NTIA Technical Memorandum TM-13-492

Antenna Selection for Monitoring of Airborne Radio Systems

Frank H. Sanders

technical memorandum

U.S. DEPARTMENT OF COMMERCE • National Telecommunications and Information Administration

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November 2012

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CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

ABBREVIATIONS/ACRONYMS

ITS	Institute for Telecommunication Sciences (NTIA)
NTIA	National Telecommunications and Information Administration
RF	radio frequency

ANTENNA SELECTION FOR MONITORING OF AIRBORNE RADIO SYSTEMS

Frank H. Sanders[1]

This Technical Memorandum describes a process for selecting an appropriate antenna for monitoring radio signals from airborne transmitters. A mathematical formula for the optimal receiver antenna gain is presented. This formula takes into account the factors of minimal required signal-to-noise ratio of signals in a monitoring receiver, airborne radio transmitted power and antenna gain, airborne radio height and resulting maximal line-of-sight coverage, free-space propagation loss, airborne radio signal bandwidth, monitoring system bandwidth, and the sensitivity of the monitoring system's receiver. The optimal monitoring antenna gain is calculated as a function of elevation angle above the local horizon. That function is used to select an antenna type that will receive signals from as many airborne radios as possible. A worked example of the selection process is presented. Although it is assumed that a terrestrial system will be used for monitoring, the process can be applied to antennas for marine and airborne monitoring systems as well.

Key words: airborne signals; antenna gain; RF measurement; RF monitoring

1 PROBLEM STATEMENT

1.1 Introduction

With increasing emphasis being placed on more efficient and effective spectrum use [1], monitoring[2] has become more important for spectrum engineers, spectrum managers, and policy makers. The receivability of signals generated at or near ground level is significantly affected by propagation factors including terrain, vegetation, structures, and atmospheric conditions between transmitters and monitoring stations; the designs and data outputs of monitoring stations must take into account these terrestrial coverage limitations.

The propagation of signals from airborne platforms to many terrestrial localities with minimal obstructions on the local horizon, in contrast, is minimally affected by terrain, vegetation, and structures. Atmospheric effects can still be significant, but to a first order of approximation, the line-of-sight (LOS) propagation of airborne signals to ground stations may be treated as free space. This unique aspect of airborne signals forms the basis of a tractable problem for the design of terrestrial systems that are to monitor the activity of airborne signals. That problem is to make an optimal choice for receiver antennas that are to be used for such monitoring. This

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[2] In this memorandum, monitoring refers to measurement of types, durations, received power levels, and spectra of radiated signals in an outdoor environment.

Technical Memorandum describes a process for optimally choosing antennas for terrestrial systems to monitor airborne signals, and provides an example for a real-world scenario. The same process may also be applied to maritime airborne monitoring platforms.

This analysis assumes that the goal is to observe all airborne signals within a given band that originate from platforms within LOS of the monitoring stations or 4/3 Earth distance of those stations, as described below. This methodology is therefore applicable to all frequency ranges above the high frequency (HF) part of the spectrum where over-the-horizon propagation factors are significant.

1.2 Methodology for Selecting Antennas for Monitoring Airborne Signals

The methodology for selecting appropriate and optimized antennas for observing airborne signals at terrestrial monitoring stations is based on first identifying the physical factors that will affect the reception of airborne signals. With those factors identified, the methodology identifies the factor that *most limits* the reception of airborne signals at monitoring stations. A corresponding monitoring antenna parameter (e.g., gain) is then selected which performs well enough to meet that particular limitation and assure that all airborne signals originating within LOS of monitoring stations will be received; that selection ensures that a maximal number of airborne signals will be received by monitoring stations. With the degree of freedom represented by that parameter having been determined, remaining antenna factors are optimized for such elements as LOS coverage. A set of optimal monitoring antenna parameters results from the process.

The coverage of radio frequency (RF) monitoring stations is limited by the factors of transmitter power level, transmitter antenna gain, propagation loss factors, monitoring antenna gain, bandwidth of the transmitted signal, bandwidth of the monitoring system, and the sensitivity or noise figure of a monitoring receiver. To address the last parameter, monitoring stations (and monitoring strategies) should have a criterion for a minimal power level, S, where measured airborne signal power levels are to be received above internally generated receiver noise, N; that is, they should have a criterion for a minimal S/N ratio for airborne signal strength in monitoring station receivers.

In this study, transmitter power levels, transmitter antenna gains, transmitter frequencies, propagation losses, receiver sensitivity, monitoring system receiver bandwidth, and the minimum acceptable S/N ratio of airborne signals in monitoring receivers are treated as quantities that are pre-determined; they cannot be adjusted in the problem of optimizing monitoring station design. The remaining parameter, which may be adjusted, is receiver antenna gain.

This memorandum describes a procedure that:

1) Establishes the relationship between LOS separations between monitoring stations and airborne platforms, and flight altitudes above a smooth round Earth, for the condition in which airborne platforms would be at zero-degree elevation angles (and maximal LOS distance) relative to monitoring stations.

2) Uses the result of (1) above to determine the relationship between separation distances and elevation angles *above* monitoring station horizons for airborne platform altitudes that are

higher than the minimum altitudes required to be at zero-degree elevation angles at monitoring station locations.

3) For both LOS distances and 4/3 Earth distances, determines the relationship between:

   - Transmitted airborne signal effective isotropic radiated power (*EIRP*)
   - Frequency of airborne platforms
   - Distance between airborne transmitters and monitoring stations
   - Monitoring station receiver sensitivity
   - On-tuned rejection factor
   - Monitoring system antenna gain
   - Received *S/N* ratios at monitoring stations

4) Determines optimal monitoring system antenna gain and elevation beam coverage angles using the information above.

A worked example is provided to demonstrate the application of the methodology above.

