WIRLESS AVIONICS INTRA-COMMUNICATIONS SYSTEMS AND BAND SHARING

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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December 2017

Major Subject: Electrical Engineering

# 1. INTRODUCTION

## 1.1 Motivation

Over the past two decades, wireless digital communication systems have become ubiquitous in the public life. As the technologies have become more proven, a broad range of players in the aerospace industry developed a significant interest in deploying these systems to electronics on airplanes. Specifically, these companies are interested in radiocommunication between devices on a single aircraft related to the regularity and safety of flight, rather than communications outside an aircraft or for passenger entertainment [1].

Avionics manufacturers are interested in the development, sale and deployment of sensors and devices in areas on a plane that were difficult or impossible to reach with wireless systems. Examples might include placing sensors to monitor a landing gear or internal to an engine, where rotating parts make monitoring difficult [1]. Airframers, Aircraft OEMs and Airlines all have a vested interest in any development which could reduce the amount of copper wiring on planes, thus reducing weight and fuel costs [2]. Regulators are interested in wireless avionics systems from a safety perspective. Critical avionics systems have redundant paths wired in in case of failure, and some or all of these redundancies may eventually be replaced with wireless ones [2] [1]. This type of dissimilar redundancy is always appealing from a safety perspective. The classic example of an engine fire which destroys the physical connection to a controller (and so can't be shut off) demonstrates the utility of a wireless backup [1].

## 1.2 History

With these diverse motivations spanning across the industry, various aerospace companies sponsored a series of working groups to implement wireless communications systems on aircraft. This systems used in this class of applications were alternatively called Wireless Sensing Networks (WSN's) in early literature, and Wireless Avionics Intra-Communications (WAIC) systems later on. WAIC related projects were sponsored and conducted through the Aerospace Vehicle Systems

Institute (AVSI), which also directed this project. AVSI projects are funded through independent grants known as Authorizations For Expenditure (AFEs)

Three AVSI projects directly relate to WAIC: AFE 56, AFE 73, and AFE 76. AFE 56 studied the feasibility of potential WAIC systems and investigated the suitability of various bands to WAIC applications. AFE 73 took the analysis done by AFE 56 and used the work to advocate to regulators for spectrum allocation for WAIC.

### 1.3 Project Goals

This work was funded through AVSI and managed under AFE 76. The goal of this project is to perform a band sharing study for WAIC with radio altimeters, and to develop a prototype for WAIC systems. The technical challenges in this project directly result from both the technical studies and the inherently political interactions with regulators performed under its predecessors. Because of this, a brief summary of the work done by the two preceding AVSI projects will be presented here, emphasizing the portions of each most relevant to this study.

### 1.4 WAIC Feasibility Study

The WAIC Feasibility study was conducted through AFE 56, and the results of this study were published in [3]. The report is summarized here for background with significant focus placed on the search for a suitable WAIC band.

AFE 56 had three primary goals [3]:

- ”Identify, Characterize and prioritize the most significant obstacles currently impeding widespread use of wireless communication in flight-critical functions”
- ”Evaluate the current aircraft RF certification process and suggest possible modifications or changes”
- ”Identify the most promising avenues to certify reliable and robust wireless intra-aircraft data transmission”

Toward these ends, investigations were performed into the certification process, suitable spectrum bands, and security concerns related to the implementation of WAIC systems.

### 1.4.1 Certification

Any device on an aircraft must go through a regulatory certification process, which functions as a way for regulatory bodies to declare the device airworthy [3]. Both civilian and military aircraft are subjected to various certification processes [3]. The AFE 56 working group surveyed the various standards imposed by the DoD, FAA, and ICAO (International Civil Aviation Organization), as well as international treaties governing the aviation industry. The committee took an in depth look at the flight clearance process in use at various agencies [3].

The AFE 56 working group then looked at the specific challenges brought to the forefront by wireless systems. The primary concerns for potential WAIC systems involved the sharing of spectrum with other legal occupants of the band, as well as intentional and unintentional interferers [3]. It was determined that a certification process for WAIC systems would need to account for and provide mitigation strategies for each of these various potential interferers to pass certification. Information security would also need to be guaranteed for critical systems. These considerations would drive the band selection process for WAIC [3].

