Final Report
UAS Command and Control Communications Feasibility Study

May 11, 2015

Prepared for:
NextGen Institute
Attn: Marke Gibson
NextGen Institute Executive Director
PO Box 34422
Washington, DC 20043-4422

Prepared by:
Exelis Inc.
12930 Worldgate Drive, Suite 400
Herndon, VA 20170-6008
Table of Contents

EXECUTIVE SUMMARY .................................................................................................................. 1
ES-1 Introduction and Study Objectives .................................................................................. 1
ES-2 Study Conclusions ................................................................................................................. 1
ES-2.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights .................... 1
ES-2.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability ...... 2
ES-2.3 Task 3: Business/Financial Assessment - Infrastructure Business Models ....... 3
ES-2.4 Task 4: Regulatory Assessment - Governance & Accountability ......................... 4
ES-3 Recommendations ................................................................................................................ 4
ES-3.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights .................... 4
ES-3.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability ...... 5
ES-3.3 Task 3: Business/Financial Assessment - Infrastructure Business Models ....... 5
ES-3.4 Task 4: Regulatory Assessment - Governance & Accountability ......................... 6

1.0 INTRODUCTION ....................................................................................................................... 7
1.1 Study Objectives ....................................................................................................................... 7
1.2 Study Team/Structure .............................................................................................................. 7
1.3 Report Organization .................................................................................................................. 7

2.0 DESCRIPTION OF UAS SCENARIO USED FOR THE STUDY .......................................... 7
2.1 Scenario Overview .................................................................................................................... 7
2.2 Alternative C2 Approach Specific Scenario Assumptions ................................................. 10
2.3 Additional Scenario Consideration – Hybrid Approaches ................................................ 11
2.4 Study Tasks ............................................................................................................................. 11

3.0 TASK APPROACHES AND FINDINGS .............................................................................. 11
3.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights .......................... 11
3.1.1 Applications and Operational Concepts for the Study Scenario ......................... 12
3.1.2 UAS PTP and Network C2 System Definitions ..................................................... 14
3.1.3 Relative Operational Suitability to Support Flight Mission Variety ................... 21
3.1.4 PTP and Network C2 Comparative Spectrum Limitations .................................... 22
3.1.5 Link/Mobility Management Issues for PTP and C2 Network Operations ........ 29
3.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability .......... 31
3.2.1 Developing Radio Site Topologies .............................................................. 31
3.3 Task 3: Business/Financial Assessment - Infrastructure Business Models .......... 54
  3.3.1 Task Approach ......................................................................................... 54
  3.3.2 Operations and Flight Hours .................................................................. 55
  3.3.3 Benefits ................................................................................................... 56
  3.3.4 C2 Provider Estimated Costs and Revenues ............................................. 57
3.4 Task 4: Regulatory Assessment - Governance & Accountability ....................... 60
  3.4.1 Operational System Safety ...................................................................... 60
  3.4.2 Aspects of C2 System Certification .......................................................... 65
  3.4.3 UAS C2 Performance Monitoring for Accountability Assurance ............... 69

4.0 SUMMARY CONCLUSIONS ......................................................................... 71
  4.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights ................. 72
    4.1.1 Fundamental Differences between PTP and Network C2 Systems .......... 72
    4.1.2 Relative Operational Suitability to Support Flight Mission Variety ......... 72
    4.1.3 PTP and Network C2 Comparative Spectrum Limitations ..................... 72
    4.1.4 Link/Mobility Management Issues for PTP and C2 Network Operations .... 74
  4.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability ..... 74
  4.3 Task 3: Business/Financial Assessment - Infrastructure Business Models ....... 76
  4.4 Task 4: Regulatory Assessment - Governance & Accountability ................... 77
    4.4.1 Operational System Safety ..................................................................... 77
    4.4.2 Aspects of C2 System Certification ....................................................... 78
    4.4.3 UAS C2 Performance Monitoring for Accountability Assurance ............. 78

5.0 RECOMMENDATIONS .................................................................................. 79
  5.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights ................. 79
  5.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability ..... 79
  5.3 Task 3: Business/Financial Assessment - Infrastructure Business Models ....... 80
  5.4 Task 4: Regulatory Assessment - Governance & Accountability ................. 80

APPENDIX A - LIST OF ACRONYMS ............................................................... A-1

List of Figures
Figure 1 – C2 Feasibility Study Team ................................................................... 7
Figure 2 – Geographic Overview of TAPS Oil Pipeline Scenario ........................... 8
Figure 3 – UAS C2 and ATC Communications High Level Operational View .......... 15
List of Tables

Table 1 – TAPS LOC BLOS Inspection Scenario Overview ........................................ 9
Table 2 – C2 Alternative Specific Scenario Assumptions ........................................ 10
Table 3 – Scenario Assessment Tasks .................................................................. 11
Table 4 – Baseline TAPS Surveillance Applications ................................................................. 12
Table 5 – Potential Hybrid and Network UAS Applications ................................................. 13
Table 6 – Comparison Between PTP and Network C2 Systems ........................................... 20
Table 7 – Spectrum Management Report Findings Applied to C2 Systems in this Study ........ 27
Table 8 – Coverage Model Selection Process Summary ..................................................... 37
Table 9 – PTP and Network C2 System Comparative Technical Evaluation Summary ........... 53
Table 10 – Typical UAV per hour Operating Costs ............................................................... 55
Table 11 – Total C2 Utilization ............................................................................................. 55
Table 12 – Potential Direct Benefits per Year ....................................................................... 56
Table 13 – Potential Indirect Cost Avoidance Benefits Per Sample Oil Spill ....................... 57
Table 14 - Total NRC (Capital + Installation + Spares) Costs .............................................. 57
Table 15 – MRC (power, comm., space) ............................................................................. 58
Table 16 – UAS Environmental Conditions ......................................................................... 63
Table 17 – Meteorological Environmental Conditions ......................................................... 63
Table 18 – UAS Flight Phases .............................................................................................. 64
Table 19 – Emergency Environmental Conditions ............................................................... 64
Table 20 – Severity Classification and Likelihood Requirements of Failure Conditions ........ 64
Table 21 – Evaluation Criteria for Selecting Performance Measurement Parameters .......... 71
Table 22 – C2 System Performance Measurement Parameters Assessment Example ............ 71
EXECUTIVE SUMMARY

ES-1 INTRODUCTION AND STUDY OBJECTIVES
This is the report for a study conducted by the Exelis Inc. (Exelis) – University of Alaska Fairbanks (UAF) Team for a feasibility assessment of alternative C-Band terrestrial based command and control (C2) communications approaches for supporting low altitude unmanned aircraft system (UAS) inspections over the 800 mile length of the Trans-Alaska Pipeline System (TAPS), also known as Alyeska Pipeline. The objectives of this C2 feasibility study were to identify and more completely understand “the practical operational advantages and disadvantages associated with UAS C2 requirements for individual flights” in four major areas: End-to-end BLOS UAS flights, Infrastructure requirements and availability, BLOS infrastructure business models for C2; and Regulatory concepts, governance, and accountability for UAS C2 infrastructure assurance for each C2 approach.

ES-2 STUDY CONCLUSIONS

ES-2.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights
Principal factors that distinguish a C2 network system from a Point-to-Point (PTP) C2 system include:

- Point-to-multipoint, multiple frequency operation (for C2 network systems)
- Greater interoperability in C2 network systems provided through “open” accessibility to C2 network airspace for potential unmanned aircraft (UA), typically enabled through “open” standards. By contrast, a PTP C2 service provider could implement a more proprietary system, since interoperability with other systems is not required.

Operational limitations in PTP C2 systems for the study scenario are generally due to coverage limitations necessitated by a single end user (i.e. Alyeska Pipeline), and lack of flexibility because of single frequency operation. The limitations in coverage area of the linear PTP Radio Station (RS) topology needed for TAPS inspection can be offset by adding new RS to fill required coverage gaps outside the coverage corridor, and by adding/upgrading radio equipment at existing PTP RS, thus creating a Hybrid C2 system. As an evolutionary path, upgrading all existing PTP RS to handle point-to-multipoint operations, along with adding any new RS required for additional coverage would ultimately result in a fully networked C2 system. These observations are applicable to other UAS operational scenarios.

In an assessment of the four spectrum management models described in the Titania Spectrum Management Report, including a high level assessment of the sufficiency of each model in providing equitable, effective and efficient spectrum management functions for the PTP and Network C2 systems covered in this study, it is found that all four models could generally meet

---

1 The study was constrained to consider terrestrial C2 solutions using the ITU-R specified 5030 – 5091 MHz UAS C-Band allocation; SATCOM solutions were not considered. Also, all ATC functions (e.g. ATC voice) were outside the scope of this study.

the spectrum management needs for these alternative C2 systems, because each of the four models was defined to accommodate both on-network and off-network UAS.

A common element in proposed dynamic spectrum assignment schemes under discussion in the RTCA SC-228 WG2 Dynamic Spectrum Assignment Subgroup, as well as in the Titania Report, is the recommendation for real time, comprehensive flight planning and interference assessment tools to be used by the spectrum management/assignment entity. Fortunately, the technology is available, so this capability is achievable. Another recommended spectrum assignment system component is web portal like functionality that allows for real time access to the spectrum management entity by the spectrum user/requester.

Unfortunately, currently proposed dynamic spectrum assignment approaches under consideration in RTCA SC-228 WG2 are hampered by the lack of interoperability standards development within WG2 that could define standard link/mobility management approaches and provide some functional platforms upon which spectrum assignment approaches, such as a common signaling channel, could be built upon.

ES-2.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability

Using a novel linear programming optimization process on an initial set of the 57 best available site locations, it was found that it is not possible to reach 100% coverage along the entire TAPS right of way (ROW) until reaching UA operational altitudes of around 1000 ft. above ground level (AGL) or greater. For the 100 foot AGL coverage goal for this study, the best that can be achieved using that set of RS sites is 83 percent coverage (for 40 total sites). Optimizing over an additional 92 sites, it was found that more than 91 percent pipeline coverage at 100 ft. AGL could be achieved, but would require 61 sites.

The optimization methodology optimized for minimum overlap and maximum total coverage, mainly in the interest of requiring the fewest sites and hence reducing costs. This leads to significant portions of the pipeline with little redundancy, which might not be the ideal case for purposes of efficient handoffs. In an actual design and implementation, further optimization would be required to balance among the competing goals of reducing interference, minimizing RS site costs, and providing sufficient overlap for the handoff process.

For those areas of the pipeline route with inadequate coverage several alternatives or combinations of alternatives could be considered:

- Increase the height of the existing towers proposed at the pump stations; however, increasing tower height is more costly, more difficult, and increases risk to air navigation (manned and unmanned)
- Provide pipeline surveillance coverage with manned aircraft for those inadequate UAS coverage areas of the ROW, which could later be augmented or replaced by UAS coverage enabled by SATCOM C2
- Provide unmanned surveillance at a higher altitude, then deploy manned aircraft to provide inspection at lower altitudes only as needed to perform closer checks on potential areas spotted at the higher altitude
- Deploy unmanned aircraft C2 “repeaters” at pump sites (which is outside of the current TOR for RTCA SC-228)
Because this study is consistent with the current RTCA SC-228 Pilot-in-the-Loop (PITL) UA control assumption, the alternative of allowing for autonomous UA operations over those pipeline sections without RS coverage was not considered.

Providing Hybrid or Network operational capabilities to augment the coverage provided for the baseline PTP C2 system in supporting the core TAPS scenario and operational needs would require the addition of:

- New multi-frequency/channel RS to provide additional coverage in areas of interest outside the TAPS ROW
- Upgrades to existing sites to provide multi-frequency/channel capabilities
- Appropriate network interconnectivity to support these other changes

To provide additional coverage for a Hybrid case, which assumes that the PTP infrastructure is already in place and operational, the new sites would have to be selected to provide the new coverage in the coverage areas most beneficial to the planned, expanded set of end users, while striving to minimize cost risks in selecting new sites.

In considering the comparative advantages and disadvantages of PTP, Hybrid, and Networked C2 systems in flexibility, scalability, and capacity, please note that the PTP, Hybrid, and Network C2 systems can be viewed as three stages in an operational continuum of the same basic C2 architecture and infrastructure as it evolves to accommodate more and more end users, with the distinguishing characteristic being to what extent point-to-multipoint capability has been implemented. Other relative advantages and disadvantages of the three systems relate to the degree to which interoperability has been designed into the system, and the possible efficiencies and optimization to be gained by designing a Network from “the top down” as a network, rather from the bottom up as an evolved system starting out as a PTP system, which then evolves into a Hybrid system, and finally transitions into being a Network system. This latter path might be chosen however, as a matter of expediency and costs.

**ES-2.3 Task 3: Business/Financial Assessment - Infrastructure Business Models**

Based on an assessment of the C2 business model viability, it is concluded that a C2 PTP infrastructure solely for Alyeska use does not appear to be cost effective, and even with all users considered, the per flight hour fee to enable an acceptable return on investment may be too costly for the market to bear for a C2 infrastructure providing coverage down to 100 ft. AGL along the entire pipeline. These rough order of magnitude (ROM) estimates are highly dependent on: the actual number of flight hours per year, spreading initial Non Recurring Costs (NRC) over multiple years, and net present value of money (which was not considered). The estimated $200 per hour C2 service fee is relatively high compared to the approximately $200 per flight hour operational cost of flying a UA excluding the C2 link. However, a total operational cost of $400 per hour (operational costs plus C2 link) is not unreasonable compared to the $1000 per hour manned helicopter cost.

Consideration should be made for the expansion of the C2 infrastructure to include additional services or to accommodate other end users, but which does not significantly increase the C2 infrastructure costs (e.g. a Hybrid C2 system). This could add substantial value to the use of the service. For example, Alyeska has a desire for real-time video during pipeline monitoring and during spill response events.
ES-2.4 Task 4: Regulatory Assessment - Governance & Accountability

A full operational safety analysis was beyond the scope of this study. The study included a brief discussion of the UAS safety analysis process conducted in the context of the FAA’s Safety Management Process, some safety relevant UAS C2 infrastructure design considerations, and some aspects of a very high level and preliminary safety analysis.

The FAA’s Small Airplane Directorate has been a visible force for FAA UAS certification efforts, and has provided RTCA SC-228 WG2 an excellent overview of the UAS certification process and issues. An important question to ask is: where does a potential UAS C2 service provider fit into the UAS certification process, i.e., what is the process for certification if the UA platform and GCS comes from one source and the C2 services come from a different source? The answer to that question is not clear at this time. Even with a Technical Standard Order (TSO) authorized C2 radio system (two radios and a C2 link), there are other elements comprising C2 end-to-end services that would need to be considered for UAS certification.

Two general observations regarding relative certification issues/problems for PTP and Network C2 system can be made at this time:

- The certification process for UAS provided as a service and composed of constituent services, such as a C2 service and a DAA service, from multiple sources needs to be better understood.

- A PTP C2 system deployed as part of a turnkey, owner/operator UAS service/system may face a less complex certification challenge because the UA type, C2 radio type, GCS, etc. and operational areas/applications will be limited in scope compared to the situation faced by a potential C2 Network service provider that may want to provide C2 services for a broad range of UA platforms, end users, and operational applications.

For this study an initial iteration of the selection of the appropriate performance measurement data parameters was conducted, based on early but ongoing efforts in RTCA SC-228 WG2 to identify appropriate parameters suitable for both C2 PTP and Network C2 Systems. Using criteria developed by Exelis to evaluate suitability of potential measurement data parameters for its Surveillance and Broadcast Services (SBS) Program, a highly preliminary comparative assessment was performed, mainly to illustrate the process, of several PTP and Networked C2 performance monitoring requirements. Because the candidate parameters are still being identified in RTCA SC-228 WG2, the assessment is not complete.

ES-3 RECOMMENDATIONS

ES-3.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights

The following recommendations are made for this Task:

1. Policy decisions based on PTP and Network C2 Systems as separate and distinct classes should be discouraged because PTP, Hybrid, and Network C2 systems can be viewed as three stages in an operational continuum of the same basic C2 architecture and infrastructure. Maintaining the PTP (or “Standalone”) vs. Network distinction has been unnecessarily polarizing, especially in the technical standards community.

2. Both ad hoc and fixed PTP C2 systems should always be accommodated in the UAS operational arena, even after C2 network systems have been deployed in the same general area. Therefore, by policy, a dynamic spectrum assignment system should
provide equal and equitable access to all qualified PTP and C2 systems, even if this means sub-banding or segregation of the spectrum to provide fixed allocations to certain C2 system categories, such as the ad hoc PTP systems.

3. The Titania Spectrum Management report sponsored by the FAA should be provided to RTCA SC-228 WG2. This would promote a more common level of understanding of the UAS regulatory environment among that group and would be of great value in informing the discussions of WG2 subgroups such as the Dynamic Spectrum Assignment subgroup.

4. Because lack of UAS C2 technical interoperability standards (at the appropriate protocol layers) presents a serious impediment to the widespread and harmonious implementation of UAS C2 systems and associated spectrum allocations/assignment processes, these should be given a higher priority in future standards development activities. This should include consideration of changing the Phase 2 Terms of Reference for RTCA SC-228 WG2.

ES-3.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability

We make the following recommendations for this Task:

1. UAS C2 system infrastructures should be implemented using radio systems based on accepted aeronautical standards, such as RTCA MOPS, as these typically lead to a more straightforward FAA certification path. Likewise, C2 system implementations should be compliant with relevant ITU-R recommendations.

2. A detailed site/coverage selection process optimizing for both performance and costs, such as that outlined in Section 3.2.1.6, should be used for planning UAS PTP, Hybrid and Network C2 radio systems with multiple, fixed RS infrastructure. The process provided in Section 3.2.1.6 is scalable for larger coverage regions, and could be extended for UAS C2 systems providing nation-wide coverage.

3. Because austere, challenging terrain areas such as Alaska drive up the number of required RS for providing low altitude coverage over an extended coverage range, consideration should be made for installing Hybrid or Network capable infrastructure (e.g. multichannel radios) at selected RS to offer increased flexibility, capacity and potential revenue capabilities to offset the relatively high capital costs.

4. Because of the safety critical nature of the services provided over UAS C2 radio system links, these systems should be designed to meet Required Link Performance values for availability, latency, and integrity consistent with FAA systems providing NAS critical services.

ES-3.3 Task 3: Business/Financial Assessment - Infrastructure Business Models

The following recommendations are made for this Task:

1. Additional analysis should be performed for the C2 business models to include additional tradeoffs across technical, operational, policy, and business considerations as those considerations become more defined. There are multiple unknowns that are apparent in these business models such as cost and management of C2 radio spectrum, the regulatory environment for BLOS UAS operations, technology acceptance by regulators, and ultimately the perception of risk with adopting new UAS technology.
2. This analysis is highly dependent on ROM estimates of UA flight hours utilizing the C2 link. It is recommended that additional analysis and modeling of flight hours be performed, as they are expected to ramp up over the proposed 20 year life cycle.

3. Consideration of the C2 infrastructure should include additional services (e.g., payload data) that do not markedly increase the C2 infrastructure costs, but can add substantial value to the use of the service.

4. This analysis is specific to the TAPS use case, including the need for dedicated on-call manned helicopters for spill response and generally higher infrastructure costs. Additional analysis should be performed as applied to pipeline use cases in the continental United States (CONUS) with possible higher replacement of manned aircraft flight hours with UA operations, typically lower infrastructure costs, and costs spread across more users and flight hours.

**ES-3.4 Task 4: Regulatory Assessment - Governance & Accountability**

The following recommendations are made for this Task:

1. UAS C2 system safety assessments should be consistent with the FAA’s Safety Management System (SMS) to facilitate the certification process.

2. Additional clarification is needed from the FAA on the process for certifying a UAS composed of facilities, equipment, and potentially services provided by multiple sources.

3. Exelis recommends that UAS C2 systems implement a technical performance monitoring (TPM) system using a methodical process similar to the presented approach to ensure selection of appropriate measurement data parameters.
1.0 INTRODUCTION

This is the report for a study conducted by the Exelis Inc. (Exelis) – University of Alaska Fairbanks (UAF) Team for a Feasibility Assessment of alternative C-Band terrestrial command and control (C2) communications approaches for supporting low altitude unmanned aircraft system (UAS) inspection over the 800 mile length of the Trans-Alaska Pipeline System (TAPS), also known as Alyeska Pipeline.

1.1 Study Objectives

The objectives of this C2 feasibility study were to identify and more completely understand “the practical operational advantages and disadvantages associated with UAS C2 requirements for individual flights” in four major areas: End-to-end BLOS UAS flights, Infrastructure requirements and availability, BLOS infrastructure business models for C2; and Regulatory concepts, governance, and accountability for UAS C2 infrastructure assurance for each C2 approach.

