

MIT Open Access Articles

IVS OBSERVATION OF ICRF2-GAIA TRANSFER SOURCES

The MIT Faculty has made this article openly available. **Please share** how this access benefits you. Your story matters.

Citation: Le Bail, K., J. M. Gipson, D. Gordon, D. S. MacMillan, D. Behrend, C. C. Thomas, S. Bolotin, et al. "IVS OBSERVATION OF ICRF2-GAIATRANSFER SOURCES." *The Astronomical Journal* 151, no. 3 (February 24, 2016): 79. © 2016 The American Astronomical Society

As Published: <http://dx.doi.org/10.3847/0004-6256/151/3/79>

Publisher: IOP Publishing

Persistent URL: <http://hdl.handle.net/1721.1/102637>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of Use: Article is made available in accordance with the publisher's policy and may be subject to US copyright law. Please refer to the publisher's site for terms of use.





IVS OBSERVATION OF ICRF2-GAIA TRANSFER SOURCES

K. LE BAIL¹, J. M. GIPSON¹, D. GORDON¹, D. S. MACMILLAN¹, D. BEHREND¹, C. C. THOMAS¹, S. BOLOTIN¹, W. E. HIMWICH¹,
K. D. BAVER¹, B. E. COREY², M. TITUS², G. BOURDA³, P. CHARLOT³, AND A. COLLIOD³

¹NVI, Inc, 7257D Hanover Parkway, Greenbelt, MD 20770, USA; karine.lebail@nasa.gov

²MIT Haystack Observatory, Off Route 40, Westford, MA 01886, USA

³Univ. Bordeaux, LAB, UMR 5804, F-33270, Floirac, France and CNRS, LAB, UMR 5804, F-33270, Floirac, France

Received 2015 October 14; accepted 2016 January 12; published 2016 February 25

ABSTRACT

The second realization of the International Celestial Reference Frame (ICRF2), which is the current fundamental celestial reference frame adopted by the International Astronomical Union, is based on Very Long Baseline Interferometry (VLBI) data at radio frequencies in X band and S band. The European Space Agency's *Gaia* mission, launched on 2013 December 19, started routine scientific operations in 2014 July. By scanning the whole sky, it is expected to observe $\sim 500,000$ Quasi Stellar Objects in the optical domain an average of 70 times each during the five years of the mission. This means that, in the future, two extragalactic celestial reference frames, at two different frequency domains, will coexist. It will thus be important to align them very accurately. In 2012, the Laboratoire d'Astrophysique de Bordeaux (LAB) selected 195 sources from ICRF2 that will be observed by *Gaia* and should be suitable for aligning the radio and optical frames: they are called ICRF2-*Gaia* transfer sources. The LAB submitted a proposal to the International VLBI Service (IVS) to regularly observe these ICRF2-*Gaia* transfer sources at the same rate as *Gaia* observes them in the optical realm, e.g., roughly once a month. We describe our successful effort to implement such a program and report on the results. Most observations of the ICRF2-*Gaia* transfer sources now occur automatically as part of the IVS source monitoring program, while a subset of 37 sources requires special attention. Beginning in 2013, we scheduled 25 VLBI sessions devoted in whole or in part to measuring these 37 sources. Of the 195 sources, all but one have been successfully observed in the 12 months prior to 2015 September 01. Of the sources, 87 met their observing target of 12 successful sessions per year. The position uncertainties of all of the ICRF2-*Gaia* transfer sources have improved since the start of this observing program. For a subset of 24 sources whose positions were very poorly known, the uncertainty has decreased, on average, by a factor of four. This observing program is successful because the two main goals were reached for most of the 195 ICRF2-*Gaia* transfer sources: observing at the requested target of 12 successful sessions per year and improving the position uncertainties to better than $200 \mu\text{as}$ for both R.A. and decl. However, scheduling some of the transfer sources remains a challenge because of network geometry and the weakness of the sources, and this will be one focus of future sessions used in this ongoing program.

Key words: astrometry – catalogs – quasars: general – reference systems – techniques: interferometric

Supporting material: machine-readable table

1. INTRODUCTION

The second realization of the International Celestial Reference Frame (ICRF), named ICRF2 is the current radio catalog, which contains accurate celestial positions of 3414 compact radio sources (extragalactic radio sources and quasars), as measured by Very Long Baseline Interferometry (VLBI; Schuh & Behrend 2012). The underlying accuracy of ICRF2 is $40 \mu\text{as}$ (Fey et al. 2009, 2015).

On 2013 December 19, the spacecraft of the ESA's *Gaia* mission was launched from French Guyana. After a seven-month commissioning phase, the mission entered into its operational phase in 2014 July. The mission's primary scientific product will be an optical catalog with the positions, motions, brightnesses, and colors of the surveyed objects. The first intermediate catalog will be released mid-2016 and the final version is expected by 2021 (see <http://sci.esa.int/gaia/>). The position accuracy anticipated after the commissioning phase is of the order of $20 \mu\text{as}$ at a magnitude of 15, $100 \mu\text{as}$ at a magnitude of 18, and $400 \mu\text{as}$ at a magnitude of 20 (F. Mignard 2014, private communication).

Gaia will survey the whole sky, including observing the extragalactic sources used for the celestial reference frame: the Quasi Stellar Objects. The *Gaia* Celestial Reference Frame (GCRF) in the optical domain should be aligned with the ICRF2 in the radio domain, ensuring the consistency of the fundamental frame in the future. This alignment will be done based on a set of common quasars among the $\sim 500,000$ quasars that *Gaia* is expected to observe. Aligning the two frames will permit many advances in science from a better understanding of the AGN physics to the quantification of the shifts between radio and optical positions (Kovalev et al. 2008).

In this paper, we describe the International VLBI Service for Geodesy and Astrometry (IVS) efforts made to regularly observe 195 ICRF2 sources that should align the ICRF and the GCRF. The IVS is an international collaboration of organizations, that operate and support VLBI components. The objectives of IVS are to provide a service to support geodetic, geophysical, and astrometric research and operational activities. The service promotes research and development activities in all aspects of the geodetic and astrometric VLBI techniques.

It fosters interaction with the community of users of VLBI products and supports the integration of VLBI into a global Earth observing system⁴ (Behrend 2013).

Section 2 describes the selection of these 195 sources, as well as the IVS monitoring program in which we included these sources and the set of sources that we schedule in specific sessions. We report on the scheduling strategy in Section 3. In Section 4, we present the improvements in observation frequency, source position accuracy, and flux information. We discuss how the station observing network could be developed to have the sensitivity to observe the entire set of 195 sources in Section 5.

2. CANDIDATE SOURCES TO ALIGN THE VLBI AND GAIA FRAMES

2.1. Selection of 195 ICRF2-Gaia Transfer Sources

The Laboratoire d’Astrophysique de Bordeaux (LAB) developed a strategy, explained in detail in Bourda et al. (2008), to select candidate sources for aligning the GCRF and the ICRF. The selected sources (1) are both contained in the ICRF and the Véron-Cetty & Véron (2006) optical catalog, (2) have an optical counterpart brighter than the apparent magnitude $V = 18$, and (3) have high astrometric quality, e.g., an acceptable observed structure as defined by the Structure Index introduced in Fey & Charlot (1997). The LAB identified 70 sources as good candidates when applying their criteria to the ICRF-Ext2 catalog. This catalog is the second extension of the first ICRF (Fey et al. 2004). It contains 717 sources, 109 more sources than are contained in the original ICRF.

