Study
Future Multiple Uplink per Aperture Access Schemes

Summary Report

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In association with

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1. INTRODUCTION

The ESA Deep Space Antenna Network is of three 35m beam waveguide (BWG) antennas, located respectively in New Norcia, Western Australia (DSA1), Cebreros, Spain (DSA2), and in Malargue, Argentina (DSA3). The primary functions fulfilled by each DSA are:

- Tracking of the spacecraft when visible from the ground station site.
- Telecommand transmission to the tracked spacecraft.
- Reception of downlink telemetry from the tracked spacecraft.
- Range and range rate measurements of the spacecraft relative to the ground station.
- Communication with the SCC of TC, TM and RG data.

The evolution in the complexity and number of concurrent of interplanetary missions in the future will lead to the need to carefully consider optimal communications network architecture. The primary objective will be to leverage the architecture topology for maximum data return at least cost, but at the same time insuring adequate margin in terms QoS and security, particular for manned missions. The current communications topology for deep space missions can be considered as a collection of dedicated peer-to-peer links, one for each mission, with each link supporting several simultaneous services (Telecommand, HK telemetry, payload telemetry, ranging). The ground stations can be used for supporting several missions but on a time shared basis.

For the future a more optimal use of ground infrastructure would be to have one ground station capable of supporting several missions simultaneously. This could be possible with a single antenna aperture provided that the several spacecraft are within the beamwidth of the ground station antenna. The capability to view several spacecraft simultaneously using the current 35m DSA has been analysed in previous studies. It has been shown that for L2 missions MSPA can be used but under some constraints of spacecraft separation (< 1000km). However, at planetary distances (e.g. Mars) the antenna beamwidth would cover most scenarios of multiple spacecraft orbiting the planet or spacecraft exploring the surface of the planet.

It is relatively straightforward to receive simultaneous downlink signals from several spacecraft that are within the ground station antenna beam by using different downlink transmit frequencies (FDMA) and simply replicating the ground station demodulator. However, the uplink is more problematic. The principle difficulty is that the uplink power must somehow be shared between the spacecraft.

A number of methods of implementing MSPA have been suggested and described in the various reference documents. A preliminary critical analysis of these methods has been undertaken in the context of this study in order to undertake the necessary trade-offs and produce a recommendation for the best methods to implement for the short term solution and for the long term solution. In the second phase of the study the selected best methods have been analysed in detail in order to assess the modifications necessary and ground station level in order to implement MSPA capability.

2. SUMMARY OF STUDY ACTIVITIES

2.1 Review of Background Work and Preparation of MSPA Requirements

As a first activity of the study a review of selected reference documents have been made. The references have been selected based on their relevance for the definition of MSPA Operational Requirements. On the basis of this review at set of MSPA requirements have been prepared, based on the preliminary set provided in the study SoW. Additional requirements based from our review of reference material have been introduced. In addition we have split and refined the requirements between those relevant for short term implementation and those relevant for long term implementation as defined as follows.

The **short term scenario** is a scheme to support MSPA where the onboard elements (the S/C transponder) cannot be modified.

The **long term scenario** focuses on future missions where there is the freedom to implement new solutions for the communications payload on-board the satellite.

The MSPA requirements are shown in Annex 1.

The main alternatives for MSPA implementation which have been suggested by previous studies are listed in the table below.

Option	Abbreviation	Description
1	SC-CCSDS-PT Uplink 2 Coh + nNon-Coh CFDMA Downlink	Present capability. Not really MSPA on uplink without modifications.
2	CFDMA Uplink CFDMA Downlink	Multiple individual uplink carriers. Multiple downlink carriers each downlink coherent with one of the uplinks.
3	SC-CCSDS-PT Uplink SFDMA Downlink	Single uplink multiplexed at data level. Multiple downlink same carrier frequency but different subcarriers.
4	SFDMA Uplink SFDMA Downlink	Multiple subcarriers at the same carrier frequency in uplink and downlink
5	SC-CCSDS-PT Uplink CFDMA/ATFR Downlink	Single uplink multiplexed at data level. Multiple downlink with different carriers and turnaround ratios
6	SC-CCSDS-PT Uplink CDMA Downlink	Single uplink multiplexed at data level. Multiple downlink at the same carrier frequency (Code Division Multiple Access)
7	CDM Uplink CDMA Downlink	Single uplink Code Division Multiplex. Multiple downlink Code Division Multiple Access

One additional option was proposed by the study team at the start of the study:

8	DSSS CDMA Uplink DSSS CDMA Downlink	Direct Sequence Spread Spectrum Code Division Multiple Access – similar to Galileo and TDRSS

The main effort in the first phase of the study was devoted to making a trade-off between the identified solutions. The analysis concentrated on the complexity and difficulty of implementation as well as performance issues associated with each alternative. For the short term solutions the complexity of implementation focused on the required modifications to the Deep Space ground stations, to their overall architecture as well as to modifications to sub-systems and to equipment. For long term solutions the impact on the re-design of spacecraft transponders has also been considered.

Performance trade-offs have been assessed with the help of some simulation work which is reported in technical notes.

The following two tables provide a summary of the options considered for the short term scenario (Table 2-1) and for the long term scenario (Table 2-2). In each table the advantages and disadvantages of each option are listed.

At the end of the first phase of the project a review meeting was held with ESA and the results of the trade-off analysis were reviewed. As a result one option for each scenario was selected for detailed analysis in phase 2. The options selected were:

1. For the Short Term Scenario – Option 2 CFDMA – but with amplitude switching modification to reduce intermodulation as will be described in section 2.2.
2. For the Long Term Scenario – Option 8 DSSS CDMA using Galileo/TDRSS like specifications.

Option No.	Abbreviation	Description	Pros	Cons
2	CFDMA Uplink CFDMA Downlink	Multiple individual uplink carriers. Multiple downlink carriers (each downlink coherent with one of the uplinks)	Simplicity Independent Flexibility Possibility to use polarisation Diversity on U/L	Intermodulation products (HPA & PIM) Realistically only 2 Users (20kW HPA)
3	SC-CCSDS-PT Uplink SFDMA Downlink	Single uplink multiplexed at data level. Multiple downlink (same carrier frequency but different subcarriers)	Easy to Implement	Limited operations Limited TC Throughput D/L Interference from 2nd S/C needs polarisation diversity to reduce interference D/L Acquisition for 2nd S/C
4	SFDMA Uplink SFDMA Downlink	Multiple subcarriers at the same carrier frequency in uplink and downlink	Relatively Easy to implement	U/L Limited to 2 users U/L Cross Modulation problem D/L Interference from 2nd S/C needs polarisation diversity to reduce interference D/L Acquisition for 2nd S/C

Table 2-1 Summary of Short Term Solutions – Trade-offs (option shaded light green was selected for detailed study in 2nd phase of study)

Option No.	Abbreviation	Description	Pros	Cons
5	SC-CCSDS-PT Uplink CFDMA/ATFR Downlink	Single uplink multiplexed at data level. Multiple downlink with different carriers and turnaround ratios	Easy to Implement on U/L (no major modifications) Very Easy to implement on D/L	Limited operations Limited TC Throughput Continuous U/L sweep or complex acquisition. Same U/L bit rate for all users. Need as many different Turn Round ratios as users.
6	SC-CCSDS-PT Uplink CDMA Downlink	Single uplink multiplexed at data level. Multiple downlink at the same carrier frequency (Code Division Multiple Access)	Easy to Implement on U/L (no major modifications) CDMA acquisition problem on GS side only. Multiple Access (users) on downlink	Limited operations Limited TC Throughput Continuous U/L sweep or complex acquisition. Same U/L bit rate for all users. Need to develop CDMA transponder and GS demodulator.
7	CDM Uplink CDMA Downlink	Single uplink Code Division Multiplex using W-H codes. Multiple downlink Code Division Multiple Access	Continuous and simultaneous commanding to all spacecraft. Full S/C Tx power available for TM and ranging.	Severe AM on uplink if no limiter used. Severe interference between command channels if limiter used. Continuous U/L sweep or complex acquisition.
8	DSSS CDMA Uplink DSSS CDMA Downlink	Similar to Galileo SS TT&C scheme	Proven for GEO/MEO missions. For Mars operations link budgets gives adequate margins. U/L Doppler pre-compensation can be used for all spacecraft	Deep Space more challenging for acquisition at C/No< 40dBhz. Need to develop CDMA transponder and GS TTC modem.

Table 2-2 Summary of Long Term Solutions – Trade-offs (option shaded light green was selected for detailed study in 2nd phase of study)

2.2 Short Term Solution

The short term solution uses Carrier Frequency Division Multiplex (CFDMA) on both Uplink Telecommand and Downlink Telemetry. The spacecraft transponders will be operated in *Coherent Mode* once locked to the uplink carriers. The advantage of this method is that the implementation on the GS could be relatively straight forward to implement and does not require any modification to the S/C transponder or the standard DS remnant carrier modulation schemes. The main problem with CFDMA on the uplink is the potential for generation of IM products in the Klystron HPA. The scheme devised, which is described below with the help of Figure 2-1, reduces the level of IM products by implementing an Amplitude Switch Multiplex in addition to the Frequency Division Multiplex.

The scheme is described using two uplink TC signals, TC1 and TC2 which are at different frequencies.[1] The time sequenced procedure is described as follows (Figure 2-1).

