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A TRADE-OFF ANALYSIS BETWEEN S AND KU BAND TCR SUBSYSTEMS IN COMMERCIAL SATELLITES

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Abstract

Telemetry, Command and Ranging (TCR) subsystem has a vital role in commercial satellite operations independent of satellite payload such as broadcasting, optical, navigation and remote sensing. This subsystem securely establishes the communication link between ground station and satellite. TCR link has to be operational and healthy during all satellite lifetime and phases. In order to efficiently design TCR subsystem, some trade-offs must be applied to finalize the subsystem architecture. A critical decision point appears with the subsystem frequency band selection. S-band and Ku-band systems behave distinctly according to satellite mission. Commercial satellites can be classified into communication, imaging, weather, remote sensing and navigation. Commercial communication satellites cover the 40% of the overall market where satellite manufacturers aim to reduce design, integration and test cost by applying appropriate trade-offs before finalizing design phase. In this study, trade-off analysis between S and Ku-band TCR subsystem is investigated in terms of applied communication link margins and integration of the subsystem with satellite payload. The trade-off analysis show that Ku-band provides 3.87dB margin for telecommand (TC) and 24.92dB margin for telemetry (TM) links. S-band offers 45.74dB margin for TC and 30.42dB margin for TM links.

Keywords: Commercial satellites, TCR, Link budget margin, Modulation index

TİCARİ UYDULARDA S VE KU BANT TKM ALTSİSTEMİ ÖDÜNLEŞİM ANALİZLERİ

Özet

TKM (Telemetri, Komut ve Mesafelendirme) alt sistemi TV yayıncılığı, gözlem, konumlandırma, uzaktan algılama gibi farklı faydalı yükler taşıyan ticari uydularda önemli bir rol oynamaktadır. Yer istasyonu ile uydu arasındaki haberleşme linkinin güvenli şekilde kurulabilmesi bu alt sistem üzerinden sağlanmaktadır. Bu haberleşme linki uydunun tüm yaşam ömrü ve farklı fazları boyunca sağlıklı bir şekilde çalışabilir olması gerekmektedir. TKM alt sisteminin verimli şekilde tasarlanıp mimarisinin dondurulabilmesi için bazı ödünleşim analizleri uygulanmaktadır. Alt sistemin çalışma frekansının seçimi kritik bir tasarım noktası olarak karşımıza çıkmaktadır; çünkü S-bant ve Ku-bant sistemler uydunun görevine göre birbirinden çok farklı özellikler göstermektedirler. Ticari uydular, haberleşme, gözlem, meteoroloji, uzaktan algılama ve konumlama uyduları olarak farklı gruplara ayrılabilirler. Ticari haberleşme uyduları uydu pazarının yaklaşık %40'ını kaplarken, uydu üreticileri de tasarım fazının bitirilmesi öncesinde tasarım, bütünleştirme ve test maliyetlerini düşürecek ödünleşimlerin yapılmasını hedeflemektedirler. Bu çalışmada, S ve Ku-bant TKM alt sistemlerinin haberleşme link payları ve alt sistemin uydu faydalı yüküyle entegrasyonu açısından ödünleşim analizleri incelenmiştir. Ödünleşim analizlerinde Ku-bant sistemlerin telekomut için 3,87dB, telemetri için 24,92dB marj sağladığı, diğer tarafta S-bant sistemlerde sırasıyla aynı haberleşme linkleri için 45,74dB ve 30,42dB marj elde edildiği görülmüştür.

Anahtar Kelimeler: Ticari uydular, TKM, Link bütçe payları, modülasyon indeksi

1 Introduction

Satellite design activities can be grouped into three major phases of design, integration and test as analogous to many other electronic equipment or system. However increased level of complexity and need of interdisciplinary work make satellite manufacturing more challenging. Design phase nestles additional concentration, since any error occurred in this phase directly impedes the succeeding integration and test phases. Design phase is evaluated via two milestones, preliminary design review (PDR) and critical design review (CDR). After CDR, satellite architecture is expected to be almost frozen. Equipment selection is completed by applying essential analysis and trade-offs for each subsystem and procurement begins in this phase.

