International VLBI Service for Geodesy and Astrometry (IVS)

http://ivscc.gsfc.nasa.gov

Chair of the Governing Board: Harald Schuh (Austria)
Director of the Coordinating Centre: Dirk Behrend (USA)

Overview

This report summarizes the activities and events of the International VLBI Service for Geodesy and Astrometry (IVS) during the report period of 2007−2009. In March 2009 the IVS completed the first ten years of its existence. The 10th anniversary was celebrated in a special event in Bordeaux, France. A new Directing Board was elected in December 2008 / January 2009. The VLBI2010 Committee (V2C) submitted a progress report on the "Design Aspects of the VLBI2010 System". The frequency range for the next generation system was fixed to ~2.2–14 GHz. A new TRF (VTRF2008) has been computed and is used for the IVS EOP determinations. The use of the ITRF2005 for this purpose has been discontinued due to a deficit partly caused by a pole tide error which was made in the IVS contribution to the ITRF2005. Combination Centres were established as new type of Analysis Centres; BKG/DGFI and KASI were approved as new Combination Centres.

Activities

Introduction

The International VLBI Service for Geodesy and Astrometry (IVS) is an approved service of the International Association of Geodesy (IAG) since 1999, an approved service of the International Astronomical Union (IAU) since 2000, and a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) since 2001. The goals of the IVS, which is an international collaboration of organizations that operate or support Very Long Baseline Interferometry (VLBI) components, are

- to provide a service to support geodetic, geophysical and astrometric research and operational activities,
- to promote research and development activities in all aspects of the geodetic and astrometric VLBI technique, and
- to interact with the community of users of VLBI products and to integrate VLBI into a global Earth observing system.

The VLBI technique has been employed in geodesy for 40 years. Covering intercontinental baselines with highest accuracy, monitoring Earth rotation at the state of the art and providing the quasar positions as the best approach to an inertial reference frame, VLBI significantly contributed to the tremendous progress made in geodesy over the last decades. VLBI is a primary tool for understanding the global phenomena within the "System Earth". Today VLBI continuously monitors Earth orientation parameters as well as crustal movements in order to maintain global reference frames, coordinated within the IVS. Science and applications set the requirements for the realization and maintenance of global reference frames at VLBI's technical limitations. VLBI, as the unique technique for providing a celestial reference frame and for deriving the full set of Earth orientation parameters, generates the basis for many applications and various research topics in the geosciences.

Being tasked by IAG and IAU with the provision of timely, highly accurate products (Earth Orientation Parameters, EOP; Terrestrial Reference Frame, TRF; Celestial Reference Frame, CRF), but having no funds of its own, IVS strongly depends on the voluntary support of individual agencies that form the IVS.

Organization and Meetings

The Directing Board determines policies, adopts standards, and approves the scientific and operational goals for IVS. The Directing Board exercises general oversight of the activities of IVS including modifications to the organization that are deemed appropriate and necessary to maintain efficiency and reliability. During the report period Directing Board elections were held in December 2008 / January 2009.

Table 0.1. Members of the IVS Directing Board during the report period (2007−2009).

a) ***Current Board members (June 2009)***

Directing Board Member	Institution, Country	Functions	Recent Term
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Patrick Charlot	Bordeaux Observatory	IAU Representative	—
Andrey Finkelstein	Institute of Applied Astronomy, Russia	At Large Member	Feb 2009 − Feb 2011
Rüdiger Haas	Onsala Space Observatory, Sweden	Technology Development Centers Representative	Feb 2009 − Feb 2013
Hayo Hase	BKG, Germany; TIGO, Chile	Networks Representative	Feb 2007 − Feb 2011
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Kerry Kingham	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Feb 2007 − Feb 2011
Chopo Ma	NASA Goddard Space Flight Center, USA	IERS Representative	—
Ray Norris	CSIRO Australia Telescope Nacional Facility, Australia	FAGS Representative	—
Axel Nothnagel	University of Bonn, Germany	Analysis Coordinator	—
Harald Schuh	Technical University Vienna, Austria	IAG Representative, Chair	—
Kazuhiro Takashima	Geographical Survey Institute, Japan	At Large Member	Feb 2009 − Feb 2011
Oleg Titov	Geoscience Australia	Analysis and Data Centers Representative	Feb 2009 − Feb 2013
Gino Tuccari	IRA/INAF, Italy	Networks Representative	Feb 2009 − Feb 2013
Alan Whitney	Haystack Observatory, USA	Technology Coordinator	—
Xiuzhong Zhang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2009 − Feb 2011

