A SPECTRUM MANAGEMENT TOOL TO AID EFFICIENT FREQUENCY ASSIGNMENTS AT TEST RANGES

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Abstract

Increasing demands for telemetry bandwidth in conjunction with commercial encroachments on telemetry spectrum have created a need for test range operations personnel to make frequency assignments in the most efficient manner possible. The Spectrum Management System (SMS) project researches a potential tool to bring advanced capabilities to the assistance of test range operations. Features that appear to have significant utility are: frequency assignment optimizations to simultaneously satisfy device and spectrum constraints, prediction of RF channel quality across airspace, and support for frequency reuse. A prototype system is currently being trialed at selected test ranges.

1. Introduction

Test ranges are experiencing increasing numbers of requests for tests and dramatically higher bandwidth needs for each test. Further, the current popularity of commercial wireless services causes telecommunications and media companies to compete for the same frequency bands that are useful for telemetry. These pressures create a need for test range operations personnel to be able to plan and manage the use of the available spectrum in the most efficient manner possible. The Spectrum Efficient Technology (SET) Spectrum Management System (SMS) project is intended to research advanced capabilities in a tool that may be used to assist test range personnel with managing the spectrum resource in the complex and demanding situations that arise on today's test ranges.

2. SMS Feature List

After discussions with frequency managers and operations personnel at multiple test ranges, the following features appear to have the most utility:

- Frequency band assignment recommendations as the result of an optimization of assignments for upcoming tests. The feature includes display of the currently-assigned frequency bands on a time-frequency chart, prior to running the optimization, and after. Conflicts between assignments are highlighted on the chart, and the optimization serves to resolve the conflicts. Constraints that may govern the optimization include:

  - Each frequency band assignment should be within the spectrum supported by the RF device to which it is assigned.
  - The center-frequencies of adjacent bands in the spectrum should have a calculated minimum separation, based on the modulation scheme of each band.
  - RF channels from the same test article should be assigned as far apart as possible in the spectrum, to minimize the effects of interference from spatial adjacency.
  - The optimization should require the least number of frequency moves, in order to minimize disruptions to currently-planned assignments.
  - It should minimize fragmentation of the available spectrum.
  - It should support operational constraints, whether frequency assignments are allowed to be moved in the spectrum, and whether test article flight start times are allowed to be moved.

- Calculation of the expected RF channel quality for each segment of a test article's flight in time and space. Channel quality is predicted in terms of signal strength and signal-to-interference-and-noise ratio (SINR). The results are presented as a channel coverage map on a 3-dimensional geographical terrain display. This feature helps to qualify upcoming tests and provides a soft alarm if the predicted RF channel quality is below the desired threshold.
- Frequency reuse. When this option is specified for a particular assignment (and there is no available spectrum), the SMS searches the used spectrum to determine the best possible assignment with frequency reuse. The optimization ensures that the reused frequency results in the best channel quality for the currently-assigned channel and for the time- and frequency-coincident channels being interfered with.
- Automated distribution of frequency plans via reports and emails to the appropriate operations personnel.

