MONTE CARLO ANALYSIS OF AIRPORT THROUGHPUT AND TRAFFIC DELAYS USING SELF SEPARATION PROCEDURES

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Abstract

This paper presents the results of three simulation studies of throughput and delay times of arrival and departure operations performed at non-towered, non-radar airports using self-separation procedures. The studies were conducted as part of the validation process of the Small Aircraft Transportation Systems Higher Volume Operations (SATS HVO) concept and include an analysis of the predicted airport capacity using with different traffic conditions and system constraints under increasing levels of demand. Results show that SATS HVO procedures can dramatically increase capacity at non-towered, non-radar airports and that the concept offers the potential for increasing capacity of the overall air transportation system.

1 Introduction

The Small Aircraft Transportation System Higher Volume Operations (SATS HVO) concept of operations was developed as part of an effort to address the capacity problem of the air traffic system in the United States by promoting more evenly distributed air traffic and reducing congestion at large hub airports. This is accomplished by increasing access to thousands of public use airports in the United States without a major impact on the air traffic controller's workload or on overall National Airspace System (NAS) structures and principles.

In today's system air traffic controllers (ATC) provide sequencing and separation for all Instrument Flight Rules (IFR) and participating Visual Flight Rules (VFR) aircraft at all towered airports: they control aircraft on the runway and in the controlled airspace immediately surrounding the airport. They coordinate the sequencing of aircraft in the traffic pattern and direct aircraft on how to safely land and depart at and from the airport. Conversely, at airports without control towers and radar coverage, IFR flights are limited to one operation at a time, severely reducing the utilization of these airports. HVO procedures can increase the rate of operations at non-radar, non-towered airports by enabling multiple simultaneous arrivals and departures in near all-weather conditions within a designated volume of airspace where pilots have the responsibility for maintaining safe separation from other traffic. A complete description of SATS HVO concept and procedures can be found in References 1, 2, 3 and 4. This concept is particularly relevant nowadays that the air transportation system is going through a complete revision intended to address the expected increased demand of the future as described in the recent Joint Planning and Development Office (JPDO) report on the Next Generation Air transportation System (NGATS) [5].

The three Monte Carlo studies presented in this paper are part of the SATS HVO validation process that included safety verification and formal methods analysis [6,7], batch studies of performance [8,9], human-in-the-loop experiments designed to measure pilot's and controllers' workload and situation awareness [10,11,12], and flight tests [13]. The three different experiments were designed to

compare measures of delay and throughput obtained using both today's procedure-based separation and SATS HVO validating the predicted capacity improvements of the SATS HVO concept.

2 Overview of the SATS HVO Procedures

The SATS HVO concept relies on the establishment of a volume of airspace, identified as the Self Controlled Area (SCA) surrounding the airports within which pilots assume responsibility for self-separation. Flights operating in the SCA, during instrument meteorological conditions, are given approach sequencing information computed by a ground based automated system referred to as the Airport Management Module (AMM). All participating aircraft are required to be equipped with Automatic Dependent Surveillance-Broadcast (ADS-B) and must be able to communicate with the AMM. The AMM functions do not include separation services, altitude assignments, or departure sequencing information.

Aircraft arriving into the SATS designated airport are managed by ATC according to an IFR flight plan to a transition fix above the SCA. The transition fix is also the Initial Approach Fix (IAF) on a GPS-T instrument approach procedure. Prior to reaching the transition fix, pilots must request landing sequence information from the AMM. The AMM message includes relative sequence information that identifies a lead aircraft to be followed. If the SCA is full, then the AMM sends a "stand by" message. An SCA configuration such as the one shown in Fig. 1 allows a maximum of four aircraft on approach at any given time. An SCA with only one IAF would have a maximum capacity of two approaches at any given time.

Pilots in the SCA initiate their approach once adequate spacing behind the lead aircraft has been met. Adequate spacing is determined through either a generic rule-based spacing procedure, safe for all combinations of aircraft

performance, or by using an on-board self-spacing tool.

