

# TELEMETRY APPLICATIONS FOR A SPACE LAUNCH

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## ABSTRACT

In space launch applications, a telemetry ground station is designed to ensure launch vehicle traceability and so the flight safety. In this study, the characterization of telemetry ground stations to be used for a space launch operation is explained with applied studies, flight characteristics of vehicle, and international practices. Present study explains step-by-step development process of a telemetry ground station for a space launch mission. Study is limited on the physical layer. At least two independent position information sources are required to ensure flight safety, so the network between telemetry ground stations and localization systems is needed. As a result, the characteristics of the telemetry ground station are determined to be used for a low earth orbit space launch mission considering mission objective, requirements and constraints.

## INTRODUCTION

Space launch is a flight which carries payloads to the space ranging from 160 km for low earth orbit (LEO) to the deep space. With respect to the objective, size, and capacity of launch vehicle (LV) varies. For every type of LV, it is crucial to ensure flight safety especially for thrusting phases of the flight due to highly explosive feature of the propellant. In order to generate a reliable flight safety structure, tracking system must include a Telemetry which provides flight safety data for pre-launch and during the flight.[1,2] During pre-mission; telemetry is required to support space segment command and control, monitoring spacecraft health, simulating spacecraft attitude. During flight; the spacecraft orbit and mission characteristics are tracked by Telemetry Ground Stations (TGS) for flight safety and mission objective achievement.

In order to maintain a dependable flight plan for space launch, flight requirements must be derived through the TGS's structural parameters, correctively. In the following sections, the correlation between requirements and ground station attributes will be explained.

## METHOD

Flight requirements must be known (range, velocity, antenna model, etc.) to determine the required telemetry characteristics. In this study, only TGS design is discussed regarding objective requirements. In Figure 1, space mission requirements are derived through the TGS parameters.

The LV must be tracked along the trajectory for flight verification and safety. Flight trajectory, flight algorithm and possible tracking station sites must be known before the flight. Therefore, velocity, thrust vector, distance between LV and the tracking sites and angle between moment vector and the heading vector of the ground station would be known. These parameters are important to analyze the link between the target LV and the ground station.

In order to perform pre-mission checkouts and to ensure initial phase telemetry capturing, the first tracking ground station is located around the launch center. Like the Kennedy Space Center, Guiana Space Center and Baikonur Cosmodrome. The initial velocity of the target LV, trajectory and ground station positions are taken into consideration while deriving the requirements of the ground station antenna pedestal degree of freedom and capability.

$$A_w > \frac{V_{\uparrow}}{R_t} \quad (1)$$

As stated in the Equation 1, antenna pedestal angular velocity must be higher than the ratio between tangential velocity of the target and the instant range. It is also important to consider the initial height difference to determine pedestal elevation movement capability.

<b>Symbol</b>	<b>Description</b>
$A_e$	Antenna effective area
$B$	Bandwidth
$D$	Antenna diameter
$f_d$	Doppler Spectrum
$G_T$	Transmitter antenna gain
$G/T$	Receiving system gain over temperature per Kelvin
$\eta$	Antenna efficiency
$k$	Boltzman constant
$\lambda$	Wavelength
$L_{atm}$	Atmospheric losses
$L_C$	Cabling losses
$L_D$	Ducting losses
$L_F$	Flame attenuation
$L_{mpth}$	Multipath losses (Interference)
$L_p$	Path losses
$L_{prc}$	Progressing losses (Windowing)
$L_{sys}$	System losses
$m$	Meter
$Ms$	Millisecond
$N_{figure}$	Noise figure
$P_r$	Receiver power level
$P_t$	Transmitter output power level
$R$	Range between related antenna and the target
$g$	Gravity (9.81m/sn <sup>2</sup> )
$sn$	Second
SNR	Signal to noise ratio
$\theta$	Antenna beam width
$V$	Velocity of Launch Vehicle
$W$	Watt

