AFFTC-TIM-09-10

A F F T C

MONOCULAR PASSIVE RANGING

(PROJECT AIR CYCLOPS)

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FINAL TECHNICAL INFORMATION MEMORANDUM

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EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

This Technical Information Memorandum, AFFTC-TIM-09-10, Monocular Passive Ranging (Project Air Cyclops), was submitted under job order number MT09A600 by the Commandant, US Air Force Test Pilot School, Edwards Air Force Base, CA 93524-6485.

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14. ABSTRACT
This report presents the results of Project Air Cyclops, an evaluation of the Monocular Passive Ranging (MPR) System capabilities. The overall test objective was to determine the accuracy of the MPR system to estimate range to an afterburning jet plume. Air Force Institute of Technology requested this testing. The USAF Test Pilot School, Class 09A, conducted 2 ground tests totaling 8 hours and 11 flights totaling 11.4 hours at Edwards AFB, CA, from 1 September to 23 September 2009. All ground test objectives were met. The flight test objective was not met.

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Figure 1. Air Cyclops Test Management Project Team

EXECUTIVE SUMMARY

This technical information memorandum presents the Monocular Passive Ranging (MPR) system test results from the Air Cyclops Test Management Project. The 412th Test Wing was the responsible test organization, Air Force Institute of Technology Department of Engineering Physics (AFIT/ENP) was a participating test organization, and Test Pilot School (TPS) was the test execution organization. All testing was accomplished under TPS Job Order Number MT09A600. The test item was an AFIT-owned MPR system.

Ground and flight testing was conducted in order to determine the MPR system's ability to estimate range to an afterburning jet plume. Previous tests with the MPR system had been conducted with ground-to-ground ranging of electrically powered halogen and incandescent lights. This was the first test of the MPR system against military-type targets, and the first air-to-air ranging tests.

The overall test objective was to determine the accuracy of the MPR system to estimate range to an afterburning jet plume. Specific test objectives were:

1. Determine the accuracy of the MPR system to estimate range to a stationary afterburning jet plume from a stationary vantage point.
2. Determine the accuracy of the MPR system to estimate range to an airborne afterburning jet plume from an airborne vantage point.
3. Gather data for the spectral analysis of the ground based afterburning jet plume.

Specific test objectives one and three were met. Specific test objective two was not met.

To accomplish the objectives, ground tests were conducted at the Air Force Flight Test Center (AFFTC). The MPR system was used to image an afterburning F-16 jet plume on a thrust stand at various aspect angles and distances from the lakebed surface surrounding the facility. Ground testing occurred from 1 to 2 September 2009, and consisted of eight hours, broken into a morning and a night portion.

The MPR system was also flown in an AFFTC-owned C-12C that was modified to allow the sensor to have a clear field-of-view out of the aircraft. The MPR system was used to image an airborne afterburning jet plume at various aspect angles and distances. Testing consisted of six C-12C sorties, four F-16C/D sorties, and one T-38A photo chase sortie, totaling 11.4 flight test hours. Flight testing occurred between 14 and 23 September 2009.

The MPR system successfully ranged to ground targets in some configurations. Range error varied with many factors including day versus night, the absorption band used, and the range to the target. Successful ranging presented an average error of 15 percent at night using the 762 nm absorption band. Other unsuccessful configurations had range errors greater than 100 percent. Images were successfully recorded during the flight test, but the system was unable to provide a valid range to airborne targets with the current data reduction techniques. The flight test images appeared to have useable signal levels, but the data reduction tools and methods that were developed to process those images did not successfully determine target range. The ground truth spectral data and the flight test data were provided to AFIT/ENP for further analysis.

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INTRODUCTION

Background

Ground and flight testing was conducted in order to determine the accuracy of the Monocular Passive Ranging (MPR) system to estimate the range to an emissive target. Testing consisted of six sorties for the C-12C, four sorties for the F-16C/D, and one T-38A photo chase sortie for a total of 11.4 flight test hours. Ground testing occurred on 1 and 2 September and flight testing occurred between 14 and 23 September 2009. The Air Cyclops Test Management Project was conducted as requested by the Air Force Institute of Technology (AFIT). The responsible test organization (RTO) for this project was the 412th Test Wing. The AFIT Department of Engineering Physics (ENP) was a participating test organization and United States Air Force Test Pilot School (TPS) was the test execution organization. All testing was accomplished under TPS Job Order Number MT09A600.

The MPR system was first developed as an AFIT research project. This system utilized the well known characteristics of oxygen (O_2) absorption in the atmosphere to estimate range to an emissive target based on the attenuation of the signal due to O_2; more detail on MPR theory can be found in appendix A. The use of passive ranging was advantageous over active ranging since it could not be detected and it had a much lower power requirement compared to active systems. Other passive ranging systems existed, but they either required multiple sensors separated from each other (stereo ranging) which operated off the concept of triangulation, or they required prior knowledge about the target, such as target size, to estimate range. Active systems were generally much more accurate than passive systems, but were however overt. One drawback of the MPR system was that it required a highly emissive target. Previous MPR testing (reference 1) was shown to effectively estimate range to stationary halogen and incandescent light sources during the night with range errors less than 1 percent. MPR operations during the day were more difficult due to additional light scattering from the sun, which increased the noise in the system. This current test was accomplished to further evaluate the MPR system's range estimating capability against military type targets under day and night conditions.

Program Chronology

Testing was conducted at Edwards AFB, California from 1 to 23 September 2009. A total of 2 ground tests totaling 8 hours were accomplished and 11 flight test sorties in the C-12C, F-16C/D, and a T-38A were flown, totaling 11.4 flight hours.

Test Item Description

The MPR system consisted of multiple pieces of equipment which worked together to collect images that were used to estimate range to an emissive target. The sensor was a Princeton Instruments PI-MAX® 512-T, Generation IV Intensified Charge Coupled Device (ICCD) camera (S/N S0900141) which was able to image in the 500-865 nanometer (nm) range. This camera had a gallium arsenide (GaAs) photocathode and a micro-channel plate capable of providing an electric potential of up to 1.2 million electron volts for image intensification. The camera was capable of imaging roughly six frames per second for the conditions of this test. A camera control box provided power to the camera as well as an interface to the laptop computer (via universal serial bus [USB]) which operated the camera using either WinView® or LabView® software. The camera was fitted with an 80-200 millimeter (mm) manual zoom lens which resulted in a field-of-view (FOV) of 3.5 degrees to 8.8 degrees. The lens aperture was adjusted from an f-number of 2.8 up to 22. A Cambridge Research Institute SNIR-20 liquid crystal display (LCD) bandpass filter was attached to the front of the zoom lens. This filter was tunable at 10 Hertz from 650 to 1100 nanometers (nm) and each filter setting had a full width half maximum (FWHM) of 5 to 7 nm. A filter control box interfaced between the LCD filter and the laptop computer. The test team developed LabView® code which enabled coordination of filter settings and camera imaging. This code also recorded the images in 16 bit tagged image file (.tif) format with a time stamp provided by global positioning system (GPS) time.

The MPR system operated by taking advantage of the O_2 absorption feature at 762 nm. The MPR system imaged at 752 nm, 762 nm, and 778 nm wavelengths and assumed that the source spectrum was linear over that range. It had been previously seen that rocket plumes contained a potassium peak in the spectrum near 762 nm. A second method, designed to use a different segment of the O_2 absorption band and to be unaffected by this peak utilized a 759 nm bandpass instead of the 762 nm bandpass. Range to an emissive target was estimated by observing the atmospheric absorption of O_2 in the 762 nm (or 759 nm) range and comparing that to model predictions of the absorption.

The camera, lens, and filter assembly (figure 2) sat together on a tripod and had the ability to image out of the open jump door of the C-12C. The camera control box (figure 3) was mounted separately in the C-12C. A block diagram of the entire MPR system is shown in figure 4.

