RECOMMENDATION ITU-R S.1716*

Performance and availability objectives for fixed-satellite service telemetry, tracking and command systems

(Question ITU-R 262/4)

(2005)

Scope

This Recommendation resulted from multi-year studies within Radiocommunication Working Party 4B and provides guidance to the designers of fixed-satellite service systems on the technical and operational aspects of telemetry, tracking and command systems.

The ITU Radiocommunication Assembly,

considering

a) that all FSS satellites have telemetry, tracking and command (TT&C) requirements;

b) that TT&C operations are carried out on FSS satellites while in transfer orbit and for on-station operation on the geostationary-satellite orbit (GSO);

c) that TT&C signal information originate and terminate under satellite operator control;

d) that TT&C carriers need higher performance reliability objectives than normal traffic carriers;

e) that loss of the uplink command carriers to the satellite and downlink telemetry and ranging carriers during orbital maneuvers or during solar eclipse periods could result in the loss of a satellite;

f) that some satellites with service links in bands above 17 GHz may also operate service links in bands below 17 GHz;

g) that some GSO FSS operators may co-locate their satellites operating above 17 GHz with satellites operating below 17 GHz;

h) that GSO FSS operators should be given some flexibility to operate TT&C in the most appropriate frequency band;

j) that the spectrum requirements for TT&C operations of satellites operating above 17 GHz may impact the satellite systems operating below 17 GHz,

recommends

1 that FSS satellite operators should design their TT&C systems based on the technical and operational considerations given in Annex 1.

NOTE 1 – Satellite operators are encouraged to provide further information on their TT&C operations.

* This Recommendation should be brought to the attention of Radiocommunication Study Group 6.

Annex 1

Technical and operational characteristics of FSS TT&C systems

1 Description of TT&C operations

This Recommendation provides the technical and operational characteristics of FSS TT&C systems including their link performance and availability objectives that should be taken into account by a satellite operator. This Recommendation provides guidance to FSS operators on the design and choice of frequency for their TT&C systems based on their particular requirements.

It should be noted that in the commercial satellite industry the acronym TT&C has been replaced by TC&R which stands for telemetry, command, and ranging. Since space telemetry, space tracking and space telecommand are defined in Article 1 of the Radio Regulations, the acronym TT&C has been used in this Recommendation even if it is referring to telemetry, command and ranging (TC&R) type functions.

The TT&C subsystem of a spacecraft is designed to provide three primary functions:

– Telecommand to enable ground controllers to command the various electronic units aboard the spacecraft.

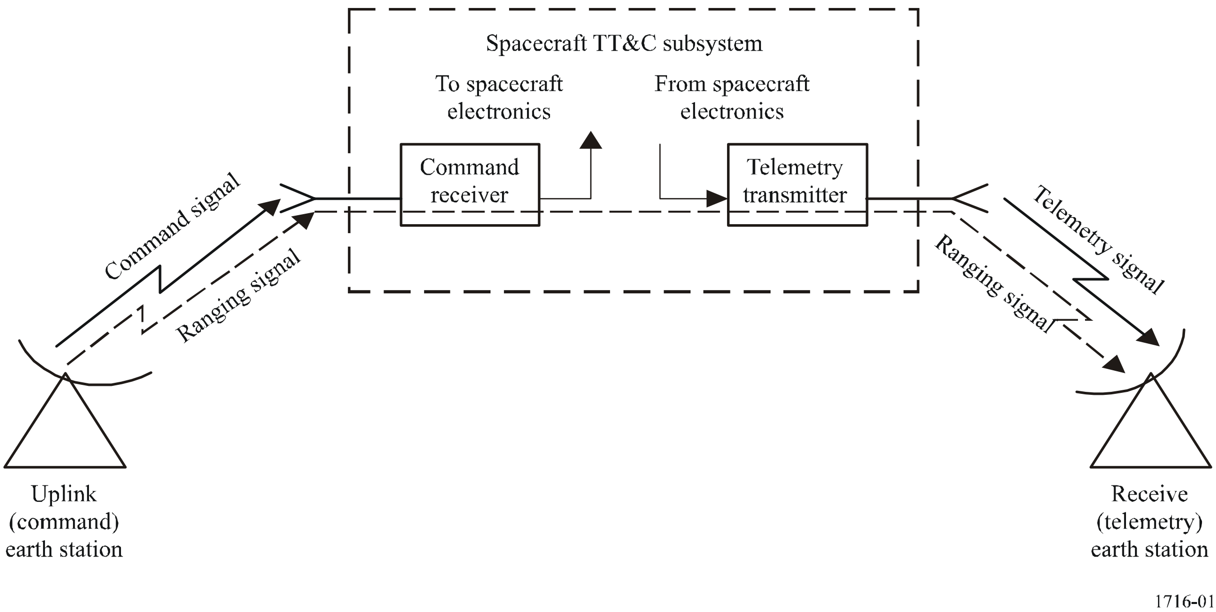
– Telemetry to enable ground controllers to monitor the operational health of the various electronic units aboard the spacecraft.

– Tracking/ranging to enable ground controllers to determine the location and orientation of the spacecraft.

A typical TT&C subsystem is shown in Fig. 1.

FIGURE 1

Typical TT&C link



For telecommand, a command signal is transmitted from the uplink earth station. This signal is in turn received and processed by the command receiver aboard the spacecraft and routed to the appropriate electronic units.

For telemetry, the designated spacecraft units provide a status signal to the telemetry transmitter. The transmitter in turn modulates and amplifies these signals onto the main telemetry carrier. From the transmitter, the modulated carrier signal is routed to the telemetry antenna, where it is transmitted to the ground for reception by the earth station.

For ranging, a command signal is uplinked to the spacecraft command receiver. This signal is then routed to the telemetry transmitter for transmission back to Earth. The distance from the ground station to the spacecraft is determined by simply measuring the change in phase between transmitted and received signals.