**Table 1 Nomenclature**

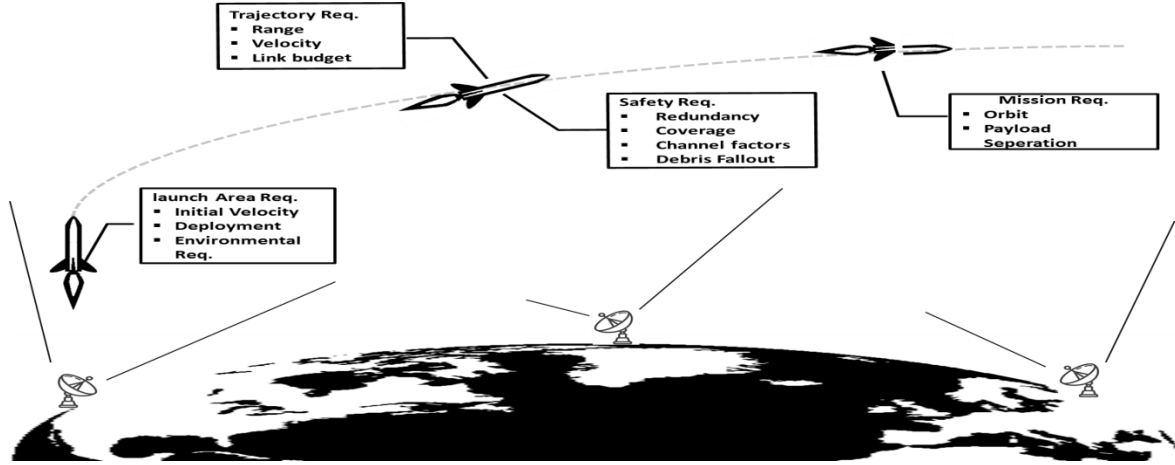


Figure 1 Mission requirements to be considered for TGS design

Meanwhile, another important parameter for short-range tracking is the requirement that the target should remain within the ground station antenna main beam for the time period that the antenna is guided through the target. Antenna beam width is determined as [3]

$$\theta = \frac{70\lambda}{D} \quad (2)$$

for parabolic antennas.

For the ease of auto track, the ratio between the main beam width and the required angular velocity of the TGS should be as wide as possible. Evaluating Equation 1, wider,  $\theta$ , beam width is required for short-range tracking. From Equation 1 and Equation 2 it is seen that if the instant range of TGS to the launch pad,  $R_t$ , is increased pedestal requirements and auto track becomes more feasible. Besides that, locating the first tracking ground station to the  $R_t$  distance in the launch direction will increase the coverage also. However, line of site between TGS and the launch pad need to be provided. Also mechanical properties of the antenna pedestal must meet the angular movement, velocity and jerk requirements occurred depending on the location.

For wider  $\theta$  value,  $D$ , antenna diameter, may be scaled down. Equation 3, shows the power flux reaches the receiver antenna (ground station antenna).

$$P_r = \frac{P_t G_t}{4\pi R^2 L_{att}} A_e \quad (3)$$

$$A_e = \frac{G_r \lambda^2}{4\pi} \quad (4)$$

$$G_r = \eta(\pi D / \lambda)^2 \quad (5)$$

If Equation 4 and Equation 5 are taken into account in Equation 3 it is seen that antenna diameter is proportional with the effective tracking range of the ground station. In order to increase the coverage area of the launch center TGS, antenna diameter is considered as large as possible. It is desired to increase coverage area to decrease required number of tracking station sites, thus minimize logistic support and communication requirements. Hence, from the statement derived above it is observed that the antenna beam width and effective tracking range is inversely

proportional. On the other hand, it is not feasible to scale down the antenna diameter, in order to provide short-range auto tracking. Instead, two possible solutions can be evaluated.

1. Using low gain short range tracking antenna (auto switching between antennas in RF site is desirable)
2. Guidance of ground station from launch/mission control center using the position data generated by localization systems such as radar and optics (radars are more reliable due to visibility conditions, thus desired).

Therefore, mechanical and data link interfaces defined for the TGS must be compatible with the launch/mission control center and/or other localization systems which provide guidance data to the TGS. To provide recent guidance data all TGS, control center and localization systems must be synchronized in time.

Up to now, local features of the launch center TGS are evaluated. Link budget calculations are performed in order to determine the other tracking station sites and the coverage of the TGSs. As it is stated above, the angle between moment vector of the target and the heading vector of the ground station is important to evaluate onboard telemetry parameters during the flight. Onboard telemetry transmitter antenna gain is directly related with the elevation and azimuth angle difference between the vectors. Link budget calculation formula is given in Equation 6.

$$R^2 = \frac{P_t G_t(\alpha, \theta) G_r / T \lambda^2}{(4\pi)^2 P_r L_{atm} L_{sys} L_{prs} L_{mpt} L_D k B} \quad (6)$$

As seen in Equation 6, link is correlated with measured onboard antenna gain which is dependent on the tracking station site and the trajectory. First of all, onboard antenna gain is calculated for all possible sites along the trajectory. Then  $B$ , bandwidth, parameter is determined with respect to the onboard requirements. Different from standard ammunition firings, data rates become very high for a space launch mission. Therefore, minor and major frame features such as word length, maximum number of words and bits and maximum number of minor frame must be compatible with onboard design. Computational challenge which TGS encounters is basically depending on these telemetry frame features and frame refresh time. Telemetry receiver, decommutator, monitoring and process computers' computational capabilities must meet the onboard requirements depending on the mission objective. On the other hand,  $B$ , bandwidth, is inversely proportional to the square root of the effective tracking range. There is a trade-off between throughput from onboard to ground station and the coverage area of the ground station. Here the designer can make different decisions:

