Geographic-Based Satellite Anti-Jam Strategies

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I. Introduction

The cancellation of the transformational Satellite (TSAT) program has created interest in commercial satellite use for military purposes. A key requirement difference between these two is the need for anti-jam (AJ) protection in military systems. Many features of present and near future commercial satellite systems can make them inherently jam resistant. One is their high data rate/bandwidth which can allow frequency spreading to mitigate jamming effects. Additionally the use of narrow and focused beam antennas make it difficult for jamming power to enter the receiver. However, we will continue to use certain commercial satellite systems today and in the future that do not offer these AJ benefits and for which we don't have a solution to the jamming threat. This study investigates "geographic-based" AJ strategies as opposed to waveform design that could be used with these commercial systems. It was motivated by a RAND Corporation proposal [1] where Blue Forces use low elevation geo-synchronous satellites. The assumption is that ground based jammers will be positioned such that their elevation angles are lower than the Blue Force terminal elevation angles and blocked by the horizon, terrain or structures as depicted in Figure 1. Finding such an ideal placement may not be practical and we investigated a variant with greater flexibility using an airborne relay shown in Figure 2. This paper presents the results of that investigation.

Geographical placements for both these arrangements are examined and the advantage of the air relay is demonstrated in Section II. The air relay's impact on the satellite communications link is assessed in Section III using standard link budget analysis with Common Data Link, CDL, equipment parameters and a Wideband Gapfiller System, WGS, satellite. Section IV summarizes our findings and provides a list of issues to be resolved if this strategy were to be pursued.

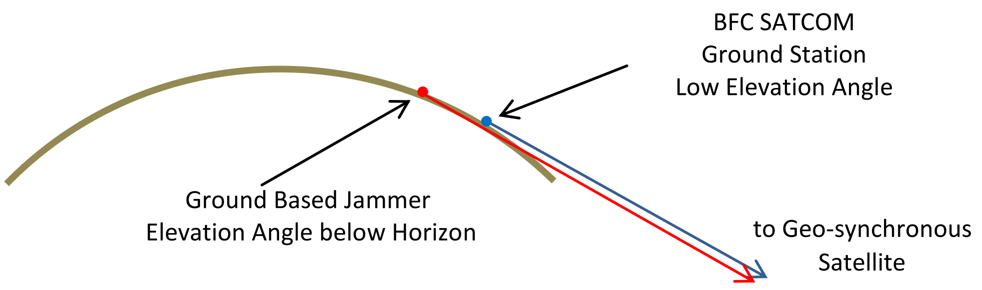

Figure 1. Depiction of anti-jamming strategy using near horizon and below horizon elevation angles for BFC SATCOM and jammer.

II Ground Terminal Jammer Positioning

A. No Air Relay Use

The relationship for elevation angle versus earth station latitude, θ_e and relative longitudinal position between earth station longitude and geo-synchronous satellite longitude, $\delta\phi$ can be found in numerous textbooks [2]. The geometry dictates that elevation angles are most favorable (largest/highest) when the geo-synchronous satellite is at the same longitude as the ground station, $\delta\phi=0$. Figure 3 shows elevation angle versus $\delta\phi$ for earth stations at four latitudes, 35, 45, 55 and 65^o north. Satellite ground terminals typically need elevation angles above 5 to 10^o for minimizing ground clutter effects, slant distance to the satellite and atmospheric attenuation. Conversely, a jamming earth station would be disadvantaged at elevation angles below 5^o. Figure 4 shows a hypothetical situation where the Blue Force SATCOM ground terminal is pointing at a geosynchronous satellite at 111.6^o E ($\delta\phi$ = 67.9^o). The BFC terminal has a 10^o elevation angle and ~ 400 by 400 km box represents a range of jammer positions. The contour plot shows jammers located to the northwest are disadvantaged relative to the Blue Force ground terminal but not greatly as the elevation angle is only ~ 7^o in the far northwest corner.

The results given in Figure 4 demonstrate the difficulty finding Blue Force SATCOM ground positions relative to jammer positions that satisfy the required RAND anti-jamming scenario. A “just right” geo-synchronous satellite for Blue Force and jammer positions must be found, and even then the jammer is not greatly disadvantaged. Given available satellite position, accessibility and geography, the RAND strategy is not practical. We now consider use of an airborne relay.