Because the number of these candidate sources is low, the LAB extended its study to weak radio sources of the NRAO VLA Sky Survey (NVSS) catalog⁵ (Condon et al. 1998). The LAB extracted 447 sources with the following characteristics: they are not ICRF or VCS sources (sources in the VLBA Calibrator Survey⁶; Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006, 2008; Kovalev et al. 2007), their optical magnitude is less than or equal to 18, their total flux density from NVSS is greater than 0.02 Jy and their decl. are above -10° . Specific VLBI observing programs were designed with the European VLBI Network and the VLBA to observe these sources. The first campaign of observations was for detection (Bourda et al. 2010), the second campaign for imaging (Bourda et al. 2011), and the third campaign for accurate astrometry of the most compact sources, where 119 suitable sources were successfully observed (Bourda et al. 2015).

In parallel, in 2012, the LAB submitted a proposal to the IVS (see Bourda & Charlot 2012) to observe 195 ICRF2 transfer sources in the context of the *Gaia* mission. These 195 sources were selected within the ICRF2 catalog the same way the 70 sources were selected from the ICRF-Ext2, i.e., for their optical magnitude and astrometric suitability (Charlot et al. 2013; Bourda et al. 2015). These sources are called ICRF2-*Gaia* transfer sources. To get an observation frequency comparable to that of the *Gaia* mission, which is scheduled to observe sources an average of 70 times each during the five years of the mission, the LAB requested most of the ICRF2-*Gaia* transfer

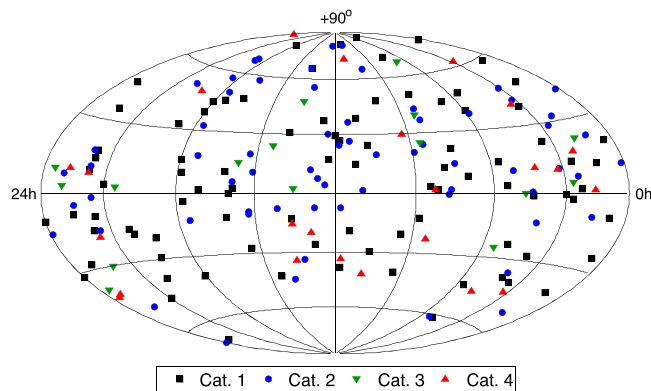


Figure 1. 195 ICRF2-*Gaia* transfer sources determined by the LAB.

sources to be observed at least once per month if possible. The LAB set an initial threshold of 200 μs for positional accuracy. This subjective threshold was selected as a reasonable value given the overall accuracy of the sources observed in the IVS monitoring program because the principal goal was to improve the position of the poorly observed ICRF2-*Gaia* transfer sources. Based on the Goddard VLBI global solution 2012a⁷ and the source list of the IVS source monitoring program at the time, the 195 sources were divided into four different categories.

1. Category 1 (89 sources): sources in the IVS source monitoring program that were sufficiently observed.
2. Category 2 (66 sources): sources in the IVS source monitoring program that were not sufficiently observed.
3. Category 3 (16 sources): sources not in the IVS source monitoring program but with a sufficient position accuracy.
4. Category 4 (24 sources): sources not in the IVS source monitoring program and with poor position accuracy.

As seen in Figure 1, the 195 ICRF2-*Gaia* transfer sources are well distributed, except for the band $[-60^\circ, -90^\circ]$ that contains only four sources.

Table 1 lists the 195 ICRF2-*Gaia* transfer sources, along with their coordinates from the latest GSFC catalog (2015a) and most recent flux values from the *sked* flux catalog⁸ (status: 2015 August 28) and from the Bordeaux VLBI Image Database⁹ (BVID; Collioud & Charlot 2009; status: 2015 September 11). The fluxes are computed from data available through 2015 August 27 for the *sked* catalog and through 2013 July 24 for BVID (see Section 4.3).

2.2. Inclusion in the IVS Source Monitoring Program

Beginning in 2003 June, the Goddard VLBI group developed a program to purposefully monitor when sources were observed and to increase the observations of “under-observed” sources. The heart of the program consists of a MySQL database that on a session-by-session basis keeps track of the number of observations that are successfully correlated and the number of observations that are used in a session. In addition, there is a MySQL table in the database that contains the target number of successful sessions over the last 12

⁴ <http://ivscc.gsfc.nasa.gov/about/index.html>

⁵ <http://www.cv.nrao.edu/nvss/>

⁶ <http://gemini.gsfc.nasa.gov/vcs/>

⁷ <http://gemini.gsfc.nasa.gov/solutions/2012a/2012a.html>

⁸ <ftp://gemini.gsfc.nasa.gov/pub/sked/catalogs/flux.cat>

⁹ <http://www.obs.u-bordeaux1.fr/BVID/>

Table 1
Candidate ICRF2-*Gaia* Transfer Sources to Align the Radio Catalog and the *Gaia* Catalog

Source Name		J2000.0 Coordinates in 2015a GSFC Catalog ^a										GSFC Flux ^b (<i>sked</i>)		BVID Flux ^b		Initial	
IVS	IAU/J2000	h	R.A. α			Decl. δ			Formal Errors		Sess.	Obs.	X Band	S Band	X Band	S Band	<i>Gaia</i> cat.
			m	s	°	'	''	$\Delta\alpha$	$\Delta\delta$	#	#						
0016+731	J0019+7327	00	19	45.7863648	+73	27	30.0175664	8	2	734	83780	4.28	0.73	0.90	0.67	1	
0025+197	J0028+2000	00	28	29.8184839	+20	00	26.7439348	17	22	78	2615	0.25	0.16	0.19	0.17	1	
0035-252	J0038-2459	00	38	14.7355028	-24	59	02.2352821	18	21	140	2696	0.23	0.18	0.65	0.40	1	
0048-097	J0050-0929	00	50	41.3173869	-09	29	05.2103565	4	6	2016	45436	0.62	0.20	0.55	0.52	1	
0059+581	J0102+5824	01	02	45.7623787	+58	24	11.1365770	2	2	2491	361024	3.36	2.49	1.69	1.91	1	
0104-408	J0106-4034	01	06	45.1079685	-40	34	19.9603641	9	9	1662	17435	1.28	3.52	0.76	0.64	1	
0119+115	J0121+1149	01	21	41.5950426	+11	49	50.4131761	3	6	1507	54260	1.81	2.34	1.55	1.80	1	
0133+476	J0136+4751	01	36	58.5948052	+47	51	29.1000322	2	2	1860	184101	1.70	0.96	3.87	1.04	1	
0215+015	J0217+0144	02	17	48.9547539	+01	44	49.6990157	6	7	216	15613	0.44	0.35	0.73	1.00	1	
0229+131	J0231+1322	02	31	45.8940565	+13	22	54.7162577	3	5	2867	86610	1.93	3.38	2.15	1.74	1	

Notes. The formal errors in the table come directly from the GSFC solution and are likely too optimistic. A more realistic estimate would be obtained by applying a scale factor of 1.5 to the formal uncertainties followed by a root-sum-square increase of $40 \mu\text{s}$ of error in quadrature to the quoted values. This was the procedure adopted for ICRF2 (Fey et al. 2009, 2015). Table 1 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

^a The coordinates are from the latest version of the GSFC solution 2015a in IERS format (status: 01 September 1 2015). Units of R.A. α are hours, minutes, and seconds; units of decl. δ are degrees, minutes, and seconds; units of uncertainties ($\Delta\alpha$ and $\Delta\delta$) are in μs . The uncertainties for α are not corrected from $\cos(\delta)$.

^b The flux values are from *sked* (status: 2015 August 28) and BVID (status: 2015 September 11). Units are Jy.

(This table is available in its entirety in machine-readable form.)

months. Initially, this table only contained two categories. Sources in the geodetic catalog had a target of 12 sessions/year; the remaining ICRF-1 defining sources had a target of two sessions/year. All other sources did not have a specific target. As the program evolved, different kinds of sources with different observing targets were added. During the scheduling process, the scheduler has the option of automatically selecting sources that have not met their target (Gipson et al. 2014). Currently, the IVS weekly R1 and R4 sessions as well as the bi-monthly RDV sessions participate in this program. Each of these sessions includes up to 10 “monitoring” sources.

