International VLBI Service for Geodesy and Astrometry (IVS)

http://ivscc.gsfc.nasa.gov

Chair of the Directing Board: Harald Schuh (Austria)
Director of the Coordinating Center: 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 2007−2011. In March 2009 the IVS completed its 10th year of its existence. The anniversary was celebrated in a special event in Bordeaux, France. Two Directing Board elections were held, one in Dec2008/Jan2009 and the other in Dec2010/Jan2011. The VLBI2010 Committee (V2C) published 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. The VLBI2010 Project Executive Group (V2PEG) was formed to give strategic leadership to the VLBI2010 project. The Second Realization of the International Celestial Reference Frame (ICRF2) was adopted by the International Astronomical Union (IAU) and replaced the previously used first realization (ICRF) effective 1 January 2010. The IVS contributed to the generation of the ITRF2008 reference frame with session-wise, datum-free normal equations based on a combination of the results from seven IVS Analysis Centers.

Activities

Introduction

The International VLBI Service for Geodesy and Astrometry (IVS) is an approved service of the International Association of Geodesy (IAG) since 1999 and of the International Astronomical Union (IAU) since 2000. 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 more than 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 was a primary tool for understanding the global phenomena changing the "Solid 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 rotation parameters, plays the fundamental role of generating the basis for many applications and research in the geo-sciences.

Table 1. Members of the IVS Directing Board during the report period (2007−2011).

a) ***Current Board members (June 2011)***

Directing Board Member	Institution, Country	Functions	Recent Term
Dirk Behrend	NVI, Inc./NASA GSFC, USA	Coordinating Center Director	—
Alessandra Bertarini	IGG Bonn, Max Planck Institute for Radio Astronomy, Germany	Correlators and Operation Centers Representative	Feb 2011 − Feb 2015
Patrick Charlot	Bordeaux Observatory	IAU Representative	—
Jesús Gómez González	National Geographical Institute, Spain	At Large Member	Feb 2011 − Feb 2013
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 2015
Ed Himwich	NVI, Inc./NASA GSFC, USA	Network Coordinator	—
Shinobu Kurihara	Geospatial Information Authority, Japan	At Large Member	Sep 2010 − Feb 2013
Chopo Ma	NASA Goddard Space Flight Center, USA	IERS Representative	—
Axel Nothnagel	University of Bonn, Germany	Analysis Coordinator	—
Harald Schuh	Technical University Vienna, Austria	IAG Representative, Chair	—
Fengchun Shu	Shanghai Astronomical Observatory, China	At Large Member	Feb 2011 − Feb 2013
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	—

b) ***Previous Board members in 2007−2011***

Andrey Finkelstein	Institute of Applied Astronomy, Russia	At Large Member	Feb 2007 − Feb 2011
Yoshihiro Fukuzaki; Kazuhiro Takashima	Geospatial Information Authority, Japan	Networks Representative	Feb 2007 − Feb 2009
Kerry Kingham	U.S. Naval Observatory, USA	Correlators and Operation Centers Representative	Feb 2007 − Feb 2011
Arthur Niell	Haystack Observatory, USA	Analysis and Data Centers Representative	Feb 2005 − Feb 2009
Ray Norris	CSIRO Australia Telescope Nacional Facility, Australia	FAGS Representative	—
Bill Petrachenko	Natural Resources Canada	Technology Development Centers Representative	Feb 2005 − Feb 2009
Kazuhiro Takashima	Geospatial Information Authority, Japan	At Large Member	Feb 2009 − Sep 2010
Xiuzhong Zhang	Shanghai Astronomical Observatory, China	At Large Member	Feb 2007 − Feb 2011

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 two Directing Board elections were held.

The IVS organizes biennial General Meetings and biennial 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 2 gives an overview of the IVS meetings during the report period.

Table 2. IVS meetings during the report period (2007-2011).

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
7-10 February 2010	6th IVS General Meeting	Hobart, TAS, Australia
11 February 2010	VLBI2010 Developers Meeting and 11th Analysis Workshop	Hobart, TAS, Australia
13 February 2010	Mini Technical Operations Workshop	Hobart, TAS, Australia
31 March 2011	12th Analysis Workshop	Bonn, Germany
9-12 May 2011	6th 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.