1.1 Transfer orbit and on-orbit operations

The TT&C subsystem of most satellites in use today have two modes of operation: on station mode and transfer orbit/emergency mode (hereafter referred to as emergency mode). The transfer orbit of a GSO FSS satellite is a critical phase in the life of a commercial satellite. As the satellite goes from low-Earth orbit to GSO, the command and telemetry channels must be continuously available, many operators have developed highly reliable networks of ground earth stations which can track a satellite during the launch and early orbit phase (LEOP) with at least two earth stations at all times.

In general, once the satellite reaches its on-orbit location in the GSO the TT&C receiver is switched from the omnidirectional antenna to a wide beamwidth horn antenna. As a result, the link requirements for on-station and emergency mode operations are usually different.

In order to determine the availability of a TT&C link, the operating parameters of both the ground earth station as well as the space station are required. On the command side, the location of the uplink earth station and its operating e.i.r.p. as well as the command threshold of the satellite are required in order to determine the actual link margin. Depending on the rain characteristic of the region in which the uplink earth station is located, the availability of the command link, signified as a percentage, can then be calculated.

For the telemetry, the location of the receive earth station and its associated receiver threshold as well as the spacecraft telemetry e.i.r.p. are required in order to determine the actual margin of this link. Again, depending on the rain characteristics of the region in which the receive earth station is located, the availability of the telemetry link can be determined.

2 6/4 GHz TT&C systems

The satellite TT&C carriers for one FSS satellite operator are located in an 18 MHz band in the range of 6 166-6 184 MHz and 3 941-3 959 MHz. Depending on the specific series of satellites there can be five TT&C carriers in this band, four being used for command and telemetry and one as a downlink beacon. Tables 1 and 2 contains further technical information on the link budgets and characteristics of the 6/4 GHz TT&C systems that are used on typical satellites. Because satellite operators often relocate their satellites to new orbital slots depending on the traffic and health of the satellites, the operational flexibility of maintaining a common set of baseline TT&C parameters has made the network more efficient and cost effective.

Each of the TT&C earth stations are normally connected via dedicated terrestrial and satellite facilities to a satellite control centre (SCC). The availability and quality of the TT&C signals is essential in maintaining the satellite's position and health (power, stability, temperature, etc.) and the data sent to and from the satellite must have the highest availability and performance, especially for the telecommand.

TABLE 1

Link budgets for a typical 6/4 GHz band telemetry carriers

Typical C-band transfer orbit telemetry and ranging	
Parameter	
Downlink carrier frequency	3 950 MHz
Tx power	13 dBW
Tx loss	–9.5 dB
Antenna gain	1.9 dBi
e.i.r.p. (typical)	1.6 dBW
Path loss (40 671 km) 10º elevation	–196.6 dB
Rx G/T	35 dB/K
C/N_0	68.2 dB-Hz
Normal and dwell sub-carrier (S/C)	
Available downlink S/C S/N_0	58.6 dB-Hz
Required S/N_0	50.2
Sub-carrier margin	8.4 dB
Ranging S/C	
Available downlink S/N_0	58.6 dB-Hz
Uplink S/N_0	60
Total S/N_0	56.2
Required S/N_0	41 dB-Hz
Ranging margin	15.2 dB

TABLE 2

Link budgets for a typical command and ranging carriers

Parameter	Transfer orbit	GSO	Units
Carrier frequency	6 175	6 175	(MHz)
e.i.r.p.	90	73.2	(dBW)
Spreading factor at GSO	–163.2	–163.2	(dB/m^2)
pfd at satellite	–73.2	–90	(dB(W/m^2))
Miscellaneous loss	–0.5	–0.4	(dB)
1 m^2 gain	–37.3	–37.3	(dBi)
Incident isotropic power	–111	–127.7	(dBW)
Satellite antenna gain	–5.1	7.3	(dBi)
Feed and split loss	–6.5	–6.6	(dB)
Rx input power	–122.6	–127	(dBW)
Rx threshold power	–142	–142	(dBW)
Margin	19.4	15	(dB)

2.1 TT&C availabilities

6/4 GHz FSS operators can maintain their TT&C link margins to ensure the link availability to be between 99.99% to 99.999% of the time. These availabilities are comparable to the availability of the space segment for a satellite network. In the case of one satellite operator, the average transponder availability for their satellites was 99.9996% for the year 2000. Their TT&C earth stations have been able to achieve availabilities of better than 99.95% and with their wide beamwidth satellite antenna coverage there are usually two TT&C earth stations visible to each satellite. A redundant path terrestrial/satellite network infrastructure connects the SCC with the TT&C earth station. The network availability objective for this terrestrial/satellite path is 99.99%. Therefore, a TT&C link availability between 99.99% to 99.999% is a reasonable objective.

Typical TT&C link budget objectives for a 6/4 GHz satellite are given in Tables 1 and 2. Similar 6/4 GHz TT&C link performance has been specified for most of the satellite TT&C systems. It should be further noted that the uplink and downlink e.i.r.p. values are typical and can vary according to the TT&C earth stations that are operating with that satellite. These do not take into account the ageing of the satellite receivers and power amplifiers, and the uplink characteristics of the TT&C earth station. The availability for a TT&C link could be calculated according to the available margin and the operating elevation and rain climatic conditions for each TT&C earth station. Examples of availabilities that could be achieved with these typical link budgets, assuming the propagation attenuation probabilities for three TT&C sites, are given in Tables 3 to 5. From the above propagation attenuation data, one can see that to achieve a performance availability of better than 99.999% in the 6/4 GHz band, a minimum margin of 6.5 dB is required on the uplink, and a minimum margin of 1.9 dB is required on the downlink.

Propagation link margins at these locations for TT&C performance at the same percentages of time have been calculated for the 14/11-12 GHz, 30/20 GHz and 50/40 GHz bands. If satellite networks operating above 17 GHz wish to achieve similar objectives they will have to locate their TT&C earth station in dry regions and with higher elevation angles.

