Application of Google Inc. for Certification to Provide Spectrum Access System and Environmental Sensing Capability Services

GN Docket No. 15-319

Appendix B: Environmental Sensing Capability (ESC) Siting Considerations

Summary

The maximum distance between ESC sensors, assuming a simplified linear oceanic coastline and redundant coverage, is $L = (R^2 - D^2)^{½}$, where D is the distance from the coastline that must be monitored for radar activity, and R is the distance over which an ESC sensor can detect a radar. For conservative inputs of D = 120 km and R = 150 km, the spacing is L = 90 km. At this spacing, every area of coastline out to a distance of D = 120 km is visible by at least two sensors. However, the maximum spacing between sensors becomes greater if the coastline need not be monitored so far out, and/or if sensors are able to detect activity out to greater distances (R). For example, for D = 70 km and R = 150 km, the maximum spacing becomes 132 km.

1. Introduction

The location of ESC sensor nodes along the coastline depends on the following considerations:

1. How far a sensor can detect an operating radar;
2. The distance from the coastline within which a radar must be detected; and
3. The necessity for redundant coverage.

The first parameter in turn depends on the characteristics of the radar signal (namely, its Effective Isotropic Radiated Power, or EIRP), propagation loss between the radar and the ESC sensor, and the sensitivity of the ESC sensor. The second parameter is determined by operational and security requirements dictated by the radar operator. The third parameter is a factor in determining the allowable spacing along the coast between sensor nodes. (Redundancy decreases the maximum allowable separation between nodes.)

This appendix provides a basic analysis of these design parameters and requirements and concludes with an estimate of the number of sensor nodes required to cover the oceanic coastline of the United States given these inputs.

2. Radar Characteristics

Google derives the radar's characteristics from a variety of sources.[1] The most important considerations are the EIRP and polarization of the radar signal, which are as follows:

- EIRP = +122 dBm
- Polarization: Horizontal or Circular

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[1] *See, e.g.*, Gary Locke and Lawrence Strickling, *An Assessment of the Near-Term Viability of Accommodating Wireless Broadband Systems in the 1675-1710 MHz, 1755-1780 MHz, 3500-3650 MHz, and 4200-4220 MHz, 4380-4400 MHz Bands* (2010) (NTIA Fast Track Report), https://www.ntia.doc.gov/files/ntia/publications/fasttrackevaluation_11152010.pdf.

3. Radio Propagation

It is assumed that ESC sensor nodes will be located on or within roughly 10 km of the coastline, with a clear and unobstructed view of the ocean. Propagation loss over the open ocean was modeled using the National Telecommunications and Information Administration (NTIA) Institute for Telecommunications Sciences (ITS) Irregular Terrain Model (ITM), an implementation of the Longley-Rice propagation model. Specifically, Google used the implementation of ITM as distributed in NTIA's Microcomputer Spectrum Analysis Models (MSAM) software.[2]

The following inputs were provided to the model:

- ESC sensor site
    - Latitude: N 36d 53m
    - Longitude: W 75d 59m
    - Antenna height above ground level: 45.7 m (150 ft)
- Radar location
    - Various distances between 10 and 300 km from ESC sensor site, along constant bearing of 90 deg true
    - Antenna height above water: 45.7 m (150 ft)
- Propagation model parameters
    - Dielectric constant of ground: 81 (appropriate for seawater)
    - Conductivity of ground: 5 S/m (appropriate for seawater)
    - Surface refractivity: 301 N-units (standard atmosphere)
    - Polarization: Horizontal[3]
    - Radio Climate: Maritime Temperate, Over Sea
    - Frequency: 3650 MHz
    - Time and Situation Variability: (10,10), (50,50), (90,90)[4]

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[2] NTIA, *Microcomputer Spectrum Analysis Models*, http://ntiacsd.ntia.doc.gov/msam/.
[3] The propagation models support only vertical or horizontal polarization, and Google's sensing antennas will be horizontally-polarized.
[4] Propagation loss will exceed the F(10,10) value 90% of the time and in 90% of situations (measurement setups); propagation loss will exceed the F(50,50) value 50% of the time and in

Figure B-1 shows the results of the propagation simulation using the inputs above.

