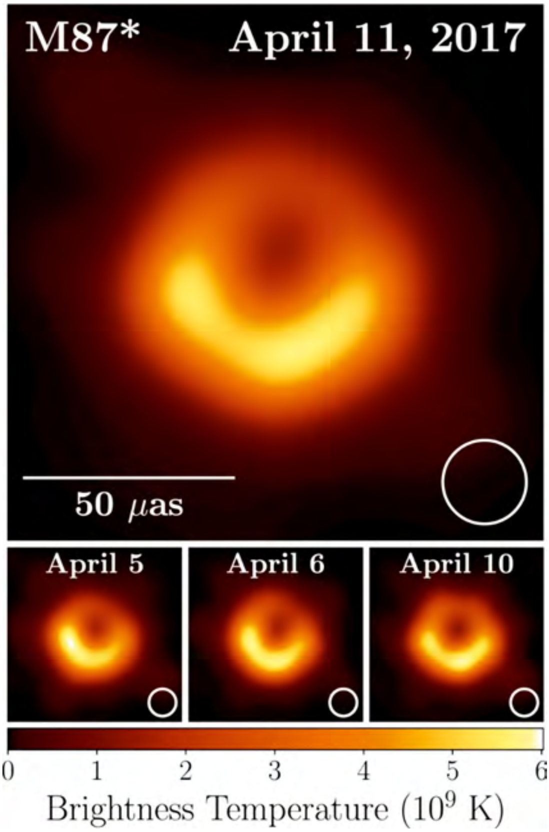
1 The reference to Heber Curtius (1918) was sourced from the bibliography of Kazunori Akiyama et al., "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole," *The Astrophysical Journal Letters*, vol. 875, no. 1 (April 2019).

2 Ibid.

3 Ibid.

4 Jean Pierre Luminet, "Image of a Spherical Black Hole with Thin Accretion Disk," *Astronomy and Astrophysics*, no. 75 (April 1979), 228–235.

9.1 The top photo shows the EHT image of M87 taken on April 11, 2017, as a typical example from the 2017 observation campaign. This image is created by averaging three different imaging methods, each adjusted to the same resolution using a circular Gaussian filter. The bottom photo presents similar images taken on different days, showing the consistency of the basic image structure and the similarity across various days.*



Courtesy of EHT.

To resolve the shadow of the M87* core, the EHT used the observational technique known as Very Long Baseline Interferometry (VLBI), creating a global array of radio telescopes. This network, operating at a wavelength of 1.3

mm, achieved a very high angular resolution, essential for revealing the finest details of such a minute and distant astronomical object. As the law of diffraction dictates, the angular resolution is inversely proportional to the telescope's diameter (D) and directly proportional to the wavelength (λ) of the observed radiation.[5] To overcome technical limitations, the EHT implemented the very long base interferometry, using the simultaneous and synergistic action of multiple detection stations in different locations on Earth. This technique allowed for the simulation of a telescope almost as large as the planet, ensuring a high capacity of resolution.

Adopting various calibration, imaging, and independent analysis methods enabled the visualization of event-horizon-scale structures around the black hole in M87. The images of the emission region show a ring structure with a diameter of 40 μas and enhanced brightness in the southern part, in line with the event-horizon-scale structures[6] and consistent with the predictions of general relativity.

In the continuation of this chapter, I will explore the techniques and methodologies used to create the M87* images and discuss its epistemological and ontological implications in photography and astrophysics. As will be elucidated throughout this chapter, particularly in the last sections which delve into the ontology of virtual photography, the broader term "image" is employed, not solely for consistency with referenced astronomical literature, but also to denote the single images that punctuate the computational phases inherent to the imaging process. Virtual photography, as I will refer to it, encompasses an amalgamation of images, an accumulation of traces and calculations, constituting a summation-correlation of different detection-imaging phases, synthesized into a coherent form, meriting the term "image synthesis."[7]

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5 To achieve a high angular resolution, using a telescope with a very large diameter or observing shorter wavelengths is desirable. Given that the wavelength of the radio emissions observed by the EHT is 1.3 mm, achieving a very high resolution necessitated a paraboloid close to the diameter of the Earth, the construction of which is clearly unfeasible.