For departures, pilots must file flight plans with a SATS HVO departure procedure to a Departure Fix (DF), obtain ATC clearance, and then use onboard information/tools to find a departure window, (e.g., safe separation from other approaching and departing traffic). Since departures are not sequenced by the AMM then they are not limited by the SCA configuration or the number of ongoing approach operations. In other words, departures have no impact on arrival delays, while in today's procedural separation; departures are separated from arrivals in a one-in-one-out manner. Figure 1 represents a nominal circular SCA with two IAFs, Cathy and Annie also serve as the missed approach holding fixes (MAHFs). The two DFs, Ginny and Ellen are located
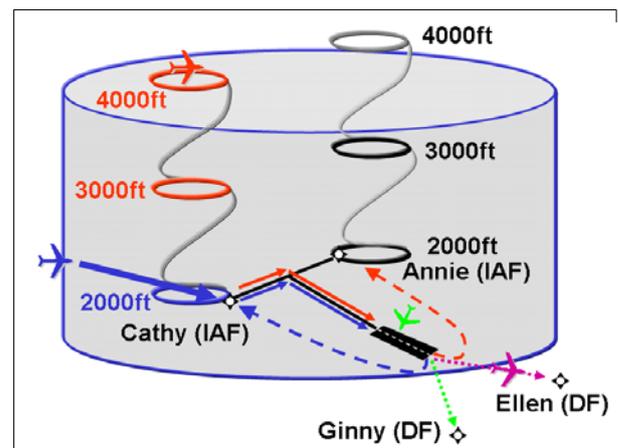

Fig. 1. Nominal SCA and approach geometry

outside the SCA. There are also two arriving aircraft (Red and Blue) with alternating MAHFs, and two departing aircraft (Green and Purple) depicted in a "snapshot" in time.

The SATS HVO concept relies on pilots complying with procedures, communicating their intentions and maintaining some degree of synchrony during operations. While minor deviations from these rules may have no negative effects, major procedure violations can be significant. A detailed description of the SATS HVO concept is out of the scope of this paper, but can be found in References 1, 2, 3, and 4.

3 Experimental Platform

The Air Traffic Operations Laboratory (ATOL) is a simulation facility developed by NASA Langley Research Center to evaluate new air traffic management concepts. The General Aviation (GA) simulation platform has been specially designed to investigate issues unique to General Aviation (GA), specifically integrating unscheduled operations into the NGATS and flight operations at airports without Air Traffic Control (ATC) services. The GA portion of ATOL is a distributed real time simulation platform that can be run in single-pilot, multi-pilot, or remote-site linked simulation experiments, all either with or without virtual traffic and/or voice communications. A number of unique software components provide both real time and batch simulation capabilities. The General Aviation Airport Traffic (GAAT) simulator used in this study is a virtual traffic generator that can operate as a real time tool for concept exploration and demonstration and as a batch tool for Monte Carlo simulation experiments.

The GAAT tool allows aircraft types, performance and characteristics to be configured to simulate different airport traffic combinations. Traffic patterns can also be configured to represent different sources of arrival streams with configurable rates. Pilot and ATC models implement all the necessary interactions to compare baseline operations with HVO. The pilot model enables the virtual aircraft to follow the sequence instructions given by the AMM model, maintain self-separation and proper spacing from a leading aircraft while in the SCA, as well as descend or climb to appropriate altitudes and maintain intended speeds. The ATC model assigns holding altitudes outside the SCA, provides departure clearances to all departing aircraft and provides approach clearances in non-HVO scenarios.

4 Experiment Design

A set of three batch experiments were conducted to compare measures of delay and throughput obtained using both today's procedure-based separation, referred to as Baseline operations, and SATS HVO. The model was implemented as a finite horizon discrete event simulation and special consideration was given to minimize both the initial state and terminating condition biases. In all runs, the first hour of simulation was discarded, and the runs were stopped after 11 hours of execution without allowing the system to clear the queues.

