

# Performance of Ship Relative GPS (SRGPS) Reference Station Diversity Reception Alternatives

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## BIOGRAPHY

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## Abstract

In the ship relative GPS system, multiple reference antennas and diversity processing can be utilized for improving signal-in-space accuracy and integrity in the presence of jamming, blockages and multipath. This paper compares conventional post-loop diversity processing with post-correlator diversity processing.

With post-loop diversity (PLD), roll-pitch-yaw compensated loop outputs from separate receiver channels and antennas are cross-checked for consistency prior to forming a combined DGPS correction for a given satellite. In interference and jamming this approach offers no advantage over single antenna operation. Moreover, transient multipath or blockage at one or more antennas will damage the individual tracking loops, thereby impacting system continuity. By contrast,

with post-correlator diversity (PCD), correlator data derived from multiple antennas is cross-checked for reception anomalies prior to loop updates, and qualified correlator data is optimally combined in an extended Kalman filter. Compared with PLD, this form of diversity reception offers potential for significant threshold improvement in jamming, as well as detection and isolation of anomalies.

In the paper, SRGPS system dynamics, which fundamentally limit tracking performance, are first established, followed by definitions of attenuation, multipath, and interference reception events to be evaluated. The signal simulation approach is then discussed. System simulations are then carried out for both diversity reception approaches, as a function of the number of antennas available, with discussion of RMS phase error and hold time statistics.

In the simulations, PCD is found to out-perform PLD in environments with single and multiple attenuations. Under strong specular multipath conditions, with and without direct path blockage, PCD was able to detect and reject corrupted data at the correlator level, thereby mitigating loop contaminations experienced with PLD. In jamming and interference, the PCD was found to extend tracking thresholds by as much as 6 dB. With data aiding, thresholds approaching 10 dB-Hz were realized with the 4-antenna PCD configuration. These improvements are significant to safety critical DGPS applications, both military and civilian.

## Introduction

**Figure 1** depicts the hardware and software elements of the conventional post-loop diversity (PLD) reception approach, for one satellite and multiple antennas. Raw observables from redundant channels pass through two stages of screening. In the first stage, Measurement Quality Monitoring (MQM) carrier phase observables are tested for cycle slip induced jump discontinuities. Current epoch measurements passing

