A communications-based mission planning tool concept for low-cost tactical UXV operations

Alan D. Thomson
DRDC Ottawa

Defence Research and Development Canada

Scientific Report

DRDC-RDDC-2014-R11

April 2014

Abstract

New concepts for communications-based tactical decision aids, which can be used for low-cost tactical UXV operations, are investigated to provide input for future mission planning tools that could be developed for the Royal Canadian Navy. The proposed tactical decision aids provide information on where and when communications between a UXV and its base station will be effective and not effective as a function of the current and future environmental conditions. The required signal propagation calculations use data from an Environment Canada numerical weather prediction model and a terrain elevation database. A description is provided of the approach used to calculate the base quantities (signal-to-noise ratio, E_b/N_o, bit error rate) that are required to form the tactical decisions aids. Example tactical decision aids are calculated for a specific case to demonstrate how this information could be used for planning UXV routes. The example case clearly shows regions where communications are effective and not effective within a realistic environment. Experimental trials are required to test the hypothesis that the proposed method is capable of accurately now-casting and forecasting the times and places for which a UXV will have effective communication with its base station.

Significance to defence and security

The Royal Canadian Navy (RCN) makes extensive use of unmanned aerial vehicles (UAV) on ships at sea. Defence Research and Development Canada is also experimenting with UAVs and unmanned surface vehicles (USV) to develop further concepts for their use in RCN operations, such as off-board jamming. Communication with UAVs or USVs (UXVs) will be lost if the UXV travels too far from the ship or if the environmental conditions are not favourable for propagation of the communication signals. In the case of low-cost tactical UXVs, loss of communications will prevent the operator from controlling the function of the UXV, in which case the UXV may enter a holding pattern until communications are restored. Restoration of communications with the UXV will require the ship’s crew to undertake additional measures that can affect the overall mission being conducted by the ship. This research demonstrates a method for now-casting and forecasting where and when communications with the UXV will be effective and not effective as a function of current and future environmental conditions. A mission planning tool based on this method would allow UXV paths to be planned to avoid areas where communications loss is predicted and to take advantage of environmental conditions that allow communications to be extended to areas beyond the expected operating range of the UXV. This should benefit RCN operations and would also be useful for planning experimental trials involving UXVs.

Résumé

De nouveaux concepts d'aide à la prise de décisions tactiques fondées sur les communications, pouvant servir aux opérations des véhicules sans pilote (VSP) tactiques économiques, sont étudiés afin d'adapter les outils de planification de mission qui pourraient être conçus pour la Marine royale canadienne. Les aides à la prise de décisions tactiques proposées fournissent des renseignements sur l'endroit et le moment où les communications entre un véhicule sans pilote et sa station de base fonctionneront ou non de manière efficace en fonction des conditions environnementales actuelles et futures. Les calculs de propagation des signaux requis sont effectués au moyen de données provenant d'un modèle numérique de prédictions météorologiques d'Environnement Canada et d'une base de données d'élévation du terrain. L'approche utilisée pour calculer les quantités de base (rapport signal sur bruit, E_b/N_o, taux d'erreur sur les bits) nécessaires pour concevoir les aides à la prise de décisions tactiques est décrite. Des aides de ce type sont calculées en exemple pour un cas donné afin de démontrer comment ces renseignements pourraient servir à planifier les routes des véhicules sans pilote. Le cas en exemple indique clairement les régions où les communications sont efficaces, et celles où elles ne le sont pas, dans un environnement réaliste. Des essais expérimentaux doivent être réalisés pour vérifier l'hypothèse selon laquelle la méthode proposée est capable d'établir, de manière précise, des évaluations en temps réel et des prévisions du moment et de l'endroit où les communications entre un véhicule sans pilote et sa station de base s'effectueront de manière efficace.

Importance pour la défense et la sécurité

La Marine royale canadienne (MRC) utilise intensivement les véhicules aériens sans pilote (VASP) à bord de navires en mer. Recherche et développement pour la défense Canada effectue aussi des essais avec les VASP et les véhicules de surface sans pilote (VSSP) pour élaborer des concepts plus poussés qui serviraient aux opérations de la MRC, comme le brouillage déporté. La communication avec un VASP ou un VSSP (VSP) est perdue si le VSP s'éloigne trop du navire ou si les conditions environnementales ne favorisent pas la propagation des signaux de communication. Dans le cas des VSP tactiques économiques, la perte des communications empêche l'opérateur de contrôler les fonctions du véhicule sans pilote, auquel cas le véhicule peut effectuer une procédure d'attente jusqu'à ce que les communications soient rétablies. Pour rétablir les communications avec le véhicule sans pilote, l'équipage du navire doit prendre des mesures supplémentaires, lesquelles peuvent avoir une incidence sur l'ensemble de la mission du navire. L'étude démontre une méthode qui permet d'évaluer la situation en temps réel et de prévoir le moment et l'endroit où les communications avec un véhicule sans pilote s'effectueront ou non de manière efficace, en fonction des conditions environnementales actuelles et futures. Un outil de planification de mission fondé sur cette méthode permettrait de planifier le parcours que doivent suivre les VSP afin d'éviter les endroits où l'on anticipe la perte de communications et de profiter des conditions environnementales qui favorisent l'extension des communications à des zones se situant au-delà de la portée opérationnelle prévue du véhicule. Il profiterait aux opérations de la MRC et servirait également à planifier les essais expérimentaux effectués sur les VSP.

Table of contents

List of figures

List of tables

This page intentionally left blank.

1 Introduction

The Royal Canadian Navy (RCN) makes extensive use of unmanned aerial vehicles (UAV) on ships at sea. Defence Research and Development Canada (DRDC) is also experimenting with UAVs and unmanned surface vehicles (USV) to develop further concepts for their use in RCN operations, such as off-board jamming. Communication with UAVs or USVs (UXVs) will be lost if the UXV travels too far from the ship where the strength of the communications signal is too low to be distinguished from noise. The strength of the UXV communications signal can also be greatly affected by anomalous propagation conditions such as radio-frequency (RF) ducting, which can decrease or increase the strength of the communications signal. In the case of low-cost tactical UXVs, loss of communications will prevent the operator from controlling the function of the UXV, in which case the UXV may enter a holding pattern until communications are restored. Restoration of communications with the UXV will require the ship's crew to undertake additional measures that can affect the overall mission being conducted by the ship. The aim of this research is to develop a concept for a mission planning tool that can be used to now-cast and forecast where and when communications with the UXV will be effective and not effective as a function of current and future environmental conditions. Such a tool would allow UXV paths to be planned to avoid areas where communications loss is predicted and to take advantage of environmental conditions that allow communications to be extended to areas beyond the expected operating range of the UXV. This should benefit RCN operations and would also be useful for planning experimental trials involving UXVs. This report provides a conceptual description of the proposed tactical decision aids (TDA) that would be the basis of the mission planning tool and a description of how the base quantities used to form the TDAs are calculated. Example TDAs are generated for environmental conditions corresponding to a real data set.

2 Overview of the mission planning tool concept

A mission planning tool is expected to use various types of graphical displays (TDAs) that provide actionable information to the user in an understandable way. Two types of displays will be discussed in this report. The first is a map-based display that presents the information in the context of the local geography and the second is an “x-y” plot format that provides more quantitative information.