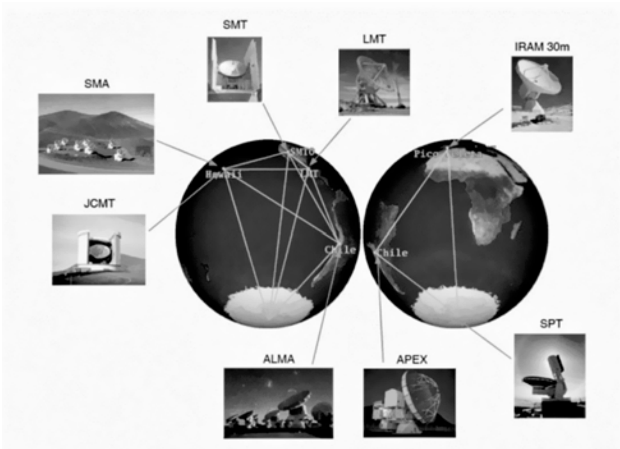
6 Kazunori Akiyama et al., "First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole," *The Astrophysical Journal Letters*, vol. 875, no. 1 (April 2019).

7 Furthermore, the term "photography" seems apt as I am of the opinion – a hypothesis that I am exploring in my current research project – that the historical trajectory of photographic techniques, from orthochromatic to panchromatic photosensitive sur-

VLBI: Principles and Operational Methodology

Launched in 2009, the Event Horizon Telescope (EHT) embarked on a technologically complex mission to enhance its sensitivity and detect electromagnetic radiation in the millimeter radio wave band with 1.3 mm wavelengths. To achieve this, the EHT set up a global array of radio telescopes consisting of eight stations in six different geographical locations (Fig. 9.2). This configuration established baselines, the distances between the radio telescopes, ranging from 160 meters to 10,700 kilometers.

9.2 During the EHT 2017 campaign, there were eight stations located in six different geographic locations.



Courtesy of EHT.

faces, extends to encompass the entire electromagnetic spectrum. This journey from capturing visible light to embracing ultraviolet, infrared rays, and ultimately, the radio waves utilized in the virtual algorithmic photographs of the M87* black hole, underscores photography's unfolding. From its inception, photography has aspired to transcend the physiological limits of human perception, progressively diminishing the centrality of human agency in favor of automation and externalization, marking a transition from human co-authorship to oversight.

The observation campaign of M87* took place on April 5, 6, 10, and 11, 2017, with scanning sessions varying between 3 and 7 minutes. During the Earth's rotation, pairs of radio telescopes sampled and recorded the radiation field of the source, "filling" the (u, v) plane to achieve optimal spatial coverage. In this context, scanning refers to capturing images of a celestial object from different moving positions, traced by the Earth's rotation[8], almost like a 3D scan performed from multiple angles. Aligning the signals received from the radio telescopes was crucial to ensure data consistency. Each radio telescope was equipped with an atomic clock and an *a priori* Earth geometry based on GPS measurements to ensure synchronization and temporal alignment of the detections.

After data collection, these were sent for correlation at the Haystack Observatory of MIT (USA) and the Max-Planck-Institut für Radioastronomie (Germany). Correlation, a process of fringe-fitting, was vital for combining the data from all the radio telescopes into a coherent image. This step corrects temporal and spatial variations in interferometric observations, maximizing signal coherence and image quality.

Three independent pipelines managed this calibration phase, making it possible to estimate systematic errors in the baselines and validate the data. An output selected from one of these pipelines was designated as the primary data set of the EHT and was deemed reliable for subsequent imaging phases.

EHT observations do not immediately translate into images. Indeed, the EHT collects complex visibilities, representing the Fourier components of the brightness distribution on the observed portion of the sky. The spatial

8 Interferometric detection exploits the rotation of the Earth and is quite different from a brief, instantaneous observation. As the Earth rotates, the relative geometry between the radio telescopes and the celestial object changes. This means that, throughout one night, the interferometer "sees" the object from different angles, as if the radio telescopes were physically moving to cover a larger area. Observations collected at different times during the Earth's rotation are then synthesized together using signal processing algorithms to create a single high-resolution image (image synthesis).

frequency[9] of these components, determined by the projected baseline[10] and expressed in units of the observing wavelength, corresponds to the brightness distribution in the sky. We can imagine the Fourier transform as a tool for decomposing an image (or any other signal) into its frequency components. In the context of interferometry, the (u, v) plane maps these spatial frequencies, with each point corresponding to a specific frequency component of the sky image. "Filling" the (u, v) plane implies sampling these components through different baselines. Once all the complex visibilities are collected, the inverse Fourier transform is used to reassemble the original image of the sky.

