FLIGHT TEST RESULTS OF A PSEUDOLITE- BASED PRECISION APPROACH AND LANDING SYSTEM

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ABSTRACT

The approval of the Minimum Aviation System Performance Specification (MASPS) for Special Category I approaches by RTCA opens the era of GPS-guided precision approach operations. Although the MASPS addresses only Category I (200 feet decision height) operations, work has already begun on extending the application of GPS to Category II and III landings. This will be done by application of the Required Navigation Performance parameters summarized in the MASPS and currently under ICAO development. These parameters include *accuracy, integrity, continuity*, and *availability*.

One approach to achieving RNP in all four parameters involves the use of ground-based pseudolites to supplement the GPS satellite constellation. This paper presents preliminary flight-test results of a Differential GPS/pseudolite system. The August 1993 test flights were flown by NASA Langley Research Facility at Wallops Island, VA, with ground and airborne equipment provided by AlliedSignal Communications Systems and NAVSYS Corporation. Preliminary results indicate accuracy performance well within the Category III requirements and recommendations for MLS equipment.

1 INTRODUCTION

The Radio Technical Commission on Aeronautics (RTCA) is currently completing its development of the Minimum Aviation System Performance Specification (MASPS) for Special Category I (SCAT I) precision approach operations utilizing Differential GPS as the primary sensor. [1]. When approved, this document will provide the basis for approval and certification of special purpose precision approaches to the Category I standards of 200 ft. decision height and 3/4 mile visibility. Completion of the SCAT I standards is an important milestone in itself, but it also marks the way for future development to achieve the event more stringent Category II (100 ft. decision height) and Category III (50 ft decision height) applications.

The SCAT I MASPS utilizes a methodology known as Required Navigation Performance (RNP) to establish the aviation system requirements. RNP is currently the topic of attention in the RTCA, FAA and ICAO communities for a variety of applications. [2,3,4].[1] RNP establishes four key parameters for defining a "tunnel in space": *accuracy, integrity, continuity*, and *availability*.

Early work in the application of GPS to precision landings focused solely on achieving the accuracy required to safely deliver the approaching aircraft to the touchdown zone. [5,6]. The possibility of using pseudolites to increase the availability and continuity properties of the GPS signal has been discussed, but an integrated systems approach addressing each of the four parameters was not presented

[1] A detailed introduction to the RNP approach may be found the work of Dr. R.J. Kelly and J. M. Davis [2].

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until 1992 [7]. In the last year, pseudolite-based solutions to the precision landing application have been investigated by several groups, most notably at Stanford University. [8,9,10]

The current flight tests are based on the system concept presented by Dr. Alison Brown of NAVSYS Corporation in her 1992 paper.

2 SYSTEM SUMMARY

The pseudolite-based precision approach and landing system, illustrated in Figure 1, consists of the following key components:

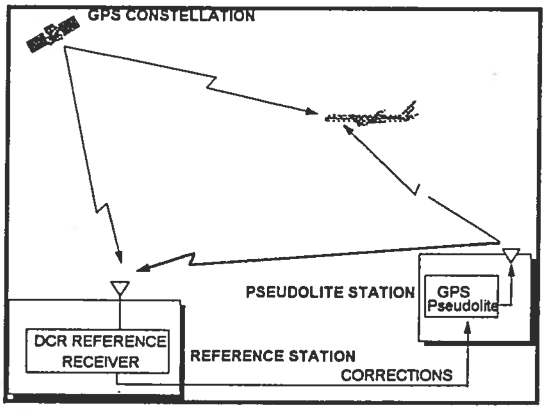

Figure 1: Pseudolite Based Landing System

(1) **Aircraft Receiver** A wide-band GPS receiver capable of receiving and tracking GPS L1 signals and pseudolite signals radiating on another L-Band frequency, referred to as Lpl, and of accepting differential corrections.

(2) **Reference/Monitor Station** A differential ground station/system monitor consisting of receiving equipment identical to the aircraft receiver.

