# RESILIENT COMMUNICATION BEYOND LINE OF SIGHT

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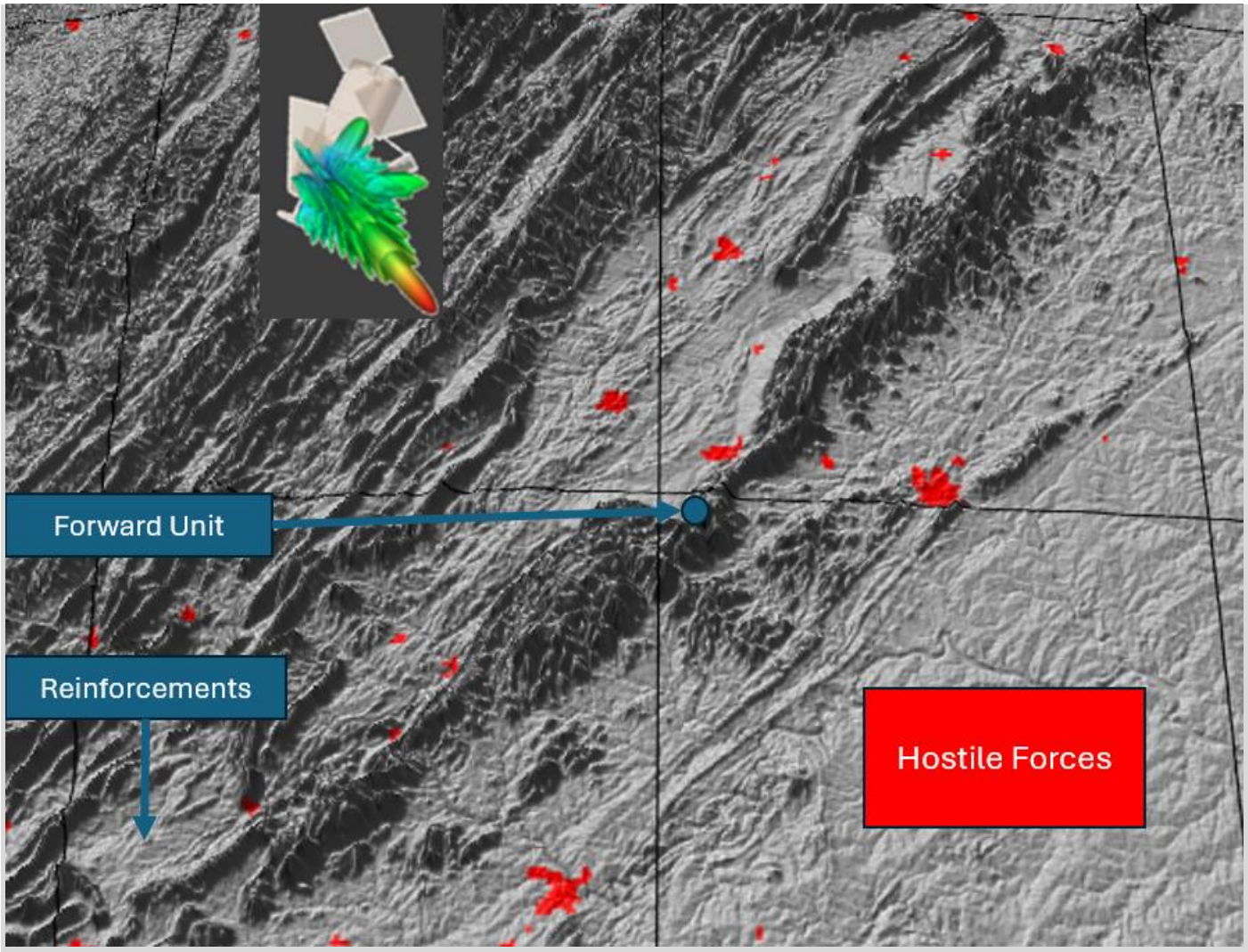


## Introduction

Studies regarding the projection of force on a modern battlefield almost always involve joint operations in which wireless communication between all assets is a key aspect. For beyond-line-of-sight communication, satellites play an important role, while for reasons of resilience and redundancy and low latency, multi-hop ground-based systems are needed as well. Concerning the assets involved, unmanned aerial vehicles (“drones”) are rapidly growing in importance.