Thinking of the EHT as a puzzle, the sky image one aims to obtain is the complete picture of the puzzle. The complex visibilities are the individual pieces, each representing a frequency component of the image. Their position in the (u, v) plane determines the spatial frequency, indicating how detailed a piece is compared to others. The Fourier transform assembles these pieces to form the overall image of the sky.

Imaging Procedures[11]

The processing of images obtained from the EHT faced significant technical limitations. The EHT array's ability to detect a limited range of spatial frequencies and the sparse sampling coverage in the (u, v) plane did not allow for a complete representation of the observed object. The limited arrangement and number of detection stations prevented data collection from all theoretically possible angles, leaving gaps in the collected data. These gaps were filled

9 Spatial frequency refers to the rate at which the signal's intensity (or brightness) varies from one point to another. For instance, in an image with very fine details or sharp edges, we will have rapid intensity variations and, thus, high spatial frequencies. Conversely, in an image with gradual variations in brightness, the spatial frequencies will be low.

10 To better understand the concept, imagine two people standing on a beach looking at a distant lighthouse. If both observe the lighthouse head-on, the distance between them is the linear distance. However, if one person moves further along the beach and views the lighthouse from a different angle, the "projected" or "perceived" distance between the two changes, even though their physical distance remains the same. This is what "from a particular perspective" means in the context of the "projected baseline" between two telescopes.

11 For further details on the imaging procedures, see Akiyama et al., "First M87 Event Horizon Telescope Results. IV."

through sophisticated imaging procedures designed to integrate missing visibilities and provide a more accurate representation of M87*.

Due to the incomplete and fragmented nature of the data, what is known in mathematics and physics as an inverse problem is under-constrained. The "inverse problem" in the context of EHT VLBI involved reconstructing an image of the sky (the cause) from data collected by radio telescopes (the effects), while "under-constrained" referred to the fact that fewer data or links than necessary existed to determine one single solution, complicating the determination of the "correct" image.

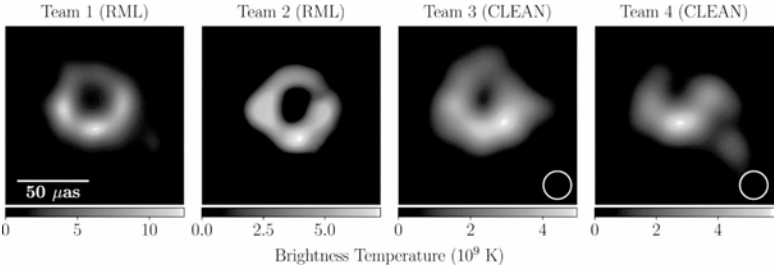
To disambiguate the interchangeability among different images, all potentially valid and reliable but incompatible with each other in reference to the data collected by the EHT, a two-phase methodological approach was adopted for processing the images of M87*.

First Stage

In the first stage of imaging, a blind imaging procedure was implemented. Four independent teams worked on synthetic data without communication for seven weeks. The use of synthetic data reduced the risk of collective biases and ensured that shared expectations or assumptions did not influence the final images. The synthetic data were designed to have properties similar to the EHT M87* visibility amplitudes, allowing for testing reconstructions under controlled conditions and with knowledge of the ground truth: a kind of reliability test or theoretical reference model used as a benchmark to evaluate and interpret experimental or observational results.

The teams adopted different approaches to select data flagging strategies, calibration, and imaging. Two classes of algorithms, RML (Regularized Maximum Likelihood) and CLEAN, were used to find the most probable image from the observed data. Despite differences in parameter choices and methodologies, the consistency among the results obtained by different teams underscored the robustness of the imaging techniques, with all produced images showing a prominent ring of a 38–44 μas diameter with enhanced brightness in the south (Fig. 9.3).

9.3: The images from Teams 1 and 2 were produced using RML methods. Teams 3 and 4, on the other hand, used the CLEAN method. All the images display a similar shape, but there are noticeable differences in brightness temperature.



Courtesy of EHT.