On-board satellite systems have limitations on power, mass and sizing parameters compared to other platforms since space electronics is exceptionally costly and on-orbit maintenance is nearly impossible. These constraints lead the spacecraft engineers to design low power and mass equipment with high reliability and heritage. Therewith subsystem reliability has to be computed for the satellite overall lifetime through designated equipment and architecture to ensure meeting design requirements. Desired reliability is obtained using redundant transmitting and receiving units which are connected with multiple antennas having high gain and broad radiation patterns.

TCR subsystem accomplishes the control and monitoring functions of the satellite by receiving ground station control signals to initiate periodic and aperiodic maneuvers and to modify equipment states. Measurements and health status of the other subsystem and equipment are transmitted to ground station through TCR chain. Ranging is also applied to determine satellite to ground station distance and orbital parameters [1-3].

In a commercial communication satellite, TCR subsystem utilizes low bit rate links since it carries executable commands and health status of the overall satellite. However optical payloads such as earth observation missions require a few tens of megabits per second data links to transfer acquired imagery of the intended regions. In both instances, links must be secure and available to perform necessary diagnostics in case of any on-board failure. Improvements on the commercial satellite TCR subsystem can be achieved using new coding options [4], reliability based architectural iterations [5, 6] and ground control systems [7].

In this study, a TCR subsystem trade-off between S and Ku bands is proposed independent of satellite mission where this trade-off gives the advantage to be applicable in commercial satellites such as communication, observation, navigation and weather. Besides the trade-off methodology can be adapted to any communication module including transmitting and receiving units considering link budget margin aspects.

2 Trade-off Methodology

System trade-offs are essential to all digital and analog communication designs. System designer aims to

- Maximize transmission bit rate,
- Minimize probability of bit error,
- Minimize required power,
- Minimize required system bandwidth,
- Maximize system utilization by providing reliable service for maximum number of users with minimum delay and with maximum resistance to interference,
- Minimize system complexity, computational load and overall production cost [8].

Since maximizing transmission bit rate and minimizing probability of bit error require more system power and bandwidth, all these design considerations can’t be achieved simultaneously due to theoretical limitations and available equipment specifications.

In commercial satellites, subsystem design is strictly dependent on the architectural trade-off analysis results. Since manufacturers are intended to meet user requirements with minimum engineering cost. Well defined trade-offs dramatically drop this cost as the subsystem functionality is proved before integration and test phases. Subsystem performance parameters must be defined prudently in order to evaluate the trade-off results. Main consideration points of the architectural trade-off analysis can be summarized as;

- TCR frequency selection
- Link budget margins
- Mass
- System complexity
- Power consumption and dissipation
- Equipment specifications
- Compatibility analysis
- Reliability
- Ground system heritage

Observation, navigation and weather type commercial satellites provide flexibility on TCR subsystem selection since these payloads are transmitting units and do not communicate with the ground users by themselves.

Once the trade-off is applied to a communication satellite, payload compatibility becomes the most important performance consideration. Because selected TCR frequencies alter the system complexity, mass, link budget margins and payload interference. For instance, a TV broadcasting satellite includes Ku-band payload equipment. Once the TCR frequency is selected in Ku-band, payload and TCR subsystem can same transponders where significant communication margin, mass and cost reduction can be achieved. On the contrary, any failure on the shared payload equipment paralyzes TCR functionality and can cause loss of the satellite. This can be avoided by introducing a switching mechanism and redundant units. Nonetheless this causes increased system complexity. Also TCR frequencies can cause interference on payload units unless separation filters work properly. All these scenarios entail applying trade-offs in detail beforehand the architecture is concretized.

