MIT Haystack Observatory Correlator Report 2019–2020

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Abstract This biennial report summarizes the major activities in space geodesy and radio astronomy that have been carried out by the VLBI correlator at the Haystack Observatory facilities of the Massachusetts Institute of Technology (MIT) during the 2019–2020 period.

1 Introduction

The MIT Haystack Observatory correlator, located in Westford, Massachusetts (herein the "Haystack correlator," also simply the "correlator"), includes a computer cluster where correlation of raw VLBI data is performed using a distributed FX-type (DiFX) software correlator [*Deller et al.,* 2011] and fine-tune post-correlation processing using the Haystack Observatory Post-processing System (HOPS) software package [*Capallo,* 2017].

The Haystack correlator is supported by the NASA Space Geodesy Program (SGP) and the National Science Foundation (NSF), and it is dedicated approximately equally to the geodetic pursuits for the International VLBI Service (IVS) and to radio astronomy imaging for the Event Horizon Telescope (EHT) project.

The Haystack correlator serves as a research and development system for testing new correlation modes, such as those needed for observations with the next-generation VLBI system—the VLBI Global Observing System (VGOS [*Niell et al.,* 2018])—and for technology developments, such as for the Mark 6 recorder system. Software support for the processing of VLBI experiments is also provided to the general IVS community including similar DiFX and/or HOPS installations at the U.S. Naval Observatory (USNO) in Washington D. C., the Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn, Germany, and other software correlators worldwide.

MIT Haystack Observatory

MIT Haystack Correlator

IVS 2019+2020 Biennial Report

2 Summary of Activities

2.1 General VGOS Activities

The primary contributions of the Haystack correlator to the now operational VGOS network continue to be the processing of geodetic session data, feedback to stations for repairing problems, equipment tests and commissioning or testing of new stations, and providing advice and assistance to other correlators. In addition to what is described later in this report, dozens of 24-hour VGOS sessions as well as mixed-mode (i.e., S/X legacy and VGOS) sessions, VGOS Intensives, and various smaller tests have been processed and analyzed under the auspices of the VLBI geodesy project. Extensive help has been rendered to station staff, VGOS engineers, analysts, and staff at other correlators. The level of activity in the last three quarters of 2020 was severely impacted by the COVID-19 pandemic.

2.2 General EHT Activities

EHT provides the lion's share of the equipment in the Haystack DiFX cluster, so a few words on work related to that project are deemed relevant to this report. By far the biggest news to come out of the EHT project was the release in April 2019 of the M87 black hole image resulting from the processing of the April 2017 observing campaign [*The EHT Collaboration,* 2019]. This is a result of fundamental astronomical importance.

Work on completing the processing of the April 2018 observing campaign concluded in February 2021, and work on a January 2020 dress rehearsal in preparation for a subsequently canceled 2020 observing run was also completed. The efficacy of observing at 345 GHz was validated by observations recorded in October of 2018. Significant help in all of this work was also provided to the MPIfR correlator for co-processing many of these efforts.

2.3 Deployment and Commissioning of MGO

Another NASA station was added to the VGOS network since the last biennial report: the McDonald Geodetic Observatory (MGO). As described in that report, the MGO data acquisition equipment underwent extensive testing during 2017–2018, including recording data in parallel with the standard backend at the Westford antenna—also known as zero-baseline tests—and processing both sets of data at the Haystack correlator. The entire build-out and commissioning process subsequently occurred very quickly due in a large part to successful engineering vetting during this pre-installation testing. MGO is now a regularly participating station in the VGOS network.

2.4 Mixed-mode Observations and Development Work

Extensive and intensive work was carried out since last reported in furthering the ability to observe in mixed mode between VGOS and legacy S/X stations. Processing of RD1804 and RD1810, which began in 2018, was completed, and databases were submitted to the IVS. In RD1804, VGOS stations Westford and GGAO were tagged along to an S/X network, while in RD1810 a third VGOS station, KPGO, was added to form a VGOS triangle. Three much larger, 16-station (eight VGOS and eight S/X) sessions were recorded in summer 2020: RD2005, RD2006, and RD2007. The first two have already been processed, and a preliminary database of session RD2005 was submitted to the IVS for inclusion in ITRF2020.

