A MODEL FOR DETERMINING SPECTRAL CAPACITY IN THE FAA's AIR/GROUND COMMUNICATIONS SYSTEM

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ABSTRACT*

A critical problem that the Federal Aviation Administration (FAA) is currently facing and which will worsen over time is the availability of spectrum to meet future air traffic needs such as adding new runways, adding new sectors, and splitting congested sectors. Growth in very high frequency (VHF) air/ground (A/G) communication due to increased levels of air traffic has led to higher demands in A/G channel requirements for the last two decades. The FAA is currently considering upgrading its A/G communications system to a new technology that promises to provide spectral relief. Concurrently with planning an A/G communications system upgrade, the FAA is also considering new concepts in airspace design (referred to as airspace re-design) to meet its operational needs. Intuitively, based on the new airspace design concepts, and on the design of the new A/G communications system, one could surmise that spectral relief could result as a by-product of either or both of these efforts. Although the main goal of airspace re-design is not to provide spectral relief, but to satisfy operational needs, at least it is hoped that airspace re-design will not worsen the spectrum problem. Because of the magnitude of the undertaking of these efforts, substantial quantitative validation of the impacts of these efforts on the spectrum problem is required before the FAA moves ahead with its plans. To assist the FAA with its decision making regarding these efforts, MITRE/CAASD developed a modeling technique called *depletion analysis*. The application of depletion analysis is described in this paper to a limited portion of the National Airspace System – the high-en route airspace in the Southeast.

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Keywords: air/ground communications, air traffic control, FAA, NAS, spectrum management

1.0 INTRODUCTION

A critical problem that the FAA is currently facing and which will worsen over time is the availability of spectrum to meet future air traffic needs such as adding new runways, adding new sectors, and splitting congested sectors. Growth in very high frequency (VHF) air/ground (A/G) communication due to increased levels of air traffic has led to higher demands in A/G channel requirements for the last two decades. The strategy had been to "split" the channels, first from 100 kHz to 50 kHz, then from 50 kHz to 25 kHz. The U.S also obtained a waiver from the International Civil Aviation Organization (ICAO) Annex 10 to lessen the degree of frequency protection between cochannel assignments of A/G communications frequencies from 20 decibels (dB) to 14 dB.

The FAA is currently in the planning stage for its future A/G radio communications system, also called the Next-Generation A/G Communications (NEXCOM) system. This future system is based upon the ICAO VHF Digital Link (VDL) Mode 3 (VDL-3) standard, which employs digital modulation and a three or four-slot time-division multiple-access (TDMA) technique that will also operate in the same VHF band on the 25 kHz channels. These slots can all operate as voice or a combination of voice and data. Examples of four-slot configurations are: 4V where a 25 kHz channel is shared among four controllers for voice only; 2V2D where two controllers share a 25 kHz channel and each have one voice and one data slot. There are similar three-slot configurations: 3V where a 25 kHz channel is shared among three controllers for voice only; 2V1D where two controllers each have their own voice slot, but share a data slot. The time slots in three-slot configurations are larger than those in four-slot configurations in order to accommodate much larger service volumes. There are other configurations as well.

The fact that 25 kHz channels can be shared amongst multiple controllers with VDL-3 means that fewer frequencies would be required to operate the A/G radio communications system than are currently used, with enough spectral resources available to accommodate future growth of A/G circuit requirements. The process of placing multiple controllers onto the same 25 kHz carrier frequency is called *bundling*. Figure 1 illustrates how spectral savings can result from bundling.

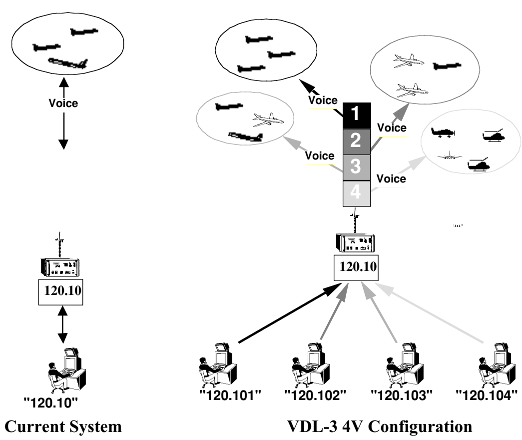

Figure 1. Spectral Savings Through Bundling

2.0 DESCRIPTION OF ANALYSIS

The main goal of the analysis was to determine the improvement in the potential for spectral growth that VDL-3 could provide over the current A/G communications system. It was assumed that VDL-3 was applied to a very limited portion of the airspace– the Southeastern high-en route airspace. Although the portion of the National Airspace System (NAS) was limited, surprisingly interesting results were obtained. Results of analysis done on the NAS with the current From hereon no indication will be made that the NAS sectors with a notional Southeastern airspace was used.