### 1.4.2 The Search for a Suitable WAIC Band

Prior to beginning the search for a suitable band, members of the project management committee held discussions with the FCC to gain insight on the regulator's perspective on allocations for potential WAIC systems. Firstly, FCC staff reccommended AVSI pursue an international spectrum allocation before focusing on domestic rule-making. Secondly, the FCC placed significant emphasis on the importance of ”picking a winner” as quickly as possible in the frequency selection process [3].

This recommendation was made in light of experience with previous international radio projects. American industry previously coordinated a global effort to upgrade the Weather Fax system which was delayed by more than two years and ultimately only partially successful. The FCC ultimately pinned these issues on the failure of American industry to ”*socialize* their specific solution” with key international players in the international spectrum allocation process [3]. The lessons from this failure would play as important of a role in the evaluating potential WAIC band as technical considerations. The band would need to be one which aerospace could get.

Initially, the committee considered the Industrial, Scientific, and Medical, or ISM bands. ISM bands are subjected to limited regulations, and were quickly eliminated from consideration for WAIC devices [3]. A wide variety of commercial devices already occupy this band, and these devices are allowed to radiate at relatively high powers. Because of the high operating powers, users are afforded no regulatory protection from hamful interference, a condition which would be unacceptable for the safety focused aerospace industry [3]. For this reason the 915 MHz, 2.4 GHz, 5.8 GHz, 24 GHz, and 61 GHz bands were eliminated from consideration for WAIC devices [3].

To find a suitable alternative, the committee stepped through both the US and international tables of frequency allocations. The committee rated alternatives according to two goals. The first was electromagnetic compatibility with wireless sensor applications [3]. The second goal was that a suitable band already be allocated or have potential to be allocated in a manner compatible with WAIC desired properties [3].

A series of criteria were used to rate the suitability of potential alternatives. A band already primarily allocated to an aeronautical service was considered beneficial from the political perspective of spectrum allocations. Benign co-primary users were considered essential [3]. The less sensitive other occupants are to the minimal level of interference from on-aircraft wireless systems, the better. Bands which possessed common allocations across international regions were also considered beneficial, to ease the process of getting approval for WAIC use of the band [3].

It was considered critical that WAIC systems be sufficiently isolated from ISM and unlicensed allotments. The relatively uncontrolled emitters were considered a significant threat to on aircraft wireless [3]. Isolation from terrestrial point to point systems was also considered critical. These systems introduce the possibility of impinging extremely high radiated power levels onto aircraft that pass through [3]. Although this risk is limited to low altitudes, it constitutes a significant safety hazard that can be avoided by the choice of band [3]. A final consideration for allocations is isolation from Satellite (Earth to Space) allocations. Up-link sites require significant RF power to maintain, and therefore consist of a safety hazard similar to point to point systems [3].

### 1.4.3 Candidate Bands

Based on these criteria, the AFE 56 committee performed a review of major candidate bands for WAIC systems. The committee provided a synopsis of relevant characteristics of each candidate band and rated the band according to it's suitability. AVSI performed this process with a goal of helping future working groups to prioritize future efforts at reserving spectrum allocation.

### 1.4.4 Channel Modeling and Security

Finally, the AFE56 committee surveyed two more obstacles to a finalized WAIC implementation. The committee looked at channel modeling for wireless sensor networks and gave an overview of security concerns.

Any implementation of WSN's on aircraft has the potential to be critical to the safety of flight. Because of this, the committee stressed the importance of developing a validated channel model for the band and air-frames in use [3]. The channel models would allow for the incorporation of the physical propagation characteristics of the wireless signals in various aircraft and could be used to improve the reliability of real WAIC designs. Because of this, the committee provided an overview of channel modeling efforts in their report and made recommendations for an approach to channel modeling efforts that might follow a new WAIC allocation [3].

