MIT Haystack Observatory Correlator Report 2021–2022

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Abstract This report summarizes the activities of the VLBI correlator at the Massachusetts Institute of Technology (MIT) Haystack Observatory that spans the 2021–2022 biennial period.

1 Introduction

The distributed FX-type (DiFX) VLBI software correlator (*Deller et al.*, 2011) and the Haystack Observatory Postprocessing System (HOPS) software package (e.g., *Cappallo*, 2017) of the MIT Haystack Observatory (herein "MIT Haystack correlator"), located in Westford, Massachusetts, is supported by both the NASA Space Geodesy Project (SGP) and the National Science Foundation (NSF). The correlator 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.

Besides contributing operationally to those science endeavors, the MIT Haystack correlator also serves as a development system for testing new correlation modes, such as those needed for observations with the next-generation broadband VLBI system—the so-called VLBI Global Observing System (VGOS; e.g., *Niell et al.,* 2018; *Merkowitz et al.,* 2019)—and for recorder/playback technology developments, such as the Mark 6 system.

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The MIT Haystack correlator also provides software support for the processing of VLBI experiments to similar DiFX-HOPS installations at the U.S. Naval Observatory (USNO), the Max-Planck-Institut für Radioastronomie (MPIfR) in Bonn, Germany, and to various other centers of the general IVS community.

2 Activities during the Past Two Years

2.1 General VGOS Activities

The processing of data from a variety of geodetic sessions is a primary contribution of the MIT Haystack correlator to the already operational VGOS network. Importantly, the correlator also continues to play a key role in providing feedback to stations for repairing problems, equipment tests, and commissioning or testing of new stations, as well as training and sharing general advice and practical assistance to other correlators worldwide.

In addition to what is described later in this report, dozens of 24-hour VGOS sessions as well as broadband/SX (or modern/legacy) mixed-mode sessions, VGOS Intensive sessions, and various smaller tests were correlated, processed, and analyzed under the auspices of the MIT Haystack correlator. Extensive help was rendered to station staff, VGOS engineers, analysts, and staff at other correlators.

The year 2021 was expressly dedicated to an intense effort to catch up from the slowdown in production that was created by the pandemic in 2020. A total of about 35 VGOS session types, including operations (VO), tests (VT), and Intensives (V2), were processed in full during the course of that year, as well as two (out of three) major R&D global mixed-mode sessions that were run in 2020. The databases from all these sessions were exported to the Crustal Dynamics Data Information System (CDDIS) repository for public availability. As a result of this effort, all pending sessions from 2020 were completed except for the third and last mixed-mode experiment (a.k.a. RD2007), which will be processed when mixed-mode correlation is further advanced and streamlined.

The year 2022 was then devoted to more contemporary VO, VGOS R&D (VR), and VT sessions, which provided a better opportunity to engage in more active diagnosis and assistance in correction of station problems that had accumulated over the previous years due to lack of proper attention and timely feedback. As a result, help was provided to other correlators for correcting existing problems, especially to USNO, and issues were encountered (e.g., Wettzell band swap, Ishioka lack of phase-calibration-signal condition, McDonald failing phase-calibration signal due to a bad 5-MHz cable, Yebes polarization swaps, sampler delay changes, and various and sundry other problems, to name a few).

2.2 Various Developmental Activities

The MIT Haystack correlator was involved in a number of additional developmental activities and projects largely on an ad-hoc basis aimed to help advance VGOS. These include:

- Local-tie observing sessions between the VGOS station at the McDonald Geophysical Observatory (MGO) and the VLBA station at Fort Davis, Texas.
- Debugging projects surrounding the vgosDb utilities and the release of nuSolve software package versions.
- Extensive testing with RDBE and R2DBE at the Westford station in zero-baseline mode to resolve the upper/lower sideband (USB/LSB) swap ambiguity problem.
- Exploration into the cause of small amounts of data loss from existing recording and correlator playback methods to assess the feasibility of short scan lengths (e.g., 7 s and shorter) in the future.
- Investigations into the potential presence of radio-frequency interference (RFI) in VGOS data from transmitting satellites at 10.7 GHz.
- Participation in a EU-VGOS R&D project involving long (10-min) scans on the radio source 4C 39.25 for cross-polarization bandpass calibration.

2.3 General EHT Activities

The EHT has provided the lion's share of the equipment that comprises the MIT Haystack correlator cluster. Therefore, a few words on work related to that project are warranted and relevant to this report.

Once again, the EHT project released news of fundamental astronomical importance. An image of the black hole at the center of our galaxy, commonly known as Sagittarius A* (SgrA*), was released in May 2022 (*The EHT Collaboration et al.,* 2022). This image was obtained using data from the processing of the April 2017 observing campaign. Production processing of an observing campaign conducted in 2018 was completed and work is in progress to complete the processing of an observing campaign conducted in 2021. A dress rehearsal for a 2022 observing campaign was also conducted and results released.

2.4 Validation of New Stations Joining the VGOS Network

Three new VGOS stations were in the process of technology readiness evaluation and validation required to seamlessly join the VGOS network. The three new VGOS stations are in Australia, Norway, and Portugal.

A new VGOS antenna at the Hobart site in Tasmania, Australia, was fully commissioned and added officially to the VGOS network after several tag-along test sessions in 2022. Moreover, one of the two new VGOS antennas at the Ny-Ålesund site in Svalbard, Norway, is currently proceeding through this same process of validation. Furthermore, a new VGOS antenna located on the island of Santa Maria in the Azores, Portugal, is soon to follow the same validation efforts.