TABLE 3

Clarksburg TT&C site (elevation angle 23.2°)

Clarksburg				
Uplink frequency	Attenuation (dB)			
	6.17 GHz	14.50 GHz	30.00 GHz	50.00 GHz
Per cent of time				
1	0.32	1.64	7.14	17.93
0.1	0.68	5.49	22.92	47.84
0.01	1.77	14.98	55.97	105.61
0.001	4.17	29.9	98.05	171.73
Downlink frequency				
	3.95 GHz	11.70 GHz	20.20 GHz	40.00 GHz
Per cent of time				
1	0.22	1.08	4.03	11.19
0.1	0.35	3.61	12.01	34.7
0.01	0.59	10.18	30.18	81.51
0.001	1.17	21.12	55.88	137.36

TABLE 4

Raisting TT&C site (elevation angle 15.8°)

Raisting				
Uplink frequency	Attenuation (dB)			
	6.17 GHz	14.50 GHz	30.00 GHz	50.00 GHz
Per cent of time				
1	0.38	1.35	5.32	16.07
0.1	0.69	4.32	16.73	38.37
0.01	1.56	11.94	41.59	83.06
0.001	3.52	24.37	74.92	136.85
Downlink frequency				
	3.95 GHz	11.70 GHz	20.20 GHz	40.00 GHz
Per cent of time				
1	0.28	0.92	3.22	8.77
0.1	0.43	2.81	9.19	26.49
0.01	0.67	7.95	23.27	63.05
0.001	1.17	16.86	44.05	108.76

TABLE 5

Beijing TT&C site (elevation angle 13.5°)

Beijing				
Uplink frequency	Attenuation (dB)			
	6.17 GHz	14.50 GHz	30.00 GHz	50.00 GHz
Per cent of time				
1	0.53	2.59	10.47	26.53
0.1	1.13	8.5	32.04	66.45
0.01	2.9	22.46	75.49	140.73
0.001	6.5	43.11	128.06	221.49
Downlink frequency				
	3.95 GHz	11.70 GHz	20.20 GHz	40.00 GHz
Per cent of time				
1	0.36	1.65	6.19	16.1
0.1	0.58	5.39	17.35	47.61
0.01	0.99	14.74	41.72	108.07
0.001	1.9	29.5	74.5	176.64

2.2 Summary

The above technical information on the 6/4 GHz TT&C characteristics of one FSS operator highlights the performance and availability objectives that have been taken into account in designing their TT&C links.

3 14/10-11 GHz TT&C systems

3.1 System description

For this study, the command and telemetry links availability of one satellite operators' spacecraft operating in the 14/12-11 GHz bands are calculated. Tables 6 and 7 provide the command link information and command link budgets for these spacecraft in on-station mode and emergency mode, respectively. Tables 8 and 9 provide the telemetry link information and telemetry link budgets for these spacecraft in the on-station and emergency mode of operation, respectively.

The data listed in these exhibits is separated into four groups:

– general signal characteristics

– spacecraft operating parameters

– uplink/downlink earth station operating parameters

– command/telemetry channel link budget.

For the command link, two availability percentages have been provided. The first availability figure is based upon the current operating e.i.r.p. of the earth station and can be considered the "operational availability" of the link. The second availability is based on the maximum e.i.r.p. that can be achieved by the earth station and is referred to as the "maximum availability" of the link. During emergency mode operation, when the attitude/orientation of the spacecraft may be unknown, it is assumed that the command earth station operates with the maximum available e.i.r.p. in order to ensure that a stable link with the spacecraft is established and sustained.

For the link budgets presented in Tables 6 to 9, a general 1 dB of additional system loss was assumed in order to account for small miscellaneous losses such as antenna misalignment, path losses due to atmospheric absorption, etc. It was assumed that the primary path losses were due to the signal spreading losses, rain attenuation, and the increase in receive earth station noise temperature due to rain. Link availability was determined using the rain rate (and probability) maps contained in Recommendation ITU-R P.618 and the calculated clear sky link margins.

TABLE 6

Normal (on station) mode command availability

Spacecraft: Name Spacecraft: Orbital location (° Elevation)	USASAT-24K –91.00	USASAT-23F –94.95	USASAT-25K –45.00	USASAT-14I-2 68.50	USASAT-14H 166.00
Command signal information					
Spacecraft: Command frequency (GHz) Spacecraft: Command polarization (LV, LH, RHCP, LHCP) Spacecraft: Operational mode (on station mode or emergency mode or both)	14.0-14.5 LV ON STATION	13.5-14.0 LV ON STATION	13.5-14.0 LH ON STATION	13.5-14.0 RHCP ON STATION	13.5-14.0 RHCP ON STATION
Spacecraft command information					
Spacecraft: Command receive antenna pattern description (Global or non-global) Spacecraft: Receive pfd at command threshold from the direction of the command earth station site (dB(W/m^2))	GLOBAL –105.00	GLOBAL –97.00	GLOBAL –108.00	GLOBAL –87.00	GLOBAL –87.00
Command earth station information					
Command earth station: Location identifier Command earth station: Site altitude (metres above mean sea level) Command earth station: Transmit antenna size (m) Command earth station: Peak gain of transmit antenna (dBi) Command earth station: Maximum available e.i.r.p. (dBW) Command earth station: e.i.r.p. (dBW) Command earth station: Rain rate for the location for 0.01% of an average year (mm/h)	ATLANTA, GA 236.22 9.30 61.26 86.00 68.00 80.00	FILMORE, CA 306.00 6.10 56.80 85.00 77.57 25.00	ATLANTA, GA 236.22 13.00 63.80 89.50 78.00 80.00	PERTH, AUS 15.00 11.00 62.00 ? 85.90 25.00	PERTH, AUS 15.00 11.00 62.00 ? 84.70 25.00
Link budget					
Uplink e.i.r.p. From command earth station (dBW) Earth station elevation angle (degrees above horizon) Distance between the command earth station and the satellite (m) Spreading loss (dB) Loss due to atmospheric effects (dB) Additional system losses (dB) Uplink command channel pfd (dB(W/m^2)) pfd at the spacecraft command threshold (dB(W/m^2)) Command margin (dB) Availability of command channel (%)	68.00 50.19 37 066 125.27 162.37 0.00 1.00 –94.37 –105.00 10.63 99.97650	77.57 42.54 37 588 473.28 162.49 0.00 1.00 –84.92 –97.00 12.08 99.99856	78.00 32.81 38 365 626.21 162.67 0.00 1.00 –84.67 –108.00 23.33 99.99597	85.90 27.33 38 853 188.51 162.78 0.00 1.00 –76.88 –87.00 10.12 99.99432	84.70 25.13 39 057 710.39 162.83 0.00 1.00 –78.13 –87.00 8.87 99.99090

NOTE 1 – All spacecraft command threshold values are specified values.

