USNO Analysis Center for Source Structure

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Abstract This report summarizes the activities of the United States Naval Observatory Analysis Center for Source Structure for the 2021 and 2022 calendar years.

1 Introduction

The Analysis Center for Source Structure is supported and operated by the United States Naval Observatory (USNO). It was accepted by the IVS as a "Special Associate Analysis Center" in January 2000, with the charter to provide products directly related to the IVS determination of the "definition and maintenance of the celestial reference frame." These products are to include radio images of International Celestial Reference Frame (ICRF) sources, intrinsic structure models derived from the radio images, and an assessment of the astrometric quality of the ICRF sources based on the radio images.

Over the past two years, USNO has developed and deployed new web pages which include the new Fundamental Reference Image Data Archive (FRIDA), in support of the Analysis Center for Source Structure hosting images of ICRF sources across the radio spectrum. FRIDA is available through USNO's new web interface located at the following link: `https://crf.usno.navy.mil/FRIDA`. FRIDA includes images of quasars at radio frequencies at 2.3 GHz (S-band), 8.4 GHz (X-band), 15 GHz (Ku-band), 22 GHz (K-band), and 43 GHz (Q-band). USNO intends to grow the number of images in the coming years and expand to other areas of the electromagnetic spectrum.

In this report, we present an overview of FRIDA and highlight some of its features and current capabilities. We also describe the calibration and imaging efforts that have enabled this data archive of radio images. We highlight some scientific interests using the results from our imaging efforts and conclude with future plans for making improvements and upgrades to explore with FRIDA.

2 Analysis Center for Source Structure Operation

The primary service of the Analysis Center for Source Structure is to populate and maintain a web-accessible data archive of radio frequency images of ICRF sources. Originally developed beginning in mid-1996, this data archive was previously known as the 'Radio Reference Frame Image Database' (RRFID). Its web-accessible database contained JPEG files of X and S images of most ICRF sources north of -30° declination, mainly from the IVS-supported Research and Development VLBI (RDV) sessions, which are sessions using the Very Long Baseline Array (VLBA) plus IVS geodesy stations. USNO images these RDV sessions jointly and in collaboration with the University of Bordeaux. The astrometry of the RDV sessions is measured and maintained in collaboration with USNO and the Goddard Space Flight Center (GSFC).

Beginning in 2017, this data archive was renamed the 'Fundamental Reference Image Data Archive' (FRIDA) and has since been developed with an

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improved and more functional interface. FRIDA[1] was made publicly available in 2022. FRIDA currently contains ∼15,000 VLBI images collected over the past ∼30 years.

2.1 FRIDA Overview

The USNO web interface for FRIDA can be found here: FRIDA, and Figure 1 displays a screenshot of the FRIDA homepage.

The top left panel shows an all-sky map of the ICRF sources available in FRIDA with right ascension along the x-axis and declination along the y-axis. The default settings when FRIDA loads are set to highlight all of the ICRF-defining sources from all three realizations of the reference frame. The selected sources are indicated with the green-filled red circles on the all-sky map. The data for all of these selections are provided in the interactive list shown on the right side of the screen. Users are able to download all of the selections by clicking on the 'Download Now' button in the top right corner. But users should be sure that the filter settings are set appropriately for downloading, as FRIDA will download all data for all sources shown in the list in the right panel. Users can search, filter, and refine searches using the options listed under the all-sky map.

If users click on one of the green-filled red circles shown on the all-sky map, a pop-up window will appear with the source images available per the search criterion selected. The default setting will show all images for all radio frequencies available for the selected source. In addition to the images, FRIDA also provides some diagnostic plots and figures on the individual images shown in the image panel. Figure 2 shows an example of ICRF-defining source IERS 0722+145.

FRIDA shows a list of the common names for the selected source in the top panel and gives the center coordinates of the source in the upper right hand corner of the pop-up window. FRIDA displays a timeline at the bottom of the window with the available bands and corresponding images for the source shown by the color-filled circles. For example, the X-band images are designated by the solid blue circles, while the K-band images are shown by the solid yellow circles. The user can load multiple images into the image panel shown in the middle left side of the window by clicking on these color-filled circles and then page through the images using the buttons under the image panel itself. In the middle panel, FRIDA displays the *uv*-coverage map and, in the far right panel, the amplitude and phase distributions as functions of *uv* distance. These three diagnostic plots can be used to gauge image quality.

Users are able to adjust the contour levels and contrast scaling shown in the image panel by clicking on the Settings wheel in the upper right of the image panel. Figure 3 shows an example of the settings that can be toggled and adjusted for a given image.