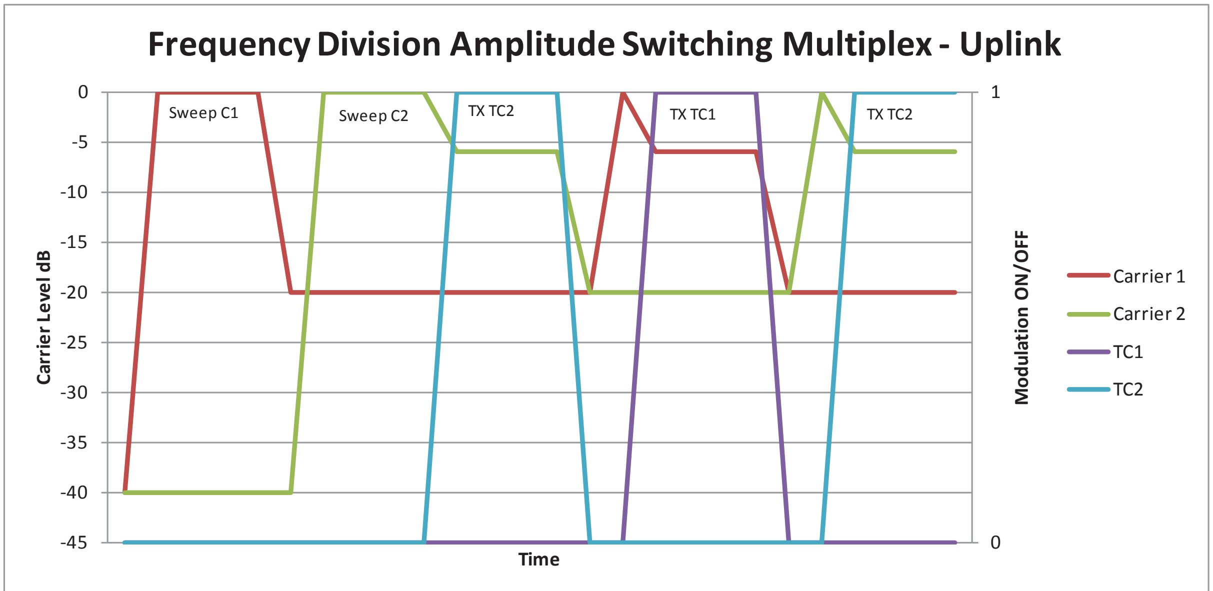

Figure 2-1 Short Term Solution for MSPA using CFDMA with Amplitude Switching

First TC1 unmodulated carrier is transmitted alone with a nominal carrier power and with normal carrier frequency sweep until the S/C 1 transponder is locked. Then TC1 amplitude is reduced by at least 20dB; however the transponder on S/C1 will remain locked as will be demonstrated later.

Next TC2 is transmitted with a nominal carrier power and with normal carrier frequency sweep until the S/C 2 transponder is locked.

It should be noted that the frequency of the uplink carriers will be adjusted at the ground station to compensate for Doppler in order to assist the spacecraft acquisition process. Each carrier will be independently Doppler compensated for Earth rotation, Earth-Moon relative velocity and for each spacecraft orbital velocity. In this way the differential Doppler between spacecraft is not a problem during uplink carrier acquisition.

[1] The two uplink frequencies should be sufficiently separated such that TC2 frequency is outside the acquisition range of S/C 1 and vice-versa.

After carrier lock TC2 is modulated and data is transmitted to S/C2 until the end of the TC transmission sequence. Then the TC2 modulation is switched off and the carrier power is reduced by at least 20dB; however the transponder on S/C2 will remain locked as will be demonstrated later.

Now TC1 carrier level can be increase again to nominal power and then modulated. The TC1 transmission sequence continues until all necessary TCs have been transmitted. Then TC1 modulation is switched off and the carrier level is reduced by at least 20dB.

The sequence described above can then be repeated according to operational needs for the duration of the pass.

On the downlink side, as both S/C transponders are in coherent mode after the initial acquisition sequence, then telemetry will be continuous from both S/C throughout the pass and will be unaffected by the amplitude switching of the uplink. Moreover, as the uplink carriers are a different frequencies so the downlink carriers will be a separate frequencies with both transponders using fixed turn round ratios. Therefore, CFDMA TM reception at the GS will be straight forward.

Simulation analysis has been done to predict the levels of intermodulation products which would be generated in the 20 kW Klystron HPA when transmission of two carriers of un-equal powers. The simulation results using ESA data sets show that the intermodulation levels are close to required limits imposed by spurious emissions given by ECSS-ST-E50. However, it was considered that this result is optimistic of what would be measured in reality at the DSA. Given this then it would be prudent to consider using linearization techniques in addition to the scheme proposed, in order to guarantee the level on IMP with the limits required.

A number of methods have been developed to reduce the non-linear distortion introduced by transmission power amplifiers of various types.

The available techniques are:

- Negative Feedback
- Feedforward
- Predistortion

The predistortion **linearizer** has been developed for satellite communications and microwave communications applications. This method has developed in popularity because of their relatively good wideband performance and that they can be implemented as standalone units.

The most recent development of the predistortion method is the addition of an adaptation feedback loop, which is now implemented in the digital domain. The pre-distorter will have a lookup table (LUT) which has a predefined model of the AM/AM and AM/PM characteristics of the non-linear amplifier. This model might have been previously "learnt" by use of the adaption loop during "training" sessions (e.g. during installation). After this the adaptation loop is used to maintain the performance by compensating for relative slow time variation effects of the non-linear amplifier, due to changes of temperature etc.

We have reviewed the available literature to find examples of the performance of linearizers. In particular we have been interested in finding quantitative figures for the level of reduction of 3rd order IMP for multicarrier amplification. The following list of parameters, which affect performance in reduction of IMP, which have been identified in the literature.

- Bandwidth of multi-carrier signals with better reduction achieved when the bandwidth is small.

- Backoff level and/or level of IMP with better relative reduction being achieved when the back-off is small, hence the IMP levels high, prior to linearizer action. It can be appreciated that reducing IMP which is 20dB less that the carrier is easier than reducing IMP which is 50dB less than the carrier due to the accuracy of the measurement in the adaptation loop.
- Quality (linearity) of feedback path components.
- The complexity of the adaptation model e.g. whether memory effects are modelled or not.

It is considered that a reduction of 15dB on the 3rd order IM would be a reasonable goal for a linearizer implementation in the DSA using state-of-the-art techniques.

Two possible architectures have been identified for the implement od the short term solution in the DSA ground station. The first is a low impact solution with no linearizer, the second is with linearizer. These two solutions are shown in Figure 2-2.

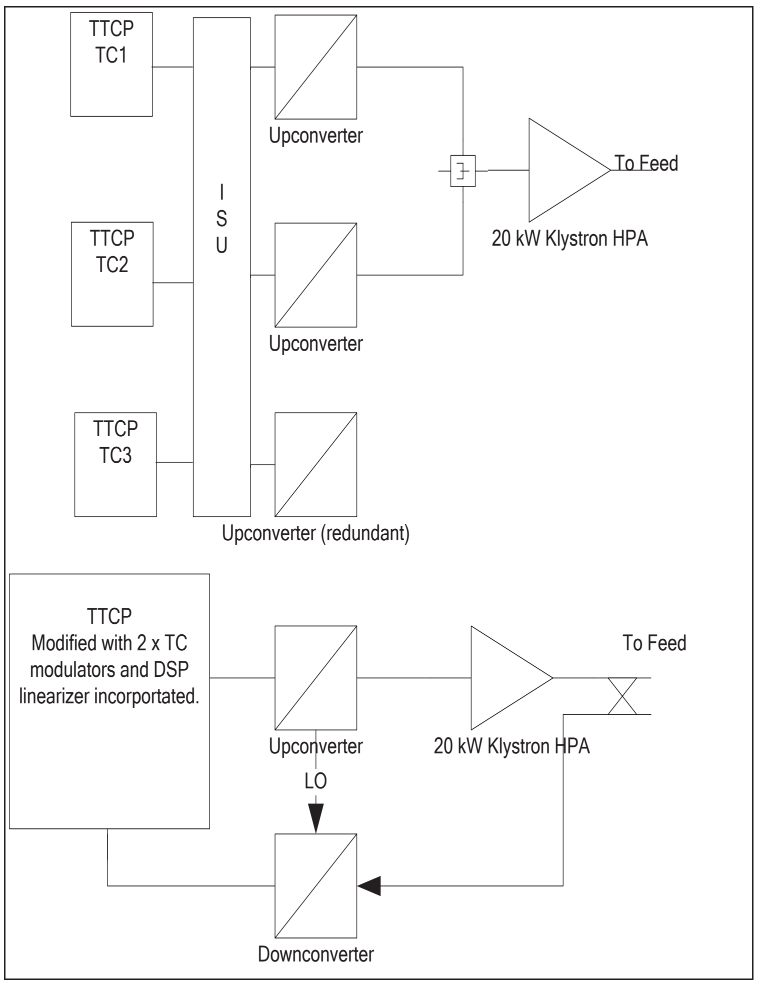

Figure 2-2 Two options for implementing CFDMA Uplink (a) combing at RF before HPA without linearizer, (b) combining at baseband in DSP with DSP linearizer.

The implementation of CFDMA on downlink is relatively straight forward and can be done without any significant GS modifications. The configuration of GS downlink chain is shown in **Figure 2-3**. .

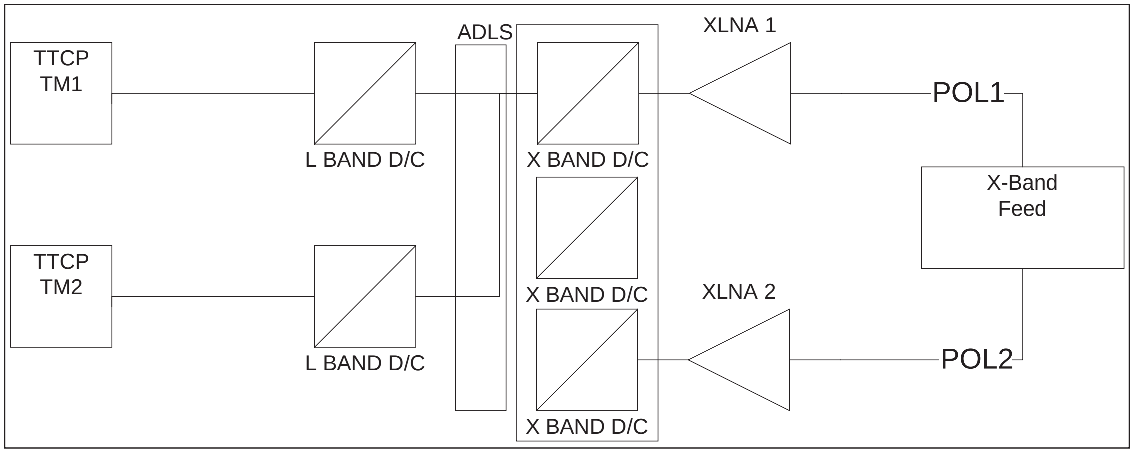

Figure 2-3 DSA Configuration for implementing CFDMA Downlink.

Extending the short term solution for MSPA for more than two spacecraft simultaneously would be feasible, in principle. The main limitation is on the ground station and the number of equipment available for simultaneous TTC links.