b) ***Previous Board members in 2007−2009***

Yoshihiro Fukuzaki; Kazuhiro Takashima	Geographical Survey Institute, Japan	Networks Representative	Feb 2007 − Feb 2009
Arthur Niell	Haystack Observatory, USA	Analysis and Data Centers Representative	Feb 2005 − Feb 2009
Bill Petrachenko	Natural Resources Canada	Technology Development Centers Representative	Feb 2005 − Feb 2009

The IVS organizes bi-annual General Meetings and bi-annual Technical Operations Workshops. Other workshops such as the Analysis Workshops and VLBI2010 Working Meetings are held in conjunction with larger meetings and are organized once or twice a year. Table 0.2 gives an overview of the recent IVS meetings.

Table 0.2. IVS meetings during the report period (2007-2009).

Time	Meeting	Location
14 April 2007	8th IVS Analysis Workshop	Vienna, Austria
15 April 2007	2nd VLBI2010 Working Meeting	Vienna, Austria
30 April – 3 May 2007	4th IVS Technical Operations Workshop	Westford, MA, USA
14 September 2007	3rd VLBI2010 Working Meeting	Bonn, Germany
3-6 March 2008	5th IVS General Meeting	Saint Petersburg, Russia
5 March 2008	VLBI2010 Committee Meeting	Saint Petersburg, Russia
7 March 2008	9th IVS Analysis Workshop	Saint Petersburg, Russia
11-12 September 2008	VLBI2010 Committee Meeting	Penticton, BC, Canada
18-20 March 2009	VLBI2010 Workshop on Future Radio Frequencies and Feeds	Wettzell, Germany
21 March 2009	VLBI2010 Committee Meeting	Wettzell, Germany
25 March 2009	IVS 10th Anniversary Celebration	Bordeaux, France
26 March 2009	10th IVS Analysis Workshop	Bordeaux, France
27-30 April 2009	5th IVS Technical Operations Workshop	Westford, MA, USA

The IVS completed its first ten years of being a service for geodetic and astrometric VLBI on March 1, 2009. To commemorate the first decade a 10th Anniversary Celebration event was held in Bordeaux, France on March 25, 2009. The event included a symposium featuring the history of VLBI and the IVS, the interrelation of the IVS with the other space geodetic services (IGS, ILRS, IDS), and IVS' place among the other VLBI networks (EVN, VLBA, Asian networks). The event was live broadcast over the Internet. A recording of the various presentations is available at http://canalc2.u-strasbg.fr/video.asp?idvideo=8558.

Call for Combination Centres and Additional Analysis Centres

In June 2008 the IVS issued a call soliciting proposals for the installation and operation of IVS Combination Centres and additional Operational Analysis Centres and Associate Analysis Centres. Combination Centres are a new type of Analysis Centres that are tasked with preparing IVS combination products in cooperation with the Analysis Coordinator in a timely fashion. At its 20th meeting in Penticton, BC, Canada in September 2008, the IVS Directing Board approved the proposals from BKG/DGFI, Germany and from the Korea Astronomy & Space Science Institute (KASI) to become Combination Centres. DGFI changed from an Associate to an Operational Analysis Centre and Sternberg Astronomical Institute (SAI) of Moscow State University became a new Operational Analysis Centre.

Working Groups

At the 16th Directing Board meeting held in September 2006 at Haystack Observatory, a *joint IERS/IVS Working Group* was formed, whose aim it is to generate the *second realization of the ICRF* from VLBI observations of extragalactic radio sources, consistent with the current realization of the ITRF and EOP data products. The goal is to present the second ICRF to relevant authoritative bodies, e.g. IERS and IVS, and submit the revised ICRF to the IAU Division I Working Group on the second realization of the ICRF for adoption at the 2009 IAU General Assembly. The ICRF, a catalogue of extragalactic radio sources and their positions, is a unique and fundamental product of the IVS. Since its adoption by the IAU effective 1 January 1998 these objects and positions have defined the axes in the sky to which all other celestial positions are now referred. The ICRF also provides the connection to the kinematically fixed inertial frame in which the variations of the Earth's orientation are measured. Only VLBI can monitor nutation/precession and UT1 because of its unique capability to connect terrestrial and celestial points.

