TRI-SERVICE C-BAND ROADMAP STUDY (TSCRS) FINDINGS and WAY AHEAD

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ABSTRACT

The purpose of the Tri-Service C-Band Roadmap Study (TSCRS) is to identify technology gaps and shortfalls associated with aeronautical mobile telemetry operations utilizing the 4400 to 5150MHz frequency band (C-Band). The goal of this study is to provide the information needed by the military services to generate an investment strategy to develop C-Band telemetry capabilities.

This paper discusses TSCRS findings. Specifically, C-Band telemetry "gaps" related to operations on ground stations and in test articles are covered. The paper addresses key C-Band telemetry challenges across mission domains and provides a quick look at the DoD investment strategy for maturing technologies relative to these challenges.

INTRODUCTION

The Tri-Service C-Band Roadmap Study (TSCRS) was launched by the Test Resource Management Center (TRMC) in June 2012. The objective of the study was to identify the technology gaps and shortfalls associated with Aeronautical Mobile Telemetry (AMT) operations utilizing the C-Bands. The basic goal was to provide the information needed by the military services to develop an investment strategy to develop C-Band telemetry (TM) capability with the same reliability as current L-Band and S-Band systems.

The TSCRS study space was divided into four (4) mission areas or *domains*. These are: a) Air-to-Air/Air-to-Surface Weapons, b) Surface-to-Air/Surface-to-Surface Missiles, c) Surface Weapons and Systems, and d) Aircraft TM. Table 1 shows the major test article categories that were assigned to each TSCRS domain. The study effort was conducted in two phases. Phase I (Mission Characterization/Requirements Definition phase) produced four "Requirements" Reports (one per domain). These reports characterize the mission environment of systems in each domain. Data is based on inputs provided by subject matter experts (SME) at several test ranges across three services. The reports also characterize the mission environment of ground tracking systems and discuss challenges associated with basic TM operations. Phase II efforts included a Gap Analysis, which then produced C-Band technology gaps (shortfalls). These gaps fall into one of two categories (Test Article or Ground Station) and may represent a technology shortfall, an information gap, or a lack of equipment. Relevant systems on the Test Article Side include transmitters/transceivers, antennas, and cabling. On the Ground Station Side, the relevant systems include, but are not limited to receivers, antennas, and towers.

This study was conducted by a government-only team with the assistance of government support contractors and SMEs. However, industry and government representatives met in May 2013 at a TSCRS project sponsored C-Band Telemetry Technical Interchange Meeting/Industry Day in Fort Walton Beach, FL. This one day session was the first to involve industry and contributed toward the generation of the Test Article and Ground Station gaps to be discussed in this paper.