2 MONITORING SYSTEM SIGNAL RECEPTION CALCULATIONS

2.1 Elevation Angles of Airborne Transmitters Above Horizon at Given Distances on a Smooth Round Earth

2.1.1 Maximum Smooth Round Earth LOS Distances. The geometry between the height, h, of a point X above the surface of a smooth round Earth and the LOS distance, d_{LOS}, from that point to a point P on the horizon is shown in Figure 1. The right triangle formed by the two legs r_{Earth} and d_{LOS} and the hypotenuse ($r_{Earth} + h$) gives the exact relationship depicted in Figure 1,

$$r_{Earth}^2 + d_{LOS}^2 = (r_{Earth} + h)^2 = r_{Earth}^2 + h^2 + 2hr_{Earth}, \tag{1a}$$

which reduces to

$$d_{LOS}^2 = h^2 + 2hr_{Earth}. \tag{1b}$$

Earth's mean radius, r_{Earth}, is 6371 km (3959 statute mi). A high altitude for an airborne platform is 30 km (100,000 ft or about 19 mi) and a low Earth orbital altitude is about 160 km (100 mi), as shown in Figure 1. Even if an airborne platform were at an orbital altitude of 160 km, which is $^1\!/_{80}$ of $2r_{Earth}$, the condition $h << 2r_{Earth}$ holds and (1b) reduces to

$$d_{LOS} \approx \sqrt{2hr_{Earth}} \tag{2}$$

for platforms as high as low Earth orbit. In units of kilometers, (3) reduces to $d_{LOS} = 113\sqrt{h}$. The result is accurate to within 0.6 percent of the true LOS distance even at h =160 km.

2.1.2 4/3 Smooth Round Earth Distances. Tropospheric radio propagation at frequencies above HF (about 50 MHz) is normally reliable at distances in excess of d_{LOS}, out to a distance in which the radius of the Earth in (2) is made larger than its true value by a factor of 4/3 as described in [2] and [3]. When this 4/3 Earth (radius) distance is calculated using (2) with units of kilometers, the result is $d_{4/3Earth} = 130\sqrt{h}$.

2.1.3 Elevation Angles of Airborne Platforms Above Monitoring Station Horizons. The geometry of Figure 1 places an airborne platform at point X exactly on the horizon of a monitoring station at point P; a platform at X is at a zero elevation angle as seen from P. If an airborne platform at a point X is at an altitude that exceeds h by an amount Δh, as shown in Figure 2, then the platform's elevation angle as observed from P will exceed zero. If the actual distance from P to a platform at height $h_{total} = (h + \Delta h)$ is still approximately d_{LOS}, (i.e., when $\overline{PX}$ in Figure 2 is nearly equal to d_{LOS}), then

$$\theta \approx tan^{-1}\left(\frac{\Delta h}{d_{LOS}}\right) \tag{3}$$

and from (2) and the geometry portrayed in Figure 2,

$$\Delta h = (h_{total} - h) \approx \left[h_{total} - \left(\frac{d_{LOS}^2}{2r_{Earth}}\right)\right]. \tag{4}$$

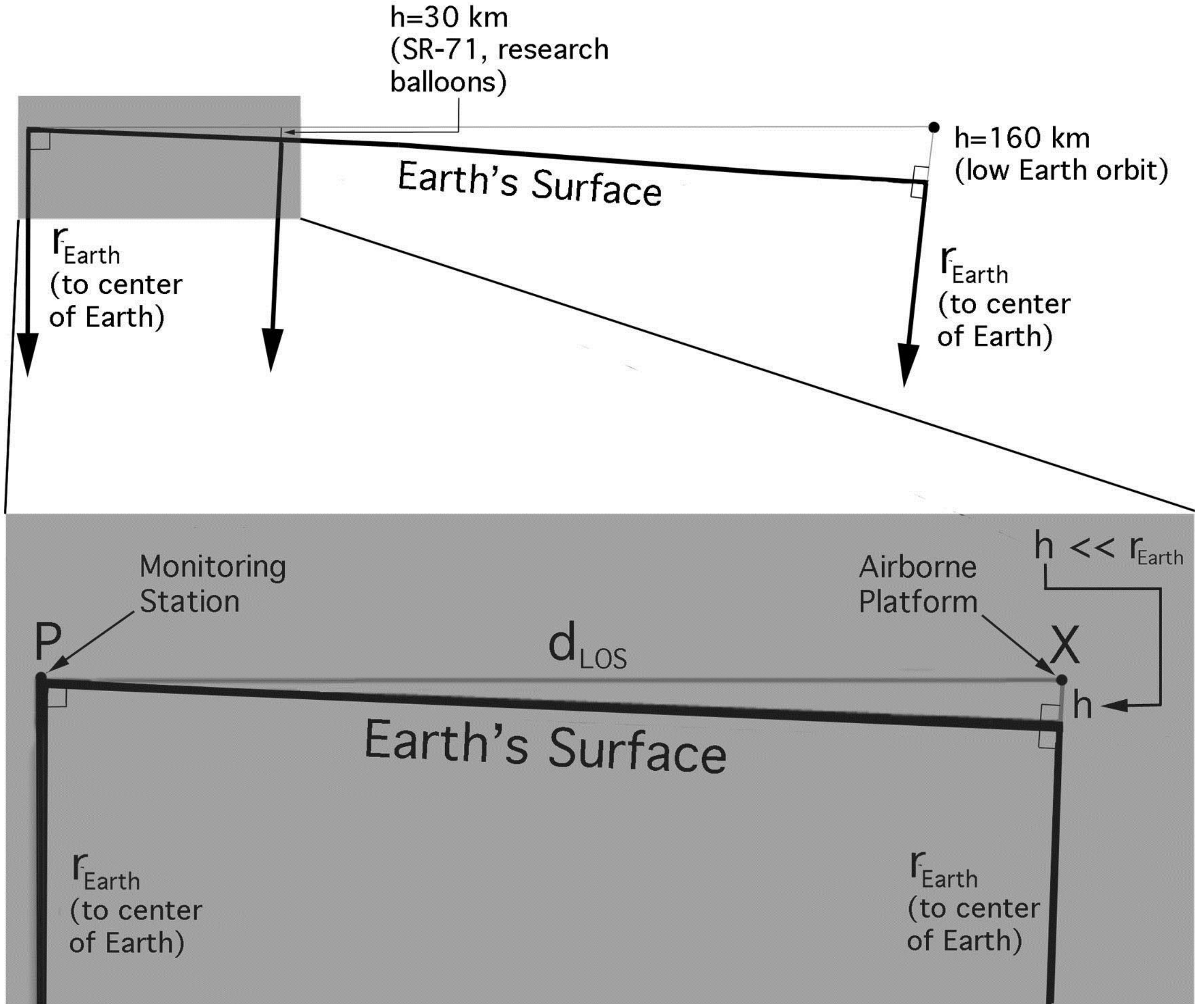

Figure 1. *Top*: Altitudes of low Earth orbit and high-altitude atmospheric platforms shown at true scale relative to the curvature of the Earth's surface. *Bottom*: Expanded true-scale diagram of line-of-sight horizon limit for airborne platforms at 30 km (100,000 ft) altitude. Most airborne platforms operate below this altitude.

