ESA PSS-04-104 Volume 1 Issue 2
March 1991

Ranging standard

Volume 1: Direct Ground to Spacecraft Ranging

Prepared by:
The Standards Approval Board (STAB)
for Space Data Communications

Approved by:
The inspector General, ESA

european space agency / agence spatiale européenne
8-10, rue Mario-Nikis, 75738 PARIS CEDEX, France

Published by ESA Publications Division,
ESTEC, Noordwijk, The Netherlands.

Printed in the Netherlands.

ESA Price code: E0

ISSN 0379 - 4059

SPACE DATA COMMUNICATIONS
PROCEDURES, SPECIFICATIONS & STANDARDS

Space Data Communications is the subject of the PSS-04 branch of the ESA Procedures, Specifications & Standards (PSS) series. This branch is further divided into two subbranches:

- the **Space Link Standards and Protocols** subbranch (document reference nos.: ESA PSS-04-1XX);
- the **Spacecraft Data Interfaces and Protocols** subbranch (document reference nos.: ESA PSS-04-2XX).

The purpose of these Space Data Communications PSS documents is to ensure the compatibility of spacecraft TT&C subsystems with the relevant ESA infrastructure (i.e. the ESA (ESOC) tracking and data-communication network and the ESA (ESTEC) satellite check-out facilities).

DOCUMENT CHANGE RECORD

Issue number and date	Sections affected	Remarks
Issue 1 April 1990	New document	This document supersedes the previous version, ref.: TTC-A-04, Issue No. 1, July 1980.
Issue 2 March 1991	Sections 2.2 (p. 12) and 2.3 (pp. 18, 20 & 21)	The changes are indicated by change bars in the margin and are only of an editorial nature. Otherwise, this Issue 2 is identical to Issue 1.

REFERENCES

[1] **Radio Frequency and Modulation Standard (ESA PSS-04-105),** Issue 1, 1989, European Space Agency

[2] **Packet Telemetry Standard (ESA PSS-04-106),** Issue 1, 1988, European Space Agency.

[3] **Packet Telecommand Standard (ESA PSS-04-107),** Issue 1, 1990, European Space Agency.

The following reference document is considered to contain certain information which can assist the understanding of the requirements of this Standard but does not contain any mandatory requirements.

[4] Study on Ranging Characteristics and Capabilities for Future Ranging Standards, ESA Contract 7518/87/NL/JG(SC), Part II, University of Stuttgart, Institute of Navigation, December 1989.

PAGE INTENTIONALLY LEFT BLANK

CONTENTS

ILLUSTRATIONS

APPENDIX

PAGE INTENTIONALLY LEFT BLANK

1. PURPOSE AND SCOPE

1.1 PURPOSE

The purpose of this Standard is to:

- ensure compatibility between ESA spacecraft TTC transponders and the Range and Doppler Tracking facilities of the ESA Earth network;
- define the compatibility between the Agency's spacecraft and other networks with which they may have to work;
- establish a minimum level of Range and Doppler Tracking accuracy for missions conforming to this standard;
- facilitate the early design of flight hardware and ensure that the resulting project interfaces and system performances are compatible with given ESA ranging configurations and specifications.

1.2 SCOPE

This document is the first part of a Ranging Standard consisting of two volumes:

Volume 1: **Direct Ground to Spacecraft Ranging** (this document) is concerned with single-access Range and Doppler Tracking on direct links between spacecraft of Category A or Category B missions and Earth-based stations.(*)

Volume 2: **Ranging via Data Relay Systems** is concerned with Range and Doppler Tracking for spacecraft operations via Data Relay Systems. (At the date of issue of the present document, Volume 2 is still in the planning stage.)

Volume 1 of the Ranging Standard is applicable to all ESA spacecraft that are supported for Range or Doppler Tracking by direct links to ESA-controlled Earth stations operating in the Space Operations Service.

Missions that are supported via Data Relay Systems and that need, for backup support, direct links to ESA-controlled ground stations are not necessarily bound by the requirements set out in this volume of the Standard.

NOTE:

(*) See Reference [1], Section 3.1.2, for definitions of Category A and Category B missions.

It defines the requirements concerning spacecraft transponder and Earth-station equipment for the purposes of range and Doppler tracking.

This document provides criteria by which one may determine the extent to which the accuracy of the measurements is influenced by equipment effects. This is not to be confused with the accuracy of the overall orbit-reconstitution process, which is also influenced by effects that are outside the scope of the Standards, i.e. modelling of gravitational and nongravitational forces, modelling of propagation effects, preprocessing and screening of data.

In exceptional cases, owing to mission-specific requirements, some deviations from this Standard may be warranted. Waivers to any requirements set forth in this Standard may be obtained only after:

- the technical and/or operational advantages of such deviations have been demonstrated, and/or
- it has been shown that the intended change is compatible with the existing systems.

Requests for waivers should be addressed by the Project Manager to the ESA Standards Approval Board (STAB) for Space Data Communications. Such requests should be submitted as early as possible, preferably during the study phase of the project.

2. REQUIREMENTS

2.1 FUNCTIONAL REQUIREMENTS

2.1.1 Functional Breakdown

The ESA Range and Doppler Tracking System is a spacecraft tracking system capable of providing information on the range and range rate between a spacecraft and an Earth station. It requires an active transponder on board the spacecraft for the retransmission to the ground of an Earth-to-Space link signal; signal generation and measurement are performed in the Earth station. As a baseline, it is assumed that the spacecraft transponder is used not only for ranging purposes but also, if necessary, for receiving PCM telecommand messages from Earth and transmitting PCM telemetry messages to Earth. Where a transponder is used exclusively for ranging, several requirements in this Standard concerning sharing with TC and/or TM have no relevance.

A functional breakdown of the Range and Doppler Tracking System is presented in Figure 2.1. It depicts the five major functions of the system, broken down into functional blocks, as follows:

- the Earth-to-Space link function, employing communication, process control, signal generation and Earth-to-Space communication;
- the transponder function, depending on application either spacecraft transponder or ground-calibration transponder;
- the Space-to-Earth link function, employing Space-to-Earth communications, Doppler measurement, replica generation, correlation, process control and interfacing to telemetry processing;
- the link-control function, resident partly in the Space-to-Earth and Earth-to-Space communication and partly in the process control;
- the data-acquisition function, concerned with collection, measurement, processing and transfer of data to the control centre, employing the process-control and communication functions.

The requirements relevant to these five major functions are listed in the following subsections.