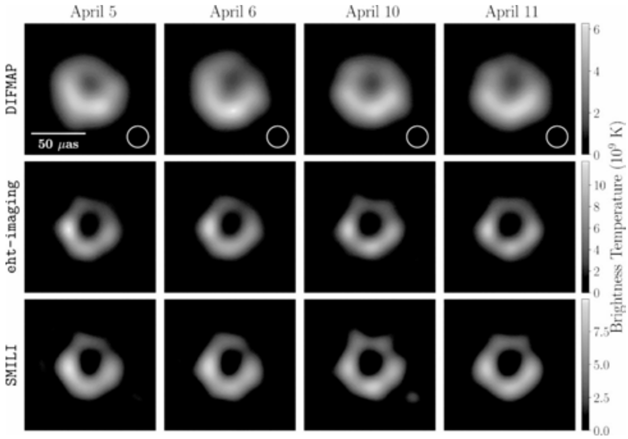
Second Stage

Biases do not solely arise from human intervention. Depending on the parameters used, imaging algorithms can significantly influence the final image, leading to potential distortions in reconstructions. For this reason, a second imaging stage was implemented using three pipelines, each equipped with a specific software package and associated methodology, to examine a certain range of parameters for their effectiveness and accuracy and to verify and validate the robustness of the imaging techniques used. This two-step process included imaging first with synthetic data applied to four simple geometric models in the training set and then with real M87* data.

Each pipeline explored a wide range of imaging parameters, producing about 10^3 to 10^4 images from different parameter combinations. This vast number of images ensured the consideration of every possible scenario, minimizing the risk of bias or errors. A Top-Set of combinations was selected, producing images of M87* consistent with the observed data and capable of accurately reconstructing images from synthetic data sets. All images in the Top-Set featured an asymmetric ring with a diameter of 40 μas.

Finally, a single combination of fiducial imaging parameters within the Top-Set was identified for each pipeline (Fig. 9.4), providing the best results across all synthetic data sets and for each specific imaging methodology. This meticulous and combinatorial approach ensured that the final image was the result of exhaustive analysis, minimizing uncertainties and ensuring maximum accuracy with a high degree of consistency, even in comparison with computer simulations.

9.4. Fiducial images of M87 from all four observation days were produced using three different imaging pipelines.*



Courtesy of EHT.

Visualizations and Imaging: Synthetic Data and Simulation Models

The detection process employed by the Event Horizon Telescope (EHT) diverges from traditional astronomical methodologies. For instance, while optical astronomy measures light intensities, radio telescopes amplify and manipulate radiation before detecting it,[12] which implies that the received energy, prior to measurement, is stored, managed, and subsequently transformed into electrical signals that are cross-correlated with other radiofrequency signals.[13] The correlation between the electric fields recorded by the EHT array anten-

12 Bernard F. Burke and Francis Graham-Smith, *An Introduction to Radio Astronomy* (Cambridge, MA: Cambridge University Press, 2010), 2; 5–6.

13 Ibid., 15.

nas produces interferometric visibilities,[14] which are susceptible to various distortions.

The EHT's imaging process thus contends with data scarcity, as the visibilities do not fully cover the (u, v) plane, leaving "holes" in the data due to factors including the geometry of the antenna array and atmospheric conditions. The resultant image, marred by interferences and imperfections, is termed a "dirty image."

This process, from creating a source image to constructing an elaborated image through synthetic images, necessitates precise calibrations, checks, and validations using advanced algorithms and probabilistic mathematical control methods. The incomplete and noisy nature of the data renders the imaging process an ill-posed problem. In mathematics, a problem is defined as ill-posed when it does not have a unique solution or when slight variations in data lead to significant changes in the solution. This is precisely the case with M87*, where multiple images are concurrently plausible from the same dataset.

At this juncture, it becomes essential to understand how the inverse problem of reconstructing an image from interferometric data was approached. This reconstruction entails inferring properties of celestial sources, which are not directly observable, by interpreting the collected data. The calibration and imaging phase operated in reverse, starting from the complex visibilities to reconstruct the image of the M87* emission ring.

The fact that visibilities are not direct measurements of the image but rather of its Fourier spectrum and are subject to noise and incompleteness may complicate the process. In this context, it is crucial to highlight how algorithms like CLEAN and RML are based on reverse logic and characterized by a trial-and-error process in which various hypotheses and models are tested and compared with the data to find the most plausible solution.

