

DEVELOPMENT OF A RADIO FREQUENCY SPACE ENVIRONMENT PATH EMULATOR FOR EVALUATING SPACECRAFT RANGING HARDWARE*

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Abstract

The Formation Flying Testbed (FFTB) at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) provides a hardware-in-the-loop test environment for formation navigation and control. The facility is evolving as a modular, hybrid, dynamic simulation facility for end-to-end guidance, navigation and control (GN&C) design and analysis of formation flying spacecraft. The core capabilities of the FFTB, as a platform for testing critical hardware and software algorithms in-the-loop, have expanded to include S-band Radio Frequency (RF) modems for inter-spacecraft communication and ranging. To enable realistic simulations that require RF ranging sensors for relative navigation, a mechanism is needed to buffer the RF signals exchanged between spacecraft that accurately emulates the dynamic environment through which the RF signals travel, including the effects of medium, moving platforms, and radiated power. The Path Emulator for RF Signals (PERFS), currently under development at NASA GSFC, provides this capability. The function and performance of a prototype device are presented.

Keywords: radio frequency signals, spacecraft crosslinks, relative navigation, delay, signal buffering, real-time, hardware-in-the-loop, formation flying, formation control.

Acronyms

ADC Analog-to-Digital Converter
BHI Black Hole Imager
CA Carrier Acquisition
CCS Crosslink Channel Simulator
DAC Digital-to-Analog Converter

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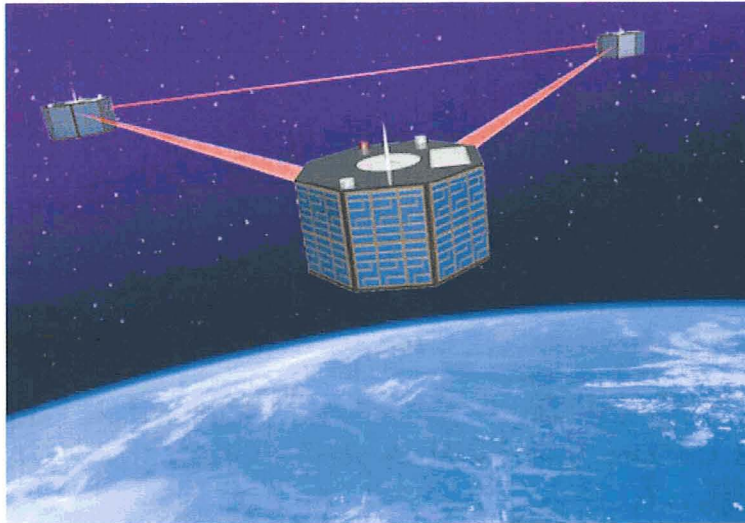


Figure 1. Artist's concept of formation flying spacecraft exchanging information via crosslink.

DDS Direct Digital Synthesizer
DSA Digital Step Attenuator
ESA European Space Agency
FFTB Formation Flying Testbed
FPGA Field Programmable Gate Array
GPS Global Positioning System
GSFC Goddard Space Flight Center
IF Intermediate Frequency
IRAS Inter-spacecraft Ranging and Alarm System
MMS Magnetospheric Multiscale
NASA National Aeronautics and Space Administration
PERFS Path Emulator for RF Signals
PRN Pseudo-Random Noise
RF Radio Frequency
SI Stellar Imager
ST9 Space Technology 9
TRL Technology Readiness Level

I. Introduction

SPACECRAFT formation flying is a concept that continues to attract significant attention; Figure 1. The President's Commission on Implementation of United States Space Exploration Policy¹ identifies formation flying as one of seventeen enabling technologies needed to meet exploration objectives.

