RECOMMENDATION ITU-R SA.1344

PREFERRED FREQUENCY BANDS AND BANDWIDTHS FOR THE TRANSMISSION OF SPACE VLBI DATA

(Question ITU-R 203/7)

(1998)

The ITU Radiocommunication Assembly,

considering

a) that the angular resolution of measurements made by very long baseline interferometry (VLBI) techniques is limited by the distance between two observing stations;

b) that, compared to the largest possible distance between two observing stations on Earth, this baseline distance may be substantially increased by locating one or more of the observing stations in space;

c) that by conducting VLBI measurements which utilize spacecraft, it is possible to eliminate the limitations of ground-based observations caused by the absorption, path length fluctuations and noise contributions by the atmosphere;

d) that space VLBI will provide knowledge of physical parameters leading to accurate determination of *inter alia*:

– radio sources structure;

– deep-space navigation;

– geodynamics;

– astrometry;

– satellite orbital parameters;

e) that the transmission of wideband space VLBI data from space-to-Earth is required and the general characteristics are described in the annex;

f) that space VLBI systems require the transmission of highly accurate time/phase reference signals from Earth-to-space and space-to-Earth with general characteristics described in Annex 1,

recommends

1 that preferred frequency bands for transmission of telemetry data and time/phase reference signals in the space-to-Earth direction are shown in Table 1 below;

2 that preferred frequency bands for the transmission of telecommand data and time/phase reference signals in the Earth-to-space direction are shown in the table below:

TABLE 1

Preferred frequency bands and bandwidths for telecommand, telemetry and phase transfer services for space VLBI

Frequency band (GHz)	Direction	Typical use	Typical RF bandwidth (MHz)
8.025 - 8.5	space-to-Earth	telemetry/phase transfer	50
7.145 - 7.235	Earth-to-space	phase transfer/command	0.1 - 2
14 - 14.3; 14.5 - 15.35	space-to-Earth	telemetry/phase transfer	300 - 500
15.25 - 15.35	Earth-to-space	phase transfer/command	0.1 - 2
37 - 38	space-to-Earth	telemetry/phase transfer	1 000
40 - 40.5	Earth-to-space	phase transfer/command	0.1 - 2
74 - 84	space-to-Earth	telemetry/phase transfer	4 000

ANNEX 1

Space VLBI telecommunication characteristics

1 Introduction

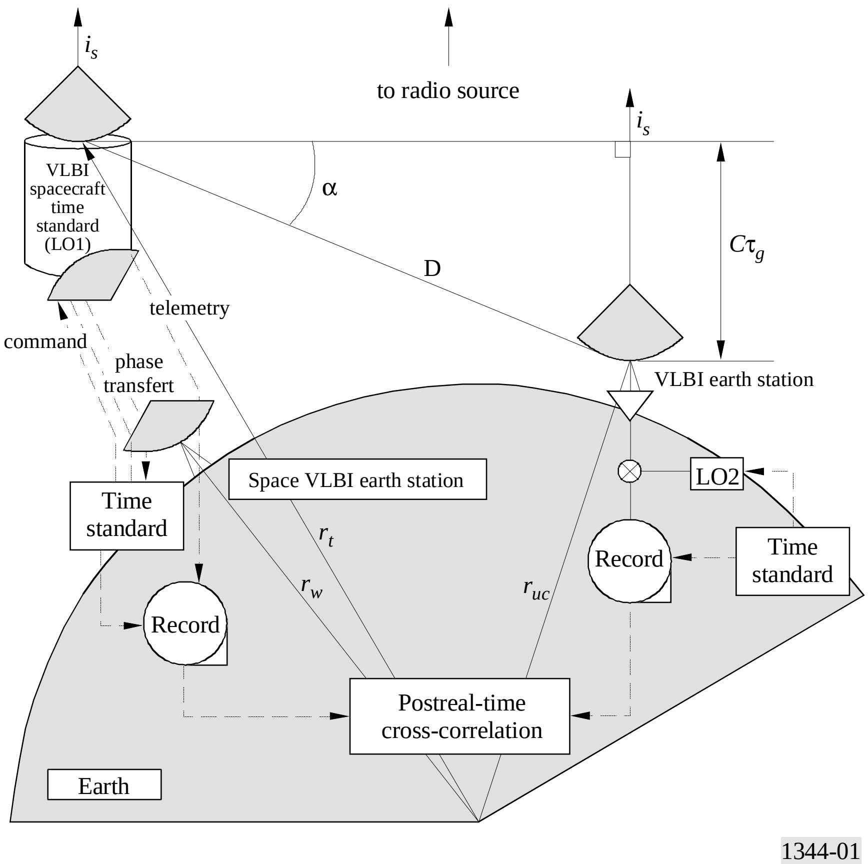
Very long baseline interferometry (VLBI) is a technique which allows experimenters to achieve angular resolution of observed radio sources that cannot be approached by other radio or optical methods. VLBI has a wide variety of scientific and engineering uses. Observation of distant radio sources with two or more VLBI stations are combined to determine the structure of extra-galactic radio sources, determine geodynamical characteristics of the Earth, study of the Moon's libration and tidal response, determine orientation of the solar system with respect to the extra-galactic inertial frame, determine vector separation between antenna sites and to provide navigation and tracking of spacecraft.