Furthermore, the inability to perceive a direct image of the astronomical object complicates not only the detection and self-calibration phases of the observations but also the imaging procedure of the EHT, whose operational

14 The van Cittert-Zernike theorem establishes that the visibility, measured by an interferometer, is connected to the brightness distribution of a celestial object through a Fourier transform. This transform is a mathematical technique that converts data from space/time to frequency, allowing for the conversion of the brightness distribution in the sky into visibility data of the interferometer. This process enables the creation of detailed images of celestial objects using data collected from multiple radio telescopes, essentially converting the observed light distribution into a clear image of the object.

strategies include a series of methods to refine and ensure the consistency and reliability of the detected data. The methodologies and techniques adopted include normalized cross-correlation, fiducial scripts, data resampling tests, quadrature sum of the measurement uncertainty, and the Mean Squared Standardized Residual.[15] Additionally, the EHT heavily utilized synthetic data to test and calibrate algorithms. This step proved crucial, providing a controlled environment to verify whether imaging methods could accurately reconstruct a theoretically known image a priori.

Synthetic data generated from simple geometric models[16] were used to test and define imaging parameters based on their similarity to data observed by radio telescopes. These data were compared and validated by employing imaging software libraries, such as eht-imaging and SMILI, to ensure their coherence and reliability. This process represented a form of reverse engineering in the astronomical context, akin to industrial or computational reverse engineering, where a system is analyzed to understand its structure and operation without access to original protocols or data. For M87*, synthetic data and simulation models were essential for interpreting the data and refining imaging techniques.

Indeed, navigating through petabytes of data originating from an inherently invisible astronomical object is complex and necessitates advanced

15 For further details on these methodologies and techniques, see Akiyama et al., "First M87 Event Horizon Telescope Results. IV."
Normalised Cross-Correlation (pNx): A method that measures how well-simulated models correspond to observed data, with values close to 1 indicating high correspondence.
Fiducial Scripts: Automated sequences for processing data uniformly, increasing accuracy and reproducibility while reducing human errors.
Data Resampling Test: A statistical technique to confirm the stability and consistency of reconstructed images, repeating analyses to estimate errors.
Quadrature Sum of the measurement uncertainty: A method for unifying different uncertainties, minimising the total error through overall aggregation.
Mean Squared Standardised Residual: A statistical measure that evaluates the fit of models to data, with low values indicating a good fit.

16 Training Sets: collections of data used to train and optimize imaging models or algorithms, consisting of synthetic data based on geometric models or simulations of accretion disks and relativistic jets. Their primary functions include: training algorithms to enhance the reconstruction of images from observed data; testing the similarity between synthetic data and observed data of M87* to define imaging parameters; and validating simulation models to verify the robustness of the imaging techniques used.

computational tools capable of comprehending and analyzing a vast volume of signals, excluding everything that does not conform to theoretical reference models. The EHT's procedures, from detection to output, have considered only those signals and data predicted by the theory of general relativity to define the event horizon of a supermassive black hole. Moreover, the M87* image is not a direct representation of the object but a visualization of what has been rendered through simulation models.[17] The customary connection between the image and the observed phenomenon diminishes, allowing for a new relationship between the image and the underlying theoretical model. These are visualizations of potential matter configurations, probable configurations of potential relationships that are visually malleable and highly adaptable.[18]

In these terms, reverse engineering emerges as the only reliable strategy to approach a form of reliability. Without a fundamental truth or a tangible referent to check the accuracy of the image reconstruction of M87*, the EHT relied on theoretically rigorous and iterative simulation methods to avoid bias and potential distortions. The apparent direct visibility of M87* is, in fact, the product of a modelling process based on computational visualization in which "the object and the medium of presentation are partly identical."[19] Notably, an intrinsically invisible astronomical object gains visibility through visual iterations and explorations facilitated by the considerable computational power of the employed technologies. These tools, characterized by remarkable responsiveness and performance-based feedback cycles, have allowed for a trial-and-error approach, greatly enhancing the manipulability throughout the imaging process.