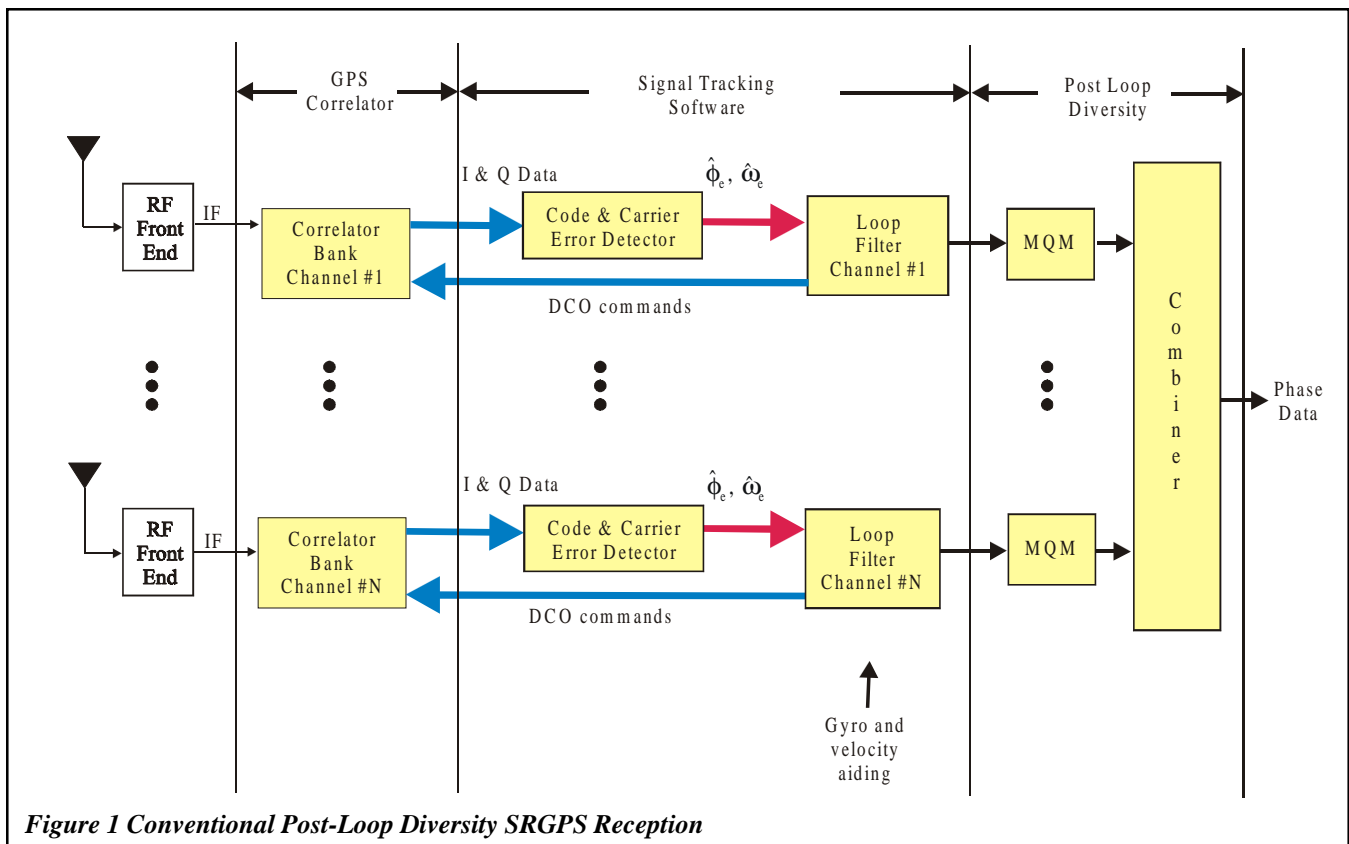


Figure 1 Conventional Post-Loop Diversity SRGPS Reception

this test make their way to the combiner element, where consistency checks are performed prior to forming a phase average value. Final residual consistency checks between DGPS corrected satellites, as computed upstream in the navigation domain processor, are not shown in the figure. [1,2] Anomalies entering a given antenna will deterministically damage the associated loop, directly impacting the availability of satellite phase data at the combiner output. Loss of data on a given satellite will in turn impact overall navigation domain continuity and/or integrity. Therefore, in the face of reception impediments, including interference, blockages, and specular multipath, PLD may prove inadequate to support navigation domain continuity and integrity constraints at the sub-meter performance level.

Unlike the PLD scheme, where post-loop phase data is monitored and averaged, a contrasting diversity methodology, Post Correlator Diversity (PCD), makes decisions earlier in the signal processing chain, at the post correlator level. The PCD technique employs an extended Kalman filter and associated residual monitoring functions in processing pre-detection data in a statistically optimum fashion, Figure 2 [3-6]. The PCD method utilizes line-of-sight dynamics redundancy as well as data bit redundancy, in screening the raw I/Q correlator data from each antenna before accepting that data for further processing. Screening includes tests for signal amplitude, multipath contamination, and interference level. Following qualification, the I/Q values from multiple antennas are used

to update the states of the carrier-phase-tracking filter.

In this preliminary study, as a preface to carrying out integrity and continuity comparisons in the navigation domain, the underlying tracking statistics of the two approaches are developed. PLD is constrained by the tracking margins of a single antenna-tracking loop path, whereas PCD offers improved tracking performance as a function of the number of antennas available. In scenarios with complex attenuations and multipaths, PLD loops are individually damaged, thereby compromising data availability and measurement quality. Before carrying out performance simulations, the underlying dynamics and reception environments of interest are first discussed.

### System Dynamics

Path bias and station clock dynamics to be tracked fundamentally limit the performance of any DGPS reference station. Additionally, in the case of SRGPS, the ship motion dynamics must also be considered, including the IMU loop aiding errors.

The path bias dynamics consist of the following terms:

- satellite clock,
- satellite ephemeris,
- ionospheric drift, and
- tropospheric drift.

