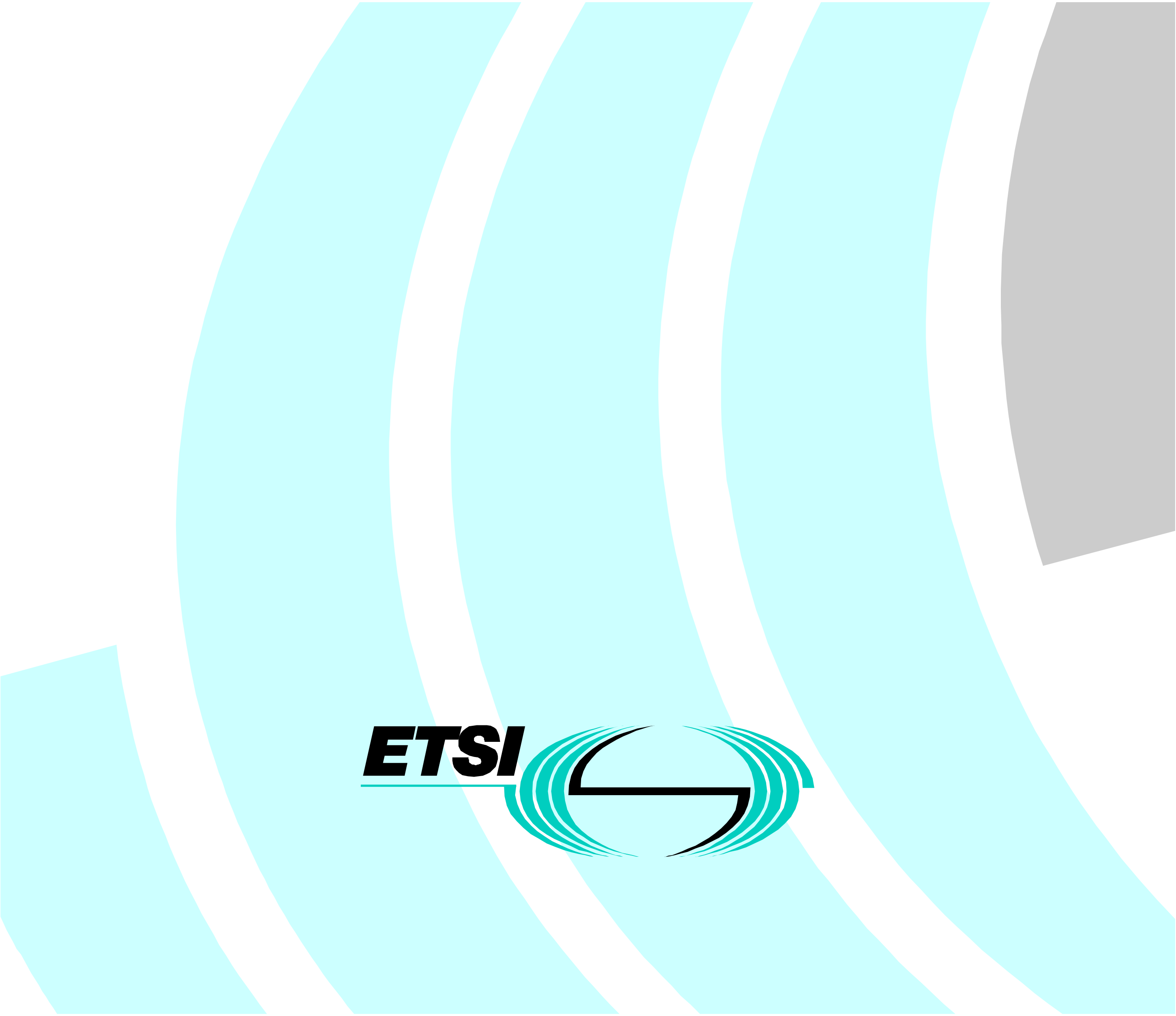
ETSI TR 101 956 V1.1.1 (2001-09)

Technical Report

Satellite Earth Stations and Systems (SES); Technical analysis of Spread Spectrum Solutions for Telemetry Command and Ranging (TCR) of Geostationary Communications Satellites



Reference

DTR/SES-000-ECSS-3

Keywords

interface, satellite, spread spectrum,
telecommand, telemetry

ETSI

650 Route des Lucioles
F-06921 Sophia Antipolis Cedex - FRANCE

Tel.: +33 4 92 94 42 00 Fax: +33 4 93 65 47 16

Siret N° 348 623 562 00017 - NAF 742 C
Association à but non lucratif enregistrée à la
Sous-Prefecture de Grasse (06) N° 7803/88

Important notice

Copyright Notification

Contents

Intellectual Property Rights

Foreword

This Technical Report (TR) has been produced by ETSI Technical Committee Satellite Earth Stations and Systems (SES).

1 Scope

The present document describes the technical analysis made on new TCR standard definition in the frame of ETSI/ECSS standardization work, according to operators' needs.

Operators' needs are summarized in annex B.

The new standard definition is mainly based on Direct Sequence Spread Spectrum techniques (DS/SS).

2 References

For the purposes of this Technical Report (TR) the following references apply:

[1] E. Kaplan, "Understanding GPS, Principals and Applications", Artech House Publishers, 1996.

[2] J.K. Holmes, "Coherent Spread Spectrum Systems", New York, NY. Wiley Interscience, 1982.

[3] ITU-R Recommendation SA.363-5: "Space operation systems. Frequencies, bandwidths and protection criteria".

[4] ITU-R Recommendation SA.1273: "Power flux-density levels from the space research, space operation and Earth exploration-satellite services at the surface of the Earth required to protect the fixed service in the bands 2 025-2 110 MHz and 2 200-2 290 MHz".

[5] Draft new ITU-R Recommendation SM. [OOB]: "Unwanted emissions in the out-of-band domain" Radiocommunication Study Group 1.

[6] VSAT Systems and Earth Stations: "Supplement 3 ITU Handbook on Satellite Communications".

3 Definitions and abbreviations

3.1 Definitions

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

Processing Gain: gain processing indicates the performance of the spreading of a jammer

NOTE 1: For PSK systems (power P_{signal}) and a particular interfere (power P_{jammer}), we define the processing gain as:

$$G_p = \left. \frac{E_b}{N_0\, jammer} \middle/ L_{implentation} \frac{P_{signal}}{P_{jammer}} \right.$$

where E_b/N_0 is the ratio (energy per bit divided by noise spectral density) at the matched filter output. This definition is the one given in [3].

Collocated 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

NOTE 2: For more details and properties, see clause 5.2.3.

3.2 Abbreviations

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

ACU	Antenna Control Unit (in TCR station)
AGC	Automatic Gain Control
AMF	Apogee Manoeuvre Firing
BB	Base-Band processor (in TCR station)
BER	Bit Error Rate
BSS	Broadcast Satellite Service
CDMA	Code Division Multiple Access
CEC	Collocation Equivalent Capacity
CNES	Centre National d'Etudes Spatiales
COM	Communication Channel
C/N_0	Carrier to Noise
DS	Direct Sequence
DSSS	Direct Sequence Spread Spectrum
DEMUX	DEMUltipleXer
DLL	Delay Locked Loop
DS/CDMA	Direct Sequence/Code Division Multiple Access
DVB	Digital Video Broadcasting
E_b/N_0	Energy per Bit/Noise Spectral Density
ECSS	European Co-operation for Space Standardization
EIRP	Equivalent Isotropic Radiated Power
FEC	Forward Error Correction
FSS	Fixed Satellite Service
GMSK	Gaussian pulse shaped Minimum Shift Keyed modulation
G/T	factor of merit
GEO	Geostationary Orbit
GTO	Geostationary Transfer Orbit
GSO	Geo-Stationary Orbit
HPA	High Power Amplifier
ID	Identity (used for satellite identity)
IEE	Institution of Electrical Engineers

IEEE	Institution of Electrical and Electronic Engineers
IMUX	Input Multiplexer
LEOP	Launch and Early Orbit Phase
LNA	Low Noise Amplifier
MPTS	Multi-Purpose Tracking System (ESA)
NF	Noise Factor
OL	Local Oscillator
OQPSK	Offset Quadrature Phase Shift Keying
PDF	Probabilities Density Function
PLL	Phase Locked Loop
PM	Pulses Modulation
PN	Pseudo Noise
PN code	Pseudo Noise Code
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RG	Ranging
Rx	Receiver
SNG	Satellite News Gathering
SRRC	Square Root Raised Cosine
SS	Spread Spectrum
STD	Standard (for standard modulation)
TBC	To Be Confirmed
TC	TeleCommand
TDRSS	Telecommunication Data Relay Satellite System (NASA)
TM	TeleMetry
TCR	Telemetry Command Ranging
TV	Television
Tx	Transmitter
UQPSK	Unbalanced Quadrature Phase Shift Keying
UOQPSK	Unbalanced Offset Quadrature Phase Shift Keying

4 Operational Scenario

4.0 General considerations

The following phases/scenarios which are foreseen to be supported by the TCR standard are defined:

- Phase 1: LEOP 1st Phase (perigee)
    - acquisition
    - tracking
- Phase 2: LEOP 2nd Phase (apogee)
    - acquisition
    - tracking
- Phase 3: LEOP drift
    - acquisition
    - tracking
- Phase 4: On-Station
    - acquisition
    - tracking

- Phase 5: One satellite in Emergency
- Phase 6: De-orbit of one satellite

For each phase, the configuration shall be detailed, in terms of signal to noise ratio, Doppler, and RF jamming.

The parameter $\mathbf{k}_{\mathbf{Doppler}}$ is defined as the ratio between Doppler shift and nominal frequency.

The parameter $\mathbf{rate}_{\mathbf{Doppler}}$ is defined as the ration between Doppler rate and nominal frequency.

All the computations of Doppler shift or Doppler rate are detailed in annex A, and only the main results are presented in this clause.

4.1 Phase 1: LEOP 1st Phase (perigee)

4.1.1 Phase 1: LEOP 1st Phase (perigee)

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	Power at TC receiver input
$k_{Doppler} = 2,2 \times 10^{-5}$ (realistic case, for anomaly higher than 40°) $rate_{Doppler} = 1,66 \times 10^{-6}$ Hz	Yes, from other satellites	N/A	N/A	High (due to small S/L-station distance)

4.1.2 Downlink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	C/N_0 at ground receiver input
Worst case Doppler: Same as uplink	Yes, from other satellites	N/A	N/A	High (due to small S/L-station distance)

4.2 Phase 2: LEOP 2nd Phase (apogee)

For this phase, a dedicated station for the satellite is considered.

No benefit due to the orbit inclination is expected, as apogee and orbit node are coincident.

4.2.1 Uplink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	Power at TC receiver input
Very few Doppler $k_{Doppler} = 6,9 \times 10^{-7}$ $rate_{Doppler} = 5,9 \times 10^{-10}$ Hz	Yes, from other satellites	applicable	N/A	Low (due to high S/L-station distance)

4.2.2 Downlink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	C/N_0 at ground receiver input
Same as uplink	Yes, from other satellites	applicable	N/A	Low (due to high S/L-station distance)

4.3 Phase 3: LEOP drift

The main difference between this phase and phase 2 is the orbit. In phase 2 (apogee phase of the LEOP), the orbit is elliptical, for phase 3, the orbit is circular. So this phase is very similar to phase 2, except concerning slight Doppler variation.

4.3.1 Uplink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	Power at TC receiver input
Very few Doppler $k_{Doppler} = 1,3 \times 10^{-8}$ $rate_{Doppler} = 0$	Yes, from other satellites	applicable	N/A	Low (due to high S/L-station distance)

4.3.2 Downlink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	C/N_0 at ground receiver input
Same as uplink	Yes, from other satellites	applicable	N/A	Low (due to high S/L-station distance)

4.4 Phase 4: On station phase

It is considered that all the stations controlling collocated satellites from a same system, will have the same geographical location.

4.4.1 Uplink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	Power at TC receiver input
Very few Doppler $k_{Doppler} = 1 \times 10^{-8}$ $rate_{Doppler} = 0$	Yes, Self-interference	applicable	applicable	Nominal (note)
NOTE: During acquisition phase, it can be accepted for a short time to increase the uplink EIRP to allow the acquisition.				

4.4.2 Downlink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	C/N_0 at ground receiver input
Same as uplink	Yes, Self-interference	applicable	applicable	Nominal

4.5 Phase 5: 1 satellite in emergency

The case of two or more satellites in non-nominal on-station phase is not considered.

Same remark as in clause 4.4 for the ground station configuration.

4.5.1 Uplink: acquisition and tracking

It shall be tolerable to allow TDMA (no simultaneous uplink signal in the TCR bandwidth).

4.5.2 Downlink: acquisition and tracking

It shall be tolerable to allow TDMA (no simultaneous downlink signal in the TCR bandwidth).

4.6 Phase 6: De-orbitation phase

One ground station is dedicated to the satellite in de-orbitation phase.

4.6.1 Uplink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	Power at TC receiver input
$k_{Doppler} = 1,3 \times 10^{-8}$ $rate_{Doppler} = 0$ $rate_{Doppler} = 0$	N/A	applicable	applicable	Nominal (note)
NOTE: During acquisition phase, it can be accepted for a short time to increase the uplink EIRP to allow the acquisition.				

4.6.2 Downlink: acquisition and tracking

frequency	**RF compatibility**			**power**
Doppler	Jamming due to COM	Jamming due to Standard TCR	Jamming due to N co-located satellites	C/N_0 at ground receiver input
Same as uplink	N/A	applicable	N/A	Nominal

5 Analysis

5.1 Ranging trade-off

This analysis compares different ranging techniques:

- Ranging method using a PN pattern and built on spread-spectrum techniques.
- Ranging method using tones (unmodulated sub-carrier on a PM/FM carrier).

In clause 5.1.3, the ESA MPTS is presented separately, because it is a "compound" method: although it uses a PN pattern for distance ambiguity, it is a ranging method which is built on ranging tone.

5.1.1 Ranging with PN code

5.1.1.1 Introduction

Ranging determination is performed by comparing transmitted code phase and received code phase. This comparison is performed by ground equipment.

From several techniques which can be used to retrieve code phase difference two are assessed:

- DS/SS with on-board processing;
- Transparent DS/SS (in communication channel).

For all ranging application using PN code, the one-way range ambiguity resolution, D_{amb}, is given by code length and chip rate with following formula:

$$D_{amb} = 0,5 \times [(\text{Code\_length}/\text{Chip\_rate}) \times \text{Speed\_Light}]$$

Table 1: Ambiguity resolution for different PN-Code/Chip Rate

Degree	Code length	Chip rate (Mchip/s)	Range ambiguity resolution (km)		Degree	Code length	Chip rate (Mchip/s)	Range ambiguity resolution (km)
10	1 023	1	153,45		20	1 048 575	1	157 286,25
		0,5	306,90				0,5	314 572,50
		3	51,15				3	52 428,75
		5	30,69				5	31 457,25
		7	21,92				7	22 469,46
		20	7,67				20	7 864,31
11	2 047	1	307,05		21	2 097 151	1	314 572,65
		0,5	614,10				0,5	629 145,30
		3	102,35				3	104 857,55
		5	61,41				5	62 914,53
		7	43,86				7	44 938,95
		20	15,35				20	15 728,63
12	4 095	1	614,25		22	4 194 303	1	629 145,45
		0,5	1 228,50				0,5	1 258 290,90
		3	204,75				3	209 715,15
		5	122,85				5	125 829,09
		7	87,75				7	89 877,92
		20	30,71				20	31 457,27
13	8 191	1	1 228,65		23	8 388 607	1	1 258 291,05
		0,5	2 457,30				0,5	2 516 582,10
		3	409,55				3	419 430,35
		5	245,73				5	251 658,21
		7	175,52				7	179 755,86
		20	61,43				20	62 914,55
14	16 383	1	2 457,45		24	16 777 215	1	2 516 582,25
		0,5	4 914,90				0,5	5 033 164,50
		3	819,15				3	838 860,75

Degree	Code length	Chip rate (Mchip/s)	Range ambiguity resolution (km)	Degree	Code length	Chip rate (Mchip/s)	Range ambiguity resolution (km)
		5	491,49			5	503 316,45
		7	351,06			7	359 511,75
		20	122,87			20	125 829,11
15	32 767	1	4 915,05	25	33 554 431	1	5 033 164,65
		0,5	9 830,10			0,5	10 066 329,30
		3	1 638,35			3	1 677 721,55
		5	983,01			5	1 006 632,93
		7	702,15			7	719 023,52
		20	245,75			20	251 658,23
16	65 535	1	9 830,25	26	67 108 863	1	10 066 329,45
		0,5	19 660,50			0,5	20 132 658,90
		3	3 276,75			3	3 355 443,15
		5	1 966,05			5	2 013 265,89
		7	1 404,32			7	1 438 047,06
		20	491,51			20	503 316,47
17	131 071	1	19 660,65	27	134 217 727	1	20 132 659,05
		0,5	39 321,30			0,5	40 265 318,10
		3	6 553,55			3	6 710 886,35
		5	3 932,13			5	4 026 531,81
		7	2 808,66			7	2 876 094,15
		20	983,03			20	1 006 632,95
18	262 143	1	39 321,45	28	268 435 455	1	40 265 318,25
		0,5	78 642,90			0,5	80 530 636,50
		3	13 107,15			3	13 421 772,75
		5	7 864,29			5	8 053 063,65
		7	5 617,35			7	5 752 188,32
		20	1 966,07			20	2 013 265,91
19	524 287	1	78 643,05	29	536 870 911	1	80 530 636,65
		0,5	157 286,10			0,5	161 061 273,30
		3	26 214,35			3	26 843 545,55
		5	15 728,61			5	16 106 127,33
		7	11 234,72			7	11 504 376,66
		20	3 932,15			20	4 026 531,83

NOTE: The choice of the chip rate will also affect the RF interference compatibility between TCR and COM channel (see clause 6).

5.1.1.2 PN code (DS/SS) with on-board processing

Presentation

Figure 1 shows the ground and space segment configuration for ranging assuming a spread spectrum TCR transponder. A ranging PN sequence is generated at the TCR ground terminal, modulated onto a carrier and transmitted to the spacecraft. At the spacecraft, the signal and its ranging sequence are tracked by a delay locked loop, which synchronizes an on board replica code to the one on the uplink. The code replica is then coherently turned around and used to modulate the downlink signal. At the ground station a delay locked loop is used to synchronize a code replica to the downlink signal. The code phase of this replica and the initial uplink code generator are then compared in terms of code phase or time delay, in order to determine round trip delay and hence range.

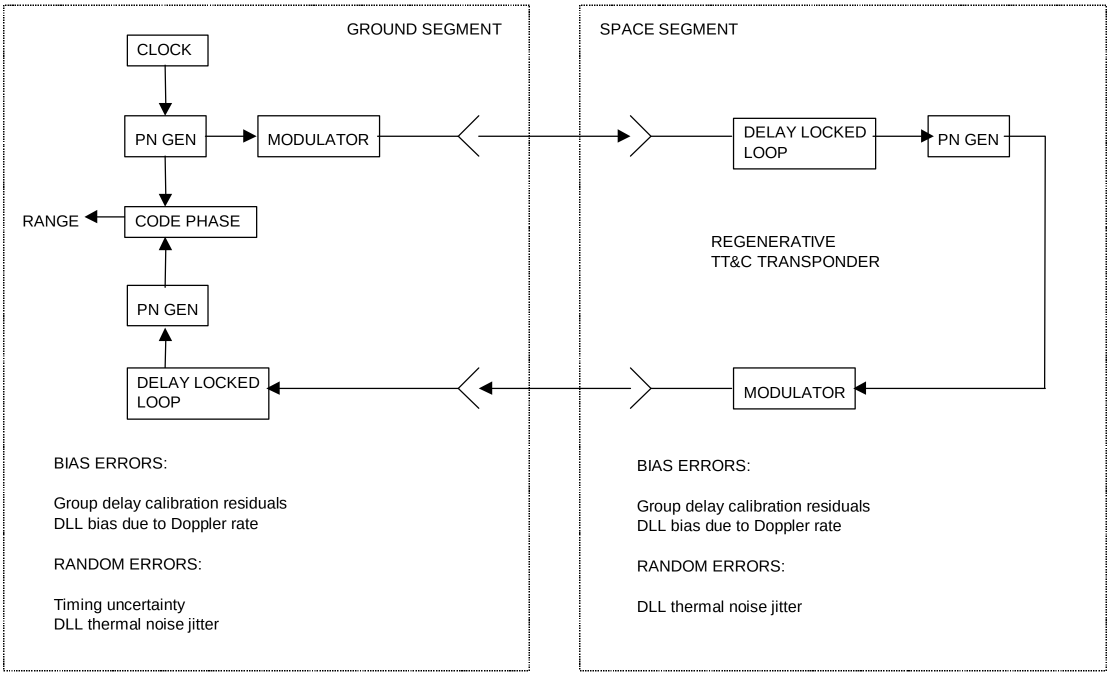


Figure 1: PN code Ranging with on-board processing

Figure 1 also shows sources of errors that can degrade the range measurement. Bias errors arise from residual uncertainties in ground station and transponder group delay calibration (which has to be subtracted from the overall time delay measurement) and for example DLL stress induced by a Doppler rate. Bias errors are assumed to add in terms of magnitude. Random errors arise from for example thermal noise induced tracking jitter in the DLLs and clock uncertainties. Random errors are "added" in a root sum square fashion.

Link assumptions

The following assumptions have been made for the up and downlink of the TCR ranging signals during LEOP:

Ku-band uplink at 18,1 GHz, Kuband downlink at 12,5 GHz, Doppler offset and rate respectively:

$k_{Doppler} = 6{,}9 \times 10^{-7}$, $rate_{Doppler} = 5{,}9 \times 10^{-10}$ Hz (see clause 4.2, apogee configuration)

- TC bit rate = 1 kbit/s (no FEC coding), TM bit rate = 4 096 kbit/s (FEC coding on)
- TC uplink C/N_0 of about 42,5 dBHz
- TM downlink C/N_0 of about 42,5 dBHz
- 3 Mchip/s code rate

For on stations in geostationary orbit the code tracking loop bias errors would disappear since Doppler rate would be very small.

The optimum DLL bandwidth for the Doppler rates detailed above can be determined (see annex B) for the hypothesis on the receiver) from:

$$B_L = \left[\frac{(\Delta\dot{\omega})^2}{\frac{2N_o}{C}(1+\frac{2N_oB}{C})} \right]^{1/5}$$

where

$$\Delta\dot{\omega} = R_c(\frac{\Delta\dot{f}}{f})$$

(B = 30 KHz for uplink)

B= IFbandwidth= 2 × CarrierDoppler + 2 × SymbolRate

and

Here R_c and $\frac{\Delta\dot{f}}{f}$ are the code chip rate and fractional Doppler rate, respectively. For the above link parameters optimum loop bandwidths of 6 Hz are obtained for the TCR transponder and ground terminal, respectively.

Then, as the DLL dynamic loop stress is defined as:

$$R_e = \frac{d^m R}{dt^m}\frac{1}{\omega_n^m} \text{ in chips,}$$

with

m = order of the loop taken as 2

R is the distance to the moving source expressed in chips, and

$$\omega_n = 2B_L(\zeta + \frac{1}{4\zeta}) \text{ ,}$$

we finally get:

$$R_e = \frac{R_c\,\Delta\dot{f}}{f}\frac{1}{\omega_n^2} = \frac{R_c\,\Delta\dot{f}}{f}\frac{1}{4B_L^2}$$

for a loop damping factor ξ of 0,707.

We also get the thermal jitter σ_e (see [2]).

$$\left(\frac{\sigma_e}{T_c}\right)^2 = \frac{N_0 B_L}{2C}(1 + 2\frac{N_0 B_{IF}}{C})$$

Accuracy

Using these loop bandwidths the table below summarizes error magnitudes in the ranging estimate.

SOURCE	BIAS ERROR	VALUE	RANDOM ERROR	VALUE
GROUND	Group delay calibration residual	±2 ns	Timing uncertainty	1 ns rms
	DLL loop stress	±5 ns	DLL thermal jitter	9 ns rms
SPACE	Group delay calibration residual	±5 ns	DLL thermal jitter	9 ns rms
	DLL loop stress	±5 ns		
TOTALS		±17 ns		19 ns rms

Distance ambiguity

On-way distance ambiguity, D_{amb}, is given by code length and chip rate with following formula:

$$D_{amb} = 0{,}5 \times [(\text{Code\_length}/\text{Chip\_rate}) \times \text{Light\_Speed}]$$

With above link assumption (3 Mchip/s PN code), in order to have ambiguity resolution compatible with operators' requirements (annex B), i.e. 4 200 km, we get the following results (see also table 1):

- Ranging PN-Code length shall be 2^{17}.
- Which gives D_{amb} = 6 550 km.