1.2 Study Team/Structure

The study team (see Figure 1) leveraged an existing UAF research project with Alyeska Pipeline Service Company (Alyeska) titled “Protecting Transportation Infrastructure with UAS” that is investigating UAS operations for pipeline surveillance (see www.snap.uaf.edu/projects/uas-rita). The UAF team included two pipeline surveillance/inspection specialists, TCQ Consulting and CR Inspection, as well as ArcticFire Development, a UAF business spinoff developing a powerful UAS ground control system.

1.3 Report Organization

This report has been structured into the following five major sections:

- Section 1: Introduction
- Section 2: Description of UAS Scenario used for the Study
- Section 3: Task Approaches and Findings
- Section 4: Summary Conclusions
- Section 5: Recommendations

2.0 DESCRIPTION OF UAS SCENARIO USED FOR THE STUDY

2.1 Scenario Overview

The selected study scenario is to assess the feasibility of alternative C2 communications implementation approaches (i.e. Point-to-Point (PTP) and Networked systems) for supporting low altitude, Beyond Line of Sight (BLOS) UAS inspection in austere environments over the...
800 mile length of the TAPS (see Figure 2). The majority of TAPS is in the remote Alaska environment, however it also transitions through Fairbanks, the second largest city in Alaska, with its denser communication infrastructure and multiple civilian and military airports.

Figure 2 – Geographic Overview of TAPS Oil Pipeline Scenario
The oil pipeline C2 scenario illustrates a C2 paradox that the easiest areas to implement C2 systems are in urban infrastructure environments; however these areas typically have denser air traffic that may be more difficult to approve for UAS operations because of airspace management and safety issues. Austere environments such as Alaska may have UAS operations being approved faster by the FAA because of operational needs and lower risks associated with aviation near rural areas. Of course, it is also understood that UAS BLOS operations in typical Alaska environments may be more difficult to implement because of the lack of C2 infrastructure, including commercial telecommunications systems.

As shown in Figure 2, the Alyeska pipeline is supported by 12 Pump Stations along the 800-mile route, and 25 AT&T leased VHF radio repeater stations to support Alyeska Operations and Maintenance of the pipeline and its Right of Way (ROW). Though about half of the pipeline is underground and the rest is above ground, it all requires periodic monitoring and inspection. The figure also depicts current and potential future ADS-B sites and commercial telecon tower sites, which, besides the 25 VHF radio sites, could serve as potential C2 communications sites.

Table 1 represents a descriptive overview of the study scenario, with elements common to both the PTP and networked C2 communications system approaches.

<table>
<thead>
<tr>
<th>Scenario Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Summary Description</strong></td>
<td>▪ Line of Communication Beyond Line of Sight (BLOS), low altitude inspection of the Trans-Alaska Pipeline System (TAPS)</td>
</tr>
<tr>
<td>Infrastructure length and end points</td>
<td>▪ 800 miles (1,287 km) from Prudhoe Bay, to Valdez, Alaska</td>
</tr>
<tr>
<td>Associated infrastructure and facilities</td>
<td>▪ Prudhoe Bay Oil Field (origin), Valdez Marine Terminal (terminus), 12 pumping stations, AT&amp;T leased VHF radio/telephone system with 25 repeater stations, one operations control center, and two remote emergency operations centers</td>
</tr>
<tr>
<td>Pipeline owner</td>
<td>▪ Alyeska Pipeline Service Company</td>
</tr>
<tr>
<td>Current Inspection Needs</td>
<td>▪ Pipeline &amp; Hazardous Materials Safety Administration (PHMSA) requires ROW visual inspection 26 times per year with additional closer inspection as needed</td>
</tr>
<tr>
<td></td>
<td>▪ Regular and persistent patrolling of the pipeline ROW and key facilities for monitoring and assessing risks (e.g., leaks, encroachments, geological instability, etc.)</td>
</tr>
<tr>
<td></td>
<td>▪ Close range inspection and imaging of 122,000 thermosiphon facilities to mitigate permafrost thaw and other Arctic geotechnical engineering issues</td>
</tr>
<tr>
<td>Current Inspection Methods</td>
<td>▪ Aerial inspection via helicopter and other manned aircraft (due to Alaska’s austere aviation environment, manned helicopter operations cost ~$14,000 per day)</td>
</tr>
<tr>
<td></td>
<td>▪ Ground vehicle (automobile, all-terrain vehicles, or snowcat) inspections when necessary, e.g. flagged via aircraft for further investigation, inclement weather.</td>
</tr>
<tr>
<td>UAS Operational range and altitudes</td>
<td>▪ Assume minimum range of ~100 nm between pump stations along a total of 800 mile pipeline ROW</td>
</tr>
<tr>
<td></td>
<td>▪ Altitudes from 100 feet to 2000 feet above ground level (AGL) (current operations is 40 to 400 ft. AGL), up to 2000+ feet AGL for Hybrid and Network operations</td>
</tr>
<tr>
<td></td>
<td>▪ Includes within and beyond visual line of sight (BLOS)</td>
</tr>
<tr>
<td>Airspace classes of operations</td>
<td>▪ Class G,E, and D airspace ranging from very remote low density airspace to a mix of commercial, general aviation, and military aircraft operations in the Fairbanks area</td>
</tr>
<tr>
<td>UAS Level of Automation Assumed</td>
<td>▪ Consistent with RTCA SC-228 assumptions, Pilot in the Loop (PITL) UAS control is exercised, i.e. UA autonomy is not allowed, except in degraded and/or off-nominal operational conditions, such as the Lost Link condition.</td>
</tr>
<tr>
<td>Regulatory Considerations</td>
<td>▪ Assumes C2 service provider is same as UAS service provider with respect to obtaining FAA certification of C2 system</td>
</tr>
<tr>
<td>Study Assumptions per the Solicitation</td>
<td>▪ Focus of study is on terrestrial C2 solutions; SATCOM solutions were not considered</td>
</tr>
<tr>
<td></td>
<td>▪ C2 spectrum will use ITU-R specified 5030 – 5091 MHz UAS C-Band allocation</td>
</tr>
<tr>
<td></td>
<td>▪ All ATC functions are provided and handled outside the scope of this study</td>
</tr>
</tbody>
</table>
2.2 Alternative C2 Approach Specific Scenario Assumptions

Table 2 summarizes the differentiating assumptions for the PTP and the networked C2 system approaches.

<table>
<thead>
<tr>
<th>Scenario Parameter</th>
<th>Point-to-Point Approach Assumptions</th>
<th>Networked Approach Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAS C2 service end user(s)</td>
<td>Single pipeline company, i.e. Alyeska, which conducts its own inspection, (not typical in the oil pipeline industry)</td>
<td>Alyeska pipeline company and other potential users/applications not necessarily within the pipeline ROW, including:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Third party pipeline inspection companies, if required</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Bureau of Land Management, State Dept. of Forestry (forest fire fighting)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Dept. of the Interior (wildlife observation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Fairbanks police and fire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Alaska State Troopers</td>
</tr>
<tr>
<td>C2 system interoperability</td>
<td>“Closed” system limits access only to UA specifically designed for that system. Specifications may be proprietary.</td>
<td>C2 service provider publishes UA interoperability standards required for use of the network</td>
</tr>
<tr>
<td>Number of simultaneous unmanned aircraft in operation</td>
<td>Multiple UAs along different sections of pipeline (they use five helicopters today), but assume one per C2 station because of single frequency operation</td>
<td>Multiple UA for multiple users</td>
</tr>
<tr>
<td>C2 service coverage capabilities</td>
<td>Only along pipeline ROW at up to 2000 ft. AGL</td>
<td>Pipeline ROW at up to 2000 ft. AGL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other areas as required for additional end users of the network</td>
</tr>
<tr>
<td>C2 communications service provision options</td>
<td>Third party C2 service provider using existing leased infrastructure (VHF radio stations), leased commercial telecon sites as needed to provide gap filler coverage, new infrastructure owned and operated by C2 service provider</td>
<td>Third party provides C2 services using combinations of:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Existing leased infrastructure (VHF radio stations)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• New infrastructure built and owned by C2 service provider to provide coverage to other users within and outside of Alyeska ROW coverage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Other existing leased commercial telecon infrastructure</td>
</tr>
<tr>
<td>UAS C-Band protected spectrum channel operational requirements options</td>
<td>• Single channel/frequency is periodically assigned to user (Alyeska or third party C2 provider) as needed, over UAS pipeline ROW flight path based on reservations</td>
<td>Multiple frequencies (within a fixed pool of frequencies assigned to the service providers radio stations) are assigned as needed to the C2 service provider for oil pipeline inspections and other end user services, based on reservations. Frequency broker has technical capability and responsibility to mitigate co-channel interference operation for C2 service providers for all assigned frequencies during UAS operations</td>
</tr>
<tr>
<td></td>
<td>• Single channel/frequency is permanently assigned to user (Alyeska or third party C2 provider), over UAS pipeline ROW flight path</td>
<td>• A sufficient number of multiple frequencies are permanently assigned to the service providers to prevent co-channel interference among the network radio sites, based on C2 service provider design. C2 service provider is responsible for mitigating co-channel interference during all UAS operations using its network.</td>
</tr>
<tr>
<td>Mobility management, including handoffs</td>
<td>Based on single channel operations</td>
<td>Multiple channel operations, may rely more on use of upper layer protocols</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Also potential for handoffs between other networks</td>
</tr>
<tr>
<td>Regulatory/Safety Considerations</td>
<td>Third party C2 provider is responsible for certifying system, which includes developing and submitting safety case. Upon approval, responsible for system safety.</td>
<td>Third party C2 provider is responsible for certifying system, which includes developing and submitting safety case. Upon approval, responsible for system safety.</td>
</tr>
</tbody>
</table>
### 2.3 Additional Scenario Consideration – Hybrid Approaches

Initially, to make the feasibility assessment more tractable, it is assumed that the system providing C2 services to the TAPS in its entirety will be homogeneous, i.e. either a PTP or a networked system. However, to accommodate the study requirement to consider simultaneous operation of a PTP and a networked system (Hybrid Approach), the study also considered the following Hybrid scenario:

- After starting out as a PTP system, the C2 service provider decides to start providing C2 network services. For the TAPS scenario, this is accomplished by transitioning distinct sections of the C2 system along the pipeline into a networked system serving other users. For this scenario variant, the sections that have transitioned to a C2 network must still accommodate operations at the single PTP frequency for UA transiting between the PTP and networked portions of the pipeline. Other users may use the networked section of the system, but on a different set of available frequencies for network operations.

### 2.4 Study Tasks

This study assessed the relative feasibility of the PTP and Networked C2 system approaches for the TAPS surveillance scenario in the four general areas shown in Table 3, each of which defined one of the four study tasks.

#### Table 3 – Scenario Assessment Tasks

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Task Activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suitability to support flight mission variety</td>
<td>Flexibility</td>
<td>End user costs/benefits</td>
<td>Safety – all operational modes</td>
</tr>
<tr>
<td></td>
<td>Spectrum limitations</td>
<td>Interoperability</td>
<td>C2 service provider costs/benefits</td>
<td>Certifiability</td>
</tr>
<tr>
<td></td>
<td>Link/Mobility Management Issues</td>
<td>Scalability</td>
<td>UAS service provider costs/benefits</td>
<td>Performance Monitoring</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spectrum efficiency/capacity</td>
<td>Hybrid operations</td>
<td></td>
</tr>
</tbody>
</table>

### 3.0 TASK APPROACHES AND FINDINGS

#### 3.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights

As shown in Table 3, for this task three somewhat three distinct investigations were conducted:

- Evaluating Relative Operational Suitability to Support Flight Mission Variety
- Determining PTP and Network C2 Comparative Operational Spectrum Limitations
- Link/Mobility Management Issues for PTP and C2 Network Operation

Potential UAS applications and operational concepts for the study scenario supporting these investigations were developed and are described first in Section 3.1.1. This is followed by a general discussion of the comparative differences between PTP and Network C2 Systems in Section 3.1.2. Finally the approach and results of each of the three task investigations are described in Sections 3.1.3 through 3.1.5.
3.1.1 Applications and Operational Concepts for the Study Scenario

The baseline operational concepts for the study scenario focus on the use of UAS to support various Alyeska TAPS surveillance applications. For the most part these applications are conducted within the TAPS Right of Way (ROW), which varies as follows:

- Federal land: 54 feet (buried pipe); 64 feet (elevated pipe).
- State land: 100 feet.
- Private land: 54 feet to 300 feet

Some of the applications involve periodic, longer range (100 miles or more, several hours) flights for small, fixed wing UA, such as the Puma, Raven or ScanEagle. These applications are currently handled by manned aircraft, typically helicopters. Other applications require shorter range flights (3 nm range, nominally 45 minute duration) for small multicopter UA. These applications are currently supported either by on the ground human inspections or via helicopter. Table 4 summarizes these baseline applications and provides information relevant to determining the needs for a UAS C2 system.

<table>
<thead>
<tr>
<th>TAPS Surveillance Application</th>
<th>Flight Distance/Range</th>
<th>UA Altitudes</th>
<th>Periodicity</th>
<th>UA Platform</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Right-of-Way Integrity Monitoring | X | 500–1000 ft., lower (down to 100 ft.) as needed | Scheduled, at least 26 times a year | X | • Looking for leaks/spills, encroachments, erosion
• ~125 nm one-way, nominally between pump stations
• Drops to lower altitude to get closer look at areas of interest |
| Close Range Inspection - Infrastructure | X | Up to ~ 200 ft. | As needed | X | Thermosiphon Inspection, Pump Station infrastructure, oil storage tanks |
| Security response | X | Up to ~ 400 ft. | As needed | X | X |
| Spill Response | X | 50 - 1000 ft. | As needed | X | X |
| Geotechnical Engineering | X | 50 - 1000 ft. | X | X | |
| Audit of equipment | X | Up to 200 ft. | | X | |
| Wildlife monitoring | X | 200 – 1000 ft. | As required | X | EPA requirements, includes beyond ROW |
| Search and Rescue | X | 50 – 1000 ft. | As needed | X | X |

Alyeska currently has other applications for manned aircraft that require moving people and/or equipment to locations along the pipeline; these applications would not be suitable for UAS. Generally, Alyeska will continue to rely on the use of manned aircraft for these and other applications; and it is most likely that the potential role for UAS would be to augment rather than replace manned flights depending on other factors, including costs and safety. Both of these factors are discussed later in this report.
A UAS PTP C2 system would be designed to accommodate the applications and associated operational conditions just described. It is envisioned that other applications and associated operational scenarios will be supported for the UAS Hybrid and Network C2 systems evaluated for this study. Though most of these other applications would be conducted outside the ROW of the TAPS\(^3\), the radio coverage of the PTP C2 system in most areas along the pipeline route would extend miles beyond the pipeline ROW. Thus these applications could be supported by the PTP C2 system infrastructure (ground radio stations) augmented by additional equipment (e.g. additional radios at these ground stations) and additional ground radio stations needed to extend the coverage further beyond the pipeline ROW in the Hybrid/Network operational areas of interest. These applications are summarized in Table 5.

### Table 5 – Potential Hybrid and Network UAS Applications

<table>
<thead>
<tr>
<th>TAPS Surveillance Application</th>
<th>Flight Distance/Range</th>
<th>UA Altitudes</th>
<th>Periodicity</th>
<th>UA Platform</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long</td>
<td>Short</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil/Gas infrastructure monitoring/spill response at Prudhoe Bay/North Slope fields</td>
<td>X</td>
<td>X</td>
<td>Long: Up to 2000 ft.</td>
<td>As needed</td>
<td>X</td>
</tr>
<tr>
<td>Valdez Pipeline marine terminal infrastructure monitoring/spill response</td>
<td>X</td>
<td>X</td>
<td>Long: Up to 2000 ft.</td>
<td>As needed</td>
<td>X</td>
</tr>
<tr>
<td>Natural gas pipeline construction adjacent to TAPS</td>
<td>X</td>
<td>X</td>
<td>Long: Up to 100s ft.</td>
<td>Scheduled, at least 26 times a year</td>
<td>X</td>
</tr>
<tr>
<td>Univ. and Gov. Research ACUASI, Univ. of AK-Fairbanks (e.g., Poker Flat Research Range), Various Universities and government agencies (e.g., climate change)</td>
<td>X</td>
<td>X</td>
<td>Long: Up to 100s ft.</td>
<td>As needed</td>
<td>X</td>
</tr>
<tr>
<td>Alaska DOT for roadway (e.g., avalanche) and infrastructure monitoring (e.g., bridge inspection)</td>
<td>X</td>
<td>X</td>
<td>Long: Up to 2000 ft.</td>
<td>As needed</td>
<td>X</td>
</tr>
<tr>
<td>Forest fire</td>
<td>X</td>
<td>Up to 2000 ft.</td>
<td>As needed</td>
<td>X</td>
<td>Interagency BLM, US</td>
</tr>
</tbody>
</table>

One notable exception is a planned natural gas pipeline that may be installed near the existing TAPS ROW.
<table>
<thead>
<tr>
<th>TAPS Surveillance Application</th>
<th>Flight Distance/Range</th>
<th>UA Altitudes</th>
<th>Periodicity</th>
<th>UA Platform</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Long</td>
<td>Short</td>
<td></td>
<td></td>
<td>Fixed Wing</td>
</tr>
<tr>
<td>Fighting</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wildlife and environmental monitoring</td>
<td>X</td>
<td></td>
<td>Up to 2000 ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alaska State Troopers – search &amp; rescue, poaching, other criminal activity</td>
<td>X</td>
<td>X</td>
<td>Long: Up to 2000 ft. Short: Up to 100 ft.</td>
<td>As needed</td>
<td>X</td>
</tr>
<tr>
<td>Fairbanks Police and Fire – search &amp; rescue, emergency response, etc.</td>
<td>X</td>
<td>X</td>
<td>Long: Up to 2000 ft. Short: Up to 100 ft.</td>
<td>As needed</td>
<td>X X</td>
</tr>
<tr>
<td>DOD/National Guard</td>
<td>X</td>
<td></td>
<td>Up to 2000 ft.</td>
<td>As needed</td>
<td>X</td>
</tr>
</tbody>
</table>

Specific applications listed in Table 5 will be described in greater detail in the following sections as needed to support the following comparative evaluations and to drive the infrastructure and business case assumptions for Tasks 2 and 3 respectively.

### 3.1.2 UAS PTP and Network C2 System Definitions

Before proceeding with discussions of the Task 1 evaluations, it is necessary to provide some high level comparative description of the UAS PTP and Network C2 system implementations assumed for this study.

Figure 3 depicts a high level operational depiction of UAS C2 and ATC communications (including communications relay of ATC voice communications through the UA). It illustrates the concept of multiple UAS radio stations (RS) communicating via C2 links to one or more UA, along with the notion of a “coverage volume” associated with each RS that nominally defines the volume of airspace through which the C2 links are physically propagated. Though ATC communications for UAS is outside the scope of this study and will not be discussed further, it is important to note that the coverage volumes of UAS C2 systems and ATC communications systems will almost never be coincident, which could complicate implementation of the ATC voice (or data) communications relay function.

The figure also illustrates the concept that a UA passes from the coverage volume of one RS to the coverage volume of another RS as it traverses through airspace during its flight. Typically, there is overlap between adjacent coverage volumes, which has both advantages and

---

4 The cylinders shown in the figure are used for convenience as a high level approximation. The shape of the coverage volumes would be actually be paraboloidal, and in reality are highly dependent on terrain and atmospheric effects, as will be discussed in Section 3.2.
disadvantages. The advantages are related to the mobility management function, especially handoffs, where usually “soft” handoffs providing a “make before break” connectivity result in lower latencies. (This is discussed further in Section 3.1.5) On the other hand, there may be disadvantages in overlapping coverage volumes due to interference effects among the different coverage volumes.

Figure 3 – UAS C2 and ATC Communications High Level Operational View

### 3.1.2.1 UAS PTP C2 Systems

Figure 4 depicts several PTP C2 system operational views. The leftmost figure in Figure 4 shows the simplest PTP case, where a single C2 link connects a single UA with a single ground radio station using a single frequency/channel for the entire flight. In this case the UAS Ground Control Station is co-located with the ground radio station, assumed to be owned and operated by the same entity.

An important subclass of this combined GCS/RS functionality serves the needs of the short range/duration applications listed in Table 6. For these applications, the UA flight is more ad hoc in nature and does not rely on the fixed infrastructure required for the longer range/duration inspection applications. But because it often requires beyond visual line of sight operations, it will rely on the use of protected UAS C-Band spectrum and an ad hoc frequency assignment. (Spectrum management issues are discussed in more detail in Section 3.1.4.