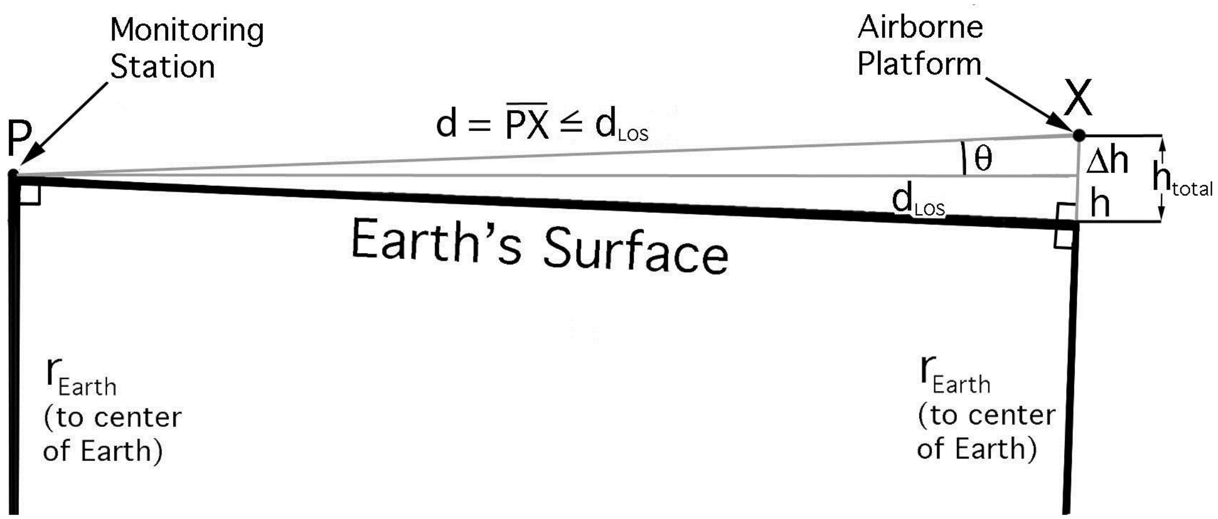

Figure 2. Elevation angles of airborne platforms as seen at monitoring stations when the platform altitudes exceed the minimum height, *h*, required for minimal line of sight coverage (zero elevation angle) at monitoring stations. This figure shows true-scale geometry for a platform at 60 km (200,000 ft) feet altitude; such altitudes are usually only achieved by sounding rockets.

Combining (3) and (4), the elevation angle, θ, of a platform at point X in Figure 2 relative to a monitoring station when its distance, d, is less than or equal to d_{LOS} is

$$\theta \approx tan^{-1}\left[\frac{h_{total}-\left(\frac{d^2}{2r_{Earth}}\right)}{d}\right] = tan^{-1}\left(\frac{h_{total}}{d} - \frac{d}{2r_{Earth}}\right). \tag{5}$$

Referring to Figure 2, when $\overline{PX} = d$ is no longer large compared to h_{total}, the ratio of d to $2r_{Earth}$ approaches zero, h becomes small, h_{total} approaches Δh, and $\overline{PX} = d$ becomes the base leg of the angle θ. For small angles this reduces (5) to the conventional relation of

$$\theta = sin^{-1}\left(\frac{h_{total}}{\overline{PX}}\right) \approx tan^{-1}\left(\frac{h_{total}}{\overline{PX}}\right). \tag{6}$$

We consider airborne platforms to be far enough from monitoring stations that $\overline{PX} = d$ is large compared to h_{total}; (5) is therefore used for this memorandum's analysis.

Results from (5) are graphed in Figures 3 and 4 for airborne platforms at altitudes between 1.5 and 10 km (5–33 kft).[3] These graphs show that, since most airborne platforms operate at or below 10 km altitude, at distances beyond 50 km (30 mi) most platforms are within 10 degrees of monitoring station horizons. This implies that monitoring antennas with beam angles that maximize gain within 10 degrees of local horizons will couple signals from most airborne platforms at distances of 50 km or more.

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[3] 1 kft = 1000 ft.

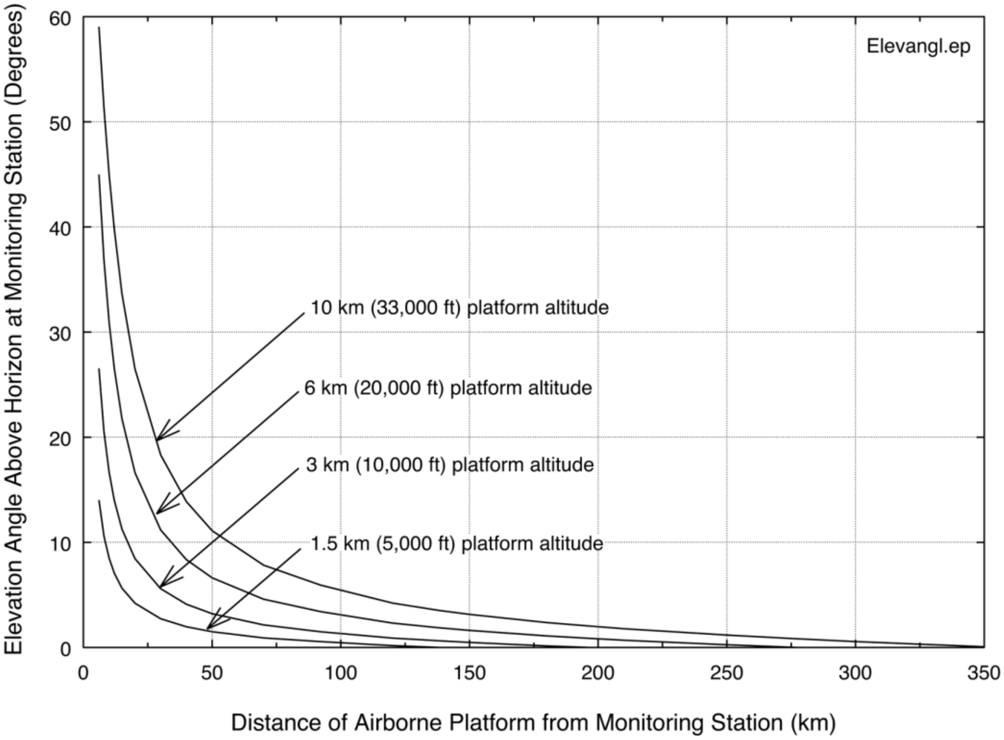

Figure 3. Elevation angles above a terrestrial monitoring station horizon for airborne platforms at various altitudes. Curves are plotted from (5); Earth curvature effect is therefore included.