TABLE 7

Emergency mode command availability

Spacecraft: Name Spacecraft: Orbital location (° Elevation)	USASAT-24K –91.00	USASAT-23F –94.95	USASAT-25K –45.00	USASAT-14I-2 68.50	USASAT-14H 166.00
Command signal information					
Spacecraft: Command frequency band (GHz)	14.0-14.5	13.5-14.0	13.5-14.0	13.5-14.0	13.5-14.0
Spacecraft: Command polarization (LV, LH, RHCP, LHCP)	LV	LV	LH	RHCP	RHCP
Spacecraft: Operational mode (on station mode or emergency mode or both)	EMERGENCY	EMERGENCY	EMERGENCY	ON STATION	EMERGENCY
Spacecraft command information					
Spacecraft: Command receive antenna pattern description (Global or non-global)	GLOBAL	GLOBAL	GLOBAL	GLOBAL	GLOBAL
Spacecraft: Receive pfd at command threshold from the direction of the command earth station site (dB(W/m^2))	–105.00	–78.00	–108.00	–82.00	–82.00
Command earth station information					
Command earth station: Location identifier	ATLANTA, GA	FILMORE, CA	ATLANTA, GA	PERTH, AUS	PERTH, AUS
Command earth station: Site altitude (metres above mean sea level)	236.22	306.00	236.22	15.00	15.00
Command earth station: Transmit antenna size (m)	9.30	6.10	13.00	11.00	11.00
Command earth station: Peak gain of transmit antenna (dBi)	61.26	56.80	63.80	62.00	62.00
Command earth station: Maximum available e.i.r.p. (dBW)	86.00	85.00	89.50	?	?
Command earth station: e.i.r.p. (dBW)	68.00	77.57	78.00	85.90	84.70
Command earth station: Rain rate for the location for 0.01% of an average year (mm/h)	80.00	25.00	80.00	25.00	25.00
Link budget					
Uplink e.i.r.p. From command earth station (dBW)	86.00	85.00	89.50	85.90	84.70
Earth station elevation angle (degrees above horizon)	50.19	42.54	32.81	27.33	25.13
Distance between the command earth station and the satellite (m)	37 066 125.27	37 588 473.28	38 365 626.21	38 853 188.51	39 057 710.39
Spreading loss (dB)	162.37	162.49	162.67	162.78	162.83
Loss due to atmospheric effects (dB)	0.00	0.00	0.00	0.00	0.00
Additional system losses (dB)	1.00	1.00	1.00	1.00	1.00
Uplink command channel pfd (dB(W/m^2))	–76.37	–77.49	–73.17	–76.88	–78.13
pfd at the spacecraft command threshold (dB(W/m^2))	–105.00	–78.00	–108.00	–82.00	–82.00
Command margin (dB)	28.63	0.51	34.83	5.12	3.87
Availability of command channel (%)	99.99884	99.19300	99.99915	99.97633	99.95327

NOTE 1 – All spacecraft command threshold values are specified values.

TABLE 8

Normal (on station) mode telemetry availability

Spacecraft: Name Spacecraft: Orbital location (° Elevation)	USASAT-24K –91.00	USASAT-23F –94.95	USASAT-25K –45.00	USASAT-14I-2 68.50	USASAT-14H 166.00
Telemetry signal information					
Spacecraft: Telemetry frequency (GHz)	11.7-12.2	11.45-11.7	11.45-11.7	11.45-11.7	12.5-12.75
Spacecraft: Telemetry polarization (LV, LH, RHCP, LHCP)	LV	RHCP	LV	LH	LH
Spacecraft: Operational mode (on station mode or emergency mode or both)	NORMAL	NORMAL	NORMAL	NORMAL	NORMAL
Spacecraft: Telemetry mode (normal or dwell mode telemetry or both)	BOTH	BOTH	BOTH	BOTH	BOTH
Spacecraft telemetry information					
Spacecraft: Telemetry antenna pattern description (global or non-global)	GLOBAL	GLOBAL	GLOBAL	GLOBAL	GLOBAL
Spacecraft: Downlink telemetry channel e.i.r.p. toward receive earth station (dBW)	5.00	10.00	11.26	12.50	12.50
Telemetry earth station information					
Telemetry earth station: Location Identifier	ATLANTA, GA	FILMORE, CA	ATLANTA, GA	PERTH, AUS	PERTH, AUS
Telemetry earth station: Site altitude (m)	236.22	306.00	236.22	15.00	15.00
Telemetry earth station: Receive antenna size (m)	9.30	6.10	13.00	11.00	11.00
Telemetry earth station: Peak gain of receive antenna (dBi)	60.01	55.30	62.20	60.00	60.00
Telemetry earth station: G/T (dB/K)	37.50	34.00	40.40	38.50	38.50
Telemetry earth station: Minimum required C/N_0 for the reception of spacecraft telemetry (dB)	48.50	48.50	48.50	48.50	48.50
Telemetry earth station: Rain rate for the location for 0.01% of an average year (mm/h)	80.00	25.00	80.00	25.00	25.00
Link budget					
Downlink e.i.r.p. in the direction of earth station (dBW)	5.00	10.00	11.26	12.50	12.50
Earth station elevation angle (degrees above horizon)	50.19	42.54	32.81	27.33	25.13
Distance between the satellite and the receive earth station (m)	37 066 125.27	37 588 473.28	38 365 626.21	38 853 188.51	39 057 710.39
Path loss (dB)	205.19	205.13	205.49	205.41	206.39
Loss due to atmospheric effects (dB)	0.00	0.00	0.00	0.00	0.00
Additional system losses (dB)	1.00	1.00	1.00	1.00	1.00
Earth station G/T – Clear sky (dB/K)	37.50	34.00	40.40	38.50	38.50
Earth station G/T degradation due to rain (dB)	–3.48	–4.30	–4.31	–4.49	–4.47
Earth station G/T – Rain (dB/K)	34.02	29.71	36.09	34.01	34.04
Boltzman constant	–228.60	–228.60	–228.60	–228.60	–228.60
C/N_0 (dB)	62.43	63.18	70.46	69.70	68.75
Required C/N_0 (dB) – @ 4 000 bit/s	54.50	54.50	54.50	54.50	54.50
Margin	7.93	8.68	15.96	15.20	14.25
Availability (%)	99.9846	99.9986	99.9962	99.9997	99.9990