The simulated airport environment consisted of a single runway non-tower, non-radar airport. The approach geometry modeled was a GPS "T" approach with two IAFs and two DFs located outside the SCA. A nominal round SCA was represented with a 15 nm diameter extending from sea level up to 3000 feet of altitude. Holding altitudes for the IAFs were 2000 and 3000 feet for aircraft inside the SCA, and 4000 feet and above for aircraft under ATC control. The approaching traffic consisted of two airport departure routes and four fixed airport arrival routes as shown in Figure 2. Input traffic streams comprised multiple aircraft types and different performance characteristics.
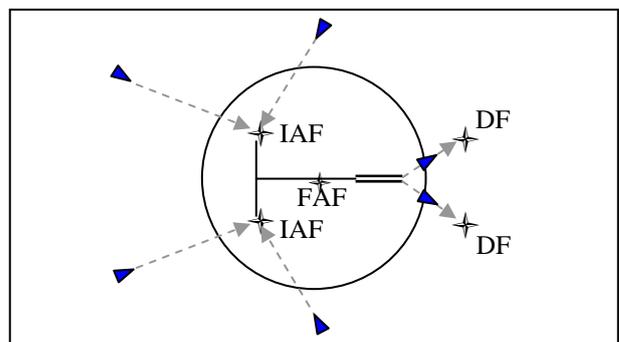

Fig. 2. Simulated Arrival and Departure Routes

Each input traffic stream had exponentially distributed inter-arrival times. Each run collected data for ten hours of simulated traffic flow.

To reduce the initial condition bias associated with queue filling, data collection did not include the first hour of simulation. Data collection stopped at the 11th hour without allowing the input queues to empty. Multiple replicates were performed for each

configuration to achieve a 95% confidence level that the mean arrival delay estimate was within a 2-minute error interval. In all scenarios, all traffic followed procedures and ATC instructions, and no non-normal operations (failures or emergency conditions) or missed approaches were simulated. The independent variable in all cases is the average input operations rate.
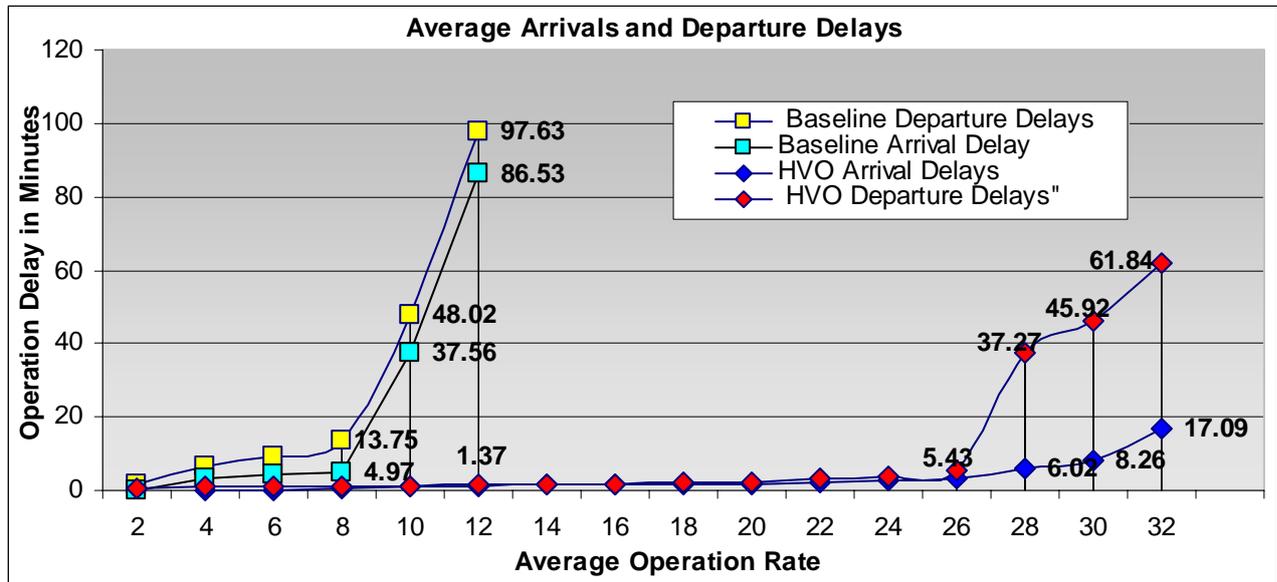