Both the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are evaluating formation flying concepts for numerous planned missions. A brief list of currently planned missions include, NASA: Magnetospheric Multiscale (MMS),² Black Hole Imager (BHI),³ Submillimeter Probe of the Evolution of Cosmic Structure,⁴ Stellar Imager (SI),⁵ ESA: Darwin.⁶ In addition, *precision formation flying* was chosen as one of the five candidate technology capability areas for the New Millennium Program's

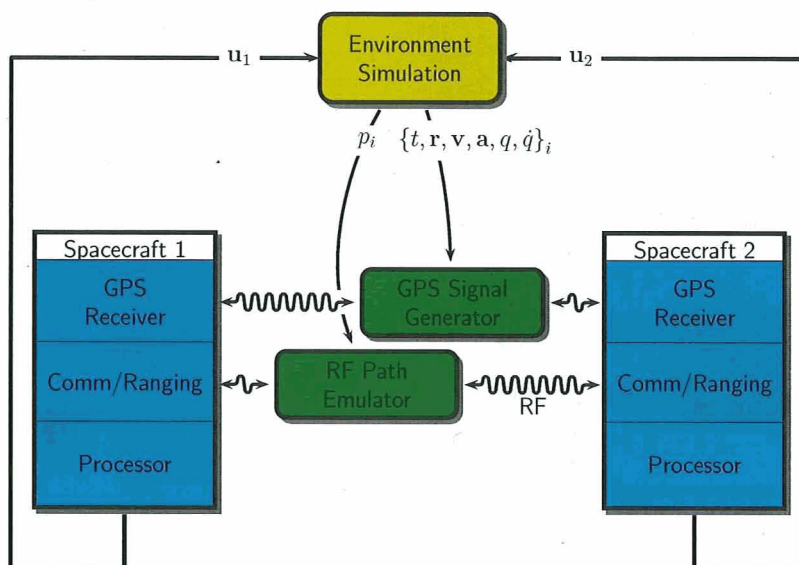


Figure 2. Information flow for sample two satellite Earth orbiting simulation employing GPS and RF ranging.

Space Technology 9 (ST9) Project.^{7,8}

To support the end-to-end guidance, navigation, and control design and analysis of formation flying spacecraft, the Formation Flying Testbed (FFTB)^{9–11} at NASA Goddard Space Flight Center (GSFC) allows formation flying navigation and control algorithms to be tested while interacting in real-time with the required flight hardware, such as relative navigation sensors and crosslink transceivers. By including hardware directly in the closed-loop testing, researchers and engineers can gain valuable information about the interaction and performance of their algorithms, and of the performance of the required hardware.

The core capabilities of the FFTB, as a platform for testing critical hardware and software algorithms in-the-loop, have expanded to include S-band Radio Frequency (RF) modems for inter-spacecraft communication and ranging. To enable realistic simulations that require RF ranging sensors for relative navigation, a mechanism is needed to buffer the RF signals exchanged between spacecraft that accurately emulates the dynamic environment through which those signals travel, including the effects of medium, moving platforms, and radiated power.

In previous work, Hunt et al.¹² describes a Crosslink Channel Simulator (CCS). This device was successfully integrated into the FFTB and emulates a dynamic bi-directional RF channel for each of two spacecraft. Mitchell and Luquette¹¹ and Mitchell et al.¹³ describe two spacecraft ST9 scenarios, Figure 2, in which the CCS was the medium for communications via hardware crosslinks. In these scenarios, the hardware crosslinks were used to exchange data between spacecraft, e.g. pseudorange and simulated range measurements, however no direct RF ranging was performed using hardware crosslinks.

In support of the MMS mission, NASA GSFC is maturing the Inter-spacecraft Ranging and Alarm System (IRAS) to Technology Readiness Level (TRL) 6. Since the MMS mission is composed of four spacecraft, each with multiple antennæ, IRAS TRL 6 testing in the FFTB will require significantly more than two bi-directional channels. The Path Emulator for RF Signals (PERFS), currently under development at NASA GSFC, provides for additional channel capacity as well as the requirements previously discussed. In the following, we

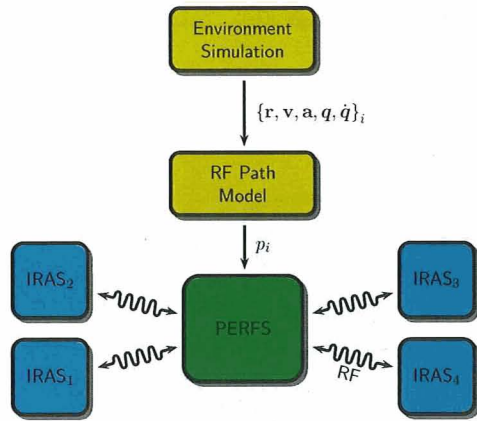


Figure 3. PERFS simulation connectivity for IRAS testing.