The forecast capability of the mission planning tool will be provided through the use of data from a re-locatable mesoscale numerical weather prediction (NWP) model. Such a model provides predictions of the thermodynamic properties of the atmosphere (e.g., pressure, temperature, relative humidity), typically for a 12 hour period, for a region spanning a few hundred kilometres, and on a grid having a horizontal resolution on the order of a few kilometers. The Environment Canada Global Environment Multiscale Limited Area Model (GEM LAM) has been used to provide this type of data to DRDC in the past for research being conducted within the ABCANZ (America Britain Canada Australia New Zealand) Focused Information Exchange Group (FIEG) on infrared, visual, and RF propagation. GEM LAM could be used to calculate a grid of predictions centred in space and time on the operations area of an RCN ship. These data could be provided to a ship at sea using the Canadian Forces Weather Office Site (CFWOS) exactly as other meteorological data are currently provided.

When appropriately combined with a surface boundary layer model and a terrain elevation database, the NWP data can be used to calculate a field of atmospheric refractivity in space and time. The refractivity data, a land cover database, and information about the UXV communications system can be used to calculate the propagation of the UXV communications signals. Link analysis can then be used to determine the signal power that would be received by the UXV as a function of space and time. If effective communication can be characterized by, for example, a particular signal-to-noise ratio being present in the UXV communications receiver, then these calculations will forecast where and when effective communications with the UXV will be possible.

A conceptual example of the map-based display is shown in Figure 1. For each forecast hour, a data field would be calculated as a function of all three spatial dimensions. The data field could be the signal-to-noise ratio (SNR) that would exist in the UXV receiver, or it could be the SNR that exists in the base station receiver. Alternatively, in the case of digital communications, the calculated data field could be E_b/N_o (ratio of energy per bit, E_b, to the spectral noise density, N_o) or the bit error rate (BER). Figure 1 could represent a horizontal slice through this field at a particular altitude or perhaps an average representation of the data field for a layer of altitude. A vertical range-height slice through the data field along a particular bearing could also be a useful product. The colours are used to distinguish where communications will be effective and where they will not be. Green colour corresponds to areas where the calculated quantity (SNR, E_b/N_o, or BER) exceeds that required for effective communications and red colour corresponds to areas where the calculated quantity does not exceed that required for effective communications. In the example shown in Figure 1, the non-circular shape of the green area would be caused by effects such as terrain shadowing and RF ducting. A proposed UXV path, defined by a set of waypoints is depicted with the white line. The display postulates conditions such that the range of effective communications is extended beyond normal expectations in areas along the coast of Devon

Island, Nunavut. This could be caused, for example, by dry air from above the land being advected over the ocean, which could create an elevated RF duct. The UXV path takes advantage of these conditions. However, the display also shows that communications will be lost at waypoint 8 and that, therefore, the chosen path should be adjusted somewhat.

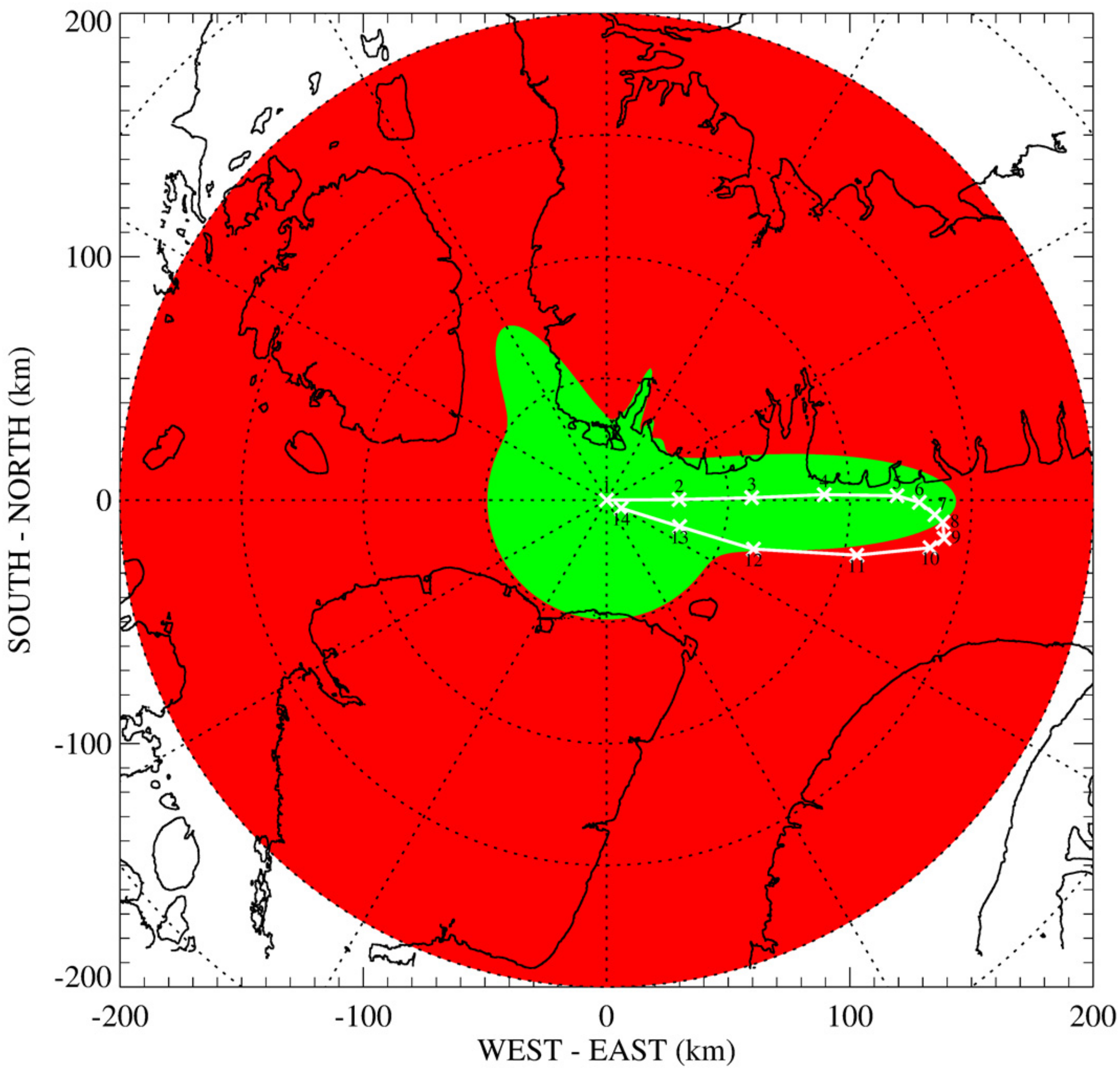

Figure 1: Conceptual map-based decision aid for UXV mission planning. The map centre corresponds to 91.369069°W longitude and 74.437813°N latitude.

The calculated data field could also be interpolated along the UXV path and displayed in a more quantitative fashion as a function of variables such as range, bearing (azimuth), altitude, longitude, latitude, and time. For example, the SNR corresponding to the UXV path displayed in Figure 1 is plotted as a function of range in Figure 2. Here a value of 0 dB has been chosen as the SNR required for effective communication. Note that the SNR values corresponding to the waypoints may be calculated using NWP data from different forecast hours, depending upon the time at which the UXV reaches a given waypoint.

