Effective Strategies for Satellite Communications RFI Mitigation

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***Abstract*—In this paper we will examine how using the improved data quality available from satellite operators and a capable analysis framework provide space operators with arguably unprecedented RFI analysis products to pre-emptively avoid some RFI events while proactively identifying causes of and/or decreasing response time to others. We also discuss RFI geolocation testing and simulation activities using satellite operator data.**

***Index Terms*—Communications, FDOA, RFI Geolocation, RFI Mitigation, TDOA**

I. Introduction

IN today's increasingly congested space environment, Radio Frequency Interference (RFI) is of primary concern for communications satellite operators. RFIs inhibit communications and ultimately cause a loss of revenue or mission capability. An effective RFI mitigation strategy combines advanced analytical techniques with inter-operator sharing of authoritative satellite positional data, maneuver plans and Radio Frequency operating characteristics. The Space Data Association (SDA) has adopted such a strategy in its new Space Data Center (SDC). In this paper we will examine how improved data quality available from satellite operators coupled with a capable analysis framework provide space operators with arguably the best and most actionable RFI analysis products to pre-emptively avoid some RFI events while proactively identifying causes of and/or decreasing response time to others. We also discuss RFI geolocation testing and simulation activities using satellite operator data.

II. RFI Mitigation Process

A. RFI Incidents Categorized by Path

The ITU-R Recommendations recognizes four principal RF interference paths between Fixed Satellite Service (FSS) networks as shown in Figure 1. The solid lines represent the desired links and the dashed lines represent the interference paths. As depicted, Case 3 and Case 4 for the second operator are mirror images of Cases 1 and 2 for the first operator.

The ITU has also identified four unique cases of interference between Inter-Satellite Services (ISS) and GEO Fixed Satellite Service (FSS)-to-Earth communications as shown in Figure 2 (revised for readability). We have given these cases unique numbers to differentiate between those in Figure 1.

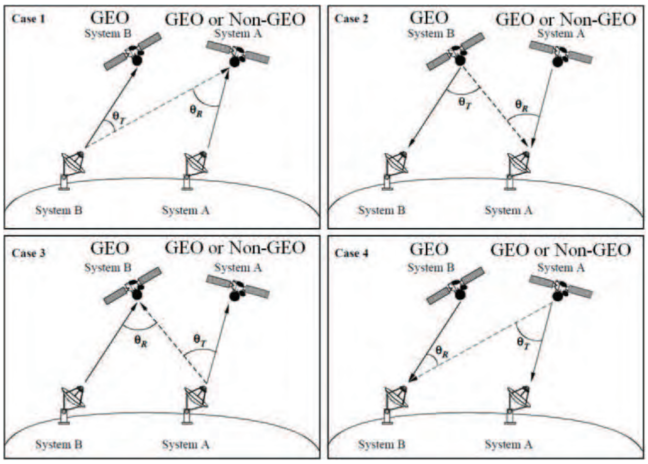

Figure 1: 4 cases of Ground-to-Satellite RFI [REF 1].

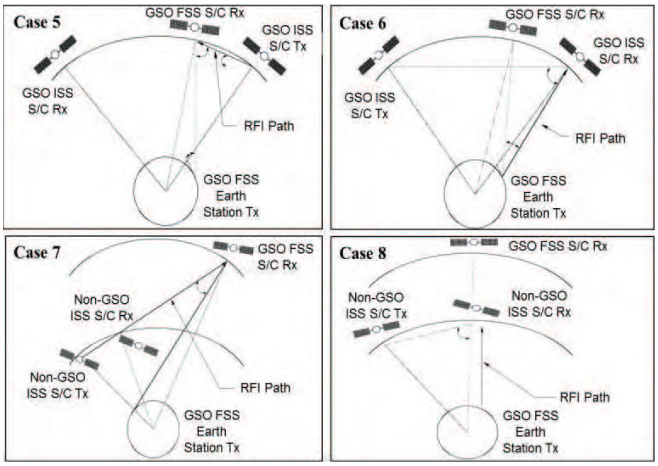

Figure 2: 4 cases of ISS/FSS RFI [REF 2].

Note that there is the additional but less-common path of one earth transmitting (Tx) antenna interfering into another's earth receiving (Rx) antenna not contained in any of these 8 cases.

B. RFI Incidents Categorized by Type

Communications satellite operators carefully monitor RFI incidents and their causes. In addition to the eight paths for interference previously discussed, operators track general statistics as shown in Figure 3 for the type and frequency of occurrence for such incidents by signal type and other factors.