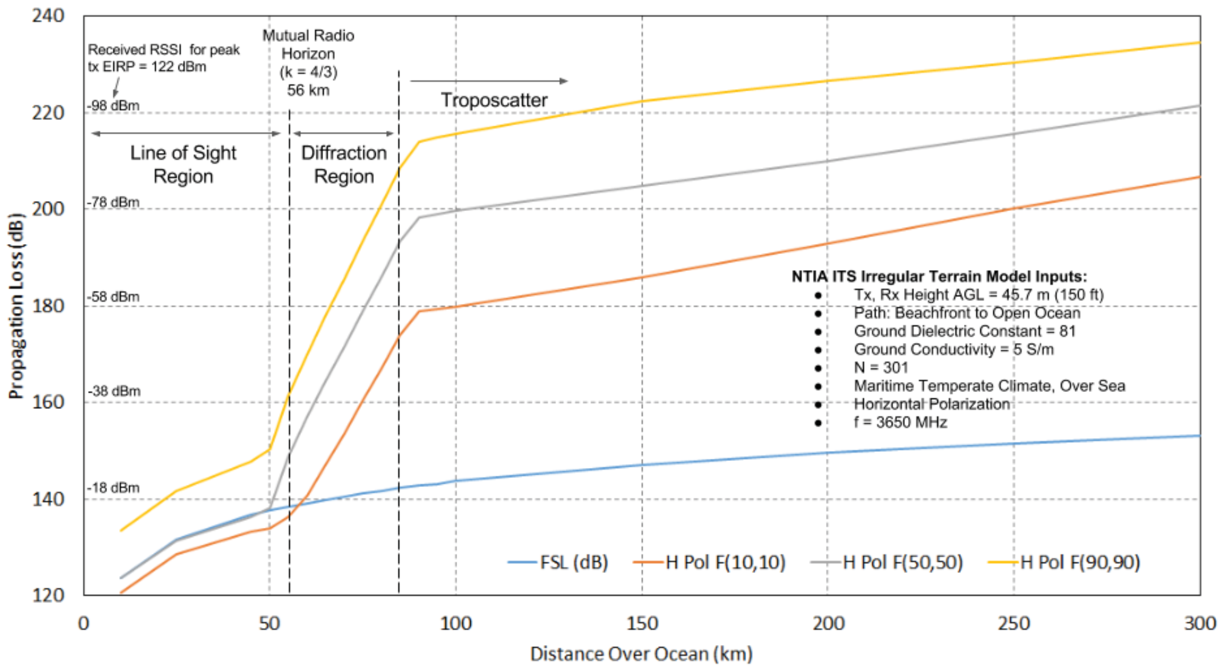

Figure B-1: Propagation loss over open ocean.

Three regions of loss are shown: the line of sight region where the transmitter and receiver have mutual radio visibility; the diffraction region where the transmitter and receiver are beyond the radio horizon from one another; and the troposcatter region, where the dominant propagation mode is scattering off of index of refraction irregularities in the atmosphere.

4. ESC Sensitivity

Figure B-1 includes the signal strength of the radar in dBm as received by an isotropic antenna, assuming a peak EIRP of the transmitted signal of +122 dBm. Under these circumstances, a sensitivity of -100 dBm is sufficient to detect the radar at a distance of approximately R = 150 km. Since the dominant propagation mode at these distances is troposcatter, signal polarization and a slight uptilt of the transmit antenna will have little impact on the received signal strength,[5] because the signal is scattering off of index of refraction irregularities in the atmosphere, and the scattering process generally results in depolarization of the signal. We expect the ESC nodes to have equivalent isotropic sensitivity better than -100 dBm, and therefore, they will be capable of detecting radar activity to at least 150 km.

50% of situations; and propagation loss will be less than the F(90,90) value 90% of the time and in 90% of situations.

[5] The radar antenna can be operated with an uptilt ranging from 0 to 6 deg from horizontal.