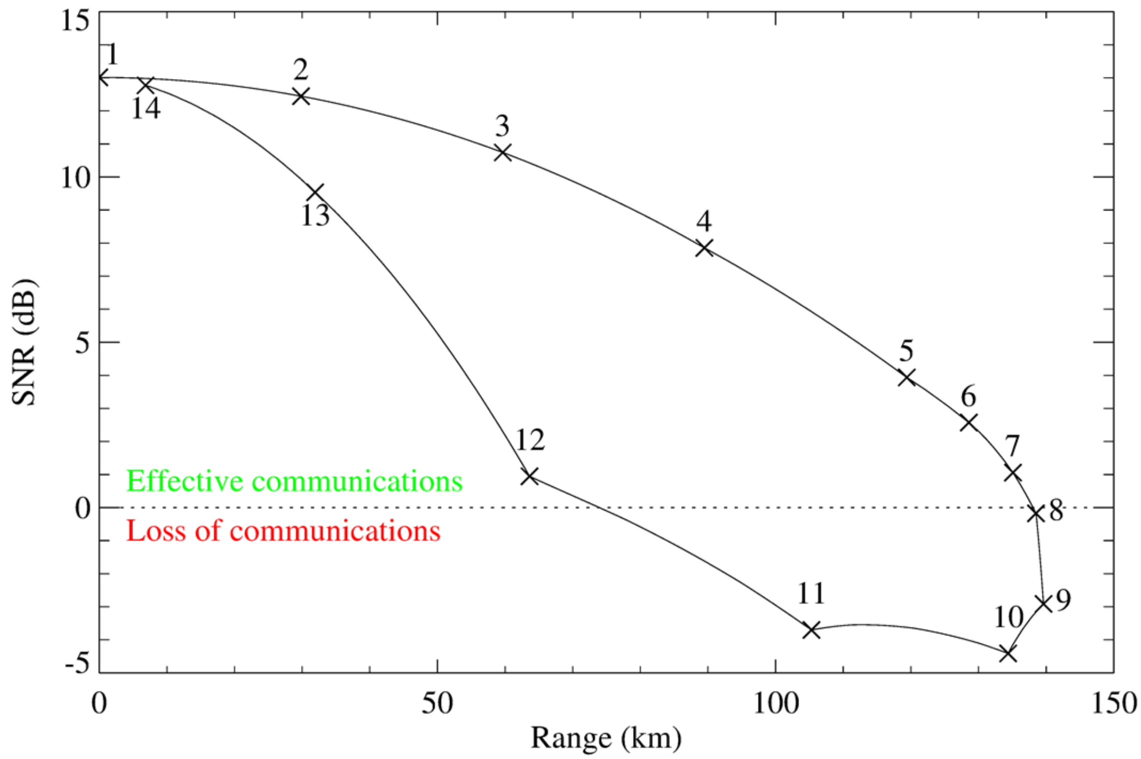

Figure 2: SNR interpolated as a function of UXV range.

If the transmission of the GEM LAM data to a ship at sea presents a problem, for example, due to low available data transfer rates, then the mission planning products could be generated using a reach-back process. This would involve the ship transmitting the necessary data to shore, such as ship location, proposed UAV flight path, etc. The mission planning products (TDAs) could then be calculated on shore more quickly using a powerful computing system, and only the final products would be transmitted back to the ship. It is expected that the data size of the final mission planning products will be much less than the size of the GEM LAM data grid. This approach removes the requirements for computing power at sea and for ship's personnel to perform the calculations.

3 Calculation of the data fields (SNR, E_b/N_o, BER)

The information flow corresponding to the data field calculations is depicted in Figure 3. The black boxes on the left show required input information. The specific information that is represented by each box is described in the parameter tables given for the examples of Section 4. NWP data files may contain data for more than one forecast hour. The forecast hour corresponding to the calculations is determined based on the proposed UXV launch time, the UXV speed, and the UXV location relative to the base station.

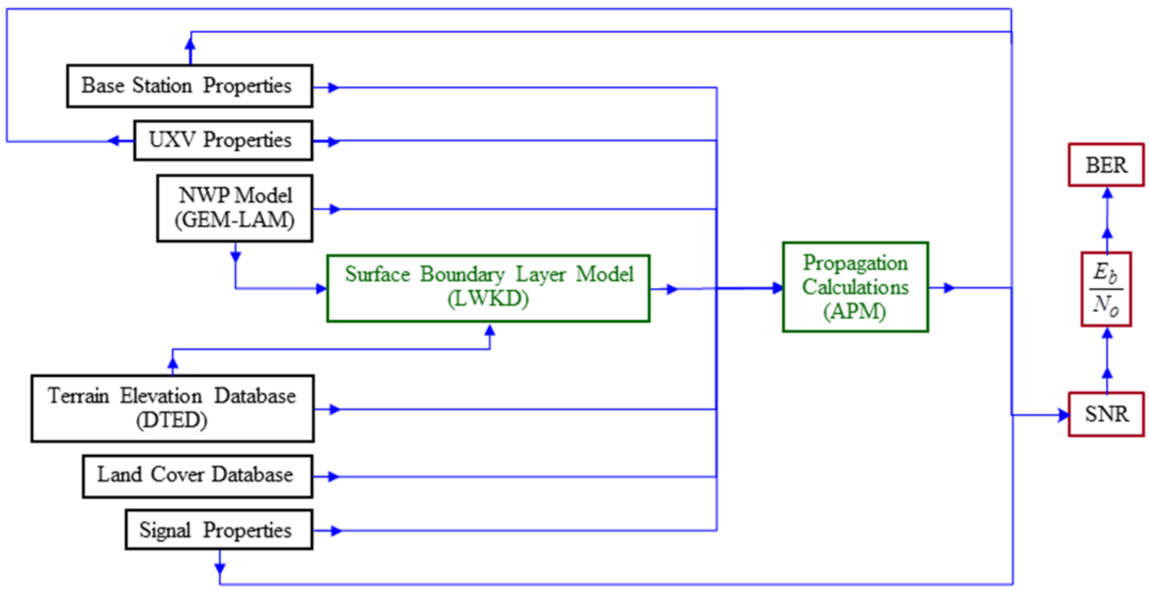

Figure 3: Information flow for SNR, E_b/N_o, and BER calculations.

The quantities E_b/N_o and BER are both dependent upon the pre-detection SNR (see [1], p 105). The SNR in the UXV receiver is calculated as

$$\mathrm{SNR}_u = \frac{P_{ru}}{N_u} \tag{1}$$

where P_{ru} is the received power given by

$$P_{ru} = \frac{P_{tb}\, G_b\, f_{\phi b}^2\, G_u\, f_{\phi u}^2\, \lambda^2\, F_\theta^2}{(4\pi\, r)^2} \tag{2}$$

and P_{tb} is the power transmitted by the base station, G_b is the boresight gain of the base station antenna, $f_{\phi b}^2$ is the azimuth pattern factor for the base station antenna, G_u is the boresight gain of the UXV antenna, $f_{\phi u}^2$ is the azimuth pattern factor for the UXV antenna, λ is the wavelength of the transmitted signal, F_θ^2 is the one-way pattern propagation factor, and r is the slant range between the base station antenna and the UXV antenna.