One of the most important analysis for frequency band selection is the compatibility calculations of TCR frequencies. Compatibility can be analyzed for three main cases.

- TCR subsystem auto compatibility RF analysis
- Compatibility with payload
- Compatibility with adjacent and co-located satellites.

Before TCR frequencies are exactly determined, compatibility analysis must be applied to prove that there will be minimum interference due to selected frequencies. Spurious, noise, EIRP, VCO harmonics etc. can cause interference on TCR subsystem, payload and nearby satellites. For instance in a Ku-band TV broadcasting satellite, selecting Ku-band TCR improves the compatibility calculation load, however S-band TCR simplifies the overall interference load.

Another concern on TM/TC frequency selection is the available ground station characteristics. Satellite lifetime can be divided into three phases; LEOP phase, on-station phase and emergency phase. LEOP phase includes the satellite maneuvers for placing it to its on-station orbit. In on-station, satellite performs its full operational activities. In the emergency phase where anomalies occur, satellite strives to keep itself in a safe mode by executable commands. Ground stations must track the satellite in all phases accurately, otherwise serious problems causing even mission lost can appear. Intelsat C-Band network, Telesat Ku-Band network, ESA/NASA/NASDA S-Band networks can be used according to satellites TCR frequencies during LEOP and emergency phases. Widely used LEOP networks have advantages on satellite tracking reliability and accuracy. In the emergency situation, operators can use many ground stations all around the world and this will increase the reliability and accuracy of satellite tracking. The trade-off flow diagram is illustrated in Fig. 1.