The middle figure in Figure 4 differs from the leftmost figure in that the GCS and RS are not co-located – the RS may even be transportable or mobile (but assumed to be stationary during the flight), and it is still assumed that the GCS and the RS are owned and operated by the same entity. In both of these two single RS cases, the flight is limited in extent to the physical RF
coverage provided by the RS, such that the RS and the aircraft always remain within radio line of sight (RLOS) of each other.

The rightmost case in the figure depicts a PTP C2 system that handles longer flights by allowing transiting between the coverage areas of multiple RS by the aircraft, which includes a handoff process where the UA “breaks” the C2 link from the first RS and establishes a new C2 link with the next RS. As with the other two cases, there is a single GCS that controls the UA as it transits from one RS to the next (assuming a small number of RS). Once again, it is assumed that the GCS and the multiple RS are owned and operated by the same entity.

In all cases depicted in the figure it is assumed that an RS can only establish a single C2 link with a single UA at any one time.

The PTP C2 operational view for the TAPS surveillance scenario would be an extension of this last case, as shown in Figure 5. As illustrated in the figure, multiple RS are spaced along the entire length of the pipeline to provide end-to-end coverage at the required altitudes for its entire length. One or more GCS could be deployed, each controlling the coverage volume(s) for one or more RS.

Figure 4 – UAS PTP C2 Operational Views/Notional Architectures
For the TAPS scenario used for this study, a UA could start its flight at one end of the pipeline and continue along the pipeline ROW transiting coverage areas of multiple RS until it reaches its operational distance limitation and/or it reaches an established landing area, such as a pumping station. This is shown as Case 1 in Figure 6.

Given the assumptions and constraints described above, it is also feasible and may be desirable to operate multiple UA simultaneously, but with each UA separated from all the others to the extent that a single RS does not need to establish more than one C2 link with more than one UA at a time. This is depicted as Case 2 in Figure 7.
3.1.2.2 UAS Network C2 Systems

For this study UAS C2 Network Systems are differentiated from PTP C2 systems by allowing for simultaneous multiple frequency operations at one or more RS to maintain multiple C2 links with multiple UA within each RS coverage area (see Figure 8). In this case, the RS may serve several end user types and applications. In other words, the C2 Network would be able to serve some of the Hybrid/Network applications listed in Table 7, in addition to the core TAPS related applications and end users listed in Table 6. Because of the potential variety of end users and applications, the C2 network may have a total service coverage area well beyond the bounds of single user/applications, such as the TAPS, so that additional RS infrastructure may be required.
Figure 9 provides an example of C2 Network operations for the TAPS.

As shown in the figure, two new radio stations, RS #A and RS #B, have been deployed to handle non-TAPS related end users/applications (e.g. UA #3) that require a coverage area beyond that provided by the original RS coverage areas outlined in red. In this example RS #8 would have to be upgraded by adding new equipment to be able to handle multiple C2 links with multiple UA.

At this point, it is necessary to define the Hybrid C2 System. For the purposes of this study, a UAS C2 system is:

- PTP, if all the RS in a single entity owned and operated C2 system are single frequency only and provide C2 link services only to a single UA/end user at any one time
- Hybrid, if some of the RS are single frequency, while a few can handle multiple frequencies; and the former only handle a single end user and the latter can handle multiple end users and applications
- Network, if all the RS can handle multiple frequencies and multiple end users

It is apparent that a Hybrid C2 system could serve as an evolutionary bridge between a PTP C2 system and a Network C2 system implemented by a particular service provider.

It should be noted that there are no standardized definitions for these three UAS C2 system types, and these are the definitions adopted for this study. It is assumed that all three C2 system types require some ground-to-ground RS interconnection networking for implementations of more than one RS to support mobility management and other centralized functions. In addition, it is assumed that C2 systems with multiple RS may have one or more GCS, depending on the needs of the C2 service provider. Finally, while it might be feasible for either an end user or a third party to own and provide a “private” UAS PTP C2 system, it seems likely that a third party...
C2 Service Provider\(^5\) would own and operate a UAS Network C2 system providing a multitude of services to a variety of end users.

### 3.1.2.3 Summary UAS PTP and Network C2 System Similarities and Differences

Table 6 provides a high level table comparing the UAS PTP and Network C2 system types in several categories.

<table>
<thead>
<tr>
<th>C2 System Type</th>
<th>Fixed Ground Radio Sites</th>
<th>Temporary Radio Sites</th>
<th>Many Sites Distributed over Large Area</th>
<th>Point-to-Point Link(s)</th>
<th>Point-to-Multipoint Link(s)</th>
<th>Fixed Radio Station Topology</th>
<th>Continual Radio Site Operation</th>
<th>“Perpetual” Spectrum Assignment</th>
<th>Interoperability/Open Access</th>
<th>Fixed Ground Radio Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTP/Standalone</td>
<td>X</td>
<td>X</td>
<td>X(^1)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Network</td>
<td>X</td>
<td>X</td>
<td>X(^1)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

Notes:

1. PTP examples include multiple sites operated by a single entity providing simultaneous or near simultaneous point-to-point C2 services in different geographic areas, or multiple sites operated by different entities and implemented along linear infrastructure, such as a railroad, power line, pipeline, etc. This latter case applies to this study.
2. Assuming C2 operator shoulders the “costs” associated with doing this
3. Assumes any UA equipped with a radio interoperable with that network can access the network. Open interoperability requirements can be normative (e.g. specified in the MOPS), or “published” by the network service provider. Assumes PTP C2 Systems implement a “closed” or unpublished radio system technology.

As shown in the table, there are many similarities and few significant differences between the two types. Based on the assessment in Table 6, the main factors that distinguish a C2 network system from a PTP system include:

- **Point-to-multipoint operation** (for networks). This might require a multiplexing technology and associated tradeoffs in its definition, design and implementation. An example of such a radio system design is being provided as an option (“Class 1”) in the RTCA SC-228 MOPS currently under development.

- **Greater interoperability** in Network Systems. “Open” accessibility by potential UAs required to operate within a C2 network airspace, require “open” standards, either by: 1) common link layer technology/protocol standardized by a standards organization, e.g. by RTCA, or 2) open link technology/protocol published by a network service provider. By contrast, a PTP C2 provider could implement a more proprietary system, especially in the link layer and higher layers in the communications protocol stack, since interoperability with other systems is not required. It has been suggested, however, that “to maximize

---

\(^{5}\) This includes “turnkey” UAS service providers that provide C2 services as part of their total service package
coverage, the FCC and NTIA could impose interoperability mandates as a condition of the license\textsuperscript{6} of fixed RS infrastructure.

\subsection*{3.1.3 Relative Operational Suitability to Support Flight Mission Variety}

The goal of this subtask was to determine whether or not there are any inherent operational limitations in a PTP C2 system compared to a Networked C2 system. Though the networked C2 system(s) in the study scenario are designed to accommodate multiple users and missions (see Table 2), this subtask evaluated how well the PTP C2 system described above could accommodate additional users/applications for which it was not designed. To do this the relative suitability of PTP and Network system infrastructure in supporting alternative flight missions on a non-interfering basis with the baseline scenario TAPS applications were assessed.

Recall that for the PTP C2 system proposed for the TAPS scenario (see Table 4) both short range and long range end users and applications are accommodated. Generally, the long range users would be served by fixed RS infrastructure situated near the pipeline (see Figure 5, Figure 6 and Figure 7), while the short range users could make use of both portable radio “stations” (e.g. handheld radio controllers) and fixed infrastructure, depending on the UA’s range and whether or not it flies out of RLOS of the portable radio controller. In the latter case, the portable radio controller would have to be interoperable with the fixed RS to support a “handoff” between the two.

An assessment of the extent to which the PTP C2 system described above could accommodate the potential non-TAPS related applications listed in Table 5 results in the following observations:

- The PTP C2 fixed RS infrastructure, without additional RS, could support any of the long range applications listed in the table, provided:
  - The desired coverage area lies within the narrow coverage volumes surrounding the RS spaced along the TAPS, subject to the limitations of the surrounding terrain. (Section 3.2 describes potential C2 system coverage in detail). This could be limiting for applications potentially spanning large areas, such as the forest fire fighting, wildlife monitoring, and search and rescue applications.
  - The additional applications can be schedule coordinated with the baseline TAPS applications, such that RS are only required to link with a single UA at any one time.
- A particularly well-suited application for the PTP C2 system is inspection of the planned natural gas pipeline to be deployed near the existing TAPS ROW, especially if inspection of both pipelines could be conducted simultaneously. Otherwise, gas pipeline inspection flight schedules would have to be coordinated with the oil pipeline inspections to avoid more than one UA in a RS coverage volume.
- There are other limitations and possible disadvantages in the linear layout of the PTP RS infrastructure required for pipeline inspection. For example, this RS topology is

\textsuperscript{6} Titania spectrum management report, p. 55.
suboptimal for the discovery/diversity process typically required for mobility management/handoff because it offers fewer opportunities for detecting and monitoring adjacent RS, simply because there are fewer adjacent RS than for a network topology with a broader coverage area. Likewise there are more opportunities for the UA to “go off the rails” by flying outside the linear coverage area, enter into a “loss link” situation, and be less likely to re-connect with the C2 system. This has some safety implications. (Safety aspects of this study are described in Section 3.4).

- Because short range UAS applications listed in both Table 4 and Table 5 do not necessarily rely on a fixed PTP C2 RS infrastructure, and, in many cases, would not be covered by any Network C2 system, there will probably always be a need for some itinerant UAS PTP C2 systems.

As already described in reference to Figure 8, the limitations in coverage area by the linear PTP RS topology needed for TAPS inspection can be offset by adding new RS to fill required coverage gaps outside the coverage corridor, and by adding/upgrading radio equipment at existing PTP RS, thus creating a Hybrid C2 system. As an evolutionary path, upgrading all existing PTP RS to handle point-to-multipoint operations, along with adding any new RS required for additional coverage would ultimately result in a fully networked C2 system.

In summary, operational limitations in PTP C2 systems for this scenario are generally due to coverage limitations and lack of flexibility because of single frequency operation. These limitations can be overcome in a straightforward manner by adding new RS and adding or upgrading RS equipment to support point to multipoint operation, that is, to handle multiple UA per RS.

### 3.1.4 PTP and Network C2 Comparative Spectrum Limitations

This subtask consists of assessing the comparative spectrum advantages and disadvantages of the PTP and Networked C2 systems for BLOS UAS flights for our scenario. Following a general description of the technical challenges of spectrum allocation, this section describes the spectrum management assessments performed for this study in three areas:

- PTP and Hybrid C2 comparative spectrum efficiencies
- Relative impact on PTP and Network C2 systems based on the type of spectrum management policy implemented for UAS
- Relative impact on PTP and Network C2 systems based on frequency assignment processes

#### 3.1.4.1 UAS C2 Spectrum Allocation Technical Challenges and Considerations

A principal challenge for allocating appropriate UAS C2 spectrum is the fact that the near continuous duty cycle of UAS telecommand and telemetry data exchange drives the requirement for continuous frequency assignments for each of the RS to UA C2 links along the entire flight.
path (see Figure 5). This places major stress on the limited L-Band and C-Band spectrum resources internationally allocated for UAS C2, especially in the L-Band, where there are many incumbent aeronautical systems using that band.

Another major consideration is the potential common mode failure issue resulting from providing several critical services over the same C2 link, including telecommand/telemetry, Detect and Avoid (DAA), and, if applicable, relayed ATC voice/data comm (out of scope for this study). This drives required link performance (e.g. availability, latency and integrity) and has a direct impact on C2 system architectures and topologies. For example, it may be advisable to provide overlapping coverage between adjacent RS overlap areas because it can improve link availability and enable more reliable handoffs, at the expense of higher costs (requires more RS) and potentially lower spectrum efficiency.

Meeting stringent C2 availability performance requirements also might compel deployment of dual band architectures with potentially negative impacts on spectrum efficiency depending on the scheme for apportioning of the data services between the two links and the degree to which identical data is carried over both links. This frequency diversity strategy relies on the fact that dynamic propagation degradations are frequency (wavelength) dependent, and therefore both L-Band and C-Band links would not likely be experiencing signal fading events at the same time.

The UAS C-Band allocation (i.e. 5030 MHz – 5091 MHz - the focus of this study) provides some advantages over L-Band for defining suitable architectures and associated spectrum allocation schemes because:

- It offers much more contiguous, useful bandwidth than L-Band (61 MHz vs. around 15 MHz)
- It has fewer potential co-site/co-location interference and compatibility issues with other aeronautical services

A slight disadvantage of C-Band is its propagation (diffraction) characteristics: it doesn’t propagate (“bend”) around obstacles as much as lower frequencies, so that terrain blockage is a bigger problem at C-Band than for L-Band. Of course this may be an advantage from an interference protection perspective.

Generally the technical challenges and considerations described above apply equally to both the PTP and Network C2 systems considered for this study. Because of the C-Band only focus of this study, dual band architectures will not be considered. Coverage redundancy will be discussed in the infrastructure/architecture Task finding presented in Section 3.2

### 3.1.4.2 PTP and Hybrid C2 Comparative Spectrum Efficiencies

According to the definitions adopted for this study, PTP C2 systems use a single channel/frequency per RS/UA link, while Network systems provide point-to-multipoint C2 services, which can be implemented in several different ways.

This study is generally consistent with the direction pursued by RTCA SC-228 in developing the CNPC Radio System MOPS. Though the MOPS being developed by that group are not intended to support interoperability among different C2 radio system designs, they do specify electromagnetic compatibility requirements to ensure that UAS C2 systems do not interfere with each other or with other aeronautical systems. Relevant compatibility requirements from the draft MOPS include:
The C2 radio system waveform shall use a Time Division Duplex (TDD) structure with specified, fixed duration frames divided into time alternating uplink and downlink subframes.

- Only ground-based radios shall transmit during uplink subframes.
- Only airborne radios shall transmit during downlink subframes.

Assuming these requirements remain in the Phase 1 Final MOPS, this means that every UAS ground radio in the U.S. using AM(R)S protected spectrum for beyond visual line of sight operations will transmit during the same uplink timeslot, while every UA airborne radio will likewise transmit during the same downlink timeslot. The intent is to avoid interference between UAS ground radios and airborne radios by making sure that they never transmit at the same time.

For single channel PTP systems this implies that ground and airborne radios could use the same frequency/channel for their C2 link. The bandwidth of that channel will be dependent on the C2 “services” carried over that C2 link. Potential services defined in RTCA SC-228 include:

- Telecommand and telemetry
- ATC voice relay and/or ATS data relay
- Navaid and Detect and Avoid (DAA) data
- Airborne weather data and video

Of these services, the ATC voice/data relay is out of scope for this study; and airborne weather, navaids data, and video are not needed or considered further for this scenario. This leaves telecommand/telemetry and DAA data as the two services included for this study for determining potential required bandwidth. (DAA data carried over the C2 link is a potential common mode failure risk that potentially impacts system safety).

The RTCA SC-228 CNPC draft MOPS include detailed normative requirements for one optional NASA sponsored/developed radio system, called the “Class 1” radio system for this study. The Class 1 radio accommodates the telecommand/telemetry and DAA data services in its C2 Basic Service channel, which requires 75 kHz for both uplink and downlink.

The Network C2 system provides point-to-multipoint, multi-channel services. Besides supporting the single C2 Basic Channel for PTP applications, the Class 1 ground radio defined in the CNPC MOPS supports point-to-multipoint services by offering a 4 to 20 channel (slot) Time Division Multiple Access (TDMA) capability supporting RS uplinks to a corresponding number of UA. This requires from 175 to 875 kHz in bandwidth respectively for the 4 to 20 slot cases. Note that a fully utilized Class 1 radio would be more spectrally efficient in the multi-UA case.

---

8 There is some pressure arising from non-participants of SC-228 to remove these requirements to allow use of current technologies (e.g. LTE) that are currently inconsistent with them.

9 C2 White Paper

10 This means that a potential UAS C2 designer and/or system integrator is not required to use that radio system, but if it does select that radio system, the designer/integrator must ensure that the radio meets the requirements specified in the MOPS for that system.
than for the single UA case (roughly 43.75 kHz per UA vs. 75 kHz per UA) for basic service cases.

Because each UA only needs to communicate with a single RS, even for the Network C2 system, the Class 1 radio design features a Frequency Division Multiple Access (FDMA) scheme for the airborne radio downlink, where each UA uses a separate, fixed bandwidth (75 kHz) downlink frequency.

For this study scenario, it is expected that the Network C2 service needs could be met by the 4-slot RS radio, requiring 175 kHz, in other words, it is assumed that no RS will need to support more than four RS/UA C2 links at any time.

Given the assumptions just described, several observations regarding comparative UAS PTP and Network C2 system spectrum efficiency for the TAPS scenario can be made:

- The PTP system requires a single 75 kHz channel for the entire time an RS maintains a C2 link with a UA. The TAPS PTP scenario for a UA flying along the pipeline conceivably could be handled by the same single frequency/channel used by every RS along the UA’s path. In this case, the UA would be required to break the RF link with one RS, and then establish a new link with a new RS, each time using the same frequency. This might present some challenges for the airborne radio ensuring that it establishes a link with the “new” RS unless a reliable handoff protocol is used. Another scheme might make use of two frequencies, where alternating RS use alternating frequencies, i.e. RS #1 uses Frequency 1 (F1), RS #2 uses F2, RS #3 uses F1, etc. This scheme also might allow for a “make before break” situation, maintaining required link performance during RS handoffs. Either case would require close coordination with the spectrum assignment authority.

- The Network C2 system using the four slot uplink TDMA channel uses at least 175 kHz of spectrum regardless of the number of UA it is actually supporting at any time. Thus it can be argued that any time it operates with less than four UA, it is being spectrally inefficient. On the other hand, any time a C2 Network RS supports three or more UA, it is more efficient per UA on the uplink than the single 75 kHz (non-TDMA) mode used for the PTP system. On the UA downlink side, because each UA requires 75 kHz regardless of the number of UAS simultaneously supported, each of the supported UA requires separate downlink frequencies, just as in the case for the PTP C2 system.

Generally, in the comparison of spectral efficiency between PTP and Network C2 systems using the draft CNPC MOPS Class 1 radio:

- The amount of spectrum per UA in operational use required for the PTP C2 system is constant for both uplink and downlink: 75 KHz/UA

- The amount of spectrum per UA in operational use required for the Network C2 system RS 4-slot uplink is lower than the PTP case whenever the RS is supporting three or more UA simultaneously (58.33 kHz/UA – 43.75 kHz/UA), and higher (less efficient) than the PTP case otherwise (87.5 kHz/UA – 175 kHz/UA).

- The amount of spectrum per UA in operational use required for the Network C2 system UA downlinks is constant and equal to the PTP C2 case: 75 kHz/UA.
This high level assessment does not take into account potential spectrum inefficiencies caused by required use of transmitter spectrum masks to mitigate adjacent channel interference for multiple FDMA downlinks.

It should be stressed that the Class 1 radio used as an example for this comparison is not required to be used in the MOPS. Other radio systems with other goals for spectral efficiency could be designed and implemented and submitted for certification, though without the TSO expected to be issued by the FAA for the Class 1 radio, it may take a little longer to get certified.

Finally, it also needs to be noted that because the current version of the SC-228 CNPC MOPS is not addressing interoperability, there are few proposed requirements addressing the layers above the Physical Layer and parts of the MAC sublayer of the protocol stack. Therefore draft standards for link management (e.g. Link Layer requirements) have not been developed, and functions such as mobility management, including handoffs are undefined (except for some guidance material provided in an appendix). At this time, these would be left up to the UAS C2 designer/integrator to develop. It is possible that these requirements would require additional spectrum. Further discussion of this topic is provided in Section 3.1.5.

### 3.1.4.3 Spectrum Impact on PTP and Network C2 Systems Based on Spectrum Management Policies

The report “Spectrum Management for Unmanned Aircraft Systems Command and Control”\(^\text{11}\) (the “Titania” Report) served as the basis of comparison for this assessment. That comprehensive report included a comparative evaluation of four alternative spectrum management models for UAS C2 links using seven criteria.

The Spectrum Management study assumed that the predominant UAS C2 systems in the mid to long term would be C2 Network systems owned and operated by C2 service providers, possibly current large wireless network service providers. The study also assumes that “Off-Network Access” would always be required and available for ad hoc UAS operators in areas not covered by C2 networks, either because they are deployed before build out of the C2 network(s) occurs, or because they are in areas too remote for fixed Network C2 infrastructure. This Off-Network Access is analogous to the subclass of PTP defined for this study for short range, short duration flights typically using non-fixed radio control systems (see Section 3.1.2.1), though it could also apply to PTP C2 systems with fixed RS infrastructure implemented by a UAS end user and used for longer flights.