The noise power, N_u, is given by

$$N_u = k_b \, T_o \, B_{ru} \, F_{nu} \tag{3}$$

where k_b (= 1.38 × 10^{-23} J/K) is the Boltzmann constant, T_o (= 290 K) is a reference temperature, and B_{ru} and F_{nu} are the bandwidth and noise figure, respectively, of the UXV receiver.

The pattern propagation factor, F_θ, is defined as the ratio of the electric field that actually impinges on a scatterer to the electric field that would exist at the scatterer under free-space conditions with the antenna positioned such that the scatterer is in the maximum-gain direction of the antenna pattern (see [2], p 8-12). This factor can account for the effects of diffraction, refraction, reflection (multipath interference), absorption by atmospheric gases, surface roughness, and the gain pattern of the antenna. Use of the pattern propagation factor in Equation 2 requires F_θ to be squared to relate the quantity to power.

In this study, F_θ^2 is calculated using version 2.3.03 of the Advanced Propagation Model (APM) [3]. The subscript θ is used to denote that these calculations factor in the normalized polar angle antenna gain pattern. The APM calculations also include attenuation due to atmospheric gases. APM employs parabolic equation methods [4] to calculate F_θ^2 on a range-height grid (constant azimuth plane) as a function of the specified environment. To generate the three-dimensional data set of F_θ^2 that is required for the map-based display, APM calculations are executed along many different azimuths from the ship to the maximum range of interest. To generate the data set of F_θ^2 that is required for the "x-y" plot displays, APM calculations are executed along the azimuth planes to a set of points that are evenly spaced in time along the UXV flight path.

The environment within the range-height grid corresponding to a given path is defined using a number of parameters that are inputted into the APM software. These parameters define surface absolute humidity, surface air temperature, surface wind speed as a function of range, refractivity as a function of range and height, surface relative permittivity as a function of range, surface ionic conductivity as a function of range, and terrain height (h_t) as a function of range. Terrain height is determined for the examples of this document by interpolating Digital Terrain Elevation Data (DTED, provided on compact disc by the U.S. National Imagery and Mapping Agency).

The atmospheric parameters required by APM are derived from the GEM LAM data. The modified refractivity required by APM is calculated as a function of range and height using the Debye equation (see [4], p. 42):

$$M(r,h) = \left[\frac{77.6}{T_a(r,h) + 273.15}\right]\left\{P(r,h) + \frac{[4807 \, e_s(r,h) \, f_r(r,h)]}{[T_a(r,h) + 273.15]}\right\} \tag{4}$$

where h is height, T_a, is air temperature in degrees Celsius, P is pressure in millibars, and f_r is the relative humidity expressed as a fraction. The saturation vapour pressure over water (in millibars) is given by (see [5], p 16)

$$e_s = 6.112 \exp\left(\frac{17.67 \, T_a}{T_a + 243.5}\right) \tag{5}$$

The pressure, temperature, and relative humidity data used in Equations 4 and 5 are calculated as height profiles that are created by merging (gradient-matching method) height profiles produced by LWKD [6] with upper air data interpolated from the GEM LAM data. LWKD is a bulk aerodynamic model that describes the surface layer of the boundary layer using standard meteorological measurements. The boundary layer is the portion of the atmosphere that is influenced by the surface of the earth. The surface layer is the lowest portion of the boundary layer and it is adjacent to the earth's surface. LWKD requires input values of water surface temperature, air temperature, air humidity, wind speed, and pressure. All of these inputs are also interpolated from the GEM LAM data.

The electrical characteristics (relative permittivity and ionic conductivity) of the surface over which the communications signal propagates are a function of the specific terrain type (land cover). APM includes data provided by the International Radio Consultative Committee (CCIR, see Recommendation 527-3 [7]) that describes the relative permittivity and ionic conductivity of several general terrain types as a function of frequency. For this study, all land areas within the region of interest were assumed to be "medium dry ground". A land area is defined as a region in which the terrain elevation is greater than zero with respect to sea level.

Depending upon the specifications of the transmitter and receiver, it is possible that the limiting factor for effective communications may be the SNR in the base station receiver and not the SNR in the UXV receiver. The signal-to-noise ratio in the base station receiver, SNR_b, is calculated in the same way as SNR_u, i.e.,

$$\mathrm{SNR}_b = \frac{P_{rb}}{N_b} \tag{6}$$

where

$$P_{rb} = \frac{P_{tu}\, G_u\, f_{\phi u}^2\, G_b\, f_{\phi b}^2\, \lambda^2\, F_\theta^2}{(4\pi\, r)^2} \tag{7}$$

and

$$N_b = k_b\, T_o\, B_{rb}\, F_{nb} \tag{8}$$

Here, P_{tu} is the power transmitted by the UXV, and B_{rb} and F_{nb}, are the bandwidth and noise figure, respectively, of the base station receiver. Assuming equivalent antenna geometry (e.g., omnidirectional antennas), the Helmholtz reciprocity theorem (see [8], p 381) dictates that the value of F_θ^2 is the same when calculated along the path from the base station to the UXV as it is when calculated along the reverse path.

The quantity E_b/N_o can be calculated from the SNR as

$$\frac{E_b}{N_o} = \text{SNR}\,\frac{B}{f_b} \tag{9}$$

where B is the receiver bandwidth, and f_b is the bit rate of the digital signal (see [1], p 105). The bit error rate, BER, can then be determined from E_b/N_o depending upon the modulation technique used to encode the digital information onto the RF carrier. For example, for the case of quadrature phase shift keying (QPSK) modulation in additive white Gaussian noise (AWGN), BER can be calculated as

$$\text{BER} = \frac{1}{2}\,\text{erfc}\left(\sqrt{\frac{E_b}{N_o}}\right) \tag{10}$$

where erfc represents the complementary error function (see [9], p 390). These relations allow the threshold for determining effective communications to be based on the BER. For example, if effective communications can be achieved only if $\text{BER} \leq 1 \times 10^{-4}$, then assuming QPSK and AWGN, and that the bit rate equals the receiver bandwidth, the required SNR is 8.4 dB or greater. In this case the map-based display (e.g., see Figure 1) would be painted such that green areas correspond to $\text{SNR} \geq 8.4$ dB and red areas correspond to $\text{SNR} < 8.4$ dB.

4 Example case

The geographic area chosen for the example calculations is the southern portion of the Delmarva Peninsula and the surrounding waters. This choice was made since GEM LAM data containing interesting propagation conditions in this area had been previously provided to DRDC by Environment Canada's Recherche en Prévision Numérique (RPN) for studies being performed within the ABCANZ FIEG.

It is assumed that the UXV is a UAV, and that it uses a radio system for communications that is identical to the base station radio system that is used by its operator. The operator and base station are assumed to be on a ship. The parameters associated with the base station and its transmitted signal are listed in Table 1.

The UAV flight and radio system parameters are listed in Table 2. Waypoint times are shown relative to the departure time and are rounded to the nearest second.

The environment parameters associated with the example calculations are listed in Table 3. Based on the UAV departure and arrival times, the GEM LAM data at forecast hour 17:00 UTC is the most relevant for all points along the UAV flight path. The sea surface salinity is used in the LWKD calculations that determine the thermodynamic profiles (temperature, pressure, relative humidity) in the surface boundary layer. The temperature, pressure, and relative humidity values listed in Table 3 are only used for calculating a global value for the gaseous absorption attenuation rate. The temperature, pressure, and relative humidity values that are used to calculate atmospheric refractivity are extracted from the GEM LAM data.

