IVS Working Group 2 for
Product Specification and Observing Programs

Final Report
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Executive Summary

For all present-day Earth and space science, high precision reference frames are an essential prerequisite. The most important reference frames are the International Celestial Reference Frame (ICRF) realized by some hundreds of extragalactic radio sources and the International Terrestrial Reference Frame (ITRF) established by globally distributed observing stations. For the transformation between these two reference frames the Earth orientation parameters (EOP) must be known with high precision. Temporal variations of EOP on different time scales allow the investigation of interactions of components of system Earth. All space techniques have their particular strengths, and VLBI gets its outstanding importance through being the only technique for establishing and maintaining the ICRF and the direct tie of the ITRF to the ICRF by monitoring the time dependent EOP.

An important part of the efforts of IVS is to provide the best ICRF, ITRF, and EOP products for the user community and to optimize the use of available global resources in making these products. The charter of IVS Working Group 2 was to review current products, recommend goals, and suggest observing programs. Users of the IVS products include the International Earth Rotation Service (IERS) for all products; individual scientist users for EOP; all geodetic activities for the TRF; the astrometric and astrophysical community for CRF.

Products can be described in terms of accuracy and reliability, frequency of observing sessions, temporal resolution of the parameters estimated by the VLBI data analysis, time delay from observing to final product, and frequency of solutions. Presently, the accuracy of EOP from 24-hour sessions is 5 μsec for UT1 and 100–200 microarcsec for the pole, observed ~3 days per week. The EOP are released with a time delay of one week to several months. A goal of improving the accuracy by a factor of 2 to 4 should be feasible over the next few years, along with observing 7 days per week and a time delay of less than five days. Comparable accuracy in both x_p and y_p is another goal. Observing should take place every day to avoid any jumps, bias, or inconsistency. The network offset problem (offsets between EOP results obtained by simultaneously observing VLBI networks) needs a solution because strictly consistent reference frames are a strong requirement. A particular strength of VLBI is its contribution to the scale of the ITRF. Present accuracy is 5–20 mm for the TRF time series (single sessions) and 1–4 mm for global solutions. More stations in the southern hemisphere are needed. For the CRF, VLBI is the unique technique. More analysis centers should provide solutions, and an improved sky distribution is needed. Besides TRF, CRF, and EOP products, IVS should provide EOP rates, and regular solutions of geodynamical parameters (solid Earth tides, ocean loading, and atmospheric loading) and physical parameters (tropospheric and ionospheric parameters, relativity parameters).

Measures that need to be taken to meet these goals depend on new technology plus a commitment from IVS member organizations for strong support of the observing program. Improvements in accuracy are expected based on technology improvements, better analysis, better observing geometry, more observables taken by more stations, and improved station reliability. The time delay from observing to final product can be reduced by assigning high priority to operational sessions and more automation. Temporal continuity and resolution can be improved by denser and longer observing sessions. Redundancy requirements emphasize more analysis centers, different software packages, plus some parallel observing networks.

IVS as a service needs to carry out regular programs, in order to deliver its products as reliably and precisely as possible, consistent with available resources. The proposed IVS observing program tries to meet the goals by extending and updating existing programs while maintaining continuity with existing time series. Features of the proposed program include combining the requirements of various users, including all techniques and new technologies (Mk4/Mk5, K4, S2), including R&D sessions, and improving global coverage.

The accuracy goal can be achieved by the above-mentioned measures that will be supported by studying results of special R&D sessions. The timeliness goal can be addressed initially through setting up a fast and routine procedure for shipping recorded media to the correlator, and ultimately through support of broadband communication links. The competitiveness of VLBI products would be significantly increased by contributing to such important tasks as:

- Support prediction of EOP.
- Allow reaction to episodic events in near real-time.
- Support atmospheric and ionospheric investigations.
- Guarantee the availability of the results in case of emergency.

The goal of daily VLBI sessions will rely on gradual augmentation of resources for station observing time, correlator capacity, and recording media and data transmission facilities. The main arguments for continuous VLBI measurements are:

- Contribute to the proposed IAG project IGGOS.
- Provide a *permanent* comparison and control of results of other techniques.
- Resolve the smaller tidal terms in solid Earth tides, ocean loading, and ocean tidal excitation of the EOP.
- Determine the amplitudes of the many short period nutation terms.
- Catch episodic events both on Earth and on extragalactic sources.
- Increase the accuracy of the results by increasing the number of observations.

For 2002 the proposed IVS program includes two 6-station rapid-turnaround sessions per week, a monthly R&D session, a monthly 9-station TRF session, a 14-day continuous session, and four short-duration one-baseline sessions per week with at least one of these sessions having independent observing. The program includes participation by S2 and K4 networks and correlators. The proposed years 2003–2005 have a gradual increase in network size, number of observing days and recording media usage. By 2005 continuous observing is possible if the projected shortfall in resources can be overcome.

Geodetic VLBI plays an essential role in geodesy and astrometry due to its uniqueness in observing UT1-UTC and the precession/nutation angles unbiased over a time span longer than a few days. It is also necessary for the ICRF and contributes to the generation of the ITRF. Due to various requirements of different users of IVS products the following aspects must be accomplished:

- Significant improvement of the accuracy of VLBI products,
- Shorter time delay from observation to availability of results,
- Almost continuous temporal coverage by VLBI sessions.

The proposed observing program to accomplish these goals increases observing time by 30–40% over the next two years and includes sessions carried out using S2 and K4 technology. This observing program is rather ambitious but it is feasible if efforts of the IVS components are concentrated and the necessary resources become available.

Abstract

After the scientific rationale is given in the introduction the Terms of Reference and the proceeding of IVS Working Group 2 are presented. Then the present status and future goals of all international activities within IVS are described. In particular the current products of IVS are described in terms of accuracy, reliability, frequency of observing sessions, temporal resolution of the parameters estimated by VLBI data analysis, time delay from observing to product, i.e. time which has passed after the end of the last session included in the VLBI solution till availability of the final products and frequency of solution (in the case of "global solutions", when all existing or a high number of VLBI sessions are used to determine so-called global parameters). All IVS products and their potential users are covered in the report. This includes the Earth orientation parameters (EOP), the reference frames (TRF and CRF), geodynamical and geophysical parameters and physical parameters. Measures which should be taken within IVS to meet the goals defined in the first steps are presented. As most of the measures are related to the observing programs, these are the main focus for improving the current status of IVS products. The report shows that due to various requirements of the different users of IVS products the following aspects must be accomplished:

- significant improvement of the accuracy of VLBI products,
- shorter time delay from observation to availability of results,
- almost continuous temporal coverage by VLBI sessions.

A first scenario of the IVS observing program for 2002 and 2003 considers an increase of observing time by about 30%-40% and includes sessions carried out by S2 and K4 technology. The midterm observing program for the next 4-5 years seems to be rather ambitious. However, it appears feasible if all efforts are concentrated and the necessary resources are made available.

1. Introduction

For all present-day Earth and space sciences high-precision reference frames are an essential prerequisite, e.g. for positioning and navigation on the Earth, Earth observation by satellites and space navigation. The most important reference frames are in space, as realized by the International Celestial Reference Frame (ICRF) with the observations of several hundred extragalactic radio sources and on Earth, as realized by the International Terrestrial Reference Frame (ITRF) with a globally distributed set of observing stations.

For the transformation between those two reference frames the Earth orientation parameters (EOP) must be known with high precision. Temporal variations of the EOP on different time scales allow us to investigate the interactions of the various components of system Earth, i.e. between the solid Earth, the atmosphere, the hydrosphere and the cryosphere. Motions of these geophysical fluids also influence the Earth's gravity field, which can be precisely monitored by the upcoming geodynamical satellite missions CHAMP, GRACE, GOCE and others. Both variations of the EOP and of the gravity field are an important source for modeling the Earth's interior and for determining the parameters of Earth models.