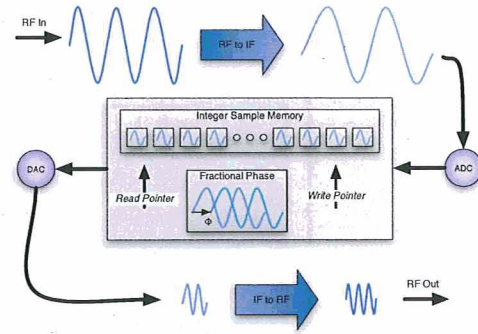


Figure 4. PERFS concept of operations.

	Min	Max	Resolution
Attenuation	90 dB	0 dB	0.5 dB
Range	100 m	3500 km	5 cm
Doppler	0 Hz	5 kHz	10 mHz

Table 1. PERFS performance indicators.

present the concept, design, and performance analysis of a prototype PERFS device.

II. Design Concept

The planned MMS mission consists of four (4) identical spacecraft each equipped with an IRAS. To maintain the relative tetrahedral formation, an individual spacecraft must communicate with its three (3) neighbors. Thus, for ground testing and simulation of the complete system, twelve (12) total bi-directional channels are necessary to enable communication between any single spacecraft and the remaining three (3) spacecraft.

For IRAS TRL 6 testing, the RF environment emulation is embedded into the simulation architecture of the FFTB as seen in Figure 3. Each IRAS device under test is connected to the PERFS as required for RF communication. The spacecraft information, which includes position, velocity, attitude, acceleration, attitude rate, and antenna pattern, flow into the RF path model. This model is responsible for computing the parameters p_i to specify the RF environment on each channel of PERFS resulting from effects of medium, moving platforms, and radiated power. Table 1 provides general performance indicators for PERFS.

The internal concept of operation used by the PERFS prototype to dynamically buffer RF signals exchanged between spacecraft is straightforward, and can be seen in Figure 4. Flowing from top-left to bottom-right, the S-band RF center frequency input, which is 2.05 GHz for IRAS, is down-converted to the Intermediate Frequency (IF) of 35.42 MHz at 1 volt peak-to-peak with a 2 MHz bandwidth. The IF is then sampled by the Analog-to-Digital Converter (ADC), with integer and fractional IF wavelengths stored in sample memory. The parameters that specify Doppler shift and delay are applied. Then, a Direct Digital Synthesizer (DDS) generates the shifted signal that is converted to analog via the

Digital-to-Analog Converter (DAC). Digital Step Attenuators (DSAs) provide the prescribed attenuation to the IF signal. Finally, the IF signal is up-converted to RF. Additional information about specific operations shown in Figure 4 follow:

IF SAMPLING: The IF input is digitized with a 12-bit ADC running at 100 MSPS, as driven by the write-pointer DDS.

SAMPLE MEMORY: The ADC output is provided to a Field Programmable Gate Array (FPGA) that implements a circular memory buffer. Each integer sample in the memory buffer represents 10 ns of delay based on the 100 MHz DDS clocks when no Doppler is applied.

DOPPLER AND DELAY: Signal data are read from sample memory and written to the DAC using a variable frequency clock generated by the read-pointer DDS. The Doppler shift is generated by this varying frequency. The instantaneous delay is determined by the difference between the DDS pointers and the fractional phase difference between DDS clocks.

ATTENUATION: Attenuation is applied via DSA in 0.5 dB steps, which are controlled by the FPGA. The applied attenuation includes free space loss, antenna gain and alignment, etc., as provided in the commanded parameters. The prototype PERFS is limited to a maximum range of 10 km, while the production units will support a maximum range of approximately 3500 km.

III. Testing

To assess the IF performance of the PERFS prototype with respect to Table 1, the following tests were performed related to attenuation, Doppler, and range. They are described in more detail below.