3. System Architecture

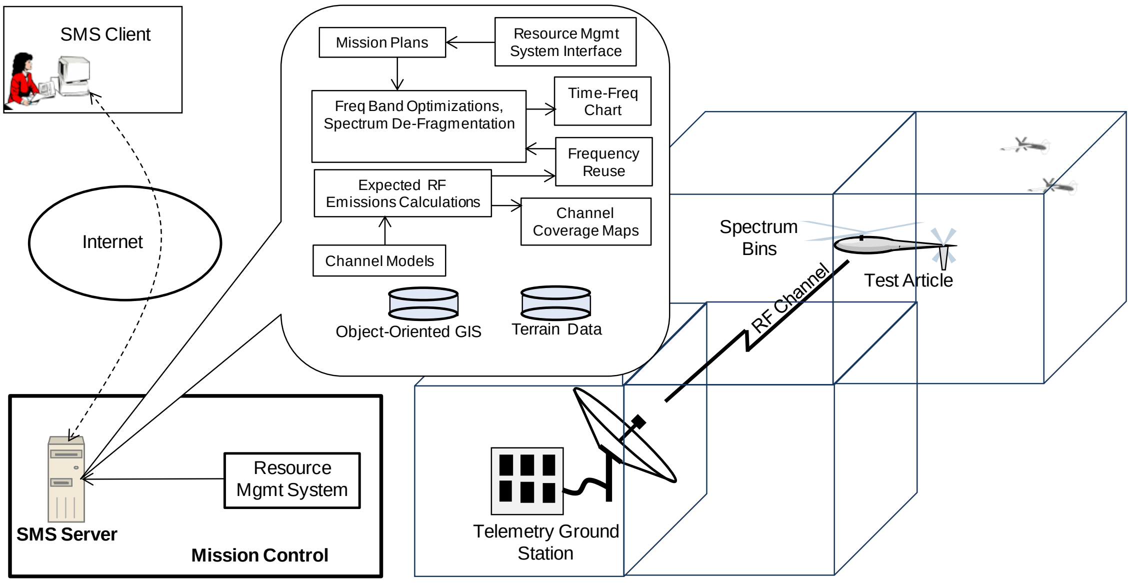

Figure 1. SMS Architecture

Figure 1 illustrates the SMS architecture. It is a client-server system. A SMS server may be located anywhere at a test range. Clients may log in remotely and get a common view of upcoming tests, frequency band assignments, spectrum occupancy, channel coverage maps and the expected RF emissions through time and space.

The SMS server is equipped with an object-oriented database, which models and tracks the evolving spectrum-related scenario at the test range. The classes of the object-oriented database implement the algorithms that support the SMS features. Major functions implemented by the algorithms include:

- An interface to the test range resource management system, which allows automatic download of upcoming test plans.
- A SMS GUI interface that allows entry and update by a user of planned tests. Elements of a test plan include: a test description, the start date/time, a lateness factor (the degree to which the test is allowed to be late), test articles and ground stations involved in the test, their RF transmitting and receiving devices and their spectrum capabilities, antennas and antenna patterns, the flight plan for each test article, and the required RF channels.
- A frequency band assignments optimization algorithm that follows a desired set of constraints (described in section 2 above), resolves conflicts, and makes frequency band assignment recommendations.
- A time-frequency chart that displays the current planned occupancy of the spectrum. The X-axis of this chart shows time in the test range planning horizon. The Y-axis displays the available telemetry spectrum bands. Colored-coded rectangles on the chart show the planned frequency band occupancy of each upcoming test, and highlight conflicts, as well as cases of planned frequency reuse.
- A calculation of expected RF emissions through time and the airspace tracked by the SMS.
- Channel models to evaluate RF propagation, to support the calculations for the expected RF emissions map through time-space.
- Use of the expected RF emissions map to evaluate RF channel quality over the flight of the test article associated with each channel. Display of this data on a 3-D terrain-based channel coverage map.
- Use of the expected RF emissions map to evaluate the viability of assignments with frequency reuse.

To support the SMS channel models and its terrain-based displays the SMS server includes a separate terrain database which provides ground elevation as a function of latitude and longitude. The source of this data is the Global Land One-Km Base Elevation (GLOBE) project [1]. The source of the data is the United States Geological Survey (USGS).

To keep the number computations required to calculate the RF emissions map down to a manageable level, the SMS segments the airspace surrounding the test range into spectrum ‘bins’. A bin is a quantum of airspace whose position is fixed in relation to the Earth. The smallest-sized bin typically measures 15” of latitude x 15” of longitude x 500 meters of elevation. In the situation where a transmitter inside a test article in flight is streaming data to a ground station, the SMS performs a single calculation of the RF propagation from the center of the bin currently enclosing the test article to the ground-station antenna. This calculation represents transmissions from all points within the bin traversed by the test article.

As a result of the bin functionality, the airspace that may be tracked by the SMS is not geographically limited. As test article flight plans traverse new airspace, the SMS determines the enclosing bins and stores them in its database for subsequent use. Thus the architecture is well-suited to supporting multiple test ranges and managing spectrum interactions between test ranges.