If users wish to download any of the images for a given source, they simply return to the main FRIDA website homepage and filter the selection to show the source they are interested in accessing and then click on the 'Download Now' button. FRIDA provides image FITS files, calibrated *uv* data files, model files created and used in the Common Astronomy Software Applications (CASA) imaging process, and imaging log files (where available), among other image-related files and information (see Section 3.1 for details).

Images of ICRF sources can also be obtained from the Bordeaux VLBI Image Database (BVID) at BVID, as well as through the Radio Fundamental Catalog (RFC).

3 Current Activities

3.1 VLBA Imaging

VLBA observations for maintenance of the celestial and terrestrial reference frames have been carried out since approximately 1994, when the VLBA was in its early commissioning days. The RDV sessions described in Section 2 are 24 hours in duration and observe approximately 80 ICRF sources at S- and X-bands (2.3/8.4 GHz) using the canonical geodetic style of observing where both bands are observed simultaneously. These sessions combine the VLBA together with up to ten additional geodetic VLBI antennas. Images have been produced from some of these sessions and made available through FRIDA.

Beginning in January 2017, USNO entered into a timeshare agreement with the National Science Foundation (NSF) for supporting 50% of the oper-

[1] https://crf.usno.navy.mil/FRIDA

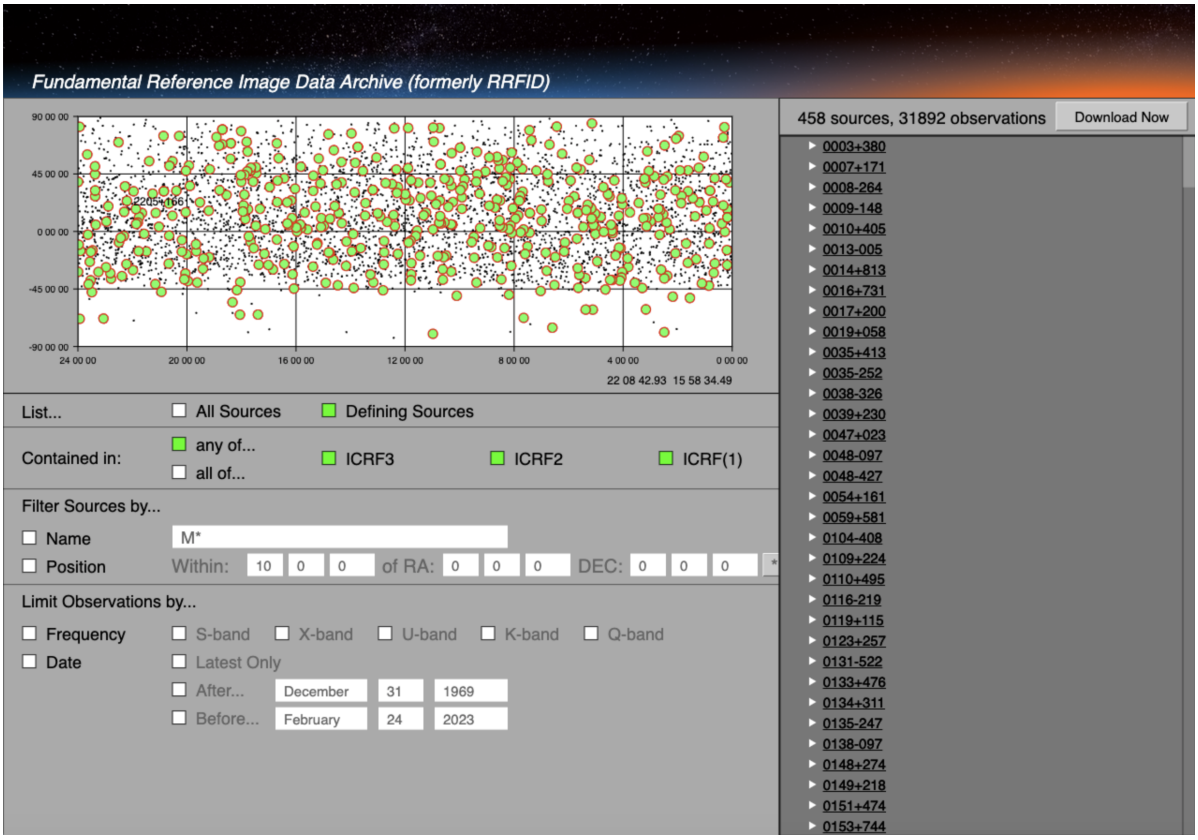

Fig. 1 FRIDA website homepage.