In this white paper, a case study is presented in which a small military unit that has been deployed close to enemy forces needs to communicate beyond line of sight to call in reinforcements, e.g., a swarm of drones. To enhance resilience against jamming, the forward unit has access not only to Low Earth Orbit (LEO) satellites but also to a terrestrial link with repeaters. The paper describes how dedicated antennas have been designed to ensure low probability of detection by hostile forces, and how propagation and communication simulations ensure functioning communication links with modest transmit power.

A companion white paper [1] analyzes the feasibility of effective and agile jamming of the opponent by a swarm of collaborating drones that has been called in by the forward unit. That paper describes ultra-broadband compact antenna design to be able to jam any frequency, and the effectiveness of *collaborating* drones to jam a hostile communication system from a distance.

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### Challenges

In the scenario of interest, a small army unit has advanced to within line-of-sight range of hostile forces. This forward unit has to remain undetected and has to communicate with friendly forces that are stationed farther back, behind a mountain range. The unit's transmit antennas have to be small and lightweight, since this is a small, mobile unit. The antennas have to be powerful enough to make a reliable connection, and be designed to maintain low probability of detection by hostile forces while communicating. Low Earth Orbit satellites are attractive for communication over a mountain range, so those will be utilized. However, since satellites could be jammed, an additional terrestrial wireless link with repeaters will be designed and deployed to ensure resilient communications.

### Design Strategy

Since the satellite orbits and satellite antennas are usually given and cannot be changed, we start with a verification of the satellite communication links: the power budget and the availability. From here, requirements for the Earth station (the SatCom device carried by the mobile unit) are derived, upon which a suitable SatCom antenna is designed with low probability of detection in mind. The design of the terrestrial communication link starts with antenna design for the mobile unit, again with low probability of detection in mind. Once the properties of that system are known, the remainder of the link, a series of repeaters at well-chosen locations in the mountains to reach back-up forces, is designed. For all simulations the Altair® Feko® tool suite [2] is used.

### Communication via Low Earth Orbit Satellites

In preparation for communication via Low Earth Orbit (LEO) satellites, the simulation tool Altair WRAP™ [3] is used to ensure that the satellite constellation covers the location of interest, specifically with which satellites at what times and with how much power. To this aim, an orbital text file in Two-Line Element set (TLE) format [4] is imported into the tool. With this orbital information, in combination with satellite-borne antenna beamwidth and transmit power, so-called footprints at any location and at any day and time can be readily determined. Figure 1 shows an example.

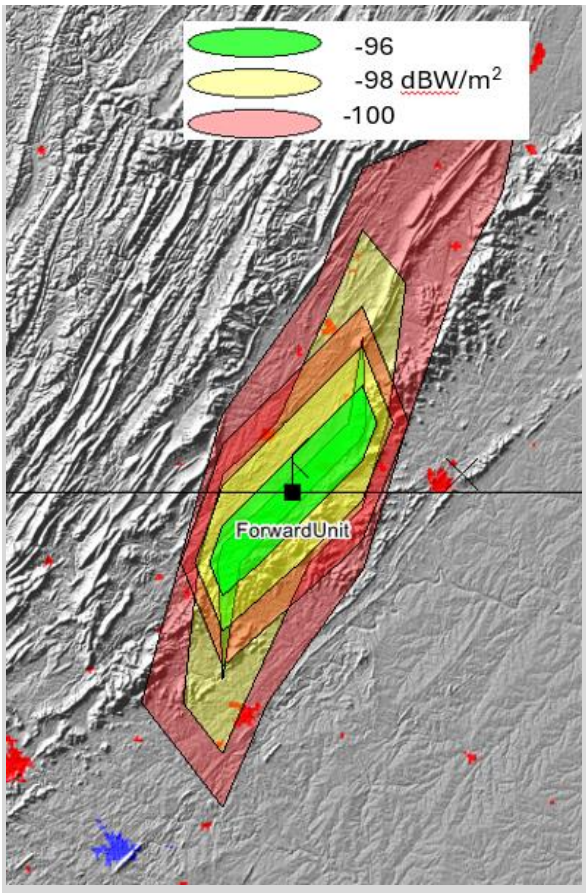


Figure 1 – Snapshot of two LEO Satellite Footprints at a Location and Time of Interest

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In addition, a convenient timing diagram can be produced that shows which satellites are available and with which potential power flux density (Figure 2). Different colors correspond to different satellites of which the orbits were imported via the TLE file; the horizontal scale shows a specific time interval during a day and time of interest; the vertical scale shows the available power flux densities from individual satellites at any point in time.