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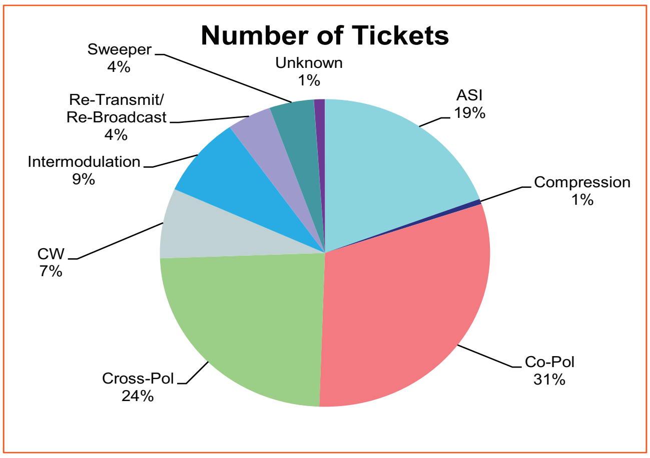

Figure 3: RFI Incidents Categorized By Type [REF 3].

As these sample annual statistics show for one operator, the most common sources of interference are from Adjacent Satellite Interference (ASI), Co-Pol and Cross-Pol. Co-Polarized (Co-Pol) interference occurs when one of an operator's own customers radiates the satellite with the intended polarization but either at the wrong time, frequency or satellite. Cross-Polarization (Cross-Pol) is interference from improperly-configured or misaligned polarization which leaks energy into services located on the opposite polarization.

In an effort to map such RFI incidents into a more meaningful metric, communications satellite operators devised a way to weight such RFI incidents by the affected bandwidth and time to resolve, as depicted in Figure 4.

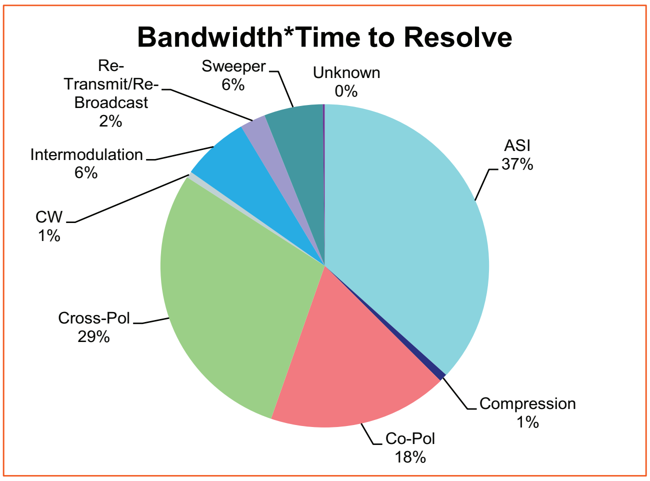

Figure 4: RFIs By Type, Weighted by Bits Lost [REF 3].

As Figure 4 shows, 84% of all communications lost to RFI incidents are attributable to ASI, Cross-Pol and Co-Pol issues. Since Cross-Pol and Co-Pol issues originate within the operator's own customer base, those issues tend to be rapidly addressed by improved coordination and communication with communications customers, equipment installer training, identifying and fixing configuration issues and clarifying communications schedules, transponder allocations, etc.

ASI (*i.e.*, ITU Case 1 and Case 3) is the single most detrimental and worrisome RFI issue facing communications operators. ASI occurs when an interfering signal (whether legitimate traffic to an adjacent satellite or from an intentional jamming source) interferes with a satellite's legitimate communications traffic as shown in Figure 5.

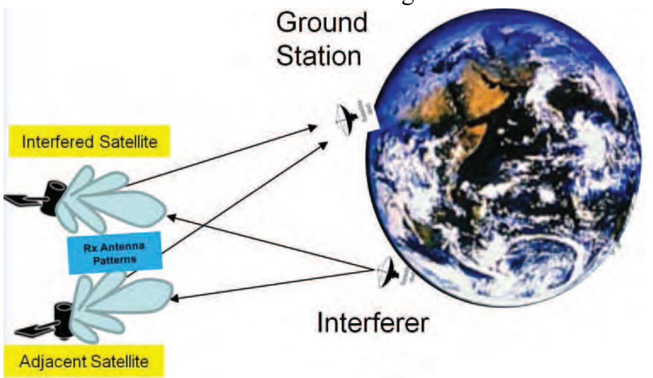

Figure 5: Adjacent Satellite Interference geometry [REF 4].