Table 7 summarizes the four spectrum management models described in the Titania Report and includes a high level assessment of the sufficiency of each model in providing equitable, effective and efficient spectrum management functions for the C2 systems covered in this study. It is not surprising that all four models could generally meet the spectrum management needs for the alternative C2 systems considered in this study, because each of the four models was defined to accommodate both on-network and off-network UAS. As noted in the table, however, there are some potential problem areas, for example in cases of End User provided PTP C2 systems.

(off-network” systems) intended to be deployed in areas already covered by existing C2 Network service providers. The Titania Report implies that these deployments would not be allowed and would not be entitled to spectrum management services. We do not agree with this implication.

Table 7 – Spectrum Management Report Findings Applied to C2 Systems in this Study

<table>
<thead>
<tr>
<th>Spectrum Management Model</th>
<th>Infrastructure Owner/Operator</th>
<th>Spectrum Management</th>
<th>Sufficiency of Spectrum Management Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Federal Users</td>
<td>Non-Federal Users</td>
</tr>
<tr>
<td>FAA Managed</td>
<td>FAA End User</td>
<td>FAA</td>
<td>1,2</td>
</tr>
<tr>
<td>Frequency Coordinator</td>
<td>Service Provider End User</td>
<td>Frequency Coordinator</td>
<td>2</td>
</tr>
<tr>
<td>Band Manager</td>
<td>Service Provider End User</td>
<td>Band Manager</td>
<td>Frequency Coordinator</td>
</tr>
<tr>
<td>Commercial Service Provider</td>
<td>Service Provider End User</td>
<td>Commercial Service Provider</td>
<td>2,3</td>
</tr>
</tbody>
</table>

Notes:
1. Titania Report states (p.44) “For off-network ground stations, the FCC would establish a licensing regime, including limits on geographic area of operation, …” Geographic limitations might be viewed by some potential off-network users to be unfair.
2. Titania Report assumes off-network implementations are either: ad hoc deployments by end users with itinerant ground radio infrastructure; fixed or temporary infrastructure deployments by end users in remote areas not likely to be covered by Networks; or deployments of fixed or temporary infrastructure by end users that occur before C2 Network build out. In those cases, the Report provides a clear indication that these users would receive equitable spectrum management services. On the other hand, the Titania Report implies that off-network deployments of fixed infrastructure by end users would not be allowed in any areas already covered by a Network C2 system, and thus spectrum management services would not be offered for this potential class of users.
3. Titania Report states (p. 70) that “An exclusive licensing model creates tension with off-network uses.”

3.1.4.4 Impact on PTP and Network C2 Systems Based on Dynamic Frequency Assignment Processes

For this subtask both the Titania Spectrum Management Report and ongoing activities in the SC-228 WG2 Dynamic Spectrum Resource Assignment Subgroup were specifically leveraged. The SC-228 WG2 subgroup includes participating representatives of UAS system providers (e.g. Aerovironment and General Atomics), an aviation Band Manager (ASRI, Inc.), the FAA Integration Office and FAA Spectrum Management, NASA, a current NAS service provider (i.e. Exelis, Inc.), and other industry stakeholders and subject matter experts.

The SC-228 WG2 Dynamic Spectrum Resource Assignment Subgroup is trying to identify/determine and evaluate frequency management/re-use policies and procedures from a technical standpoint. This includes identifying and evaluating alternative channelization plans and operating procedures, e.g. static vs. dynamic channel assignments; determining how frequencies are to be allocated among different, potentially competing PTP and Network C2 service providers; and evaluating ground station licensing requirements and process and their potential impact on C2 system designs. The goals of these activities include developing appropriate spectrum assignment recommendations and providing these in an appendix to the C2 MOPS.

The Dynamic Spectrum Resource Assignment Subgroup has developed a useful set of criteria for assessing the dynamic spectrum assignment challenges. These include:
Several candidate Dynamic Spectrum Resource Assignment schemes have been proposed for discussion.

Proposal “A” is based on a reservation based Priority Approach: First Come, First Served. In this approach a UAS end user, possibly the PIC, can only make one CNPC channel request at a time and can only make the request within 20 minutes of takeoff. An assignment goes away and the requester goes to the end of the line if the request is rejected or the UA has not taken off in 20 minutes. This approach is dependent on a strong spectrum broker role of ensuring that a proposed frequency assignment will not interfere with any current assignment, which requires comprehensive 3D interference assessment tools.

Proposal “B” is similar to “A,” except that the assessment and assignment of the channel is performed by the UA, possibly in addition to the ground system. Based on its location the aircraft looks for any clear channel available to it in the list of channels published in a geographic/altitude frequency plan for the proposed flight path.

Proposal “C” offers features common to both “A and “B” and places more emphasis on dynamic RS involvement in the process and also proposes the use of a “common signaling channel” similar to what is used for VDL mode 2, to provide some fallback capabilities, in the case of difficulties in acquiring or maintaining newly assigned frequencies.

Discussion of all three proposed approaches is ongoing, and the group may reach consensus on a “hybrid” approach using best features from all three concepts, especially because they are not significantly different.

A common element in all three proposed schemes, as well as in the Titania Spectrum Management Report, is the recommendation for real time, comprehensive flight planning and interference assessment tools to be used by the spectrum management/assignment entity. Fortunately, the technology is available, so this capability is achievable. Another recommended spectrum assignment system component is web portal like functionality that allows for real time access to the spectrum management entity by the spectrum user/requester.

Unfortunately, currently proposed dynamic spectrum assignment approaches under consideration in RTCA SC-228 WG2 are hampered by the lack of interoperability standards development within WG2 that could define standard link/mobility management approaches and provide some
functional platforms upon which spectrum assignment approaches, such as a common signaling channel, could be built upon.

The Titania report in Appendix H provides some useful examples of existing dynamic allocation schemes that could provide useful inputs to the efforts in the SC-228 WG2 Dynamic Spectrum Resource Assignment Subgroup. The Titania report in its entirety would be of great value to the entire SC-228 WG2 and it is strongly recommended that the FAA make this report available to RTCA WG2.

Regarding comparative applicability of dynamic spectrum assignment to PTP and Network C2 Systems, as noted earlier, both ad hoc and fixed PTP C2 Systems should always be accommodated in the UAS operational arena, even after C2 Network Systems have been deployed in the same general area. Therefore, by policy, a dynamic spectrum assignment system should provide equal and equitable access to all qualified PTP and C2 systems, even if this means sub-banding or segregation of the spectrum to provide fixed allocations to certain C2 system categories, such as the ad hoc PTP systems.

3.1.5 Link/Mobility Management Issues for PTP and C2 Network Operations

Referring to Figure 4 and Figure 8 above, note that both PTP and Network C2 systems allow for both single RS and multiple RS operations. In the single RS case both PTP and Network systems operate in a “point-to-point” mode, with single PTP links in PTP systems, and multiple PTP links in Network systems. In both cases operating with a single RS allows for relatively simple connection architectures and C2 link protocols, regardless of whether or not the GCS is collocated with the RS.

Things get more complicated in both systems when a UA must transit between radio stations during flight. In this operational case, link/mobility management protocols or processes must be implemented to provide:

- Handoff Management – To enable safe and efficient UA handoffs from one RS to another, including frequency/channel changes while maintaining connectivity to the GCS
- Location Management - Provides RS with the information necessary to know which GCS needs to be connected to which UA and how to maintain that connectivity while the UA is moving, for example for PTP Operational Case #2 depicted in Figure 7, or for C2 Network operations with multiple end users.

Link management protocols are also necessary to allow RS in C2 Network systems to establish and maintain links with multiple UA.

A large body of technical work has been conducted to address the wireless mobility management issue because of the evolution of network technologies. Some key handoff related concepts relevant to this study include:

- “Hard” vs. “soft” handoff
  - Hard handoff (also known as “break before make”) breaks the physical layer UA connection between the first RS before establishing a new physical connection with a second RS. This is a simpler and less expensive process than a soft handoff, but may result in loss of data, and possible performance degradation during time between connections. During the period of no RF connection there is...
also a risk of terminating the end to end (UA to GCS pilot) connection, which is handled at a higher protocol layer.

- Soft handoff (also known as “make before break”) maintains the UA physical layer connection with the first RS while establishing a connection with a second RS, after which it breaks the first connection. It is more complicated, briefly requires more spectrum than the hard handoff, but offers less risk of total loss of end-to-end connectivity. Soft handoffs in some technologies also include the capability of establishing connections with more than two physical access points (RS), and selecting the access point with the best link.

- “Vertical” vs. “horizontal” handoff

  - Vertical handoff is a handoff between RS using different link layer/access technologies. A commonly experienced vertical handoff example is when a laptop changes from a WiFi connection to a 3G/4G connection. Vertical handoffs require interoperability at protocol layers above the link layer to maintain end to end connectivity, in our case between the UA and the pilot at the GCS. Vertical Handoffs would be necessary for UA that need to transit from one Network C2 system to another, adjacent Network C2 system implementing a different link technology.

  - Horizontal handoff is a handoff between different wireless access points (RS) that use the same physical and link layer technologies. For the TAPS scenario, the PTP C2 system will require horizontal handoffs as the UA travels along the pipeline. Horizontal handoffs are typically less complex and don’t extend as far into the protocol stack as vertical handoffs.

A detailed discussion of mobility management technologies is beyond the scope of this study. It is mentioned because it is vital to providing interoperability among and between different C2 systems, including the ground-to-ground networks interconnecting the UAS RS and GCS. Suitable standards should be developed as soon possible to forestall significant problems in the near- to mid-term future in the implementation of viable C2 Network systems into the NAS.

As already noted, because the Phase 1 version of the SC-228 CNPC MOPS is not addressing interoperability, there are not any proposed requirements addressing protocol layers above the Physical Layer and parts of the Link layer. Therefore draft standards for link management (i.e. Link Layer requirements) have not been developed, and functions such as mobility management, including handoffs are undefined. These are being left up to the UAS C2 designer/integrator in the interest of providing flexibility in designs. This may come, however, at the expense of lack of interoperability between implementations using the same radio system.

---

12 The Class 1 radio mentioned above does have some of the MAC defined/specified, e.g. in its Time Division Multiple Access (TDMA) uplink option.

13 The developers of the Class 1 radio are developing and testing Link Layer and Network Layer capabilities; however, these are not planned to be required, and will not result in normative requirements in the current version of the MOPS. It is expected that informative material describing these capabilities will be provided in a non-normative MOPS appendix to provide design guidance to UAS integrators that plan to deploy systems with the Class 1 radio.
3.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability

The goals of this task were to develop potential PTP and Network C2 infrastructure topologies for the C2 service provisioning options defined in Task 1; develop the associated coverage plots, and comparatively characterize the advantages and disadvantages of each of these implementations in the following areas.

- Flexibility
- Interoperability
- Scalability
- Spectrum efficiency/capacity

The activities and flow for this task are depicted in the center of Figure 10, which also depicts Task 3 interdependencies on Tasks 1 and 3.

![Figure 10 – Infrastructure Requirements & Infrastructure Task Flow](image)

3.2.1 Developing Radio Site Topologies

The main objective of the Service Volume (SV) engineering effort is the selection of radio sites and their configuration to provide the RF coverage required in offering the service(s) in predefined 3-dimensional airspaces. For this step the first two steps of the Exelis process developed to design and develop the 650 radio station Surveillance and Broadcast Services (SBS/ADS-B) system for the FAA were performed. This process includes:

- Selection and adaptation of an RF coverage model
- Model-based solution architecting for optimal RS siting
- Complex geospatial/RF design model development and sharing
- Flight campaign for model verification / risk reduction (used for network implementation – out of scope for this study)

This is described in the following sections.
3.2.1.1 Coverage Requirements and Assumptions

The following coverage requirements and assumptions developed during Task 1 were used to perform the radio site engineering:

- Radio Site Service Volume Engineering - Coverage Requirements
  - PTP C2 System
    - Single user/UA per RS coverage volume
    - Coverage Requirements: Normal operating altitudes of 1000 feet AGL, down to 100 feet for closer inspection as needed along the 800 mile TAPS ROW
  - Network C2 System
    - Multiple users/UA per RS coverage volume
    - Coverage Requirements:
      - Same as for PTP C2 system, plus:
      - Extended coverage outside TAPS ROW based on Network user needs

- Ground radio site engineering and licensing considerations
  - PTP C2 System
    - Single UA per RS coverage volume
    - Single frequencies per RS/UA link
    - UA licensed by rule
    - Ground RS licensed by rule or subject to site licensing requirements
    - Frequency assignments - permanent or dynamic (as needed)
    - Proprietary, “closed” mobility management and handoffs between radio stations
  - Network C2 System
    - Multiple UA per RS coverage area
    - Ground RS - Multiple frequencies, multiple radios
    - UA – Single frequency
    - UA licensed by rule
    - Ground RS licensed by rule or subject to site licensing requirements
    - Frequency assignments - permanent or dynamic (as needed)
    - Standardized, “open” interoperability requirements for mobility management and to handle handoffs between radio stations
3.2.1.2 Radio Site Layout Design Requirements and Analysis Process

RS site layout and optimization are typically performed as part a more comprehensive System Engineering process, as shown in Figure 11. For this study, a two-step process was used:

- Analyze/Capture Coverage Requirements/Constraints
  - Service Volume (SV) boundaries and floor definition: these were derived from Task 1 and listed in Section 3.2.1.1
  - SV Environment: interference and traffic density (if applicable)
  - Required services in the SV
  - Spectrum constraint and interference (limits and location)

- Radio Site Analysis and Design
  - Develop coverage prediction model
  - Develop link budgets
  - Use a bottom-up approach for site selection (low altitudes drive the infrastructure need)
  - Iterate to meet requirements and minimize site cost

![Figure 11 – Radio Site Engineering as part of the Exelis System Engineering Process](image)

3.2.1.3 Selection/Adaptation of RF Coverage Prediction Model

This section provides a brief discussion of the potential coverage prediction model and tools to be applied to this study and the process and motivation for selecting the model/tool used in the study.

3.2.1.3.1 Coverage Model Selection for the Study Scenario
Generally, coverage prediction models can be grouped in the following three major categories:

- Empirical
- Statistical
- Deterministic
  - Ray-Tracing
  - Viewshed (Line-Of-Sight)
  - Field-Integral

Deterministic prediction models were selected for our coverage analysis because they achieve a high level of accuracy at the expense of longer simulation time (compared to the other model types), which is necessary because the deterministic models make predictive computations using actual detailed terrain and building data. This can be a disadvantage if the appropriate terrain or building data is not available. Each of the three Deterministic prediction models was evaluated for this study.

### 3.2.1.3.1.1 Ray-Tracing Model

3D Ray-Tracing prediction is very effective for surface coverage analysis. The 3D ray-Tracing tool Exelis uses combines 30m USGS Regular Square Grid (RSG) terrain data and high resolution (+/-2m accuracy) Triangulated Irregular Network (TIN) layer data\(^{14}\) to create a high resolution RF simulation building and terrain environment. However, this is complex to set up and requires detailed (high accuracy) terrain and building structure data not available for this study. Therefore, it was ruled out early in the evaluation.

### 3.2.1.3.1.2 CRC-Predict Model

Exelis’ CRC-Predict tool was considered for this study, as it is consistent with ITU-R recommendations and it has been extensively validated in developing coverage predictions for the SBS/ADS-B service network implemented for the FAA. ITU-R recommends using the “IF-77 Electromagnetic Wave Propagation Model” to determine transmission loss. Though the IF-77 model considers ‘terrain type’ and ‘average terrain’ parameters, it does not consider detailed terrain data. Exelis’ “CRC Predict” model/tool does use detailed terrain and clutter data and also closely matches the IF-77 predictions for time variability, as shown in Figure 12. It is less complex to set up than the 3D ray Tracing model but more complex than the ViewShed model/tool.

### 3.2.1.3.1.3 Viewshed Model

The Viewshed model uses detailed terrain data only for a visibility analysis to determine coverage based on radio line of sight (RLOS). It is the simplest of the three deterministic models considered and provides excellent predictions in cases where there is both RLOS and where the

\(^{14}\) For the airport coverage prediction performed for the SBS RS network, High resolution TIN data was derived from LIDAR scanning of airports, where building structures are captured as well as terrain. FAA provided this data to Exelis in DWG (AutoCAD) format. This type of detailed data is not available for this study.
RF link “closes,” that is, there is sufficient power received at the radio to meet its integrity requirements (e.g. Signal-to-Noise ratio, Bit Error Rate, etc.). It is not as accurate for other cases, such as when there is adequate RLOS between the RS and the UA, but not enough received signal power at the receiver because the RS and UA are too far away from each other. For our TAPS scenario, the C2 link is typically terrain limited instead of power limited. In other words, the RS spacing (10 to 40 nm) needed to provide adequate coverage at the altitudes of interest in the rough Alaska terrain means that there is ample link margin to maintain the links as long as the terrain does not block RLOS.

3.2.1.3.1.4 Summary of Prediction Model Assessment
The three deterministic prediction models were evaluated for four coverage cases with prediction accuracy and set up complexity as the two principal evaluation criteria. As part of this evaluation, side-by-side comparisons were made between Viewshed and CRC-Predict 5GHz RF Model Prediction predictions at 100 ft. AGL along one portion of the TAPS (see Figure 14). Given the frequency and terrain surrounding the pipeline, there are high diffraction losses predicted for both models, leading to comparable results. As mentioned earlier, for this scenario link budget closure is not an issue because of the close proximity of selected radio sites to the pipeline. This results in the aforementioned terrain limited, not power limited coverage condition.

![Figure 14 – Comparison of Viewshed and CRC Predict Model Predictions](image)
The summary of the coverage model evaluation is provided in Table 8. The Viewshed coverage model was selected for this study because:

- It is simplest to set up and implement
- It provides excellent first order coverage estimation for most situations (Cases A and D), i.e. those regions with both LOS and link closure and cases with neither LOS or link closure.

USGS high resolution terrain (75m) was used in the Viewshed model for this study.

For an implementation project, the other models would be used as required for coverage and site selection optimization, to validate the Viewshed estimates and to accommodate the marginal cases (i.e. Cases B and C).

**Table 8 – Coverage Model Selection Process Summary**

<table>
<thead>
<tr>
<th>Case</th>
<th>Possible Coverage Combinations</th>
<th>Coverage Model Prediction Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOS ?</td>
<td>RF Link Closed ?</td>
</tr>
<tr>
<td>A</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>B 1</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>C 2</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>D</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

Notes:
1. *Even without* radio LOS, RF link closes because of diffraction, which at C-Band is not a major factor
2. *Even with* radio LOS, RF link does not close, possibly because of multipath

### 3.2.1.4 Potential RS Site Locations

For this study several site categories were considered. For the TAPS scenario sites were required to be as close as possible to the TAPS ROW. This necessarily is difficult to do, mainly because of the rugged Alaska terrain (see Figure 15).

The categories of sites considered included the following (see Figure 15):

- Pump Stations (12 sites)
  - Assumes use of existing tower structures at each of the pump station locations
- AT&T sites\(^{15}\) (24)
  - Assumes co-location with existing AT&T sites.

\(^{15}\) The existing VHF radio system infrastructure used by Alyeska for maintenance personnel and originally thought to be owned by Alyeska is actually part of a leased service provided by AT&T. Some of these 24 sites also are used for providing radio coverage of the Dalton Highway to other end users.
- SBSS ADS-B (8)
  - Assumes co-location with SBSS ADS-B sites.
- FCC tower database listed sites (141)
  - Assumes sites/structures identified in the FAA database are available for site installation.
- GCI identified sites (92)
  - These sites are fiber-optic drops along the TAPS and have existing telco and power infrastructure but not necessarily towers.

*Figure 15 – (Left) Terrain along the TAPS and (Right) RS Sites Considered*
3.2.1.5 Coverage Predictions for TAPS Scenario

A small section of the pipeline (PS01 to PS02) is used to illustrate the process and results of site selection and Viewshed coverage prediction analysis. This preliminary analysis considered limited infrastructure: three sites (see Figure 16). The figure depicts how combined coverage from multiple RS sites is required to provide coverage at several altitudes of interest, in this case 100, 200, and 400 ft. AGL. Note that even with all three sites, coverage down to 100 feet is not possible for some small portions of the pipeline.