2.1.2 Earth-to-Space Link Function

The Earth-to-Space Link Function consists of:

- reception of control signals for signal composition (i.e. tone-frequency and ambiguity-resolution code, modulation index, etc.);
- generation of the ambiguity-resolution code;

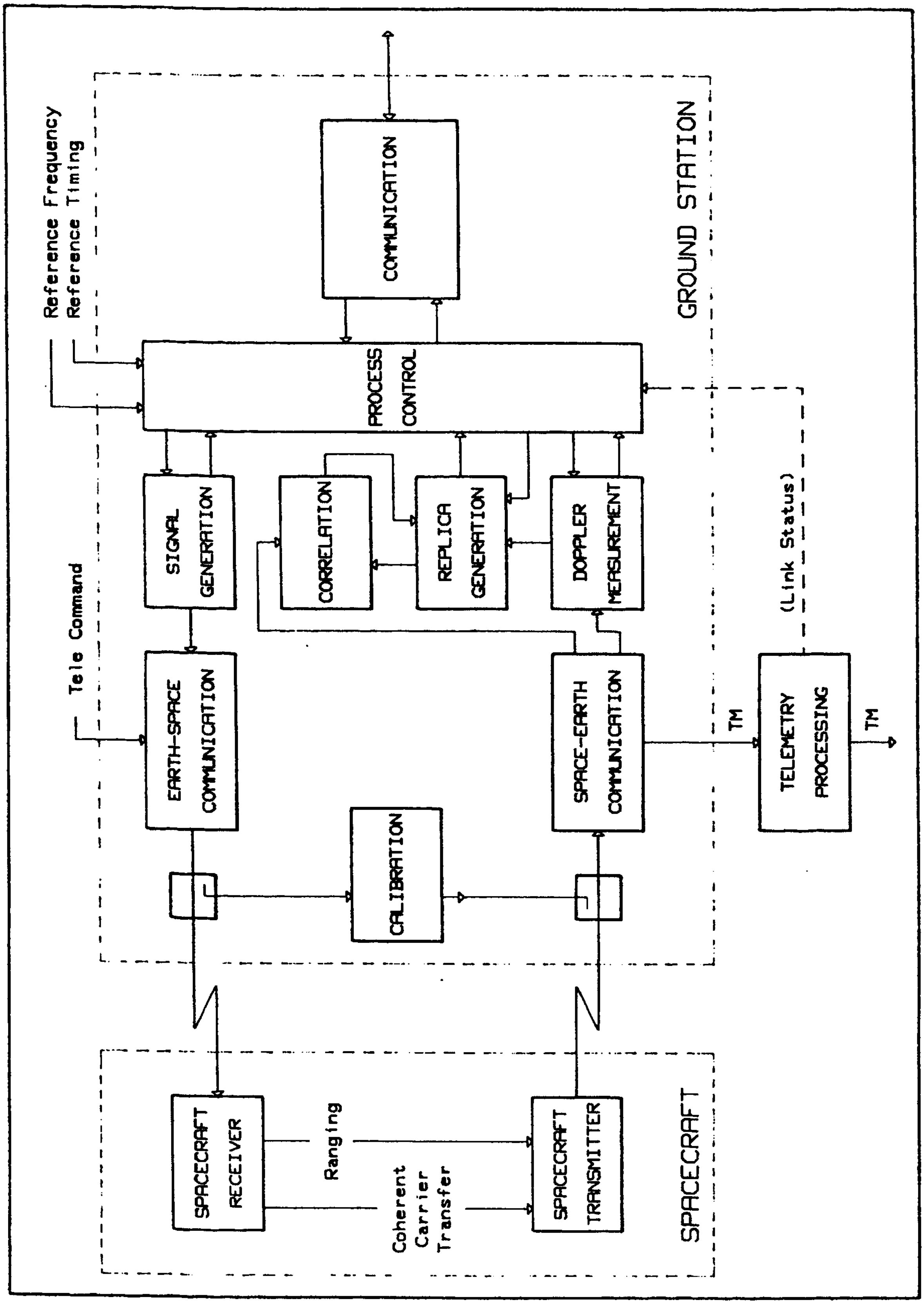


Figure 2.1 RANGING AND DOPPLER TRACKING: FUNCTIONAL BLOCK DIAGRAM

- generation of the composite ranging signal, consisting of tone and code;
- selection of the modulating source, between:
  - ranging;
  - telecommand;
  - ranging and telecommand;
- generation and phase modulation of the first Earth-to-Space link intermediate-frequency (IF) carrier;
- local-oscillator (LO) frequency selection and up-conversion of the modulated IF carrier to the assigned Earth-to-Space link radio frequency (RF);
- power amplification of the RF signal;
- transmission to spacecraft.

2.1.3 Transponder Function

2.1.3.1 Spacecraft Transponder

The spacecraft transponder function consists of:

- reception of the RF signal;
- coherent down-conversion and phase tracking of the remnant carrier;
- demodulation of ranging and telecommand signals;
- independent automatic gain control (AGC) of the remnant carrier and baseband signal chains;
- selection of the Space-to-Earth link frequency source between a free-running oscillator and the phase-locked reference frequency of the receiver;
- selection of the modulating source, between:
  - ranging (i.e. the demodulated video signal);
  - telemetry(*);
  - ranging and telemetry(*);
- modulation of the carrier;
- upconversion of the carrier to the assigned Space-to-Earth link frequency;
- transmission to Earth.

NOTE:

(*) If required, the TM shall include information allowing delay correction of the transponder.

2.1.3.2 Ground Calibration Transponder

This function consists of:

- frequency conversion of the RF signal from the Earth-to-Space link carrier frequency to the Space-to-Earth link carrier frequency for the purpose of calibrating the ground equipment delay; the ranging calibration measurement is implemented before and/or after ranging operations with the spacecraft;
- frequency conversion of the RF signal from the Earth-to-Space link carrier frequency to an offset Space-to-Earth link carrier frequency for Doppler calibration; the Doppler calibration measurement is implemented simultaneously with the Doppler measurement on the spacecraft.

2.1.4 Space-to-Earth Link Function

The Space-to-Earth Link function consists of:

- reception and amplification of the Spacecraft signal;
- downconversion to a suitable IF band, by means of local oscillators coherent with the station reference frequency or with the Earth-receiver phase-locked reference;
- phase tracking of the IF signal;
- automatic gain control;
- extraction, from the telemetry, of the spacecraft transponder status as contained in the Command Link Control Word (CLCW: see References [2] and [3]) and transfer of this information to the process control function. If the CLCW is not in the telemetry, a default process control mode will be used; (*)

NOTE:

(*) Housekeeping information which is embedded in the telemetry data stream, is normally not decommutated at the ground stations but, transmitted for spacecraft control purposes to the Control Centre:

- Information allowing delay correction of the spacecraft transponder (see Section 2.4.3) is used to support ranging data processing for orbit reconstitution.
- Transponder status, in addition to the CLCW, is needed for confirmation of relevant control commands and to initiate operational activities (e.g. start of range or Doppler operations).

- measurement of integrated Doppler shift on the Space-to-Earth link reconstructed carrier;
- optionally: simultaneous measurement of the integrated Doppler shift on the signal generated by the Doppler calibration function; this function may be needed to correct phase variations along the signal path in the station;
- generation of ranging signal replica, taking into account:
  - the frequency and phase information from the integrated Doppler function;
  - the transmitted ambiguity resolution code and the estimated two-way propagation delay towards the spacecraft;

- correlation of the generated replica with the received ranging signal;
- feedback of filtered correlation signal to the replica generation function for phase-alignment of the replica signal with the received signal;
- maintenance of ranging signal replica during interruptions of ranging modulation on the Earth-to-Space link (e.g. due to telecommand transmission), by the use of information from the Doppler function. This serves a time-sharing operation between telecommand and ranging).