In the last two decades different space geodetic techniques have been developed for measuring the EOP and realizing the above-mentioned reference frames. While each of the different space techniques has its particular strengths and merits, VLBI earns its outstanding importance from being the unique technique for the establishment and maintenance of the ICRF and the direct tie of the ITRF to the ICRF by monitoring the time dependent Earth orientation parameters that relate the ITRF to the ICRF. In particular VLBI is unique in observing the UT1-UTC parameters that correspond to the rotational speed of the Earth and the direction of the rotation axis of the Earth in space expressed by the precession/nutation angles (?e, ??). This has been recognized by the International Astronomical Union (IAU) at its XXIVth General Assembly in Manchester in Resolutions B1.1 and B1.6 approved in August 2000.

The International Association of Geodesy (IAG), which presented a plan for reorganization at its recent Scientific Assembly in Budapest (Sept. 2001), demonstrates the importance of the new space geodetic techniques by assigning the international services representing these techniques to the same level as the four scientific Commissions (Beutler et al. 2001). In the proposed internationally organized long-term project IGGOS (Integrated Global Geodetic Observing System) the IAG will combine the fundamental areas of geodetic research into one integrated global observation and analysis system for Earth sciences. This requires in particular the combination of modern space geodetic techniques into a joint system (Rummel et al., 2001). As redundancy and independent control are the strongest requirements for the IGGOS, an essential aspect of IGGOS is that the different techniques observe on all time scales with a global network as dense as possible. The need for regular and simultaneous observations by all space geodetic techniques, as recognized by IAG, alone justifies the extension of the present international VLBI activities within IVS: more globally distributed stations should carry out continuous measurements. Furthermore this will yield results of highest relevance for the Earth sciences by monitoring parameters describing global geodynamics needed to model effects such as global plate motion, earthquakes or postglacial rebound.

An important part of the IVS efforts is to provide the best products for the user community and to optimize the use of available global resources. During the 5th IVS Directing Board meeting on February 15th, 2001 the IVS products and related programs were discussed with respect to the general goals described above. It was decided to set up an IVS Working Group (WG2) for Product Specification and Observing Programs. Members of WG2 were chosen among experts in the field of geodetic/astrometric VLBI. The Terms of Reference (ToR) of WG2 are to:

- review the usefulness and appropriateness of the current definition of IVS products and suggest modifications,
- recommend guidelines for accuracy, timeliness, and redundancy of products,
- review the quality and appropriateness of existing observing programs with respect to the desired products,
- suggest a realistic set of observing programs which should result in achieving the desired products, taking into account existing agency programs,
- set goals for improvements in IVS products and suggest how these may possibly be achieved in the future,
- present a written report to the IVS Directing Board at its next meeting.

An overview of the activities of Working Group 2 and the results achieved are presented in this report.

2. Proceeding of the Working Group

During the first weeks after its establishment, the procedure for how to achieve the Terms of Reference was thoroughly discussed. It was decided to proceed step by step:

Step 1: Description of the present status of international VLBI activities within the IVS

In particular the current products of IVS should be described in terms of

- accuracy;
- temporal resolution of the parameters estimated by the VLBI data analysis;
- time delay from observing to product, i.e. time which has passed after the end of the last session included in the VLBI solution until availability of the final products;
- frequency of observing sessions;
- frequency of solution (in the case of "global solutions", when all existing or a high number of VLBI sessions are used to determine so-called global parameters);
- reliability of the IVS products (for details see below).

All these features are essential for comparing the products delivered by IVS to those provided by other space geodetic techniques and their international services. Another very important criterion is the reliability of the IVS products, which can be assessed by the measures that are taken to independently check the IVS results provided to the users. As for the reliability criterion, any external checks, i.e. comparison with other space geodetic techniques, were not considered here because they are beyond the scope covered by IVS. There are also several IVS products that cannot even be estimated by other techniques because VLBI is unique for the respective parameters. The reliability was specified by the following rating scheme:

1 – reliability does not exist, e.g. results were obtained by only one IVS Analysis Center using one software package;
2 – reliability almost does not exist, e.g. results were obtained by different IVS Analysis Centers, but using the same software package;
3 – reliability clearly exists, e.g. results were obtained by different Analysis Centers which used different software packages, but only from sessions of one network;
4 – strongly redundant, same as 3 but results were obtained from sessions of several VLBI networks, partly running in parallel.

In parallel with presenting the IVS products, their various users were also described (see section 4).

Step 2: Description of the goals for future IVS products

In this step the requests from the users' point of view should be described because the most important factor for activities of IVS should be the needs and wishes of the users of the products. The goals should be defined according to the same criteria as given above. For instance it would not be very useful to increase the temporal resolution of a particular parameter down to a couple of hours when an accepted theory shows that the periodic variations and other temporal changes of that parameter occur on time scales never shorter than one month. The required accuracy also strongly depends on the magnitude of the effect to be investigated. An important basis for these considerations was a memo by Benjamin F. Chao on "Global science enabled by Earth rotation observations" (Word document vlbicore.doc at *http://ivscc.gsfc.nasa.gov/mhonarc/core-panel/msg00030.html* 2001) and a very thorough examination of the present accuracy of IVS products by Richard S. Gross (*http://ivscc.gsfc.nasa.gov/mhonarc/core-panel/msg00038.html* 2001). Sometimes step 2 also includes some "vision" of the VLBI experts, i.e. what could be done within the IVS without considering the limited resources.

Step 3: Definition of future observing programs, technological improvements and further changes

In this step the goals defined above were matched to the real world with its limited resources in funding and manpower and its many organisational restrictions. The highest priority should be given to all VLBI products that are unique compared to other techniques. Thus, the task was to develop ideas for VLBI observing schemes that allowed achieving the goals defined in the previous step without considerably increasing the present resources and efforts. The different interests of all users of VLBI products should be equally considered. First, the existing observing programs carried out by various agencies and organizations within IVS (see tables in section 4) had to be reviewed with respect to the desired products. The central role of VLBI in geodesy and astrometry is clearly described in a memo by W. Cannon (*http://giub.geod.uni-bonn.de/vlbi/IVS-AC/divers/cannon.html* 2001):

- the establishment and maintenance of the International Celestial Reference Frame (ICRF);
- the direct tie of the International Terrestrial Reference Frame (ITRF) to the ICRF;
- the monitoring of the time dependent Earth orientation parameters (EOP) that relate the ITRF to
- the ICRF especially the UT1-UTC and precession/nutation angles (?e, ??) which are uniquely determined by VLBI.

Step 4: Final Report

The results obtained from the considerations described above shall be summarized and presented in a written report to the IVS Directing Board as well as to the international VLBI community and its sponsoring agencies. The recommendations presented in that report should be used for further discussions of future observing programs and analysis strategies and should consequently become the basis for the future of geodetic and astrometric VLBI within IVS in the next five to ten years.

3. Present status and future goals

The international VLBI activities within the IVS are comprehensively represented in tables 1a,b,c. The left part of tables 1a,b,c shows the present status, the right part the future goals. In subsections 3.1-3.5 the tables will be discussed in more details.