The parameters for the synthetic Top-Sets (Fig. 9.5) processed by the three pipelines are derived from their respective simulation models through an iterative comparison process between simulated experiments and visual

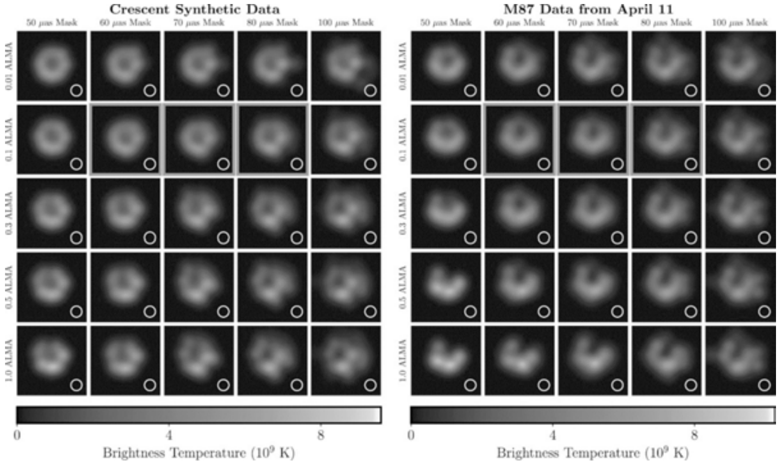
17 See Jean-François Bordron, "Expérience d'objet, expérience d'image," *Visible*, no. 5 (2009), 118.

18 See Maria Giulia Dondero, "La fotografia scientifica tra impronta e matematizzazione," in *La fotografia. Oggetto teorico e pratica sociale – Atti del XXXVIII Congresso dell'Associazione Italiana di Studi Semiotici*, ed. Vincenza Del Marco and Isabella Pezzini (Rome: Nuova Cultura, 2011), 169.

19 Johannes Lenhard, *Calculated Surprises. A Philosophy of Computer Simulation* (Oxford: Oxford University Press, 2019), 50. For further details on this concept, see also Hans-Jörg Rheinberger, "Objekt und Repräsentation," in *Mit dem Auge Denken: Strategien der Sichtbarmachung in Wissenschaftlichen und Virtuellen Welten*, ed. Bettina Heintz and Jörg Huber (Zurich: Edition Voldemeer, 2001), 55–61.

results, wherein visualization plays a pivotal role as a tool for parameter validation. This further illustrates an inverted process through which one accomplishes the adaptation between the theoretical foundation and the observed phenomenon, following a logic that, starting from the resulting simulation image, leads to the definition of an appropriate set of parameters.

9.5. The images delineated in green conform to the criteria for inclusion in the Top Set, thereby highlighting an exceedingly selective subset in comparison to the extensive suite of images generated during the parameter survey employing DIFMAP (CLEAN) on both synthetic and real M87 data. This image utilizes one of the pipelines employed in the complete imaging procedure, specifically pertaining to the EHT baseline coverage on April 11.*



Courtesy of EHT.

Epistemological Issues Concerning Computational Simulations of M87*

The space-time dimension of the images of M87* transcends our perceptual limits. The visualized space of the event horizon adds to reality without replacing it. In this context, machines and visualizations emerge as a new spatial dimension, augmenting and integrating with our experience of the world.

The EHT's experiments do not take place in the phenomenological world but in its computational extension, so much so that machines and visualizations become a different kind of nature.[20] Hence, the empirical verification of the existence of supermassive black holes is not pursued through direct observation in nature but realized through the creation of controlled experimental conditions, within which the theoretical models of these celestial bodies are subjected to validation via computational processing and visualization in the EHT's laboratories. We are thus witnessing the inauguration of a sort of neo-terraforming[21]: an expansion of the phenomenological horizon that transcends and reformulates our perceptual environment where simulation and machine synthesis not only gain prominence but establish themselves as constructive entities of a renewed regime of experience and knowledge.

In this context, simulation becomes a tool for exploring unprecedented scenarios, offering an understanding of the phenomenon beyond mere representation, and surpassing the limits of empirical experiments. This approach, which challenges the traditional division between instrumentalism and realism in science, alters the epistemic landscape wherein simulation is not merely a substitute for experiment but a means that transforms how we comprehend and interact with the world.

Simulation exceeds mere representation of reality and actively contributes to its construction, thereby diminishing the distance between scientific representation and what it represents, between the world and the model. While aiming for near-real fidelity, simulation models gain greater autonomy from their phenomenological referent, creating a world that not only imitates but expands upon the observed one.[22]

Thus, the epistemological issue raised by the images of M87* concerns not only the reduction of the distance between the world and the model – their near overlap – but also highlights the transition from the transparency of mathe-

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20 In this regard, recall the words of Marshall McLuhan, *From Cliché to Archetype* (New York: The Viking Press, 1970), 9. "Since Sputnik and the satellites, the planet is enclosed in a manmade environment that ends 'Nature' and turns the globe into a repertory theatre to be programmed."