4. SMS Design Topics

The Class Model

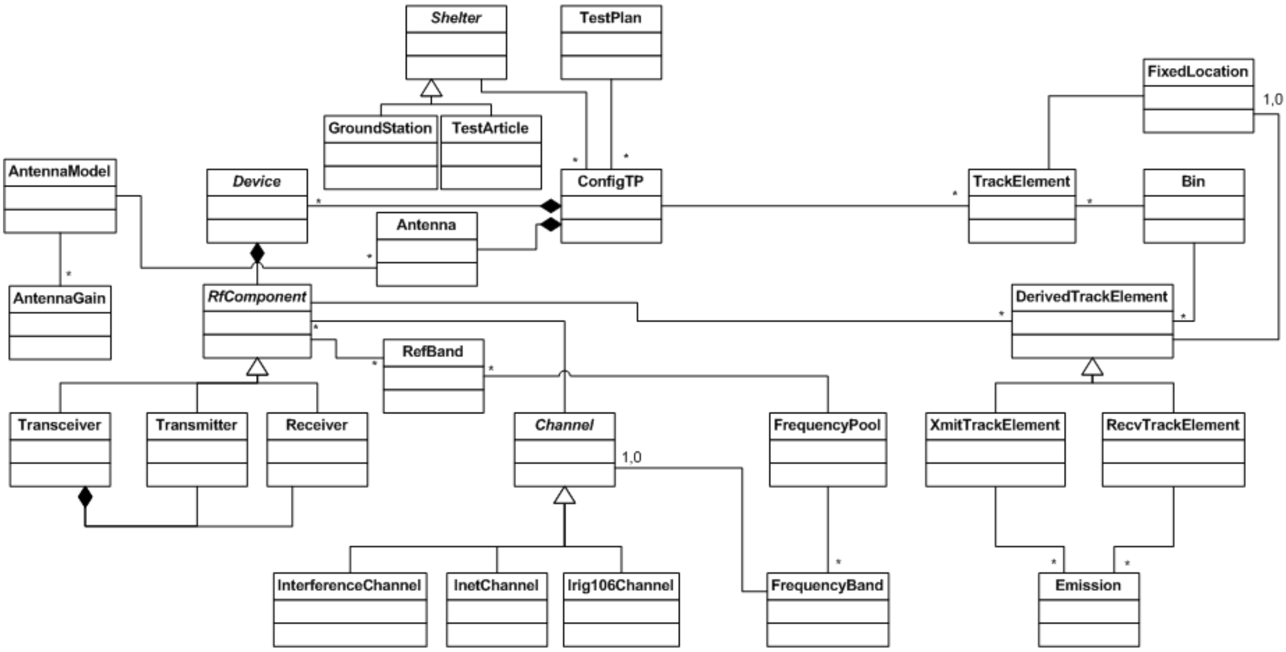

Figure 2. Part of the SMS Class Model.

To track the spectrum related scenario at a test range through time-space the SMS uses an object-oriented database with a significant class model. Figure 2 illustrates a part of it. The following is a description of some interesting aspects of it, relevant to the rest of this paper.

The classes 'TestArticle' and 'GroundStation' have common aspects subsumed in a super-class called 'Shelter'. Each Shelter may engage in multiple 'TestPlans'. Conversely, each TestPlan has multiple Shelters. This many-to-many relation is described by a bridging object called 'ConfigTP' (test plan configuration). Each TestArticle or GroundStation engaged in a test is equipped with a set of RF 'Device' instances. Each RF Device contains multiple 'Transmitter', 'Receiver' or 'Transceiver' components.

Each TestArticle's flight through the airspace is described by a sequence of 'TrackElement' objects. A TrackElement is associated with a 'Bin' object, which, as mentioned earlier, represents a fixed quantum of airspace. The TrackElement object expresses the fact the TestArticle will be inside the associated Bin for a specified time-interval. Often, a test may run late, and the precise moment at which the TestArticle begins its flight is uncertain. Each test therefore has a 'lateness' attribute, which is the maximum time the test may run late before it is cancelled and re-planned. The time interval contained in the TrackElement, therefore, ranges from the earliest time the TestArticle is expected to enter the associated Bin to the latest time that it is expected to leave it. Thus the TrackElement handily expresses a time-space quantum, which is a part of the TestArticle's flight. A single TrackElement correspondingly provides a time-space quantum for the stationary GroundStation.

Once a set of TrackElements are generated for the TestArticles and GroundStations involved with a test, these can be used to create a set of 'XmitTrackElement' (transmit track element) objects for each Transmitter contained in a TestArticle or GroundStation, and a set of 'RecvTrackElement' (receive track element) objects for each Receiver. The SMS now has the basis for creating a RF emissions map through time-space. For a given RecvTrackElement the SMS queries the database for all time-overlapping and frequency-coincident XmitTrackElements. It creates an 'Emission' object from each such XmitTrackElement to the RecvTrackElement, and uses its channel models to compute RF propagation and the power received at the RecvTrackElement. With a number of Emission objects impinging on a RecvTrackElement, it is possible to calculate the SINR and signal strength for the time-space quantum represented by the RecvTrackElement.