- Attenuation
 - Free space loss
 - Sideband suppression
- Doppler
 - Coarse range steering
 - Tracking/Carrier Modulation (coarse delay)
 - Resolution (fine/group delay)

FREE SPACE LOSS: A sequence of ranges is commanded to the PERFS prototype and the resulting attenuation is measured with a spectrum analyzer. The measured result is then compared to the computed value for each range setting.

SIDEBAND SUPPRESSION: Signal products resulting from mixing must not interfere with the center frequency of interest. To determine the sideband suppression, an IF sine wave is input to the PERFS prototype and the output sideband peak power is measured.

COARSE RANGE STEERING: As a basic functional test, the PERFS prototype is started at its minimum range, and provided a sequence of commanded range values. The output signal is recorded and the result is post-processed to determine the range and range error.

TRACKING/CARRIER MODULATION: It is important that data modulated on the carrier frequency input are accurately reproduced on the PERFS output. Reproduction of carrier modulation and Doppler tracker is accomplished by injecting Global Positioning System (GPS) Pseudo-Random Noise (PRN) 1 onto the IF input. The carrier frequency is then stepped by a 10 Hz Doppler shift every 100 ms for a duration of 10 s, producing a 1 kHz total frequency shift. The output signal is recorded and the result is post-processed to determine the range and range error.

RESOLUTION: It is important to know the minimum measurable change in range that the device, in sum, can support. To do this, an input IF sine wave is split. One input signal is recorded directly, without passing through the PERFS prototype. The second input signal is passed into the PERFS prototype with constant Doppler applied, and the output is recorded. This is repeated with several constant Doppler values. The resulting signals are post-processed to determine phase residual and estimated measurement noise.

III.A. Test Equipment

The following equipment was used in the testing:

- Network analyzer: HP 8753D
- Spectrum analyzer: HP 8561E
- Universal counter: HP 53132A
- Power meter: HP 4418B
- Time interval analyzer: Timing Solutions Corp 5110A
- Signal generators: R&S SIMQ series (GPS), Agilent E4421B (carrier only)
- Signal recorder
- Software GPS receiver

Only the signal recorder and the software GPS receiver are non-standard test equipment. While the software GPS receiver is self-descriptive, the signal recorder requires a brief description.

The signal recorder produces an interleaved 32-bit complex sample, divided into two 16-bit in-phase and quadrature words, respectively. Each signal is sampled at 2.048 MHz. Thus, any two recorded signals can be compared easily. More Detailed information about these two items can be found in Heckler and Garrison.^{14,15}

IV. Results

The tests described in the previous section were performed incrementally and repeated frequently during the PERFS prototype development. This approach was necessary to provide feedback and direction to transition from concept and components to an integrated prototype. The results that follow are snapshots of tests that demonstrate the viability of the design concept and efficacy of the PERFS prototype.

IV.A. Attenuation

The free space loss and sideband suppression test results are shown in Figures 5 and 6. From Figure 5, the lower range free space loss values disagree by one DSA step. This identified an

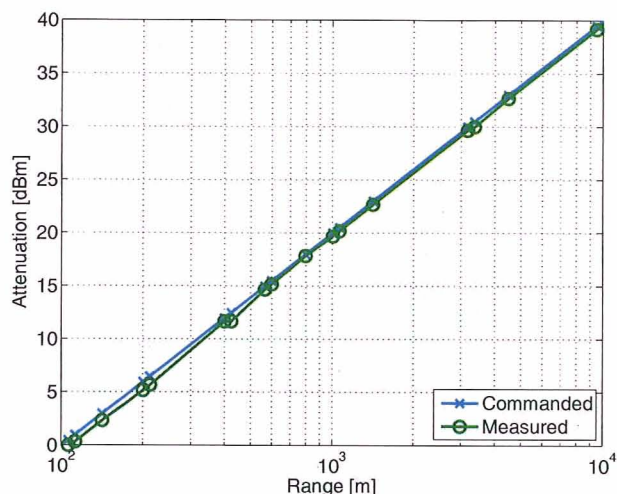


Figure 5. Commanded and measured free space loss attenuation.



Figure 6. Sideband suppression of next strongest mixing multiple.