NOTE 1 – All spacecraft telemetry e.i.r.p. values are predicted values.

NOTE 2 – The earth station C/N_0 correspond to a demodulated bit rate of 4 000 bit/s and a bit error rate of 10^{-6}.

TABLE 9

Emergency mode telemetry availability

Spacecraft: Name Spacecraft: Orbital location (° Elevation)	USASAT-24K –91.00	USASAT-23F –94.95	USASAT-25K –45.00	USASAT-14I-2 68.50	USASAT-14H 166.00
Telemetry signal Information					
Spacecraft: Telemetry frequency (GHz)	11.7-12.2	11.45-11.7	11.45-11.7	11.45-11.7	12.5-12.75
Spacecraft: Telemetry polarization (LV, LH, RHCP, LHCP)	LV	RHCP	LV	LH	LH
Spacecraft: Operational mode (on station mode or emergency mode or both)	EMERGENCY	EMERGENCY	EMERGENCY	EMERGENCY	EMERGENCY
Spacecraft: Telemetry mode (normal or dwell mode telemetry or both)	BOTH	BOTH	BOTH	BOTH	BOTH
Spacecraft telemetry information					
Spacecraft: Telemetry antenna pattern description (global or non-global)	GLOBAL	GLOBAL	GLOBAL	GLOBAL	GLOBAL
Spacecraft: Downlink telemetry channel e.i.r.p. toward receive earth station (dBW)	5.00	5.00	6.73	0.00	0.00
Telemetry earth station information					
Telemetry earth station: Location identifier	ATLANTA, GA	FILMORE, CA	ATLANTA, GA	PERTH, AUS	PERTH, AUS
Telemetry earth station: Site altitude (m)	236.22	306.00	236.22	15.00	15.00
Telemetry earth station: Receive antenna size (m)	9.30	6.10	13.00	11.00	11.00
Telemetry earth station: Peak gain of receive antenna (dBi)	60.01	55.30	62.20	60.00	60.00
Telemetry earth station: G/T (dB/K)	37.50	34.00	40.40	38.50	38.50
Telemetry earth station: Minimum required C/N_0 for the reception of spacecraft telemetry (dB)	48.50	48.50	48.50	48.50	48.50
Telemetry earth station: Rain rate for the location for 0.01% of an average year (mm/h)	80.00	25.00	80.00	25.00	25.00
Link budget					
Downlink e.i.r.p. in the direction of earth station (dBW)	5.00	5.00	6.73	0.00	0.00
Earth station elevation angle (degrees above horizon)	50.19	42.54	32.81	27.33	25.13
Distance between the satellite and the receive earth station (m)	37 066 125.27	37 588 473.28	38 365 626.21	38 853 188.51	39 057 710.39
Path loss (dB)	205.19	205.13	205.49	205.41	206.39
Loss due to atmospheric effects (dB)	0.00	0.00	0.00	0.00	0.00
Additional system losses (dB)	1.00	1.00	1.00	1.00	1.00
Earth station G/T – Clear sky (dB/K)	37.50	34.00	40.40	38.50	38.50
Earth station G/T degradation due to rain (dB)	–3.48	–3.53	–4.18	–3.25	–2.97
Earth station G/T – Rain (dB/K)	34.02	30.47	36.22	35.25	35.53
Boltzman constant	–228.60	–228.60	–228.60	–228.60	–228.60
C/N_0 (dB)	62.43	58.95	66.06	58.44	57.74
Required C/N_0 (dB) – @ 4 000 bit/s	54.50	54.50	54.50	54.50	54.50
Margin	7.93	4.45	11.56	3.94	3.24
Availability (%)	99.9846	99.9913	99.9905	99.9823	99.9526

NOTE 1 – All spacecraft telemetry e.i.r.p. values are predicted values.

NOTE 2 – The earth station C/N_0 correspond to a demodulated bit rate of 4 000 bit/s and a bit error rate of 10^{-6}.

TABLE 10

Ranging link availability

Spacecraft: Name Spacecraft: Orbital location (° Elevation)	USASAT-24K –91.00	USASAT-23F –94.95	USASAT-25K –45.00	USASAT-14I-2 68.50	USASAT-14H 166.00
Spacecraft: Operational mode (normal on station mode or emergency mode or both)	ON STATION	ON STATION	ON STATION	ON STATION	ON STATION
Availability of command channel (%)	99.97650	99.99856	99.99597	99.99432	99.99090
Availability of telemetry channel (%)	99.9846	99.9986	99.9962	99.9997	99.9990
Availability of ranging channel (%)	99.96110	99.99716	99.99217	99.99402	99.98990
Spacecraft: Name Spacecraft: Orbital location (° Elevation)	USASAT-24K –91.00	USASAT-23F –94.95	USASAT-25K –45.00	USASAT-14I-2 68.50	USASAT-14H 166.00
Spacecraft: Operational mode (normal on station mode or emergency mode or both)	EMERGENCY	EMERGENCY	EMERGENCY	EMERGENCY	EMERGENCY
Availability of command channel (%)	99.99884	99.19300	99.99915	99.97633	99.95327
Availability of telemetry channel (%)	99.9846	99.9913	99.9905	99.9823	99.9526
Availability of ranging channel (%)	99.98344	99.18437	99.98965	99.95863	99.90589

3.2 TT&C availabilities

As listed in Table 6, during normal on-station operation, the "operational availability" of the command link ranges from 99.97650% to 99.99856%, with an average value of 99.99125%. Similarly for on-station telemetry, the link availability's range from 99.9846% to 99.9997% with an average value of 99.99562% (see Table 8).