Fig. 3. Average Arrival and Departure Delays for Baseline and HVO Operations

4.1 Experiment 1: Balanced Traffic Load

In this experiment, approaches were uniformly distributed and "balanced" (evenly distributed) among all four sources. The average operation rate was increased for each run of 10 simulated hours of operations from 2 to 32 operations per hour. Operations were on average 50% approaches and 50% departures.

The goal of the study was to analyze the impact of SATS HVO procedures on airport capacity and traffic delays.

Performance metrics collected for SATS HVO scenarios includes:

1. *Arrival-Delay*: The sum of Stand-By-Delay plus Time-on-Hold. The Stand-by-Delay is computed as the elapsed time between a "STAND-BY" message and the entry notification sent by the AMM. Time-on-Hold is zero for an aircraft that is first on approach. Otherwise, it is the time elapsed between reaching the IAF and the time the pilot initiates the approach. This distinction allows considering only holding time and not the descent path up the IAF.

2. *Queue-Size:* Number of aircraft on Stand-By or Hold.

3. *Departure-Delay*: Computed as the time elapsed between a clearance request and the time the pilot turns on the runway. During a SATS operation this happens when there is enough separation from traffic, at least a 5 miles separation from approaching traffic and either 3 or 10 miles separation from other departing traffic depending on whether the previous departure was on the opposite or same departure fix (DF).

4. *Throughput:* Computed as the average number of operations completed per hour. Throughput is computed as the average of the means for all replicates. This includes both approaches and departures.

Performance metrics collected for Baseline scenarios include:

1. *Total-Delay:* The time elapsed between reaching the IAF and crossing the IAF on approach.

2. Queue-Size: Number of aircraft on Stand-By or Hold.

3. Departure Delay: The time elapsed between a departure clearance request and the clearance being granted.

4. Throughput: Same as above.

4.1.1 Arrival Delay Analysis

Figure 3 shows the comparative average arrival and departure delays of Baseline and SATS HVO operations for an airport demand ranging from 2 to 32 operations per hour.

SATS HVO arrival operations can sustain a combined average demand of 26 operations (13 approaches and 13 departures) per hour with an average delay of 5.43 minutes. When the input rate increases to 28 operations per hour the system reaches saturation and the delay curves begin to grow.

Baseline arrival operations show an average delay of 13.75 minutes for an average combined input rate of 8 average operations per hour (4 approach and 4 departure operations) and the system reaches saturation at 10 average

operations per hour. These results seem to indicate that SATS HVO can accept an input rate three times that of Baseline. To experience comparable average delays the Baseline input rate must be less than six average operations per hour, in which case SATS HVO input rate is four times higher.

4.1.2 Departures Delay Data

As shown in Figure 3 departure delay results are consistent with the arrivals results.