ational costs of the VLBA in exchange for 50% of the observing time. USNO began observing ICRF sources for the purposes of astrometry, geodesy, and imaging under this timeshare agreement. Since the start of the 50% timeshare agreement, in collaboration with GSFC, USNO has been running a VLBA-only series of observations called the UF/UG/UH-series. This series is observed at S/X-band (2.3/8.4 GHz) and is dual purpose in that the 24-hour experiments are designed for astrometry and geodesy but scheduled to optimize the *uv* coverage of each source for imaging. The UF/UG/UH-series contains roughly 225 sources per 24-hour session, most of which have been either ICRF-defining sources or weaker ICRF sources under-observed in IVS sessions. Understanding the source structure characteristics of these sources is paramount to improving and maintaining the ICRF because they constitute the majority of the ICRF and future ICRF sources.

In addition to the UF/UG/UH-series, USNO has also been supporting a series of K-band observations with the VLBA through the timeshare agreement. The principal investigator of this project is Dr. Aletha de Witt from the South African Radio Astronomy Observatory. Nearly all of the K-band data that are included in the recently adopted ICRF3 have come from this VLBA project. These observations are also optimized for imaging, and these data and images are planned to be included in a future version of FRIDA.

3.2 CASA Imaging Pipeline

A CASA calibration and imaging pipeline for producing the VLBA images in FRIDA was developed by Dr. Lucas Hunt over the course of several years. The details of the calibration and imaging process used for FRIDA are described in Hunt et al. 2021. The CASA pipeline

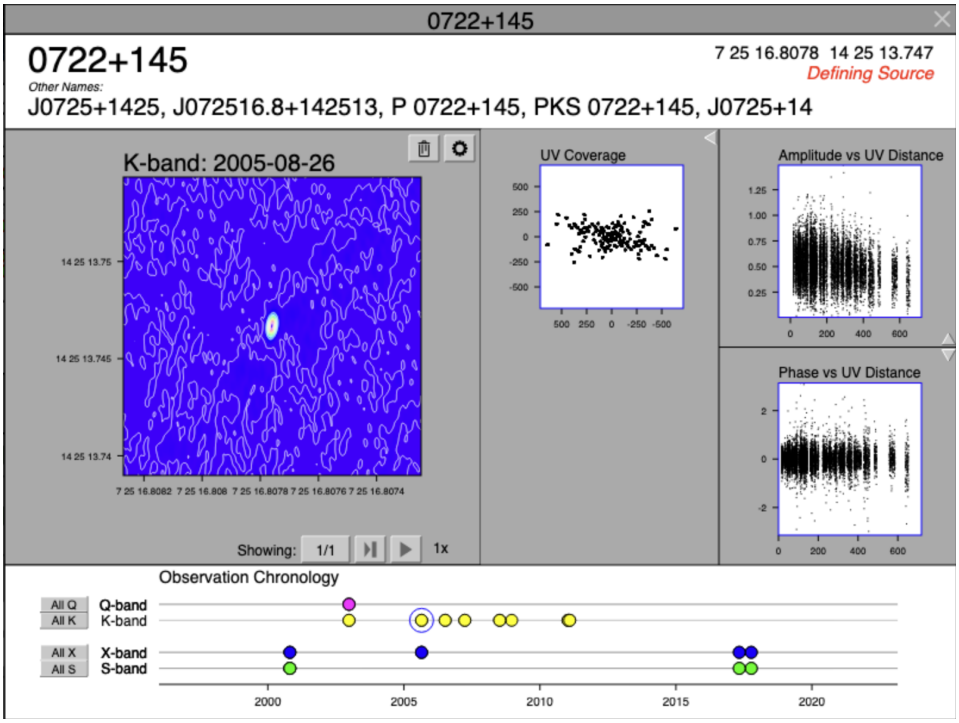

Fig. 2 FRIDA pop-up window displaying single source data and images.

