Safety Study Report
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Safety Study Report on Required Navigational Performance (RNP) Parallel Approach Transition (RPAT) Operation Concept Flight at San Francisco International Airport

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12. Abstract

Flight Technologies and Procedures Division, AFS-400, conducted a Required Navigational Performance (RNP) Parallel Approach Transition (RPAT) operation concept flight using an Area Navigation (RNAV) RNP approach to San Francisco International Airport (SFO) Runway 28R with simultaneous operation of the Instrument Landing System (ILS) approach to Runway 28L. Special aircraft, aircrew, and Air Traffic Control (ATC) personnel training was required and utilized a No Transgression Zone (NTZ) monitored by an Airport Surveillance Radar Model 9 (ASR-9). Two aircraft and two sets of aircrews, an Alaska Airlines Boeing 737-700 Next Generation (NG) aircraft and aircrew, and a United Airlines Airbus 320 and aircrew were used in conducting this RPAT operation. The B-737 flew an RNAV approach to SFO 28R while the A-320 simultaneously flew an ILS approach to SFO 28L. These parallel runway centerlines are separated by 756 feet. AFS-400 was the lead organization in test plan formulation. AFS-440, responsibilities included Test Director and data collection and analysis. Northern California TRACON (NCT) and SFO tower personnel performed appropriate air traffic control duties for the duration of this concept flight. A Federal Aviation Administration (FAA) Test Director, a Human Factors expert, two representatives from SFO All-Weather Operations, a representative from the Denver Flight Standards District Office, and a MITRE representative were aboard the RNP aircraft (B-737). An FAA Observer was aboard the ILS aircraft (A-320). Eight (8) RPAT operation concept flight approaches were accomplished with Run #8, a planned missed approach by the RNP aircraft. Technical data was collected from three sources: 1) Data Acquisition Replay Tool (DART) data, 2) truth system with precision 1 Hz accuracy, known as Time Space Position Information System (TSPI), and 3) Automatic Terminal Radar System (ARTS) data from the ASR-9 radar. Subjective analysis data were provided from Controllers, Aircrew, Test Director and Observers.

Major areas that need further review and/or mitigation are: 1) Controller training for RPAT operations, 2) Aircrew workload issues for airspeed management, in-trail spacing, and closure rate judgment and coordination, 3) Validation of autopilot and ASR-9 for RPAT operations, 4) SFO RNAV (RNP) Y 28R construction that resulted in multiple flight path angles, NTZ not equidistant, and missed approach procedure issues during the curved path, and 5) Traffic Collision Advisory System (TCAS) usage for in-trail spacing and Resolution Advisories (RA). Two TCAS RAs occurred from large airspeed deltas generating an unacceptable closure rate. The conclusion is that aircraft airspeed, vertical velocities, and point at which to be on-speed and fully configured exceeded FAA and company standards for stabilized flight.

13. Key Words
Area Navigation (RNAV)
Required Navigation Performance (RNP)
RNP Parallel Approach Transition (RPAT)
San Francisco International Airport (SFO)
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EXECUTIVE SUMMARY

Flight Technologies and Procedures Division, AFS-400, proposed conducting a Required Navigational Performance (RNP) Parallel Approach Transition (RPAT) operation concept flight at San Francisco International Airport (SFO). This RPAT operation used SFO Runway 28R with dual stream simultaneous operation of the Instrument Landing System (ILS) approach to Runway 28L. These runway centerlines are separated by 756 feet.

The general concept is for two aircraft, on approach paths laterally separated by 5,000 feet or greater, to be paired by Air Traffic Control (ATC), with the RNP aircraft aft of the ILS aircraft. Prior to the Precision Final Approach Fix (PFAF), the RNP aircrew visually acquires the ILS aircraft. While the RNP aircrew visually monitors the ILS aircraft, the RNP aircraft continues to remain on its Flight Management System (FMS) Area Navigation (RNAV) course using the aircraft flight director and Lateral/Vertical Navigation (LNAV/VNAV) guidance. Aircraft separation is maintained through Radius-to-Fix turns (curved path) along the RNAV course to achieve runway alignment. The RPAT operation utilizes a No Transgression Zone (NTZ), monitored by an Airport Surveillance Radar Model 9 (ASR-9) (see Figure 1 in 2.0 Introduction). Special aircraft, aircrew, and Air Traffic Control (ATC) personnel training are required. Required ceiling is 500 feet above the Minimum Vectoring Altitude (MVA) or PFAF crossing altitude, whichever is higher. This allows approximately 30-seconds for the RNP aircrew to visually acquire the ILS aircraft before the convergence begins. Minimum visibility requirement is 4 miles, aiding in visual acquisition of the ILS aircraft, but without the requirement to have the landing runway in sight passing the PFAF.

On September 30, 2005, from 0130 PDT to 0330 PDT, two aircraft and two sets of aircrews, an Alaska Airlines Boeing 737-700 Next Generation (NG) aircraft and aircrew, and a United Airlines Airbus 320 and aircrew conducted this RPAT operation. The B-737 flew an RNAV approach to SFO 28R while the A-320 simultaneously flew an ILS approach to SFO 28L. AFS-400 was the lead agent in test plan formulation. Flight Operations Simulation and Analysis Branch, AFS-440, responsibilities included Test Director and data collection and analysis. Northern California TRACON (NCT) and SFO tower personnel performed appropriate air traffic control duties for the duration of the concept flight. An FAA Test Director, a Human Factors expert, two representatives from SFO All-Weather Operations, a representative from the Denver Flight Standards District Office, and a MITRE Company representative were aboard the RNP aircraft (B-737). An FAA Observer was aboard the ILS aircraft (A-320).

A series of telecommunications with the RNP Office, NCT, SFO Tower, Flight Operations Branch, AFS-410, Flight Technology Requirements Branch, AFS-430, AFS-440, Alaska Airlines, and United Airlines were conducted to develop the concept flight test plan. The concept flight test plan outlined the concept of operations, requirements and responsibilities, evaluation procedures, and criteria for success.

Eight (8) RPAT operation concept flight approaches were accomplished with Run #8, a planned missed approach by the RNP aircraft. Technical data was collected from three sources: 1) Data Acquisition Replay Tool (DART), data which recorded the RNP aircraft's Flight Management

System (FMS) information, 2) truth system with precision 1 Hz accuracy, known as Time Space Position Information System (TSPI), which records actual aircraft position in space using a differential (one on the aircraft and one on the ground) Global Positioning Systems (GPS), and 3) Automatic Radar Terminal System (ARTS) which is radar information collected directly from the ASR-9 radar system. Subjective analysis data was collected from Controllers, Aircrew, Test Director, and Observers.

This RPAT operation provided valuable technical and operational data for a first-look at this procedure using industry aircraft and ATC infrastructure. The truth data showed that the RNP aircraft remained within 100 feet of the planned horizontal and vertical ground track. Additionally, there was less than a 1:1 million probability that the two aircraft could cross paths at the same time and place (i.e., less than 10^{-6} that there could be a wing collision). However, the test data and subjective analysis also indicated that there are several hurdles to overcome before actual implementation. Among these issues are resolving Traffic Collision Avoidance System (TCAS) Resolution Advisory (RA) alerts, airspeed management, aircrew (individual and collective) workload and coordination, controller training to properly pair aircraft, and validation of the autopilot and ASR-9 radar for RPAT operations.

In-trail spacing between the ILS aircraft and RNP aircraft initially started at 2-3 miles. This spacing was not acceptable for wake vortex mitigation and aircrews attempted to close this gap to inside 1 mile by the use of airspeed control. In this chain of events, as in-trail spacing difficulties occurred, it directly impacted the RNP aircrew's airspeed management, which in turn impacted aircrew workload and coordination, and on two occasions resulted in TCAS RAs. Controller training may aid in improving pairing and in-trail spacing operations. There was no wake vortex encountered during this concept flight.

Airspeed management is pivotal to the success of an RPAT operation. Airspeed ranges varied widely for both aircraft during all the approach attempts. To safely achieve proper in-trail spacing, there must be a stable target (the ILS aircraft) upon which to maintain relative positioning. If the ILS aircraft's airspeed changes rapidly or is inconsistent, difficulties will exist for the RNP aircraft, aircrew, and controllers to achieve a stabilized and properly spaced approach. Additionally, higher airspeeds will result in higher vertical velocities and becomes problematic for aircrew workload, configuration changes, and stabilized flight. Lastly, as seen from this test, the high airspeed delta between the two aircraft directly caused TCAS RA alerts while at low altitude in the final approach segment.

Finally, the SFO RNAV (RNP) Y 28R approach designed for this RPAT operation required a minus 5.2 degrees flight path angle from the BATKE Initial Approach Fix to GUTTS waypoint. The flight path angle adjusted to a minus 1.29 degrees from GUTTS waypoint to the DONNG PFAF, finally reaching a minus 2.8 degrees flight path angle after DONNG (see Figure 2 in 4.0 Concept of Operations).

This multiple flight path angle approach design resulted in additional aircrew workload and multiple high rates of vertical velocity changes.

Recommendations are:

a) Enhance the current RPAT procedure design tool to allow design flexibility in mitigating closure rates and incorporating a means to include and determine/display the design envelop for TCAS RA for evaluation/procedure design.

b) Develop an aircrew and controller training program for RPAT operations to answer in-trail spacing, workload, aircrew coordination, and airspeed management issues.

c) Conduct additional studies on wake vortex mitigation, to include aircrew and controller responsibilities, for RPAT-type operations.

d) Validate the use of the autopilot to reduce aircrew workload and the use of the ASR-9 radar for RPAT-type operations.

e) Redesign the RNAV approach to reflect an optimum continuous flight path descent angle throughout the RPAT operation and require this for all RPAT operations.

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1.0. PURPOSE

The purpose of this safety report is to provide data analysis and subjective observations from Required Navigation Performance (RNP) Parallel Approach Transition (RPAT) operation concept flight utilizing an Area Navigation (RNAV) RNP approach at San Francisco International Airport (SFO).

2.0. INTRODUCTION

The 2005 Federal Aviation Administration (FAA) Flight Plan goals included implementing one RPAT operation in fiscal year 2005. Flight Technologies and Procedures Division, AFS-400, completed an initial evaluation of the RPAT operation for SFO and proposed that a RPAT operation concept flight could provide additional information and benefit to the evolution of the RPAT concept.

RNP aircraft technology is providing certified navigation systems with the ability to maintain aircraft lateral and vertical flight path guidance within a specified approach design that can 'mold' the approach course around in-flight obstacles such as noise sensitive areas and mountainous terrain. This capability provides an opportunity to evolve new standards and procedures to enhance the safety and capacity of the National Airspace System. The manner in which the aircraft is operated is essential to ensure that the technology is applied safely, correctly, and efficiently. RPAT, as a derivative of RNP technology, could potentially enhance capacity at airports with closely spaced parallel runways.

An RPAT operation encompasses two instrument approaches, a straight-in precision Instrument Landing System (ILS) approach to one runway and a Special Aircraft Aircrew Authorization Required (SAAAR) offset RNAV RNP approach to the other runway. Figure 1 is a schematic of an RPAT operation with the blue dotted line the ILS approach and the red solid line the RNAV RNP approach. RPAT is envisioned to be used at airports with parallel runway centerlines as close as 750 feet apart. The concept is for two aircraft, on intermediate approach segment courses laterally separated 5,000 feet or greater, to be paired by Air Traffic Control (ATC), with the RNP aircraft in-trail of the ILS aircraft. Prior to the Precision Final Approach Fix (PFAF),
the RNP aircrew visually acquires the ILS aircraft. While the RNP aircrew visually monitors and maintains visual separation from the ILS aircraft, the RNP aircraft continues to remain on the Flight Management System (FMS) RNAV course using the aircraft flight director and Lateral/Vertical Navigation (LNAV/VNAV) guidance. The RNAV course uses Radius-to-Fix turns (curved path circled in blue as shown in Figure 1) that establishes a converging track with the ILS approach course, leading to runway extended centerline alignment.

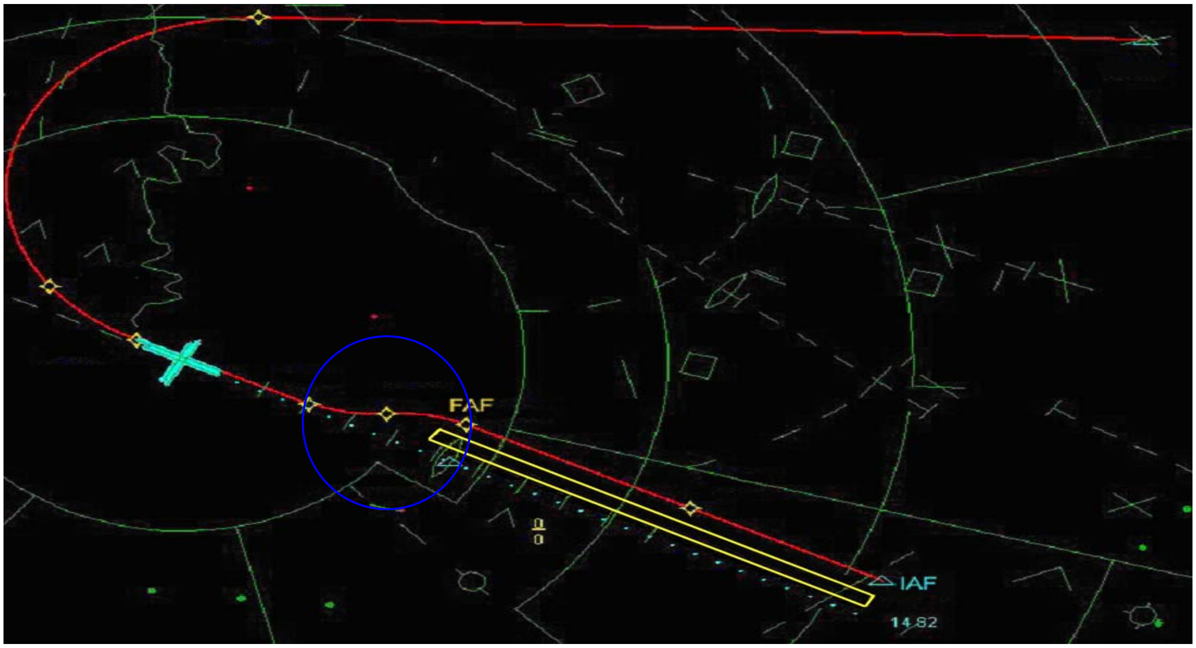

Figure 1: RPAT Pictorial with NTZ

A 2,000-foot wide No Transgression Zone (NTZ) was positioned between the RNAV and ILS intermediate approach segments (yellow rectangle in Figure 1). ATC was required to issue appropriate "breakout" instructions, if the NTZ was breached by either aircraft. Once the participating RNP aircraft was beyond the PFAF and in the final approach segment, the RNP aircrew was responsible for determining and reacting to a blunder and/or lost sight/missed approach situation.

