REPORT ITU-R SA.2132

Telecommunication characteristics and requirements for space VLBI systems

(2008)

This Report describes the characteristics of the space VLBI systems. These characteristics form a technical basis for Recommendations related to space VLBI systems.

The contents of this Report were originally included in the Recommendation ITU-R SA.1344 – Preferred frequency bands and bandwidths for the transmission of space VLBI data, as an annex. That annex material has been removed from the Recommendation and is maintained in this Report. In preparing this Report, many revisions have been made to the material formerly in the Recommendation and the topics have been rearranged to improve clarity.

The Report includes a general description of the space VLBI systems and detailed descriptions of telemetry link for science data and of phase transfer link for time and frequency synchronization. Also included are the explicit equations for cross-correlation SNR and its degradation due to interference, required carrier frequencies and telemetry bandwidths, an interference criterion for the telemetry channel, effects of noise on the phase-transfer link, the characteristics of existing and planned space VLBI systems, and the characteristics of earth stations.

Contents

1 Introduction

Very long baseline interferometry (VLBI) allows experimenters to observe radio sources with angular resolutions that cannot be approached by other methods. In addition, VLBI has other scientific and engineering uses. Observations of distant radio sources with two or more VLBI stations can be combined to determine the structure and positions of extra-galactic radio sources, to determine the geodynamical characteristics of the Earth, to study the Moon's libration and tidal response, to determine orientation of the solar system with respect to the extra-galactic inertial frame, to determine the vector separation between antenna sites, and to provide navigation and tracking of spacecraft.

2 Description of the space VLBI system

Space very long baseline interferometry (SVLBI) is a highly useful extension of very long baseline interferometry (VLBI), which in turn is a development from conventional radio interferometry. In all three cases, a specified bandwidth of cosmic or other radio emission is received simultaneously at two or more antennas that are distributed over distances much larger than the size of individual antennas. These bands, which can be described as time-varying spectra, are downconverted to a lower frequency so that they can be further amplified and then cross-correlated. In conventional interferometry this processing is done in real time. To preserve the amplitude and relative phases of the spectral components the downconversion has to be based upon a common local oscillator or frequency reference. The attraction of interferometry is that the angular resolution of the interferometer is related to the separations between the antennas rather than their physical size. However, there is a practical limit to how far antennas can be separated and still use real-time signal transfer, and that the largest conventional interferometers lack the angular resolution needed for the investigation of many types of cosmic radio source or determination of the position of distant space probes.

The development of ultrastable oscillators, accurate clocks and large-bandwidth data recording systems (using discs or magnetic tape) made it unnecessary to connect the antennas or use common local oscillator references, so the antennas could be moved further apart and the data taken after the experiment to a processing station where they could be synchronized and correlated, yielding a map of the source region. Antenna separations (interferometer baselines) of thousands of kilometres have been used successfully. However the diameter of the Earth sets a hard limit to the usable antenna spacings. Source visibility above the horizon in most cases limits the spacing even further.

Space very long baseline interferometry (SVLBI) removes this limitation by putting one of the interferometer antennas in space. Although in essence the process is still that of conventional ground-based VLBI there are some additional complications. Firstly the spacecraft carrying the spaceborne antenna element is moving at orbital velocity, and the motion has to be known quite accurately, and secondly the data have to be downlinked to a ground station for recording. Maintaining accurate time tagging of the data is much more complicated.