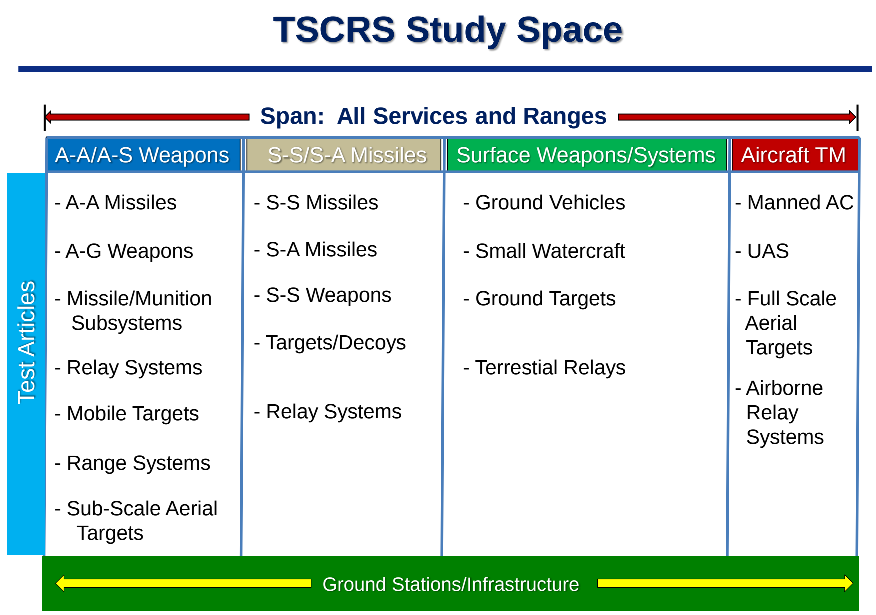

Table 1 – TSCRS Study Space

DISCUSSION

Figure 1 shows the TSCRS project at a glance. In this view, the phased, but overlapping approach can be seen. The Gap Analysis work produced the gaps and shortfalls that are the focus of this paper. This was accomplished by a) Assessing current C-Band TM capabilities, b) comparing those capabilities to what is needed on a system by system basis within a mission domain, and c) then identifying shortfalls. In total, eighteen (18) distinct gaps were identified by the TSCRS team. The generation of many of these gaps was facilitated by the 15 May 2013 C-Band TM Technical Interchange Meeting/Industry Day held in Ft. Walton Beach, Florida. During this event, two breakout sessions were held (one for Test Articles, one for Ground Stations) before re-convening as a larger government and industry group. To set the stage for technical discussion, the reference diagrams shown in Figures 2 and 3 were used. These diagrams show the interaction between the constraints and characteristics of a modern telemetry transmitting and receiving system.