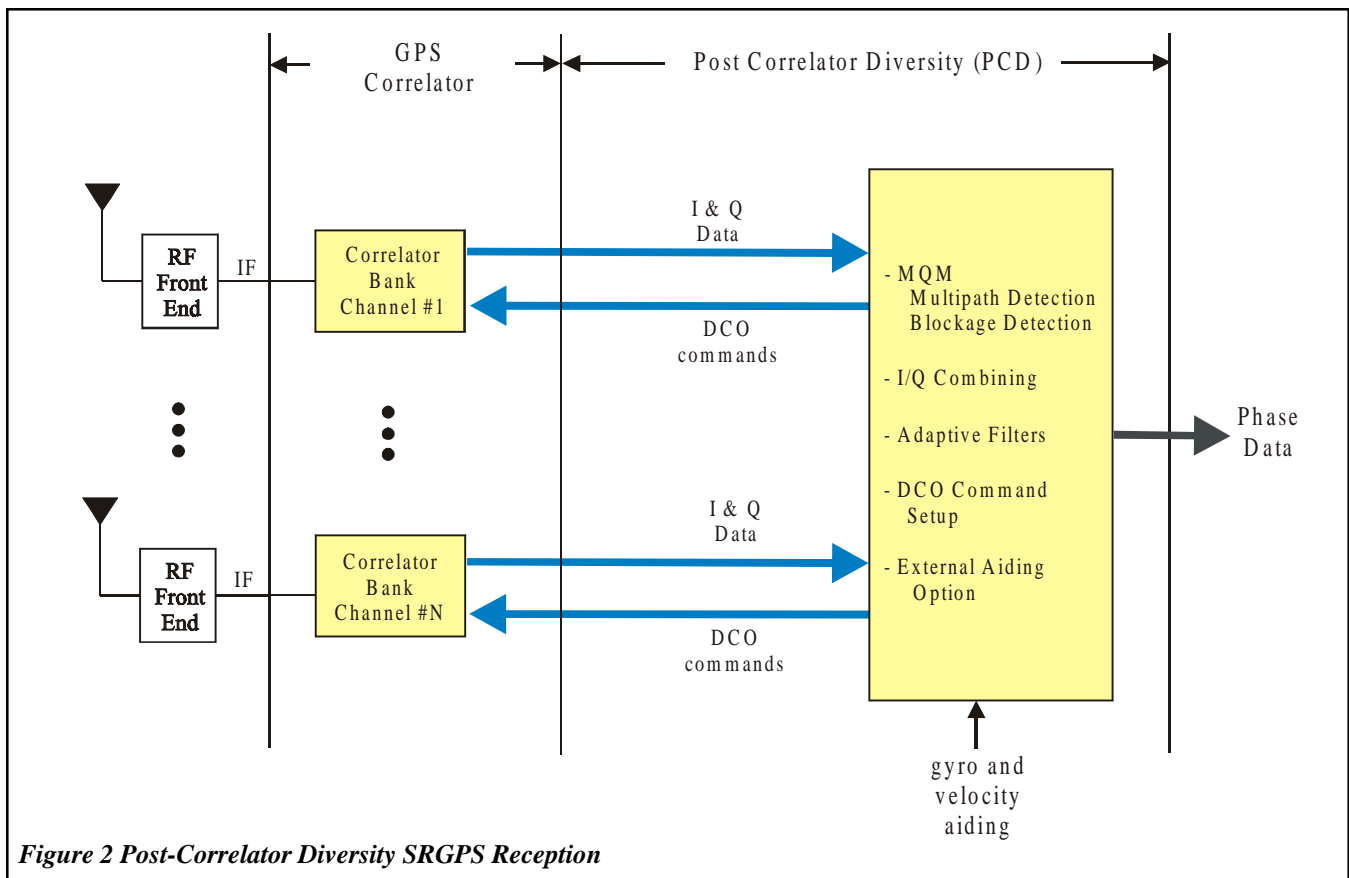


Figure 2 Post-Correlator Diversity SRGPS Reception

To characterize the cumulative drift rates associated with these terms, double difference carrier-phase observables were formed between live data and predicted phase values. The phase data was collected following the removal of GPS selective availability, as implemented by DOD on May 1, 2000. The temporal decorrelations in these double difference terms were examined for prediction times out to 100 seconds. Based upon this analysis, the path bias drift was conservatively modeled as Gauss Markov, with a correlation time of 10 seconds and with a velocity standard deviation of 0.002 m/sec.