However, for easy choice of codes and heritage/commonality from TDRS-type systems, it is recommended to increase the long code length by one power of 2, that is:

- Ranging PN-Code length of 2^{18}
- Giving D_{amb} = 13 100 km

Modulation/Spectral efficiency

As this ranging technique needs on-board processing, this signal shall be processed by TCR on-board transponder. Consequently Ranging signal shall share bandwidth reserved to TCR. It shall "overlay" with TC and TM data.

The solution foreseen is to use QPSK type-modulation (I and Q channel):

- used for both TC and ranging for uplink,
- used for TM and ranging for downlink.

It is proposed to use unbalanced QPSK (UQPSK) where minimal power is reserved for channel supporting ranging code. The envisaged power-ratio is 1/10 on ranging code channel (TDRSS standard).

Impacts

As the ranging code shall be coherently demodulated and modulated on-board, the chip rate will be impacted twice by Doppler effect. This shall be taken into account in the TM ground receiver design.

5.1.1.3 Transparent DS/SS (in communication channel)

Presentation

Figure 2 shows the ground and space segment configuration for ranging assuming no need for spread spectrum TCR transponder. The ranging signal passes through satellite communication transponders in a transparent way.

A ranging PN sequence is generated at the TCR ground terminal, modulated onto a carrier and transmitted to the spacecraft. At the spacecraft, the signal is transparently transmitted to the ground terminal.

At the ground station a delay locked loop is used to synchronize a code replica to the downlink signal. The code phase of this replica and the initial uplink code generator are then compared in terms of code phase or time delay, in order to determine round trip delay and hence range.

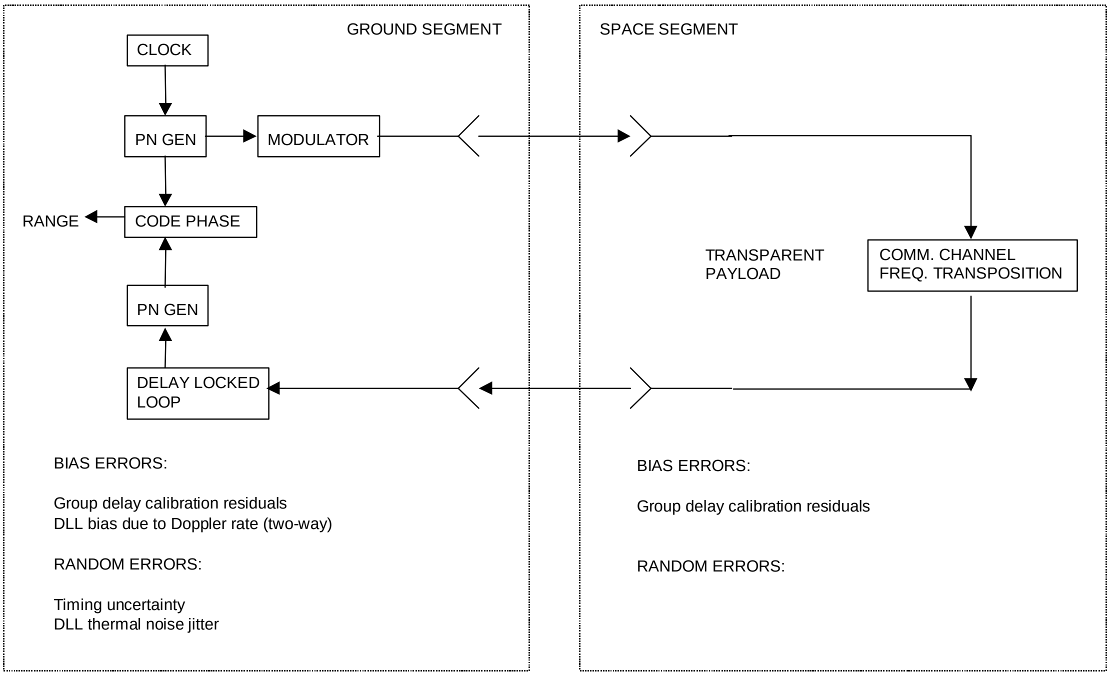


Figure 2: PN code transparent ranging

Link assumptions

The following assumptions have been made for the up and downlink of the TCR ranging signals during drift orbit and on-station phase:

- Ku-band uplink at 18 GHz, Doppler offset = 180 Hz
- Ku-band downlink at 12,5 GHz, Doppler offset = 125 Hz
- Full link Doppler = up + down contribution = 180 Hz + 125 Hz = 305 Hz
- Overall C/N_0 = 32 dBHz
- A 18 Mchip/s code rate (choice made in relation with standard bandwidth -36 MHz- for a communication channel)

Accuracy

The optimum DLL bandwidth is calculated using the formula presented in clause 5.1.1.2 (Link assumption). For this transparent link, DLL loop bandwidth is set to 10 Hz. With this setting, the following table summarizes the error magnitude in the ranging estimate.

SOURCE	BIAS ERROR	VALUE	RANDOM ERROR	VALUE
GROUND	Group delay calibration residual	±2 ns	Timing uncertainty	2 ns rms
SPACE	Group delay Calibration residual DLL loop stress	±5 ns ±1 ns	DLL thermal jitter	4 ns rms
TOTALS		±8 ns		6 ns rms

Distance ambiguity

For a chip rate of 20 Mchip/s, the results of the calculation (given by table 1) are:

- Ranging PN-Code length shall be 2^{20}.
- Which gives D_{amb} = 7 864 km.

NOTE: - A very long code is suggested, this has an impact on acquisition times: however, since this method will only be used while on station, epoch estimation should be easy (~36 000 km altitude).

- The acquisition time may not be so important for the ranging function (separate from the TM function).

Impacts

As the communication resources are needed for this type of ranging, it will be not possible to use this ranging technique during LEOP where satellite communication payload is off.

This imposes a need for an alternate ranging method to be used for the LEOP phase.

5.1.2 Ranging with tones

Presentation

Ranging with tones is the conventional ranging method used for geo-stationary satellites.

Two standards exist. They are based on the same principle:

- ESA-100K standard: (PM on uplink and PM on downlink, frequency of major tone at 100 kHz).
- TELESAT-27K standard: (FM on uplink and PM on downlink, frequency of major tone at 27,7 kHz).

The TCR ground terminal generates successively a set of ranging tones (unmodulated sub-carrier) which modulate an FM or PM carrier. This signal is transmitted to the spacecraft which FM or PM demodulates the received signal to recover the ranging tone.

Then this ranging tone is looped back to the spacecraft transmitter: the ranging tone is PM modulated (FM modulation is no longer used on spacecraft downlink signals) by the spacecraft.

At the TCR ground station, a PLL is used to phase synchronize on the ranging tone (sub-carrier) in order to perform a phase comparison between the transmitted signal and the received signal.

From the phase delay, the round trip delay of the signal and the range is deduced.

The ranging is performed in two steps:

- In a first step, the minor tones (low frequency sub-carrier) are transmitted in sequence to reduce distance ambiguity,
- In a second step, the major tone is transmitted continuously and the accurate measurement is made on phase comparison on this major tone.

Link assumptions

The following assumptions have been made for the up and downlink of the TCR ranging signals during on-station phase:

- Overall S/No of about 49 dBHz (for major tone).

Distance ambiguity

On-way distance ambiguity, D_{amb}, is given by the low frequency minor tone, following the formula:

$$D_{amb} = 0{,}5 \times [\text{Light\_Speed/Frequency\_minor\_tone}]$$

For ESA standard, minor tone is set to 8 Hz which gives D_{amb} = 18 750 km.

For TELESAT standard, minor tone is set to 35 Hz which gives D_{amb} = 4 280 km.

Distance ambiguity given by those standards is compatible with operators' requirements (annex B).

Accuracy

Measurement accuracy, $Th_{1\delta}$ (given at 1δ), is constrained by thermal noise and is expressed with the following formula:

$$Th_{1\delta} = \frac{C}{4 \times \Pi \times Fmajor} \sqrt{N_0 \times B \big/ 2 \times S}$$

Where:

C: Light speed

Fmajor: Frequency of the major tone

S: Signal power

N_0: Noise power spectral density

B: Tracking loop (PLL) bandwidth

According to the link assumption and choosing a bandwidth B = 2 Hz for PLL (on-station phase), the accuracy depends on the major tone frequency.

- For ESA-100 K, the major tone is set to 100 kHz, $Th_{1\delta}$ = 0,9 m or 6 ns ($Th_{3\delta}$ = 18 ns).
- For TELESAT-27 K, the major tone is set to 27 kHz, $Th_{1\delta}$ = 3 m or 20 ns ($Th_{3\delta}$ = 60 ns).

5.1.3 ESA MPTS standard

Presentation

The MPTS is an ESA standard which uses ranging tones technique to issue the ranging measurement (see clause 5.1.2).

The main difference is on minor tone management. The MPTS uses a code sequence over the minor tone to set distance ambiguity.

The MPTS standard is scalable:

- The major tone frequency is settable to meet ranging measurement accuracy requirements.
- The Code Length is settable to meet distance ambiguity requirements.

Distance ambiguity

On-way distance ambiguity, D_{amb}, is given by the code length (2^N) with the following formula:

$$D_{amb} = 0{,}5 \times [(\text{Light\_Speed} \times 2^N)/\text{Frequency\_major\_tone}]$$

If major tone frequency is set to 100 kHz, in order to have ambiguity resolution compatible with operators requirements (annex B), i.e. 4 200 km:

- Ranging PN-Code length shall be 2^{12} ($N = 12$).
- Which gives $D_{amb} = 6\ 144$ km.

Accuracy

Measurement accuracy is given by thermal noise (see clause 5.1.2).

According to link assumption ($C/N_0 = 45$ dBHz) and choosing a bandwidth B = 10 Hz for PLL (on-station phase):

- If major tone is set to 100 kHz, $Th_{1\delta} = 3$ m or 10 ns ($Th_{3\delta} = 30$ ns).
- If major tone is set to 1 MHz, $Th_{1\delta} = 0{,}3$ m or 1 ns ($Th_{3\delta} = 3$ ns).
- If major tone is set to 3 MHz, $Th_{1\delta} = 0{,}1$ m or 0,33 ns ($Th_{3\delta} = 1$ ns).

5.1.4 Hybrid Ranging (uplink Spread Spectrum, downlink Standard Modulation)

Presentation

For the uplink, a PN code is transmitted to the satellite, in a way similar to clause 5.1.1 (PN code with a chip rate of a few MHz).

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 0 of the tone correspond to the beginning of the PN code, and there is an integer multiple of tones period during the PN code epoch). This ranging is transmitted to the ground by using classical modulation (typically PM modulation), and the ground baseband unit measure the delay between this tone and the original transmitted PN code (see figure 3).

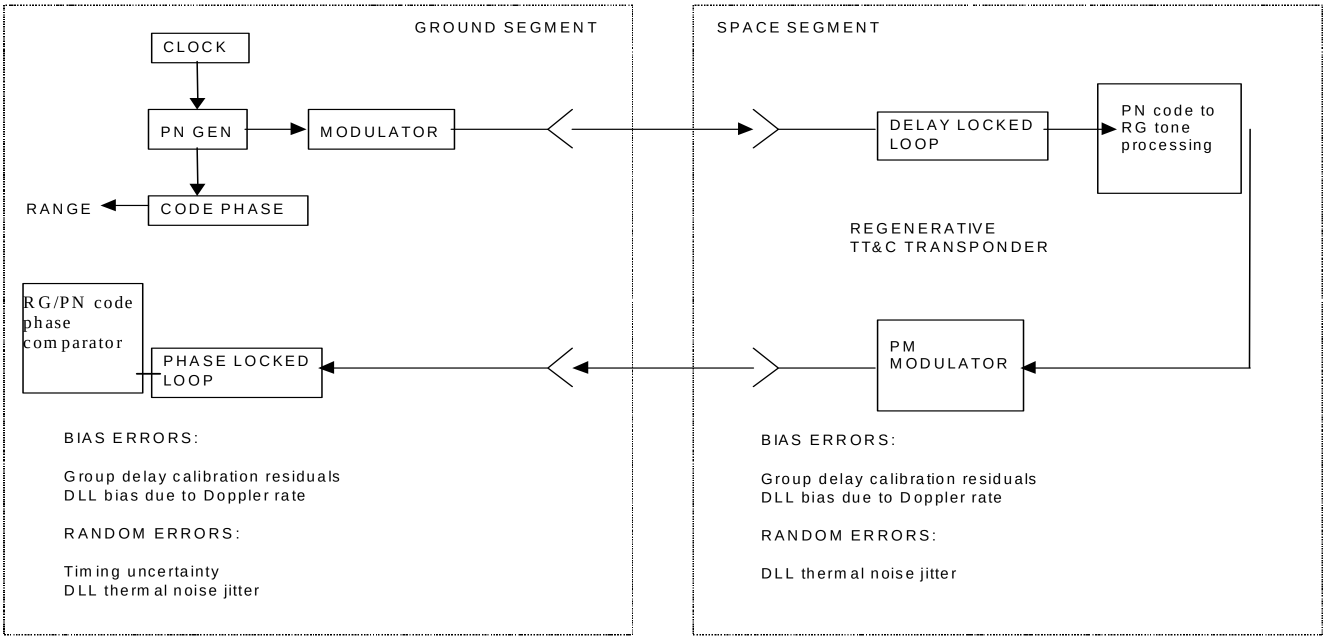


Figure 3: Hybrid Ranging presentation

The timing diagram of the sequence is detailed in figure 4.

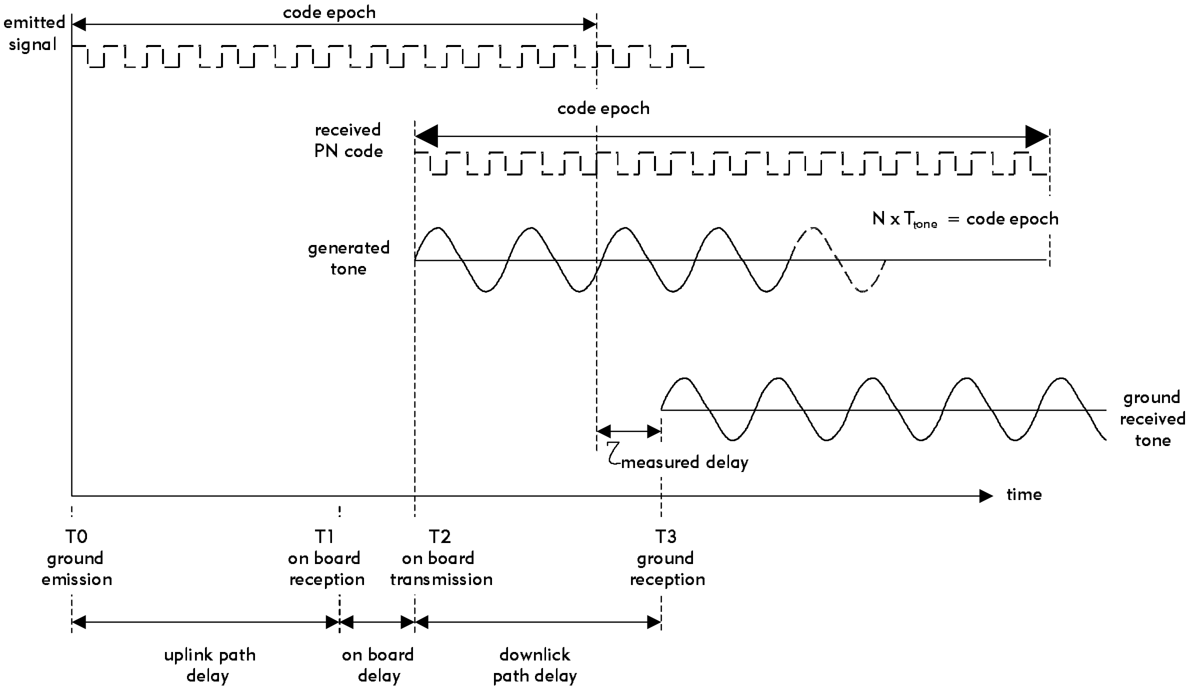


Figure 4: RG hybrid timing diagram

Link assumptions

The following assumptions have been made for the up and downlink of the TCR ranging signals during on-station phase:

- uplink signal characteristics: identical to clause 5.1.1.2,
- downlink signal characteristics: identical to clause 5.1.2.

Distance ambiguity

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 in figure 5.

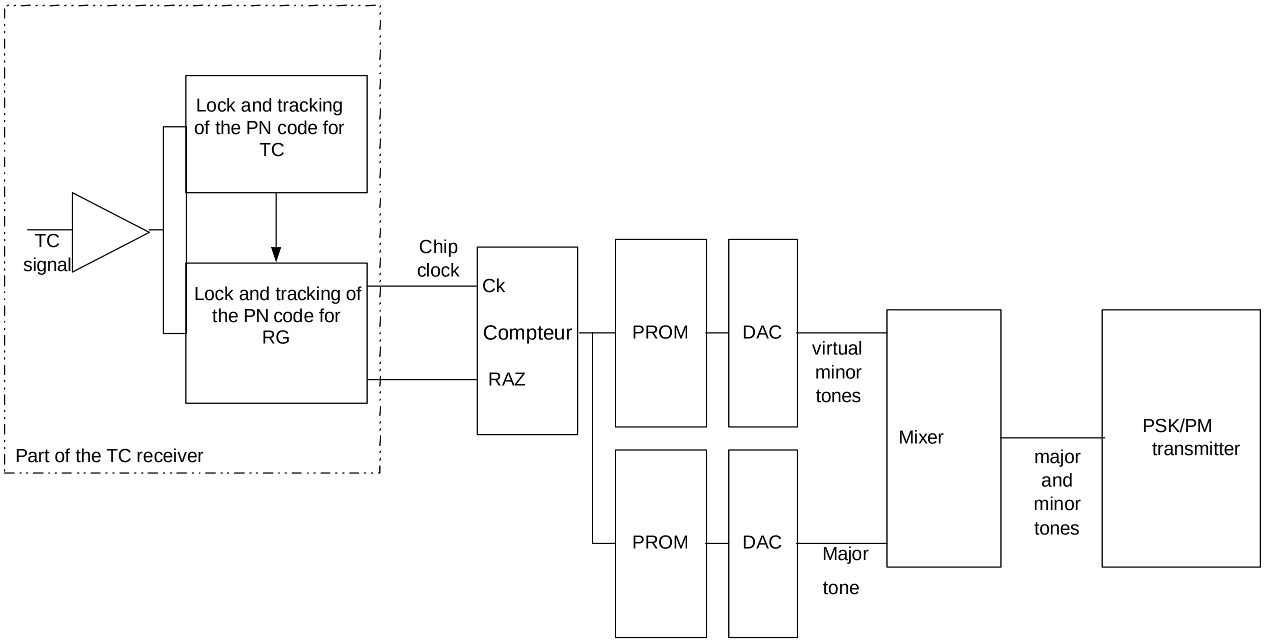


Figure 5: Hybrid Ranging On Board processor architecture

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

The 2nd 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 simultaneously with the major tone to solve ambiguity. As virtual minor tones being difficult to send (very low frequency), real tones equal to the linear combination of those tones can be sent.

The on board processor will have to send sequentially each minor tone (for example by changing the minor tone each N chips epochs).

At ground level, the RG tone 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).

RG Calibration

1st possible implementation of the calibration.

For the RG calibration (estimation of the on board delay and/or of the ground delay), a short loop (connection of the ground baseband unit output directly to the ground baseband unit input) is possible, but it is more difficult than using standard modulation, as uplink and downlink modulation are different. An example of ground station implementation of the Hybrid RG solution is described in figure 6, including the necessary hardware for frequent calibration.

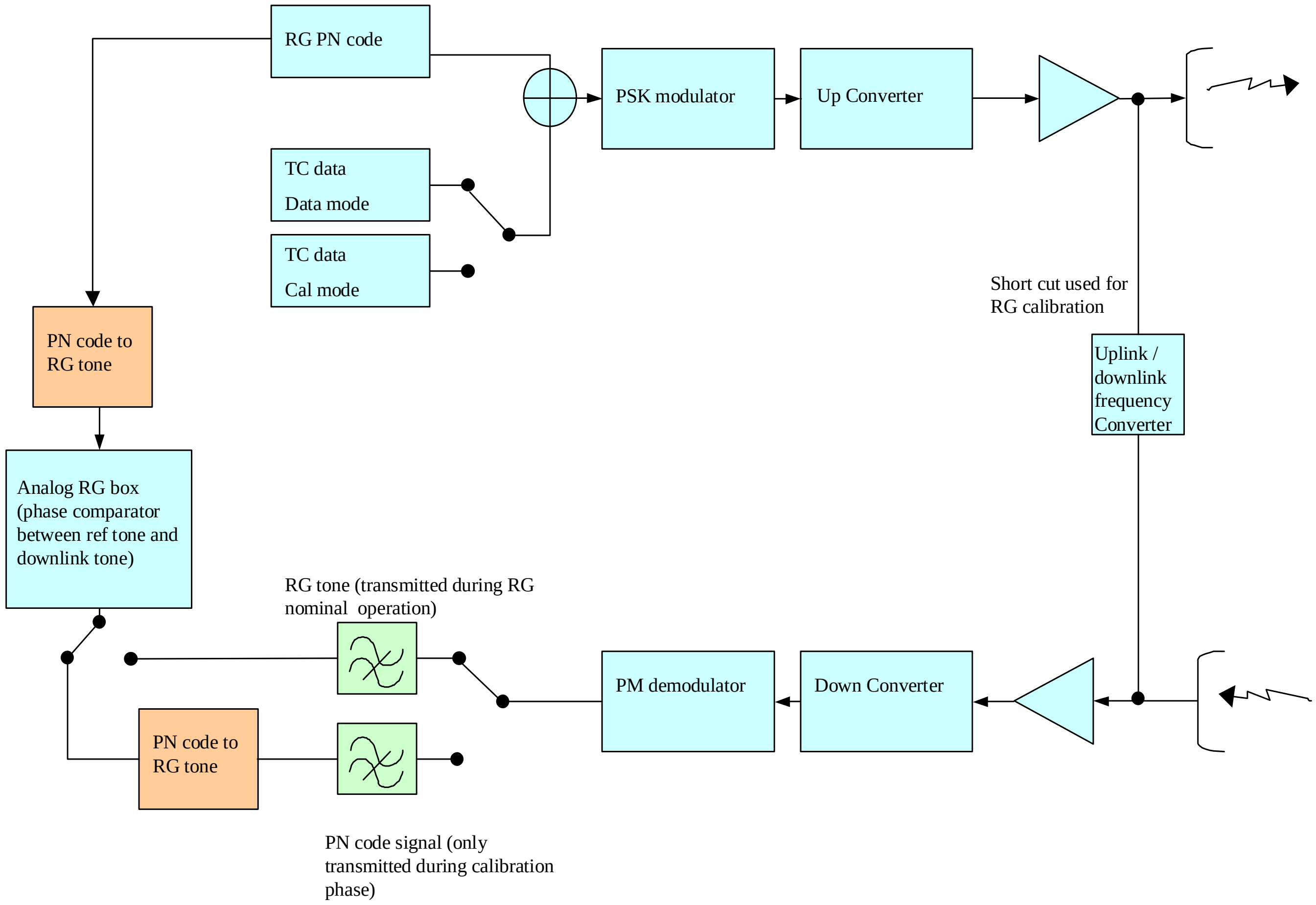


Figure 6: Hybrid RG implementation in a TCR station

The RF short loop used for RG calibration temporarily sends the RG UQPSK uplink signal to the PM demodulator. If steady state data are sent on the TC channel, the RG UQPSK signal is equivalent to a PM signal. This signal can thus be expressed as follows:

$$S(t) = \cos(\omega_0 t + B(t) \times m)$$

where B(t) is the PN code sequence (B(t) = +1 or -1 with a rate equal to the chip rate), and m = I/Q imbalance.

The PM demodulator will PM demodulate this signal and generate the RG PN code sequence. This enables the RG calibration, as the phase can be compared with the one of the initial RG PN code for calibration.

2nd possible implementation of the calibration

Another solution is to measure the delay of the link, with the real ground equipment and the satellite hardware, 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, by the temporary use (for the calibration phase) of standard modulation.

Accuracy

- Uplink signal accuracy: identical to clause 5.1.1.2.
- Downlink signal accuracy: identical to clause 5.1.2.

5.1.5 Pros and cons of each RG solution

5.1.5.1 Ranging with code

This method gives the best results in terms of accuracy and meets operators' requirements.

Transparent:

- The advantage of the transparent method is that the communication channel can be used (independent of TCR band, no need for a dedicated bandwidth).
- Moreover, for the transparent method, signal processing is fully performed in the TCR ground terminal so it does not add costly implementations on the satellite.
- The main drawback of the transparent method is that it is impossible to use it during LEOP phase (Payload off), as opposed to the method using on-board processing. This limitation leads to:
    - the mandatory need for an alternate ranging system for LEOP phase (dual-mode transponder);
    - weak protection against jamming, when the satellite meets the geostationary orbit during LEOP (this is the case during critical phases like AMF);
    - another drawback is the necessity of coordinating COM and RG, to ensure RF compatibility between both signals.