Received carrier signal levels that are less than 10 dB above the combination of (noise + interference) may be susceptible to interference [REF 5] with reduced operational performance below a 10^{-6} BER, as shown in a sample evolution of the ratio of [Carrier] to [Noise + Interference] (CONI) using an actual parabolic dish antenna pattern in Figure 6. Note that angular separation between the two adjacent satellites is a rough indicator of potential RFI, but detailed antenna patterns and computation of CONI is required to best identify potential RFI times.

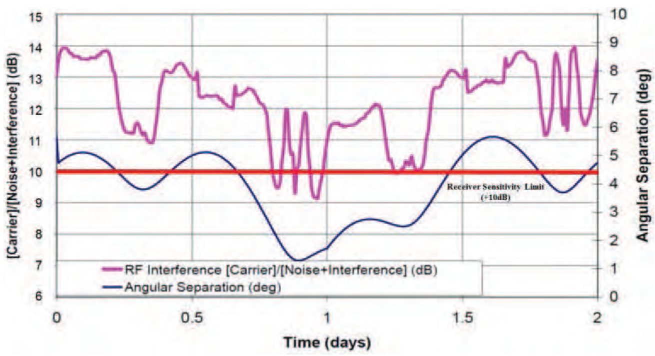

Figure 6: Sample C/[N+I] and Angular Sep. Vs Time.

C. Non-Geosynchronous RFI Events & Analysis

The common (and likely accurate) perception is that RFI is primarily a concern for satellite operators with Geosynchronous Earth Orbit assets. While many RFI incidents involve satellites in Geosynchronous Earth Orbit (GEO) with each other (ITU Cases 1-4), non-GEO satellites can also experience RFI events (ITU Cases 5-8), and these events can be even more difficult to detect, isolate and prosecute due to the rapidly-changing geometries involved. Large LEO constellations (*e.g.*, 50 satellites) can experience as many as 4000 RFI events per year [REF 6].

It is important to remember that any satellite transit with suitably-compatible RF characteristics can experience RFI, to include Low-Earth Orbit (LEO) and Middle Earth Orbit

(MEO) orbital regimes. In addition to the strict understanding of RFI, LEO operators have stated that they've seen satellite transits between any/all of these orbital regimes even lead to failure in standard azimuth/elevation auto-track implementations, sometimes resulting in temporary tracking of the wrong satellite. Such transits are typically of very short duration, however, and procedures utilized to identify and/or mitigate RFI for GEO satellites can also be used to mitigate RFI for LEO and MEO satellites. Applications of pro-active "Fly-By" RFI predictive screening (as described above) can help operators anticipate when such events may occur.

III. Operator Workflow for RFI Mitigation

We now examine a typical satellite communications operator's RFI mitigation approach to RFI mitigation and resolution. For communications satellite operators, RFI is such a significant concern that regimented procedures and work flows have been implemented to address it, as shown in Figure 7. This implementation is fairly common across the major communications satellite operators and uses a two-tiered "Level 1" and "Level 2" staffing approach.

The primary focus of the Level 1 (L1) Ops Center staff is to field customer reports of interference issues and to restore service as quickly as possible. Once service is restored, Level 1 staff attempt to identify and mitigate the RFI threat. Based upon operator statistics, the leading causes of RFI are from operator or customer errors (including miscues on scheduling, polarity, frequency); such issues are usually solved quickly by Level 1 Support Teams.

The incidence of intentional jamming ranges from very low (<<1%) to moderately high and appears to be highly dependent upon the operator and their individual satellite region(s).

Typically, about 15% of RFI incidents fail to be addressed by L1 staff and are handed over to an L2 RFI forensics team that will dedicate effort, tools and techniques to resolve them.

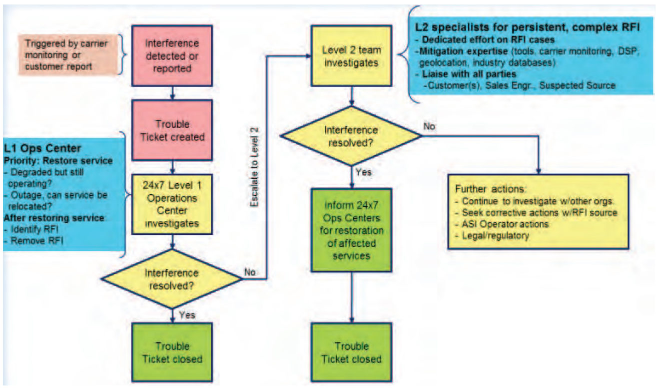

Figure 7: Operator RFI Mitigation Typical Workflow

IV. RFI Analyses, Simulation & Procedures

We now describe analyses, simulation, testing and procedures available to support RFI mitigation and resolution.