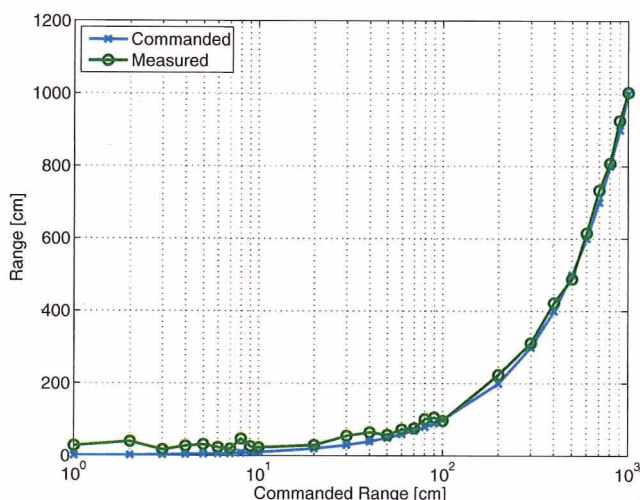


Figure 7. Doppler driven range measurement.

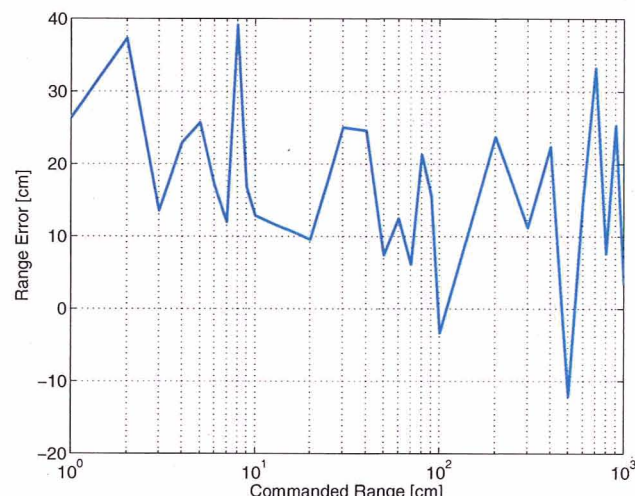


Figure 8. Doppler driven range measurement error.

FPGA table look-up error which was later corrected. While the prototype is limited to two DSAs spanning a range of 100 m to 10 km, the production unit will include an additional DSA to span the desired physical range.

Figure 6 shows that in an initial configuration, the first sideband frequency was approximately 6 MHz and 50 dB below the nominal center frequency. This spur was later determined to be powersupply noise and was removed, pushing the next sideband outside the 20 MHz span to approximately 29 MHz below peak power and significantly closer to the noise floor.

IV.B. Doppler

The coarse range Doppler steering test was an early functional test. From Figures 7 and 8, the initial results clearly show that steering the range with applied Doppler was effective, and agreed to within 40 cm of absolute magnitude. Additionally, Figure 8 indicates that the group delay through the PERFS prototype must be determined to quantify the minimum measurable range change. This is discussed later in this section.

The tracking/carrier modulation test was used to ensure that modulated data are not

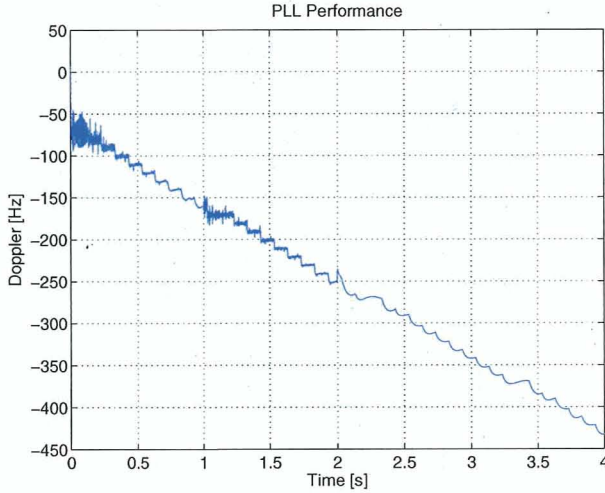


Figure 9. Phase lock loop tracking performance.