Table 1: Base station and signal parameters.

Description	**Value**
Longitude	75.3°W
Latitude	37.8°N
Height above sea level	30 m
Transmitted power	1 W
Transmitted frequency	900 MHz
Polarization	Horizontal
Receiver bandwidth	1 MHz
Receiver noise figure	6 dB
Antenna type	Omnidirectional ($f_{\phi b}^2 = 1$)
Antenna gain	0 dB

Table 2: UAV and signal parameters.

Description	Value
Departure time	16:31:00 UTC
Arrival time	17:25:46 UTC
Waypoint 1 (longitude, latitude, height, time)	75.3°W, 37.8°N, 10 m, 0 s
Waypoint 2 (longitude, latitude, height, time)	75.219543°W, 37.993362°N, 500 m, 227 s
Waypoint 3 (longitude, latitude, height, time)	75.219543°W, 38.096401°N, 1000 m, 341 s
Waypoint 4 (longitude, latitude, height, time)	75.501770°W, 38.311432°N, 1000 m, 685 s
Waypoint 5 (longitude, latitude, height, time)	75.492813°W, 38.427906°N, 1000 m, 815 s
Waypoint 6 (longitude, latitude, height, time)	75.331535°W, 38.414467°N, 1000 m, 956 s
Waypoint 7 (longitude, latitude, height, time)	75.341499°W, 37.746975°N, 1000 m, 2099 s
Waypoint 8 (longitude, latitude, height, time)	75.278778°W, 37.612579°N, 1000 m, 2258 s
Waypoint 9 (longitude, latitude, height, time)	75.413117°W, 37.536423°N, 1000 m, 2404 s
Waypoint 10 (longitude, latitude, height, time)	75.062752°W, 37.845531°N, 500 m, 3072 s
Waypoint 11 (longitude, latitude, height, time)	75.3°W, 37.8°N, 10 m, 3286 s
Transmitted power	1 W
Transmitted frequency	900 MHz
Polarization	Horizontal
Receiver bandwidth	1 MHz
Receiver noise figure	6 dB
Antenna type	Omnidirectional ($f_{\phi u}^2 = 1$)
Antenna gain	0 dB

Table 3: Environment parameters.

Description	Value
Forecast hour	17:00 UTC, May 1, 2000
Sea surface salinity	32 g/kg
Terrain type	"medium dry ground" [7]
Surface air temperature (attenuation by gaseous absorption)	15 °C
Surface atmospheric pressure (attenuation by gaseous absorption)	1013.25 mb
Surface relative humidity (attenuation by gaseous absorption)	90 %

Figure 4 shows a portion of the GEM LAM data in the Hazard Prediction and Assessment Capability (HPAC) format. The 17:00 UTC forecast contains data for 43584 locations with horizontal grid spacing of 4 km. The header for each location contains the date, time, longitude, latitude, and ground elevation in m, as well as values for the surface heat flux in W m^{-2}, the Monin-Obukhov length in m, the friction velocity in m s^{-1}, the temperature scaling parameter in °C, the specific humidity scaling parameter in g g^{-1}, the wind speed roughness height in m, the temperature on the surface in °C, and the relative humidity on the surface as a percentage. The remaining data for each location consists of vertical profiles of height in m (Z values in Figure 4), wind direction in degrees, wind speed in m s^{-1}, atmospheric pressure in mb, temperature in °C, and relative humidity as a percentage. Although listed as 0 m, the first height level of each profile actually corresponds to 10 m above local ground level for wind speed and direction values, and 1.5 m above local ground level for pressure, temperature, and relative humidity values. The data for only two locations are shown in the figure.

```
# CREATOR:         stephane.gaudreault@.ec.gc.ca
# DATE:            2010-02-22  14:31:05 UTC
# SOURCE:          GEM LAM 4KM & hpac.tcl v1.0
# PROFILE HEIGHT:  ASL
# WIND DIRECTION:  true
# TYPE:            NorWat forecast
# ANALYSIS:        200005011200
# START:           200005011700
# END:             200005011700
# TIME REFERENCE:  UTC
# MODE:            HPAC profile all Type 1
# LOCATIONS:       43584
PROFILE
ID       YYMMDD   HOUR     LAT      LON      ELEV     HFLUX    MOL      U*       T*       q*       z0       Tsurf    RHsurf
                  HOURS    N        E        M        W/M2     M        m/s      oC       g/g      m        oC       %
Z        WDIR     WSPD     P        T        HUMID
M        DEG      M/S      MB       C        %
1        000501   17       33.6418  -77.5962 0.00     5.59e+01 -2.78e+02 1.64e-01 1.36e-02 -1.18e-04 4.89e-05 20.31   100.00
0.00     235.13   4.95     1023.14  20.60    80.84
18.88    235.41   5.16     1020.91  20.49    77.73
55.86    235.38   5.44     1016.55  20.16    77.62
105.93   235.39   5.76     1010.68  19.73    77.49
167.52   235.64   6.27     1003.48  19.26    75.28
242.55   235.20   6.79     994.77   18.72    71.65
328.67   233.76   7.53     984.84   18.39    60.09
427.03   229.29   7.72     973.59   17.75    56.18
537.95   224.34   7.55     961.03   16.96    54.49
660.90   219.89   7.10     947.25   16.08    52.31
794.39   216.93   6.40     932.46   15.08    51.02
940.72   215.69   5.64     916.45   13.92    51.55
1098.42  215.44   4.87     899.43   12.62    52.94
1267.02  218.30   3.91     881.50   11.24    53.86
1446.96  227.61   3.00     862.66   9.71     55.27
1637.79  244.65   2.30     843.00   8.07     56.39
1839.08  277.10   1.85     822.64   6.85     45.71
2050.93  290.46   2.03     801.67   6.67     21.99
2275.74  280.75   2.72     779.98   6.82     11.60
2511.05  280.91   3.53     757.90   5.95     16.28
2        000501   17       33.6771  -77.6044 0.00     4.92e+01 -7.04e+02 1.62e-01 1.61e-02 -1.06e-04 4.79e-05 20.14   100.00
0.00     233.32   4.94     1023.12  20.48    82.00
18.86    233.72   5.17     1020.89  20.39    78.82
55.84    233.92   5.54     1016.53  20.08    78.33
105.91   234.21   5.97     1010.65  19.67    77.40
167.48   234.67   6.53     1003.46  19.23    74.50
242.51   234.85   7.06     994.75   18.74    69.50
328.61   233.78   7.76     984.82   18.49    56.43
426.99   229.62   7.89     973.57   17.85    52.85
537.91   225.13   7.65     961.01   17.05    51.66
660.88   221.26   7.15     947.23   16.15    50.29
794.39   218.83   6.46     932.44   15.12    49.88
940.72   217.55   5.75     916.43   13.95    50.98
1098.44  216.78   4.99     899.41   12.65    52.47
1267.06  219.61   4.01     881.48   11.27    53.41
1447.00  228.51   3.14     862.64   9.73     55.07
1637.85  244.57   2.45     842.98   8.08     56.19
1839.14  275.02   1.99     822.62   6.84     45.99
2050.97  289.08   2.13     801.65   6.64     22.38
2275.76  280.54   2.80     779.97   6.79     11.71
2511.05  280.78   3.60     757.88   5.94     16.23
```

Figure 4: Example GEM LAM data in HPAC format.