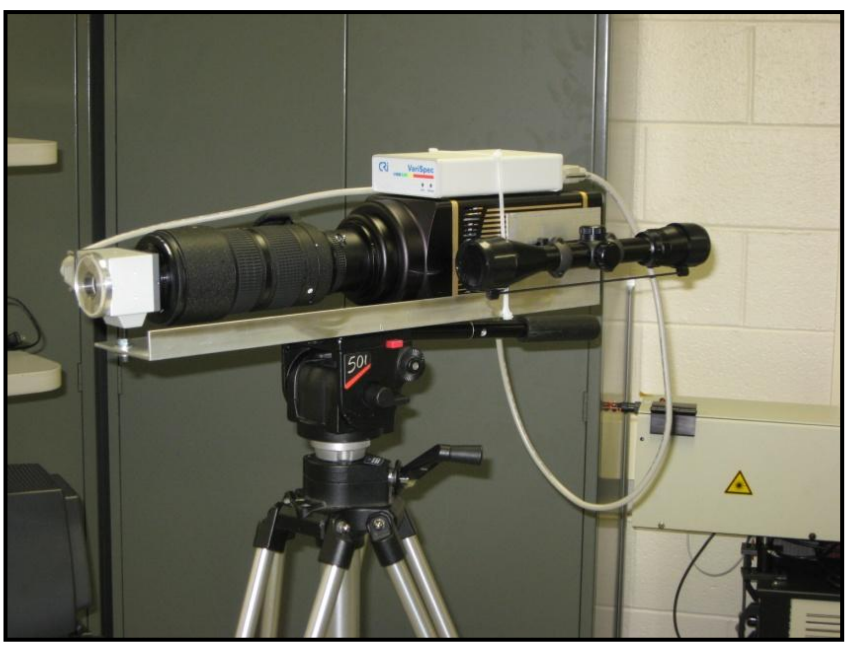


Figure 2. PiMax Camera with LCD Filter and Filter Controller

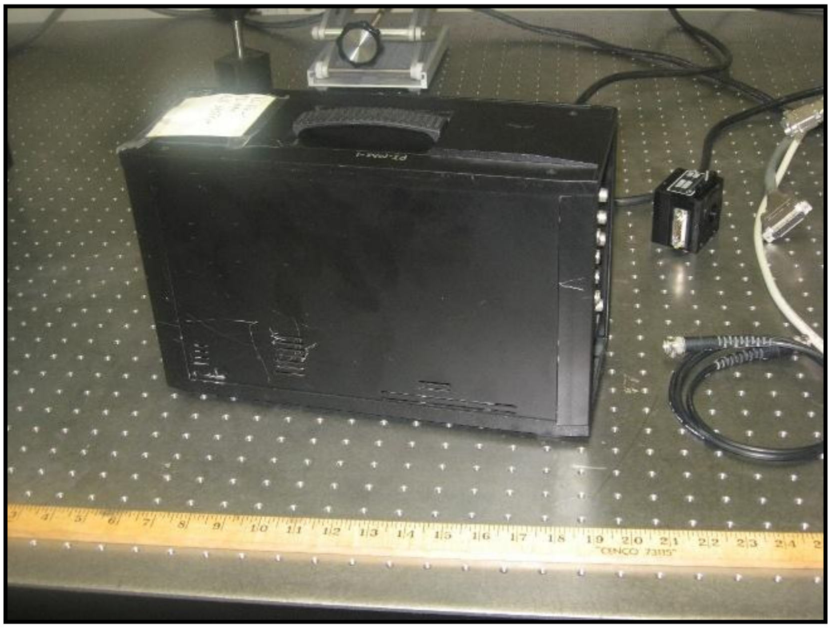


Figure 3. Camera Control Unit

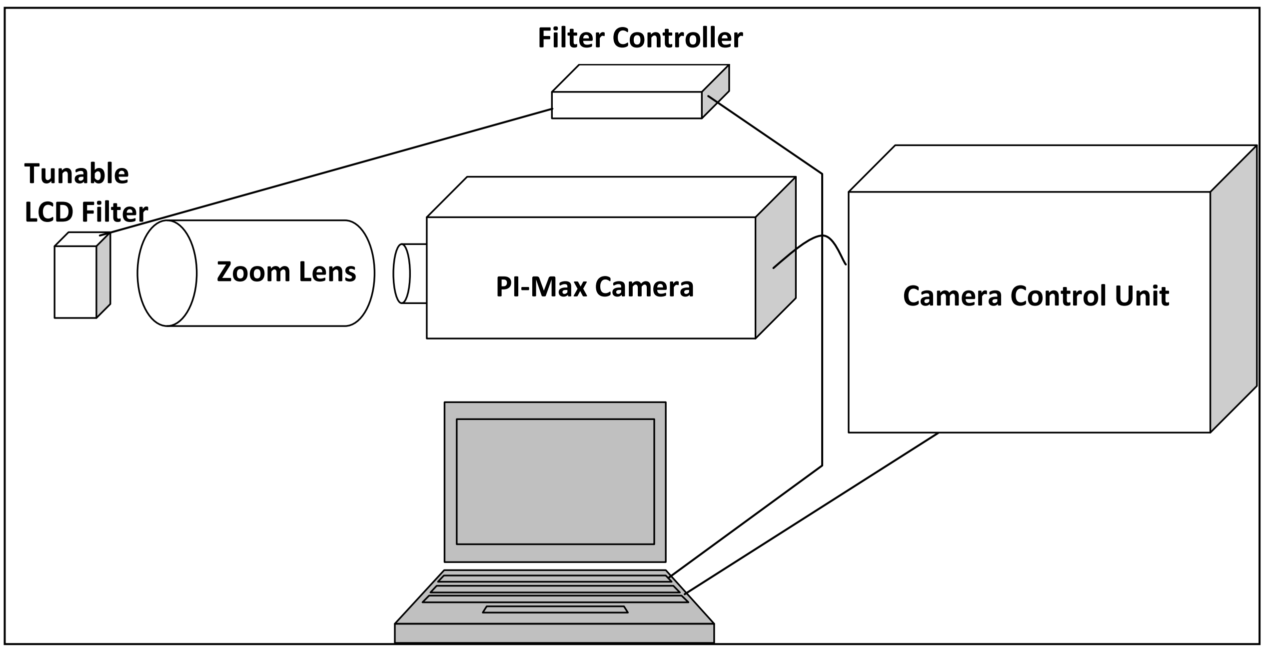


Figure 4. MPR Block Diagram

Appendix B contains details on the modification process of the C-12C test aircraft.

AFIT Ground Truth Instrumentation

AFIT/ENP provided several detector systems to collect ground truth data of the stationary afterburning jet plume spectrum during the ground test. The primary detectors were two ABB-Bomem MR-304 Fourier transform spectrometers (FTS). Each had a different detector that recorded interferograms in the range from 1,800-15,000 centimeter^{-1}. A standard video camera was boresighted through the same input telescope to visually monitor the detector's pointing and focus. One additional detector was a Telops FIRST Imaging FTS. Each detector system had its own tripod mounting system, and its own laptop computer for operating the detector. All equipment was powered by AFIT-owned Briggs and Stratton portable generators.

Test and Target Aircraft Description

The test aircraft was a C-12C and the target aircraft was an F-16C/D with a General Electric F-110-GE-100 engine burning JP-8 fuel. Descriptions of both aircraft are contained in appendix C.

Test Objectives

The overall test objective was to determine the accuracy of the MPR system to estimate range to an afterburning jet plume. Specific objectives of this test were the following.

- Determine the accuracy of the MPR system to estimate range to a stationary afterburning jet plume from a stationary vantage point. This objective was met.
- Determine the accuracy of the MPR system to estimate range to an airborne afterburning jet plume from an airborne vantage point. This objective was not met.
- Gather data for the spectral analysis of the ground based afterburning jet plume. This objective was met.

Limitations

The data reduction tools and methods that had been developed were not able to satisfactorily process the airborne collected images due to serial imaging, stabilization, and light scattering issues.

TEST AND EVALUATION

General

Ground and flight testing was accomplished to test the monocular passive ranging (MPR) system's ability to estimate range to an afterburning F-16 jet plume.

The MPR ground test was conducted from 1 to 2 September 2009 at the Air Force Flight Test Center (AFFTC) thrust stand under the supervision of 412th Test Wing Special Instrumentation personnel. The MPR imaged an afterburning F-16 jet plume at various look angles and ranges of 1200 feet up to 3 statute miles from the lakebed surface surrounding the facility (figure 5). Ground testing took eight hours, split between both morning and night, to determine the accuracy of the MPR to range a target at various sunlight conditions.

Flight testing was accomplished in the R-2508 complex from 14 to 23 September 2009 at ranges from approximately 500 feet up to approximately 7 nautical miles. The C-12C carried the MPR system for the flight test, and the F-16 afterburner jet plume was the target (figure 6). Look angles to the target varied horizontally as well as vertically through the atmosphere. The flight test used 11.4 total flight test hours. Reference appendix D for flight test details.

Figure 5. MPR Ground Testing on Lakebed

Figure 6. MPR Flight Testing in the C-12C

Ground Testing

The objectives were to determine the accuracy of the MPR system to estimate range to a stationary afterburning jet plume from a stationary vantage point, and to gather truth data for the spectral analysis of the ground based afterburning jet plume.

Ground Test Procedures

Prior to ground testing, the MPR system accomplished a non-uniformity measurement. This was accomplished by imaging an illuminated white projector screen. The camera and projector were de-focused to ensure that pixilation did not affect the results. This non-uniformity measurement was applied to the results as described in appendix A.

For the ground test, the F-16 was tied down on the thrust stand, Pad 18 Edwards Air Force Base. An F-110-GE-100 engine was used. The MPR system recorded filtered images of the F-16 afterburner plume from the lakebed at the locations indicated by stars in figure 7. An initial calibration run was used to optimize the MPR system settings prior to the day and night test phase. These system settings are not included in this report due to data sensitivity. Data were collected for a minimum of three minutes for each location, and collected during the day and night.

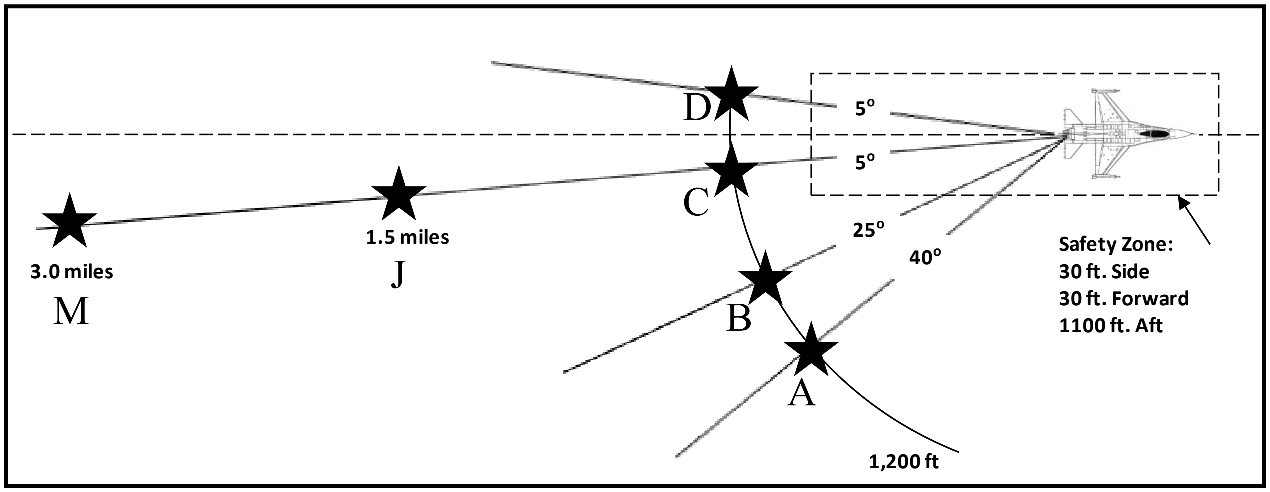


Figure 7. Illustration of Ground Test Locations

Conditions

The day ground test was conducted on 1 September 2009 between 1055 and 1241 hours local time. The night ground test was conducted on 2 September 2009 between 2025 to 2341 hours local time. All data collection points were the same for day and night, with the exception of point C. The night ground test shifted the 1,200 feet 5 degree point from point C to point D, as illustrated in figure 7, due to surface winds blowing debris into point C. The atmospheric conditions for each run are recorded in appendix E.

Results and Analyses

The following equation was used to calculate MPR system range error:

$$Range\ Error\ (\%) = \frac{MPR\ Range - TSPI\ Range}{TSPI\ Range} \times 100$$

Ground test results are listed in tables 1 and 2. The data were collected over 3 continuous minutes of data recording. Images were recorded at a sample rate of 6 cycles per second. A single range estimate was made using three consecutive images. The result for each run consists of the average of approximately 300 separate range estimates. The uncertainty for these range estimates were well over 100 percent except for runs 1 and 2 during the night test, which were 47 and 51 percent respectively. When the range estimation method was modified to combine the images over 10 seconds to produce a single range estimate however, the data uncertainties were significantly reduced. These are the uncertainties that are reported in table 1 and table 2. One possible cause of this high uncertainty was variations in the intensity of the afterburning plume as a function of time. Since the MPR system recorded the three different wavelength images at different times, random fluctuations in the target intensity add significant errors between two or three frames, but are quickly accounted for when averaging the data over 10 second intervals. The data showed that the MPR system was able to achieve minimum range error at night using the 762 nm wavelength. System recording errors resulted in the data from day ground test at ranges greater than 1200 feet not being recorded. Occasional random camera errors also caused the night test data at the 25˚ offset location (point B) to be unusable. Due to test team communication errors, no tests were accomplished using the 762 nm absorption band during the day.

The ground truth data were recorded and transmitted to AFIT/ENP.