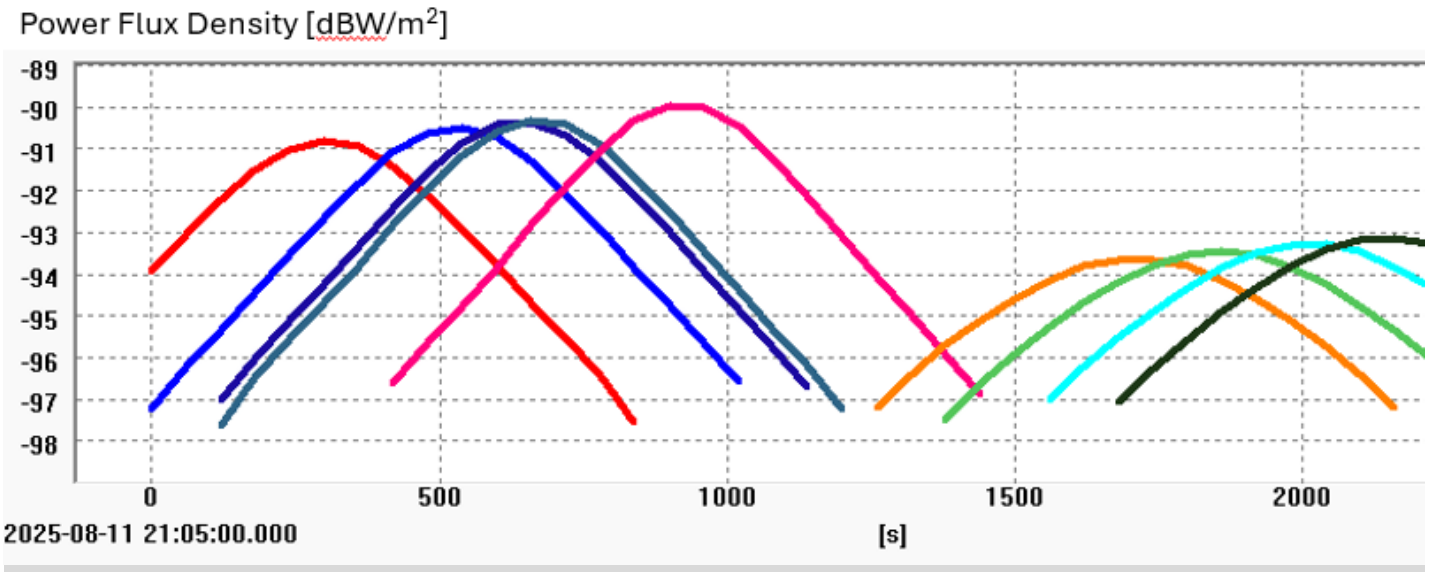


Figure 2 – Timing Diagram for the Location of Interest

The carrier frequencies are 12.75 GHz for uplink and 11.2 GHz for downlink. The power flux densities have been computed with ITU-R P.619 [5], a dedicated propagation model for Earth-Space communication. While it may be tempting to work with free-space equations, that would be too optimistic. In SATCOM, link budgets tend to be tight, and one cannot afford to overestimate the available power. ITU-R P.619 takes the following phenomena into account:

- Free-space loss (with visibility check)
- Attenuation due to hydrometeor depolarization
- Attenuation due to atmospheric gases
- Attenuation due to beam spreading
- Ducting-enhanced diffraction loss
- Ray bending
- Precipitation scatter

In this example, the satellite transmitter and antenna produce an Effective Isotropic Radiated Power (EIRP) of 46 dBW, which is the combination of 10 dBW transmit power and 36 dBi antenna gain. The satellite timing diagram shows that, at any instant in time, one can count on a power flux density of at least -96 dBW/$m^2$ at the location of interest, which is the location of the forward army unit. A power flux density of -96 dBW/$m^2$ means that 1 $m^2$ of surface area on the ground receives $10^{-9.6}$ W = 0.25 nW of power. This information is crucial to derive requirements for the ground-based receiver and antenna.

The ground-based antenna has to be easily portable by a mobile army unit, and has to be small enough to remain hidden, even when deployed. In spite of this, it should preferably have a decent antenna gain (to be determined) in the main beam, to avoid a high transmit-power requirement. This will limit how small the antenna can be. Furthermore, to reduce the probability of detection while transmitting, the side lobes should be as low as possible.