Regenerative:

- With on-board processing, the drawback linked to communication channel utilization is suppressed since the ranging signal uses on-board TCR separate band.
- One major problem for regenerative ranging with code is that the ground station has to Doppler compensate (needed only during LEOP) in order to simplify acquisition (to reduce time and implementation complexity in the spacecraft). This may also apply for the ground receiver. An alternative solution could be the use of a pilot tone to aid carrier frequency acquisition. Another alternative is the use of a dual-mode transponder, using standard modulation during LEOP, to avoid any Doppler concern.

5.1.5.2 Ranging with tones

The main advantage of this method is that it is a well-known method which proves to be accurate enough to control geostationary satellites even if it does not meet operators' requirements for accuracy needs (see annex B) (it is not foreseen in the base-line to set the major tone frequency above 100 KHz).

But its main drawback is that it uses a modulation scheme incompatible with DS/SS technique (PM/FM modulation is not used in DS/SS techniques).

Moreover, it has a severe impact on bandwidth occupancy, where a dedicated bandwidth for tones shall be reserved (2 × Frequency_major_tone so 200 KHz in the base-line).

This method is not designed for multiple access so is not well suited for collocated satellites.

The ranging tone method is a good alternate method for ranging to be used when the ranging code method proves to be hard or impossible to implement (LEOP phase).

5.1.5.3 ESA MPTS standard

The ESA MPTS ranging seems to have few advantages over ranging tone standards; it does however allow Ranging and Telecommand to be performed simultaneously, and can be applied to all types of satellite mission (from LEO to Deep Space). However, for GEO missions of commercial communications satellites, this functionality is not required, so there is no need to change from tone ranging standards (for the case of standard FM or PM modulation). MPTS is not particularly optimized to GEO orbit missions. Thus MPTS ranging is discarded as an option.

5.1.5.4 Hybrid RG system

These solutions avoid the use of SS CDMA on the downlink, while keeping SS CDMA on the uplink. This particularity allows:

- No update of the ground TCR station receive section (Standard modulation receiver already exists);
- No update of all the COM stations using TM signal as a beacon for the tracking.

But this solution is more complicated to implement on-board, and requires more complex calibration procedure of the full RG chain.

5.2 Power Control

Power balance between multiple users shall be assumed by the system. It has impact on ground equipment for transmission of TC signal and it has impact on board equipment if TM signal uses SS/DS techniques.

5.2.1 Ground equipment

The parameter to be controlled on-station is the EIRP for TC signal.

The value of the EIRP transmitted to the satellite shall be controlled with 1 dB accuracy (TBC: value directly given by capacity analysis calculation where 1 dB is the worst case for power imbalance).

The control of transmitted power on-ground can be achieved using two methods:

- Close-loop control;
- Open-loop control.

5.2.1.1 Open-loop control

The EIRP in the ground station is specified with 1 dB and can be controlled using Amplifier variable gain on Up-Converter to adjust the power.

The major drawback of this method is that there is no control on the effective power received by the satellite. If the ground station suffers bad climatic environmental conditions, the power received by the satellite will be affected by several dB.

If the variations due to RF link are judged acceptable, the open-loop control is the simplest method to implement.

5.2.1.2 Close-loop control

If ground station environmental conditions create too much power unbalance on the co-located satellite, a close-loop control shall be implemented.

The ground station shall be able to estimate the power received by the satellite and consequently estimate the environmental degradation.

In a first approach, two means can be used to estimate satellite received power:

- Retrieve the AGC value for satellite input power from satellite telemetry:
  - it assumes that the ground station have TM decommutation equipment;
  - it also assumes that the AGC value is accurate enough.
- Retrieve the power of a power calibrated beacon transmitted by the satellite:
  - it assumes dedicated hardware for beacon acquisition and power estimation;
  - it assumes dedicated hardware on the satellite to generate beacon.

Implementation of this close-loop control implies specification for additional hardware on ground and specific performance requirements on board the satellite to have well known power sent by the satellite.

5.2.1.3 Conclusion

The close-loop solution is very costly and open-loop control shall be considered as the base-line in standard definition.

The close-loop control implies additional hardware and complexity.

5.2.2 Space equipment

The TM downlink EIRP is fixed on existing satellites, and cannot be changed (as it can be for the uplink TC ground station EIRP).

For this reason, no power control is possible on existing satellites.

The only power control strategy that can be applied on future satellites is to fix a typical TM EIRP for all the satellites of a new generation (that means that during the following 15 years, all the collocated satellites will have to be designed with nearly identical EIRP).

A compromise could be to allocate a range of power imbalance compatible with the mission requirement. A typical 10 dB range can be assumed for the capacity analysis.

5.2.3 Collocation Equivalent Capacity (CEC) concept

To integrate the power imbalance of every signal of a multiple access system, the concept of Collocation Equivalent Capacity (CEC) is introduced below.

The Collocated Equivalent Capacity (C.E.C) is defined as the number of collocated satellites that can be controlled with a perfect power balanced link between the ground and the satellite.

This concept is introduced to quantify, in RF budget, the contribution of the power imbalance to the full link performance.

If all the satellites are controlled by TCR stations located in the same geographical site, the Collocated Equivalent Capacity (CEC) may be expressed by the following formula:

$$(\Sigma_{i=1,n} P_i)/P_{min}$$

where P_i and P_{min} are:

- uplink:
  - P_i is the power received by the SS TC receiver from the TCR station.
  - P_{min} is the minimum received power.
- Downlink:
  - P_i is the power received by the Ground station baseband receiver from the satellite.
  - P_{min} is the minimum received power.

For example, consider that the dynamic of EIRP of a system is 3 dBW. In linear, if the min power is normalized to 1, it means that the power range can vary from 1 to 2.

It can be considered that the distribution of the EIRP from every satellite of this system follows a Gaussian behaviour, as shown in figure 7.

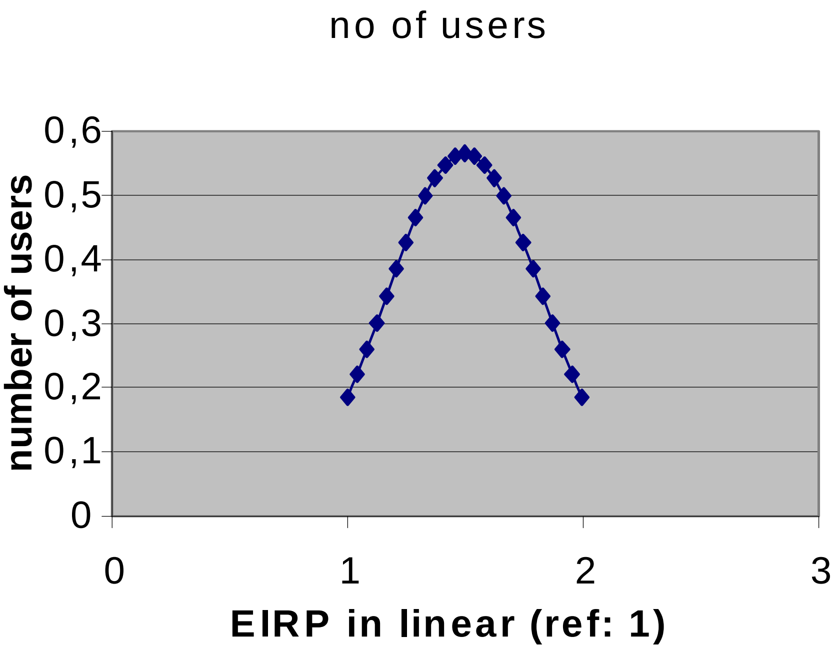


Figure 7: Gaussian distribution

In figure 7, the X axis represent the normalized EIRP (linear) and the Y axis represent the number Y_I of users who have an EIRP equal to X_i. Y_i is estimated through the following formula:

$$Y_i = k \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2}$$

- σ is known, as 3σ = the EIRP range in linear.
- m is the X average (average linear EIRP).
- and k is calculated, so that:

$$\sum_i Y_i = no\_of\_users$$

Numerical application.

number of users		10	10	10	10	10	10
EIRP range	dB	3	3	5	7	9	10
equivalent CEC		14,98	14,98	20,81	30,06	44,72	55,00

We can see, that for 10 users, an EIRP range of 3 dB leads to a CEC of 15, and an EIRP range of 10 dB leads to a CEC of 55.

5.3 Modulation and Filtering Trade-off

5.3.1 Requirements

In order that TCR spread spectrum systems can be used along side communication channels at RF, some form of band limiting of the signal is required. Band limiting the signal at RF with very narrow bandwidth analogue filters is not generally practicable. Consequently control of the spectrum is generally implemented by pulse shaping at the chip level at baseband.

The capacity analysis assumes a minimum of about -25 dBc spurious noise relative to the peak spread spectrum spectral density falling into the communication channel. This -25 dBc limit of the spread spectrum signal can be considered for this purpose as defining the spread spectrum bandwidth.

The choice of modulation scheme and filtering must be consistent with the following requirements:

- Bandwidth limited to -25 dBc relative to peak spectral density.
- Consistent with ranging requirements e.g., it is desirable to have simultaneous TC, TM and ranging.
- Low implementation complexity (ground and spacecraft level).
- Space heritage if possible.
- Good performance under non linear amplification (e.g. TM downlink) with controlled spectral regrowth.

5.3.2 Choice of Modulation

The following modulation schemes have been considered for band limited direct sequence spread spectrum systems application:

- SRRC BPSK
- SRRC QPSK
- SRRC OQPSK
- GMSK

Where SRRC stands for Square Root Raised Cosine filtering or pulse shaping and GMSK is Gaussian pulse shaped Minimum Shift Keyed modulation. The impulse response and transfer function of the root raised cosine filter are detailed below:

Transfer Function:

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

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

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

Impulse Response:

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

The RF bandwidth of a SRRC pulse is given by:

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

Table 2 gives details of the trade-off between the various signalling formats. On balance for minimum complexity and risk SRRC OQPSK is recommended.

Table 2: Modulation Trade Off

OPTION	COMMENT
SRRC BPSK and QPSK	In terms of bandwidth occupancy both modulation schemes are equivalent since the symbol rate is just the chip rate in both cases. BPSK cannot give simultaneous TC, TM and ranging. When band limited, both schemes suffer from envelope fluctuations which, in order to limit spectral re-growth, would require linear amplification. Simple to implement with generic space heritage e.g. TDRSS type transponders.
SRRC OQPSK	Equivalent to BPSK/QPSK in terms of bandwidth performance. However, since the I and Q channels are staggered by ½ chip period, when band limited, the envelope fluctuations are less than those of either BPSK or QPSK. Consequently this modulation scheme behaves well with non-linear amplification giving reduced spectral re-growth. Generic space heritage exists e.g. TDRSS type TCR transponders. SRRC band limited spread spectrum systems have been studied extensively and implemented commercially.
GMSK	Potentially the most bandwidth efficient of the modulation schemes considered. However, since GMSK is essentially a binary communication scheme it would appear that simultaneous TC, TM and ranging would not be possible. Although extensively used in land mobile communications it has not yet been implemented at spacecraft level.

5.3.3 TM downlink Modulation and Processing Gain

Three different implementations of the SS TM downlink in coherent mode are possible, for the channel allocation in QPSK.

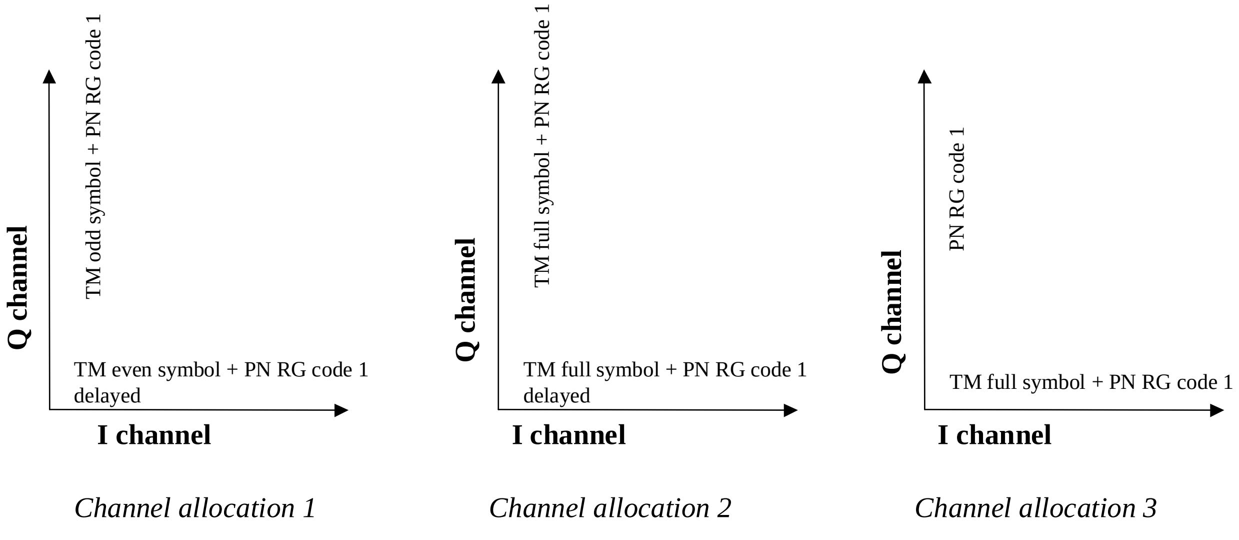
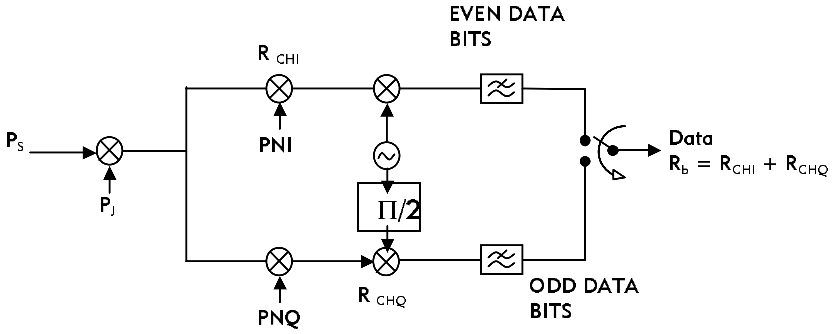


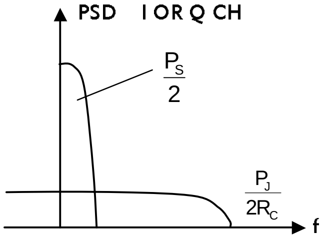
Figure 8: TM downlink symbol channel allocation

5.3.3.1 Option 1: OQPSK, even and odd data at half the rate in I and Q channel

The RF link budget performance is identical to BPSK. Impact on Processing gain is described below.

Demodulator:





Signal power in I CH $S_I = \frac{P_S}{2}$ $E_{ICH} = \frac{S_I}{R_{ICH}} = \frac{P_S}{2R_{ICH}}$

where $R_{ICH} = R_{QCH}$ = data rate in the channel = $\frac{R_b}{2}$

Jammer spectral density is channel $N_{OI} = \frac{P_j}{2R_C}$

$$\frac{E_{ICH}}{N_{OI}} = \frac{P_S}{2R_{ICH}} \times \frac{2R_C}{P_J} = \frac{P_S}{P_J} \times \frac{R_C}{R_{ICH}}$$

The $\frac{E_b}{N_O} = \frac{1}{2}\frac{E_{ICH}}{N_{OI}}$ (Standard expressions relating bits to symbols (no coding) for QPSK).

$$\frac{E_b}{N_O} = \frac{1}{2}\frac{P_S}{P_O}\frac{R_C}{R_{ICH}} \text{ , but } R_{ICH} = \frac{R_b}{2}$$

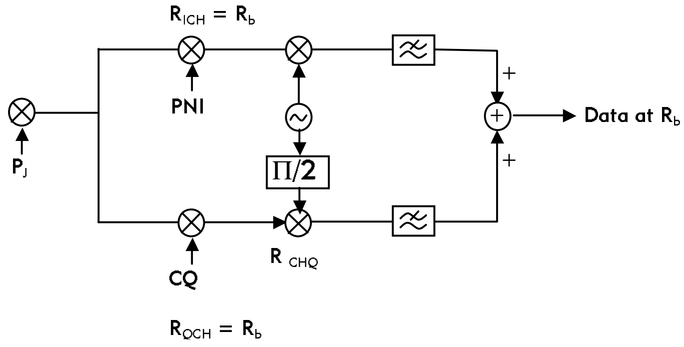
$$\frac{E_b}{N_O} = \frac{1}{2}\frac{P_S}{P_O}\frac{R_C}{R_{bI}} \times 2 = \frac{P_S}{P_J} \times \frac{R_C}{R_b}$$

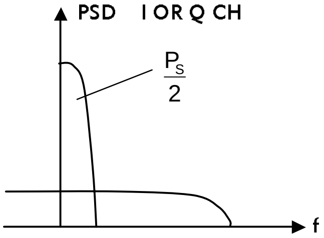
we finally get $G_P = \frac{R_C}{R_b}$, what is equivalent to BPSK modulation.

5.3.3.2 Option 2: same data at full bit rate in both channels

From the RF link budget point of view, if the data bits are voltage added from each channel, there is no power share problem. The impact on Processing gain is described below.

Demodulator :





Signals: The I and Q channel bits are added voltage use (coherently) after detection in the filters.

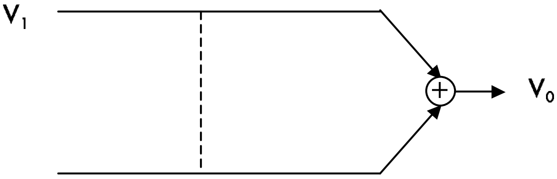
Jammer: The channel jammer noise floors are independent random variables since different PN sequences are used. This means that the noise floors add in an RMS manner.

The next result is that a 3 dB improvement of E_b/N_0 occurs compared with option1 and 3: $G_P = \frac{2R_C}{R_b}$, see below.

Explanation:

For an "N" way summation, junctions have output voltage V_0 for a given input voltage V_i given by:

$$V_O = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} V_i$$



Have $P = \frac{V^2}{2}$ or $V = \sqrt{2P}$, P = power

$$2P_O = \frac{1}{\sqrt{N}} < \left(\sum_{i=1}^{N} \sqrt{2P_i} \right)^2 > = \frac{1}{N} \left\langle \left(\sqrt{2} \sum_{i=1}^{N} \sqrt{P_i} \right)^2 \right\rangle$$

$$= \frac{2}{N} \left\langle \left(\sum_{i=1}^{N} \sqrt{P_i} \right)^2 \right\rangle$$

$$P_O = \frac{1}{\sqrt{N}} \left\langle \left(\sum_{i=1}^{N} \sqrt{2P_i} \right)^2 \right\rangle$$

Where < > are operators meaning expectation or average and P_i can be either coherent (voltage addition) or non-coherent (power addition).

For option 2, both signals $P_i = \frac{P_S}{2}$ and are coherent, (N = 2).

$$\mathrm{P_{OS}} = \frac{1}{2}\left\langle\left(\sqrt{\frac{P_S}{2}} + \sqrt{\frac{P_S}{2}}\right)^2\right\rangle$$

$$= \frac{1}{2}\left\langle\left(2 \times \sqrt{\frac{P_S}{2}}\right)^2\right\rangle = \frac{1}{2} \times 4 \times \frac{P_S}{2} = P_S$$

$$\mathrm{P_{OS}} = \mathrm{P_S}$$

Jammer : $\mathrm{N_{oj}} = \frac{1}{2}\left\langle\left(\sqrt{N_{0I}} + \sqrt{N_{0Q}}\right)^2\right\rangle \rightarrow \mathrm{N_{0I}}, \mathrm{N_{0Q}}$ independent error

$$\mathrm{N_{OI}} = \mathrm{N_{OQ}} = \frac{P_J}{2\,Rc}$$

$$\mathrm{N_{OJ}} = \frac{1}{2}\left\{\left\langle\left(\sqrt{N_{OI}}\right)^2\right\rangle + \left\langle\left(\sqrt{N_{OQ}}\right)\right\rangle + 2\,\underbrace{\left\langle\sqrt{N_{OI}} - \sqrt{N_{OQ}}\right\rangle}_{0}\right\}$$

$$= \frac{1}{2}\left\{\left\langle\left(\sqrt{N_{OI}}\right)^2\right\rangle + \left\langle\left(\sqrt{N_{OQ}}\right)^2\right\rangle\right\}$$

$$= \frac{1}{2}\left(\mathrm{N_{OI}} + \mathrm{N_{OQ}}\right)$$

$$= \frac{1}{2}\left(\frac{P_J}{2\,R_C} + \frac{P_J}{2\,R_C}\right)$$

$$\Rightarrow \mathrm{N_{OJ}} = \frac{P_J}{2\,R_C}$$

$$\frac{P_S}{N_{OJ}} = \frac{P_S}{P_J} \times 2\,R_C$$

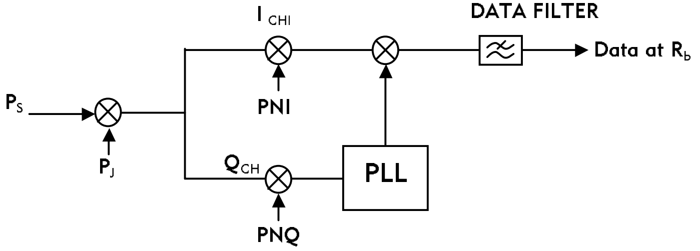
$$\frac{E_b}{N_{OJ}} = \frac{P_S}{P_J} \times \frac{2\,R_C}{R_b}$$

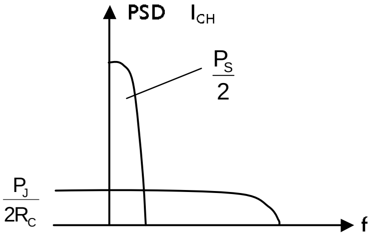
and we finally get $\mathrm{G_P} = \frac{2\,R_C}{R_b}$

5.3.3.3 Option 3: OQPSK, equal power split between I and Q channels, data on I channel only

The RF link budget will have a 3 dB power share. The impact on Processing gain is described below.

Demodulator:





Signal power in I channel $S_I = \frac{P_J}{2}$

Jammed spectral density in I channel $N_{OI} = \frac{P_J}{2R_C}$, R_C = chip rate

$$\frac{S}{N_{OI}} = \frac{P_I}{P_J} \times R_C \qquad \frac{E_b}{N_{OI}} = \frac{1}{R_b} X \frac{S}{N_{OI}} = \frac{P_S}{P_J} \times \frac{R_c}{R_b}$$

processing gain: $G_P = \frac{R_c}{R_b}$

5.3.4 Recommendations

5.3.4.1 General recommendation:

It is recommended that the TC and TM data shall be modulo 2 added to the appropriate spread spectrum uplink or downlink PN codes.

Pulse shaping on the I and Q channels will be root raised cosine. Roll of factors vary typically between 1 and 0,2, a roll off factor of 0,5 is judged to feasible without undue complexity. This implies an RF bandwidth of 1,5 Arc which is assumed (conservatively) to be the -25 dBc bandwidth. A schematic SRRC OQPSK modulator is shown in figure 9.

Time domain and frequency domain representations of the pulse are shown in figures 10 and 11, respectively.