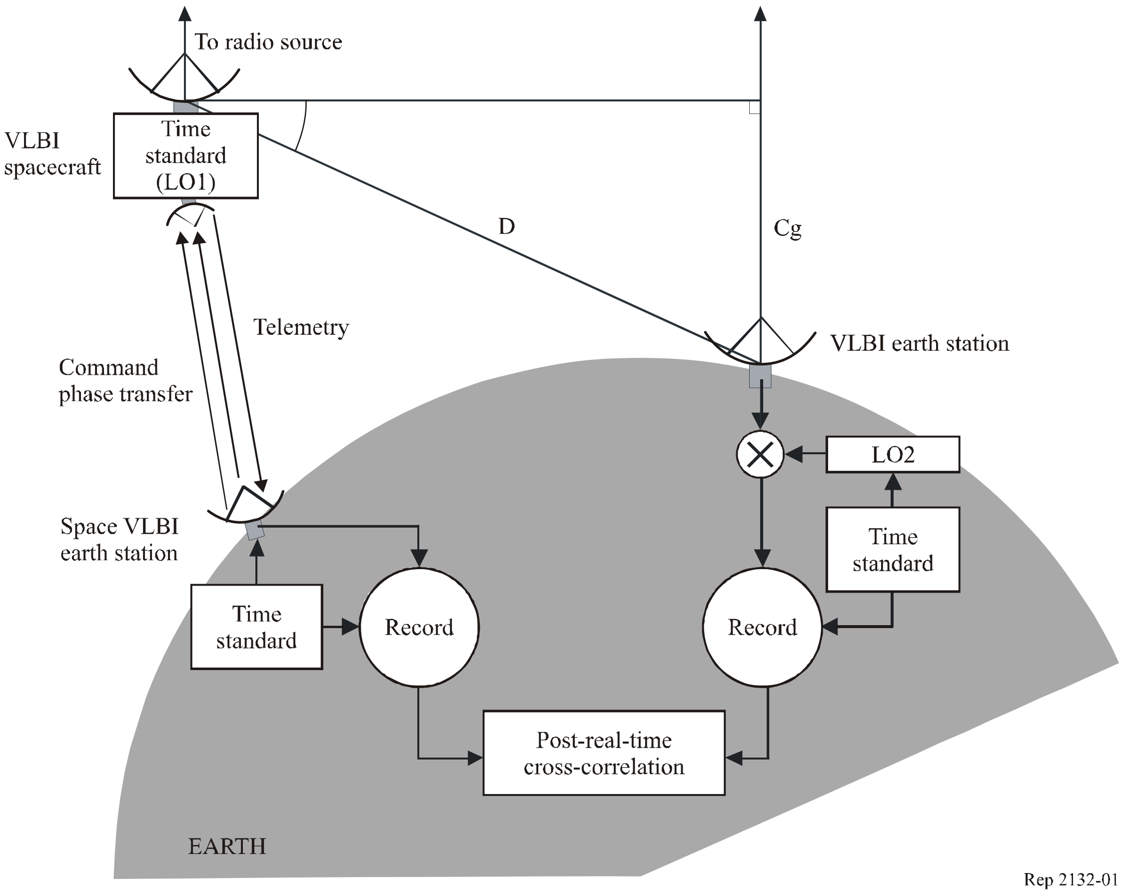
The configuration of a typical SVLBI experiment is shown in Fig. 1.

2.1 Telecommunication links for space VLBI

The telecommunication links of the space VLBI system are represented in Fig. 1 by the four dashed lines between the space VLBI spacecraft telecommunication antenna and the space VLBI earth station. A description of the radio links follows.

FIGURE 1

Outline of a typical space VLBI experiment, in which a spaceborne antenna is used in parallel with one or more VLBI observing stations on the ground



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2.1.1 Earth-to-space (E-s) telecommand link

This radio link is used for reliable transmission of telecommands required for operation and correction of possible spacecraft malfunctions.

2.1.2 E-s phase transfer link for time and frequency synchronization

In VLBI accurate knowledge of the time, the signal frequency, and the signal phase is needed for post-real-time cross-correlation. This requirement is met by using high-stability oscillators, often referred to as “atomic clocks,” at every station and also by utilizing the Global Positioning System (GPS).

At present an Earth-to-space phase-transfer link is used to impart the required time/phase reference to the spacecraft on-board clock and local oscillators. In the future the space VLBI spacecraft may have a space-qualified atomic clock. However, the distant space VLBI station may not be able to utilize the GPS system for time synchronization. Hence, the E-s phase transfer link will still be needed for time synchronization.

2.1.3 Space-to-Earth (s-E) telemetry link for science data

The space VLBI spacecraft observes the radio source over a selected bandwidth. This observed spectrum is transmitted to the space VLBI earth station using this s-E telemetry link for science data for recording and subsequent cross-correlation with the spectrum observed by the VLBI earth stations.

2.1.4 S-E phase transfer link

This radio link will be a coherent frequency translation of the Earth-to-space phase transfer link described above and will be used to calibrate the phase errors introduced in the Earth-to-space phase transfer link by different causes. This radio link may be dedicated to this phase transfer operation or may be combined with the s-E telemetry link for science data to transfer the observed spectra from the spacecraft as described in § 2.1.3.

3 Technical characteristics

A detailed characterization of the space VLBI telemetry link for science data and the phase-transfer link for time and frequency synchronization is given below.

In a space VLBI system, we need to consider two issues: firstly the observing system itself, which is similar to a terrestrial VLBI system except that at least one antenna is moving at a high and varying velocity compared with the rest of the network, and consequently establishing the velocity and position vectors is more complicated. This requires the transfer of timing and frequency standard signals between the ground and the spacecraft. Secondly, the data have to be transferred to the ground receiving station by a telemetry link. There could be quantization effects and also phase scintillation produced by the ionosphere.