The analysis made use of a MITRE/CAASD-developed tool called Spectrum Prospector™ [2]. First a discussion of Spectrum Prospector is provided followed by the analysis.

2.2 SPECTRUM PROSPECTOR

Spectrum Prospector models the desired and undesired electromagnetic interactions of large populations of A/G radios. It accepts environmental data, lists of available frequencies, and frequency-assignment rules (e.g., cosite, intersite, intermodulation constraints, etc.) provided by the user. Those user-defined assignment rules embody constraints imposed by the architecture and design parameters currently under consideration. Spectrum Prospector employs the input data to generate a frequency plan for the postulated environment in accordance with the user-specified rules. In the modeling exercises documented in this paper, the existing environment of A/G circuits is taken into account. Any new A/G circuits or any modifications made to existing sectors (resulting in new A/G circuits) must be done with this backdrop of existing A/G circuits. Spectrum Prospector has the capability to make minimal changes to the existing frequency assignments in order to accommodate new assignments. The strategy used in this approach is called a *progressive* strategy. It is not always possible to find a frequency assignment for a new A/G circuit because assignments in the backdrop of the existing environment may "block" any new assignments. The only way around this problem is to find the blocking assignments and retune the corresponding radios to new frequencies that will allow an assignment to be found for the new A/G circuit. Sometimes in order to find an assignment for a new A/G circuit, several existing radios must be retuned. Spectrum Prospector provides a detailed report of the order in which radios must be *progressively* retuned to accomplish a transition to a given end state, whether it be a new set of A/G circuits in the existing system, or to VDL-3, or to some other end state.

This capability of progressively transitioning to a new system provided by Spectrum Prospector is particularly important for the transition to VDL-3 since it is not possible to simply replace a current DSB-AM radio with a VDL-3 radio and use the same frequency. Because the spectral characteristics of VDL-3 are much different than those of DSB-AM, the frequency used by the DSB-AM radio when transferred to the VDL-3 radio will usually cause interference to surrounding A/G circuits. Thus, a new frequency must be found for the VDL-3 radio, one that will require retunings of existing radios.

Since retunings of existing radios are required to accommodate any new VDL-3 assignments, field personnel must perform a certain number of actions. Spectrum Prospector provides the number of radios requiring retunings in order to accommodate the transition.

2.3 DEPLETION ANALYSIS DESCRIPTION

Depletion analysis is a modeling strategy using Spectrum Prospector to determine *spectral capacity* provided by the current system and by VDL-3. The strategy to measure spectral capacity is to determine the approximate maximum number of new A/G circuits that, when added to the existing inventory of A/G circuits at existing radio sites in different ATC environments, can be assigned frequencies by Spectrum Prospector. By measuring spectral capacity assuming the current A/G communications system is in place, and then measuring it assuming that VDL-3 is in place is tantamount to comparing the growth potential of the current system with that of VDL-3.

Depletion analysis measures the spectral capacity of an *environment* of interest. The key idea of depletion analysis is to approximate the maximum number of new circuits in a given environment to which frequency assignments can be made. The new circuits are assumed to arrive randomly in the given environment at appropriately selected radio sites. Four operational environments were analyzed – Tower, Terminal, Low-En route (L-ENRT), and High-En route (H-ENRT). Each Environment is analyzed separately, in order to provide an upper bound estimate of the best that can be done in that environment. In general, the depletion analysis methodology is as follows.