At the 18th Directing Board meeting held in September 2007 at Bonn University, IVS *Working Group on VLBI Data Structures (WG4)* was formed. This working group examines the data structure currently used in VLBI data processing and investigates what data structure is likely to be needed in the future. It will design a data structure that meets current and anticipated requirements for individual VLBI sessions including a cataloguing, archiving and distribution system. Further, it will prepare the transition capability through conversion of the current data structure as well as cataloguing and archiving software to the new system.

At the 21st Directing Board meeting held in March 2009 at Bordeaux Observatory, two new working groups were created. The *Working Group on Space Science Applications (WG5)* will investigate synergies between IVS and VLBI space science applications, look for mutually beneficial collaborations, and eventually give recommendations for future actions. The *Working Group on VLBI Education and Training (WG6)* will explore educational activities, such as summer schools or training seminars, which will help in the formation of a new generation of VLBI experts. For both new working groups the charter and membership are currently being put together.

Observing Program and Special Campaigns

Observing Program

The observing program for 2007–2009 included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with seven stations, some with six or eight stations depending on station availability. These networks were designed

with the goal of having comparable x_p and y_p results. Data bases are available no later than 15 days after each session. Daily 1-hour UT1 Intensive measurements on five days (Monday through Friday, Int1) on the baseline Wettzell (Germany) to Kokee Park (Hawaii, USA), on weekend days (Saturday and Sunday, Int2) on the baseline Wettzell (Germany) to Tsukuba (Japan), and since August 2007 on Monday mornings (Int3) in the middle of the 36-hour gap between the Int1 and Int2 Intensive series on the network Wettzell (Germany), Ny-Ålesund (Norway), and Tsukuba (Japan).

- TRF: Quarterly (2007) and bi-monthly (2008, 2009) TRF sessions with 12–14 stations using all stations at least two times per year. Since 2008 the Japanese domestic VLBI stations of the GARNET (GSI Advanced Radio telescope NETwork) network (Aira, Chichijima, and Shintotsukawa) regularly participate in the TRF sessions.
- CRF: Bi-monthly RDV sessions using the Very Long Baseline Array (VLBA) and up to eight geodetic stations, plus astrometric sessions to observe mostly southern sky sources where the number of sessions had to be reduced from 16–17 in 2007–2008 to six in 2009 due to the non-availability of Hartebeesthoek (South Africa). HartRAO suffered a major failure of a polar shaft bearing in October 2008 and is down for an undetermined time. A repair or replacement of the bearing or the provision of a substitute antenna is expected to take two years or longer.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Tri-annual ~two-week continuous sessions to demonstrate the best results that VLBI can offer, aiming for the highest sustained accuracy.

Although certain sessions have primary goals, such as CRF, all sessions are scheduled so that they contribute to all geodetic and astrometric products. Sessions in the observing program that were recorded and correlated using K5 technology had the same accuracy and timeliness goals as those using Mark 5. On average, a total of about 1200 station days per year were used in around 180 geodetic sessions during the year keeping the average days per week which are covered by VLBI network sessions at 3.5.

CONT08

In August 2008, a 15-day continuous VLBI observation campaign called CONT08 was observed. The network consisted of eleven IVS stations (see Figure 0.1). Unlike the CONT05 campaign, CONT08 was observed on the basis of UT days, i.e., an observing day was run from 0 UT to 24 UT. Observational gaps between the single observation days (30 min in the CONT05 case) were avoided by performing the daily station checks (e.g., pointing) not at the change of schedules but at well-coordinated, staggered times for all stations (i.e., different daily check times for each station). In the CONT05 campaign the 30-min gaps had resulted in unrealistic peaks in the sub-daily EOP time series. The CONT08 data set is of excellent quality and will be the basis for studies of inter-technique comparisons, searches for geophysical signals, and technique improvement. The UT-day observation scheme will shed light on the question of whether the combination with the other geodetic space techniques (GPS, SLR, DORIS) improves with commensurate observation periods.