Lastly, the committee commissioned a follow up investigation which looked into the security concerns associated with WAIC systems. A report [4] was commissioned through the University of Minnesota, which aimed to analyze the various potential threats to wireless networks on aircraft. The threat vectors considered included physical layer attacks such as jamming, as well as higher layer attacks such as distributed denial of service and hacking risks. The report then looked at potential mitigation strategies for each of these threat vectors. The solutions listed were meant to be a comprehensive overview, but to acquire certification each device would have to provide a detailed overview of their implementation to the relevant certification authority [4].

### 1.4.5 Summary and Conclusions

The AFE 56 project committee performed a feasibility study for wireless sensing network on aircraft. The committee first looked at the existing path to certification for instrumentation, and came to the conclusion that this path would work for WSN's as well, provided that the applicant for certification perform the necessary extra step of explaining to the FAA the added risks of the wireless device and how these risks were mitigated [3]. The committee then performed an in depth survey of potential bands for WSN use, summarizing the desirable characteristics possessed by any candidate band. The committee provided an in depth overview of the pros and cons of each serious candidate for WAIC allocation, a brief summary of which has been included in this report for reference. Finally, the committee looked at potential channel modeling techniques and security concerns associated with wireless systems on aircraft and outlined how these would need to be addressed for a real WAIC implementation [4].

The committee came to the conclusion that although there were numerous hurdles in the way of fully realizing WAIC systems, WAIC systems were feasible and these challenges could be overcome with industry expenditure and effort. The tasks necessary for WAIC implementation were as follows:

- Acquire spectrum for WAIC use
- Perform a band sharing study for WAIC and existing band occupants
- Develop industry standards for channel modeling of air-frames
- Develop industry standards for addressing security concerns for wireless networks on aircraft
- Work with regulators to develop a streamlined certification process for wireless sensing networks once these standards are developed

With the feasibility study complete, the AVSI partners moved on to the task of acquiring spectrum for wireless networks on aircraft.

## 1.5 Selecting a Suitable WAIC Band

In AFE 73, AVSI followed up on the work completed in AFE 56. The list of candidate bands was narrowed down to three at the World Radio Conference in 2015 (WRC-15), which then were the subject of a compatibility study. This process concluded with the final selection of a final WAIC band which was approved at WRC-15.

### 1.5.1 Assessment of Bands between 960 MHz and 15.7 GHz

At WRC-12, the ITU recommended in Resolution 423 that bands from 960 MHz to 15.7 GHz be considered for potential WAIC allocation [5]. The ITU eliminated bands below this range because the antenna size requirements were incompatible with WAIC implementation requirements. Bands above this range were to be considered only after all possibilities in this range were exhausted.

The ITU took all bands with existing allocations to aeronautical mobile or aeronautical radionavigation services into consideration. Bands in this range which fit this criteria were considered in an initial assessment. The purpose of the initial assessment was to eliminates bands with undue burden of a regulatory or technical nature. Technical burdens could involve an excessive number or difficulty of necessary band-sharing studies, while regulatory burdens could involve co-occupants of a band outside of the aerospace industry. After the initial assessment, the 2.7-2.9 GHz, 4.2-4.4 GHz, and 5.35 - 5.46 GHz bands were considered the three most promising candidates for a potential WAIC Allocation. This recommendation precipitated a theoretical compatibility study for these bands at WRC-15 [5].

### 1.5.2 Compatibility Study

The three bands selected in the initial assessment for more detailed analysis underwent a theoretical compatibility study. Existing ground based radar systems in the 2.8 and 5.4 GHz bands were found to be incompatible with the requirements for WAIC implementations, which left the 4.3 GHz band as the only remaining option. The ITU recommended this band for allocation for WAIC Systems [5].

### 1.5.3 Relevant WRC-15 Allocations

The 2015 World Radio Conference (WRC-15) made changes to the spectrum allocations in and around the radio altimeter (RA) band [6]. The 4.2-4.4 GHz band received an allocation for WAIC systems pending the experimental verification of compatibility. Additionally, new allocations for 5G systems in the 3.7 GHz (3600-4200 MHz) and 4.5 GHz (4400 - 4900 MHz) bands directly adjacent to the altimeter band would lead to experimental band-sharing studies.

