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European Standard (Telecommunications series)

Satellites Earth Stations and Systems (SES); Radio Frequency and Modulation Standard for Telemetry, Command and Ranging (TCR) of Geostationary Communications Satellites

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Contents

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Foreword

This European Standard (Telecommunications series) has been produced by ETSI Technical Committee Satellite Earth Stations and Systems (SES), and is now submitted for the Public Enquiry phase of the ETSI standards Two-step Approval Procedure.

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1 Scope

The present document applies to Geostationary Communications Satellites operating their Telemetry, Command and Ranging (TCR) systems in C- and Ku-Band.

The present document sets out the minimum performance requirements and technical characteristics of the ground/satellite Radio Frequency (RF) interface partially based on Spread Spectrum Multiple Access (SSMA).

With the growing number of satellites, the co-location constraints and the maximization of bandwidth for Communications Missions, and interference has motivated the elaboration of the present document for geostationary satellites based on Spread Spectrum techniques.

The present document addresses the following requirements:

- Telemetry;
- Command (Telecommand);
- Ranging.

Currently, no RF and Modulation standard exists for the TCR of geostationary communication satellites. The aim of the present document is to respond to such requirements. There are consequently similarities with existing agency standards, like [2], [3] and [4], although some specifics have been introduced to respond to the requirement of multiple access for collocated geostationary communication satellites.

2 References

The following documents contain information, which through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication and/or edition number or version number) or non-specific.
- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, the latest version applies.

[1] ETSI TR 101 956 (V1.1.1): "Satellite Earth Stations and Systems (SES); Technical analysis of Spread Spectrum Solutions for Telemetry Command and Ranging (TCR) of Geostationary Communications Satellites".

[2] ESA PSS-04-105 (Issue 2.4, 1996): "Radio Frequency and Modulation Standard".

[3] ESA PSS-04-109 (Issue 1.6, 1996): "Radio Frequency Standard for Data Relay Systems".

[4] ESA PSS-04-104 (Issue 1, 1990): "Ranging Standard - Volume 1: EUR 10 Direct Ground to Spacecraft Ranging".

[5] ESA PSS-04-103 (Issue 1, 1989): "Telemetry Channel Coding Standard".

3 Definitions and abbreviations

3.1 Definitions

For the purposes of the present document, the following terms and definitions apply:

Equivalent Isotropic Radiated Power (EIRP): product of transmitter power and maximum antenna gain, equivalent to an isotropic source radiating uniformly in all directions

Binary Channel: binary communications channel (BPSK has 1 channel, QPSK has 2 channels)

Spread Spectrum Multiple Access (==Code Division Multiple Access): modulation of a carrier by a code sequence, with association of a code to each user

Data Rate: total number of uncoded data bits per second after packet and frame encoding

NOTE 1: See figure 1 and figure 2. This is the Data Rate used in Link Budgets in [1]

Symbol Rate: total symbol rate after FEC coding

NOTE 2: See figure 1 and figure 2.

Channel Symbol Rate: symbol rate per channel after FEC channel coding and channel allocation

NOTE 3: See figure 2. This applies only to multi-channel modulations, thus to spread spectrum QPSK modes and not to standard PM/FM modes.

Co-located Equivalent Capacity (C.E.C): number of collocated satellites that can be controlled with a perfect power balanced link between the ground and the satellite

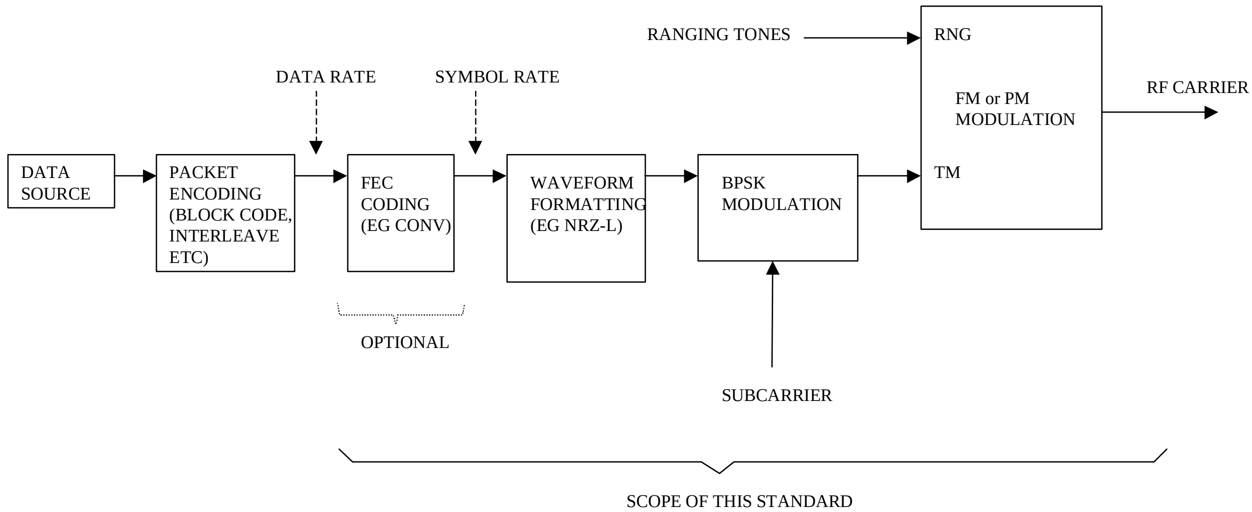

Figure 1: Functional stages of transmit chain for standard modulation

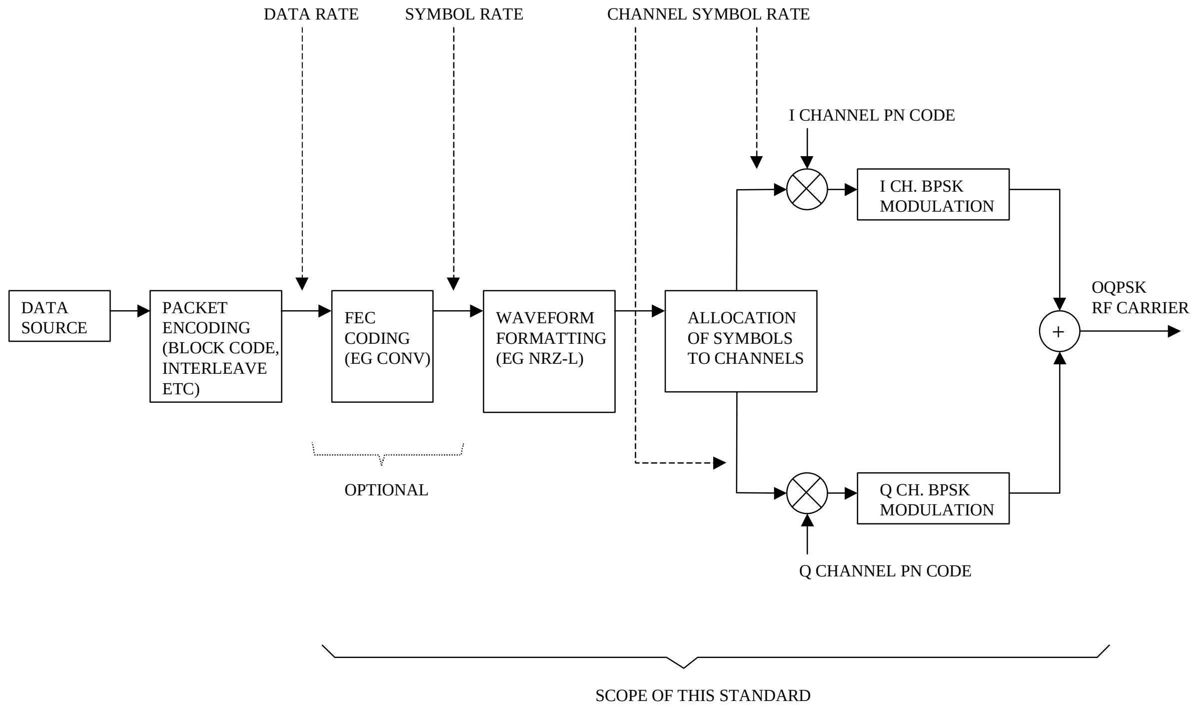

Figure 2: Functional stages of transmission chain for spread spectrum modulation

3.2 Abbreviations

For the purposes of the present document, the following abbreviations apply:

BPSK	Binary Phase Shift Key
CDMA	Code Division Multiple Access
COM	COMmunication channel
CW	Continuous Wave
DS	Direct Sequence
DSSS	Direct Sequence Spread Spectrum
DRSS	Data Relay Satellite System (ESA)
DRTS	Data Relay & Tracking System (NASDA)
ECSS	European Co-operation for Space Standardization
EIRP	Equivalent Isotropic Radiated Power
FEC	Forward Error Correction
FM	Frequency Modulation
GTO	Geostationary Transfer Orbit
HPA	High Power Amplifier
IEE	Institution of Electrical Engineers
LEOP	Launch and Early Orbit Phase
MTC1	TeleCommand mode 1
MTC2	TeleCommand mode 2
MTM1	TeleMetry mode 1
MTM2	TeleMetry mode 2
MTM3	TeleMetry mode 3
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Astronautics and Space Development Administration (Japan)
NRZ-L	Non Return to Zero-Level
NRZ-M	Non Return to Zero-Mark
OQPSK	Offset Quadrature Phase Shift Key
PCM	Pulse Coded Modulation
PDF	Probability Density Function
PM	Phase Modulation

PN	Pseudo Noise
QPSK	Quadrature Phase Shift Key
RF	Radio Frequency
RG	RanGing
SP-L	Split Phase-Level (== Bi-Φ -Level or Manchester encoded) signal waveform
SRRC	Square Root Raised Cosine
SS	Spread Spectrum
SSMA	Spread Spectrum Multiple Access
STD	STanDard (for standard modulation)
TC	TeleCommand
TCR	Telemetry, Command and Ranging
TDRSS	Tracking and Data Relay Satellite System (NASA)
TM	TeleMetry
TTC/TT&C	Telemetry Tracking and Command (== Telemetry, Command and Ranging, TCR)
UQPSK	Unbalanced Quadrature Phase Shift Key
w.r.t	with respect to

4 Applicability

The present document applies to the typical TCR scenario shown in figure 3. The scenario comprises k satellites, which may be co-located on the same orbital position. Each satellite also goes through other mission phases like LEOP, drift and possibly emergency mode. These satellites may be controlled/monitored by N different TCR Ground Stations. The TCR links defined in the present document have to coexist with the Communication ground terminals and associated links also shown in figure 3.

The present document defines the modulation on the TCR links. Modulation formats are described in clause 5 modulation requirements, and the associated mission phases are described in annex A.