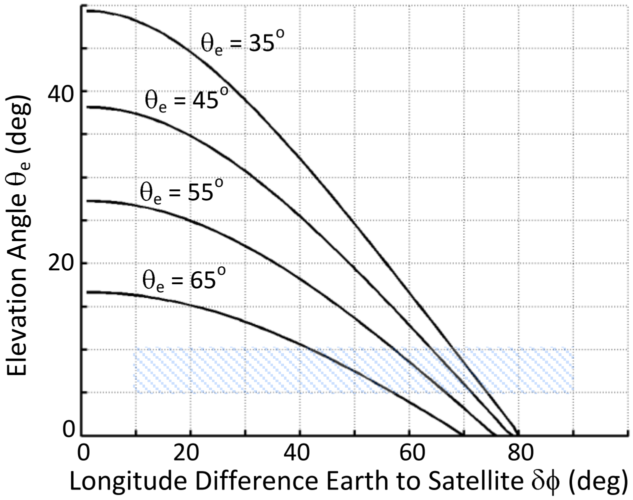

Figure 3. Elevation angle, θ_e, at four latitudes as a function of the relative difference in ground station and satellite longitude, $\delta\phi$.

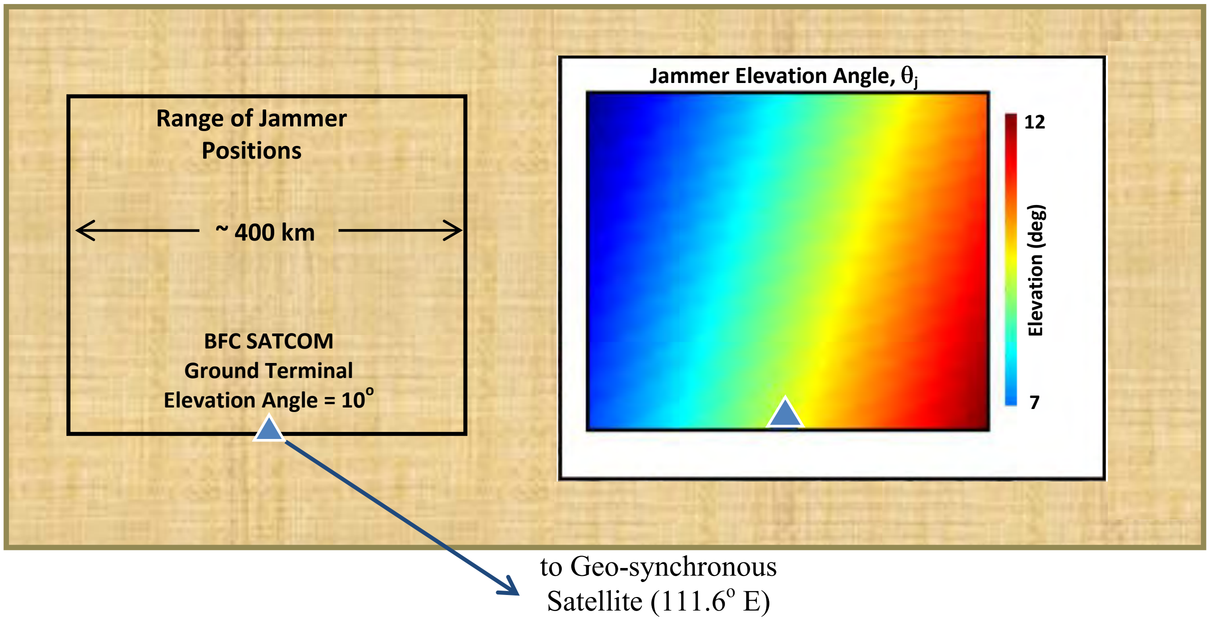

Figure 4. Hypothetical scenario of BFC terminal and jammer positions. The contour plot depicts jammer elevation angle within the range of jammer positions.

B. Air Relay Use

Figure 5 again depicts the air relay scenarios where the ground terminal, satellite and aircraft are all at the same longitude and the Blue Force ground terminal elevation angle to the satellite is 0^o. All potential jammer positions northward of the ground terminal will have negative jammer elevation angles, θ_j, and southward positions will have low elevation angles. Using a high altitude aircraft (*e.g.* Global Hawk at 20 km, 60,000 ft) the relay will have a clear view to the satellite. Figure 6 shows the jammer elevation angles in the vicinity of the ground terminal. Any jammer within the boxed area (~800 by 940 km) will have negative or low elevation angles to the geo-synchronous satellite. A best case scenario has been assumed and it may not be possible to find an optimally placed satellite (123.4^o E for this example) but airborne relay use greatly benefits the Blue Force communications and disadvantages the jammer.