Airport Surveillance Radar Model 9 radar (ASR-9) surveillance and the use of two NTZ monitor controllers for Normal Operating Zone (NOZ) containment assurance and mitigation were not changed from current simultaneous independent Instrument/Microwave Landing System (ILS/MLS) operations.

Required RPAT ceiling is 500 feet above the Minimum Vectoring Altitude (MVA) or PFAF crossing altitude, whichever is higher. This allows approximately 30 seconds for the RNP aircrew to visually acquire the ILS aircraft before the convergence begins. Minimum visibility requirement is 4 miles, aiding in visual acquisition of the ILS aircraft. However, there is no requirement to have the landing runway in sight passing the PFAF.

In this report, the term 'diagonal spacing/distance' refers to the straight-line distance between aircraft. The term 'in-trail spacing/distance' refers to a point ahead or behind the leading ILS aircraft. This point is defined by a line emanating from the adjacent RNP aircraft, which perpendicularly crosses the leading ILS aircraft's track or projected track.

Convergence resulting in parallel track spacing inside 2,500 feet requires vigilance for potential wake vortex encounters. An FAA SFO wake vortex safety study determined that if a trailing aircraft's in-trail spacing is less than a variable 0.8 to 1.2 miles, depending on the aircraft's airspeed, the potential for a wake vortex encounter is mitigated for runway centerlines as close as 750 feet apart. Therefore, ATC controllers must establish the trailing aircraft in a position where the RNP aircrew can both visually acquire the ILS aircraft and maintain a position within nominally 1 mile in-trail spacing. Under current RPAT operation guidance, during the convergence and final approach segment beyond the PFAF, the RNP aircrew assumes collision avoidance and wake vortex responsibility and must take action where necessary to maintain a position to avoid collision or wake vortex encounter. The capability to maintain this separation is essential to wake vortex mitigation**.**

3.0. OVERVIEW

Flight Technologies and Procedures Division, AFS-400, conducted an RPAT operation concept flight at SFO on September 30, 2005, from 0130 PDT to 0330 PDT (night operations). Two aircraft and two sets of aircrews, an Alaska Airlines Boeing 737-700 Next Generation (NG) aircraft and aircrew, and a United Airlines Airbus 320 and aircrew were used in conducting this RPAT operation. The B-737 flew an RNAV approach to SFO 28R while the A-320 simultaneously flew an ILS approach to SFO 28L. These parallel runway centerlines are separated by 756 feet. AFS-400 was the lead organization in test plan formulation. Flight Operations Simulation and Analysis Branch, AFS-440, responsibilities included Test Director and data collection and analysis. Northern California TRACON (NCT) and SFO tower personnel performed appropriate air traffic control duties for the duration of this concept flight. An FAA Test Director, a Human Factors expert, two representatives from SFO All-Weather Operations, a representative from the Denver Flight Standards District Office, and a MITRE representative were aboard the RNP aircraft (B-737). An FAA Observer was aboard the ILS aircraft (A-320).

Air Traffic Organization-Terminal Services provided controller guidance and authorization in order to perform duties for this RPAT operation concept flight. Operational parameters for the RPAT operation concept flight were fully vetted, agreed upon, and documented in advance of this concept flight by all stakeholders.

A series of telecommunications with the RNP Office, NCT, SFO Tower, Flight Operations Branch, AFS-410, Flight Technology Requirements Branch, AFS-430, AFS-440, Alaska Airlines, and United Airlines were conducted to develop the RPAT operation concept flight test plan. This test plan outlined the concept of operations, requirements and responsibilities, evaluation procedures, and criteria for success. This test plan is available upon request.

4.0. CONCEPT OF OPERATIONS

A prototype SFO RNAV (RNP) Y 28R approach chart was used to support this RPAT operation concept flight (Figure 2).

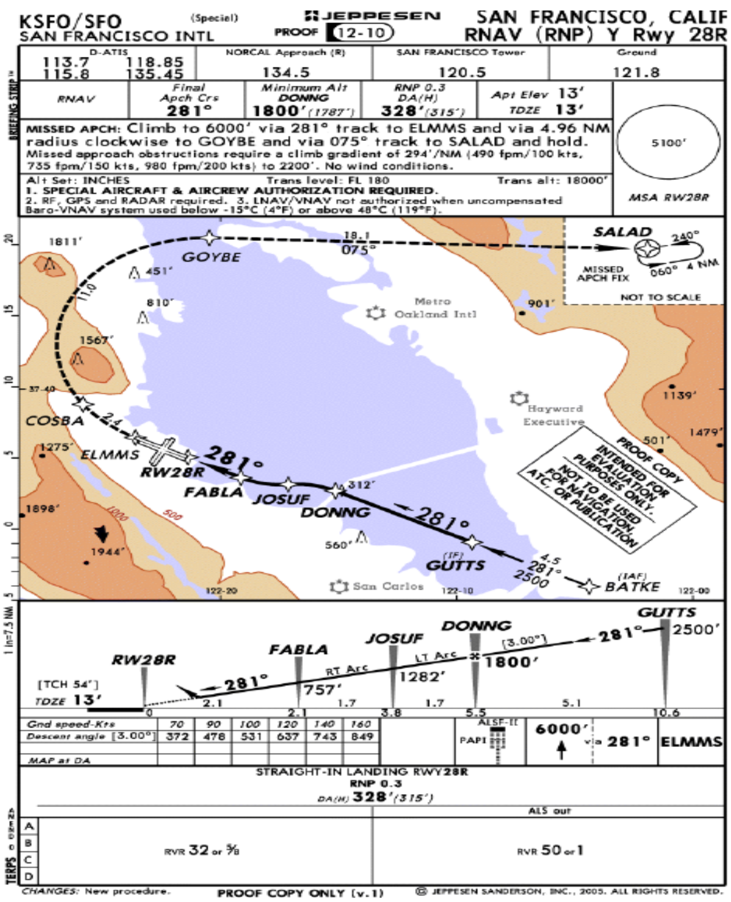

Figure 2: SFO RNAV (RNP) Y Rwy 28R

Note: For RPAT operation clarification, DONNG PFAF is the Start Turn Point (STP), JOSUF the curved path turn reversal waypoint, and FABLA the Final Roll-Out Point (FROP).

The parallel ILS and RNAV intermediate approach course segments were separated by 6,600 feet and only required an ASR-9 radar for NTZ monitoring. The RNP aircraft was the trailing aircraft in all cases.

All approaches were flown in Traffic Collision Avoidance System (TCAS) RA/TA (Resolution Advisory/Traffic Advisory) mode for both aircraft. Aircrews were required to appropriately respond to any TCAS RA warning resolutions in accordance with their company directives.

The aircrews informed ATC of any resulting action taken with regard to resolution alerts. No formal TCAS RA written reports were required in conjunction with this RPAT operation concept flight.

Autopilot and auto-throttles 'engaged' and LNAV/VNAV 'coupled' to the Decision Altitude (DA) were required for the first three approaches. The RNP aircrew elected to use the autopilot and auto-throttles for all eight approaches. The RNP Captain flew the first three approaches, the First Officer the next three approaches, and the Captain flew the final two approaches. The RNP and ILS aircraft remained in radio contact with each other (inter-plane) using the Alaska Airlines company operations very high frequency (VHF).

Meteorological conditions of 2,300-foot ceilings and 5-mile visibility were required for this RPAT operation concept flight (5-mile visibility was the initial visibility requirement for RPAT, subsequently changed to 4 miles). If visual acquisition was not obtained and maintained, a missed approach was required to be executed. Actual weather was clear skies, full moon, and greater than 10 miles visibility. Winds were 120 degrees at 5 to 10 knots (tailwind of 5 to 10 knots).

The Alaska B-737-700 departed the Seattle-Tacoma International Airport (SEA) gate at approximately 0630Z (2330 PDT, September 29). The United Airlines A-320 departed the SFO gate at approximately 0715Z (0015 PDT, September 30). NCT provided radar vectors to each simultaneous approach, using the ASR-9 radar, so that the RNP aircraft was in position to visually acquire the ILS aircraft before the DONNG PFAF waypoint (See Figure 2). NCT was responsible for Instrument Flight Rules (IFR) separation on the respective approach course centerlines <u>until visual acquisition was transmitted by the RNP aircrew.</u> ATC controllers were tasked in the test plan to position both participating aircraft, using standard radar vector techniques (intercept angle, distance, and airspeed), to arrive *"approximately the same time or with the RNP aircraft slightly trailing the ILS aircraft when the RNP aircraft is over the DONNG PFAF."* Air Traffic personnel provided ATC radio communication including weather information, traffic advisories, clearance to land, and "breakout" instructions (for blunder evasion) to aircrews.

Once visual acquisition was achieved, the RNP aircrew was responsible for maintaining visual separation during these closely-spaced operations, including the diverging turn during the initial portion of the missed approach climb-out. Both participating RNP and ILS aircrews were verbally briefed on the aircraft in-trail spacing goal of inside 1 mile for wake vortex mitigation and SFO tower operations. Note that aircraft in-trail spacing goal of less than 1 mile was eliminated from the test plan at NCT's request (further discussed in Paragraph 7.1., ATC Radar Vectors). If the RNP aircrew was unable to maintain visual contact with the parallel adjacent ILS aircraft or could not remain abeam or behind the ILS aircraft, the RNP aircrew was required to execute a missed approach. If at anytime during the RNAV approach (i.e., inside DONNG PFAF) a missed approach was executed due to weather, aircraft, aircrew, and/or ATC issues, the RNP aircrew would execute that missed approach maneuver by performing a climbing right turn to 040 degrees and 4,000 feet.

The ILS aircraft, when executing a missed approach, would begin a climb to 600 feet in accordance with the published missed approach instructions for the ILS 28L unless otherwise directed by ATC. Both aircraft were required to execute a go-around at 50 feet above the runway. On go-around execution, the ILS aircraft would proceed straight-out, per the published ILS 28L missed approach instructions, to 3,000 feet and the RNP aircraft would begin a turn at a minimum of 400 feet to a heading of 040 degrees and climb to 4,000 feet. The ILS aircraft was subsequently vectored for a left downwind pattern at 4,000 feet and the RNP aircraft for a right downwind pattern at 5,000 feet.

The last approach was planned as a RNP aircraft-only missed approach initiated between DONNG PFAF and JOSUF (first half of the curved path). Last approach notification was passed on downwind to NCT and to the ILS aircraft (common freq) from the Test Director. The RNP aircraft received clearance to depart SFO and returned to SEA while the ILS aircraft landed at SFO.

5.0. TECHNICAL DATA ANALYSIS.

Eight (8) RPAT operation concept flight approaches were accomplished with Run #8, a planned missed approach by the RNP aircraft. Technical data was collected from three sources:

1) The Data Acquisition Replay Tool (DART) data which recorded the RNP aircraft's Flight Management System (FMS) information including true airspeed, mean sea level altitude, and course deviations such as statistical Navigational System Error (NSE). Statistical NSE is commonly characterized as Actual Navigation Performance (ANP).

2) Time Space Position Information System (TSPI), a truth system with precision 1 Hz accuracy which records actual aircraft position and ground speed in space using a differential, one on the aircraft (antenna in the cockpit) and one on the ground, Global Positioning Systems (GPS). The GPS receiver placed at the survey point compares its known position with its calculated position and determines a positional error, caused by anomalies such as ionospheric conductions and selective availability. The position error is then transmitted as a real-time correction that is incorporated into the airborne GPS receiver's final calculated position. Truth data was collected on both the RNP and ILS aircraft.

3) Automatic Terminal Radar System (ARTS) which is radar track data and ground speed information collected directly from the ASR-9 radar system. This is not the presentation depicted on the controller's display.

For clarification, the following definitions will aid in understanding the types of aircraft system errors:

a) **RNP** - Required Navigation Performance is a statement of the navigation performance accuracy necessary for operation within a defined airspace. (U.S. Standard Flight Inspection Manual 8200.1B, Chg 2)

b) **ANP** - Actual Navigation Performance is an onboard computation of the estimated 95% Navigation System Error (NSE) using knowledge of the real world navigation environment (i.e., number of satellites tracked, number/geometry of ground facilities, and statistical error models of the various navigation sources). ANP is continuously compared to RNP, and the aircrew is alerted if ANP exceeds RNP. (U.S. Standard Flight Inspections Manual 8200.1B, Chg 2)

c) **FTE** - Flight Technical Error is a measure of how well the aircraft is tracking the lateral and vertical paths estimated by the navigation system. The aircrew observes FTE with deviation scales by using the aircraft's digital Control Display Unit (CDU) or by noting how far the airplane symbol on the navigation display (ND) has deviated from the programmed route. This is better known as cross-track error. (Boeing Aero 16 document)

d) **TSE** - Total System Error is the square root combination of NSE^2 and FTE^2. (U.S. Standard Flight Inspections Manual 8200.1B, Chg 2)

Figure 3 is a pictorial representation of the overall ARTS data with the RNP aircraft on a right-hand pattern ground track and the ILS aircraft on a left-hand pattern ground track. As seen from Figure 3 and highlighted in each run description below, the wider downwind flown by the RNP aircraft and the one continuous turn by the ILS aircraft to final approach resulted in the RNP aircraft on average 2 to 3 miles in-trail of the ILS aircraft at the BATKE IAF. Additionally, the ILS aircraft was directed to turn first in all approaches except the seventh run, where the RNP aircrew requested to turn first. The greater distance the RNP aircraft had to travel, the one continuous turn to final for the ILS aircraft, and the ILS aircraft turning first all contributed to the larger than expected aircraft in-trail spacing while on the intermediate approach segment. This issue is further discussed in paragraph 7.1, ATC Radar Vectors.

No aircraft entered the NTZ. However, on Run #8, the ILS aircrew was late in activating the 'Approach Mode' and overshot the localizer final approach course before the beginning of the NTZ. This overshoot of the localizer final approach course is circled in red in Figure 3.