2.2 Received *S/N* Level at a Monitoring Station via Free Space Propagation

The next step is to calculate the strength of the platform's signal in the monitoring station receiver via free-space propagation. This signal strength needs to be calculated relative to the ultimate limit of the receiver itself, namely the receiver's internally generated noise level. From (45) in [4],[4] and if the monitoring bandwidth is equal to or greater than the emission bandwidth,

$$P_r = EIRP + G_r - 32.5 - 20log(f) - 20log(r), \tag{7}$$

where:

P_r = power received in monitoring station circuitry (in units of the $EIRP$ parameter);[5]
$EIRP$ = airborne transmitter power, P_t, plus transmitter antenna gain, G_t (dBi);
G_r = monitoring station receiver antenna gain (dBi);
f = frequency[6] (MHz);
r = distance from airborne platform to monitoring station (km).

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[4] In this Technical Memorandum, physical quantities are in decibel units when they are represented in upper case and are in linear units when represented by corresponding lower case letters. The gain of an antenna relative to isotropic, for example, is $g = 1$ and $G = 10\log(g) = 0$ dBi.

[5] The received power units are the same as the units of the transmitted power.

[6] The dependence of this equation on frequency is *not* due to any physical frequency dependence in free-space propagation. The frequency term results from the wavelength-dependent definition of an isotropic antenna's effective aperture, as explained on page 12 of [4].

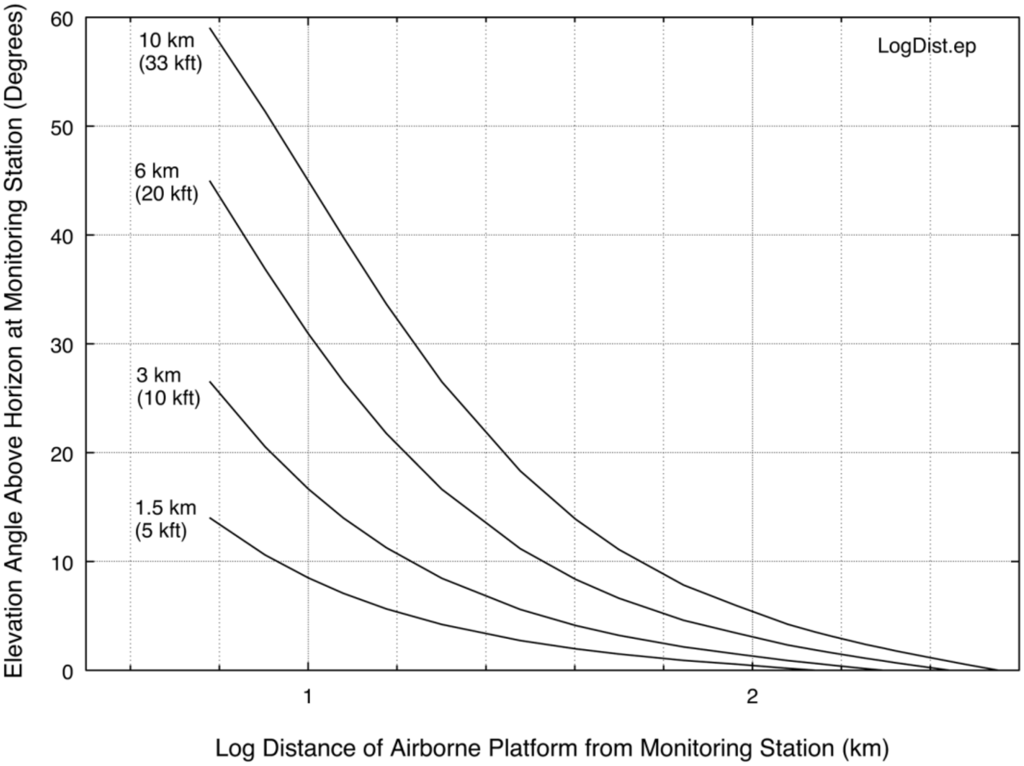

Figure 4. The curves of Figure 3, plotted with logarithms of distances between airborne platforms and monitoring stations. 1 kft = 1000 ft.

Above HF (about 50 MHz), a radio receiver is limited by internally generated thermal electron noise.[7] This noise is generated by two sources: unavoidable, random electron motion as described by statistical mechanics; and additional, excess noise that is introduced by circuit components such as mixer-downconverter stages in superheterodyne receivers. The first source is determined by Boltzmann's constant and the temperature of the receiver. The second source is a multiplicative factor (amplification) of the inherent noise and must be empirically determined. The total amount of noise power that is generated by both sources is proportional to receiver bandwidth. In decibel terms, the total amount of noise in a given bandwidth in any radio receiver is:

$$P_{noise} = 10log(ktb_{monitor}) + 10log(nf) = -174\ dBm + 10log(b_{monitor}) + NF, \qquad (8a)$$

where:

$b_{monitor}$ = receiver system bandwidth (Hz);
k = Boltzmann's constant ($1.38\cdot10^{-23}$ J/K);
t = monitoring station receiver temperature (taken to be 290 K);
nf = multiplicative noise factor of the receiver (dimensionless);
NF = noise figure = 10log(nf) (decibels).

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[7] At and below HF frequencies, noise from atmospheric and galactic sources is dominant over internally generated receiver noise.

10log(kt) = -204 dBW/Hz = -174 dBm/Hz. For P_{noise} in units of dBm and bandwidth in units of megahertz, a factor of 10log(10^6 Hz) = 60 dB is added to -174, and (8a) becomes

$$P_{noise} = 10\log(ktb_{monitor}) + 10\log(nf) = \left(-114\frac{dBm}{MHz}\right) + 10\log\left(b_{monitor(MHz)}\right) + NF. \tag{8b}$$

The airborne signals that are to be monitored need to be received at power levels, s, that are high enough to discriminate them from receiver noise, n, so as to properly analyze them. This desired power level is expressed as signal-to-noise ratio (s/n). In decibel terms, the notation used here is (S/N) = 10log(s/n) and an on-tuned rejection (OTR) bandwidth mismatch factor is included:

$$\frac{S}{N} = 10log\left(\frac{p_r}{p_n}\cdot\frac{b_{monitor}}{b_{emission}}\right) = 10log\left(\frac{p_r}{p_n}\cdot otr\right) = P_r - P_{noise} + OTR, \tag{9}$$

or

$$\frac{S}{N} = EIRP + G_r + 81.5 - 20log(f) - 20log(r) - 10log(b_{monitor}) - NF + OTR, \tag{10a}$$

where OTR (on-tuned rejection) is:

OTR = $10log\left(\frac{b_{monitor}}{b_{emission}}\right) = 10log(b_{monitor}) - 10log(b_{emission})$ and may not exceed zero;
$b_{emission}$ = emission bandwidth of the airborne radio system.