The restriction of finding a geo-synchronous satellite at the horizon ($\theta_e=0^o$) was relaxed and ground jammer elevation angles, θ_j, were computed over a large area ~ 1700 by 1800 km for Blue Force terminal elevations angles of 0, 2.5 and 5^o (by appropriate choice of geosynchronous satellite longitudinal position). The results are shown in Figure 7. $\theta_j = 10^o$ was used as the criterion for ineffective jammer elevation angle and nearly the entire area will have the jammer elevation angle below 10^o for the $\theta_e = 0$ and 2.5^o cases. Of course jammers placed sufficiently southward of the BFC ground terminal can still pose a threat. In those cases protection may be obtained from narrow satellite beams; an aspect not considered here.

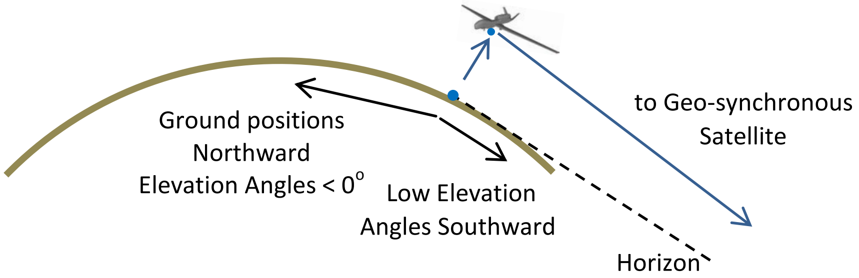

Figure 5. Depiction of anti-jamming strategy using an airborne BFC SATCOM relay where the ground terminal has a 0^o elevation angle to the satellite.

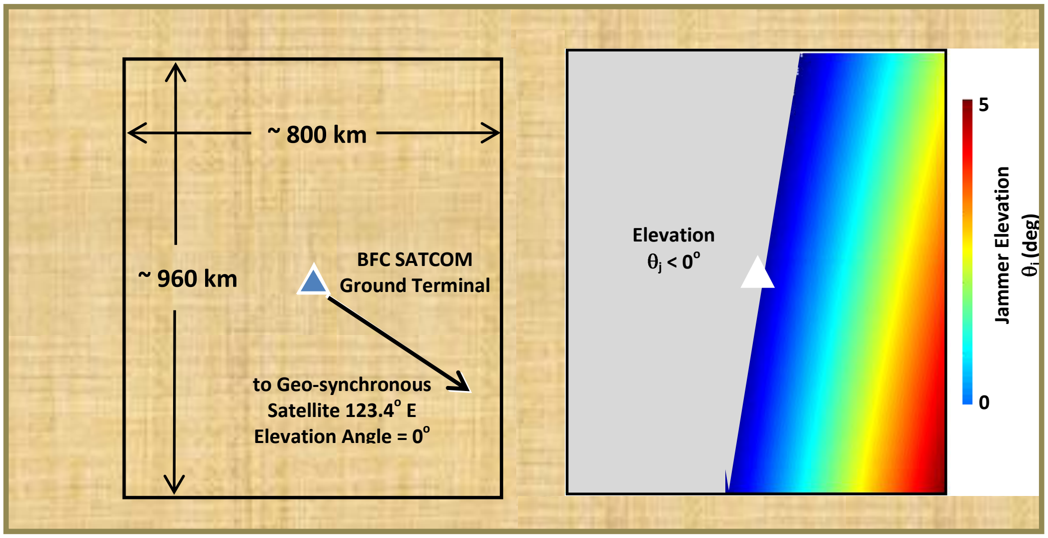

Figure 6. Hypothetical scenario of BFC terminal and jammer positions. The ground station has a 0^o elevation angle and uses an airborne relay for communications to the satellite.