## 1.6 Overview of Radio Altimeter Functionality

The allocation of the 4.3 GHz band for WAIC necessitates an experimental study on the effects of interference on radar altimeters. This section provides background information on the functionality of radar altimeters which is relevant to the experimental design and setup.

### 1.6.1 Basic Overview and Applications

The 4.2-4.4 GHz band was previously allocated exclusively to radio altimeters and transponder systems associated with altimetry. The altimeter functions to actively and continuously provide height measurements of an aircraft above the surface of the Earth [7]. The highest degree of accuracy is expected in the approach, landing, and climb phases of flight. This accuracy must be maintained through all types of ground reflectivity. The height measured by an altimeter has a variety of uses in safety critical systems. The height functions as an input The Terrain Awareness Warning System, which gives the pilot a ”Pull Up” warning at a predetermined unsafe altitude and descent rate. The height from altimeters also functions as input for Collision Avoidance, Weather, Navigation, and Autopilot systems. Radio Altimeters are expected to operate in these functions through the lifetime of the Aircraft they are installed on, which results in Altimeters used in excess of 30 years.

### 1.6.2 Calculating the Height From a Time Delay

There are two primary types of altimeters in use today. The first are Frequency Modulated Carrier Wave (FMCW) Altimeters [7]. FMCW altimeters use a transmitter and receiver with separate

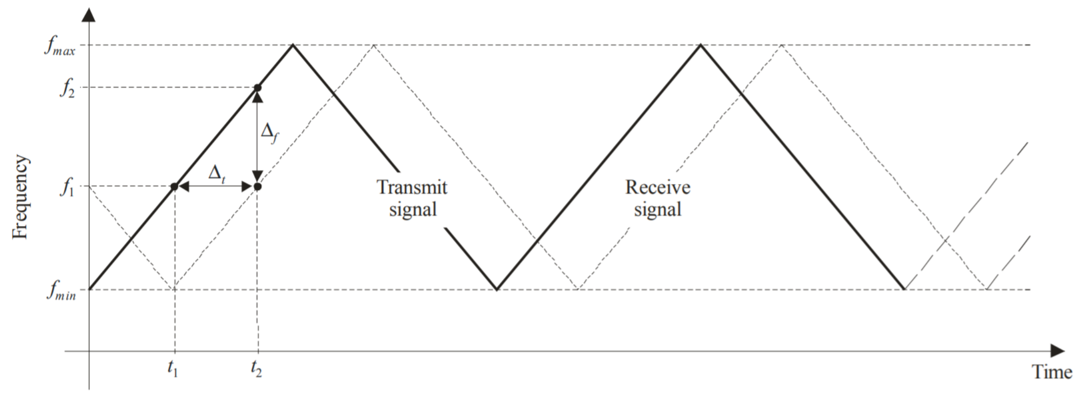


Figure 1.1: FMCW Waveform from ITU-R M.2059-0 [7]

antennas. The signal from the transmit antenna travels to the ground, is reflected, and returns to the aircraft. Due to the constant propagation speed, the return time of the signal is proportional to the height of the aircraft above the surface.

The signal travel time is based on the return of a signal of the same frequency as the transmit signal [7]. One method for calculating the travel time of a signal involves taking the difference between the frequency of the return signal at the current time and the frequency of the transmit signal at the current time, $\Delta f$. As shown in Figure 1.1, given a constant waveform, the return time of a signal is:

$$\Delta t = \frac{\Delta f}{df/dt}$$

Once $\Delta t$ is calculated, it the height can be determined using the speed of light:

$$H = \frac{c}{2\Delta t}$$

While not relying on a frequency modulated waveform, pulsed radar altimeters use a series of discrete pulses to track the current height of the aircraft. The $\Delta t$ between two pulses is used to calculate the height in the same manner that an FMCW altimeter does. Thus, for any altimeter under test in a lab setting, the time delay of the signal between the Altimeter TX and RX must be simulated to provide an accurate representation of real conditions.