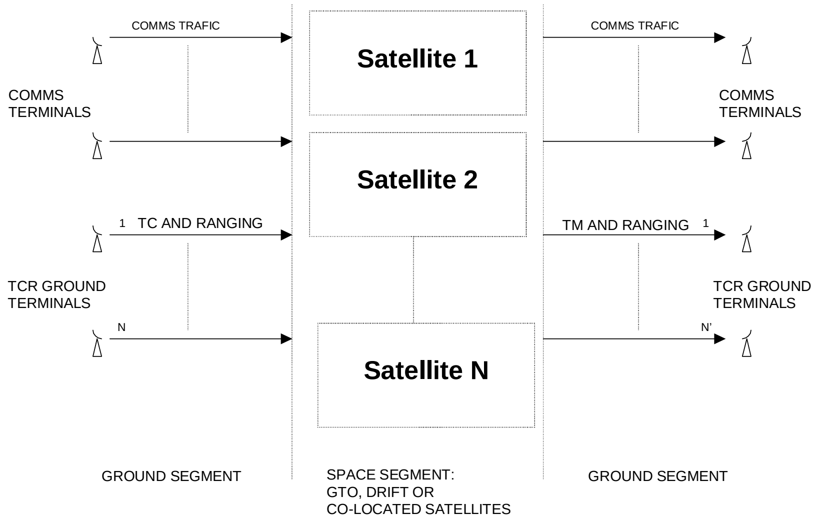

Figure 3: Typical applicable scenario

5 Modulation Requirements

5.1 General

The generic system functional block diagram is shown in figure 4. Modulation modes and configurations are shown in table 1.

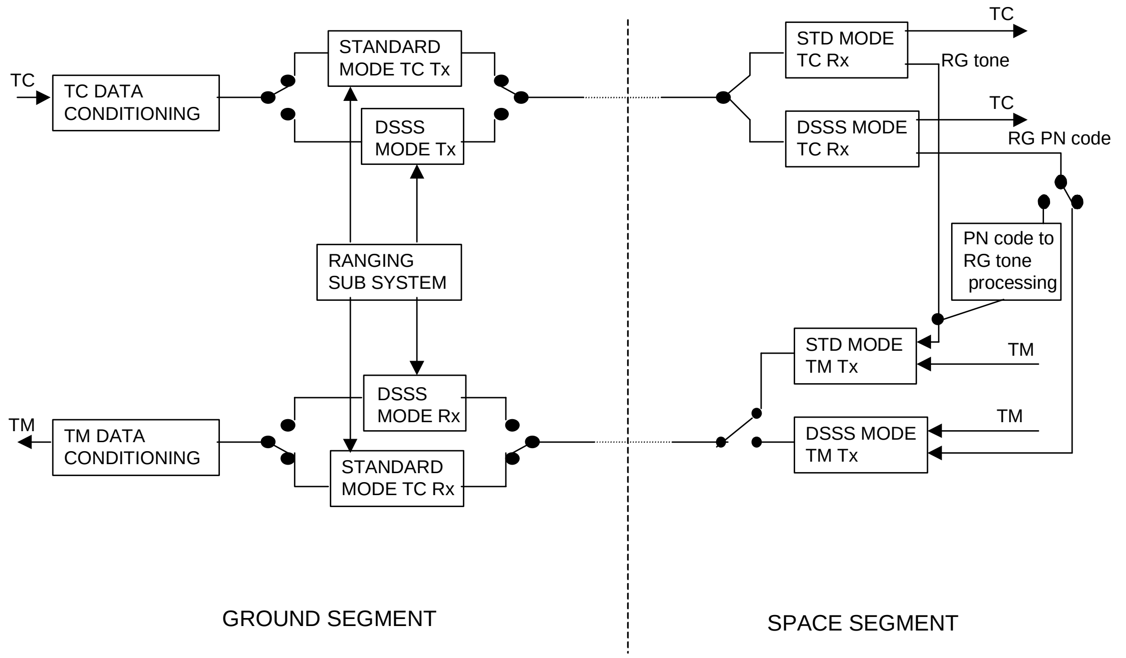

Figure 4: Generic system functional block diagram

Table 1: Modulation Modes and Potential Configurations

	All Standard Mode	All Spread Mode	Hybrid Mode
Uplink	MTC1: PCM/BPSK/FM	MTC2: PCM/SRRC-UQPSK	MTC2: PCM/SRRC-UQPSK
Downlink (with Ranging (see note): requires uplink present)	MTM1: PCM/BPSK/PM	MTM2: PCM/ SRRC-OQPSK (PN code clock/epoch sync to uplink clock/epoch)	MTM1: PCM/BPSK/PM
Downlink (without ranging: can operate without uplink present))	MTM1: PCM/BPSK/PM	MTM3: PCM/ SRRC-OQPSK (PN code clock/epoch independent of uplink clock/epoch)	MTM1: PCM/BPSK/PM
NOTE: Further definition of ranging signals is given in following clauses.			

In order to retain backward compatibility with existing ground networks and to allow simple operation during LEOP, in addition to the new Spread Spectrum modes, the existing "standard" FM/PM modulation modes are retained. It is envisaged that telecommand and telemetry modulation formats shall be independently configurable, allowing for example the following configuration possibilities (see also annex A for implementations and TR 101 956 [1]):

- all standard mode (as has existed in previous systems) using tone ranging on FM uplink (MTC1) and PM (MTM1) downlink;

- all spread mode (Direct Sequence Spread Spectrum: DSSS) using PN spreading code regenerative ranging on suppressed carrier up-and down-links (MTC2 and MTM2);

- hybrid mode using PN spreading code ranging on suppressed carrier DSSS uplink (MTC2), and tone ranging on PM downlink (MTM1).

In addition, on the spread spectrum (DSSS) mode downlink, there are 2 PN code sets defined, for coherent and non-coherent modes (modes MTM2 and MTM3 respectively). The physical partitioning of the functions may not exactly follow that shown in the system functional block diagram. The modulation configuration of the various modes is described in the rest of clause 5 modulation requirements. Possible allocation of modes to mission phases is defined in annex A.

5.2 Standard modulation

The Standard mode modulation formats shall be Frequency Modulation (FM) on Telecommand uplink and Phase Modulation (PM) on Telemetry downlink. The standard modes shall be known as MTC1 and MTM1 respectively.

5.2.1 Modulating waveforms

The following modulating waveforms are permitted in standard modes:

- Telemetry (mode MTM1): a sine wave sub carrier, itself BPSK modulated by PCM data;
- Telecommand (mode MTC1): a sine wave subcarrier, itself BPSK modulated by PCM data;
- Ranging (mode MTC1 + MTM1): an unmodulated sinewave subcarrier or combination of a number of such subcarriers.

5.2.2 PCM waveforms and symbol rates

PCM data signals shall be limited to the waveforms and symbol rates given in table 2.

Table 2: PCM waveforms and rates

Function	Symbol rate (symbols/second)	PCM waveform	Special Requirements
Telecommand (Mode MTC1)	Between 8 symbols/s up to 4 000 symbols/s (see note)	NRZ-L NRZ-M	n=0 is limited for use with 16 kHz subcarrier
Telemetry (Mode MTM1)	Between 64 symbols/s up to 20 ksymbols (see note)	NRZ-L NRZ-M SP-L	
NOTE: Coherency between symbols and sub-carrier is required.			

5.2.3 Use of subcarriers

The subcarriers and modulating waveforms that shall be used are listed in table 3.

Table 3: Subcarriers used with FM Or PM Rf carriers

Function	Subcarrier (kHz)	Modulation Waveform	Subcarrier Waveform
Telecommand (Mode MTC1)	8 or 16	NRZ-L NRZ-M	Sine
Telemetry (Mode MTM1)	0,1 to 1 000	NRZ-L NRZ-M SP-L	Sine
Ranging (Mode MTM1 + MTC1)	0,1 to 100	None (CW Tone)	Sine

5.2.4 Choice of Subcarrier Frequencies

For telecommand transmission using a subcarrier, only two subcarrier frequencies are permitted.

The subcarrier frequency shall be 8 kHz for all telecommand rates up to 2 000 sym/s. A 16 kHz subcarrier shall be used only in cases where the 4 000 sym/s symbol rate is needed or when required by the operator.

The choice of the ranging and telemetry subcarrier frequencies shall take into account the requirements of:

- carrier acquisition by the ground receivers;
- compatibility between ranging and telemetry;
- occupied bandwidth.

Modulation of subcarriers used for telemetry and telecommand shall be BPSK (for ranging the subcarriers are unmodulated tones).

The following requirements shall be met for TC and TM subcarriers:

- for NRZ-L and NRZ-M signal waveforms, the subcarrier frequency shall be a multiple (integer) of the symbol rate from 4 to 1 024;
- for SP-L signal waveforms, the subcarrier frequency shall be an even integer multiple of the symbol rate from 4 to 1 024;
- at each transition in the PCM waveform, the subcarrier shall be reversed in phase;
- the transitions in the PCM waveform shall coincide with a subcarrier zero crossing to within ±2,5 % of a subcarrier period;
- at all times, for more than 25 % of a subcarrier period after a phase reversal, the phase of the modulated subcarrier shall be within ±5° of that of a perfect BPSK signal;
- for NRZ-L and SP-L waveforms, the beginning of the symbol intervals shall coincide with a positive-going subcarrier zero crossing for symbols "1" and with a negative-going zero crossing for symbols "0";
- for NRZ-M waveforms, the beginning of the symbol intervals shall coincide with a subcarrier zero crossing.

5.2.5 Uplink carrier deviation (Frequency Modulation)

The FM deviation (modulation depth) is stated in table 4.

Table 4: FM uplink frequency deviation

Function	Deviation (kHz)
Telecommand (PCM/FM) (Mode MTC1)	Up to ±400 kHz
Ranging Earth-to-space (FM) (Mode MTC1) (total deviation of all simultaneous major and minor tones)	Up to ±400 kHz

5.2.6 Downlink PM modulation index

Minima and maxima of the modulation index are stated in table 5.

Table 5: PM modulation index

Function	Min. (radians peak)	Max. (radians peak)
Telemetry (PCM/NRZ/PM) (Mode MTM1)	0,1	1,5
Ranging space-to-Earth (PM) (Mode MTM1)	0,01	1,5

5.2.7 PM sense of modulation

A positive-going video signal (modulated TM subcarrier and/or ranging) shall result in an advance of the phase of the downlink Radio Frequency carrier.

5.3 Spread Spectrum Modulation

The spread modulation formats shall be:

- Telecommand Uplink: Square Root Raised Cosine filtered Unbalanced QPSK (SRRC-UQPSK);
- Telemetry Downlink: SRRC filtered Offset QPSK (SRRC-OQPSK).