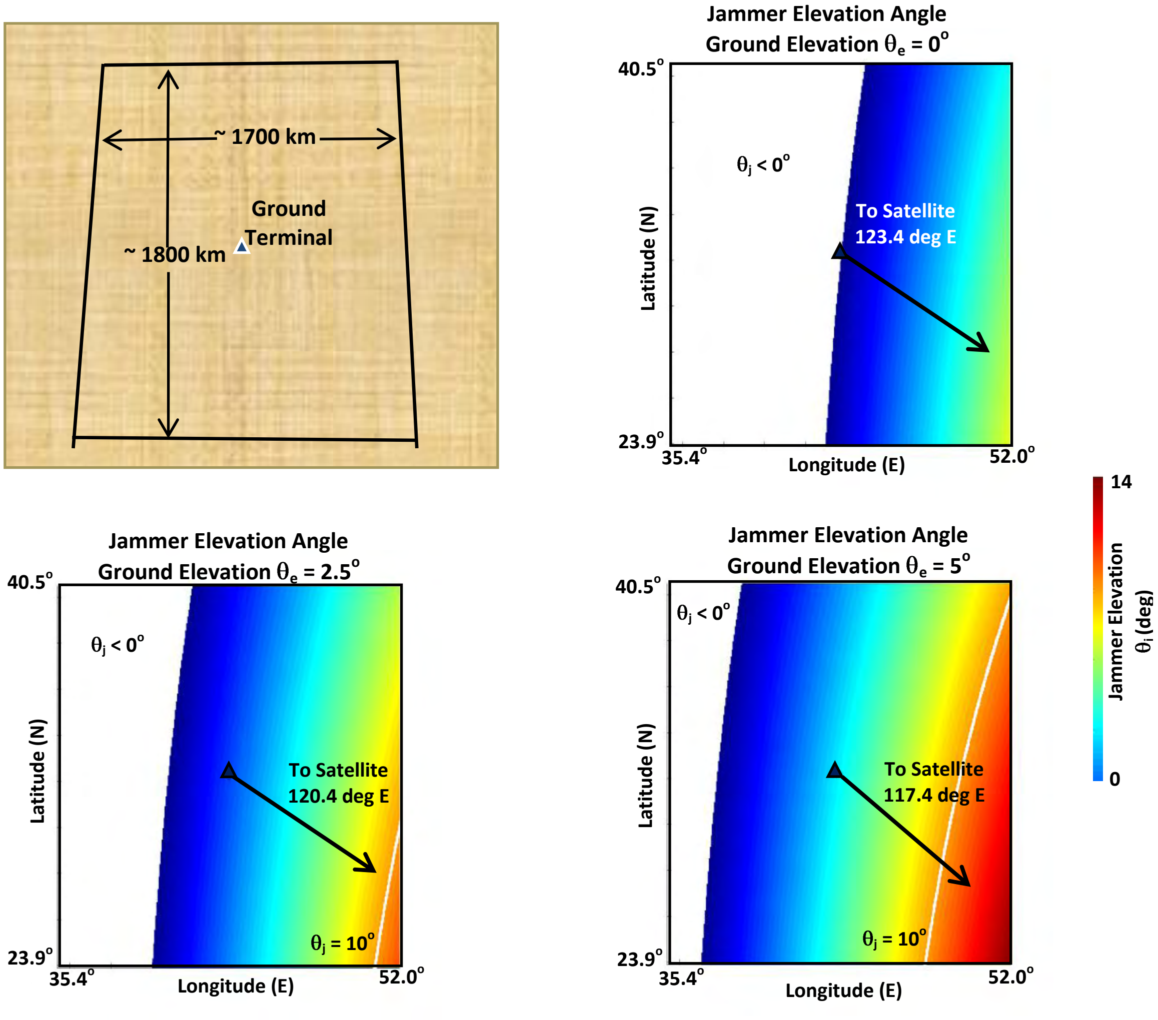

Figure 7. Hypothetical scenarios of BFC terminal and jammer elevation angles, θ_j. BFC ground stations elevation angles, θ_e, = 0, 2.5 and 5°.The 10° line demarks the edge of acceptable elevation angle for jamming.

One further benefit of an airborne relay is the lack of atmospheric absorption. The left side of Figure 8 shows the atmospheric density as a function of altitude. Atmospheric density is approximately 1/10 the ground values for an aircraft at 20 km (60,000 ft) and RF attenuation will be negligible. Ground jammers with low elevation angles, 5 to 10°, will suffer ~ 2 to 3 dB atmospheric loss in the Ka band (27 to 40 GHz) as shown on the right of Figure 8.