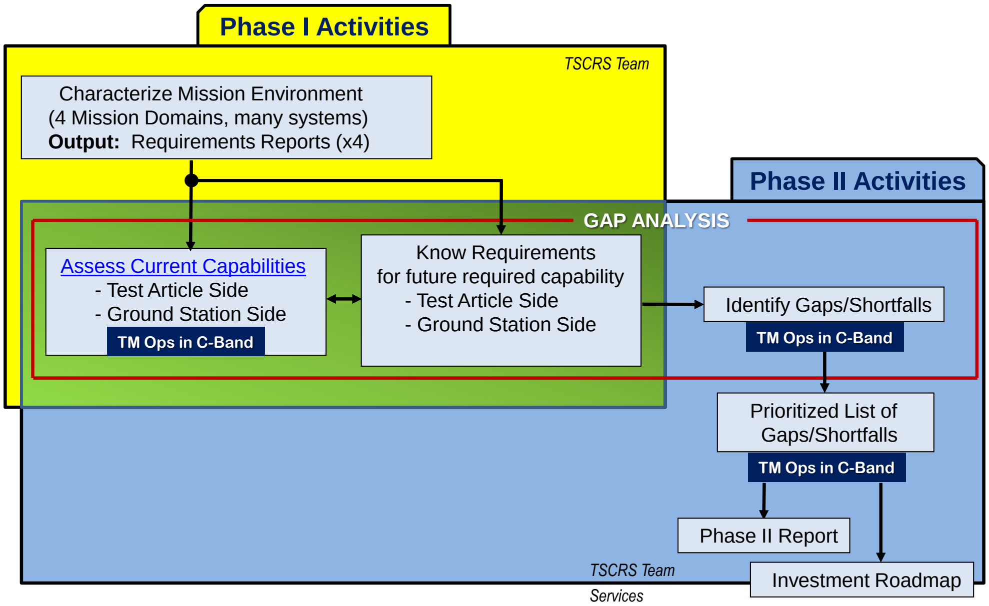

Figure 1 – TSCRS Project at a Glance

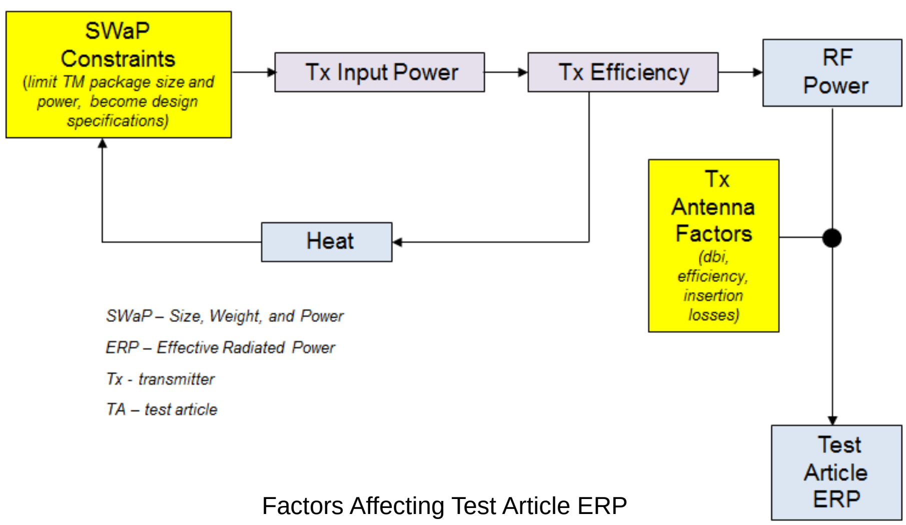

Figure 2 – Telemetry Functionality – Test Article Side

On a test article, the primary radio frequency (RF) parameter that impacts the quality of the telemetry data is the Effective Radiated Power (ERP) or the power of the RF signal that is radiated from the article toward the ground station. Factors that influence test article (TA) ERP include Size, Weight, and Power (SWaP) constraints, cabling and connector losses, and antenna losses. The efficiency of the transmitter determines how much energy is converted into RF signal. The lower the transmitter efficiency, the less RF signal will be produced by the transmitter and the more heat will be generated. This heat will then need to be dissipated by the TA. This could mean adding an active cooling system or a large heat sink. Adding these components may detract from the volume and power available for the transmitter itself.

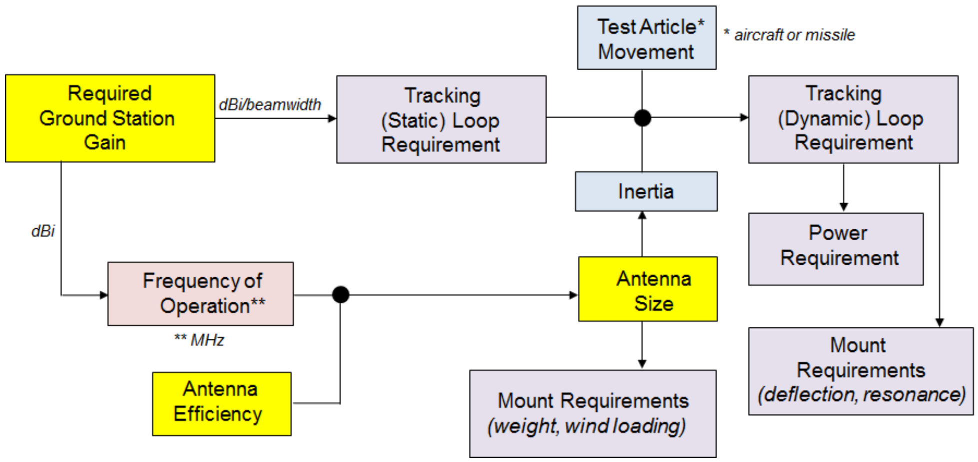

Figure 3 – Telemetry Functionality – Ground Station Side

Per Figure 3, TM ground station design is determined by the ground station gain required to produce quality data from TM received from the test article. Ground station gain, commonly expressed in dBi, is primarily impacted by altering the antenna pattern directionality (beamwidth). Another way to visualize RF directionality is to think of it as using a telephoto lens to zoom in on an image. The image becomes larger but the field of view is reduced. The gain and beamwidth have separate but related impacts on the effectiveness of a telemetry ground station.