The reference station clock dynamics was considered next. In keeping with current practice at shore-side government DGPS reference stations, an atomic time standard was assumed. For such clocks, short term frequency stability over a reference station smoothing time of seconds is on the order of 5 parts in  $10^{12}$ . This translates to a path drift of under .0015 m/sec., which is commensurate with above path bias dynamics.

In the absence of loop aiding by IMU, uncompensated SRGPS platform motion is clearly the predominant term seen by the reference filter tracking loops. For large ships the velocity process correlation time is on the order of 50 seconds, and the process velocity standard deviation is on the order

of 12 m/sec (20 knots).

Finally, IMU loop aiding drift rates and alignment errors are considered. With the SRGPS architecture still in its development stage, uncertainty exists concerning the IMU aiding source for reference receiver tracking channels. A quoted stability for the AN/WSN-7 RLG Ship Inertial Navigation System (SINS) is 1 nautical mile in 24 hours. Whether the SINS would be available for receiver aiding or is, in fact, the most desirable aiding source, is an open question. To minimize lever arm effects it may be desirable to employ an IMU of poorer quality in the vicinity of the SRGPS antenna system. In the simulations carried out below, an IMU with 1 nmi/hr drift is assumed. This drift rate term then substantially dominates the other dynamics discussed above.

#### Overview of RF Reception Events

Four signal fault condition groups were considered in this study:

##### (1) Signal attenuation patterns on multiple antennas

Signal amplitude and noise levels are adjusted such that nominal reception is at 40 dB-Hz CNR at run onset. At time step 1000 (10 seconds) attenuations are applied, simultaneously, to one or more available antennas.

(2) Strong specular multipath on a single antenna  
Signal amplitude and noise levels are adjusted such that nominal reception is at 40 dB-Hz CNR at run onset. At time step 200 (2 seconds) multipath is applied at a single antenna. Multipath amplitude is set equal to GPS signal amplitude. Multipath delay difference is less than 0.1 chip and Doppler difference is adjusted for maximum carrier phase multipath error.

(3) Strong specular multipath on a single antenna, plus direct path attenuation  
Same reception conditions as above, but at multipath onset the direct path of the affected satellite is attenuated by 20 dB.

(4) Interference applied to all antennas  
Signal amplitude and noise levels are adjusted such that nominal reception is at 40 dB-Hz CNR at run onset. At time step 750 (7.5 seconds), jamming at a fixed power level is applied, equally, on all available antennas. Antenna spacing is assumed large enough such that post correlator noise processes are statistically independent. At each CNR value simulations were performed with 20 randomizations.

The objective is to establish RMS phase error statistics, time to cycle slip from onset of the reception event, and telemetry data bit error rates, conditioned on these fault conditions. In future task efforts, this data will be utilized in developing SRGPS navigation continuity and integrity for multiple antenna PLD and PCD options.

### Simulation Approach

The simulation tool applied in this study is TrackView, which was extended from previous work to model multiple RF paths and correlators for each satellite [7]. Referring back to **Figures 1 and 2**, TrackView models the correlator bank I/Q output data in response to loop filter DCO commands. The correlator model and input conditions supplied by TrackView are identical for both diversity options. For PLD, the correlator command loop closure is de-coupled between tracking paths. For the PCD, the correlator command loop closure for all signal paths is through a central filter.

Mean and variance of correlator bank outputs is driven by RF input noise power, as well as by the offset in carrier phase and frequency between current DCO values and line-of-sight truth. In addition to the primary I/Q output components, correlator channels are configured to generate a multipath component, whose amplitude, delay and Doppler offset relative to the direct path is programmable. Although available in the simulator, and applied in other studies by TISI, antenna gain and phase anomalies are not treated in the present

simulations [8].