2.1.5 Link Control Function

Link control functions required exclusively for the Ranging function are:

- spacecraft carrier frequency determination for noncoherent operations; this is carried out by calculation of the Doppler shift from the two-way tone transmission;
- code acquisition for ranging; sequentially:
  1) transmission of pure tone;
  2) transmission of the tone modulated with a sequence of codes;
  3) transmission of tone modulated with final code.

The control function concerned with reception and acknowledgment of link parameters, antenna beam direction control, Space-to-Earth link frequency control and Earth-to-Space link frequency control is also required for telemetry and telecommand functions. This is beyond the scope of the present Standard.

2.1.6 Data Acquisition Function

2.1.6.1 Integrated Doppler Function

This function consists of:

- reception and corresponding acknowledgment of Doppler shift measurement request messages from the communication function;
- reception and corresponding acknowledgment of station configuration and link status messages from the communication function;
- preprocessing of Doppler shift data, in support of the ranging function;
- verification of Doppler data using spacecraft status information (from the CLCW, if available) and ground equipment performance information;
- storage of Doppler data in a standard format and optional transmission to the communication function in 'on-line' mode;
- reception and acknowledgment of transfer request messages for stored Doppler data;
- Doppler shift data transfer.

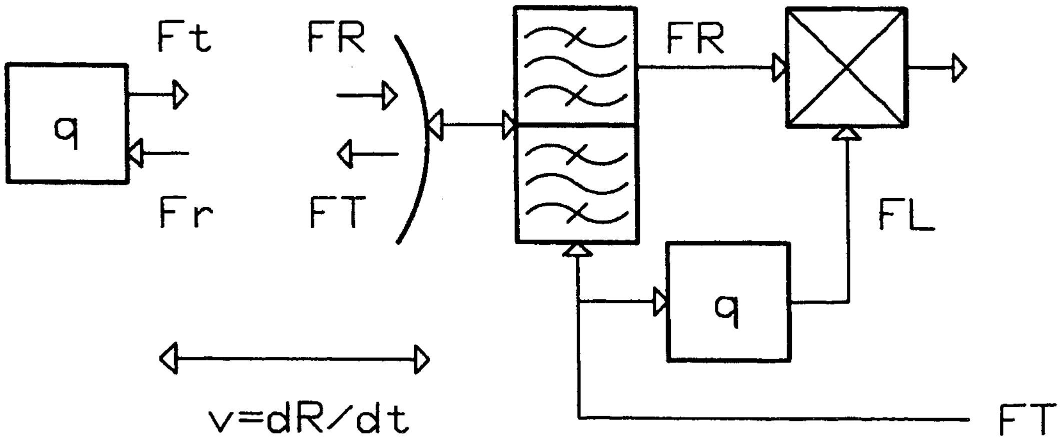
NOTE: Integrated Doppler Measurement

The radial velocity of the spacecraft is determined by measuring the two-way shift of the Earth-to-Space link carrier frequency, with the aid of a coherent transponder. A simplified diagram showing the various frequencies involved is presented in Figure 2.2.

Integrating the Doppler shift yields a change in phase angle, which represents a change in distance between the spacecraft and the Earth station.

The consecutive Doppler frequency measurements are not processed as independent velocity measurements, but the continuous phase-development versus time is measured, i.e. the Doppler frequency is read out, but the counter is not reset after the reading. This method turns the measurement into a high-resolution determination of the range, to within an unknown integration constant: since the phase, ϕ, of the Space-to-Earth link frequency is measured from an initial phase ϕ_0 at time t_0 onwards, the phase difference $(\phi - \phi_0)$ corresponds to the change in the propagation path.

This method is referred to as 'Integrated Doppler measurement' or 'Nondestructive range-rate measurement'.



v = spacecraft velocity.
c = speed of light.
Ft/Fr = FL/FT = q = turnaround ratio.

Fr = transponder received frequency.
Ft = transponder transmitted frequency.
FR = ground station received frequency.
FT = ground station transmitted frequency.
FL = ground station local oscillator frequency.

The formula for Doppler shift is :

$$FR/Ft = Fr/FT = \sqrt{\frac{1 - v/c}{1 + v/c}}$$

from which :

$$v = c * (FL - FR) / (FL + FR)$$

and

$$R - R0 = \int_{t_0}^{t} v \, dt$$

Figure 2.2 INTEGRATED DOPPLER MEASUREMENT

2.1.6.2. Range Tracking Function

The Range Tracking Function consists of:

- reception and acknowledgment of ranging initialisation request messages;
- control for generation of ranging signals and selection among different modes (i.e. Deep Space, Coherent Near Earth, Noncoherent Near Earth);
- execution of an ambiguity resolution acquisition sequence;
- execution of ranging measurements by determination of the time interval between generated and reconstructed ranging signals;
- verification of ranging data by the use of spacecraft status information (from the CLCW, if available) and ground equipment performance information;
- storage of ranging data in a standard format (output in ns, time-tagging at the transmission time etc.) and optional transmission to the communication function in 'on-line' mode;
- reception and acknowledgment of transfer request messages for stored ranging data;
- ranging data transfer.

2.2 FREQUENCY AND SPECTRUM REQUIREMENTS

2.2.1. Frequency Assignments

The Range and Doppler Tracking system can, in principle, operate in any radio frequency band, provided that sufficient bandwidth is allocated and that assignment criteria allow for the special characteristics of the signals (e.g. presence of identifiable spectral lines). Requirements concerning frequency assignment proper are defined in Reference [1].

2.2.2. Spectral Requirements

The ranging baseband signal consists of a sine wave (tone), which is phase modulated by a series of codes, used for ambiguity resolution. Each code is synchronised to the tone and can be derived from it by means of the following expression:

$$C_n = Q_1 \oplus Q_2 \oplus + \ Q_3 \oplus \ ...... \ Q_n$$

where

C_n is the n-th code

$\oplus$ stands for Exclusive Or

Q_i are squarewaves at frequencies $2^{-i} \times f_t$.
They may be generated as the outputs of a divide-by-two flip-flop chain driven by the tone.

A simple way to generate the code C_n is to transmit the previous code C_{n-1} followed by its logical complement. Each code is transmitted for a fixed period of time to perform correlation and phase alignment at the receiving site.

The RF carrier is phase modulated with this baseband signal.

The tone frequency is selectable within the range 100 kHz — 1.5 MHz.

The ranging signal spectrum changes during the ambiguity resolution process, owing to different transmitted codes. The spectrum produced when the tone alone modulates the carrier has discrete lines at the carrier frequency plus or minus integral multiples of the tone frequency (see Fig. 2.3). During the acquisition process, the code number increases and the code power is spread over an increasing number of lines (see Figs. 2.4 and 2.5). When the last step of the ambiguity resolution is completed, the code has created a quasi-continuous baseband spectrum which extends (between first nulls) from 0 Hz to twice the tone frequency (see Fig. 2.6).