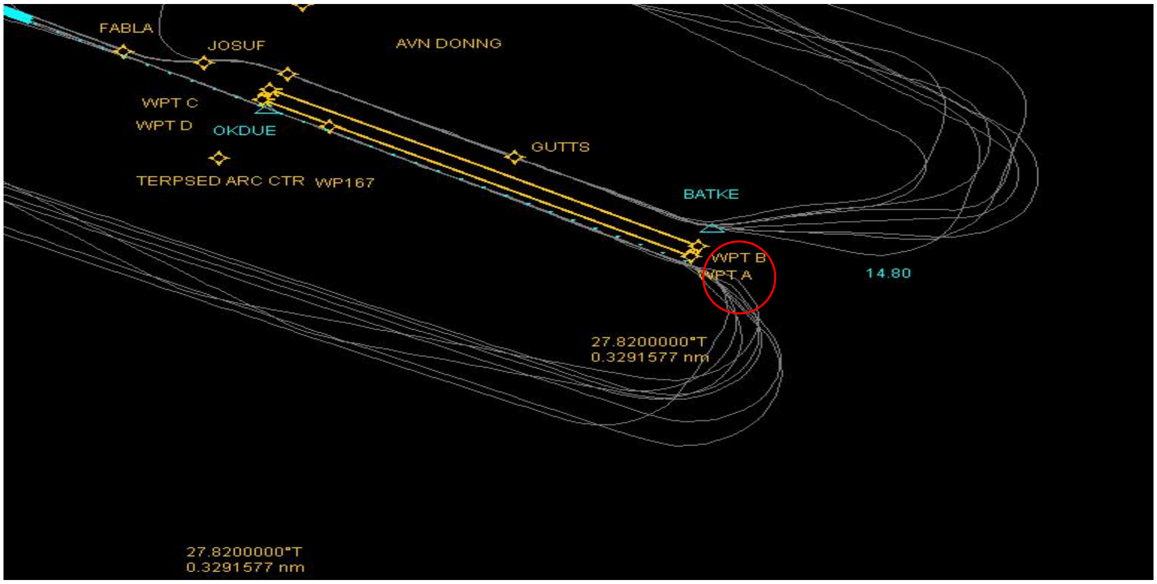

Figure 3: ARTS Data All Approaches

Figure 4 shows a close up of the ARTS picture of all the final approach segment runs. <u>There was no wake vortex or jet wash experienced on any of the runs.</u>

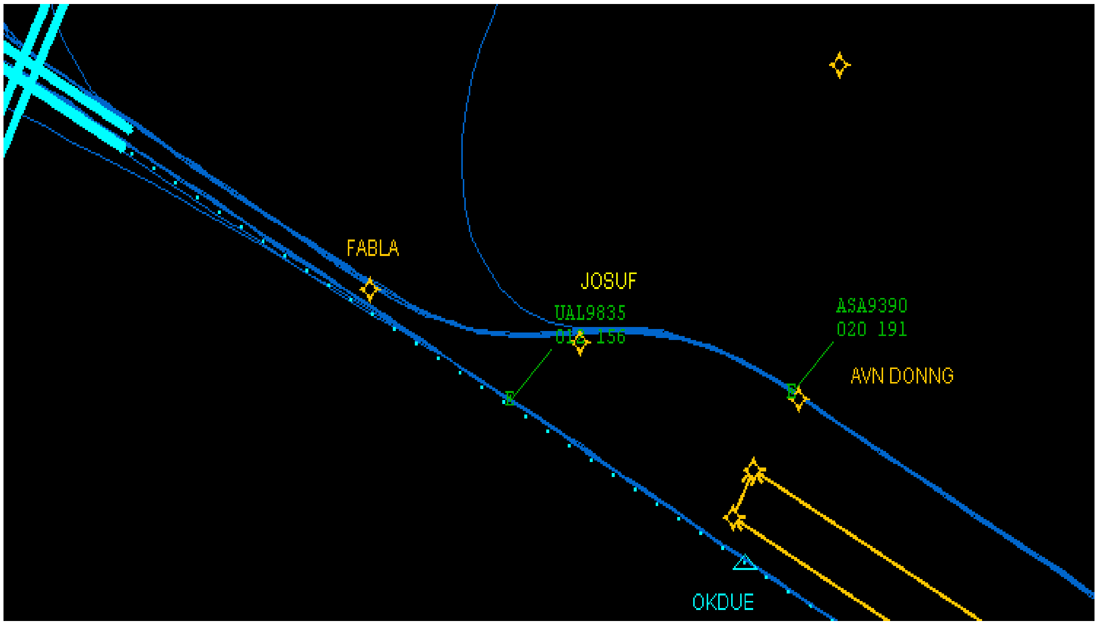

Figure 4: Overall Final Approach Segment ARTS Picture

Note: The ILS OKDUE PFAF is not directly abeam the RNAV DONNG PFAF. Also, The RNP aircraft right turn at JOSUF is the Run # 8 planned missed approach. The parallel ILS and RNAV intermediate approach segments are separated by 6,600 feet. The yellow rectangular box between the ILS and RNAV courses is the NTZ.

For this test, the NTZ was positioned 1,150 feet from the ILS course, not equidistant between the ILS and RNAV courses in conformance with current FAA requirements. This is further discussed in paragraph 7.3, SFO RNAV (RNP) Y 28R Construction.

Table 1 shows the overall RNP aircraft flight management system (FMS) DART data numbers. The average ANP of 0.06, highlighted in green, means the RNP aircraft's average position was 95% of the time within a 720-foot diameter circle, whose center was the estimated desired position or within 360 feet either left or right of course. This average ANP was well within the RNP 0.3 (1,800 feet) limit set for the SFO RNAV (RNP) Y 28R approach. Further defined, the FMS cross track error (FTE) average, highlighted in green, was less than 9 feet. The cross track errors highlighted in red occurred during the intermediate approach course segment intercept. The cross track error during the curved path (DONNG-JOSUF-FABLA) did not exceed the 200-foot centerline overshoot limit for all cases and is shown in the tables listed for each run (Para. 6.0, Operational Data). The 200-foot limit was established from previous simultaneous approach tests as a curved path course overshoot limit for aligning with the runway centerline during simultaneous close-in parallel operations.

All Runs	AVERAGE	MIN	MAX	MEDIAN	STDEV
True Air Speed	182.42809	128.3	242.2	187.9	30.0875
Vertical velocity	-911.9467	-2921	408	-954	295.4883
ANP	0.0612506	0.036	0.111	0.048	0.02292
Cross Track Error (FTE)	8.8126849	-349.8	325.8	3.1	71.70092

Table 1: RNP Aircraft FMS Data All Runs

Figure 5 shows a truth data pictorial for all the runs. The red line represents two-sigma envelope, or a 95% normal distribution of the flight paths. The blue lines represent six-sigma, or a 99.999999% of the normal distribution of the flight paths. Said another way, six-sigma is a 1:1 million probability. With the gap between the two blue lines, circled in red in Figure 5, there was less than a 1:1 million probability that the two aircraft could occupy the same airspace at the same time and place (i.e., less than 10^{-6} that there could be a collision).

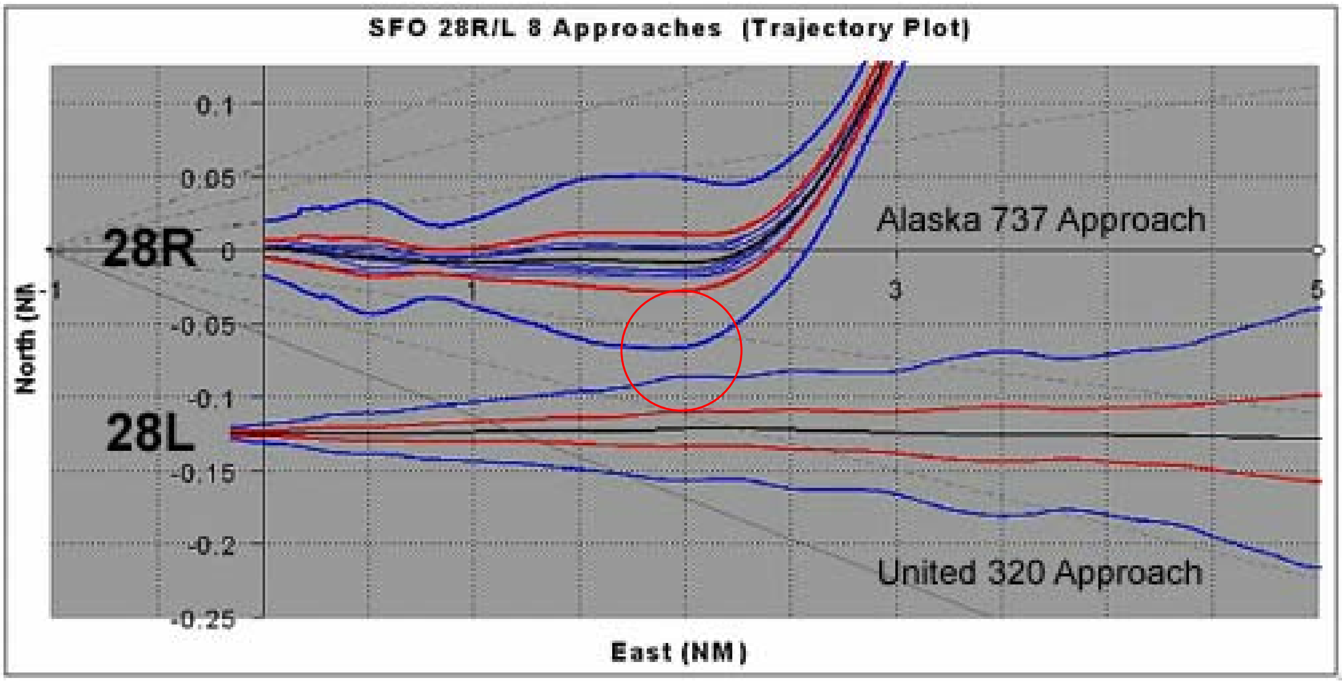

Figure 5: Truth Data Pictorial

Table 2 shows the overall truth data (TSE) numbers. They further support the DART data and indicate that the actual horizontal (H) ground track error (from the planned ground track) was on average less than 100 feet during the 7 primary approaches. Note that Runs #5 and #6 were TCAS alerts, necessitating discontinuing the approach, resulting in a maximum horizontal deviation of 117 feet during Run #6 (this is explained in the Para. 6.6 and 6.7. Operational Data Analysis. In addition, the vertical (V) error was equally less than 100 feet. In all cases, the ground track error met the RNP 0.3 (1,800 feet) value set for this approach and the 200-foot centerline overshoot limit.

	H-Max(feet)	**H-Min(feet)**	**V-Max(feet)**	**V-Min(feet)**
1	63.93445335	0.098111267	77.20967405	0.059263721
2	57.31611094	0.090983797	56.39380539	0.041060754
3	98.16337757	0.208087189	50.98747167	0.03997607
4	61.97305581	0.013068649	23.56297797	0.014426315
5	51.47865663	0.009601974	52.44823828	0.045430034
6	117.6218696	11.12198365	170.5728948	0.153473033
7	41.81024053	0.058617862	39.24995341	0.018094167
	H-Mean(feet)=	40.3807273	**V-Mean(feet)=**	35.82968843

Table 2: Truth Data Horizontal/Vertical Error

6.0. OPERATIONAL DATA ANALYSIS

A number of issues surfaced from this RPAT operation concept flight. An analysis of the RNP aircraft's runs indicates that portions of each run radar vector in-trail spacing, airspeed management, and vertical velocities, singularly and/or collectively, exceeded the established approach and landing phase operating envelope.

6.1. ALL RUNS: All approaches were accomplished with autopilot and auto-throttles 'engaged' and LNAV/VNAV 'coupled' to the programmed FMS RNAV approach. NCT vectored both aircraft to a position approximately 16 miles from SFO and slightly outside of the BATKE Initial Approach Fix (IAF). The RNP aircrew visually acquired the ILS aircraft while in the turn to the intermediate approach course segment (base leg), approximately 10 miles from DONNG PFAF. This visual acquisition was acknowledged to NCT. Once established on the intermediate approach course segment, the RNP aircraft was switched to SFO Tower frequency. There were no additional aircraft in the SFO pattern.

It is important to note that for all runs, the planned RNP aircraft's initial intercept altitude of the lateral and vertical paths was at 5,000 feet and the planned ILS aircraft's intercept of the localizer course was at 4,000 feet. The 1,000-foot vertical altitude separation is an ATC requirement prior to either established on the course and inside the monitored airspace or cleared to maintain visual separation. After acknowledging visual acquisition while in the turn outside of BATKE IAF, the RNP aircrew was cleared for the approach and to maintain visual separation. From 5,000 feet, the RNP aircraft attempted to descend to the GUTTS altitude of 2,500 feet (see Figure 2). This resulted in a DART data recorded BATKE crossing altitude that varied from 4,010 feet to 4,648 feet. Based on this crossing altitude, the RNP aircraft required a minus 3.3 degree flight path angle from 4,010 feet, to a minus 4.8 degree flight path angle from 4,648 feet between BATKE IAF and GUTTS waypoint. From the GUTTS waypoint to DONNG PFAF required a minus 1.29 degree flight path angle and from DONNG PFAF to FABLA waypoint a minus 2.8 degree flight path angle. This varying flight path angle had a significant impact on each run's aircraft vertical velocity (measured as feet per minute rate of climb/descent) profile as highlighted in each run analysis below. This approach design issue is further discussed in paragraph 7.3, SFO RNAV (RNP) Y 28R Construction.

6.2. RUN #1: On downwind, the RNP and ILS aircrew verbally coordinated final approach speeds. In-trail spacing between the RNP and ILS aircraft, during the intermediate approach segment course interception (10 miles from DONNG PFAF), began at approximately 3 miles (controller observation). The RNP aircrew estimated visually and confirmed by using the TCAS (use of TCAS is further discussed in paragraph 7.4., TCAS Usage and Warnings) that the aircraft spacing was going to be in excess of the DONNG PFAF in-trail 1.0-mile objective. The RNP aircrew requested and was assigned an ATC directed airspeed increase during the base leg to the intermediate approach segment. However, after verbally acknowledging visual acquisition of the ILS aircraft, the RNP aircrew continued to adjust airspeed to close the gap. ARTS data indicated that the DONNG PFAF in-trail spacing between the RNP aircraft and ILS aircraft was 1.85 miles. The ILS aircraft crossed the OKDUE PFAF at 200-knots while the RNP aircraft crossed DONNG PFAF at 190-knots. Figure 6 DART data shows a complete

picture of the RNP aircraft airspeed changes throughout the approach. The DART and ARTS data both indicate that the ILS aircraft was at 150-knots abeam JOSUF (the start of the second half
R-F leg/curved path) while the RNP aircraft was indicating 170-knots (approximately a 20-knot overtake). The RNP aircraft was continuing to slow to final approach speed at or near idle power. Note that JOSUF is 1,282 feet above the ground level (AGL).