Table 1a: Present status and future goals of geodetic and astrometric VLBI within IVS - single session products (EOP and TRF)

		Present status					Goals						
	IVS data products	***accuracy***	***frequency of session / solution***	***resolution***	***delay from observing to product***	***reliability by indep. checking****	***accuracy (per 24h)*** **in 2005**	***frequency of session*** **in 2005**	***resolution***		***timeliness *****		***reliability by indep. checking****
EOP	***UT1 from 24h sessions :***	5 microsec	~3d/week	1d	NEOS: 1-4 weeks other 24h sessions: 1-4 months	24h sessions: 3	2-3 microsec	7d/week (continuous)	2002 1h	2005 10 min	2002 3-4d	2005 1d	4
	from 60min intensive sessions :	20microsec	~4d/week	1d	intensives: 1 week	intensives: 2	5-7 microsec		-	-			
	dUT1/dt (lod) from 24h sessions	only preliminary results	~3d/week	-	-	-	0.3-0.5 microsec/day	7d/week	1h	10 min	-	-	4
	x_p, y_p	for x_p: 200 microarcsec for y_p: 100 microarcsec	~3d/week	1d	NEOS: 1-4 weeks other 24h sessions: 1-4 months	3	25-50 microarcsec (for xp, yp)	7d/week	2002 1h	2005 10 min	2002 3-4d	2005 1d	4
	dx_p/dt, dy_p/dt from 24h sessions	only preliminary results	~3d/week	-	-	-	8-10 microarcsec/day	7d/week			-	-	4
	? e, ? ?	100-400 microarcsec	~3d/week	1d	NEOS: 1-4 weeks other 24h sessions: 1-4 months	3	25-50 microarcsec	7d/week	1d		2002 3-4d	2005 1d	4
TRF (single sessions)	***time series (one solution per session) x, y, z (b, h, v)***	5-20 mm	~3d/week	1d	3-4 months	2	2-5 mm	7d/week	1d		2002 3-4d	2005 1d	3
	episodic events (also in EOP)	(10 mm)			to be investigated		2-3 mm	7d/week	1h		2002 3-4d	2005 1d	4

** timeliness starts at the end of the last session used for the solution
b - baseline length, h - horizontal component, v - vertical component

Table 1b: Present status and future goals of geodetic and astrometric VLBI within IVS multi-session products (TRF and CRF)

		Present status					**Goals**							
	IVS data products	***accuracy***	***freq. of solution***	***resolu-tion***	***delay from observing to product***	***reliability by indep. checking****	***accuracy*** **in 2005**	***freq. of solution*** **in 2005**		***resolution***		***timeli-ness *****		***reliability by indep. checking****
								2002	2005	2002	2005	2002	2005	
TRF (multi sessions)	***annual solu-tions (all ses-sions used)*** ***coordinates:*** ***velocities:***	1-4 mm 0.1-1 mm/y	1y	-	3-6 months	2	improved distribution of stations, 1-2 mm 0.1-0.3 mm/y	1y		-		3m	1m	3
	non-linear changes (e.g. periodic variations or irregular changes)	(10 mm)	to be investigated				2-3 mm	1y		sufficient sessions per year to detect annual and semiannual periodic variations		3m		3
CRF + **astro-physics**	***a, d***	0.25-3 mas	1y	-	3-6 months	3	0.25 mas for as many sources as possible + improved sky distribu-tion	1y		-		3m	1m	4
	time series of a, d	variable	-	-	3-6 months	1	0.5mas	1y	1m	1m		3m	1m	4
	source struc-ture	-	2m	2m	2-3 years	1	-	2m	1m	2m	1m	1y	3m	2
	flux density	-	irregular	6h - 6d	1-2 years	1	-	7d/w	7d/w	6h	1h	3-4d	in real time	2

** timeliness starts at the end of the last session used for the solution

Table 1c: Present status and future goals of geodetic and astrometric VLBI within IVS - geodynamical and physical parameters

		Present status					**Goals**				
	IVS data products	***accuracy or uncer-tainety***	***frequency of solution***	***resolution***	***delay from observing to product***	***reliability by indep. checking****	***accuracy or uncer-tainety***	***freq. of solution***	***reso-lution***	***timeli-ness***	***reliability by indep. checking****
geodyn-amical parame-ters	***solid Earth tides h,l (frequency and site de-pendent)***	5-10%	1-3y	-	1year	1-2	0.1%	1y	1y	1m	3
	ocean load-ing A, f (site depen-dent)	10-20%	1-3y	-	1year	1	1%	1y	1y	1m	3
	atmospheric loading (site de-pendent)	30-40%	1-3y	-	1year	1	10%	1y	1y	1m	3
physical parame-ters	***tropospheric parameters: zenith delays gradients***	4-8 mm .3-.5 mm	~3d/week ~3d/week	1h 6h	1w-4m 1w-4m	1 1	1-2 mm 0.1 mm	7d/week 7d/week	10min 2h	1d 1d	3 3
	ionospheric mapping	1-5 TEC-units	~3d/week	1h	1w-4m	1	0.5 TEC-units	7d/week	1h	1d	3
	light deflec-tion para-meter ?	0.3%	1-3y	-	1y	1	0.01% + second order effects	1y	all sessions used	1m	2

[*] rating scheme for 'reliability' in tables 1a,b,c

1 - not existing	(only one Analysis Center using one software package)	(present status) /	not important (required)
2 - almost not existing	(different Analysis Centers, but using the same software package)	(" ") /	desired (")
3 - clearly exists	(different Analysis Centers use different software packages; but only sessions from one network)	(" ") /	important (")
4 - strongly redundant	(as 3, but several VLBI networks, partly running in parallel)	(" ") /	very important (")

3.1 Earth orientation parameters (EOP)

At present, the Earth orientation parameters are usually observed in three 24h sessions per week (NEOS, CORE, IRIS-S, ...). In addition, so-called intensive sessions of 60min (INTENSIVE) take place on a single baseline with a long east-west extension (Wettzell - Kokee Park) four times per week. The latter can only be used to determine UT1-UTC. It should be noted that the accuracy obtained from the 24h sessions is worse for the x_p than for the y_p component of polar motion (200 microarcsec versus 100 microarcsec), due to the unfavourable geometry of most of the networks. Concerning the time delay from observing to product of these sessions it should be pointed out that the results of the NEOS program normally become available between one and four weeks after the session, whereas the data of the other programs are usually not correlated and analysed before one to even four months after the session. This generally too long time delay from observing to product is a clear disadvantage with respect to other space geodetic techniques. The EOP rates, i.e. dUT1/dt and dx_p/dt, dy_p/dt, are geophysically very interesting because they can be directly connected to atmospheric and oceanic excitation. Thus, EOP rates will be needed in the future as another product of IVS; so far VLBI has obtained only preliminary results.

Concerning the goals given on the right hand side of tables 1a,b,c a further improvement of the accuracies by a factor of 2 to 4 seems feasible, e.g. UT1-UTC should be determined to ±2-3 microsec and the pole position to ±25-50 microarcsec in both components. In particular for the x_p component of the pole, this requires an improved network geometry. The same holds for the precession/nutation angles. All measures for improving the accuracy of the IVS products will be dealt with in sections 5 and 6.2.1. As VLBI is unique for the unambiguous determination of UT1-UTC and of nutation (with periods as short as 2 days), the VLBI sessions should take place every day, i.e. continuously 7 days per week, to avoid any jump, bias or other inconsistency. One of the main problems which still has to be solved within the IVS are the offsets and drifts between results obtained by different VLBI networks. Strictly consistent reference frames are a prerequisite for solving this problem.

Short period variations of the EOP occur with periods of a few days, of one day (diurnal variations due to ocean tides) and of half a day (semidiurnal variations due to ocean tides). To resolve the 11 main ocean tidal terms requires a time resolution of at least 1h which can already be achieved with the presently available VLBI data. In order to get the whole picture of ocean tides induced EOP variations at least several hundreds of smaller terms in the near-by side bands should be determined, too. Only then would the full information become available on resonance effects close to the K_1-tide and on the so-called effective load Love number k'. A separation of *all* the ocean tidal terms in the EOP is only possible from VLBI observing sessions which cover at least 18.6 years continuously using a well adjusted TRF. In that respect it should be mentioned that in the period range of diurnal and semi-diurnal terms most of the satellite techniques suffer from resonances with the satellite orbital periods, a problem that does not occur in VLBI. Thus, GPS is not able to resolve several of the diurnal periods of the EOP, e.g. K_1, S_1, and $?_1$ due to resonances with the orbital period.