For each of the four environments, existing radio sites within a certain distance (7 nmi for Tower, 20 nmi for Terminal, 50 nmi for L-ENRT and 100 nmi for H-ENRT), providing services appropriate to the environment, are selected around 57 high-density Tower Data-Link System (TDLS) airports . (*As these high-density airports are distributed in high-density areas across the CONUS, their use was mainly to provide good geographical focal points around which radio sites could be selected.*) For example, radio sites that currently provide only en route services and happen to be within 7 nmi of a TDLS airport would not be used in a simulation of the Tower environment. Radio sites that would be used to accommodate new circuits added in the Tower environment would be those that, in addition to being within 7 nmi of a TDLS airport, currently provide at least one service appropriate to the Tower environment such as local control, ground control, departure control, etc. Services used for the Tower and Terminal environments are the same. (The Low-En route and High En route environments likewise have the same services but they are different from the those used for the Tower and Terminal environments.) Each circuit added to a selected radio site in the Tower environment is given a service volume ceiling of 6,000 ft. and a service volume radius (SVR) of 20 nmi. The service volume center (SVC) is taken as the location of the radio site to which the new circuit is added. Table 1 shows the service volume dimensions used for each circuit in all four environments.

Table 1. Service Volume (Sector) Dimensions

	SVR (nmi.)	SV Ceiling (ft.)
H-ENRT	120	45,000
L-ENRT	60	24,000
Terminal	40	12,000
Tower	20	6,000

Thus, each of these environments differs not only in the radio site-to-airport distance criterion used, but also in the current offered services at the selected radio sites. Whenever results are presented for a section of the NAS (i.e., the Southeast), they are taken from a subset of results for the NAS.

The progressive strategy described above is also used for the depletion analysis where retunings of radios corresponding to existing blocking assignments are performed in order to accommodate an assignment of a new A/G circuit. In addition, all co-channel, adjacent channel, cosite, and intermodulation rules have been applied in Spectrum Prospector. The application of cosite and intermodulation rules is in a sense one aspect of the simulation that results in worst-case results. There are techniques that can be used to reduce the effects of intermodulation and cosite radio frequency interference (RFI) such as introducing filters, relocating radio sites, or other physical means of corrective actions.

The depletion analysis is done separately for each ATC environment. This means that new circuits are added to only one ATC environment at a time, and an attempt is made by Spectrum Prospector to find frequency assignments for as many of those new circuits as possible, with the existing A/G circuits in all environments present. When the depletion analysis is done for the tower environment, new A/G circuits are added to the tower environment only.

As an example of the application of depletion analysis to compare the spectral capacity of the current A/G communications system with that of VDL-3, consider the Tower environment. With the new circuits in the tower environment, a depletion analysis is performed with the current DSB-AM communications system and then again with VDL-3 applied in the high-en route Southeastern airspace. For each depletion analysis, the number of new A/G circuits in the tower environment for which Spectrum Prospector could find assignments is noted. The *improvement in spectral capacity provided by VDL-3* is taken as the extra number of new A/G circuits for which Spectrum Prospector could find frequency assignments. Since VDL-3 is applied only in the high-en route environment in the Southeast, the results would indicate how much benefit is obtained in the tower environment by applying VDL-3 in the high-en route environment. The expected result is that since frequencies are freed-up in the high-en route environment through the bundling process, these frequencies can be reassigned where needed. As will be seen, the expected benefits did not materialize especially in the tower and terminal environments. The same strategy is applied to the other three environments.

2.4 DEPLETION RESULTS

Table 2 shows a comparison of the channel capacity before and after converting the Southeastern airspace to VDL-3. Based on one random arrival of new circuits, the results show the following. In the airspace where VDL-3 is applied, the improvement is large. An additional 162 circuits can be assigned frequencies just in the Southeast; another 25 circuits (total 187) can be assigned frequencies in the NAS. While the additional number of circuits that can be assigned frequencies outside of the Southeast is not large, this can be expected since VDL-3 was not applied there. VDL-3 applied to the high-en route Southeastern airspace may not provide as much capacity gains as 25 kHz applied to the high-en route airspace in the environments not converted to VDL-3. However, the differences are small and can be attributed to random effects. The next section provides a basis for this claim by providing the results of some statistical analyses.