Table 1. Oxygen Absorption Band Range Error (Day)

Run #	Look Angle (˚)	Day/ Night	Wavelength (nm)	Transmission (%)	Range (m)		% Error ± Uncertainty
					Actual	MPR	
1	5	Day	759	90.23	366	639	75 ± 92
2	25	Day	759	88.12	365	939	158 ± 167
3	40	Day	759	86.60	365	1211	232 ± 200

Table 2. MPR Range Error (Night)

Run #	Look Angle (˚)	Day/ Night	Wavelength (nm)	Transmission (%)	Range (m)		% Error ± Uncertainty
					Actual	MPR	
1	5	Night	762	55.76	4827	5555	15 ±10
2	5	Night	762	66.47	2393	2782	16 ± 7
3	5	Night	762	87.01	364	394	8 ± 29
5	40	Night	762	86.17	365	442	21 ± 21
6	5	Night	762	90.02	364	419	15 ± 21
7	5	Night	759	90.02	364	658	81 ± 58
8	5	Night	759	82.13	2393	2201	9 ± 23

Range errors were compared against many factors including look angle, absorption, range, filter wavelength, and signal to noise ratio. Corresponding graphs can be found in appendix F. Although many of these variables did not show any clear correlation, a few correlations were worth discussing. First, the day results were much worse than the night results, potentially due to additional scattering from the sun. Any sunlight reaching the MPR system that was reflected either from the background or indirect scattering had the effect of increasing the range estimate. This was due to the light in the absorption wavelength being attenuated through the entire atmosphere from its path from the sun and not just through the atmosphere between the MPR system and the target. Figure 8 shows two MPR images that were both taken from the 25 degree offset location. One was imaged during the day ground test and the other was imaged during the night ground test. These images illustrate the additional noise caused by the sunlight. The red color indicates a high signal level, and the blue color indicates a low signal level.

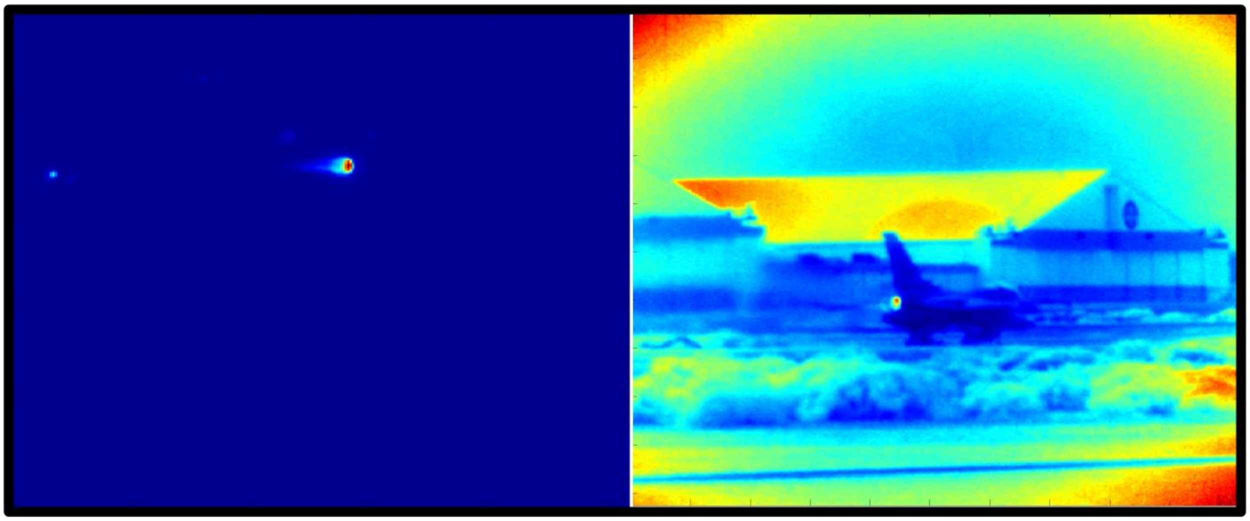


Figure 8. MPR System Images During Nighttime (left) and Daytime (right) Testing

In the daytime image, there was as much or more signal coming from background areas, such as the roof behind the F-16, as from the F-16 exhaust. In the nighttime image, there was little background light that could scatter into the MPR system. Although the direct signal from the hangar roof or other areas was ignored for the data analysis, the significant increase in total signal illustrates the increased potential amount of scattered light that also would enter the MPR system. In general, the 759 nm wavelength absorption did not perform as well as the 762 nm absorption band at the close ranges. The 759 nm bandpass filter was not centered on the oxygen absorption band, and therefore did not utilize the entire range of the oxygen absorption. This resulted in the 759 nm wavelength results being less sensitive to range than the 762 nm band, which meant that the 759 nm wavelength should have had better results at longer ranges than closer ranges. This was observed. It was noteworthy that none of the 762 nm range estimates were shorter than the actual range. The range errors for the 762 nm wavelength band were all between 8 percent and 21 percent at night. This indicated a possible systematic error in the range calculation since the range estimates were all longer ranges than the actual range. The ground truth data will need to be evaluated and compared to the MPR system's calculated absorption to determine if this was a cause of the systematic error. **Perform further analysis of the ground truth data to characterize its effect on the test results. (R1)**[1]

The MPR system ground test estimated the range to a stationary afterburning jet plume from a stationary imaging point. The range error was higher than expected. Additionally, data for the spectral analysis of the ground based afterburning jet plume were successfully gathered and delivered to AFIT/ENP. The best system accuracy (fifteen percent average range error) was achieved at night with an absorption wavelength of 762 nm.

Flight Test

The objective was to determine the accuracy of the MPR system to estimate range to an airborne afterburning jet plume from an airborne vantage point.

[1] Numerals preceded by an R within parentheses at the end of a sentence correspond to the recommendation numbers tabulated in the Conclusions and Recommendations section of this report.

Flight Testing Procedures

The C-12C was in straight and level flight with the Lexan© door open and the MPR system imaging through the opening. The target aircraft flew away from the left side of the C-12C in afterburner while a camera operator manually tracked and imaged the afterburning exhaust with the MPR system.

Target Elevation

MPR system images of the target aircraft were taken at various horizontal and vertical look angles through the atmosphere. A look up angle of less than or equal to 20 degrees and a look down angle of less than or equal to 15 degrees was used. The intent was to determine the ability of the MPR system to range target aircraft from different backgrounds.

Target Distance

Images were continuously taken of the target aircraft using the MPR system. The range was from initial visual acquisition of the target aircraft outbound to 7 nautical miles, where the target could no longer be seen and tracked by the camera operator, or the point at which the F-16 reached its minimum altitude.

Target Heading Crossing Angle

The F-16 target aircraft optimized the time inside the field of regard by starting each run passing behind the C-12C above final approach speed, approximately 200 knots indicated airspeed (KIAS). The target aircraft continued with a heading angle calculated to ensure it remained perpendicular to the C-12C flight path. The calculated heading crossing angles and airspeeds are listed in table 3.

Table 3. Target Heading Crossing Angle and Airspeed

C-12C Airspeed	F-16C/D Airspeed	Heading Crossing Angle
100 KIAS	200 KIAS	60 degrees
100 KIAS	300 KIAS	70 degrees
100 KIAS	400 KIAS	75 degrees
100 KIAS	500 KIAS	78 degrees
100 KIAS	600 KIAS	80 degrees

Set-Up

The set-up for all flight test techniques (FTTs) followed the same procedure with few exceptions. This consisted of the C-12C maintaining a constant heading with gear and flaps down at 100 KIAS and constant altitude of 9,500 feet Pressure Altitude (PA). For best data quality, the C-12C maintained a heading towards the sun. The target aircraft began outside of 3,000 feet to the right and aft of the C-12C. Next, the target aircraft turned towards the C-12C above final approach speed with a 60 degree heading crossing angle as shown in figure 9. The target aircraft ensured nose-tail separation, a 100 feet altitude differential, a 200 feet bubble and was in visual contact at crossing. At or just prior to crossing, the target aircraft selected maximum afterburner, full speed brakes, and followed the heading crossing angle calculations as described above in table 3.

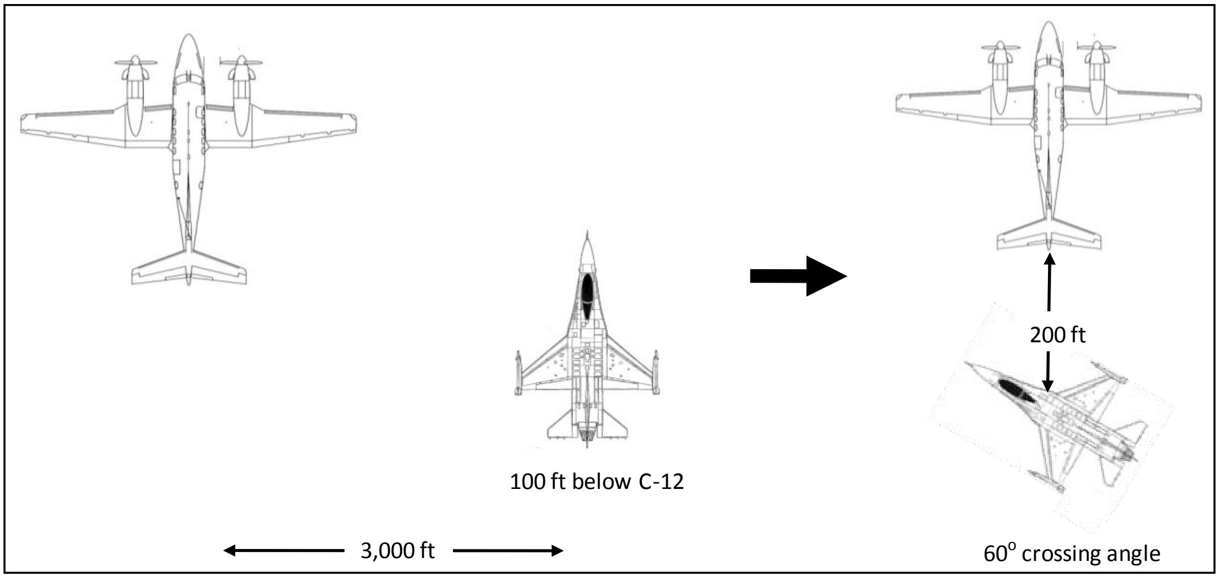


Figure 9. Flight Test Set-Up Illustration

Level Imaging Flight Test Technique (FTT)

The Level Imaging FTT collected data on a co-altitude target that moved away from the C-12C. The purpose of this FTT was to image a target with constant oxygen concentration. The set-up was as described above. The target aircraft maintained altitude and remained maximum afterburner and full speed brakes until approaching within 25 KIAS of an aircraft limit. The FTT was terminated when the F-16C/D approached an aircraft speed limit, the camera operator lost track, or when 7 nautical miles of separation was reached.

Climb Imaging FTT

The Climb Imaging FTT was designed to collect data on a target that climbed away from the C-12C. The purpose of this FTT was to image a target through a decreasing oxygen concentration. The set-up was as described above. Next, the target flew the same procedures as described in the Level Imaging FTT with up to a 20 degree climb angle. The FTT was terminated when the camera operator lost track or 7 nautical miles of separation.

Dive Imaging FTT

The Dive Imaging FTT was designed to collect data on a target that dove away from the C-12C. The purpose of this FTT was to image a target through an increasing oxygen concentration. This FTT procedure mirrored the Climb Imaging FTT with the only difference being that the F-16C/D had up to a 15 degree dive angle. The FTT was terminated when the camera operator lost track or the F-16C/D leveled off.