In 2013 March, we added all 195 ICRF2-*Gaia* transfer sources to the IVS source monitoring program with an observation target of 12 successful sessions per year.

2.3. Focus on a Specific Set of Sources

Because of the network geometry and/or their low flux (flux values lower than 0.10 Jy), some of the 195 ICRF2-*Gaia* transfer sources were not automatically scheduled in the IVS source monitoring program. We decided to schedule them manually in dedicated R&D and RDV sessions. The R&D sessions are for research and development purposes and the RDV sessions for research and development with the VLBA (see Section 3.2 for more details).

The first set of sources we focused on was the set of 24 sources in category 4 described in Section 2.1. The main goals were to improve their position accuracy and to increase their observation frequency. This set of sources was then updated depending on the overall progress of the program.

In 2014 August, we revised the threshold for good accuracy to $100 \mu\text{as}$ in both R.A. (α) and decl. (δ). Four sources in category 3 (0528–250, 1330+022, 1424+240, and 2029+024) had larger position uncertainties than the revised threshold. In addition, one source in category 1 (1348+308) and four sources in category 2 (1022+194, 1125+366, 1215+303, and 1736+324) were not observed in the previous 12 months (2013 July to 2014 August). These nine sources were added to the initial set for dedicated sessions.

In 2015 June, the four sources in category 3 (0528–250, 1330+022, 1424+240, and 2029+024) were removed because their position uncertainties ($32\text{--}50 \mu\text{as}$ in α , $50\text{--}98 \mu\text{as}$ in δ) reached the required level of precision. Four other sources were added. One source in category 3 (2254+024) had not been observed in the previous 12 months (May 2014 to 2015 June). One source in category 1 (0454+844) and two sources in category 2 (2353–686 and 0522–611) still had large position uncertainties.

The resulting 37 sources of this set are represented in Figure 2. Except for sources in the IVS source monitoring program (categories 1 and 2) and for the source 0528–250, sources in this set were observed very poorly at the beginning of the observing program: 74% of the sources were observed 1 to 3 times and the other 26% were observed 4 to 17 times. We show the sessions in which each of the sources were scheduled and observed during this observing program in Figure 5 (see Section 3.3) when discussing the network used in R&D and RDV sessions.

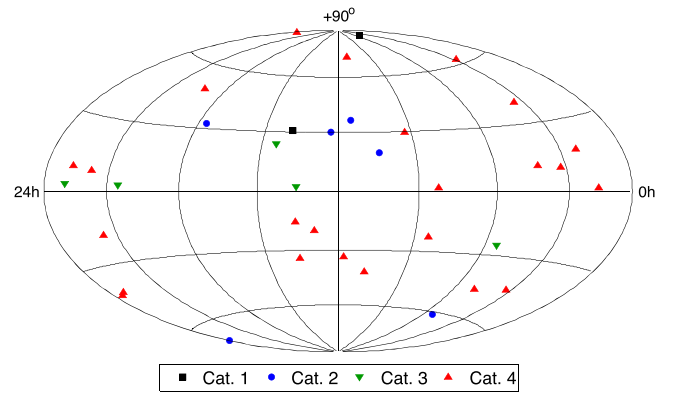


Figure 2. The 37 ICRF2-*Gaia* transfer sources scheduled in dedicated R&D and RDV sessions.

3. SCHEDULING

3.1. VLBI Scheduling Software *sked*

All of the observing schedules were made using the VLBI scheduling software *sked* (Gipson 2012).

Sked is widely used within the IVS community to schedule geodetic and astrometric VLBI sessions. A full description of this software is beyond the scope of this article, but a few words about how *sked* works, and, in particular, how it was used in these sessions is useful. *Sked* can be run in manual mode, where the user explicitly specifies all or part of the information required to schedule a scan (with *sked* calculating the remaining parameters, e.g., start time and duration), or in automatic mode, where *sked* will automatically choose a series of scans until some end point, or a combination of both modes. For example, the scheduler can have *sked* automatically schedule scans until 18:00, then schedule a few scans by hand, and then resume automatic scheduling.

In automatic mode *sked* uses a heuristic rule-based approach in scheduling using a two-step approach. It initially finds the universe of all possible scans at a given epoch with a given network, source list, SNR targets, and additional hard constraints. These constraints include factors such as minimum and maximum angular distance between scans, whether a source has been observed in the last N minutes, angular distance of the source to the Sun, or minimum number of stations in a scan. Once *sked* has generated a list of all candidate scans, it then scores each scan against a variety of criteria such as duration, number of observations, start time, end time, sky coverage, particular sources or stations included in the scan, calculates a weighted sum, and chooses the scan with the highest weighted score. The scheduler can choose what criteria to include as well as their weights.

In scheduling the ICRF2-*Gaia* transfer sources in R&D sessions, we use the *astrometric* mode of *sked*. This is actually a subset of automatic scheduling in which part of the scan-score is based on which source is in the scan. In this mode, the user specifies a list of sources together with minimum and maximum observing targets expressed in terms of the percentage of the total number of observations in a schedule. In our case, the astrometric sources were some subset of the ICRF2-*Gaia* transfer sources. If a candidate scan contains an astrometric source and the percentage of the observations is above the maximum target, then the scan will not be scheduled.

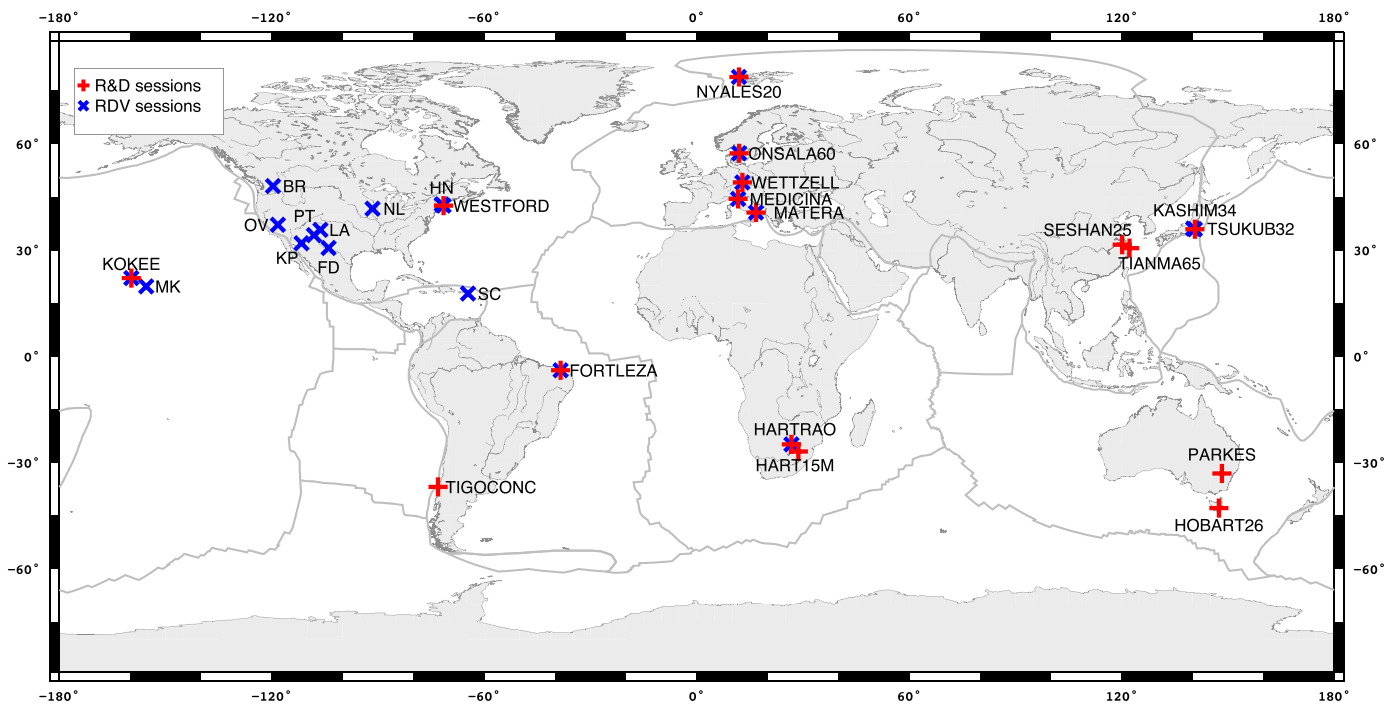


Figure 3. Stations used in R&D and RDV sessions including observations of 37 specific ICRF2-*Gaia* transfer sources.