Bin Patterns

Bin size is crucial for ensuring a meaningful calculation of expected RF channel quality over a test article's flight while at the same keeping the number of computations required to a manageable level. Bins close to the ground need to be small, to capture spatial variations in RF propagation. Bins at higher elevations above the ground can afford to be larger, since there is not much variation in RF propagation at greater heights.

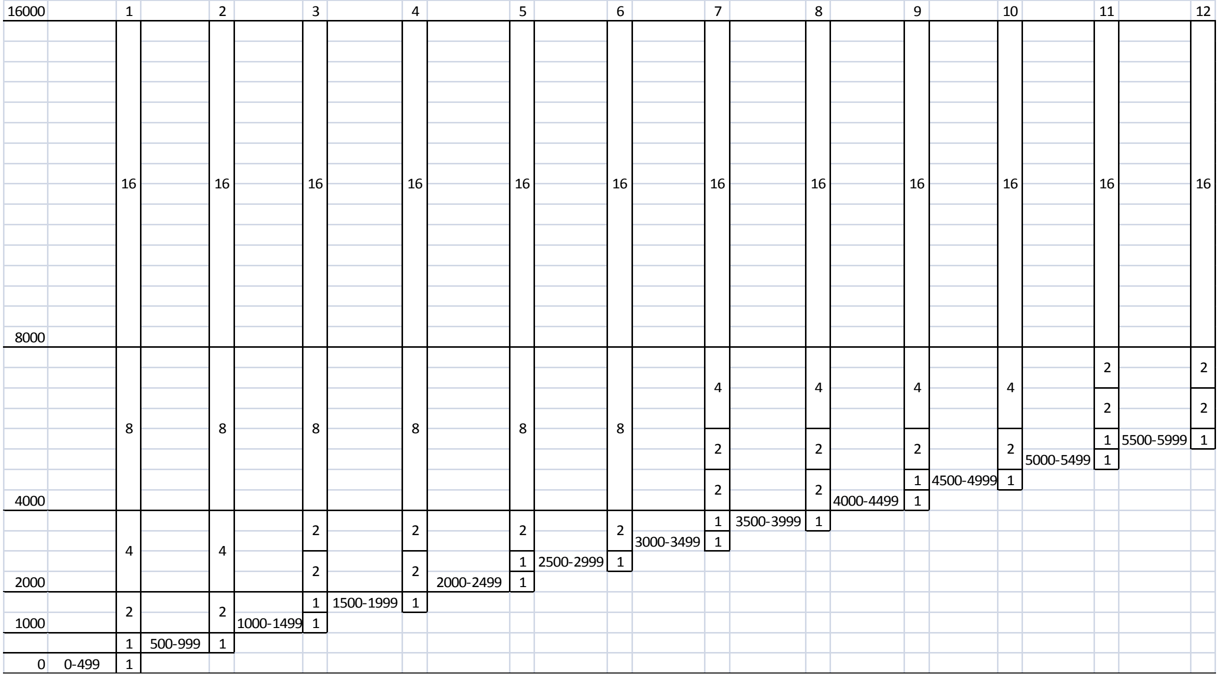

Figure 3. Bin Pattern for Each Ground Elevation Value.

Bin sizes, furthermore, need to be designed such that smaller Bins stack perfectly into larger Bins. This greatly simplifies calculations as well as the terrain-based views of channel coverage. Bin size in the SMS is specified with a multiplier that has the values: 1, 2, 4, 8, 16. A 1-sized bin has the dimensions: (15” latitude) x (15” longitude) x (500 meters elevation).

For any given point in the airspace, the SMS first uses its terrain database to determine the ground elevation at the point’s latitude and longitude. The ground elevation determines a bin pattern above that point on the ground. Figure 3 shows a sample set of mappings from ground elevation to the bin pattern. The SMS then uses the actual elevation and the bin pattern to determine the size of the bin enclosing the point. The goal with each bin pattern is start with small-sized bins close to the ground, but to converge to the same bin size at a significant height above sea-level.