### 1.6.3 Attenuation of the Altimeter Signal in Free Space

A signal traveling from Altimeter Transmit and back to receive passes through multiple different sources of gain and attenuation [8]. There is attenuation from cable losses, gain from the TX antenna, free space path loss as the signal travels toward the ground, loss from the scattering of the signal by the ground, path loss of the return signal, a gain from the receive antenna, and finally the attenuation from return cable losses. The combination of each of these gains and losses comprises the external loop-loss $L$ for a signal leaving an aircraft. DO-155 defines the loop loss as the ratio of the power received by the RX antenna, $P_R$ to the power sent by the transmit antenna, $P_T$.

$$L = \frac{P_R}{P_T}$$

The DO-155 standards specify loop loss for different heights, standardized antennas, ground scattering environments, and standardized cable attenuations, and expands the formula shown here to derive these [8]. Like the time delay, any Altimeter lab setup has to simulate the DO-155 attenuation for various heights to be realistic.

### 1.6.4 Conclusions

Radio Altimeters are a safety critical system in any aircraft, the output of which is used by other important airborne systems. Altimeters use the time it takes a signal to travel to the ground and back to calculate the height of an aircraft off the ground, and must be able to pick up a return signal which has been attenuated significantly depending on the height. To test radio altimeters in a lab setting, both the time delay and attenuation experienced by a real signal must be simulated.

# 2. METHODS

## 2.1 Basic Altimeter Test Bed Setup

In addition to laying out performance standards for radar altimeters, the DO-155 standards [8] also specify a basic test setup for verifying an altimeter is functioning properly. Figure 2.1 shows the diagram of this test setup. The standards also elaborated on the necessary characteristics of the most critical part of the testbed, the altitude simulator.

The altitude simulator needed to ”consist of variable and fixed RF attenuators” [8] to simulate the loop loss an altimeter experiences aboard an aircraft (see section 1.6.3). The altitude simulator also needed a length of ”coaxial cables or other suitable delays” [8] to simulate the physical time delay experienced by an altimeter signal between the transmitter and receiver (see section 1.6.2). To complete the test setup, the altitude simulator directed the attenuated and delayed RF energy from the transmitter fed back into the receiver.

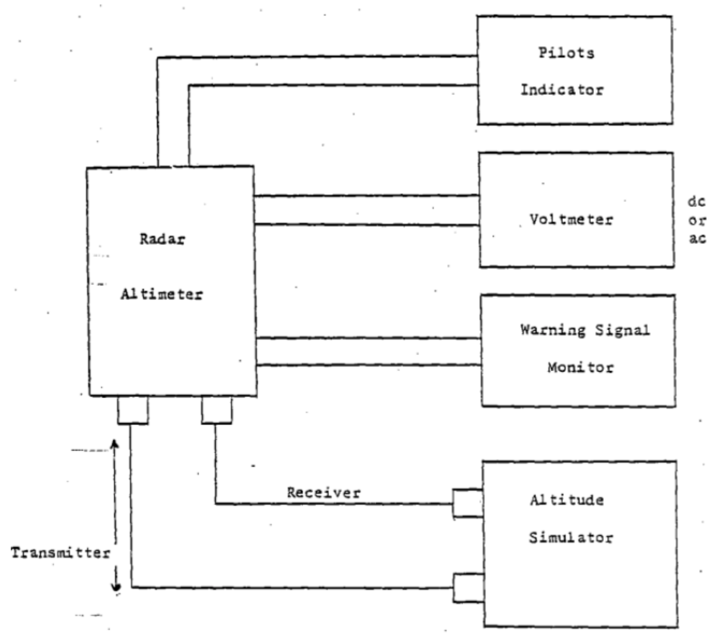


Figure 2.1: Basic Altimeter Test Setup from DO-155 [8]

Additionally, the standards specified that any test equipment must account for cross coupling between transmitting and receiving antennas. DO-155 emphasized that the altitude simulator should achieve the desired altitude within 1% and the correct attenuation within 2.5dB [8].

## 2.2 Modified Altimeter Test Setup

AVSI designed a modified version of the altimeter test setup specified by DO-155, shown in Figure 2.2. The modifications allow the controlled injection of interference into the line after the altimeter signal passes through the altitude simulator.