Link budgets have been prepared to analyse the end-to-end performance for a Mars missions. All the budgets were based on a spacecraft having the same communications specifications as Mars Express using a High Gain Antenna, at maximum range for Mars (370E6 km). Summary of the results for the TC uplink are shown in the following tables.

In Table 2-3 the TC uplink power for S/C 1 is 5kW (same as nominal) and for S/C 2 50W so 20dB less. The S/C 2 uplink carrier is unmodulated and the carrier recovery margin at the transponder is over 4dB with the carrier receiver bandwidth set to wide. On the downlink side the TM margin is nominal for both S/C 1 and S/C 2; in fact the TM margin for S/C 2 is slightly better than for S/C 1 as there is no ranging modulation loss.

In Table 2-4 the TC uplink power S/C 1 is 3kW and for S/C 2 30W so 20dB less. The TC data recovery margin for S/C 1 is now 6dB compared to just over 8dB for the nominal case. The S/C 2 uplink carrier is unmodulated and the carrier recovery margin at the transponder is over 2dB with the carrier receiver bandwidth set to wide. It should be noted that a higher margin of carrier recovery on S/C 2 could be obtained by setting the transponder carrier receiver PLL to NARROW. On the downlink side the TM margins are the same as nominal. However, the ranging tone recovery margin for S/C 1 is reduced by around 2dB compared to the nominal condition due to the reduced uplink power. However, the ranging performance is still within the normal capability of the ground station ranging receiver.

	Nominal	S/C1	S/C2
GS Tx Power (kW)	5	5	0.05
GS EIRP (dBW)	102	102	82.1
Mod Index (Rad)	1	1	0
S/C Carrier PLL	WIDE	WIDE	WIDE
S/C Carrier PLL Margin (dB)	21	21	4.6
TC Bit Rate (bps)	2000	2000	-
TC Data Margin (dB)	8.2	8.2	N/A

Table 2-3 Short Term MSPA TC Uplink Performance (1)

	Nominal	S/C1	S/C2
GS Tx Power (kW)	5	3	0.03
GS EIRP (dBW)	102	100	79.9
Mod Index (Rad)	1	1	0
S/C Carrier PLL	WIDE	WIDE	WIDE
S/C Carrier PLL Margin (dB)	21	19	2.4
TC Bit Rate (bps)	2000	2000	-
TC Data Margin (dB)	8.2	6.0	N/A

Table 2-4 Short Term MSPA TC Uplink Performance (2)

It has also been shown that it would even be possible to transmit TC data to S/C 2 with a low uplink Tx power (30W) and with a reduced bit rate (100bps).

2.3 Long Term Solution: Galileo like DSSS CDMA TT&C

The DSSS scheme currently used by Galileo adheres to an international standard first defined by NASA/JPL for use on the "user channel" of the S-Band DRS satellite network (and now specified in CCSDS 415.1-B-1 [RD58]) . This standard provides coherency and ranging using:

- A TC modulated 1023 chip balanced Gold code for the "Forward Command Channel" transmitted on the I Channel of the UQPSK uplink modulation.
- A forward range code consisting of a truncated maximum length sequence of 256 * 1023 (=261,888) chips transmitted on the Q channel at a power 10 dB lower than the command code. This ranging code is phase locked to the forward command code. This allows rapid acquisition of the ranging code once the command code is acquired at the spacecraft.
- A Non-coherent OQPSK downlink modulation (mode 2) using return codes consisting of a pair of 2047 chip Gold codes, one for the I channel, the second delayed ½ a chip for the Q.
- A coherent OQPSK downlink modulation (mode 1 & 3) using a truncated maximum length sequence of 256 * 1023 chips on I and Q channels, with the Q channel delayed by > 20,000 chips. The downlink code sequence is locked to the uplink forward range code which permits two-way time of flight and hence range determination.

The requirements of the MSPA are surprisingly similar, the obvious difference being the much greater range of Mars missions compared to Earth orbit relay operations. This greater range has implications for the spacecraft acquisition and tracking thresholds and the choice of the ranging spread code length (which dictates the ranging ambiguity).

Consideration of the MSPA requirements suggests that the existing DSSS standard, suitably adapted for X-Band, is in fact well suited to MSPA use. The standard chip rate of 3 Mcps gives ranging accuracy similar to the existing Deep-space ranging standard, and higher chip rates could be used if greater accuracy was required. Similarly the existing range code length of 2^{18} -256 chips gives, at the normal 3 Mcps chip rate, a one-way ranging ambiguity of ~12,500 km. While somewhat less than the maximum ESA Tone/Code ranging ambiguity of ~100,000 km, 12,500 km is more than the diameter of Mars so it thought to be sufficient in most circumstances. Should a larger ambiguity distance be needed then a longer maximum length sequence could be specified without significant side effects, it would just require more time to acquire a longer code, both in the spacecraft and the ground demodulator.

2.3.1 Doppler Pre-compensation

One of the key benefits of having completely independent uplink signals for each spacecraft is that the Doppler to each spacecraft can be independently pre-compensated. In particular for a spacecraft in orbit round Mars the uplink code and carrier Doppler can be pre-compensated for both the common Doppler components of:

1. Earth rotation; and
2. Earth Mars relative motion;
3. as well as for the components "unique" to each spacecraft of
4. spacecraft motion with respect to Mars;
5. predicted variations in spacecraft reference oscillator frequency.

This means the only remaining uncompensated frequency error is due to:

- un-modelled drift components of the spacecraft reference oscillator and;

- any errors in the estimated Doppler due primarily to inaccuracies in the spacecraft orbit estimation.

As the frequency errors from both these sources are proportional to the carrier frequency, which is proposed to be X-Band rather than S-Band as used in Galileo, it may be necessary to specify somewhat better reference oscillators in the spacecraft than would otherwise be needed, and to ensure the best possible orbit determination to minimise Doppler estimation erros.

2.3.2 Uplink Acquisition

A key consideration in using Galileo standard CDMA for a deep space mission is the signal acquisition given the significantly lower C/No.

Uplink Signal acquisition is typically performed in several stages:

(1) Acquisition of the Forward Command code (1023 chip Gold) on the I channel using a correlator.
(2) Tracking of the forward command code using a Delay Locked Loop (DLL).
(3) Acquisition and tracking of the uplink carrier phase typically using a frequency aided PLL (the uplink is NOT modulated with TC during acquisition).
(4) Switching the carrier tracking loop to a Costas loop to accommodate uplink modulation.
(5) Acquisition and tracking of the Data timing;
(6) Acquisition of the Q channel Forward Range (1023 x 256 chip) code.

The critical part of the acquisition process is the first stage, acquisition of the I channel Forward command code. This is typically done using a correlator (in either time of frequency domains) to find the phase of the forward code. The correlator correlates the complex near baseband signal with the I local code (it does not use the Q local code as this is 10 dB lower power and anyway too long). Once the I channel code is acquired code tracking begins and carrier and bit sync are acquired.

A key consideration in the acquisition of the Uplink spread code is that the correlator must be able to acquire the code sufficiently rapidly that the code phase has not changed more than ~1/2 a chip during the acquisition. This requirement drives the need for Doppler (and LO offset) pre-compensation of the code rate. Similarly to minimise the correlation loss due to carrier rotation the carrier frequency must also be Doppler pre-compensated. Based on a typical parallel correlator acquisition the expected acquisition times considering a 3000 Hz carrier frequency offset are tabulated in Table 2-5 below.

Based on the results reported above we suggest that a realistic code acquisition **C/No is 37.0 dB**, assuming a frequency uncertainty of 0.41 ppm, or 3000 Hz at X-Band. This is considering only the I channel power or C/No = 37.4 dB including the Q channel power. This will allow acquisition with a single fully parallel correlator without the need to search in frequency. Note that at a data rate of 2,000 bps a C/No of 37 dB implies an Eb/No of only 4 dB, so there seems little point in acquisition at lower C/No. The exception to this is in emergency situations where (for example) the high gain antenna can not be deployed.

Configuration		
Code family	Ideal	
Chip rate	3	Mcps
Acquisition Probability (per correlation)	0.9	
False Alarm Probability (per correlation)	1.00E-05	
Carrier frequency	7.235	GHz
Max Carrier uncertainty (Doppler/USO stability)	3000	Hz (+/-)
Max allowed carrier rotation	120	degrees
Samples per chip	2	
Calculated		
Max Coherent Correlation for	333.3	chips
Worst case code misalignment	0.25	chips
Fractional frequency uncertainty	0.41	ppm

C/No	Non_Coherent correlations	Acquisition time mS	Max Code Doppler cps	ppm
30.0				
33.0	20,137	2,237.4	0.22	0.074
36.0	4,465	496.1	1.01	0.336
37.0	2,772	308.0	1.62	0.541
39.0	1,093	121.4	4.12	1.373
42.0	291	32.3	15.48	5.160
45.0	80	8.9	56.18	18.727

Table 2-5 Predicated CDMA Acquisition performance 3000 Hz uncertainty

To accommodate these situations it is suggested a similar strategy to Galileo is used, namely:

- The spacecraft transponder is "dual standard" so can be switched by the on-board computer to a "standard" deep space PCM/BPSK/PM mode, this will allow acquisition and operation at much lower C/No
- In the event of the Transponder frequency uncertainty exceeding the 0.41 ppm target (either due to LO drift in the transponder or Doppler uncertainty) the ground station uses a slow carrier and code frequency sweep, centred on the best guess of the transponder rest frequency.

2.3.3 G/S Transmit Spectrum and Non-Linear HPA

While the Galileo CDMA system is well proven, it is NOT generally used to address several satellites simultaneously through a single ground station HPA. For this reason the effect of the HPA non-linearity was explored via simulation. This is to address two concerns:

- The generation by the HPA of tones and/ or noise outside the main lobe bandwidth of the CDMA uplink. These tones/noise may cause unacceptable interference.
- The generation of intermodulation products within the main lobe bandwidth which may degrade the uplink signal and lead to a BER degradation.

The CCSDS RF and Modulation Systems Bluebook recommend that the total power contained in any spurious emission shall not exceed -60 dBc. Spurious inter-modulation frequencies and spectral re-growth (side-lobe re-growth) are generated by a non linear HPA when its operating region falls within the non linear portion of its transfer curve. The magnitude of these spurious and side lobe regrowth was evaluated by simulation. The Klystron HPA non linearity AM/AM and AM/PM curves [RD7] were modelled using a polynomial fit . The simulation used a representative spread code of 1024 chips sampled at 16 samples per chips and without TC modulation. Thus the signal spectrum was a series of discrete spectral lines repeating every (Chip_rate/number of chips in PN sequence) = 2928.68Hz. A 2M point FFT was used to give a spectral resolution of 23 Hz, so spectral lines should appear every 128 FFT bins.