(3) **Pseudolite Transmitter** A ground-based transmitter broadcasting a "GPS look-alike" signal with an unused Gold Code on the Lpl frequency. Use of Lpl avoids the "near-far" problem characteristic of many pseudolite solutions. A single pseudolite provides coverage to multiple runways.

Use of an Lpl frequency allows the transmitter to remain small (less than 10 mw) while allowing a range of coverage sufficient to serve as a high integrity data link of the differential corrections at a rate of up to 1000 bps. Within the airborne equipment, the pseudolite transmission is received, the data stripped off, and a ranging solution computed. When combined with the pseudoranges (PRs) to the various in-view satellites, the pseudolite transmission allows resolution of the multiple cycle ambiguities and provides a position estimate accurate to tens of centimeters, far exceeding the Category III accuracy requirements. This combination of pseudorange, carrier phase, and differential corrections is call Differential Carrier Ranging (DCR).

3 TEST CONFIGURATION

A test-bed DCR data collection system was assembled by AlliedSignal and NAVSYS and installed on the NASA Transportation Systems Research Vehicle (TSRV) at NASA's Langley Virginia research facility during the early summer of 1993. Figure 2 illustrates the data collection system.

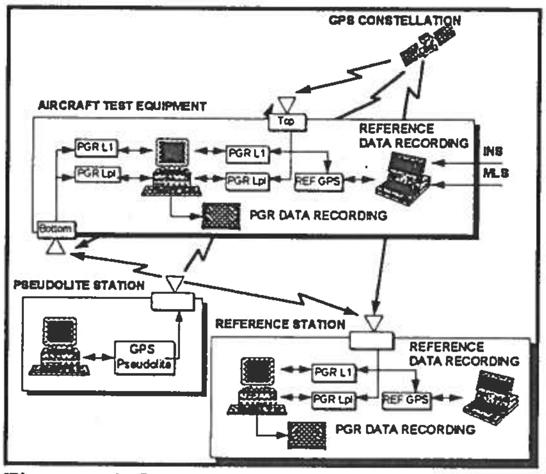

Figure 2: DCR Test Data Collection

The key component within the system is the NAVSYS Predetection GPS Receiver (PGR). The PGR consists of a standard GPS front end and down converter followed by a digital back-end which quantizes the intermediate frequency at 2 million samples per second and writes the quantized information to a Honeywell/Metrum Very Large Data Store tape recorder. The aircraft installation used four such PGRs: two tuned to the standard L1 frequency of 1575.42 MHz, and two tuned to the Lpl test frequency of 1615 MHz.[2] One pair of PGRs was connected

[2] The use of 1615 MHz for Lpl was chosen for RF interference reasons at the Wallops Island Facility. [9] recommends an Lpl in the 1610-1625 band.

to the top antenna and one to a second antenna located in front of the aircraft nose gear. This configuration allowed collection of ranging data and measurement of signal amplitude at both antennas throughout the approach.

The test avionics also included a NOVATEL 951 GPS receiver and a laptop PC for collection of NOVATEL data and real-time recording of the Inertial Navigation System (INS) outputs. Since the Wallops Island facility is instrumented with a high precision AlliedSignal MLS ground station, real-time MLS receiver outputs were also recorded during the approaches.

The pseudolite ground station consisted of a NAVSYS signal generator with AlliedSignal final amplifier and a circularly polarized horn antenna. The equipment was located within a mobile test van. The antenna was mounted on the test van roof, approximately 4 meters above ground level. The pseudolite transmissions were modulated with a repeating 30 bit test pattern at 1000 and 500 bps to test the effectiveness of the pseudolite data link. Use of a mobile pseudolite facility allowed us to verify operation at multiple locations on the Wallops Island airfield.

The reference/monitor ground station consisted of two PGRs, a Honeywell/Metrum data recorder, and a NOVATEL 951 GPS. Use of two PGRs allowed collection of both the received GPS data and a ground verification of the pseudolite transmissions, including data transmissions.

4 TEST DESCRIPTION

The flight tests were designed to answer several questions about the pseudolite-based landing system in addition to collecting accuracy data.