The ground station gain requirement is combined with the operation frequency and the overall antenna efficiency to yield the antenna physical size requirement. For a given antenna diameter, as the frequency increases the gain and directionality increases proportionally. Generally, as frequency increases, the efficiency of the antenna slightly decreases, although this is not a first order effect. The antenna physical size determines the static antenna mounting requirements such as weight and wind loading. The physical size of the antenna also determines the moments of inertia that will be used in designing the antenna movement or tracking control loops.

A second offshoot of the ground station gain requirement comes from the by-product of antenna directionality. An increase in directionality that yields a higher gain decreases the antenna beamwidth. Decreasing the antenna beamwidth effectively reduces the margin for error that the control system has for pointing the antenna. The antenna control system must be able to point the antenna with greater accuracy to receive the signal from a transmitter. The requirement of the antenna to accurately point the antenna at a stationary target is identified as the antenna static pointing requirement.

The antenna static pointing ability, combined with the movement of the target, and the antenna moments of inertia, yield the antenna control system dynamic requirements. The antenna control system must be able to remain pointed at a test article that is moving in relation to the ground system. Increases in the antenna size increase the moment of inertia and can limit or, at a minimum, will affect the ability of the control system to keep the antenna pointed at a moving target. These control requirements set the dynamic antenna mounting requirements such as deflection and resonance. Additionally the power requirements for the antenna system are determined by the required size and dynamic tracking requirements of the antenna.

There is significant coupling between the constraints and parameters of the ground station. Due to this coupling any one of the identified parameters may become a limiting factor for ground station performance. For example, if the antenna mount is extremely flexible, it will limit the ability of the antenna control system to effectively and predictably move the antenna. This will in turn place limits on the movement of the target, the beamwidth of the antenna, or the antenna moments of inertia. Restricting the antenna beamwidth and moments of inertia will limit the gain the system is able to produce.

C-BAND TELEMETRY GAPS IDENTIFIED BY THE TSCRS PROJECT

As a result of the Gap Analysis work performed by the TSCRS project team, a total of eighteen (18) gaps were identified. Ten of the eighteen were associated with ground stations. The following tables list short descriptions of these gaps.

Test Article Gaps – Short Descriptions

(Numerical Order, Not Prioritized)

Gap ID	Gap Title	Technical Gap	S&T Needed ?
TA-01	Small C-Band Telemetry Antennas	Inability to conduct C-Band TM operations on small test articles such as artillery, hand launched UAVs, and SUGVs	Yes
TA-02	Power Efficient C-Band Telemetry Transmitters	Inability to conduct C-Band TM operations on test articles such as missiles*, artillery shells, hand launched UAVs, and SUGVs * - A-A/A-S and S-S/S-A	Yes
TA-03	Uplink C-Band Interference Uncertainty	Uncertainty of potential for test article TM to experience interference from satellite uplink signals	Potentially
TA-04	Multi-Band Telemetry Antenna Performance Uncertainty	Lack of test data to assess multi-band TM antenna performance on a wide range of test articles	Yes
TA-05	Power Efficient Multi-Band Telemetry Transmitters	Inability to conduct multi-band TM operations on challenging test articles	Yes

* - Air-to-Air/Air-to-Surface and Surface-to-Surface/Surface-to-Air

Table 2 – TSCRS Test Article Gaps

Gap ID	Gap Title	Technical Gap	S&T Needed ?
TA-06	Target Scoring System Downlink	Inability to conduct C-Band TM operations (downlink)	No
TA-07	High Altitude C-Band Antenna Performance Uncertainty	Inability to quantify the effects of coronal discharge on C-Band TM operations on test articles such as S-S and S-A missiles	No
TA-08	Miniaturized, Efficient Batteries	Inability of test articles to provide required levels of power for TM operations in C-Band	Yes

Table 2 – TSCRS Test Article Gaps (cont'd)