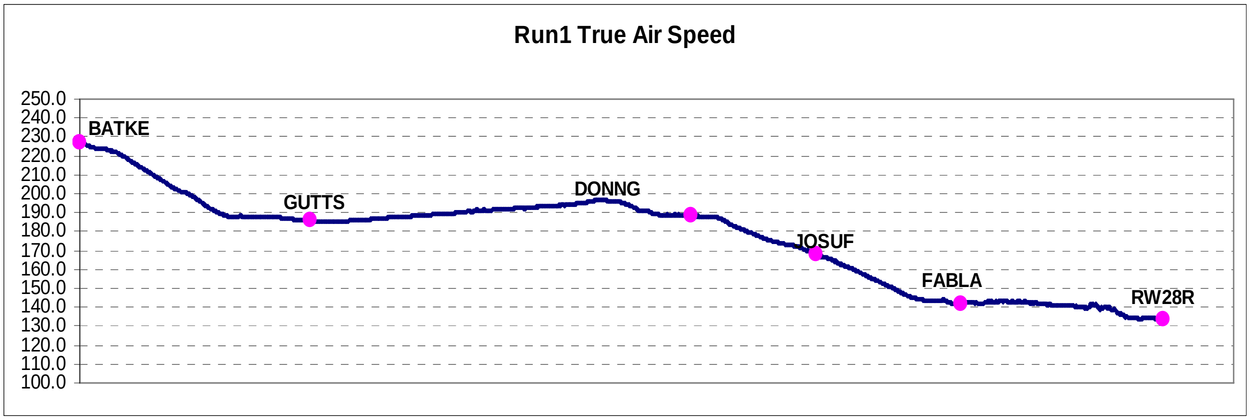

Figure 6: RNP Aircraft Airspeed Range Run #1

Figure 7 shows the RNP aircraft vertical velocity throughout the approach. It is surmised that during the turn to BATKE IAF, the aircrew selected 'Level Change' mode from 5,000 feet to 2,500 feet (GUTTS waypoint altitude restriction) versus using the FMS VNAV mode. This commanded idle thrust and a vertical velocity that required in excess of minus ~5 degrees flight path angle to maintain the airspeed selected (somewhere between 185-knots to 230-knots). The BATKE crossing altitude was 4,010 feet resulting in a minus 3.3 degree flight path angle to GUTTS waypoint. After the BATKE IAF, the RNP aircrew selected VNAV and the Flight Director recognized a below flight path situation from the minus ~5 degrees flight path angle to a minus 3.3 degree flight path angle, commanding a climb to intercept the calculated flight path. As the RNP aircraft attempted to level off at the DONNG PFAF altitude restriction, the auto-throttles commanded a large engine thrust increase (from idle power) to hold what airspeed was set by the aircrew. This will cause a momentary pitch-up aerodynamic moment and can be seen by the decrease in vertical velocity from almost negative 900 feet per minute to just over a negative 500 feet per minute (configuration changes can also cause these rapid vertical velocity changes).

As the RNP aircraft passed DONNG PFAF and began the curved path turn towards the ILS aircraft, the Flight Director commanded a large negative pitch change to recapture the programmed minus 2.8-degree flight path angle and the auto-throttles once again commanded idle power. This resulted in the RNP aircraft achieving approximately negative 1,300 feet per minute vertical velocity in the final approach segment (red circle in Figure 7). As the RNP aircraft recaptured the proper flight path and airspeed decreased, the vertical velocity stabilized at less than the 1,000 feet per minute threshold.

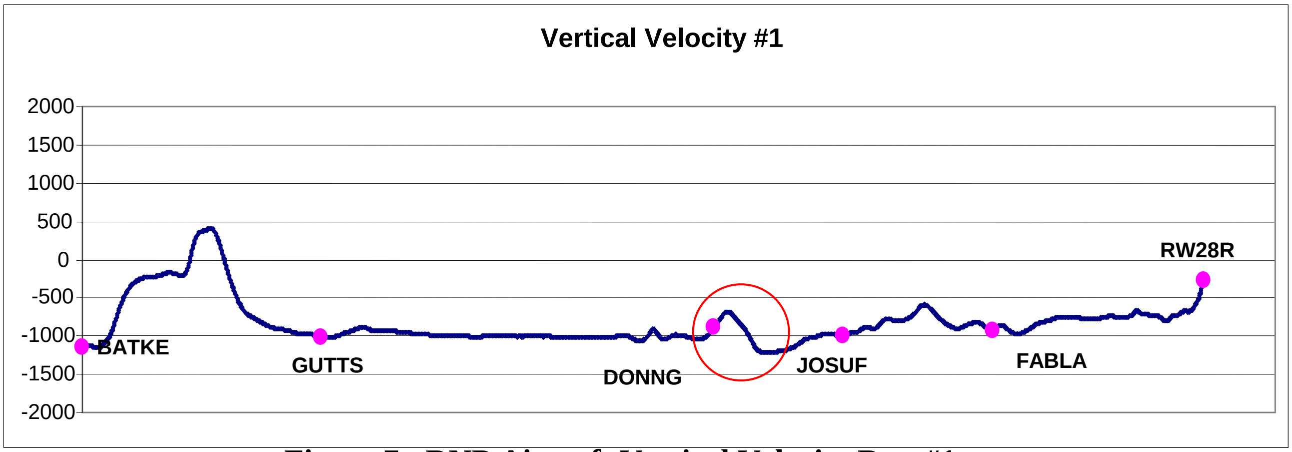

Figure 7: RNP Aircraft Vertical Velocity Run #1

TCAS warnings were not exhibited by either aircraft. ARTS data indicated the RNP aircraft was 1.64 miles in-trail of the of the ILS aircraft as it crossed runway 28L threshold.

Table 3 shows that the RNP aircraft cross track and ANP errors kept the aircraft within the 200-foot centerline overshoot limit standard from a curved path and RNP 0.3, respectively.

Run1	AVG	MIN	MAX	MEDIAN	STDEV	BATKE	GUTTS	DONNG	JOSUF	FABLA	28R
True Air Speed	176.9	133.2	227.3	187	24.32	227.3	185.9	188.6	168.3	141.9	133.9
Vertical Velocity	-828.5	-1215	408	-926	295.99	-1137	-1008	-890	-991	-925	-282
ANP	0.0899	0.086	0.094	0.09	0.0023	0.086	0.088	0.09	0.091	0.093	0.094
Cross Track Error	-7.34	-109.7	148.9	-27.1	63.39	-40.8	-25.9	51.8	9.5	-5.2	-5.3

Table 3: RNP Aircraft FMS Data Run #1

6.3. RUN #2: After the ILS aircraft entered a left-hand approach pattern and the RNP aircraft entered a right-hand approach pattern (see Figure 2), the RNP and ILS aircrews again coordinated final approach speeds while on the downwind leg. The ATC vectors were similar to Run #1.

With the ILS aircraft vectored ahead of the RNP aircraft to intercept the intermediate approach segment, the RNP aircrew recognized visually and used the TCAS to support their view that aircraft in-trail spacing was again going to be outside the DONNG PFAF 1.0 mile goal. Based on the RNP aircrew's experiences from Run #1's intermediate approach segment in-trail spacing that began at 3 miles and was still 1.64 miles at the runway threshold, the RNP aircrew received permission from ATC to make self-initiated airspeed adjustments after intercepting the intermediate approach segment.

Figure 8 shows the RNP aircraft airspeed range throughout the approach. ARTS data shows that the ILS aircraft was at 162 knots at the OKDUE PFAF. RNP aircraft airspeed at the DONNG PFAF was 202 knots, about a 40-knot overtake. Furthermore, ARTS data shows that the aircraft in-trail spacing at DONNG PFAF was 0.92 miles. It would be difficult for the aircrew to determine this in-trail spacing from using TCAS. Note that the RNP aircraft was still maintaining 185 knots at JOSUF while the ARTS data shows the ILS aircraft at 146 knots, still about a 40-knot overtake. Just prior to JOSUF at approximately 1,300 feet AGL and 0.5 mile in-trail spacing between the two aircraft, the ILS aircraft received a TCAS TA warning. It is surmised that the TA was generated from the high closure rate by the RNP aircraft due to a combination of the curved path turn towards the ILS aircraft and the airspeed delta. The ILS aircrew elected to execute a missed approach as they reported uncertainty with the RNP aircraft's location. The RNP aircraft continued the RNAV approach. Also note that the B-737 flaps 25 degrees limiting speed is 170 knots. Thus, the RNP aircraft was not fully configured at JOSUF (1,282 feet AGL). The RNP aircrew had to continue configuring their aircraft while in the second curved path between JOSUF and FABLA and while at or near idle power.

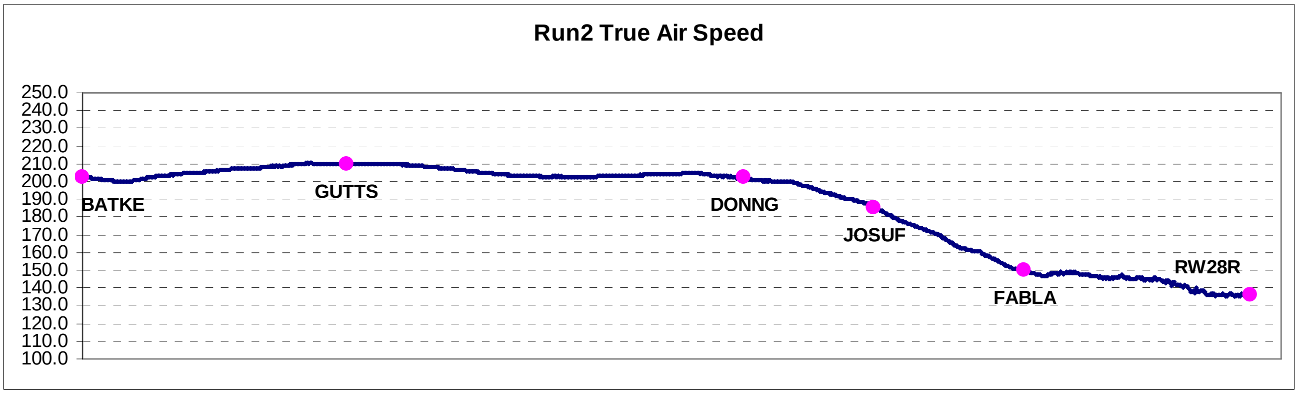

Figure 8: RNP Aircraft Airspeed Range Run #2

Figure 9 shows the RNP aircraft vertical velocity for Run #2. The BATKE crossing altitude was 4,214 feet resulting in a minus 3.8 degree flight path angle to GUTTS waypoint. Between BATKE IAF and DONNG PFAF, the 200 knots to 210 knots airspeed at minus 3.8 degrees resulted in a greater than normal vertical velocity, exceeding negative 1,200 feet per minute. Additionally, at the higher than normal airspeed, the large increase in negative vertical velocity (red circle) was likely due to the Flight Director still commanding VNAV Speed versus VNAV Path. VNAV Speed is defined as maintaining the selected airspeed by adjusting the pitch attitude with a fixed engine thrust. VNAV Path is defined as a fixed flight path with engine thrust adjusting to maintain the selected airspeed. In this case, VNAV Speed was commanding idle power in a descent and increasing the descent pitch angle to maintain the selected airspeed (approximately 200 knots). This is normal operations and may result in a higher vertical velocity. Once the proper FMS calculated flight path was captured, VNAV Path was commanded and the pitch remained fixed with the engine thrust adjusting to maintain the selected airspeed. At the DONNG PFAF, the RNP aircraft's vertical velocity was still a negative 1,134 feet per minute due to the selected higher airspeed. After the DONNG PFAF, the vertical velocity varied substantially while LNAV/VNAV remained coupled to the autopilot.
This was due in part to the rapidly changing thrust settings and high airspeed while the flight

director attempted to maintain the minus 2.8 degree flight path angle during configuration changes. After FABLA, the RNP aircraft pilot disconnected the autopilot and manually flew the aircraft to the runway.

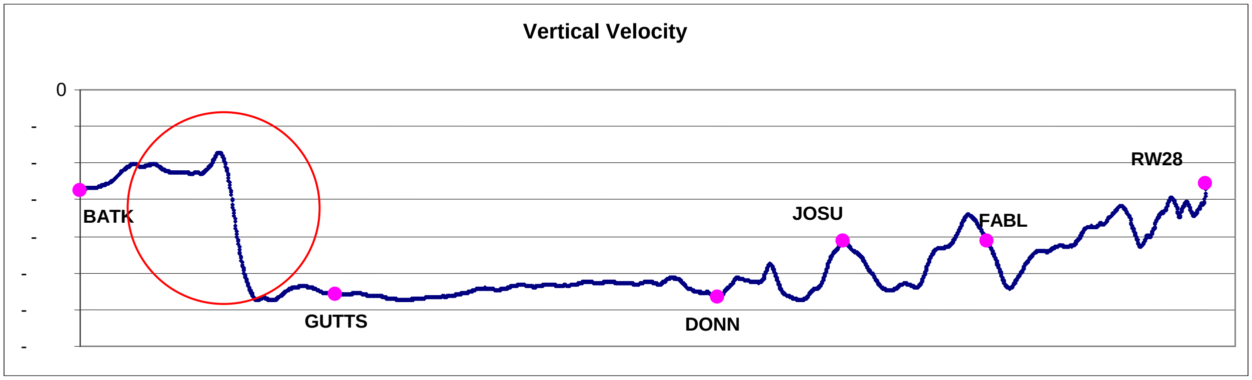

Figure 9: RNP Aircraft Vertical Velocity Run #2

It is important to note that RPAT is designed for Instrument Meteorological Conditions (IMC) until approximately 30 seconds prior to the PFAF (500 feet above the MVA or PFAF crossing altitude, whichever is higher). Thus, the higher approach airspeeds and vertical velocities are outside established norms for IMC conditions. Since the ILS aircraft executed a missed approach near JOSUF, the threshold crossing spacing was not attainable.

Table 4 shows that the RNP aircraft cross track and ANP errors kept the aircraft within the 200-foot centerline overshoot limit standard from a curved path and RNP 0.3, respectively.