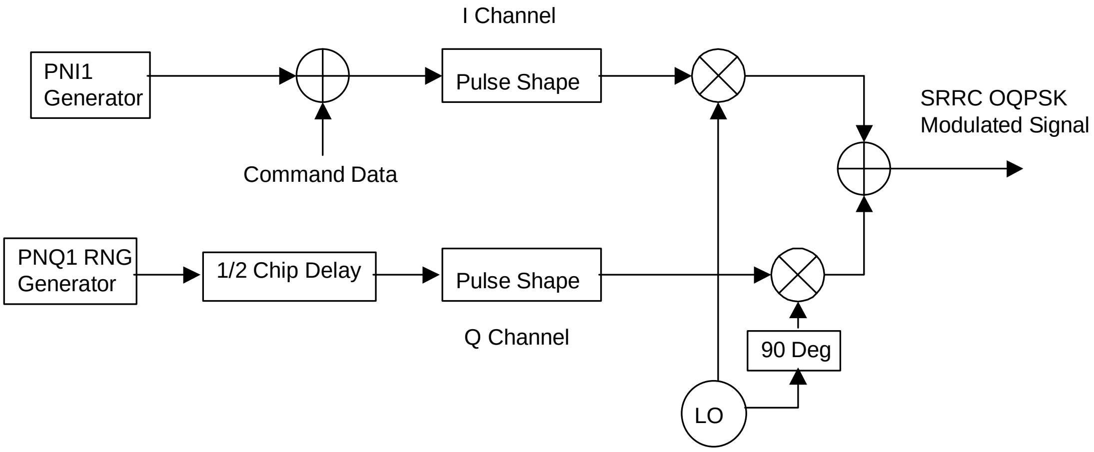


Figure 9: OQPSK Modulator With Pulse Shaping

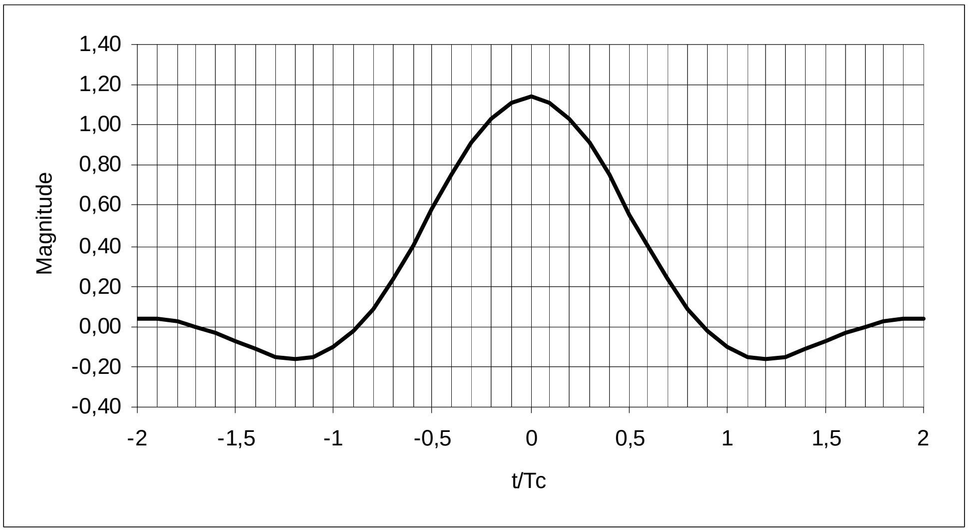


Figure 10: SRRC Pulse With A Roll Off Factor Of 0,5, Time Domain

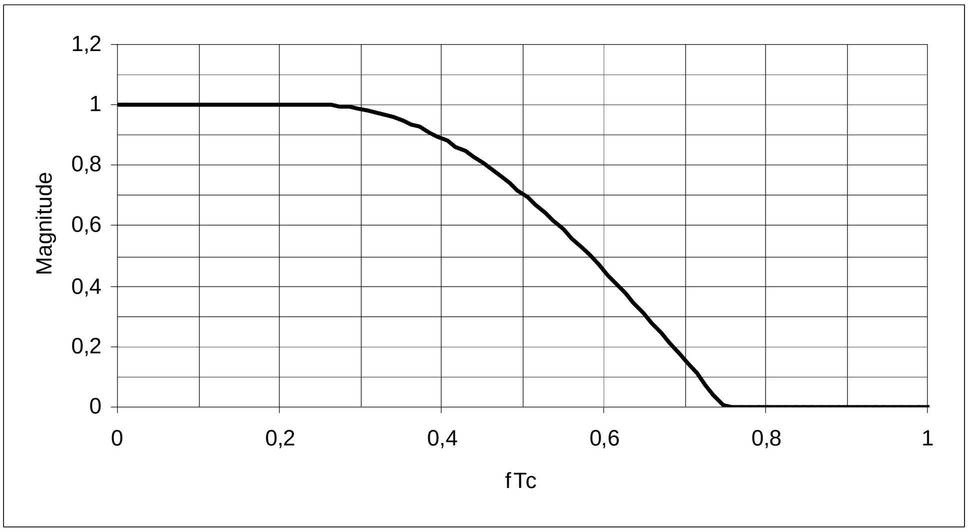


Figure 11: SRRC Pulse With A Roll Off Factor of 0,5, Frequency Domain

5.3.4.2 Specific recommendation for SS TM

For the standard, option 2 (see clause 5.3.3.2) is recommended, as the best compromise performances/implementation. This enables a 3 dB improvement on the processing gain wart option 1.

5.4 PN CODE ACQUISITION

5.4.1 Introduction on PN code Acquisition

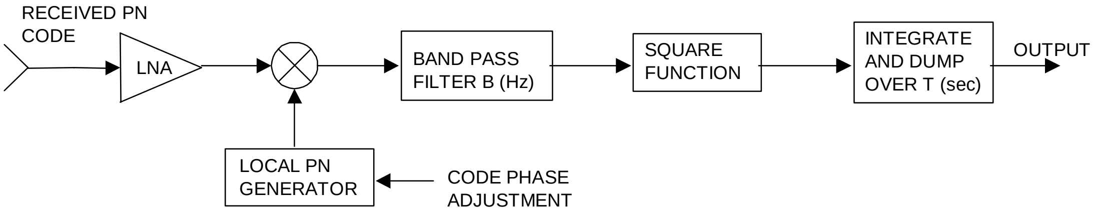


Figure 12: simplified acquisition process at the satellite

Figure 12 shows a very simplified PN code acquisition configuration for a satellite command spread spectrum receiver. Since in general the uplink frequency is uncertain (due to for example oscillator instability and Doppler shift), the acquisition process is assumed to be non-coherent. At the satellite the received PN code is correlated against a local replica. If the replica is within a chip of the correct phase of the received code, then the spectrum is essentially de-spread and significant energy can pass through the IF filter of bandwidth B. The signal is then squared and then averaged by an integrate and dump detector. If the detector output is above a threshold then code tracking is instigated using a delay locked loop. If the detector output is below the threshold (i.e. the received and local codes out of phase) then the local PN code phase is incremented in usually ½ chip intervals and the acquisition measurement made again.

Some factors that can affect acquisition performance are:

- Doppler dynamics on the received PN code.
- Integrate and dump times.
- Filter bandwidth B.

These factors are discussed in clause 5.4.2.

5.4.2 Integrate and Dump Dwell Time and Doppler Offset

Worst case Doppler offset for a GTO are estimated to be ±600 KHz at 18 GHz. During the acquisition process Doppler offset also appears proportionately on the PN code chip rate and is given by:

$$\Delta R_C = \frac{\Delta f R_C}{f} \quad chip/s$$

Where Δf , f and R_c are the RF Doppler offset frequency, the carrier frequency and the PN code chip rate, respectively. For the above Doppler characteristics the chip offset frequency becomes 33,3 chip/s for an I Maps PN code rate.

Because of the Doppler offset in received chip rate, during the acquisition procedure the replica code generated at the satellite will be continuously sliding past the received code. If the code slip during a dwell time exceeds one chip then both codes are de-correlated and the acquisition process fails. As a rule of thumb the change in code phase due to Doppler offset during the dwell time should be no more than a quarter of a chip. From the above this implies dwell times of less than or equal to 7,5 ms.

Potential frequency uncertainty due to Doppler offsets turns the acquisition from a one-dimensional search over code phase to a two-dimensional one over code phase and frequency. This is illustrated graphically in figure 13.

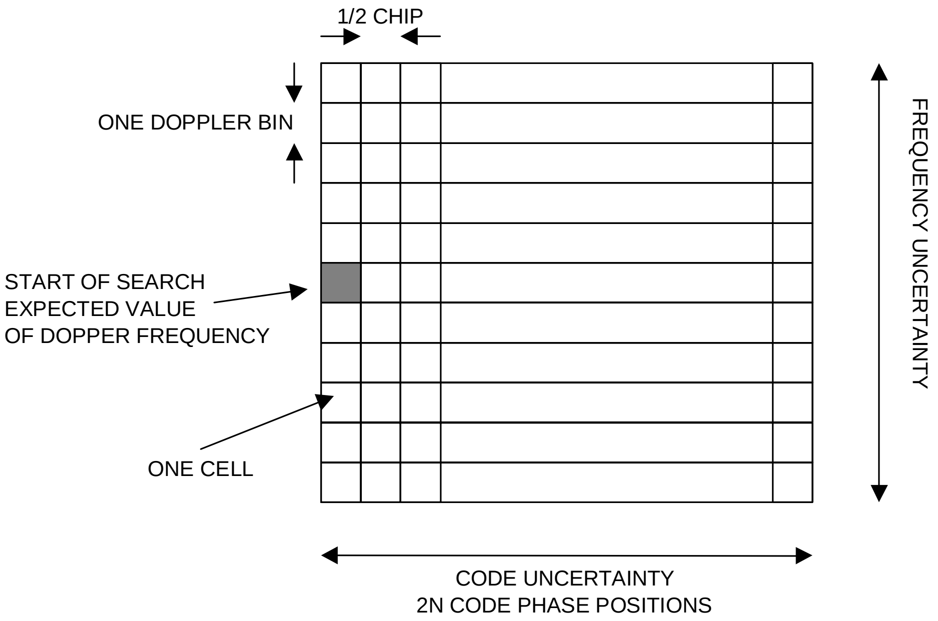


Figure 13: Two dimensional PN code search pattern

Annex B defines the frequency search unit, a Doppler bin, as 2/(3T) Hz, where T is the integration or dwell time per cell. For the Doppler offset and chip rates assumed above, a dwell time of 7,5 ms and a code length N of 1 023 the Doppler bin size is 89 Hz. Consequently 13,500 Doppler bins would potentially have to be searched in addition to the uncertainty in code phase positions. In practice the dwell time is dependent on C/N_0 and filter bandwidth B.

It can be seen that if no Doppler compensation is used on the uplink, the search space for the receiver can be very large (millions of cells) which could lead to very long acquisition times. The above result applies for the case of a filter bandwidth B just large enough to pass the modulated carrier bandwidth. Alternatively, the filter bandwidth B could be made large enough to accommodate modulation and frequency uncertainties but at the penalty of reducing signal to noise at the detector and hence reducing detection probabilities.

Probability of detection and false alarms for PN code acquisition are discussed in clause 5.4.3.

5.4.3 Approximate Probabilities of Detection and False Alarm

The discussion here on probabilities of detection and false alarm of a PN code acquisition are based on [2], p. 422. The discussion applies to a fixed dwell integrate and dump detector following square law detection as depicted above.

Figure 14 shows the probability density functions (PDF) at the output of the integrate and dump detector for noise only and signal plus noise. Also shown are the axis of normalized variables used in the cumulative probability integral for evaluation of detection probability.

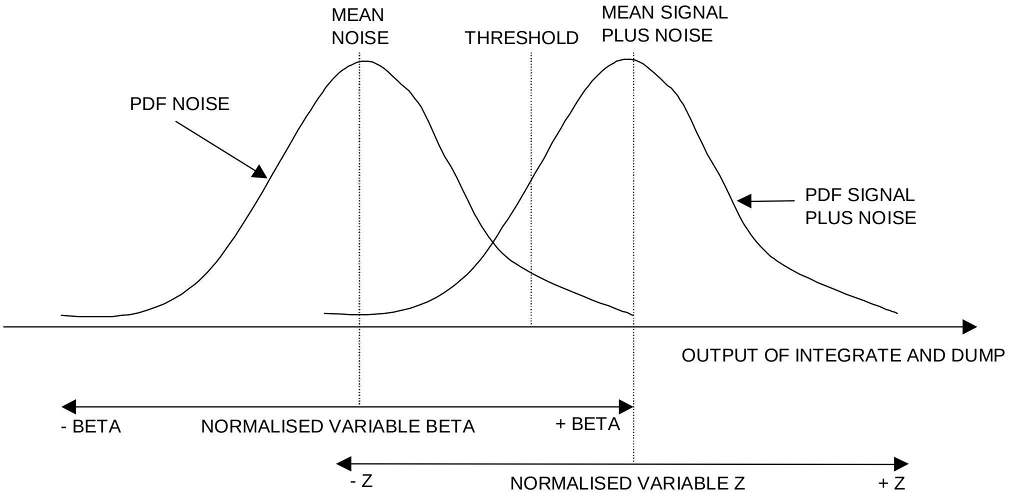


Figure 14: probability densities for noise and signal plus noise at the output of the integrate and dump filter

Considering the noise only case and referring to the figure, a false alarm probability is first chosen which using probability tables, allows the evaluation of a threshold relative to the system noise. Having determined the threshold, then for given C/N_0, and filter bandwidth B the probability of detection can be evaluated as a function of dwell time.

The probability of false alarm is given for the noise only case by:

$$P_{FA} = Q\left(\frac{\delta - N_o B\tau}{N_o\sqrt{B\tau}}\right)$$

$$Q(\beta) = \frac{1}{\sqrt{2\pi}}\int_{\beta}^{\infty}\exp(-x^2/2)dx$$

$\delta = threshold$

$B = bandwidth$

$\tau = dwell\ time$

Considering a false alarm probability of 1 %, then P_{FA} = 0,01 from which $\beta = 2{,}33$ at threshold.

The probability of detection is given for the noise plus signal case by:

$$P_D = Q\left(\frac{\beta - \sqrt{B\tau}\rho}{(1+2\rho)^{1/2}}\right)$$

$$z = \frac{\beta - \sqrt{B\tau}\rho}{(1+2\rho)^{1/2}}$$

$$\rho = \frac{C}{N_o B}$$

The filter bandwidth B is generally chosen to be at least twice the bit rate plus twice the Doppler offset frequency. However for large Doppler frequency offsets this implies a large B and reduced signal to noise ratios at the detector, with a corresponding reduction in probability of detection. Conversely choosing B to just accept the main lobe of the digital signal will imply frequency aiding in the acquisition process or search over many frequency bins as depicted above.

The effect of C/N_0 and filter bandwidth B on dwell time and P_D are investigated in clauses 5.4.3.1 to 5.4.3.3.

5.4.3.1 Case 1: Mean of the signal plus noise PDF equals the threshold level

P_D = 0,5 in this case (i.e. the integral under the curve from the mean = threshold to plus infinity) therefore:

$$\beta = \sqrt{B\tau}\rho \quad and$$
$$\tau = B\beta^2\left(\frac{N_o}{C}\right)^2$$

For a false alarm probability of 1 % we obtain:

C/N_0 (dB)	Bandwidth (B)	Dwell Time
30	1 KHz	5,4 ms
30	1 MHz	5,4 s
45	1 MHz	5,4 ms

5.4.3.2 Case 2: Very good C/N_0

For this case we have:

$$z = \frac{\beta - \sqrt{B\tau}\rho}{(1+2\rho)^{1/2}} \to -\sqrt{\frac{B\tau\rho}{2}} = -\left(\frac{C\tau}{2N_o}\right)^{1/2} \quad provided \quad \frac{\beta}{\sqrt{2\rho}} << 1$$
$$Say \quad \frac{\beta}{\sqrt{2\rho}} \le 0{,}01 \quad implies \quad \frac{C}{N_o} \ge 44 + 10\log(B) \ dBHz$$
$$and \quad P_D \to 1 \quad independant\ of\ B$$

That is if the condition $\frac{C}{N_o} \ge 44 + 10\log(B)$ is met then good probability of detection is assured.

5.4.3.3 Case 3: Intermediate values of C/N_0

Have: $z = \frac{\beta - \sqrt{B\tau}\rho}{(1+2\rho)^{1/2}}$

Choose:

$$\frac{C}{N_o} = 45 \ldots dBHz$$
$$\beta = 2{,}33$$
$$\tau = 1\,ms$$
$$B = \text{var}iable$$

By varying B we can obtain z and P_D for the other fixed parameters. Examples are given in the table below.

Bandwidth B (Hz)	Normalized Variable z	Probability of Detection P_D
10^3	-3,65	0,9999
10^4	-2,83	0,9977
10^5	-0,65	0,7422
10^6	+1,29	0,0985

It can be seen that for large B the probability of detection can very rapidly become small and approach the false alarm probability. This in turn implies lengthened acquisition times. [2], page 418 gives an approximate expression for average acquisition time for a single dwell, which in the limit of small P_{FA} can be expressed as:

$$\overline{T} = \frac{(2 - P_D)N\tau}{2P_D(\Delta T_c / T_c \pm \Delta R_c \tau)}$$

$$N = PN\ code\ length$$

$$\Delta T_c / T_c = 1/2$$

For B = 1 MHz (e.g. full Doppler uncertainty), P_D = 0,0985, ΔR_c = 33,3 chip/s, N = 1 023 chips and a 1 ms dwell time we obtain $\overline{T}$ = 21,2 s.

For the case of no Doppler and P_D equal to unity the average acquisition time simplifies to:

$$\overline{T} = N\tau$$

For N = 1 023 chips and a 1 ms dwell time we obtain $\overline{T}$ = 1 s.

Note that the P_D determined above is approximate and for low signal to noise ratios the probability of detection becomes:

$$P'_D = P_D P_{HO}$$

$$where$$

$$P_{HO} = probabilit\,y\ of\ \ handover$$

Here P_{HO} represents the probability of successful handover to subsequent stages of synchronization (e.g. transition to a DLL etc). Typically for the Space Shuttle P_{HO} ranged from 0,06 to 0,5 depending on Doppler effects and on average with no Doppler was 0,25. This results in acquisition times lengthened by approximately by $1/P_{HO}$.

5.4.4 Long Code Acquisition

The ranging code or long code provides the ambiguity resolution for ranging. The long code modulates the Q channel of the unbalanced QPSK up link (no data modulation is present). Both the short code (command code) and the long code have to be epoch synchronized at the ground terminal.

It is advantageous to have the long code length an integral multiple of the command code length. For example in the TDRS system, the long code has a length of 256 times the length of the short code, itself of length 1 023 chips. The long code is generated from a truncated shift register sequence of length (2^{18} - 256) chips. Consequently, since the short and long codes are epoch synchronized, the spacecraft long code generator needs to check only 256 positions in its code phase for synchronization.

The long code acquisition only takes place after:

- Short code acquisition and tracking via a delay locked loop.
- Carrier acquisition and tracking usually by a PLL/Costa's loop.

As a consequence, long code acquisition can be a coherent process (i.e. carrier acquired and locked) allowing significant reductions in the acquisition IF filter bandwidth with respect to the short code case. Long code acquisition times will therefore be significantly decreased with respect to the short code case. TDRSS figures suggest a reduction of long code relative to short code acquisition time by about a factor of 20 for sequential search and a single Doppler bin.

In conclusion, overall acquisition times will be dominated by short code acquisition and carrier acquisition times, which must occur before the long code is acquired.

5.4.5 Preliminary Conclusions on PN code acquisition

The above results on acquisition are approximate and have to be ultimately determined by simulation and measurement. However, trends in the results demonstrate that:

- Narrow filter bandwidths give good performance without Doppler or with Doppler aided carrier tracking loops. Otherwise with Doppler uncertainty many Doppler bins have to be searched implying either long acquisition times or sophisticated parallel signal processing in the receiver.

- Large filter bandwidths that can accept all frequency uncertainties and data modulation can potentially reduce detection probabilities to small values, again implying long acquisition times.

- In both the above cases Doppler offset limits integrate and dump dwell times on the PN code rate.

- In practice an optimum acquisition strategy would involve trade-offs between ground system complexity, space segment complexity and operational issues during the various operational phases of the satellite.

- Use of spread spectrum communications during LEOP is probably best implemented by some form of Doppler compensation on the uplink (implemented at the TCR ground station) which would minimize complexity for the spacecraft TCR transponder.

5.5 DS/CDMA code trade-off

Different codes can be used for DS/CDMA techniques. Each code has its own characteristics.

5.5.1 Description of different codes family

5.5.1.1 M sequences

- few polynomials available.

- even cross correlation: $\approx 1/N$.

- ideal for synchronization with sequence of 1 1 1 1 1 1 1 1.

5.5.1.2 Gold codes

- (N+2) polynomials available

- even cross correlation: $\approx 1/\sqrt{N}$

5.5.1.3 Kasami codes

- $\approx \sqrt{N}$ polynomials available (better than Gold).

- even cross correlation: $\approx 1/\sqrt{2N}$.

5.5.1.4 Walsh Hadamard codes

- synchronized codes.

- unbalanced number of "1"and 0": necessity to add another spreading code.

- perfectly orthogonal code.

5.5.1.5 Gold code with preferential phase

- synchronized codes.
- similar to Gold, but quasi orthogonal codes.
- ≈ N polynomials available.

5.5.2 Pros and cons of code synchronization

- Advantage:
  - theoretically perfect correlation between codes.
- Drawback:
  - very complex to implement for the uplink (different TCR stations are used for a group of co-located satellites);
  - very complex to implement for the downlink (all the co-located satellites clock would have to be perfectly synchronized);
  - very sensitive to:
    - frequency shift;
    - synchronization error.

Code synchronization is very complex to implement. It is also sensitive to frequency & time error. This solution is not recommended for the baseline standard.

However, in cases where one station controls many collocated satellites, it makes sense (if possible) to synchronize the uplink PN code so that cross correlation isolation (and thus multiple access performance) is maximized.

For non-synchronized code, Gold code is a good compromise of performance. This is what is recommended for multiple access techniques, with non-synchronous transmission.

5.6 Tracking Receiver on Spread Spectrum (SS) signal

5.6.1 Hypothesis

Spread spectrum signal for TM is used by antenna tracking receiver.

The tracking receiver uses mono-pulse technique, which reveals to be well suited for meeting pointing accuracy requirements for Ku-Band signals.

5.6.2 Analysis

Need for de-spreading the error signal: As the TM signal is spread, the tracking receiver will not be able to lock on the signal. A de-spreading/demodulator module shall be implemented to recover error signals (ΔAz/ΔEl) from sum (Σ) signal and delta (Δ) signal (orthomode coupler), then the tracking receiver will be able to track on error signal.

Use of TM acquisition module: In a first analysis, it is possible to use the same module as used for TM signal acquisition in the base-band equipment in the TCR station.

Then, the tracking function will be included in the base-band equipment and there is no need for a separate tracking receiver unit (as opposed to today standard TCR station design where tracking receiver is separated from base-band equipment).

No performance issue: The performance specification for TM acquisition (acquisition shall be done within a few seconds) is compatible with current TCR station design. In fact, as long as the mono-pulse is not activated, the antenna can be programmed in program track mode which guarantee (if ephemerides files are correct) that the antenna is always pointed towards the satellite for mono-pulse acquisition phase. This also guarantees that TM signal is always received by TM/tracking receiver module.

In conclusion, if the TM module meet operators' requirement (annex B), there is no performance issue for tracking spread spectrum signals if TM module is used to process error signals.

Impact on TCR station design: The proposed solution need major modifications on base-band equipment (base-band equipment implements TM acquisition module) to be able to process mono-pulse error signals.

Those error signals (ΔAz/ΔEl) shall be shaped to be delivered to base-band equipment (amplification, down-conversion, etc.).

The base-band equipment, after processing of the error signals, delivers command values to ACU (ACU drives antenna axis motors).

5.6.3 Conclusion

It is possible to use spread-spectrum signals to track satellites using mono-pulse antenna system, using TM acquisition module.

Nevertheless, today, no engineering model exists to validate this analysis. As a consequence, achieving an antenna tracking system using satellite spread spectrum signals will require additional industrial development that may not be completed when the SSMA TCR standard is introduced.

Thus a simple beacon is recommended initially (probably using a CW signal) as currently.

6 Trade-off between different solutions

The trade-off between the solutions will be done, depending of the performance of:

- Capacity
- Operational constraints
- RF compatibility with the COM signal
- Equipment feasibility

6.1 Description of the potential solution

6.1.1 Telecommand function

Three possible command solutions are envisaged:

- Wide band SS TC: The TC is spread over a COM channel (typically over 36 MHz).
- Narrow band SS TC: the TC is spread in a bandwidth adjacent to the COM channel, in edge of the COM channels frequency bandwidth. Typically, this bandwidth left for TCR is a few MHz wide.
- STD TC modulation.

6.1.2 Telemetry function

Three possible TM solutions are envisaged:

- Wide band SS TM: the TM is spread over a COM channel (typically over 36 MHz).
- Narrow band SS TM: the TM is spread in a bandwidth adjacent to the COM channel, in edge of the COM channels frequency bandwidth. Typically, this bandwidth left for TCR is a few MHz wide.
- STD TM modulation.

6.1.3 Ranging function

4 possible RG solutions are envisaged:

- Wide band SS RG: the RG is spread over a COM channel (typically over 36 MHz) and the RG signal is directly down converted and amplified by the COM repeater.
- Wide band SS RG: the RG is spread over a COM channel (typically over 36 MHz) and the RG regenerated on-board.
- Narrow band SS RG: the RG is spread in a bandwidth adjacent to the COM channel, in edge of the COM channels frequency bandwidth. Typically, this bandwidth left for TCR is a few MHz wide.
- Hybrid RG (uplink, SS narrow band, and downlink, STD modulation).

6.1.4 Selection of the potential solutions

The detailed analysis of all the combinations of telemetry, command and Ranging solutions cannot be performed (3 × 3 × 4 cases = 36 cases).

Certain configurations have to be directly discarded, as explained in table 3.