If the percentage of observations is below the minimum observing target, the score for the potential scan is increased based on how far below the target it is. By adjusting the observing targets of the astrometric sources one can influence how many observations these sources have in a given schedule. The process is highly nonlinear, and it may take several iterations to get a satisfactory schedule. For some weak sources, or sources with poor visibility, it may be difficult or impossible to have *sked* automatically schedule enough scans. In this case, the scheduler has the option of manually scheduling observations on these sources.

3.2. Scheduling Strategies Using *sked*

The IVS schedules around 10 R&D sessions per year. The IVS Observing Program Committee allocates these sessions based on proposals. We requested the use of six R&D sessions per year over a five-year period for the observation of ICRF2-*Gaia* transfer sources that were not being picked up in the regular monitoring program or had poor uncertainty. We were approved for four sessions in 2013, six in 2014, and six in 2015. The strategy for scheduling remains mostly the same since the beginning of this program. Schedules were made with a 512 Mbps recording mode, except RD1307 and RD1308, which use a 256 Mbps recording mode. The data were sampled at two bits. Of the geodetic sources, 40 were selected as the base set of stable sources and to ensure a uniform sky coverage. The *astrometric* mode was chosen for the set of sources in which we are interested. All of these R&D sessions were correlated at the MIT Haystack Observatory.

We also used 11 RDV sessions. These sessions were recorded at 256 Mbps, using the VLBA plus 6 to 10 non-VLBA geodesy stations. Schedules were made using a combination of auto-scheduling for most sources and manual scheduling for the ICRF2-*Gaia* transfer and other weak sources. The ICRF2-*Gaia* transfer sources were typically

scheduled for two six-to-eight-minute scans using only the more sensitive VLBA antennas. The RDV sessions were correlated at the National Radio Astronomy Observatory (NRAO) correlator in Socorro, NM.

3.3. Stations Used

The stations used in the program are represented in Figure 3. The actual observing networks were subsets of these stations. For each station, Table 2 gives information on the diameter of the primary reflector and the number of times each station was in dedicated R&D and RDV sessions. It also lists the a priori System Equivalent Flux Density (SEFD) used by *sked* in both X band and S band, as a measure of the sensitivity of the antenna. Figure 4 shows the observation history of each station since the beginning of this program.

The stations used in most of the R&D sessions are stations in Europe, China, South America, South Africa, and Australia. The diameter of the antenna dish for most of these stations is 18–20 m. These are relatively small antennas, which impacts the ability to successfully observe weak sources (SEFDs from 1000 to 2500 Jy). Stations with larger antennas such as Parkes (64 m) or Tianma65 (65 m), or with a higher sensitivity such as Kashim34 in Japan or Seshan25 in China, were used in some sessions: Parkes in RD1306; Kashim34 in RD1404; Seshan25 in RD1412, RD1501 and RD1502; Tianma65 in RD1404 and RD1504.

The stations used in every RDV session are the 10 VLBA stations. They are 10 identical antennas of 25 m, located in the USA (continental and outlying islands). They are sensitive antennas with nominal SEFDs of 500 Jy in X band and 400 Jy in S band. The IVS stations contributing to the RDVs are located in Europe, Japan, South Africa, and South America.

Figure 5 shows the R&D and RDV observation history of the 37 ICRF2-*Gaia* transfer sources since the beginning of this program. The sources are marked with a square for a session if

Table 2

Characteristics of Stations Used in Dedicated R&D and RDV Sessions between 2013 June and 2015 September

Station	Diameter (m)	SEFD (Jy)		R&D #	RDV #
		X Band	S Band		
NYALES20	20.0	1000	1500	14	11
ONSLA60	20.0	2000	2500	7	6
WETTZELL	20.0	750	1115	11	9
MEDICINA	32.0	1100	1500	2	1
WESTFORD	18.0	1500	1400	6	5
MATERA	20.0	1600	2200	7	6
TSUKUB32	32.0	320	360	...	1
KASHMI34	34.0	550	430	1	3
SESHAN25	25.0	700	1100	3	...
TIANMA65	65.0	60	90	2	...
KOKEE	20.0	2000	750	12	2
FORTLEZA	14.2	5000	5000	4	1
HART15M	15.0	1400	1050	3	...
HARTRAO	26.0	1500	1300	12	6
PARKES	64.0	200	300	1	...
TIGOCONC	6.0	20000	15000	1	...
HOBART26	26.0	1200	800	11	...
VLBA	25.0	500	400	...	11

Note. Antenna Parameters from the *sked* Catalog Files (Status: 2015 April). The 10 VLBA Stations are BR, HN, NL, OV, LA, KP, FD, MK, SC, and PT.

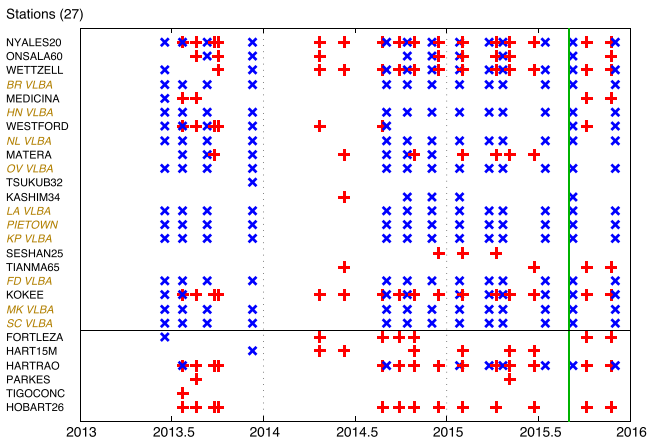


Figure 4. R&D sessions (red plus signs) and RDV sessions (blue crosses) used to observe the 37 specific ICRF2-*Gaia* transfer sources. The green vertical line indicates the sessions planned from the writing of the paper until the end of 2015. The black horizontal line represents the equator. The stations are ordered by latitude and the VLBA stations are italicized.

they have been scheduled. If they have been successfully observed and their data is of good quality, the square is filled with a dot.