A. *The Space Data Center as a Key RFI Mitigation Tool*

For communications satellite operators, time is money. The ability to rapidly mitigate RFI incidents is a key component to both customer income and customer satisfaction.

Accordingly, many space operators have banded together to form and join the Space Data Association (SDA) to participate in its Space Data Center (SDC). Analytical Graphics Inc. (AGI) serves as the designer, developer and operator of the SDC, as well as technical advisor to the SDA. The current GEO satellites populating the SDC (214 satellites, or approximately 65% of the operational GEO population) are shown in green in Figure 8.

The SDC currently provides collision risk mitigation and RFI alerting capabilities. Operator "Phonebook" and inter-operator communication of experienced RFI events via such RFI alerts are vital first steps to addressing RFI problems. The SDC accomplishes all of this within a trusted legal and technical framework that can ingest, fuse and automatically analyze multi-source, sensitive or proprietary satellite data from both satellite owner/operators and Non-Cooperative Tracking (NCTs) organizations (*e.g.*, radar and telescope space surveillance organizations).

Conjunction Assessment (CA) analysis and RFI analyses have a common input: authoritative and actionable ephemerides for all satellites to be analyzed. Obtaining actionable and authoritative ephemerides that properly reflects past, present and future orbit maneuvers is a subject worthy of separate papers and dissertations. Operators have good quality data, but tend toward inconsistent terminology and disparate data products stemming from cultural differences and the wide variety of Orbit Determination (OD) and RF analysis tools and techniques available. But it is sufficient to note that the SDC serves as a "universal translator" to rigorously "rectify" or "normalize" disparate operator ephemerides into common reference frame and units to facilitate data fusion for actionable CA and RFI analyses.

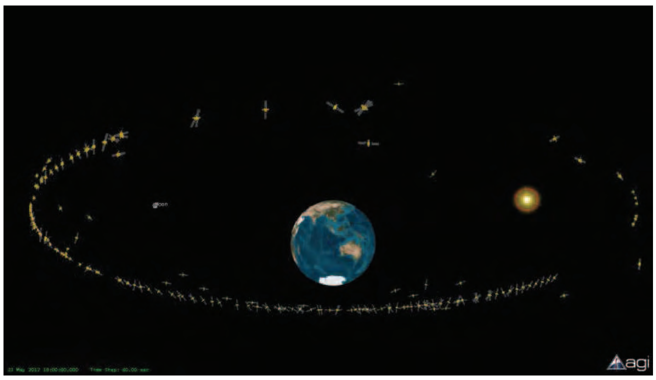

Figure 8: Current GEO satellites populating the SDC.

With such authoritative and actionable ephemerides and RFI Alerts in place, the SDC is by itself an ideal tool for the RF analyst to promote rapid RFI mitigation. The SDC provides unified access to the world's largest aggregate collection of actionable, authoritative satellite position, RF & Points-of-Contact commercial space data. While more detailed testing is underway, initial testing indicates that using SDA operator ephemerides yields as much as fifty-times improvement in RFI geolocation accuracy.

The SDA plans to further augment the SDC's native satellite ephemeris, points-of-contact, RFI Alert Report and RFI Alert Notification capabilities with additional capabilities as shown in Figure 9.

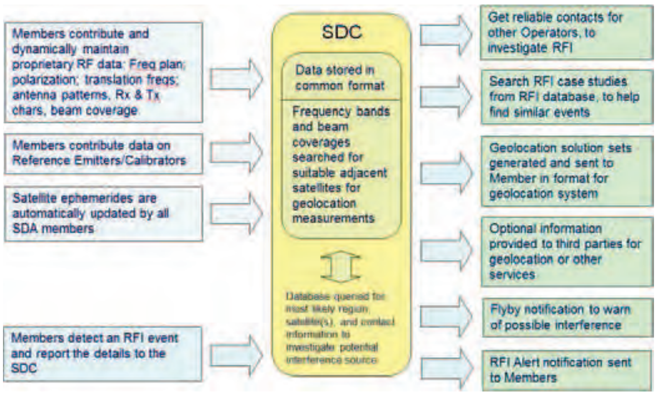

Figure 9: Planned RFI mitigation workflow.

Dynamically populating the SDC's Radio Frequency (RF) database with current and actionable RF data may constitute the biggest and perhaps most daunting task to meeting RFI mitigation needs. Once accomplished, however, RF analysts will be able to generate actionable forensic and predictive RF and RFI assessments.

