ANTENNA TRACKING AND COMMAND DESTRUCT CAPABILITIES BASED ON ANGULAR VELOCITY AND ACCELERATION

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ABSTRACT

Most range safety telemetry tracking systems have antenna designs that feature an S-band (2200-2400 MHz) Telemetry Tracking and UHF-Band (400-450 MHz) Command Destruct feed along side an omni-directional antenna. The antennas must have, by design, high angular velocity (w) and acceleration (α) parameters to achieve these tasks. Generally, these parameters are user configurable through software and monitored through BIT (Built In Test) log files. The parameters are nominally set to their maximum values (ie. w=10 deg/sec and α = 15 deg/sec^2.) Considering the dynamics of a sample satellite launch vs. the ground tracking and omni antennas' combined capabilities, this document analyzes whether the target will stay within the beam.

KEY WORDS

Command destruct, range safety, tracking antenna, omni-directional antenna, beam angles

INTRODUCTION

While selecting a telemetry tracking system with a directional high-gain antenna, the following need to be taken into consideration:

- Gain - high enough for closure of the link for a satisfactory G/T (Figure of Merit - Gain over Noise Temperature - of the antenna),
- Resultant beam angle - large enough to keep the target in the beam during high and hypersonic speed operations
- Initial capture and destruct inaccuracies - such as initial pointing errors and flame retardation (resulting in a blackout of the communication).

Most command destruct system (CDS) users complement the system with a low gain omnidirectional antenna for the shorter distance, wider angle coverage to alleviate these initial tracking issues with a high gain antenna.

IMPLEMENTATION

During the study, MathCAD was used to model the antenna behavior while tracking to determine if the vehicle could possibly leave the tracking and coverage beam angles. The reader should refer to the Appendix for the MathCAD file contents.

DUAL ANTENNA RECEIVE AND TRANSMIT SYSTEMS

Taking into consideration the receive sensitivities of the standard flight termination receivers, the maximum distance for S-band tracking and command destruct signals for a high gain antenna (5.4 meter dish) is calculated to be 2000 km. (Figure 1) The maximum UHF system coverage distance for the Omni-directional (low gain) antenna is calculated to be 168 km, with the desired link margins of 12 dB in each case. (Figure 2)

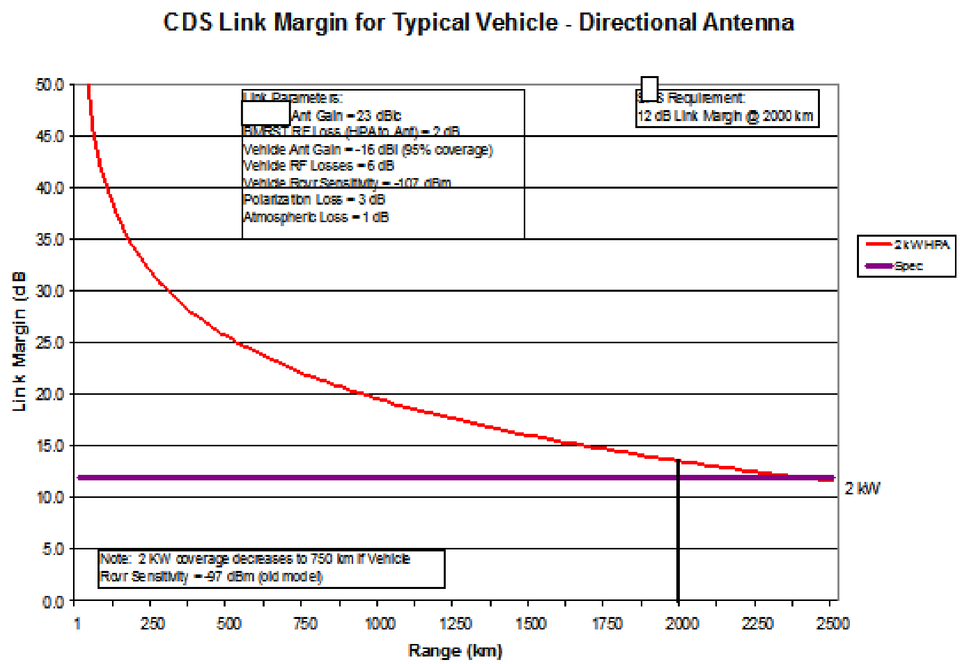


Figure 1 Directional Antenna Command Destruct System Link Margin vs. Distance for a Typical Vehicle