From recent Fourier and wavelet analyses of the EOP observed by GPS, variations with sub-semidiurnal periods (8h, 6h, 4.8h, 4h, ...) were found. It is still an open question whether these periods really exist and are due either to higher harmonics of the ocean tides or to atmospheric tones. Other explanations could be that they appear in the spectra due to some asymmetry of a 24h quasi-sinusoidal wave or just that it is a pure artefact caused by resonances with GPS satellite orbits. The ratio of the higher harmonics of a solar day plays an important role as for instance in recordings of various geophysical phenomena the S_7 (period 3.43h) is usually stronger than the S_5, S_6 and S_8. Anyhow, some resonances or modes of the Earth might affect Earth rotation on very short time scales, too, and scientists hope to catch episodic events, caused by earthquakes, volcanoes or strong typhoons. As these many open questions need to be investigated from independent EOP measurements by VLBI, almost continuous VLBI sessions and a temporal resolution of 10min are highly desirable by 2005. This becomes in particular important if VLBI is required to control not only satellite techniques (GPS, Glonass, ...) but also new observation technologies such as laser gyros which are designed to observe the rotation of the Earth almost continuously.

A timeliness of 3 to 4 days (one or two days for tape transport, one day for correlation, one day for data analysis) could be achieved with the present VLBI technology although this is a rather challenging goal. The 1-day timeliness, which is given as the goal for 2005, can only be achieved if tape transport is replaced by broadband communication links allowing real-time correlation of the signals. Direct connection between radiotelescopes and the correlators have been under discussion for several years (e.g. Proceedings of the Real-Time VLBI Forum, MIT Haystack Observatory, 1998) and were successfully demonstrated by Japanese VLBI groups within the Key Stone Project (see various TDC News of the CRL, *http://www.crl.go.jp/ka/radioastro/*).

The reliability of the EOP (which are one of the most important products of IVS) is in rating class 3, i.e. there is a redundancy because different analysis centers use different software packages for data analysis. However, in the future the redundancy should still be improved to rating class 4 by using several VLBI networks that partly run in parallel to allow an independent checking of the IVS results.

It was already mentioned in sections 1 and 2 that VLBI is a unique technique for unbiased monitoring of the precession/nutation angles ?e, ??. New theoretical models were developed in nutation theory during the last 10 years and also a semi-empirical model was derived recently by Mathews et al. (2001). This model was adopted by the International Astronomical Union (IAU) at its XXIVth General Assembly in Manchester in Resolution B1.6 approved in August 2000, which will be the future standard for many applications in geodesy and astronomy.

Comparing nutation models with VLBI observations is important for various reasons that were described in detail in a comprehensive paper by Dehant et al. (1999) and also by Mathews at al. (2001). The modeling of nutation involves a frequency-dependent transfer function and the rigid Earth nutation amplitudes. The transfer function is different for each nutation term because of the existence of resonances, because of the mantle inelasticity and of the ocean loading effects. The transfer functions for individual nutation terms deviate from a value computed from a mean frequency-dependent transfer function (Mathews et al., 2001). A small error in the transfer function can only be seen in the largest nutations. The others are very small and so they are less sensitive to changes in the transfer function. For instance, for a small nutation amplitude of 1 milliarcsec, a one percent error in the transfer function would give a 1 µarcsec error in the nutation; while a large nutation of 100 milliarcsec would have a 1 milliarcsec error. So the observation of the 100 milliarcsec nutation, if the rigid nutation is “perfectly” known, at a precision of 20 µarcsec in the observation, will provide constraints on the transfer function at the 10^{-5} level. This is in particular the case for the 13.66 day nutation term with a mean amplitude of 91 milliarcsec. From the other short period nutations according to the new model mentioned above (Mathews et al., 2001) the following terms are of particular importance for the determination of the transfer function (the mean amplitudes are in parentheses): 31.81 days (3 milliarcsec), 27.55 days (15 milliarcsec), 23.94 days (1 milliarcsec), 14.77 days (1 milliarcsec), 13.78 days (1 milliarcsec), 9.56 days (2 milliarcsec), 9.13 days (12 milliarcsec), 7.10 days (1 milliarcsec), 6.86 days (1 milliarcsec).

Also the question arises how long do we have to observe by VLBI to monitor the Free Core Nutation (FCN) at about 430 days, the annual and semi-annual nutation terms and the longer nutation periods? For obtaining geophysical information from the nutation measurements, it is necessary to observe the following long periods: 386.00 days, 365.26 days, 346.64 days, 182.62 days, 121.75 days. In order to be able to separate those terms and the longer periods of 9 years (3399.19 days), 18.66 years (6798.38 days), and precession, at least two times the 18.66 year period should be covered by VLBI observations.

Based on these requirements, there is a great need for monitoring the precession/nutation angles regularly. The main arguments are summarized, below:

- The amplitude of the retrograde Free Core Nutation (FCN) at ~430 days cannot be predicted and is therefore not contained in the new astronomical nutation models; the attenuation of the FCN amplitudes requires a regular and frequent monitoring of the nutation angles by VLBI; the same holds for the prograde Free Inner Core Nutation (FICN) with a predicted period of 1025 days which has not been observed so far.
- There are seasonal (annual and semi-annual) influences of the atmosphere and the oceans on nutation which also must be monitored.
- The shortest nutation period which is of greater interest for astronomers and geophysicists is at 13.66 days; to recover that period by VLBI needs precise observations at least every 3.4 days considering the Nyquist frequency and prograde and retrograde terms. If the period at 6.86 days has to be resolved, too, VLBI observations every 1.7 days would be necessary.

It should be mentioned here, that the need for *regularly* monitoring precession/nutation angles by VLBI was explicitly encouraged in the IAU resolution referred to above.

3.2 Terrestrial reference frame (TRF)

The TRF determined from single session solutions or from a global solution is another very important IVS product because this is an essential part for creating the ITRF by the corresponding IERS Product Center. A particular strength of VLBI is its contribution to the scale of the ITRF. Usually the TRF is computed from the same 24h sessions that are dedicated to observing the EOP. However, only a few analysis centers provide TRF single session solutions and these are not released as official IVS products. In addition, the TRF global solution in the past has been published by only one IVS analysis center (GSFC) using the Global SOLVE software. Other global solutions exist (by GIUB/BKG and Shanghai Observatory) but all of them were obtained by program SOLVE. Thus, the TRF received a rating of 2 for redundancy. A combined IVS TRF solution in terms of individual time series and also of global station positions and velocities should be established as soon as possible based on individual solutions of various analysis centers using different software. Another important aspect is the distribution of VLBI stations on the Earth, which should be generally improved. There is a need for having more stations in the southern hemisphere, with at least two stations on each main tectonic plate. Episodic events and non-linear changes of the baseline components are aspects that are mainly interesting for geophysicists and seismologists. Such effects might be detect-able by the still rapidly increasing accuracy of space geodetic techniques. Thus, it is important that the temporal continuity of VLBI sessions should be sufficient to detect such effects. A successful detection of non-linear changes of baseline rates was reported in August 2000 by the Japanese Key-Stone Project (KSP) (*http://ksp.crl.go.jp/*)

3.3 Celestial reference frame (CRF)

For the ICRF realized by extragalactic radio sources VLBI is again the only technique. Thus, the ICRF can be seen as another very important IVS product. This has been explicitly recognized by the International Astronomical Union (IAU) at its XXIVth General Assembly in Manchester in Resolution B1.1 approved in August 2000. For the ICRF, again, a lack of redundancy of the results can be noticed because the ICRF and its extension were produced only by a single analysis center of the IVS. (It should be noted, however, that using the results of a single solution was the consensus of the IAU subgroup that generated the ICRF). Additional CRF solutions by other IVS analysis centers for detailed comparison are highly desirable. The idea of deriving a combined IVS CRF solution should be investigated in cooperation with the IAU Working Group on Celestial Reference Systems.