Figure 0.1: Geographical distribution of the eleven IVS stations that participated in the CONT08 campaign in August 2008.

Analysis

Earth Orientation Parameters

The official IVS Earth orientation parameter (EOP) series are produced and published routinely by the IVS Analysis Coordinator's office at the Institute of Geodesy and Geoinformation of the University of Bonn, Germany. Two separate series are computed: one as a rapid product with the emphasis on fast correlation and data reduction based on special observing sessions every Monday (IVS-R1) and every Thursday (IVS-R4), the other one as a complete series of all geodetic VLBI sessions and generated every three months. In January 2007 the combination of the input of up to six IVS Analysis Centres was changed from a combination on the level of EOP results to a combination on the basis of datum-free normal equations in SINEX format. The new approach improved the robustness and quality of the combination product significantly.

The advantages of the new combination strategy are (1) that the full variance-covariance information of the individual input solutions is rigorously carried over and (2) that one common terrestrial reference frame is applied after the combined datum-free normal matrix is generated. Thus, it is guaranteed that an identical datum is used in the combination process for all input series. After datum definition, the combined system of normal equations is solved (inverted) and the full set of EOP (pole components, UT1−UTC, and their time derivatives as well as two nutation offsets in $d\psi$, $d\varepsilon$ w.r.t. the IAU2000A model) are extracted into separate files. These results are then added to the two EOP time series, the rapid solution file and the quarterly solution file, in the IVS EOP exchange format. Companion files containing the nutation offsets in the X, Y paradigm are routinely generated through a standard transformation process. Today, the input of the Analysis Centres agrees to better than 60 microarcseconds, while the combined IVS polar motion results agree with the IGS pole at the 100−130 microarcsecond level.

Comparisons of Long-term Station Position Time Series

As part of the quality assessment for the IVS combined products, long-term time series of station positions of each individual IVS Analysis Centre, derived from the submitted normal equations, have been compared with each other. Through this, systematic offsets in the height component of up to 1 cm have been detected between solutions analysed with the VLBI analysis software packages OCCAM and CALC/SOLVE. In order to find the reason for these discrepancies several models used in both software packages have been compared. It turned out that the systematic offsets were mainly caused by differences in the pole tide model. In the CALC/SOLVE solutions, a model for the annual mean pole was used, which was not in agreement with the IERS Conventions 2003. Therefore, all analysis centres using CALC/SOLVE reprocessed their solutions with the conventional pole tide model according to the IERS Conventions 2003 and most of the discrepancies disappeared. Since the IVS input to ITRF2005 was affected by the same inconsistency, the ITRF2005 was also affected by this oversight, though not to the full extent.

VTRF2008

In 2008, it became obvious that a new TRF for the IVS EOP determinations had to be computed for several reasons. ITRF2005, used in 2007 and 2008, has a noticeable deficit due to the pole tide error which had been made in the IVS contribution to ITRF2005. The post-quake movements of Gilmore Creek (Fairbanks, Alaska) in ITRF2005 lacked the continuity of the piece-wise linear elements, thus, introducing discontinuities. In addition, for the Russian sites of Svetloe, Zelenchukskaya, and Badary either only a limited number of observations or no observations at all were available for the computation of ITRF2005. This has changed and, of course, all other stations took their benefit from more data in the new computations as well.

A new TRF (VTRF2008) has been computed from the individual combined SINEX files of all geodetic VLBI sessions available. These have been pre-reduced for EOP so that only the coefficients for the site coordinate parameters remained. In a stacking process, these sets of normal equations have then been combined to a full TRF normal equation system for site positions and velocities. The subsequent inversion process provided the complete TRF including its variance-covariance information. VTRF2008 is being used for all combinations since December 2008.

Other IVS Products

In addition to the aforementioned products EOP, CRF, and TRF the IVS continued to provide tropospheric parameters as well as time series of baseline lengths on a regular basis. These two products were described in more detail in the IAG Travaux 2007. More information on these products and the previously mentioned products is available on the IVS Web site at the URL: http://ivscc.gsfc.nasa.gov/products-data/products.html.