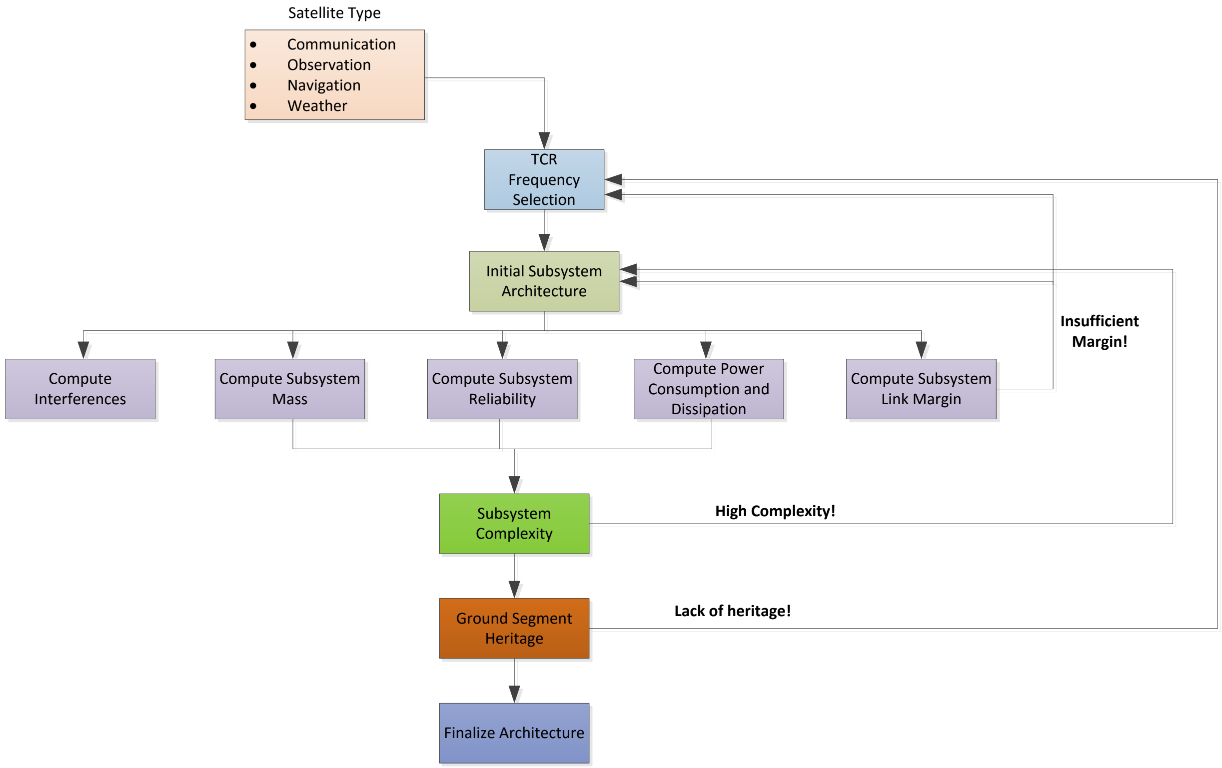

Figure 1. Subsystem trade-off flow diagram.

3 TCR Subsystem Architecture

TCR subsystem comprises telecommand receivers, telemetry transmitters, receive and transmit antennas, number of switches, waveguides and coaxial cables for connections and amplification chains (CAMP, EPC and TWTA) to amplify telemetry signal during emergency and LEOP phases. All these equipment specifications are depended on the selected TCR frequencies. Preferred TCR band will alter the mass of the subsystem even if the same number of equipment is allocated. Consequently, increment on the system mass will raise production cost and system complexity. Main TCR subsystem equipment are receivers and transmitters which can be chosen operational in dual or single frequency. State-of-the-art designs in equipment manufacturing lead them to merge in single units as TCR transponders available in various frequency bands. Equipment specifications given in Table 1 are utilized to adjust system power level, mass and power consumption.

Table 1. TCR Transponder comparison

Equipment Parameter	S-Band	Ku-Band
Rx Carrier Acquisition Threshold (dBm)	-128	-142
Rx Power Consumption (W)	5	7
Tx Power Consumption (W)	25	44
RF Output Power (dBm)	37	28
Mass (kg)	2.6	4

Other equipment like antennas and TWTAs can be selected as integrated with payload equipment in communication satellite where on-station antennas can be chosen as communication antennas integrated with payload or separated TM/TC antennas dedicated to TCR subsystem. If the same frequency band is allocated to TCR and payload (Ex: Ku-Band or S-Band), communication antennas can be used instead of a separated TC antenna.

However in a separated TCR subsystem an additional antenna for TM and TC must be included to design. On the other hand, for LEOP and emergency cases, omni antennas are assigned to cover maximum earth surface. These omni antennas have to be separated than payload modules and dedicated for TCR communication. They are attached to +Z /–Z axis of the satellite. For providing best visibility performances, +Z omni antenna boresight is tilted by 45^0 in the plane +Z/-X, while –Z omni antenna boresight is tilted by 45^0 in the plane –Z/+X.

Omni antennas have relatively small gains compared to on-station telemetry and telecommand antennas. Accomplishing the required EIRP value to accurately communicate with ground station is possible when TWTAs are applied to TM transmitter output. These TWTAs can be shared with payload structure or TCR subsystem shall have dedicated TWTAs in accordance with its frequency band. TWTA amplification is necessary for LEOP and emergency phases where omni antenna gain is low compared to nominal satellite antennas. Fig 2. depicts the subsystem architecture for an S-band TCR subsystem.