Table 3: selection of the potential solution

	TM STD modulation				**TM SS NB**				**TM SS WB**
	RG SS WB Transparent	**RG SS WB Regene-rative**	**RG SS NB Regene-rative**	**RG hybrid**	**RG SS WB Transpa-rent**	**RG SS WB Regene-rative**	**RG SS NB Regene-rative**	**RG hybrid**	**any RG**
TC SS WB	▨	🟨	🟨	▨	🟩	🟨	🟦	🟩	S2A
TC SS NB	🟪	🟨	🟨 S5	S4	🟪	🟨	S1	🟩	S2B
TC STD	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

NOTE: TC: Telecommand.
TM: Telemetry.
RG: Ranging.
SS: Spread Spectrum.
STD: Standard.
WB: Wide Band.
NB: Narrow Band.

legend:

🟥	no interest w.r.t today standard
🟦	requires different demodulator/bandwidth of the on board receiver for RG or TC
🟨	requires different modulator/transmitter for RG and for TM
▨	impossibility to have dual mode receiver with Wide Band TC, in the same bandwidth
🟩	incoherent choice: TM SS downlink RF budget is more critical than RG: but if it works, the same modulation shall be used for RG
🟪	operational constraint: RG cannot be performed during Drift orbit or apogee manoeuver, because Payload is OFF during those phases.

Note that the RG SS Wide Band transparent solution has been discarded, due to its non-compliance with the operators' requirements (this solution does not allow any multiple access during LEOP or beginning of drift orbit, because Payload is kept OFF during those phases).

Finally, 3 solutions are left (identified in blank in table 3):

- Solution 1: on board regenerative narrow bandwidth SS TCR.
- Solution 2: any RG, TC SS (narrow or wide band), TM wide band SS.
- Solution 4: narrow bandwidth SS TC, STD TM modulation, hybrid RG.

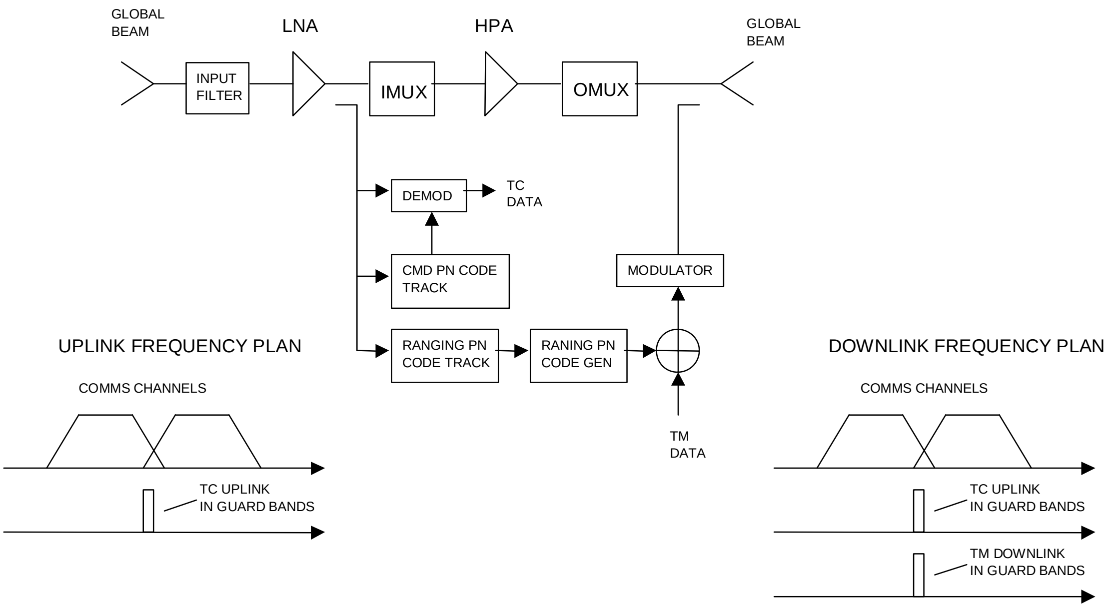
6.2 Hypothesis and principle of the analysis:

6.2.1 General hypothesis on the system

6.2.1.1 Satellite configuration

Figure 15 shows just one possible satellite configuration. Features include:

- Communication antennas covering TCR stations locations.
- Transparent transponder for communication traffic.
- TC signals are tapped off after amplification from the LNA.
- TM signals added into the downlink path after HPA.



NOTE: This figure shows the on station configuration when the TCR uses the payload communications antenna. During LEOP and drift, the payload communications are off, and the TCR uses an omni-directional antenna.

Figure 15: Proposed implementation of spread spectrum TCR for inter- compatibility analysis

6.2.1.2 Possible sources of interference for TCR signals for co-located satellites and ground terminals

With respect to figure 16 potential sources of interference are:

- Communication traffic spill over into TC/TM signals.
- On frequency multiple access interference from other uplink TC signals to collocated satellites (i.e. auto compatibility of collocated uplink signals).
- Jamming from external sources.
- TC breakthrough on the communication channel which overlays the TM signal (i.e. TC echo).
- Contributions from other co-located satellites to the TM at the TCR ground terminal of interest.

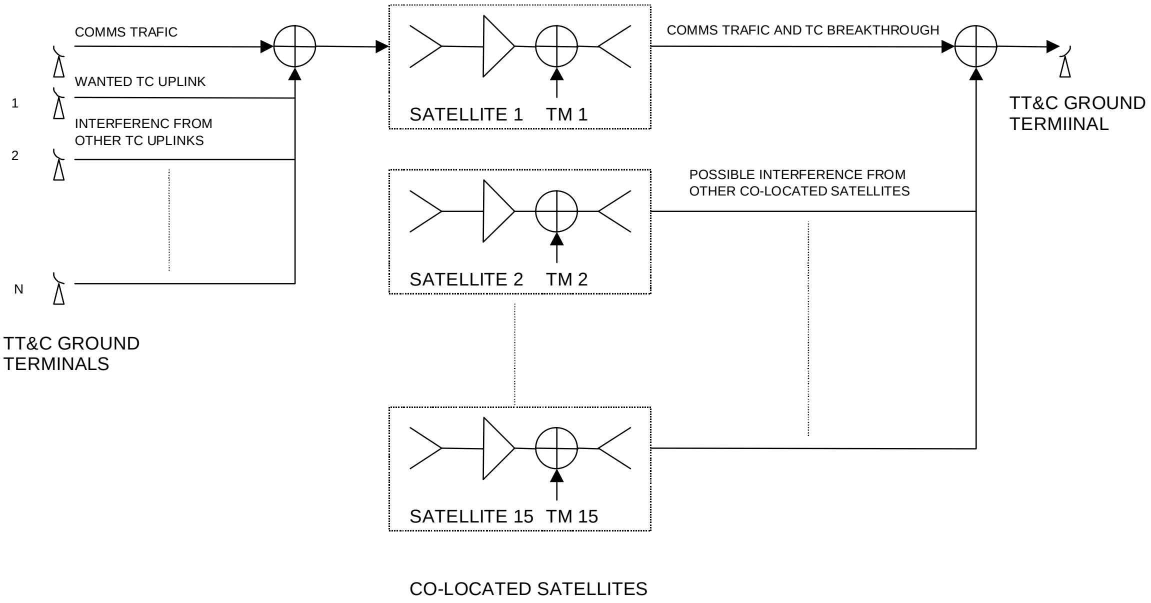


Figure 16: possible interference for spread spectrum TCR

Figure 17 indicates various interference mechanisms onboard the satellite, for spread spectrum in edge of COM channels.

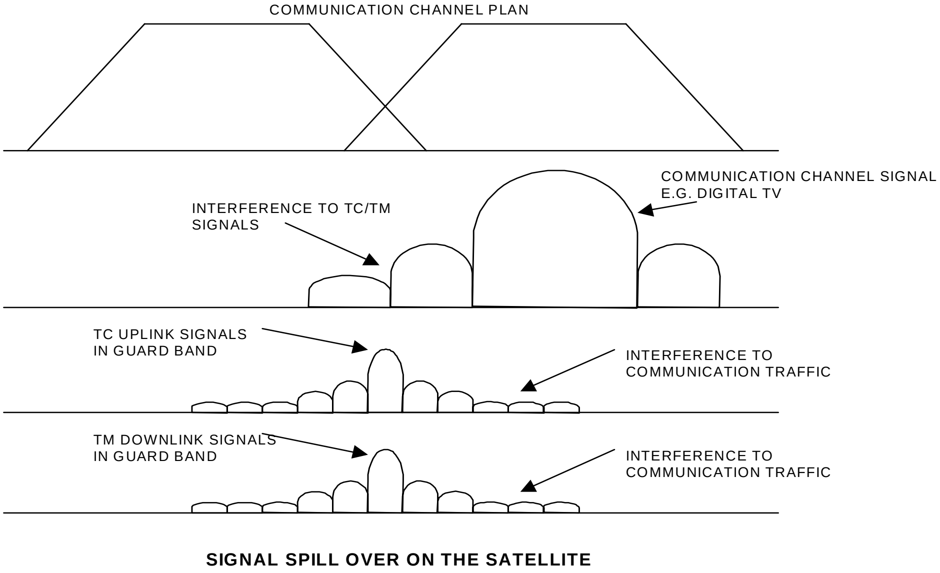


Figure 17: Various interference mechanisms onboard the satellite

6.2.1.3 TCR frequency plan adjustment for narrow band Spread Spectrum

The location of the TCR frequencies in the frequency plan can affect the inter-compatibility properties of the system. Six cases are possible for narrow band Spread Spectrum (see figure 18).

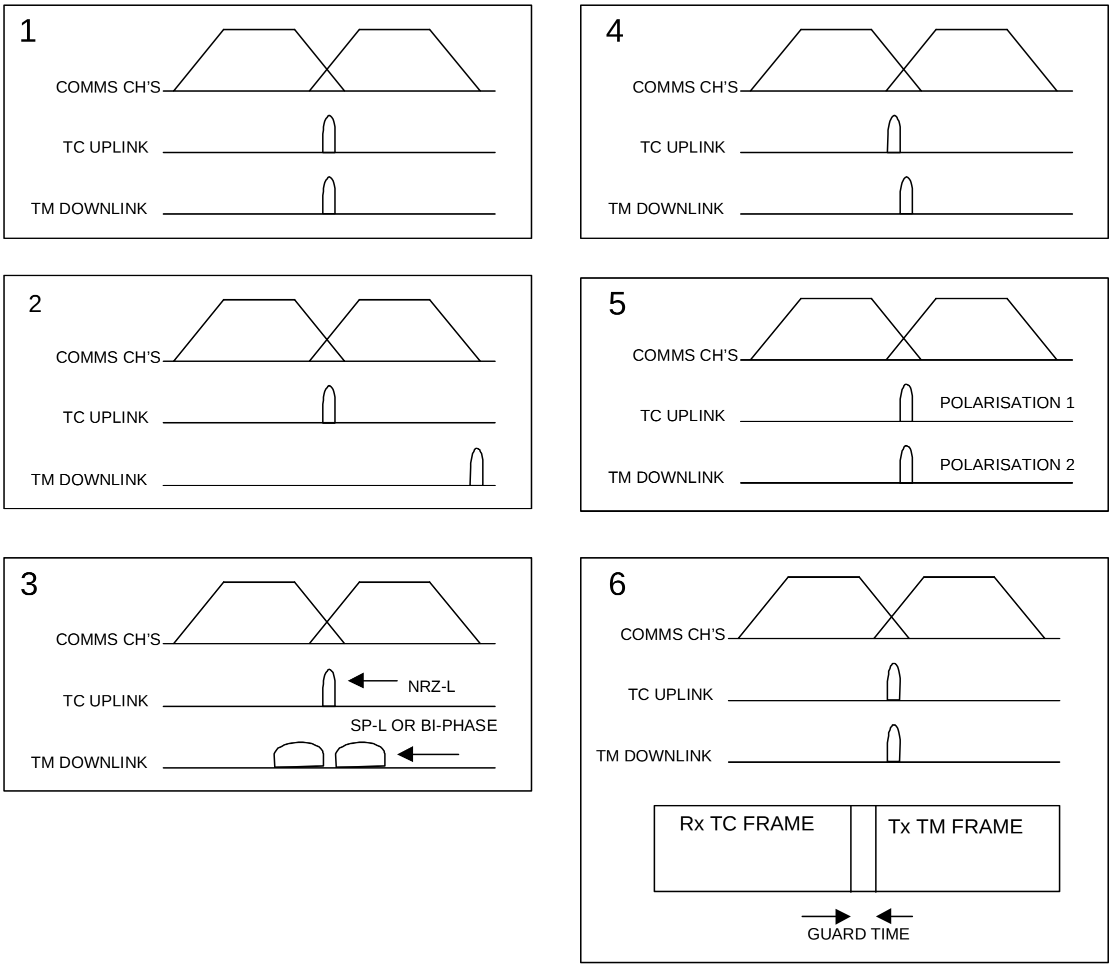


Figure 18: Frequency plan options

OPTIONS:

1) Both TC and TM signals are placed in the same guard band between communications channels (as is used for conventional TCR). TC signals are partially rejected by IMUX and DEMUX channel filters in the communications path but are recombined and overlayed with TM signals on the downlink.

2) This option avoids interference between TC and TM by using a different guard band for the TM signal.

3) Interference between TC and TM is avoided by using a combination of modulation techniques e.g. DSSS/NRZ-L on TC and DSSS/SP-L on the downlink.

4) Use bandwidth constrained TC and TM signals which are orthogonal in frequency but within the same guard band.

5) Use opposite hands of polarization for isolation between TC and TM at same frequency.

6) Use common frequencies for TC/TM signals but make them orthogonal in time, average data rate maintained by bursting the data in a transmission frame.

Table 3a: Characteristics of the different options

OPTION	COMMENT
1	TC signal would interfere with TM and so degrade multiple access performance, etc. on down link Would require different PN codes for ranging since uplink is echoed through to downlink Relatively bandwidth unconstrained
2	No interference between TC and TM Relatively bandwidth unconstrained Would this be acceptable to the service provider?
3	Use of different modulation formats e.g. NRZ-L and SP-L can minimize interference between TC and TM SP-L spread spectrum would occupy more bandwidth and potentially give more interference to communications signals, need to check link budgets
4	Isolation between TC and TM by using orthogonal frequencies but within the same guard band Need tight constraints on signal bandwidths e.g. approx. 500 KHz Would need "complex" modulation like GMSK
5	Isolation between TC and TM via polarization re-use (about 20 dB) Would this be acceptable to the service provider?
6	Here both TC and TM occupy the same guard band but not at the same time A scheduled approach is used where, at the satellite, TC and TM signals use alternate transmission frames and are therefore orthogonal in time

Option 2 would appear to be the simplest one giving relatively unconstrained signal bandwidths and TC/TM isolation.

Sometimes TC and TM carriers are sharing the same guard band, but at the edge of all the COM channels on the satellite.

Nevertheless, for further analyses of Narrow Band Spread Spectrum, it is assumed (and this assumption covers most of the existing configuration) that the TC and TM carriers are sufficiently separated in frequency so that the TC echo interference into TM can be ignored, and is thus not treated in the analysis.

6.2.2 RF hypothesis

The standard shall be applicable for C and Ku band; but all the simulations are performed in the worst case in terms of band, that is the Ku band.

In this clause, RF link budgets results will be presented. Those RF budgets are given for TCR signals, and for COM signals, to evaluate any interference between both signals.

6.2.2.1 Principle of the analysis

Parameters that are fixed

COM signal characteristics (power at repeater input, on board EIRP, bandwidth).

Architecture of the TCR of existing satellite (standard modulation). This architecture defines typical losses between repeater input and TC receiver. It defines also TC threshold , and TM on board EIRP.

Parameters that can be adjusted

Ground station TC EIRP of existing satellites. This EIRP can be decreased as far as the uplink budget has positive margin.

TC EIRP of Spread spectrum signals. This EIRP can be adjusted, as far as the uplink budget has positive margin.

Architecture of the TCR of SS satellite: the losses between repeater input and TC receiver can be adjusted, and the TM EIRP can be decreased as far as link budgets have positive margins.

Principle of the uplink analysis

First, we fix the TC ground station EIRP of the spread spectrum signal, to ensure a reasonable RF compatibility with COM and standard TCR uplink signal.

Once this level is fixed, we fix, on the satellite with SS TCR, the losses between repeater input and TC receiver. We than adjust the uplink EIRP of the standard modulation to allow positive margin of the STD modulation uplink budget, keeping the inter-compatibility of SS and standard modulation.

Principle of the downlink analysis

We adjust, on the satellite with SS TCR, the downlink TM EIRP, to ensure the auto-compatibility with standard modulation. We then check the compatibility with the COM signal.

6.2.2.2 RF Assumptions for the COM signals

No generic COM signal exists that can represent every COM scenario.

To show something representative of real system, three typical COM scenarios have been envisaged.

The technical parameters associated to those scenarios are presented in table 4.

Table 4: Description of the different COM scenarios

	unit	scenario 1: Analog TV	scenario 2: SNG	scenario 3: data DVB
uplink				
uplink frequency	GHz	14,5		
channel bandwidth	MHz	36	7,8	20
COM signal power level at repeater input	dBm	-76	-90	-98
COM uplink C/N0 (without TTC jammer)	dBHz	93,7	79,5	71,9
downlink				
downlink frequency	GHz	12,5		
downlink COM EIRP	dBW	51,6	34,14	25,98
COM downlink C/N0 (without TTC jammer)	dBHz	91,15	76,30	71,72
total (up+down) COM C/N0 (without jammer)	dBHz	89,23	74,6	68,8

COM uplink characteristics

Uplink COM channel characteristics: 26 dB of out of band emission in edge of COM bandwidth (where the narrow band TCR signals are located).

COM downlink characteristics

Downlink COM channel characteristics: 26 dB of out of band emission in edge of COM bandwidth (where the narrow band TCR signals are located).

6.2.2.3 RF Assumptions for the TCR signals

6.2.2.3.1 Uplink

For the TC uplink SS signal

Assume PSK modulation (BPSK or QPSK with RG), occupied bandwidth of the main lobe = 2 x chip_rate).

For narrow band SS TCR, the main lobe of the PN spreading sequence is NOT in the communication channel. Then the highest PSD will be at the 1st side lobe, which is 13 dB down from that at the TC carrier frequency; in addition, some simple main lobe filtering can easily achieve 10 dB additional suppression of the side lobe.

The required E_b/N_0 of the TC data at TC on board receiver output shall correspond to a BER better than 10^{-6}. If FEC is present, it corresponds to an E_b/N_0 ratio up to 5,6, otherwise, it corresponds to an E_b/N_0 ratio up to 10,6.

TC Receiver hypothesis: NF = 3 dB, implementation losses = 3 dB

For the TC uplink STD modulation signal

Required C/N_0 at STD receiver input = 63 dBHz

Receiver Noise Figure = 3 dB

For existing communication satellite (standard modulation), it is assumed that the losses between LNA input and the TC receivers are equal to -10 dB (see figure 15).

6.2.2.3.2 Downlink

SS TM downlink

TCR Ground station G/T = 25 dB/K

SS modulation implementation losses = -3 dB

The required E_b/N_0 of the TM data at TM ground receiver output shall correspond to a BER better than 10^{-5}. If FEC is present, it corresponds to an E_b/N_0 ratio up to 4,6, otherwise, it corresponds to an E_b/N_0 ratio up to 9,6.

STD modulation TM downlink

S/C TM EIRP of STD modulation satellite: 10 dBW

TCR Ground station G/T = 25 dB/K

STD modulation implementation losses = -2,5 dB

6.2.3 Success criteria

Success criteria for the jamming of the COM

The analysis will have to prove that, for each of this scenario, the COM will not be degraded by more than 3 %.

Success criteria for the jamming of the STD TC uplink signal

The C/N_0 (N_0 being the contribution of every jammer, including spread spectrum link, COM link, thermal noise of nominal TC link) shall be higher than 63 dB/Hz, with a margin above 2 dB.

Success criteria used for the jamming of the SS TC uplink signal

The E_b/N_0 at the TC receiver output shall be compatible with the required BER, with at least 2 dB margin.

Success criteria used for the jamming of the TM downlink signal (for SS and STD modulation).

The E_b/N_0 at the ground receiver output shall be compatible with the required BER, with at least 2 dB margin.

6.2.4 Description of the method used to estimate the multiple access degradation

Different approaches can be considered, to evaluate the characteristics of the jamming of a SS signal due to the multiple access:

1) To consider the other users contribution like white noise (the jamming will then be evaluated through the processing gain). easy computation.

2) The approach of MBB in its report "Study of spread spectrum Techniques for TCR". This approach is based on an article of M.B PURSLEY (see Bibliography). This method is adapted for BPSK modulation. Long computation, but simulation possible.

3) The approach presented by D.LAFORGIA in his article ("Bit error rate evaluation for spread spectrum multiple access systems", IEE transaction on communication, vol. com-32, august 1984), based on "moment" evaluation. This method is nearly the only one to have considered the QPSK case. Not many results available. Very complex algorithm, difficult to implement for further simulations.

4) CNES approach (internal note CNES 85-CT/DRT/TIT/TR no 200). Easy to compute, very similar to approach no 1.

Those approaches give very similar results.

The most pessimistic is method no 3, that is the only one adapted to QPSK modulation. But this method is too complex to be used, and not matched for our application.

Method 1) 2) and 4) are very similar, and are easy to compute.

Conclusion: Method 2 will be used (if simulation results are available in MBB report), otherwise method 4 will be used.

Once the method is chosen to evaluate the "multiple access interference correlation contribution", this parameter is taken into account in the evaluation of the E_b/N_0 through the following formula:

- assume k earth stations with equal transmit power using CDMA;
- we can write for the received energy per bit to noise density ratio of the SS nominal signal:
  - $(N_0/E_b)rx = Rb(N_0/C) + (k-1)\ Kcode + (1/Gp)(I/C)$;
  - where the terms are respectively;
    - thermal noise to carrier ratio,
    - multiple access interference correlation contribution Kcode: term to be evaluated with method previously presented (Kcode can be the processing gain at first approximation),
    - external interference contributions; taking into account the gain processing Gp = Wss/Rb (Where Wss is the single sided spread spectrum bandwidth and Rb is the bit rate).

6.3 Solution 1: on board regenerative narrow bandwidth SS TCR

6.3.1 Description of the solution

Uplink: modulation SRRC-UOQPSK, ratio I(TC)/Q(RG) = 10/1 dB, roll-off factor $\alpha = 0,5$

- TC bit rate: 500 bit/s or 1 kbit/s
- TC code length = 2^{10} -1 = 1 023, Gold code
- TC chip rate: 500 kchip/s to 3 Mchip/s
- synchro bit TC/chip TC: not foreseen
- RG code length: compatible with a 5 000 km ambiguity
- RG chip rate = TC chip rate
- FEC convolutional_rate = 1/2

Downlink: modulation SRRC-UOQPSK, ratio I(TM)/Q(RG) = 10/1 dB, roll-off factor α = 0,5

- RG code length = same as uplink
- RG chip rate = same as uplink = TM chip rate
- TM bit rate: 2 048 bit/s to 4 096 bit/s
- TM code length = 1 023 chips (non coherent) or as RG code length (in coherent mode)
- FEC convolutional_rate = 1/2

Implementation: dual mode transponder.

6.3.2 RF performances

6.3.2.1 Specific hypothesis for solution 1

As explained in clause 6.2.2.1, some parameters shall be adjusted for the RF link budget:

- It is decided, arbitrarily, to fix the on-board losses between COM LNA and TC SS receiver to -5 dB.
- The SS TC EIRP is adjusted between 44,5 dBW (no FEC) and 39,5 dBW (FEC present).
- The SS TM EIRP is adjusted between 9 dBW (no FEC) and 4 dBW (FEC present).

The COM degradation is estimated in the worst case of the 3-presented COM scenario (see table 4).

Inversely, the TCR degradation due to the COM has been estimated in a generic COM configuration being a worst case in terms of TCR degradation (COM power level at repeater input = -55 dBm, COM downlink EIRP = 55 dBW).

It has been shown in clause 5.2.3 that, for a Gaussian distribution of unbalanced EIRP, the CEC value could be evaluated.

For 10 users, for an EIRP range of 3 dB (typical value for the uplink), CEC = 15.

For 10 users , for an EIRP range of 10 dB (typical value for the downlink), CEC = 55.

This means that the ratio CEC *downlink/* CEC *uplink* can be estimated equal to 55/15 = 3,67.

This ratio has been used for the analysis.