OTR accounts for reduction in measured power if monitoring bandwidths are less than emission bandwidths. The sign of *OTR* is negative, and if $b_{emission} \geq b_{monitor}$ then $OTR=0$.

OTR varies as *10log* of the ratio of monitoring bandwidth to emission bandwidth for average detection of high-duty cycle signals because power in a receiver bandwidth is ordinarily proportional to the receiver's bandwidth. However, *OTR* goes as *20log* of this ratio for peak-detected, pulsed signals such as from radars, as described in [5] and [6]. To achieve optimal *S/N*, monitoring system bandwidth should be less than or equal to airborne radio emission bandwidth.

Since $OTR = 10log(b_{monitor}) - 10log(b_{emission})$ under the condition that $b_{emission} > b_{monitor}$ (and *OTR*=0 otherwise), (10a) reduces in this case to

$$\frac{S}{N} = EIRP + G_r + 81.5 - 20log(f) - 20log(r) - NF - 10log(b_{emission}), \tag{10b}$$

with $b_{monitor}$ dropping completely out of the equation; *S/N* in this case depends only on $b_{emission}$.

Otherwise, for the condition $b_{monitor} \geq b_{emission}$, *OTR* = 0. This condition forces $10log(b_{monitor})$ to be retained while the $10log(b_{emission})$ variable drops out. In this case,

$$\frac{S}{N} = EIRP + G_r + 81.5 - 20log(f) - 20log(r) - NF - 10log(b_{monitor}). \tag{10c}$$

If a minimum *S/N* (e.g., 10 dB of signal) is required above measurement system noise, then (10b) and (10c) can be re-arranged to provide the minimum value of receiver antenna gain that is required to meet this measurement criterion. When $b_{emission} > b_{monitor}$:

$$G_r \geq \frac{S}{N} - EIRP - 81.5 + 20log(f) + 20log(r) + NF + 10log(b_{emission}). \tag{11a}$$

Otherwise, for the condition $b_{monitor} \geq b_{emission}$,

$$G_r \geq \frac{S}{N} - EIRP - 81.5 + 20log(f) + 20log(r) + NF + 10log(b_{monitor}). \tag{11b}$$

If the parameters of *S/N*, *EIRP*, *f*, *NF*, $b_{emission}$, and b_{monitor} are constrained by monitoring operation requirements, then the only free parameters in (11a) and (11b) are G_r and *r*. The minimum value of G_r will therefore be determined by all of the non-free parameters including the maximum possible value of *r*; the maximum value of *r* at which we need G_r to work is $d_{4/3Earth}$. This parameter can be incorporated into our calculations via the use of maximum operational altitudes of airborne platforms, as shown below.

2.3 Received *S/N* Level Versus Distance as a Limiting Factor in Monitoring Station Reception

With horizon-limited spatial coverage of an airborne platform's field of view established via (2) and (5), and the free-space signal strength from a platform's radio transmitter determined via (6), the next step in determining the limiting factor in a monitoring station's reception of a signal from the platform is to compare these two factors. With the altitudes of airborne platforms used in lieu of the distances, *r*, at which they are visible above monitoring station horizons, and under the condition that $b_{emission} > b_{monitor}$, (11a) becomes

$$G_{r,LOS} \geq \frac{S}{N} - EIRP - 81.5 + 20log(f) + 20log\left(113\sqrt{h}\right) + NF + 10log(b_{emission}) \tag{12a}$$

while for $b_{monitor} \geq b_{emission}$, (11b) becomes

$$G_{r,LOS} \geq \frac{S}{N} - EIRP - 81.5 + 20log(f) + 20log\left(113\sqrt{h}\right) + NF + 10log(b_{monitor}). \tag{12b}$$

Combining constants in (12a) and (12b) into one term,

$$G_{r,LOS} \geq \frac{S}{N} - EIRP - 40.4 + 20log(f) + 10log(h) + NF + 10log(b_{emission}), \tag{13a}$$

and

$$G_{r,LOS} \geq \frac{S}{N} - EIRP - 40.4 + 20log(f) + 10log(h) + NF + 10log(b_{monitor}) \tag{13b}$$

for the conditions $b_{emission} > b_{monitor}$ and $b_{monitor} \geq b_{emission}$, respectively.

For maximum (4/3 Earth) distance, where is $d_{4/3Earth} = 130\sqrt{h}$, the requirement for the monitoring station receiver antenna gain is just $20log\sqrt{4/3}$ = 1.25 dB higher than the value that is required to receive LOS signals. This changes (13a) and (13b) to

$$G_{r,4/3Earth} \geq \frac{S}{N} - EIRP - 39.2 + 20log(f) + 10log(h) + NF + 10log(b_{emission}) \qquad (13c)$$

and

$$G_{r,4/3Earth} \geq \frac{S}{N} - EIRP - 39.2 + 20log(f) + 10log(h) + NF + 10log(b_{monitor}). \qquad (13d)$$

2.3.1 Units

Regarding units in (13a)–(13d), note that *EIRP* is in decibels relative to a milliwatt (dBm), due to milliwatts having been used for the units of *kt* in (8a). The variables f, $b_{monitor}$ and $b_{emission}$ are in megahertz, h is in kilometers, and all other quantities are dimensionless decibels. If other units are to be used, then the constant terms must be adjusted accordingly.

2.4 Optimal Monitoring Antenna Gain and Elevation Angle Coverage

Equations (13a)–(13d) are for airborne platforms with elevation angles at a monitoring station that are zero or (for the 4/3 Earth distance) slightly below zero. If the airborne platforms come closer to the monitoring station than d_{LOS} while maintaining altitude h, their elevation angles will increase, as described by (5) and shown in Figures 3 and 4. The minimum gain for monitoring station antennas therefore needs to maximize at the horizon and decrease with decreasing distance and increasing elevation angles. The functional forms of these relationships are shown in Figures 5 and 6 for an airborne platform at 10 km (33,000 ft) altitude. Figure 6 can be translated into a required elevation antenna pattern, as shown in the next section.