21 Benjamin Bratton, *The Terraforming* (Moscow: Strelka Press, 2019); see also Cosimo Accoto, *Il mondo in sintesi. Cinque brevi lezioni di filosofia della simulazione* (Milan: EGEA, 2022), 4; 167–168.

22 See Accoto, *Il mondo in sintesi*, and Lenhard, *Calculated Surprises*.

matical models, characteristic of modern scientific method, to the epistemic opacity of simulation models.[23]

Moreover, the simulation of M87* relies on data that are not traditional empirical measurements but detections, transformations, and combinations of a vast amount of synthetic and real data. For this reason, entrusting machines with the management of calculations becomes a strategic requirement, despite the inscrutability that marks simulation modelling due to its high number of computational steps and the division of tasks into increasingly intricate and complex sub-tasks.

If simulations contribute to extending spatial boundaries,[24] this also occurs timewise in at least two ways. Not only because they compress temporal fossils from deep space onto the screen, but also due to the procedural nature of the imaging process. The concatenation of phases, iterative modularity, and exploration-interactivity of the imaging processes develop over time, leading to a stratification through the combination of images to such an extent that the images of M87* can be defined as the result of an accumulation of traces and calculations, a sort of mosaic/map constructed by summation-correlation of the different detection-imaging phases, where each provisional image constitutes a kind of notational text for subsequent algorithmic operations.[25]

This unstable and recursive process is dotted with a series of images whose role is to halt the computational flow so that each image allows for the control, manipulation, and refinement of data for coherent structuring. Consequently, each image of M87* becomes a sort of temporary stop in what we might define as an "event-image,"[26] understood as the sum of all algorithmic operations of halting and then resuming that occur during the experimental journey.

It is precisely the digital treatment of images through algorithmic processing that liberates these operational freeze frames from their temporal fixity: individual images do not merely "freeze" a specific phase of the imaging process, but rather configure a kind of composite photography whose plural and multidimensional nature is conducive to exploration and manipulation. From

23 See Lenhard, *Calculated Surprises*.

24 See Pier Luigi Capucci, *Realtà del virtuale. Rappresentazioni tecnologiche, comunicazioni, arte* (Bologna: CLUEB, 1993).

25 See Maria Giulia Dondero, "La rappresentazione della stratificazione temporale in astronomia e archeologia," *E|C – Rivista dell'Associazione Italiana di Studi Semiotici* (October 2008), 1–19.

26 Bordron, "Expérience d'objet, expérience d'image," 120–121.

the succession of computational experiments to the establishment of a visualization as the final result of shaping the experiments, we deal with a composite photographic image that records and fixes the various phases of computation, serving an indexical function while simultaneously crystallizing the processing phases and potential configurations through a process of computational formalization.

Ontological Questions about the Computational Simulations of M87*

These composite photographs of M87*, where traces of detections and calculations of the possible coexist in a balance between temporarily stable freeze frames and potential relationships heralding developments,[27] partly transcend the indexical nature inherent in retinal images to open to the manipulable visualization of the computational process. We witness the shift from the ontological primacy of photography as a trace to the procedural nature of manipulable images characteristic of virtual photography. Indeed, the images of M87* result from a process whose visualizations shape potential relationships between the regime of perceptibility and that of virtuality, understood as the iconisation of computational thought lines and their interactions-intersections. Here, photographs are no longer to be understood as a stable and unique point in an indexical relationship between representation and referent; instead, they constitute organizing ideas of a vast number of operations along an intricate procedural line. The photographs form a flow conceived as a set of experimental events, the purpose of which lies in negotiating and stabilizing deduced and reliable visual forms of a purely theoretical object.[28]

In this sense, the image itself becomes an experimental device, a virtual environment in which to practice science with objects resulting from transductions and transcoding, phenomenal data, and physical-mathematical theories: that is, diagrammatic simulations in which there is no plausible representation of M87*, but a symbolic reduction of a complex phenomenon through the iconisation of operational physical models responsible for multiple actualizations of data into images.[29]

27 Maria Giulia Dondero, "Sémiotique de l'image scientifique," *Signata Annales des sémiotiques / Annals of Semiotics*, no. 1 (2010), §103.

28 Ibid., §24.

29 Ibid., §24; §40.

These images are neither indexes nor icons but rather diagrams or icons of relationships[30] insofar as they combine the visual with computational reasoning procedures, traces of detections with their subsequent mathematization-modelling, through a process of selecting data relationships, extracting rules, and transposing results,[31] which makes M87* a combinatorial and virtual image of a theoretical object.