The spread modulation modes shall be as follows:

- Mode MTC2: spread spectrum telecommand uplink;
- Mode MTM2: spread spectrum telemetry downlink, coherent mode (long PN code);
- Mode MTM3: spread spectrum telemetry downlink, non-coherent mode (short PN code).

The Spread Spectrum modulation characteristics shall be as defined in table 6. The modulation modes listed shall be available for communications between the Spacecraft and the Earth Terminal for a range of data rates. Symbol rates referred to in the present document include the channel coding overhead whenever channel coding is applied. The Symbol rate shall be selected depending on requirements, link budget and multiple access capabilities. Modulator imperfections are defined in annex C.

Table 6: Spread Spectrum Link Modulation Modes

	Telecommand link, Mode MTC2	**Coherent Telemetry link, Mode MTM2**	**Non-Coherent Telemetry Link, Mode MTM3**
Symbol Rate	4 000/2^n n=0,1..9	2^n n=6..14	2^n n=6..14
Channel Symbol rate on I channel (sym/s)	=Symbol Rate	=Symbol Rate (Same symbols on both channels)	=Symbol Rate (Same symbols on both channels)
Channel Symbol rate on Q channel (sym/s)	PN code only	=I channel symbol rate (Same symbols on both channels)	=I channel symbol rate (Same symbols on both channels)
Data format	NRZ-L NRZ-M	NRZ-L NRZ-M	NRZ-L NRZ-M
PN code family I channel	Gold code	Truncated m-sequence	Gold code
PN Code length I channel	2^{10}-1	(2^{10}-1) × 256	2^{11}-1
Code I epoch reference	None	Received Q code of MTC2	None
PN code family Q channel	Truncated m-sequence	Truncated m-sequence	Gold code
PN Code length Q channel	(2^{10}-1) × 256	(2^{10}-1) × 256	2^{11}-1
Code Q epoch reference	I code	x + 1/2 chips (x > 20 000) Delay w.r.t I ch of MTM2	1/2 chip delay w.r.t I of non-coherent mode return link
Spreading code rate (Mc/s)	1 Mchip/s or 3 Mchip/s	Identical to Received code	1 Mchip/s or 3 Mchip/s
Modulation	SRRC-UQPSK	SRRC-OQPSK	SRRC-OQPSK
I/Q power ratio	10:1	1:1	1:1
Ranging service possible	Yes	Yes	No
Modulator Imperfections (see annex C):			
Phase Imbalance (°)	< 2°	< 5°	< 5°
Amplitude Imbalance (dB)	< 0,25	< 0,25	< 0,25
Data asymmetry	< 0,03	< 0,03	< 0,03
Data bit jitter	< 0,01	< 0,01	< 0,01
PN code chip asymmetry	< 0,01	< 0,01	< 0,01
PN code chip jitter	< 0,01	< 0,01	< 0,01
Chip transition time	< 0,05	< 0,05	< 0,05
I/Q data bit skew	< 0,01	< 0,01	< 0,01
I/Q PN code chip skew	< 0,01	< 0,01	< 0,01

The Telecommand uplink signal in mode MTC2 shall be a spread spectrum SRRC-UQPSK modulated signal with the data and a short PN code on the I Channel and a long PN code on the Q channel. It has Square Root Raised Cosine (SRRC) chip shaping.

The coherent mode telemetry downlink signal in mode MTM2 shall be a spread spectrum SRRC-OQPSK modulated signal with data on the Q channel and on the I channel. MTM2 supports ranging by transmission of a long PN code on the downlink I channel synchronized to the code received on the mode MTC2 uplink Q channel. A delayed version of this code is transmitted on the downlink Q channel.

Mode MTM3 shall be a spread spectrum SRRC-OQPSK modulated signal with the data on the Q channel and on the I channel. MTM3 does not support ranging. A short (Gold) PN code is transmitted on the I channel and a half chip delayed Gold code is transmitted on the Q channel.

For all spread PN coded transmissions, the data shall be modulo-2 added asynchronously to the PN code and any pulse shaping (i.e. SRRC) performed before being applied to the carrier modulator.

5.3.1 Chip shaping

Pulse or chip shaping shall be applied to the baseband signal prior to linear modulation, in order to achieve bandwidth restriction of the spread spectrum signal. To implement a symmetric band limited channel, Square Root Raised Cosine (SRRC) filtering (see annex D) shall be used at both the transmitter and the receiver on the telecommand and telemetry links.

SRRC filtering is defined in terms of a roll off factor α which has a value between 0 and 1, with the RF bandwidth of the spread spectrum signal given by $(1 + \alpha)$Rc, where Rc is the chip rate.

For the purposes of the present document $\alpha = 0{,}5$ shall be used, giving an RF bandwidth of 1,5 Rc.

5.4 Coherency properties

In mode MTM1 and MTC1, coherency between symbols rate and sub-carrier is required.

In non-coherent spread mode (MTM3), all of the clocks/carriers shall be derived from references local to the spacecraft and independent of the uplink: downlink RF carrier, TM data clock, PN chip clock and PN Epoch shall be local to the spacecraft.

In coherent spread mode (MTM2), the downlink PN code Epoch and chip clock shall be synchronized to the uplink Q channel PN code. However, other downlink clocks/carriers may be local to the spacecraft and independent of the uplink: downlink RF carrier and TM data shall be local to the spacecraft.

5.4.1 FEC Channel Coding

In order to achieve all requirements for the present document (see [1], annex B), following the analysis documented in [1], it has been concluded that a minimum FEC coding gain of up to 5 dB may be required in spread spectrum modes on both Telecommand and Telemetry links. Selection of FEC code type is outside the scope of the present document. An example of a coding scheme that can achieve such gain is documented in annex G.

6 Requirements on transmitted signals

6.1 Frequency stability requirements

6.1.1 Uplink

In mode MTC2 (spread spectrum), the on-board receiver shall tolerate:

- A frequency shift due to Doppler effect of 1,4 ppm (for RF carrier, chip rate and data rate);
- A ratio $\frac{\textit{Doppler rate}}{\textit{Frequency}}$ of $1{,}2 \times 10^{-9}$ Hz (for RF carrier, chip rate and data rate).

In mode MTC1 (FM), the on-board receiver shall tolerate:

- A frequency shift due to Doppler effect of 22 ppm (for RF carrier, subcarrier and data rate);
- A ratio $\frac{\textit{Doppler rate}}{\textit{Frequency}}$ of $1{,}7 \times 10^{-6}$ Hz (for RF carrier, subcarrier and data rate).

The ground contribution to those deviations shall be negligible.

6.1.2 Downlink

The Doppler values to take into account for the downlink shall be identical to uplink.

The stability of the on-board generated RF frequency (for modes MTM1 or MTM2) shall be better than 5 ppm (end of life).

The stability of the on-board generated downlink chip rate (for mode MTM3) shall be better than 5 ppm (end of life).

6.2 Turnaround frequency ratio

No turnaround frequency ratio is required between the up and down RF links, since there shall be no coherency between uplink and downlink carriers.

6.3 Polarization

Polarization is operator and mission phase dependent, and its definition is beyond the scope of the present document.

6.4 Phase noise

The phase noise measured on a unmodulated carrier between 10 Hz and 100 kHz around the carrier shall be less than:

Frequency w.r.t. the carrier	Noise density (dBc/Hz)
10	-35
100	-63
1 000	-63
10 000	-72
100 000	-105

7 Link Acquisition requirements

The acquisition time of the uplink signal shall be better 3 s, with a success probability better than 99 %.

For the downlink, the acquisition time of the downlink signal shall be better 10 s, with a success probability better than 99 %.

In Modes MTC2, MTM2 and MTM3, the maximum Doppler that can be acquired without precompensation is specified in clause 6 requirements on transmitted signals. For mission phases where Doppler is greater than this amount, either Standard Mode (MTC1/MTM1) shall be used, or Doppler precompensation shall be used to reduce the uncertainty below that specified in clause 6 requirements on transmitted signals.

In Mode MTM3, a long (truncated m-sequence) PN code is used, of length 256 × 1 023 chips. In order for the Ground demodulator to acquire this code, epoch estimation is required. This estimation shall be within ±1 000 chips, as used on Agency Data Relay Systems.

Annex A (informative): Operational configuration

Communications satellites faces different radio-frequency environment, depending on mission phase. There are 4 main different mission phases to consider: LEOP phase, drift orbit, nominal on station phase and emergency on station phase.

Depending of the on-board implementation of the standard, spread spectrum or standard modulation can be used for uplink or downlink. The aim of this annex is to describe the operational configuration of three different possible implementations of the standard.

These three configurations are:

- Configuration 1: on board dual mode receiver and on board dual mode transmitter;
- Configuration 2: on board dual mode receiver and Standard transmitter;
- Configuration 3: on board dual mode receiver, Standard transmitter and dedicated RG SS transmitter.

A typical frequency plan is shown in figure 5.

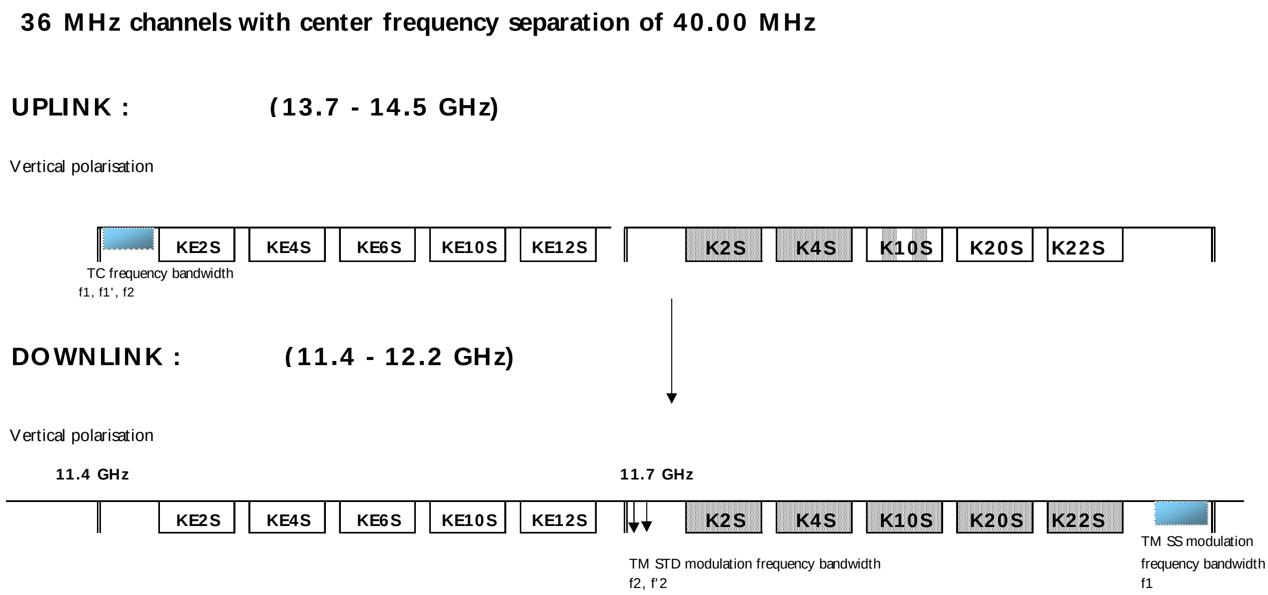

Figure 5: Typical TCR Frequency Plan (Ku-Band)

This frequency plan defines various TCR frequencies, but depending of the implementation; some of the frequencies are not used. It has been assumed for the analysis of SS modes (see [1]) that any TC-echo effect on the TM signal is negligible.