Major investments in personnel time and software development were made in modifying software in the mixed-mode processing chain so as to ensure valid results and to simplify and streamline the process of producing them. One major improvement was modifying parts of the software processing chain to make possible the production of all full-bandwidth VGOS, mixed legacy-VGOS, and legacy-only products in one single pass through the correlator. For RD1804 and all prior mixed-mode sessions, processing required a three-pass strategy, but from RD1810 on, all mixed-mode processing used a one-pass method, greatly simplifying the effort needed to produce the final products. Another improvement was the ability to manually assign *fourfit* [*Capallo,* 2017] channel labels to keep them consistent between the three different product flavors, greatly simplifying the *fourfit* control file structure and reducing the chance for errors.

2.5 TOW and Follow-Up Correlator Workshop

The 10th Technical Operations Workshop (TOW) was held at Haystack Observatory in May 2019. Immediately after the TOW, whose main objective is the training of station staff in IVS operations, a VGOS correlation workshop was conducted to transfer knowledge of the newly developed procedures for processing the VGOS sessions to staff at other correlators.

Following the VGOS correlation workshop, and to further broaden VGOS correlation knowledge and capabilities across the IVS community, the VGOS Intensive session VI9290 was processed at several correlators, and the 24-hour VGOS session VO0009 was correlated at the MPIfR correlator and post-processed at various others. The results of these correlations were compared among themselves and with those from the Haystack correlator to validate the practices at the other correlators. These hand-on exercises culminated in the production of several comparison memos [*Barrett et al.,* 2020a, *Barrett et al.,* 2020b, *Barrett et al.,* 2020c].

2.6 Effects of the Pandemic

The pandemic that descended upon us in March 2020 had a major impact on operations. The Haystack site was closed to all personnel except for those deemed essential to maintain the building infrastructure. It is important to note that scientific research operations were deemed non-essential, and this included operation of the correlator. Correlation activities had to move mostly off-site. As this had not been done extensively heretofore, the infrastructure to support it had to be built. After some development work, the correlator is now in a much better position to conduct remote operations fairly efficiently. There is definitely great disadvantage to operating remotely relative to operating on-site, as there are correlation-related activities such as mounting of Mark 6 modules and overall trouble shooting and testing that require physical presence and benefit from in-person exchange, but the best is being made of the situation.

2.7 DiFX Version Control

The level of complexity in VGOS and mixed-mode operations has resulted in a complex amalgam of different versions of the DiFX software correlator package that need to be used to produce quality results. Efforts are being made to correct various software flaws in various versions in order to consolidate all of the needed fixes into a single version of the DiFX build that all correlators can use.

2.8 Correlator Infrastructure Upgrades

Although no new major additions of hardware or capability were made to the Haystack cluster in the last two years, the physical infrastructure supporting and surrounding it changed in a major way. A new special-purpose room with customized cooling was designed and constructed to support, isolate, and protect the correlator equipment. This project was a necessity as the 60-year-old air conditioning system for the correlator equipment was failing and was not in conformance with environmental regulations regarding ozone-layer-depleting gas emissions. The execution of this project necessitated two major moves of the entire cluster. In the spring of 2020 the correlator was moved to a new temporary location in the large room where it is housed. The new room, including new electrical infrastructure, was then constructed in the area from which the cluster had been moved. Upon completion in the fall of 2020, the cluster was moved into its newly constructed space (Figure 1).

2.9 Clock Summit Meetings

The clock teleconference series referred to in the last report culminated in a memo and GitHub repository intended to standardize and facilitate consistent clock setting practices among correlators [*Himwich and Corey,* 2020]. Although this is a work still in progress, the fundamentals are now documented, and it is only a matter of establishing best practices at all facilities. Determining whose job it is to maintain and update station “peculiar offsets” and sampler delays over time remains to be done.