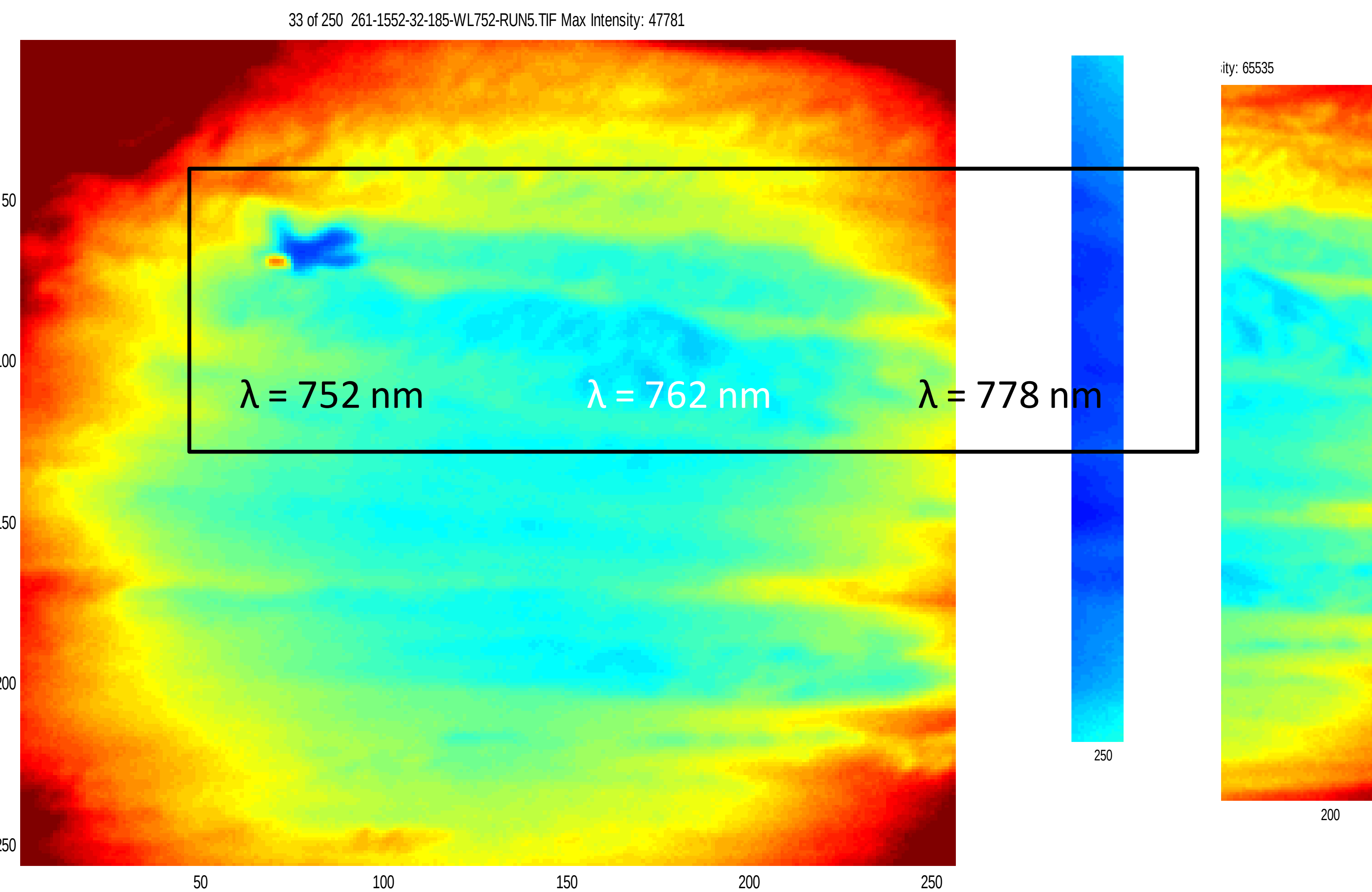
Conditions

All testing occurred in visual meteorological conditions with minimal turbulence. The C-12C flew at 9,500 feet PA while imaging the F-16C/D.

Temperature, humidity, and atmospheric pressure data were obtained by a weather balloon. Absolute humidity was less than 4 grams/meter^3 for all test conditions.

Results and Analyses

The flight testing was accomplished for the Level Imaging, Climb Imaging, and Dive Imaging FTTs. All flight testing was executed during daylight conditions, and there was significant background illumination. The images collected from the FTTs appeared to have valid signal levels, as determined by the high intensity signal from the exhaust nozzle. The recorded images also showed that the overall intensity decreased with range. These observations indicated



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were so scattered that no correlations could be made between range error and any of the test variables. Due to these inconsistencies, the range errors could not be determined and the objective was therefore not met.

The MPR system recorded each of the three wavelength images in succession, and one of each was required to get a single range estimate. Imaging the three wavelengths at different times resulted in different levels of blurring of the signal intensity. As the camera was tracking the F-16, some images were blurred by camera movement, while others were clear because the camera was relatively stationary. This resulted in signal from the F-16C/D sometimes being focused into a few image pixels, while other times, the signal from one image was blurred across many image pixels. With the large amount of background signal from the flight test, the full signal levels were difficult to determine when the exhaust images were blurred. Recording the different wavelength images in succession also caused errors due to target range variations. The target was at a different range for each successive image. It was expected that these errors could be minimized by fitting the data points to a curve and then estimating range at the same point in time based on the fit of the data, but due to the errors due to blurring noted previously, the data were not consistent enough to use this method to produce repeatable range estimates. Both of these errors could be eliminated by creating a system capable of imaging all three wavelengths at the same time. **Modify the MPR system to image all three wavelength signals simultaneously. (R2)**

During ground and flight tests, signal intensity variations in the afterburning exhaust plume contaminated the signal and caused errors in the ranging solution of the MPR system. These errors could be minimized by improving the signal to noise ratio of the camera as well as by optimizing the absorption filter to maximize sensitivity. **Improve the signal collection and filtering of the MPR system for future testing. (R3)**

The data reduction process for the MPR system with moving targets required a manual image analysis process. This was a time consuming process that was partially arbitrary in determining signal intensity levels. This reduced the repeatability and accuracy of the moving target range estimates. **Improve the data reduction and analysis process. (R4)**

Military Utility

While the military application of passive range surveillance was well known, passively calculating a range to an optically observed target had been a difficult problem to solve. Monocular passive ranging provided a low energy and potentially low-cost solution to the passive ranging problem. The military usefulness of a passive ranging system was widespread, and could be employed in concert with a multitude of other sensors to provide a non-emitting means of target detection and ranging.

When ranging stationary ground targets under optimal conditions, the MPR system proved to work according to theory. The additional complexity of air to air ranging, with a multitude of additional variables and contaminates to the signal proved to be too problematic for the system. It was unable to accurately estimate range to the airborne F-16 target. While the theory was shown to be valid, the MPR system as tested did not show significant military utility against airborne moving targets.

CONCLUSIONS AND RECOMMENDATIONS

The Monocular Passive Ranging (MPR) system was tested on the ground against a stationary F-16 in afterburner during daylight and nighttime conditions, and the accuracy of the MPR system to estimate the range to a stationary afterburning jet plume from a stationary vantage point was determined for the limited conditions tested. Ground truth data were collected by the Air Force Institute of Technology Remote Sensing Group for spectral analysis to characterize the plume signal. The MPR system was tested airborne from a C-12C imaging an airborne F-16 afterburner jet plume. It was determined that the MPR system, with its current data reduction methods, was not able to estimate range with confidence to an airborne afterburning jet plume from an airborne vantage point. Therefore, two of the three objectives were met.

The ground test results showed that the best system performance was obtained when using the 762 nm absorption wavelength at night. The range errors in these conditions varied from 8 to 21 percent. Using the 759 nm absorption wavelength in daylight and nighttime conditions resulted in highly inconsistent range errors that varied from 9 percent (a range of 2200 m at night) to 230 percent (a range of 360 m during the day). The ground truth data need to be analyzed to determine if the F-16 afterburner spectrum contributed to these errors.

Perform further analysis of the ground truth data to characterize its effect on the test results (R1, page 9).

One source of range estimation error was the imaging of the three wavelengths in series and not at the same time. This induced errors with anything that fluctuated over time. This was most problematic for the flight test since camera movement caused blurring of the image. The manual target tracking resulted in each consecutive image being blurred differently. This caused difficulty in signal processing that was never fully overcome. In the ground test, the plume signal appeared to have small fluctuations over time which averaged out, but significantly increased the uncertainty in the measurement. To improve the data quality, to reduce variability, and to improve the data reduction process, the signal intensity of all three wavelengths needs to be recorded simultaneously.

Modify the MPR system to image all three wavelength signals simultaneously (R2, page 13).

During ground and in-flight tests, instability in the afterburning plume contaminated the signal and caused errors in the ranging solution of the MPR. Airborne testing of the MPR system showed that the MPR system was unable to provide a range estimate. These errors could be minimized by improving the signal to noise ratio of the camera as well as by optimizing the absorption filter.

Improve the signal collection and filtering of the MPR system for future testing (R3, page 13).

Imaging was greatly affected by daylight conditions where signal to noise ratios were low and problematic to the ranging solution. Ground based night testing proved to be significantly more effective. One significant influence on range estimation error was the scattered light from the sun which entered the camera in addition to the emitted light from the afterburning exhaust, resulting in longer range estimates.

The data reduction process for the MPR system required a time consuming post mission image analysis process. Parts of this process were manual, which also reduced the repeatability of the results.

Improve the data reduction and analysis process (R4, page 13).

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1. Anderson, Joel R., *Air Force Institute of Technology Thesis Mini-Defense,* November 2008.

2. Anderson, Joel R., *Monocular Passive Ranging by an Optical System with Band Pass Filtering,* November 2008.

3. Hawks, Michael R., *Passive Ranging Using Atmospheric Oxygen Absorption Spectra*, January, 2006.

4. Modification Operational Supplement Number 09-03, Flight Manual USAF Series C-12C Aircraft, 24 July 2009.

5. Technical Order 1C-12A-1, Operator's Manual, USAF Series, 1 November 2003.

6. Technical Order 1F-16C/D-1 Operator's Manual, USAF Series, 15 May 2008

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APPENDIX A – MONOCULAR PASSIVE RANGING THEORY AND DATA REDUCTION

A.1. Data Collected

Monocular passive ranging (MPR) system imaging data were recorded onto the system laptop hard drive and were time stamped with global positioning system (GPS) time. Time space position information (TSPI) truth data for the C-12 and the F-16 were collected. The test aircraft was modified with a GPS/INS navigation experimental ranger version II system, which had a stated position error of ± 1.5 feet. The target was configured with an advanced range data system pod, which had a stated accuracy of ± 10 feet, which provided the TSPI data. Handheld time, indicated airspeed, outside air temperature, and pressure altitude data for the C-12 were collected for each test point. Weather data to include temperature, pressure, and dew point information at 100 feet intervals for all test altitudes were collected within three hours of each sortie. The data collected are shown in table A1.

Table A1. Data Collected

C-12C	F-16C/D	Other
MPR System Image (time stamped)	N/A	Temperature (weather balloon)
Time (handheld)	Time (handheld)	Pressure (weather balloon)
Magnetic Heading (handheld)	Magnetic Heading (handheld)	Dew Point (weather balloon)
Indicated Airspeed (handheld)	Calibrated Airspeed (handheld)	Flat Field Images (400 Frames)
Pressure Altitude (handheld)	Pressure Altitude (handheld)	
Outside Air Temperature (handheld)	TSPI Data	
TSPI Data		

A.2. Media and Data Format

The MPR system recorded imaging data to a system laptop hard drive in a MATLAB-readable format. Handheld data were recorded on data cards.