Uplink:

- f2 is the SS frequency;
- f1 and f1' are in the same bandwidth as f2.

Downlink:

- f1 is the SS frequency;
- f2 and f2' are the STD modulation frequency, in a different bandwidth than the SS bandwidth.

For each configuration below, the modulation mode (MTC1, MTC2, MTM1, MTM2, MTM3) refers to the definition given in clause 5 modulation requirements.

A.1 Configuration 1: on board dual mode receiver and on board dual mode transmitter

On board the satellite, a dual mode receiver shall be used, enabling the demodulation of either spread spectrum or standard modulation signal (both demodulations are done in parallel but only one is successful, depending of the modulation of the uplink signal). Dual mode transmitters (or two different transmitters, one for STD and one for SS modulation) are used for the downlink.

The receiver and the transmitter simultaneously use spread spectrum in Spread Spectrum mode, and simultaneously use standard modulation in Standard Mode.

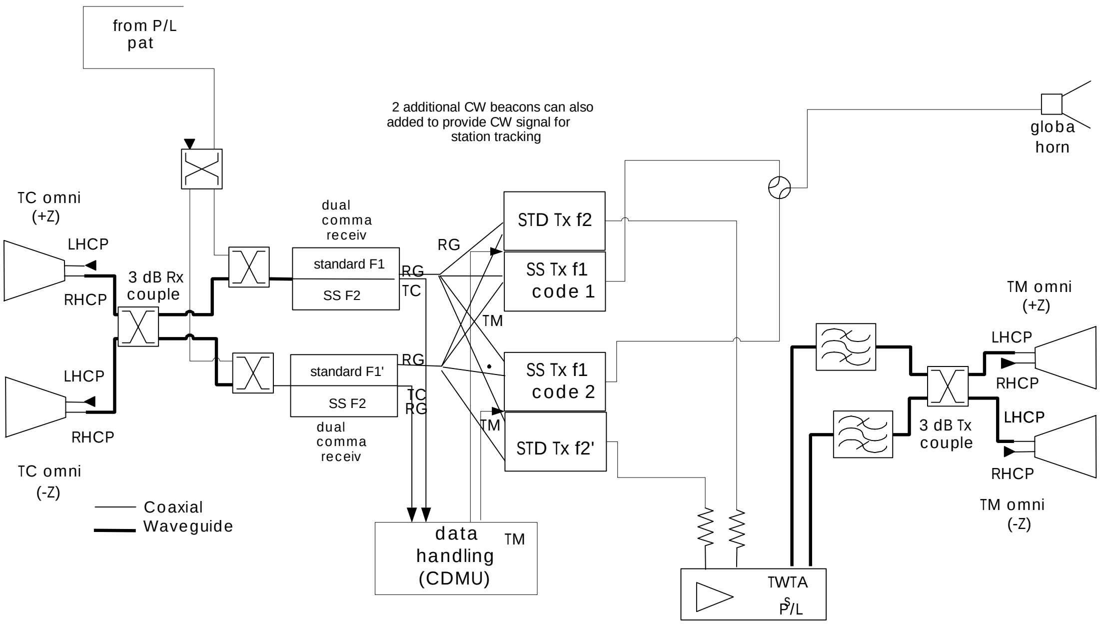

Figure 6: Configuration 1 typical TCR/RF architecture

The associated on-board TCR/RF architecture is shown in figure 6.

The different operational configurations and the associated bandwidth are described in table 7.

Table 7: Configuration 1 frequency and modulation assignment

	Beginning of the LEOP	**LEOP, apogee phase (low Doppler, possibility of jamming with Geo satellites)**	**Drift orbit (low Doppler, possibility of jamming with Geo satellites)**	**On station nominal**	**On station emergency**
TC	STD (*MTC1*), F1 or F'1	SS (*MTC2*), F2	SS (*MTC2*), F2	SS (*MTC2*), F2	STD (*MTC1*), F1 or F'1
TM	STD (*MTM1*), f2 or/and f'2	SS (*MTM2 or 3*), f1	SS (*MTM2 or 3*), f1	SS (*MTM2 or 3*), f1	STD (*MTM1*), f2 or/and f'2
RG	Idem TC/TM (see note 1)	Idem TC/TM (see note 2)	Idem TC/TM (see note 2)	Idem TC/TM (see note 2)	Idem TC/TM (see note 1)
NOTE 1: TC and RG can be done simultaneously, depending of RF link budget margin and compatibility between RG tones and TC sub-carrier. NOTE 2: TC and RG can be done simultaneously.					

Note that for the emergency:

- it may be necessary to command sequentially each satellite of a fleet of collocated satellites using the same bandwidth;
- it may be necessary to foresee for the downlink an additional bandwidth ("emergency bandwidth"), distinct from the nominal TM bandwidth.

A.2 Configuration 2: on board dual mode receiver and Standard transmitter

On board the satellite, a dual mode receiver shall be used, enabling the demodulation of either spread spectrum or standard modulation signal (both demodulations are done in parallel but only one is successful, depending of the modulation of the uplink signal). Standard transmitters are used for the downlink, whatever the mission phase of the satellites. A specific process (see annexe) enables the transformation of a PN code into a RG tone, so that for certain phases of life, SS modulation can be used for the uplink (including RG) while STD modulation is used for the downlink.

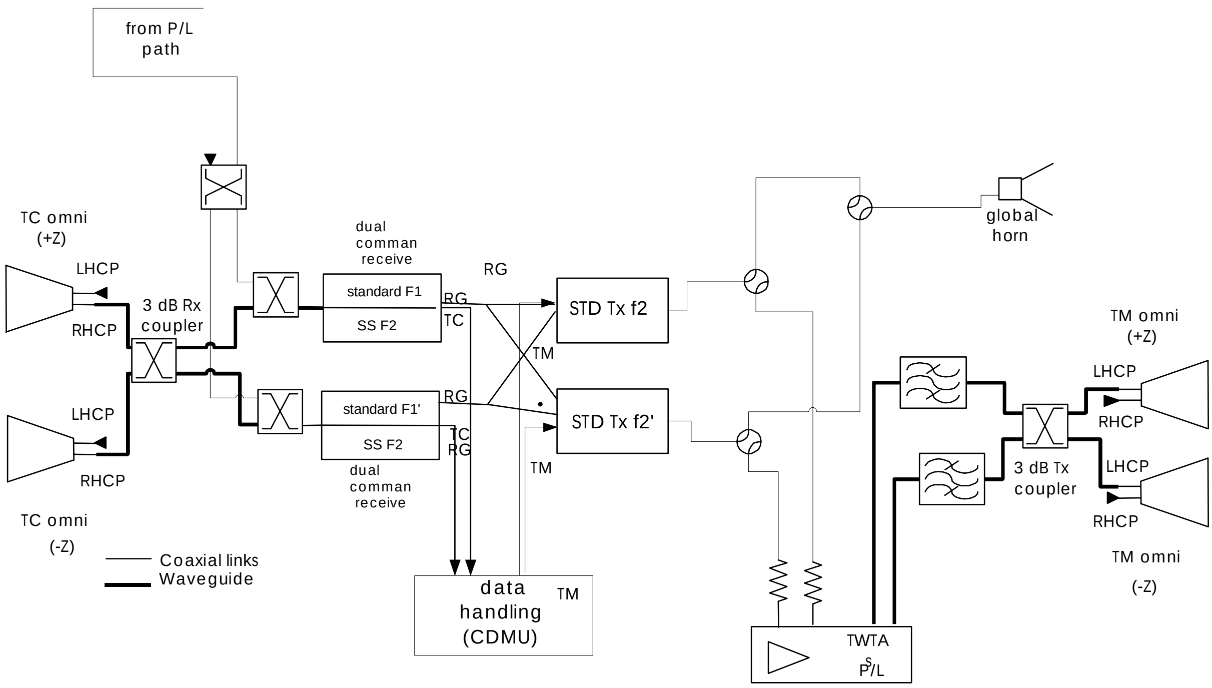

Figure 7: Configuration 2 typical TCR/RF architecture

The associated on-board TCR/RF architecture is presented in figure 7.

The different operational configurations and the associated bandwidth are described in table 8.

Table 8: Configuration 2 frequency and modulation assignment

	Beginning of the LEOP	LEOP, apogee phase (low Doppler, possibility of jamming with Geo satellites)	Drift orbit (low Doppler, possibility of jamming with Geo satellites)	On station nominal	On station emergency
TC	STD (*MTC1*), F1 or F'1	SS (*MTC2*), F2	SS (*MTC2*), F2	SS (*MTC2*), F2	SS (*MTC2*), F2
TM	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2
RG	Idem TC/TM (hybrid RG) (see note 1)	Idem TC/TM (hybrid RG) (see note 2)	Idem TC/TM (hybrid RG) (see note 2)	Idem TC/TM (hybrid RG) (see note 2)	Idem TC/TM (hybrid RG) (see note 2)
NOTE 1: TC and RG can be done simultaneously, depending of RF link budget margin and compatibility between RG tones and TC sub-carrier. NOTE 2: TC and RG can be done simultaneously.					

Note that for the emergency:

- it may be necessary to command sequentially each satellite of a fleet of collocated satellites using the same bandwidth;
- no additional bandwidth ("emergency bandwidth") is required for the emergency downlink.

A.3 Configuration 3: on board dual mode receiver, Standard transmitter and dedicated RG SS transmitter

On board the satellite, a dual mode receiver shall be used, enabling the demodulation of either spread spectrum or standard modulation signal (both demodulations are done in parallel but only one is successful, depending of the modulation of the uplink signal). Standard transmitters are used for the downlink TM, whatever the mission phase of the satellites. Concerning the RG, a dedicated SS transmitter is used each time SS RG is used for the uplink.