1. Data rate may be reduced (smaller minor and/or major frames) which is not feasible for most of the cases.
2. Two or more onboard telemetry transmitter can be implemented on the LV for different stages. Therefore, bandwidth requirement would be lower for each transmitter. In this case, ground station antenna main beam will cover both transmitters. However, receiver and decommutator line are duplicated in order to gather data from both transmitters.
3. Onboard transmission rate would be reduced after certain phases are completed. In this case, initial tracking will be ended due to the frame structure mismatch. Meanwhile, other TGSs' located on different tracking sites parameters must be arranged to track this new frame

structure. In order to ensure this transition, localization systems are required to verify that other tracking stations are locked on the target.

4. Another and mostly utilized technique is onboard recording for uncovered period of the flight. These records are broadcasted when the target is recovered by a TGS.

Two main differences with respect to standard ammunition tracking are considered when the wireless communication channel of space mission is characterized [4]. One of them is multipath components thus fading of the received signal and the other one is frequency offset called Doppler Shift.

Unlike standard ammunition firing, it can be envisaged that the TGS antenna has higher elevation values, since the mission is in the orbit. At low elevation angles, the transmission of the target will be reflected from objects in the line of sight, creating a higher multipath effect. The multipath effect can be considered lower in space missions with respect to standard ammunition firings. On the other hand, as can be seen in the link budget calculation given in Equation 6, the increased system noise temperature reduces the tracking range of the system. For telemetry systems, the system noise temperature can range from 200K at 0 degrees elevation to 10K at higher elevation values [3]. Considering this, it can be predicted that target tracking at higher elevation angles will increase the effective tracking range of the system. Meanwhile, other different feature of a space mission from a conventional flight is the maximum velocity rates which the target can reach, thus the Doppler shift. Doppler spread is other important parameter to characterize the wireless communication channel. For the orbital missions LV reaches the orbital velocities before separation of the payload. Using gravity equation (7), in the centrifugal force equation (8) the velocity equation is obtained as in the Equation 9, while  $r$  is the radius of the Earth,  $h$  is the altitude of the orbit and  $g'$  is gravity at the orbit. It is seen that the velocity of the LV is at the order of  $7500m/sn$  for LEO missions between 160km to 2000km.

$$g' = GM / (r + h)^2 \quad (7)$$

$$mg' = \frac{mV^2}{r + h} \quad (8)$$

$$V = \sqrt{g' \frac{r^2}{r + h}} \quad (9)$$

Therefore, for space missions telemetry receiver encounters much more Doppler shift than standard ammunition firings. Doppler spread shall be handled with the receiver defined for the ground station. Furthermore, Doppler shift can be used to localize the LV when another localization system is not available in ground segment. Doppler frequency can be calculated from the received RF signal comparing the reference transmitted signal. Thus TGS receiver may produce normal component of the LV velocity vector. Low Allen Variance thus high center frequency stability is required in order to obtain highly precise velocity calculation [5]. Therefore, IRIG 106 chapter 2 approach may not be sufficient for accurate applications. One should note that IRIG 106 standard also underlines a figure of merit for frequency stabilization unless otherwise is dictated by a different application. Receiver antenna azimuth and elevation angles are utilized to reduce ranging information from cumulative velocity information. Conventionally, TGS used for standard ammunition firings has lower antenna gain and wider

main beam angle regarding. This specification causes higher ranging errors relative to GPS because of higher angular position errors. However, larger diameter antennas especially using in Deep Space applications are more accurate in angular position error to track on-board signal automatically due to their narrow main beam angle. Thus, one-way Doppler Tracking can be putted into practice for space applications with auto-track antennas.

As an important safety measure, LV must be tracked by a system which consists of at least two independent data sources for certain phases of the flight [1]. In many of space missions, onboard telemetry system record telemetry data in floating phase, and broadcast the recorded data to the TGS with down-link within payload separation phase. However, it is also possible to maintain an uninterrupted link between the target and TGS, especially, for manned flights. Therefore, safety measures and so coverage areas of the TGS vary with respect to mission objective. Considering calculations and approaches explained above, covered period of the trajectory and so total number of tracking station sites are determined, starting from the launch center. Here another constraint is the available number of communication points. For the feasibility analyses of the flight test of a space mission every constraint must be considered. Compatibility with mission objective must be analyzed for not only coverage but also, communication hub, localization systems, command and control and tele-command for every tracking sites. It is common to construct a satellite communication system near by a tracking site.