The nominal tone frequency, f_t, plus and minus its expected Doppler shift, should be selected within the range 100 kHz — 1.5 MHz and in a region of the transponder bandwidth where the group delay is stable within the required accuracy. In selecting, the frequency f_t, one should take into account the following requirements.

a) Interference between Ranging and Telemetry

In order to minimise this interference, the following conditions should be met:

$|f_t - f_{sc}| \geq 2.5 \, f_{symb}$

$|f_t - 3 \times f_{sc}| \geq f_{symb}$

$|k \times f_{symb} - f_t \times D| \geq 5 \text{ Hz}$

where

f_t = tone frequency
f_{symb} = telemetry symbol rate
f_{sc} = telemetry subcarrier frequency
k = integer
D = one-way Doppler factor = $\sqrt{\frac{1 - v/c}{1 + v/c}}$
v = spacecraft radial velocity
c = speed of light

If SPL modulation is used for the telemetry signal, $f_{sc} = f_{symb}$ shall be assumed.

The interference level is strongly dependent on the ranging signal-to-noise density ratio in the spacecraft's transponder. These guidelines are applicable for high S/N_0 ratios. When the above conditions cannot be satisfied, the tone frequency shall be selected by means of an optimisation tailored to the requirements of the mission concerned.

b) Interference between Ranging and Telecommand

If the simultaneous Ranging and Telecommand mode is selected (see also Section 2.2.3.4) the following conditions should be met:

$$|2 \times m \times f_{TC} - f_t \times D| \geq 5 \text{ Hz}$$

$$|(2 \times n - 1) \times f_{TC} - f_t \times D| \geq 2 \times f_{bTC}$$

where

f_t = tone frequency
f_{bTC} = telecommand bit rate
f_{TC} = telecommand subcarrier frequency
m, n = integers
D = one-way Doppler factor = $\sqrt{\frac{1 - v/c}{1 + v/c}}$
v = spacecraft radial velocity
c = speed of light

c) Ground Equipment Frequency Plan

In order to avoid interferences with higher-order mixing products in the ground equipment, the following condition should be met:

$$|k \times f_t \times D^2 - 10 \text{ MHz}| \geq 3 \text{ kHz}$$

where

f_t = tone frequency
k = integer

D = one-way Doppler factor = $\sqrt{\frac{1 - v/c}{1 + v/c}}$

v = spacecraft radial velocity
c = speed of light

d) Deep Space Mode

In the case of Category B missions (Deep Space Mode), the selected code period shall be a submultiple of ten seconds, in order to keep the start pulse synchronised to the UTC reference. This synchronisation procedure reduces the number of possible range-tone frequencies, which are given by the following formula:

$$f_t = A \times 2^n / T$$

where

f_t = tone frequency
n = code number ($0 \leq n \leq 20$)
T = sampling period (10 s)
A = integer number of code periods in T ($1 \leq A \leq 200$)

Further explanation can be found in Reference [4].