The TrackView environment permits high fidelity 2 kHz simulations of non-linear tracking behavior, in approximately real-time. Additionally, to minimize interactions with the operator, the environment is configured for automation of repeated runs with differing diversity reception and environment parameters.

### Attenuation Comparisons

In this test group, multiple attenuations were introduced across one or more antennas. As anticipated, the tracking loops of the PLD system broke down individually following attenuation onset, whereas the PCD system was able to prevent channel damage, even with up to 3 of 4 RF paths attenuated. **Table 1** summarizes hold time statistics, for time until first cycle slip. In all cases with one or more redundant antennas, PCD provided cycle slip immunity while PLD loops experienced tracking damage.

Station Antenna Configuration	Number of Antennas Attenuated	Diversity Reception Type	Aggregate Hold Time (100Hz TIC units)
<b>4</b>	<b>1</b>	Post Correlator	2000
		Post Loop	<b>1377</b>
	<b>2</b>	Post Correlator	2000
		Post Loop	<b>1330</b>
	<b>3</b>	Post Correlator	2000
		Post Loop	<b>1330</b>
<b>3</b>	<b>1</b>	Post Correlator	2000
		Post Loop	<b>1647</b>
	<b>2</b>	Post Correlator	2000
		Post Loop	<b>1366</b>
<b>2</b>	<b>1</b>	Post Correlator	2000
		Post Loop	<b>1292</b>

**Table 1: Antenna Attenuations Summary**

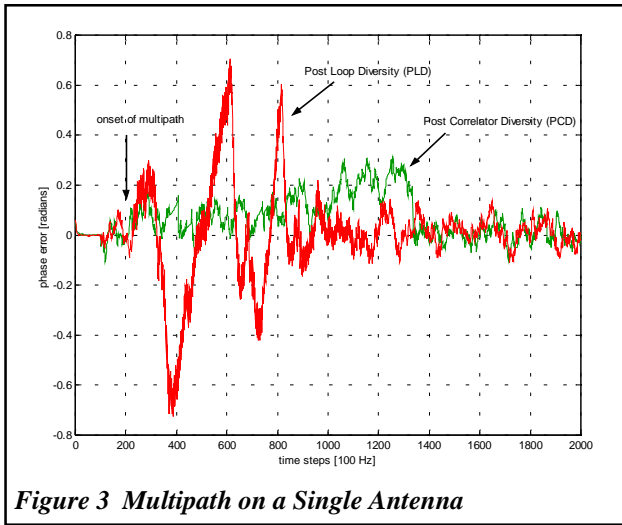
While the MQM functions of the PLD might detect these events, the resulting tracking loop damage would be difficult to correct in the combining network, resulting in either a shutdown of the satellite by the PLD logic, or a subsequent rejection of the measurement by upstream navigation integrity functions. In either case, navigation continuity would be

impacted. The effect of these tracking disruptions upon overall system continuity awaits further analysis in follow-on tasking.

### Multipath Comparisons

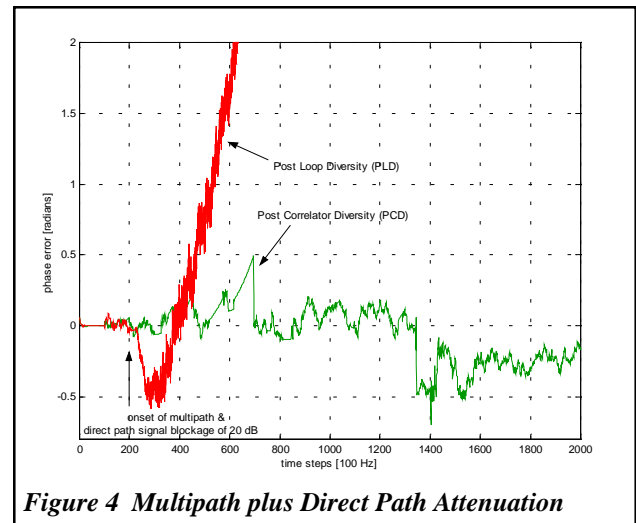
As described above, two basic group conditions were applied as a single antenna input a) multipath without direct path blockage, and b) multipath with direct path blockage. In both cases multipath amplitude was set equal to the nominal unattenuated GPS signal level, and was applied on one of two available antennas. This minimal 2-antenna diversity configuration was considered worst-case. With additional redundant antennas PCD performance would be further improved.