The space VLBI spacecraft receives the radio source frequency spectrum contaminated with background and system noise in the observation bandwidth. This observed spectrum is transmitted to the space VLBI earth station where it is recorded and cross-correlated with the frequency spectrum observed at the earth station of the same radio source. The transmission of the observed spectrum from the space station to the earth station may be analogue or digital. In digital transmission, the observed analogue signal is first converted to a digital format and then transmitted to the space VLBI earth station for recording.

The transmission of a telemetry signal through space degrades the signal before it is detected at the earth station receiver. In digital transmissions, this degradation increases the errors in detecting the information bits. These degradations, thus, affect the final cross-correlation process of the space VLBI experiment by lowering the cross-correlation signal-to-noise ratio (SNR).

3.1 Telemetry link

3.1.1 Space VLBI cross correlation function

The basic observables in radio interferometry are the amplitude and relative phase of the cross-correlation of the two observed spectra. This cross-correlation process is usually performed in non-real time and may be expressed as:

$$R_{xy}(\tau_g) = \langle x(t) \cdot y(t - \tau_g) \rangle \qquad (1)$$

where R_{xy} is the cross-correlation function, < > is the estimated mean for the observation over time, $x(t)$ and $y(t)$ are the recorded signals at sites 1 and 2, and τ_g is the wave front time delay.

In the cross-correlation function of equation (1), the pre-recorded signals will be contaminated with noise from the receiving systems. For each receiving station, we can define an observer signal-to-noise ratio (ξ) as:

$$\xi_m = \frac{\frac{1}{2} \cdot S_m \cdot A_m \cdot B}{kT_m \cdot B} = \frac{S_m \cdot A_m}{2kT_m} \qquad m = 1, 2 \tag{2}$$

where:

- S_1: spectral flux density of observed source at antenna 1 (W/(Hz · m^2))
- A_1: effective area of receive antenna 1 (m^2)
- T_1: system noise temperature of receiver 1 (K)
- S_2: spectral flux density of observed source at antenna 2 (W/(Hz · m^2))
- A_2: effective area of receive antenna 2 (m^2)
- T_2: system noise temperature of receiver 2 (K)
- k: Boltzmann's constant (= 1.38 × 10^{-23} W/(Hz · K))
- B: observation bandwidth (Hz).

Note that equation (2) has a factor 1/2, since the spectral flux densities refer to the total emission from the source, which is almost always largely unpolarized, and any practical antenna system can only receive half of this total.

The effective area of a receive antenna can be written as:

$$A_m = \eta_m \pi \frac{D_m^2}{4} \qquad m = 1, 2 \tag{3}$$

where η_m is the aperture efficiency and D_m is the diameter of the antenna (in metres). Using the effective area of the antenna, we can define a system noise equivalent flux density (S^*) for each receiver as:

$$S_m^* = \frac{2kT_m}{A_m} = \frac{8kT_m}{\eta_m \pi D_m^2} \qquad m = 1, 2 \tag{4}$$

Now, using the system noise equivalent flux density for the receivers, we can express the observer signal-to-noise ratios as:

$$\xi_m = \frac{S_m}{2kT_m / A_m} = \frac{S_m}{S_m^*} \qquad m = 1, 2 \tag{5}$$

It has been shown that the cross-correlation signal-to-noise ratio ($X_{1,2}$) may be expressed as a function of the two observing signal-to-noise ratios ξ_1 and ξ_2 as:

$$X_{1,2} = \sqrt{\xi_1 \cdot \xi_2 \cdot 2B\tau} \tag{6}$$

where B is the observation bandwidth and τ is the integration time of each observation. This cross-correlation SNR can also be expressed in terms of the mean flux density $S_{1,2} = \sqrt{S_1 \cdot S_2}$ of the observed source and the system noise equivalent flux densities of the observing stations as:

$$X_{1,2} = S_{1,2} \cdot \sqrt{\frac{2B\tau}{S_1^* \cdot S_2^*}} \tag{7}$$

The cross-correlation SNR should be maintained as large as possible to decrease the measurement error of the τ_g in equation (1).