The simulation showed that with a single DSSS carrier an IBO of about 15 dB (corresponding to an Output Backoff of about 10 dB [RD2]) was required to bring the C/I within the 60 dB specification.

2.3.4 Two carrier system

The spectra for a two carrier system, with carrier separated by ~91.5 Hz, with IBO of 3 dB (left hand graphs) and 15 dB (right Hand graphs) are shown in Figure 2-4 below. Note that a 3 dB input back off with two carriers gives a maximum input power (when the two carriers are in phase) equal to the saturation power, so represents the minimum IBO that can be used without driving the amplifier hard into saturation.

The first graph shows that although the input signal side lobes are suppressed ~80 dB they re-grow in the HPA to around -22 dB with 3 dB IBO or about -32 dB with 15 dB IBO. The second pair of graphs show a "zoom" of the input signals showing the discrete spectral lines of the two input signals at intervals of 2928.68 Hz.

We can see in the third pair of graphs the emergence of inter-modulation products between the desired signal tones. Similarly on the final pair of graphs we see the in-band intermodulation products (in green). These are much reduced, as are the out of band spuriae, by increasing the IBO from 3 to 15 dB.

C/I computations based on these simulations show that an IBO of about 15 dB is required to bring the out-of-band spurious below 60 dBC. Such a high input back-off means that the transmitted power is only about 63.7 dBm or 2340 Watts (compared to the single carrier Tx power at 0 dB IBO of 72.25 dBm or 16,800 Watts). With fours CDMA carriers this means the power available to each carrier is only about 600 Watts. Such a low TX power is insufficient for the target link budgets. It is therefore strongly recommended that a linearizer is used to make the Klystron amplifier transfer curve more linear so that it can be operated closer to saturation.

The simulation also showed that both the degradation due to the HPA distortion and that due to the multiple access interference are small (< 0.3 dB total). Thus from a "distortion" point of view there is little to be gained from the introduction of a lineariser – the benefit of linearization is largely the prevention of out-of-channel transmissions.

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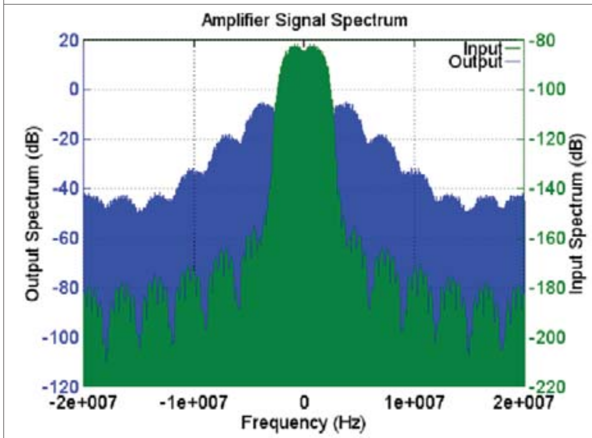
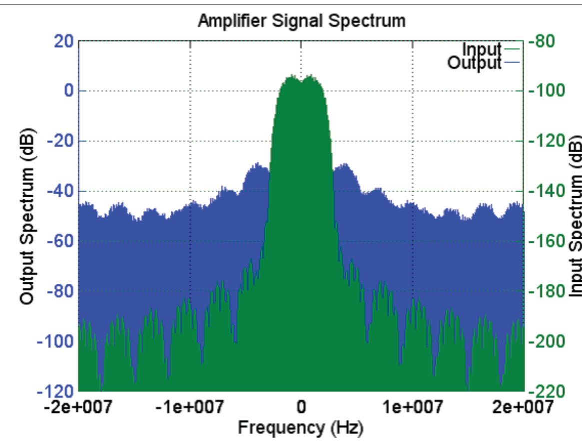
<tr><td>
</td><td>
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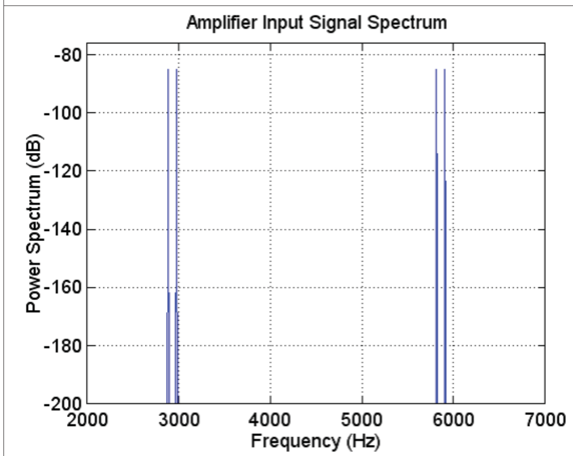
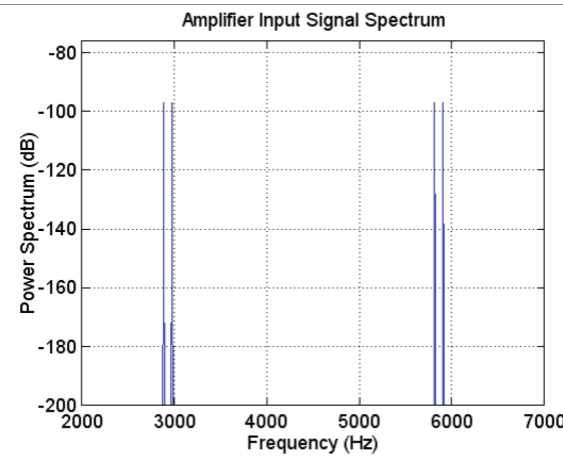
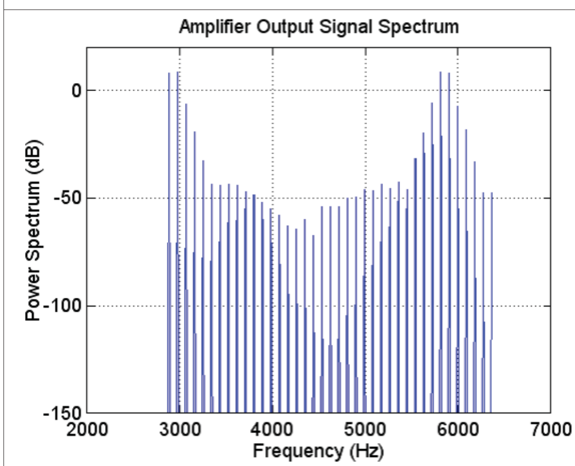
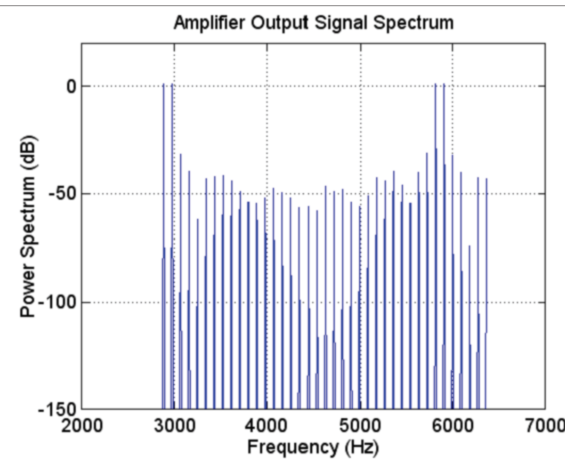
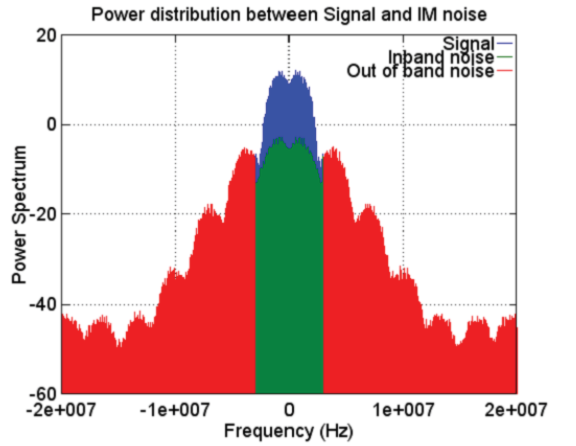
<tr><td>
</td><td>
</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>



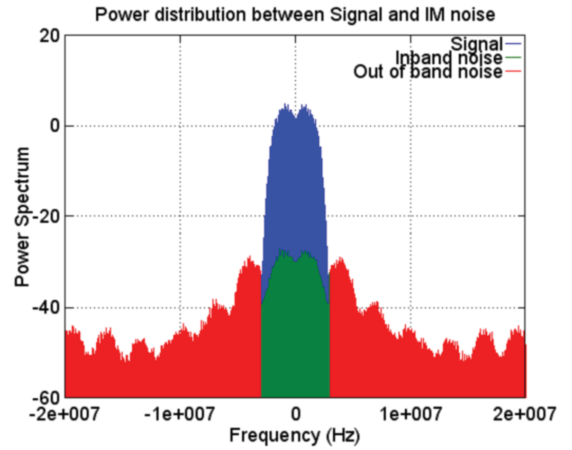


Figure 2-4 Two Carrier system with Non linear HPA

2.3.5 Baseband design – Spacecraft

The DSSS spacecraft Transponder requires no significant new technology. It can be based on the RF sections of existing deep space transponders (albeit wide band to accommodate the relatively wide band CDMA signal) and the digital baseband section very closely based on a Galileo TTC transponder. Acquisition performance is strongly dependant on the accuracy with which the transponder rest frequency can be predicted. A target of 1500 Hz is suggested, allowing a further 1500 Hz of Doppler uncertainty, whilst staying within the 3000 Hz overall uncertainty.

A suitable "Dual Standard" signal processing architecture, based on the existing TeSat GmbH Galileo transponder is shown in Figure 2-5 below. This supports a emergency PCM/BPSK/PM subcarrier mode as well as the DSSS standard.

A fully parallel correlator is used for code acquisition and to detect and correct any false acquisitions on correlation side-lobes.