**Figure 3** shows typical comparative phase tracking performance for PLD and PCD tracking, at the nominal CNR of 40 dB-Hz, without direct path blockage. The PLD loop impacted by multipath exhibits peak swings of 0.7 radians while PCD is able to recognize and attenuate the multipath component. A gradual phase drift is evident in PCD data, until the I/Q measurements are again accepted by the filter.



**Figure 3** Multipath on a Single Antenna

In the next set of multipath scenarios, the direct path was blocked simultaneously with the onset of the multipath signal. As would be expected, the decoupled loops of PLD are captured by the multipath component. This is contrasted with PCD performance in **Figure 4**. Shortly after multipath onset the PLD tracking loop experiences phase mistracking. By contrast, with PCD, MQM functions were able to detect the presence of the multipath contamination reliably prior to filter incorporation of the corrupted I/Q outputs, maintaining continuous phase tracking.



**Figure 4** Multipath plus Direct Path Attenuation

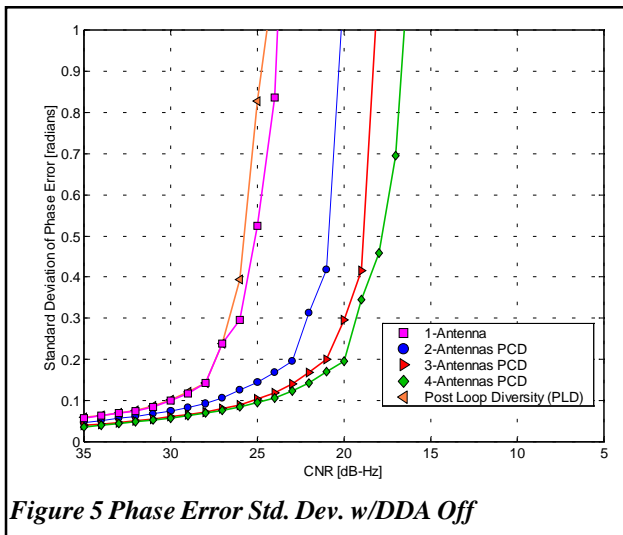
### Interference Comparisons

Unintentional interference and jamming pose threats to service continuity that must be considered in the SRGPS reference station design. The solution to this problem can encompass several techniques: reference station nulling and beamforming, post correlator diversity, loop aiding, and data aiding. In this paper, the later three techniques were evaluated. Specifically, the above PLD and PCD processing methods were contrasted, as a function of the number of available diversity antennas, with and without data aiding. In evaluating interference responses, a substantial battery of simulations were carried out for each configuration. In each of these runs, constant and equal interference levels were applied at each antenna. Runs were repeated with twenty different noise randomizations for each interference level, with levels varied in 1 dB increments.

### Data Demodulation Aiding (DDA) Off

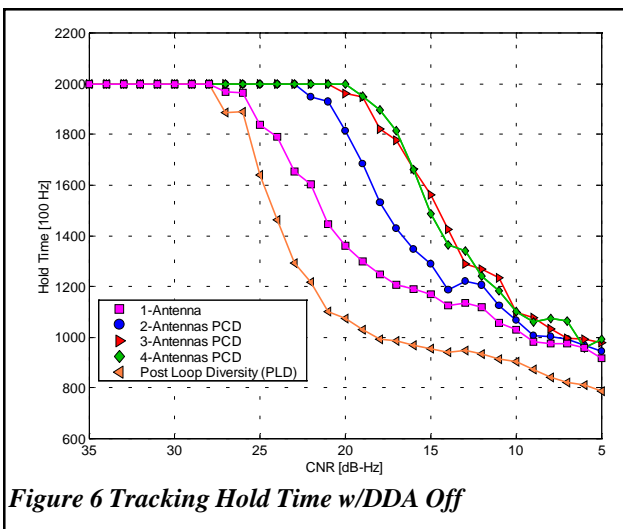
The first group of runs were carried out with data aiding off. For comparative purposes both PLD and PCD approaches employed extended Kalman filter structures for estimation of correlator bank phase and frequency errors. The PLD carried out data bit demodulation and carrier phase tracking independently on each antenna. By contrast, PCD data demodulation routines took advantage of the telemetry bit streams shared by all antennas.