A.3. Data Reduction

A non-uniformity correction was performed to the MPR system before testing, and was re-accomplished after completion of the testing for comparison. This ensured that the intensity measured for every pixel in the system was the same as all other pixels. The flat field images were averaged together and then processed in MatLab®. The processing consisted of averaging the entire frame to get a single value for the intensity. Next, the images were averaged pixel by pixel, the dark current value was subtracted, and then a ratio between each pixel intensity and the average field intensity was calculated for each pixel. Finally, this ratio for each pixel was multiplied into each image that was used for range calculation purposes.

The goal was to correlate TSPI range data to the MPR system images at each test point. MPR images were reduced using a previously developed MatLab® algorithm (reference 2). This algorithm required input variables of pressure, temperature and dew point in addition to the system images to estimate a range to the target. This algorithm first located the emissive target within the frame and summed the intensity of all of those pixels to output a single intensity value that was recorded. For the flight tests, this algorithm was unable to locate the afterburning exhaust, so this process occurred manually. For this, each frame was individually examined, and the pixels which contained the exhaust plume were noted and summed. The surrounding pixels were then observed to estimate the background signal intensity. The background intensity was then subtracted from the intensity of the plume to determine the net signal from the plume. This was done for all of the images from a single run and then these values were categorized by the wavelength filter (752 nm, 759 nm, 762 nm, or 778 nm) that was used to create the image. All of the data for each filter type was averaged and normalized by the 778 nm data set. The code then performed a linear interpolation between the 778 nm data set and the 752 nm data set, to determine the nominal value of the 762 nm (or 759 nm) data. This was the intensity value that would have been observed if there was no absorption due to the O_2. The actual 762 nm (or 759 nm) intensity was divided by the nominal 762 nm (or 759 nm) intensity to determine the total transmission in the spectral region for the 762 nm (or 759 nm) filter. The code then held this value while performing a separate calculation.

The actual atmospheric conditions of temperature, pressure, and dew point were loaded into the MatLab ® code. The code then used a line by line radiative transfer model to query the HITRAN database to determine the theoretical optical depth (σ) for each wavelength (λ) of light across the spectrum for the MPR and for the actual atmospheric conditions. The transmission (τ) due to the O_2 was determined by equation A1. For the ground test case and the co-altitude testing in flight, where the pressure was constant between the source and the target, the concentration path length [N(l)] was assumed to have a constant O_2 concentration (n) as a function of length (L) so that it can then be brought outside the integral and further simplified as in equation A2.

$$\tau_{O2}(\lambda) = \exp\left(-\int_0^L \sigma(\lambda)\, N(\ell)\, d\ell\right) \qquad \text{(A1)}$$

$$\tau_{O2}(\lambda, L) \approx \exp(-\sigma(\lambda)\, nL) \qquad \text{(A2)}$$

For the flight testing with the target above and below the MPR system, this was no longer a valid assumption, and a more in depth calculation was used which incorporated a varying O_2 concentration (reference 3). This expression was then used to determine a theoretical total O_2 transmission as a function of length (or target range) by integrating this over the bandpass of the filter through which it travelled as shown in equation A3.

$$\tau_{O2}(L) = \int_{\text{bandpass}} \tau_{\text{filter}}(\lambda)\tau_{O2}(\lambda, L)d\lambda$$

This calculation was then used to create a table of the target range as a function of transmission. The measured transmission from the captured images was then compared to the theoretically generated table to estimate the range to the target. Some outputs of this routine were range, signal intensity for each filter, and atmospheric transmission as a function of time.

A.4. Data Analysis

The MPR estimated range was compared to the TSPI range to determine the accuracy of the MPR system. The range error was compared against several factors that affect system accuracy. Some of these factors were: signal to noise ratio, range, and atmospheric absorption.

A.5. MatLab® Code

Many different MatLab® routines were developed and used for processing the ground and flight test data. Although the following sample of the routines does not include all of the information (databases, constants, subroutines) required to reproduce the results, it does document the overall process of the data reduction.

```
%%              Read LabView Files and Determine Range
%Fill out data and run entire file
binning=1;% 1x1 binning=1 and 2x2 binning=2
wavelength=759;% Enter 762 or 759 for absorption wavelength
run_num=1;
day_num=244;
folder='Data/EdwardsDayTest/RealRun1';
runst=num2str(run_num);
dayst=num2str(day_num);

xRange=333:342;%Range of Pixels to avg
yRange=262:271;

temperature=29.28;% in C
dew_pt=9.1667;% in C
pressure=932.8;% in mBar
if wavelength==762
    if binning==1
      %               1X1 Binning      762
     string1=strcat(dayst,'*WL778-RUN',runst,'.tif');
     string2=strcat(dayst,'*WL762-RUN',runst,'.tif');
     string3=strcat(dayst,'*WL752-RUN',runst,'.tif');

[m778,n778,m762,n762,m752,n752,t778,t762,t752]=read_labv(2008,10,8,folder,str
ing1,string2,string3,yRange,xRange);

               % Use average values
            a752=mean(t752);
            a762=mean(t762);
            a778=mean(t778);
```

```
            clear s778 s762 s759 s752;
              for i=1:length(n762);
                  s762(i)=(n762(i)-n778(1))*24*3600;
              end;
              for i=1:length(n752);
                  s752(i)=(n752(i)-n778(1))*24*3600;
              end;
              for i=1:length(n778);
                  s778(i)=(n778(i)-n778(1))*24*3600;
              end;
              plot(s778,t778);hold all;plot(s762,t762);hold
all;plot(s752,t752);hold off; figure(gcf)

              [transm,c762,b762,c752]=trans_sl_from_vals_762(a778,a762,a752);
              range=range_from_trans_762(transm,temperature,dew_pt,pressure);

          end;



      %%             Read Files and average the signal levels
      function
[m2high,n2high,m2mid,n2mid,m2low,n2low,a2high,a2mid,a2low]=read_labv22(year,m
onth,day,folder,shigh,smid,slow,r1,r2)

      temp=dir(strcat(folder,'/',shigh));
      for i=1:(length(temp)-1)
      data=imread(strcat(folder,'/',temp(i+1).name));
      cdata=nuc_corr22(data);
      mhigh(:,:,i)=cdata(r1,r2);
      ahigh(i)=mean(mean(mhigh(:,:,i)));
      timestr=strrep(temp(i+1).name,'-','.');
      nhigh(i)=datenum(year,month,day,str2num(timestr(5:6)),str2num(timestr(7
:8)),str2num(timestr(10:15)));
      flaghigh(i)=median(cdata(:));
      end

      temp=dir(strcat(folder,'/',smid));

      for i=1:length(temp)
      data=imread(strcat(folder,'/',temp(i).name));
      cdata=nuc_corr22(data);
      mmiddle(:,:,i)=cdata(r1,r2);
      amid(i)=mean(mean(mmiddle(:,:,i)));
      timestr=strrep(temp(i).name,'-','.');
      nmiddle(i)=datenum(year,month,day,str2num(timestr(5:6)),str2num(timestr
(7:8)),str2num(timestr(10:15)));
      flagmid(i)=median(cdata(:));
      end

      temp=dir(strcat(folder,'/',slow));

      for i=1:length(temp)
      data=imread(strcat(folder,'/',temp(i).name));
      cdata=nuc_corr22(data);
```

```
      mlow(:,:,i)=cdata(r1,r2);
      alow(i)=mean(mean(mlow(:,:,i)));
      timestr=strrep(temp(i).name,'-','.');
      nlow(i)=datenum(year,month,day,str2num(timestr(5:6)),str2num(timestr(7:
8)),str2num(timestr(10:15)));
      flaglow(i)=median(cdata(:));
      end

      avhigh=median(flaghigh(:));
      avmid=median(flagmid(:));
      avlow=median(flaglow(:));

      highcutoff=10000+avhigh;
      midcutoff=10000+avmid;
      lowcutoff=10000+avlow;

      j=1;
      for i=1:length(flaghigh);
          if flaghigh(i)<highcutoff;
               if flagmid(i)<midcutoff;
                   if flaglow(i)<lowcutoff;
              m2high(:,:,j)=mhigh(:,:,i);
              a2high(j)=ahigh(i);
              n2high(j)=nhigh(i);

               m2mid(:,:,j)=mmiddle(:,:,i);
              a2mid(j)=amid(i);
              n2mid(j)=nmiddle(i);

              m2low(:,:,j)=mlow(:,:,i);
              a2low(j)=alow(i);
              n2low(j)=nlow(i);

              j=j+1;
                   end
               end
          end;
      end;


      %%              Takes the Signal Levels from the PiMax and
      %%              Normalizes based on wavelength filters and the
      %%              detectivity of the camera at that wavelength
      function
[trans,cor762,base762,cor752]=trans_sl_from_vals_762(m778,m762,m752);

      load constants/Norm_factors.mat;

      cor778=m778;
      cor762=m762.*c762./norm762.*norm778;
      cor752=m752.*c752./norm752.*norm778;

      base762=(cor778-cor752).*(10/26)+cor752;

      trans=real(cor762./base762);
```

```
%%              Takes the normalized Signal Levels and
%%              looks up the corresponding range based on the
%%              temperature, pressure, and dew point of the atmosphere
function range=range_from_trans_762(trans,temp,dp,press);
%trans - %transmission temp and dew point in celcius and pressure in
%millibar

load 'constants/transmission_data_new.mat';

tau=373.16/(dp+273.16);
vp=10^(-7.90298*(tau-1)+5.02808*log10(tau)-1.3816*(10^-
7)*(10^(11.344*(1-1/tau))-1)+8.1328*10^-3*(10^(-3.4915*(tau-1))-1)+5.00571);
q=0.622*vp/(100*press-0.378*vp);
tv=(1+0.61*q)*(temp+273.16);
length=path_length.*(1./(press*.000986923267)).*(tv./300);
fit=spline(t762,length);
fit2=spline(length,t752);
fit3=spline(length,t778);
range1=ppval(fit,trans);
base752=ppval(fit2,range1);
base778=ppval(fit3,range1);
base762=(base778-base752)*10/26+base752;
range=ppval(fit,trans.*base762);



%%              Takes the Signal Levels from the ground test and
%%              Subtracts the background signal that was present
%%              before and after the test run to give the actual
%%              signal for each wavelength, then query the other
%%              routines to calculate range.
bkrangeA=1:5;
bkrangeB=204:213;
sigrange=15:194;
wavelength=759;

if wavelength==762;

bg762=(mean(t762(bkrangeA))*numel(bkrangeA)+
mean(t762(bkrangeB))*numel(bkrangeB))/(numel(bkrangeA)+numel(bkrangeB));
bg752=(mean(t752(bkrangeA))*numel(bkrangeA)+
mean(t752(bkrangeB))*numel(bkrangeB))/(numel(bkrangeA)+numel(bkrangeB));
bg778=(mean(t778(bkrangeA))*numel(bkrangeA)+
mean(t778(bkrangeB))*numel(bkrangeB))/(numel(bkrangeA)+numel(bkrangeB));

sig_b762=mean(t762(sigrange));
sig_b752=mean(t752(sigrange));
sig_b778=mean(t778(sigrange));

sig762=sig_b762-bg762;
sig752=sig_b752-bg752;
sig778=sig_b778-bg778;
```

```
      dev762=std(t762(sigrange));
      dev752=std(t752(sigrange));
      dev778=std(t778(sigrange));

      SNR762=sig_b762/bg762;
      SNR752=sig_b752/bg752;
      SNR778=sig_b778/bg778;
      SNR_avg=mean([SNR762,SNR752,SNR778]);
      SNR_tot=SNR_avg*sqrt((length(sigrange)));


[transm,c762,b762,c752]=trans_sl_from_vals_762(sig778,sig762,sig752);
              range=range_from_trans_762(transm,temperature,dew_pt,pressure);

             [transm,c762,b762,c752]=trans_sl_from_vals_762([sig778],[sig762-
dev762],[sig752]);

rangehigh=range_from_trans_762(transm,temperature,dew_pt,pressure);


[transm,c762,b762,c752]=trans_sl_from_vals_762([sig778],[sig762+dev762],[sig7
52]);

rangelow=range_from_trans_762(transm,temperature,dew_pt,pressure);
      end
```

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APPENDIX B – TEST AIRCRAFT MODIFICATION DETAILS

The modification process began in February 2009 at the beginning of the Air Cyclops test management project (TMP). The objective was to install the Air Cyclops camera and associated equipment into C-12C 76-0161. A modification manager was selected at the 412th Test Wing modification shop, which formally began the modification process.