Because they were included in the IVS source monitoring program and their fluxes are suitable (for example, 0454–463 or 0812+020), some of the 37 sources are now automatically scheduled in other IVS sessions (e.g., R1, R4, *Intensives*, or *AUST*). The network and antenna sensitivities impact the observational success for very weak sources. We notice in Figure 5 that the three most successful R&D sessions are RD1306, RD1404, and RD1504; in these, more than 94% of the scheduled sources were successfully observed. The network for these three sessions included large and sensitive antennas:

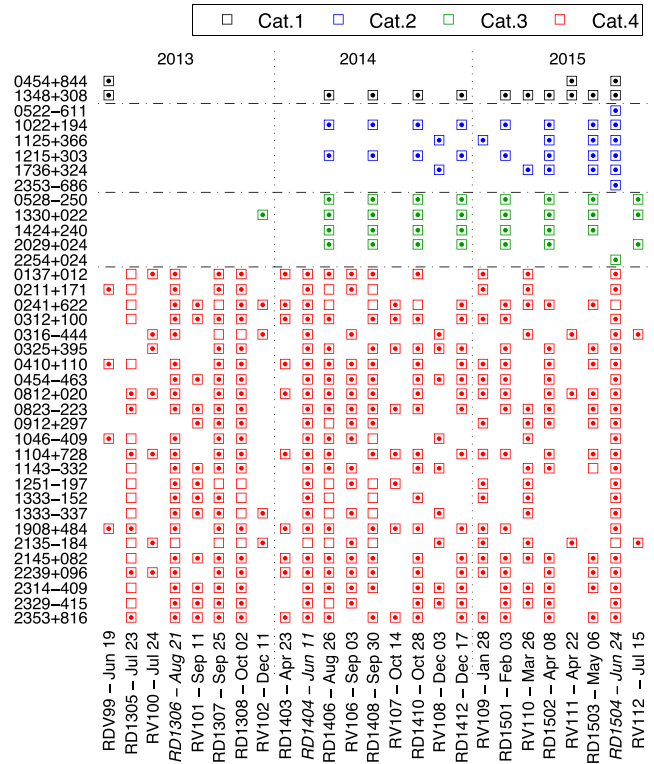


Figure 5. 37 ICRF2-*Gaia* transfer sources specifically scheduled in some R&D and RDV sessions. The square means the source was scheduled on the given date and the dotted square means the source observations were successful and were used in a VLBI data solution for the latest GSFC quarterly solution. The most successful sessions are those with larger antennas (RD1306, RD1404, and RD1504).

Parkes in RD1306, Kashim34 in RD1404, and Tianma65 in RD1404 and RD1504.

4. IMPROVED INFORMATION ABOUT THE ICRF2-GAIA TRANSFER SOURCES

4.1. Frequency of Observations

Since the operational start of this observing program in 2013 June, all 195 sources were observed at least once, 93% of the sources were observed at a rate of at least five successful sessions per year, and 59% of the sources reached the required target of 12 successful sessions per year.

The four charts in Figure 6 summarize the number of sources that met their target over the preceding 12 months as a function of time. Each chart corresponds to one category of the ICRF2-*Gaia* transfer sources and covers the period of 2011 January 1 to 2015 September 1. They include only data from sessions that have been correlated and analyzed at the time of this paper. As a consequence, the number of sessions falls off on the right-hand side.

Since 2013 October, the number of successful observations has increased significantly for the sources in categories 2, 3, and 4. On 2015 September 1st, the target of 12 successful sessions per year is reached for 67% of the category 1 sources, 35% of the category 2 sources, and 25% for the category 3 sources. Respectively, 94%, 86%, and 81% in category 1, 2, and 3 were successfully observed at least four to six times in the past year. Only one source in category 1, two sources in

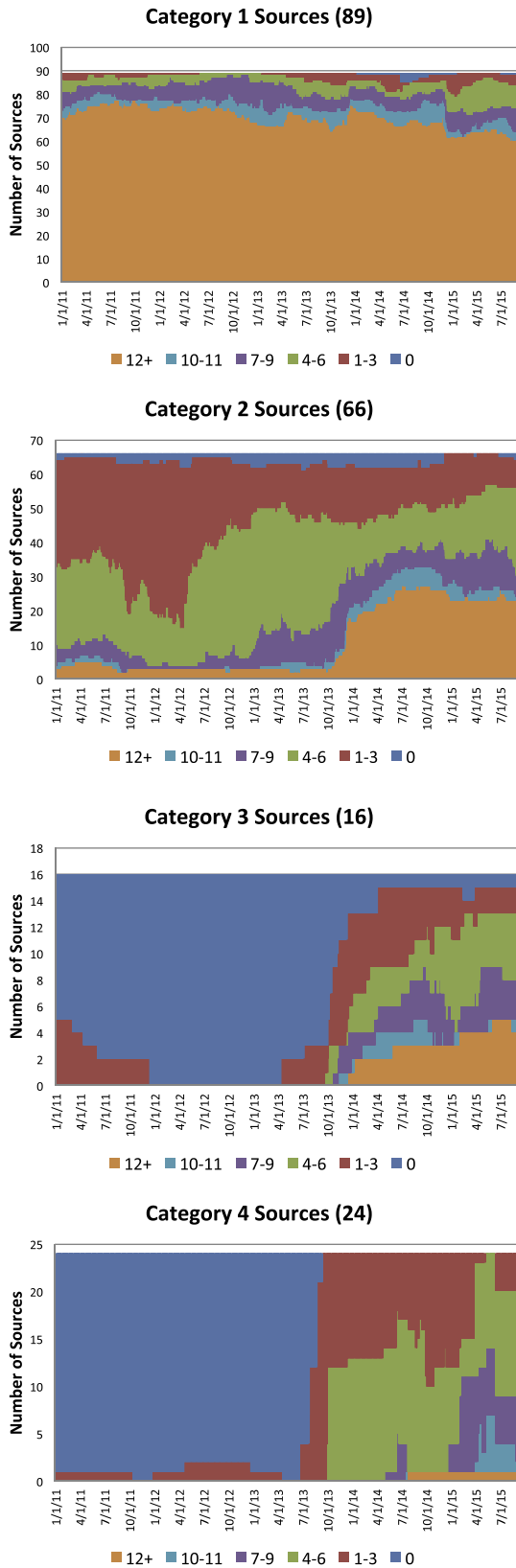


Figure 6. Evolution of the observational coverage of the 195 ICRF2-*Gaia* transfer sources from 2011 January 1 to 2015 September 1. The color coding indicates the number of observations of a source over the previous year. For example, for cat. 3 on 2013 July 1, two sources had 1–3 observations, the others had none. The observation target is set to 12 per year.

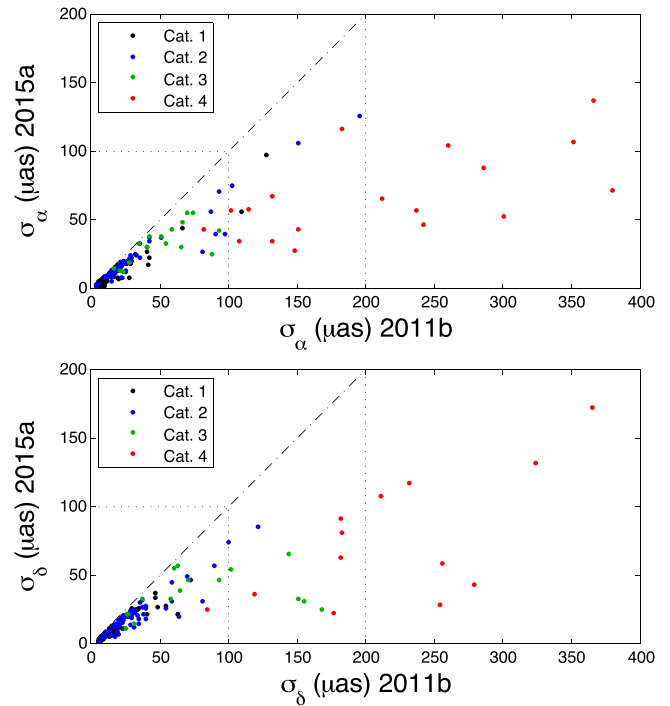


Figure 7. Position uncertainties of R.A. α and decl. δ for all 195 ICRF2-*Gaia* transfer sources. GSFC solution 2011b vs. GSFC solution 2015a. Some sources in category 4 are not in the plot because of their large uncertainties (see Table 3): 6 sources in the α plot, 11 sources in the δ plot. The dotted lines indicate the 200 and 100 μas thresholds.

category 2, and one source in category 3 have not been observed in the past year. In category 4, 20 sources out of 24 reached at least four successful sessions per year, and all sources were successfully observed at least once in the past year.