Note that for this space VLBI system with two elements, if we define the noise flux density threshold (S_{th}) of the cross-correlation as:

$$S_{th} = \sqrt{\frac{S_1^* \cdot S_2^*}{2B\tau}} \tag{8}$$

we can then write the cross-correlation SNR as:

$$X_{1,2} = \frac{S_{1,2}}{S_{th}} \tag{9}$$

This equation does not account for the ionospheric scintillation, that is, for the rapidly fluctuating ionospheric delays. The phase error introduced lowers the amplitude of the cross-correlation of a space VLBI system. Thus, the actual, measured cross-correlation SNR with ionospheric scintillation is more accurately modelled as:

$$X_{1,2} = \frac{g \cdot S_{1,2}}{S_{th}} = \frac{S_{1,2}}{S_0} \tag{10}$$

where g is called the coherence factor and $S_0 = S_{th}/g$ is the effective sensitivity threshold of the space VLBI system. Note that when coherence factor is one, the VLBI sensitivity threshold equals the cross-correlation noise flux density threshold, an ideal situation. Normally coherence factor will be less than one, and the sensitivity threshold will rise above the noise density threshold. The coherence factor used in equation (10) is determined experimentally.

The amount of ionospheric delay fluctuation is represented by an experimentally determined scintillation index. Low scintillation index means less ionospheric delay fluctuation, whereas high scintillation index means a large ionospheric delay fluctuation.

Equation (9) shows that, in order to increase cross-correlation SNR, we need to decrease the space VLBI noise flux density threshold. This we can accomplish by using wider observation bandwidths and longer integration times, and by having stations with lower equivalent flux densities, which in turn means having larger antennas with low system noise temperatures.

3.1.2 Cross-correlation SNR degradation

The space VLBI spacecraft receives the radio source frequency spectrum contaminated with noise (background, system, etc.) in a selected observing bandwidth, B, at a given observing SNR, ONR_1. This observed spectrum has to be transmitted to the space VLBI earth station to be recorded and further processed (cross-correlated). This transmission may be an analogue transmission or the observed analogue signal may be converted to a digital format and transmitted to the space VLBI earth station for recording.

The transmission of a telemetry signal through space implies some signal degradation when detected at the intended receiver. In digital transmissions, this degradation is due to the probability of information bits being in error and is dependent on the received symbol signal-to-noise ratio (SSNR). This link degradation will affect the final process of the space VLBI experiment, i.e. the cross-correlation function of equation (1).

For an analogue telemetry link, the cross-correlation SNR that includes the telemetry link losses is shown to be:

$$X_a = \sqrt{\frac{\xi_{tlm}}{1+\xi_1+\zeta_{tlm}}} \cdot \sqrt{\xi_1 \cdot \xi_2 \cdot 2B\tau} \qquad (11)$$

where ζ_{tlm} is the telemetry-link SNR. The first factor is the cross-correlation SNR degradation for analogue telemetry, i.e.:

$$X_a \text{ degradation (analogue)} = \frac{X_a}{X_{1,2}} = \sqrt{\frac{\zeta_{tlm}}{1+\xi_1+\zeta_{tlm}}} \qquad (12)$$

For the digital telemetry link with 1-bit quantization (see Report ITU-R SA.2065 – Protection of the space VLBI telemetry link), the cross-correlation SNR is written as:

$$X_q = \left[\left(1-\text{Erfc}\sqrt{\xi_{tlm}}\right)^2 \cdot \frac{2}{\pi}\right] \cdot \sqrt{\xi_1 \cdot \xi_2 \cdot 2B\tau} \qquad (13)$$

where ξ_{tlm} is the telemetry link symbol SNR, and Erfc is the complementary error function. The factor in brackets is the cross-correlation SNR degradation for digital telemetry, i.e.:

$$X_d \text{ degradation (digital)} = \frac{X_q}{X_{1,2}} = \left(1-\text{Erfc}\sqrt{\xi_{tlm}}\right)^2 \cdot \frac{2}{\pi} \qquad (14)$$