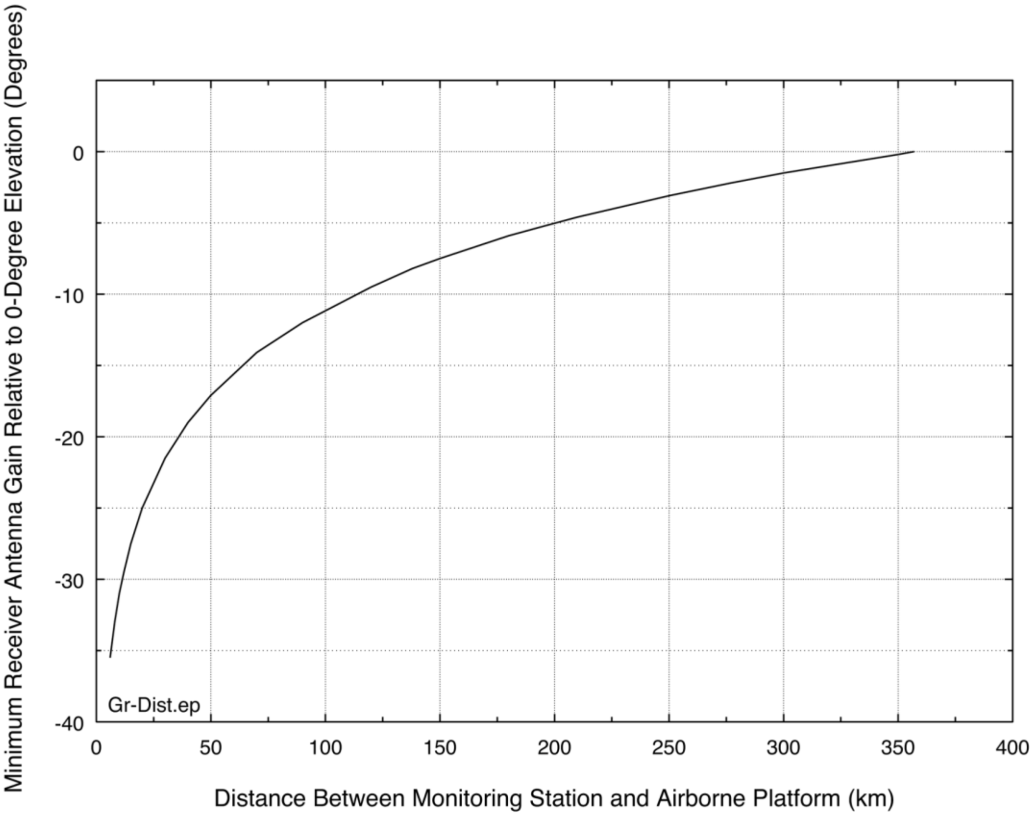

Figure 5. Relationship between minimum monitoring antenna minimum gain (normalized to 0 dBi at 0 degrees elevation angle) and distance for an airborne platform at 10 km (33 kft) altitude, from (11).

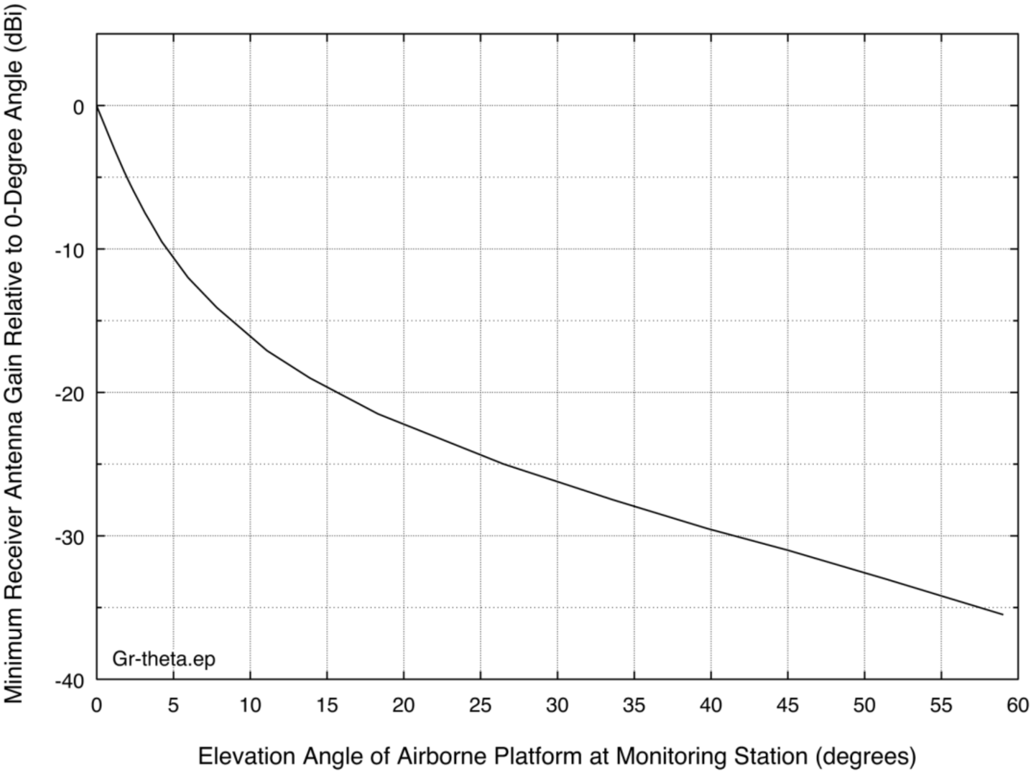

Figure 6. Relationship between monitoring antenna minimum gain (normalized to 0 dBi at 0 degrees elevation angle) and angle above horizon for an airborne platform at 10 km (33 kft) altitude, from (5) and (11).

3 EXAMPLE DEVELOPMENT OF AN OPTIMIZED RADIATION PATTERN FOR A MONITORING ANTENNA

3.1 Introduction

The functional form of a monitoring station antenna's elevation-angle response that would be well-adapted to receiving signals from airborne platforms is shown in Figure 6. In this section a worked example of the development of such an antenna pattern is presented for a set of real-world conditions. This example can be followed by anyone who needs to design or select a receiving antenna for this sort of monitoring.

3.2 Parameter Settings

An example set of airborne radio and monitoring station parameters are presented in Table 1.

Table 1. Example airborne radio and monitoring station parameters.