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This ground-based antenna has to work with a receiver system that has the following parameters:

- Signal bandwidth 20 MHz
- Receiver sensitivity -130 dBW
- Noise Figure 1 dB
- Desired bit rate 50 Mbit/s including error codes and overhead.

We will derive the minimum received signal strength from the required signal-to-noise ratio. From there, we derive the required antenna gain.

Knowing the signal bandwidth, the thermal noise power can be calculated from

$$N = k_B T B N_F$$

where $k_B = 1.38 \times 10^{-23}$ J/K, T is the temperature, B is the signal bandwidth, and $N_F$ is the noise figure. The result is

$$N = -129.8\ dBW = -99.8\ dBm\ .$$

Here, dBm stands for dB relative to 1 milliWatt. The next step is to determine the required signal-to-noise ratio. According to Shannon's theorem [6], the (theoretical maximum) channel capacity C is given by

$$C = B\ log_2\left(1 + \frac{S}{N}\right).$$

where S is the signal power. A channel capacity of 50 Mbit/s, using a bandwidth of 20 MHz, can be achieved theoretically when

$$\frac{S}{N} = 4.7 = 6.7\ dB\ .$$

In practice, the theoretical channel capacity cannot be achieved, and we choose to add a margin of 1 dB. With that, we obtain for the minimum received signal power

$$S = -129.8\ dBW + 6.7\ dB + 1\ dB = -122.1\ dBW\ .$$

From the WRAP results, we know that the power flux density is -96 dBW/m$^2$. In other words, an area of 1 m$^2$ receives -96 dBW. The receiving antenna has to have a large enough effective area to intercept -122.1 dBW. Hence, the antenna effective area $A_{eff}$ has to be

$$A_{eff} = -122.1\ dBW - -96\ dB\frac{W}{m^2} = -26.1\ dBm^2 = 0.0025\ m^2.$$

This effective area leads to a requirement for the gain at the receiving frequency, 11.2 GHz:

$$G = \frac{4\pi}{\lambda^2} A_{eff} = \frac{4\pi}{0.027^2} \times 0.0025 = 43 = 16.3\ dBi\ .$$

Figure 3 shows the antenna that was designed for this purpose.

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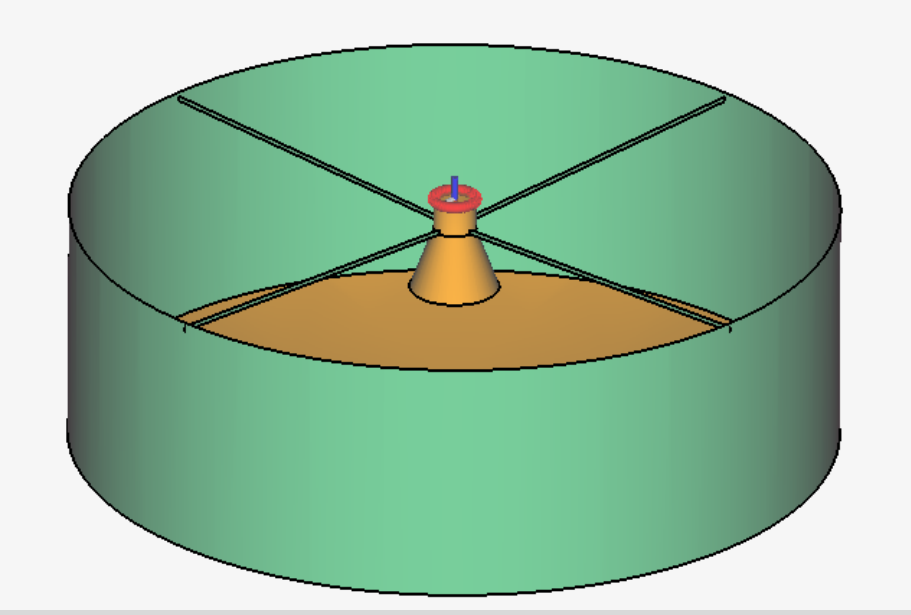

Figure 3 – Proposed Ground-Based Antenna for SatCom. Diameter 30 cm; height 9.6 cm.