Working Groups

ICRF2. The Second Realization of the International Celestial Reference Frame (ICRF2) was adopted at the XXVII General Assembly of the International Astronomical Union (IAU) in Rio de Janeiro, Brazil as Resolution B3. The ICRF2 replaced the previously used first realization (ICRF) effective 1 January 2010. The determination of the new frame was an effort of a joint IERS/IVS working group and was overseen by an IAU working group. ICRF2 contains precise positions of 3,414 compact extragalactic radio sources, more than five times the number in the ICRF. Further, the ICRF2 is found to have a noise floor of ~40 μarcseconds, some 5−6 times better than ICRF, and an axis stability of ~10 μarcseconds, nearly twice as stable as ICRF. Alignment of ICRF2 with the International Celestial Reference System (ICRS) was made using 138 stable sources common to both ICRF2 and ICRF-Ext2.

VLBI Data Structures. The Working Group 4 on VLBI Data Structures 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.

Space Science Applications. The Working Group 5 on Space Science Applications investigates synergies between IVS and VLBI space science applications, looks for mutually beneficial collaborations, and prepares a white paper giving recommendations for future actions.

VLBI Education. The Working Group 6 on VLBI Education explores educational activities, such as summer schools or training seminars, which will help in the formation of a new generation of VLBI experts.

Observing Program and Special Campaigns

Observing Program

The observing program for 2007–2011 included the following sessions:

- EOP: Two rapid turnaround sessions each week, mostly with 7 stations, some with 6 or 8 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 (2008−2011) TRF sessions with 12–14 stations using all stations at least two times per year.

- 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.
- Monthly R&D sessions to investigate instrumental effects, research the network offset problem, and study ways for technique and product improvement.
- Triennial ~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 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. A special issue of Journal of Geodesy with several peer-reviewed publications about the scientific use of CONT08 data is under preparation and will be published in 2011.

Figure 1. Geographical distribution of the eleven IVS stations that participated in the CONT08 campaign in August 2008.

IYA09 Very Large Astrometry Session

As an activity for the International Year of Astronomy 2009 the IVS organized the largest astrometric VLBI session observed to date. On 18 November 2009, thirty-five stations (see Figure 2) observed 243 out of the 295 defining sources of the ICRF2. All scientific, outreach, and ancillary goals (see Table 3) that were staked out for the session were successfully accomplished.

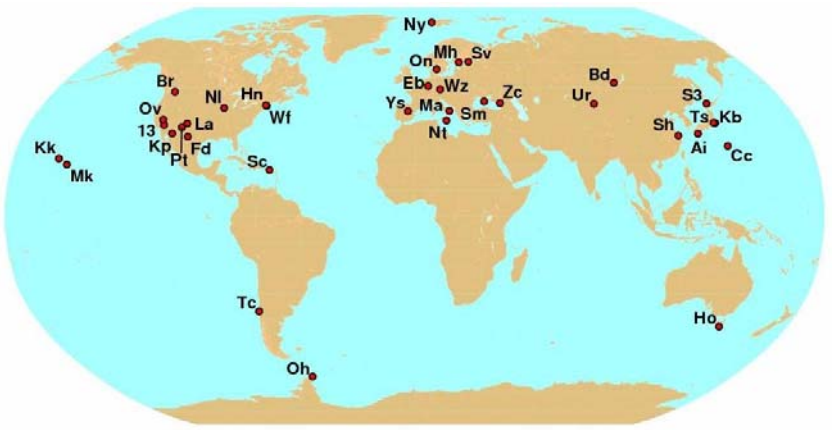

Figure 2: Observational network of the IYA09 Very Large Astrometry Session.

Analysis

Earth Orientation Parameters.

The official IVS Earth orientation parameter (EOP) series were produced and published by the IVS Analysis Coordinator's office at the Institute of Geodesy and Geoinformation of the University of Bonn, Germany until October 2009 when this operational task was taken over by the IVS Combination Center at the German Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt a.M. 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 Centers 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.

Table 3. Key goals of the IYA09 session.

Scientific goals	Strengthen ICRF2 by observing as many sources as possible in a single session. / Measure arc-lengths between observed sources.
Outreach goals	Press releases through IYA2009 (IAU), IVS, and other organizations. / News coverage in regional and national media. / Open doors at stations.
Ancillary goals	Celebrate 40 years of geodetic and astrometric VLBI. / Demonstrate capability of handling large networks. / Tie stations into global frame.

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 Centers agrees to better than 60 μarcseconds, while the combined IVS polar motion results agree with the IGS pole at the 100-130 μarcsecond 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 Center, 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, the annual mean pole offset was set to zero until early 2007, which was not in agreement with the IERS Conventions 2003. Therefore, all analysis centers using CALC/SOLVE reprocessed their solutions in 2007 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 affected by this oversight, though not to the full extent.

Contribution to ITRF2008.