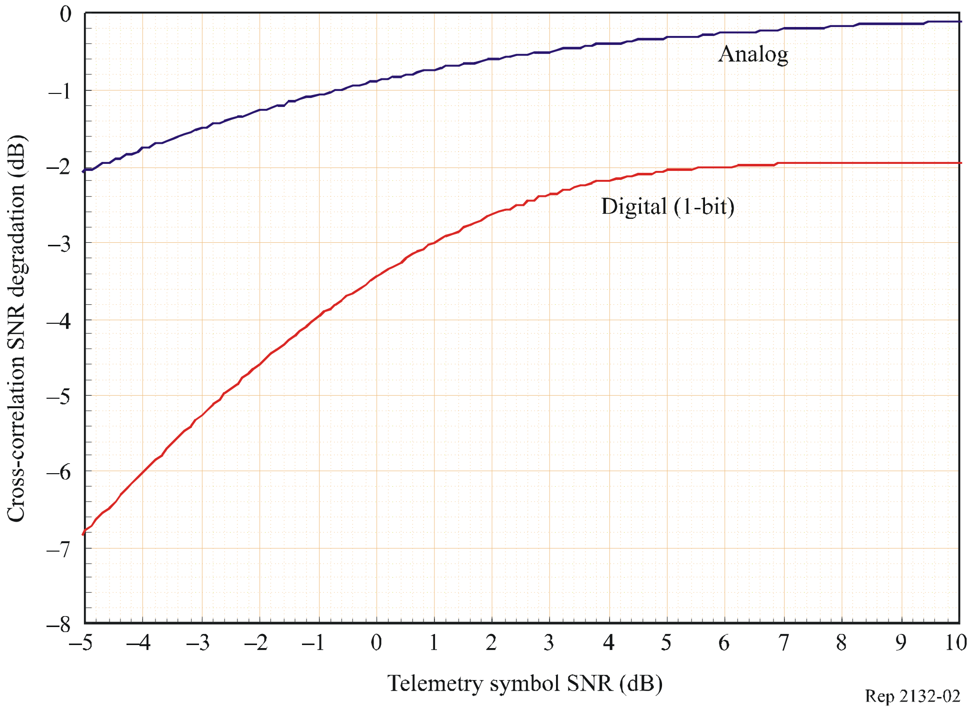
Note the inherent degradation introduced by the quantization of the normally distributed observed source, i.e. when the telemetry symbol SNR (ξ_{tlm}) is large, the cross-correlation SNR degradation approaches to $2/\pi$.

Figure 2 shows the degradation of cross-correlation SNR for analogue and digital telemetry links, when the observer signal signal-to-noise ratio ONR_1 = –20 dB. The analogue and digital cross-correlation SNR degradations are plotted in the same graph by using $SNR_{tlm} = 2 \cdot SSNR_{tlm}$.

In Fig. 2, the curve for digital telemetry transmission clearly shows an inherent degradation of the cross-correlation SNR introduced by the quantization of the noise signal the observed source; i.e., even with a very high telemetry symbol SNR, the cross-correlation SNR degradation approaches to –1.96 dB (=10 log(2/π)).

FIGURE 2

Cross-correlation SNR degradation vs. telemetry symbol SNR for analogue and digital telemetry links



3.1.3 Required interference criterion for the telemetry link

Since the interference in the space VLBI telemetry link causes data errors and hence degrades the SNR of the final VLBI cross-correlation, an interference criterion has to be specified. The degradation of the cross-correlation SNR caused by the thermal noise and external interference in the space VLBI telemetry link is analyzed in detail in Report ITU-R SA.2065 for the 37-38 GHz band. The tolerable interference level is recommended to be 0.02 dB degradation in the cross-correlation SNR. For the 37-38 GHz band, the results indicate that, for a cross-correlation SNR degradation tolerable to the VLBI measurement, the interference power received from any interfering system should not exceed –135.5 dB(W) per GHz at the input of the low-noise amplifier of an SRS earth station. In addition, Recommendation ITU-R RA.1513 – Levels of data loss to radio astronomy observations and percentage-of-time criteria resulting from degradation by interference for frequency bands allocated to the radio astronomy on a primary basis, presents data loss criterion for the VLBI observations to be no more than 2% of the time per interfering system, and no more than 5% of the time from all interfering systems.

For the 25.5-27 GHz band, since the system noise temperatures are comparable with the 37-38 GHz band, the interference received in any 1-GHz band should not exceed –135.5 dB(W) for more than 2% of the time.

For the 74-84 GHz band, the interference criterion will have to be determined depending on the system noise temperatures in this band.

3.1.4 Required bandwidths for the telemetry channel

Phase modulation has been shown to attain optimum performance on satellite telecommunications links. Therefore binary phase shift keying (BPSK) or quadri-phase shift keying (QPSK) will be considered as the preferred digital modulation schemes.

When digitizing the observation bandwidth of *B* Hz, the required Nyquist sampling rate will be twice the bandwidth or *2B* samples per second. Each observed voltage sample is quantized either at two levels (1-bit representation), four levels (2-bit representation), eight levels (3-bit representation), etc. The total telemetering channel symbol rate, R_s, required will therefore follow the equation:

$$R_s = 2B \cdot \log_2(L) = 2Bn \tag{15}$$

where *L* is the total number of quantization levels and *n* is the number of bits.