Baseline and SATS HVO departures experience comparable delays with input rates f 8 and 28 operations (4 and 14 departures) per hour respectively. HVO departures still show acceptable departure delays at an average rate of 30 operations per hour (15 departures) and begin to degrade at 30 average operations per hour. These results show that SATS HVO operations can support much higher traffic loads and about four times as many departures per hour with lower departure delays relative to baseline operations.
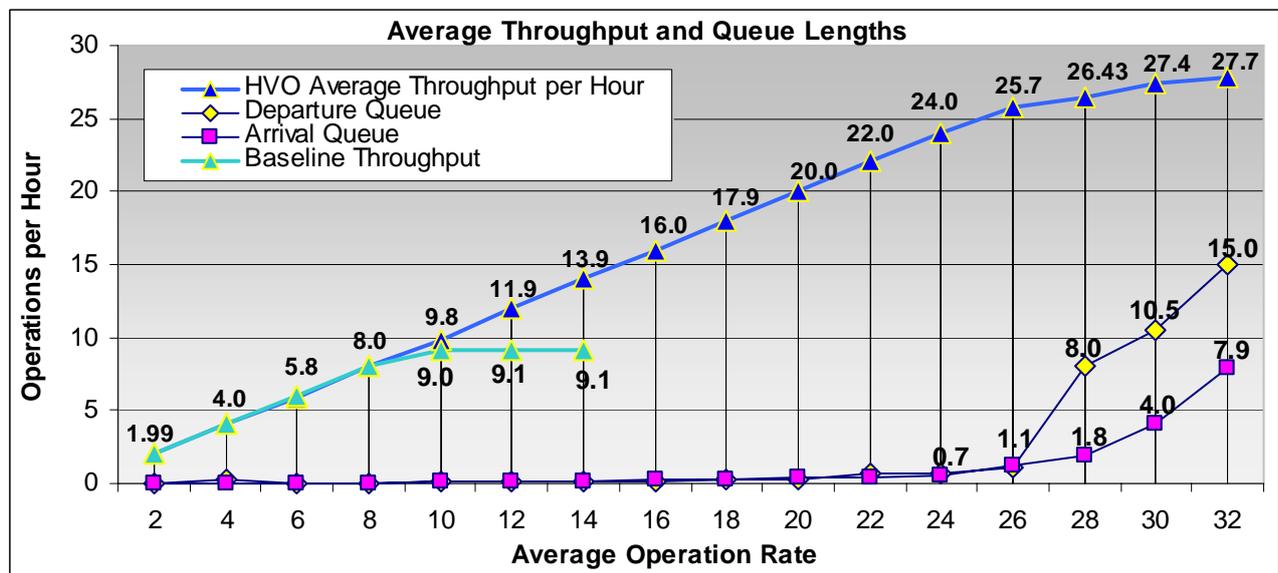

Fig 4. Average HVO Throughput and Queue Lengths

4.1.3 Throughput Analysis

Figure 4 shows the SATS HVO and Baseline throughput and queue lengths observed during the study under increasing traffic loads. The results complement the delays results from

Figure 3 showing the SATS HVO throughput increasing with input rate until it reaches an average of 26 operations per hour. At that point the system reaches saturation and the queues begin to build up. In fact, the peak sustainable combined throughput is reached at 24

operations per hour. As is was described in Section 2, the frequency of arrivals have no impact on departures in the SATS HVO concept, therefore, the arrivals and departure queues reflect different points of saturation that depend on the duration of the respective operations. Baseline throughput also shown in Figure 4, increases until the input rate reaches eight operations per hour and from that point on the system becomes saturated, with a peak sustainable average completion rate of eight and a maximum throughput of 9.1 operations per hour.

4.2 Experiment 2: Unbalanced Traffic Load

The goal of this study was to estimate the system capacity metrics in the presence of unevenly distributed arrivals. The study looked at delay times of SATS HVO vs. Baseline operations under increasing (unbalanced) traffic loads.

Two separate set of runs were performed. In both of them, the initial conditions were similar to the previous experiment but the approaching traffic pattern was modified to

cause overloading of one IAF. In this case, the ATC model made no effort to balance the load between the two IAFs causing the arriving traffic additional delays. As before, 50% of the operations were arrivals and 50% were departures.

In one set of runs, arrivals were distributed between 40% to one IAF and 10% to the opposite IAF. As shown in Figure 5, the average arrival delay for SATS HVO operations reflect the impact of unevenly distributed arrival traffic. The average delay for an average input rate of 20 operations per hour is about five minutes, about twice the delay in the balanced load experiment. At this point the system begins to reach saturation, and delay times begin to rise. As expected, the Baseline operations were virtually unchanged since they were always one operation at a time.