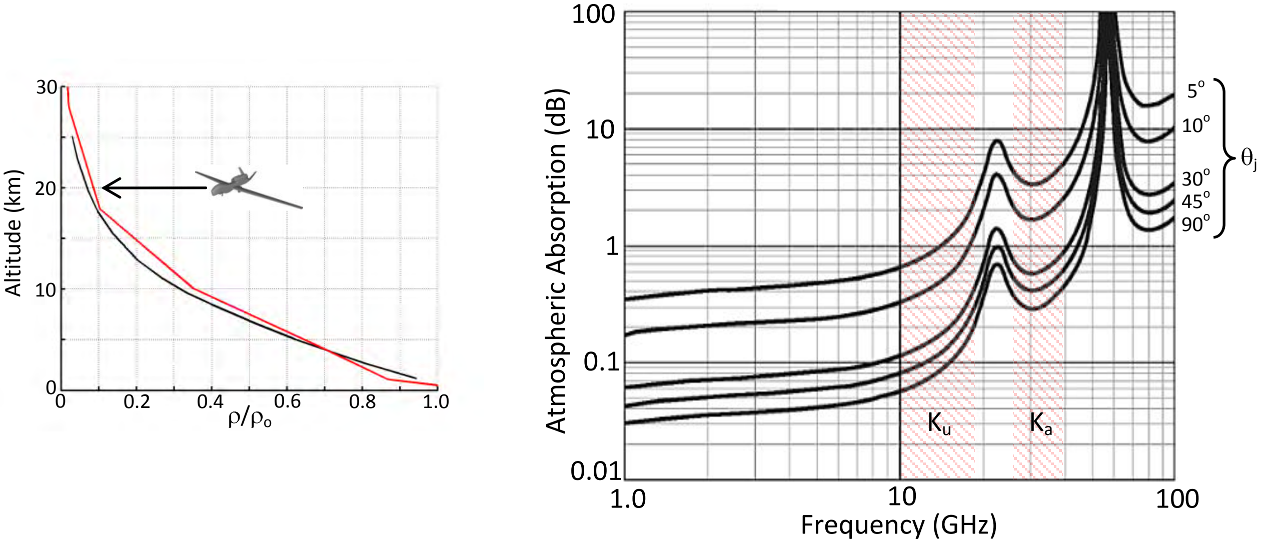

Figure 8. Atmospheric density versus altitude (left side) and RF atmospheric absorption versus frequency for ground terminals with elevations angles of 5, 10, 30, 45 and 90°.

III Link Budget Analysis

An airborne relay will modify the link quality; it will be either improved or diminished depending on the differences between ground terminal and airborne relay equipment characteristics. These effects are quantified assuming a communications link with a "bent pipe" (non-processing) satellite. A bent-pipe design is effectively a repeater while a processing satellite completely decodes the message (removing errors if possible), re-encodes and transmits back to the earth. The present analysis is general with no specific satellite systems in mind and choices can range from commercially available satellite providers to DoD systems. Figure 9 shows a map of the satellite positions for Intelsat (commercial) and the Wideband Gapfiller System (DoD). Both are bent pipe systems and although there is a greater choice of satellites with Intelsat, we used the WGS satellite characteristics based on it being a DoD asset. Link budgets were computed as shown in Figure 10 to determine the link quality both with and without an air relay.

Figure 9 Satellite positions for Intelsat and the Wideband Gapfiller System.

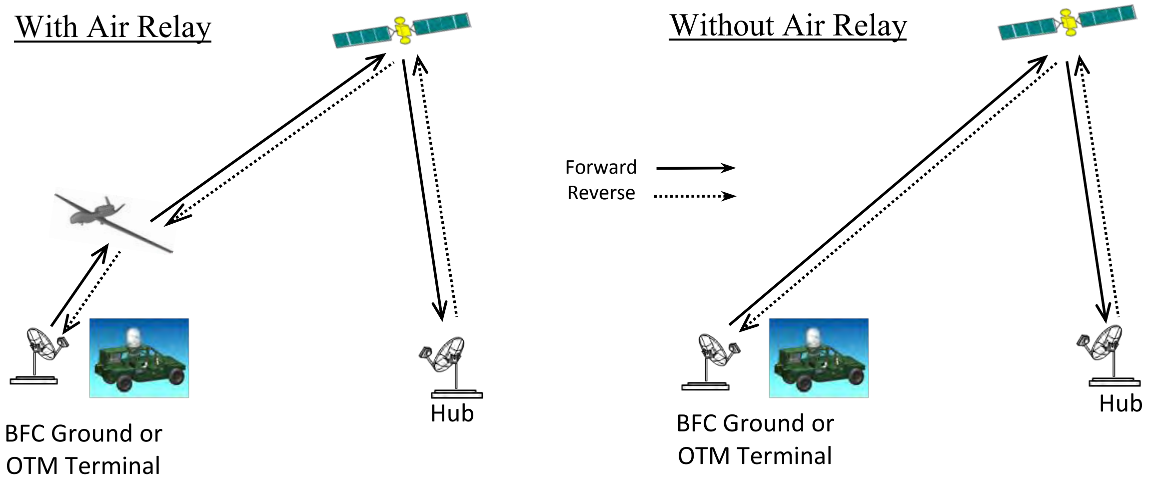

Figure 10. Schematic depiction of BFC ground or OTM terminal reverse and forward links (solid and dashed lines) both with and without an airborne relay.