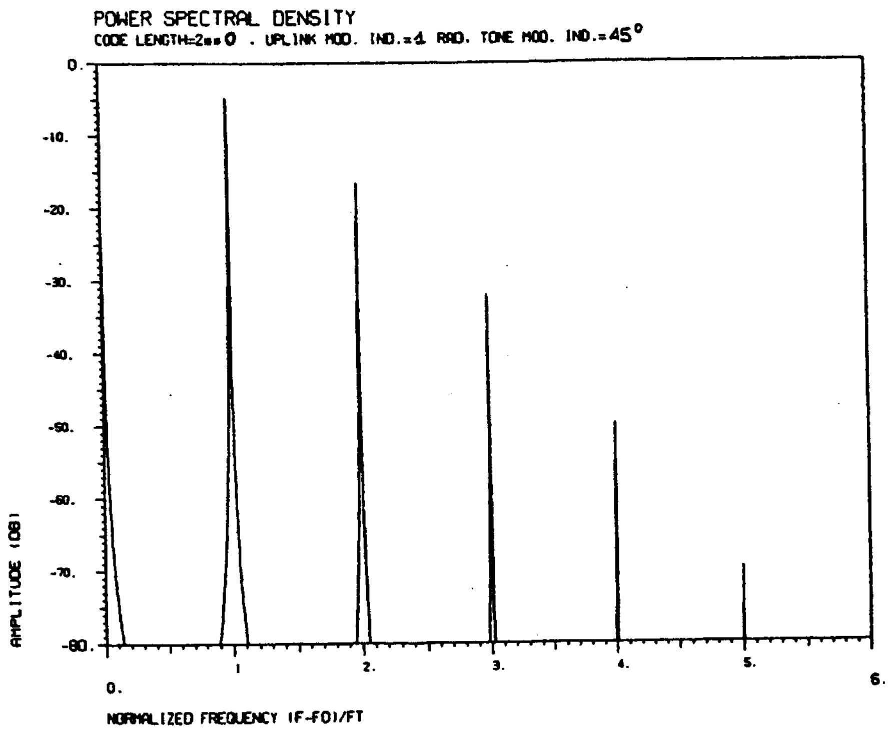


Figure 2.3

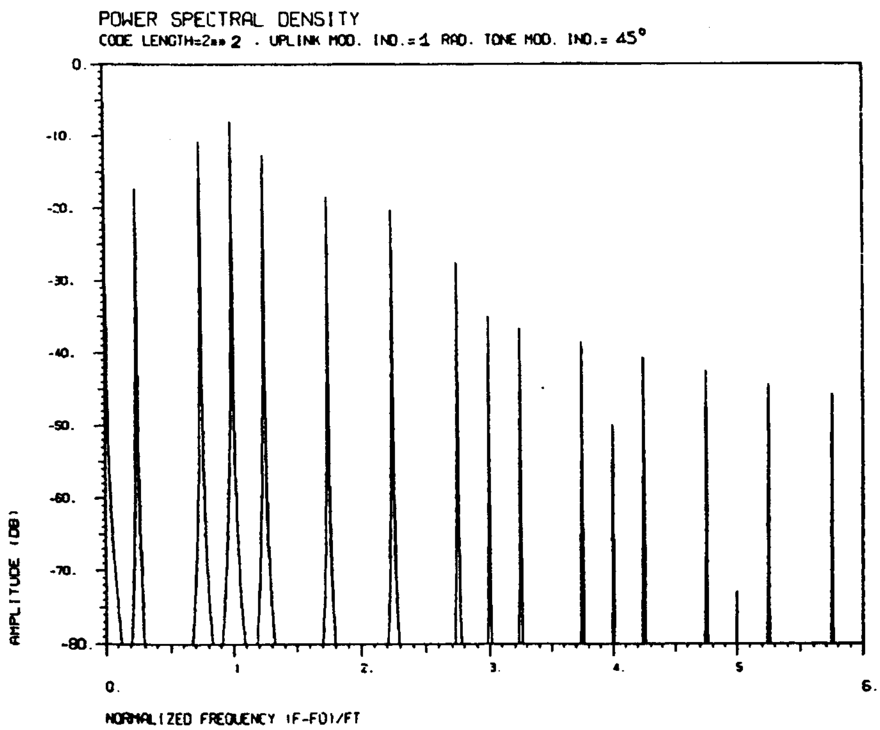


Figure 2.4

Figures. 2.3 and 2.4 RANGING SIGNAL SPECTRA

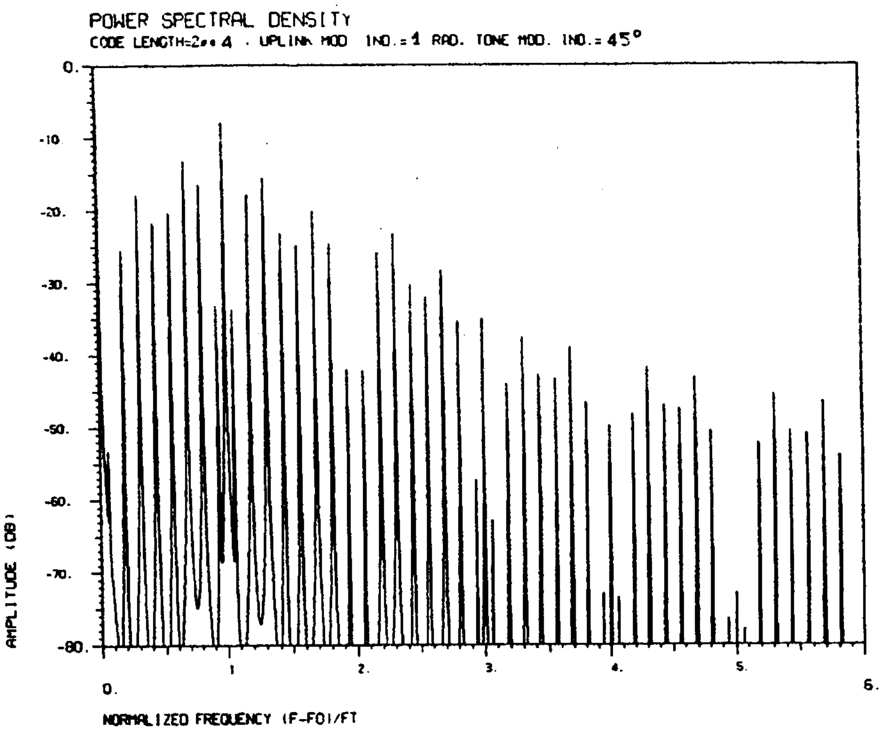


Figure 2.5

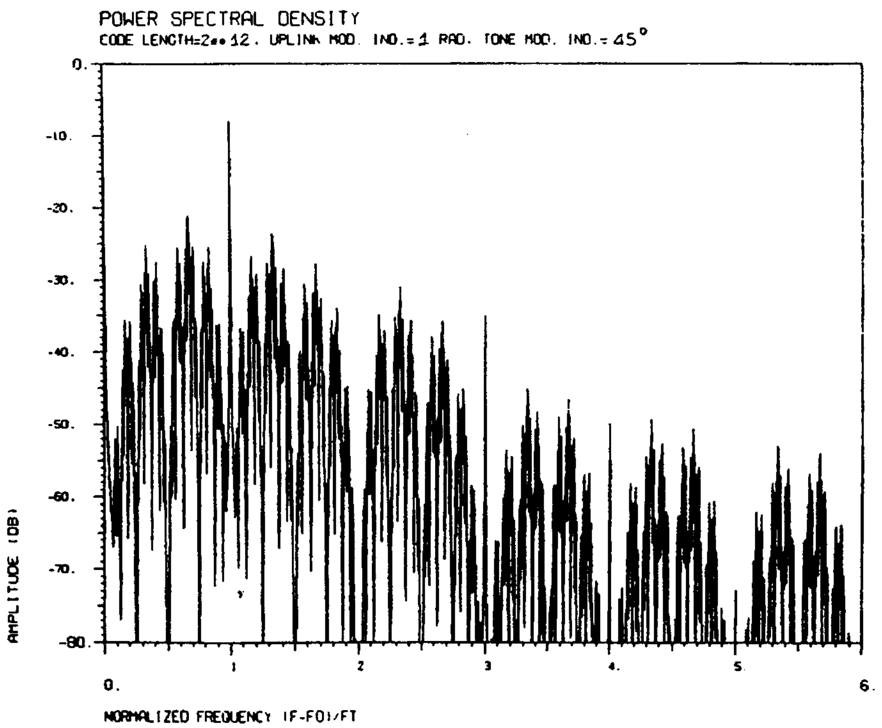


Figure 2.6

Figures 2.5 and 2.6 RANGING SIGNAL SPECTRA

2.2.3. Modulation Requirements

2.2.3.1. Modulation Technique

The modulation on both Earth-to-Space and Space-to-Earth links shall be PM. Requirements concerning modulation indexes are stated in Sections 2.3 and 2.4.

Two effects are to be considered:

1. power sharing between two or more additive signals, all phase modulated on the same link;
2. interference of the resulting overlying spectra.

2.2.3.2. Incompatible Modulation Schemes

Suppressed carrier modulation schemes (BPSK, QPSK or UQPSK), which may be selected for the telemetry, are not compatible with the ranging modulation according to this Standard. In these cases, the orbit reconstitution process may be supported by one of the following:

- Integrated Doppler tracking only, provided that on-board carrier generation is coherent. The Space-to-Earth link function generates the carrier from suppressed carrier signals.
- Time sharing between suppressed carrier telemetry and ranging. For this operation, the transponder must be fitted with the necessary (linear) phase modulator; limited (housekeeping) telemetry should be present during ranging, for spacecraft-control purposes.
- Use of a separate ranging transponder. The status of this transponder shall still appear in the telemetry stream.

2.2.3.3. Telemetry and Ranging

When an optimum choice of the tone frequency has been established, on the basis of the criteria set out in Section 2.2.2, modulation indexes shall be selected for both signals, the following being taken into account:

- power sharing between the two signals;
- mutual interference between telemetry and Ranging,
- suppression of the effective ranging-signal modulation index due to the effect of the on-board baseband AGC, which keeps the average signal-plus-noise power constant,
- a proper balance of the thresholds of the telemetry and ranging processes and the signal-to-noise ratio required in the ranging measurement.

2.2.3.4. Telecommand and Ranging

In the operations designed for the mission, telecommand and ranging can be carried out either in time sharing or simultaneously. For normal operations, and if the link performance permits this approach, simultaneous ranging and telecommand should be adopted to avoid scheduling conflicts. The following constraints shall be taken into account:

- The telecommand signal will form part of the demodulated (baseband) signal in the spacecraft transponder and will therefore appear in the modulated Space-to-Earth link. Telecommand retransmission might create undesirable effects on the transmitted spectrum, owing to power sharing and spectral overlap.
- Overmodulation of the Space-to-Earth link and telemetry signal loss may occur owing to the slow response of the on-board baseband AGC when the telecommand signal appears in an essentially noise-limited amplifier. These effects can generally be avoided operationally, by ensuring the presence of a ranging signal in the ranging channel for the whole period in which this is operational.

For cases where the link performance makes continuous ranging operations undesirable, the mission should be designed to operate ranging and telecommand in time sharing.