Run2	AVG	MIN	MAX	MEDIAN	STDEV	BATKE	GUTTS	DONNG	JOSUF	FABLA	RW28
True Air Speed	187.3	134.9	210.4	202.4	25.41468	202.6	210.1	202.1	185.6	150.1	136.3
Vertical Velocity	-918.3	-1149	-342	-1048	232.7016	-550	-1119	-1134	-828	-825	-516
ANP	0.097	0.085	0.111	0.096	0.007841	0.111	0.105	0.094	0.091	0.089	0.085
Cross Track Error	-5.34	-111.1	106.6	-9.7	37.64875	-49.5	0.3	-39.5	79.3	6.9	35.5

Table 4: RNP Aircraft FMS Data Run #2

6.4. RUN #3: Because of the learning curve from Run #2, the RNP and ILS aircrews began a running commentary on airspeed changes. The base turns for both aircraft began at approximately the same location as the previous two runs and the resulting in-trail spacings were about the same (see Figure 3). However, at this point, ATC authorized the RNP aircrew to continuously maintain airspeed at pilot's discretion. Figure 10 shows the RNP aircraft speed range throughout the approach. Although within the established Federal Air Regulations for Class B airspace, it would be highly unlikely that aircrews would accept and ATC assign 240-knot airspeed at the IAF. Additionally, the RNP aircrew continued to adjust the airspeed in a slow/fast oscillation while approaching the DONNG PFAF. ARTS data recorded the RNP aircrew achieving a 0.62-mile in-trail spacing at the DONNG PFAF with approximately a 20-knot overtake on the ILS aircraft.

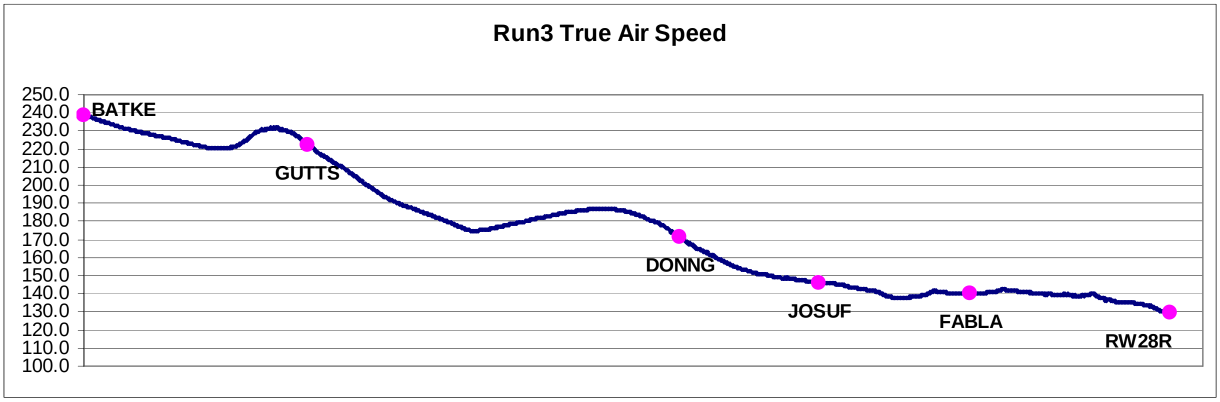

Figure 10: RNP Aircraft Airspeed Run #3

Figure 11 shows the vertical velocity for Run #3. The BATKE crossing altitude was 4,648 feet resulting in a minus 4.8 degree flight path angle to GUTTS waypoint. As described in Run #2, vertical velocity synopsis, the RNP aircraft was in VNAV Speed between BATKE and GUTTS. To maintain the pilot selected speed of 230 knots to 240 knots in idle power, the VNAV Speed commanded a negative vertical velocity approaching negative 3,000 feet per minute (minus ~7 degrees flight path angle). Once the flight path was intercepted, VNAV Path began to stabilize the vertical velocity profile. However, the negative vertical velocity remained high (circled in red), primarily due to the multiple, pilot-selected, airspeed adjustments, subsequent pitch aerodynamic moment changes due to engine thrust, configuration changes, and the Flight Director/Autopilot attempting to remain on the flight path with these simultaneous multiple changes.

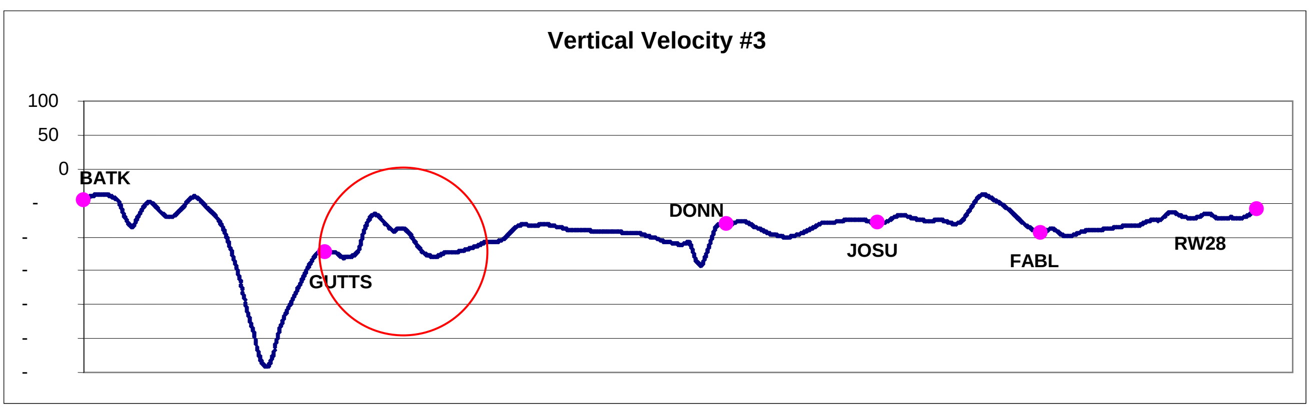

Figure 11: RNP Aircraft Vertical Velocity Run #3

TCAS warnings were not exhibited by either aircraft. ARTS data indicated the RNP aircraft was 0.44 miles in-trail of the of the ILS aircraft as it crossed runway 28L threshold. Table 5 shows that the RNP aircraft cross track and ANP errors remained within the 200-foot centerline overshoot limit standard for a curved path and RNP 0.3, respectively. The highest negative vertical velocity inclusive of all the runs occurred on Run #3 and is highlighted in red.

Run3	AVG	MIN	MAX	MEDIAN	STDEV	BATKE	GUTTS	DONNG	JOSUF	FABLA	RW28R
True Air Speed	176.01	129.3	238.6	176.8	33.90	238.6	222.4	171.3	146.3	139.9	129.6
Vertical Velocity	-934.2	-2921	-372	-850	405.4	-456	-1230	-818	-801	-942	-592
ANP	0.046	0.042	0.051	0.046	0.0025	0.051	0.048	0.045	0.044	0.043	0.042
Cross Track Error	4.19	-119	109	15.3	47.46	-102.8	-92.5	-0.7	3.2	23.7	54.2

Table 5: RNP Aircraft FMS Data Run #3

6.5. RUN #4: ATC vectors, in-trail spacing, and inter-cockpit airspeed coordination remained approximately the same as the previous runs. Figure 12 shows the RNP aircraft airspeed range. RNP aircraft airspeed was very controlled during this run. However, it would be unlikely that 190 knots to 200 knots would be maintained to the DONNG PFAF. To reiterate, the 25-degree flap limiting speed is 170 knots. ARTS data shows that the ILS aircraft crossed OKDUE PFAF at 165 knots and the RNP aircraft crossed DONNG PFAF at 192 knots (30 knot overtake).
In-trail spacing at DONNG was 0.92 miles.

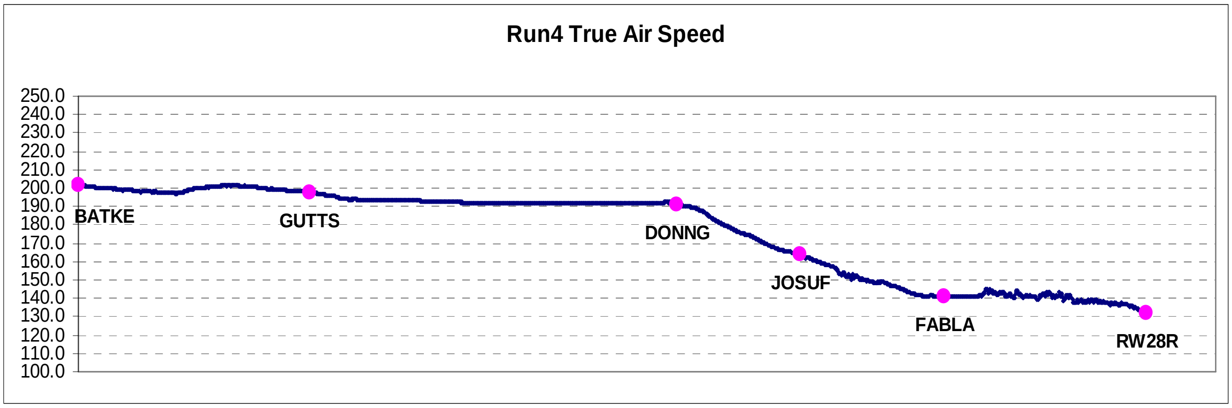

Figure 12: RNP Aircraft Airspeed Run #4

Figure 13 shows the vertical velocity for Run #4. The BATKE crossing altitude was 4,338 feet resulting in a minus 4.1 degree flight path angle to GUTTS waypoint. The significant negative vertical velocity increase between BATKE and GUTTS was explained earlier in the discussion concerning VNAV Speed/Path. After the DONNG PFAF, this run looks very similar to Run #2. Note the nearly 1,200 feet per minute negative vertical velocity during the final approach segment, circled in red. With the rapidly changing thrust settings from approximately 85% to 90% to hold 190 knots with the gear down to idle power and flap configuration changes (170-knot 25 degree flap limiting speed) after passing DONNG PFAF, the Flight Director/Autopilot was challenged to maintain the minus 2.8 degree flight path angle.

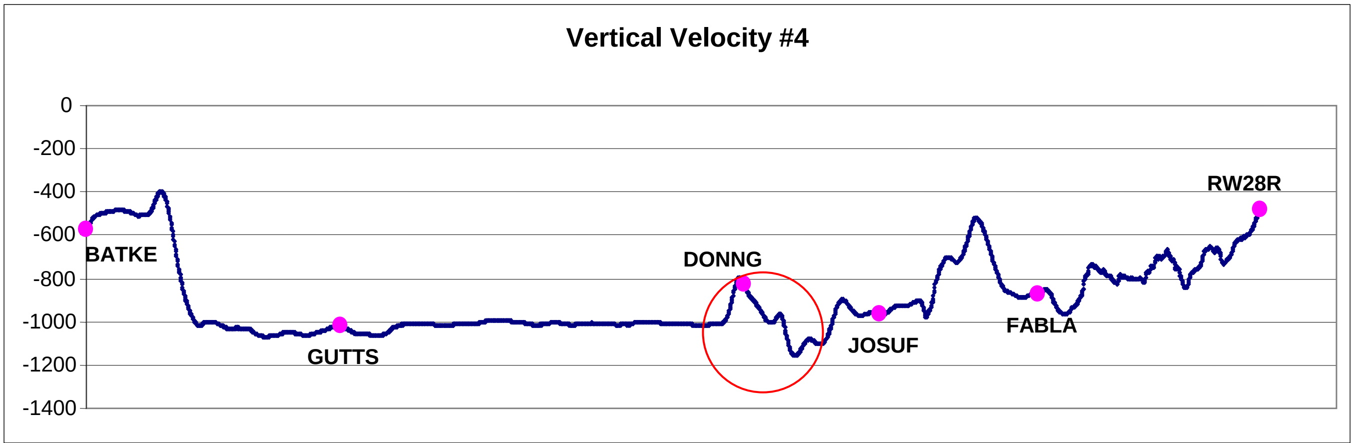

Figure 13: RNP Aircraft Vertical Velocity Run #4

TCAS warnings were not exhibited by either aircraft. ARTS data indicated the RNP aircraft was 0.52 miles in-trail of the of the ILS aircraft as it crossed runway 28L threshold.

Table 6 shows RNP aircraft cross track and ANP errors. The large cross track error shown in red occurred while intercepting the intermediate approach segment and is unexplained. However, the cross track error dampened and the 200-foot centerline overshoot limit standard from a curved path and RNP 0.3 was not exceeded.

Run4	AVG	MIN	MAX	MEDIAN	STDEV	BATKE	GUTTS	DONNG	JOSUF	FABLA	RW28R
True Air Speed	176.53	132	202	191.7	23.93	201.8	197.9	191.1	163.6	140.8	132
Vertical Velocity	-896.2	-1157	-396	-993.5	175.65	-570	-1016	-823	-964	-873	-480
ANP	0.036	0.036	0.037	0.036	0.0005	0.037	0.037	0.036	0.036	0.036	0.036
Cross Track Error	30.68	-120.6	325.8	4.4	101.16	221.8	62.6	-7.5	42.8	-51.4	0.6

Table 6: RNP Aircraft FMS Data Run #4

6.6. Run #5: ATC vectors, in-trail spacing, and inter-cockpit airspeed coordination remained approximately the same as the previous runs. Figure 14 shows the RNP aircraft speed range throughout the approach. As in the previous runs, the RNP aircraft airspeed remained high throughout the approach with 210 knots to the DONNG PFAF. The ILS aircraft was at 190 knots at OKDUE PFAF. In-trail spacing at DONNG was *0.29 miles* with a 20-knot overtake airspeed. While in the curved path approaching the JOSUF waypoint, with the RNP aircraft at approximately 187 knots and the ILS aircraft at 163 knots and at a Test Director estimated 2,000 feet diagonal spacing, the RNP and ILS aircraft both received TCAS RA warnings. The ILS aircraft executed a climbing RA recovery while the RNP aircraft executed a descending RA recovery. The TCAS logic reacted as expected by dictating a descent for the RNP aircraft due to the already higher negative vertical velocity versus the ILS aircraft. The RNP aircrew elected to continue the approach to runway 28R once determining the ILS aircraft was not a conflict.