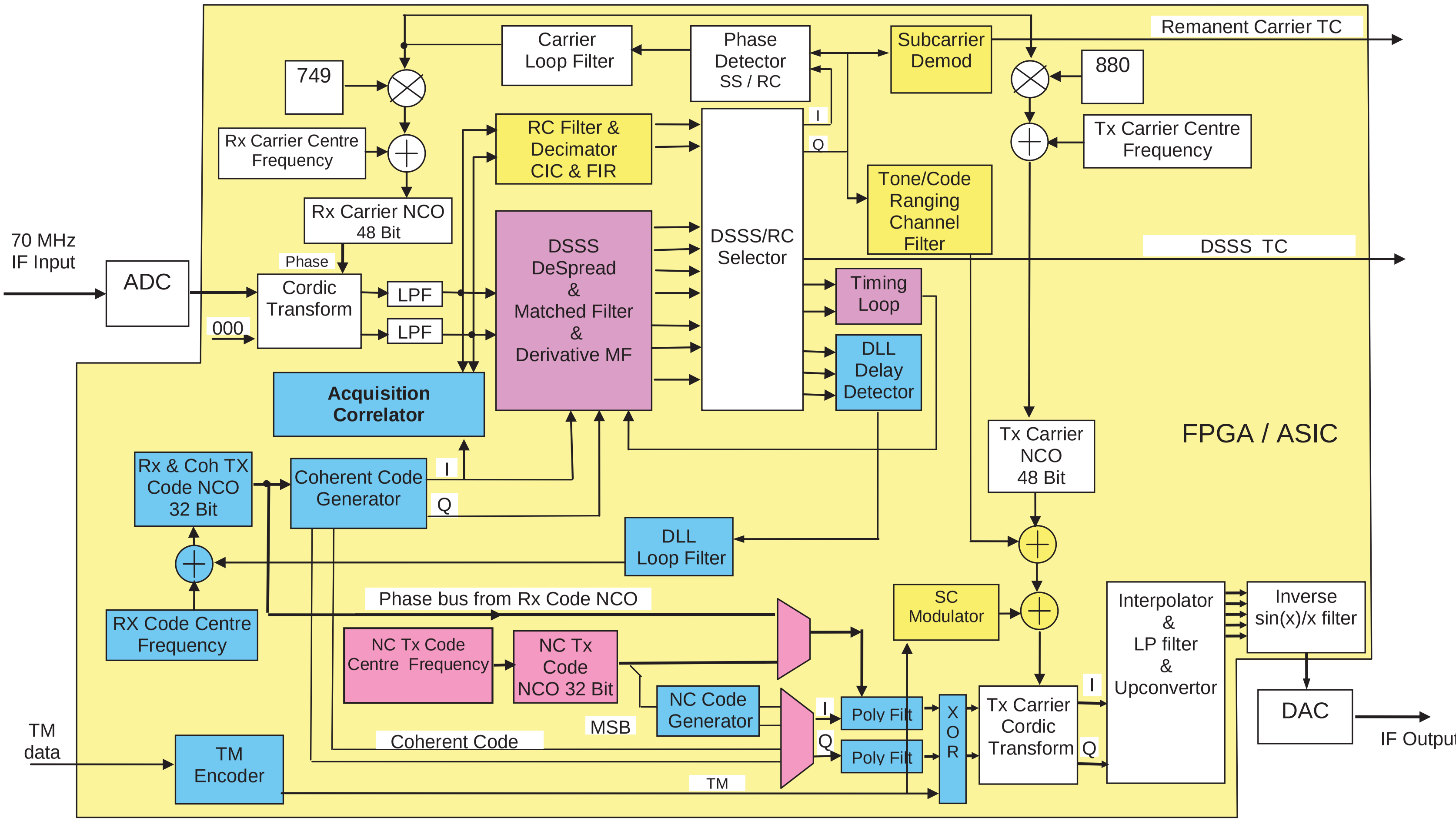


Figure 2-5 Dual Mode CDMA/RC Transponder Baseband Processor

2.3.6 Delta DOR

Delta DOR tones can be inserted in the Tx signal located at nulls of the DSSS spectrum (ie multiples of the chips rate). This ensures no interference between Delta DOR tones and the TM signal, and vice-versa.

2.3.7 CDMA Baseband Signal processing Design – Groundstation

The ground station processing architecture is shown in Figure 2-5 below. Again the design requires little fundamental development beyond that that already available in the existing Galileo ground station modems. The only major differences are :

- Integration of more than one TC uplink modulator and TM Downlink demodulator in a single unit
- Provision of an integrated lineariser.

Given that designs for dual standard Galileo modems exist it is largely a matter of using a larger FPGA to allow more than one Modulator and Demodulator to be "instantiated" within the FPGA. An architecture such as this could be implemented within the TTCP.

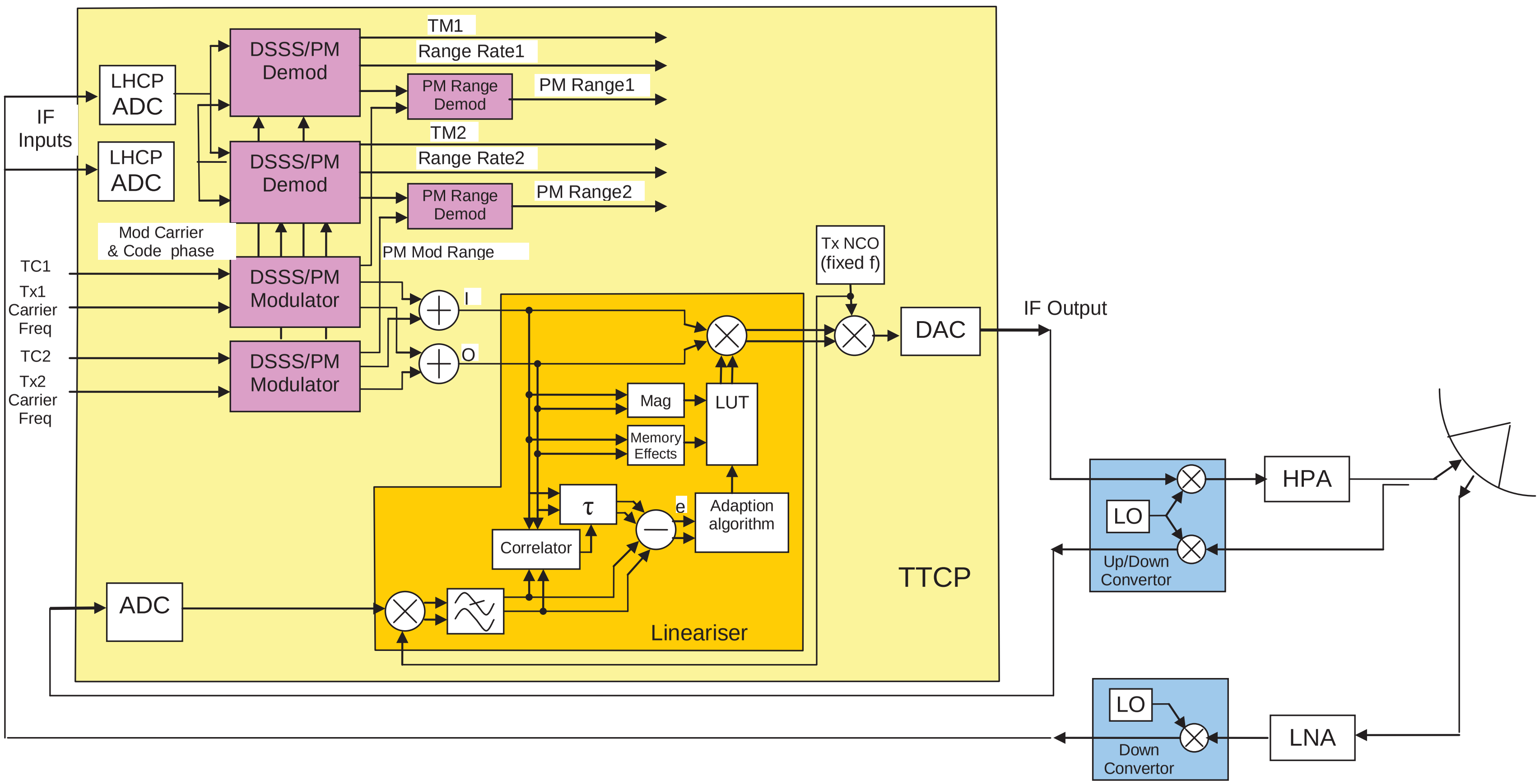


Figure 2-6 Overall DSSS/PM Ground Station Block Diagram showing integrated lineariser

2.3.8 Link Budgets

A number of sets of link budgets have been prepared to illustrate the end to end performance for both uplink and downlink. The link budgets results are summarised in the tables below and show how the scheme described above would work for a Mars scenario. All the budgets are based on a spacecraft having the same communications specifications as Mars Express using a High Gain Antenna, at maximum range for Mars (370E6 km). The GS performance is based on the DSA X-band performance.

Figure 2-7 shows a link budget for a single CMDA TTC link for various levels of uplink power between 5kW (max) and 500W (min). The code acquisition threshold (C/No=37dB) has been established by analysis done in WP 3200 and reported in SD.9. It can be seen that for all scenarios, for both uplink and downlink, the code acquisition margin is more than adequate. The TC data recovery for a TC data rate of 4 kbps (max required) is within a comfortable margin for GS Tx power > 1 kW. However, for 500W Tx power the TC data rate would either have to be reduced or FEC used on the TC channel, which is not usual, but we see no technical reason why it cannot be implemented for a new development of transponder. The TM downlink data recovery is also comfortably with margin with the bit rate set the same as for the classical TT&C case. In fact the margin is slightly better for the CDMA link that classical PM/BPSK/PCM TM, because of the fact that the CDMA modulation scheme is suppressed carrier.

Figure 2-8 now shows the scenario for multiple CDMA links with full overlay and with the uplink Tx power limited to ensure operation in the Klystron HPA linear region with 9.8dB back-off. The number of simultaneous CDMA links runs from 1 to 5 in the columns of the table running from left to right. It will be noticed that as the number of channels increases so the GS Tx power per signal is reduced to respect the maximum power limit. In order to compensate for the reduction in GS Tx power per channel, the TC data rate is decreased to maintain a positive TC link margin. However, it will be noticed that in all columns the code acquisition margin is above 10dB. On the TM downlink side the impact of mutual interference on the link margin is more pronounced than on the uplink side due to the fact that the operating C/No is higher and the C/I degradation is dependent on this parameter.