In the second set of runs, only a single IAF was used, so all the arrivals were assigned to a single IAF. In this case the SATS HVO delays indicate a sustainable demand of 18 operations (nine arrivals) per hour, still about twice the sustainable Baseline demand.
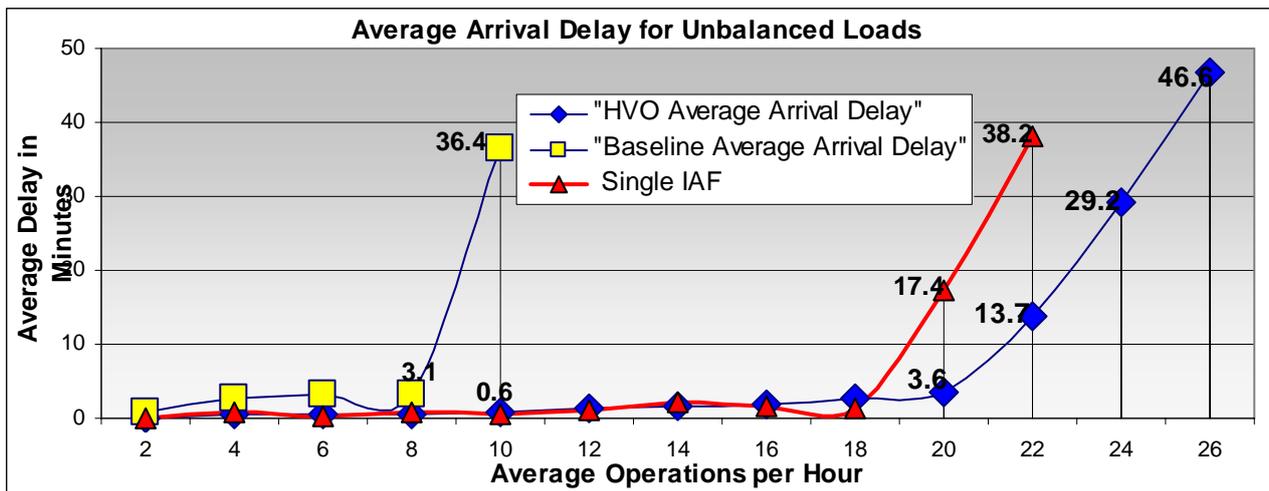

Fig. 5. Average Arrival delay for unbalanced loads

4.3 Experiment 3: Spacing Constraints

The goal of this study was to estimate the impact of approach spacing constraints on delay times and throughput of SATS HVO operations under increasing (balanced) traffic

loads. In-trail spacing constraints between approaching an aircraft and its lead on SATS HVO are affected by the equipage of the aircraft. Aircraft equipped with an advisory system such as the "Pilot Advisor" (PA) [14] are expected to maintain a minimum spacing of

3 nm with their lead aircraft on approach. The PA advises pilots on when to initiate the approach based on position reports and intended speed range of the lead aircraft. In addition, the PA monitors the spacing during approach and provides pilots speed adjusting advisories. More information on the PA can be found in Reference 14 and 15. For aircraft not equipped with this kind of automation, procedures require that pilots wait for the lead aircraft to be at the Final Approach Fix (FAF) before initiating the approach, resulting in more conservative spacing of about 10 nm. Pilots in this case must monitor the lead aircraft on their Cockpit Display of Traffic Automation (CDTI) and use their own judgment to initiate approach.

This study sought to estimate the impact of conservative spacing constraints on SATS HVO delays and throughput. All the initial conditions were the same as the first study of

balanced loads in section 4.2 except for the minimum spacing constraints that ranged from 3 nm to 10 nm of spacing between pairs of leading and trailing arriving aircraft. Input rates ranged from 12 to 30 average operations per hour.