The basic design is a dish antenna fed by a small horn with circular polarization. This was readily obtained from Feko's Component Library [7]. The initial antenna from the Component Library, which was fully parameterized, was modified easily to reduce the illumination of the edges of the dish, at a modest expense of the gain. This was a step towards side-lobe reduction. Further side-lobe reduction was achieved by placing a shroud around the rim of the dish. The shroud was made of metal coated with a 0.5 mm layer of absorbing material ($\varepsilon_r = 2.46$, $\tan(\delta_e) = 0.78$, $\mu_r = 3.14$, $\tan(\delta_m) = 0.70$). The resulting antenna pattern is shown in Figure 4.

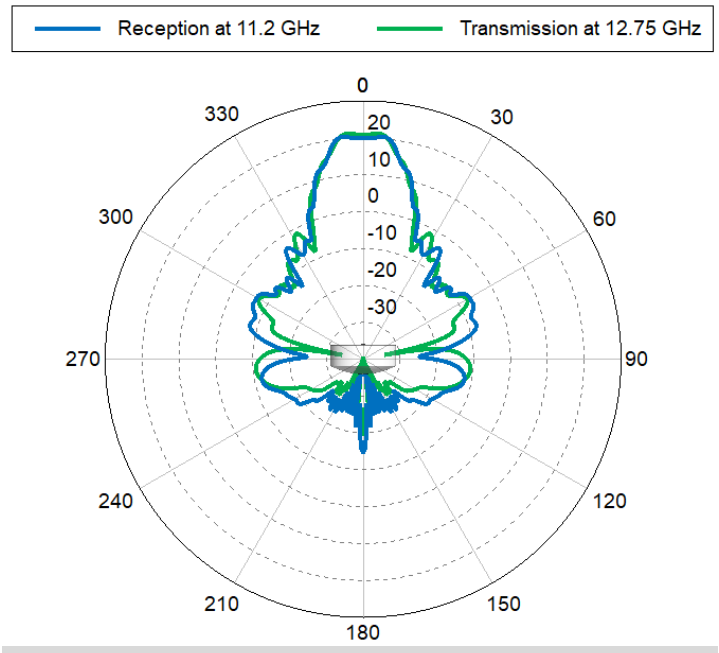


Figure 4 – Antenna Pattern [dBi] of the Ground-Based SATCOM Antenna

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Note that the peak gain is around 20 dBi. This is more than 3 dB higher than the required 16.3 dBi. This provides a useful margin.

Also note that the sidelobes past 40 degrees never exceed -7 dBi. Given that the antenna will be directed mostly upwards, the sidelobes past 40 degrees matter most for probability of detection by the opponent.

The former calculations were about the downlink. We have seen that the transmitting satellite system, with an Effective Isotropic Radiated Power (EIRP) of 46 dBW, produces enough power flux density on the ground to communicate via a receiving antenna of which the gain is at least 16.3 dBi (we actually had 20 dBi, but 16.3 dBi was the calculated minimum requirement). For the uplink, in first approximation, we can use reciprocity to estimate the required EIRP of the transmitting system on the ground. If the ground-based system were to have an EIRP of 46 dBW, then a space-based receiving antenna of 16.3 dBi would be sufficient. However, the space-based antenna has a gain of 36 dBi, which is 19.7 dB higher than the aforementioned 16.3 dBi. That means that the EIRP of the ground-based transmitter can be 19.7 dB lower than the aforementioned 46 dBW. For the ground-based transmitter, an EIRP of 46 dBW – 19.7 dB = 26.3 dBW would be sufficient. The EIRP, in dB, is the sum of gain and transmitted power. Since the gain of the antenna in Figure 3 is 20 dBi, as shown in Figure 4, a transmitted power of 6.3 dBW = 4.3 W is sufficient. This is a low power level, easy to achieve with a lightweight, mobile system.

### Communication via Terrestrial Repeaters

For the terrestrial communication link with repeaters, the LoRa (“Long Range”) technology [8] will be used. This is a technology that enables long-range communication with low power. It operates at frequencies around 900 MHz. Hence, in addition to the SatCom antenna, the forward army unit will need a sub-GHz antenna, which will have to be lightweight and have low probability of detection. This antenna will be designed before repeaters are considered, because options for placement of the nearest repeater will be limited to locations that this antenna can reliably reach.

The starting point for this lightweight antenna is a Log-Periodic Dipole antenna, which is readily available from Feko’s Component Library. The directivity of a log-periodic dipole antenna is better than that of an omni-directional antenna. This better directivity reduces the required transmit power, while the beam is not too narrow to be pointed reliably by hand. The log-periodic dipole antenna was, however, not designed for low probability of detection: its back- and side lobes are significant. To suppress those, a wire-mesh shield is added, as shown in Figure 5.