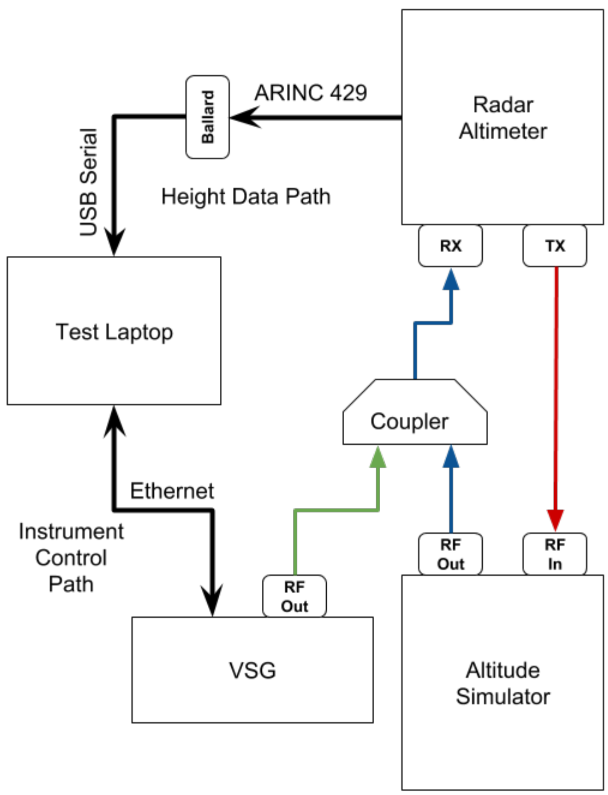


Figure 2.2: Modified Altimeter Test Setup

### 2.2.1 Reading the Altimeter Output

The altimeter outputs labeled height data on a standardized ARINC 429 cable configuration. The modified setup uses a Ballard ARINC device to convert the data from ARINC 429 to USB serial format, providing each data point with a time stamp. On the test laptop, Ballard CoPilot software reads the serial data and provides a display which allows the real time monitoring of all altimeter output and labels. The labels are critical because some data points may be labeled NCD, or No Computed Data, when conditions are insufficient for a reliable height measurement. CoPilot software also allows for the easy export of test data to Microsoft Excel documents for post processing.

### 2.2.2 Implementing the Altitude Simulator

#### *2.2.2.1 Time Delay*

Different test altitudes required the use of different methods of delaying the RF energy output by the altimeters. For higher altitude tests, spools of fiber optic cables created a time delay. The RF output from the altimeter transmitter was fed by coax connection to the fiber optic transceiver, which could either pass the signal to a single fiber optic spool or a series of cascaded spools to achieve a desired height. This setup contained optical spools of 500, 1000, 2000, and 4500 feet, each of which could be used individually or in conjunction with any or all of the other spools to implement a delay.

The optical transceiver and cascaded spools also contribute an attenuation to the loop loss which varies based on the number of spools cascaded. A single spool setup has an attenuation verified experimentally to be 29dB, with an additional 2dB loss added for each additional cascaded spool.

Later tests would modify this delay setup to test an altimeter in takeoff and landing scenarios. The much lower height in these scenarios meant that a spool of coax could be used tor the delay instead of fiber optic cables. Two coax spools provided a height of 40 ft and 95 ft for testing these scenarios, with a 6dB and 36dB attenuation contributed to the loop loss respectively.

| Height | Loop Loss |
|---|---|
| 40ft | 76 dB |
| 95ft | 84 dB |
| 500ft | 100 dB |
| 1500ft | 109 dB |
| 3000ft | 116 dB |
| 5000ft | 120 dB |
| 8000ft | 124 dB |

Table 2.1: DO-155 Loop Losses

##### *2.2.2.2 Achieving Standard Loop Losses*

DO-155 specifies loop loss for various heights and antenna types. For these tests, the loop loss used for each height is listed in Table 2.1 To achieve the Loop Losses specified by DO-155 standards for each height, the attenuation inherent in the delay method used for each height must be taken into account. Once the attenuation from the delay line is subtracted from the loop loss, 10, 20 and 30dB Pasternack fixed attenuators are inserted into the setup to get within 10dB of the desired loop loss. These are located within the setup in part to protect the fiber optic transceiver from damage. Finally, a step attenuator capable of 1 to 11 dB is used to achieve the desired loop loss with a 1 dB precision.