4.2. Accuracy of Source Positions

Figure 7 illustrates a comparison of position uncertainties of α and δ of the sources in all categories between the GSFC solution 2011b¹⁰ (prior to the program) and the GSFC solution 2015a (internal solution, status: 2015 September 01). These are unscaled uncertainties. For reference, the ICRF2 uncertainties were scaled by a factor of 1.5, and a noise floor of 40 μas was applied. These factors were determined by dividing the full set of observing sessions into two independent sets and analyzing the differences in source positions from the two independent solutions (Fey et al. 2009, 2015).

In category 4, 6 sources are not represented in the top plot (α) and 11 sources are not represented in the bottom plot (δ) because their position uncertainties are larger than the scale used. Table 3 focuses on the position uncertainties of the 37 ICRF2-*Gaia* transfer sources described in Section 2.3. The sources not represented in Figure 7 are in bold in Table 3.

All sources in categories 1, 2, and 3 have unscaled position uncertainties less than 100 μas in both α and δ , except 0522–611 and 2353–686 (cat. 2), which have position uncertainties between 100 and 200 μas in α . These two sources are far south in decl. They are not weak sources but they have not been observed often in the past year (one to two sessions). They

¹⁰ <http://gemini.gsfc.nasa.gov/solutions/2011b/2011b.html>

Table 3

Position Uncertainties Comparison between the GSFC Solutions 2011b and 2015a for the 37 ICRF2-*Gaia* Transfer Sources Specifically Scheduled in R&D and RDV Sessions

Sources	Number of Sessions		$\sigma(\alpha)\mu\text{as}$		$\sigma(\delta)\mu\text{as}$	
	2011b	2015a	2011b	2015a	2011b	2015a
Cat. 1						
0454+844	238	337	128	97	14	11
1348+308	32	57	41	27	49	27
Cat. 2						
0522-611	21	32	196	126	100	74
1022+194	42	64	19	17	29	24
1125+366	13	22	93	71	122	85
1215+303	29	42	29	24	38	27
1736+324	9	17	51	37	90	57
2353-686	35	51	151	106	59	45
Cat. 3						
0528-250	21	42	51	38	102	54
1330+022	1	18	66	30	155	31
1424+240	9	20	93	42	151	33
2029+024	2	14	59	43	144	66
2254+024	25	41	35	33	61	55
Cat. 4						
0137+012	1	13	242	47	469	79
0211+171	1	10	380	72	581	147
0241+622	6	16	517	275	211	108
0312+100	1	14	237	57	460	68
0316-444	1	9	5827	236	27968	503
0325+395	3	13	557	51	470	45
0410+110	1	14	151	43	256	59
0454-463	16	67	148	28	177	23
0812+020	1	16	108	35	279	43
0823-223	9	21	82	43	182	91
0912+297	17	25	115	58	183	81
1046-409	2	11	183	116	365	172
1104+728	9	22	366	137	119	36
1143-332	2	12	132	67	324	132
1251-197	1	9	212	66	500	128
1333-152	2	9	102	57	232	117
1333-337	1	9	618	101	1087	151
1908+484	2	15	260	104	182	63
2135-184	3	10	8972	1015	9222	1473
2145+082	2	15	301	53	869	132
2239+096	2	15	132	35	254	29
2314-409	1	13	286	88	600	94
2329-415	1	11	351	107	589	113
2353+816	4	18	570	174	85	25

Note. The uncertainties for α are not corrected from $\cos(\delta)$. The sources not represented in Figure 3 have their uncertainties in bold font in this table.

were recently included in the list of sources to be observed in dedicated R&D and RDV sessions. For the sources in category 4, 9 sources (out of 24) have position uncertainties in both α and δ smaller than $100\mu\text{as}$, 11 sources between 100 and $200\mu\text{as}$, 2 sources between 200 and $300\mu\text{as}$, and 2 sources (0316-444 and 2135-184) still have position uncertainties larger than $300\mu\text{as}$. Overall, the target level of $200\mu\text{as}$ in both α and δ was reached for 98% of all 195 sources and 92% of the sources have accuracies better than $100\mu\text{as}$.

4.3. Improved Source Flux Information for Scheduling in *sked*

We used different flux values when scheduling the set of 37 ICRF2-*Gaia* transfer sources in R&D sessions: flux values provided by the LAB, flux values from the *sked* catalog, and composite flux values taking into account information from these catalogs and previous sessions in which the sources of interest were successfully observed.

The flux values provided by the LAB for the 195 ICRF2-*Gaia* transfer sources were derived from the BVID (Collioud & Charlot 2009). The BVID includes 4499 VLBI images of 1212 extragalactic radio sources, essentially all derived from RDV sessions. The flux information is determined from these images. The BVID, as of 2015 September 11, contains fluxes computed from data available through 2013 July 24.

The flux values in the *sked* catalog are computed in an alternative way. They are flux estimates derived from the analysis of observed SNRs, which depend on the station sensitivities and spatial distribution as well as the source fluxes. For each observation, the observed SNR is expressed as a product of the a priori SNR and factors for the source and the two stations taking part in the observation. The a priori (scheduled) SNR is computed from the a priori source flux density and SEFDs of each of the stations. If the actual flux density and actual SEFDs at the time of observation equalled their a priori values, then the corresponding factors would equal one. SNR analysis performs a least-squares fit of the ratio of observed/scheduled SNRs to derive the source and station factors for an observing session, typically 24 hr long. Each observed flux is then the product of its source factor and the a priori flux. Each observed SEFD is the product of its station factor and the a priori SEFD. The analysis assumes that the uncertainty of a priori fluxes and station SEFDs are good to within about 20%. For scheduling purposes, as long as the a priori fluxes and SEFDs are consistently derived, the scheduled SNRs will be reasonable. The values reported in the *sked* catalog are an average over sessions in the most recent two months. The *sked* catalog used in this study contains fluxes computed from data available through 2015 August 27.

In 2013, we used the flux values provided by the LAB in their proposal (see Bourda & Charlot 2012), as *sked* flux information was not available for most of the category 4 sources, because these sources were not observed in previous sessions (sessions over the period 1996 to now). After several sessions, we realized the BVID values were too large since some of the sources, which were scheduled using the BVID fluxes, were not detected during the session. For this reason, in 2014, we used a composite catalog combining these flux values with the *sked* flux catalog, taking into account the observations done in previous R&D sessions. For the R&D sessions in 2015, we used the current *sked* catalog as well as the updated values provided by the LAB for a few sources.

When comparing the two current catalogs for the 195 ICRF2-*Gaia* transfer sources, a majority of the BVID flux values are found to be larger for categories 3 and 4: 75% of the 40 sources have a flux in X band larger than in the *sked* catalog, the same for S band. This is illustrated in Figure 8. We can clearly see that most of the sources in category 4 have a flux value larger than 0.10Jy for BVID, while it is lower for *sked* (the yellow area of the right plots).