(1) Is a single airborne antenna sufficient to receive both satellite and pseudolite signals?

(2) Is a single pseudolite sufficient to provide RNP accuracy for Category II/III applications?

(3) Is a single pseudolite sufficient to provide coverage for multiple runways?

(4) can the pseudolite data link sustain 1000 bps data with an acceptable error rate?

(5) Does the off-channel pseudolite provide sufficient near/far protection to the L1 signal?

To address these questions, a series of 30 approaches was performed in the NASA 737 during three flight sessions spread over two days, as summarized in Table 1. Approaches were made to both Runway 22 and Runway 28 without moving the pseudolite. To investigate the sensitivity of the DCR solution to various pseudolite positions, several flights to each runway were repeated with a second pseudolite position, as shown in Figure 3. All 30 approaches were tracked by the Wallops laser tracking facility. In addition, MLS data was collected on all approaches to Runway 22, thus providing a second source of position reference information.

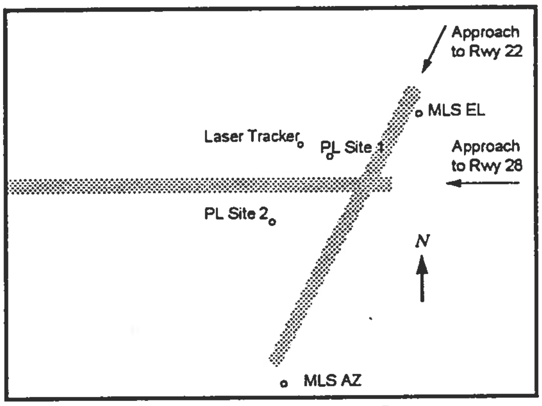

Figure 3: Approximate Ground Geometry

The 30 flights resulted in a massive amount of real-time data available for post flight processing. Due to the use of the PGRs, this post-flight processing is *not* the typical assessment of pseudoranges and carrier phases, but involves the full range of GPS receiver operations including code and frequency tracking loops, data demodulation, application of differential corrections, and resolution of ambiguities to achieve the DCR solution. Thus, the data base allows the flights to be *re flown* in real time to evaluate modifications to the tracking algorithms and loop bandwidths.

Processing the data included the following steps:

(1) Establish GPS data, ephemeris, and almanac values using the NOVATEL data.[3]

[3] NOVTATEL data was used to construct this data, since the time necessary to receive a complete almanac would require far

(2) Establish a system clock by selecting a single satellite clock as the reference and using it to synchronize ground, pseudolite, and airborne data..

(3) Measure pseudolite SNR for both Top and Bottom receive antennas at the aircraft.

(4) Measure bit error rate on pseudolite data.

(5) Compute PR and Carrier Phase (CP) range to satellites for Top, Bottom, and Ground antennas.

(6) Compute PR and CP range to the pseudolite for Top, Bottom, and Ground Reference antennas.

(7) Merge pseudolite/satellite data in navigation solution.

(8) Compare to available laser tracker and MLS estimates of true position.

(9) Compute lateral and vertical Path Following Error (PFE) and Control Motion Noise (CMN).

5 TEST RESULTS

The test results not only confirmed the excellent performance of the DCR system, but also presented new questions to be addressed in later tests. Figure 4 shows the measured signal-to-noise ratio (SNR) on the top and bottom antennas, indicating adequate signal This result was unexpected, since simple Geometric Theory of Diffraction models predict heavy shadowing of the top antenna from any pseudolite transmissions. As expected with this data, the bit error rates for both top and bottom antennas are excellent, with no errors observed in over 500,000 bits received. This allows us to estimate an error rate of at most 1.3 x 10^{-6} with at least 50% confidence.