2.5 Mixed-mode Observations

There was a concerted push to get the first two of the three fundamentally important VGOS/legacy mixed-mode observing sessions run in 2020 exported in time for their inclusion in the latest TRF realization, ITRF2020. These (RD2005 and RD2006) were very significant 24-hour sessions involving a total of sixteen stations (i.e., eight VGOS and eight legacy S/X) designed to obtain a global tie between the S/X and VGOS network stations, for which new correlation and post-processing modes needed to be devised and developed.

A third mixed-mode session, RD2007, was also recorded during this biennial period. This session is in the processing queue pending assessment of the efficacy and usefulness of the RD2005 and RD2006 experiments for their intended purpose.

2.6 2021 TOW and Follow-Up Mixed-Mode Correlation Workshop

A virtual Technical Operations Workshop (TOW) was conducted at Haystack in May of 2021. Immediately after the workshop, which concentrated on training station staff in IVS operations, a VGOS correlation workshop was conducted to inform staff at other correlators about Haystack-developed procedures for processing IVS mixed-mode sessions (*Barrett et al.,* 2019). Notes are available at: https://www.haystack.mit.edu/conference-2/past-conferences/tow2021/

2.7 Recovery from Effects of the Pandemic

Conditions have mostly returned to normal since the pandemic hit back in 2020. However, it is deemed important to note that remote work on setups, operations, and analysis are now routine and fully incorporated into a significant portion of the modus operandi at the MIT Haystack correlator. Production processing significantly caught up in 2021, as described above.

2.8 DiFX Version Controls

DiFX version testing for validating 2.5.4, 2.6.2, 2.7.1 and trunk versions used for the R/2DBE USB/LSB tests, CALC11 incorporation, and other DiFX features were conducted over this two-year period. Still to this day, 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 which need to be used in order to produce valid results. Efforts continue to be made to correct various software flaws in various versions in order to consolidate all the needed fixes into a single version of the DiFX build that all correlators can use.

3 Electronic Transfers of VLBI Data

Non-real-time electronic transfers (e-transfers) of VLBI data have continued during this period. Data from various stations and sessions (e.g., standard legacy S/X stations participating in the bi-monthly session with the ten-station VLBA network, as well as R4 and R&D sessions) were transferred to MIT Haystack during the past two years for in-house correlation and data hosting, and/or for conversion to Mark5/Mark6 media prior to shipping for off-site correlation. There has also been a significant increase of handled e-transfers for VGOS data from VO stations to MIT Haystack, such as for Onsala and Yebes. Also, all data from VGOS Intensive (V2) sessions that were processed by the MIT Haystack correlator over this period were e-transferred. This includes data from KPGO, Wettzell, GGAO, and Westford.

4 Experiments Correlated

A total of approximately 74 geodetic VLBI sessions were processed, at least in part, during the 2021–2022 period. These include three VGOS Tests (VT, all released), four VGOS R&Ds (VR, all released), 32 VGOS Operationals (VO, 23 released), 13 VGOS Intensives (V2, six released), and two mixed-mode VGOS+S/X (both released). Various other VGOS-related test sessions make up the remainder of the count, some of which are described above in the developmental activities section. As mentioned earlier, this includes the completion of all sessions from 2020, which were impacted by the pandemic.

5 Existing Correlator Capabilities

5.1 Correlator Infrastructure Upgrades

One major enhancement to the capabilities of the MIT Haystack correlator cluster over the last two years was the addition of four new Mark 6 playback units. This was an essential upgrade needed in order to be able to continue to process IVS sessions in tandem with EHT processing, both of which are expanding in the number of stations participating. VGOS sessions now include up to ten stations and the EHT regularly uses at least ten, with more soon to be added.

5.2 Dedicated Room Backup A/C Improvements

Enhancements to the A/C infrastructure are currently in the process of implementation in order to increase the safety and robustness of cooling capacity in the new correlator room as described in the last report.

5.3 Description of the Correlator Cluster

The correlator cluster, as described in the last biennial report, was enhanced by the addition of the four new Mark 6 playback units and cooling improvements, as mentioned above. The correlator consists of 16 cluster PCs (each with a single deca core 2.8-GHz Intel Xeon processor controlled by two equivalent master nodes) to which 38 PCs (each with dual deca core Intel Xeon CPUs) were subsequently added. 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 15 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. All of this equipment is housed in a dedicated climate-controlled room, enhanced with further cooling redundancy, and with dedicated 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
- Dan Hoak - HOPS software development and support
- Tim Morin - 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

- John Barrett - technique development
- Alex Burns - Mark 6 and general technical support
- Brian Corey - correlation oversight, station evaluation, and technique development
- Dan Hoak - 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

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

7 Conclusions and Outlook

A return to normalcy means that fresh efforts to expand and improve the VGOS network can accelerate. As has always been the case for the MIT Haystack correlator, a major focus will be on producing correlation and post-processing products of high quality, especially for the challenging mixed-mode sessions, and on improving the overall data quality when and where possible.

Close collaboration with the expanding list of operational correlators as they take on more of the VGOS processing load will continue, as will commissioning and testing activities as the VGOS station network expands. Perhaps a prime example of network expansion is the buildout of the new VGOS station at the Fortaleza Geophysical Observatory (FGO) in Brazil, which is to occur during the next (i.e., 2023–2024) biennial period.

References

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