We now describe a typical satellite communications operator's wide spectrum of RFI analyses, ranging from RFI Fly-By analyses to pre-computed solution sets for cueing RFI geolocation to the geolocation analysis itself.

B. Technical Approach

Most interference sources span international borders, where all participants must conform to ITU-R recommendations governing potential interference. AGI was part of the FCC delegation which helped the ITU collaboratively develop these ITU-R consensus methodologies and technical approaches to assess permissible vs. unacceptable levels of interference. Space limitations prevent us from detailing this ITU-R approach which we adopted in this paper, but we instead direct the reader to relevant definitions in recommendations ITU-R S.1323, S.1324, S.1325, S.1503, S.1523, S.1529, S.1554, S.1556 and S.1673.

C. RFI "Fly-By" Pre-Emptive Analyses

So-called "Fly-By" events happen when a newly-launched or drifting satellite transit other communicating satellites. Such events are of particular concern when the launching or drifting satellite is located in the same orbital plane (*e.g.*, launch to GEO from Sea Launch or French Guiana) or GEO satellites drifting from one orbital station to another.

If sufficient detail is available on all pertinent satellite RF parameters, antenna patterns/orientation (Figure 10) and orbital positions, then detailed predictions of CONI may be generated as shown in Figure 11. Such predictions help RF analysts coordinate with impacted space operators.

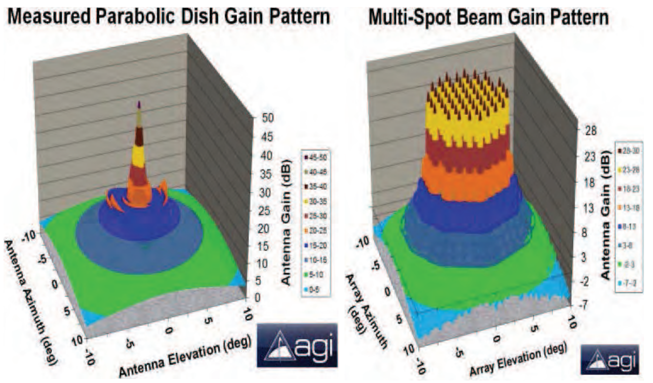

Figure 10: Parabolic and Multi-Spot antenna patterns.

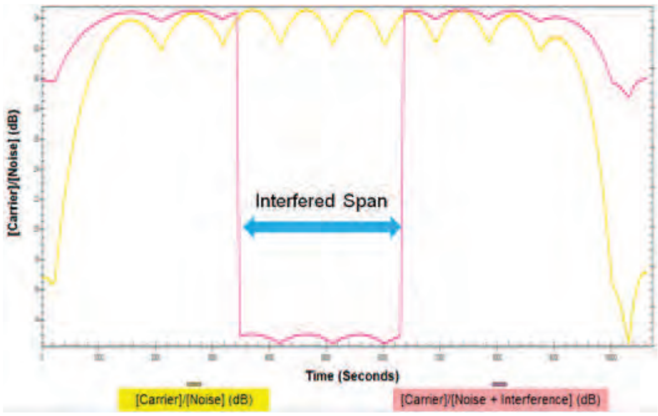

Figure 11: Pre-Emptive Fly-by RFI analysis.

D. RFI Geolocation Reactive Analyses

When RFI impacts an operator's communications, RFI geolocation techniques can be used to determine the location of the interfering signal. Geolocation techniques allow the RF analyst to reactively identify and mitigate interference sources. Geolocation is one of the principal RFI mitigation tools in an RF analyst's arsenal.

Geolocation techniques can be categorized as (a) Time-Difference-of-Arrival (TDOA), Frequency-Difference-of-Arrival (FDOA) or combined TDOA/FDOA-based methods [REF 7, 8, 9, 10, 11 and 12]; (b) received signal power amplitude analysis based upon a single pre-determined antenna pattern [REF 4]; (c) received signal power amplitude comparison methods based upon measurements from an array consisting of two or more antennas with pre-determined antenna patterns [REF 13, 14, 15, 16, 17 and 18]; and (d) Angle of Arrival (AOA) using two simultaneous measurements of azimuth/elevation; and (e) Line-of-Bearing, using two simultaneous measurements on two platforms or 2 times. Methods (a) and (b) have an advantage for existing satellites in that existing satellite hardware can be used. By using a combination of TDOA and FDOA measurements gathered from two adjacent satellites, a geolocation solution can be determined as shown in Figure 12.