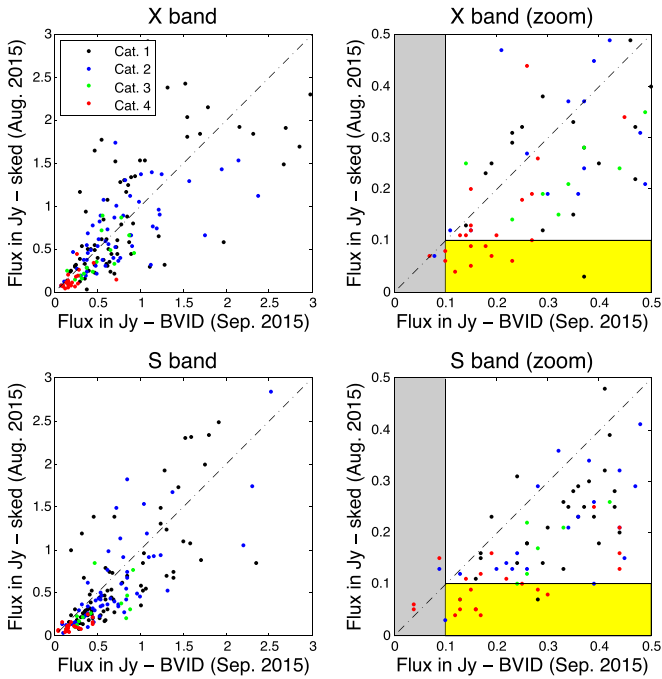


Figure 8. Flux comparisons of BVID (as of 2015 September 11 with data available through 2013 July 24) vs. *sked* (status: 2015 August 28). The plots on the left do not show sources with flux values higher than 3.00 Jy (19 sources in X band and 13 in S band). The plots on the right focus on a zoomed region. The BVID fluxes tend to be larger than the *sked* fluxes.

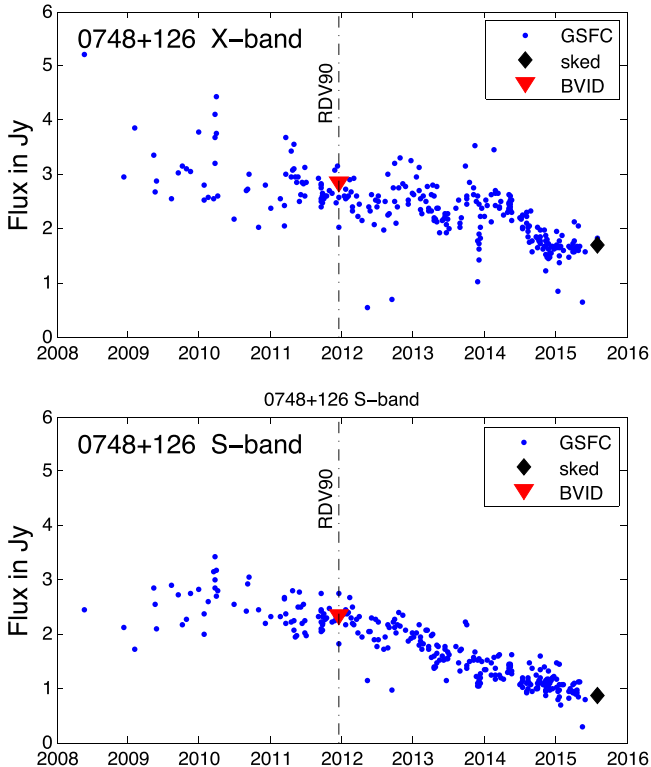


Figure 9. Flux values in X band and S band of the source 0748+126 calculated by GSFC for each session (blue dots), reported in the *sked* catalog (black diamond), and from the BVID (red triangle). The GSFC values are empirical fluxes based on analyses of individual sessions' SNRs. The *sked* values are from the latest *sked* catalog (status: 2015 August 28). The BVID values are, as of 2015 September 11, based on data available through 2013 July 24.

The fluxes for the source 0748+126 calculated over the period 2008 to 2016 are plotted in Figure 9. The BVID flux values, which were computed for the RDV session RDV90 (vertical dashed line), are comparable to the values computed at GSFC. In these plots, we see the flux values of the source decreasing after 2012 for both X band and S band. The values in 2015 are 1.17 Jy lower in X band and 1.50 Jy lower in S band than the values in 2012. This type of behavior may explain some of the discrepancies in Figure 8 because the compared fluxes are not necessarily based on data from the same session. Another explanation for the discrepancies may also be the different methodologies for the flux determination. This is currently under investigation.

To schedule a source in a session, we use the most recent flux values available as a current state of the source. This may be the cause of the difficulties we encountered when scheduling with BVID fluxes because the choice of flux values impacts the detection of the source in a session. Flux values, station SEFDs, length of the scan, and SNR are all linked by the following equation (see Gipson 2012).

$$\text{SNR} = \frac{F}{\sqrt{\text{SEFD}_1 \times \text{SEFD}_2}} \times \sqrt{\text{Rate} \times \text{NC} \times \text{SL}} \times \eta \quad (1)$$

where F is the flux density, Rate is the sample recording rate per channel, NC is the number of channels of the mode used, SL is the scan length, and η is a factor (<1) that accounts for the number of bits sampled and how the correlation is done. If the a priori flux is larger than the actual flux, a source may be scheduled but not detected. If the a priori flux is too small, the source may never be scheduled in automatic mode.

5. IMPROVING THE OBSERVATIONAL PROGRAM

5.1. More Sensitive Antennas

In Figure 5, we showed that RD1404 is one of the most successful R&D sessions dedicated to the observation of 37 of the ICRF2-*Gaia* transfer sources. The network for this session contains Tianma65 (T6). To better understand the impact that T6 has, solutions were made with and without the Tianma65 baselines. Table 4 shows the differences in the number of observations of each of the category 4 sources. Flux values computed at GSFC from the RD1404 session SNRs are indicated in the last two columns. The values in the table for 2135–184 are from the *sked* catalog because it was not successfully observed in RD1404. The 24 sources are mostly weak sources with flux values lower than 0.10 Jy. Most of these sources have significantly more observations using Tianma65, 2.6 times more on average, and quite a few would not have enough observations to be useful without Tianma65 because a minimum of three good observations is a requirement in the processing to select a source in a given session.

Figure 10 illustrates which sources can be detected depending on the baseline observing them and their flux values (see Equation (1)) as applied to our scheduling strategy for the R&D sessions. The maximum scan length SL was set to 600 s. The SNR targets are set to 20 in X band and 15 in S band. Two-letter codes are used for four stations: T6 for Tianma65, Ny for Nyales20, On for Onsala60, and Ft for Fortleza. These stations

Table 4Number of Successful Observations of the 24 ICRF2-*Gaia* Transfer Sources in Category 4 When Using Tianma (T6) in the Network or Not

Sources	Number of Observations			Flux (Jy)	
	w/ T6	w/o T6	Ratio	S Band	X Band
2135–184	0	0	...	0.03	0.10
0316–444	4	0	...	0.05	0.05
0211+171	10	3	3.3	0.06	0.06
1251–197	22	7	3.1	0.07	0.07
1333–152	28	9	3.1	0.07	0.10
0325+395	9	0	...	0.07	0.33
0912+297	43	22	2.0	0.08	0.07
0137+012	57	34	1.7	0.08	0.17
0312+100	74	57	1.3	0.09	0.10
1046–409	7	2	3.5	0.09	0.12
1333–337	20	6	3.3	0.09	0.17
1908+484	69	39	1.8	0.10	0.06
1143–332	15	5	3.0	0.13	0.16
2329–415	7	2	3.5	0.14	0.13
1104+728	84	56	1.5	0.16	0.12
0410+110	102	76	1.3	0.16	0.15
0812+020	99	68	1.5	0.20	0.13
2145+082	23	10	2.3	0.22	0.09
0241+622	20	18	1.1	0.24	0.52
2314–409	10	1	10.0	0.30	0.15
2239+096	59	45	1.3	0.33	0.23
0823–223	20	11	1.8	0.40	0.76
2353+816	106	89	1.2	0.49	0.36
0454–463	3	0	...	0.74	0.50
Average	2.6

Note. The flux values are computed from the RD1404 session SNRs, except the values for 2135–184, which are from the *sked* Catalog.