5. Required Detection Distance

Within the ESC Task Group of the Wireless Innovation Forum (WinnForum) Spectrum Sharing Committee, the distance over which an operating radar must be detected has been preliminarily derived based on interference-to-noise (I/N) considerations of interference to the radar receiver. That analysis determines that the radar must be protected to a distance corresponding to a propagation loss of 184 dB. Based on the ITM analysis in section 3, the corresponding distance is approximately D = 70 km, based on F(90,90) time and situation variability (i.e., near worst-case). The discussion of appropriate values of the loss and distance is still underway in the WinnForum ESC Task Group and may require modification of this analysis.

6. Detection Geometry (Non-redundant Coverage)

Figure B-2 shows a highly simplified geometry of ESC sensor placement that ensures coverage along the coastline out to a given detection limit. The diagram illustrates the maximum separation distance in terms of the required detection distance D (section 5) and the sensor detection distance R (section 4). From these values, the maximum separation along the coast among neighboring sensors can be derived:

$$L_{max,1} = 2\sqrt{R^2 - D^2}, \quad \text{(B-1)}$$

and each sensor covers an area of coastline:

$$A_1 = D\sqrt{R^2 - D^2}, \quad \text{(B-2)}$$

where the subscript *max* refers to the maximum distance between the two nodes such that the coastline is covered to a distance of D, and 1 refers to single (non-redundant) coverage of every point off the coast within that distance. Note that the maximum distance between nodes depends on the relative size of R and D. If a sensor can only detect out to the minimum distance of D, then, theoretically, an infinite number of nodes is required, one at every mathematical point along the coast, in order that all points within D of the coastline are monitored.

Here, we've derived in equation (B-1) the maximum distance between sensors such that every point within a distance D of the coast is covered by at least one sensor. If the spacing were any greater, then some areas within D of the coast would not be covered by any sensors. Even in this case, where separation is equal to $L_{max,1}$, there is a small area of overlapping coverage between neighboring nodes (i.e., where the semicircles of radius R, denoting the sensor detection distance, overlap halfway between the nodes). However, for separation distances between nodes given by equation (B-1), the majority of the oceanic coastline within a distance D is covered by only one sensor.