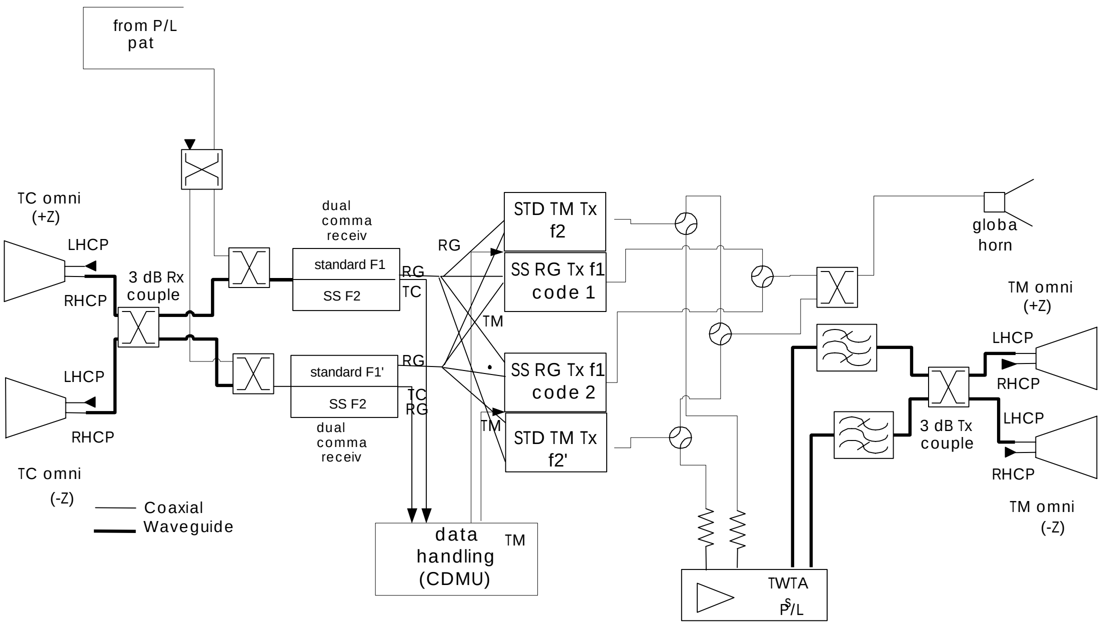

Figure 8: Configuration 3 typical TCR/RF architecture

The associated on-board TCR/RF architecture is presented in figure 8.

The different operational configurations and the associated bandwidth are described in table 9.

Table 9: Configuration 3 frequency and modulation assignment

	Beginning of the LEOP	LEOP, apogee phase (low Doppler, possibility of jamming with Geo satellites)	Drift orbit (low Doppler, possibility of jamming with Geo satellites)	On station nominal	On station emergency
TC	STD (*MTC1*), F1 or F'1	SS (*MTC2*), F2	SS (*MTC2*), F2	SS (*MTC2*), F2	SS (*MTC2*), F2
TM	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2	STD (*MTM1*), f2 or/and f'2
RG	Idem TC/TM (see note 1)	SS up F2, SS down f1 (see notes 2 and 3)	SS up F2, SS down f1 (see notes 2 and 3)	SS up F2, SS down f1 (see notes 2 and 3)	STD up F2, STD down f1 (see note 2)
NOTE 1: TC and RG can be done simultaneously, depending of RF link budget margin and compatibility between RG tones and TC sub-carrier. NOTE 2: TC and RG can be done simultaneously. NOTE 3: The modulation used for RG is identical to *MTM2* (see clause 5 modulation requirements) except that no TM data is down linked.					

Note that for the emergency:

- it shall be necessary to command sequentially each satellite of a fleet of collocated satellites using the same bandwidth;
- it shall be also necessary for the system to foresee 2 downlink bandwidths, one for SS RG, and one for STD modulation TM&RG.

Annex B (informative): Hybrid Ranging process description

The hybrid RG process enables the use of spread spectrum RG for the uplink, and the use of standard RG tone for the downlink.

B.1 Presentation

For the uplink, a RG PN code is transmitted to the satellite, in accordance with the standardized modulation of clause 4 applicability.

The satellite receives the uplink spread spectrum signal (PN code) and uses the clock of this PN code to generate some synchronized RG tones. The phase of the tone corresponds to the beginning of the PN code, and there is an integer multiple of tone periods during the PN code epoch. This ranging is transmitted to the ground by using standard modulation (PM modulation), and the ground baseband unit measured the delay between this tone and the original transmitted PN code (see figure 9).

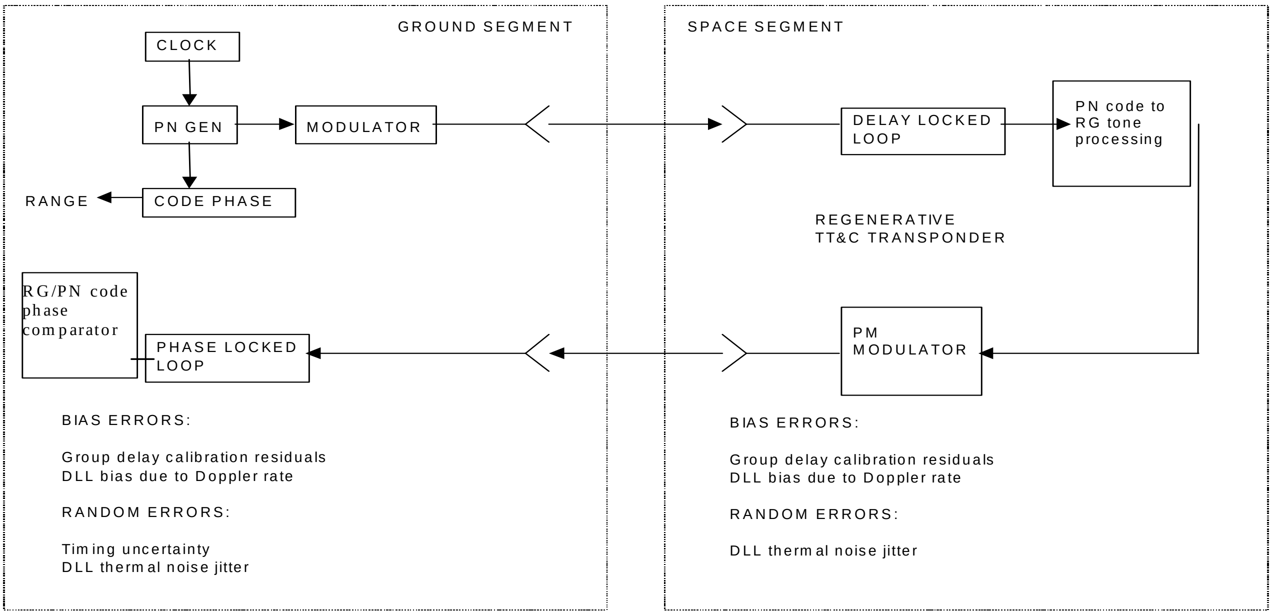

Figure 9: Hybrid Ranging presentation

The timing diagram of the sequence is detailed in figure 10.

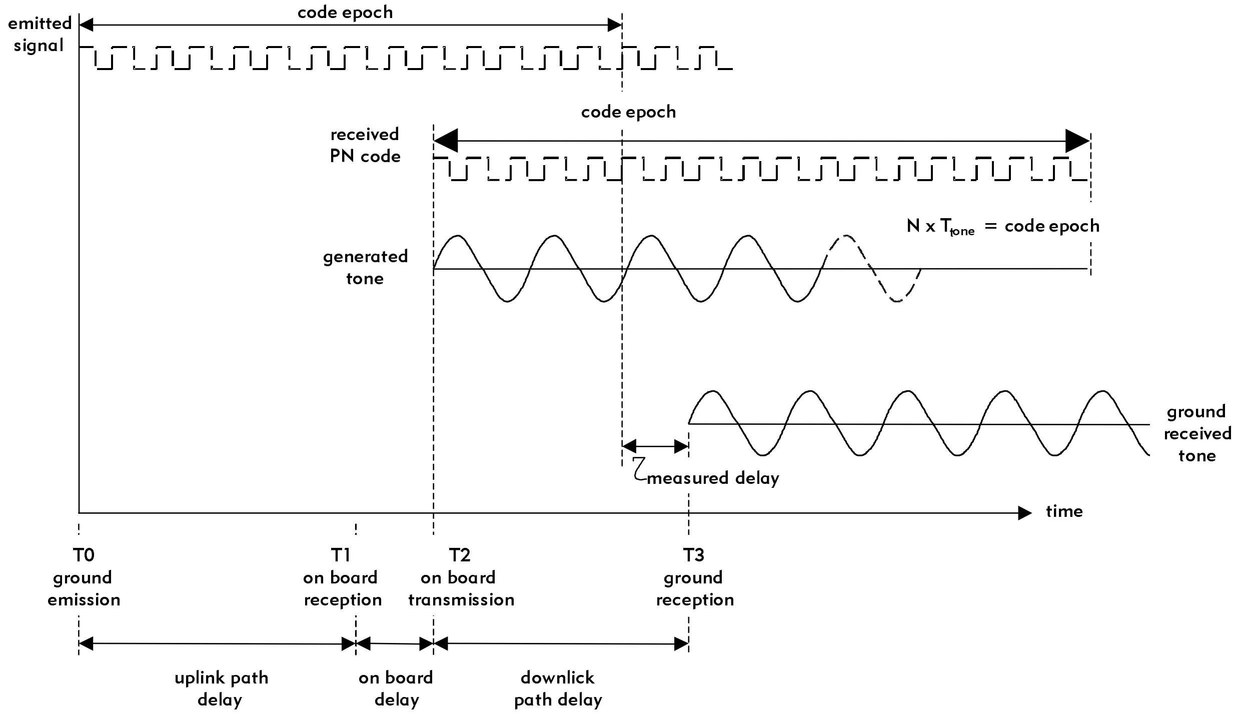

Figure 10: RG hybrid timing diagram

B.2 Distance ambiguity resolution

The ambiguity of the distance is resolved by using major and minor tones.

The generation of the different tones is processed on board, as explained through figure 11.