AFIT shipped the Air Cyclops equipment to Edwards in May 2009. Aircraft 76-0161 underwent a phase inspection in August 2009. While the aircraft was not mission capable, the Air Cyclops Modification (Control Number: M09A161A) underwent initial design (reference 4). The Air Cyclops camera and equipment were installed into a 19 inch rack, capable of being fastened to the C-12C seat rails.

To provide power to the Air Cyclops system, the Initial Instrumentation Power Installation Modification (Control Number: M08A161A) was added to the aircraft. This modification installed a Master Power Switch and a Main Power Junction Panel in support of all future instrumentation power requirements (figures B1 and B2). For this modification, power was acquired from both aircraft generators through the shared power isolation bus. Losing either generator would automatically de-energize the power tap. It would remain inactive until both generators were again fully functional and the Master Power Switch was manually toggled.

Figure B1. Instrumentation Ground Power Disconnect Panel

Figure B2. Instrumentation Power Disconnect Panel

Because the Air Cyclops camera could not image through an aircraft window, the cabin entrance door had to be removed for test flights. The Paratroop Door Modification was installed (Control Number: M05A161A). It entailed a Lexan© door in place of the cabin entrance door capable of being raised in flight. Also part of the paratroop door modification, D-rings (for harnesses) were installed on the right side of the aircraft floor. In total, the Air Cyclops TMP required the Air Cyclops, Initial Instrumentation Power Installation, and Paratroop Door Modifications.

APPENDIX C – TEST AND TARGET DESCRIPTION

C-12C

The C-12C aircraft was a twin engine turboprop transport built by Beechcraft (figure C1). The aircraft was powered by two Pratt & Whitney PT6A-41 engines, each rated at 850 horsepower. The model used in the test was configured for parachute testing. The entry door was removed and replaced with a stowable Lexan© covering. The aircraft was 43 feet, 10 inches long and 15 feet, 5 inches high. It had a wingspan of 54 feet, 6 inches. Minimum speed was from 100-120 knots indicated airspeed (KIAS) depending on aircraft weight and configuration. Maximum speed was 259 knot calibrated airspeed (KCAS). Maximum speed with entry door removed was 205 KIAS. See C-12C Modification Flight Manual (reference 5) for more information.

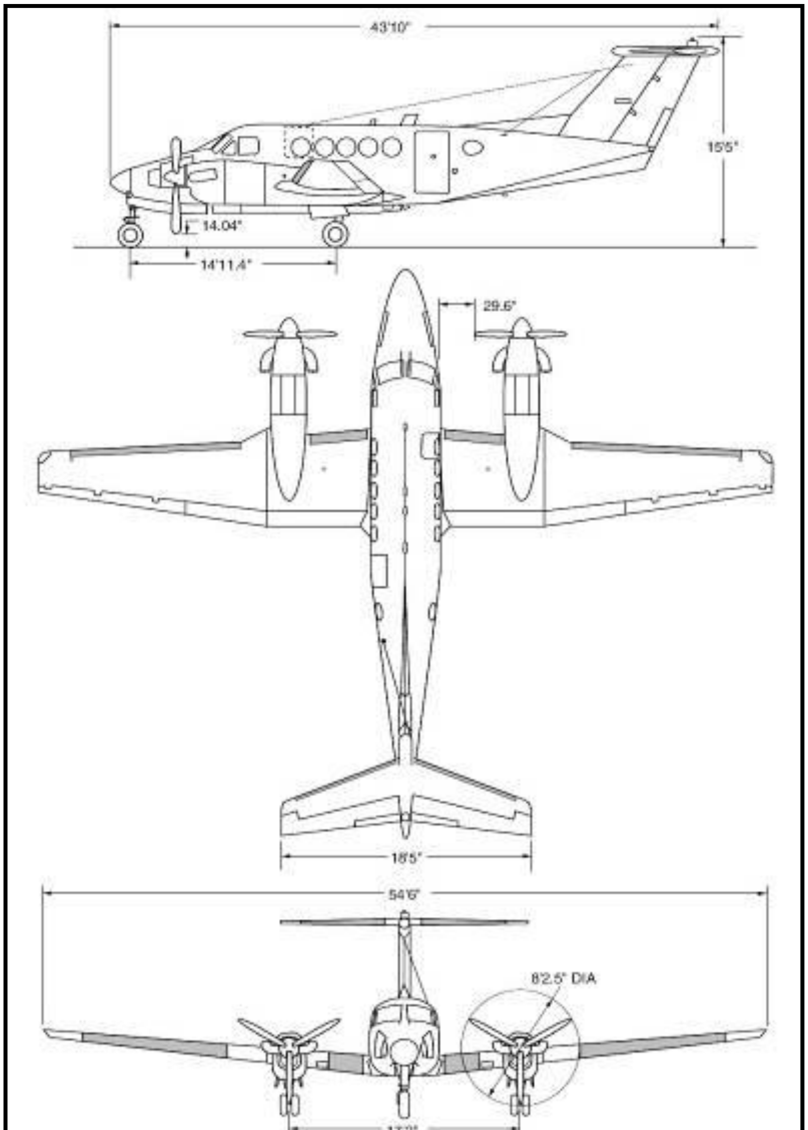

Figure C1. C-12C 3-View

F-16C/D

The F-16 was a single-seat (C-model) or two seat (tandem) (D-model), multi-role tactical fighter built by Lockheed Martin (figure C2). The aircraft had a large bubble canopy, forebody strakes, and an under-fuselage, fixed geometry engine air inlet. It was 49 feet, 5 inches long and 16 feet high. It had a wingspan of 32 feet, 8 inches. Minimum speed was defined by 11° angle of attack (AOA) based on aircraft weight, which was typically 140-160 KCAS. The F-16 was equipped with an F-110-GE-100 engine which consumed JP-8 fuel. At maximum afterburner power the engine produced 28,000 pounds of thrust and consumed over 35,000 pounds per minute of fuel. See F-16C/D Flight Manual (reference 6) for more information.

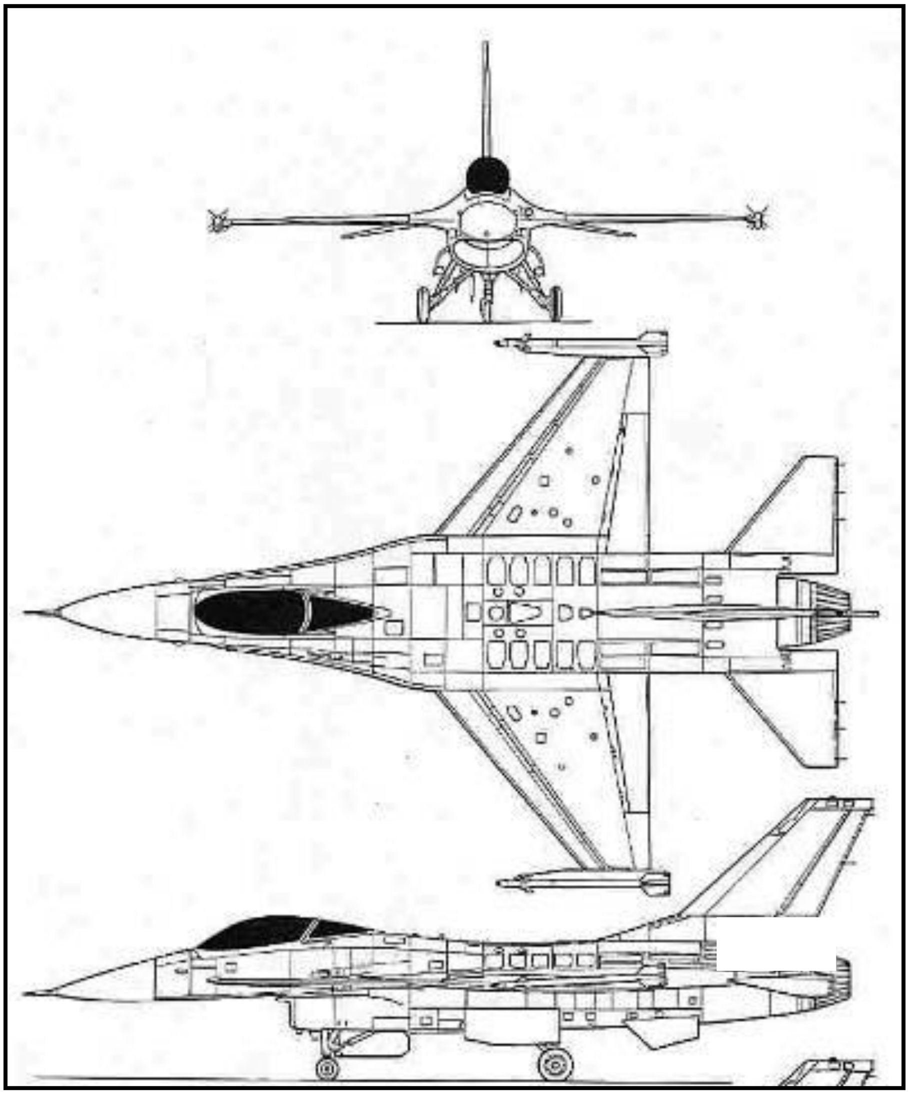

Figure C2. F-16C 3-View

APPENDIX D – FLIGHT TESTS SUMMARY

The following table summarizes the test day sorties. The sortie on 14 September was an air abort for C-12C inter-cockpit communication problems. The sortie on 17 September was an air abort for an F-16D ground abort. The first sortie on 23 September was an early return for an F-16C oil pressure malfunction. For these sorties the sunrise was at approximately 0640 (L) and sunset was at approximately 1845 (L).