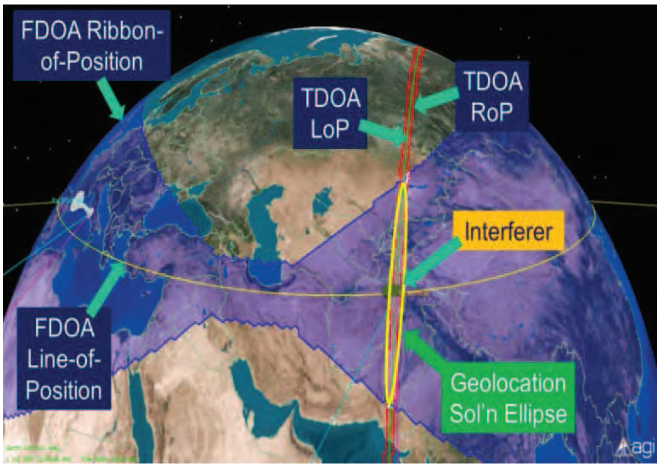

Figure 12: TDOA & FDOA Ribbons- and Lines-of-Position [REF 7 and19].

E. Pre-Computed Figures-of-Merit & Solution Sets

The "Fly-By" analysis shown previously is an example of figures-of-merit and RFI alerts can be computed if sufficient RF data are available to analysts. We now examine additional figures of merit that can be pre-computed if satellite operator RF parameters (including detailed antenna pattern) are well-known.

We first consider interference from a LEO satellite into the downlink from a GEO satellite to a receiving antenna located on a ship as shown in Figure 13. While the ship antenna is receiving communications from a GEO satellite, a LEO satellite transits through the ship-to-GEO line-of-sight and interferes with ship's reception of GEO satellite as shown in Figure 14.

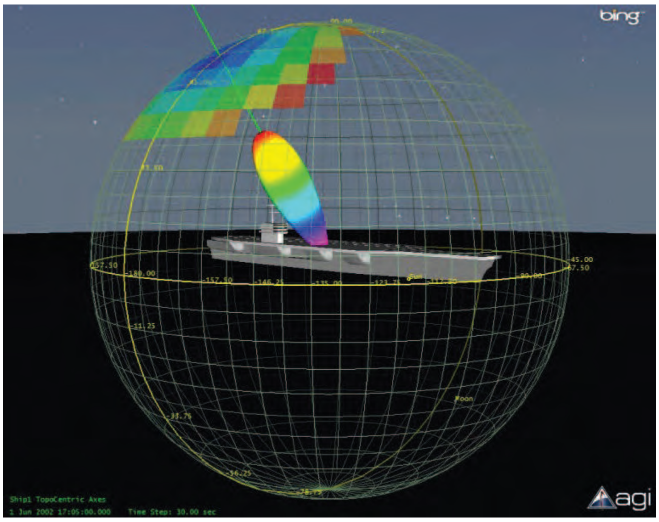

Figure 13: Receiver antenna pattern with attitude sphere overlaid with received Carrier/Noise

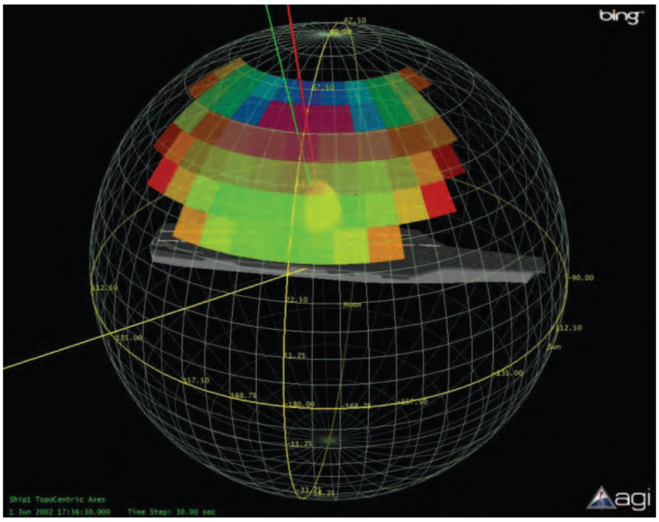

Figure 14: Attitude sphere overlaid with received Carrier/[Noise+Interference] during LEO interference event.

Next, we consider predicting received signal power associated with a well-quantified interfering uplink signal impacting an adjacent satellite's communications (Case 1, S.1526-1). For this case, an earth station A is transmitting into satellite A, while an earth station B (at an unknown location but with a known antenna pattern) is transmitting into satellite B (placed 2 degrees away from A in the GEO belt). Because of their proximity, earth station B is interfering into satellite A uplink (and subsequently into the downlink).