The curves presented are for typical vehicle receivers, therefore the results will vary depending on the receiver sensitivity and RF losses on the vehicle. The following parameters and typical values were taken into consideration during generation of the curves:

- Atmospheric and various losses of -3dB
- Vehicle antenna gain of -16 dBi (for a 90 % coverage)
- Vehicle RF losses of -6 dB
- Polarization losses of -3 dB
- Vehicle receiver sensitivity as -107 dBm
- Antenna gain at the operational UHF frequency (usually p-band) 23 dBi therefore 8 degree 3-dB beamwidth (assumed)
- Antenna telemetry tracking S-band gain 38 dBi, therefore 1.6 degree 3-dB beamwidth with 10 deg / sec angular speed and 15 deg/sec^2 angular acceleration
- RF cable loss from the high power amplifier to the antenna -2 dB
- Omnidirectional antenna gain 0 dBi
- Link margin 12 dB

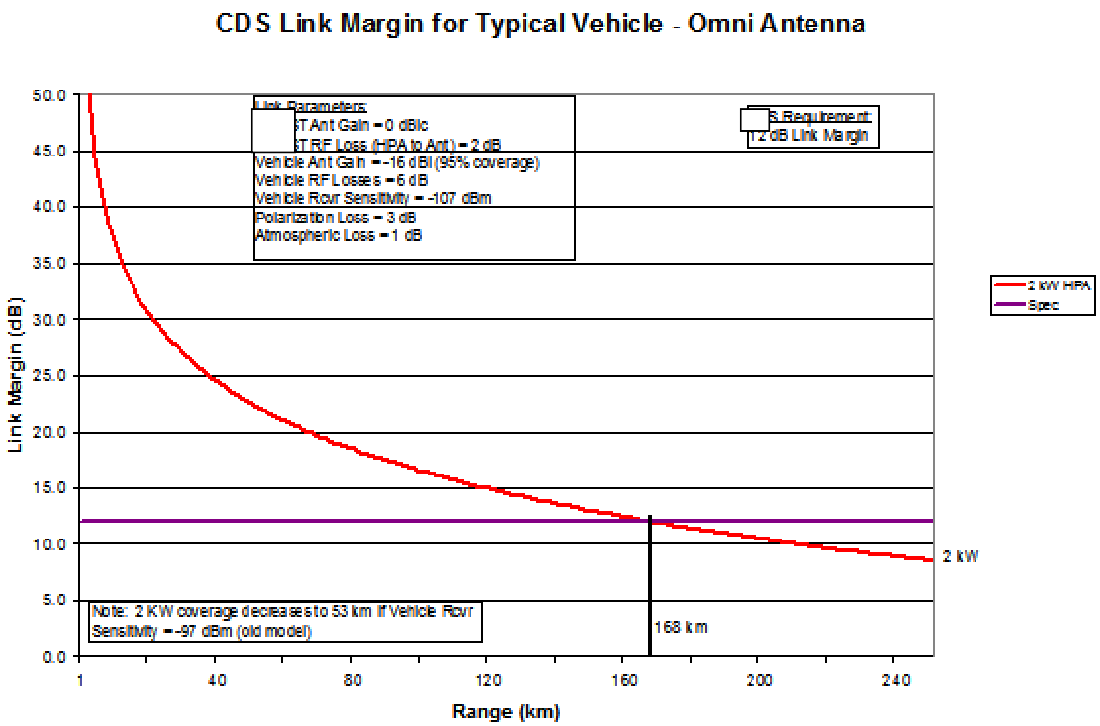
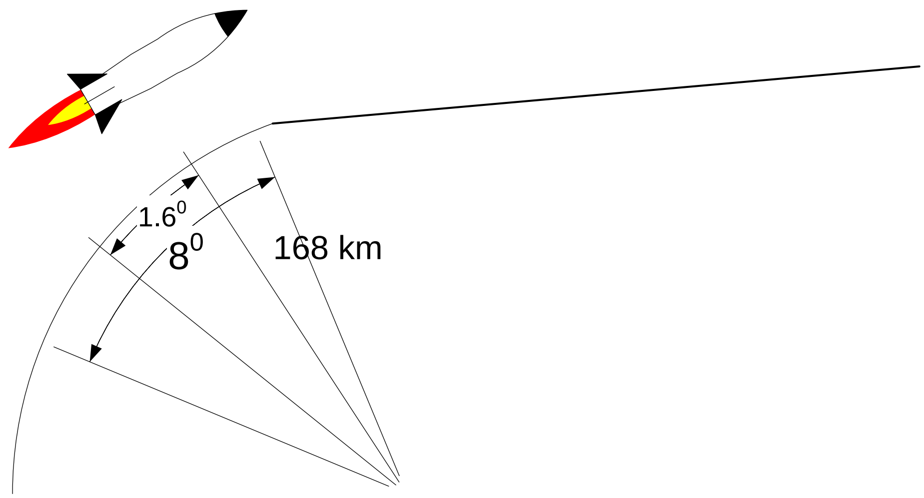