Table D1. Test Day Flight Data

Date	Aircraft	Takeoff (L)	Duration (Hrs)	FTTs Flown
14 September 2009	C-12C	0806	0.6	-
16 September 2009	C-12C	0842	1.9	MPR Calibration Photo Chase
16 September 2009	F-16C	0859	1.5	
16 September 2009	T-38A	0858	0.8	
17 September 2009	C-12C	0806	0.9	-
18 September 2009	C-12C	0819	1.3	Level Imaging Climb Imaging Dive Imaging
18 September 2009	F-16C	0825	1.1	
23 September 2009	C-12C	1213	0.5	-
23 September 2009	F-16C	1219	0.3	
23 September 2009	C-12C	1359	1.3	Climb Imaging Dive Imaging
23 September 2009	F-16D	1404	1.2	

The 18 September and 23 September flights were the only two that successfully ran flight test technique maneuvers with valid global positioning system truth data.

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APPENDIX E – GROUND TEST ATMOSPHERICS

The following table documents the atmospheric conditions for each ground test run. The data were obtained from a handheld Kestrel 4000 weather meter.

Table E1. Test Run Atmospheric Data

Date	Run	Temperature (˚C)	Dew Point (˚C)	Pressure (millibars)
1 September 2009	1	32.0	1.6	935
1 September 2009	2	32.5	0.4	935
1 September 2009	3	35.2	-1.2	935
2 September 2009	1	29.3	9.2	933
2 September 2009	2	29.5	7.6	933
2 September 2009	3	28.8	7.6	933
2 September 2009	4	28.3	6.3	933
2 September 2009	5	27.9	5.8	933
2 September 2009	6	28.3	4.6	933
2 September 2009	7	28.1	4.9	933
2 September 2009	8	26.2	5.6	933