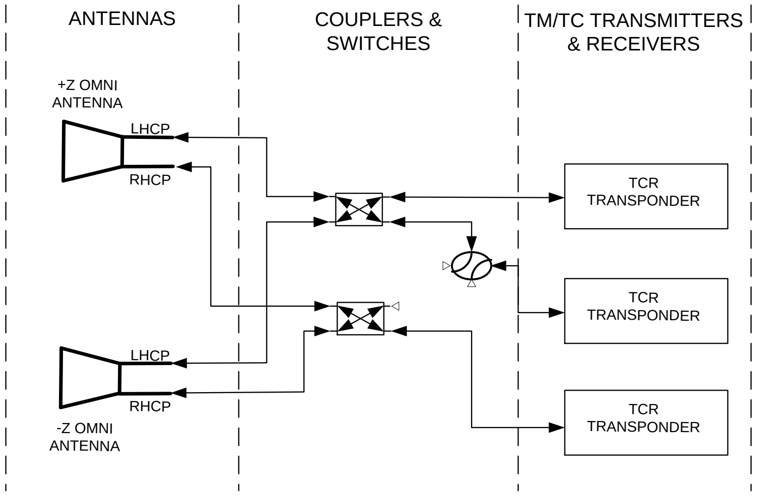

Figure 2. S-band TCR subsystem architecture.

4 Link Budget Calculation

Link budget calculations in TCR subsystem include many parameters such as operating frequency, satellite to ground station distance, ground and satellite antenna directivities, antenna noise temperature and secure link budgets. In this case, S and Ku-band trade-off has direct impact on each of the mentioned parameters. Since TC and TM carrier frequencies widely alter in S-band (2-4 GHz) and Ku-band (12-18 GHz).

In satellite operations, ground station employs reflector antennas which provide high directivity and narrower beams avoiding adjacent orbit interference. Antenna directivity for a given aperture dimension and operating frequency can be calculated using Equation (1).

$$Directivity = 10 \times log_{10}\left(\frac{\pi D}{\lambda}\right)^2 \qquad (1)$$

Where D is the antenna aperture diameter and λ is the carrier wavelength. Another vital parameter dependent on the carrier frequency is the free space loss (FLS) given in Equation (2).

$$FSL = 10 \times log_{10}\left(\frac{4\pi d}{\lambda}\right)^2 \qquad (2)$$

Where d is the satellite to ground station distance. Once the antenna diameter is assumed to be 1.8m, and satellite to ground station distance is taken as 40,000km, antenna directivity and FSL variation over communication frequency ranges can be observed in Fig. 3.

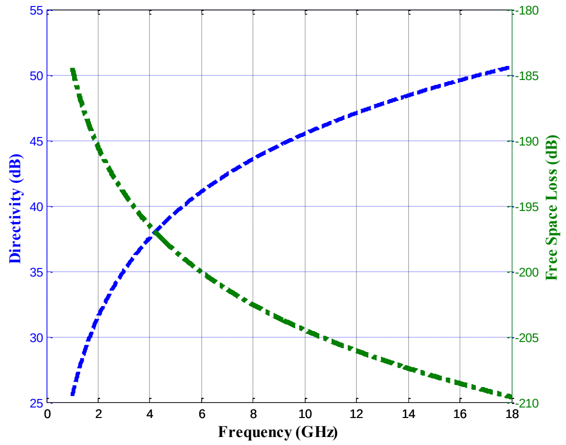

Figure 3. Antenna directivity and FSL variation over frequency ranges.

FSL is computed around -206dB and -193dB in Ku-band and S-band respectively. Furthermore, antenna directivity is around 46 dB and 34 dB in the same bands correspondingly. When the lower equipment losses are taken in the account for S-band, total of 3 dB power difference occurs between signal levels in Ku and S-band systems. This 3dB margin manages the design engineer to occupy half the power used in Ku-band for S-band applications.

The critical point on the communication link budget design is the margins on TM and TC links. In a Ku-band subsystem at 14.5 GHz with the ground station EIRP (Equivalent Isotropic Radiated Power) of 61 dBW, TC link parameters are given Table 2. Power flux density (PFD) at spacecraft is computed using FSL, ground station specifications and atmospheric attenuation in Ku-band. Then the spacecraft equipment specifications and losses are inserted to compute total received power at receiver (Rx) input. Finally carrier to noise ratio (C/N₀) at Rx input is calculated using Rx noise temperature and secure TC link margin is calculated as 3.87dB which means an unexpected 3.87dB loss through our TC chain can be compensated by the system.

Table 2. Ku-band TC link parameters.