![Figure 16 – Example - Viewshed Analysis PS01 to PS02](image)

To illustrate a more difficult and complicated case, a Viewshed analysis was performed on another pipeline section, PS04 to PS05, using eight sites (see Figure 17). As shown in the figure, in this section of pipeline, there is no predicted low altitude visibility for many sections of the pipeline, primarily due to terrain and lack of infrastructure for additional sites. Please note (in the right side of the figure) that Google Earth views and Viewshed analysis are consistent and also note how the Google Earth views vividly illustrate the coverage challenges the mountainous Alaska terrain present. On one hand the best coverage can be provided by sites deployed as high as possible, for example, on top of a mountain. On the other hand, this presents the obvious logistical difficulties of actually building infrastructure at such high elevations, which typically do not have access to power and telecommunications and often rely solely on helicopter access for construction and maintenance activities.
Figure 18 presents the coverage problem from a different perspective. It shows at what altitudes a UA flying along the pipeline ROW must fly to maintain RLOS with at least one of the 40 optimized RS sites located along its entire length. As shown in the figure, there are significant stretches of pipeline where there is no RLOS at 100 feet altitude.

From an operational standpoint, without the addition of additional and costly (up to $1M per site) “greenfield” RS sites, the desired operational concept of conducting the pipeline inspection at the fixed nominal altitude of 1000 feet, and then being able to descend to as low as 100 feet for closer inspection if problem areas are spotted, would not be attainable for this stretch of the pipeline. Several alternative mitigations to this problem are discussed in the next section.
3.2.1.5.1 RS Site Optimization using Linear Programming

From the pool of total possible RS sites listed above, an initial set of 57 sites was identified as the most suitable for providing best TAPS ROW coverage along its total length. Sites with the closest proximity to the pipeline and with some infrastructure, especially an existing tower, were given priority for selection. In addition, the Pump Station sites are assumed to be telco and power equipped and present a better recurring cost case than other sites that would have to be leased. The GCI fiber optic network drop sites mentioned above were not included in the initial 57 selected sites because they do not include wireless infrastructure and are typically at low elevations (i.e. near the pipeline). (Later coverage optimizations including the GCI sites were conducted, if it is determined through further cost benefit analysis that the increase in potential coverage is worth the costs to implement RS at these additional sites).

The problem is to select the fewest sites while providing the maximum coverage, for the flight altitudes of interest. Without an efficient site optimization process, given the large number of potential site locations, it can be very difficult and time consuming to select an optimized set of sites providing the required coverage. We performed site optimization using an efficient linear programming approach.

Linear programming (LP) is a widely used optimization technique in the operations research field. Since our coverage solution strives to optimize (minimize) the number of radios sites while achieving the required coverage along the pipeline, we formulated this coverage optimization problem to take full advantage of the linear programming algorithm.

3.2.1.5.1.1 Different formulations of LP problems

Our radio site formulation of an LP problem is minimization of a linear objective function subject to linear inequality constraints:

\[
\text{Minimize } \sum_{i=1}^{n} c_i x_i \\
\text{Subject to } \sum_{i=1}^{n} a_{ij} x_i \leq b_j, \quad j = 1, 2, \ldots, m \\
\text{where } x_i \geq 0, \quad i = 1, 2, \ldots, n
\]
Objective function: Minimize \( \sum_{j=1}^{n} c_{j} x_{j} \)

subject to

\[ \sum_{j=1}^{n} \text{los}_{ij} x_{j} > b_{i} \quad i = 1, \ldots, m \]

\[ x_{j} = \{0, 1\} \quad j = 1, \ldots, n \]

where

\( x_{j} \) - the \( j \)th site with allowed values of 0 if the site is not required 1 if the site is required

\( c_{j} \) - the cost associated with the deployment of \( j \)th site

\( \text{los}_{ij} \) - the predicted line-of-site (LOS) from \( j \)th site to the desired 3D \( i \)th point in space with allowed values of 0 if no LOS is predicted and 1 if LOS is predicted

\( b_{i} \) - required LOS coverage at \( i \)th 3D point in space with allowed values of 0 if no LOS is required, 1 if single coverage is required, … and \( m \) if \( m \)-redundant LOS coverage is required

### 3.2.1.5.1.2 Pipeline Coverage LP Parameters

For our optimization problem, we used 18,295 geo sample points along the pipeline with an average sample distance of 0.1 nmi = 185m. The initial set of selected radio station sites along the pipeline was 57. For these sites, we generated LOS predictions along the pipeline for each site at the following altitudes in ft. AGL [100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400, 2500, 2600, 2700, 2800, 2900 and 3000].

The LOS predicted data set is on the order of \( 18,295 \times 57 \times 30 \approx 31 \) million data points.

To optimize our solution from the coverage perspective, we set the \( c_{j} \) to 1. Our LP formulation includes 57 variables (number of sites) and 18,295 constrains forcing the optimized solution to maintain the initial coverage achieved from the initial set of 57 sites.

Objective function: Minimize \( \sum_{j=1}^{57} x_{j} \)

\[ \sum_{j=1}^{57} \text{los}_{ij} x_{j} \geq b_{i} \quad i = 1, \ldots, 18295 \]

\[ b_{i} = \begin{cases} 1 & \text{if at least one radio achieves LOS} \\ 0 & \text{if no LOS from all radios} \end{cases} \]

The resulting solution is summarized in Figure 19.

The graph depicts, over a range of 100 ft. to 3000 ft. AGL in UA altitude, the minimal number of sites (blue curve) needed to provide the highest possible total percentage of RLOS coverage (red curve) along the entire pipeline. As seen in the graph, with the 57 available site locations it is not possible to approach 100% coverage along the entire pipeline until reaching altitudes of about
1000 ft. or greater. For 100 foot coverage, the best that can be achieved with that set of RS sites is about 83 percent coverage.

Optimizing over an additional 92 sites, it was found that more than 91 percent pipeline coverage at 100 ft. AGL could be achieved, but would require 61 sites.

For those areas of the pipeline route with inadequate coverage several alternatives or combinations of alternatives may be considered:

- Increase the height of the existing towers at the pump stations; however, increasing tower height is more costly, more difficult, and increases risk to air navigation (manned and unmanned)
- Provide pipeline surveillance coverage with manned aircraft for those inadequate UAS coverage areas of the ROW, which could later be augmented by UAS coverage enabled by SATCOM C2
- Provide unmanned surveillance at a higher altitude, then deploy manned aircraft to provide inspection at lower altitudes only as needed to perform closer checks on potential areas spotted at the higher altitude
- Deploy unmanned aircraft C2 “repeaters” at pump sites (which is outside of the current TOR for RTCA SC-228)

Because this study is consistent with the current RTCA SC-228 Pilot-in-the-Loop (PITL) UA control assumption, the alternative of allowing for autonomous UA operations over those pipeline sections without RS coverage was not considered.

Figure 20 illustrates predicted LOS coverage directly over the TAPS ROW for two cases: 100 ft. and 1000 ft. AGL, and Figure 21 illustrates total coverage at 100 ft., 1000 ft., and 2000 ft. for the entire TAPS route. As noted earlier and as shown in the figures, the most difficult stretches are in
some sections of the northern part of the pipeline where coverage is challenged by a combination of rugged terrain and lack of existing infrastructure.

The following set of figures better illustrate the results of the optimization process. One of the goals of optimization is to reduce the amount of redundant (overlapping) coverage along the pipeline. As mentioned earlier in this report, having less coverage overlap reduces the adjacent-channel and co-channel interference engineering planning problem. On the other hand, for purposes of safe and effective handoffs, it is desirable to have some overlap between adjacent RS coverage areas to reduce the risk of a lost link situation.

Figure 20 – Pipeline Coverage at (left) 100 ft. and (right) 1000 feet AGL
**Figure 21 – Coverage Optimized Siting for: 100 ft., 1000 ft., and 2000 ft. AGL**
Figure 22 and Figure 23 depict optimization for minimal overlap and maximum end-to-end TAPS coverage percentage, which provides the lowest number of RS sites required for the 100, 500, 1000, and 2000 ft. AGL altitude cases. Note how well the process works to significantly decrease the coverage overlap for different stretches of the pipeline. It should be mentioned that each of the optimization cases was conducted independently, so that the 28 sites shown for the 100 ft. case are not necessarily a subset of the 40 optimized sites identified for the 500 ft. case, and so on for the other cases computed. This must be taken into consideration when actually selecting the sites that would provide the best coverage over the complete altitude range of interest. Figure 24 is particularly useful for that purpose, in that it shows which of the 57 sites are selected for each coverage altitude computed and each site’s percentage contribution the total pipeline coverage percentage. The graph clearly shows which sites are most often selected among the altitude range (clusters of colored “bars” over a site name, e.g. COLDFOOT_BCS_TWR north of PS05), and which are mainly useful for filling gaps at different altitudes (e.g. the 100 ft. darker blue bars shown on the graph, e.g. FRANKLIN_BLUFFS_TWR near PS01).

It is important to note that our optimization example optimized for minimum overlap and maximum total coverage, mainly in the interest of requiring the fewest sites and hence reducing costs. As shown in Figure 22 and Figure 23, this leads to significant areas along the pipeline with no redundancy, which, as mentioned above might not be the ideal case for purposes of efficient handoffs. In an actual design and implementation, further optimization would be required to balance among the competing goals of reducing interference, minimizing RS site costs, and providing sufficient overlap for the handoff process.

Up to this point the discussion has focused on the baseline coverage required to support the core PTP TAPS scenario and operational needs. As discussed earlier, providing Hybrid or Network operational capabilities would require the addition of:

- New multi-frequency/channel RS to provide additional coverage in areas of interest outside the TAPS ROW
- Upgrades to existing sites to provide multi-frequency/channel capabilities
- Appropriate network interconnectivity to support these other changes

To provide additional coverage for a Hybrid case, which assumes that the PTP infrastructure is already in place and operational, the new sites would have to be selected to provide the new coverage in the coverage areas most beneficial to the planned, expanded set of end users, while striving to minimize cost risks in selecting new sites. Using Exelis as an example of an existing NAS service provider with existing critical SBS/ADS-B infrastructure already in place in Alaska, it would be logical to consider leveraging existing (and planned) SBS RS to provide the expanded coverage for Hybrid operational services.\textsuperscript{16}

\textsuperscript{16} This assumes that the expanded, point-to-multipoint coverage would be provided to new end users on a non-interference basis with the existing, baseline TAPS PTP end users.
Figure 22 – Pipeline LOS Site Overlap Optimization at (top) 100 Ft. and (bottom) 500 Ft. AGL
Figure 23 – Pipeline LOS Site Overlap Optimization at (top) 1000 Ft. and (bottom) 2000 Ft. AGL
Figure 24 – Percentage C2 System Coverage Provided by each Site over a Range of Altitudes of Operational Interest
Figure 25 illustrates the additional coverage capabilities at 100 ft. and 1000 ft. AGL that would be added if additional, UAS specific equipment (i.e. radios and antennas) was added to the existing and planned Alaska SBS sites. Of course, these sites are only useful if the new end users need to operate in those areas, which is highly dependent on the users’ operational missions and needs.

A C2 Network system being planned with multiple end users in mind at the start would need to optimize coverage for all planned, potential end users’ operational ranges, altitudes and associated UA traffic densities. From a coverage standpoint, this would require performing the
optimization process described above including potential additional sites more consistent with the desired expanded network coverage area. This also would require detailed network capacity assessments based on UA traffic predictions over time. Figure 26 provides an example of an output of a VDL Mode 2 assessment performed by Exelis in its pursuit of the FAA Data Comm program acquisition. This type of assessment is highly dependent on clear understanding of planned traffic message statistics, the knowledge of the protocols being used and the interference requirements that must be met, and is beyond the scope of this study.

![Figure 26 – Example of Network Capacity Assessment Results](image)

### 3.2.1.6 General Recommendations for Design and Implementation of UAS C2 Radio System Infrastructure

The following recommendations go beyond the scope of this preliminary study, and include a detailed recommended process applicable to the design and implementation of UAS C2 radio system infrastructure. These are based on: 1) our experience in the design and implementation of over 650 SBSS radio systems across the United States and 2) the optimization technique specifically designed and used to address pipeline scenario. This process is quite applicable to UAS C2 system infrastructure design and implementation across a broader area, including on a nation-wide scale.

1. The coverage requirements for the planned operational area should be clearly specified by giving the required altitude of coverage as well as a tolerance in meeting such requirements (e.g. 98%). 3D coverage requirements do not make the solution effort any more challenging, rather this would be preferred way in defining coverage requirements.
2. The coverage solution should be driven by computer aided algorithms. Sensitivity analysis is very important when designing coverage solution in terrain driven areas, thus no solution should be accepted unless a full sensitivity analysis is performed.

3. The coverage driven site selection analysis and potential solutions are an integral part of the overall site selection process. The site research and visits are very important in determining the exact locations of available infrastructure and the availability of such site. Without this prior knowledge an optimized solution may not be feasible. Early sites research and in some cases site visits are recommended.

4. Costs and coverage requirements should drive the problem formulation and optimization. Decoupling cost from coverage may result in more expensive solutions even if the final number of sites is the smallest. Other parameters can be coupled in the formulation of optimization problem, such as time required to acquire sites, required availability and maintainability of sites, spectrum utilization based on the number and location of sites etc.

5. All coverage analysis should be performed based on well accepted RF predictions models that imbed the link budget associated with the UAS link. Optimization should also be performed to reduce the spectrum utilization and interference (e.g. reduced Tx power level, use of directional antennas, etc.).

6. The complexity and large amount of data required to search for the best solution should not hamper such analysis since tools and techniques for handling large amount of data are already available. The ability to handle and analyze vast amounts of data is a key element leading to the optimum and reliable solution.

7. Use of test data to drive the implementation model is of paramount importance. Use collected test and TOO (Target of opportunity) data to further characterize the effect of terrain on the selected UAS link. For the TAPS scenario, ADS-B collected data can be used to validate the prediction model for enhanced fidelity even for the 5 GHz frequency. Also use lessons learned and validate any prediction model based on deployment of similar infrastructure in other areas of similar nature. For example, Colorado WAM design/implementation/results and Alaska SV designs/ implementations/results provide very good insight that would help in designing the coverage solution for the TAPS pipeline scenario.

8. Select the Key Site to align with the use case requirements and at the same time be challenging for design perspective. For example, the PS04-PS06 portion of the TAPS would be a good example as a key site for that scenario for which low altitude coverage is required.

**3.2.1.7 PTP and Network C2 System Comparative Technical Evaluation**

The goals of Task 2 were to develop potential PTP and Network C2 infrastructure topologies for the C2 service provisioning options defined in Task 1; develop the associated coverage plots, and comparatively characterize the advantages and disadvantages of each of these implementations in the following areas.

- Flexibility
- Interoperability
- Scalability
Spectrum efficiency/capacity

This section describes the comparative advantages and disadvantages, considering the discussions in the preceding sections. Table 9 summarizes this evaluation for PTP, Hybrid, and Networked C2 systems for the four parameters listed above. Please note that the PTP, Hybrid, and Network C2 system could be viewed as three stages in an operational continuum of the same basic C2 architecture and infrastructure as it evolves to accommodate more and more end users, with the distinguishing characteristic being to what extent point-to-multipoint capability has been implemented. Other relative advantages and disadvantages of the three systems relate to the degree to which interoperability has been designed into the system, and the possible efficiencies and optimization to be gained by designing a Network from “the top down” as a network, rather from the bottom up as an evolved system starting out as a PTP system, which then evolves into a Hybrid system, and finally transitions into being a Network system. This latter path might be chosen however, as a matter of expediency and costs.

<table>
<thead>
<tr>
<th>System</th>
<th>Flexibility</th>
<th>Interoperability</th>
<th>Scalability</th>
<th>Spectrum Efficiency/Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTP</td>
<td>Limited to single frequency per RS/UA link</td>
<td>Only needs enough interoperability to allow for efficient RS handoffs and location management</td>
<td>Not necessarily designed for scalability, though additions to infrastructure to improve system performance (e.g. availability, latency, or Integrity) is feasible</td>
<td>Depends on the radio system used</td>
</tr>
<tr>
<td></td>
<td>Can choose “closed” system parameters and protocols for expediency, at the possible expense of interoperability</td>
<td>Poses risks for UA that stray away from PTP RS sites; limited chance for recovering lost link</td>
<td>Further scalability is possible if Hybrid system operations is desired</td>
<td>Using the MOPS defined Class 1 radio system, it’s fairly efficient in that it only uses a single frequency sized for the specified end user for a single RS/UA pair and for the specified flight duration, but consumes no spectrum otherwise</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Increased flexibility compared to PTP system as it allows for limited point to multipoint operation as needed, at the possible risk of reduced design optimization compared to purpose built Network System</td>
<td>Provides only the level of interoperability that exists in the PTP system on which it is built</td>
<td>Scalable to the point at which all existing point-to-point sites have been upgraded to point-to-multipoint capability, at which time it has become a C2 Network system</td>
<td>Depends on the radio system used</td>
</tr>
<tr>
<td></td>
<td>Flexibility is limited if it’s based on a closed PTP design</td>
<td></td>
<td>Scalability is also dependent on radio system used. MOPS defined Class 1 radio can accommodate up to 20 users, though this may be complicated by the need for frequency coordination at RS of multiple FDMA downlinks (i.e. each downlink needs a separate frequency)</td>
<td>If using the MOPS defined Class 1 radio, point-to-multipoint sites are more efficient only when more than two simultaneous users can be accommodated</td>
</tr>
<tr>
<td>Network</td>
<td>“Open” design and protocols maximizes flexibility and interoperability</td>
<td>Designed as an “open” system for interoperability by publishing system requirements and parameters and relying</td>
<td>Should be inherently designed for scalability</td>
<td>Depends on the radio system used</td>
</tr>
<tr>
<td></td>
<td>Greatest flexibility to accommodate</td>
<td></td>
<td>Scalability is also dependent on radio system used. MOPS defined Class 1 radio can accommodate</td>
<td>If using the MOPS defined Class 1 radio, point-to-multipoint sites are more efficient only</td>
</tr>
<tr>
<td>Criteria</td>
<td>Flexibility</td>
<td>Interoperability</td>
<td>Scalability</td>
<td>Spectrum Efficiency/Capacity</td>
</tr>
<tr>
<td>------------------</td>
<td>------------------------------</td>
<td>------------------------------------------------------------</td>
<td>-----------------------</td>
<td>-----------------------------</td>
</tr>
</tbody>
</table>
|                  | multiple user types and C2 services at the expense of highest complexity | on industry standards as much as possible.  
- Desirable for interoperability of adjacent C2 Networks; however, this requires cooperation with the other network providers  
- Highly desirable to have a mobility management industry standard through RTCA or other standards body | up to 20 users, though this may be complicated by the need for frequency coordination at RS of multiple FDMA downlinks (i.e., each downlink needs a separate frequency) | when more than two simultaneous users can be accommodated |

3.3 Task 3: Business/Financial Assessment - Infrastructure Business Models

3.3.1 Task Approach

For the C2 service provisioning options described, an assessment of the business model viability was performed. As shown in Figure 27, this task makes use of the PTP and Networked C2 architecture/infrastructure solutions as inputs to a comparative costs/benefits assessment of the solutions. For this task we determined C2 service provider costs by leveraging comprehensive communications system cost models to estimate capital costs (radio equipment, towers, power, etc.), nonrecurring costs (NRC, e.g., site setup, civil works, licensing, etc.), and recurring costs (tower leases, networks, O&M, utilities, etc.). An estimate of operations and flight hours is provided with variable per flight hour fees used to calculate possible return on investment. Concurrently we conducted “voice of the customer” surveys and Technical Interchange Meetings in Alaska with UAF, Alyeska Pipeline Services Company, Maritime Helicopters Inc. (provides current manned helicopter support to Alyeska), UAS providers, and AT&T (provider of much of the current communications infrastructure along the pipeline) to qualify operational and infrastructure costs and the end-user UAS business case (e.g., price point to utilize UAS services vs. current inspection methods).

![Figure 27 – Infrastructure Requirements & Infrastructure Business Models Task Flows](image-url)
3.3.2 Operations and Flight Hours

For each of the applications described in Table 4 and Table 5 an estimate of UA type (fixed wing or multicopter) and flight hours were calculated. Currently five manned helicopters are stationed along the pipeline with an estimated $1000 per flight hour cost and a total yearly operating budget of approximately $3.5M. It is estimated that initially an equivalent number of fixed wing long duration UAs (five) would be used and similarly stationed along the pipeline. The capital cost of these are estimated at $200k each for a total investment of approximately $1M, to include sensors such as high definition video/images, electro-optical (EO), infrared (IR), and LIDAR. UAS flight hours for these five fixed wing UAs are estimated at 1,200 flight hours per year. Life cycle and replacement costs are estimated at approximately five years.