Figure 2 Typical Command Destruct Coverage with an Omni Antenna

One critical assumption to make is where the ground station will be positioned relative to the tracked vehicle for the antenna to experience the most dynamic environment for speed and acceleration. Per Figure 2 above, the Omni Directional antenna will cover (with a 12 dB link margin) the vehicle track up to 168 km from the antenna location. As vehicle travels beyond 168km, the tracking antenna needs to track the vehicle, keep it in its tracking and commanding angle, and deliver the UHF signal to the vehicle if/when needed.

Therefore, the critical point at which the antenna tracking capabilities (most complex point of tracking) should be calculated is when the vehicle leaves the omnidirectional antenna coverage sphere. As the vehicle reaches the 168 km point the linear antenna tracking speed is calculated, correlating (projecting) it on the arc the vehicle is moving. Linear speed and acceleration is compared against the vehicle flight speed and acceleration. (Figure 3).



Note: ***Angles are exaggerated for clarity***
1.6 degrees for S-band tracking assumed
8 degrees is for UHF command destruct

Figure 3 Conceptual Drawing for the Most Dynamic Geometry for CDS System

Test results for actual flight-demonstrated tracking errors for the typical tracking antennas were far under 0.1 degrees for targets beyond 20 miles. (For the calculations provided in the appendix, these errors considered to be within margin.)

The tracking antenna feed's S-band tracking 3dB beamwidth is 1.6 degrees and UHF commanding-target 3dB beamwidth is 8 degrees. Therefore, the tracking and target coverage angles from the boresight of the antenna are 0.8 degrees for S-band and 4 degrees for the UHF band. The antenna will need to keep the target vehicle within the S-band angle of 0.8 degrees of the boresight to track and UHF-angle of 4 degrees to destruct.

For this analysis fairly common vehicle characteristics were used to make the calculations and comparisons. Table 1 outlines the typical trajectory parameters used:

Table 1 Typical Vehicle Data for Altitude, Velocity, Range and Acceleration

Some critical sample parameters	First Stage Cutoff	Second Stage Cutoff
ALTITUDE: (km)	110	230
VELOCITY INERTIAL: (km/sec)	4.831	8.022
RANGE: (km)	275	4000
ACCELERATION: (G)	4.6	0.8
TIME: (SEC)	235	935

Per Table 1, the 168 km range puts the system into First Stage Cutoff region (column 1 of Table 1) of the vehicle trajectory. The closest point to start tracking with the highest linear speeds being experienced before the First Stage Cutoff is around 168km within coverage area of the omnidirectional antenna. Tracking (using high gain antenna) starts with an approximate (worst case) speed of 4.831 km/sec and acceleration of 4.6g. The acceleration gradually drops down to 0.8g by the time the Second Stage Cutoff is reached with speeds reaching 8.022km/sec. (Table 1, second column.) at a distance of 4000 km (beyond the antenna coverage distance.) As the vehicle moves away from the tracking antenna system position, the look angle narrows, making the analysis more complicated, however, reducing the stresses on the antenna due to no high speed tracking and high acceleration needs. In this case, the antenna movement covers an acute angle rather than a 90 degree or larger angle. (Figure 4)