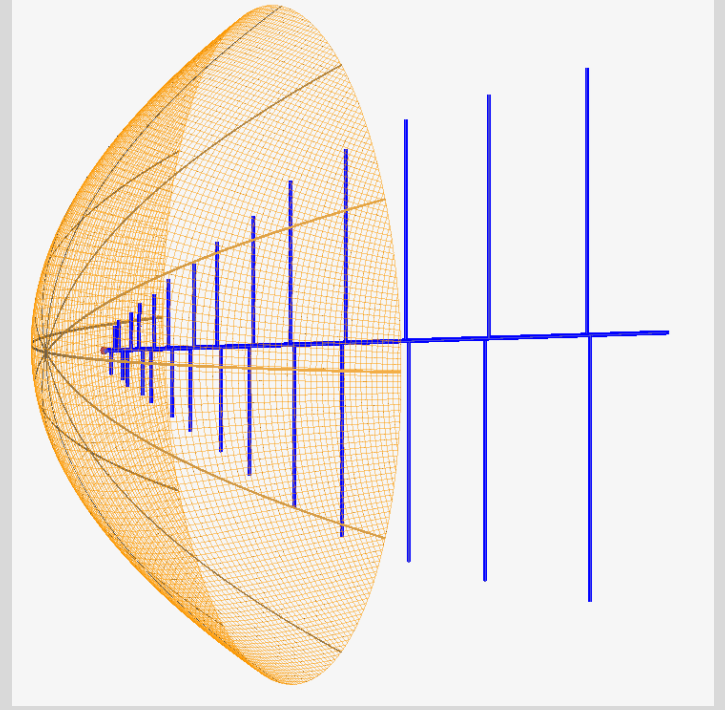

Figure 5 – Log-Periodic Dipole antenna for the forward army unit to connect to the nearest repeater. Antenna length 1.2 m; diameter 1.5 m.

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The antenna is not small, but is lightweight and can be folded. The radiation pattern is shown in Figure 6. The peak directivity is well above 10 dBi in a broad angular range, which makes manual operation easy, while the directivity sideways and in the back lobe is close to -10 dBi., which is beneficial for low probability of detection.

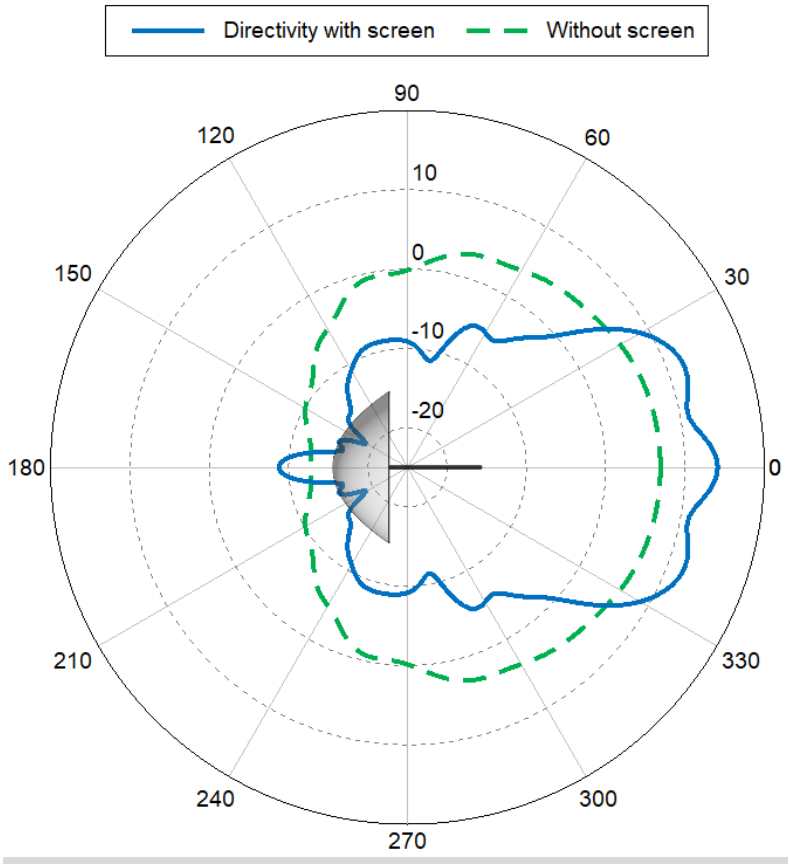


Figure 6 – Log-Periodic Dipole antenna pattern, with and without screen

The transmitter power is chosen to be 10 W. This is easily achievable with lightweight equipment, while it is expected to be sufficient to provide a suitable signal range for the scenario at hand.