Under emergency mode conditions, when the orientation of the spacecraft may be unknown, it is reasonable to assume that the command signal would be transmitted with the maximum available e.i.r.p. of the ground station to ensure a reliable link to the spacecraft. Accordingly, in this mode of operation, the "maximum availability" of the link is the relevant and applicable factor. From Table 7, the maximum availability of the command link during emergency mode of operation ranges from 99.193% to 99.99915% with an average of 99.82411%. For the telemetry link (see Table 9), the availability ranges from 99.9526% to 99.9913% with an average of 99.98026%.

For ranging, no direct measured data was obtained. However, a good estimate of the availability can be arrived at by multiplying the availability of the command and telemetry links for each case shown. Using this methodology, the availability of this link ranges from 99.9611% to 99.99716% with an average value of 99.98687% (see Table 10), when the spacecraft is assumed to operate in the normal mode for both the command and telemetry links. The corresponding availabilities for emergency mode (for both command and telemetry) range from 99.18437% to 99.98965% with an average value of 99.8044%.

3.3 Telecommand antenna size constraints

In order to ensure the reliable operation of TT&C operations in the 14/11-12 GHz range the command uplink to a spacecraft must be very reliable, and consequently the command receiver on the spacecraft must be sensitive and able to operate over a wide dynamic range in order to accommodate large uplink rain fade margins. Such sensitive command receivers are also sensitive to interference from other co-frequency carriers that could cause false commands in the TT&C receiver on the spacecraft. In order to ensure the uplink and downlink interference from communication and telecommand carriers from adjacent satellite networks will have a negligible impact on reducing the available fade margin, large highly directive transmitting earth station antennas are normally used for sending commands to and receiving telemetry from spacecraft. The most constraining factor in determining the size of the TT&C antenna diameter is the minimum inter-satellite spacing required for reusing the same command frequency on an adjacent spacecraft.

In order to model the situation of adjacent satellites reusing the same frequency for provision of the command uplink, the aggregate interference from uplink earth stations transmitting to the four closest adjacent satellite networks was considered. This interference level was calculated and compared to the command receiver interference criterion. It was assumed that all satellites were equally spaced at a whole number multiple of 2°. Under this assumption, the closest two satellites are $\varphi°$ away and the next closest satellites are $2\,\varphi°$ away from the wanted satellite network. Given a satellite command receiver interference sensitivity level of –125 dB(W/m^2) plus a 1 dB additional margin, for the system analysed, the command earth station antenna size was varied in increments of approximately 2 m from a minimum of 9 m up to a maximum of 15 m to assess the impact of antenna diameter on the co-frequency satellite spacing.

Table 11 provides the resulting orbital spacing as a function of the uplink antenna diameter. As expected, the results show that as the uplink antenna diameter is increased from 9 m to 15 m, the spacing between the satellites could be decreased from 12° to 8°. In the case of a satellite network, with a very sensitive command receiver interference criterion, the satellite spacing is driven by the protection of the command receiver. Given that the uplink and downlink C/I for typical command uplinks and telemetry downlinks resulting from the spacing are in excess of 50 dB, the adjacent satellite interference component in the total noise for the command uplink is negligible and for that reason, the adjacent satellite interference was not considered in the calculation of availability for the command uplink or the availability of the telemetry downlink.

TABLE 11

Example of required minimum orbital spacing for adjacent satellites reusing the same command uplink frequency as a function of antenna diameter for 14 GHz

Command uplink antenna diameter (m)	9	11.3	13	15
Uplink antenna gain (dBi)	60.19	62.17	63.38	64.63
Orbit separation, *X* (degrees)	12	10	10	8
C/*I* from aggregate of four closest satellites (dB)	52.41	52.39	53.61	52.41
Aggregate pfd at wanted satellite from four closest interfering satellites dB(W/m^2)	–126.1	–126.1	–127.3	–126.1

NOTE 1 – Each satellite network is assumed to use homogeneous earth station parameters. Each earth station is assumed to transmit at a command uplink e.i.r.p. of 89 dBW at the same frequency and that the occupied bandwidth of each command carrier is the same.

NOTE 2 – It is assumed that the uplink antenna diameters are the same for each satellite network. The radiation pattern envelope over the angles of interest for each transmitting earth station antenna was:

29 – 25 log(φ)	dBi	for	$2° < \varphi \leq 7°$
7.9	dBi	for	$7° < \varphi \leq 9.2°$
32 – 25 log(φ)	dBi	for	$9.2° < \varphi \leq 48°$

where φ is the topocentric separation angle from the interfering satellite.

Operators using larger antennas would be able to reduce the orbital spacing between their satellites which might utilize the same command frequency. In addition, some telecommand receivers have more relaxed protection requirements and thus could accomplish frequency reuse with a reduced satellite spacing.

In spite of using an aggregate interference criterion of –125 dB(W/m^2) this level would not preclude the co-frequency operation of uplink digital carriers on the adjacent satellite, which could result in smaller satellite separation requirements than in the case where the command uplink is coordinated with a similar carrier.

3.4 Comparison of TT&C availabilities for FSS networks above and below 17 GHz

A sensitivity analysis of TT&C command uplinks and telemetry downlinks in the 30/20 GHz and the 50/40 GHz bands was conducted using a 14/12 GHz band TT&C link design as the baseline performance objective. A list of the basic system parameters for the three different frequency bands, along with their associated command and telemetry links, is given in Table 12. Note that the use of different assumed parameters for links in the 30/20 GHz and the 50/40 GHz bands could produce different results than were obtained in this analysis. The transmitter power levels, earth station antenna gains, earth station and space station noise temperatures for the 30/20 GHz and 50/40 GHz bands and the satellite antenna gains were based on typical or representative values from available information. For all links, the TT&C earth stations were located at 44.2° N, 80.9° W.