Rather than improving the current ICRF source position accuracy, it is felt that finding new sources to improve the overall sky distribution is more important for the immediate future. If the ICRF will be used as a catalog of calibrators for phase-referencing VLBI observations (most of the VLBI experiments with astrophysical goals are of this type now), then a reference source (calibrator) every few degrees on the sky is needed. For geodesy and astrometry, better observing schedules can be made if there is a more dense distribution of sources available. In this respect, the ICRF suffers from a deficit of sources with an average of only one source per 8º x 8º on the sky. Moreover, the distribution of the ICRF sources is found to be largely non-uniform. For example, the distance to the nearest ICRF source for any randomly-chosen sky locations can be up to 13º in the northern sky and up to 15º in the southern sky. Charlot et al. (2000) showed that adding 150 new sources at specific location in the northern sky would reduce this distance to about 6º, and progress is being made towards this goal. An even larger effort is required for the southern sky since most of the sources far in the south have only a limited number of observations because of the lack of VLBI stations in the southern hemisphere.

The temporal variations of the source positions should also be investigated by solving for time series of source coordinates since these may be affected by source structure variations. Maps of the source structures can be derived from geodetic VLBI sessions if the number of observing stations is large enough, as are total flux density variations. Just recently, Koyama et al. (2001) showed that flux density variations of compact radio sources could be monitored within the Key Stone Project. The real-time property of that VLBI network even enables on-line monitoring of rapid flux density variations. Such monitoring is necessary to optimize observing schedules but is also useful to study source physics.

In the longer term the accuracy and precision of the ICRF will be improved with the goal of generating refined realizations for adoption by the IAU. The IVS will work together with the IERS and the IAU Working Group on Celestial Reference Systems in this matter. The current level of accuracy is ~0.25 mas. A VLBI frame that is better by at least an order of magnitude is needed to match the projected precision of some planned astrometric satellite programs. To improve the current level requires reduction of systematic errors through better modeling and analysis as well as reduction of random errors through further observations of all ICRF sources. Routine non-CRF observing programs should allot a small portion of the time to cycling through the extended ICRF catalog. The ultimate accuracy of the VLBI reference frame may be set by variations in radio source structure or gravitational microlensing, so these effects require study by the IVS analysis centers and other researchers.

3.4 Geodynamical parameters

In the last decades VLBI has proved to be a very powerful technique for the determination of various geodynamical parameters. These are Love and Shida numbers used in the model of the solid Earth tides deformations, site-dependent amplitudes and phases of the ocean loading models, and site-dependent deformations due to atmospheric pressure variations (atmospheric loading). All the relevant parameters can be determined with an accuracy sufficiently high to detect and verify the particular effect (Schuh and Haas, 1998; Haas et al., 2001). However, the modelers also want to use the VLBI results to validate and possibly to improve their models. This is only possible if the present accuracies are increased by another factor of 5 to 50 and if the VLBI results are more reliable in terms of consistency and redundancy. Thus, it is highly recommended that the parameters described above are determined on a regular basis (e.g. once per year) and published as an IVS research product. The solutions should be carried out by several IVS analysis centers to increase the redundancy. As a mid-term goal for 2005 the individual results should be combined and be published as the "official" IVS product. Considering the hundreds of closely-spaced tidal terms which are contained in the models for solid Earth tides and for ocean loading, an unambiguous and uncorrelated determination will only be possible when almost continuous observations over 18.6 years are available. The problem gets even more difficult when complex Love numbers corresponding to anelasticity of the Earth's crust and latitude dependent Love numbers are to be derived. Again, continuous 18.6 years of VLBI observations by stations distributed all over the Earth are needed.

3.5 Physical parameters

Lately, tropospheric and ionospheric parameters have been determined by IVS analysis centers not just within the standard EOP or TRF solutions but to specifically investigate the troposphere and/or ionosphere. As so far only preliminary results exist, that field could be clearly extended by further investigations. A need in this context is a continuous monitoring, i.e. 7 days per week, and the availability of the results with a very short time delay. Only then can the IVS results be useful for comparison with other space geodetic techniques and for meteorological purposes such as climate studies. The improvement in accuracy of the tropospheric and ionospheric parameters results indirectly from the goals set for the other IVS major products like EOP. Additional research in this area is necessary to study the degree of usefulness of such by-products.

There are other physical parameters which can be estimated from VLBI data, e.g. the so-called light deflection factor ? of the theory of general relativity. This parameter was determined for the Sun several years ago. Regular re-estimates are desirable as well as investigation of other relativistic effects. These and other activities should be organized under the umbrella of IVS. Thus, the IVS should be open for new observing sessions dedicated to special research tasks, e.g. for observing parameters of special or general relativity or for VLBI observation of spacecraft to investigate solar system dynamics.

4. Users of VLBI products

The users of VLBI products can be divided into different categories according to different IVS products (table 2):

Table 2: IVS products and their users

IVS products	users and their tasks
operational EOP	IERS Rapid Service and Prediction Product Center for predicting the EOP, other EOP prediction centers
EOP	IERS for generating final EOP series; individual users for precise positioning and navigation on Earth and in space (by interplanetary spacecrafts) and for geophysical studies
TRF	IERS for determination of ITRF, many users of ITRF which is a basis for almost all geodetic activities
TRF series	individual users for geodynamical studies
ICRF	geodesists, astronomers and astrophysicists, users in space research
source structure and other astrophysical parameters	astrophysicists
tropospheric and ionospheric parameters	meteorologists, climatologists and geodesists
geodynamical parameters	scientists in Earth dynamics and geophysics
relativistic parameters	physicists, scientists in cosmology and relativity

5. Measures to meet the goals for IVS products

Table 3 gives a short overview of the measures which should be taken within IVS to meet the goals defined in tables 1a,b,c. As most of the measures are related to the observing programs, these are the main focus for improving the current status of IVS products. Thus, new observing programs will be proposed in the next section.

Table 3: Measures to be taken in order to improve important criteria

Improvement of	Measures
accuracy	- technological improvement (higher data rates, digital Mk5 recording systems, …) - more precise models in data analysis - more observables taken by more stations with a stronger geometry (distribution of stations on the Earth and of sources in the sky) - surveying of local parameters at antennas - improvements in station performance (better reliability, improved sensitivity, faster slewing)
time delay from observing to products	- strict organization of observing programs (tape or disc transport, correlation ...) - broadband communication - acceleration of correlation procedure - acceleration and automation of data analysis
temporal continuity	- denser observing programs
temporal resolution	- observing programs (networks, schedules, …) - improve stochastic model of data analysis
redundancy	- data analysis by different analysis centers - data analysis using different software - more than one VLBI network in parallel
coverage of Earth by VLBI stations	- more stations on southern hemisphere, e.g. by use of mobile stations
coverage of sky by radio sources	- more sources, especially in the southern sky
regular releases of: ICRF and TRF, geodynamical parameters	- release official IVS products once per year with timeliness of one month
availability and distribution of: physical parameters (e.g. tropospheric and ionospheric mapping), source structure and other astrophysical parameters	- regular release as IVS products

6. Proposed observing programs

6.1 Overview of existing programs

IVS currently has no observing program of its own for the generation of IVS products; only existing observing programs have been used so far. The NEOS, CORE and INTENSIVE programs established and coordinated by USNO and/or NASA are the basis for observing the EOP. The same VLBI sessions are used for determining the TRF. Additional observing programs coordinated by other organizations, e.g. by FGS (German Research Group on Satellite Geodesy) and GSI (Japan), have been established for specific research purposes such as the EOP and/or the TRF. Only very few programs are dedicated to observing the CRF. Some extended programs have been organized by NASA for special R&D requirements. Only NEOS and INTENSIVE sessions are strictly organized to optimize timeliness, i.e. the time from observation to availability of final products is kept as short as possible.

The observing programs for the year 2001 (as of mid August) are summarized in table 4. A total of 968 observing days per year ("station days") are planned for 2001, approximately equivalent to 2.9 observing days per week for the typical network size of 6 stations; this does not include the INTENSIVE sessions. The table shows the type of program, the responsible Operation Center (OC) and Correlator (CO), and the average time delay for sessions already correlated. Table 5 lists the number of observing days for each Network Station (NS) in 2001, plans for 2002 and goals for several years in the future.