6.3.2.2 Parametric analysis results

Parameters being modified during the parametric analysis:

- Capacity
- Chip rate
- SS TC Data rate
- FEC coding for SS TC (and depending of this option, SS TC EIRP is adjusted)
- FEC coding for SS TM (and depending of this option, SS TM EIRP is adjusted)

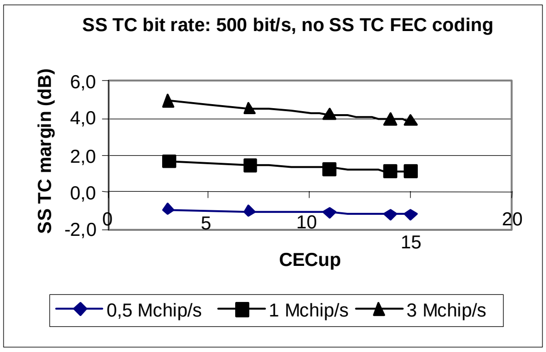
Parameters that are analysed, as result of the analysis:

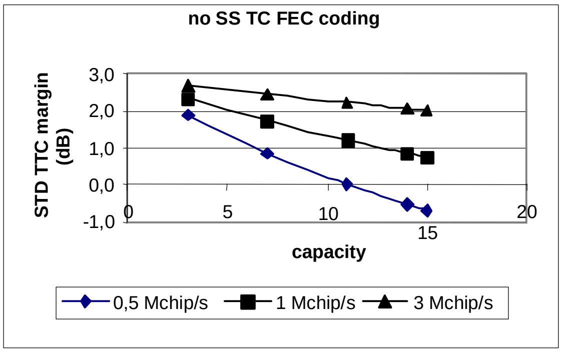
- STD TC uplink RF budget margin (in dB)
- SS TC uplink RF budget margin (in dB)
- STD TM downlink RF budget margin (in dB)
- SS TM downlink RF budget margin (in dB)

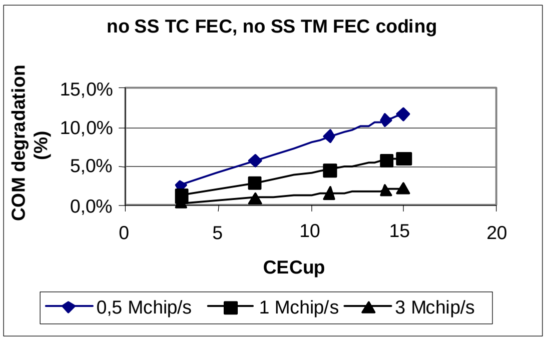
- COM degradation in %

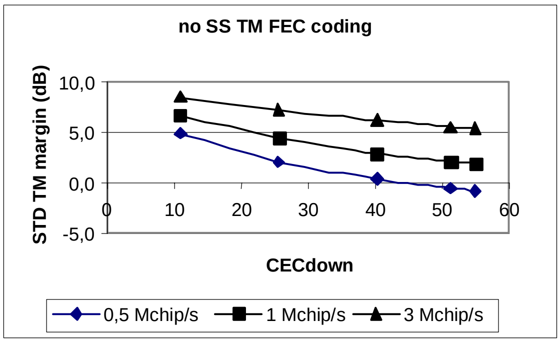
All the details are given in annex A, for one configuration of parameters.

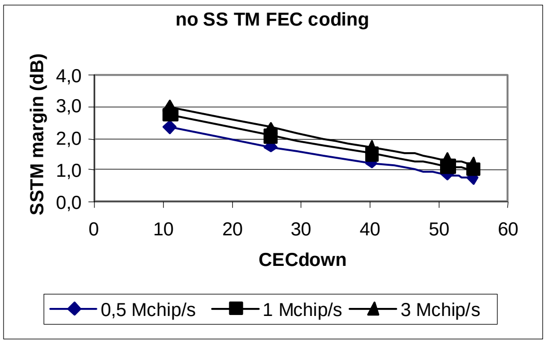
6.3.2.2.1 No SS TC FEC, no SS TM FEC

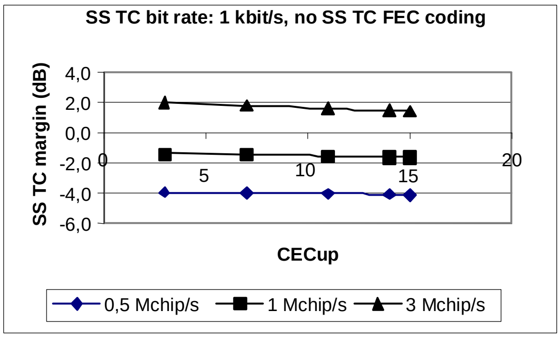




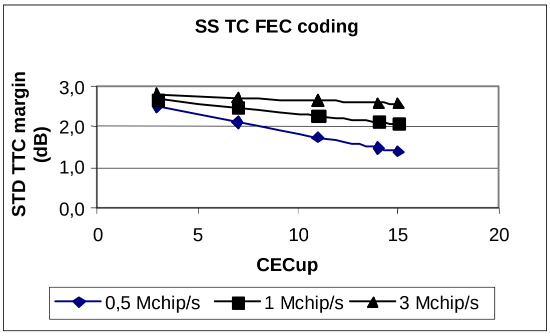


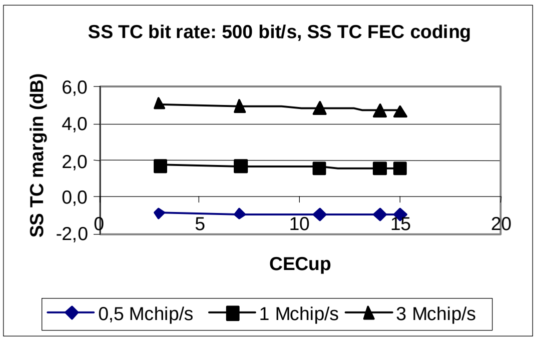


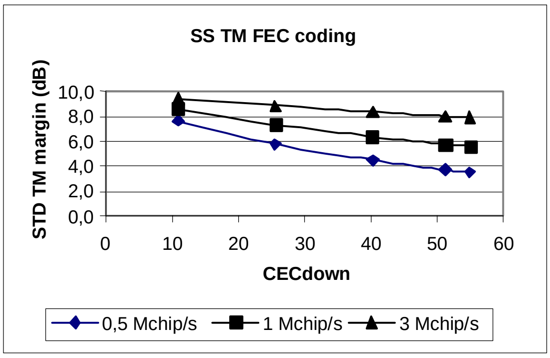


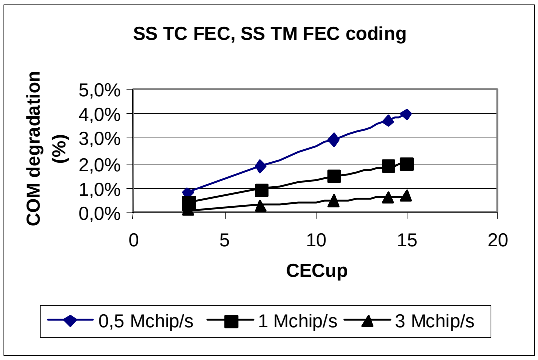


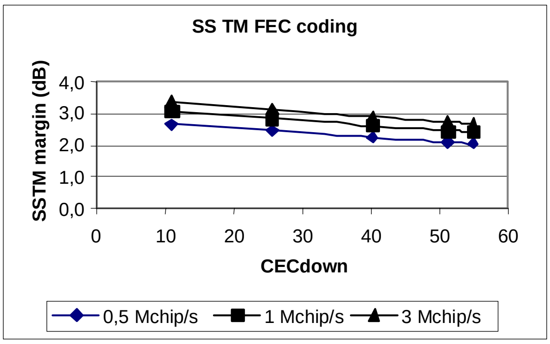
6.3.2.2.2 SS TC FEC, SS TM FEC

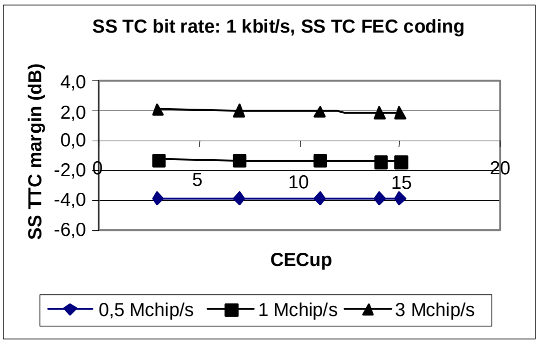




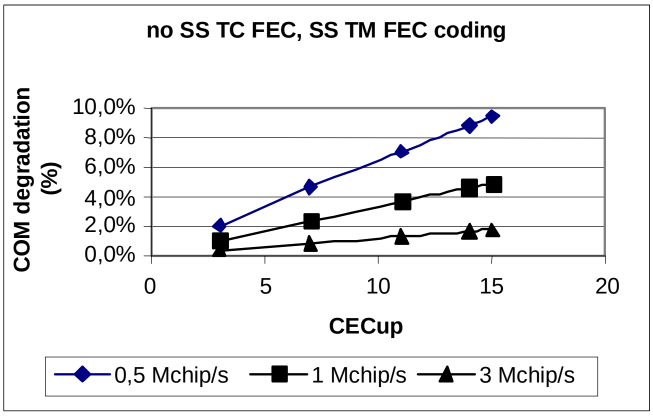








6.3.2.2.3 No SS TC FEC, SS TM FEC



The results shown below are given for different configurations.

6.4 Solution 2: any RG, TC SS (narrow or wide band), TM wide band SS

6.4.1 Description of the solution

Uplink: like solution 1, for example.

Downlink: modulation UQPSK, ratio I(TM)/Q(RG) = 10/1 dB.

- TM bit rate: 2 048 bit/s to 4 096 bit/s.
- TM code length = 1 023 chips (non coherent) or as RG code length (in coherent mode).
- FEC optional.
- TM chip rate: compatible with the use of the COM channel: 18 Mchip/s max.

Implementation: dual mode transponder.

6.4.2 RF performances

6.4.2.1 Specific hypothesis for solution 2

As explained in clause 6.2.2.1, some parameters shall be adjusted for the RF link budget:

- It is decided, arbitrarily, to fix the on-board losses between COM LNA and TC SS receiver to -5 dB.
- The SS TC EIRP is adjusted between 44,5 dBW (no FEC) and 39,5 dBW (FEC present).
- The SS TM EIRP is adjusted to give positive margin on the TM link budget.

The COM degradation is estimated in the worst case of the 3-presented COM scenario (see table 4).

The SS TM degradation is also estimated in those 3 COM scenarios.

No multiple access contribution is taken into account, as we consider that every TCR user can use distinct COM channel.

- FEC coding has been considered for TM.
- 4 096 bit/s bit rate has been considered for TM.

6.4.2.2 Parametric analysis results

All the details are given in annex A.

We see that it is mandatory to fix the SS TM EIRP equal to 24 dBW, to guarantee the required 2 dB margin on the SS TM link, for scenario with analogue TV. But such an EIRP leads to 2 major problems.

- It is not standard at all to have such high EIRP.
- This EIRP is not compatible with the DVB scenario (12 % of degradation of the DVB signal).

Those RF budget shows that this solution is not viable.

6.5 Solution 4: narrow bandwidth SS TC, STD TM modulation, hybrid RG

6.5.1 Description of the solution

- TC Uplink : spread spectrum modulation, same as for solution 1
- TM downlink: standard PM modulation
- RG
    - RG uplink: same as TC (PN code)
    - RG downlink: same modulation as TM (TELESAT like tones)
- Implementation: dual mode transponder

For the downlink, the multiple access requirement is treated through use of FDMA: each satellite uses PM modulation, with different frequencies.

The distance between 2 PM carriers can be estimated as follows:

2 × 62,5 KHz (carrier instability) + 2 × 90 KHz (sub carrier + data) + 2 × 50 KHz (margin) = 405 KHz.

It means that there are 12 frequencies available in 5 MHz bandwidth.

If those frequencies are allocated to the satellites as follows:

Sat 1: (f1, f2), Sat 2: (f2, f3), sat 3: (f3, f4), …sat 10 (f10, f11), it means that 11 satellites can be telemetried within 5 MHz.

6.5.2 RF performances

6.5.2.1 Specific hypothesis for solution 4

- The hypothesis is identical to solution 1, for the uplink.
- The TM downlink RF budget is not presented (standard RF budget).
- The COM degradation only takes into account the uplink (so COM RF compatibility is better than for solution 1).

6.5.2.2 Parametric analysis results

Parameters being modified during the parametric analysis:

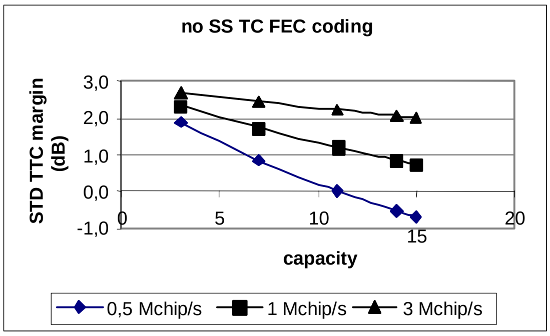
- Capacity
- Chip rate
- SS TC Data rate
- FEC coding for SS TC (and depending of this option, SS TC EIRP is adjusted)

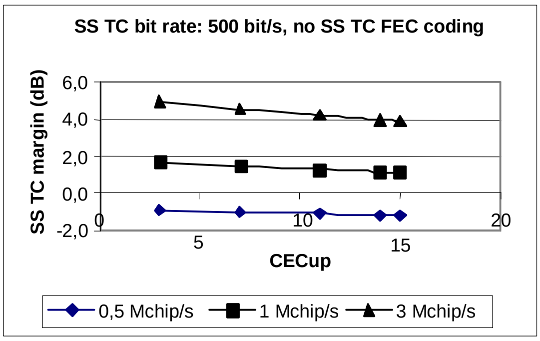
Parameters that are analysed, as result of the analysis :

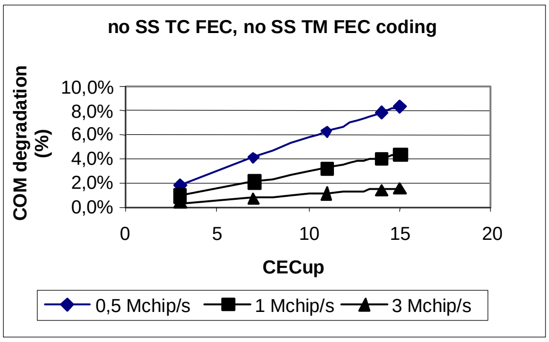
- STD TC uplink RF budget margin (in dB)
- SS TC uplink RF budget margin (in dB)
- COM degradation in %

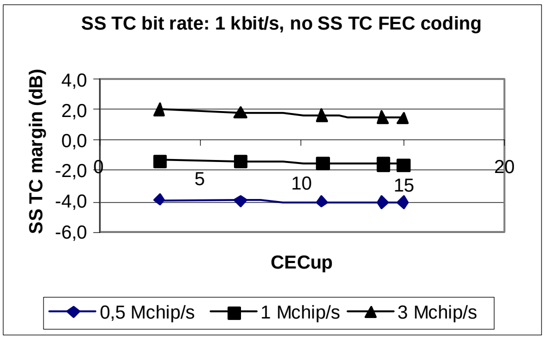
The principle of analysis being identical to solution 1, the detail of one configuration is not given in the annex.

6.5.2.2.1 No SS TC FEC

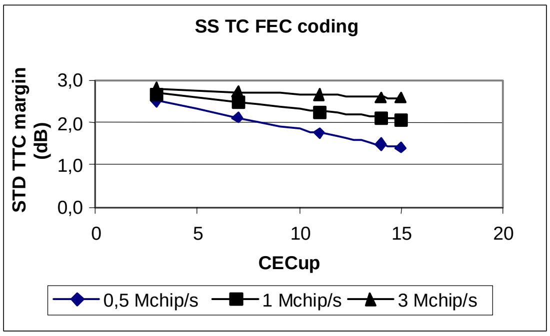


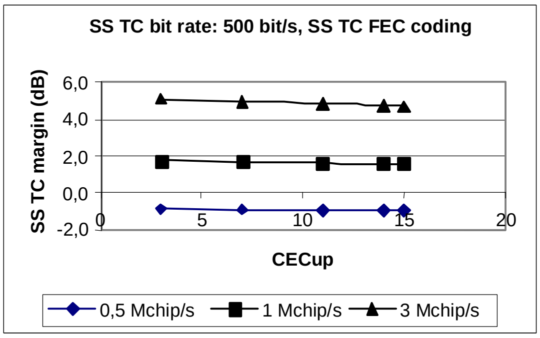


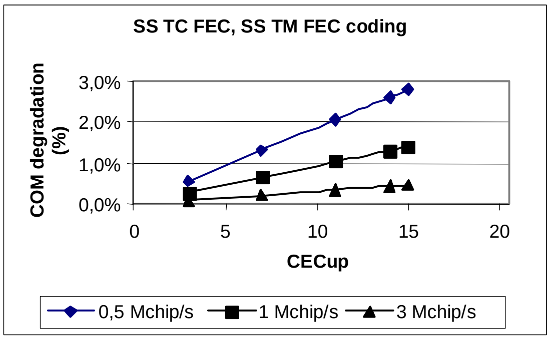


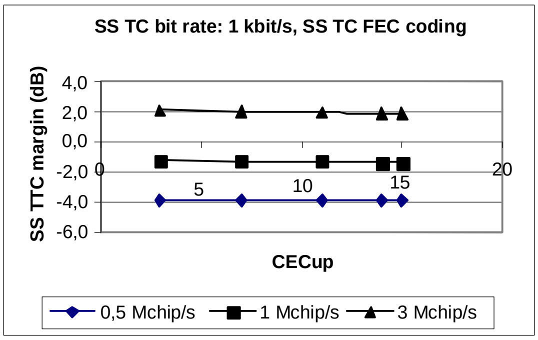


6.5.2.2.2 SS TC FEC









6.6 Trade-off

The previous clauses have shown that:

- Solution 2 shall be discarded.
- Solution 1 and 4 are viable.

For solution 1 and 4, a chip rate of 1 Mchip/s can be enough, to pass a TC bit rate of 500 bit/s with TC FEC coding. But a TC bit rate of 1 kbit/s will require 3 Mchip/s with FEC coding.

It can be concluded that both solutions 1 and 4 respect the key requirements of:

- Link Budget margins, TC and TM
- Compatibility with STD mode TC and TM (one in-band TC/TM taken into account) (RFI to/from)
- Compatibility with COM channel, for RFI to/from, assuming ~25 dBc PSD rejection either way
- Occupied bandwidth for TC (defined by rejections to/from COM above)
  - Eutelsat configuration: 1,5 MHz
  - Other operators configuration: 4,5 MHz
- Occupied bandwidth for TM (defined by rejections to/from COM above)
  - Solution 1: Eutelsat 1,5 MHz, others 4,5 MHz
  - Solution 4: 500 KHz per channel (total 5 MHz for 10 channels)
- Data rates:
  - Eutelsat: 500 bit/s TC, 4 kbit/s TM
  - Other operators: 1 kbit/s TC, 4 kbit/s TM

Thus the following table concentrates on the areas where there are differences and advantages/disadvantages between solutions.

Item	Solution 1	Solution 4
Description	SS TC SS TM SS RG Regenerative	SS TC STD TM (PM) Hybrid RG: SQPN code uplink/Ranging tones downlink
Technical Performance and implementation		
CW Downlink Beacon Function	- Need carrier to be placed in null of spectrum: could implement simply on Transmitter or on separate beacon transmitter. Bandwidth allocation should be no problem for pure carriers.	+ Inherent in downlink modulation
Potential improvement	To incorporate FEC coding, with no penalty on processing gain, or occupied bandwidth. This will improve the link budget	OL stability can be improved to reduce occupied bandwidth per channel. Potentiality to increase date rate, limited by sub-carrier frequency and link budget
RG resolution	DLL jitter Proportional to chip period	PLL jitter proportional to RG tone period
RF protection (protection of the own system, and protection of external system)	+ Processing gain gives some protection against jammers; PN codes selected can give security (in case of secret code). Use of PN code eases the frequency co-ordination during apogee and drift phase	- Reduced protection, only security is spacecraft ID word. Frequency co-ordination can be eased for the downlink by using 2 distinct frequencies for each satellite
Onboard equipment		
Development Effort/NRE Cost	-- Significant: need Spread Spectrum Receiver and Transmitter. But there is heritage from TDRS, GPS and other spread spectrum systems	- Significant: need Spread Spectrum receiver and new hybrid ranging system. No existing experience of hybrid ranging system which will be complex and require autonomy onboard.

Item	Solution 1	Solution 4
Equipment Recurrent Cost	- 2 new units (SS Rx and SS Tx) Possibly higher cost transmitter than standard one	- 1 new unit (SS Rx), 1 existing unit (STD Tx)
Mass and power	- 2 dual mode transmitter	+ (2 standard transmitters)
On Ground Equipment		
Development Effort/NRE Cost	-- Need Spread Spectrum Tx and Rx: But known techniques for ranging measurement	- Need Spread Spectrum Tx and new hybrid Ranging measurement system.
Equipment Recurrent Cost	-- 3 new unit functions (SS Rx, SS Tx, SS Ranging measurer). Probably combined in one unit	- 2 new unit functions (SSTx, hybrid ranging measurement system) 1 existing unit (standard Rx)
RG calibration	+	-
Decision	Keep it	Keep it

7 Conclusions

A lot of different combinations of TC, TM and RG solutions have been proposed.

Three of them have been analysed in detail, in terms of RF budget and compatibility, and one of these solutions (solution 2) has been discarded.

The "two" solutions left (solutions 1 and 4) lead to the following conclusions:

- Preference for TC in spread spectrum (better protection against jamming and convenient for satellite co-location strategy).
- Preference for uplink RG in spread spectrum (better protection against jamming and convenient for satellite co-location strategy).

The choice has been to introduce in the standard the short term solution with standard downlink (solution 4) along with longer term solution in full spread spectrum (solution 1).

The standard shall thus include:

- TC in Spread Spectrum
- Ranging in Spread Spectrum
- Hybrid Ranging (Uplink in Spread Spectrum and Downlink in current standard modulation
- TM in Spread Spectrum

This is compliant in particular with solutions 1, 4, and 5 (see table 3 for the definition of solution 5), and is fully coherent with annex B.

Annex A: Technical Information

A.1 Doppler/Doppler rate

Doppler and Doppler rate have to be evaluated to define requirements to be fulfilled by TCR on-board and on-ground receiver.

Due to the apparent movement of the satellite relative to the ground station, the carrier frequency "seen by the receiver" is different from the carrier frequency transmitted (Doppler Effect). As the movement of the satellite has no reason to be "uniform", the variation of the frequency (Doppler rate) is not null.

Doppler and Doppler rate influence greatly the design of signal synchronization and tracking loops.

As the TCR standard shall cover all satellite phases, calculations are performed for:

- LEOP phase: Doppler/Doppler rate is assessed during GTO.
- Drift phase: Doppler/Doppler rate is assessed when satellite rallies its final position (geostationary orbital window).
- On-station phase: Doppler/Doppler rate is assessed during GSO.

It is also important to assess clock drift (on-board and on-ground) because clock drift contributes also to create long-term effect on Doppler.

A.1.1 Basic formulas

As we want to assess maximum value expected for Doppler/Doppler rate, the analysis will be conducted assuming TCR ground station is located on the equatorial plane. Inclination for satellite orbit is set to 0.

The Doppler effect is calculated using the following formulas:

$$\Delta F_{\text{Doppler}} = V_{\text{proj\_sat\_radial}} \times F_{\text{emission}}/c$$

where c: light speed (3×10^8 m/s)

and F_{emission}: frequency of signal carrier

$$V_{\text{proj\_sat\_radial}} = V_{\text{sat}} \times \cos(\theta)$$

where θ: projection angle for satellite speed on ground station satellite visibility axis. We consider the case for a station located on the equatorial plane (worst case for doppler effect).

$$Vsat = \sqrt{\mu \times (2/r - 1/a)}$$

with $r=p/(1+e \times \cos(v))$

and $p=a \times (1-e^2)$

e: Orbit eccentricity

a: Orbit semi major axis

v: Orbit true anomaly

So Doppler depends on:

- Carrier Frequency of the transmitted signal. The analysis will take into account all frequency value possibilities (C and Ku-Band for downlink and uplink).
- Location of ground station relatively to the satellite in equatorial plane.
- Type of satellite orbit.

The "Doppler rate" is the time derivative of Doppler. The Doppler value (depending on true anomaly in previous formula) shall be expressed against time.

This can be done numerically using additional calculation.

Time (t) is deduced numerically from true anomaly (v) using following equations:

$\cos(E) = (\cos(v)+e)/(1+e \times \cos(v))$:v true anomaly

$E - e \times \sin(E) = M$:E eccentric anomaly

$M = t \times \sqrt{(\mu/a^3)}$:M mean anomaly

:t time

The Doppler rate is calculated numerically:

Doppler_rate= d(Doppler)/dt

A.1.2 LEOP phase

A.1.2.1 Orbit definition

For LEOP phase, the orbit to be considered is the GTO (Geostationary Transfer Orbit).