2.3 EARTH STATION REQUIREMENTS

2.3.1. Earth-to-Space Link Requirements

Tone frequency selectable range (f_t)	100 kHz — 1.5 MHz
Code period	$2^n/f_t$ with n = 0, 1, 2..., 20
Modulation scheme	PCM/PSK/PM
Tone modulation index (*)	45° or 28°
Carrier modulation index:	
minimum, ranging only	0.1 rad peak
nominal, ranging only	1.2 rad peak
ranging and telecommand	≤1.4 rad peak

NOTE:
(*) As a baseline, 45° is used during ambiguity resolution and 28° during the measurement phase.

Spurious signals	< -60 dBc
Phase noise density:	
for 10 Hz$<f<$1 MHz	$-48 - 10 \times \log(f)$ dBc/Hz
for $f>$1 MHz	< -108 dBc/Hz
Earth-to-Space link carrier frequency stability	see Fig. 2.7
– reference frequency stability	depends on mission requirements; see also Section 2.3.3
– upconverter phase stability	see Fig. 2.7
Group delay variation vs. time	
– Category A	20 ns/12 h
– Category B	2 ns/12 h
Group delay variation over bandwidth	
– Category A	5 ns
– Category B	included in overall accuracy requirements

In Deep Space Mode, a tone frequency and code period that repeat after 10 s shall be selected; the transmitted code shall then be synchronised to a full 10 seconds UTC. The measurements shall be time-tagged with an accuracy better than 1 μs relative to the station time.

2.3.2. Space-to-Earth Link Requirements

(a) Remnant Carrier Modulation:

Carrier/noise density	see Reference [1]
Remnant carrier under PM modulation	see Reference [1]
Ranging effective modulation index	0.01 to 0.7 rad peak
Receive chain phase stability	see Fig. 2.7
Acquisition and Tracking Requirements:	
– Minimum ranging signal/noise ratio in PLL closed-loop bandwidth ($2B_L$)	19 dB
– PLL natural frequency, selectable	1.5 r/s to 10^{-3} r/s

	Category A	Category B
Maximum Doppler Rate: (*)		
– Tracking limit	10 Hz/s	1 Hz/s
– For specified accuracy	2 Hz/s	0.02 Hz/s
Tone and code correlation period	0.5 s	1000 s
Number of codes to be resolved	n	n
Acquisition time for $n = 10$ (**)	<12 s	<1500 s
Doppler sampling rate	≤ 10/s	≤ 10/s
Ranging sampling rate	≤ 1/s	≤ 1/s

Ranging performance:

- jitter: as from link budget
- loop natural frequency (selectable): 1.5 to 10^{-3} r/s
- damping factor: 1 ± 0.1
- technological degradation: <3 dB; <4 dB at 1.5 r/s

Phase error in Integrated Doppler Measurement

- quantisation: <5 ns on offset frequency (50 kHz — 3 MHz)
- jitter: as determined by carrier demodulator dynamic behaviour (a theoretical second-order PLL dynamic behaviour can be assumed)

(b) Suppressed Carrier Modulation:

Doppler tracking is only possible in this mode (BPSK, (U)QPSK).

NOTES:

(*) The figures given here apply to the Ranging system performance only. A carrier tracking loop with sufficient bandwidth must be used to avoid losing carrier lock; this bandwidth should be considered in the relevant link budget calculations.

(**) For a probability of incorrect ambiguity resolution of 10^{-2}.

Carrier suppression	see Reference [1]
Energy per data symbol over noise density E_s/N_0	> -1.5 dB
Receive chain phase stability	see Fig. 2.7
Maximum Doppler rate:	depends only on dynamic behaviour of carrier demodulator(*)
Doppler sampling rate	≤ 10/s
Phase error in Integrated Doppler Measurement	
– quantisation	< 5 ns on offset frequency (50 kHz — 3 MHz)
– jitter	as determined by dynamic behaviour of carrier demodulator (A theoretical second-order PLL dynamic behaviour can be assumed.)

(c) Definition of the Allan variance:

$$\sigma^2(T) = \lim_{m \to \infty} \frac{1}{2m} \sum_{j=1}^{m} (d_{2j+1} - d_{2j})^2$$

where

$$d_i = \frac{\Phi(iT + T) - \Phi(iT)}{2\pi f_o T}$$

NOTE:

(*) A carrier tracking loop with sufficient bandwidth must be used to avoid losing carrier lock; this bandwidth should be considered in the relevant link budget calculations.