WGS satellite parameters were used in this analysis; their nominal positions make them a poor choice for a Blue Force terminal at our hypothetical location. Figure 11 provides ground elevation angles for this Blue Force position as a function of satellite longitude. The three WGS positions are denoted and the two visible satellites have approximately 20 and 50^o elevation angles. The difficulty in finding a satellite with an ideal elevation angle is a short coming of this strategy.

It is possible to have ground Blue Force terminal positions with elevation angles $< 0^o$ and a line of sight to the satellite from air relay to satellite. Figure 11 showed that any satellite farther east than 123^o is below the horizon, $\theta_e < 0^o$. An airborne relay can access satellites farther eastward and this "excess" satellite longitudinal position is a function of ground terminal latitude and relay altitude. For the present example with the air relay at 20 km, a satellite ~ 5^o further eastward will have an unblocked line of sight assuming a perfectly spherical earth and neglecting any atmospheric effects. Realistic values are probably in the 3 to 4^o range.

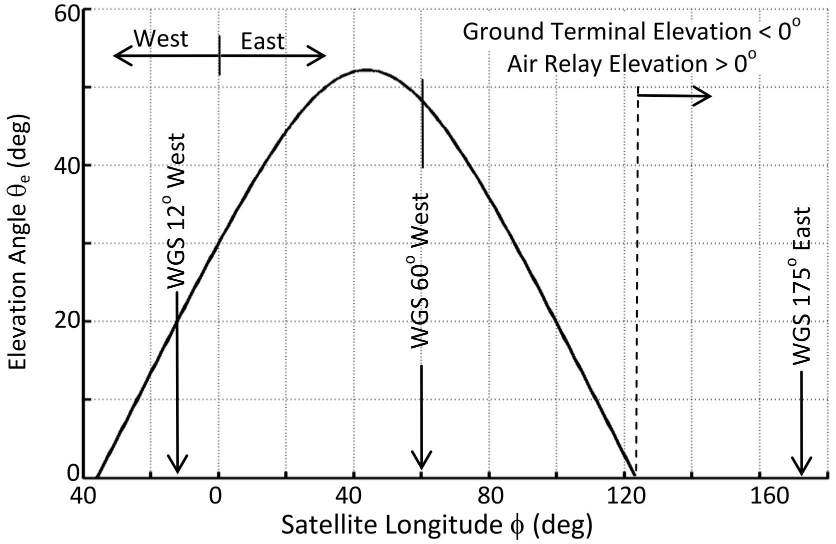

Figure 11. Elevation angle, θ_e, as a function of satellite longitude for the hypothetical earth station. The planned positions for the Wideband Gap Filler System satellites are shown.

Link budgets are based on the following carrier to noise (signal to noise) expression,

$$C/N = \frac{P_t G_t / 4\pi R_s^2 \;\; G_r \lambda^2 / 4\pi \; L_a}{k T_r B} \qquad \text{Eq. (1)}$$

where:

P_t Transmitter power (watts)
G_t Transmit antenna gain
R_s Transmitter to receiver distance (meters)
G_r Receiver antenna gain
λ Wavelength (meters)
K Boltzmann's constant (watts/Hz-K)
T_r Receiver system noise temperature (K)
B Receiver bandwidth (Hz)
L_a Assorted losses in the transmit/receive chain

This expression is simply the transmitted power flux density times the effective antenna area divided by system noise. Eq. (1) is written in decimal form but a logarithmic (decibel) form is generally used for computations. Antenna efficiency is not explicitly given but is embodied in antenna gain values.

It is common to combine terms and express C/N directly in dB; manufacturers typically provide values for combined parameters in appropriate decibel units.

$$C/N\ (\mathrm{dB}) = EIRP + G/T - 10\log_{10}(kB) + 20\log_{10}(\lambda/4\pi R_s) - L_a \qquad \text{Eq. (2)}$$

EIRP is effective radiated power and G/T is the aggregated receiver gain and noise temperature. Ground and air platform systems parameters are based on representative Tactical Common Data Link (T-CDL) values for systems and manufacturer specifications from L3 Communications [3]. These parameters are given in Table I where the WGS EIRP is over a 125 MHz bandwidth.