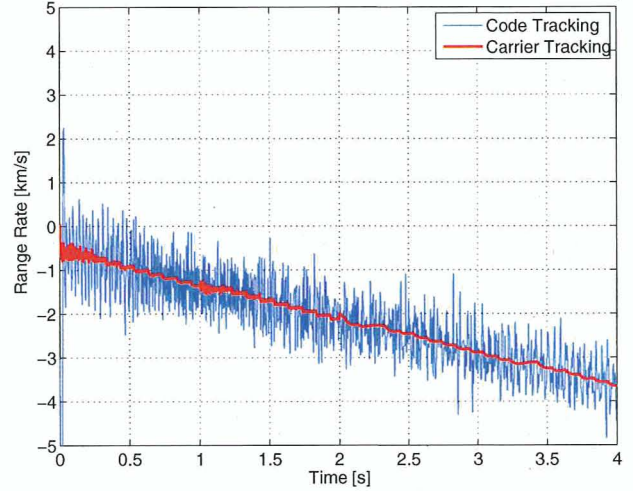


Figure 10. Code tracked and Doppler-commanded range rate.

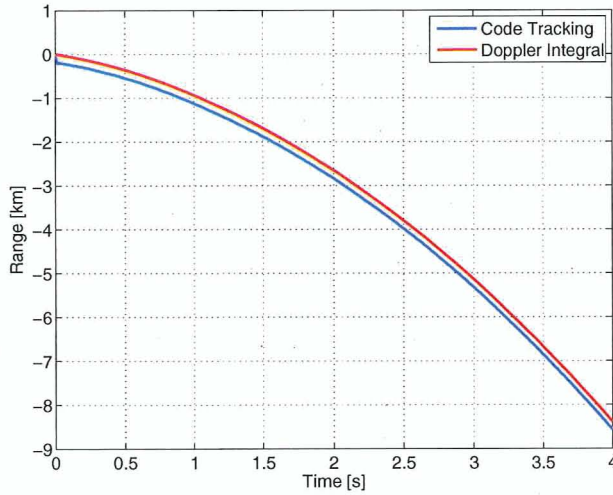


Figure 11. Code tracked and Doppler integrated range.

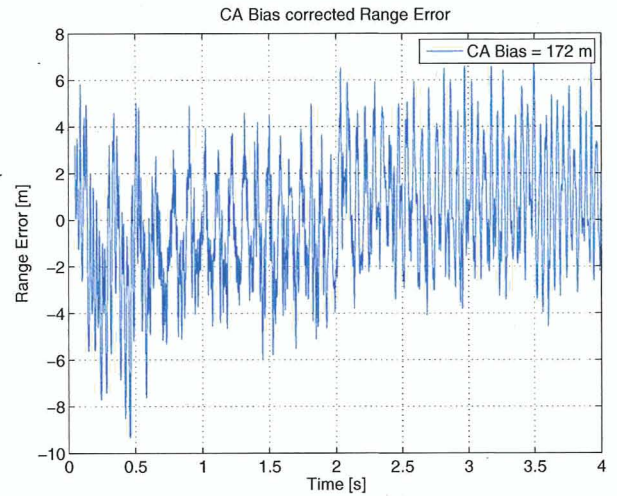


Figure 12. Biased corrected code tracked range error.

corrupted by PERFS. This test required additional post-processing of the recorded signal with a software GPS receiver. The results summary for this test can be seen in Figures 11–12.

Figure 9 clearly indicates that the modulated code data (PRN 1) were successfully passed through the PERFS prototype and tracked by the software GPS receiver. The measured phase resulting from the Doppler stepping agrees well with the commanded Doppler shift. Coarse acquisition was achieved within approximately 6 steps. The code and carrier tracked range-rate can be seen in Figure 10. The range rate trends agree after initial Carrier Acquisition (CA). The code tracked range shown in Figure 11 indicates a clear bias with respect to the Doppler integrated range that, again, results from initial CA. Comparing the integrated and code tracked range, Figure 12 indicates the bias is approximately 172 m and the range error magnitude is less than 10 m for the duration of the test.

For group delay testing to determine the phase resolution, the phase measurement residual $\Delta\phi_e$ is computed as

$$\Delta\phi_e = \phi_p - \phi_m, \quad (1)$$

where ϕ_p and ϕ_m are the linear model predicted phase and the measured phase, respectively.