Assuming that earth station B is boresighted on satellite B and that satellites A & B are positionally well known, contours of [Interference : Noise] can be created across all possible earth station B transmitter locations as shown in Figure 15.

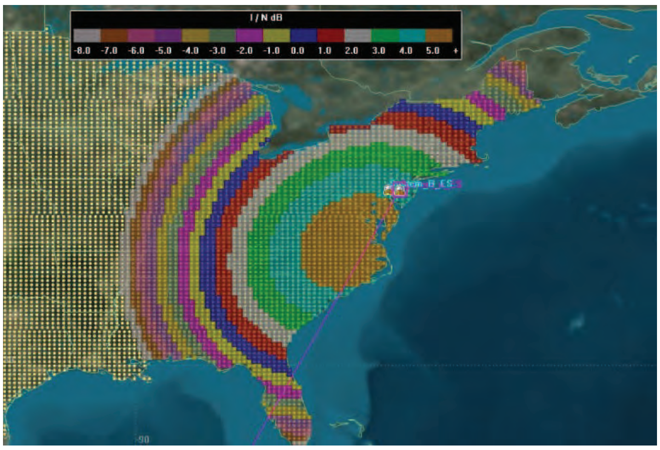

Figure 15: Uplink ASI Figure of Merit Associated with RFI into GEO Satellite (Case 1, S.1526-1).

With such contours in hand and the normalized interference level actually observed at earth station A, the likely location area of admissibility can be determined. For example, for a received interference normalized power level that's 3 dB above noise in Figure 15, the interfering signal would likely be transmitted from the light green (turquoise) region. This region can be further narrowed to an individual transmitting site (or a small group of sites) by using a time series of measurements or additional normalized power observations using other adjacent satellites.

Conversely, contours of received normalized power from interfering adjacent satellite B's communications into earth station A (Case 2, S.1526-1) as a function of satellite B's boresight direction can be generated as shown in Figure 16. Accordingly, direct measurements of normalized power can be used to determine the area(s) where satellite B is likely to be pointing at.

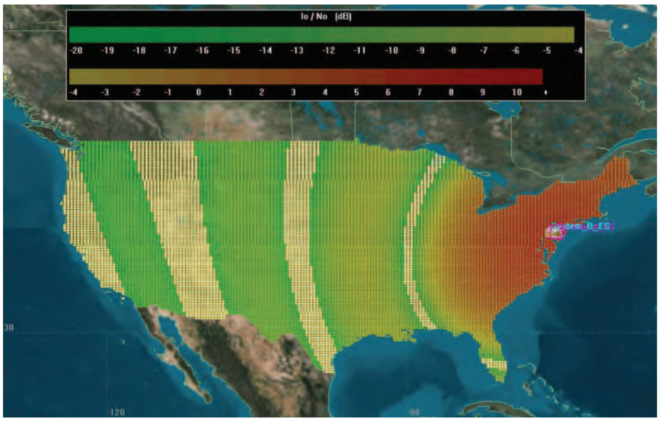

Figure 16: Downlink ASI Figure of Merit Associated with RFI into GEO Satellite (Case 2, S.1526-1).

V. Figures of Merit for Pre-Computed Sol'n Sets

As we've described, RFI mitigation can best be accomplished by combining (a) points-of-contact information for all operators; (b) aggregation and data fusion of authoritative, actionable operator ephemeris and RF data; (c) pre-emptive and predictive RF analyses; and (d) reactive RFI geolocation analyses. For the reactive RFI geolocation analyses, analysts can continually identify the optimal inputs and conditions to obtain the most accurate RFI geolocation results. That is, by pre-computing and assigning Figures-Of-Merit (FOMs) to the many pairings (solution sets) of compatible satellites, measurement times and geometries for the TDOA/FDOA process, the RF analyst will be prepared to rapidly select the best conditions with which to perform TDOA/FDOA RFI geolocation.