6.2 Requirements and recommendations for new observing programs

Now the question arises how the existing observing programs can be extended to match the goals defined in tables 1a,b,c. There are three main areas which need to be improved considerably within IVS:

1. accuracy of results (see 6.2.1),
2. time delay from observation to final product (see 6.2.2),
3. frequency of sessions in order to achieve a more continuous time series (see 6.2.3).

For the scientific requirements, the temporal resolution and the accuracy of the products must be increased to be able to detect many of the effects mentioned in sections 3.1 and 3.2. Individual local information and local measurements such as permanent surveying of the shape of the antennas and in particular of motions of the VLBI reference point must be provided additionally.

Requirements for extending and upgrading the existing IVS products are:

- improve the coverage of the week towards a continuous service,
- decrease time delay in order to improve timeliness,
- improve reliability of IVS products by independent checking,
- increase the accuracy and temporal resolution,
- develop networks that increase the accuracy of x_p up to the level of y_p.

Recommendations for updating existing programs and establishing new ones for the IVS are:

- combine the requirements of various users,
- include all techniques (Mk4/Mk5, K4 and S2),
- include R&D programs to explore and extend the full capacity of geodetic VLBI,
- improve global coverage of VLBI stations,
- include CRF observing programs,

- maintain continuity with the existing time series, mainly NEOS, INTENSIVE, and existing CORE,
- incorporate new VLBI technologies.

Table 4: Observing Programs for 2001 (OC-Operation Center, CO-Correlator, NS-Network Station)

Day	Start UT	Dur Hr	Type	Purpose	OC	CO	#/yr	#NS	#stn days	Tapes/ station	Delay (days)
Monday											
	8:00	24	SYOWA	TRF	JARE	Mitaka	5	3	15		90
	12:00	24	EUROPE	Vertical	Bonn	Bonn	2	8	16	1	60
	14:00	24	C-OHIG	TRF	Bonn	Bonn	2	5	10	1	60
	14:00	24	C-IRIS-S	EOP	Bonn	Bonn	12	6	72	1	60
	14:00	24	RDV	TRF/CRF	NASA	VLBA	6	20	120	3	45
	16:00	24	APSG	TRF	NASA	WACO	2	6	12	1	60
	17:30	24	CORE-1	EOP	NASA	Hays	12	6	72	2	100
	17:30	24	CORE-B	EOP	NASA	WACO	4	6	24	1	90
	17:30	24	CORE-C	EOP	NASA	WACO	7	6	42	1	90
	17:30	24	CONTM	EOP	NASA	WACO	2	6	12	1	80
	18:30	1	NEOS-INT	UT1	USNO	WACO	52	2	4.3		5
Total Monday 24h sessions				54	(some sessions are actually on Thursday)						
Tuesday											
	18:00	24	NEOS	EOP	USNO	WACO	52	6	312	1	17
	18:00	24	CONTM	EOP	NASA	WACO	1	6	6	1	80
Total Tuesday 24h sessions				53							
Wednesday											
	18:30	24	CONTM	EOP	NASA	WACO	2	6	12	1	80
	18:30	24	CRF	CRF	USNO	WACO	4	7	28	1	60
	18:30	24	CORE-3	EOP	NASA	Hays/Bonn	34	6	204	2	100
	18:30	1	NEOS-INT	UT1	USNO	WACO	52	2	4.3		5
Total Wednesday 24h sess.				40							
Thursday											
	19:00	24	SURVEY				2	3	6		90
	18:30	1	NEOS-INT	UT1	USNO	WACO	52	2	4.3		5
Total Thursday 24h sessions				1							
Friday											
	18:30	1	NEOS-INT	UT1	USNO	WACO	52	2	4.3		5
Total Friday 24h sessions				0							
Saturday, Sunday											
			no programs								
Total number of station days									**968**		
Total number of 24-hr sessions							**149**				
Total number of 1-hr sessions							**156**				
Avg days/week covered by 24-hr sessions							**2.9**				
Avg tapes/session										**1.3**	
Avg time delay											**60.0**

Table 5: Number of observing days for each network station

Geodetic Station Usage				
Station Name	Code	2001 Actual	2002 Plan	2005 Goal
Algonquin	Ap	64	76	208
Effelsberg	Ef	1	1	1
Fortaleza	Ft	79	79	208
Gilmore Creek	Gc	101	110	208
GGAO/MV3	Gg	3	4	4
HartRAO	Hh	59	52	108
Hobart	Ho	23	40	104
Kokee	Kk	101	104	208
Kashima	Ka	3		
Matera	Ma	37	104	208
Medicina	Mc	26	52	52
Ny Alesund	Ny	82	83	208
Noto	No	5	5	52
Onsala	On	24	26	52
O'Higgins	Oh	7	7	12
Seshan	Se	16	12	12
Simeiz	Sm	6	6	12
Syowa	Sy	7	6	6
TIGO	Ti	8	52	208
Tsukuba	Ts	32	32	208
Urumqi	Ur	6	6	12
Westford	Wf	72	72	72
Wettzell	Wz	112	112	208
Yebes	Yb	6	12	12
Yellowknife	Ye	13	13	12
DSS15	15	3	15	26
DSS45	45	6	15	26
DSS65	65	6	6	6
VLBA (10 antennas)	Va	60	60	60
Total		968	1162	2517

6.2.1 Accuracy of Results

Achieving the accuracies listed in the goals of table 1 can mainly be achieved through further technological improvements, e.g. by extending the observing program to higher data rates, and by improved operational reliability. Also the models used for data analysis can still be improved following the most recent scientific research in various fields such as solid Earth tides, atmospheric and ocean loading and tropospheric refraction. This can be complemented by incorporating local survey done at the antennas. Special efforts should be devoted to use more stations in each network and to design new networks to achieve the best possible EOP and TRF measurement accuracy. In particular, networks should be designed so that x_p and y_p results are of comparable accuracy. Station performance is critical to the accuracy of results, too. Stations should be encouraged to aim for the highest possible standards for high quality, reliable recorded data.

Special R&D sessions should be scheduled depending on scientific requirements and to further develop VLBI accuracy and time resolution. Following the extremely successful CONT94 and CONT96 sessions, such special CONT-type sessions should be carried out once or twice per year, if possible for a continuous 14 days to investigate the full capacity of geodetic VLBI. As many stations as can be correlated in one correlator pass (8-12) should participate and the highest standards of technical excellence must be used. Such special R&D sessions might be less critical with respect to timeliness.

The offsets and drifts between EOP series determined by different VLBI networks, demonstrated by the CORE-A/NEOS sessions, represent the current accuracy of results. Additional R&D sessions should be devoted to studies of the offset problem. To detect and remove the reasons for the problems described above partially concurrent observing sessions are proposed which overlap by a couple of hours. In addition, at least two identical stations should observe in successive networks.

6.2.2 Timeliness

As long as global transmission of observed data cannot be realized via the Internet, magnetic tapes or discs will have to be shipped between stations and correlators. One of the objectives of the IVS observing program is to set up a fast and routine procedure to ship the recorded media immediately after the sessions to the correlator. Assuming that shipping tapes will start instantly after each session, 1 or 2 days will be needed for transportation, 1 day for correlation and 1 day for data analysis and providing the products. This roughly means a minimum delay of at least 3 to 4 days, longer from stations that are not located near convenient transportation hubs.

Besides faster shipping of tapes to the correlator, we recommend that the correlators give priority to processing certain types of sessions, as is the current practice for the NEOS sessions. A second regular session should receive similar priority attention so that regular results will be available with a short time delay.

The research and development on broadband communication links for geodetic and astrometric VLBI should be strongly supported within IVS, as well as the development of a more rapid data analysis by faster processing and automation. Direct links between the components of a VLBI system (radio telescopes, correlators, analysis centers) would not only improve the data flow but is the only chance to considerably improve the timeliness of IVS products because it will allow the IVS to provide final products in near real-time. In May 1998 a forum on Real-Time VLBI was held at MIT

Haystack Observatory (Proceedings ed. by J. Ray and A.R. Whitney, 1998) where the various aspects of direct broadband communication links were discussed. As the data transmission rates have increased significantly since 1998 with steadily decreasing costs, real-time VLBI seems to be feasible and affordable in the near future. The K4 system has demonstrated that reliable, sustained daily VLBI operations can be accomplished with minimal time delays of less than one day, if use is made of near real time data transmission, automated correlation procedures, and automated analysis.