**Figure 5** is a comparative phase error plot for five different station configurations. The baseline case is the single antenna configuration. With the given system dynamics and tuning parameters the threshold “knee” occurs at around 27 dB-Hz, with 0.5 radians phase error (1.6 cm) at 25 dB-Hz. PLD tracking loop performance, with four antennas, follows this same path, within the variation limits of the twenty randomizations performed at each CNR point. In the threshold region this is expected, since the PLD tracking loops are operating independently of each other. PCD tracking



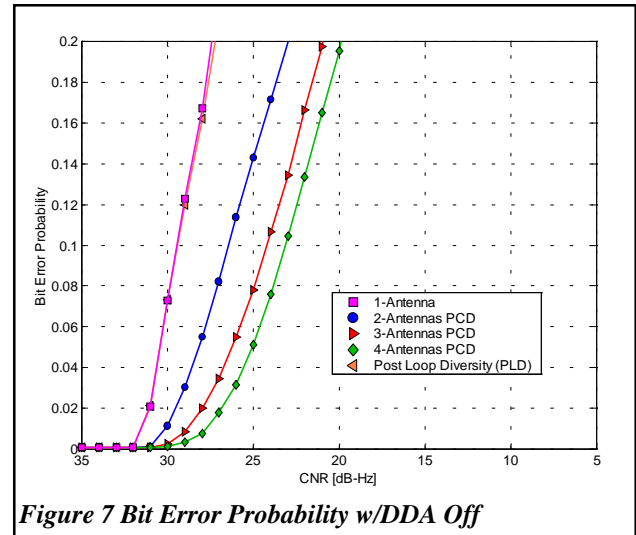
performance varies with the number of antennas utilized in the configuration. With two antennas the improvement is within 1 dB of the 3 dB value expected by theory, reaching 0.5 radians RMS tracking error at 21 dB-Hz. With four antennas an additional 3 dB improvement is achieved, with 0.5 radians RMS tracking error reached at around 18 dB-Hz. Also shown in this figure is the three antenna case, which is marginally worse than with four antennas.

An alternate way of viewing and interpreting these results is in terms of tracking hold time before loss of phase lock. Average hold times as a function of CNR are shown in **Figure 6**. The maximum available hold time is 2000 time steps, or 20 seconds, which is the duration of each run. An interesting contrast is between 1-antenna (PLD or PCD) and 4-antenna PLD configurations. Poorer hold times of the 4-antenna PLD over the 1-antenna configuration demonstrate sub-optimality of post-loop diversity in the threshold region. As the number



of PLD antennas and tracking channels is increased, the probability of one or more of the independent tracking channels failing per unit time increases. This performance loss is eliminated with PCD processing, as seen in the plotted results for 2, 3 and 4-antenna configurations.

Finally, **Figure 7** shows plots of raw data bit error probability for the five configurations, illustrating the fact that, without forward error correction techniques, data bit errors will degrade well before the carrier phase tracking errors reach threshold.



#### Data Demodulation Aiding on

In the DGPS reference station context, the actual telemetry data stream is highly redundant. Usage of this redundancy can be utilized to further extend the phase tracking thresholds of the system. With direct incorporation of I/Q data in the extended Kalman filter, effective pre-detection integration time is controlled by the setting of filter process noise and dynamics tuning parameters. Post correlator diversity threshold improvements are realized then solely on the basis of line-of-sight process dynamics correlations between the multiple antennas.

**Figure 8** contrasts the phase tracking performance of the five options previously considered. For the 4-antenna PCD configuration 0.5 radian RMS tracking performance is extended to below 10 dB-Hz, an 8 dB improvement over the case without data aiding. The improvement of PCD over PLD is about 5 dB with the 4-antenna configuration, and 3 dB with the 2-antenna configuration. **Figure 9** contrasts the processing options on the basis of cycle slip free hold time vs. CNR. In other simulation efforts the data aiding improvement has been found to be insensitive to data aiding error rates up to 0.15.