Frequency Band Optimizations (without Reuse)

To assign a single frequency band without reuse to a RF channel, the SMS searches the telemetry spectrum for an unused band that corresponds to an optimization of the search constraints. An example list of the search constraints is provided in the feature list in section 2. Two important flags governing the search are: i) whether the channel is allowed to move from its currently assigned frequency band (if any), and ii) whether the start time of the test article flight is allowed to move in time. A channel may have a previous frequency band assignment, either made in the upstream resource management system (see Figure 1) or in the SMS itself. If the frequency band is allowed to move, the SMS attempts to find the band that best meets the search constraints. If not, the SMS takes no action. If the test article flight start time is allowed to move, the SMS attempts to make the frequency band assignment that best matches the search constraints as soon as possible after the current flight start time.

A more nuanced algorithm comes into play when the user selects a set of test plans and initiates a “rack-and-stack” algorithm, with the goal of making assignments optimizing search constraints for all the selected channels simultaneously. The two over-arching constraints are likely to be: i) Resolve assignment conflicts. ii) Minimize fragmentation of the available telemetry spectrum. One possibility would be to conduct an exhaustive search, changing the order in which the channels are assigned. This algorithm would create all N factorial permutations of the channel set. For each permutation the channels would be assigned in the order specified. The resultant assignments would be checked against the search constraints, and the optimal assignment would be chosen. This approach is impractical from a computing perspective because of the potential number of permutations.

In an easier approach, the SMS seeks to arrive at the first “good” set of assignments, rather than the “best” set. Criteria for a good set simply entail no conflicts and a reasonable level of spectrum defragmentation. The search constraints themselves are used in preliminary filtering process to eliminate vast numbers of channel permutations. In the end, only a small number of channel permutations are compared with one another, to arrive at a functional rack-and-stack solution.

Channel Quality Calculations

To calculate RF channel quality, the SMS uses the technique discussed above to create an Emission object between each RecvTrackElement belonging to the Channel and every time-coincident and frequency coincident XmitTrackElement in the airspace. (If the Channel is traditional downlink IRIG-106 Channel, there is just a single RecvTrackElement associated with the Channel Receiver in the GroundStation.) A subset of the Emission objects thus created are from a XmitTrackElement belonging to the same Channel. These are termed Channel Emissions, and the received power attribute stored in them comprises the Channel signal. The rest of the Emission objects belong to other time-coincident, frequency-coincident Channels (if there is frequency reuse), or are from other types of interference sources in the area. These objects are termed interfering Emissions.