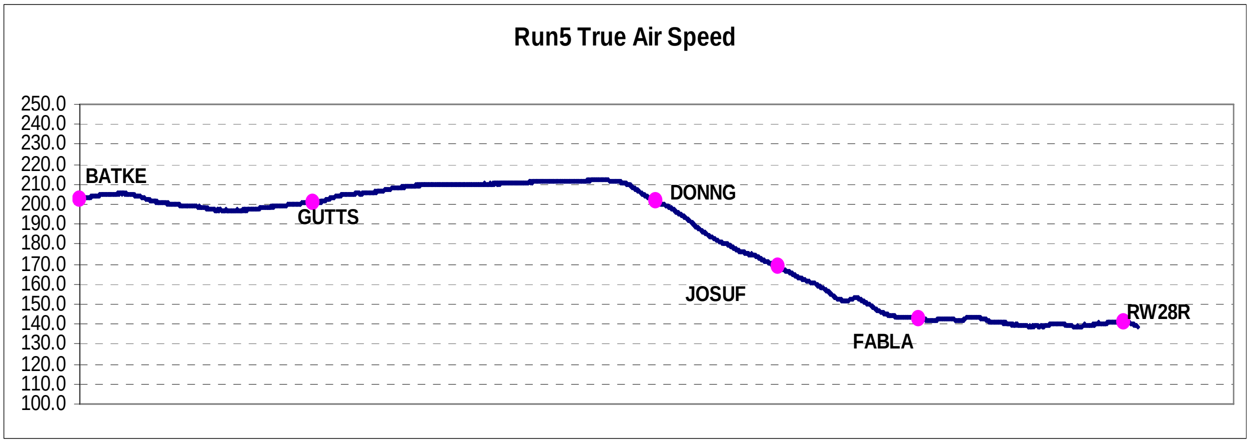

Figure 14: RNP Aircraft Airspeed Run #5

The negative vertical velocity can be seen in Figure 15 exceeding almost 1,200 feet per minute (red circle) at approximately 1,300 feet AGL during the TCAS RA recovery. Note that ALL RA recoveries are flown without the use of autopilot (i.e., hand flown). The BATKE crossing altitude was 4,365 feet resulting in a minus 4.1 degree flight path angle to GUTTS waypoint. As in previous runs, the negative vertical velocity between BATKE and DONNG was high due to the high airspeed. Note that after DONNG PFAF, the RNP aircrew was attempting to configure their aircraft when the RA occurred. The fluctuating vertical velocity after the TCAS RA is the RNP pilot attempting to manually reestablish the proper flight path and continue the configuration process.

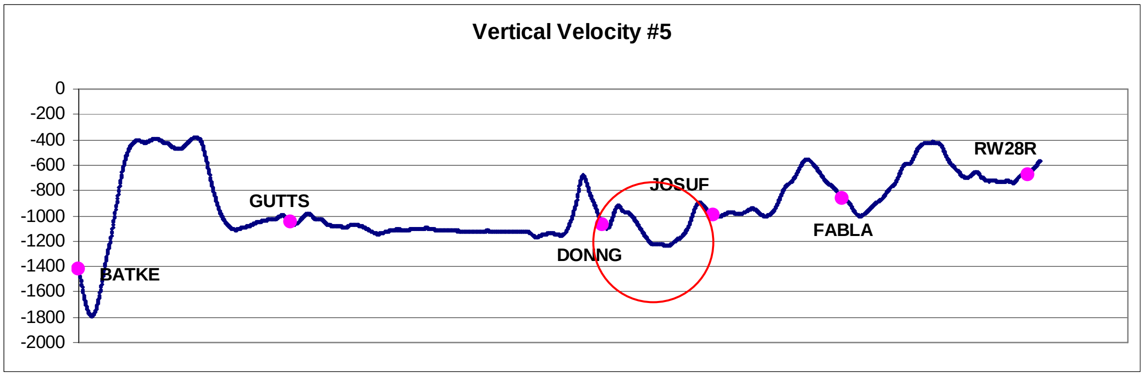

Figure 15: RNP Aircraft Vertical Velocity Run #5

Since both aircraft executed a TCAS RA recovery, threshold-crossing distance was not attainable.

Table 7 shows that the RNP aircraft cross track and ANP errors kept the aircraft within the 200-foot centerline overshoot limit standard from a curved path and RNP 0.3, respectively.

Run5	AVG	MIN	MAX	MEDIAN	STDEV	BATKE	GUTTS	DONNG	JOSUF	FABLA	RW28R
True Air Speed	182.6	138.4	212.3	198.3	28.17	202.8	200.8	201.3	168.7	142.8	140.9
Vertical Velocity	-921.2	-1790	-384	-994	270.9	-1426	-1048	-1072	-991	-864	-675
ANP	0.042	0.042	0.042	0.042	0	0.042	0.042	0.042	0.042	0.042	0.042
Cross Track Error	2.83	-87.8	96.5	2.6	39.4	-21.8	3.1	-58	63.4	-58.9	44.2

Table 7: RNP Aircraft FMS Data Run #5

6.7. RUN #6: The RNP aircraft intermediate approach segment airspeed was flown at the highest airspeed of all the runs. Figure 16 shows the RNP aircraft airspeed range on the approach. The airspeed was flown between 220 knots to 240 knots to DONNG PFAF. The ILS aircraft crossed the OKDUE PFAF at 188 knots while the RNP aircraft crossed the DONNG PFAF at 220 knots. In-trail spacing was measured at 0.44 miles. ATC broadcasted to the RNP aircrew that they had a 50-knot airspeed overtake on the ILS aircraft just after passing DONNG PFAF. Just as in Run #5, both aircraft received a TCAS RA warning while in the curved path to the JOSUF waypoint. The RNP aircraft was still doing 185 knots at JOSUF (25 deg flap limiting airspeed is 170 knots) while the ILS aircraft indicated 150 knots. The RNP aircraft continued the descending RA recovery while the ILS aircraft executed a climbing RA recovery.

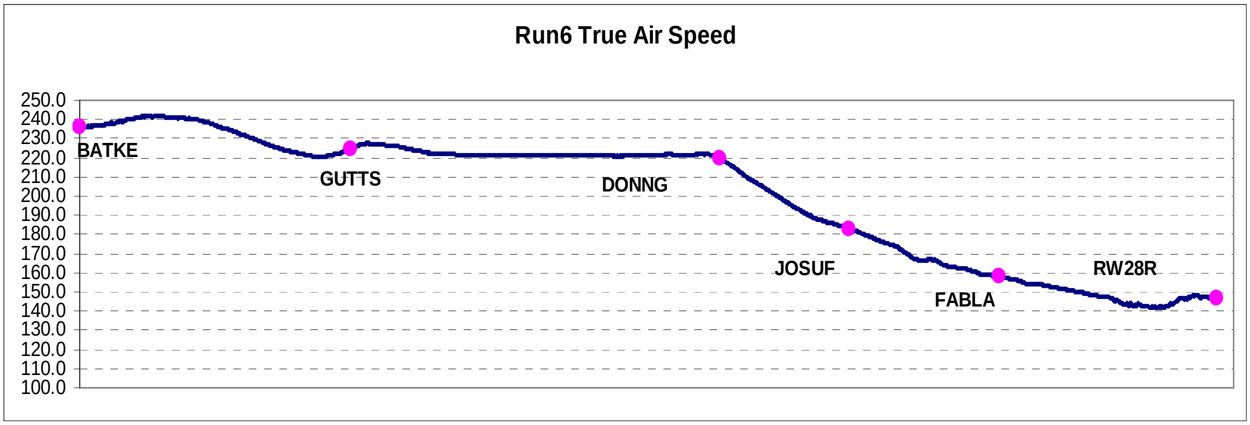

Figure 16: RNP Aircraft Airspeed Run #6

Figure 17 shows the RNP aircraft vertical velocity and reflects the expected higher negative vertical velocity due to the higher airspeed. The BATKE crossing altitude was 4,200 feet resulting in a minus 3.8 degree flight path angle to GUTTS waypoint. Circled in red is the negative 1,288-foot vertical velocity during the TCAS RA recovery. The RNP aircrew elected to execute a missed approach after the TCAS RA recovery primarily due to not being able to establish final approach configuration and airspeed.

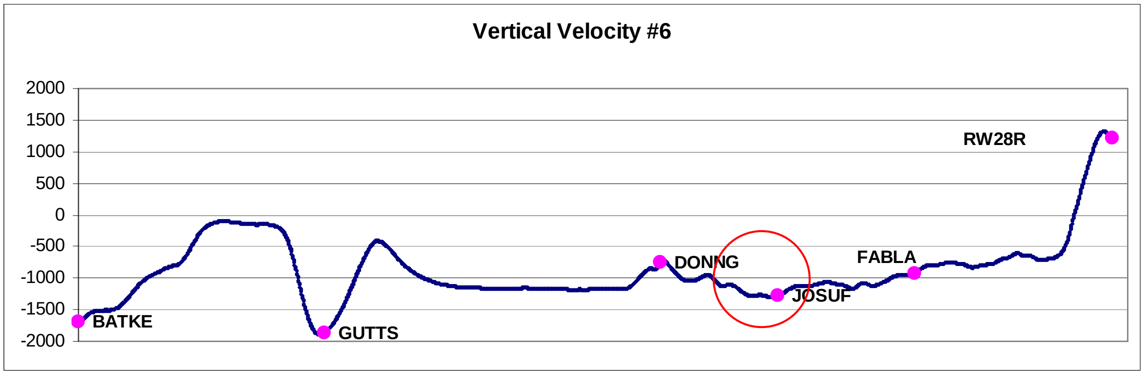

Figure 17: RNP Aircraft Vertical Velocity Run #6

Since both aircraft executed a TCAS RA recovery, threshold-crossing distance was not attainable.

Table 8 shows that the RNP aircraft cross track and ANP errors kept the aircraft within the 200-foot centerline overshoot limit standard from a curved path and RNP 0.3, respectively.

Run6	AVG	MIN	MAX	MEDIAN	STDEV	BATKE	GUTTS	DONNG	JOSUF	FABLA	RW28R
True Air Speed	200.99	141.4	242.2	221.1	33.08	236	224.8	219.8	183.1	158.3	146.9
Vertical Velocity	-886.9	-1898	1325	-1029	512.3	-1701	-1871	-758	-1288	-920	1209
ANP	0.047	0.046	0.048	0.047	0.0008	0.047	0.047	0.046	0.047	0.048	0.048
Cross Track Error	26.15	-44.5	168.1	17.1	41.2	60.4	-14.3	1.1	134.7	54.2	26.2

Table 8: RNP Aircraft FMS Data Run #6

6.8. RUN #7: During this run, the RNP aircrew requested to turn first to the intermediate approach segment ahead of the ILS aircraft. This helped to reduce the in-trail spacing to DONNG PFAF and as seen in Figure 18, contributed to a controlled aircraft deceleration. It is estimated the in-trail spacing began at less than 1.5 miles. The ILS aircraft crossed OKDUE PFAF at 190 knots and the RNP aircraft crossed DONNG PFAF at 180 knots with an in-trail spacing of 0.36 miles.

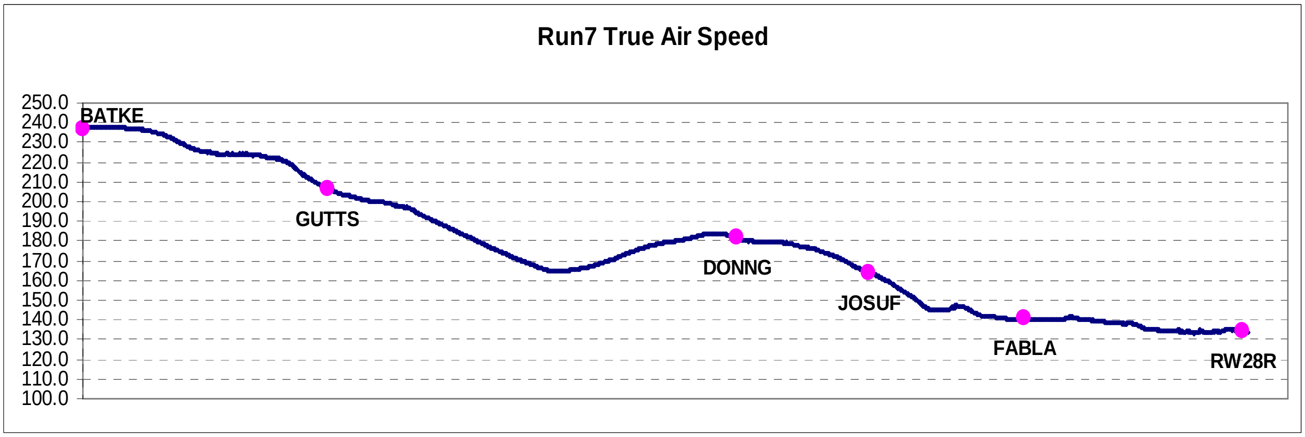

Figure 18: RNP Aircraft Airspeed Run #7

Figure 19 shows the RNP aircraft vertical velocity for Run #7. The BATKE crossing altitude was 4,639 feet resulting in a minus 4.8 degree flight path angle to GUTTS waypoint. As explained earlier, it is likely the Flight Director was still in VNAV Speed at the beginning of the intermediate approach segment and upon flight path intercept, dampened the vertical velocity rate while in VNAV Path. Additionally, note that once the airspeed decelerated below 180 knots, the vertical velocity rate remained consistently above negative 1,000 feet per minute. Once past DONNG PFAF, the RNP aircraft continued to remain above negative 1,000 feet per minute except for a small deviation due to engine thrust and configuration changes.

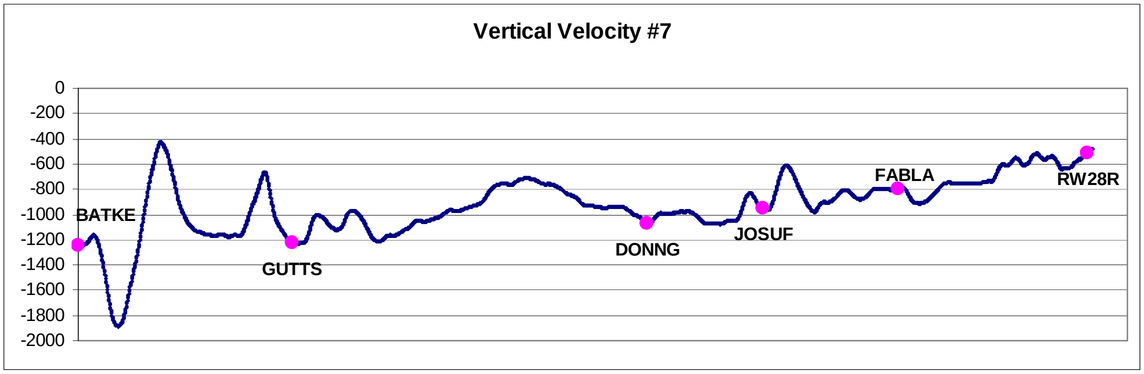

Figure 19: RNP Aircraft Vertical Velocity Run #7

Unlike Runs #5 and #6 that showed an overtake airspeed of 30 to 40 knots, <u>TCAS warnings were not exhibited by either aircraft.</u> ARTS data indicated the RNP aircraft was 0.56 miles in-trail of the of the ILS aircraft as it crossed runway 28L threshold.