The competitiveness of VLBI products would be significantly increased by contributing to such important tasks as:

- Support prediction of EOP by IERS Rapid Service and Prediction Product Center and other EOP prediction centers. EOP predictions are needed for various tasks, e.g. for deep space navigation.
- Allow reaction to episodic events in near real-time (both geophysical phenomena on Earth and astrophysical phenomena on extragalactic sources).
- Support atmospheric and ionospheric investigations.
- Guarantee the availability of the results (in particular of rapid UT1-UTC) in case of emergency, e.g. if air traffic is stopped.

6.2.3 Frequency of Sessions

The justification for daily, continuous VLBI sessions was given in several sections of the report.
The main arguments for continuous VLBI measurements are repeated here:

- Contribute to the proposed IAG project IGGOS that can only be realized by regular, if possible continuous, contributions of *all* space geodetic techniques; VLBI is essential as it plays a unique role (from those diurnal tidal terms that cannot be observed by GPS to short and long period nutation parameters).
- Provide a *permanent* comparison and control of results of other techniques, such as GPS, SLR, absolute gravity and ringlaser systems.
- Resolve the smaller tidal terms in solid Earth tides, ocean loading, and ocean tidal excitation of the EOP.
- Determine the amplitudes of the many short period nutation terms; this allows the investigation of the transfer functions, in particular how each term deviates from a mean frequency-dependent transfer function.
- Catch episodic events both on Earth and on extragalactic sources.
- Increase the accuracy of the results by increasing the number of observations.

Continuous VLBI sessions can only be achieved in gradual steps as we augment resources available for the observing programs. It is recommended that we carry on and extend the existing types of regular observing programs, such as CORE and NEOS, in order to maintain continuity with existing time series. As a next step we recommend establishment of a regular weekly 24-hour session in addition to the weekly NEOS. Also, a regular weekly or monthly session could be observed by including S2 and K4 components. In future years, Saturday and Sunday observations should be considered. This may be a staff and budget problem, but it should be considered nevertheless. We should support development of new technologies and control systems that will enable unattended observing.

A strong demand exists for INTENSIVE type experiments to determine UT1-UTC, one of the most important parameters provided by IVS due to the unique capability of VLBI. Daily INTENSIVE measurements with very small delay (3-4 days with tape recording and less than one day in case of broadband data transmission, see sub-section 6.2.2) would be desirable in order to provide reliable UT1 predictions and a high-frequency UT1 series for geophysical studies. As many days as possible should include a short-duration one-baseline session optimized for UT1 measurement. Additional independent observations on a second baseline would be highly desirable in order to provide independent control and robustness, i.e. if one session should fail there would be another available.

6.3 Resources

A realistic observing program requires careful balancing of available resources. Within the geodetic VLBI community there are three types of resources:

1. Station observing time,
2. Correlator capacity,
3. Recording media and data transmission facilities.

At various times in the past years, each of these types of resources has taken its turn as the least available resource. In recent years correlator time was in the shortest supply, but now the efficiency of the Mk4 correlators is improving rapidly, and the observing programs will probably be limited by availability of tapes in 2002. If we improve the tape shipping procedures, and if the correlator efficiency continues to improve, we may be limited by availability of station observing days by 2003. The estimated resources that will be available for the next few years are shown in table 6.

The most-used stations observe up to two or three 24-hour sessions per week on average; many stations observe only once per month. A continuous program of 6-station networks will require 2190 station days per year, more than double the current resource availability. For 8-station networks, nearly 3000 station days are required annually. Besides additional observing burdens in sheer numbers, continuous observing also means that stations will be observing on weekends.

It is anticipated that the efficiency of the Mk4 correlators will continue to increase, doubling their 2001 efficiency so that by 2005 they can process one day of observing in one day of correlator time: a processing factor of one. The correlator capacity is shown in the table as the number of sessions that can be processed, taking into account the expected Mk4 processing factors. The calculations assume that the number of supported correlator operational days for each of the three Mk4 correlators remains the same throughout the period (Haystack 50, Washington 200, and Bonn 110 days). The anticipated availability of the S2 and K4 correlators is shown as increasing over the next years.

The number of required tapes depends on the recording technology (Mk4, S2, or K4), the recording data rate, and on the average time delay between observing and export of data from the correlator. Each recording technology uses a different type of tape. The Mk4 tapes are 1-in wide and loaded on 14-in glass reels; tape capacity is ~4.7 Tb. At a recording rate of 128 or 256 Mb/s one station uses typically two tapes in a 24-hr session. There are 468 Mk4 tapes in the geodesy pool; no further purchases are planned because of the imminent deployment of the disc-based Mk5 recording systems. S2 tapes are standard VCR tapes and are counted in “boxes” of eight cassettes each. The capacity of one box is ~1.8 Tb; a station uses 3-4 boxes for a 24-hr session recorded at 128 Mb/s. Requirements for S2 tapes are expected to be met from the existing Space-VLBI/geodesy supply. K4 tapes are D1 type cassettes used in the commercial VCR business. One tape has a capacity of ~0.6 Tb, and typically a station uses 6-7 tapes of the size usually used for VLBI in a 24-hr 64 Mb/s session. Additional K4 tapes would need to be purchased to support a monthly K4 network session. The Mk5 will record on a set of 16 100-GB discs for a capacity of ~12.8 Tb per set. One set of discs per station will be needed for a 256 Mb/s 24-hr session. The numbers of recording media in table 6 are shown in equivalent Mk4 tape capacity, so that the totals can be used in table 7.

Table 6: Estimated resource availability for the years 2000-2005

		2000	2001	2002	2003	2004	2005
Observing Time (station days)							
		834	968	1162	1500	1800	2517
Correlator Capacity (sessions)							
	Mk4	103	144	171	180	180	180
	S2			12	26	52	52
	K4				12	12	12
	VLBA	6	6	6	6	6	6
	Total	109	150	189	224	250	250
Recording media (equivalent Mk4 tapes)							
	Mk4	363	468	468	468	468	468
	S2			75	100	200	200
	K4				50	50	50
	Mk5			50	100	200	200
	Total	363	468	593	718	918	918

6.7 Proposed IVS observing programs for 2002-2005

IVS as a service needs to carry out regular programs, in order to deliver its products as reliably and precisely as possible with respect to the available resources. Special R&D programs will have to be scheduled, too, to support scientific research and improvement of the VLBI technique.

Table 7 outlines a proposed IVS observing program for the years 2002-2005, including 2001 as a reference point. Each section of the table shows one year's program in columns giving the type of session, number of stations, number of sessions, number of tapes, and time delay in days. At the bottom various statistics and totals show the resource usage (station days, correlator time, tapes), estimated resource availability for that year (from table 6), and resource shortfall (or excess, shown as negative numbers). The table shows 24-hr sessions, short INTENSIVE-type sessions, and R&D sessions. The IVS Coordinating Center will implement the details of the program, table 7 gives the outline and overview.