The IVS contribution to the ITRF2008 was generated at the IVS Analysis Coordinator's office. It consists of session-wise datum-free normal equations which are the result of a combination of individual series of session-wise datum-free normal equations provided by seven IVS Analysis Centers (BKG, DGFI, GSFC, IGGB, OPA, SHAO, and USNO). All these individual series are completely reprocessed following homogeneous analysis options according to the IERS Conventions 2003 and the IVS Analysis Conventions.

Based on the experience gathered since the combination efforts for ITRF2005, the consistency of the individual VLBI solutions has improved considerably. The agreement in terms of the WRMS of the terrestrial reference frame (TRF) horizontal components is 1 mm and of the height component is 2 mm. Comparisons between ITRF2005 and the combined TRF solution for ITRF2008 yielded systematic height differences of up to 5 mm with a zonal signature. These differences can be related to the pole tide correction mentioned above which was referenced to a zero mean pole used by four of the five IVS ACs in the ITRF2005 contribution instead of a linear mean pole path as recommended in the IERS Conventions. Periodic annual variations in scale are reduced considerably from 2.7 mm to 1.7 mm due to the correction for thermal expansion of the radio telescopes.

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 modeling 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 reduce. Consequently, Earth orientation parameters from VLBI observations may also be affected, mainly with an annual signature.

Technology Development

VLBI2010

The IVS VLBI2010 Committee (V2C) published a Progress Report with the title "Design Aspects of the VLBI2010 System" about 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 at ftp://ivscc.gsfc.nasa.gov/pub/misc/V2C/PR-V2C_090417.pdf.

An important meeting organized by the V2C 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 and backward compatibility of

the VLBI2010 system. 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.

In spring 2012 it is foreseen to hold a similar meeting intended to fully define the VLBI2010 system. The capability of VLBI2010 will be demonstrated in a campaign in 2012 or 2013.

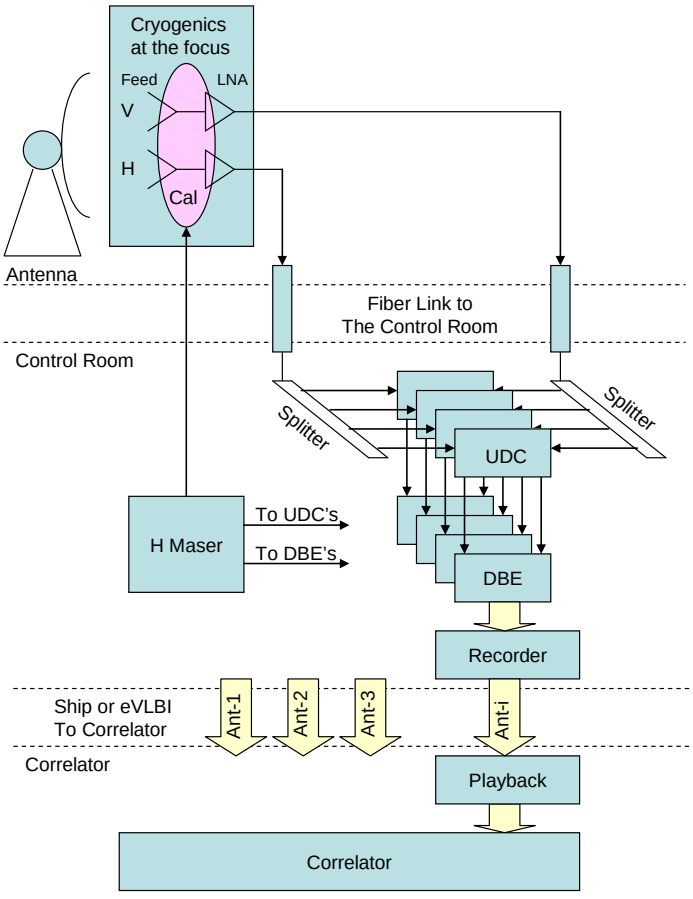

Figure 3: VLBI2010 block diagram. The architecture differs significantly from the existing geodetic VLBI systems. This is driven by the needs for short source-switching intervals, improved delay measurement precision, smaller drifts of the electronics, and improved automation and operational efficiency. 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.

In spring 2009 the IVS created the VLBI2010 Project Executive Group (V2PEG) in order to provide strategic leadership to the VBI2010 project. Many VLBI2010 developments were carried out by the different stakeholders of the IVS in a loosely organized manner. The V2PEG is tasked with coordinating and streamlining these activities and functions as the focal point for gathering and disseminating information about VLBI2010 and for promoting the new system.

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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