To reduce execution time, the calculations are performed in parallel using 12 CPU (central processing unit) cores. For the example case, all calculations were completed in less than 7 minutes using version 8.2 of Interactive Data Language (IDL) on an HP Z800 Workstation (2 Intel Xeon X5660 processors @ 2.80 GHz and 2.79 GHz) running the Windows 7 Enterprise 64-bit operating system. The IDL code called version 2.3.03 of APM and version 8.20 of LWKD. SNR values are calculated on a three-dimensional grid in range, height, and azimuth. Depending upon the time the calculations are performed relative to the UAV flight time, the results can represent a now-cast or a forecast of the communications effectiveness that the UAV will experience along its flight.

The calculated SNR that would be present in the UAV receiver at an altitude of 1000 m above sea level is displayed in Figure 5. The slice through the SNR data field at 1000 m was chosen for this display since the UAV spends most of its times at an altitude of 1000 m. In Figure 5, the solid black line represents the coastline, the solid white line represents the UAV flight path, and the white X symbols represent the defined UAV waypoints. The range rings (dashed black circular lines) are shown at 20 km intervals. The SNR data field represented by the colours shows the effects of multipath interference as ringed structures centred at the ship location. The SNR value is low in the multipath nulls and high in the multipath peaks. Figure 5 also shows that the SNR field varies with azimuth. This is a result of non-uniform atmospheric refractivity and terrain elevation.

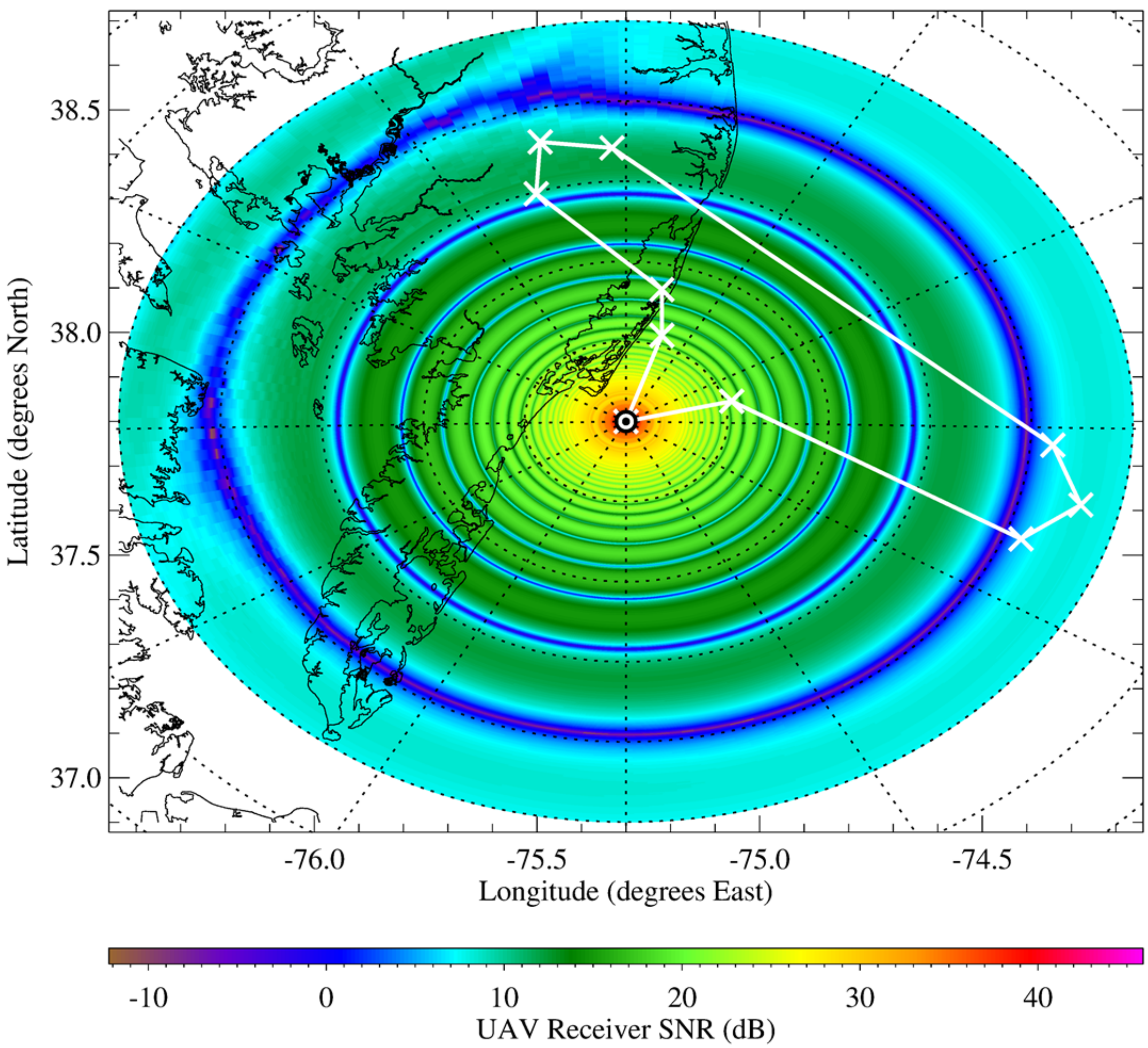

Figure 5: SNR that would be present in the UAV receiver at 1 km above sea level.

A similar picture to that shown in Figure 5 can be created from the SNR calculated to be present in the base station receiver. However, in this case the colour at any given location represents the SNR value that would exist in the base station receiver if the UAV were at the given location. An example figure for the base station receiver SNR is not shown since it would be exactly the same as that for the UAV receiver SNR, due to the chosen parameter set and the reciprocity associated with the propagation calculations.

Figure 5 could be used as a map-based tactical decision aid or it could be simplified further based on a threshold BER that is required for effective communications. As discussed in Section 3, for the case of QPSK, AWGN, a bit rate equal to the receiver bandwidth, and a requirement that $\mathrm{BER} \leq 1 \times 10^{-4}$, the SNR required for effective communications is 8.4 dB or greater. Figure 6 shows the SNR data of Figure 5 contoured only at 8.4 dB. That is, values greater than 8.4 dB are shown as green and values less than 8.4 dB are shown as red. The red and green colours are displayed as transparent so that the local geography can also be seen. The display shows that effective communications are easier to achieve in areas that are north-west and south-west of the ship. The display also suggests that communications may be disrupted at a few points along the UAV flight path due to multipath interference and that communications will be lost as the UAV travels to it farthest points from the ship in the eastern direction. This type of map-based tactical decision aid can be used quickly and easily to determine that the UAV path should be altered to avoid loss of communications, and to determine which areas the UAV flight path should be limited to.

Within a mission planning tool, more quantitative information could be added to the tactical decision aid in Figure 6 by creating a mouse-over feature that displays specific numbers such as SNR or UAV flight path parameters when the user moves the mouse over a particular location. Alternatively, more quantitative information could be provided through an “x-y” plot type display. Figure 7 shows the SNR for both the UAV and base station receivers as a function of time along with the UAV flight path parameters. Note that the SNR for both receivers is identical in this case. Hence, the dark blue and light blue lines in the SNR plot are coincident. For this display, the SNR data does not correspond to a specific altitude or azimuth. Rather the data correspond exactly to the UAV position for all plotted data points. This type of tactical decision aid will allow the user to determine at what times communications will be effective and ineffective, and, for those times, to read the SNR value off the plot along with the corresponding longitude, latitude, range, azimuth, and height of the UAV.