Table I Performance Parameter for Ground, Air Relay and Satellite

	Ground	On the Move	Hub	Air Relay	WGS Satellite
EIRP (dBm)	80.7	75.7	90.0	83.5	86.0
G/T (dBi/K)	12.7	6.1	33	10.5	8.4

A baseline set of C/N's was established with no air relay and the power at the satellite was adjusted to close the most disadvantage link, the forward link to the OTM vehicle. This resulted in the transponder providing more power than would be provided on a "fair basis" of equal power/equal bandwidth, and is a well known feature for small terminal communication. A bandwidth of 256 KHz was assumed based on typical mobile SATCOM data rate requirements. A fair transponder power use basis would allot ~ 0.2% of the transponder power, 59 dBm, while 2% was necessary, 69 dBm to close the links. This higher value was used.

Link analysis is done by computing the C/N for each segment of the communication chain, *e.g.* ground to air relay, air relay to satellite and satellite to hub for the air relay reverse link. The C/N's are inversely combined as given in Eq. (3) where the summation is over each communication chain segment.

$$C/N = 1/\sum_i (C/N)_i^{-1} \qquad \text{Eq. (3)}$$

Eq. (3) effectively represents adding the noise at each segment and in many instances one segment's poor quality (low C/N due to low ERIP and/or G/T) will dominate and determine the overall performance. C/N values are summarized in Table II where the annotation better, worse or no difference is used to assess the effect of the air relay. These results can be understood based on which segment has the lowest C/N and the differences in air relay and ground EIRP and G/T.

There is one important assumption regarding air relay use. No additional noise was assumed for the air relay transponder amplifier, making the results in Table II best case estimates. The only case where the relay diminished performance was for the forward link from the large Hub to the portable 4 ft ground terminal where there was approximately 2 dB degradation.

Table II C/N for Ground and OTM Hub Links with and without Air Relay

	Ground-Hub	OTM-Hub
Forward Link No Air Relay	12.1	5.7
Forward Link with Air Relay	10.1 (worse)	10.1 (better)
Reverse Link No Air Relay	19.1	14.6
Reverse Link with Air Relay	22.4 (better)	22.4 (better)

Figures 12 and 13 provide the C/N over each communication link segment. The C/N values for ground to air relay links are high due to the relatively short distance and no power control was assumed. That is, the full EIRP's were used which would not be necessary. In all instances, it is the satellite to ground or air relay link that is the weakest. However the link budgets shows that the air relay strategy would provide adequate margin for the links.

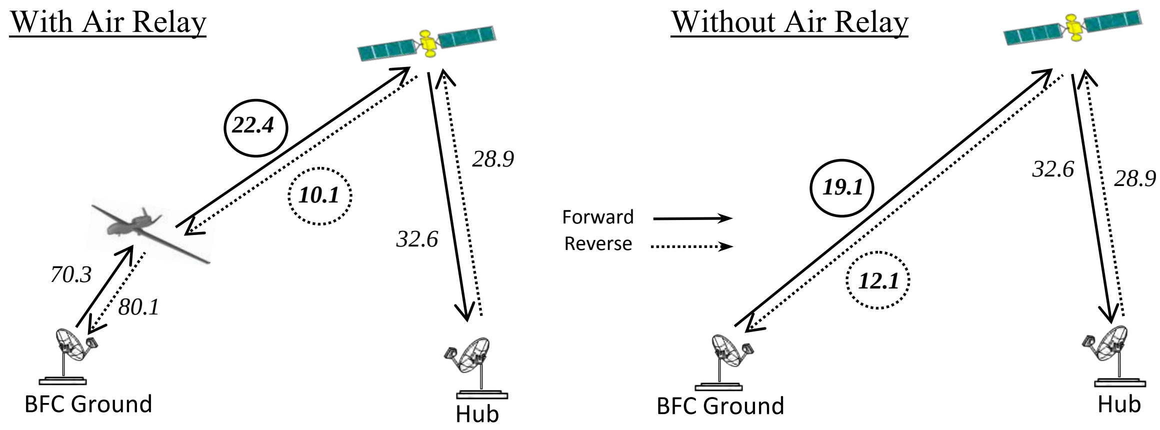

Figure 12. C/N values for each link segment using a BFC portable terminal with a 4 ft antenna. The circled values show which segment effectively determined the overall C/N.