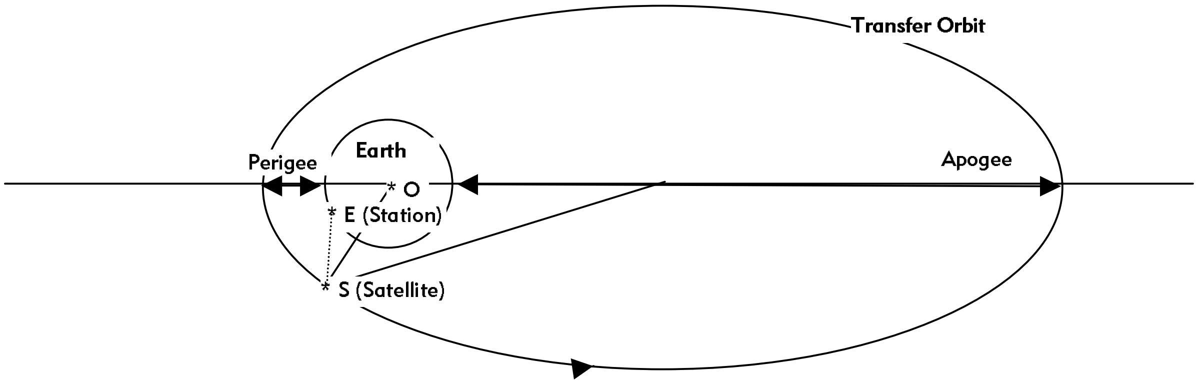


Figure A.1: Position of the satellite (S)° and the ground station (E)° for GTO

GTO is characterized by:

$R_{apogee} =$ 35 788 km

$R_{perigee} =$ 200 km

So,

a = 24 372 km

e = 0,73

p = 11 381 km

The following constants are used in the equations:

Earth_radius = 6 378 km

$\mu = 398\ 600\ km^3/s^2$: universal gravitation constant

Remark: for Doppler/Doppler rate calculation, we do not take into account Earth rotation. It leads to overvalue Doppler since earth radial speed has the same orientation as satellite on its orbit. This hypothesis has insignificant consequence on the Doppler rate evaluation.

A.1.2.2 Doppler calculation

In figure A.2 value of Doppler has been calculated according to different ground station elevation (from 0 degree elevation to 180 degree elevation).

Once the elevation of the ground station is set, the Doppler is calculated for every satellite position and the curve is traced.

The curve has been calculated for a transmitted frequency of 14,5 GHz so represent the Doppler shift frequency seen by the satellite receiver for an uplink in Ku-Band (FSS service).

The goal is to estimate the absolute maximum for Doppler value whatever the position of the ground station (characterized by the visible elevation angle) and the satellite position (characterized by the true anomaly) are.

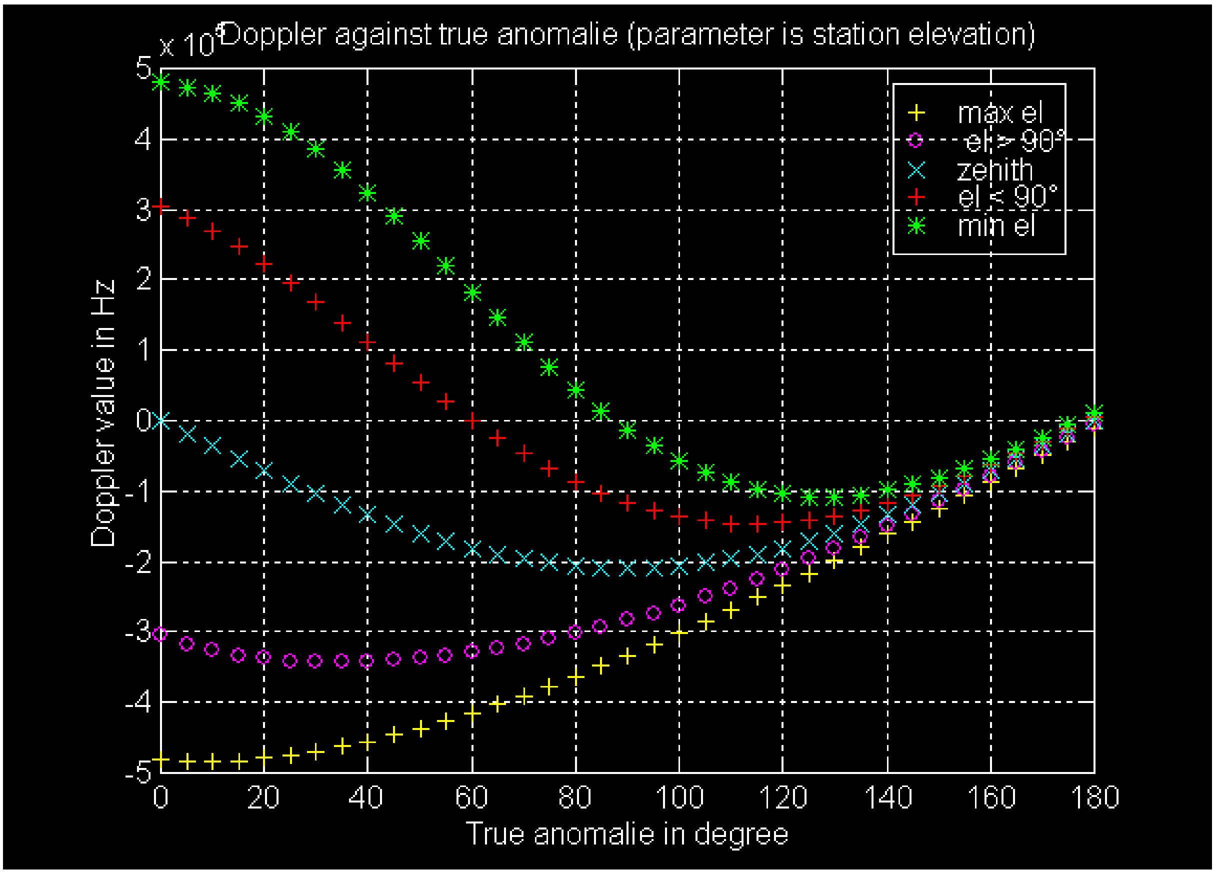


Figure A.2: Doppler shift for Ku-band uplink (Freq = 14,5 GHz)

The maximum Doppler Shift is obtained:

- when the satellite is near the perigee (around 10°); and,
- when the ground station (located near the perigee) "sees" the satellite at null (or 180 degree) elevation.

But it is more realistic to cope with real operational conditions and real launcher orbit, to consider the Doppler characteristics for anomaly higher than 40° (taking into account that a more pessimistic case would oversize the system).

The following table gives the maximum values for frequency bands under consideration (Ku and C-band), for anomaly higher than 40° (what corresponds to a maximum Doppler shift/frequency ratio of $2,2 \times 10^{-5}$).

Freq. Range	**Uplink Ku-Band/BSS**	**Uplink Ku-Band/FSS**	**Downlink Ku-Band**	**Uplink C-Band**	**Downlink C-Band**
Freq. Value Upper limit -GHz-	18,1	14,5	12,75	6,725	4,2
Max Doppler -KHz-	±400	±320	±281	±150	±92

Conclusion:

To cope with LEOP phase, the on-board receiver shall face with a Doppler shift up to:

- ±400 KHz if Ku-band/BSS frequency range is used;
- ±320 KHz if the used frequency range is limited to Ku-band/FSS.

A.1.2.3 Doppler rate calculation

Now the Doppler rate is calculated according to the basic formula. The Doppler rate needs to be assessed as it influences the design and the performance of the phase tracking loop for SS/PSK demodulation.

In figure A.3 the Doppler rate is calculated as seen by a ground station located at the perigee. The Doppler rate is calculated for each value of the ground station elevation angle.

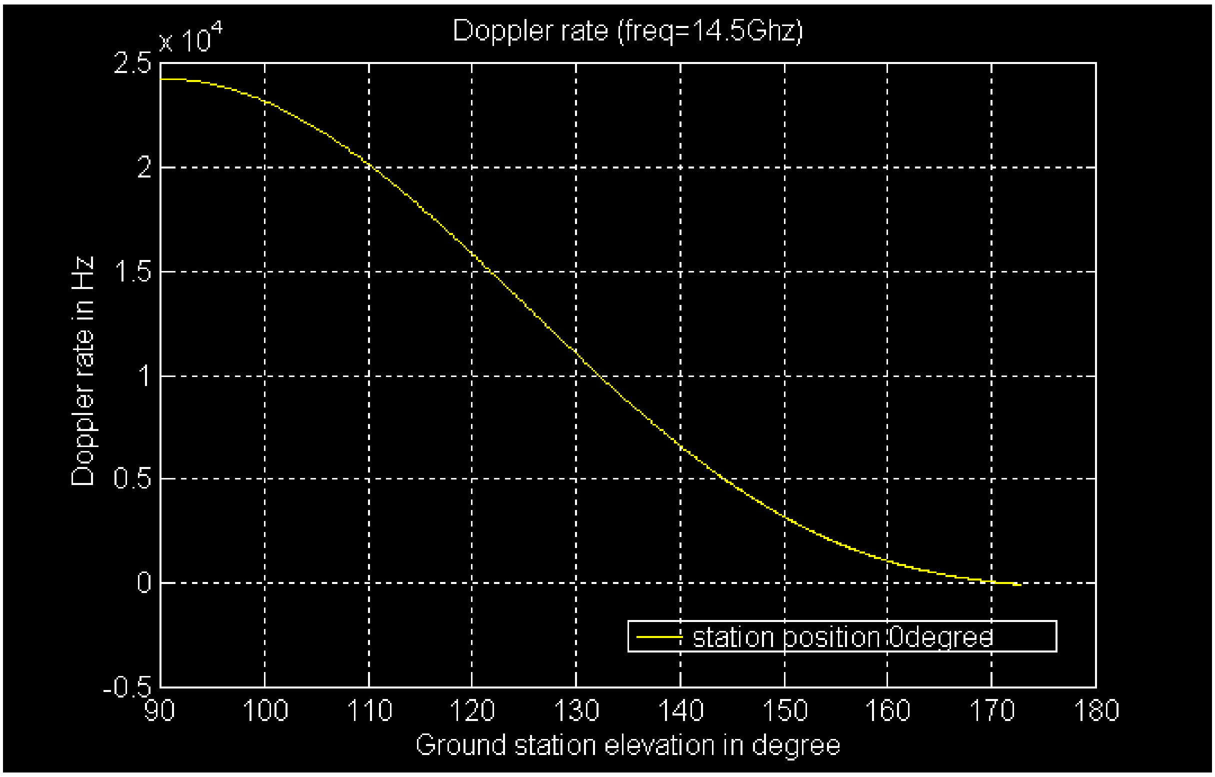


Figure A.3: Doppler rate calculation (perigee)

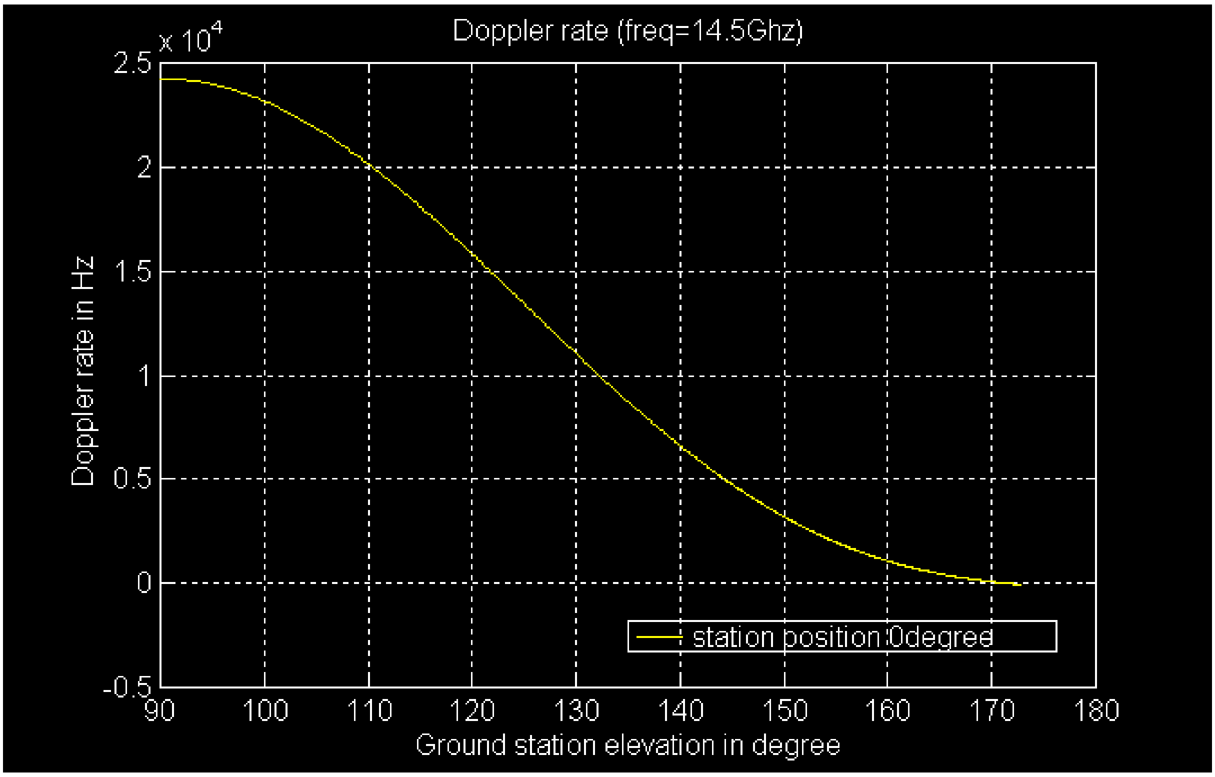


Figure A.4: Doppler rate calculation (apogee)

When performing numerical calculation on all possible configurations, we can conclude that the Doppler rate is maximum when:

- the satellite is at the perigee; and,
- the ground station is located under the perigee and "sees" the satellite at zenith.

The following table gives the maximum values for frequency bands under consideration (Ku and C-band).

Freq. Range	**Uplink Ku-Band/BSS**	**Uplink Ku-Band/FSS**	**Downlink Ku-Band**	**Uplink C-Band**	**Downlink C-Band**
Freq. Value Upper limit -GHz-	18,1	14,5	12,75	6,725	4,2
Max Doppler rate -KHz-	±30,3	±24,3	±21,3	±11,25	±7

Conclusion:

To cope with LEOP phase, the on-board receiver shall face with a Doppler rate up to:

- ±30,3 KHz if Ku-band/BSS frequency range is used.
- ±24,3 KHz if frequency range used is limited to Ku-band/FSS.

A.1.3 Drift phase

A.1.3.1 Orbit definition

The drift phase starts when the satellite is put on a near-circular orbit and lasts until the satellite has reached its final position.

The drift phase lasts several days (7 days is a maximum) and each LEOP operator tends to shorten the drift phase duration.

During this phase, it is assumed, in a first approximation, that the satellite follows a circular orbit.

The semi-axis value of this orbit is slightly inferior to the value for GSO orbit in order to create a relative movement of the satellite on the geostationary arc.

The value for the drift rate depends on each mission type. For the justification, we take a commonly used value for the drift rate with typical range:

- from 1°/day,
- up to 3°/day.

A.1.3.2 Doppler/Doppler rate Calculation

For the calculation, we apply the following approximations:

- the orbit is circular so the radial speed (w.r.t earth station direction) is assumed to be constant (null),
- the satellite altitude is approximated to GSO altitude for the ground station view angle calculation.

In the worst case (satellite viewed at null elevation angle by the ground station), the Doppler effect can be expressed for a circular orbit:

$$Doppler = (F_{emission/c}) \times V_{sat} \times (\frac{Earth\_radius}{Earth\_radius + R_{apogee}})$$

With:

Earth_radius = 6 378 km

R_{apogee} = 35 788 km

And:

V_{sat} = velocity

Drift rate (/day)	Satellite velocity (m/s)
1	8,5
3	25,5

Numerical Application:

For $F_{emission}$ = 14,5 GHz (Ku-Band/FSS) and Drift rate = 3°/day, Doppler = 186 Hz

For $F_{emission}$= 18,2 GHz (Ku-Band/FSS) and Drift rate = 3°/day, Doppler = 233 Hz

Conclusion:

The Doppler effect and, as a consequence, the Doppler rate (satellite movement relative to earth surface is very slow) is negligible for drift phase.

A.1.4 On-station

East/West/North/South), the radial velocity (w.r.t Satellite/earth station direction) of the satellite is limited to $V_{sat} = 3$ m/s.

In the worst case, the Doppler effect can be expressed:

$$Doppler = (F_{emission/c}) \times V_{sat}$$

Numerical Application:

For $F_{emission}$=14,5 GHz (Ku-Band/FSS), Doppler = 145 Hz

For $F_{emission}$=18 GHz (Ku-Band/FSS), Doppler = 180 Hz

Conclusion:

The Doppler effect and, as a consequence, the Doppler rate (satellite movement relative to earth surface is very slow) is negligible for on-station phase.

A.1.5 Clock drift

Clock generation on ground equipment is commonly performed using GPS clock reference so clock accuracy can be as good as 10^{-10}. This clock drift value will be taken as an assumption/requirement for ground equipment.

Clock generation on board satellite is not synchronized to GPS reference so current value of accuracy is around 10^{-6} over satellite lifetime.

So ground equipment clock drift effects can be neglected relatively to on-board clock drift effects.

This clock drift contributes to frequency shifting and shall be added to the Doppler shift value to specify TCR receivers:

Freq. Range	**Uplink Ku-Band/BSS**	**Uplink Ku-Band/FSS**	**Downlink Ku-Band**	**Uplink C-Band**	**Downlink C-Band**
Freq. Value Upper limit -GHz-	18,1	14,5	12,75	6,725	4,2
Clock shift -KHz-	±18,1	±14,5	±12,75	±6,7	±4,2

Conclusion

Clock drift shall be taken into account especially for On-station/where Drift phase is of prime importance concerning frequency range for receiver acquisition.

For LEOP, this value is small relatively to Doppler encountered. Moreover, the LEOP phase last for few days and the clock does not drift during this period.

A.2 Link budget

A.2.1 Solution 1 RF budget

A.2.1.1 Uplink budget

UPLINK RF BUDGET		
CEC uplink		3
frequency	GHz	18,00
satellite - TCR station distance	km	39 000
free space losses	dB	-209,37
STD modulation characteristics:		
STD uplink EIRP	dBW	61,00
atmospheric losses	dB	-1,00
on board antenna gain	dB	30,00
S/L antenna to Rx losses	dB	-10,00
STD Rx threshold on station	dBm	-108,00
STD Rx noise figure	dB	3,00
STD TC power level at repeater input	dBm	-89,37
STD Rx nominal input level	dBm	-99,37
STD Rx nominal C/N_0	dBHz	71,63
C/N_0 required at STD Rx input	dBHz	63,00
SS modulation characteristics:		
modulation		UQPSK
I/Q ration (if UQPSK modulation)	dB	10,00
associated losses on I channel	dB	-0,41
associated losses on Q channel	dB	-10,41
SS data rate	bit/s	1 000
SS uplink EIRP	dBW	44,50
atmospheric losses	dB	-1,00
on board antenna gain	dB	30,00
S/L antenna to Rx losses	dB	-5,00
SS power level at repeater input	dBm	-105,87
SS Rx input level	dBm	-110,87
SS Rx NF	dB	3,00
Gold code length		1 023,00
chip rate	chip/s	3 000 000,00
BT	Hz/bit	2,00
main lobe double sided bandwidth	Hz	6 000 000,00
SS signal out of band emission (including side lobes + filtering)	dB	23,00
gain processing	dB	34,77
implementation losses	dB	3,00
E_b/N_0 nominal (without any external contributor)	dB	26,72
cross correlation factor for one user	dB	31,90
delta STD/SS	dB	16,50
COM channel degradation:		

UPLINK RF BUDGET		
COM channel power at repeater input	dBm	-55
COM channel power at SS Rx input	dBm	-60,00
COM channel power at STD Rx input	dBm	-65,00
COM channel bandwidth	MHz	36
COM channel out of band emission (including side lobe contribution + filtering)	dB	-26
I_0 com at TC SS Rx input	dBm/Hz	-161,56
I_0 com at TC STD Rx input	dBm/Hz	-166,56
E_b/N_0 at SS output due to COM channel contribution	dB	17,28
E_b/N_0 at SS output due to STD TC contribution		14,86
required E_b/N_0	dB	10,60
1) K SS collocated satellites:		
E_b/N_0 due to collocation	dBHz	28,89
E_b/N_0 nominal (without any external contributor)	dBHz	26,72
E_b/N_0 due to COM channel	dBHz	17,28
total E_b/N_0	dB	16,55
required E_b/N_0	dB	10,60
margin	dB	5,95
2) 1 S/L standard, 1 S/L SS		
a) jamming of the standard S/L:		
C/N_0 due to SS	dBHz	84,28
C/N_0 due to COM channel	dBHz	67,19
C/N_0 total at STD Rx input	dBHz	65,80
required C/N_0	dBHz	63,00
margin	dB	2,80
b) jamming of the SS S/L:		
E_b/N_0 due to STD modulation after dispreading	dBHz	14,86
E_b/N_0 nominal (without any external contributor)	dBHz	26,72
E_b/N_0 due to COM channel	dBHz	17,28
total E_b/N_0	dB	12,72
required E_b/N_0	dB	10,60
margin	dB	2,12
3) 1 S/L STD, K S/L SS		
a) jamming of the standard S/L:		
C/N_0 due to SS	dBHz	79,51
C/N_0 due to COM channel	dBHz	67,19
C/N_0 total at STD Rx input	dBHz	65,68
required C/N_0	dBHz	63,00
margin	dB	2,7
b) jamming of the SS S/L:		
E_b/N_0 due to nominal S/L + collocated satellites + COM	dB	16,6
E_b/N_0 due to STD modulation	dBHz	14,9

UPLINK RF BUDGET		
after dispreading		
total E_b/N_0	dB	12,6
required E_b/N_0	dB	10,6
margin	dB	2,0
RG C/N_0 at Rx demodulator output	dBHz	32,61

A.2.1.2 Downlink budget

downlink RF BUDGET		
	unit	C band
CEC downlink		11
satellite parameters:		
fmax downlink	GHz	6,80
COM downlink EIRP	dBW	50,00
side lobe + filtering rejection	dB	-26,00
COM spreading	MHz	36,00
a) STD modulation		
STD modulation EIRP	dBW	10,00
STD modulation data rate	bit/s	2 048,00
b) SS modulation:		
modulation		UQPSK
I/Q ratio (if UQPSK modulation)	dB	10,00
associated losses on I channel	dB	-0,41
associated losses on Q channel	dB	-10,41
SS modulation EIRP	dBW	8,00
SS modulation data rate	bit/s	4 096
Gold code length		1 023,00
cross correlation factor for one user	dB	31,90
chip rate	chip/s	3 000 000,00
BT	Hz/bit	2,00
main lobe double sided bandwidth	Hz	6 000 000,00
processing gain	dB	28,65
SS signal out of band emission (including side lobes + filtering)	dB	23,00
	unit	C band
SS Ground station parameters:		
G/T		20,00
demodulation techno losses		-3,00
required E_b/N_0	dB	4,60
STD modulation Ground station parameters:		
G/T	dB	20,00
demodulation techno losses	dB	-2,50
TM demodulation losses	dB	-3,04
TM demodulation losses due to RG	dB	-0,80
total TM demodulation losses (including modulation effect+ techno losses)	dB	-6,34
RG demodulation losses	dB	-7,84
RG demodulation losses due to TM	dB	-3,46
total RG demodulation losses (including modulation effect+ techno losses)	dB	-13,80

downlink RF BUDGET		
required E_b/N_0	dB	4,60
system parameters		C band
Boltzmann constant	dB	-228,60
SS TCR station/satellite distance	km	39 000
associated free space losses	dB	-200,91
STD TCR station/satellite distance	km	39 000
associated free space losses	dB	-200,91
downlink budget for SS modulation:		C band
free space losses	dB	-200,91
G/T	dB	20,00
techno losses	dB	-3,00
data rate	dB	36,12
C/N_0 of the SS signal alone		52,69
TM E_b/N_0 alone	dB	16,15
C/N_0 due to COM at TCR station level	dB	59,56
E_b/N_0 due to COM at TCR station level	dB	20,03
downlink budget for STD modulation:		C band
free space losses	dB	-200,91
G/T	dB	20,00
C/N_0 at ground antenna input	dB	57,69
total demo losses	dB	-6,34
data rate	dB	33,11
E_b/N_0 alone	dB	18,23
C/N_0 due to COM	dB	61,56
1) K SS collocated satellites:		C band
E_b/N_0 alone	dB	16,15
E_b/N_0 due to COM at TCR station level	dB	20,03
E_b/N_0 due to collocation:	dBHz	21,91
total E_b/N_0	dB	13,91
required E_b/N_0	dB	4,60
margin	dB	9,31
2) 1 S/L standard, 1 S/L SS		
a) jamming of the standard S/L:		
C/N_0 due to SS	dBHz	69,78
C/N_0 due to COM	dBHz	61,56
C/N_0 STD modulation alone, at ground antenna input	dBHz	57,69
degradation	dB	-1,68
E_b/N_0 alone	dBHz	18,23
degraded E_b/N_0	dBHz	16,56
required E_b/N_0	dBHz	4,60
margin	dB	11,96
b) jamming of the SS S/L:		
E_b/N_0 due to STD modulation after dispreading	dBHz	23,23
E_b/N_0 due to COM at TCR	dB	20,03

downlink RF BUDGET		
station level		
E_b/N_0 alone	dBHz	16,15
total E_b/N_0	dB	14,09
required E_b/N_0	dB	4,60
margin	dB	9,49
3) 1 S/L STD, K S/L SS		
a) jamming of the standard S/L:		
C/N_0 due to SS	dBHz	59,38
C/N_0 due to COM	dB	61,56
C/N_0 STD modulation alone, at ground antenna input	dBHz	57,69
degradation	dBHz	-3,20
E_b/N_0 alone	dBHz	18,23
degraded E_b/N_0	dBHz	15,04
required E_b/N_0	dBHz	4,60
margin	dB	10,44
b) jamming of the SS S/L:		
E_b/N_0 due to collocation + current SS satellite+ COM	dB	13,91
E_b/N_0 due to STD modulation after dispreading	dBHz	23,23
total E_b/N_0	dB	13,43
required E_b/N_0	dB	4,60
margin	dB	8,83