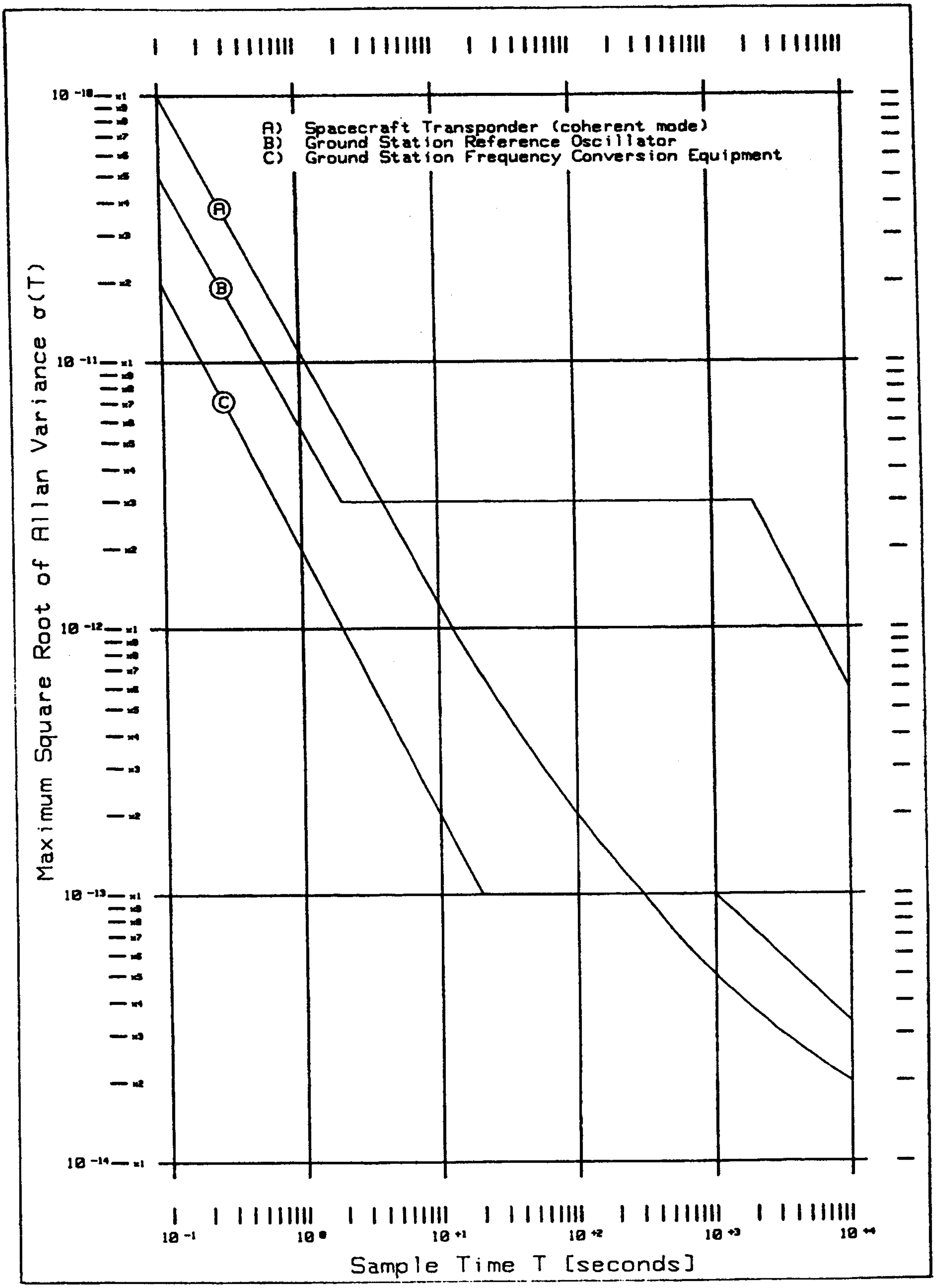


Figure 2.7 PHASE-STABILITY REQUIREMENTS

2.3.3 Requirements concerning phase and time stability

2.3.3.1 Requirements for Doppler Tracking

Coherent transponders used for Doppler tracking shall meet the phase-stability requirements of curve A in Figure 2.7. The values are applicable to the complete assembly of the equipment concerned, from uplink reception to downlink transmission. Moreover, for the combined influence of temperature and supply voltage over the operational range, input power over any 10 dB within the transponder dynamic range and uplink frequency shifts of $\pm 3 \times 10^{-5}$, the peak-to-peak phase shift of the transmitted carrier shall not exceed $\pi/2$. The ground station Doppler errors, introduced by the frequency conversion system, shall meet the requirements of Curve C in Figure 2.7. For both curves A and C, the sample time, T, to be used is the duration over which the Integrated Doppler measurement is carried out. In the phase-stability requirements concerning the ground-station reference frequency (Curve B in Fig. 2.7), the sample time T represents the signal round-trip duration. The latter requirement will ensure that the contribution to the overall error is negligible up to lunar distances. For libration-point missions, it limits the Doppler accuracy to 0.5 mm/s. For optimum performance in Category B missions, a frequency standard of better stability than that provided by the ESTRACK configurations is required.

2.3.3.2 Requirements for Ranging

For ranging, only the phase-stability requirements of Curve B in Figure 2.7 have to be met. This results in a negligible contribution to the ranging error for Category A missions. For Category B missions, the contribution to the ranging error becomes 6 ns for distances in excess of 2 AU.

2.3.3.3 Time Stability

Time shall be derived from the station reference frequency. The station time shall be correlated with UTC with an accuracy of better than 10 μs.

2.4 SPACECRAFT TRANSPONDER REQUIREMENTS

The following requirements shall apply to spacecraft transponders employed for Category A and Category B missions, except where explicitly stated otherwise.

2.4.1. Range and Range Rate Operations

For deep space operations and for those missions requiring Doppler measurements, the transponder shall be of the coherent type, i.e. the Space-to-Earth link carrier shall be derived coherently from the Earth-to-Space link carrier through multiplication by the turnaround ratio, as specified in Reference [1]. The ranging signal shall be demodulated in the transponder, from the Earth-to-Space link carrier, and then be remodulated on to the Space-to-Earth link carrier.

Two independent mode selections shall be accessible by telecommand:

1. Transponder coherent/noncoherent;
2. Ranging modulation on/off.

2.4.2. Range Only Operations

For near-Earth missions that require ranging measurements only, the Space-to-Earth link carrier does not need to be coherent with the Earth-to-Space link carrier, and the ratio between the Space-to-Earth link and the Earth-to-Space link frequencies does not need to be as specified in Reference [1].

The ranging signal shall be demodulated in the transponder, from the Earth-to-Space link carrier, and then be remodulated on to the Space-to-Earth link carrier.

One mode selection shall be accessible by telecommand:

1. **Ranging modulation on/off.**

2.4.3. Group Delay

For both Category A and Category B missions, the group delay of the ranging channel shall be constant to within ±30 ns within the range 100 kHz to 1.5 MHz from the residual carrier as seen from the diplexer/transponder interface. This specification applies over the nominal range of Doppler, input level, power supply, temperature and lifetime. If required by mission analysis, it shall be possible to know the total on-board delay at any time to a mission-specific accuracy, by means of telemetered data of voltage, temperature and predicted Doppler. This mission-specific calibration accuracy shall never be required to be better than ±5 ns for Category A and ±2.5 ns for Category B.

Calibration data of group delay measured at the agreed tone frequency (or frequencies) versus Doppler, input level, temperature and voltage shall be produced by the manufacturer, unless he can demonstrate that the data are insensitive to one of these parameters.

2.4.4. Telemetered Monitoring

In order to verify correct functioning of the system, telemetry information must be available regarding the chosen mode of operation, the receiver AGC, the receiver static phase error (SPE), the lock status and the transponder temperature and voltage.

2.4.5. Amplitude Response

The amplitude response of the ranging channel (RF in to RF out) for both Category A and Category B missions shall be:

$\pm$0.5 dB from 3 kHz to 1 MHz; (*)

$-$3 dB at frequencies below 1 kHz and above 3 MHz.

The noise bandwidth shall be $\leq$3.5 MHz. (*)

2.4.6. Phase Modulation

A positive phase shift on the Earth-to-Space link shall give rise to a positive shift on the Space-to-Earth link.

2.4.7 Baseband AGC

An AGC system in the video ranging channel, working to keep constant rms or average level of signal-plus-noise, shall be employed. The AGC response time shall be more than 10 ms and less than 30 ms.

2.4.8 Carrier Phase Stability

The requirements for coherent transponders used for Doppler tracking are stated in Section 2.3.3.1.

NOTE:

(*) In agreement with CCSDS recommendations, transponders with $\pm$0.5 dB from 3.5 kHz to 100 kHz and with noise bandwidth $\leq$200 Hz can be supported. In support of such missions, the tone frequency to be used will be approximately 100 kHz. See also Section 4.3.

2.4.9 Modulation Index

The nominal Space-to-Earth link modulation index for the ranging channel shall be in the range 0.1 to 0.7 rad. For Category B missions, this index shall be selectable by telecommand to at least two values between 0.2 and 0.7 rad. Link design shall ensure that the effective Space-to-Earth link ranging modulation index is always >0.01 rad.

2.5 PERFORMANCE REQUIREMENTS

2.5.1 Integrated Doppler Performance

The maximum measurement rate shall be ten samples per second. The Doppler shift shall be measured on carriers downconverted in the range 50 kHz to 3 MHz. Downconverted carrier frequency shall be such that, with the maximum expected Doppler shift, the offset frequency is >50 kHz.

The Doppler Unit shall measure:

- the number of zero crossings of the downconverted carrier;
- the time interval between the 10 Hz UTC pulses and the next positive zero-crossing of that signal.