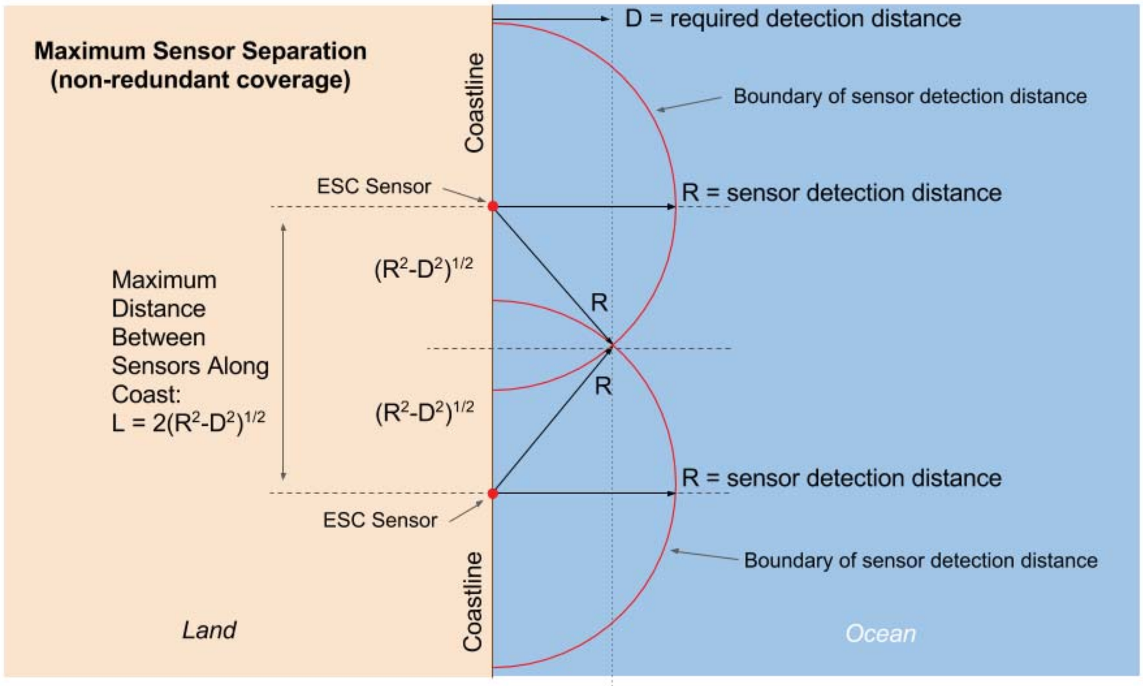

Figure B-2: Geometry of ESC sensor placement for non-redundant coverage.
The locations of neighboring sensor nodes are indicated by the two red dots, and the radius over which they are capable of detecting radar activity is shown by red semicircles. The distance beyond the coastline over which the radar must be detected is D, which is indicated by the dotted vertical line.

7. Detection Geometry (redundant coverage)

Ideally, an ESC sensor network will be deployed such that the coastline out to a distance D is covered by a minimum of two sensors. Two sensors could be co-located to meet this objective, but are then subject to correlated failures (for example, a localized power outage). An alternative is that each sensor node provides overlapping coverage for the neighboring sensor nodes. For example, the coastline out to a distance D, north of one sensor, is also covered by the sensor to the north, which has coverage back to the south. That way, the coastline between the two sensors (to the north of the first one and to the south of the other) is covered by the two sensors, and a temporary outage of one of the two sensors does not leave the area between them unmonitored. The geometry of the redundant coverage case is shown in figure B-3, where each point within D of the coastline is covered by at least two sensors. To provide redundant coverage, sensor nodes must be closer together than the distance calculated in equation (B-1), by a factor of two:

$$L_{max,2} = \sqrt{R^2 - D^2} \quad \text{(B-3)}$$

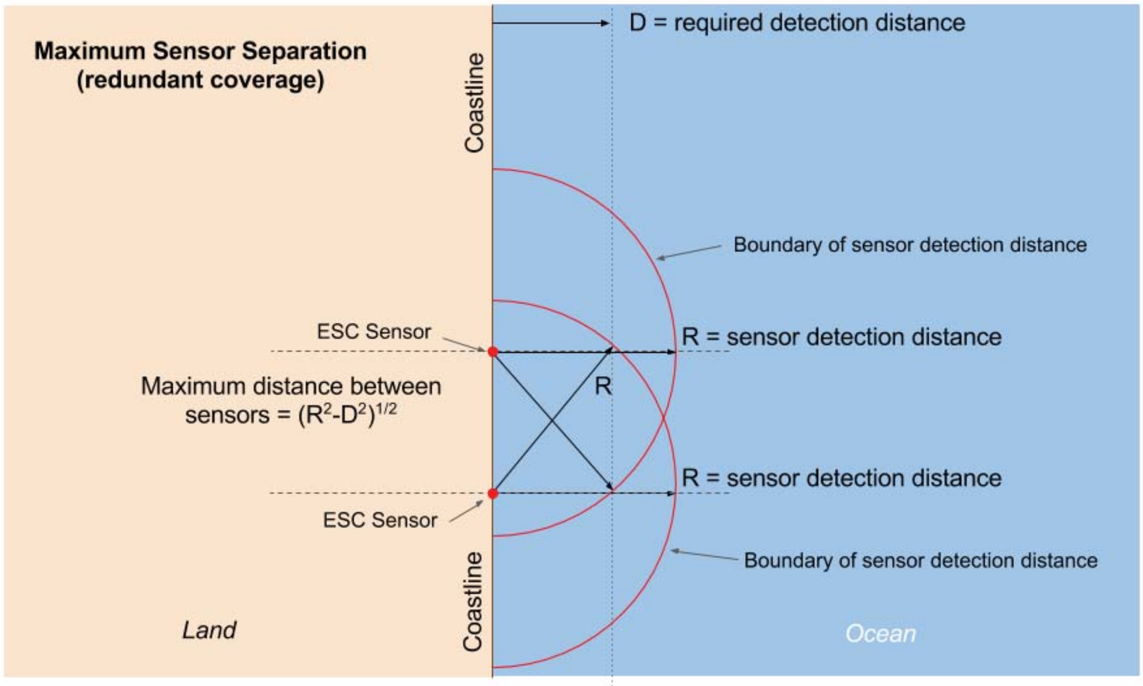

Figure B-3: Geometry of ESC sensor placement for redundant coverage.
All points between the two sensor nodes out to a distance D from the coastline are covered by both sensors.

8. How Many Sensors are Needed to Cover the U.S. Coastline?

The minimum number of sensors required to cover the oceanic coastline of the United States is determined by dividing the length of the coastline by the maximum separation between sensor nodes. The length of the coastline has been determined by the National Oceanic and Atmospheric Administration[6] and is incorporated in table B-1. The United States has substantial non-oceanic coastlines (for example, the Great Lakes and the St. Lawrence River) not included in table B-1, but the geometry of those areas and the extent of military radar activity in the vicinity of those coastlines requires additional study.

A rough estimate of the number of sensors needed for a redundant ESC network is obtained by dividing the coastline measurements in table B-1 by the distance between sensor nodes in equation (B-3). Conservatively, we assume that the sensor detection threshold distance is R = 150 km, and the required detection distance is D = 120 km (65 nm). Then, the maximum spacing between nodes, from equation (B-3), is 90 km, and the number of sensor nodes required is listed in column 3 of table B-1. Alternatively, if D = 70 km (Longley-Rice loss = 184 dB) and R remains 150 km, the required maximum spacing is 132 km, and the number of sensor nodes is shown in column 4 of table B-1.

[6] U.S. Department of Commerce, National Oceanic and Atmospheric Administration, *The Coastline of the United States*, NOAA/PA 71046 (1975), *available at* http://shoreline.noaa.gov/_pdf/Coastline_of_the_US_1975.pdf.

Region	General Coastline (km)	Number of Sensor Nodes, L = 90 km	Number of Sensor Nodes, L = 132 km
Atlantic	3,330	37	25
Gulf of Mexico	2,625	29	20
Pacific (not including Hawaii or Alaska)	2,081	23	16
Total Contiguous United States	*8,036*	*89*	*61*
Hawaii (Pacific)	1,207	13	9
Alaska (Pacific + Arctic)	8,980 + 1,706 = 10,686	100 + 19 = 119	68 + 13 = 81
U.S. Possessions and Territories (Atlantic and Pacific)	710 + 336 = 1,046	8 + 4 = 12	5 + 3 = 8
Total U.S. Coastline (without and with Alaska)	*10,289/20,975*	*114/233*	*78/159*

Table B-1: Approximate number of ESC sensor nodes required to cover the U.S. coastline.
This table assumes D = 120 km and R = 150 km (corresponding to a maximum separation between nodes of 90 km), and D = 70 km and R = 150 km (corresponding to a maximum separation between nodes of 132 km).

Because the oceanic coastline of the United States does not match the ideal straight line assumed in the derivation of equation B-3, the actual number of sensor nodes will vary from those derived in the table. Regions where the coastline is concave will reduce the required number of nodes, for example. Figure 4 in section 2.5.3 shows a notional deployment of sensors along the Atlantic/Pacific/Gulf coasts that meets the redundant coverage requirement, assuming the same values of D = 120 km and R = 150 km used in table B-1. In that simulation, the total number of nodes required to cover the coastline of the contiguous landmass of the United States is 103, compared to 89 in this simulation. Most of the difference is the result of coverage surrounding the complex coastlines near the Florida keys, Chesapeake Bay, the Massachusetts coast, and Puget Sound. The placement of sensors in the notional deployment scenario has not been optimized, and Google believes that effective coverage can be obtained with fewer sensors.