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APPENDIX F – RESULTS

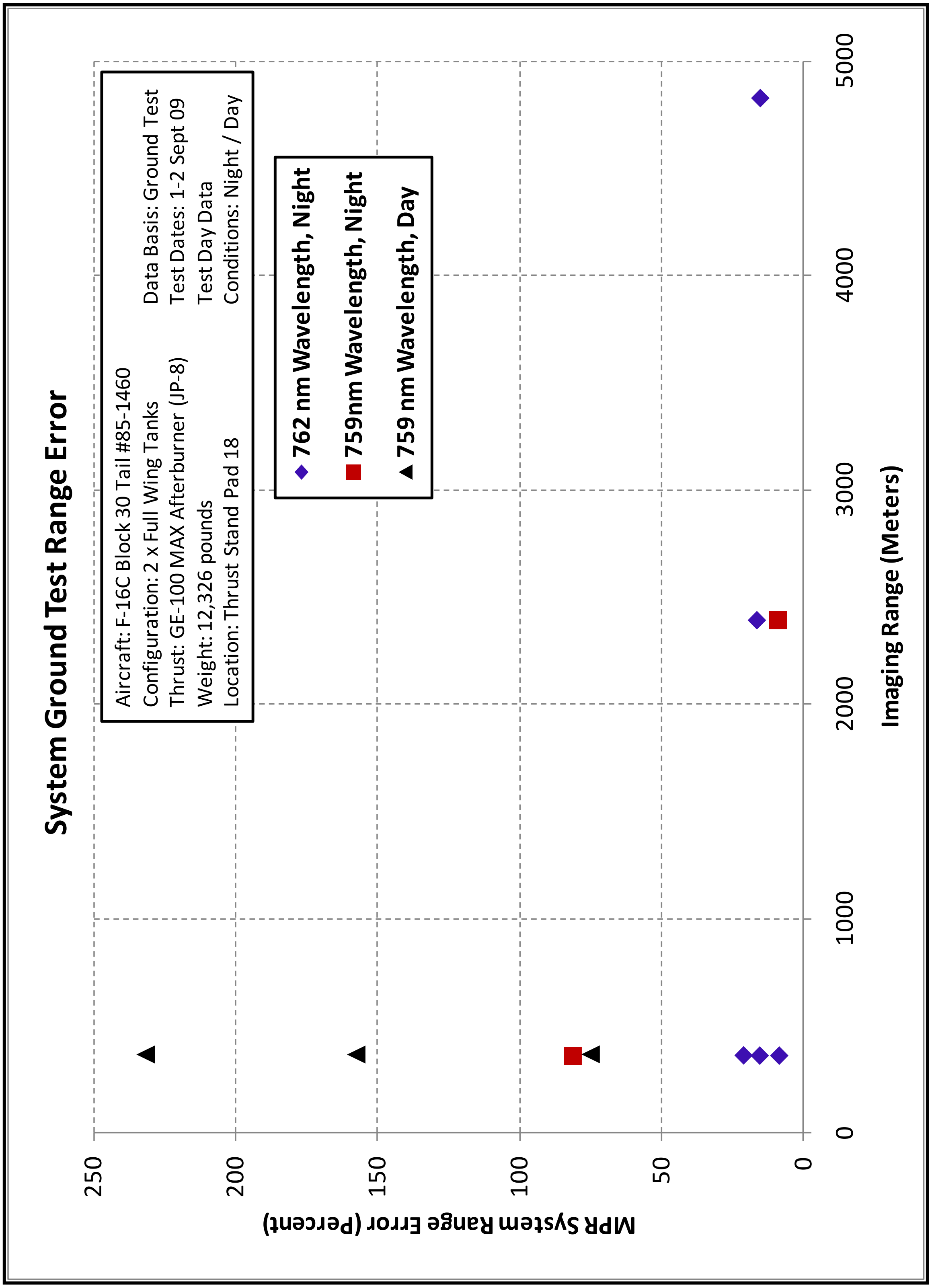

Figure F1. Range Error versus Range

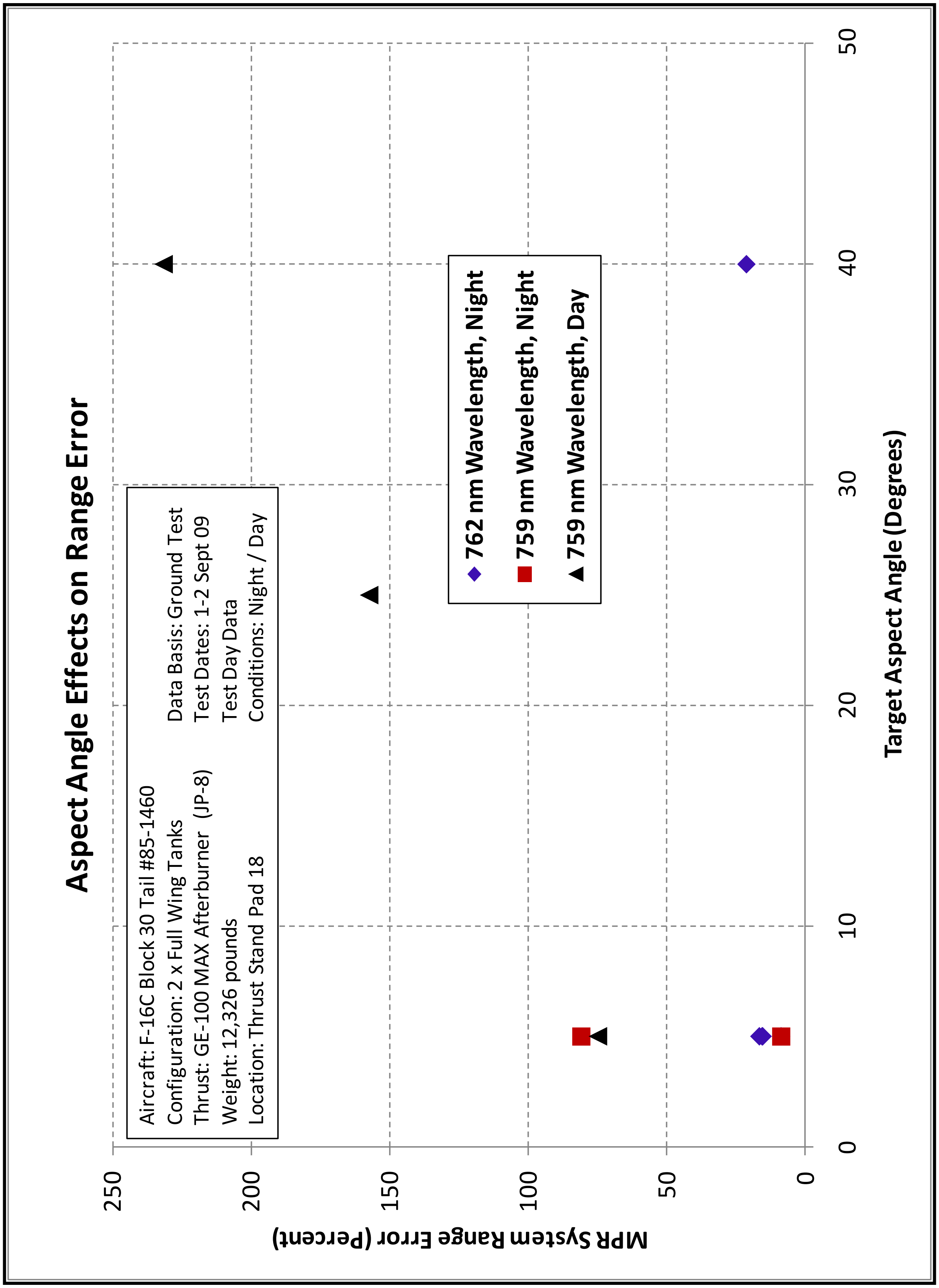

Figure F2. Range Error versus Target Aspect Angle

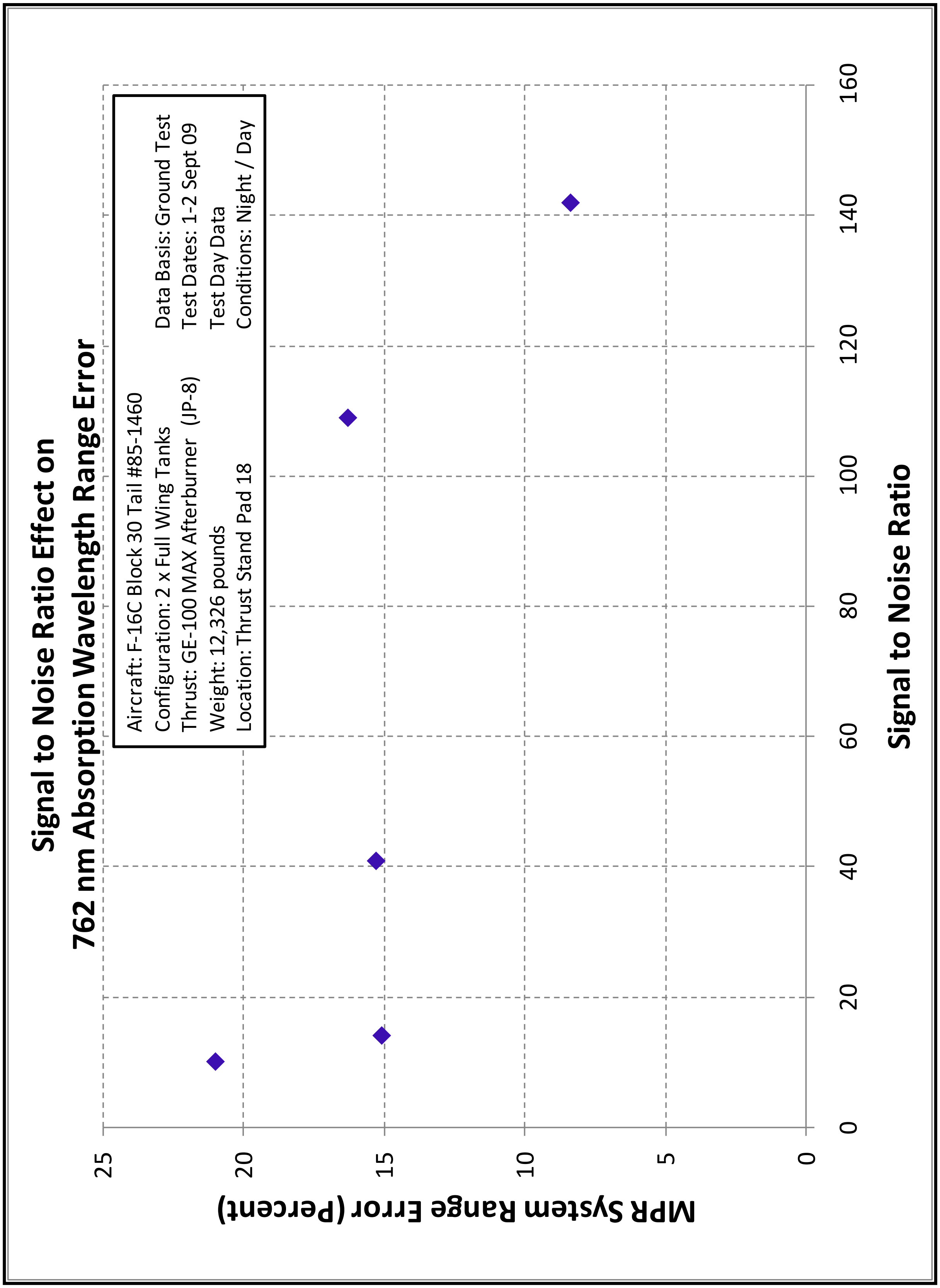

Figure F3. Range Error versus Signal to Noise Ratio

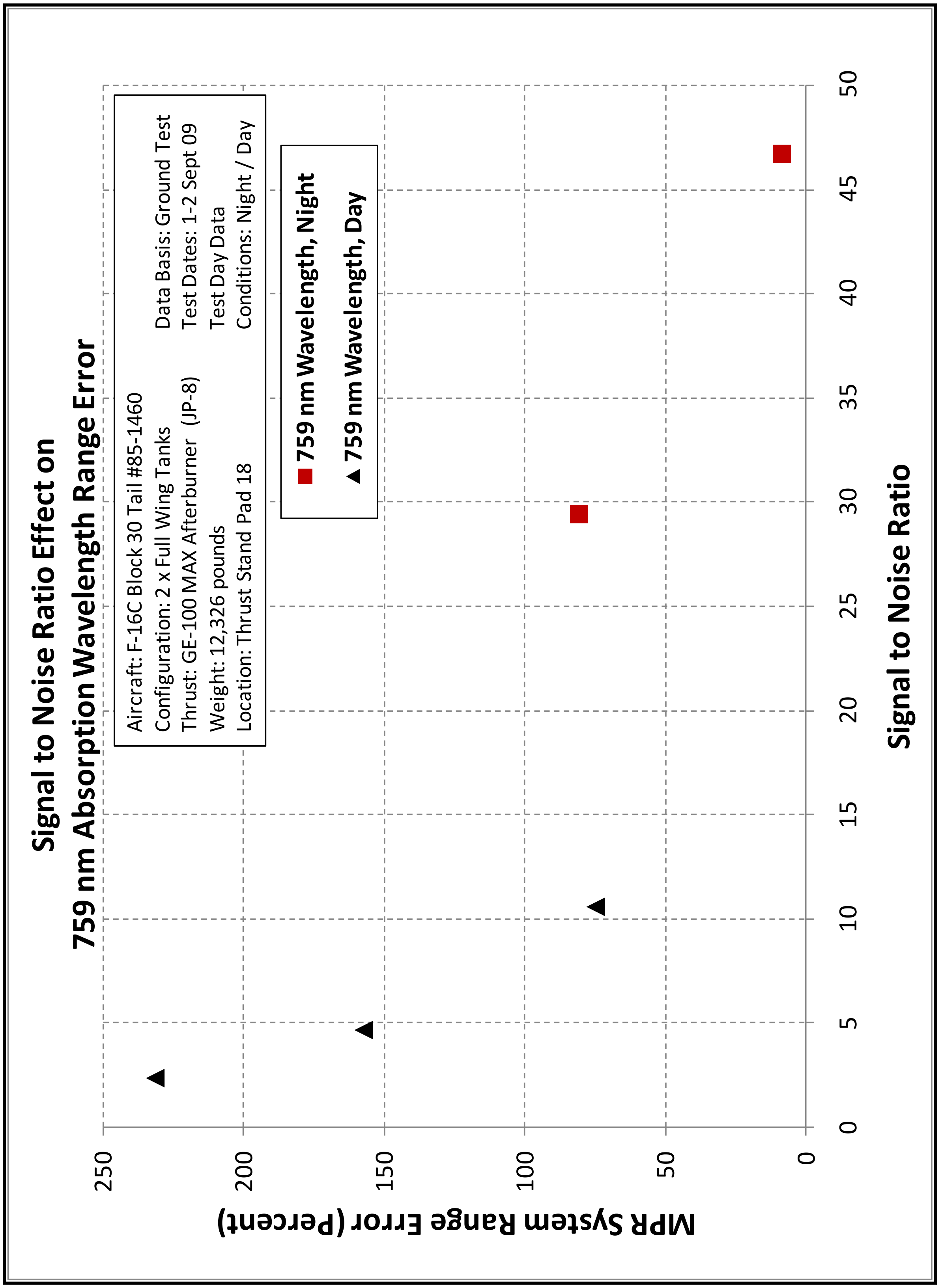

Figure F4. Range Error versus Signal to Noise Ratio

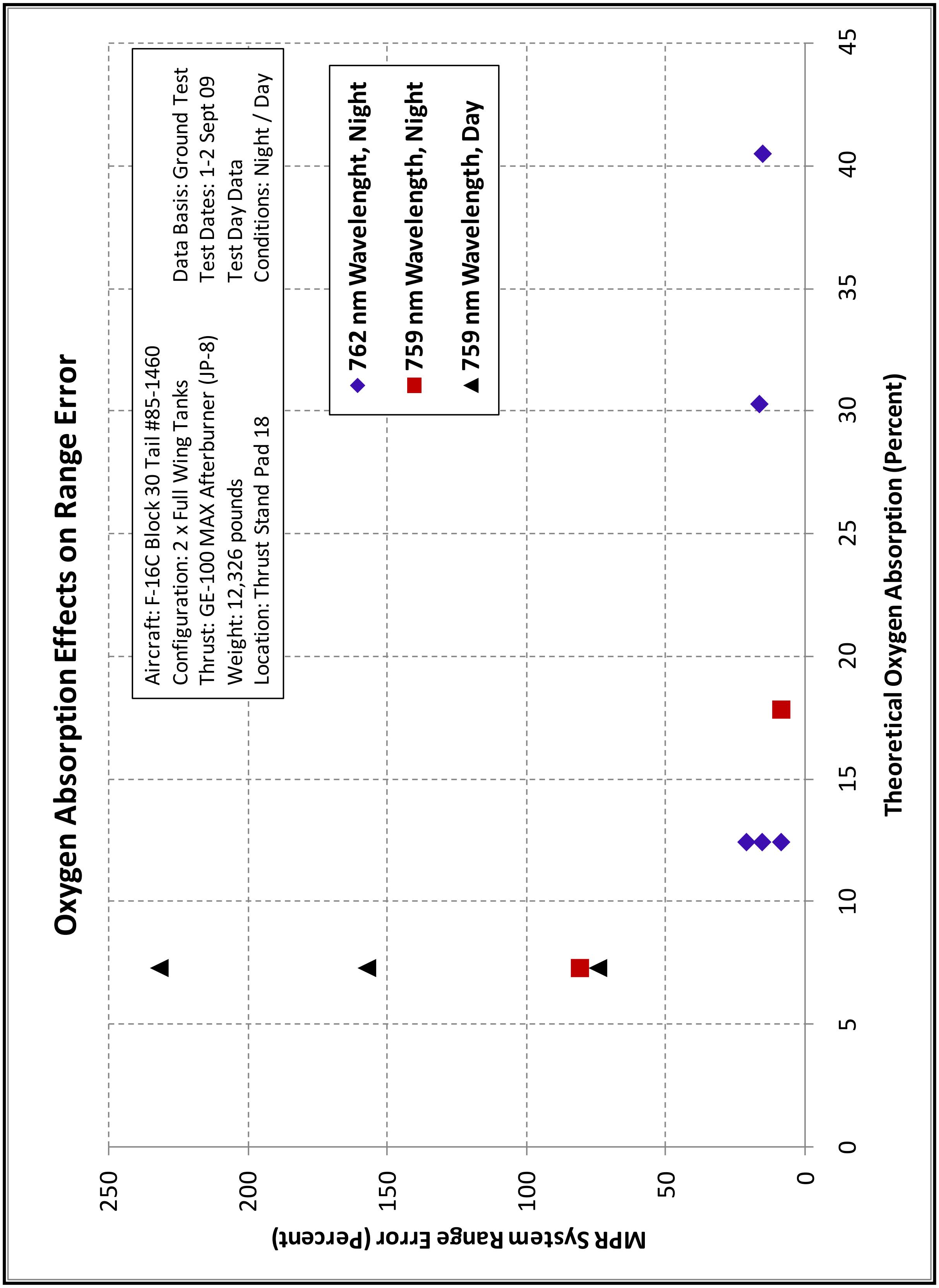

Figure F5. Range Error versus Oxygen Absorption

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APPENDIX G – LIST OF ACRONYMS AND SYMBOLS

AFFTC	Air Force Flight Test Center
AFIT	Air Force Institute of Technology
AOA	Angle of Attack
ENP	Department of Engineering Physics
FWHM	Full Width Half Maximum
FOV	Field of View
FTS	Fourier Transform Spectrometer
FTT(s)	Flight Test Technique(s)
GaAs	Gallium Arsenide
GAINER II	GPS/INS Navigation Experimental Ranger Version II
GPS	Global Positioning System
ICCD	Intensified Charge Coupled Device
KIAS	Knots Indicated Airspeed
KCAS	Knots Calibrated Airspeed
LCD	Liquid Crystal Display
mm	Millimeters
MPR	Monocular Passive Ranging
nm	Nanometers, Nautical Miles
O_2	Oxygen
PA	Pressure Altitude
RTO	Responsible Test Organization
TMP	Test Management Project
TPS	Test Pilot School
TSPI	Time Space Position Information
USB	Universal Serial Bus

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