3 e-VLBI

Non-real-time electronic transfers (e-transfer) of VLBI data have continued during this period. Data from 15 stations for 124 VLBI sessions (including R4, RDV, and R&D) were transferred to MIT Haystack Observatory during the past two years for in-house correlation and data hosting or conversion to Mark5/Mark6 media prior to shipping for off-site correlation. Moreover, Haystack also handled e-transfers of VGOS data for Onsala and Yebes. Furthermore, all VGOS Intensive sessions processed by the Haystack correlator over this period were e-transferred (e.g., data from stations KPGO, Wettzell, Westford, and GGAO).

Fig. 1 Cluster correlator (background) and Mark 6 playback units (foreground) at the MIT Haystack Observatory.

4 Experiments Correlated

A total of approximately 58 geodetic VLBI sessions were processed, at least in part, during the 2019–2020 period. These include 36 VGOS Trials (VT), six VGOS Operations (VO, which are the evolution of VT starting in 2020), eight VGOS Intensives (VI), four mixed-mode sessions, four S/X-only R&D sessions, and various other VGOS-related test sessions that are not included in the count because they were too small to warrant individual experiment numbers. If not for the pandemic effect, significantly more VO and VI sessions would have been processed. These will be done in 2021.

5 Existing Correlator Capabilities

The cluster as described in the last report remains as is, i.e., the “first generation” of 16 EHT cluster PCs (each with a single deca core 2.8 GHz Intel Xeon processor controlled by two equivalent master nodes) and the 38 subsequently purchased PCs (each with dual deca core Intel Xeon CPUs) still comprise the full cluster. This merged monolithic (but easily subdivided) “super cluster” has over 1,152 cores. Connecting, providing data to, and supporting this computing infrastructure are a Gb Ethernet fabric with three 100 Gb Ethernet switches, 197 TB of data storage space, and three file storage servers that can also act as DiFX compute nodes providing $>$200 TB of file storage. A total of 11 Mark 6 playback units with DiFX fully installed are connected to the Gb Ethernet fabric. In addition, racks and uninterruptible power supplies condition and stabilize power provided from a 208-volt power distribution fabric. As mentioned earlier, all of this equipment is now housed in a dedicated climate-controlled room with new electrical infrastructure. The integrated cluster (Figure 1) is used to correlate data from EHT, VGOS, and legacy S/X observing sessions.

6 Staff

The following staff have participated in various aspects of correlation, post-processing, Mark 6, and e-VLBI development and operations.

6.1 Correlator Software Development

- John Barrett - software development and support
- Roger Cappallo - HOPS software development
- Geoff Crew - DiFX, HOPS, and Mark 6
- Tim Morin - cluster IT, hardware/software support
- Jon Rose - cluster IT, hardware/software support
- Jason SooHoo - cluster IT, Mark 6, and e-VLBI
- Chester Ruszczyk - Mark 6 and e-VLBI

6.2 Correlator Operations

- Peter Bolis - correlator maintenance
- Alex Burns - Mark 6 and general technical support
- Brian Corey - correlation oversight, station evaluation, technique development
- Glenn Millson - correlator operations
- Dhiman Mondal - post-processing analysis
- Arthur Niell - technique development
- Don Sousa - media management and shipping
- Mike Titus - correlator operations setup, oversight, and hardware/software testing
- Ken Wilson - correlator and Mark 6 maintenance

7 Conclusions and Outlook

The correlator at the MIT Haystack Observatory has significantly contributed to the advancement of VGOS from a budding concept to an operational network capable of generating high-quality geodetic products. Specific topics during the reporting period include the development of new VGOS correlation and post-processing software, knowledge transfer of this capability to other correlators, and the development of correlation software to process mixed-mode (S/X legacy and VGOS) observing sessions.

Recovery from reduced operational levels caused by the COVID-19 pandemic will be a major effort in the coming year. As always, a major focus will be on producing correlator products of high quality, especially for the challenging mixed-mode sessions, and on improving the quality where possible. Close collaboration with other correlators as they take on more of the VGOS processing load will continue, as will commissioning and testing activities as the VLBI station network expands [*Merkowitz et al.,* 2019].

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