Thermal Expansion of Radio Telescopes

Thermal expansion effects have been considered already for a long time but concerted activities to include it in IVS data analysis have only started in 2008. At the Ninth IVS Analysis Workshop in St. Petersburg, it was decided to make thermal expansion modelling the first chapter of the IVS Analysis Conventions. This should serve as a proper reference for all analysis descriptions. In addition, a decision was made to use the GPT model (Boehm et al. 2007) to compute the reference temperature for each telescope. Any expansion effect can and

should now be computed relative to these mean temperatures. In the meantime, the current status of thermal expansion modelling has been documented in a refereed paper (Nothnagel, 2008) which is the written documentation of Chapter 1 of the IVS Analysis Conventions.

One of the necessary parts of a model for expansion effects is a list of all telescopes' construction dimensions. In such a list, all dimensions like effective height of the elevation axis above the ground for azimuth-elevation telescopes or height of primary axis above secondary axis for polar or XY antennas, just to name a few, have to be tabulated for all telescopes. Quite some effort has been invested to collect the information for this list and further efforts are still necessary to gather the missing information for a few more telescopes. The list is available under http://vlbi.geod.uni-bonn.de/IVS-AC/Conventions together with the reference paper.

Since the reference temperatures of all telescopes are long-term means from a model, no effective change in the realizations of terrestrial reference frames are expected. However, annual variations in station coordinates, especially in the height component, are expected to get partly reduced. Consequently, Earth orientation parameters from VLBI observations may also be affected, mainly with an annual signature.

Technology Development

VLBI2010

The IVS VLBI2010 Committee (V2C) submitted a Progress Report on the status of the development of the next generation geodetic VLBI system (VLBI2010 system), which summarizes the progress made in the development of the new system up to the end of 2008. The report covers Monte Carlo simulations showing the impact of the new operating modes on the final products. A section on system considerations describes the implications for the VLBI2010 system parameters by considering the new modes and system-related issues such as sensitivity, antenna slew rate, delay measurement error, RFI, frequency requirements, antenna deformation, and source structure corrections. This is followed by a description of all major subsystems and recommendations for the network, station, and antenna. Then aspects of the feed, polarization processing, calibration, digital back end, and correlator subsystems are covered. A section is dedicated to the NASA proof-of-concept demonstration. Finally, sections on operational considerations, on risks and fallback options, and on the next steps complete the report. The report was published as a NASA Technical Memorandum and is available online on the IVS Web site.

In addition to writing the Progress Report, the V2C was active in several face-to-face meetings (see e.g. Table 0.2) and numerous telecons. A very important meeting was the VLBI2010 Workshop on Future Radio Frequencies and Feeds (FRFF), which was held over a period of three days in Wettzell, Germany and brought together experts from many VLBI areas. An outcome of the FRFF was recommendations pertaining to the choice of frequencies for the VLBI2010 system as well as its backward compatibility. The recommendations have been endorsed by the IVS Directing Board and read as follows:

- The initial implementation of the VLBI2010 system needs to be capable of observing the broadband frequency range of ~2.2−14 GHz.
- The VLBI2010 system needs to be capable of S/X operation.
- The antenna should allow for a possible future inclusion of Ka-band (32 GHz) operation.

- The complete end-to-end operation of the VLBI2010 system should be demonstrated in a campaign in early 2012. As many antennas as possible should participate.
- A plan should be established for the transition from the legacy S/X system to the VLBI2010 broadband delay system. Such a transition plan can be beneficial for obtaining future funding and will support a timely changeover.