Ground Station Gaps – Short Descriptions

(Numerical Order, Not Prioritized)

Gap ID	Gap Title	Technical Gap	S&T Needed ?
GS-01	C-Band Interference	Inability to mitigate interference issues between telemetry ground stations and certain in-band systems which may operate in close proximity (i.e.: threat simulators, TSPI radar)	Yes
GS-02	Antenna Pointing Capability Assessment	Inability to verify dynamic tracking performance of ground antennas operating in C-Band.	Yes
GS-03	Acquisition/Re-Acquisition	Legacy Acquisition aids lack the accuracy to support C-band tracking.	Yes
GS-04	Small Medium Gain Multi-Band Antennas	Lack of commercially available multi-band tracking antennas to support low dynamic ground vehicle applications.	Yes
GS-05	Radome Wide Frequency Transparency	Lack of radome designs capable of supporting multi-band TM operations.	Yes

Table 3 – TSCRS Ground Station Gaps

Gap ID	Gap Title	Technical Gap	S&T Needed ?
GS-06	Antenna Pointing Accuracy	Inability to accurately point existing ground antennas when operating in C-Band. Control systems used in current L and S Band tracking antennas are not accurate enough	Yes
GS-07	Interface Acceptability Assessment	Uncertainty of the suitability of legacy system interface protocols to support decreased system tolerances (as in C-Band operation)	Potentially
GS-08	Antenna Geometry Measurement Techniques	Need for antenna geometry measurement tools and techniques for ground antennas operating in C-band.	No
GS-09	Antenna Efficiency Improvements	Need for smaller tracking antennas with gain and tracking performance similar to larger reflectors.	Yes
GS-10	Uplink Interference in C-Band	Need for algorithms and system changes that prevent ground antennas from interfering with satellite links	Yes

Table 3 – TSCRS Ground Station Gaps (cont'd)

The gaps shown may represent a technology shortfall, an information gap, or a lack of equipment. The tables also give an indication as to whether Science and Technology (S&T) work is required to advance the Technology Readiness Level (TRL) or mature a relevant technology. The relevant TRL range for S&T work is TRL 3 (analytical and experimental critical function and/or characteristic proof of concept) to TRL 6 (system/subsystem model or prototype demonstrated in a relevant environment). The following provides additional detail on the presented gaps:

1) **Small C-Band Telemetry Antennas (TA-01**): This need pertains to C-Band (only) telemetry antennas that reside on the test article. Telemetry antennas on test articles are typically of the following configurations: a) blade, b) conformal (to include wrap-around designs), and c) button. The DoD test community requires C-Band (only) TM antennas that are capable of meeting mission needs of systems in each of the four TSCRS mission domains. Stressing systems include air-to-air missiles, artillery shells, hand-launched UAVs and SUGVs.

2) **Power Efficient C-Band TM Transmitters (TA-02):** This need pertains to C-Band (only) telemetry transmitters used in test articles. The DoD test community requires transmitters that are capable of meeting mission needs of systems in each of the four TSCRS mission domains. C-Band transmitters which exhibit form, fit, function, efficiency, and power output comparable to existing L and S-Band transmitters are required. Stressing systems include air-to-air and surface-to-air missiles, artillery shells,

hand-launched UAVs and Small Unmanned Ground Vehicles (SUGV). Development challenge: New power efficient TM architectures which are based on the use of amplifier transistors operating at higher DC voltages.

3) **Uplink C-Band Interference Uncertainty (TA-03):** There is currently a prohibition on telemetry uplink in the Middle C-Band (5091 - 5150 MHz), imposed at the World Radio-communication Conference 2007 (WRC-07), due to risk of interference with satellite vehicles. Some ranges foresee a need to operate a telemetry network system (TmNS) in the Middle C-Band, thereby necessitating a need to find ways to safely share the band. One proposed solution may be in the form of an agreement between the DoD and satellite vehicles to share the Middle C-Band. If an agreement to share this portion of the Middle C-Band can be achieved, the potential exists that Network Telemetry uplinks to test articles will experience interference from ground-based transmitters such as satellite vehicle ground stations transmitting to orbiting satellites. Interference analyses will be required to determine the impact of satellite vehicles and other ground transmitters on the performance of C-Band transmitters.