Solid pseudolite ranging solutions were obtained on both the antennas throughout the approach. Figure 5 illustrates the errors in the measured "pseudorange-to-pseudolite" for a typical approach. The 25 second oscillations are typical

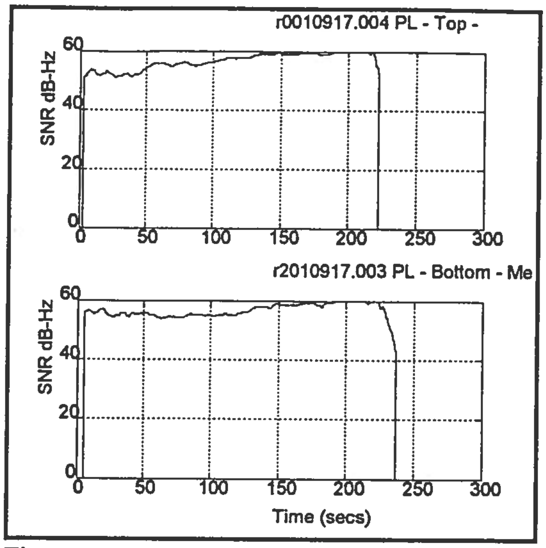

Figure 4: SNR Measurements Top and Bottom Antenna, NASA 737

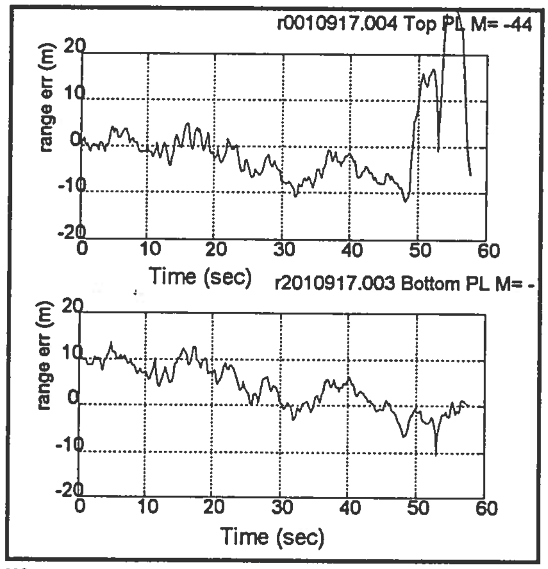

Figure 5: Pseudorange to Pseudolite Measurements Top and Bottom Antenna

of ground multipath, and can be reduced by use of a shaped pattern on the pseudolite transmit antenna.

Lateral and vertical accuracy of the DCR navigation solution is excellent. We will present this data in terms of the Path Following Error (PFE) and Control Motion Noise (CMN). These parameters, which have been accepted as the standard means to describe landing system performance by ICAO, assess the effects of

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too much Metrum storage capacity to allow for meaningful flight results.

errors in guidance on the position and control status of the user aircraft.[12].[4]

Path Following Error consists of those errors having spectral content within the bandwidth of the aircraft guidance loop. Since these errors can be tracked by the guidance loop, they cause physical displacement of the aircraft from its desired course and, therefore, may create a hazard condition. Lateral PFE is modeled by a low-pass filter with corner frequency of 0.5 radians/second. Vertical PFE is modeled by a 1.5 radian/second filter.

Control Motion Noise consist of errors having spectral content outside the guidance loop bandwidth, but inside the pass band of the control loop. CMN does not cause physical displacement of the aircraft, but does create motion of the control surfaces. A high level of CMN results in pilot mistrust of the guidance data. CMN levels have been established to achieve a Cooper Level 2, "Pleasant to Fly", rating by pilots.

Lateral Data

Figure 6 illustrates the lateral laser tracker data for flights 040 and 151 to Runway 22. Since the laser data is used as the "truth" reference, the laser data dropouts will be pruned from the lateral PR and CP data.