The radio-frequency bandwidth (*W*) required for the transmission of BPSK with telemetry losses less than 0.3 dB has been recommended (see Recommendation ITU-R SA.1015 – Bandwidth requirements for deep-space research) to be:

$$W = 4R_s = 8Bn \tag{16}$$

If QPSK is used, the same bandwidth can accommodate twice the symbol rate with approximately the same performance as the BPSK case, or for the same symbol rate the required bandwidth is half the bandwidth for BPSK.

Table 1 is a summary of the above considerations and shows the required radio-frequency (RF) bandwidths as a function of observation bandwidth, *B*. Note that smaller bandwidths than those recommended may be used with a reduced link performance (smaller data rate).

TABLE 1

Required radio-frequency (RF) bandwidth

Observation bandwidth	Hz	*B*		
Analogue telemetry bandwidth	Hz	$\geq 2B$		
Digital telemetry				
Sampling rate	samples/s	2*B*		
Number of bits/sample		1	2	3
Quantization levels		2	4	8
Symbol rate	sym/s	2*B*	4*B*	6*B*
BPSK bandwidth	Hz	8*B*	16*B*	24*B*
QPSK bandwidth	Hz	4*B*	8*B*	12*B*

3.1.5 Preferred space-to-Earth telemetry carrier frequencies

One old and one planned space VLBI system require a maximum RF transmission bandwidth of less than 500 MHz. These systems would require high carrier frequencies with enough allocated bandwidth. In this respect, the SRS 8.4-8.45 GHz band is not suitable since it does not have enough bandwidth allocation. Future RF bandwidth requirements (1 GHz to 10 GHz), however, indicate the need for carrier frequencies larger than 20 GHz.

3.2 Phase-transfer link

The phase transfer link is used to derive a stable on-board frequency reference from a clock on the ground. The frequency of the on-board reference must be precisely known to support science data processing.

A prime requirement for an on-board local oscillator of a space VLBI spacecraft is that its frequency/phase stability be nearly as good as that of a VLBI earth station's local oscillator driven by the atomic standard. No space-qualified atomic standard exists today; therefore, the required stability will be transferred to the space VLBI spacecraft via an Earth-to-space radio link. The carrier frequency of this radio link, f_{up}, is recovered at the spacecraft to generate the on-board reference frequencies to be used in the radio source observing process. In order to calibrate all the unknown phase errors introduced in this Earth-to-space phase-transfer radio link, this carrier frequency is coherently down-converted and transmitted back to the space VLBI earth station, f_{down}. In this two-way phase calibration, phase errors are mainly introduced by the propagation medium, spacecraft receiver, and space VLBI earth station receiver. These phase errors will contribute to the uncertainty in the determination of the amplitude and relative phase of the non-real-time cross-correlation process of equation (1) effectively lowering the cross-correlation SNR of equation (6).

3.2.1 Phase noise introduced in propagation

There are three primary sources of error in determining the on-board frequency:

– error in the model value of the uplink Doppler shift due to spacecraft orbit uncertainty,

– unmodelled uplink path delay changes due to troposphere, and

– unmodelled uplink path delay changes due to ionosphere.

To calibrate these errors the round-trip phase is measured and used to derive an estimate of the uplink phase error. At the beginning of the analysis, it is assumed that errors are reciprocal, meaning that the uplink and downlink delay errors are the same.

The phase, φ_{up}, of the on-board reference frequency, f_{up}, is retrieved from the measured round-trip phase, φ_{round}, measured on the ground station through the equation (17):

$$\varphi_{up} = \frac{f_{up}}{2 \cdot f_{down}} \varphi_{round} \tag{17}$$

Equation (17) gives an accurate value of the uplink phase error assuming that all error sources are non-dispersive and reciprocal. The spacecraft orbit uncertainty and the tropospheric path delay are non-dispersive and nearly reciprocal, so the equation (17) does a good job calibrating these error sources. However, the ionospheric path delay change is dispersive, so an error is made when using this formula when the transponder turnaround ratio, f_{down}/f_{up}, is not equal to unity. If the transponder turnaround ratio is nearly equal to unity, then the equation (17) also does a good job of calibrating the ionosphere.

There exists frequency dependent path delay, τ_i, in the propagation of an electromagnetic wave through the ionosphere. Therefore, equation (17) should be modified to:

$$\varphi_{up} = \frac{f_{up}}{2 \cdot f_{down}} \varphi_{round} + f_{up} \cdot \pi \cdot \left[\tau_i(f_{up}) - \tau_i(f_{down})\right] \tag{18}$$

where:

$$\tau_i(f) = \frac{40.3}{c \cdot f^2} TEC_i \qquad \text{s} \tag{19}$$

c: velocity of light (m/s)

f: propagation frequency (Hz)

TEC_i: total electron content (electrons/m^2).