2 Technical characteristics

The operating approach of the most simple VLBI system, composed of two VLBI earth stations, may be summarized as follows: the VLBI earth antennas will point to the radio source, common to both antennas for the planned experiment. Because of engineering limitations the resulting observed frequency spectrum is usually translated down to a lower frequency. The amplitude and phase characteristics of this observed spectrum is maintained by using a highly stable reference frequency (local oscillator, LO). The observed spectrum at each antenna is recorded independently in some supported medium (i.e., magnetic tape). In the case of space VLBI, one of the antennas used for the radio source observation is space-borne and the down-converted spectrum is transmitted to and recorded at a space VLBI earth station (Fig. 1).

FIGURE 1

Space VLBI geometry



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:

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

where:

R_{xy} = cross-correlation function

< > = estimated mean for the observation time

x(t) = recorded signal at site 1

y(t) = recorded signal at site 2

τ_g = 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. It has been shown that the cross-correlation signal-to-noise ratio (SNR_{cros}) may be expressed as a function of the two observing signal-to-noise ratios SNR_{obs1} and SNR_{obs2} as:

$$SNR_{cros} = (SNR_{obs1}SNR_{obs2}BT)^{1/2} \qquad (2)$$

where B is the observing bandwidth and T is the integration time of each observation. The SNR_{cros} should be maintained as large as possible to decrease the error in the τ_g measurement in equation (1).

The sensitivity (signal-to-noise ratio = 1) of this two-element VLBI interferometer may be determined by:

$$S_d = 4(2)^{1/2}10^{26}k(T_1T_2)^{1/2}(\pi g D_1 D_2)^{-1}(\eta_1\eta_2)^{-1/2}(BT)^{-1/2}, \text{ (Janskys)} \qquad (3)$$

where:

1Jansky = $1 Wm^{-2} Hz^{-1}$

k = Boltzmann’s constant = 1,38 x 10^{-23} ($WK^{-1} Hz^{-1}$)

T_1, T_2 = system temperatures

D_1, D_2 = antenna diameters

η_1, η_2 = antenna aperture efficiencies

g = coherence of the VLBI system

T = integration time

B = noise bandwidth.

This is equivalent to the root-mean-square (r.m.s.) noise divided by the coherence, g.

In VLBI a “quasi-common” time reference frame at both observing stations is essential because of the need for precise knowledge of the signal frequency down-converted by the local oscillators (LO) as well as its phase. Also, precise time information is needed for the post-real-time cross-correlation. These requirements are met with high-stability oscillators often referred to as “atomic clocks”. It is desired to provide the space VLBI spacecraft with a space-qualified atomic clock in the future. For the time being, an Earth-to-space phase transfer radio link will be needed to impart the required timing or phase reference to the spacecraft on-board clock.

2.1 Telecommunication links for space VLBI

The telecommunication radio links to be considered in a space VLBI system have been 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.

2.1.1 E-S (Earth-to-space) telecommand radio link

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

2.1.2 E-S phase transfer radio link

The main use of this link will be for translation to the spacecraft of the phase and frequency stability of the atomic clock located at the space VLBI earth station. This high stability is needed for the duration of the observation time and should be of the same order of magnitude as the one in the atomic clock at the space VLBI earth station.