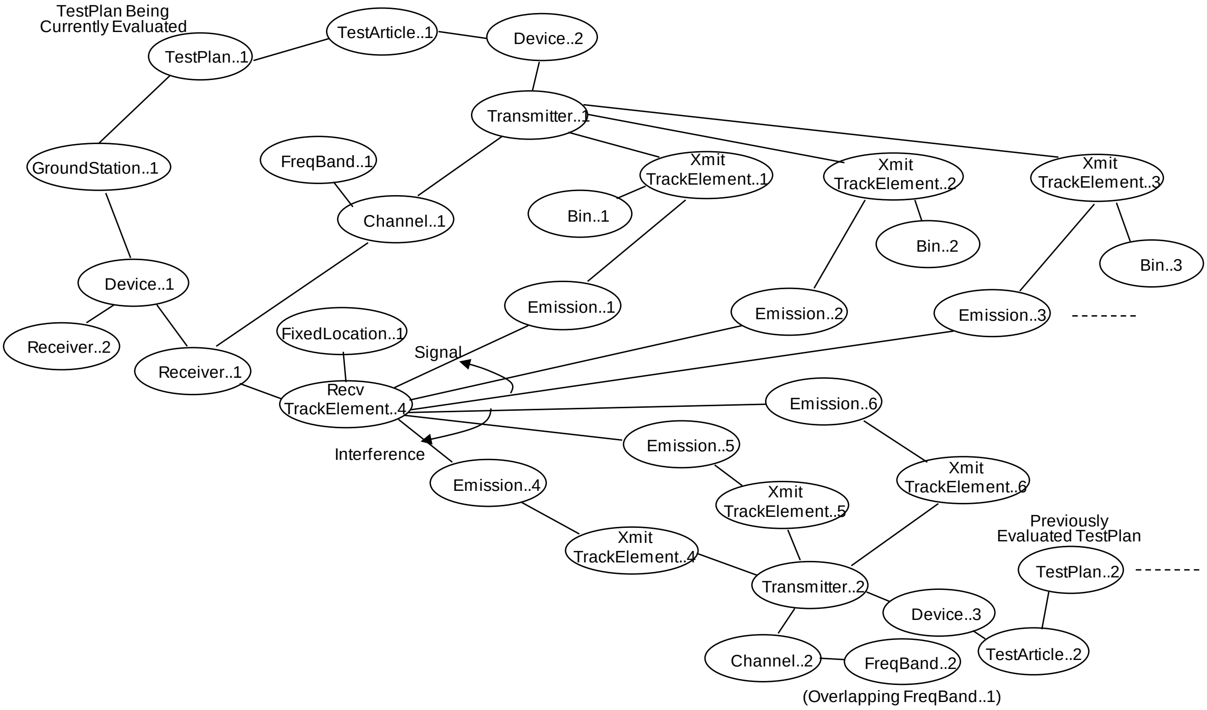

Figure 4. Object Diagram Showing RecvTrackElement Receiving Multiple Emissions.

Figure 4 illustrates a snap-shot of object instances in the SMS that enable signal strength and SINR calculation. Transmitter..1 and Receiver..1 both support Channel..1 in TestPlan..1. Transmitter..1 spawns XmitTrackElements 1, 2 and 3 because of its passage through Bins 1, 2 and 3. Receiver..1 just has the single RecvTrackElement..4, because it remains at a fixed location in Groundstation..1 for the entire test. We term the intersection of time between a XmitTrackElement and a RecvTrackElement the 'track interval'. The Emission object linking the pair therefore describes the track interval characteristic of the pair. In the figure Emission 1, 2 and 3 are channel Emissions, each with its separate track interval. Emission objects 4, 5 and 6 are interfering Emissions, since they are the result of Transmitter..2 from another TestPlan.

For each channel Emission, the SMS now goes through some tortuous code to determine the maximum interference level resulting from time-overlaps with the interfering Emissions. Each Emission object now has the received power of the signal and the maximum interference for its particular track interval. It computes signal strength and SINR. The sequence of Channel Emissions now contain worst-case channel quality measures, even accounting for lateness, over the entire flight path of the TestArticle. As is evident from the design, the algorithm does not depend on the GroundStation being stationery, and will in fact work with any set of air or ground vehicles moving through time-space.

Assignment with Frequency Reuse

With the aid of channel coverage maps, assigning a frequency band with reuse is straight-forward, if rather computation-intensive. The SMS walks through the used spectrum, hypothetically assigning a used frequency band of the desired width to the Channel and reviewing the resultant Channel quality in each case. The first order of business is to ensure that the present Channel, with its hypothetical assignment, will not harm the time- and frequency-overlapping Channels that will be interfered with. The SMS queries the database for these Channels. It generates Emission objects for the present Channel. Now with the changed spectrum picture in time-space, it re-computes the Channel qualities of the Channels being interfered with. If any of these Channel qualities falls below permissible thresholds, the hypothetical assignment is abandoned. If other Channels are not unduly harmed, the SMS evaluates overall signal strength and SINR for the present Channel, accounting for interference. It holds on to these values.

The SMS repeats the process for each hypothetical assignment, determining the one that yields the best overall Channel quality. It now makes the assignment with the best Channel quality, re-generates the Channel Emissions and re-evaluates the Channel quality.

Channel Models and SMS Calibration

The SMS is critically dependent on being able to calculate RF propagation through the airspace. It has had some success using a combination of the publicly-available Johnson Gierhart and Longley-Rice channel models [2]. When the horizon angle between the test article and the ground station is under 12^o, the SMS uses the terrain-aware Longley-Rice model. When it is greater than or equal to 12^o, it uses the Johnson Gierhart model.

Even given that the use of channel models in the algorithm is effective, a number of unknowns have to be accounted for in the propagation algorithm. These include:

- Model-specific antenna patterns for the test articles and ground stations.
- System loss, for the path from the antenna to the transmitter/receiver/transceiver.
- Building and other clutter. Building data may be added in future to the SMS, but notwithstanding this, variables such as tree growth and parked vehicles may cause errors in propagation calculations, while the aircraft is standing or taxiing.
- Test article orientation during flight. This can only be roughly estimated, and may introduce significant error into the calculation.
- Ambient RF noise. This may vary from test range to test range, and even within the airspace of a single test range.