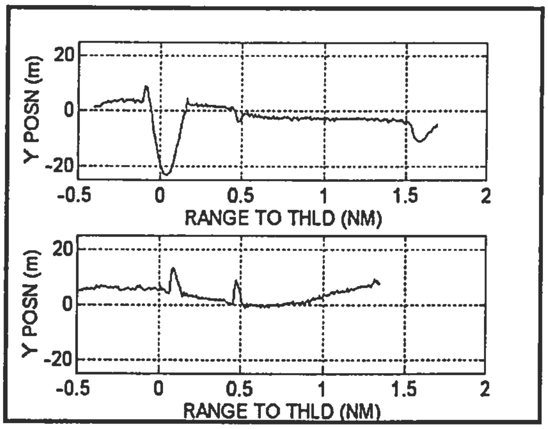

Figure 6: Ranger Tracker Reference for 2 Flights - Y coordinate (Cross-track)

Figures 7 and 8 show the lateral PFE obtained from the pseudorange and carrier-phase solutions, respectively. Data is uniformly excellent, especially compared with the Category III requirement of ±4.1 meters on a 95 percentile basis. Typical errors are less than ±1.0 meter when the laser tracker dropouts are removed. A slight bias in carrier-phase indicates that the position ambiguities have not been fully resolved.

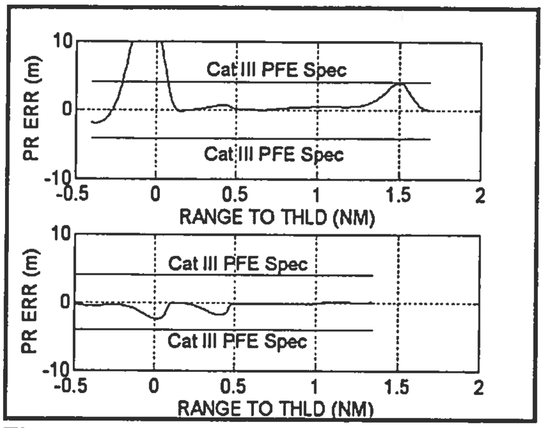

Figure 7: Lateral PFE for PR Solution

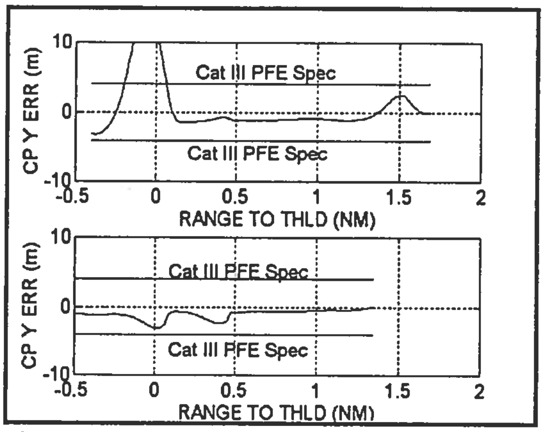

Figure 8: Lateral PFE for CP Solution

Figures 9 and 10 show the lateral CMN obtained from the pseudorange and carrier-phase solutions, respectively. Data is again excellent, far exceeding the Category III requirement of ±3.2 meters on a 95 percentile basis. Effects of laser dropouts match the "truth data of Figure 6, and can be ignored. Comparison of these figures with the laser truth data of Figure 6 illustrates the fact the much of the high-frequency noise is in fact due to laser tracker scintillation and not DCR errors.

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[4]An excellent tutorial in the foundations of PFE and CMN may be found in Reference 14, by Kelly and Cusick.