2.1.3 S-E (space-to-Earth) telemetering radio link

The space VLBI spacecraft observes the radio source over a selected bandwidth. This observed spectrum is transmitted to the space VLBI earth station for recording and future cross-correlation with the observed spectrum from one or more VLBI earth stations.

2.1.4 S-E phase transfer radio link

This radio link will be a coherent frequency translation of the Earth-to-space phase transfer radio link described above and will be used to calibrate the phase errors introduced in the Earth-to-space phase transfer radio link by different causes. This radio link may be dedicated to this phase transfer operation or may simultaneously be used to transfer the observing spectra from the spacecraft as described in § 2.1.3.

2.2 Telemetering link characterization

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, SNR_{obs1}. 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.

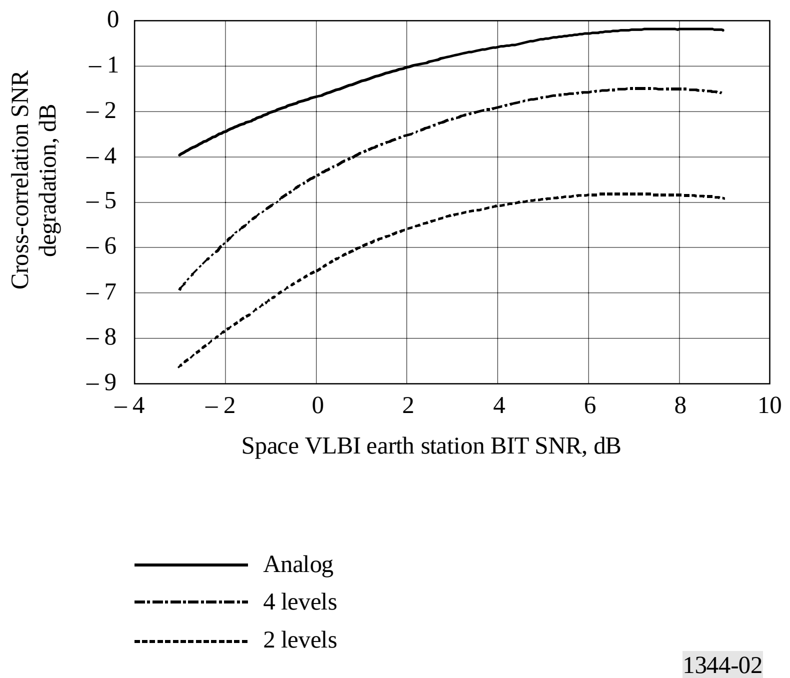
The transmission through space of a telemetry signal implies some signal degradation when detected at the intended receiver. In digital transmissions this degradation is due to the probability of information bits being in error and is dependent on the received symbol signal-to-noise ratio (SSNR). This link degradation will affect the final process of the space VLBI experiment, i.e. the cross-correlation function of equation (1). Degradation results for an analogue SNR cross-correlation of -24 dB when the same observed normally distributed signal ($SNR_{obs1} = SNR_{obs2}$) is received by the VLBI earth station with no errors and by the space VLBI earth station with the shown SSNR, are shown in Fig. 2. Results for analogue, 1-bit and 2-bit binary representations have been included. Note the inherent degradation introduced by the digital conversion. This degradation is a function of the quantization levels utilized in the analogue-to-digital conversion of the normally distributed observed source.

2.2.1 Required telemetering channel bandwidth

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.

FIGURE 2

Cross-correlation SNR degradation as a function of binary representation and telemetry SNR.



When digitizing that observing 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 required will therefore follow the equation:

$$SR = 2B\log_2(L) \tag{4}$$

where:

SR = total data rate (symbols/s)

B = observed bandwidth (Hz)

L = total number of quantization levels.

The radio-frequency bandwidth, BW, required for the transmission of BPSK (telemetry losses less than 0.3 dB) has been recommended to be (Recommendation ITU-R SA.1015, "Bandwidth Requirements for Deep-Space Research").

$$BW = 5\ SR \tag{5}$$

If QPSK is used, the same bandwidth can accommodate twice the symbol rate with approximately the same performance as the BPSK case. Table 2 is a summary of all the above considerations, showing the required radio-frequency (RF) bandwidths as a function of observation bandwidth, B. Note that smaller bandwidths than those recommended may be used at a cost of link performance.