Table 9 shows RNP aircraft cross track and ANP errors. The large cross track error shown in red occurred while intercepting the intermediate approach segment and is unexplained. However, the cross track error dampened and the RNP aircraft cross track and ANP errors showed the aircraft remained within the 200 feet centerline overshoot limit standard. *<u>This run was considered by the aircrew and observers as the best run of all the runs</u>*.

Run7	AVG	MIN	MAX	MEDIAN	STDEV	BATKE	GUTTS	DONNG	JOSUF	FABLA	RW28R
True Air Speed	177.5	133	237.8	176.2	32.1	236.8	206.6	181.6	164.2	140.9	134.5
Vertical Velocity	-930.5	-1886	-425	-935	236.6	-1243	-1226	-1070	-953	-799	-517
ANP	0.071	0.068	0.073	0.071	0.0016	0.068	0.069	0.071	0.072	0.073	0.073
Cross Track Error	11.56	-350	205	5.6	112.5	-195.2	179.7	-47.9	57.4	-41.7	25.5

Table 9: RNP Aircraft FMS Data Run #7

6.9. RUN #8: The RNP aircrew coordinated with NCT and the ILS aircraft that this was the final run and that the RNP aircraft would be executing a missed approach in accordance with the test plan. Both aircraft were at corresponding airspeeds of 190 knots upon reaching the DONNG PFAF at an in-trail spacing of 0.59 miles. Both aircraft slowed and were configured on schedule arriving at, or abeam of, JOSUF waypoint within 10 knots of each other and at the same in-trail spacing as was observed at the DONNG PFAF. Upon reaching JOSUF waypoint, the RNP aircraft executed a missed approach by a right turn away from the ILS aircraft on a heading of 040 degrees, climbing to 4,000 feet. The ILS aircraft continued the approach and landing at SFO. The RNP aircraft coordinated a flight plan and returned to SEA.

7.0. SUBJECTIVE ANALYSIS

Subjective analysis data were collected from Controllers, Aircrew, Test Director, and Observers. Four main topics of discussion emerged from their feedback: 1) ATC radar vectors, 2) Aircrew workload, 3) SFO RNAV (RNP) Y 28R construction and 4) TCAS usage and warnings.

7.1. ATC Radar Vectors: This was the first time that ATC controllers were involved with an RPAT-type operation. A major issue was controller's difficulty in radar vectoring the RNP aircraft to within 1-mile in-trail of the ILS aircraft. To reiterate test plan guidance, NCT's direction was to achieve *"approximately the same time or with the RNP aircraft slightly trailing the ILS aircraft when the RNP aircraft is over the DONNG PFAF."* As noted by controllers, there is a major difference between "being required to keep aircraft apart and being required to keep aircraft together." As demonstrated during this concept flight, achieving and maintaining close in-trail spacing appeared to be a major challenge. A discussion of several issues is presented below:

a) Test Set-up: There was no formal radar training conducted for this concept flight, and feedback indicates that a more detailed briefing to the controllers on the *specific* in-trail spacing goal might have better facilitated this RPAT operation. In future data collections, a more comprehensive controller briefing stressing the need for establishing more closely spaced pairs may assist in reducing the in-trail separation outside of the PFAF.

To maximize data collection during actual concept flights (in-flight versus simulator costs/realism tradeoffs), multiple approaches needed to be accomplished in a finite time limit/period (due to airspace, fuel, and crew duty costs). *Non-standard* racetrack patterns at SFO were determined to be the optimum way to achieve multiple approaches and maximize data collection, given time and resource constraints. In this case, pairing was accomplished from direct aircraft 'nose-on-nose' base legs. During SFO Simultaneous Offset Instrument Approaches (SOIA), pairings are normally accomplished by melding the aircraft from multiple directions versus direct aircraft 'nose-to-nose' base legs. Additionally, differing tailwinds at the initial 4,000 and 5,000-foot separation altitudes further challenged the controllers with achieving close-in pairings. The different pattern spacing, base turn vectors, and winds aloft impacted the RNP aircraft's in-trail spacing on the ILS aircraft.

b) Airspeed control: Controllers initially attempted to manage both aircraft airspeeds to facilitate the pairing. However, initial pairings were resulting in 2-3 mile in-trail spacing. Aircrew began requesting airspeed increases/decreases to facilitate the pairing and ultimately, assumed all control of airspeed management once visual acquisition was acknowledged. Hence, the controllers were essentially 'cut out of the loop' concerning airspeed management.

They had no learning curve on what adjustments to make from the previous runs. As is customarily done, the controllers expected that the pilots would assume in-trail spacing responsibilities once visual acquisition was confirmed (which occurred during every base leg). The pilots expected ATC to direct airspeed adjustments to facilitate the nominal 1-mile in-trail spacing goal. In addition, as noted from the ARTS data, the ILS aircraft's airspeed was not stable and consistent, i.e., a 'moving target'. Thus, the RNP aircrew consistently had to chase that 'moving target' resulting in an excessively high aircrew workload and destabilized approaches.

Visual acquisition at or near the beginning of the intermediate approach segment may be highly unlikely in 'real world' operations of this nature. In this test, visual acquisition occurred at a very early stage because there were no other aircraft conducting approaches and clear night conditions made the ILS aircraft's lights easily seen. RPAT operations are constructed to be flown under IMC conditions until approximately 30 seconds before the PFAF. Thus, it is highly unlikely that very high airspeeds flown to the PFAF and early visual acquisition in high-density traffic environments would occur, especially in IMC conditions.

Lastly, and most importantly, the final monitor controller issues airspeed adjustments along side of the NTZ. The more exact the in-trail spacing requirements (and wake vortex separation), the more radio transmissions issued, especially under an ASR-9 radar scenario. Every radio transmission made by the final monitor controller steps on the local controller's transmissions. This was not a problem during this concept flight as there were no other aircraft conducting approaches and visual acquisition occurred very early in the process. However, it is a safety concern for future RPAT operations performed under normal traffic volume.

c) Radar: For discussion purposes only and not a specific result from this concept flight, under SOIA operations, final approach controllers begin the pairing using an ASR-9 radar (4.8 second update). Prior to the beginning of the NTZ and once established on the final approach course, aircraft responsibility transfers to the final monitor controllers, who use a Precision Runway Monitoring (PRM) radar (1 second update). Airspeed adjustments are the only option to maintain required in-trail spacing (for wake vortex separation). Although not a direct impact on the aircraft in-trail spacing during this concept flight due to the early visual acquisition, the use of only an ASR-9 radar (no PRM) nevertheless provides a new challenge with less precision in attempting to obtain and maintain in-trail spacing, nominally 1 mile while along side of the NTZ. Figure 20 depicts a picture of the SFO ASR-9 controller scope with the RNAV approach used for this concept flight. The UAL nomenclature (lower numbers) is the radar return of the ILS aircraft and the ASA nomenclature (upper numbers) is the radar return of the RNP aircraft. Since the radar antenna is located north of the final approach course, the radar updates from the rear of the final approach towards the front (right to left). Thus, for each radar sweep, the RNP aircraft moves forward first, followed by the ILS aircraft. This radar 'compression' impacts controller ability to obtain and maintain 'precise' in-trail spacing for wake vortex separation.

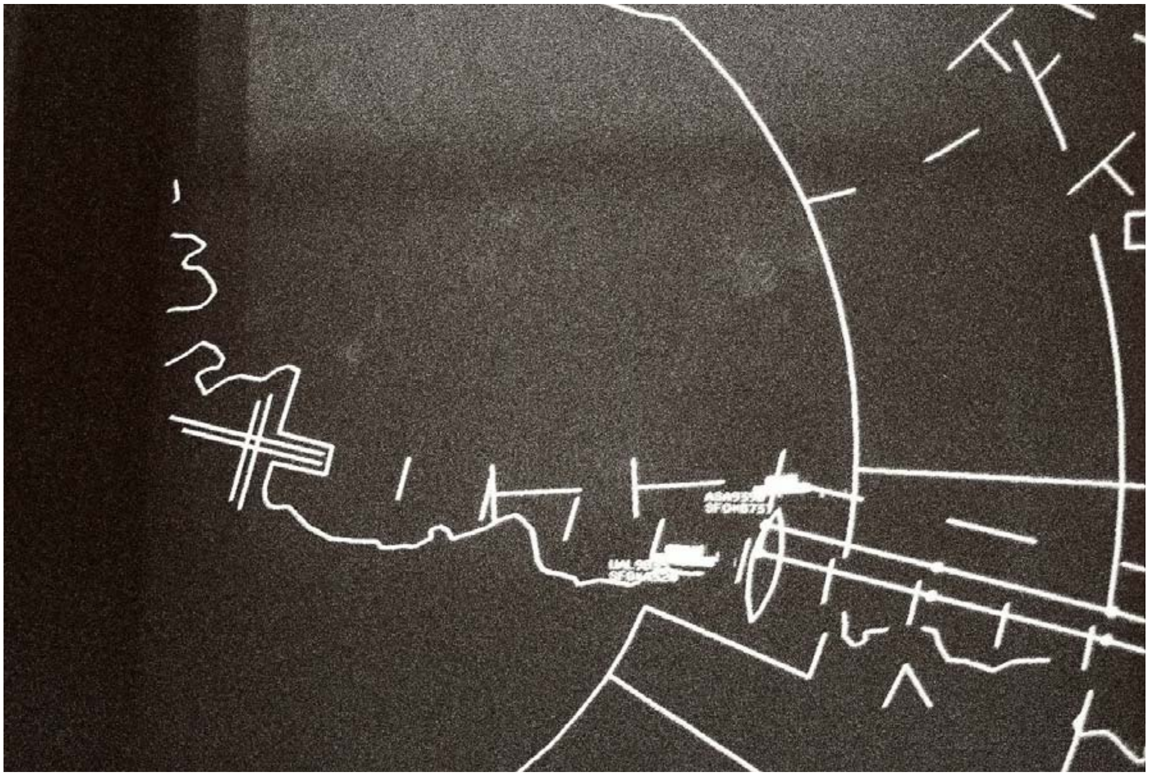

Figure 20: ASR-9 Controller Scope Picture

Additionally, specific to SFO, the ASR-9 radar antenna is located about 8 miles north and 90 degrees to the runway final. The radar slash marks are always presented perpendicular to a line drawn from the antenna to the target. Along the final approach, the targets are therefore canted toward the antenna, and inside the PFAF they appear nearly parallel to the final approach course, rather than perpendicular to it which is the more customary depiction. The target cant and the target size using an ASR-9 radar affects the controller's ability to determine the exact in-trail spacing. This is magnified as both aircraft approach or inside the PFAF (Note: current RPAT operation guidance is for the RNP pilot to assume separation and wake vortex responsibilities once past the PFAF). Also the primary target slash is about 0.4 mile long, and the actual aircraft position can be anywhere within the length of the slash mark. While controllers are permitted to assume that the aircraft is located at the center of the primary slash mark for separation purposes, the actual separation between aircraft for wake purposes could be as much as 0.4 mile different than the distance between the slash centers, and as much as 0.8 mile measured between the near end of one primary slash and the far end of the other. These factors may have exacerbated the difficulty in SFO controller's providing a nominal 1-mile in-trail due to the particular radar orientation and configuration.

7.2. Aircrew Workload: A number of aircrew discussion points emerged from this concept flight. The RNP pilots experienced a change in both mental and physical workload. This RPAT operation necessitated an adjustment of their attention resources both in and out of the cockpit. This was due to increased visual acquisition and scanning demands, taking aircrew attention away from normal cockpit duties, in this case away from the primary flying duties (e.g., instrument monitoring, course tracking, checklist completion, etc.) A discussion of several aircrew and cockpit variables and its effect on workload follows:

a) Airspeed control: RPAT operations are defined as independent simultaneous instrument approaches. Since this was a 'first-look' concept flight, both the RNP and ILS aircrew engaged in a continuous airspeed running commentary on the discrete frequency. This was to facilitate airspeed adjustments. This running commentary would be unrealistic and outside the scope of actual RPAT pairing operations. When the RNP aircrew assumed airspeed management, post-flight aircrew comments indicated that mental and physical crew workload dramatically increased. This was validated to some degree by direct observation of the Test Director and observers. The multiple airspeed adjustments and corresponding throttle responses necessitated increased cockpit communications between the Captain and First Officer thereby creating a commensurate increase in cumulative aircrew workload. Airspeed management will have to be further addressed, as it was critical in this particular RPAT-type operation. However, to the extent it was used for this RPAT operation concept flight, the higher approach speeds flown, and constantly changing excursions in vertical velocity, were well beyond normal operations.

b) Situational Awareness: While situational awareness was not significantly degraded, from the standpoint of safely flying the aircraft, pilot comments indicate that there was a cumulative effect on situational awareness due to the already-reduced visual acuity during night RPAT operations. They offered a number of areas of concern, which included: 1) judging closure rates and making airspeed adjustments based on the ILS aircraft's landing and wing tip lights while simultaneously monitoring airspeed, altitude, course alignment, TCAS operation, sighting the runway environment, configuration and checklist completion challenges, cumulatively affecting situational awareness and potential for spatial disorientation, 2) Weather for this concept flight was clear with a full moon, and greater than 10-mile visibility. In reality, visibility could be as low as 4 miles with overcast weather, thus potentially compounding the visual acuity and aircrew workload issue, and 3) the RNP aircrew elected to fly all the runs with the use of autopilot and auto-throttles. Even with the use of automation, maintaining situational awareness required a high degree of vigilance and relied heavily on experience and skill.

c) Crew Coordination: As this is a first-look concept flight, no formal training program has been developed to clarify crew coordination issues. As such, a number of crew coordination issues surfaced during this RPAT operation concept flight. Primarily, division of responsibilities both in and outside the cockpit (i.e., who is doing what and when), were not clarified before this concept flight. The resultant was a blending Pilot Flying and Pilot Monitoring cockpit duties between the Captain and First Officer. When the ILS aircraft was visually acquired, it appeared to the Observers that both crewmembers fixated on the ILS aircraft with reduced monitoring of the RNAV course. This fixation was primarily generated as a result of the airspeed and in-trail spacing challenges. As such, the potential exists that primary pilot in charge of aircraft control may not be absolute (i.e., "who is flying the jet?"). Therefore, the potential for critical in-the-cockpit tasks inadvertently expedited, not confirmed, or shed during RPAT operations is a real possibility. Additionally, as seen from RPAT simulator tests and verified by the RNP aircrew for this concept flight, the RNP aircraft's seat that was in a position closest to the ILS aircraft appeared to be in a better position for monitoring the ILS aircraft while the seat farthest from the ILS aircraft was better positioned at flying the approach. In addition, during abnormal operations such as go-around, missed approach, TCAS RAs, and aircraft system abnormalities, monitoring the ILS aircraft from the farthest seat was difficult due to the cockpit glare shield and the other pilot's body and seat position. That is to say, cockpit cutoff angles, configuration, and the physical layout may facilitate better visual acquisition from one seat versus the other and most likely will be type-aircraft dependent.