Now the phase error can be written as:

$$\varphi_{error} = \varphi_{up} - \frac{f_{up}}{2 \cdot f_{down}} \varphi_{round} = f_{up} \cdot \pi \cdot \left[\tau_i(f_{up}) - \tau_i(f_{down}) \right] \tag{20}$$

This phase error is due to the frequency dependent ionospheric delay. Unless additional information about the total electron content (TEC_i) in the ionosphere is provided, a proper correction for this error cannot be made. Nevertheless, this error becomes smaller if frequencies of both f_{up} and f_{down} are made higher and closer to each other.

Table 2 gives the calculated results of the ionospheric time delay error in units of picoseconds (psec) for two frequency pairs (7.2-8.46 GHz and 15.3-14.2 GHz). A total electron content of 8×10^{17} electrons/m^2 has been assumed. It is clear that the phase transfer errors at higher frequencies is much smaller than at lower frequencies.

TABLE 2

Ionospheric propagation effects

Link frequencies			
f_{up}	GHz	7.2	15.3
f_{down}	GHz	8.46	14.2
Period	psec	125	67
Absolute value of ionospheric error (TEC = 8×10^{17} electrons/m^2)	psec	286	37

Note that in these cases, the phase error introduced due to ionosphere is more than twice the wavelength of the lower frequency pair (7.2 GHz, 8.46 GHz), but only about half the wavelength of the higher frequency pair (15.3 GHz, 14.2 GHz).

The contribution of the ionospheric delay to the phase of the received signal is inversely proportional to the frequency used. Therefore, the phase fluctuation induced by the ionosphere is approximately twice as low at the (15.3 GHz, 14.2 GHz) bands than at the (7.2 GHz, 8.46 GHz) bands. Thus, the expected coherency losses due to ionosphere are lower at the higher frequencies.

3.2.2 Phase noise introduced in carrier recovery

At the space VLBI spacecraft receiver of the Earth-to-space radio link as well as at the space VLBI earth station's receiver, the carrier recovery process considered may be the result of any combination of the following modulation schemes: an unmodulated carrier, or a binary phase shift keying (BPSK), or a quadri-phase modulation (QPSK).

It has been shown that the phase error variance, σ^2, for carrier recovery processes may be expressed as a function of the phase lock loop receiver closed-loop bandwidth (B_L), one-sided noise spectral density (N_0), and carrier power (P). For unmodulated carrier, the phase error variance is:

$$\sigma^2 = \frac{B_L N_0}{P} \tag{21}$$

For BPSK modulation, it is given as:

$$\sigma^2 = \frac{B_L N_0}{P}\left(1 + \frac{0.5}{SSNR}\right) \tag{22}$$

where P is the suppressed-carrier power and $SSNR$ is the symbol signal-to-noise ratio, i.e. $SSNR = PT_s / N_0$ with T_s being the symbol period. For QPSK modulation, the phase error variance is given as:

$$\sigma^2 = \frac{B_L N_0}{P}\left(1 + \frac{2.25}{SSNR} + \frac{1.5}{SSNR^2} + \frac{0.1875}{SSNR^3}\right) \tag{23}$$

where $SSNR$ is the binary symbol SNR, i.e. $SSNR = PT_b / N_0$ with T_b being the binary symbol period. Note that quaternary symbol period $T_s = 2T_b$. For very strong SSNR, the three cases converge to:

$$\sigma^2 = \frac{B_L N_0}{P} \tag{24}$$

It is clear that to reduce the phase noise introduced in carrier recovery, narrower loop bandwidth, lower system noise density, and higher signal power are needed.

4 Preferred frequency bands and bandwidths within the space research service (SRS) allocated bands

The list of frequency bands given in Table 3 is intended to identify those frequency ranges that are preferred for the operation of the science data telemetry and phase-transfer links with minimum degradation in the space VLBI measurements. The use of these frequency bands for space VLBI systems, however, is also guided by frequency sharing considerations, technical equipment limitations, and necessary bandwidth. The RF bandwidths indicated could be assigned anywhere within the frequency band and could be increased without exceeding the frequency band limits. Also, the number of such RF links could be increased to make use of the allocated frequency band to support any single or multi-spacecraft system.