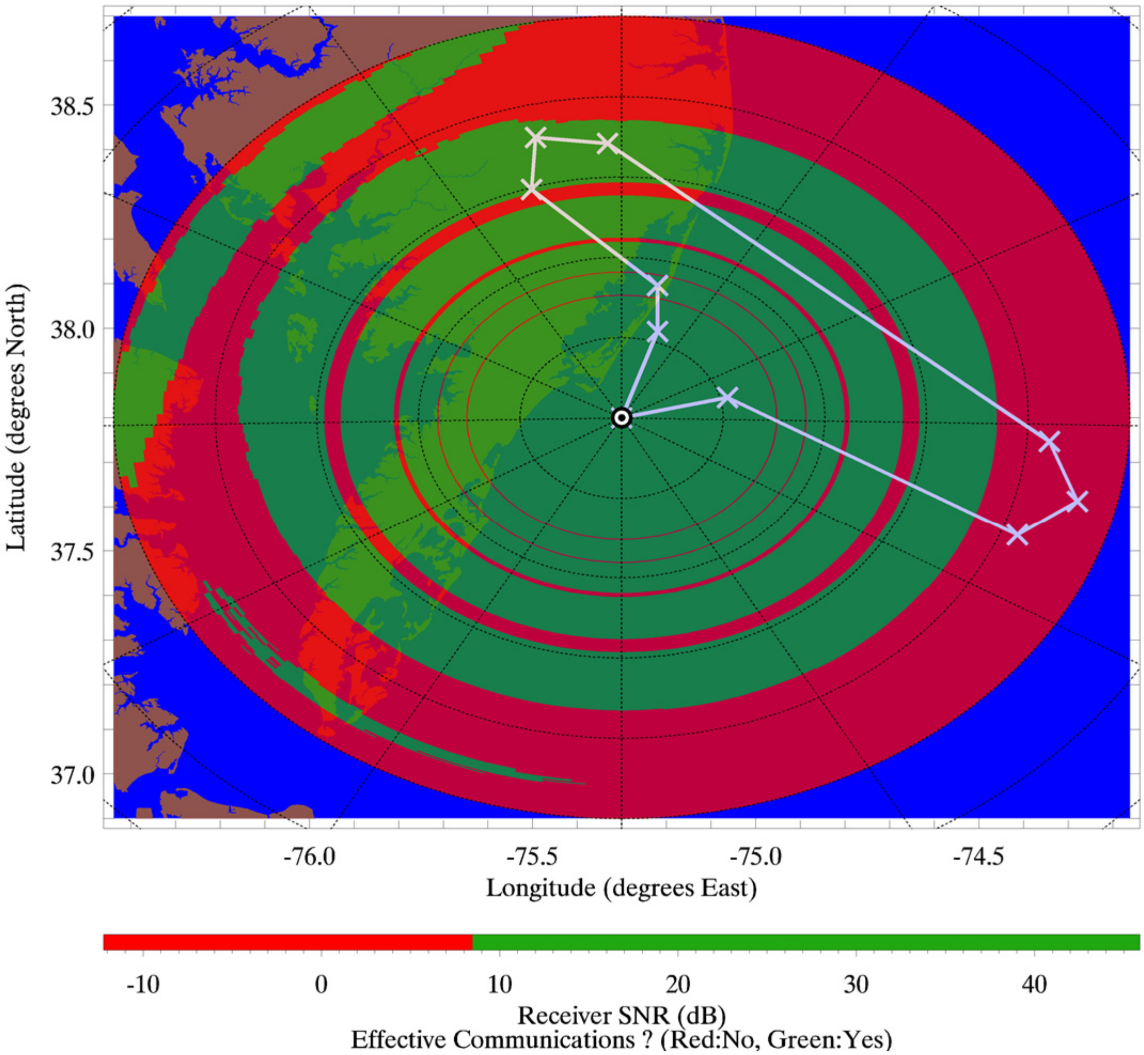

Figure 6: Map-based tactical decision aid showing communications effectiveness.

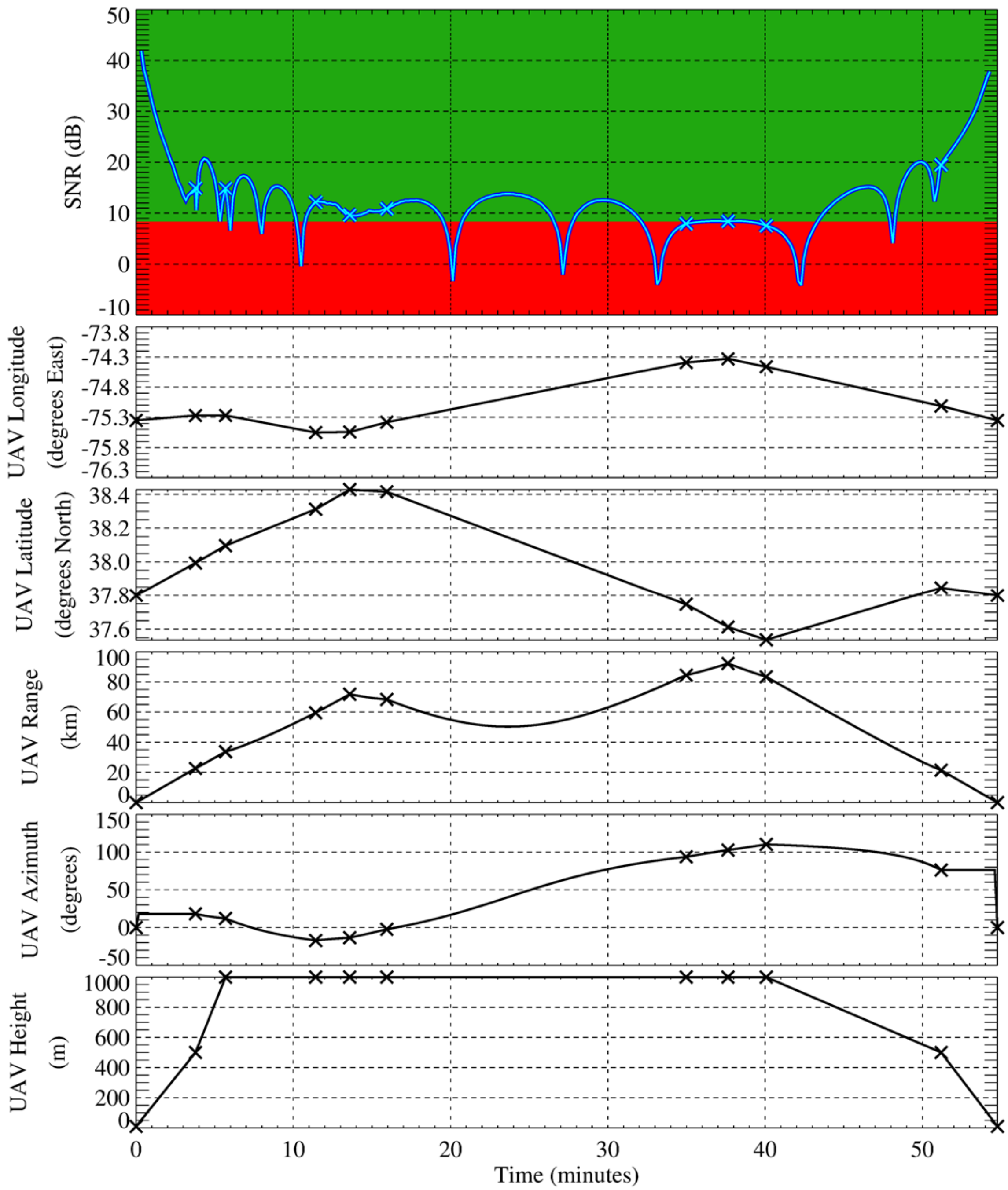

Figure 7: Tactical decision aid showing communications effectiveness along the UAV flight path.