We witness a reversal of the referential value, no longer anchored to iconic recognition but emerging from a chain of mathematical-scientific inferences. This referential impression is no longer an immediate datum but instead supported by referential beliefs mediated by measurability, the computational nature of the images, and the objects represented. This fact shifts the focus from the image's adherence to an inaccessible phenomenological reality to the authenticity of the physical-mathematical theories from which the image takes shape. Thus, the images of M87* configure themselves as cartographies of energy flows and electromagnetic radiations.

The photographs of M87* do not represent a phenomenon in itself but offer a reductive window on the phenomenon to enhance its intelligibility and accessibility. They are virtual entities that actualize themselves in multiple versions, translations, and exemplars[32]: they are the translation and visualization of their logical-mathematical model. In this case, the image of the black hole is not simply the reproduction of a pre-existing visible, but rather the representation of what exists in potential[33] and is actualized each time in a cascading/chain manner through computerized exploration-visualization. Moreover, as Lévy[34] reminds us, everything that is an event, like the images of M87* whose nature is based on the dialectic of the process, is characterized by a specific dynamic of actualization and virtualization.

The images of M87*, reflecting an inaccessible space, primarily manifest as the repositioning of an ordering *logos*, taking shape not from phenomenological reality but rather emerging from the intersection of ideology, theory, and simulation from which the virtual image materializes.

30 Charles Sanders Peirce, "Collected Papers 4.418," in *Collected Papers of Charles Sanders Peirce Volumes 1–5*, eds. Charles Hartshorne and Paul Weiss (Cambridge, MA: Harvard University Press, 1931–1935).

31 See Dondero, "La fotografia scientifica tra impronta e matematizzazione," 164.

32 See Pierre Lévy, *Becoming Virtual: Reality in the Digital Age*, trans. Robert Bononno (New York: Plenum Trade, 1998).

33 Ibid.

34 Ibid., 74–75.

Simulation and machine synthesis transform the body from an instance that puts into images the sensory experience into an interlocutor-recipient of a synthetic-algorithmic model. Moving from an approach traditionally rooted in *physis*, in physicality and direct sensory experience, we shift towards *logos*,[35] that is, towards a domain characterized by theorization and computation where images are never stable, never complete but subject to multiple manipulations and combinations for formulating new hypotheses and discoveries.

Conclusion

In exploring the transformative impact of virtual photography on scientific exploration, particularly evident in observations like M87*, a kind of virtual realism emerges, where a phenomenon is filtered and reinterpreted through a prism of computational and theoretical models. By integrating computational power with theoretical frameworks, virtual photography not only expands visual representation of astronomical phenomena but also shifts epistemological and ontological perspectives. This method prompts re-evaluation of empirical evidence's nature and simulation's role in knowledge production.

Facilitating direct interaction with theoretical models and enabling visualization of phenomena beyond traditional imaging's reach, virtual photography becomes a tool in redefining scientific exploration. It encourages questioning of former methodologies' limitations and welcomes a future where technology and theory integration unveils new understanding horizons. M87*'s case exemplifies virtual photography's capacity to conceptualize the universe in previously unimaginable ways. It emphasizes the evolving relationship between observer and observed, redefining visualization's essence in scientific pursuit.

M87*'s imaging procedures constitute a "flat laboratory,"[36] where images extend the referent[37] to the point of questioning whether virtual synthetic images impose certain ideologies so that the body, or its substitute, adapts to the

35 See Jean Claude Coquet, *Physis et logos. Une phénoménologie du langage* (Paris: Presses Universitaires de Vincennes, 2007).

36 Bruno Latour, "The Netz-Works of Greek Deductions – A Review of Reviel Netz's The Shaping of Deductions in Greek Mathematics," *Social Studies of Science*, vol. 38, no. 3 (2008), 442.

37 Bruno Latour, *Pandora's Hope: An Essay on the Reality of Science Studies* (Cambridge, MA: Harvard University Press, 1999).

virtual context, to the demands of the brain-machine, necessitating a critical assessment of how these technologies influence our understanding and the ideologies they may perpetuate. Indeed, if the virtual synthetic image emerges from ideology, theory, and simulation, might it mean that it, rather than representing an inaccessible space, is the repositioning of an ordering *logos*?