4) **Multi-Band Antenna Performance Uncertainty (TA-04)**: There is currently a lack of multi-band antenna test data to make a determination of performance compared to dedicated, single-band antennas. Thus far, multi-band (L, S & C) antennas tested have not provided performance comparable to single-band antennas. Recommended actions are to a) procure additional representative samples of multi-band antennas, and b) conduct further investigations and flight testing required to evaluate the RF performance of samples and determine the viability of use.

5) **Power Efficient Multi-Band Telemetry Transmitters (TA-05):** There is a need for multi-band (L, S, and C) transmitters which can deliver comparable performance across the bands. Existing power transistor technology may be the limiting factor.

6) **Target Scoring System Downlink (TA-06):** For full scale and sub-scale aerial targets, a C-Band TM downlink will be needed in the future to send scoring information to ground stations. This function is currently performed with an L/S Band TM downlink.

7) **High Altitude Antenna Performance Uncertainty (TA-07):** This need pertains to the requirement to understand the coronal effects due to C-Band RF and antenna systems (wrap and otherwise) when installed in high altitude vehicles (rockets, sounding rockets, and target vehicles) capable of ionospheric and exo-ionospheric flight. The need centers on the effective design of these RF and antenna systems to avoid coronal discharge effects observed previously in L/S Band in designs. Some of the recommended actions include: a) Study and investigate historical coronal effects encountered at L and S Bands during testing; document findings including root causes, b) Perform analysis of potential coronal effects as a result of C-Band operations to quantify potential effects, c) Conduct high altitude chamber testing to investigate coronal effects at L, S, and C-Bands.

8) **Miniaturized, Efficient Batteries (TA-08):** The relevant technology gap is a need for advanced energy and power systems which support weapon system and other test article

instrumentation applications. Key technical parameters are: Higher Power density for a given physical size, miniaturization, and resistance to vibration and shock environments. Safety and low temperature operation are also key requirements. For example, for systems that incorporate a flight termination system (FTS), the telemetry and the FTS must have separate dedicated batteries independent from the rest of the missile.

9) **C-Band Interference (GS-01):** This need pertains to the mitigation of interference issues that have been noticed when certain systems operate in proximity to C-Band telemetry ground stations. This is expected to be a significant issue when integrated testing using threat simulators or TSPI radar is conducted. These devices are much higher in power than a telemetry transmitter and have a great potential to drown out the telemetry signal. Current indications are that there is a high potential for in-band interference at levels that may cause permanent damage to telemetry RF reception components. Ground stations require the means to mitigate the effects of high power signals in C-Band and adjacent frequencies as these pose a significant risk of harmful and damaging interference.

10) **Antenna Pointing Capability (GS-02):** Legacy antenna tracking test techniques are not sufficient to assess modern, software controlled antenna systems. This deficiency in the telemetry community will become a significant weakness as systems migrate to the reduced beamwidth of C-Band operations. The T&E community requires means to test the entire antenna system dynamic response and tracking accuracy. Recommendations include a) Modify existing hardware and software for large scale antenna testing. An example of software than be used is the Antenna Track Assessment System (A-TAS) (ref. ITC 2013 13-05-05). A second recommendation is to establish a baseline at several test ranges so that as frequency transitions occur, existing reliability can be retained.