Doppler	max $\Delta\phi_e$		max $\Delta^2\phi_e$		$3\sigma_{\Delta^2\phi_e}$	
[Hz]	[°IF]	[cm]	[°IF]	[cm]	[°IF]	[cm]
0.0	0.04	0.1	0.05	0.12	0.05	0.12
0.1	7	16.5	0.7	1.5	0.3	0.7
1.0	7	16.5	4.0	10.0	2.0	5.0

Table 2. PERFS minimum range resolution summary.

The double-differenced residual $\Delta^2\phi_e$ provides an estimate of the measurement noise for the phase residual $\Delta\phi_e$ and the 3σ value of $\Delta^2\phi_e$ provides the degree of confidence. A summary of the minimum phase change test can be seen in Table 2.

V. Conclusions

This work presents the concept, design, and prototype performance of a Path Emulator for Radio Frequency Signals.

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References

- ¹Aldridge, Jr. (Chairman), E. C., “A Journey to Inspire, Innovate, and Discover,” Tech. rep., President’s Commission on Implementation of United States Space Exploration Policy, June 2004, <http://tinyurl.com/d28rx>, Accessed January 23, 2007.
- ²Smith, D. and Colón, G., “Magnetospheric Multiscale Mission,” 2007, <http://stp.gsfc.nasa.gov/missions/mms/mms.htm>, Accessed January 23, 2007.
- ³White, N. E. and Newman, P., “Micro-Arcsecond X-ray Imaging Mission,” 2007, <http://maxim.gsfc.nasa.gov/>, Accessed January 23, 2007.
- ⁴Leisawitz, D., “Submillimeter Probe of the Evolution of Cosmic Structure,” 2007, <http://space.gsfc.nasa.gov/astro/specs/>, Accessed January 23, 2007.
- ⁵Carpenter, K., “Stellar Imager,” 2007, <http://hires.gsfc.nasa.gov/~si/>, Accessed January 23, 2007.
- ⁶European Space Agency, “Darwin Mission,” 2007, <http://tinyurl.com/86n5h>, Accessed January 23, 2007.
- ⁷Fisher, Diane, K. and Leon, N. J., “New Millennium Program’s Space Technology 9 (ST9) Project,” 2007, <http://nmp.jpl.nasa.gov/st9/>, Accessed January 23, 2007.
- ⁸Beasley, D. and Hupp, E., “NASA Selects Advanced Technology Providers,” NASA News, July 2005, <http://tinyurl.com/aztru>, Accessed January 23, 2007.
- ⁹Leitner, J., “A Hardware-in-the-Loop Testbed for Spacecraft Formation Flying Applications,” *Proceedings of the IEEE Aerospace Conference*, Vol. 2, 2001, pp. 615–620.
- ¹⁰Naasz, B. J., Burns, R. D., Gaylor, D., and Higinbotham, J., “Hardware-in-the-Loop Testing of Continuous Control Algorithms for a Precision Formation Flying Demonstration Mission,” *18th International Symposium on Space Flight Dynamics*, 2004.

¹¹Mitchell, J. W. and Luquette, R. J., "Recent Developments in Hardware-in-the-Loop Formation Navigation and Control," *NASA Goddard Flight Mechanics Symposium*, 2005.

¹²Hunt, C., Smith, C., and Burns, R., "Development of a Crosslink Channel Simulator," *Proceedings of the IEEE Aerospace Conference*, Vol. 2, 2004, pp. 1322–1328.

¹³Mitchell, J. W., Zakar, D. M., Burns, R. D., and Luquette, R. J., "A Message Oriented Middleware for a Soft Real-Time Hardware-in-the-Loop Spacecraft Formation Flying Testbed," *AIAA Modeling and Simulation Technologies Conference*, 2006.

¹⁴Heckler, G. W. and Garrison, J. L., "Architecture of a reconfigurable software receiver," *Institute of Navigation GNSS*, 2004.

¹⁵Heckler, G. W. and Garrison, J. L., "Experimental Tests of Unaided Weak Signal Acquisition Methods Using a Software Receiver," *Institute of Navigation GNSS*, 2006.