Parameter	Value
Airborne platform altitude	10 km (33 kft)
Airborne radio transmitter power	5 W, 10 W, 20 W
Airborne radio transmitter antenna gain	0 dBi (hemispherical downward)
Airborne radio *EIRP*	+37 dBm, +40 dBm, +43 dBm
Airborne radio frequency	1770 MHz
Airborne radio emission bandwidth	1 MHz
Monitoring station receiver bandwidth	1 MHz
OTR	0 dB
Monitoring station receiver noise figure	5 dB
Minimum acceptable *S/N* ratio at monitoring station	10 dB

3.3 Graph of Optimal Monitoring Station Antenna Elevation Pattern

Figure 7 shows the curves for optimal G_r (calculated from (13) as a function of elevation angle at a monitoring station location for the example parameters given in Table 1. This curve is equivalent to an optimal elevation-angle antenna pattern for the monitoring antenna.

3.4 Comparison with a Commercially Available Antenna

The antenna patterns (elevation angle and horizontal) of a collinear, stacked-dipole array antenna such as can be procured commercially are shown in Figure 8. In Figure 9, this pattern is superimposed on the curves of Figure 7 for comparison purposes. The antenna pattern exceeds the minimum requirements everywhere except below an elevation angle of 1 degree, and then it only falls short by about 2 dB for relatively low-power (5 W EIRP) airborne transmitters.

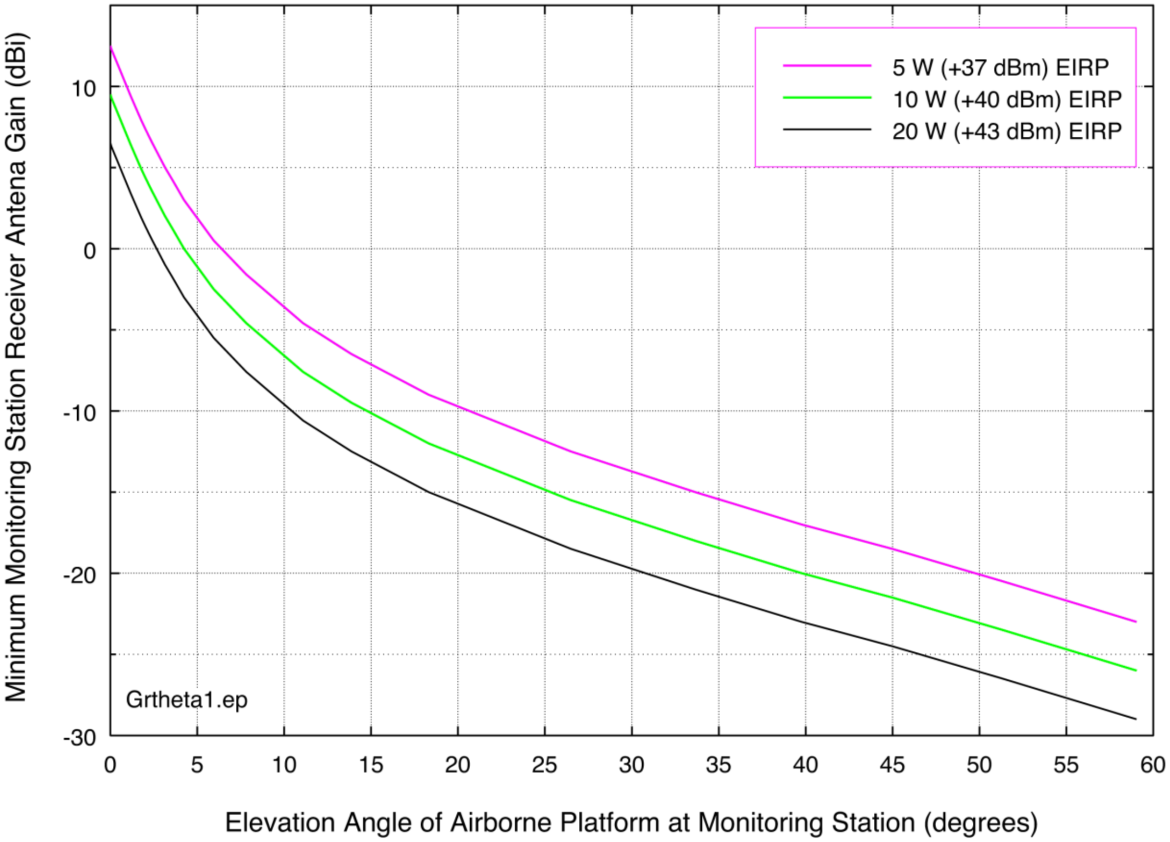

Figure 7. Elevation-angle antenna pattern responses needed for a monitoring station antenna for the parameters in Table 1.

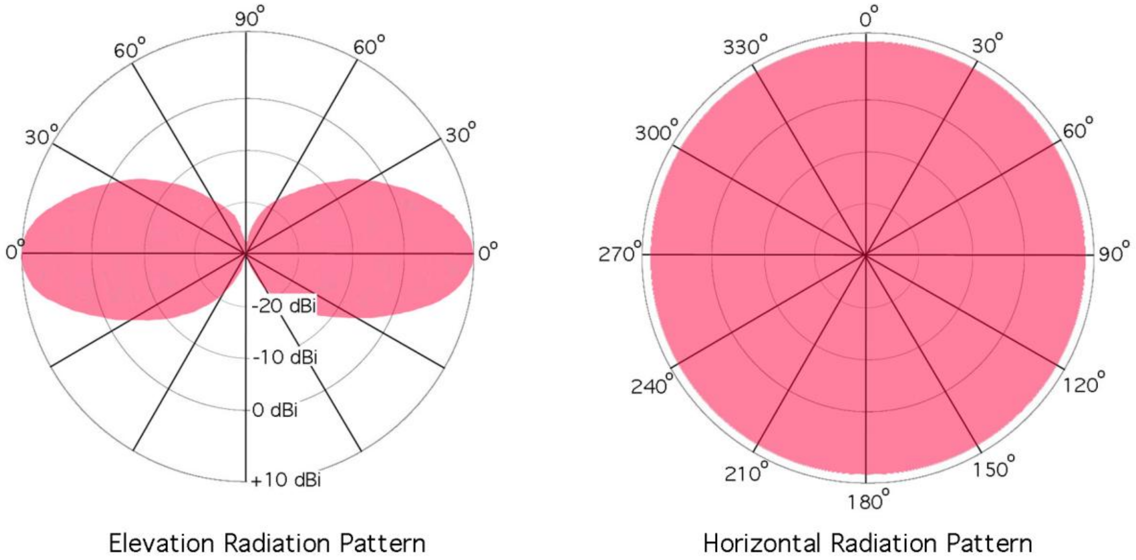

Figure 8. Idealized elevation and azimuthal radiation patterns of a collinear, stacked-dipole array antenna.