11) **Acquisition/Re-Acquisition (GS-03):** The acquisition of telemetry targets is often one of the more challenging tasks accomplished by a ground station telemetry system. Most telemetry ground stations to date do not retain significant information about the movement of the target so that when a ground station locks on a target there is very little the system can do but begin a blind search for the target. These issues are exaggerated by the reduced beamwidths due to operations at C-Band frequencies. The two primary methods for acquisition of a target can be broken into two categories, external and internal. External acquisition methods consist of using external TSPI sources to provide pointing information to the antenna (slaving). Often the error of the pointing angles provided by these systems is significantly large when compared to the beamwidth of a C-Band telemetry antenna. Internal acquisition methods consist of using a wide beam, low gain antenna to initially acquire the target. The use of these wide beam antennas can be troublesome due to the relatively low gain and difficulty in collimation of the wide beam to the main antenna. It is anticipated that additional development is required to address this gap.

12) **Small, Medium-Gain Multi-Band Antennas (GS-04):** There is currently a lack of commercially available small, medium-gain multi-band antennas. Market research has indicated that at least some antenna manufacturers have designs for 2- 4 ft. multi-band dishes with the major components in hand, but to date, have not actually built any.

Relatively large (6 ft. diameter and up) multi-band ground station telemetry antennas are currently available for L-, S- & C-Bands. However, for many surface vehicle weapons systems tests, ground station antennas in the 2 – 3 ft. diameter range are more suitable. A gain range of approximately 15-25dB is required across the bands. While vendor-supplied antenna design specifications for 2 and 3 ft. dishes indicate performance fairly comparable to existing single-band antennas, actual testing of multi-band antennas in the past has generally shown degraded performance in the lower L-Band. Recommendations include a) development of prototype small, medium gain multi-band ground station antennas, and b) lab characterization/field testing to evaluate performance.

13) **Radome Wide Frequency Transparency (GS-05):** Some receive antenna locations are subject to weather conditions requiring the protection provided by radomes. A well-designed radome provides environmental protection with minimal effect on the RF performance of the antenna for specific frequency bands. From an electrical standpoint, the main concern for the radome is its contribution of insertion loss at specific operational frequencies. Insertion loss degrades the signal, resulting in increased error rate and decreased maximum slant range. Radomes can also increase antenna side lobes, resulting in interference with other communication systems and decreases in overall antenna efficiency. Radomes can also impact antenna polarization schemes by distorting circularly polarized waveforms. Other electrical effects include changes in antenna beamwidth and shifting of the antenna boresight. Although there are very good radome designs available for L/S-Band and very good radome designs for C-Band frequencies, very little work has been accomplished regarding a single radome design that can cover the very wide frequency span from L- to C-Band. Single radome designs that can cover the wide frequency span from L to C-Band and still meet mission requirements are required.

14) **Antenna Pointing (GS-06):** Due to the reduced beamwidth of C-Band antennas, some antenna control system designs are not capable of providing the required level of target tracking capability when operating at C-Band. Although this gap is not currently quantifiably defined (see GS-02), it is assumed the gap is significant enough to warrant innovative tracking techniques. It is likely that, in addition to software modifications, this gap could be addressed by altering the physical RF collection method used. Software advancements could include adoption of advanced control filtering techniques or prediction methods. Hardware advancements could include focusing the antenna pattern to an off boresight angle. Pursuing solutions designed to fill this gap will likely impact other GS gaps.

15) **Interface Acceptability Assessment (GS-07):** The potential of new protocols to enhance the capability of telemetry ground stations is high. The scope of the impact is yet to be determined due to insufficient information regarding the impact of signal conversions and associated delays on antenna sub-system performance. A technical investigation of existing antenna system designs is needed to determine the impact of the retention of legacy protocols on the performance of antenna systems. This investigation would potentially validate a requirement to update these interfaces. Operation in C-Band frequencies further drives this need.

16) **Antenna Geometry Measurement Techniques (GS-08):** Decreased system tolerances are anticipated as a result of C-Band frequency operations. This will require the physical components of the antenna system to be more accurately aligned. For example, a primary source of error in the installation of a system can be the alignment of the feed with respect to the antenna reflector. As with other physical factors, this alignment will become more critical as frequency increases. Potentially, new tools will be needed to properly measure and tune the physical structures of the antennas. This will become particularly critical for larger aperture antennas >12ft. An initial step of surveying existing C-Band antenna systems, combined with an academic assessment of the found variations on antenna performance will determine if additional development is needed in this area.