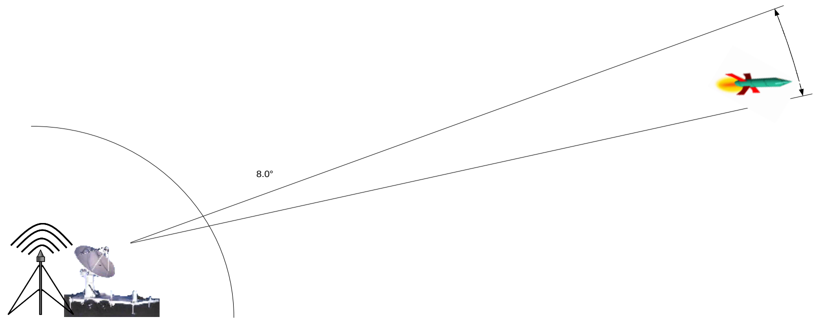


Figure 4 Antenna Tracking with the Vehicle at a Distance is Less Stressful on the Antenna

Therefore, the speed and acceleration demand from the antenna would be at the closest tracking area, but just outside the omnidirectional antenna coverage area (168 km distance) when the vehicle is entering the antenna's coverage angle of 1.6 degrees for tracking, and 8 degrees for Command Destruct. The characteristics of the two antennas are outlined under paragraph 2.0 in the Appendix and in Figure 5 below. For verification, the link calculations are done (but not included here for brevity.)

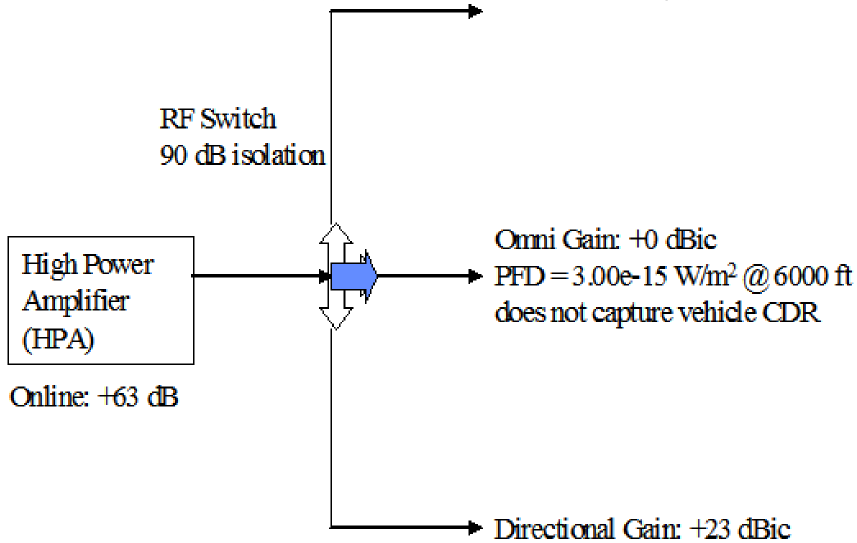


Figure 5 Output Power and Gain Characteristics of the Command Destruct (CD)System to reach Command Destruct Receiver (CDR)

Following the conclusion is the MathCAD analysis details and results of the calculations for antenna speeds and accelerations, S-band tracking and UHF Command Destruct capabilities.

CONCLUSION

The MathCAD spreadsheet can adapt to other vehicles by quickly changing the parameters when needed. The mathematical analysis showed the following results for the parameters used:

At the closest point when the antenna is needed to be most agile, the antenna linear tracking speed at 168 km range was approximately 6 times faster than vehicle's linear moving speed 4.831 km/sec on the 168 km arc. Even if the vehicle speed is increased at this point (at 168 km) to the Second Stage Cutoff speed of 8.022 km/sec, the antenna's linear speed was calculated to be approximately 3 times faster than the vehicle's speed. This gives the user confidence that the antenna would be within the UHF command destruct system's target angle.