One final note, normal instrument approach operating procedures is for the aircraft to be fully configured prior to the PFAF. However, due to the higher airspeeds flown, full configuration was not achieved until within the curved path after the DONNG PFAF. This could be a training issue that needs clarification for RPAT-type operations.

7.3. SFO RNAV (RNP) Y 28R Construction: A number of approach construction issues surfaced during this RPAT operation. Principle among them is the flight path angle for each waypoint segment. As discussed earlier, ATC operations require a minimum of 1,000-foot altitude separation between the two participating aircraft until established on course and abeam the beginning of the NTZ, or cleared to maintain visual separation. Therefore, based on the SFO required intercept altitudes of 5,000 feet for the RNP aircraft and 4,000 feet for the ILS aircraft at BATKE IAF on course, the RNP aircraft might be required to maintain a minus 5.2-degree flight path angle to the 2,500 foot altitude at GUTTS waypoint (see Figure 2). At 190 knots, this would generate a negative vertical velocity of approximately 1,660 feet per minute. It would also be very difficult for an aircraft to maintain a minus 5.2-degree flight path angle without aircraft configuration drag devices and/or speed brakes to control airspeed (10 miles from the PFAF). Normal intermediate approach segment flight path angle is minus 3 degrees. This issue may have had a direct bearing on the aircrew workload discussed previously. From the GUTTS waypoint to the DONNG PFAF, the flight path angle lessens to minus 1.29 degrees, which would result in
a large pitch aerodynamic moment change due to large thrust increases (due to configuration) and corresponding vertical velocity changes. From DONNG PFAF to FABLA, the flight path angle then changes again to a nominal minus 2.8 degrees. Overall, the autopilot, the auto-throttles and most importantly, the aircrew, were working 'overtime' due to these flight path descent angles. In addition:

a) Initial simulator tests were accomplished at the 5,000-foot parallel intermediate approach segment spacing. The RPAT operation concept flight was conducted at the 6,600-foot parallel intermediate approach segment spacing due to TCAS RA warnings experienced during the simulator tests (discussed below in TCAS Usage and Warnings). In all cases, the industry pilots involved with these tests commented on the aggressively high closure rate while navigating the curved path (DONNG-JOSUF-FABLA). This directly contributed to the mental and physical workload, fixation on the ILS aircraft, and potentially missed cockpit duties because of closure rate concerns. Adjustments to the curved path, such as stretching the final approach segment and use of fly-by waypoints may aid in a more gradual closure rate, thus mitigating aircrew concerns. Of note these changes may require the ceiling to be raised and visibility increased due to moving the PFAF further from the airport.

b) The NTZ depiction on the monitor controller's display was not centered for the 6,600 feet approach courses, which conflicts with current TERPS Vol 3, Ch 2, Simultaneous Independent Approach Courses. This NTZ was built for a 5,000-foot parallel intermediate approach segment spacing with the NTZ located 1,150 feet from the ILS course and 1,850 feet from the RNAV intermediate approach segment. Eleven hundred fifty (1,150) feet is a minimum width permitted for the Normal Operating Zone (NOZ) for ILS based on 4300 feet approach centerline spacing.

c) Missed Approach: The missed approach procedure used in this concept flight was a diverging 120-degree right turn away from the ILS aircraft. This missed approach design was used only for this RPAT operation concept flight to meet FAA Order 8260.3B, which requires at least a 45-degree missed approach course divergence for simultaneous approaches. However, the 120-degree divergent turn used was artificial, as it would not be employed in the current NCT airspace structure due to airspace and traffic conflicts with Oakland airport. Initial RNAV design of the missed approach procedure required the pilot to remain on the RNAV course and follow the track, but this did not meet FAA Order 8260.3B requirements for simultaneous approaches. The simultaneous missed approach issue for RPAT operations needs further clarification and/or
should conform to current FAA design criteria, unless specifically modified.

7.4. TCAS Usage and Warnings: TCAS is a tool used to warn aircrews of potential traffic conflicts. It also helps build aircrew situational awareness in highly congested air traffic environments such as around major airports. TCAS is not designed, nor does it have the accuracy, especially in angular computations, which are made in 15-degree increments, to be used for RPAT in-trail spacing determinations. However, the RNP aircrew extensively relied on the TCAS in attempting to determine in-trail spacing from the ILS aircraft throughout the approach. Once visual acquisition was achieved for this concept flight (base leg), the RNP aircrew essentially assumed responsibility for aircraft safe separation and in-trail spacing. As such, it can reasonably be expected that aircrews will use this tool in an attempt to maintain proper in-trail spacing, especially at night or during low visibility conditions. The TCAS is a good aid in building situational awareness, but may give a 'false sense' of proper in-trail spacing and should not be used in determining in-trail spacing accuracy.

More importantly, there is no formal training program established for pilots to determine and maintain *specific* in-trail spacing behind another aircraft. ATC radar for initial pairing is the start of the pairing process. However, once the RNP aircrew acknowledges visual acquisition and reaches the PFAF, the in-trail spacing responsibility shifts to the pilot and the only cockpit tool, other than visual determination, is the use of TCAS. The TCAS display may provide an inaccurate/false sense concerning the proper in-trail spacing because it is difficult for pilots to determine the difference between diagonal and in-trail separation, especially at night/low visibility. This concern is reflected in the data where during Run's # 5 and #6 TCAS RA events, the RNP aircraft was properly spaced in-trail, but continued at an overtake speed to a point where the TCAS issued a warning.

A major outcome from the RPAT simulator testing was TCAS RA warnings. Consequently, the decision was made to move the parallel intermediate approach segment spacing from the simulator tested 5,000 feet, to a RPAT operation concept flight 6,600 feet, as the wider spacing in the simulator showed a less likelihood of TCAS RAs. Based on the simulator testing, the prevailing view was the TCAS RAs were being generated because of a flaw in the RNAV 5,000-foot intermediate approach segment designed to support RPAT operations, hence the wider 6,600-foot parallel spacing was evaluated. However, during the concept flight at the 6,600-foot spacing, both aircraft received TCAS RA warnings on Runs #5 and #6 resulting in one aircraft climbing and the other descending in accordance with the advisory directions. Although a flawed RNAV approach design can not be ruled out, it appears in this concept flight that the cause of the TCAS RAs were due to the RNP aircraft's excessive closure rates (30 to 40 knots overtake) and while inside 0.5 mile in-trail spacing on the ILS aircraft. On Run #7 with the same track as Run #5 and #6, the overtake airspeed was under 20 knots and inside 0.5 miles in-trail spacing. TCAS RAs were not exhibited by either aircraft during Run #7. That notwithstanding, the TCAS RA issue needs resolution either by approach redesign to reduce the closure rate angles, airspeed restrictions/windows to reduce airspeed delta induced RAs, a combination of both, or use of TA only.

Finally, TCAS is a warning tool. As such, many company procedures make it mandatory to follow all TCAS RA warnings. Receiving a TCAS RA warning, while on approach and in the landing phase which directs a descent resolution while low altitude, is a recipe for loss of situational awareness and very high aircrew workload.

8.0. CONCLUSION

Overall, this RPAT operation provided valuable technical and operational data for a 'first-look' type procedure. The truth data shows that the RNP aircraft remained within 100 feet of the planned horizontal and vertical ground track, even with the rapidly changing vertical velocities. The normal distribution of the flight paths indicates that there was less than a 1:1 million probability that the two aircraft could occupy the same airspace at the same time and place, or less than 10^{-6} that there could be a collision. However, the test data and subjective analysis also show that there are hurdles to overcome before actual implementation. Chief among them are resolving TCAS RA issues, airspeed management, aircrew workload and coordination, controller training and validation of use of the autopilot and ASR-9 radar for RPAT operations. Additionally, wake vortex was not encountered during this RPAT operation. However, wake vortex mitigation issues remain to be addressed for RPAT-type operations.

In-trail spacing between the ILS aircraft and RNP aircraft initially started at 2-3 miles. This spacing became problematic for wake vortex mitigation and as such, aircrews attempted to close this gap to inside 1 mile by the use of airspeed control. In this chain of events, as in-trail spacing difficulties occurred, they directly impacted the RNP aircrew's airspeed management, which in turn impacted aircrew workload and coordination and on two occasions resulted in TCAS RAs. Solving in-trail spacing issues will have a significant impact on RNP aircrew workload and could potentially mitigate TCAS RA issues. Better controller awareness of the RPAT pairing requirement will aid in improving pairing and in-trail spacing operations.

Airspeed management is an important element in being able to execute an RPAT operation. Airspeed ranges varied widely for both aircraft. To be able to safely achieve proper in-trail spacing, there must be a stable ILS aircraft airspeed as a starting point. If the ILS aircraft's airspeed changes rapidly or is inconsistent, it will increase difficulties for the controllers and RNP pilot to achieve a stabilized and properly spaced approach. Higher airspeeds result in increased vertical velocities. It becomes problematic for aircrews to properly execute (workload) configuration changes and maintain stabilized flight during these higher airspeeds and increased vertical velocities. Lastly, as seen from this test, the high airspeed delta between the two aircraft may cause TCAS RA alerts and subsequent resolution advisories in the final approach segment.

A key element to stakeholders in the test plan concerned the potential for wake vortex encounters. Although wake vortex was not encountered during this RPAT operation, even when the in-trail spacing was greater than 1 mile, additional RPAT wake vortex studies need to be conducted to define acceptable criteria. Some issues discussed to be addressed included: 1) formal pilot training to visually maintain proper in-trail spacing and/or approved on-board equipment for monitoring wake vortex separation inside the PFAF, 2) pilot responsibilities for wake vortex mitigation while conducting RPAT 3) f controller responsibility for monitoring wake vortex separation inside the PFAF, and 4) development of ground based equipment/procedures to accurately determine that the RNP aircraft is established within the wake free area. Until resolved wake vortex mitigation will continue to be a major issue to implementation of close space parallel runway operations.

The criteria for success as outlined in the test plan and findings were:

a) All participating aircraft will be operated in accordance with their respective company flight operations manual (FOM) and Pilot Operating Handbook (POH) at all times.

   Finding: Airspeed, vertical velocities, and the point at which to be on-speed and fully configured exceeded FAA and company standards for stabilized flight.

b) Recover from any approach course deviation in accordance with airline operating guidelines for terminal operations.

   Finding: The largest cross track error occurred during the intermediate approach segment interception at a high rate of airspeed. Once on final approach, DART data cross-track error averaged less than 9 feet, with ANP averaging less than 360 feet. Truth data (ground track) indicated less than a 100-foot error. This is well within the RNP 0.3 set for this approach.

c) A stabilized approach to the threshold. (A stabilized approach, for the purposes of this flight validation, means arrival at 500 feet AGL, wings level, on speed, aligned with the runway centerline.)

Finding: A number of runs resulted in the RNP aircraft being greater than 10 knots faster then the computed final approach airspeed. Although manageable on an 11,870-foot runway such as SFO 28R, excess airspeed can lead to long landings at higher than normal touchdown speeds. Additionally and potentially a greater negative impact, un-spooled engine power (idle thrust) at below 500 feet AGL while attempting to achieve the computed final approach airspeed, could seriously impact aircraft recovery if a high sink rate is encountered.

d) For the RNP aircraft, sustained (sustained means 3 seconds or more) bank angles during the approach not greater than 25 degrees above 500 feet and 3 degrees below 500 feet AGL.

Finding: All bank angles were within test criteria.

e) Sustained (3 seconds or more) rates of descent not exceeding 1,000 feet per minute during any portion of the final approach segment.

Finding: All runs exceeded this criteria due to the high airspeed maintained on final approach, engine power management, and configuration changes.

f) For the RNP aircraft, overshoots beyond the extended runway centerline not exceeding 200 feet. (Note: the 200-foot limit is specific to the close-in parallel operations of SFO).

Finding: The 200-foot runway centerline overshoot limit standard was not exceeded on any runs.

g) Successful resolution of any blunders.

Finding: No NTZ blunders occurred. However, on run #8, the ILS aircrew was slow to activate the "Approach Mode" while intercepting the intermediate approach segment resulting in a slight overshoot of the ILS final approach course. At this point, the RNP aircraft was cleared to maintain visual separation.

h) Successful execution of missed approaches with no increase in risk to other traffic.

Finding: The missed approach recovery was accomplished in accordance with the test plan. However, TCAS RA low altitude recoveries resulted in a significant risk potential to both aircraft. Note: The missed approach was designed strictly for this concept flight and would generate airspace conflicts if used for real world operations at SFO.

i) Successful wake turbulence avoidance.

Finding: No wake vortex was encountered.

9.0. RECOMMENDATIONS

a. Enhance the current RPAT procedure design tool to allow design flexibility in mitigating closure rates and incorporating a means to determine/display the design envelop for TCAS RAs for evaluation procedure design purpose.

b. Develop an aircrew and controller training program for RPAT operations to address in-trail spacing, workload, aircrew coordination, and airspeed management issues.

c. Conduct additional studies on wake vortex mitigation, to include aircrew and controller responsibilities, for RPAT operations.

d. Validate the use of the autopilot to reduce aircrew workload and the use of the ASR-9 radar for RPAT-type operations.

e. Redesign the RNAV approach to reflect an optimum continuous flight path descent angle throughout the RPAT operation and require this for all RPAT operations.