5 Summary and conclusions

This research has proposed concepts for TDAs that could be used in a mission planning tool to now-cast and forecast the effectiveness of communications between a ship and a UXV as a function of environmental conditions and the planned UXV path. The methods used to calculate the TDAs were described and example TDAs were generated for real environmental conditions. The example case showed the variation in communications effectiveness that can be caused by multipath interference and non-uniform atmospheric refractivity. In addition, the example TDAs clearly indicated at which portion of the UXV path communications would be affected and how the path could be altered to improve communications effectiveness.

The main uniqueness of this work is the use of re-locatable mesoscale NWP model data to determine a four-dimensional (space and time) field of atmospheric refractivity that can be used to calculate the propagation environment for the communications signals. The example case showed variation in communications effectiveness as a function of both range and azimuth. If the propagation calculations were performed using an atmospheric refractivity field that was horizontally extrapolated from a single refractivity profile, such as that determined from a radiosonde, then these range and azimuth variations in communication effectiveness would not be observed, even though they may actually exist in the current or future environment. This issue would be most important in a littoral environment where a single refractivity profile will not accurately represent the environment within the full potential operating area of a UAV.

Only two example TDAs have been constructed in this report. However, once the propagation calculations have been performed, many different measures of effectiveness beyond SNR, E_b/N_o, and BER could be calculated, and many different types of TDA products could be used to relay this information to an operator. Further TDAs along these lines, as well as a productized mission planning tool, should be developed in consultation with the end user.

Initial plans for this research included experimental trials to test the hypothesis that the use of NWP data in the manner described can produce accurate now-casts and forecasts of communications effectiveness. These trials would involve laboratory measurements to determine the appropriate threshold (e.g., SNR level) that defines effective communications for the UXV system under investigation and field tests to determine if communications are maintained and lost as predicted (where and when) by the generated TDAs. However, the sponsoring project was ended prematurely due to funding restrictions. Consequently, this research will conclude with this report unless further interest arises from potential users.

References

[1] Adamy, D.L. (2009). EW 103: Tactical battlefield communications electronic warfare, Artech House, p 330.

[2] Blake, L. V. (1986). Radar range-performance analysis. Artech House, Inc., Massachusetts, p 443.

[3] Barrios, A. E. (2003). Considerations in the development of the Advanced Propagation Model (APM) for U.S. Navy Applications. In *Proceedings of the International Radar Conference*, Adelaide, Australia.

[4] Levy, M. (2000). Parabolic equation methods for electromagnetic wave propagation. The Institution of Electrical Engineers, London, p 336.

[5] Rogers, R. R., Yau, M. K. (1989). A short course in cloud physics. 3rd edition. Pergamon Press, p 293.

[6] Forand, J. L. (2008). The LWKD surface boundary layer model. (DRDC Valcartier TM 2007-467). Defence R&D Canada – Valcartier.

[7] International Radio Consultative Committee (1992). 1992-CCIR Recommendations. International Telecommunication Union, RPN series: Propagation in Non-ionized Media. 9ISBN 92-61-04531-6). Geneva.

[8] Born, M., Wolf, E. (1986). Principles of Optics: Electromagnetic theory of propagation interference and diffraction of light, 6th ed., Pergamon Press, p 808.

[9] Wilfred, L., Wittman, K., Hallmann, W. (2009). Handbook of space technology, Wiley, Chichester, UK, p 882.

List of acronyms

ABCANZ	America Britain Canada Australia New Zealand
APM	Advanced Propagation Model
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CCIR	International Radio Consultative Committee
CFWOS	Canadian Forces Weather Office Site
CPU	Central Processing Unit
DRDC	Defence Research and Development Canada
DREV	Defence Research Establishment Valcartier
DTED	Digital Terrain Elevation Data
FIEG	Focused Information Exchange Group
GEM LAM	Global Environment Multiscale Limited Area Model
HPAC	Hazard Prediction and Assessment Capability
IDL	Interactive Data Language
LWKD	Luc (Wavy) Walmsley KEL DREV
NWP	Numerical Weather Prediction
QPSK	Quadrature Phase Shift Keying
RCN	Royal Canadian Navy
RPN	Recherche en Prévision Numérique
SNR	Signal to Noise Ratio
SR	Scientific Report
TDA	Tactical Decision Aid
UAV	Unmanned Aerial Vehicle
USV	Unmanned Surface Vehicle
UTC	Universal Time Constant
UXV	Unmanned Vehicle of general type

DOCUMENT CONTROL DATA

(Security markings for the title, abstract and indexing annotation must be entered when the document is Classified or Designated)

1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g., Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.) Defence Research and Development Canada – Ottawa 3701 Carling Avenue Ottawa, Ontario K1A 0Z4	2a. SECURITY MARKING (Overall security marking of the document including special supplemental markings if applicable.) UNCLASSIFIED 2b. CONTROLLED GOODS (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC APRIL 2011

3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)

A communications-based mission planning tool concept for low-cost tactical UXV operations

4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)

Alan D. Thomson

5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
April 2014	28	9

7. DESCRIPTIVE NOTES (The category of the document, e.g., technical report, technical note or memorandum. If appropriate, enter the type of report, e.g., interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Scientific Report

8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)

Defence Research and Development Canada – Ottawa
3701 Carling Avenue
Ottawa, Ontario K1A 0Z4

9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)
01aa	

10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)
DRDC-RDDC-2014-R11	

11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)

Unlimited

12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.))

Unlimited

13. ABSTRACT (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.) New concepts for communications-based tactical decision aids, which can be used for low-cost tactical UXV operations, are investigated to provide input for future mission planning tools that could be developed for the Royal Canadian Navy. The proposed tactical decision aids provide information on where and when communications between a UXV and its base station will be effective and not effective as a function of the current and future environmental conditions. The required signal propagation calculations use data from an Environment Canada numerical weather prediction model and a terrain elevation database. A description is provided of the approach used to calculate the base quantities (signal-to-noise ratio, E_b/N_o, bit error rate) that are required to form the tactical decisions aids. Example tactical decision aids are calculated for a specific case to demonstrate how this information could be used for planning UXV routes. The example case clearly shows regions where communications are effective and not effective within a realistic environment. Experimental trials are required to test the hypothesis that the proposed method is capable of accurately now-casting and forecasting the times and places for which a UXV will have effective communication with its base station.
14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g., Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.) UXV, propagation, communications, littoral, mission planning tool, tactical decision aid