A. Factors affecting RFI geolocation accuracy

Factors affecting RFI geolocation [REF 7 &20], include:

- Ephemeris uncertainty;
- Selection of best time of day;
- Selection of satellite pair w/non-synch movement;
- Accumulation of multiple measurements over time;
- ASI relative geometry (incl. Ref in line w/satellites & target)
- Adjacent satellite RF Compatibility and frequency bandwidth overlap
- Collector clock synchronization;
- Uncertainty in center frequency and phase noise;
- Geoid and terrain model uncertainties;
- Processing and TDOA measurement errors;
- Ionosphere-induced TDOA and FDOA errors;
- Troposphere-induced path length errors;

B. RFI Geolocation FOM expression

From the above list of factors, a FOM is proposed for automated computation within an SSA system such as the SDC:

$$FOM_{GeolocSolnSet} = A\sigma_{ephA}(t) + B\sigma_{ephB}(t) + C \cdot f\_Geom(t) + D \cdot f(RF) + E \cdot f(Freq\_BW\_Overlap)$$

Determination of the functional relationships and weighting factors A, B, C, D, and E depend upon the influence of satellite positions, positional errors and reference emitter geometries on geolocation accuracy. The need for FOM functional dependence on time can be seen in positional error trends for three satellites as a function of time-of-day as shown in Figure 17, with nighttimes shaded in light blue; degradation of up to 30 km in TLE positional prediction due to sensor lighting constraints and classic under sampling are evident.

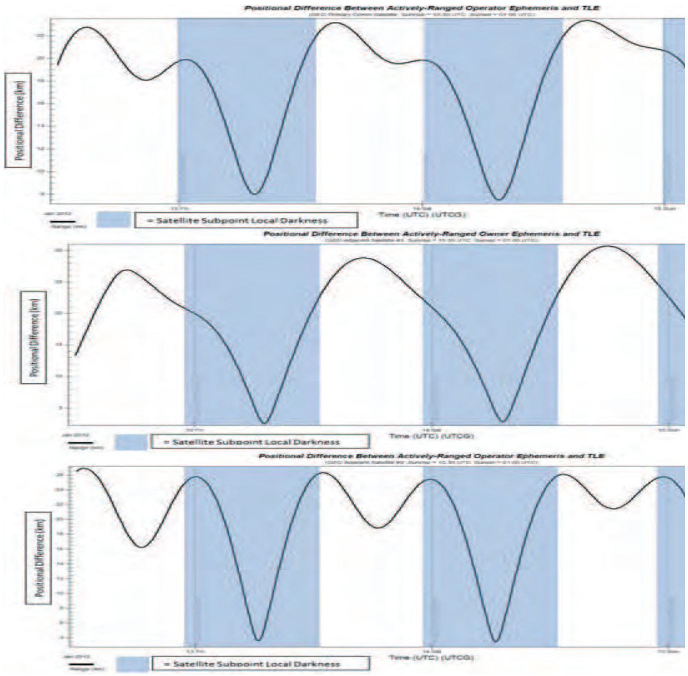

Figure 17: GEO Accuracy Degradation vs Time-of-Day.

VI. RFI Mitigation Timeliness

Consider now the responsiveness of the entire RFI mitigation process for Operator Level 1 and Level 2 procedures as shown in Figure 18. We consider (a) current operations; (b) current operations augmented by an SDC "phonebook" of space operators and RFI Alerts; (c) the above plus sharing of RF parameters and reference emitters; (d) the above plus pre-computed geolocation solution sets with integrated geolocation data sharing. Consideration is given to latencies from reference emitter identification, difficulties in identifying suitable and compatible adjacent satellites from both a geometrical and an RF standpoint, inter-agency coordination latencies, incompatible reference frames and non-standard RFI and ephemeris data formats and content.

Based on these assumptions, an RFI mitigation timeline is estimated for each case. Using the full set of tools and data planned for the SDC, time-to-mitigation is estimated to be reduced by as much as 60%.

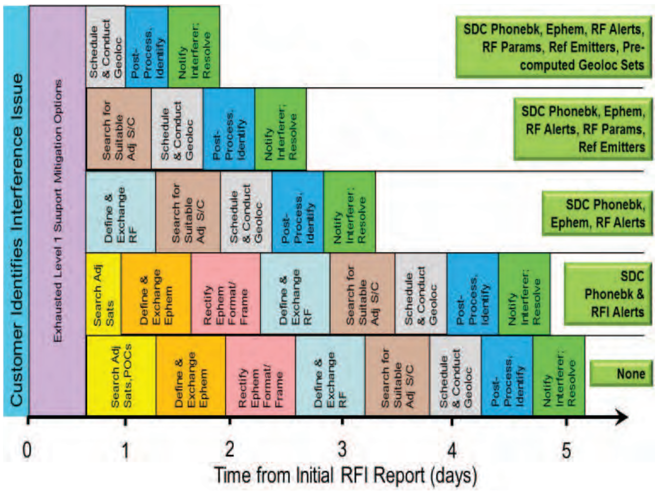

Figure 18: RFI Responsiveness For Various Operator Mitigation Approaches.

Acknowledgment

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