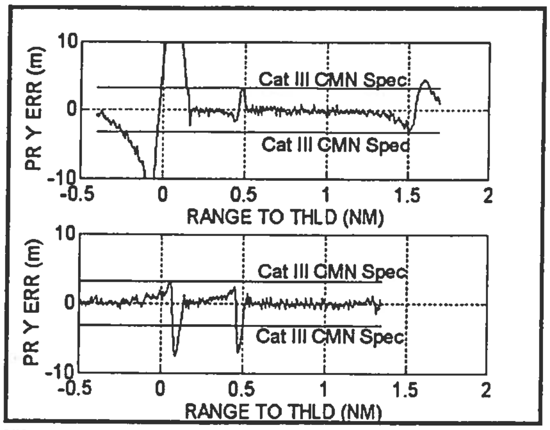

Figure 9: Lateral CMN for PR Solution

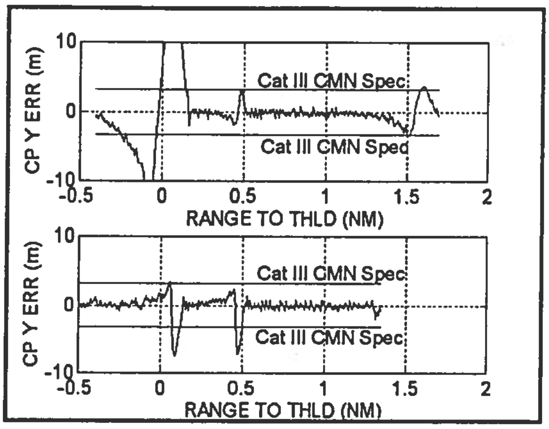

Figure 10: Lateral CMN for CP Solution

Vertical Data

Achieving the Category III vertical accuracy requirement of ± 0.6 meters PFE is the ultimate goal of any precision landing system. The pseudorange solution PFE data shown in Figure 11 comes close in both flights. The carrier phase solution shown in Figure 12 indicates that the goal is achieved once final resolution of carrier ambiguities is complete. Carrier phase PFE remains well within the requirement. Slight excursions beyond the specification are due to tracker errors, as shown in Figure 6. In any event, these excursions are unimportant, since the PFE requirement is a 95th percentile specification.

Vertical CMN is also within to the Category III requirement of ± 0.3 meters, as shown by Figures 13 and 14 for pseudorange and carrier phase solutions, respectively. Slight outages around 0.5 NM from threshold can be directly traced to laser tracker error in Figure 6.