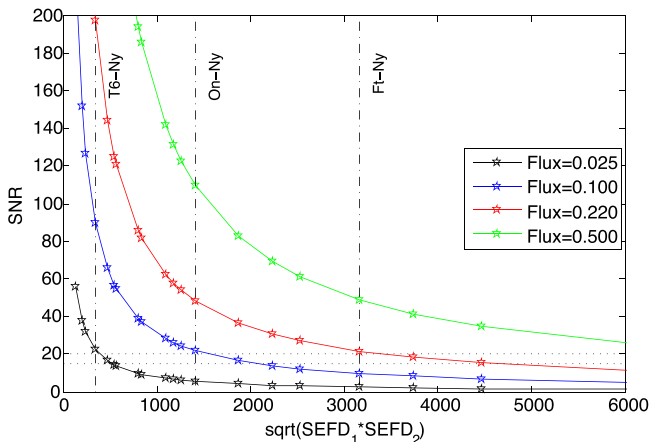


Figure 10. SEFD vs. SNR. Four different cases are illustrated for sources with flux values of 0.025, 0.100, 0.220, and 0.500 Jy. Baselines T6-Ny, On-Ny, and Ft-Ny are indicated for reference. To be scheduled, a source must be above the dotted lines indicating the SNR targets used in *sked* (20 for X band, 15 for S band) and 600 s scans.

are chosen because they represent the different cases in this study: Tianma65 has a large dish and low SEFDs, Nyales20 and Onsala60 are European stations with typical SEFDs, and Fortleza has large SEFDs (see Table 2).

In the mode we use in *sked* for the R&D sessions, the baseline T6-Ny can observe sources with a flux as low as 0.025 Jy, while the baseline On-Ny can only observe sources

with flux values larger than 0.100 Jy, and the baseline Ft-Ny can only observe sources with flux values larger than 0.220 Jy.

This shows that large and sensitive antennas are needed to successfully observe the weak sources of our set (e.g., 0316–444, 0912+297, 1251–197, and 2335–184).

5.2. Better Geographical Distribution

A few sources in the far south are difficult to observe and their position uncertainties are still significant. Sources like 2329–415 are still not observed sufficiently even with a flux larger than 0.10 Jy. Their observing would benefit from a more suitable geometry: more stations in the south are necessary, e.g., stations in the Australian networks. In collaboration with the University of Tasmania and the Vienna University of Technology, we were able to have five of the sources in the south scheduled in the session AUA003 (2015 May 6) that is composed of six stations in Australia and New Zealand. Three of these sources (0454–463, 0823–223, and 2314–409) were successfully observed.

6. CONCLUSIONS

Since mid-2013, the observation of the 195 ICRF2-*Gaia* transfer sources has improved significantly resulting in more observations, better position accuracies, and a better knowledge of the flux information of the sources.

The main goal was to successfully and regularly observe a set of 195 ICRF2-*Gaia* transfer sources and to improve their positions. Since the operational start of this observing program in 2013 June, all sources were observed at least once, 93% of the sources were observed at a rate of at least five successful sessions per year, and 59% of the sources reached the required target of 12 successful sessions per year. The position uncertainties were improved for all sources and the level of 200 μ s in both α and δ was reached for 98% of the sources. 92% of the sources have better accuracies than 100 μ s.

This observing program is very successful. It will continue until the release of the final catalog derived from the *Gaia* mission observations. All 195 sources will be continuously monitored in our IVS program and we will continue to schedule in R&D and RDV sessions sources that do not reach the requested frequency of observation or position accuracies.

When looking at the observation history of the 37 sources specified in Section 2.3, some sources are still scarcely observed and their position uncertainties are still significant. They require more observing, which would benefit from a network of large and sensitive antennas to observe the weak sources and stations in the south to observe the sources in the southern hemisphere.

We acknowledge the International VLBI Service for Geodesy and Astrometry (IVS) and all of its components for their efforts in observing, correlating, and providing the VLBI data used in this study. We thank the anonymous referee for a thoughtful reading and valuable comments. This research has made use of material from the Bordeaux VLBI Image Database (BVID). The VLBA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, and operated under cooperative agreement by Associated Universities, Inc. This work made use of the Swinburne University of Technology software correlator, difx,

developed as part of the Australian Major National Research Facilities program and operated under license. For a description of the difx correlator, see Deller et al. (2011). This work was supported by NASA contract NNG12HP00C.

REFERENCES

- Beasley, A. J., Gordon, D., Peck, A. B., et al. 2002, *ApJS*, **141**, 13
- Behrend, D. 2013, *DatSJ*, **12**, WDS81
- Bourda, G., & Charlot, P. 2012, IVS Memorandum 2012-001v01, (<ftp://ivscc.gsfc.nasa.gov/pub/memos/ivs-2012-001v01.pdf>)
- Bourda, G., Charlot, P., & Collioud, A. 2015, in Proc. 22nd EVGA Working Meeting, European VLBI for Geodesy and Astrometry, ed. R. Haas, & F. Colomer, 220
- Bourda, G., Charlot, P., & Le Campion, J.-F. 2008, *A&A*, **490**, 403
- Bourda, G., Charlot, P., Porcas, R., & Garrington, S. T. 2010, *A&A*, **520**, A113
- Bourda, G., Collioud, A., Charlot, P., Porcas, R., & Garrington, S. T. 2011, *A&A*, **526**, A102
- Charlot, P., Bellanger, A., Bouffet, R., et al. 2013, Int. VLBI Service for Geodesy and Astrometry 2013 Annual Report, ed. K. D. Baver, D. Behrend, & K. L. Armstrong, 200
- Collioud, A., & Charlot, P. 2009, in Proc. 19th EVGA Working Meeting, European VLBI for Geodesy and Astrometry, ed. G. Bourda, P. Charlot, & A. Collioud, 19
- Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, *AJ*, **115**, 1693
- Deller, A. T., Brisken, W. F., Phillips, C. J., et al. 2011, *PASP*, **123**, 275
- Fey, A. L., & Charlot, P. 1997, *ApJS*, **111**, 95
- Fey, A. L., Gordon, D., Jacobs, C. S. (ed) 2009, IERS Tech. Note 35, The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, (Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie) (<http://www.iers.org/TN35>)
- Fey, A. L., Gordon, D., Jacobs, C. S., et al. 2015, *AJ*, **150**, 58
- Fey, A. L., Ma, C., Arias, E. F., et al. 2004, *AJ*, **127**, 3587
- Fomalont, E. B., Petrov, L., MacMillan, D. S., Gordon, D., & Ma, C. 2003, *AJ*, **126**, 2562
- Gipson, J. M. 2012, Web document (http://lupus.gsfc.nasa.gov/files_user_manuals/sked/sked.pdf)
- Gipson, J. M., Le Bail, K., & Ma, C. 2014, in Proc. IVS 2014 General Meeting Proc., VGOS: The New VLBI Network, ed. D. Behrend, K. D. Baver, & K. L. Armstrong (Beijing: Science Press), 390
- Kovalev, Y. Y., Lobanov, A. P., Pushkarev, A. B., & Zensus, J. A. 2008, *A&A*, **483**, 759
- Kovalev, Y. Y., Petrov, L., Fomalont, E. B., & Gordon, D. 2007, *AJ*, **133**, 1236
- Petrov, L., Kovalev, Y. Y., Fomalont, E., & Gordon, D. 2008, *AJ*, **136**, 580
- Petrov, L., Kovalev, Y. Y., Fomalont, E. B., & Gordon, D. 2005, *AJ*, **129**, 1163
- Petrov, L., Kovalev, Y. Y., Fomalont, E. B., & Gordon, D. 2006, *AJ*, **131**, 1872
- Schuh, H., & Behrend, D. 2012, *JGeod*, **61**, 68
- Véron-Cetty, M.-P., & Véron, P. 2006, *A&A*, **455**, 773