ACRONYM LIST

BIT	Built-In Test
CDS	Command Destruct (Flight Termination) System
dBi	decibel in reference to an isotropic antenna gain
dBm	dB of power referenced to miliwatts
dBW	dBWatts
Deg/sec	Degrees/second
Fig	Figure
ft/sec	Foot per second
G	Gain
G/T	Gain over (Noise) Temperature (Figure of Merit) of antenna system
GHz	Giga Hertz
Hz	Hertz
km	Kilometers
km/sec	Kilometers/second
kW	KiloWatt
L	Loss
MathCAD	A mathematical notation and solution program
MHz	Mega Herz
MHz	Mega Hertz
mph	Miles Per Hour
NMI	Nautical Miles
REF	Reference
RF	Radio Frequency
SEC	Second
UHF	Ultra High Frequency
vs	Versus

Note: Many configuration parameter names were used and assigned to the values during MathCAD use. These acronyms are explained or given in a self-explained manner in the text of the MathCAD file.

REFERENCES

MathCAD Documentation.

APPENDIX

1.0 MATHCAD FILE CONTENTS

Verify if antenna can keep up with the vehicle speed in flight:

For the sample case, the speed of the vehicle is given as 4831 m/sec:

AT 168 km distance ONE degree translates to an arc length of:

$\text{Vehiclespeed} = 4.831\times 10^{3}\ \frac{\text{m}}{\text{s}}$ $\qquad$ $\text{OneDegAt168} := 2\cdot\pi\cdot\frac{168\text{km}}{360}$

$\text{OneDegAt168} = 2.932\times 10^{3}\ \text{m}$ One degree arc equivalent travel distance

Note: Arc length and segment length can be approximated for small angles as this paper is applied to (1 or 4 degree arc at the perimeter of 168 km radius).

For the vehicle to move 1 degree

$\text{TimeToMove1Deg} := \frac{\text{OneDegAt168}}{\text{Vehiclespeed}}$ $\qquad$ $\text{TimeToMove1Deg} = 0.607\text{s}$

For the vehicle to move 4 degrees (within the UHF coverage angle of the antenna):

$\text{TimeToMove4Deg} := \text{TimeToMove1Deg}\cdot 4$

For this vehicle to leave the 4 degree half beamwidth of the antenna it will take:

$\text{TimeToMove4Deg} = 2.428\text{s}$

At 10degrees/sec angular speed antenna will take 0.4 sec to move 4 degrees:

$\text{AntennaLead} := \frac{\text{TimeToMove4Deg}}{0.4\text{sec}}$ $\qquad$ $\text{AntennaLead} = 6.07$ times.

At 10 deg/sec angular speed, antenna is over six times faster (ahead of) the target at its most critical position to track.

Conclusion:

Antenna tracking can cover 10 degrees/second. Therefore it would take the antenna only 0.1 sec to move 1 degree.

Under normal flight conditions, the vehicle will stay in the antenna's tracking angle of .8 degrees in S band and 4 degrees in the UHF band.

Verify if antenna can keep up with the acceleration:

Let us start at the point when the vehicle is at the edge of the omnidirectional antenna coverage point. Antenna can accelerate in any direction at 15 degrees/sec^2.

The worst case is at this point of 168 km radial distance when the system switches to directional antenna coverage area. At this point, the vehicle acceleration is 4.6g (Vehicle parameters in Table-1):

$g = 9.807\frac{\text{m}}{\text{s}^2}$ $\qquad$ $\text{VehicleAcc} := 4.6g$ $\qquad$ $\text{VehicleAcc} = 45.111\frac{\text{m}}{\text{s}^2}$

At 168 km, in 1 sec, this translates to a speed change of:

$$Speed1secChange := VehicleAcc \cdot 1sec \qquad Speed1secChange = 45.111\frac{m}{s}$$

In TimeToMove1Deg seconds, as shown above, meaning during 1 degree of movement at 168 km distance: $TimeToMove1Deg = 0.607s$

vehicle speed will increase by: $VehicleAcc \cdot TimeToMove1Deg = 27.381\frac{m}{s}$

Meaning during one degree movement the vehicle will change its linear speed to :

$$Vehiclespeed + VehicleAcc \cdot TimeToMove1Deg = 4.858 \times 10^{3}\,\frac{m}{s}$$

Can Antenna match this or do better? : $AntennaSpeed := 1($ degrees per second.