Planned space VLBI systems (see Table 3) typically use data rates in the order of 72 mega-symbols/s and QPSK modulation. The maximum RF bandwidth required would therefore be in the order of 360 MHz (from Table 2). 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 - 4 GHz may very well be envisioned in future space VLBI systems.

TABLE 2

Required radio-frequency (RF) bandwidth

Signal presentation	Quantization levels	Bits, number	Symbol rate, symbols/s	RF bandwidth, Hz		
				Analogue	QPSK	BPSK
Analogue	---	---	---	2B (minimum)	---	---
[0,1]	2	1	2B	---	10B	5B
[00,01,10,11]	4	2	4B	---	20B	10B
[000,001,010,011,100,101,110,111]	8	3	6B	---	30B	15B

TABLE 3

Characteristics of planned space VLBI systems

Parameter	Radioastron	VSOP	IVS
Observing antenna diameter, m	10	10	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 ---	4.5; 8.5 15; 23 42; 63 86; 120
Nominal integration time, sec	300	300	---
Space-to-Earth			
Frequency, GHz	14.8 - 15.25	14 - 15.35	---
Modulation type	QPSK	QPSK	---
Maximum bit rate, MB/s	144	128	---
Quantization levels	2, 4	2, 4	---
RF bandwidth, MHz	500	500	---
Minimum Eb/No, dB	11.2	9.1	---
Earth-to-space (phase transfer)			
Frequency, GHz	7.145 - 7.235	15.25 - 15.35	---
Modulation type	None	None	---
Maximum bit rate, MB/s	---	---	---
RF bandwidth, MHz	50	100	---
PLL bandwidth, Hz	1 000	1 000	---
Minimum Eb/No, dB	63	60	---
Orbital characteristics			
Inclination, degrees	51.5 - 65.0	31	63
Height at perigee, km	2 000	1 000	5 000
Height at apogee, km	78 980	20 000	150 000
Period, hr	28	6.06	67.14

2.2.2 Required space-to-Earth telemetering carrier frequencies

Planned space VLBI systems with maximum RF transmission bandwidth requirements of less than†500 MHz will be very well allocated at carrier frequencies larger than 3 GHz. Future RF bandwidth requirements (4 GHz) indicate the need of carrier frequencies larger than 20 GHz.

2.3 Phase transfer link characterization

A prime requirement for an on-board clock of a space VLBI spacecraft is that its frequency/phase stability be nearly as good as that of a VLBI earth station's atomic clock. No space qualified atomic clocks exist 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 transfer system, phase errors are mainly introduced by the propagation medium and the receiving systems (spacecraft and space VLBI earth station). 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 SNR_{cros} of equation (2).

2.3.1 Radio-frequency propagation induced phase noise

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 following equation:

$$\phi_{up} = [f_{up}/(f_{up}+f_{down})]\,\phi_{round} \tag{6}$$

There exists frequency dependent path delay, τ_i, in the propagation of an electromagnetic wave through the ionosphere. Therefore, equation (6) should be modified to:

$$\phi_{up}= [f_{up}/(f_{up}+f_{down})]\phi_{round} + 2\pi\, [f_{up}f_{down}/(f_{up}+f_{down})][\tau_i(f_{up})-\tau_i(f_{down})] \tag{7}$$

where:

$\tau_i(f)$ = $[40.3/(cf^2)]TEC_i$, (sec)

with:

c = velocity of light (m s^{-1})

f = propagation frequency (Hz)

TEC_i = total electron content (electrons m^{-2}).

The second term in the right side of equation (7) is an error term due to a 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 4 gives the calculated results of this error in units of picosecond (psec) time delay, i.e. $\phi_{up}/(2\pi f_{up})$, for two frequency pairs (7.2-8.46 GHz, and 15.3-14.2 GHz). A total electron content of 8 x 10^{17} electrons m^{-2} has been assumed.

From Table 4 it is concluded that the phase transfer at higher frequencies is much better than at lower frequencies. Note that in this particular case the lower frequency phase error introduced is about a wave length of the highest observing band planned in VSOP (VLBI Space Observatory Project) and Radioastron (22 GHz with a period of 45.4 psec). If the ionospheric delay fluctuates rapidly (ionospheric scintillation) the phase error introduced cannot be removed in the post-real-time cross-correlation process. The optimum coherence factor of 1.0 is reduced. Note that at the higher pair of frequencies shown, almost optimum coherency is kept even for a scintillation index of†0.5. For the lower band coherency is almost completely lost. The coherence factor is inversely proportional to the sensitivity equation (3) of the interferometer. When the coherence factor is 1 the sensitivity is equal to the root-mean-square noise. When the coherence factor is below 1 the sensitivity rises above the root-mean-square noise, a non-ideal situation.