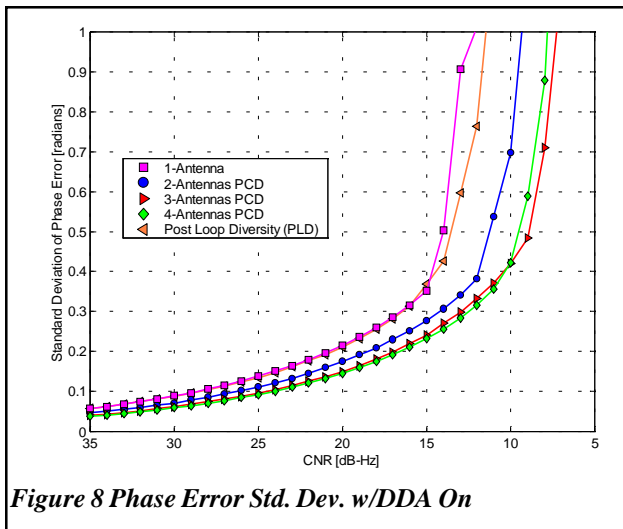


Figure 8 Phase Error Std. Dev. w/DDA On

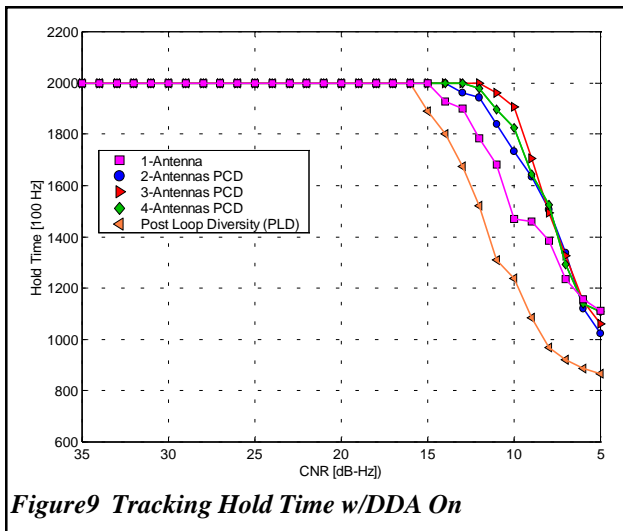


Figure 9 Tracking Hold Time w/DDA On

### Summary and Conclusions

In the SRGPS application, integrity and continuity performance is sensitive to the number of satellites deemed to have sufficiently small carrier phase tracking errors, under current reception environment conditions. Reception redundancies from multiple antennas can be utilized to improve the phase tracking performance available on individual satellites. It is recognized that beyond reception redundancy, redundant hardware components may also be needed to maintain adequate levels of station continuity.

In this paper, contrasting diversity techniques for reception redundancy were considered. Post Loop Diversity monitors the outputs of phase trackers to identify and reject tracking loop phase events from antennas impacted by attenuation, multipath, and interference. Post Correlator Diversity monitors

signal quality earlier in the processing chain, at the correlator outputs prior to loop updates. Upon detection of faulty correlator data the PCD has the option of blocking the bad correlator outputs, while maintaining lock with information obtained from correlators which pass measurement quality tests.

In attenuation, multipath and interference tests the basic tracking performance of PCD substantially exceeded the conventional PLD approach:

(1) In multiple attenuations PCD provided continuous phase observables without tracking loop damage.

(2) In strong specular multipath, with and without simultaneous blockage, the PCD technique detected the offending correlator data prior to measurement incorporation.

(3) In interference and jamming, unlike conventional diversity, PCD extended the phase tracking margins. Utilizing TISI's extended Kalman approach, together with data aiding, station tracking margins approaching 10 dB-Hz were obtained.

In ongoing work, the tracking statistics of this paper will be applied to the analysis of overall system navigation continuity and integrity. Additionally, TISI has successfully tested its advanced GPS receiver, TAGR, which is based upon its Integrated Demodulation/Navigation technique. This unit is adaptable to PCD operations for the DGPS reference station.

### Acknowledgements

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