For a given pre-planned forward position, on a ridge but not on a peak, because the unit is to remain undetected, candidate locations for repeaters can now be identified. Figure 7 shows the coverage of the log-periodic dipole antenna with screen when it's aimed in a certain direction by the forward unit. The hostile forces are in the southeast. The reinforcements are located behind mountains in a valley in the southwest corner of the map. The log-periodic antenna is ***not*** pointing towards the southwest, because multiple mountains are in the way.

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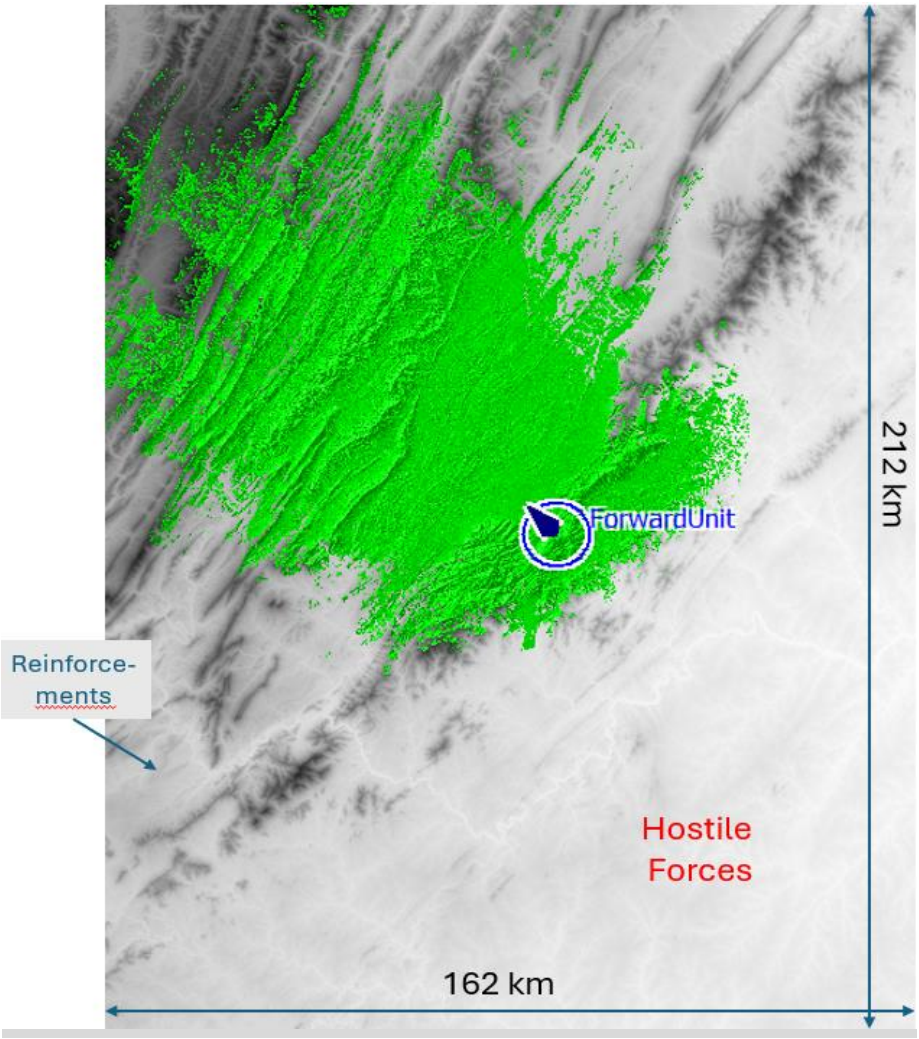


Figure 7 – Coverage of the log-periodic dipole antenna with screen

The coverage was determined with Altair WinProp™ [9]. This tool determines precisely where communication is possible, taking into account

- the radio-frequency propagation over terrain,
- the antenna patterns,
- the communication parameters of the transmission mode, such as the modulation, error-correction code rates, the required signal-to-noise-and-interference ratio,
- system parameters such as output power and receiver sensitivity
- network architecture with repeaters in a rural scenario [10].