Figure 2-9 shows a similar scenario to the previous one with between 1 and 5 simultaneous CDMA channels. However, now we have limited the total GS Tx power to 6dB back-off, so there is a likelihood of some non-linear distortion due to peak power levels exceeding the saturated power. We could assume that some measures could be put in place to reduce the impact of non-linear distortions such as the implementation of a linearizer in the ground station. In this link budget we also assumed that FEC can be used on the TC uplink and so the maximum required TC data rate of 4 kbps is achieved for all multiple channel cases. It should be noted that FEC implementation is recommended in some references to mitigate clipping in DACs which might occur with multiple carrier systems, when the signals are generated and combined in digital circuits. The TM downlink is the same as for the previous one.

Finally for completeness, **Figure 2-10** shows the same scenario as in Figure 2-9 except in this case no FEC is used in the uplink and the TC data rate is reduced to 2 kbps for the 4 x CDMA and 5x CDMA columns.

Link Budget		Single CDMA TC/TM	Single CDMA TC/TM	Single CDMA TC/TM	Single CDMA TC/TM	Single CDMA TC/TM
Uplink						
Link Parameters	Unit					
GS Tx Power	kW	5.00	2.00	1.00	0.50	0.50
GS EIRP	dBW	102.09	98.11	95.10	92.09	92.09
Signal Frequency	MHz	7167.00	7167.00	7167.00	7167.00	7167.00
Range	Km	370000000	370000000	370000000	370000000	370000000
Free Space Loss	dB	280.92	280.92	280.92	280.92	280.92
Uplink S/No	dB/Hz	58.58	54.60	51.59	48.58	48.58
Code Acquisition & Recovery						
C/No Code Acquisition Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00
Margin on Code Acquisition	**dB**	**21.58**	**17.60**	**14.59**	**11.58**	**11.58**
Data Recovery						
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20
Uplink HPA Distortion	dB	0.50	0.50	0.50	0.50	0.50
Multicarrier IM Distortion	dB	0.00	0.00	0.00	0.00	0.00
Number CDMA Channels		1.00	1.00	1.00	1.00	1.00
C/I Loss due to CDMA	dB	0.00	0.00	0.00	0.00	0.00
Demodultor Tech Loss	dB	1.00	1.00	1.00	1.00	1.00
Bit Rate	Hz	4000.00	4000.00	4000.00	4000.00	4000.00
FEC Coding Gain	dB	0.00	0.00	0.00	0.00	5.40
EbNo	dB	20.86	16.88	13.87	10.86	10.86
EbNo Threshold for 1e-5 BER	dB	9.60	9.60	9.60	9.60	5.10
Margin data Recovery	dB	11.26	7.28	4.27	1.26	5.76
Downlink						
Link Parameters	Unit					
S/C EIRP	dBW	58.27	58.27	58.27	58.27	58.27
Signal Frequency	MHz	8420.00	8420.00	8420.00	8420.00	8420.00
Range	Km	370000000	370000000	370000000	370000000	370000000
Free Space Loss	dB	282.32	282.32	282.32	282.32	282.32
Downlink S/No	dB/Hz	55.27	55.27	55.27	55.27	55.27
Code Acquistsion & Recovery						
C/No Code Acquiistion Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00
Margin on Code Acquisition	**dB**	**18.27**	**18.27**	**18.27**	**18.27**	**18.27**
Data Recovery						
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20
S/C Modulator Distortion	dB	0.10	0.10	0.10	0.10	0.10
Transponder SSPA Distortion	dB	0.50	0.50	0.50	0.50	0.50
Number CDMA Channels		1.00	1.00	1.00	1.00	1.00
C/I Loss due to CDMA TM	dB	0.00	0.00	0.00	0.00	0.00
Demodultor Tech Loss	dB	0.50	0.50	0.50	0.50	0.50
Bit Rate	Hz	28570.00	28570.00	28570.00	28570.00	28570.00
Bit Rate	dBHz	44.56	44.56	44.56	44.56	44.56
FEC Coding Gain	dB	7.60	7.60	7.60	7.60	7.60
EbNo	dB	9.41	9.41	9.41	9.41	9.41
EbNo Threshold for 1e-6 BER	dB	2.88	2.88	2.88	2.88	2.88
Margin data Recovery	dB	6.53	6.53	6.53	6.53	6.53

Figure 2-7 Link Budget for Single CDMA TT&C Link Mars

Link Budget		Single CDMA TC/TM	2 x CDMA TC/TM	3 x CDMA TC/TM	4 x CDMA TC/TM	5 X CDMA TC/TM
Uplink						
Link Parameters	Unit					
GS Tx Power	kW	2.10	1.05	0.70	0.55	0.42
GS EIRP	dBW	98.32	95.31	93.55	92.50	91.33
Signal Frequency	MHz	7167.00	7167.00	7167.00	7167.00	7167.00
Range	Km	370000000	370000000	370000000	370000000	370000000
Free Space Loss	dB	280.92	280.92	280.92	280.92	280.92
Uplink S/No	dB/Hz	54.81	51.80	50.04	48.99	47.82
Code Acquisition & Recovery						
C/No Code Acquisition Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00
Margin on Code Acquisistion	**dB**	**17.81**	**14.80**	**13.04**	**11.99**	**10.82**
Data Recovery						
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20
Uplink HPA Distortion	dB	0.50	0.50	0.50	0.50	0.50
Multicarrier IM Distortion	dB	0.00	0.05	0.06	0.07	0.08
Number CDMA Channels		1.00	2.00	3.00	4.00	5.00
C/I Loss due to CDMA	dB	0.00	0.21	0.28	0.33	0.34
Demodultor Tech Loss	dB	1.00	1.00	1.00	1.00	1.00
Bit Rate	Hz	4000.00	3000.00	2000.00	1500.00	1000.00
Bit Rate	dBHz	36.02	34.77	33.01	31.76	30.00
FEC Coding Gain	dB	0.00	0.00	0.00	0.00	0.00
EbNo	dB	17.09	15.07	14.99	15.13	15.70
EbNo Threshold for 1e-5 BER	dB	9.60	9.60	9.60	9.60	9.60
Margin data Recovery	**dB**	**7.49**	**5.47**	**5.39**	**5.53**	**6.10**
Downlink						
Link Parameters	Unit					
S/C EIRP	dBW	58.27	58.27	58.27	58.27	58.27
Signal Frequency	MHz	8420.00	8420.00	8420.00	8420.00	8420.00
Range	Km	370000000	370000000	370000000	370000000	370000000
Free Space Loss	dB	282.32	282.32	282.32	282.32	282.32
Downlink S/No	dB/Hz	55.27	55.27	55.27	55.27	55.27
Code Acquistsion & Recovery						
C/No Code Acquiistion Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00
Margin on Code Acquisition	**dB**	**18.27**	**18.27**	**18.27**	**18.27**	**18.27**
Data Recovery						
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20
S/C Modulator Distortion	dB	0.10	0.10	0.10	0.10	0.10
Transponder SSPA Distortion	dB	0.50	0.50	0.50	0.50	0.50
Number CDMA Channels		1.00	2.00	3.00	4.00	5.00
C/I Loss due to CDMA TM	dB	0.00	0.46	0.88	1.26	1.61
Demodultor Tech Loss	dB	0.50	0.50	0.50	0.50	0.50
Bit Rate	Hz	28570.00	28570.00	28570.00	28570.00	28570.00
Bit Rate	dBHz	44.56	44.56	44.56	44.56	44.56
FEC Coding Gain	dB	7.60	7.60	7.60	7.60	7.60
EbNo	dB	9.41	8.95	8.53	8.15	7.80
EbNo Threshold for 1e-6 BER	dB	2.88	2.88	2.88	2.88	2.88
Margin data Recovery	**dB**	**6.53**	**6.07**	**5.65**	**5.27**	**4.92**

Figure 2-8 Link Budget for Multiple CDMA Links to Mars

Link Budget		Single CDMA TC/TM	2 x CDMA TC/TM	3 x CDMA TC/TM	4 x CDMA TC/TM	5 X CDMA TC/TM
Uplink						
Link Parameters	Unit					
GS Tx Power	kW	5.00	2.50	1.60	1.00	0.80
GS EIRP	dBW	102.09	99.08	97.14	95.10	94.13
Signal Frequency	MHz	7167.00	7167.00	7167.00	7167.00	7167.00
Range	Km	370000000	370000000	370000000	370000000	370000000
Free Space Loss	dB	280.92	280.92	280.92	280.92	280.92
Uplink S/No	dB/Hz	58.58	55.57	53.63	51.59	50.62
Code Acquisition & Recovery						
C/No Code Acquisition Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00
Margin on Code Acquisistion	**dB**	**21.58**	**18.08**	**16.01**	**14.00**	**13.00**
Data Recovery						
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20
Uplink HPA Distortion	dB	0.50	0.50	0.50	0.50	0.50
Multicarrier IM Distortion	dB	0.00	0.07	0.10	0.20	0.30
Number CDMA Channels		1.00	2.00	3.00	4.00	5.00
C/I Loss due to CDMA	dB	0.00	0.49	0.62	0.58	0.62
Demodultor Tech Loss	dB	1.00	1.00	1.00	1.00	1.00
Bit Rate	Hz	4000.00	4000.00	4000.00	4000.00	4000.00
Bit Rate	dBHz	36.02	36.02	36.02	36.02	36.02
FEC Coding Gain	dB	0.00	0.00	0.00	5.40	5.40
EbNo	dB	20.86	17.29	15.19	13.08	11.98
EbNo Threshold for 1e-5 BER	dB	9.60	9.60	9.60	5.10	5.10
Margin data Recovery	dB	11.26	7.69	5.59	7.98	6.88
Downlink						
Link Parameters	Unit					
S/C EIRP	dBW	58.27	58.27	58.27	58.27	58.27
Signal Frequency	MHz	8420.00	8420.00	8420.00	8420.00	8420.00
Range	Km	370000000	370000000	370000000	370000000	370000000
Downlink S/No	dB/Hz	55.27	55.27	55.27	55.27	55.27
Code Acquistsion & Recovery						
C/No Code Acquiistion Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00
Margin on Code Acquisistion	**dB**	**18.27**	**17.81**	**17.39**	**17.01**	**16.66**
Data Recovery						
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20
S/C Modulator Distortion	dB	0.10	0.10	0.10	0.10	0.10
Transponder SSPA Distortion	dB	0.50	0.50	0.50	0.50	0.50
Number CDMA Channels		1.00	2.00	3.00	4.00	5.00
C/I Loss due to CDMA TM	dB	0.00	0.46	0.88	1.26	1.61
Demodultor Tech Loss	dB	0.50	0.50	0.50	0.50	0.50
Bit Rate	Hz	28570.00	28570.00	28570.00	28570.00	28570.00
Bit Rate	dBHz	44.56	44.56	44.56	44.56	44.56
FEC Coding Gain	dB	7.60	7.60	7.60	7.60	7.60
EbNo	dB	9.41	8.95	8.53	8.15	7.80
EbNo Threshold for 1e-6 BER	dB	2.88	2.88	2.88	2.88	2.88
Margin data Recovery	dB	6.53	6.07	5.65	5.27	4.92