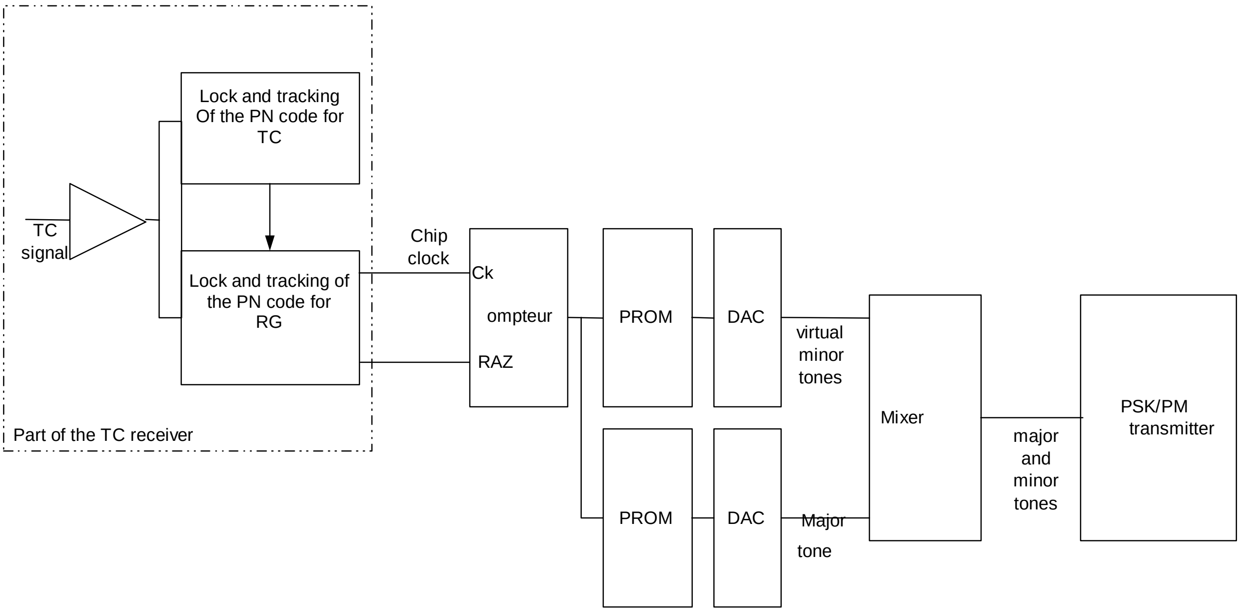

Figure 11: Hybrid ranging on board processor architecture

A first DAC delivers virtual tones, from 8 Hz to 20 kHz.

The second DAC delivers the major tone.

The RG measurement is performed:

- with the major tone for the accurate measurement (but the ambiguity will have to be solved);
- with the minor tones sent sequentially, but simultaneous with the major tone to solve ambiguity. Virtual minor tones being difficult to send (very low frequency), real tones equal to linear combination of those tones can be sent.

The on board processor will have to send sequentially each minor tone (for example we change of minor tone each N chips epochs).

At ground level, the RG tones null is compared to the origin of the PN code epoch, and this measured delay is used to determine (with the ambiguity of the major tone) the distance. This measurement is repeated for every minor tone, so that at the end of the measure, the ambiguity is solved (existing ambiguity resolution algorithm shall be used).

B.3 Calibration

For the RG calibration (estimation of the on board delay and/or of the ground delay), short loop (connection of the ground baseband unit output directly to the ground baseband unit input) is possible, but more difficult than using standard modulation, as uplink and downlink modulation are different. Details of the implementation are given in [1].

Another solution is to measure with the real ground equipment, and the satellite hardware, the delay of the link, without knowing what is specifically the on-board or the ground contribution.

Once in orbit, the ground station can be re-calibrated frequently in relative value, through the temporarily use (for the calibration phase) of standard modulation.

Annex C (informative): Modulator imperfections

C.1 Phase imbalance

The modulated signal, at the output of the modulator, is a sum of two signal components called In Phase Channel (I-channel) and Quadrature Phase Channel (Q-channel) respectively. The two signal components have the same carrier with an ideal phase difference of 90°.

The modulated signal has two signal states for BPSK modulation and four signal states for QPSK modulation. Each signal state, N, is characterized by an amplitude, $A_{(N)}$, and a phase, $\Phi_{(N)}$, where $\Phi_{(N)}$ is defined as the difference between the phase of the modulated carrier, when in state N, and the phase of the unmodulated carrier.

C.2 BPSK phase imbalance

For BPSK the ideal phase between the two signal states, with phase $\Phi_{(1)}$, where $\Phi_{(2)}$ respectively, is 180°. The phase imbalance is defined as:

$$\text{BPSK Phase Imbalance (deg)} = 180° - \left|\Phi_{(1)} - \Phi_{(2)}\right|$$

where |argument| denotes the absolute value of the argument.

C.3 QPSK phase imbalance

For QPSK the ideal phase between the four signal states depend on the ideal In Phase to Q channel power ratio. The ideal phase difference, θ_{ideal}, is provided in versus In Phase to Q channel (I/Q) power ratio.

Table 10: Ideal signal state phase differences

I/Q Power Ratio	θ_{ideal}
1:1	90°
1:10	35,1° and 144,9°

Let $\Phi_{(N)}$ denote the phase difference between the actual signal states. The phase $_{(N)}$ imbalance is then defined as:

$$\text{QPSK Phase Imbalance (deg)} = \text{Maximum}\left(\left|\Phi_{(N)} - \Phi_{(ideal)}\right|, N = 1, 2, 3, 4\right)$$

C.4 Amplitude imbalance

The modulated signal has two signal states for BPSK and four signal states for QPSK modulation. Each signal state, N, is characterized by an amplitude, $A_{(N)}$, and a phase, $\Phi_{(N)}$. The modulated signal from a Phase Shift Keying modulator, being either BPSK, QPSK, UQPSK or OQPSK, is ideally a constant envelope signal or the ratio between the maximum and minimum signal state amplitude is 1:1. Let A_{max} and A_{min} denote the actual amplitudes for the signal state with the maximum amplitude and the signal state with the minimum amplitude as follows:

$A_{max} = \text{Maximum}(A_{(N)}, N = 1, 2, 3, 4)$

$A_{min} = \text{Minimum}(A_{(N)}, N = 1, 2, 3, 4)$.

The amplitude imbalance is then defined as:

Amplitude Imbalance (dB) = 20 × log(A_{max}/A_{min}).

C.5 Data asymmetry

The data signal is a continuous sequence of symbols. For NRZ data format, two different symbols exist where one denotes logical zero and the other logical one. The length or duration of the symbol denoting logical zero is ideally equal to the length of the symbol denoting logical one.

The actual length of the symbol denoting logical zero might not be equal to the actual length of symbol denoting logical one. Let L_1 denote the average length of symbols denoting logical one in a data sequence and L_0 denote the average length of symbols denoting logical zero in the data sequence. The data asymmetry is defined as:

$$\text{Data Asymmetry} = \left| (L_0 - L_1)/(L_0 + L_1) \right|$$

C.6 Data bit jitter

The data signal is a continuous sequence of symbols. For NRZ data format, two different symbols exist where one denotes logical zero and the other logical one. The length or duration of the symbol denoting logical zero is ideally equal to the length of the symbol denoting logical one.

The actual length of the symbol denoting logical zero might not be equal to the actual length of symbol denoting logical one. Let L_1 denote the average length of symbols denoting logical one in a data sequence and L_0 denote the average length of symbols denoting logical zero in the data sequence. Moreover, let VL_0 denote the variance of the length of symbols denoting logical zero, which is defined as the average of (length of logical zero symbol $L_0)^2$, and let VL_1 denote the variance of the length of symbols denoting logical one. The data bit jitter is defined as:

$$\text{Data Bit Jitter} = \frac{\sqrt{VL_1 + VL_0}}{L_1 + L_0}$$

C.7 PN code asymmetry

Defined as for data asymmetry but with chips in place of bits.

C.8 PN code chip jitter

Defined as for data bit jitter but with chips in place of bits.

C.9 Chip Transition Time

The modulated signal has two signal states for BPSK modulation and four signal states for QPSK modulation. Each signal state, N, is characterized by an amplitude, $A_{(N)}$, and a phase, $\Phi_{(N)}$, where $\Phi_{(N)}$ is the steady state phase angle.

Ideally the phase $\Phi_{(N)}$ changes from the one signal state to the other signal state in an infinitely short time. The actual transition time from the phase $\Phi_{(1)}$, for signal state 1, to change to the subsequent phase $\Phi_{(2)}$, for signal state 2, lasts a finite duration.

Chip Transition Time = the time duration to switch from 90 % of $\Phi_{(1)}$ to 90 % of $\Phi_{(2)}$ divided by the average chip duration

C.10 I/Q Data Bit Skew

When the data rate modulating the I channel and the data rate modulating the Q channel are the same, there is as ideal relative time delay between the instants of data transitions on the one channel and the instants of data transitions on the other channel. The I/Q data bit skew defines the deviation from this ideal relative time delay. For QPSK the ideal relative time delay is zero whereas for staggered QPSK the relative time delay is 0,5.

Let $t(I_i)$ and $t(Q_i)$ denote the actual data bit transition instants on the I channel and the Q channel respectively. Moreover, let L_d denote the average length of the data bits and let δ denote the ideal relative time delay. The I/Q data bit skew is defined as:

$$\text{I/Q Data Bit Skew} = \text{Average}((t(I_i) - t(Q_i)))/ L_d - \delta)$$

where i denotes the data bit number i in a data sequence and the average is taken over all data bits in the complete data sequence.

C.11 I/Q PN Code Chip Skew

Defined as for data bit skew but with chips in place of bits.

Annex D (informative): SRRC Chip filtering

Transfer Function:

The transfer function for the SRRC filter H(f) is detailed below.

$$H(f)/\sqrt{T} = 1 \quad for \quad 0 \le |f| \le (1-\alpha)/2T$$

$$H(f)/\sqrt{T} = \left(0{,}5\left(1+\cos\left(\frac{\pi T}{\alpha}\left(f-\frac{(1-\alpha)}{2T}\right)\right)\right)\right)^{1/2} \quad for \quad (1-\alpha)/2T \le |f| \le (1+\alpha)/2T$$

$$H(f)/\sqrt{T} = 0 \quad for \quad (1+\alpha)/2T \le |f|$$

The bandwidth of the SRRC filter is a function the roll off factor α, which has a value between 0 and 1. The RF bandwidth of the filtered signal is given by:

$$B = (1+\alpha)/T = (1+\alpha)Rc$$

Where Rc is the chip rate of the spreading sequence.

Impulse Response:

The corresponding impulse response for the SRRC filter is detailed below.

$$h(t)\sqrt{T} = \frac{\frac{4\alpha t}{T}\cos\left(\frac{(1+\alpha)\pi t}{T}\right)+\sin\left(\frac{(1-\alpha)\pi t}{T}\right)}{\frac{\pi t\left(1-\left(\frac{4\alpha t}{T}\right)^2\right)}{T}}$$

For a roll off factor α = 0,5 frequency and time domain responses are shown in figure 12 and figure 13 respectively.