As depicted in Figure 6, results indicate that approach spacing constraints have an effect on throughput and delays for both arrivals and departures. Arrivals throughput is increased with a spacing constraint of 3 nm, reaching an average of 14.4 completed arrivals per hour while departures reach an average of 13.0 completed departures per hour with an input rate of 30 operations per hour. In contrast, arrivals throughput is sharply reduced with 10 nm of spacing reaching a maximum of 9.4 completed arrivals per hour while departures reach 19.1 operations per hour within the tested input   range.
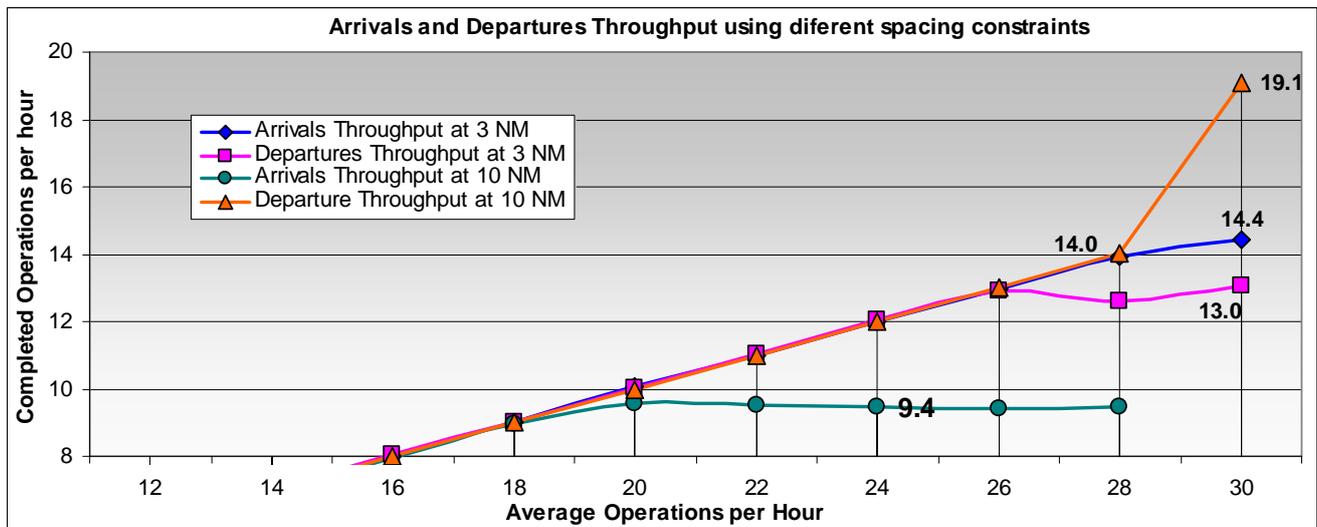

Fig. 6. Arrivals and Departure Throughput at different Spacing Constraints

The delays statistics are complementary of the throughput in that at 3 nm of spacing, arrivals experience the least delays and departures the highest while at 10 nm the opposite happens, arrivals experience the highest delays and departures the least ones.

5 Conclusion

This paper presented the results of three Monte Carlo studies of throughput and delay of SATS

HVO operations and today's procedural separation. The study showed that HVO operations can increase dramatically the capacity of non-tower, no-radar airports and in turn potentially increase the overall capacity of the NAS.

The impact of the SATS developed concepts and technologies is reflected in the interest generated in the aviation community and some policy making organizations such as the Joint Planning and Development Office

(JPDO) that recognized SATS in a recent report on the plans for the Next Generation Air Transportation System (NGATS). In particular, the 2005 NGATS Integrated Plan [5], mentions the SATS demonstration in June 2005 as a highly successful event and a very important milestone achieved by NASA in cooperation with the FAA and industry partners. "A whole new generation of safe and affordable small new aircraft will take advantage of the SATS enabling technologies and start delivering service where there is little or none before, thereby taking the pressure off busy airports while conveying other economic and quality of life benefits to literally thousands of smaller communities". The report goes on to say that the assessment of future system performance allows for both hub-and-spoke operations and a shift to the use of smaller regional airports for point-to-point operations. No matter what the expected demand growth, results indicate that the baseline system will not provide enough capacity to accommodate the levels and types of demand in future years.

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