Figure 2-9 Multiple CDMA Links to Mars

Link Budget		Single CDMA TC/TM	2 x CDMA TC/TM	3 x CDMA TC/TM	4 x CDMA TC/TM	5 X CDMA TC/TM	Comments
Uplink							
Link Parameters	Unit						
GS Tx Power	kW	5.00	2.50	1.60	1.00	0.80	
RF Circuit Losses	dB	1.10	1.10	1.10	1.10	1.10	
GS Antenna Gain (Tx)	dBi	66.20	66.20	66.20	66.20	66.20	
GS EIRP	dBW	102.09	99.08	97.14	95.10	94.13	
Signal Frequency	MHz	7167.00	7167.00	7167.00	7167.00	7167.00	
Range	Km	370000000	370000000	370000000	370000000	370000000	Mars Max Range
Free Space Loss	dB	280.92	280.92	280.92	280.92	280.92	
Atmospheric Loss	dB	0.24	0.24	0.24	0.24	0.24	
Polarisation Loss	dB	0.01	0.01	0.01	0.01	0.01	
Pointing Loss	dB	0.20	0.20	0.20	0.20	0.20	
Flux Density at Satellite	dBW/m^2	-140.27	-143.28	-145.21	-147.26	-148.23	
Spacecraft G/T	dB/K	9.26	9.26	9.26	9.26	9.26	
Boltzman's Constant	dBW/HzK	-228.60	-228.60	-228.60	-228.60	-228.60	
Uplink S/No	dB/Hz	58.58	55.57	53.63	51.59	50.62	
Code Acquisition & Recovery							
C/No Code Acquisition Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00	
Margin on Code Acquisistion	**dB**	**21.58**	**18.08**	**16.01**	**14.00**	**13.00**	
Data Recovery							
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00	
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20	
Uplink HPA Distortion	dB	0.50	0.50	0.50	0.50	0.50	Simulation Results
Multicarrier IM Distortion	dB	0.00	0.07	0.10	0.20	0.30	
Number CDMA Channels		1.00	2.00	3.00	4.00	5.00	Parameter m in Equation [1]
C/I Loss due to CDMA	dB	0.00	0.49	0.62	0.58	0.62	Equation [1]
Demodultor Tech Loss	dB	1.00	1.00	1.00	1.00	1.00	
Bit Rate	Hz	4000.00	4000.00	4000.00	2000.00	2000.00	Max TC rate MSPA req. LINK-3
Bit Rate	dBHz	36.02	36.02	36.02	33.01	33.01	
FEC Coding Gain	dB	0.00	0.00	0.00	0.00	0.00	
EbNo	dB	20.86	17.29	15.19	16.09	14.99	
EbNo Threshold for 1e-5 BER	dB	9.60	9.60	9.60	9.60	9.60	
Margin data Recovery	**dB**	**11.26**	**7.69**	**5.59**	**6.49**	**5.39**	
Downlink							
Link Parameters	Unit						
S/C EIRP	dBW	58.27	58.27	58.27	58.27	58.27	
Signal Frequency	MHz	8420.00	8420.00	8420.00	8420.00	8420.00	
Range	Km	370000000	370000000	370000000	370000000	370000000	
Free Space Loss	dB	282.32	282.32	282.32	282.32	282.32	
Atmospheric Loss	dB	0.24	0.24	0.24	0.24	0.24	
Polarisation Loss	dB	0.01	0.01	0.01	0.01	0.01	
Pointing Loss	dB	0.00	0.00	0.00	0.00	0.00	
Receive Flux Density	dBW/m^2	-184.34	-184.34	-184.34	-184.34	-184.34	
Ground Station G/T	dB/K	50.97	50.97	50.97	50.97	50.97	
Boltzman's Constant	dBW/HzK	-228.60	-228.60	-228.60	-228.60	-228.60	
Downlink S/No	dB/Hz	55.27	55.27	55.27	55.27	55.27	
Code Acquistsion & Recovery							
C/No Code Acquiistion Threshold	dB/Hz	37.00	37.00	37.00	37.00	37.00	
Margin on Code Acquisistion	**dB**	**18.27**	**17.81**	**17.39**	**17.01**	**16.66**	
Data Recovery							
CDMA chip rate	cps	3000000.00	3000000.00	3000000.00	3000000.00	3000000.00	
Data Modulation loss	dB	0.20	0.20	0.20	0.20	0.20	
S/C Modulator Distortion	dB	0.10	0.10	0.10	0.10	0.10	
Transponder SSPA Distortion	dB	0.50	0.50	0.50	0.50	0.50	Simulation Results
Number CDMA Channels		1.00	2.00	3.00	4.00	5.00	Parameter m in Equation [1]
C/I Loss due to CDMA TM	dB	0.00	0.46	0.88	1.26	1.61	Equation [1]
Demodultor Tech Loss	dB	0.50	0.50	0.50	0.50	0.50	
Bit Rate	Hz	28570.00	28570.00	28570.00	28570.00	28570.00	
Bit Rate	dBHz	44.56	44.56	44.56	44.56	44.56	
FEC Coding Gain	dB	7.60	7.60	7.60	7.60	7.60	
EbNo	dB	9.41	8.95	8.53	8.15	7.80	
EbNo Threshold for 1e-6 BER	dB	2.88	2.88	2.88	2.88	2.88	
Margin data Recovery	**dB**	**6.53**	**6.07**	**5.65**	**5.27**	**4.92**	

Figure 2-10 Multiple CDMA Links to Mars

3. CONCLUSIONS & RECOMMENDATIONS

3.1 Summary for the Short Term Solution

The method proposed and analysed in this study for the short term solution will allow TT&C operations with at least two spacecraft simultaneously. The use of amplitude switching on the uplink side allows CFDMA to be used which is the most flexible multiplex method for Deep Space operations using current transponders. A key advantage is that all spacecraft can be operated simultaneously in fully coherent mode. The other main advantage is that the RF subsystems of the DSA Ground Stations do not require substantial modification. Intermodulation products will be generated in the HPA but these will be at relatively low levels.

The end-to-end link performance has been analysed and shown to be feasible with positive link margin in excess of 6dB for the TC channel at 2kbps for a Mars mission at max range. The second spacecraft with low level carrier, will have at the same time over 2dB margin in the carrier tracking loop, which could be improved by selection of the NARROW loop bandwidth on the transponder.

The main uncertainty identified concerns the residual level of intermodulation products. This is because a precise model of the ESA 20kW Klystron HPA including both AM/AM and AM/PM characteristics, is not currently available. If this information was available it would be possible to say whether linearization techniques would be required or not to bring the residual intermodulation levels within spurious emission limits. However, the investigation conducted has identified that linearization techniques are available and can be implemented if required.

3.2 Summary for Long Term Solution

It has been shown that the proposed long term solution for MSPA based on DSSS CDMA techniques will allow at least five multiple TT&C operations simultaneously from one ground station. Using frequency overlay of the DSSS multiple uplink signals is advantageous as it will avoid intermodulation products from the multiple signals interfering with adjacent frequency bands. However, there will be mutual interference due to the signal overlay and due to non-linear distortion, but these are allowed for in the link budgets. Nevertheless, linearizer techniques can be used to reduce spectral spreading and multi-user interference.

The code acquisition threshold at the spacecraft for a Mars mission at maximum range has been analysed and shown to be well within the margin which can be obtained by the link budgets. The code acquisition margin is in excess of 10dB for all the cases examined and the TC recovery margin is above 5dB. However, the TC data rate must be reduced as the number of simultaneous users increases as the total uplink power must be shared between users. However, if FEC is used on the TC uplink service then a TC data rate of 4kbps can be supported for up to 5 simultaneous Users.

3.3 Technology Development

The study has identified solutions which can be implemented, by and large, using readily available technologies and solutions, even for the long term scenario. The DSSS CDMA method proposed for the long term scenario is based on the already established TDRSS/Galileo CDMA implementation, for which both ground and spacecraft modems have been developed. Furthermore, as dual standard transponder has already been developed for Galileo which implements both classical PCM/BPSK/PM modulation as well as DSSS CDMA modulation, this solution would be attractive for Deep Space operations as it would allow a fall back to classic remnant carrier operations for emergency modes.

The principle new technology development which has been indentified in the study is that of linearizers. Although linearizers are not essential for the end to end performance in both short and long term scenarios, they might be necessary to avoid interference on adjacent parts of the spectrum. The study has investigated linearizer techniques and proposed that the best method for implementation would be the digital baseband pre-distortion technique. If required, this technology would be best introduced into the new TTC processor in the ground station for controlling intermodulation products and/or spectral spreading generated by the ground station HPA.

3.4 Technology Roadmap

The following figure represents the key activities for implementation of linearizer technology in the ESA Deep Space Ground stations.