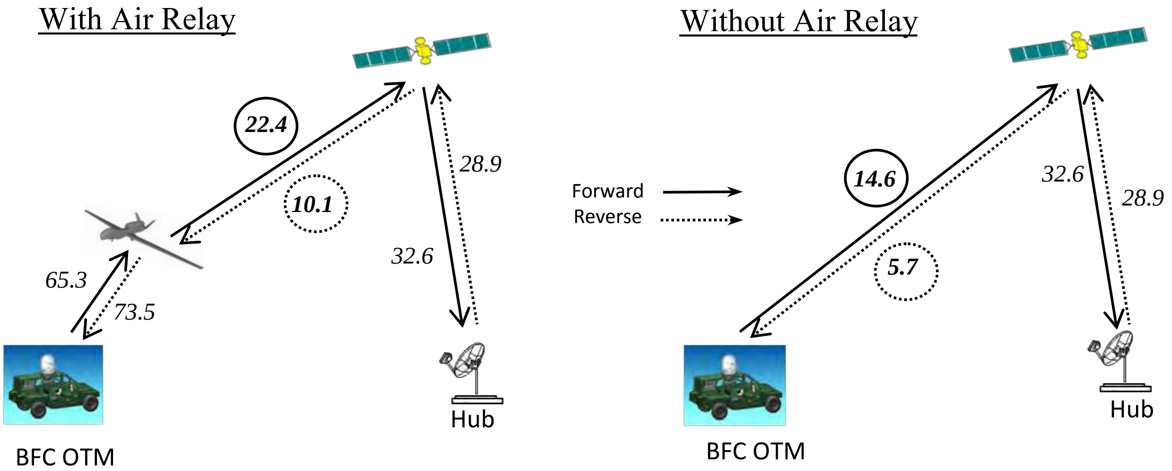

Figure 13. C/N values for each link segment using the OTM terminal with a 2 aft antenna. The circled values show which segment effectively determined the overall C/N.

IV Summary, Conclusions and Future Work

The geographical aspects for two SATCOM anti-jamming strategies were inspected. Both were based on Blue Force ground terminals using low elevation geo-synchronous satellites thereby forcing jammers to lower and more unfavorable elevation angles. The first considered only ground units, Blue Force and jammer. This was RAND’s proposal and deemed impractical based on the required Blue Force terminal and jammer positions for an effective strategy. The second method used an airborne communications relay to provide improved Blue Force communications and create a wider area where jammers have unfavorable elevation angles. Geographically, the latter method is far more applicable but still requires a “just right” choice of relative Blue Force terminal, jammer and satellite positions.

A link budget analysis showed that communications performance using realizable carrier to noise ratios (and commensurate data rates) will not suffer from use of air relays for portable or on-the-move communications to large hub terminals.

Based on the above findings, the use of airborne relays in conjunction with low ground based elevation geo-synchronous satellites may have potential. A number of questions still need to be addressed:

- What power levels at the satellite will disrupt communications?
    - What types of jammers are to be considered?
    - What is the effect of low elevation on propagation, both in terms of clutter and increase atmospheric absorption?
- How effective will commercial near-future narrow beam be with regard to this AJ strategy?
- How close to optimal conditions with regard to Blue Force terminal, jammer and satellite positions can be realistically achieved?
    - A thorough inspection of all geo-synchronous satellites is necessary to assess above.
- How far “over the ground horizon” can an airborne platform see?
    - This requires a more careful inspection of atmosphere and terrain effects than done in the body of this work.

Note this strategy assumes that the link from the ground to the UAV is somehow protected from an electronic attack by the jammer either through waveform design or by narrow beam antennas. Additionally it would require terminals to be multiband and have the ability to switch from a satellite mode to an Airborne CDL mode (such as the system in [3]), as well as the ability to switch between satellites as needed to avoid electronic attacks. Further terminal engineering is required to allow for this type of flexibility and reduce the size of the system, but the strategy has the potential to defeat electronic attacks while using existing unprotected satellite systems.

References

[1] Bonds, T., "Employing commercial satellite communications: Wideband investment options for the Department of Defense ," Chapter 6, The RAND Corp. 2000.

[2] Seybold, J., "Introduction to RF Propagation," Chapter 11, Wiley Ed. 20xx.

[3] L3 Communications Specification Data for "Multi-role tactical commom Data Link", http://www.l-3com.com/products-services/docoutput.aspx?id=1246.