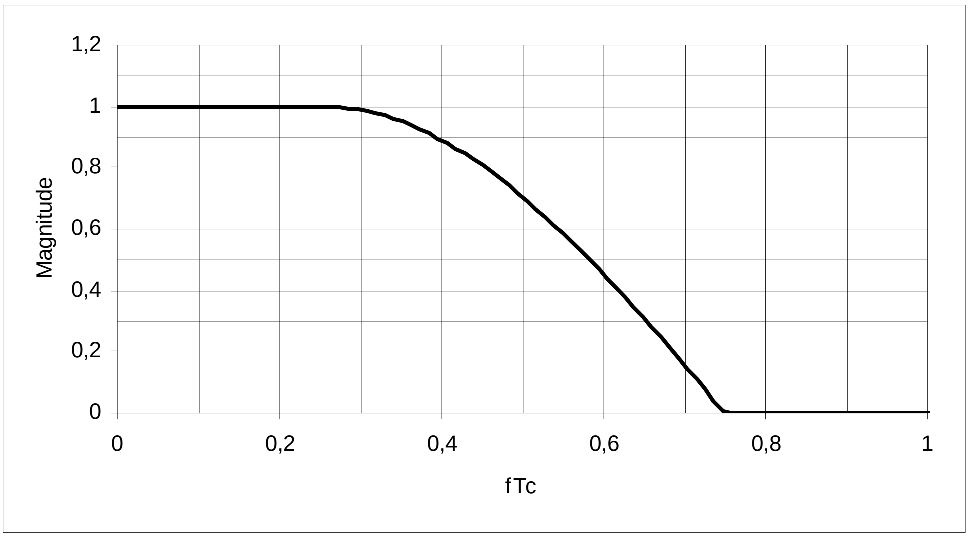

Figure 12: SRRC Frequency Response for Alpha = 0,5

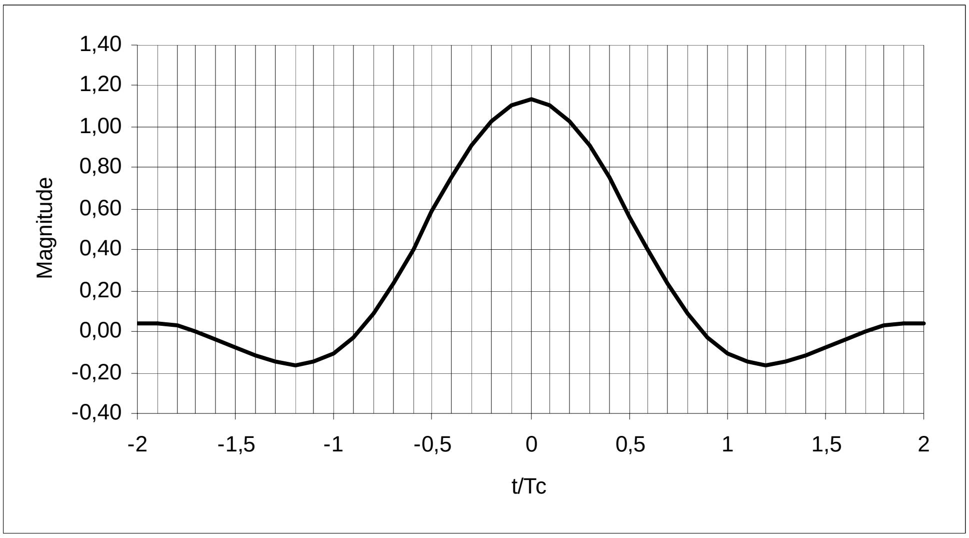

Figure 13: SRRC Impulse Response for Alpha = 0,5

Annex E (normative): PN Code Allocation, Assignment and Generation

E.1 PN Code Allocation

PN spreading codes to be used for the present document are from the same family as those used for Space Agency Data Relay systems: ESA DRSS (Artemis), NASA TDRSS and NASDA DRTS. The codes, when added modulo 2 to data (Direct Sequence Spread Spectrum), give the potential for Code Division Multiple Access, resistance to jamming, and minimized jamming to other users.

Because the present document is aimed at Geostationary satellites which operate at different TC/TM frequencies from any of the Agency Data Relay systems, the existing code configuration libraries can be re-used without any co-ordination problems for this application. These libraries contain 85 code sets per agency (total 255 code sets). For the purposes of the present document, only the ESA code set shall be adopted. This code set is defined in ESA standards [3] and repeated later in this annex.

E.2 PN Code Assignment

One set of PN codes must be assigned per satellite and each set comprises:

- Uplink (Mode MTC2) PN code: Telecommand or In-phase channel, 1 023 chip length Gold code;
- Uplink (Mode MTC2) PN code: Ranging or quadrature channel, maximal length sequence of (2^{18} -1) chips truncated to 256 × 1 023 chips;
- Downlink PN code:
    - Coherent Ranging Mode (Mode MTM2): Telemetry and ranging, a maximal length sequence of (2^{18} -1) chips truncated to 256 × 1 023 chips;
    - Non Coherent Mode (Mode MTM3): Telemetry only, a Gold code sequence of (2^{11} - 1) chips.

Each user satellite must request an assignment from the competent body responsible, applicable to the present document. The competent body is TBD.

E.3 PN Code Generation

E.3.1 Telecommand Uplink or In-phase Channel (Mode MTC2)

In mode MTC1, the PN codes for the Telecommand data channel, the In-phase channel, are Gold codes with a length of 1023 chips. These codes are balanced and give good cross-correlation performance, allowing their use for Code Division Multiple Access with the advantage of relatively short acquisition times.

The uplink PN Gold code generator is shown in figure 14 and consists of two maximal length generators. In order to ensure generation of balanced codes, the register contents (initial seed value) or relative phases must be specified. Register B has a fixed initial seed value and feedback taps as shown in figure 14. For the purposes of the present document, the configuration of bits A and B of Register A relative to different operators shall be the same as that for ESA. Register A contents for ESA is given below:

- ESA Register A initial seed value assignment: A = B = 1, X = from library assignment.

The 7 bits of register A from PN code library assignment (see clause E.5) give at least 85 balanced Gold codes.

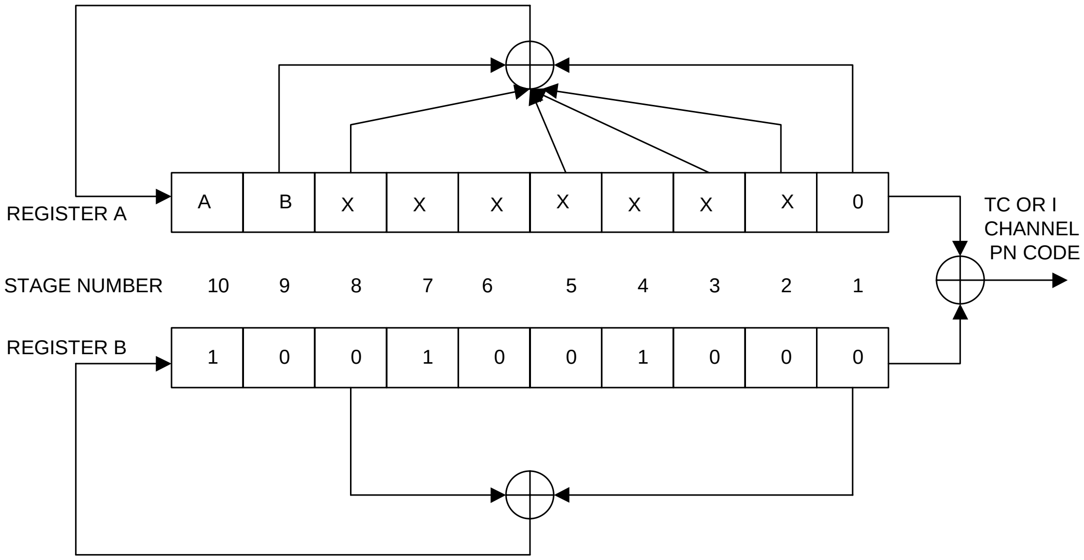

Figure 14: Gold Code Generator for the Telecommand Uplink In-phase Channel

E.3.2 Ranging Uplink or Quadrature Channel (Mode MTC2)

In mode MTC2, the PN codes used for the uplink ranging or quadrature channel are maximum length sequences with a code length given by (2^{18} -1) but truncated to length (256 × 1 023). This is done in order to synchronize them to an integral number of the short (Gold) command code epoch lengths. This aids in acquiring the longer ranging code since now only 256 ranging code positions need be searched following Gold code acquisition.

The Uplink Ranging code generator configuration is shown in figure 15. The number of feed back taps should generally not be too large (e.g. of order 6) in order to minimize implementation complexity. The feed back tap configurations are specified in the PN code library (see clause E.5).

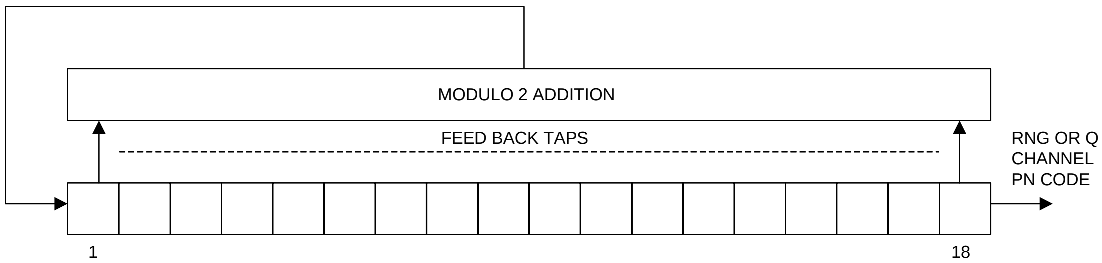

Figure 15: Ranging Uplink or Quadrature Channel PN Code Generation

E.4 Telemetry Downlink

E.4.1 Coherent Ranging Mode (Mode MTM2)

In this mode (MTM2) the uplink ranging PN code epoch timing is coherently transferred to the downlink PN code, as is the PN code chip clock. This thus allows two-way ranging with ambiguity resolution.

The PN code for the telemetry downlink is a maximal length sequence used for the In-phase channel with a phase shifted version of it used for the Quadrature channel. The Coherent downlink PN code generator configuration is shown in figure 16. The telemetry and ranging downlink PN codes, as for the uplink ranging code, have length truncated to (256 × 1 023) chips. The feedback tap configuration is specified in the PN code library (see clause E.5).