17) **Antenna Efficiency Improvements (GS-09):** Many of the ground station technical gaps relate to reductions in ground station beamwidths. These concerns stem from an assumption that current antenna physical sizes must be maintained to achieve the required ground station gain. An alternative method for providing this gain would be to increase the efficiency of the antennas. By increasing the efficiency of C-Band antennas, smaller antennas with wider beamwidths could be used in place of large, narrow beamwidth antennas, thereby reducing the majority of tracking and acquisition concerns. Antenna efficiencies are a function of numerous components including resonant elements, reflector coatings, and internal feed electronics. The ability to increase antenna efficiency to a level where a significant impact on antenna size is realized requires advancements in numerous technologies and likely the creation of materials that do not currently exist.

18) **Uplink Interference in C-Band (GS-10):** There are currently regulatory restrictions on AMT uplinks in the Middle C-Band (5091 - 5150 MHz), imposed at the World Radiocommunication Conference 2007 (WRC-07), due to risk of interference with satellite vehicles. Some ranges foresee a need to operate a TmNS in the Middle C-Band, thereby driving a need to find ways to safely share the band. Satellite vehicle communications would then require protection from interference by Network Telemetry uplinks. A topic in the S&T/Spectrum Efficient Technology Broad Agency Announcement (BAA) topic exists.

Additional Notes:

A strong interaction exists between the GS-03 and GS-06 gaps. Both of these gaps exist because of the reduced antenna beamwidth of C-Band frequencies. Historically, telemetry systems have not had to employ exotic techniques to maintain track or acquire targets. With a 50% reduction in beamwidth, it is likely that both acquisition and tracking will become more problematic. As both tracking and acquisition issues are anticipated to be a result of beamwidth reductions, it stands to reason that the solutions aimed at addressing these two gaps would be related. However, it may be more beneficial to characterize the potential solutions aimed at targeting these two gaps as either software or hardware solutions.

The gaps as identified highlight specific technical shortfalls. It is likely that individual efforts or developments required to improve C-Band system performance may address more than one of the identified gaps.

C-BAND TM GAPS AND THE INVESTMENT PROCESS

Follow-on tasks assigned to the TSCRS team include the generation of a C-Band Telemetry Investment Roadmap. The purpose of this roadmap is to present an optimized strategy for C-Band telemetry related investment projects stemming from TSCRS project findings. While this roadmap is not a C-Band implementation plan for the ranges, it will be used in conjunction with other spectrum documents to facilitate C-Band transition planning by the services.

SUMMARY

The objective of the TSCRS project was to identify technology shortfalls/gaps associated with telemetry operations in the C-Bands. A Request for Information (RFI) was posted on the FedBizOpps website in April 2014 to solicit feedback from industry. The expectation is that most projects that may be initiated to address the gaps described in this paper will come out of the T&E/S&T Program. That is, Broad Agency Announcements (BAAs) associated with Test Technology Areas (TTA) such as Spectrum Efficient Technologies (SET) and Advanced Instrumentation Systems Technology (AIST) are likely to contain topics associated with TSCRS gaps. The TSCRS team hopes to socialize the above findings within government circles such as the Range Commander's Council (RCC) Telemetry Group (TG) as well as at T&E related conferences.

LIST OF ACRONYMS

A-A/A-S: Air-to-Air/Air-to-Surface (Weapons Domain)

AMT: Aeronautical Mobile Telemetry

S-S/S-A: Surface-to-Surface/Surface-to-Air (Missile Domain)

SUGV: Small Unmanned Ground Vehicle

TmNS: Telemetry Network System

TSPI: Time, Space, and Position Information