Alyeska uses survey teams to perform close in inspection and geotechnical engineering. These are typically 2-man teams and, depending on time of year, there could be between 3 to 15 teams in the field. Yearly budget for survey teams is approximately $7.0M. There are also security personnel stationed along the pipeline and may be deployed to investigate security risks such as trespassers or other encroachments in the ROW. It is proposed that several of these survey and security teams be equipped with a multicopter short range UAV. It was estimated that initially 10 multicopter UAs may be procured at a cost of $15,000 each for a total of $150K investment. Total flight hours for the 10 multicopters are estimated at 500 hours per year, with a five year lifecycle for replacement. The majority of these multicopter flights are assumed to be within visual and radio line of sight, but it is estimated that 20% of the time these multicopter UAs will fly beyond visual line of site and use the C2 network (e.g., launch from road and fly three miles to inspect pipeline ROW).

Typical UAS operating costs are estimated at $200 per hour for operator/observer labor and operational support (fuel, maintenance training, insurance, mobilize/demobilize, etc.) (Table 10). This estimate does not include the C2 link or other potential beyond visual line of site costs (e.g., payload datalink, detect and avoid, and data processing).

Table 11 provides an estimated number of fixed wing and multicopter UAs with total flight hours per year for Alyeska and other potential users of the C2 link. The total yearly C2 flight hours for Alyeska is 1,300 per year, and the total C2 flight hours for all users is estimated at 7,720 per year.

<table>
<thead>
<tr>
<th>Users and Applications</th>
<th>Area of Operations</th>
<th># UAs</th>
<th>Flight Hours Per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alyeska Pipeline</td>
<td>TAPS</td>
<td>5</td>
<td>1200</td>
</tr>
<tr>
<td>Oil/Gas infrastructure monitoring/spill response at Prudhoe Bay/North Slope fields</td>
<td>North Slope</td>
<td>10</td>
<td>2400</td>
</tr>
<tr>
<td>Valdez Pipeline marine terminal infrastructure monitoring/spill response</td>
<td>Valdez - PWS</td>
<td>1</td>
<td>240</td>
</tr>
<tr>
<td>Natural gas pipeline construction along TAPS ROW</td>
<td>TAPS</td>
<td>2</td>
<td>480</td>
</tr>
<tr>
<td>Univ. and Gov. Research ACUASI, Univ. of AK-</td>
<td>TAPS +</td>
<td>2</td>
<td>480</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 10 – Typical UAV per hour Operating Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$50 Operator</td>
</tr>
<tr>
<td>$50 Observer</td>
</tr>
<tr>
<td>$100 Operations &amp; Support (fuel, maintenance, training, insurance, mobilize/demobilize, etc.)</td>
</tr>
<tr>
<td>$200 Typical Operating Cost per hour without C2 link</td>
</tr>
</tbody>
</table>
### Users and Applications

<table>
<thead>
<tr>
<th>Users and Applications</th>
<th>Area of Operations</th>
<th># UAs</th>
<th>Flight Hours Per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fixed Wing</td>
<td>Multicopter</td>
</tr>
<tr>
<td>Fairbanks (e.g., Poker Flat Research Range), Various Universities and government agencies (e.g., climate change)</td>
<td>TAPS</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Alaska DOT for roadway (e.g., avalanche) and infrastructure monitoring (e.g., bridge inspection)</td>
<td>TAPS +</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Forest fire fighting – interagency BLM, US Forest Service, Alaska Div. of Forestry, …</td>
<td>TAPS +</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Wildlife and environmental monitoring – US Dept. of Interior, State Dept. of Fish &amp; Game</td>
<td>TAPS +</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Public safety</td>
<td>TAPS +</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Alaska State Troopers – search &amp; rescue, poaching, other criminal activity</td>
<td>FAI</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Fairbanks Police and Fire – search &amp; rescue, emergency response, …</td>
<td>FAI-Delta-Gulkana +</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>DOD/National Guard – TAPS transits three military bases and various Military Operations Areas, will they use or want to monitor civil C2 frequency (e.g., terrorist threat training) (NOTE: Civil UAVs)</td>
<td>FAI-Delta-Gulkana +</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Fixed Wing</th>
<th>Multicopter</th>
<th>Fixed Wing</th>
<th>Multicopter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>52</td>
<td>7200</td>
<td>2600</td>
</tr>
</tbody>
</table>

Total Yearly Alyeska UAV Flight Hours using C2 link = 1200 (fixed wing) + (500 * 20%) (multicopter) = 1300 hrs.
Total Yearly All-Users UAV Flight Hours using C2 link = 7200 (fixed wing) + (2600 * 20%) (multicopter) = 7720 hrs.

### 3.3.3 Benefits

It is difficult to quantify the direct and indirect benefits of UAS operations along TAPS due to current unknowns and limitations in technical, operational, policy, and business considerations. For example, a benefit of flying UAs vs. manned helicopters is when you cannot or do not want to fly manned aircraft (e.g., flight safety, helicopters limited to day/VFR). However, the FAA is currently limiting UAS operations during those times when you could extend flight operations beyond manned helicopter capabilities. Another example is that UAS operations and sensors typically produce additional data not currently collected. This can provide added benefits, but also incur additional costs of analyzing that data.

Two areas of direct benefits estimated in this study are 1) possible reduction in manned helicopter flight hours, and 2) increased efficiency of survey teams. Table 12 summarizes these potential benefits, hypothesizing a 3, 5, 10, or 20% savings.

<table>
<thead>
<tr>
<th>Potential Saved</th>
<th>Direct Benefit</th>
<th>Per UAS Flt Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>3%</td>
<td>$147,000</td>
<td>$86.47</td>
</tr>
<tr>
<td>5%</td>
<td>$245,000</td>
<td>$144.12</td>
</tr>
<tr>
<td>10%</td>
<td>$490,000</td>
<td>$288.24</td>
</tr>
<tr>
<td>20%</td>
<td>$980,000</td>
<td>$576.47</td>
</tr>
</tbody>
</table>

A major benefit for utilizing UAS is for the potential increase capability of detecting oil leaks and spills earlier or before they occur, and if they do occur to provide enhanced spill response. During a major spill, manned helicopters may be fully utilized in transporting people and equipment, while UAs can be used to better monitor the extent of the spill and command oversight of the response. A 2006 oil spill on the North Slope of Alaska ([http://en.wikipedia.org/wiki/Prudhoe_Bay_oil_spill](http://en.wikipedia.org/wiki/Prudhoe_Bay_oil_spill)) was used as a sample scenario to estimate costs if this type of spill occurred on TAPS. The costs include pipeline shutdown time, repair and...
cleanup, fines and other lawsuits with a rough order of magnitude (ROM) cost calculated at $2.1B. Table 13 provides a summary of potential benefits, hypothesizing a 1, 3, 5, 10, 15, or 20% in potential cost avoidance.

**Table 13 – Potential Indirect Cost Avoidance Benefits Per Sample Oil Spill**

<table>
<thead>
<tr>
<th>Potential Saved</th>
<th>Indirect Benefit (Cost Avoidance)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>$21,643,235</td>
</tr>
<tr>
<td>3%</td>
<td>$64,929,705</td>
</tr>
<tr>
<td>5%</td>
<td>$108,215,175</td>
</tr>
<tr>
<td>10%</td>
<td>$216,432,350</td>
</tr>
<tr>
<td>15%</td>
<td>$324,648,524</td>
</tr>
<tr>
<td>20%</td>
<td>$432,864,699</td>
</tr>
</tbody>
</table>

### 3.3.4 C2 Provider Estimated Costs and Revenues

An estimate of C2 NRC capital costs (e.g., equipment, installation, spares) and monthly recurring costs (e.g., power, communications, and space) is provided using models and actual costs of the Exelis SBS/ADS-B system both in CONUS and in Alaska. We adjusted our estimates through discussions with AT&T, which recently performed a co-location radio project along the northern half of TAPS. Note that these costs do not include spectrum and frequency assignment, which must be considered in the context of a national/international market. The optimized number of C2 radio sites to obtain coverage at a variety of altitudes is provided in Figure 19. These sites were categorized into three types: 1) SBS-leased sites (least cost), Non-SBS leased sites (medium cost), and Non-SBS leased sites-major modification (highest cost). Greenfield sites (i.e., no infrastructure) were not included in this analysis, given these can easily cost upwards of $1M each in remote areas of Alaska. At 1000ft AGL we were able to have close to complete coverage using 22 pre-existing sites (98%). Below that altitude there are tradeoffs in installation of greenfield sites (or in some cases other alternatives, such as GCI sites) vs. flying manned aircraft, flying UAs higher to be in coverage, or autonomous UA operations for short durations outside of C2 coverage.

Table 14 provides the NRC for the optimized 40 sites at 100 ft. AGL, 28 sites at 500ft, 22 sites at 1000 ft., 15 sites at 2000 ft., and 11 sites at 3000ft. Table 15 provides the MRC for the similar coverage altitudes, and then calculated for a yearly recurring cost.

**Table 14 - Total NRC (Capital + Installation + Spares) Costs**

<table>
<thead>
<tr>
<th>Coverage</th>
<th># Sites</th>
<th>% Coverage</th>
<th>Total Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>100ft</td>
<td>40</td>
<td>83%</td>
<td>$8,431,086</td>
</tr>
<tr>
<td>500ft</td>
<td>28</td>
<td>94%</td>
<td>$5,923,710</td>
</tr>
<tr>
<td>1000ft</td>
<td>22</td>
<td>98%</td>
<td>$4,663,949</td>
</tr>
<tr>
<td>2000ft</td>
<td>15</td>
<td>99%</td>
<td>$3,669,022</td>
</tr>
<tr>
<td>3000ft</td>
<td>11</td>
<td>100%</td>
<td>$2,457,848</td>
</tr>
</tbody>
</table>

17 If permitted.
Table 15 – MRC (power, comm., space)

<table>
<thead>
<tr>
<th>Coverage</th>
<th># Site</th>
<th>% Coverage</th>
<th>Monthly</th>
<th>Yearly</th>
</tr>
</thead>
<tbody>
<tr>
<td>100ft</td>
<td>40</td>
<td>83%</td>
<td>$128,131</td>
<td>$1,537,573</td>
</tr>
<tr>
<td>500ft</td>
<td>28</td>
<td>94%</td>
<td>$89,153</td>
<td>$1,069,836</td>
</tr>
<tr>
<td>1000ft</td>
<td>22</td>
<td>98%</td>
<td>$68,212</td>
<td>$818,539</td>
</tr>
<tr>
<td>2000ft</td>
<td>15</td>
<td>99%</td>
<td>$48,723</td>
<td>$584,671</td>
</tr>
<tr>
<td>3000ft</td>
<td>11</td>
<td>100%</td>
<td>$33,934</td>
<td>$407,210</td>
</tr>
</tbody>
</table>

The C2 costs were calculated over a 20 year life cycle, with capital investment assumed to be incurred in the first year and MRC for each year after as shown in Figure 28.

Figure 28 – C2 Infrastructure Costs over 20 yr. Life Cycle

Potential cumulative revenue was calculated based on estimated C2 flight hours (Table 11) for Alyeska and all users with a hypothetical $50, $100, $200, or $300 per flight hour C2 fee. Figure 29 provides the cumulative revenue over 20 years for Alyeska flight hours, and Figure 30 provides revenue for all user flight hours.
From these estimates, a C2 infrastructure solely for Alyeska use does not appear to be cost effective, and even with all users the per flight hour fee to enable a return on investment may be too costly for the market to bear for a complete 100ft infrastructure. More analysis is needed in this area to include additional tradeoffs across technical, operational, policy, and business considerations.

### 3.3.4.1 Example Return on Investment (ROI)

Based on the above graphs an example ROI is provided in Figure 31 with a $200 per flight hour fee and cumulative costs based on the 1000ft and 500ft infrastructure estimates. For the 1000ft
infrastructure ROI (blue circles) begins at approximately 5 years and for the 500ft infrastructure it begins at approximately 10 years. These ROM estimates are very dependent on actual number of flight hours per year (estimated as constant each year, even though more realistic is to have less in near-term and more in far-term), spreading initial NRC over multiple years, and net present value of money (which was not considered). This ROI example appears plausible, and may be enhanced by including additional services (e.g., payload data, real-time video). A $200 per hour fee is relatively high compared to the approximately $200 per flight hour operational cost of flying a UAV without the C2 link. However, a total operational cost of $400 per hour (operational and C2 link) is not unreasonable as compared to the $1000 per hour manned helicopter cost. Consideration should be made for the expansion of the C2 infrastructure to include additional services or additional end users that do not markedly increase the C2 infrastructure costs, but can add substantial value to the use of the service. For example, Alyeska has a desire for real-time video during pipeline monitoring and during spill response events.

![Example ROI: Cumulative Cost (500ft, 1000ft) vs. Revenue ($200 fee/hr) All Users](image)

*Figure 31 – Example ROI: Cumulative Cost (500ft, 1000ft) vs. Revenue ($200 fee/hr.)*

### 3.4 Task 4: Regulatory Assessment - Governance & Accountability

For Task 4 we assessed regulatory considerations for PTP and Networked C2 systems in three areas: operational system safety; aspects of C2 services certification; and UAS C2 performance monitoring. These are presented in the next three sections.

#### 3.4.1 Operational System Safety

A full operational safety analysis is beyond the scope of this study. The following includes a brief discussion of the UAS safety analysis process conducted in the context of the FAA’s Safety Management Process, some safety relevant UAS C2 infrastructure design considerations, and some aspects of a very high level and preliminary safety analysis.
3.4.1.1 *UAS Safety Analysis Background*

The key difference between manned and unmanned aviation lies in the separation of the pilot from the cockpit and the level of automation introduced. The difference introduces new failure modes and increased safety risks that need to be evaluated and mitigated.

This potential risk from the use of a UAS is quantified by a risk metric defined as both the “likelihood of an accident, and the severity of the potential consequences.” The FAA System Safety Handbook (SSH) provides general guidance on implementing a risk management process.

To determine the safety implications of potential UAV UAS operations, the risk assessment methodology from FAA’s Safety Management System (SMS) is to be used. Figure 32 illustrates FAA’s Safety Management System process.

![FAA’s Safety Management Process](image)

*Figure 32 – FAA’s Safety Management Process*

The first step is “Describe System,” which includes defining the scope and objectives of the system safety work, defining stakeholders and identifying criteria and the plan for safety risk management efforts. The second step is “Identify Hazards”, which uses a structured approach so as not to dismiss hazards prematurely. Lessons learned and experience from other similar programs help for this phase. The third step is “Analyze Risk,” which involves identifying existing controls and determining risk based upon the severity and likelihood of the outcome. The fourth step is “Assess Risk,” which assigns a risk level for each hazard based on severity and likelihood. The last step is “Treat Risk,” which identifies mitigation strategies, develops safety performance targets, and develops a monitoring plan.

The preliminary safety analysis for this work involves primarily Steps 2, 3, and 4 described above.
The first step is to identify prospective safety hazards resulting from the operation of UASs, and their associated severity. Next, the expected likelihood of occurrence of each hazard is ascertained from the risk matrix below, with the goal of keeping safety risk out of the high risk (red) area. The risk of a given hazard is defined as the combination of the severity of the hazard and its likelihood of occurrence, as Figure 33 illustrates. For identified risks in the “red” zone, suitable mitigations should be identified, which, if implemented, move the risks out of the red. The definitions for both severity and likelihood can be found in the FAA SMS.

![FAA Safety Risk Matrix](image)

**Figure 33 – FAA Safety Risk Matrix**

For quantitative and qualitative safety analyses, two key terms used are "hazard" and "accident"; the first is defined as the necessary conditions that may lead to the second, and the latter as an unwanted outcome with associated damages. Subsequently, the expected rate of occurrence of an accident can be calculated from the expected rate of hazards, which in turn can be traced back to the failure rate of the UAS. Given an a particular accident rate limit, which can be derived from the Allocation of Safety Objectives and Requirements (ASOR) process, a UAS can be designed so that its components have sufficient reliability to ensure that the required rate is not violated. The overarching objective in safety risk management is to ensure that hazards in the UAS are controlled or mitigated to an acceptable level of risk, thereby reducing the accident rate.

### 3.4.1.2 Design Decisions for UAS C2 Infrastructure

Three major system safety concerns for UAS C2 system infrastructure assurance for both C2 system approaches, are the link availability, latency, and integrity performance parameters. Often degradations in the three major performance parameters are correlated, and can jointly impact system safety.

Communications links robustness is typically measured in terms of link availability. Determining system availability assumes that a Mean Time between Failure (MTBF) analysis can be performed on the system components. In the case of transient link unavailability, disconnections could occur during the inter-RS handoff process and during intermittent periods of deep signal “fading” caused by C2 link signal blockages by terrain and UA structures. Design considerations should focus on at both of these issues to ensure adequate link availability performance.
Latency is the difference between the time a data packet is transmitted by the source unit (e.g. a ground radio) and when it is received by the destination unit (UA radio). Latency includes propagation time over the interconnection network from the UAS GCS to the RS, any radio processing delays, radio to UA signal in space delay, and UA airborne radio system processing time.

Like integrity is a measure of the absence of unintended changes or errors in data carried over the link, often characterized in terms of an error rate per second (e.g. Bit Error Rate – BER).

### 3.4.1.3 Preliminary Safety Analysis

For this analysis, we consider five Environmental Conditions that the UAS is expected to operate in, as shown in Table 16. The table is derived from information in RTCA DO-320\(^\text{18}\). The ATC functions considered in the table include flight planning, flight data management, aircraft-to-aircraft separation, aircraft to terrain/obstacle separation, and advisories. Because ATC functionality is out of scope of this study, only three of the five environments in the table are considered further.

#### Table 16 – UAS Environmental Conditions

<table>
<thead>
<tr>
<th>Ref #</th>
<th>Environment Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENV_1</td>
<td>Surface environment with ATC Participating Airport: UAS operations at towered airports where ATC services are required for movement</td>
</tr>
<tr>
<td>ENV_2</td>
<td>Surface environment with Non-ATC Participating Airport: UAS operations at any public non-towered or towered airport where ATC services are not offered</td>
</tr>
<tr>
<td>ENV_3</td>
<td>Surface environment with Non-ATC Participating Surface: UAS operations at any off-airport location, privately-owned airfield, or airports that can be temporarily cleared to allow for UAS</td>
</tr>
<tr>
<td>ENV_4</td>
<td>Airborne environment with ATC participation: UAS operations interacting with the ATC system under IFR or VFR while under air traffic control</td>
</tr>
<tr>
<td>ENV_5</td>
<td>Airborne environment with no ATC participation: UAS operations under VFR in Class G and E airspace outside of air traffic control</td>
</tr>
</tbody>
</table>

Additionally, two meteorological conditions are considered in this analysis:

#### Table 17 – Meteorological Environmental Conditions

<table>
<thead>
<tr>
<th>Ref #</th>
<th>Meteorological Environment Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET_1</td>
<td>IMC (Instrument meteorological conditions)</td>
</tr>
<tr>
<td>MET_2</td>
<td>VMC (Visual meteorological conditions)</td>
</tr>
</tbody>
</table>

In addition to the environmental conditions listed above, there are eleven (11) phases of applicable UAS operations listed in Table 18. This table assumes a fairly large and well equipped UA that may not be representative of the aircraft used for the study scenario; however, it is used as an example because it provides a broad range of flight operations. Most UA operations for the study scenario would include many or most of these phases. The flight phases listed in the table are used to develop a complete safety assessment by providing a time-ordered sequence of activities and information exchanges. The primary phases of UAS flight are described below.