TABLE 4

Ionospheric propagation effects

Link frequencies, GHz		Absolute value of ionospheric error, PS-picosec (for TEC = 8×10^{17} electrons/m^2)	Coherence factor scintillation index, S	
F_{up}	F_{down}		S=0.1	S=0.5
7.2	8.46	308.8	0.867	0.028
15.3	14.2	35.2	0.998	0.954

2.3.2 Carrier recovery phase noise

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 for carrier recovery processes, σ^2_{rcvr}, may be expressed as a function of the symbol signal-to-noise ratio (SSNR), the phase lock loop receiver closed-loop bandwidth, B_l, and the symbol period, T_s, as:

$$\sigma^2_{rcvr}/(B_l T_s) = 1/SSNR \quad (8)$$

for unmodulated carrier, as:

$$\sigma^2_{rcvr}/(B_l T_s) = 1/SSNR + 1/SSNR^2 \quad (9)$$

for BPSK modulation, and as:

$$\sigma^2_{rcvr}/(B_l T_s) = 1/SSNR + 9/(2\ SSNR^2) + 6/SSNR^3 + 3/(2\ SSNR^4) \quad (10)$$

for QPSK modulation. For very strong SSNR the three cases converge to 1/SSNR.

2.3.3 Required phase transfer-link frequencies

In choosing the phase transfer-frequencies it seems that the most important consideration should be given to the ionospheric propagation effects. Therefore frequencies around 14 GHz or higher are the most suitable for phase transfers for space VLBI missions. Also, the uplink and downlink frequencies should be kept as close as possible.

2.4 Space VLBI system characteristics

Table 3 is a summary of the salient radio link and orbital characteristics of the Radioastron (Russia) and the VLBI Space Observatory Project (Japan). These are space VLBI spacecrafts to be launched in 1997. Many telemetry receiving stations spread around the Earth will be used. An example of these is the Deep Space Network Orbiting VLBI Subnet (United States) with main characteristics summarized in Table 5. A next generation space VLBI mission being considered, the International VLBI Satellite (IVS), has also been included in Table 3.

TABLE 5

Summary of space VLBI earth station characteristics

Parameter	X-band	Ku-band
Receive frequency tuning, GHz	8.025 - 8.5	14.0 - 15.35
-1 dB receive bandwidths, MHz	50	500
Receive zenith G/T, dBi/K	33.7	37.3
Transmit frequency tuning, GHz	7.145 - 7.235	15.25 - 15.35
Transmit antenna gain, dBi	54.7	61.0
Transmit power levels, W	5	0.5
-1 dB transmit bandwidths, MHz	50	100
Receive or transmit polarizations	RHCP or LHCP	RHCP or LHCP
Telemetry receiver capability, MB/s	144	144
Antenna diameter, m	11	11

3 Preferred frequency bands and bandwidths

The list of frequency bands given in Table 6 is intended to identify those frequency ranges which are preferred from a technical standpoint. Exclusion of other frequencies from the table does not necessarily preclude operations in these bands where frequency sharing considerations and state-of-the-art equipment limitations dictate their use.

The single spacecraft typical radio-frequency (RF) bandwidths included in Table 6 are not intended to indicate the frequency band in which the individual link may be required to operate nor to limit the numbers of such links that may be required to support any single or multi-spacecraft system.

TABLE 6

Preferred frequency bands and bandwidths for space VLBI

Frequency band (GHz)	Direction	Typical use	Typical RF bandwidth (MHz)
8.025 - 8.5	space-to-Earth	telemetry/phase transfer	50
7.145 - 7.235	Earth-to-space	phase transfer/command	0.1 - 2
14 - 14.3; 14.5 - 15.35	space-to-Earth	telemetry/phase transfer	300 - 500
15.25 - 15.35	Earth-to-space	phase transfer/command	0.1-2
37 - 38	space-to-Earth	telemetry/phase transfer	1 000
40 - 40.5	Earth-to-space	phase transfer/command	0.1-2
74 - 84	space-to-Earth	telemetry/phase transfer	4 000