The conclusion that should be drawn is that any benefits or lack of benefits in the environments where VDL-3 is not applied are small, regardless of whether VDL-3 is applied to the high-en route environment. VDL-3 has little affect where it is not applied Figures 2 and 3 provide a geographical depiction of the depletion analyses applied to the *before* and *after* VDL-3 conversion scenarios, respectively. The large light gray (yellow in color print) circles show where the model could assign frequencies to only an additional 2 high-en route circuits at radio sites within 100 nmi of the indicated TDLS airport. The dark gray (blue in color print) sections of airspace indicate where air traffic growth may lead to additional sectors by the year 2015. The black (red in color print) sections of airspace indicate the intersection of the light gray circles with the blue sections of airspace. Thus, the black sections of airspace indicate where there may be a need to add ATC sectors, but there will be limited VHF spectrum to support A/G communications.

The small black (purple in color print) stars show where the model could assign frequencies to 4 or fewer new circuits in the Tower environment. The large black stars indicate the same thing, but are located at airports where runway upgrades are planned [2]. These runway upgrades may require additional frequencies.

Note that in comparing the two figures, there is a reduction of the red and yellow areas as a result of applying VDL-3. This translates into a reduction in the spectral congestion due to the application of VDL-3. The square boxes in the figures can be used as a guide to see the reduction in spectral congestion in the Southeast. In addition, there is little or no change in the location of the small and large stars, indicating the lack of significant improvement in the environments where VDL-3 is not applied.

Comparing Figures 2 and 3 provides a visual illustration of the effects of applying VDL-3 to the Southeaster high-en route airspace. This comparison does show a benefit outside of the Southeast in the high-en route airspace of applying VDL-3 to the Southeastern high-en route airspace.

Table 2. Channel Capacity Improvement of VDL-3 Over 25 kHz DSB-AM

Number of available Channel Assignments							
Airspace [Approximate Number of Existing Circuits Before New Circuits Added (SE:1340/NAS: 7090)]	25 kHz DSB-AM		VDL-3		Improvement VDL-3 Over 25 kHz DSB-AM		
H-ENRT	132	689	294	876	162	25	187
L-ENRT	223	952	228	945	5	-12	-7
Terminal	153	815	152	816	-1	2	1
Tower	13	234	13	233	0	-1	-1

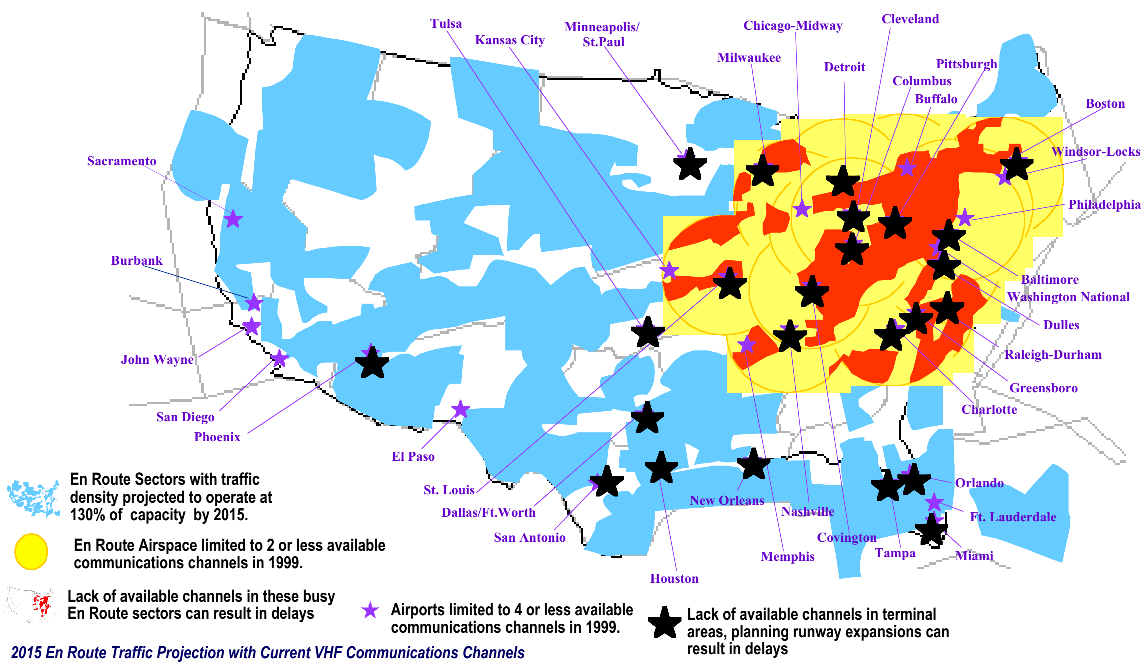

Figure 2. Spectrum Depletion Before Conversion of Southeaster High En Route Airspace to VDL-3