Multiple repeaters will be needed to carry the signal over the mountains, especially since the repeaters will be omni-directional transmitters that are mounted not high off the ground (a height of 5 m has been chosen, e.g., in a small tree). Figure 8 shows how a succession of repeaters is able to carry the message to the destination. With LoRa technology, the data rate will not be sufficient for video, but high enough for voice and text. Since this is a back-up link, the lower data rate is acceptable.

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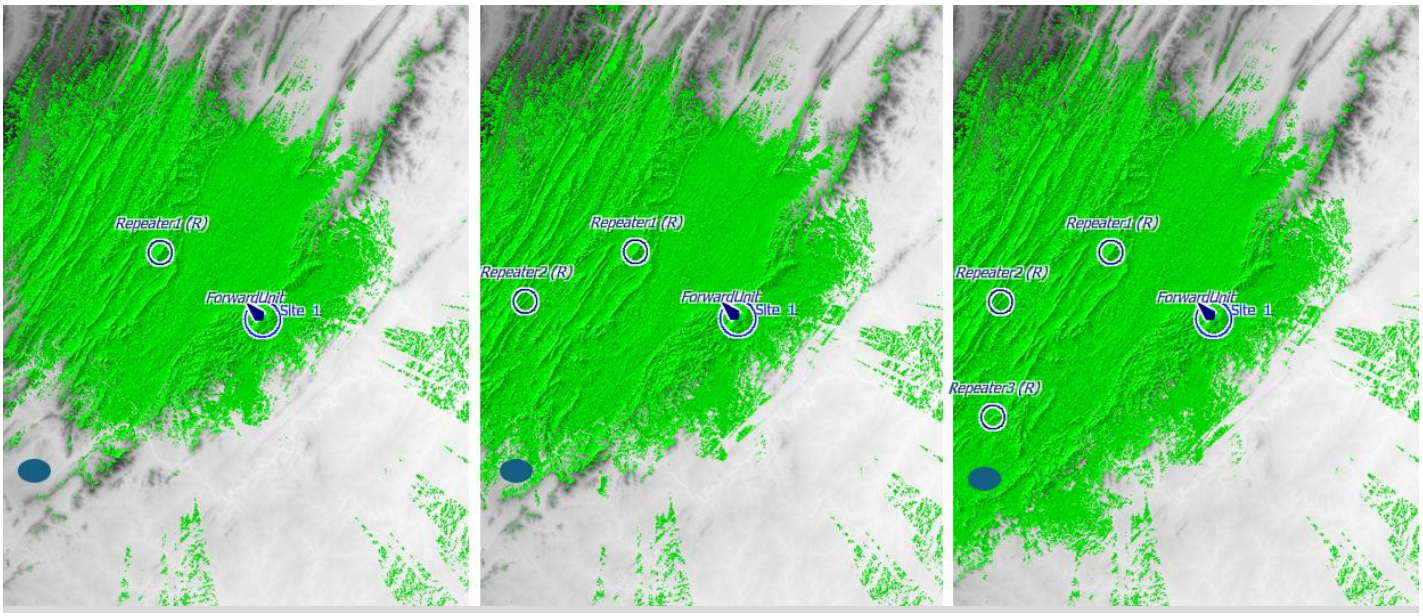


Figure 8 – Successive steps in repeater placement planning, and the resulting signal coverage

Note that the path of the successive repeaters takes a detour, in order to minimize the signal that reaches the hostile forces. Although a fraction of the signal from repeater 1 does reach the hostile forces, this signal is extremely weak, and would in the worst case only reveal the location of a small and remote unmanned low-cost device that the opponent might not even be able to access.

All these analyses are done in the planning phase. The mobile forward unit might take the repeaters along when setting out from the base camp towards the intended forward position, and place the repeaters at suitable locations along the way.

In a different scenario where a certain area needs to be covered by a larger number of repeaters, the Cost and Coverage Optimizer [11] in WRAP could be used. This tool automatically finds the optimum distribution, taking into consideration the device parameters, the topography, no-go areas like lakes and swamps and almost-vertical slopes, maximum number of devices, and other user-defined constraints.

## Conclusion

The Feko tool suite, which includes WinProp and WRAP software, was used to ensure resilient and reliable beyond-line-of-sight wireless communications, both via space with Low Earth Orbit satellites and terrestrial with repeaters. To achieve low probability of detection for the mobile forward army unit in the hostile environment, dedicated antennas were designed that minimize low side- and back lobes while maintaining small size and low weight.

References

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