TABLE 3

Preferred frequency bands and bandwidths for space VLBI within the space research service (SRS) allocated bands

		Frequency band	**RF bandwidth**
Direction	**Typical use**	**GHz**	**MHz**
space-to-Earth	Phase transfer	8.45-8.5	0.1
	Telemetry and phase transfer	14-14.3	300
		14.5–15.35	300-500
		25.5–27	1 000
		37-38	1 000
		74-84	10 000
Earth-to-space	Phase transfer and command	7.190-7.235	0.1-2
		15.20-15.35	0.1-2
		40-40.5	0.1-2

5 Characteristics of existing and planned space VLBI systems

Existing and planned space VLBI systems are shown in Table 4. VSOP systems typically use data rates in the order of 128 Mbit/s and QPSK modulation. The Radioastron will use a data rate of 144 Mbit/s with QPSK modulation. The maximum RF bandwidth required would therefore be in the order of 128 MHz for VSOP and 144 MHz for Radioastron. For VSOP-2 the symbol rate will be about 1 GSymbol/s, which will require RF bandwidths greater than 1 GHz. Theoretical studies of propagation effects on wide bandwidth transmissions have indicated that the atmosphere can support several gigahertz of bandwidth at carrier frequencies above 10 GHz. Therefore, transmission bandwidths in the order of 3 GHz to 4 GHz may very well be envisioned in future space VLBI systems.

TABLE 4

Characteristics of existing and planned space VLBI systems

Parameter		**Radioastron**	**VSOP**	**ASTRO-G (VSOP-2)**	**IVS**
Observing antenna diameter	M	10	8	9	20
Observing frequency and system temperature	GHz; K	0.3; 90 1.6; 60 5.0; 70 22.0; 135	1.6; 40 5.0; 60 20; 110 ---	8.0-8.8; 30 20.6-22.6; 30 41.0-45.0; 40 ---	4.5; 8.5 15; 23 42; 63 86; 120
Nominal integration time	s	300	300	300	---
Space-to-Earth					
Frequency	GHz	14.8-15.25 8.4 (phase transfer only)*	14-14.3 14.3-15.35	37-38	---
Transmitting power	W			8.5	
Modulation type		QPSK	QPSK	QPSK	---
Maximum bit rate	Mbit/s	144	128	1 000	---
Quantization levels		2	2, 4	2, 4	---
RF bandwidth	MHz	144	128	1 000	---
Minimum E_b/N_0	dB	11.2	9.1	9.1	---
Telemetry link interference criteria		Received interference power ≤ –135.5 dB(W) in any 1-GHz band (not to be exceeded by more than 2% of the time)			
Earth-to-space (phase transfer)					
Frequency	GHz	7.207	15.25-15.35	40.288	---
Modulation type		None	None	None	---
Maximum bit rate	Mbit/s	---	---	---	---
RF bandwidth	MHz	50	100	500	---
PLL bandwidth	Hz	1 000	1 000	1 000	---
Minimum E_b/N_0	dB	63	60	60	---

TABLE 4 (*end*)

Parameter		**Radioastron**	**VSOP**	**ASTRO-G (VSOP-2)**	**IVS**
Orbital characteristics					
Inclination	degrees	0-90	31	31	63
Height at perigee	km	1 000-70 000	560	1 000	5 000
Height at apogee	km	310 000- 390 000	21 300	25 000	150 000
Period	h	228	6.3	7.5	67.14

NOTE 1 – Radioastron will continue to use the frequency 8.4 GHz for phase transfer under existing ITU-R publication API/A/3957.

Table 4 above summarizes the salient radio link and orbital characteristics of the current and planned space VLBI systems. The space VLBI spacecraft for the VLBI Space Observatory Project (VSOP, Japan) was launched in 1997. The VSOP-2 and the International VLBI Satellite (IVS) systems are being considered as the next generation space VLBI missions.

6 Characteristics of earth stations

In space VLBI systems many telemetry receiving stations around the Earth are used; for example the Deep Space Network Orbiting VLBI Subnet (United States). The main characteristics of these earth stations are summarized in Table 5.

TABLE 5

Summary of space VLBI earth station characteristics

Parameter		**Frequency bands**		
Receive frequency band	GHz		14.0-14.3 14.5-15.35	37-38
–1 dB receive bandwidths	MHz		500	1 000
Receive zenith *G*/*T*	dBi/K		37.3	56.9
Transmit frequency band	GHz	7.190-7.235	15.20-15.35	40-40.5
Transmit antenna gain	dBi	54.7	61.0	78.6
Transmit power levels	W	5	0.5	5
–1 dB transmit bandwidths	MHz	50	100	500
Receive or transmit polarizations		RHCP or LHCP	RHCP or LHCP	RHCP or LHCP
Telemetry receiver capability	Mbit/s	144	144	1 000
Antenna diameter	m	11	11	34