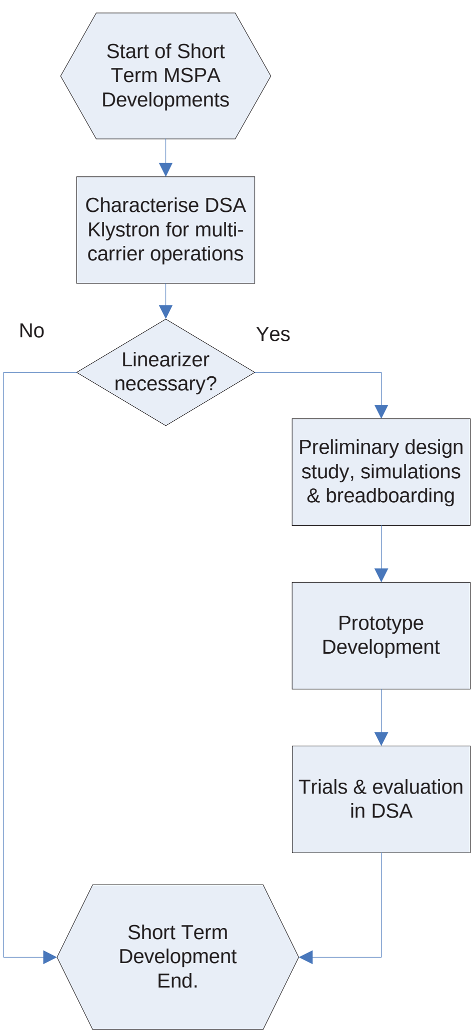


Figure 3-1 Technology Roadmap for Short Term MSPA

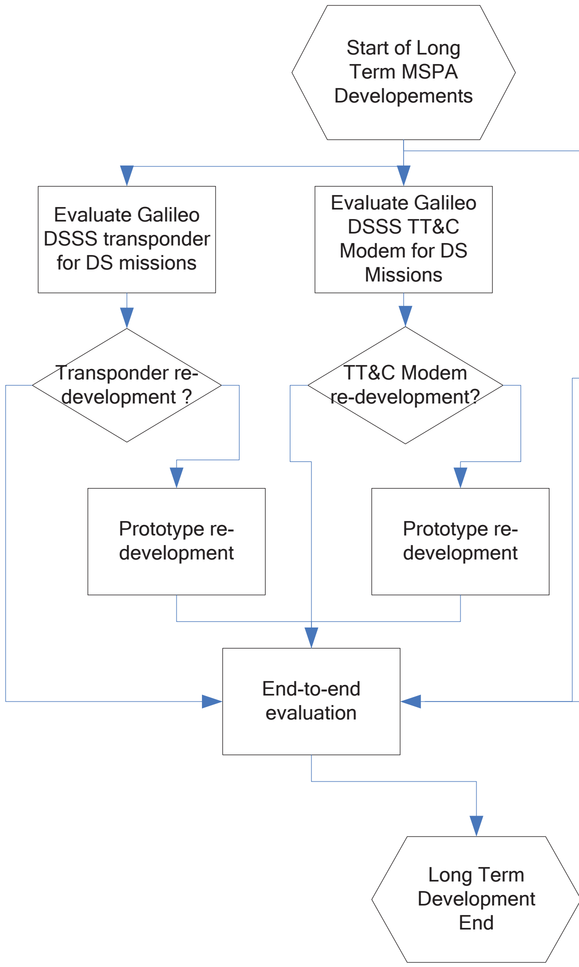


Figure 3-2 Technology Roadmap for Long Term MSPA

3.5 List of Abbreviations

Acronym	Meaning
AD	Applicable Document
ADC	Analogue to Digital Convertor
AM	Amplitude Modulation
ASIC	Application Specific Integrated Circuit
ATFR	Adjustable Turnaround Frequency Ratio
AZ	Azimuth
BER	Bit Error Rate
Bps	Bits per second
BPSK	Binary Phase Shift Keying
BW	Bandwidth
CCSDS	Consultative Committee for Space Data System
CCSDSPT	CCSDS Packet Telecommand
CDMA	Code Division Multiple Access
CDM	Code Division Multiplex
CFDMA	Carrier Frequency Division Multiple Access
CIC	Cascaded Integrated Comb
COTS	Commercial Off The Shelf
CSD	Canonic Signed Digit
CW	Continuous Wave
DAC	Digital to Analogue Convertor
DC	Direct Current
DFT	Discrete Fourier Transform
DDM	Digital Demodulator Module
DMA	Direct Memory Access
DSP	Digital Signal Processing
DSSS	Direct Sequence Spread Spectrum
ESOC	European Space Operations Centre
FPGA	Field Programmable Gate Array
FEC	Forward Error Correction
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
GMSK	Gaussian Minimum Shift Keying
GS	Ground Station
HMI	Human Machine Interface
HPA	High Power Amplifier
ISI	Inter Symbol Interference
IF	Intermediate Frequency
ID	Indentifier
JPL	Jet Propulsion Laboratory
k	Boltzman's Constant
K	Kelvin
Kbps	Kilo bps
Kcps	Kilo cps

LAN	Local Area Network
LHCP	Left Hand Circular Polarisation
LNA	Low Noise Amplifier
LFSR	Linear Feedback Shift Register
LO	Local Oscillator
LUT	Look Up Table
MC	Mode Command
ML	Maximum Length
MS	Most Significant
MSB	Most Significant Bit
MAI	Multiple Access Interference
MSPA	Multiple Satellite per Aperture
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
NCO	Numerically Controlled Oscillator
NF	Noise Figure
OCXO	Oven Controlled crystal Oscillator
OQPSK	Offset Quadrature Phase Shift Keying (=SQPSK)
PM	Phase Modulation
PLL	Phase Locked Loop
PSD	Power Spectral Density
PTS	Payload Test System
QPDC	Quad Programmable Digital Downconverter
QPSK	Quadrature Phase Shift Keying
QoS	Quality of Service
RF	Radio Frequency
RHCP	Right Hand Circular Polarisation
RTC	Real Time Clock
S/C	Spacecraft
SCC	Satellite Control Centre
SFDMA	Subcarrier Frequency Division Multiple Access
SLE	Space Link Extension
SoW	Statement of Work
SQPSK	Staggered Quadrature Phase Shift Keying (=OQPSK)
SSPA	Single Satellite per Aperature
SS	Spread Spectrum
SPS	Symbols per second
SRRC	Square Root Raised Cosine
SQPSK	Staggered QPSK (same as OQPSK)
STC	Station Computer (Monitor & Control applications)
STDM	Spacecraft Tracking Data Message
TBC	To Be Confirmed
TBD	To Be Defined
VHDL	VHSIC Hardware Description Language
VHSIC	Very High Speed Integrated Circuit
WP	Work Package

3.6 ANNEX - MSPA Requirements

Ref.	Requirement	Short Term	Long Term	Notes
LINK-1	The system shall provide simultaneous and independent support for the different missions and can provide all the following services for each Spacecraft as requested: Telemetry downloading Command transmission Two-way Doppler Tracking Ranging (TBC). Some links may not require all the services. The system shall be able to provide also only part of these services.	X	X	One way Doppler accuracy is limited by on board clocks and is already feasible with the present stations (no need to consider this in the scope of this study).
LINK-1-s	The system shall provide full TT&C and Ranging for one primary mission and basic TT&C with one-way Doppler tracking for and secondary missions, simultaneously.	X		
LINK-1-l	The system shall provide full TT&C and coherent ranging for at least two primary missions simultaneously.		X	
LINK-2	The system shall be able to support simultaneously spacecraft of different characteristics (example: orbiters with high gain antennas and high G/T, together with landers/rovers/probes with low gain antennas and low G/T).		x	
LINK-3	The system shall be able to support simultaneously spacecraft at different data rates: TC data rates in the range 7.8125 – 4000 bps (TBC) TM Data Rates in the range 100 bps- 1 Mbps (TBC)	x	x	TM max data rate is also constrained by Earth/Mars distance.
LINK-4	The system shall avoid limiting all the links to the performances of the least performing spacecraft.	X	X	
LINK-5	The system shall be able to support different Doppler profiles on each one of the links. This shall be implemented by a combination of Doppler compensation (pre-steering) at the ground station, Doppler tracking on the transponder and Doppler tracking on the ground station (for TM). For Mars missions at X-Band this shall allow up to ±300KHz with ± 900 KHz pre-steering. For other planetary pairs see RD24.	X	x	
LINK-6	The system shall be able to support independent access to each one of the links. This requirement is linked to OPS -3.	X		
LINK-7	The system shall allow for TC acquisition by the spacecraft with the possibility of re-acquisition during the pass by one spacecraft independently of the other.	X	x	
LINK-8-s	The MSPA shall be implemented with limited modifications to the existing Ground Segment and with	X		35m DSA assumed for MSPA

	no modifications to the standard X/X-band Deep Space transponder.			
LINK-8-l	The MSPA shall be implemented by modifications to the Ground Segment and the spacecraft communications sub-system which do not compromise overall Deep Space communications performance for classic single mission per aperture support (SSPA).		X	Changes to 35m DSA to be considered if justified by cost compared to the provision of a second antenna.
LINK-9	The degradation in overall communications performance shall be less than 1dB when switching between SSPA and MSPA.	X	x	
LINK-10	The minimum duration of a MSPA session for uplink shall be 40 minutes excluding the s/c acquisition time.	x	x	AI.1 of KO MoM
OPS -1	The system shall be able to support CCSDS compatible spacecraft	x	x	Extension of current CCSDS standards to accommodate MSPA is not ruled out.
OPS -2	The system shall provide the way for real time confirmation (acknowledgement) of any SC commanding, i.e. each uplink of the MSPA shall be combinable with a Downlink of the MSPA at the same time.	x	x	Using normal CCSDS packet TM/TC protocols.
OPS -3	The system shall provide services for the different spacecrafts independently of the operations on spacecrafts using the other links in a transparent way. In particular one spacecraft's link shall not be degraded by the acquisition procedure or the end of link of another spacecraft.	x	X	
OPS -4	The maximum number of simultaneous missions shall be optimised. A realistic scenario would limit the maximum number of S/C to not more than 5 (TBC), and optimise the system for 2 or 3 S/C (TBC).	x	x	
OPS-4-s	The system shall support at least 2 simultaneous missions with full operational availability and one additional "piggy-back" mission on a "best endeavours" basis.	x		
OPS-4-l	The system shall support at least 3 simultaneous missions with full operational availability and two additional "piggy-back" mission on a "best endeavours" basis.		x	
OPS -5	The system shall be transparent to the operations user. There shall be no need of verification of compatibility for each pass. In case there is need of a verification of compatibility, this verification shall be performed only once per combination of missions and shall fix the valid combinations of parameters (power level, modulations, data rates) and the non valid.	x	x	
OPS-6	It shall be possible to define support priority for each individual mission in an MSPA Operations session (pass). (High priority or low priority)	x	x	

Table 3-1 MSPA Requirements