---

\(^{18}\) Operational Services and Environment Description (OSED) for Unmanned Aircraft Systems (UAS), RTCA DO-320, June 10, 2010.
Table 18 – UAS Flight Phases

<table>
<thead>
<tr>
<th>Ref #</th>
<th>UAS Flight Phases</th>
<th>UAS Flight Phase Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP_1</td>
<td>Pushback/Towing</td>
<td>UA is moving in the ramp or parking area, assisted by a tow vehicle.</td>
</tr>
<tr>
<td>AP_2</td>
<td>Takeoff</td>
<td>From the application of takeoff power, through rotation and to an altitude of 35 feet above runway elevation.</td>
</tr>
<tr>
<td>AP_3</td>
<td>Initial Climb</td>
<td>From the end of the Takeoff phase to the first prescribed power reduction, or until reaching X feet above runway elevation.</td>
</tr>
<tr>
<td>AP_4</td>
<td>Maneuvering</td>
<td>Low altitude flight operations.</td>
</tr>
<tr>
<td>AP_5</td>
<td>Enroute</td>
<td>From completion of Initial Climb through cruise altitude</td>
</tr>
<tr>
<td>AP_6</td>
<td>Approach</td>
<td>and completion of controlled descent to the Initial Approach Fix</td>
</tr>
<tr>
<td>AP_7</td>
<td>Landing</td>
<td>From the Initial Approach Fix (IAF) to the beginning of the landing flare.</td>
</tr>
<tr>
<td>AP_8</td>
<td>Emergency Descent</td>
<td>From the beginning of the landing flare until aircraft exits the landing runway, comes to a stop on the runway, or when power is applied for takeoff in the case of a touch-and-go landing.</td>
</tr>
<tr>
<td>AP_9</td>
<td>Uncontrolled Descent</td>
<td>A controlled descent during any airborne phase in response to a perceived emergency situation.</td>
</tr>
<tr>
<td>AP_10</td>
<td>Post Impact</td>
<td>A descent during any airborne phase in which the aircraft does not sustain controlled flight</td>
</tr>
<tr>
<td>AP_11</td>
<td>Unknown</td>
<td>Any of that portion of the flight which occurs after impact with a person, object, obstacle or terrain.</td>
</tr>
</tbody>
</table>

From our consideration of the navigation procedures within each of these phases, we reduce the scope of our analysis and introduce two (2) specific emergency conditions, listed in Table 19.

Table 19 – Emergency Environmental Conditions

<table>
<thead>
<tr>
<th>Ref #</th>
<th>Environment Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG_1</td>
<td>Violation of UA to aircraft separation requirements</td>
</tr>
<tr>
<td>EMG_2</td>
<td>Violation of UA separation to terrain or obstacle requirements</td>
</tr>
</tbody>
</table>

Table 20 illustrates the preliminary analysis for a set of failure conditions, their associated failure effects, severity and rationale. From the severity assessment, the corresponding likelihood requirement was defined based on FAA’s safety matrix in Figure 33. The list of failures is by no means comprehensive and should be considered as preliminary only.

A formal Preliminary Hazard Assessment (PHA) adherent to FAA’s SMS methodology should expand the list of failure conditions to make it as comprehensive as possible. Additionally, the UAS Environmental Conditions, Meteorological Environmental Conditions, Flight Phases, and Emergency Environmental Conditions, as listed in the tables above, will be examined thoroughly to include all additional possible scenarios. Following the PHA, Subsystem Hazard Analysis, System Hazard Analysis, Operations and Support Hazard Analysis, and System Safety Assessment Report would be the next tasks performed for a formal Safety Risk Management Documents process conformant to FAA’s SMS.

Table 20 – Severity Classification and Likelihood Requirements of Failure Conditions

<table>
<thead>
<tr>
<th>Ref #</th>
<th>Failure Conditions</th>
<th>Failure Effects</th>
<th>Severity / Rationale</th>
<th>Required Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEC_1</td>
<td>Erroneous UAV telemetry info</td>
<td>UAS pilot unable to determine its operating environment; pilot can mitigate with maps and other tools, resulting slight increase in workload</td>
<td>4 (Minor)</td>
<td>A (Frequent)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slight increase in pilot workload; slight increase in ATC workload, if available</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEC_2</td>
<td>Loss of UAV flight information</td>
<td>Pilot unable to validate nearby target positions, and has to revert to UAS fail-safe mechanisms</td>
<td>2 (Hazardous)</td>
<td>D (Extremely Remote)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hazard is likely to be detected given UAS monitoring of deviations. If hazard goes undetected, a reduction in separation consistent</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 3.4.2 Aspects of C2 System Certification

#### 3.4.2.1 FAA’s Approach to UAS Certification

According to the FAA:\(^\text{19}\):

A civil UAS cannot be operated in air commerce in the National Airspace System unless there is an appropriate and valid airworthiness certificate issued for that UAS. U.S. registration is a prerequisite for the issuance of an airworthiness certificate.

Eligible individuals may apply for the following:

- 21.17b type certificate for special class aircraft and a 21.183 standard airworthiness certificate for special class aircraft
- 21.25 type certificate for restricted category aircraft and a 21.185 special airworthiness certificate in the restricted category

---

\(^\text{19}\) Special Airworthiness Certification - Certification for Civil Operated Unmanned Aircraft Systems (UAS) and Optionally Piloted Aircraft (OPA).
[https://www.faa.gov/aircraft/air_cert/airworthiness_certification/sp_awcert/experiment/sac/](https://www.faa.gov/aircraft/air_cert/airworthiness_certification/sp_awcert/experiment/sac/)
The FAA’s Small Airplane Directorate has been a visible force for FAA UAS certification efforts, and has presented to RTCA SC-228 WG2 an excellent briefing package: “Concepts for Certification of UAS”\textsuperscript{20}. This section will summarize some of the UAS certification concepts outlined in that presentation and make some relevant observations based on those concepts regarding certification of PTP and Network C2 systems for the study scenario.

Four major certification areas that apply to UAS include:

- COA Process
- Experimental Airworthiness
- 333 Exemption Process
- Type Certification, 21.17(b)

This study focuses on the last item: Type Certification (TC). According to the FAA, some TC in the Restricted Category already have been completed (e.g. Scan Eagle, Puma), and other TC approvals have been getting started using 21.17(b). To support that effort, the FAA has been developing a Draft Fixed Wing Advisory Circular (AC) for UAS that uses existing certification concepts, based on risk, and requirements for Design, Airworthiness, and Operation. This work will be expanded to include rotorcraft. The draft AC is expected to be released for public comments in 2015.

Type Certification is FAA certification of design and production, not just basic airworthiness. It requires documentation of design, production, and limitations/conditions for airworthiness. The UAS design certification basis will be negotiated, agreed upon, documented, and published for public review in Fed Register.

The AC being drafted for UAS provides detailed steps for 21.17(b) Certification – Special Class. In the AC the certification basis depends on the vehicle, its intended use, and area of operation, which leads to designated Risk Classes. Consistent with existing certification concepts, the certification approach uses existing standards, where applicable – ASTM, FAA, RTCA, etc., and compliance and data expectations vary for each risk class.

Figure 34 summarizes the FAA’s approach for UAS certification, and outlines the following certification “driving principles”:

- Tailored TC Requirements,
  - Vehicle, Mission, and Area of Operation - Managed Risk
  - Use Industry & FAA Standards
- Single TC Approach Will Not Work

\textsuperscript{20} Concepts for Certification of UAS, Earl Lawrence, Manager of the FAA’s Small Airplane Directorate in Kansas City, MS, Oct. 2014, presented to RTCA SC-228 WG2 in December 2014.
Follow Safety Continuum
  - Manage Risks - Do-No-Harm
  - UAS Must Meet Existing NAS Requirements, Not The Other Way Around

As shown in Figure 34, the FAA requires an increasing level involvement as UAS become larger and more complex, and when UAS operate beyond visual LOS. To help quantify the level of risk, the FAA has defined risk classes based on the kinetic energy of the UA and whether or not the operational area is in populated or unpopulated areas (see Figure 35).

The FAA’s general steps for Type Certification include:
  - Identify Requirements Based on Mission etc.
  - Document Requirements and Method of Compliance
  - Published in Federal Register as Acceptable Design Standard – Sets Precedent for Others
  - Method of Compliance and Expectations for Data Package Must be Clear from Day One
  - Data Will Be Proprietary and Protected by FAA
    - May Not Be Held by FAA, But Covered by Agreement for Access

The detailed process steps are shown in Figure 36.

---

21 Concepts for Certification of UAS, slide 19.
Figure 35 – Certification by Risk Classes\textsuperscript{22}

Figure 36 – UAS TC Process Steps\textsuperscript{23}

\textsuperscript{22} Concepts for Certification of UAS, slide 26.

\textsuperscript{23} Concepts for Certification of UAS, slide 20.
### 3.4.2.2 Relative Impact of UAS Certification on PTP and Network C2 Systems

The C2 systems that are the focus of this study are just one piece of the total UAS that would get type certified to operate in the NAS, as just described. One of the intended uses of the CNPC MOPS being developed by RTCA SC-228 WG is to provide a basis for a UAS radio system Technical Standard Order (TSO), defined as\(^24\):

A minimum performance standard for specified materials, parts, and appliances used on civil aircraft. When authorized to manufacture a material, part, or appliances to a TSO standard, this is referred to as TSO authorization. Receiving a TSO authorization is both design and production approval.

Receiving a TSO Authorization is not an approval to install and use the article in the aircraft. It means that the article meets the specific TSO and the applicant is authorized to manufacture it.

The motivation for doing this is that a UAS integrator may select a UAS radio system for which a TSO has been issued because it is expected that this could speed up the UAS certification process – the C2 radio built to that standard is recognized by the FAA certification community. Use of this radio does not relieve the burden on the UAS integrator to prove to the FAA that UAS using that C2 radio is safe and meets all applicable requirements for certification.

An important question to ask is: where does a potential UAS C2 service provider fit into the UAS certification process, in other words, what is the process for certification if the UA platform and GCS comes from one source and the C2 services come from a different source? The answer to that question is not clear at this time. Even with TSO authorized C2 radio system (two radios and a C2 link), there are other elements comprising C2 end-to-end services (as shown In Figure 4 and Figure 8) that would need to be considered for UAS certification.

Two general observations regarding relative certification issues/problems for PTP and Network C2 system can be made at this time:

- The certification process for UAS provided as a service and composed of constituent services, such as C2 service and DAA service, from multiple sources needs to be better understood.
- A PTP C2 system deployed as part of a turnkey, owner/operator UAS service/system may face a less complex certification challenge because the UA type, C2 radio type, GCS, etc. and operational areas/applications will be limited in scope compared to the situation faced by a potential C2 Network service provider that may want to provide C2 services for a broad range of UA platforms, end users, and operational applications.

### 3.4.3 UAS C2 Performance Monitoring for Accountability Assurance

The goal of this subtask is to describe some aspects of a viable UAS C2 system performance monitoring process that could provide appropriate C2 system performance accountability assurance to UAS end users and/or Government regulators. The goal of the performance monitoring process is to ensure that the C2 system stays within required performance parameters and thus minimizes operational safety risks in both controlled and uncontrolled airspace in the NAS. The approach for this subtask was patterned after Exelis’ successful Technical

---

\(^24\) [https://www.faa.gov/aircraft/air_cert/design_approvals/tso/]
Performance Monitoring system used to provide performance assurance to the FAA for Exelis provided Surveillance and Broadcast System Services.

Exelis utilizes a closed loop feedback system to assess program metrics and provide corrective action, as shown in Figure 37.

![Figure 37 – Performance Monitoring Process](image)

The process shown in the figure results in an approved set of base measures, derived measures, and indicators to support the changing information needs throughout the project. Key to UAS C2 system technical performance monitoring (TPM) is the selection of the appropriate measurement data parameters – the “Information Needs” process block in the figure.

For this study, we conducted, as an example, a highly preliminary iteration of the steps outlined in Figure 38, based on early but ongoing efforts in RTCA SC-228 WG2 to identify appropriate TPM parameters suitable for both C2 PTP and Network C2 Systems.

![Figure 38 – Process Used for Selection of the Appropriate Measurement Data Parameters](image)

Taking these activities into consideration is important, because there is value in basing TPM metrics on a common set of parameters that are standardized in the CNPC MOPS and thus will be available (mandatory) for all system implementations. This could support comparisons of different PTP and/or Network C2 implementations by different C2 service providers.

Though availability, latency (or transaction time), and integrity are the major performance parameters typically tracked for communications systems, some are more difficult to accurately
track than others. Likewise, there may be other related parameters that should be tracked for various reasons. Because it is preferable to optimize the selection of TPM metrics to manage the collection and processing burden, we have used a set of evaluation criteria for selecting appropriate UAS C2 system performance measurement parameters (see Table 21).

Using these criteria, we have performed a highly preliminary comparative assessment, mainly to illustrate the process, of several PTP and Networked C2 performance monitoring requirements.

Table 21 – Evaluation Criteria for Selecting Performance Measurement Parameters

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevance</td>
<td>The degree to which the measurement data satisfies the information need for the respective project phase.</td>
</tr>
<tr>
<td>Benefit</td>
<td>The degree to which the measurement data would be (or is) used for decision making by project management, and the extent the data has been effective in supporting the information need.</td>
</tr>
<tr>
<td>Accuracy</td>
<td>The degree to which the measurement data reflects the actual condition being assessed within the granularity needed to make decisions.</td>
</tr>
<tr>
<td>Ease of Collection</td>
<td>The degree to which the measurement data can be collected and processed within existing tools and processes.</td>
</tr>
<tr>
<td>Understandability</td>
<td>The degree to which the measurement data can be (or is) understandable and interpretable by project management.</td>
</tr>
<tr>
<td>Repeatability</td>
<td>The degree to which the collection and processing of a set of data using the same process would yield the same result.</td>
</tr>
<tr>
<td>Timeliness</td>
<td>The degree to which the measurement process provides data in a timely manner sufficient for making proactive decisions.</td>
</tr>
</tbody>
</table>

The assessment is summarized in Table 22.

Table 22 – C2 System Performance Measurement Parameters Assessment Example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Criteria¹</th>
<th>Relevance</th>
<th>Benefit</th>
<th>Accuracy</th>
<th>Ease of Collection</th>
<th>Understandability</th>
<th>Repeatability</th>
<th>Timeliness</th>
</tr>
</thead>
<tbody>
<tr>
<td>End-to-end availability</td>
<td></td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>0</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Downlink Signal Strength²</td>
<td></td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>“Raw” Downlink BER²</td>
<td></td>
<td>0</td>
<td>0</td>
<td>−</td>
<td>−</td>
<td>0</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>SNR</td>
<td></td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Frame Erasure Rate²</td>
<td></td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>UA Direct/ Reflected Signal Ratio²</td>
<td></td>
<td>0</td>
<td>0</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>One-way latency</td>
<td></td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Notes:
1. Ranked as either “−” for “low”, “0” for neutral, or “+” for high
2. A data integrity measure

Because the candidate parameters are still being identified in RTCA SC-228 WG2, the assessment is not complete.

4.0 SUMMARY CONCLUSIONS

This section provides summary conclusions for each of the four tasks.
4.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights

4.1.1 Fundamental Differences between PTP and Network C2 Systems

The main factors that distinguish a C2 network system from a PTP system include:

- Point-to-multipoint, multiple frequency operation (for networks). An example of such a radio system design is being provided as an option in the RTCA SC-228 MOPS currently under development.

- Greater interoperability in Network Systems. “Open” accessibility to potential UAs to C2 network airspace, require “open” standards, either by: 1) common link layer technology/protocol standardized by a standards organization, e.g. by RTCA, or 2) open link technology/protocol published by a network service provider. By contrast, a PTP C2 provider could implement a more proprietary system, especially in the link layer and higher layers in the communications protocol stack, since interoperability with other systems is not required. It has been suggested, however, that “to maximize coverage, the FCC and NTIA could impose interoperability mandates as a condition of the license”\(^{25}\) of fixed RS infrastructure.

4.1.2 Relative Operational Suitability to Support Flight Mission Variety

Operational limitations in PTP C2 systems for the study scenario are generally due to coverage limitations necessitated by a single end user and lack of flexibility because of single frequency operation. The limitations in coverage area by the linear PTP RS topology needed for TAPS inspection can be offset by adding new RS to fill required coverage gaps outside the coverage corridor, and by adding/upgrading radio equipment at existing PTP RS, thus creating a Hybrid C2 system. As an evolutionary path, upgrading all existing PTP RS to handle point-to-multipoint operations, along with adding any new RS required for additional coverage would ultimately result in a fully networked C2 system.

These observations are applicable to other UAS operational scenarios.

4.1.3 PTP and Network C2 Comparative Spectrum Limitations

4.1.3.1 UAS C2 Spectrum Allocation Technical Challenges and Considerations

Generally the technical challenges and considerations relative to spectrum allocation meeting stringent C2 availability performance requirements apply equally to both the PTP and Network C2 systems considered for this study.

4.1.3.2 PTP and Hybrid C2 Comparative Spectrum Efficiencies

In the comparison of spectral efficiency between PTP and Network C2 systems using the draft CNPC MOPS Class 1 radio:

\(^{25}\) Spectrum management report, p. 55.
The amount of spectrum per UA required for the Network C2 system RS 4-slot uplink is lower than for the PTP case whenever the RS is supporting three or more UA simultaneously, and higher (less efficient) than the PTP case otherwise.

The amount of spectrum per UA required for the Network C2 system UA downlinks is constant and equal to the PTP C2 case.

It should be stressed that the Class 1 radio used for this comparison is not required to be used. Other radio systems with other goals for spectral efficiency could be designed and implemented and submitted for certification; however, without the TSO expected to be issued by the FAA for the MOPS defined Class 1 radio, it may take a little longer for a radio system not defined in the MOPS to get certified.

It also should be noted that because the current version of the SC-228 CNPC MOPS is not addressing interoperability, there are not many proposed requirements addressing layers above the Physical Layer of the protocol stack. It is possible that higher protocol layer requirements for higher would require additional spectrum.

4.1.3.3 Spectrum Impact on PTP and Network C2 Systems Based on Spectrum Management Policies

In an assessment of the four spectrum management models described in the Titania Report, including a high level assessment of the sufficiency of each model in providing equitable, effective and efficient spectrum management functions for the C2 systems covered in this study, it is found that all four models could generally meet the spectrum management needs for the alternative C2 systems considered in this study, because each of the four models was defined to accommodate both on-network and off-network UAS. As noted in the summary assessment table, however, there are some potential problem areas, for example in cases of End User provided PTP C2 systems intended to be deployed in areas already covered by existing C2 Network service providers. The Titania Report implies that these deployments would not be allowed and would not be entitled to spectrum management services. We do not agree with this implication.

4.1.3.4 Impact on PTP and Network C2 Systems Based on Dynamic Frequency Assignment Processes

A common element in proposed schemes under discussion in the RTCA SC-228 WG2 Dynamic Spectrum Assignment Subgroup, as well as in the Titania Spectrum Management Report, is the recommendation for real time, comprehensive flight planning and interference assessment tools to be used by the spectrum management/assignment entity. Fortunately, the technology is available, so this capability is achievable. Another recommended spectrum assignment system component is web portal like functionality that allows for real time access to the spectrum management entity by the spectrum user/requester.

Unfortunately, currently proposed dynamic spectrum assignment approaches under consideration in RTCA SC-228 WG2 are hampered by the lack of interoperability standards development within WG2 that could define standard link/mobility management approaches and provide some functional platforms upon which spectrum assignment approaches, such as a common signaling channel, could be built upon.
The Titania report in Appendix H provides some useful examples of existing dynamic allocation schemes that could provide useful inputs to the efforts in the SC-228 WG2 Dynamic Spectrum Resource Assignment Subgroup. The Titania report in its entirety would be of great value to the entire SC-228 WG2

Regarding comparative applicability of dynamic spectrum assignment to PTP and Network C2 Systems, as noted earlier, both ad hoc and fixed PTP C2 Systems should always be accommodated in the UAS operational arena, even after C2 Network Systems have been deployed in the same general area. Therefore, by policy, a dynamic spectrum assignment system should provide equal and equitable access to all qualified PTP and C2 systems, even if this means sub-banding or segregation of the spectrum to provide fixed allocations to certain C2 system categories, such as the ad hoc PTP systems.

4.1.4 Link/Mobility Management Issues for PTP and C2 Network Operations

A detailed discussion of mobility management technologies is beyond the scope of this study. It is mentioned because it is vital to providing interoperability among and between different C2 systems, including the ground-to-ground networks interconnecting the UAS RS and GCS. Suitable standards should be developed as soon possible to forestall significant problems in the near- to mid-term future in the implementation of viable C2 Network systems into the NAS.

As already noted, because the Phase 1 version of the SC-228 CNPC MOPS is not addressing interoperability, there are not any proposed requirements addressing protocol layers above the Physical Layer and parts of the Link layer\textsuperscript{26}. Therefore draft standards for link management (i.e. Link Layer requirements) have not been developed, and functions such as mobility management, including handoffs are undefined\textsuperscript{27}. These are being left up to the UAS C2 designer/integrator in the interest of providing flexibility in designs. This may come, however, at the expense of lack of interoperability between implementations using the same radio system.

4.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability

Based on an assessment of three possible coverage prediction models to be used for this study, the Viewshed coverage model was selected for this study because:

- It is simplest to set up and implement
- It provides excellent first order coverage estimation for most situations, i.e. those regions with both LOS and link closure and cases with neither LOS or link closure.