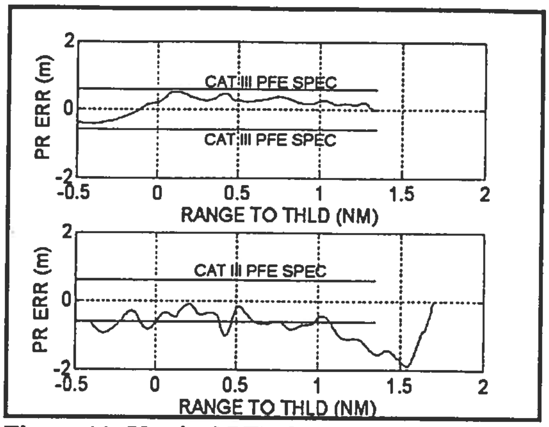

Figure 11: Vertical PFE for PR Solution

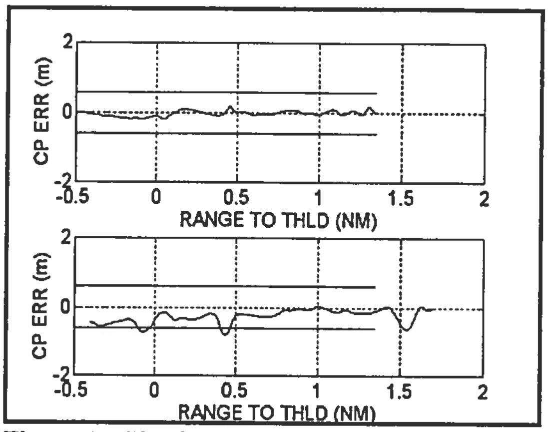

Figure 12: Vertical PFE for CP Solution

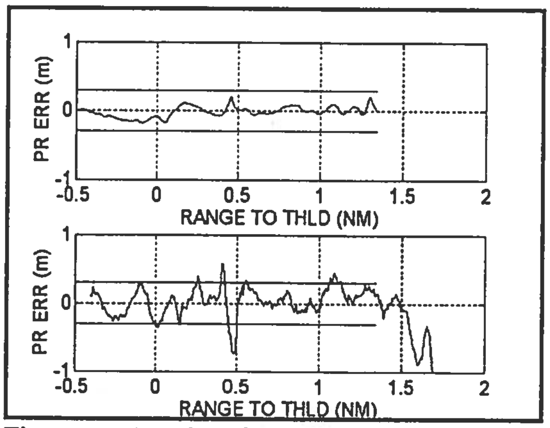

Figure 13: Vertical CMN for PR Solution

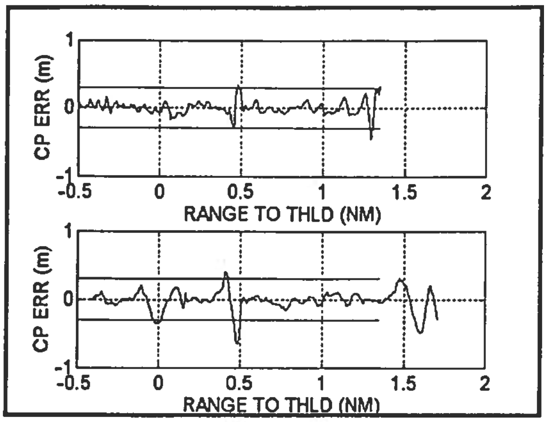

Figure 14: Vertical CMN for CP Solution

6 CONCLUSIONS

This first look at data collected from a DCR precision landing system using an "off-channel" Lpl pseudolite answers many of the original systems questions. Pseudolite data *can* be received at both top and bottom antennas, although the mechanism for this is not sufficiently understood to recommend a single antenna implementation. A single pseudolite *does* offer Category III accuracy, and provides sufficient coverage for multiple runways. The pseudolite link *can* sustain a 1000 bps uplink of differential correction data with an error rate of less than 1.3×10^{-6}. The off-channel pseudolite *does* provide sufficient near/far protection.

These experiments establish the off-channel pseudolite as a prime candidate for the Category III DGPS precision approach application..

7 ACKNOWLEDGMENTS

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BIOGRAPHIES

E.F. Charles LaBerge - is a Principal Engineer at AlliedSignal Communications Division in Towson, Maryland where he is the System Engineering Manager for the Air Traffic Control Directorate. He has 19 years of systems engineering experience in Air Traffic Control and landing systems. His current responsibilities include technical oversight of Mode S ADS, Precision Runway Monitor, and Embedded GPS projects within Communications Division. He holds Bachelor of Engineering Science and Master of Science in Engineering degrees from The Johns Hopkins University in Baltimore.

Dr. Alison Brown - is the President of NAVSYS Corporation, which specializes in the development of GPS technology. She has 14 years experience in GPS receiver design and has seven GPS related patents. She has published numerous technical papers on GPS applications. Dr. Brown currently conducts research in various areas of GPS, including advanced GPS receiver design, high accuracy GPS, differential GPS techniques, GPS integrity monitoring, and low cost GPS receivers. Dr. Brown completed her graduate studies at MIT and UCLA. Prior to NAVSYS, Dr. Brown was a GPS systems engineer at Litton Aero Products.

Dr. Frank van Diggelen - is a GPS Design Engineer at NAVSYS Corporation. Dr. van Diggelen received his PhD in control theory from Cambridge University in 1992 and has worked and published in the filed of automatic control. he has organized and participated as demonstrator in control workshops for engineers in Britain and South Africa. Dr. van Diggelen current conducts research in the areas of real-time kinematic processing and integrity monitoring in GPS.

Dr. Thomas M. Kelecy - is a GPS Navigation Engineer at NAVSYS Corporation where he is involved with GPS navigation systems design and analysis. Tom has worked in the area of GPS kinematic positioning of remote sensing platforms for the past six years while at NOAA, and at the University of Colorado, Boulder. As a guidance and control Engineer with Martin Marietta Aerospace Corporation, he contributed to the design and analysis of the attitude determination and control system for the Magellan spacecraft now orbiting Venus. Tom received his PhD[*] in Aerospace Engineering Sciences from the University of Colorado at Boulder in 1990.

[*] Presented at ION Satellite Division 6th International Technical Meeting, GPS-93, Salt Lake City, September 1993.