TABLE 12

Satellite network system parameters

Frequency band	(GHz)	50/40	30/20	14/12
Spacecraft: Orbital location	(degrees E)	–107.3	–107.3	–107.3
Earth station elevation angle	(degrees)	32.7	32.7	32.7
Earth station rain rate exceeded for 0.01% of year	(mm/h)	35.7	35.7	35.7
Earth station site above mean sea level	(km)	0.3	0.3	0.3
Uplink budget				
Uplink frequency	(GHz)	50.0	30.0	14.0
Uplink polarity		C	C	C
Earth station antenna diameter	(m)	2.4	6.3	9.0
Earth station antenna gain	(dBi)	60.1	64.0	60.5
Earth station e.i.r.p.	(dBW)	77.0	91.8	89.0
Atmospheric absorption	(dB)	4.4	1.6	0.4
Earth station pointing error	(dB)	0.2	0.4	0.1
Uplink bandwidth	(kHz)	1 300.0	1300.0	1 300.0
C/*N* uplink thermal (nominal clear sky)	(dB)	44.2	60.5	55.2
Nominal uplink operating levels				
Spacecraft uplink receive power	(dBW)	–99.3	–99.3	–99.3
Spacecraft uplink threshold pfd	(dB(W/m^2))	–96.2	–94.8	–90.0
Uplink pfd (nominal clear sky)	(dB(W/m^2))	–90.2	–72.9	–74.2
Uplink range margin	(dB)	6.0	21.9	15.8
Range uplink availability	(%)	98.476	99.965	99.998
Downlink budget				
Downlink frequency	(GHz)	40.0	20.2	11.7
Downlink polarity		C	C	C
Earth station antenna diameter	(m)	2.4	6.3	9.0
Earth station antenna gain	(dBi)	58.1	60.6	58.9
Nominal clear sky operating levels				
Earth station low noise amplifier noise temperature	(K)	300.0	200.0	160.0
Earth station system noise temperature	(K)	447.7	367.8	242.1
Earth station *G*/*T* (clear sky)	(dB/K)	31.6	34.9	35.1
Downlink bandwidth	(kHz)	300.0	300.0	300.0
C/*N* downlink thermal (nominal clear sky)	(dB)	19.7	22.4	18.0
C/*N* threshold	(dB)	5.0	5.0	3.3
Spacecraft parameters				
Spacecraft e.i.r.p.	(dBW)	32.4	26.5	15.0
Spacecraft Tx antenna gain	(dBi)	52.4	46.5	35.3
Spacecraft Tx power	(dBW)	–20.0	–20.0	–20.3
Spacecraft *G*/*T* (clear sky)	(dB/K)	22.4	17.0	6.5
Downlink degradations during rain				
Atmospheric absorption	(dB)	1.8	2.4	0.2
Feeder system loss	(dB)	1.0	1.0	1.0
Earth station pointing error	(dB)	0.1	0.2	0.1
Rain fade A1(p1)	(dB)	13.7	16.3	12.4
C/*N* thermal degradation	(dB)	1.0	1.0	2.4
Downlink margin	(dB)	14.7	17.4	14.8
Downlink availability	(%)	99.771	99.987	99.999

On the uplink, the "threshold" pfd of the reference 14/12 GHz band satellite network was used to calculate the receive power level at the input to the command receiver on the spacecraft. This receive power level is the minimum required for nominal operations. The "threshold" pfd level for the 14/12 GHz band was –90 dB(W/m^2).

A sensitivity analysis was performed at the 14/12 GHz band to show the effect of TT&C earth station location (elevation angles and rain rate) on the achieved performance for command uplinks and telemetry downlinks. Based on typical 14/12 GHz band links, the availabilities achieved on the command uplinks and the telemetry downlinks for satellites are typically on the order of 99.98%. This availability, achieved under normal operation, was used as a guideline for determining what levels or performance would be achieved in other frequency bands such as the 30/20 GHz and the 50/40 GHz bands. Note that only the "normal" mode of operation is considered in the sensitivity analysis.

In order to achieve a valid method of comparison between data, a constant latitude of 18° N was used. This latitude provided a large range of rain rates over a minimal longitude range, between –20° W and –70° W. It was also chosen as it required minimum interpolation from the digitized coefficients required for the rain rate, rain height and atmospheric absorption calculations referred to in Recommendations ITU-R P.837, ITU-R P.839 and ITU-R P.676 respectively.

In general, when the local rain rate increases for a given elevation angle, the availability decreases. The availability of TT&C operations for a given rain rate also decreases with decreasing elevation angle. In this example a maximum rain rate of 100 mm/h was considered. Figure 2 shows the minimum required elevation angle versus varying rain rates in order to achieve a 99.98% availability. Figure 3 shows the maximum rain rates allowed for varying elevation angles required to achieve a 99.98% availability. These figures show data for the 14/12 GHz and 30/20 GHz frequency bands. No data is shown for the 50/40 GHz band since the 99.98% availability could not be met under any rain rate and elevation combination.

FIGURE 2

Minimum elevation angle that permits an availability of 99.98% to be achieved as a function of rain rate