TC Link Parameter	Value	Unit
PFD at Spacecraft	-103.59	dBW/m^2
Power at Rx Input	-107.59	dBm
Rx Noise Temperature	608.03	K
C/N$_0$ at Rx Input	63.17	dBHz
TC Margin	3.87	dB

Power flux density (PFD) at spacecraft is computed using FSL, ground station specifications and atmospheric attenuation in Ku-band. Then the spacecraft equipment specifications and losses are inserted to compute total received power at receiver (Rx) input. Finally carrier to noise ratio (C/N₀) at Rx input is calculated using Rx noise temperature and secure TC link margin is calculated as 3.87dB which means an unexpected 3.87dB loss through our TC chain can be compensated by the system.

The system link and mass budget calculations are done using Microsoft Excel environment which is a common and simple tool for satellite design applications. Since MS Excel provides a flexible modeling environment with VBA. This yields design engineer to store equipment specifications and compute necessary budgets with high visualizations.

In order to achieve a secure link from spacecraft to ground station, an additional margin must be computed for TM links. Assuming a -3dBW output power unit is utilized as a transmitter, the computed TM link parameters for Ku-band (11.696 GHz) applications is presented in Table 3.

Table 3. Ku-band TM link parameters.

TM Link Parameter	Value	Unit
TM EIRP	12.85	dBW
PFD at Ground Station	-151.34	dBW/m^2
Received C/N$_0$	66.45	dBHz
TM Margin	24.92	dB

As shown in Table 3, spacecraft to ground station links (downlink TM) provide higher margins compared to ground station to spacecraft links (uplink TC). High gain spacecraft antennas and low FSL due to lower downlink frequencies can be stated as the foremost explanations for this improved link margin.

On the contrary, in an S-band TCR subsystem with TC and TM frequencies of 2.12 and 2.3 GHz respectively, uplink and downlink communication chain parameters are recomputed and given in Table 4 and Table 5.

Table 4. S-band TC link parameters.

TC Link Parameter	Value	Unit
PFD at Spacecraft	-90.69	dBW/m^2
Power at Rx Input	-91.60	dBm
Rx Noise Temperature	946.46	K
C/N$_0$ at Rx Input	77.24	dBHz
TC Margin	45.74	dB

Table 5. S-band TM link parameters.

TM Link Parameter	Value	Unit
TM EIRP	5.99	dBW
PFD at Ground Station	-158.7	dBW/m^2
Received C/N$_0$	70.22	dBHz
TM Margin	30.42	dB

The TC and TM margins in S-band are computed using Thales Alenia Space and GOLIAT nanosatellite equipment specifications [9-10].

The TM recovery margins calculated in Table 3 and Table 5 depend on the selected TM modulation index as given in Equation (3).

$$Modulation\ Loss = 10 \times log_{10}(Besselj(MI)^2) \qquad (3)$$

Where MI represents the modulation index used TM recovery process. As the modulation index increases overall modulation losses increase and TM link margins decrease. On the other hand, once the modulation index is selected to low, the modulation does not utilize the carrier efficiently. Thus an optimum modulation index level must be selected to securely modulate carrier, but minimize modulation losses.

5 Conclusion

Space-ground station communication links have to be established in a secure and consistent way. Thus TCR subsystem employs a vital and common role in spacecraft design independent of its mission. The design phases of satellite engineering aim to optimize overall spacecraft size under acceptable link margins and equipment heritage.

In this study, TCR subsystem trade-off is examined in terms of communication link budget parameters of C/N$_0$ and margins for Ku and S-band applications independent of spacecraft mission. It is observed that S-band provides incomparably high margins for both TC and TM links. This leads the advantage of secure and high data bandwidth link for imaging, weather, remote sensing and navigation applications. However communication satellites carrying Ku-band TV broadcasting transponders can utilize integrated TCR and payload equipment to reduce overall design and launch cost.

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