The quantisation error of the measurement shall be <5 ns. Time tagging of data shall be at the above-mentioned 10 Hz UTC pulses; time-tagging accuracy shall be better than 1 μs with respect to station time (see Section 2.3.3.3). Cycle slippage shall be detected by processing of the Doppler data.

2.5.2 Ranging Performance

Range measurement accuracy must not be confused with the orbit-determination accuracy. The aim of this section is to emphasise those requirements which determine the end-to-end performance of the ranging system. The accuracy of the range measurement is affected by several error sources, which are the following:

a) the error due to the uncertainty in the delay through the on-board transponder;

b) the error due to the Earth ranging equipment, excluding the influence of thermal noise at the receiver input;

c) the error due to the influence of thermal noise at the input of the Earth-to-Space link and Space-to-Earth link receivers.

The minimum requirements concerning system accuracy are as follows:

a) **On-board Transponder Error**
This error is proportional to the instability of the transponder group delay. In the absence of calibration requirements, the specified overall group delay stability must be taken, i.e. 30 ns leading to 4.5 m for ESA missions and 50 ns leading to 7.5 m for CCSDS support. If mission-specific calibration requirements exist (see Section 2.4.3.), the error shall be derived from the allowed calibration accuracy.

b) **Earth Ranging Equipment Error**
The ranging phase measurement accuracy shall be better than 0.01 rad of the tone or 3 ns, whichever is larger, plus the error due to the reference oscillator stability (only of importance for Category B missions).

c) **Influence of Thermal Noise at the Earth Receiver Input**
The influence of thermal noise at the Earth receiver input requires the specification of minimum signal-strength levels. The minimum requirements for the Earth equipment are specified in Section 2.3.2.

The variance in the ranging measurement due to the above-mentioned thermal-noise levels depends on the selected loop bandwidth and tone frequency. The actual variance to be expected should be derived from the link budget (degradation on tone jitter <3 dB; <4 dB for 1.5 r/s loop bandwidth). The ground ranging equipment can produce ranging samples, at a maximum rate of 1 Hz, which might be preprocessed for the purpose of decreasing the variance of the measurement.

2.5.3 Ancillary measurements

The accuracy of the orbit determination process is also determined by the error due to the propagation of electromagnetic waves through the atmosphere (both tropospheric and ionospheric propagation errors, multipath effects and scintillations) and the error in the station position measurement.

For the correction of the tropospheric error, the following measurements shall be available with the specified accuracy:

- atmospheric pressure ± 2 mbar
- temperature ± 1°C
- relative humidity ± 1%

The station location shall be determined to an accuracy of 2 m.

For modelling of ionospheric density variation, two measurement methods can be supported:

- Dual-frequency Doppler (this requires a dual carrier-frequency transmission from the spacecraft);
- Differenced Range Versus Integrated Doppler (DRVID).

PAGE INTENTIONALLY LEFT BLANK

3. VERIFICATION OF COMPLIANCE

The compatibility of ranging transponder and Earth equipment must be demonstrated by a series of tests. Such tests may be combined with similar telecommand and telemetry compatibility tests and shall be made with spacecraft and Earth station equipment which is electrically representative of the operational units. Such equipment might, for example, be engineering or qualification models which are integrated, for ease of use, into a portable 'Compatibility Test Unit' (sometimes referred to as 'suitcase').

The following tests will be run in order to demonstrate compatibility:

a) Frequency measurement of Space-to-Earth link carrier as a function of time after switch-on.

b) Spectrum examination of Space-to-Earth link:
   (i) Check for spurious signals;
   (ii) Measurements of modulation indices;

c) Output power of the transponder transmitter.

d) Phase jitter of the Space-to-Earth link carrier.

e) Ranging signal group delay as a function of ranging-tone frequency, Earth-to-Space link power and Doppler shift, power supply, temperature and lifetime, and comparison with the values established during spacecraft-system testing.

f) Demonstration of correct ambiguity resolution, as a function of input signal level.

g) Acquisition and hold of the phase-locked loop of the transponder receiver.

h) Coherent transponder phase stability (Allan variance).

PAGE INTENTIONALLY LEFT BLANK

4. COMPATIBILITY WITH OTHER GROUND NETWORKS

The degree of compatibility between the ESA Ranging system described in this Standard and other networks is given below. This listing is indicative and not exaustive. Details have to be agreed with the competent operator of the network concerned.

4.1 TONE RANGING

Some networks employ a 100 kHz tone ranging system (e.g. CNES and INPE; ESA also does so, but it is currently being phased out). Transponders compliant with Section 2.4 of this Standard will be compatible with that system provided that the following requirements are met:

- **Space-to-Earth link Modulation Index**
  The Space-to-Earth link modulation index shall be between 0.2 and 0.7 rad peak.

- **Input Signal Range**
  Correct functioning of the transponder, for ranging purposes, shall be possible over an input signal range of −115 dBm to −50 dBm (300 K noise input).

There are still some stations that are fitted with equipment according to the GSFC Aerospace Data Systems Standards, Part 2, Standard 2.3 'S-Band Ranging System Standard', dated 1975-08-08. Transponders compliant with Section 2.4 of this Standard will be compatible with such a system, provided that the following requirements are met:

- **Range Tone Frequencies**
  The ranging channel of the transponder shall be capable of operating with tone frequencies down to 3840 Hz;

- **Minimum Space-to-Earth Link Index**
  The Space-to-Earth link index of any tone shall not be less than 0.2 rad peak for an Earth-to-Space link consisting of a major tone, a minor tone and noise.

4.2 DSN

Transponders compliant with the requirements concerning Category B missions (Section 2.4) will be compatible with the DSN Ranging System.

4.3 CCSDS

In the recommendations of the Consultative Committee for Space Data Systems, it is agreed that minimum requirements shall be recommended for cross support between networks. This Ranging Standard puts more stringent requirements on both ground and space equipment for ESA's internal use. Cross support for spacecraft meeting CCSDS recommendation will be provided by ESA, but performance requirements are degraded with respect to ESA performance (see Section 2.5).

APPENDIX

Glossary of Acronyms

AGC	Automatic Gain Control
AU	Astronomical unit
BPSK	Binary Phase Shift Keying
CCSDS	Consultative Committee for Space Data Systems
CLCW	Command Link Control Word
CNES	Centre National d'Etudes Spatiales
DRVID	Differenced Range Versus Integrated Doppler
DSN	Deep Space Network
ESA	European Space Agency
ESOC	European Space Operations Centre
ESTEC	European Space Research and Technology Centre
GSFC	Goddard Space Flight Center
IF	Intermediate Frequency
LO	Local Oscillator
NRZ	Non Return to Zero
PCM	Pulse Code Modulation
PLL	Phase Locked Loop
PM	Phase Modulation
PSK	Phase Shift Keying
QPSK	Quaternary Phase Shift Keying
RF	Radio Frequency
rms	root mean square
SPE	Static Phase Error
SPL	Split Phase Level
STAB	Standards Approval Board
TC	Telecommand
TM	Telemetry
TTC	Telemetry, Tracking and Command
TT&C	Telemetry, Tracking and Command
UQPSK	Unbalanced Quaternary Phase Shift Keying
UTC	Coordinated Universal Time