The SMS uses two strategies: Calibration, using Time-Space Position Information (TSPI) data at the test range, and preemption of calculated RF propagation loss values by actual loss values, wherever and whenever these measurements have been made and can be relied on.

Figure 5 shows the results of a SMS calibration, using actual TSPI data from a flight at a test range. The jagged curve plots the measured TSPI SNR data. The smooth curve plots SNR values calculated by the SMS using its channel models. The unknowns listed above were adjusted as constants to make the curves as close to each other as possible. The most variations in the TSPI SNR curve occur while the aircraft is taking off and landing, and near the middle of the flight. Land-based clutter and changes in the aircraft's orientation are good explanations for these variations. The time-shift in the SMS-calculated curve is attributed to the fact that the aircraft's position, after being measured on the aircraft, took some time to make its way to the ground station, where the position data was paired with the current time. In the comparison, 89.7% of the calculated values proved to be within ± 10 dB of the TSPI SNR values.

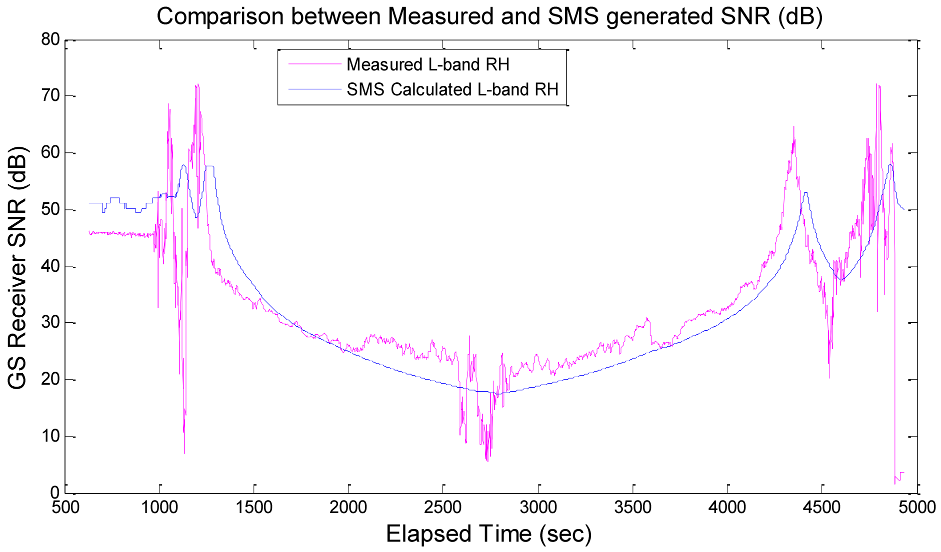

Figure 5. SMS Calibration Curves – TSPI Data vs Actual.

After the unknowns in the RF propagation calculations are accounted for by a calibration such as this, the SMS can make predictive calculations of the propagation at the test range with a useful degree of accuracy.

With regard to the second strategy, where measured RF path loss data between pairs of points around the test range are available, they are stored in a table in the SMS database. Before embarking on a path loss calculation, the SMS queries the table and uses the actual value if found. Thus, over time, the SMS "learns" its RF environment at the test range. A caution with this approach is not to depend on data which is expected to be time-variant.

5. Measuring Improvements to Test Range Operations

The SMS project is currently in its transition phase. There are ongoing collaboration efforts at test ranges where an SMS prototype is being trialed on an experimental basis to determine if a tool such as this can actually result in spectral operations improvements. A useful guide for measuring improvements is the set of (draft) spectrum management metrics standards proposed to the Range Commanders Council (RCC). Examples of spectrum management metrics are:

- Ad hoc mission availability – the probability of being able to successfully schedule an ad hoc mission (without being blocked by lack of spectrum).
- Spectrum utilization over time.
- Test article flight throughput – the maximum number of test article flight hours that can be handled in a day.
- Total data throughput over the spectrum.
- Scheduling requests satisfied.
- Assignments canceled, delayed or rescheduled.

The goal of this effort is to compare spectrum management metrics at the test range without the use of the SMS, and with. The trials are currently in the early stages. Their results should be interesting.

6. Acknowledgements

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7. References

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