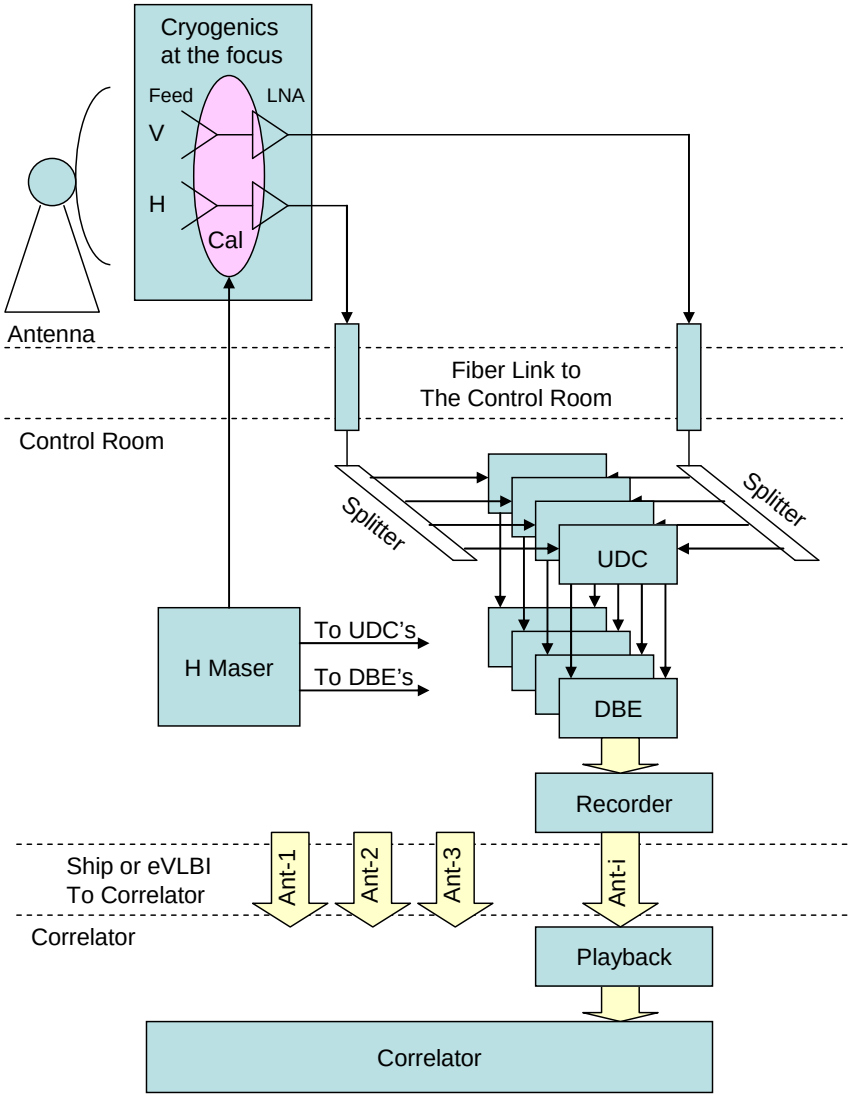

Figure 0.1: VLBI2010 block diagram. The architecture differs significantly from the existing geodetic VLBI systems. This is driven by the needs for short source-switching intervals, improved delay measurement precision, smaller drifts of the electronics, and improved automation and operational efficiency. Of particular note is the change from a system with two fixed bands (S and X band) to a system with four bands, each of which can be placed anywhere in the 2−14 GHz range.

It is foreseen that the VLBI2010 system will be fully defined by the end of 2010 and its capability demonstrated in the aforementioned campaign in 2012.

In order to provide strategic leadership for VLBI2010 and to give a face to the outside world for the project, a VLBI2010 Project Executive Group (V2PEG) was formed. The strategic

tasks of V2PEG include developing time lines, transition plans, maintaining specifications and cost estimates, and promoting the expansion of the VLBI2010 network toward a global distribution. The V2PEG members are at a high level of recognition in the geodetic and astrometric community and thus are closer to the places where actual decisions are made, are more aware of the larger context of VLBI2010, and in general add credibility to outside interactions.

Digital Back End and Recorder

A next generation of digital back end (DBE2) and recorder (Mark 5C) are under development at Haystack Observatory. Two important features of this system are a) the ability to record at 4096 Mbps and b) communication via 10 Gbps Ethernet. The DBE2 board was completed in 2008 and received at Haystack Observatory. The board was powered up and initial communication was achieved. Much of the digital signal processing firmware has been simulated, and programming of the Power PC is about to begin.

The Mark 5C is derived from a Mark 5B+ by the addition of a daughter board containing the 10 GigE interface and the deletion of the I/O board. The daughter board has recently been completed and tested, thus enabling testing of communication between the DBE2 and the Mark 5C.

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