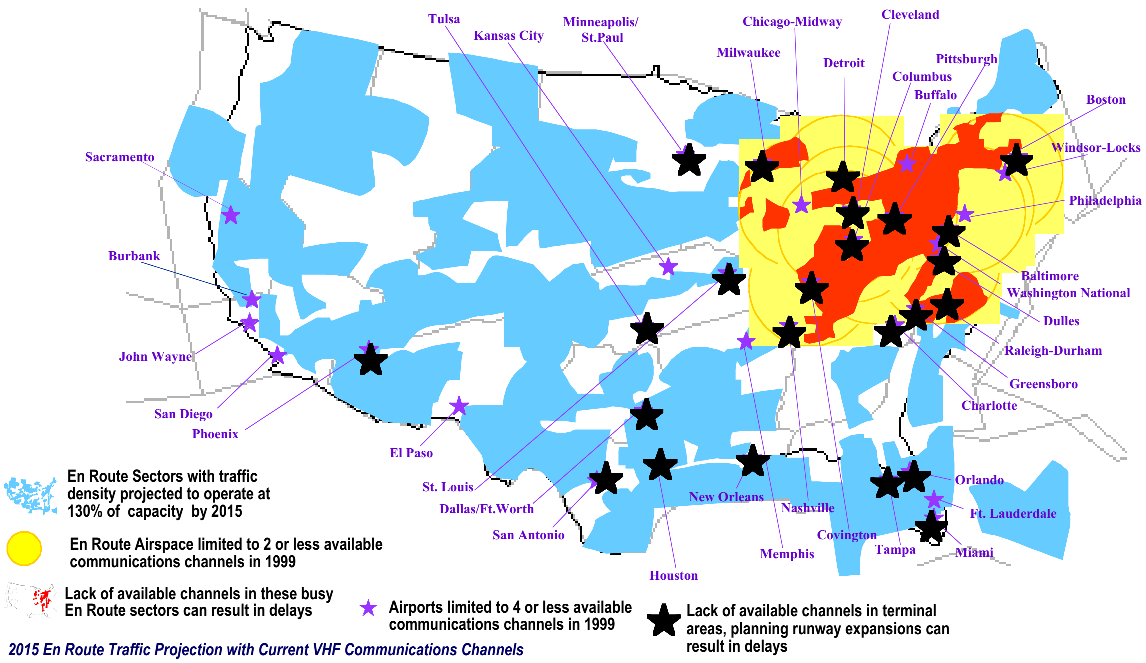

Figure 3. Spectrum Depletion After Conversion of Southeastern High-En Route Airspace to VDL-3

2.4.1 STATISTICAL ANALYSIS

Due to the random nature of the arrival of new circuits, a single depletion analysis reflects an approximate maximum rather than an absolute maximum. Because the model produces different results for each new set of random arrivals, it was necessary to perform a number of trial runs of the model with different random arrival sets. In order to obtain good estimates of the mean or average number of new A/G circuits that could be assigned frequencies by the model, a sufficient number of trials had to be determined. Based on the criterion provided in reference [3], it was determined that 30 trials would be sufficient. In addition, to obtain a 95% confidence interval reference, a t distribution with $n-1$ (n = number of trials) degrees of freedom was used. This was recommended in reference [4].

Thirty trials of the depletion analysis were performed for the terminal environment for both 25 kHz and VDL-3 applied to the Southeast airspace in order to demonstrate this fact. Table 3 shows the statistical results for 30 simulation trials, and Figures 4 and 5 show the corresponding capacity gains achieved for both 25 kHz and VDL-3 for each of the 30 trials for the NAS and for the Southeast, respectively. For both the NAS and the Southeast, Table 3 shows that VDL-3 provides a very slight advantage over 25 kHz. With 95% confidence, Table 3 shows that NAS-wide approximately 808 – 812 additional channels can be assigned frequencies assuming the high-en route airspace has been converted to VDL-3, and 805 – 808 when it remains analog. For the Southeast, the range is 154 – 155 for VDL-3 and the same for analog. Figure 4 shows that in all but about 3 simulations out of 30 for the NAS, the additional channels that can be assigned frequencies is greater with VDL-3 than without. For the Southeast, Figure 5 shows that, in 20 out of 30 simulations, VDL-3 has the potential to provide more spectral capacity than the current analog system.