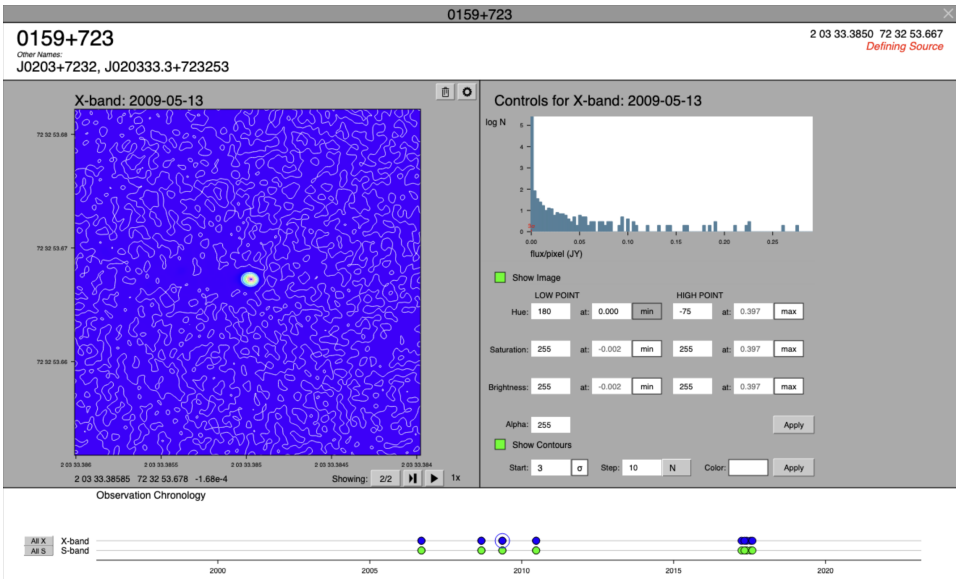

Fig. 3 FRIDA control settings pop-up display.

includes an automated Radio Frequency Interference (RFI) removal algorithm that is implemented in the calibration process using a standalone flagging algorithm called AOFlagger (Offringa et al. 2012). The current versions of the calibration and imaging pipelines can be applied to S- and X-band VLBA datasets, and users can access these scripts through the USNO website at the following links: calibration and imaging.

4 Conclusion and Future Work

Over the past two years, USNO has taken on a large initiative to revamp, improve, and refine its role as the Analysis Center for Source Structure and has developed and deployed a new image archive called FRIDA. FRIDA is available through a website interface where users have access to ∼15,000 images of ICRF sources that span a temporal baseline of nearly three decades. USNO has many research initiatives underway that make use of the VLBA imaging work described herein.

During April, May, and June of 2021, the Analysis Center for Source Structure participated in consecutive X/S-, K-, and Q-band VLBA astrometry sessions using the same source lists and schedule files. The goal was to obtain near-simultaneous images of approximately half of the K-band ICRF sources at four frequencies. Our collaborators in the project were Dr. Aletha de Witt at the South African Radio Astronomy Observatory and Christopher Jacobs at the Jet Propulsion Laboratory. Source images have been made for all of these sessions, and each source is being compared at the four frequencies. Details of these observations and first results can be found in Hunt et al. 2022. Exploring the ICRF source structure and flux intensity at higher frequencies is an ongoing effort for understanding what the optimal frequency band(s) are in the radio domain for future iterations of the ICRF.

The Analysis Center for Source Structure is working on improving, modifying, and adding new features and data to FRIDA over the coming few years. Some features we aim to improve are mitigating the latency issues users have experienced when first loading the homepage to FRIDA as well as adding new data to the archive. USNO also aims to add new information such as measured fluxes from the images at the different frequencies observed.

5 Staff

The staff of the Analysis Center for Source Structure during 2021–2022 consisted of Lucas Hunt[2], Megan Johnson, Phil Cigan, Christopher Dieck, and David Gordon. Lucas Hunt has been the primary lead in developing the CASA imaging pipeline and generating new images displayed in the current instance of FRIDA.

[2] Now at NRAO

6 Relevant Publications

Publications of relevance to Analysis Center activities:

1. “Imaging Sources in the Third Realization of the International Celestial Reference Frame”, Hunt, Lucas R., Johnson, Megan C., Cigan, Phillip J., Gordon, David, & Spitzak, John, 2021, The Astronomical Journal, 163, 121
2. “Comparing Images of ICRF Sources at X-, K-, and Q-band”, Hunt, Lucas R., de Witt, Aletha, Gordon, David, Jacobs, Christopher S., & Johnson, Megan C., 2023, IVS 2022 General Meeting Proceedings, Kyla L. Armstrong, Dirk Behrend, and Karen D. Baver, editors, NASA/CP-20220018789
3. “CASA Architecture and Applications,” McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K., 2007, Astronomical Data Analysis Software and Systems XVI (ASP Conf. Ser. 376), ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
4. “A morphological algorithm for improving radio-frequency interference detection,” Offringa, A. R., van de Gronde, J. J., & Roerdink, J. B. T. M., 2012, Astronomy & Astrophysics, 539, A95

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