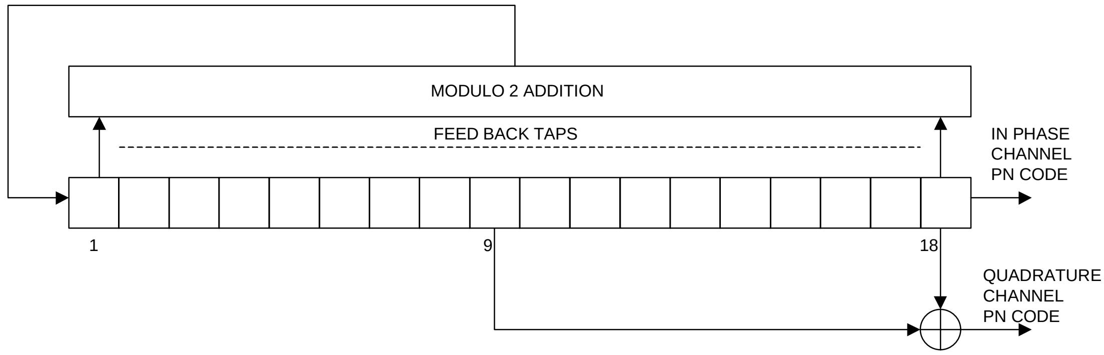

Figure 16: Telemetry Downlink and Ranging PN Code Generator

E.4.2 Non Coherent Mode (Mode MTM3)

This downlink mode operates if there is no Telecommand and Ranging uplink present at the satellite. PN code generator configurations for ESA format is shown in figure 17. Having different PN codes for the in phase and quadrature channels solves channel ambiguity.

Register B values ensure that the code generator produces balanced codes. The contents of the other registers are determined the PN code libraries (see clause E.5).

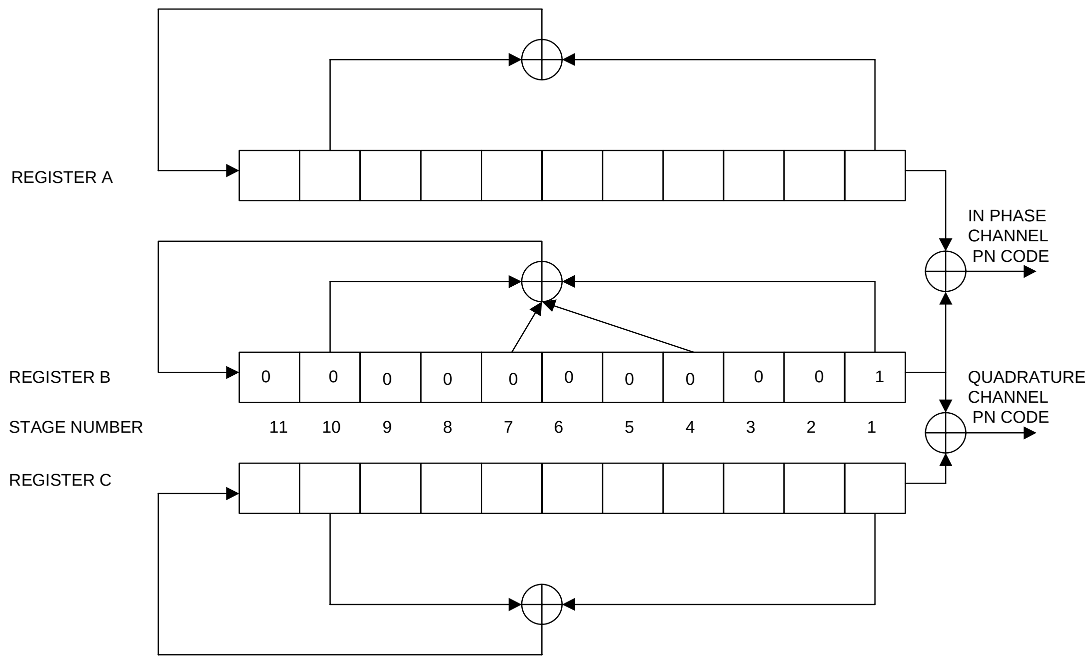

Figure 17: Non Coherent Mode Telemetry PN Gold Code Generator, ESA Format

E.5 PN code libraries

The numbers in table 11 are the initial register loading and feedback tap connections in octal presentation. The only exception is the forward in-phase channel, where binary representation was selected. For the command channel, stage 1 is always 0 and stages 9 and 10 are agency specific and both set to 1 for ESA.

Table 11: PN Code Set Assignments (ESA only)

Code Set	Forward In-Phase Channel	Mode 2 Return Link Reg.A	Mode 2 Return Link Reg.C	Forward Quadrature Channel	Mode 1 and 3 Return Link
	Initial Register Loading			Feedback Tap Connections	
1	0101101	0514	0752	1124013	1320067
2	0100001	1231	1725	1624021	1105265
3	1011011	2462	3653	1524003	1062127
4	0011001	1144	3526	1550005	1211465
5	0010001	2310	3254	1011505	1036123
6	0110011	0621	2531	1240423	1406551
7	0011011	1443	1262	1006113	1146065
8	0110010	3107	2544	1221411	1023551
9	0011010	2176	3101	1502025	1041467
10	0100101	0375	2203	1014027	1071701
11	1111010	0772	0407	1110311	1126611
12	0010111	1765	1017	1001651	1442625
13	1000100	3753	2036	1500341	1430351
14	0001000	3726	0075	1200211	1720215
15	0011100	2604	3506	1634001	1423521
16	1000000	1410	3214	1401125	1201617
17	0000000	3021	2431	1402423	1070447
18	1101110	2043	1062	1400043	1003715
19	1011100	1625	1137	1101223	1433601
20	1000111	3453	2276	1242043	1443251
21	0001110	3032	0427	1004447	1470215
22	1101011	2065	1057	1114015	1626023
23	1010110	0153	2136	1111023	1247013
24	0010101	0326	0275	1010051	1244427
25	0011000	0654	0572	1101511	1264415
26	0111111	3161	2511	1214103	1500437
27	1110001	2343	1222	1021611	1203543
28	1100010	0707	2444	1602051	1065505
29	0001001	3076	0441	1104101	1161053
30	0001101	3666	0155	1111045	1620613
31	0101100	2613	1516	1210047	1500731
32	0001111	1335	1663	1056021	1446511
33	0101111	3247	2764	1321011	1331411
34	0011101	2517	1750	1224411	1076405
35	1010111	1703	1042	1406421	1136045
36	0101110	0714	0452	1132011	1111331
37	1001001	1776	3001	1442205	1222227
38	1011110	0022	0033	1016141	1125053
39	1100100	0044	0066	1420113	1530215
40	1001000	0550	0734	1220123	1342701
41	1111001	2114	3152	1014251	1311065
42	1110010	0231	2325	1001705	1472013
43	0010011	3604	0106	1306101	1120475
44	0110001	0414	0612	1054121	1217601
45	1010100	2247	1364	1206221	1341611
46	0010010	1536	3361	1604043	1073141
47	1111101	1366	3615	1506003	1534023
48	1110101	0366	0215	1424205	1710215
49	0000010	0754	0432	1232201	1442515
50	1101001	3771	2005	1204151	1544621
51	0100100	3762	0013	1300213	1603251
52	0111100	3440	0260	1550401	1641113
53	1001011	0403	2602	1360401	1056251
54	1011111	0035	2023	1224045	1460417
55	0111110	1676	3141	1402251	1225303
56	1110011	3575	2303	1440425	1122253
57	1100110	3372	0607	1760001	1024157
58	0001011	3250	0774	1212045	1101355

Code Set	Forward In-Phase Channel	Mode 2 Return Link Reg.A	Mode 2 Return Link Reg.C	Forward Quadrature Channel	Mode 1 and 3 Return Link
	Initial Register Loading			Feedback Tap Connections	
59	0111001	2504	3746	1046025	1502453
60	0010100	1040	3460	1262003	1165025
61	1000001	1204	3706	1120341	1042715
62	1101010	0450	0674	1142061	1071341
63	1111011	1213	1716	1500261	1047641
64	1110110	2426	3635	1013421	1506213
65	1101100	1235	1723	1203105	1443461
66	1011000	2350	3234	1120113	1303243
67	0110000	0721	2471	1210065	1204565
68	0110110	1643	1162	1461011	1054631
69	1100000	2435	1623	1404055	1055261
70	1001111	3513	2356	1464003	1546501
71	0011110	1514	3352	1244045	1532421
72	1000110	2314	3252	1401035	1432541
73	1110100	3147	2524	1604103	1422447
74	0110111	0525	2777	1111051	1061153
75	0111000	3225	2737	1441001	1160721
76	0000011	0603	2502	1401225	1026315
77	1011001	1761	1011	1305401	1206427
78	0010110	0157	2130	1642011	1651045
79	1010001	1647	1164	1502105	1660047
80	0000101	2735	1463	1452003	1146461
81	0100011	1240	3760	1040351	1742405
82	0000111	2500	3740	1021143	1563011
83	1111110	1200	3700	1200057	1730111
84	1111100	2400	3600	1005341	1574005
85	1111000	1000	3400	1404213	1072321

Note that the loading for the shift registers is given from left to right whereas the feedback tap connections are specified from right to left according to mathematical definitions. See also figure 14, figure 15, figure 16 and figure 17. An example for the loading and for the tap connections is given below based on code set 1.

Gold Code on Forward I-Channel (Initial loading):	0101101	-> 1101011010
Gold Codes on Return Channels (Initial loading):	I: 0514	-> [0]00101001100
	Q: 0752	-> [0]00111101010
Maximum Length Codes Forward Channel (feedback taps):	1124013	-> [00]1001010100000000101[1]
Maximum Length Codes Return Channels (feedback taps):	1320067	-> [00]1011010000000011011[1]

Annex F (informative): Performance computations

For performance computations, refer to TR 101 956 [1].

Annex G (informative): FEC coding example

In order to achieve all requirements for the present document (see [1], annex B), following the analysis documented in [1], it has been concluded that a minimum FEC coding gain of up to 5 dB may be required in spread spectrum modes on both Telecommand and Telemetry links. Selection of FEC code type is outside the scope of the present document.

One coding scheme that achieves the required 5 dB gain is the rate 1/2, constraint length 7 convolutional code as defined in [5].

Annex H (informative): Bandwidth considerations and assumptions

In order to guarantee sufficient protection between TCR and COM channels, the following has been assumed for the background analysis to the present document for SS modes (see [1]):

- COM channel suppression in TC and TM bands has been assumed for the analysis to be <-25 dBc in relation to the COM channel PSD.
- TC and TM suppression in COM bands shall be <-25 dBc in relation to the TC and TM PSD respectively. This is achieved by the selected Spread Spectrum Modulations:
  - Uplink Mode MTC2: SRRC-UQPSK modulation through linear Groundstation HPA gives TC Bandwidth of 1,5 × Rc (1,5 MHz or 4,5 MHz, where Rc = chip rate).
  - Downlink Mode MTM2: SRRC-OQPSK modulation (almost constant amplitude envelope) through (possibly saturated) Spacecraft HPA gives TM Bandwidth of 1,5 × Rc (1,5 MHz or 4,5 MHz, where Rc = chip rate).

History

Document history		
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