For all practical purposes, the variation in the channel capacity gain is small in the unconverted environments (Tower, Terminal, L-ENRT) when comparing depletion-analysis results for the NAS with the *converted* and *unconverted* high-en route Southeast airspace. In other words, channel capacity in the environments ***where VDL-3 is not applied*** is unaffected by the application of VDL-3 in other environments.

Table 4 shows the results from thirty trials of the depletion analysis applied to the low-en route airspace from applying VDL-3 in the high-en route airspace. Figures 6 and 7 show the corresponding capacity gains achieved for both 25 kHz and VDL-3 for each of the 30 trials for the NAS and for the Southeast, respectively. The 95% confidence intervals do not overlap, and the VDL-3 confidence intervals are better than the 25 kHz confidence intervals. In comparing these results to the terminal case of Figures 4 and 5, a clearer sign of benefit from applying VDL-3 in the high-en route environment filters down to the low-en route environment. In Figures 4 and 5, the is a lot of intertwining of the VDL-3 and 25 kHz graphs, whereas in the low-en route environment, the VDL-3 graph in each of Figures 6 and 7 is in most cases above the 25 kHz graph.

Thirty simulation trials were also performed for the high-en route airspace. Table 5 shows the statistics on the channel capacity for these simulations. In this case, a clear benefit is seen from applying VDL-3 in the high-en route airspace. Figures 8 and 9 also clearly illustrate the benefit. The 95% confidence intervals for the NAS are 686-692 and 825-838 for 25 kHz and VDL-3, respectively. For the Southeast, they are 130-135 and 260-272 for 25 kHz and VDL-3, respectively. Thus, there is a large enough separation between the confidence intervals for 25 kHz and VDL-3 to say that there is a benefit in the high-en route airspace from applying VDL-3 to the high-en route airspace. Figures 8 and 9 clearly show the benefit. Thus, it can be said that in the high-en route environment **where VDL-3 is applied**, there is a significant increase in channel capacity as a result of applying VDL-3 there.

Table 3. Statistical Analysis of Channel Capacity Improvement in Terminal Airspace

Terminal Airspace	NAS		Southeast	
	25 kHz	VDL-3	25 kHz	VDL-3
Mean	806	811	154	155
95% Conf. Interval	804–809	808–812	153–155	154–156

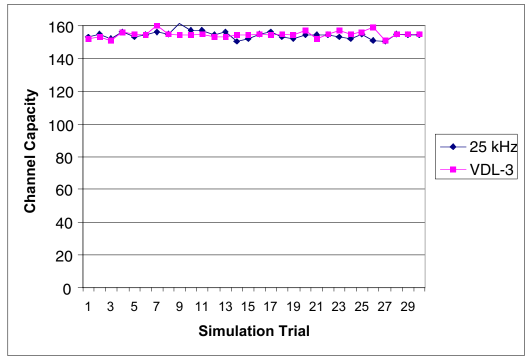

Figure 4. Southeast Channel Capacity Results in the Terminal Environment for 30 Simulation Trials

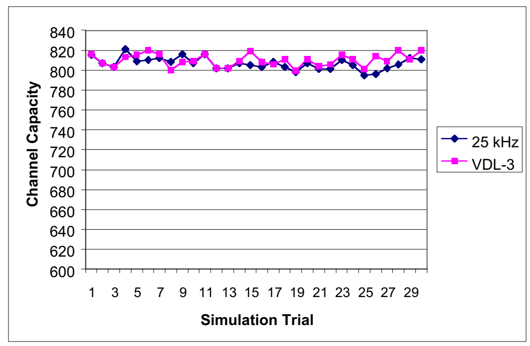

Figure 5. NAS Channel Capacity Results in the Terminal Environment for 30 Simulation Trials