For an implementation project, the other models (CRC-Predict and the 3D Ray Tracing Model) would be used as required for coverage and site selection optimization, to validate the Viewshed estimates and to accommodate the marginal cases

\textsuperscript{26} The Class 1 radio mentioned above does have some of the MAC defined/specified, e.g. in its Time Division Multiple Access (TDMA) uplink option.

\textsuperscript{27} The developers of the Class 1 radio are developing and testing Link Layer and Network Layer capabilities; however, these are not planned to be required, and will not result in normative requirements in the current version of the MOPS. It is expected that informative material describing these capabilities will be provided in a non-normative MOPS appendix to provide design guidance to UAS integrators that plan to deploy systems with the Class 1 radio.
Sites selected for this study fell into several categories of available sites:

- Pump Stations (12 sites)
- AT&T sites\textsuperscript{28} (24)
- SBSS ADS-B (8)
- FCC tower database listed sites (141)
- GCI identified sites (92)

From the pool of possible RS sites listed above, an initial set of 57 sites was identified as the most suitable for providing best TAPS ROW coverage along its total length. This represents coverage for the baseline PTP C2 system coverage case. Sites with the closest proximity to the pipeline and with some infrastructure, especially an existing tower, were given priority for selection. In addition, the Pump Station sites are assumed to be telco and power equipped and present a better recurring cost case than other sites that would have to be leased. The GCI fiber optic network drop sites mentioned above were not included in the initial 57 selected sites because they do not include wireless infrastructure and are typically at low elevations (i.e. near the pipeline).

The problem is to select the fewest sites while providing the maximum coverage, for the flight altitudes of interest. Without an efficient site optimization process, given the large number of potential site locations, it can be very difficult and time consuming to select an optimized set of sites providing the required coverage. We performed site optimization using an efficient linear programming approach.

It was found that with the initially evaluated 57 available site locations it is not possible to approach 100% coverage along the entire pipeline until reaching altitudes of about 1000 ft. or greater. For 100 foot coverage, the best that can be achieved with that set of RS sites is about 83 percent coverage.

Optimizing over an additional 92 sites, it was found that more than 91 percent pipeline coverage at 100 ft. AGL could be achieved, but would require 61 sites.

For those areas of the pipeline route with inadequate coverage several alternatives or combinations of alternatives may be considered:

- Increase the height of the existing towers proposed at the pump stations; however, increasing tower height is more costly, more difficult, and increases risk to air navigation (manned and unmanned)
- Provide pipeline surveillance coverage with manned aircraft for those inadequate UAS coverage areas of the ROW, which could later be augmented by UAS coverage enabled by SATCOM C2

\textsuperscript{28} The existing VHF radio system infrastructure used by Alyeska for maintenance personnel and originally thought to be owned by Alyeska is actually part of a leased service provided by AT&T. Some of these 24 sites also are used for providing radio coverage of the Dalton Highway to other end users.
- Provide unmanned surveillance at a higher altitude, then deploy manned aircraft to provide inspection at lower altitudes only as needed to perform closer checks on potential areas spotted at the higher altitude.

- Deploy unmanned aircraft C2 “repeaters” at pump sites (which is outside of the current TOR for RTCA SC-228).

Because this study is consistent with the current RTCA SC-228 Pilot-in-the-Loop (PITL) UA control assumption, the alternative of allowing for autonomous UA operations over those pipeline sections without RS coverage was not considered.

Our optimization example optimized for minimum overlap and maximum total coverage, mainly in the interest of requiring the fewest sites and hence reducing costs. This leads to significant areas along the pipeline with no redundancy, which might not be the ideal case for purposes of efficient handoffs. In an actual design and implementation, further optimization would be required to balance among the competing goals of reducing interference, minimizing RS site costs, and providing sufficient overlap for the handoff process.

Providing Hybrid or Network operational capabilities to augment the coverage provided for the baseline PTP C2 system in supporting the core TAPS scenario and operational needs would require the addition of:

- New multi-frequency/channel RS to provide additional coverage in areas of interest outside the TAPS ROW.
- Upgrades to existing sites to provide multi-frequency/channel capabilities.
- Appropriate network interconnectivity to support these other changes.

To provide additional coverage for a Hybrid case, which assumes that the PTP infrastructure is already in place and operational, the new sites would have to be selected to provide the new coverage in the coverage areas most beneficial to the planned, expanded set of end users, while striving to minimize cost risks in selecting new sites. Using Exelis as an example of an existing NAS service provider with existing critical SBS/ADS-B infrastructure already in place in Alaska, it would be logical to consider leveraging existing (and planned) SBS RS to provide the expanded coverage for Hybrid operational services.

4.3 Task 3: Business/Financial Assessment - Infrastructure Business Models

An assessment of the C2 business model viability was performed. The C2 service provider costs were estimated by leveraging comprehensive communications system cost models to estimate capital costs (radio equipment, towers, power, etc.), NRC (site setup, civil works, licensing, etc.), and recurring costs (tower leases, networks, O&M, utilities, etc.). The infrastructure costs for various optimized coverage at multiple altitudes is presented in Tables 14 and 15. The total C2 costs were calculated over a 20 year life cycle, with capital investment incurred in the first year and MRC for each year after as shown in Figure 28.

---

29 This assumes that the expanded, point-to-multipoint coverage would be provided to new end users on a non-interference basis with the existing, baseline TAPS PTP end users.
An estimate of operations and flight hours is provided with variable per flight hour fees used to calculate possible ROI. The total C2 flight hours for Alyeska is estimated at 1,300 per year, and the total C2 flight hours for all users is estimated at 7,720 per year.

From these estimates, an ROI with a $200 per flight hour fee and cumulative costs based on the 1000ft and 500ft infrastructure appears plausible (Figure 31). A C2 infrastructure solely for Alyeska use does not appear to be cost effective, and even with all users the per flight hour fee to enable a return on investment may be too costly for the market to bear for a C2 infrastructure to cover 100ft AGL along the entire pipeline. These ROM estimates are very dependent on actual number of flight hours per year, spreading initial NRC over multiple years, and net present value of money (which was not considered). A $200 per hour fee is relatively high compared to the approximately $200 per flight hour operational cost of flying a UAV without the C2 link. However, a total operational cost of $400 per hour (operational and C2 link) is not unreasonable as compared to the $1000 per hour manned helicopter cost.

Consideration should be made for the expansion of the C2 infrastructure to include additional services or to accommodate other end users, but which does not significantly increase the C2 infrastructure costs (e.g. a Hybrid C2 system). This could add substantial value to the use of the service. For example, Alyeska has a desire for real-time video during pipeline monitoring and during spill response events. Lastly, more analysis is needed for the C2 business models to include additional tradeoffs across technical, operational, policy, and business considerations as those are better defined.

4.4  Task 4: Regulatory Assessment - Governance & Accountability

4.4.1  Operational System Safety

A full operational safety analysis is beyond the scope of this study. The following includes a brief discussion of the UAS safety analysis process conducted in the context of the FAA’s Safety Management Process, some safety relevant UAS C2 infrastructure design considerations, and some aspects of a very high level and preliminary safety analysis.

To determine the safety implications of potential UAS operations, the risk assessment methodology from FAA’s Safety Management System (SMS) is to be used. The overarching objective in safety risk management is to ensure that hazards in the UAS are controlled or mitigated to an acceptable level of risk, thereby reducing the accident rate.

Three major system safety concerns for UAS C2 system infrastructure assurance for both C2 system approaches, are the link availability, latency, and integrity performance parameters.

A Preliminary Safety Assessment was initiated based on identified Environmental Conditions, Metrological Conditions, UAS Flight Phases, and Emergency Environmental Conditions, which resulted in a set of failure conditions, their associated failure effects, severity and rationale. From the severity assessment, the corresponding likelihood requirement was defined based on FAA’s safety matrix. The list of failures is by no means comprehensive and should be considered as preliminary only.

A formal Preliminary Hazard Assessment (PHA) adherent to FAA’s SMS methodology should expand the list of failure conditions to make it as comprehensive as possible. Additionally, the UAS Environmental Conditions, Meteorological Environmental Conditions, Flight Phases, and Emergency Environmental Conditions, already listed, will be examined thoroughly to include all
additional possible scenarios. Following the PHA, Subsystem Hazard Analysis, System Hazard Analysis, Operations and Support Hazard Analysis, and System Safety Assessment Report would be the next tasks performed for a formal Safety Risk Management Documents process conformant to FAA’s SMS.

4.4.2 Aspects of C2 System Certification

The FAA’s Small Airplane Directorate has been a visible force for FAA UAS certification efforts, and has provided RTCA SC-228 WG2 an excellent overview of the UAS certification process and issues.

The C2 systems that are the focus of this study are just one piece of the total UAS that would get type certified to operate in the NAS, as just described. One of the intended uses of the CNPC MOPS being developed by RTCA SC-228 WG is to provide a basis for a UAS radio system Technical Standard Order (TSO).

The motivation for doing this is that a UAS integrator may select a UAS radio system for which a TSO has been issued because it is expected that this could speed up the UAS certification process – the C2 radio built to that standard is recognized by the FAA certification community. Use of this radio does not relieve the burden on the UAS integrator to prove to the FAA that UAS using that C2 radio is safe and meets all applicable requirements for certification.

An important question to ask is: where does a potential UAS C2 service provider fit into the UAS certification process, in other words, what is the process for certification if the UA platform and GCS comes from one source and the C2 services come from a different source? The answer to that question is not clear at this time. Even with TSO authorized C2 radio system (two radios and a C2 link), there are other elements comprising C2 end-to-end services (as shown in Figure 4 and Figure 5) that would need to be considered for UAS certification.

Two general observations regarding relative certification issues/problems for PTP and Network C2 system can be made at this time:

- The certification process for UAS provided as a service and composed of constituent services, such as C2 service and DAA service, from multiple sources needs to be better understood.

- A PTP C2 system deployed as part of a turnkey, owner/operator UAS service/system may face a less complex certification challenge because the UA type, C2 radio type, GCS, etc. and operational areas/applications will be limited in scope compared to the situation faced by a potential C2 Network service provider that may want to provide C2 services for a broad range of UA platforms, end users, and operational applications.

4.4.3 UAS C2 Performance Monitoring for Accountability Assurance

For this study, we conducted an initial iteration of the selection of the appropriate measurement data parameters, based on early but ongoing efforts in RTCA SC-228 WG2 to identify appropriate parameters suitable for both C2 PTP and Network C2 Systems. Using criteria by Exelis to evaluate suitability of potential measurement data parameters, we have performed a highly preliminary comparative assessment, mainly to illustrate the process, of several PTP and Networked C2 performance monitoring requirements. Because the candidate parameters are still being identified in RTCA SC-228 WG2, the assessment is not complete.
5.0 RECOMMENDATIONS

5.1 Task 1: Operational Assessment - End-to-End BLOS UAS Flights

Based on the conclusions stated in Section 4, we make the following recommendations for this Task:

1. Policy decisions based on PTP and Network C2 Systems as separate and distinct classes should be discouraged because PTP, Hybrid, and Network C2 systems can be viewed as three stages in an operational continuum of the same basic C2 architecture and infrastructure. Maintaining the PTP (or “Standalone”) vs. Network distinction has been unnecessarily polarizing, especially in the technical standards community.

2. Both ad hoc and fixed PTP C2 systems should always be accommodated in the UAS operational arena, even after C2 network systems have been deployed in the same general area. Therefore, by policy, a dynamic spectrum assignment system should provide equal and equitable access to all qualified PTP and C2 systems, even if this means sub-banding or segregation of the spectrum to provide fixed allocations to certain C2 system categories, such as the ad hoc PTP systems.

3. The Titania Spectrum Management report sponsored by the FAA should be provided to RTCA SC-228 WG2. This would promote a more common level of understanding of the UAS regulatory environment among that group and would be of great value in informing the discussions of WG2 subgroups such as the Dynamic Spectrum Assignment subgroup.

4. Because lack of UAS C2 technical interoperability standards (at the appropriate protocol layers) presents a serious impediment to the widespread and harmonious implementation of UAS C2 systems and associated spectrum allocations/assignment processes, these should be given a higher priority in future standards development activities. This should include consideration of changing the Phase 2 Terms of Reference for RTCA SC-228 WG2.

5.2 Task 2: Technical Assessment - Infrastructure Requirements & Availability

We make the following recommendations for this Task:

1. UAS C2 system infrastructures should be implemented using radio systems based on accepted aeronautical standards, such as RTCA MOPS, as these typically lead to a more straightforward FAA certification path. Likewise, C2 system implementations should be compliant with relevant ITU-R recommendations.

2. A detailed site/coverage selection process optimizing for both performance and costs, such as that outlined in Section 3.2.1.6, should be used for planning UAS PTP, Hybrid and Network C2 radio systems with multiple, fixed RS infrastructure. The process provided in Section 3.2.1.6 is scalable for larger coverage regions, and could be extended for UAS C2 systems providing nation-wide coverage.

3. Because austere, challenging terrain areas such as Alaska drive up the number of required RS for providing low altitude coverage over an extended coverage range, consideration should be made for installing Hybrid or Network capable infrastructure (e.g. multichannel radios) at selected RS to offer increased flexibility, capacity and potential revenue capabilities to offset the relatively high capital costs.

4. Because of the safety critical nature of the services provided over UAS C2 radio system links, these systems should be designed to meet Required Link Performance...
values for availability, latency, and integrity consistent with FAA systems providing NAS critical services.

5.3 Task 3: Business/Financial Assessment - Infrastructure Business Models

We make the following recommendations for this Task:

1. Additional analysis should be performed for the C2 business models to include additional tradeoffs across technical, operational, policy, and business considerations as those considerations become more defined. There are multiple unknowns that are apparent in these business models such as cost and management of C2 radio spectrum, the regulatory environment for BLOS UAS operations, technology acceptance by regulators, and ultimately the perception of risk with adopting new UAS technology.

2. This analysis is highly dependent on ROM estimates of UA flight hours utilizing the C2 link. It is recommended that additional analysis and modeling of flight hours be performed, as they are expected to ramp up over the proposed 20 year life cycle.

3. Consideration of the C2 infrastructure should include additional services (e.g., payload data) that do not markedly increase the C2 infrastructure costs, but can add substantial value to the use of the service.

4. This analysis is specific to the TAPS use case, including the need for dedicated on-call manned helicopters for spill response and generally higher infrastructure costs. Additional analysis should be performed as applied to pipeline use cases in the continental United States (CONUS) with possible higher replacement of manned aircraft flight hours with UA operations, typically lower infrastructure costs, and costs spread across more users and flight hours.

5.4 Task 4: Regulatory Assessment - Governance & Accountability

We make the following recommendations for this Task:

1. UAS C2 system safety assessments should be consistent with the FAA’s Safety Management System (SMS) to facilitate the certification process.

2. Additional clarification is needed from the FAA on the process for certifying a UAS composed of facilities, equipment, and potentially services provided by multiple sources.

3. Exelis recommends that UAS C2 system implement a technical performance monitoring (TPM) system using a methodical process similar to the presented approach to ensure selection of appropriate measurement data parameters.
# APPENDIX A - LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Advisory Circular</td>
</tr>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>ACUASI</td>
<td>Alaska Center for Unmanned Aircraft Systems Integration</td>
</tr>
<tr>
<td>ADS</td>
<td>Automatics Dependent Surveillance</td>
</tr>
<tr>
<td>AGL</td>
<td>Above Ground Level</td>
</tr>
<tr>
<td>AM(R)S</td>
<td>Aeronautical Mobile (Route) Service</td>
</tr>
<tr>
<td>ASOR</td>
<td>Allocation of Safety Objectives and Requirements</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>ATS</td>
<td>Air Traffic Services</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
</tr>
<tr>
<td>BLM</td>
<td>Bureau of Land Management</td>
</tr>
<tr>
<td>BLOS</td>
<td>Beyond Line of Sight</td>
</tr>
<tr>
<td>C2</td>
<td>Command and Control</td>
</tr>
<tr>
<td>CNPC</td>
<td>Control and Non Payload Communications</td>
</tr>
<tr>
<td>COA</td>
<td>Certificate of Waiver or Authorization</td>
</tr>
<tr>
<td>CONUS</td>
<td>Continental United States</td>
</tr>
<tr>
<td>DAA</td>
<td>Detect and Avoid</td>
</tr>
<tr>
<td>DC</td>
<td>District of Columbia</td>
</tr>
<tr>
<td>DO</td>
<td>Delivery Order?????</td>
</tr>
<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DOT</td>
<td>Department of Transportation</td>
</tr>
<tr>
<td>DWG</td>
<td>Drawing</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>GCS</td>
<td>Ground Control Station</td>
</tr>
<tr>
<td>GHz</td>
<td>Giga-Hertz</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating, Ventilation and Air Conditioning</td>
</tr>
<tr>
<td>IAF</td>
<td>Initial Approach Fix</td>
</tr>
<tr>
<td>IFR</td>
<td>Instrument Flight Rules</td>
</tr>
<tr>
<td>IMC</td>
<td>Instrument Meteorological Conditions</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>ITU</td>
<td>International Telecommunication Union</td>
</tr>
<tr>
<td>KHz</td>
<td>Kilohertz</td>
</tr>
<tr>
<td>LIDAR</td>
<td>Light Detection And Ranging</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of Sight</td>
</tr>
<tr>
<td>LP</td>
<td>Linear Programming</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Layer</td>
</tr>
<tr>
<td>MHz</td>
<td>MegaHertz</td>
</tr>
<tr>
<td>MOPS</td>
<td>Minimum Operational Performance Standards</td>
</tr>
<tr>
<td>MTBF</td>
<td>Mean Time Between Failure</td>
</tr>
<tr>
<td>NAS</td>
<td>National Airspace System</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NRC</td>
<td>Non Recurring Costs</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Meaning</td>
</tr>
<tr>
<td>--------------</td>
<td>---------</td>
</tr>
<tr>
<td>NTIA</td>
<td>National Telecommunications and Information Administration</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operations and Maintenance</td>
</tr>
<tr>
<td>OPA</td>
<td>Optionally Piloted Aircraft</td>
</tr>
<tr>
<td>PHA</td>
<td>Preliminary Hazard Assessment</td>
</tr>
<tr>
<td>PHMSA</td>
<td>Pipeline &amp; Hazardous Materials Safety Administration</td>
</tr>
<tr>
<td>PIC</td>
<td>Pilot in Command</td>
</tr>
<tr>
<td>PTP</td>
<td>Point-to-Point</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RLOS</td>
<td>Radio Line Of Sight</td>
</tr>
<tr>
<td>ROI</td>
<td>Return on Investment</td>
</tr>
<tr>
<td>ROM</td>
<td>Rough Order of Magnitude</td>
</tr>
<tr>
<td>RS</td>
<td>Radio Station</td>
</tr>
<tr>
<td>RSG</td>
<td>Regular Square Grid</td>
</tr>
<tr>
<td>SATCOM</td>
<td>Satellite Communications</td>
</tr>
<tr>
<td>SBS</td>
<td>Surveillance and Broadcast Services</td>
</tr>
<tr>
<td>SMS</td>
<td>Safety Management System</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>SSH</td>
<td>System Safety Handbook</td>
</tr>
<tr>
<td>SV</td>
<td>Service Volume</td>
</tr>
<tr>
<td>TAPS</td>
<td>Trans-Alaska Pipeline System</td>
</tr>
<tr>
<td>TBD</td>
<td>To Be Determined</td>
</tr>
<tr>
<td>TC</td>
<td>Type Certificate</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TIN</td>
<td>Triangulated Irregular Network</td>
</tr>
<tr>
<td>TOR</td>
<td>Terms of Reference</td>
</tr>
<tr>
<td>TPM</td>
<td>Technical Performance Monitoring</td>
</tr>
<tr>
<td>TSO</td>
<td>Technical Standard Order</td>
</tr>
<tr>
<td>TWR</td>
<td>Tower</td>
</tr>
<tr>
<td>UA</td>
<td>Unmanned Aircraft</td>
</tr>
<tr>
<td>UAF</td>
<td>University of Alaska Fairbanks</td>
</tr>
<tr>
<td>UAS</td>
<td>Unmanned Aircraft System</td>
</tr>
<tr>
<td>US</td>
<td>United States</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>VDL</td>
<td>VHF Digital Link</td>
</tr>
<tr>
<td>VFR</td>
<td>Visual Flight Rules</td>
</tr>
<tr>
<td>VHF</td>
<td>Very High Frequency</td>
</tr>
<tr>
<td>VMC</td>
<td>Visual Meteorological Conditions</td>
</tr>
<tr>
<td>WAM</td>
<td>Wide Area Multilateration</td>
</tr>
<tr>
<td>WG</td>
<td>Working Group</td>
</tr>
</tbody>
</table>