Additionally, explained maximum velocity requirements are also effective in radar equation as telemetry equation. Maximum velocity tracked by radar determines the Doppler Spectrum in radar signal as given in Equation (10). Sampling number (FFT) used in processing of the Doppler spectrum will determine the frequency difference between samples. The obtained velocity resolution of LV is determined with this difference (delta frequency) in frequency domain. Related equation is given in Equation (11).

$$f_d = \frac{2V_{\max}}{\lambda} \quad (10)$$

$$\Delta f_d = \frac{2\Delta v}{\lambda} \quad (11)$$

On the other hand, time domain equivalent of this sampling interval is observation time,  $T_o$ .

$$T_{obs} = \frac{1}{\Delta f_d} \quad (12)$$

Time intervals while producing data must not be over maximum time determined in pre-mission. Especially, in space mission where target is very fast, the target can cover a long distance between two observations. Likewise, the repetition time of the trajectory and position data acquired from telemetry must be arranged to meet the mission safety requirements. The LV tracking losses or error from all tracking source, including data latency, any possible gaps or dropouts in coverage areas shall be compatible with flight safety limits and the flight safety system time delay [1]. It is possible to mitigate with negative channel effects on the signal; however, they always cause SNR losses and increased BER. If we assume BER is equal to  $q$  then probability of correctly detecting synchronization word with the length of  $n$  bits is equal to  $P_{sync}=(1-q)^n$ . By the way, probability of false lock for a random series of received signal is  $P_{false}=(0.5)^n$ . In order to decrease the probability false lock it is reasonable to increase synchronization word length,  $n$ . However increasing the word length also causes probability of

synchronization to decrease. If  $n$  is assumed to be 16 and 32 while  $q=1e-3$  then probability of synchronization is  $P_{sync} = 0.984$  and  $P_{sync} = 0.968$ , respectively. Thus, to increase synchronization probability, it is common to allow  $K$  error bits. Then probability equations for synchronizations and false lock becomes as in Equation 13 and Equation 14, respectively.

$$P_{sync} = \sum_{k=0}^K \frac{n!}{(n-k)!k!} q^k (1-q)^{n-k} \quad (13)$$

$$P_{false} = (0.5)^n \sum_{k=0}^K \frac{n!}{(n-k)!k!} \quad (14)$$

It is seen from Equation 13 and 14, increasing  $n$  increases the ratio  $P_{sync} / P_{false}$ ; however, decreases  $P_{sync}$  also. Better way is to allow some error bits while increasing the  $n$ . IRIG 106-11 recommends the optimum correlation patterns for frame synch words. Additionally, IRIG 106-06 provides help with the synch word length selection with respect to calculation of the probability of false lock.

The importance of  $q$  is another significant result derived from Equation 13. BER calculations vary depending on utilized modulation. However, for all type of modulation BER level is strictly effected by SNR. Therefore, the channel specifications shall be modelled properly considering the noise factors signified in Equation 6. Additive noise is statistically independent from the signal. High ionic density flame burst is a matter of lift-off period of the space launch in this channel. Bit rate will decrease due to this plume effect. Likewise, effects which will occur in atmosphere causes disturbance of signal and increasing bit error rate. It is known that these effects in the channel reduce SNR and effect telemetry broadcasting like frame synch lock. Therefore, these attenuations have been modelled in link analysis.

Another significant safety issue is debris created by the separated stages. Stages may be tracked by TGS with respect to mission objective. In this case, the analysis and methods performed within the scope of the present study shall be repeated for each of the stages and final TGS tracking sites shall be decided.

## CONCLUSION

To sum up, this study is instructive for TGS designer/user in space mission. Sub-requirements are derived from mission requirements within the concept of the study and a comprehensive telemetry applications literature, international standards and practices are summarized and explained to analyze the requirements. During evaluations differences between conventional telemetry applications and a space launch mission are highlighted (Doppler, bandwidth, beam width, etc.).

Starting from the TGS which is located around launch center, factors are evaluated like mechanical capabilities, coverage areas, bandwidth, channel effects and reliability. In accordance with the results, possible solution alternatives for space missions are submitted. Subsystem and configuration effects such as commutation, quantization noise, encoding, modulation type, equalizer, etc. are not considered. Study is limited on the physical layer. Ground station and onboard features are specified with link budget calculation. Especially, enhanced disturbance in a broadband channel was analyzed and their effects on link were evaluated and mitigation ways are declared.

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