$LinearSpeedAntAt168km := AntennaSpeed \cdot 2.\!($

10 deg/sec * 2.9 km/deg at 168 km $\qquad LinearSpeedAntAt168km = 29\,\frac{km}{sec}$

This antenna's 29 km/sec linear speed *at 168 km* compared to 4.9 km/sec (approximate) linear speed of the vehicle at the 168 km radial distance point (worst case study point) will keep the antenna easily in step with the vehicle's linear movement (from speed perspective.)
Considering the 4 degree tolerance we have from the boresight to the UHF half-beamwidth, the vehicle will always be in the Command Destruct System coverage.

At further distances, as the angular velocity shall be smaller, the required angular speed and linear speed to track the vehicle shall be less.

Vehicle continues to fly for 4 degrees to reach the UHF antenna beam edge:
Let us add acceleration during 4 degrees of movement to the vehicles speed.
Vehicle will take TimeToMove4Deg seconds to move 4 degrees (UHF antenna coverage angle.)
At 168 km 4 degrees will take $TimeToMove4Deg = 2.428s$ to fly.

$$VehicleAcc = 45.111\frac{m}{s^2} \qquad Vehiclespeed = 4.831 \times 10^{3}\,\frac{m}{s}$$

$$NewVehicleSpeed := Vehiclespeed + TimeToMove4Deg\,VehicleAcc$$

$$NewVehicleSpeed = 4.94 \times 10^{3}\,\frac{m}{s}$$

Vehicle will be at 4 deg. Starting from 0 speed at 15 deg / sec^2 antenna would need to gain a speed of:
$AntAcc := 1\!($ deg/sec^2 AntNewSpeed:= 0 + Ant.Acc* TimeToMove4Deg
AntNewSpeed =: 36.42 deg/sec

Antenna cannot reach this speed. Antenna's maximum angular speed is 10deg/sec. Will this be enough to catch up from a stationary position of the antenna?

At speed of 10 degrees per second it will take antenna $\qquad AntMaxSpeed := 10\frac{deg}{sec}$
4 deg /10 deg * 2.428 sec = 0.971 seconds more to catch up with the vehicle.

At this point vehicle will be : 4*0.971 /1.462 = 2.66 deg 4+2.66 = 6.66 degrees away from starting point. (Vehicle took 2.428 seconds to move 4^0, antenna took 0.971 seconds.)

Even if the antenna would not track, this 6.7-degree point is still within the 8 degree side lobe coverage of the antenna. Vehicle can be reached by the command destruct signal.

If we check the levels calculated below, we can assume that the side lobes that are at approximately +/- 8 degrees, at the power levels of -20 dBc (off the boresight levels) would be enough to reach the vehicle.

In reality antenna did not stop and will continue to move and track the vehicle to keep it within the 1.6 degree boresight angle (+/-0.8 degrees).

It will take the antenna : 6.66 / 10 = 0.666 seconds 15 deg/sec^2 * .666 sec = 9.99 deg/sec (antenna is capable of 10 deg / sec speed.)

Approximately [0.67 seconds] to swing to the 4 degree point from 0 deg/sec starting point of acceleration. Vehicle can be reached by the signal out of the directional antenna (within +/-4 degrees) at this point.

2.0 TYPICAL ANTENNA CHARACTERISTICS

Flight Termination System antenna :
Operating Frequency Bands: 400-450 MHz
Power output: 1 to 2 kW
Polarization: LHCP
Gain: 0 dBi nominal
Azimuth Beamwidth: Omnidirectional (+/- 3dB)
Elevation Beamwidth: > 120 degrees typical (3 dB) (+/- 60 deg)
> 180 degrees nominal (10 dB)

A high gain tracking antenna:
5.4 m Antenna Dish Summary Performance when used in S band (receive) and P band (transmit)

Item	Receive	Transmit
Band	S-band	UHF band
Freq Range	2200-2400 MHz	400-450 MHz
Antenna Gain	38 dBi min @ feed port	23 dB min at feed port
Data Tracking		
G/T @5deg	17 dB K min	N/A
Half Power BW	1.6 deg min	8 deg min
Transmit Capability	NA	32 dBW min