A.2.1.3 Up+down RF link budget for the COM

	unit	scenario 1: Analog TV	scenario 2: SNG	scenario 3: data DVB
channel bandwidth	MHz	36	7,8	20
COM signal power level at repeater input	dBm	-76	-90	-98
COM uplink C/N_0 (without jammer)	dBHz	93,7	79,5	71,9
TC power level at repeater input	dBm	-105,87	-105,87	-105,87
uplink I_0 due to the TC jammers	dBm/Hz	-191,88	-191,88	-191,88
COM uplink C/I_0 (only with jammer)	dBHz	115,88	101,88	93,88
COM uplink C/N_0 (with jammer)	dBHz	93,67	79,47	71,87
uplink C/N_0 degradation:	%	0,60 %	0,57 %	0,63 %
total (up+down) COM C/N_0 (without jammer)	dBHz	89,23	74,6	68,8
downlink COM EIRP	dBW	51,6	34,14	25,98
downlink COM C/I_0 due to TM jammers		127,98	110,52	102,36
total (up+down) COM C/N_0 (with only uplink jammer)	dB	89,22	74,59	68,79
total (up+down) COM C/N_0 (with jammer)	dB	89,22	74,59	68,78
C/N_0 degradation of the full link	%	0,23 %	0,21 %	0,35 %
C/N_0 degradation of the full link, only due to the uplink contribution	%	0,22 %	0,19 %	0,31 %
total C/N_0 degradation	dB	-0,01	-0,01	-0,02

A.2.2 Solution 2 RF budget

A.2.2.1 Downlink TM budget, for each COM scenario

downlink RF BUDGET				
		scenario 1: Analog TV	scenario 2: SNG	scenario 3: data DVB
	unit	Ku band		
CEC downlink		1		
satellite parameters:		Ku		
fmax downlink	GHz	12,75		
COM downlink EIRP	dBW	51,60	34,14	25,98
side lobe + filtering rejection	dB	0,00		
COM spreading	MHz	36,00	7,80	20,00
SS modulation:				
modulation		UQPSK		
I/Q ration (if UQPSK modulation)	dB	4,00		
associated losses on I channel	dB	-1,46		
associated losses on Q channel	dB	-5,46		
SS modulation TM EIRP	dBW	24,00	24,00	24,00
SS modulation data rate	bit/s	4 096		
Gold code length		1 023,00		
cross correlation factor for one user	dB	31,90		
chip rate	chip/s	18 000 000,00		
BT	Hz/bit	2,00		
main lobe double sided bandwidth	Hz	36 000 000,00		
processing gain	dB	36,43		
SS signal out of band emission (including side lobes + filtering)	dB	0,00		
SS Ground station parameters:				
G/T		25,00		
demodulation techno losses		-3,00		
required E_b/N_0	dB	4,60		
system parameters				
Boatman constant	dB	-228,60		
SS TCR station/satellite distance	km	39 000		
associated free space losses	dB	-206,37		
STD TCR station/satellite distance	km	39 000		
associated free space losses	dB	-206,37		
downlink budget for SS modulation:				
free space losses	dB	-206,37		
G/T	dB	25,00		
techno losses	dB	-3,00		
data rate	dB	36,12		
C/N_0 of the SS signal alone		68,23	68,23	68,23
TM E_b/N_0 alone	dB	30,65	30,65	30,65
C/N_0 due to COM at TCR station level	dB	47,96	58,78	71,03
E_b/N_0 due to COM at TCR station level, Rx output	dB	7,38	18,20	30,45

downlink RF BUDGET				
		scenario 1: Analog TV	scenario 2: SNG	scenario 3: data DVB
1) K SS collocated satellites:				
E_b/N_0 alone	dB	30,65	30,65	30,65
E_b/N_0 due to COM at TCR station level, Rx output	dB	7,38	18,20	30,45
E_b/N_0 due to collocation	dBHz	48,89		
total E_b/N_0	dB	7,36	17,96	27,51
required E_b/N_0	dB	4,60		
margin	dB	2,76	13,36	22,91

A.2.2.2 Down RF link budget for the COM

	unit	scenario 1: Analog TV	scenario 2: SNG	scenario 3: data DVB
channel bandwidth	MHz	36	7,8	20
downlink:				
total (up+down) COM C/N_0 (without jammer)	dBHz	89,23	74,6	68.8
downlink COM EIRP	dBW	51,6	34,14	25,98
TM EIRP	dBW	24,00	24,00	24,00
downlink COM C/I_0 due to TM jammers		103.08	85,62	77,46
total (up+down) COM C/N_0 (only due to TM jammer)	dB	89,05	74,27	68,25
COM C/N_0 degradation of the full link due to TM jamming	dB	3,96 %	7,33 %	11,99 %
SS TM margin	dB	2,76	13,36	22,91

Annex B:
Requirements for the TCR standard

This annex provides a set of requirements for the standard, based on the answers of some operators to a questionnaire, and on the analysis of existing standards and data.

B.1 Scope of the standard

The standard shall define the physical layer of a Spread Spectrum Multiple Access (SSMA) Tracking Telemetry and Command (TT&C) link for transparent Geo-stationary (GEO) satellites:

- Telecommand
- Telemetry
- Ranging
- Beacon

The objective of the standard is to:

- Simplify Frequency Allocation
- Minimize frequency co-ordination constraints
- Manage co-located satellites within bandwidth constraints
- Allow continuous high accuracy ranging

The physical layer definition shall include:

- Signal Coding
- Signal Modulation
- Signal Filtering

The standard shall provide protection against jamming.

The standard shall offer opportunity for cost effective solutions with respect to existing solutions.

The standard shall be compliant with the ITU-R Recommendation SA.363-5 [3] which states that TT&C shall be preferably carried out in the same service as the communication one or in the bands allocated to Space Operations Services.

The standard shall comply with ITU-R Recommendation SA.1273 [4], regarding TT&C (Off-axis emissions, etc.).

B.2 Mission and Performance requirements of the Standard

B.2.1 General

The standard shall define the TC up-link with the following characteristics as a minimum:

- TC Mask compliant with Communications mask (see annex C) and a Typical total bandwidth of 1 MHz)

- TC bit rate: 500 bit/s to 1 000 bit/s (TBC)
- TC Bit Error Rate (BER): 10^{-6}
- The TC signal shall allow on-board antenna fine pointing (typical 0,05°).

The standard shall define the TM down-link with the following characteristics as a minimum:

- TM Mask: Mask compliant with Communications mask (see annex C)
- TM bit rate: 4 000 bit/s
- TM Bit Error Rate: 10^{-5} to 10^{-6}

The standard shall define the Ranging Up-link and down-link with the following characteristics:

- Ranging Accuracy after calibration (bias + random) at 1 σ: 15 ns or 5 m (up-down way)
- Ranging ambiguity : 4 200 km

The standard shall define beacon capacity allowing:

- Power up-link control
- Polarization alignment

It shall be proven that the acquisition time for the on-board TC receiver is less than 10 s with a success probability of 0,99. The probability of false lock is less than 0,3 % (10^{-5} TBC).

It shall be proven that the acquisition time for the ground TM receiver is lower than 3 s with a success probability of 0,99. The probability of false lock is less than 0,3 % (10^{-5} TBC).

B.2.2 Degradation

The standard shall not degrade the telecommunication mission signal to noise ratio of more than 0,27 dB (ITU Regulation 6 %), for the overall up and downlink.

The standard shall protect TT&C signals from the telecommunication signals.

B.3 Operational Requirements

B.3.1 Life phases

The standard shall be applicable for on-station life phase of the satellites.

The standard shall allow drift and emergency phases with operational constraints to be defined.

B.3.2 Co-location

The standard shall allow operation of a fleet satellite with a CEC of 35.

The Colocated Equivalent Capacity (CEC) may defined by the following formula:

$$(\Sigma_{i=1,n} P_i)/P_{min}$$

P_i	is the power received by the station from the satellite i.
P_{min}	is the minimum received power.

As an example a CEC of 35 corresponds to the distribution given in table B.1.

Table B.1: Example of distribution for a CEC of 35

Relative EIRP	-4	-3	0	+3	+4
Number of satellites	0,5	1	7	1	0,5

The mission and performance requirements shall be met with the following constraints:

- Different TT&C stations may be used
- EIRP balance between TT&C stations is performed when all satellites are on-station in nominal mode

When one satellite is in emergency, the associated TT&C stations TC EIRP is increased by 25 dB, and correspondingly the satellite TM EIRP is decreased by 25 dB.

It shall be possible to allocate to at least one satellite one supplementary TC or TM channel to increase the up-link or downlink bit rates.

B.3.3 Interoperability

On a given satellite fleet it shall be possible to apply simultaneously the present document and other existing standards.

B.3.4 Applicability domain

The band may be C, Ku or Ka.

The standard shall be applicable when the satellite payload has the following characteristics:

- Maximum Communications Repeater input power: -55 dBm per 36 MHz channel.
- Repeater System temperature: 500 K.
- Up-link C/N_0 ~ 112 dBHz.

The standard shall be applicable with a ground station with the following characteristics:

- Maximum Station Receiver input power: from -82 dBm to -72 dBm per 36 MHz channel.
- Station receiver system temperature: 160 K.
- Downlink C/N_0 ~ from 95 dBHz to 105 dBHz.

B.4 Design requirements

B.4.1 General

The standard shall not depend on the frequency band.

The standard shall be based on direct sequence spread spectrum.

The standard shall allow a progressive implementation, and thus update of existing systems.

It shall be possible to apply the standard partially: i.e. TC only, TM only, TC and ranging, etc.

The standard shall be scaleable. This means that by the modification of its parameters, as spreading factor, it can be applicable to other types of satellites (LEOs, Processed Payload), test application, rates or bandwidths.

The solution to reserve a dedicated access for drift or emergency shall be envisaged.

B.4.2 Coding and Modulation

The modulation shall be one of combination of the following ones: BPSK, QPSK, OQPSK and GMSK.

The codes used shall be Gold codes and/or maximum length codes.

B.5 Analysis requirements

The standard performance shall be evaluated with the method which considers the Formula defined in document SC5d05 (see Bibliography).

For balanced power this formula writes :

$$(N_0/E_b)rx = Rb(N_0/C) + (k-1)\ K_{code} + (1/Gp)(I/C)$$

The processing Gain shall be defined as :

$$Gp = (\text{Single sided main lobe bandwidth})/\text{bit rate}.$$

Where the terms are respectively:

- thermal noise to carrier ratio,
- multiple access interference correlation contribution K_{code}: term to be evaluated with method previously presented (K_{code} can be the processing gain at first approximation),
- external interference contributions.

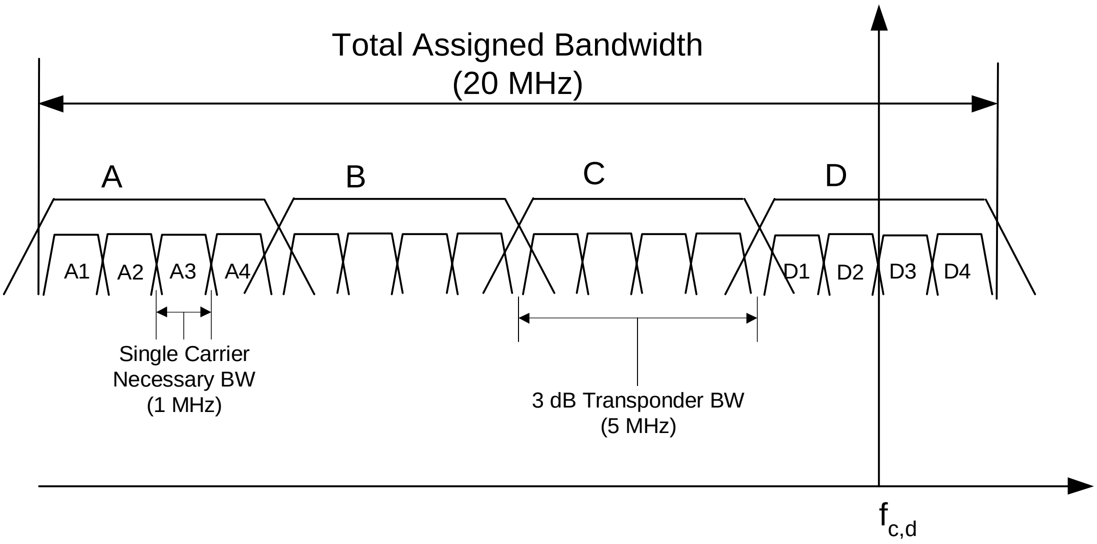
NOTE: For BPSK Gp = Chip Rate/Bit Rate.

Annex C: Communication Spectrum masks

C.1 Generalities

The uplink and downlink communication transmission masks are necessary to perform the compatibility analysis between the TM/TC signals and the Communications signals.

A typical band allocation is given in figure C.1.



NOTE: The BW are generally higher, typically 36 MHz, but the scheme is valid.

Figure C.1: Typical band allocation [5]

To our knowledge no standardized masks exist. For the various applications we define this mask as the convolution of the transponder frequency/gain response and the signal spectrum.

This means that we assume for simplicity that the transponder does not work at saturation.

The signal spectrum is expressed in terms of relative power flux density w.r.t. centre frequency.

The compatibility analysis requires relative power between communication payload. It is of course impossible to derive general figures. We assume that the downlink power is comprised in the following domain:

Communications:	20 dBW to 50 dBW per 36 MHz bandwidth
Telemetry:	8 dBW to 10 dBW

Note, that the reasoning uses relative figures w.r.t. bandwidth, and thus shall be adapted, depending on the elements in consideration. For example a transponder can process a single signal or a set of signals, through dedicated sub-bands.

We assume also that the up-link and downlink are symmetrical.

The definitions of ITU-R Recommendation SM.[OOB] [5] apply theoretically to used bandwidth (BN). We apply them by extension to the transponder, for our own purpose.

C.2 Definitions

Taking into account the Alcatel Satellite Specifications (see Bibliography) we use the following definitions:

- Reference Bandwidth (BWr): Bandwidth used for power density computation : typically 4 KHz (1 MHz for Wide band).
- Transponder Bandwidth (Bt): 3(TBC) dB bandwidth of the transponder: (BB' in figure C.2). This bandwidth shall include the Necessary bandwidth for the signal (99 % (TBC) of the energy).
- Centre Frequency (Fc): centre frequency of the transponder bandwidth.
- Out Of Band Domain: between 50 % and 250 % of Bt see extension definition (EB) + (B'E').
- Roll-Off Band Domain: Edge of the Transponder bandwidth where it is possible to place TM and TC frequencies: inside the OOBD (CB) + (B'C').
- Inter Bands separation: D, D'.
- Spurious Domain: away from 250 % Bt of the centre frequency: before E, After E'.
- DBsd: db relative to the maximum spectral power density. In AA' dBsd is equal to 0.

The spectrum is defined by a set of points symmetrical w.r.t. centre frequency. In figure C.2 the current points of the signal are labelled X and X'.

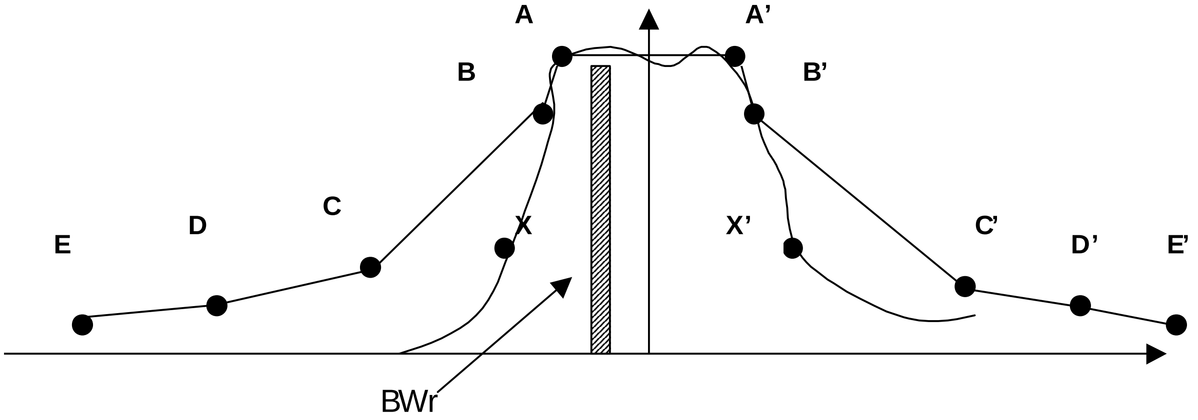


Figure C.2: Transponder Frequency Gain Mask (Not at scale)

Attenuation of B, and B' may be equal to 3dB (TBC), and (BA) to 5 % (TBC).

Standard attenuation values for Out Of Band are:

Attenuation limit for Out Of Band in dBsd: 40 × log(F/50 + 1) where F is the frequency deviation from the points (B or B') expressed as a percentage of BN (Varies from 0 to 200 %).

Attenuation Limit for Spurious: Min ((43 + 10 × logP), 60 dBc) - 10 × log (Bt/BWr).

The attenuation for the different key points for the Transponder Gain Frequency response are proposed in table C.1. The second column indicates the distance to the centre frequency in percentage of Bt, signal attenuation, the third indicates the mean power density attenuation proposed in dBsd w.r.t. Bt, derived from current Alcatel Payload characteristics (OMUX filter), with margins due to dispersion of figures, and the last one gives the result of the computation for this power density attenuation using ITU formula for Out Of Band.

Table C.1: Communication Masks Definition

Point	Delta Frequency F w.r.t. Central frequency in %	Signal Attenuation in dBsd	OOB ITU Attenuation in dBsd (note 2)
Formula	100 × |F - Fc|/Bn		(40 × log(F/50)) (note 1)
A, A'	47,5	0	0
B, B'	50	3	0
C, C'	66	15	4,8
Other reference	100	20	12
E, E'	250	43	28
After E, E' (End of allocated band)	> 250	31	Min(43 + 10 × logP, 60) - 10 × log(BN/BWr) for BWr = 4 KHz (note 2)
NOTE 1: In Study Group 1/33 [5] F writes 40 × log(F/50+1) as F represents the distance to the edge of Bt. NOTE 2: Specific spurious recommendation may be found in ITU-R Recommendation SM.329.			

The signals are modelled by a symmetrical polygon defined by a set of points Ni (see figure C.3).

The table C.2 gives typical values extracted from ITU-R Recommendation SM. [OOB] [5].

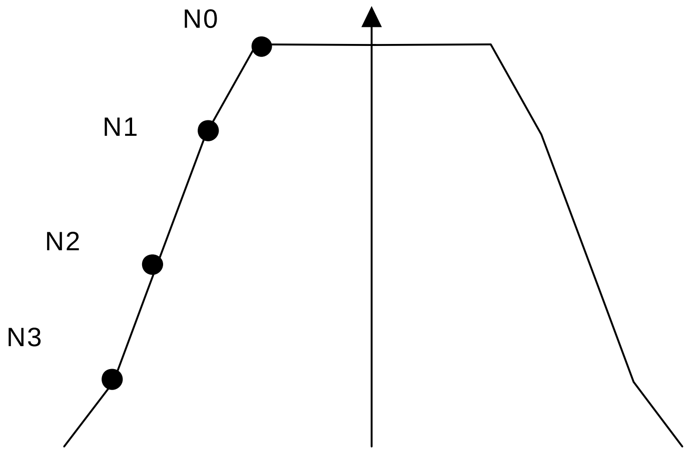


Figure C.3: Typical representation of the signal

Table C.2: Typical Symmetrical Signal Spectrum for different applications

Type of signal	Point	Delta Frequency w.r.t. Central frequency in %	Signal Attenuation in dBsd
Typical QPSK with SQRT 0,25 Roll-Off (30,5 Ms/s in a 36 MHz channel)	N0	38	3
Typical QPSK with SQRT 0,25 Roll-Off	N1	48,4	20
Typical QPSK with SQRT 0,25 Roll-Off	N2	50,7	25
Typical QPSK with SQRT 0,25 Roll-Off	N3	51,9	30
DVB-T for memory (note 1)	N1	37,5	35
DVB-T for memory (note 1)	N2	140	58
TV Carrier PAL 15 MHz/V (26 MHz) (note 2)	N0	10	0
TV Carrier PAL 15 MHz/V	N1	42	12,7
TV Carrier PAL 15 MHz/V	N2	59,6	24
TV Carrier PAL 15 MHz/V	N3	76,9	38,7
TV Carrier PAL 15 MHz/V	N4	96	65
TV Carrier PAL 25 MHz/V (36 MHz) (note 2)	N0	11	0
TV Carrier PAL 25 MHz/V	N1	44	13,3

Type of signal	Point	Delta Frequency w.r.t. Central frequency in %	Signal Attenuation in dBsd
TV Carrier PAL 25 MHz/V	N2	55	22,7
TV Carrier PAL 25 MHz/V	N3	69	34,3
TV Carrier PAL 20 MHz/V (32 MHz) (note 2)	N0	10	0
TV Carrier PAL 20 MHz/V	N1	50	17,9
TV Carrier PAL 20 MHz/V	N2	62	29
TV Carrier PAL 20 MHz/V	N3	78	43
Two carriers QPSK and 0,25 dB roll-off with 0dB IBO (Simulation)	N0	41	0
Two carriers with 0 dB IBO	N1	50	15
Two carriers with 0 dB IBO	N2	83	15
Two carriers with 0 dB IBO	N3	150	25
NOTE 1: See Alcatel Satellite Specifications. NOTE 2: See [6].			

As an example we give the result of the combination of the two masks for two Carriers with amplifier at saturation.

Frequency in % of Bt from centre frequency	Transponder Mask	Signal Mask	Total mask
49	0	0	0
50	3	15	18
66	15	15	30
100	20	15	35

Annex D:
Bibliography

NASA Space Network User Guide, 530-SNUG.

Young C.Yoon, "Simple and accurate BER analysis of band limited DS-CDMA systems with multi-class services".

A.Bateman, "Digital Communications", Addison-Wesley 1999.

M.A.Landolsi & W.E.Stark, "DS-CDMA Chip Waveform Design for Minimal Interference Under Bandwidth, Phase, and Envelope Constraints", IEEE Trans.Comm., vol.47, No.11, page 1737-1746, November 1999.

H.Olson & H.Tenhunen,"Implementation Aspects for Noncoherent Tracking Based on a Time-Discrete Delay-Locked, Loop", proc. of IEEE PIMRC'98, 1998.

J.Talvitie & G.Povey, "Performance of Pilot Carrier Based Doppler Compensation for CMDA Land Mobile Satellite Links".

"Study of Spread Spectrum Techniques for TCR", final report, prepared by MESSERSCHMITT-BOLKOW-BLOHM, December 1990, doc no OTN-KT315-1/90.FR.

M.B PURSLEY: "Performance evaluation for phase coded spread spectrum multiple access communication", IEEE transaction on communication, vol. com-25, August 1977.

D.LAFORGIA: "Bit error rate evaluation for spread spectrum multiple access systems", IEE transaction on communication, vol. com-32, August 1984.

A note from CNES (internal note CNES 85-CT/DRT/TIT/TR no 200).

Alcatel Satellite Specifications.

History

Document history		
V1.1.1	September 2001	Publication