Table 4. Statistical Analysis of Channel Capacity Improvement in Low-En Route Airspace

Low-En Route Airspace	NAS		Southeast	
	25 kHz	VDL-3	25 kHz	VDL-3
Mean	940	949	220	227
95% Conf. Interval	937–942	946–951	218–222	225–229

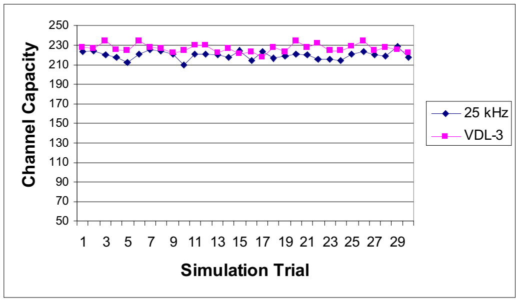

Figure 6. Southeast Channel Capacity Results in the Low-En Route Environment for 30 Simulation Trials

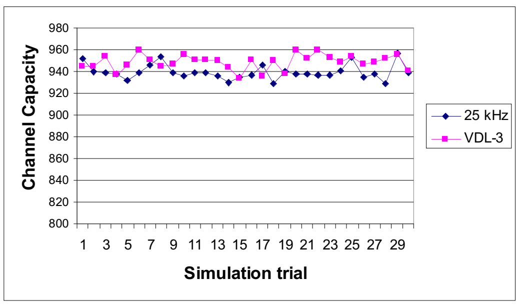

Figure 7. NAS Channel Capacity Results in the Low-En Route Environment for 30 Simulation Trials

Table 5. Statistical Analysis of Channel Capacity Improvement in High-En Route Airspace

High-En Route Airspace	NAS		Southeast	
	25 kHz	VDL-3	25 kHz	VDL-3
Mean	689	831	132	265
95% Conf. Interval	686–692	825–838	130–135	260–272

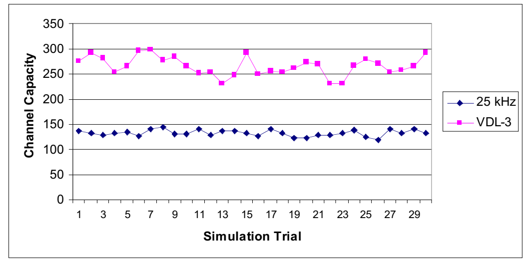

Figure 8. Southeast Channel Capacity Results in the High-En Route Environment for 30 Simulation Trials

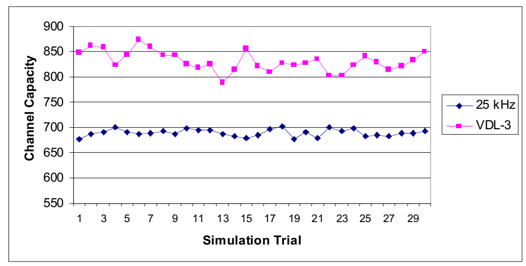

Figure 9. NAS Channel Capacity Results in the High-En Route Environment for 30 Simulation Trials

3.0 SUMMARY

This paper has demonstrated the effectiveness of *depletion analysis* in helping the FAA in its decision-making process regarding the impact of a new communications system on spectral capacity. Depletion analysis is based upon the MITRE/CAASD-developed tool called Spectrum Prospector which can simulate many aspects of spectrum use by a communications system.

This paper considered the application of depletion analysis to the VDL-3 system currently under consideration by the FAA for its next-generation A/G communications system. This application of depletion analysis has demonstrated that there is spectral benefit in H-ENRT airspace where VDL-3 is applied. However, the spectral benefit does not occur at altitudes where VDL-3 is not applied.

Further applications of depletion analysis, not reported in this paper, have demonstrated that the benefits of VDL-3 applied to the H-ENRT airspace did not filter down into the lower-altitude airspace because of the possibility for cosite and intermodulation RFI at those lower altitudes Such problems are potentially resolvable by introducing appropriate RFI mitigation techniques. Some physical mitigation techniques are the use of filters and the relocation of radio sites and antenna towers.

Thus, the application of depletion analysis, with the underlying Spectrum Prospector tool, has helped the FAA identify many of the root causes for its spectral problems, and in so doing has helped in determining potential solutions.

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