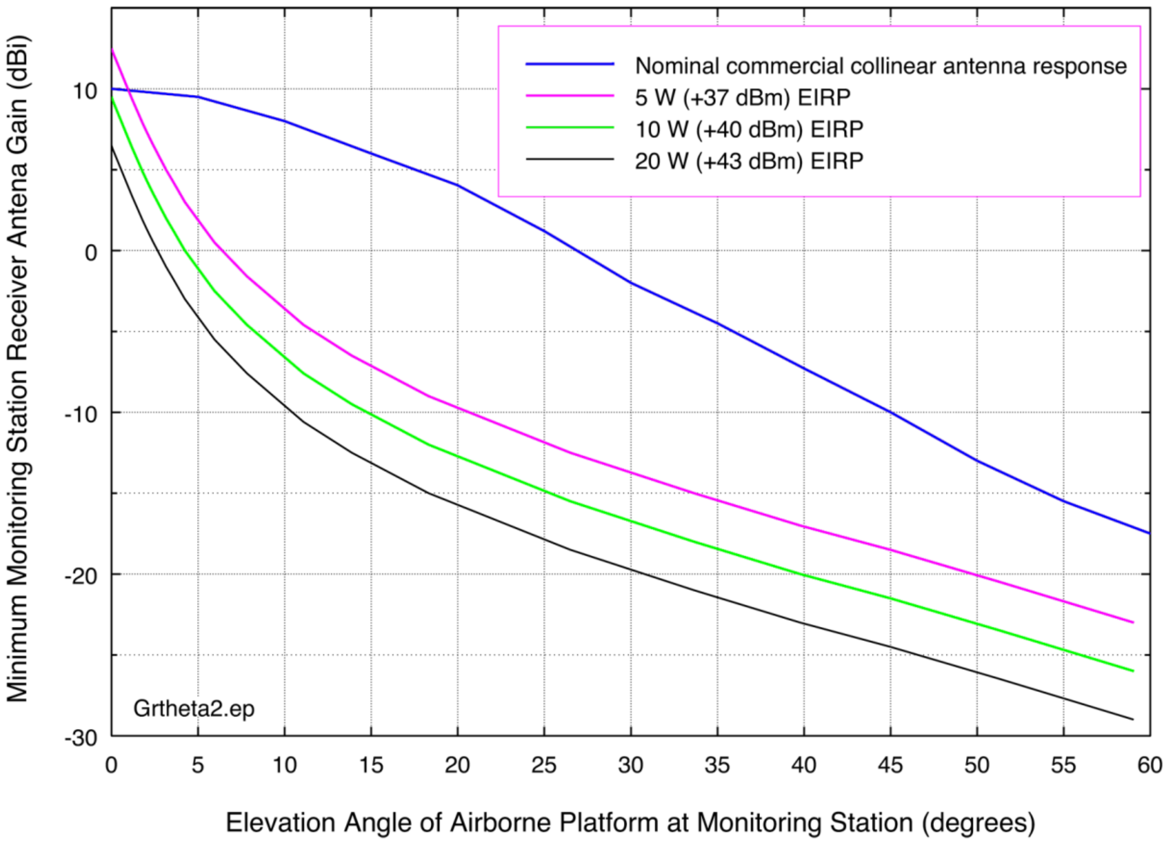

Figure 9. Minimum required monitoring antenna gain curves of Figure 7 compared to the collinear stacked-array antenna elevation pattern of Figure 8. The stacked-array antenna pattern exceeds the minimum gain requirements at all angles except below 1 degree, where it is about 2 dB lower than needed for 5 W airborne transmitters.

3.5 Summary

The methodology presented in this memorandum may be used to determine the minimal elevation-angle versus gain requirements for any monitoring station antennas that are to receive signals from airborne platforms. The methodology provides a way to compare the patterns of commercially available antennas to these minimum requirements. The procedure may be extended to monitoring antennas that are themselves mounted on airborne platforms, and to monitoring stations on ships.

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FORM **NTIA-29**
(4-80)

U.S. DEPARTMENT OF COMMERCE
NAT'L. TELECOMMUNICATIONS AND INFORMATION ADMINISTRATION

BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION NO. TM-13-492	2. Government Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE Antenna Selection for Monitoring of Airborne Radio Systems	5. Publication Date November 2012
	6. Performing Organization Code ITS.T
7. AUTHOR(S) Frank H. Sanders	9. Project/Task/Work Unit No. 3105011-300
8. PERFORMING ORGANIZATION NAME AND ADDRESS Institute for Telecommunication Sciences National Telecommunications & Information Administration U.S. Department of Commerce 325 Broadway Boulder, CO 80305	10. Contract/Grant Number.
11. Sponsoring Organization Name and Address National Telecommunications & Information Administration Herbert C. Hoover Building 14th& Constitution Ave., NW Washington, DC 20230	12. Type of Report and Period Covered Technical Memorandum, FY13

14. SUPPLEMENTARY NOTES

15. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

This Technical Memorandum describes a process for selecting an appropriate antenna for monitoring radio signals from airborne transmitters. A mathematical formula for the optimal receiver antenna gain is presented. This formula takes into account the factors of minimal required signal-to-noise ratio of signals in a monitoring receiver, airborne radio transmitted power and antenna gain, airborne radio height and resulting maximal line-of-sight coverage, free-space propagation loss, airborne radio signal bandwidth, monitoring system bandwidth, and the sensitivity of the monitoring system's receiver. The optimal monitoring antenna gain is calculated as a function of elevation angle above the local horizon. That function is used to select an antenna type that will receive signals from as many airborne radios as possible. A worked example of the selection process is presented. Although it is assumed that a terrestrial system will be used for monitoring, the process can be applied to antennas for marine and airborne monitoring systems as well.

16. Key Words (Alphabetical order, separated by semicolons)
airborne signals; antenna gain; RF measurement; RF monitoring

17. AVAILABILITY STATEMENT ☒ UNLIMITED. ☐ FOR OFFICIAL DISTRIBUTION.	18. Security Class. (This report) Unclassified	20. Number of pages 30
	19. Security Class. (This page) Unclassified	21. Price:

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