Table 7: Proposed IVS Observing Program

	2001					2002					2003					2004					2005				
	Type	# stn	# sess	tap	delay	Type	# stn	# sess	tap	delay	Type	# stn	# sess	tap	delay	Type	# stn	# sess	tap	delay	Type	# stn	# sess	tap	delay
Monday	CORE-1	6	12	38	90	IVS-R1	6	52	88	15	IVS-R1	8	52	87	10	IVS-R1	8	52	89	10	IVS-R1	8	52	94	10
	C-IRIS-S	7	12	35	60																				
	INT	2			5																				
	Other	6	30	100	100																				
Tuesday						Other	6	18	54	60	Other	6	12	35	60										
						IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5
	NEOS	6	52	81	17	IVS-T2	7	12	42	60	IVS-T2	7	0	0	30	IVS-T2	7	26	64	30	IVS-T2	8	52	129	20
Wednesday											Science	8	12	46	60	Science	8	12	53	60	Science	8	12	61	60
	CORE-3	6	34	114	100	R&D	8	12	48	60	R&D	8	26	66	30	R&D	8	26	73	30	R&D	8	26	64	20
						IVS-E3	8	12	34	30	IVS-E3	8	26	66	30	IVS-E3	8	26	73	30	IVS-E3	8	26	64	20
	INT	2			5	IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5
	Other	6	8	27	100	CONT02	8	15	216	90	CONT03	8	15	240	60	CONT04	8	12	53	60	R&D	8	12	61	60
Thursday						IVS-CRF	6	4	12	60	IVS-CRF	6	4	12	60	IVS-CRF	6	4	12	60	IVS-CRF	6	4	12	60
	CRF	6	4	13	90	IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5
	RDV	10	6		45	RDV	10	6		45	RDV	10	6		45	RDV	10	6		45	RDV	10	6		45
	INT	2			5	IVS-R4	6	52	88	15	IVS-R4	8	52	87	10	IVS-R4	8	52	89	10	IVS-R4	8	52	94	10
Friday						IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5	IVS-INT1	2			5
						IVS-INT2	2			5	IVS-INT2	2			5	IVS-C5	6	26	55	30	IVS-C5	8	52	129	20
Saturday																IVS-C6	6	26	48	20	IVS-C6	8	52	129	20
Sunday											IVS-C7	6	26	50	30	IVS-C7	6	52	109	30	IVS-C7	8	52	129	20

	2001	2002	2003	2004	2005
Days/ week observed:	3,0	3,5	4,4	6,2	7,7
Average Session Parameters (fixed)					
avg ship to stn (weeks):	8	6	4	3	2,5
avg tapes/session:	1,3	1,8	2	2,5	3
Resource usage					
sessions to be correlated:	158	183	231	320	398
station days used:	984	1212	1776	1862	3188
recording media:	407	583	689	718	966
Resource availability					
correlatable sessions:	150	215	270	310	430
station days:	968	1162	1500	1800	2313
recording media:	468	468	468	500	500
Resource shortfall					
correlator:	8	-32	-39	10	-32
station days:	16	50	276	62	875
recording media:	-61	115	221	218	466

Highlights of the proposal for each year are:

- 2002: The proposed program moves the current NEOS session from Tuesday to Monday with the new name IVS-R1, and adds a second weekly rapid-turnaround session on Thursday named IVS-R4. This provides continuity with the current NEOS and concentrates resources currently used for CORE sessions into a second weekly session. (The R in the name stands for **R**apid.) The monthly IVS-E3 will emphasize EOP and will use S2-technology. A 14-day continuous session named CONT02 is proposed. A monthly R&D session should be used for technique improvement studies. The RDV (Research and Development VLBA) sessions would continue to serve as the main source of data for the CRF; other CRF sessions are proposed for observing southern sources not visible to the VLBA. The "other", mainly regional, sessions continue. The IRIS-S sessions are renamed IVS-T2 for TRF emphasis. INTENSIVE sessions would be on Tuesday, Wednesday, Thursday and Friday and at least one of these days would have a second independent session for robustness and independent control, e.g. by K4. Real-time data transfer for the INTENSIVES should be investigated. Testing and initial deployment of Mk5 units should be carefully coordinated.

- 2003: The two rapid-turnaround sessions are increased to 8 stations. A weekend day observing is added on a bi-weekly basis. It will probably take at least all of year 2002 to figure out how to support weekend observing. A monthly session is available for proposal-based scientific experiments. Deployment of additional Mk5 units should be done this year.

- 2004: The first weekend day is made weekly this year, and a second bi-weekly session on the weekend is added.

- 2005: This year shows the full 7-day observing program. There are serious shortfalls in resource usage of stations days, correlator time, and tapes. This program may not be realistic unless we can find significant new resources, but it is shown for completeness. It is possible that some real-time facilities for data transmission might be in place by this time, but it is difficult to estimate either the time scale or resources needed.

7. Recommendations

It is recommended that IVS components devote the resources necessary to accomplish the observing program proposed in the previous section, with special emphasis on the following points:

- Network stations should commit to shipping tapes more efficiently to the correlators so that the time delays in the plan can be accomplished. The correlators should commit to assign priority to certain sessions.
- It is strongly recommended for the success of the proposed plan that initially the S2 correlator support one day per month of observations, rising to one day per week in the future. Likewise, it is strongly recommended that the K4 correlator support one INTENSIVE observing session per week, with more days coming in the future.
- Unattended operations should be considered by each Network Station during 2002 so that weekend observing by a network can begin in 2003.
- Some R&D sessions should be devoted to studying the network offset problem.
- The 14-day R&D continuous sessions will require additional station resources and planning for the high tape usage.
- The CRF and RDV sessions should be used to expand the source catalog used for regular geodetic sessions. Inclusion of new, weaker sources will fill in gaps in sky coverage and facilitate better schedules.
- A vigorous R&D program should be part of every year's observing program to study methods for technique improvement, identify and eliminate instrumental effects, and study other systematic error sources.

Recommendations concerning the VLBI data analysis within IVS:

- Increase the EOP time resolution to 1h in 2002 with a goal of 10min in 2005.
- Determine EOP rates as another IVS product.
- Establish a combined TRF solution (time series or global solution of station positions and velocities) as an IVS product on a regular basis.
- Encourage additional CRF solutions for detailed comparison.
- Investigate the idea of a combined ICRF solution.
- Continue investigation of temporal variations of source positions and of monitoring source structures and encourage investigation of source structure delay corrections.
- Determine regularly geodynamical parameters such as solid Earth tides Love numbers and oceanic and atmospheric loading coefficients with clearly increased accuracy to be published as IVS research products.
- Continue investigation of tropospheric parameters and ionospheric mapping by VLBI.
- Incorporate local surveying results done at the antennas.
- Encourage development of partially automated data analysis.
- Encourage data analysis by more analysis centers using different software packages.
- Improve models used for data analysis wherever possible.

Recommendations on technological upgrades and developments:

- All stations that are Mk3 should be upgraded to Mk4 or Mk5 capability as soon as possible so that they can participate in higher data rate sessions and use Mk4 recording modes.
- Deployment of geodetic S2 and K4 systems at more stations is encouraged so that good geodetic networks can be designed that use these systems and be integrated into the international geodetic observing program.
- Additional media equivalent to the capacity of at least 100 Mk4 tapes will be necessary to carry IVS through the proposed program.
- Improved technologies should be strongly pursued because higher data rates, advanced data transmission techniques, and automated observing and processing methods lead to increased accuracy, timeliness, reliability, and efficient use of resources.

Recommendations concerning IVS organization:

- IVS should establish and publicize procedures for submitting and reviewing proposals with R&D, technique improvement, technique validation, and/or scientific goals.
- IVS should establish a permanent Program Committee (PC) to advise the Coordinating Center in implementing the observing program. The PC would review proposals, discuss and recommend the observing program, and carry out policies related to the observing program as determined by the Directing Board.

8. Conclusions

Geodetic VLBI plays an essential role in geodesy and astrometry due to its uniqueness in observing UT1-UTC and the precession/nutation angles unbiased over a time span longer than a few days. It is also needed for the establishment of the ICRF and contributes extensively to the generation of the ITRF. The report shows that due to various requirements of the different users of IVS products the following aspects must be accomplished:
- significant improvement of the accuracy of VLBI products,
- shorter time delay from observation to availability of results,
- almost continuous temporal coverage by VLBI sessions.

A first scenario of the IVS observing program for 2002 and 2003 considers an increase of observing time by about 30%-40% and includes sessions carried out by S2 and K4 technology. The midterm observing program for the next 4-5 years seems to be rather ambitious, although it is feasible if all efforts are concentrated and the necessary resources become available.

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