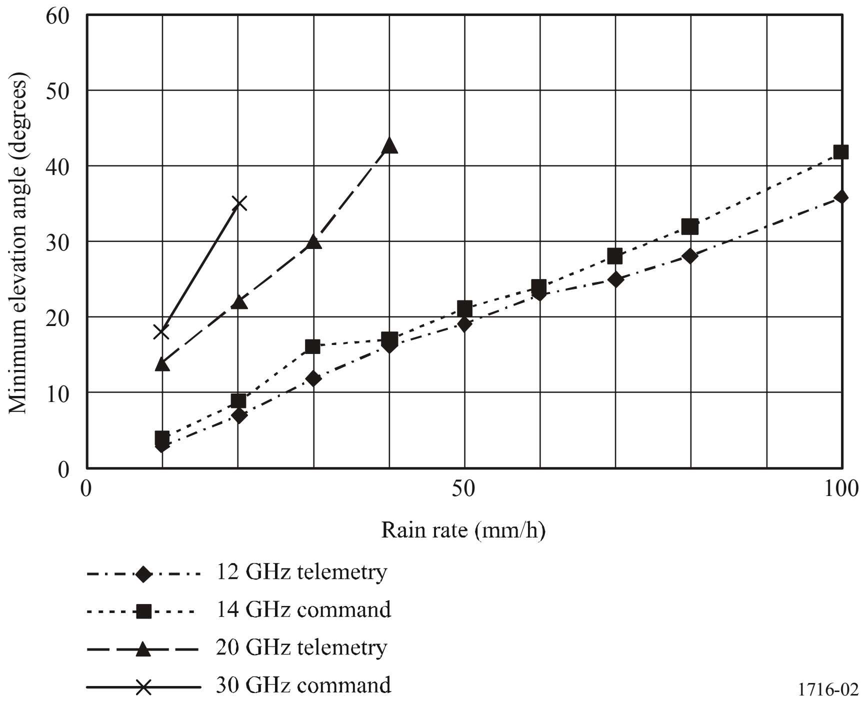
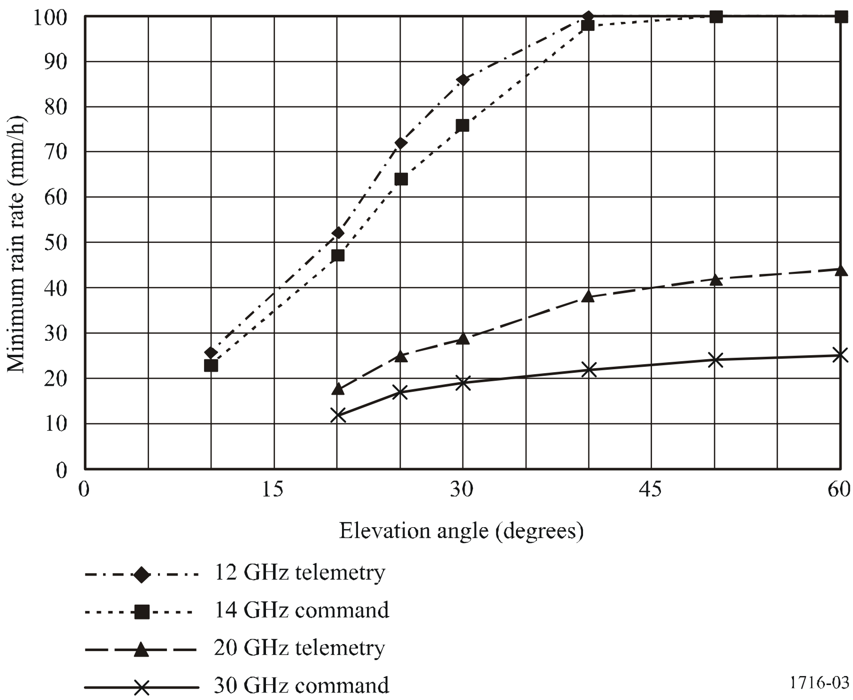


FIGURE 3

Minimum rain rate that permits an availability of 99.98% to be archived as a function of elevation angle



4 30/20 GHz FSS network TT&C availability objectives

One domestic 30/20 GHz FSS network has filed their TT&C uplink command carriers for operation at the lower edge of the 29.5-30 GHz band, and have designed their links to have an availability objective ranging from 99.98 to 99.95% for normal or on-station operation depending on the satellite receive antenna configuration, and 99.97% for transfer orbit operation.

The telemetry downlink carriers would be similarly located at the low edge of the 19.7-20.2 GHz band with an availability objective of 99.95% during normal or on-station operations, and an availability objective of 99.9% during transfer orbit. The BER performance objective of the data demodulator at the TT&C receive earth station was 1×10^{-6}.

5 Summary

The above sections presented typical TT&C performance data. Upon examination of the data, it is apparent that the link availability' varies over a fairly wide range, with the command link availability's being, in general, less than those for the telemetry link. However, one must bear in mind that for most modern spacecraft, the telemetry stream is generally continuous in nature. For the command link, the operator does not provide a continuous stream of commands to the spacecraft; and, accordingly the operator has control over the period(s) and number of times in which the command can be sent. One can then expect the average telemetry, command and ranging link signal reliability to be, in practice, much greater than the availability values listed in Tables 6 and 7.

Comparing the performance and availabilities of TT&C systems operating in the 30/20 GHz and 50/40 GHz bands when similar TT&C link design parameters as those in the 14/11-12 GHz bands are utilized, it was shown that a number of factors limit the performance of TT&C links above 17 GHz.

In addition, Radiocommunication Bureau (BR) Circular Letter CA/99 requested administrations and Sector Members to provide technical and operational characteristics of their FSS TT&C systems. A database has been created by BR at the ITU website: http://web.itu.ch/brsg/srg4/info/wp4b/index.html. Table 13 provides a summarized analysis of the data gathered in response to BR Circular Letter CA/99.

TABLE 13

Summary of the availability and link margins from BR Circular Letter CA/99

Link availability (%)	6/4 GHz			14/11 GHz			20 GHz		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Ranging	99.7	99.998	99.76859	94.9981	99.9923	99.14992	99.42525	99.97716	99.70121
Telemetry	99.7	99.999	99.80755	99.9	99.999	99.96253	Not applicable	Not applicable	Not applicable
Command	99.7	99.999	99.83424	99.3403	99.99874	99.89163	99.9	99.99511	99.94756

Link margin (dB)	6/4 GHz			14/11 GHz			20 GHz		
	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average
Ranging	0.7	42.31633	13.07245	0.48482	30.9111	16.26529	1.306482	7.30482	4.305651
Telemetry	0.5	39.45	24.40857	6	30.8	19.41385	Not applicable	Not applicable	Not applicable
Command	0.5	24.5	7.307692	2.38	22.2	10.97929	13.7	19.6	16.65