### 2.2.3 Generating Interference Signals

A Rhode and Schwarz SMU200A Vector Signal Generator (VSG) is used to generate simulated WAIC signals of varying modulation types, bandwidths and power levels. The VSG has a SCPI interface which allows an external computer to control any functionality on the instrument through commands sent over either a serial or an Ethernet connection.

The VSG allows full control of an RF generator along with two baseband generators. The RF generator gives the user control of RF carrier frequency as well as the output power level of the carrier in dBm. The baseband generators allow the modulation of two potentially unique waveforms onto the carrier wave, with a possible offset frequency from the center.

## 2.3 Python Test Software

Python code written by the author pieces together the various parts of this setup into a complete test bench. Different Python scripts handle different functions necessary to the test bench. These include:

- Creating a database to transfer data between different Python Scripts
- Interface with the VSG to generate interference signals
- Parse the CoPilot log
- Mapping time stamped height measurements to time stamped interference signals
- Plotting and analyzing the results

The software uses Standard Commands for Programmable Instruments or SCPI to control the vector signal generator. In this test bed, the SCPI instructions are processed through an object-oriented hierarchy shown in Figure 2.3. The superclass, $SCPI$ interfaces directly with all lab equipment. The subclass, called *RS_Signal_Generator* in this implementation, contains python functions associated with all instrument specific commands. The helper functions from $SCPI$ send and receive communication with the instrument. Finally, the main loop exists at the highest level, which times the calls of different instrument commands and creates a database to store them.

### 2.3.1 Test Main Loop

The highest level of this design is the test main loop. The test main loop creates the SQLite database which stores all important information for easy transfer between the different python scripts necessary for the test bed. This program also contains variables for various test parameters, which are stored in an SQLite database for easy reference and sometimes directly control the sequence of a test. Finally, this program loops through the sequence interference signals specified by the various test parameters, and sends the commands to the VSG to generate them. The commands

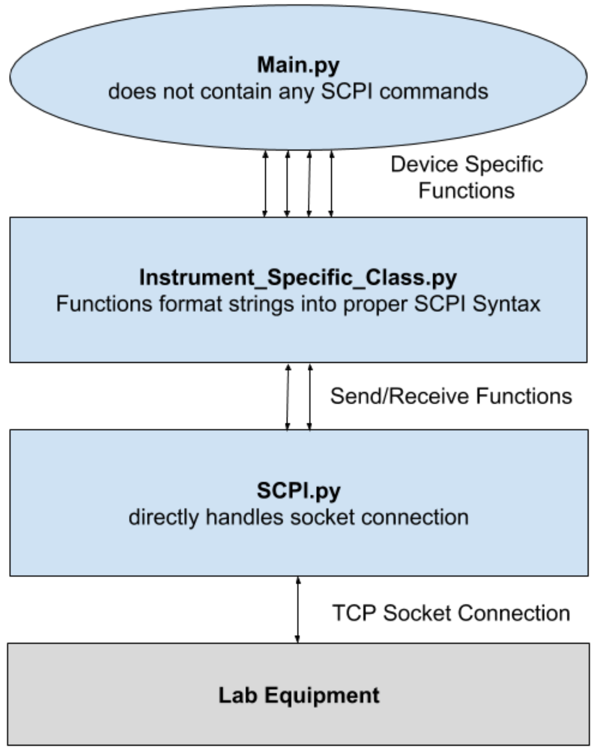


Figure 2.3: SCPI Class Hierarchy

sent to the VSG are time stamped as precisely as possible, and recorded in the *Generated Signals* table in the database.

Certain test parameters are stored for reference or calculation but do not directly affect the sequence of interference signals to be generated. These include the altimeter make and model, the nominal height of the test setup, the loss experienced by interference signals traveling to the altimeter RX, and the loop loss used in the setup. Other parameters directly control the sequence of the test, including interference on and off times, power levels to be used, modulation formats to be tested, and RF carrier frequencies to be used.

#### 2.3.1.1 Nominal Height vs Correct Height

*Nominal height* is the term used to refer to the height of the test setup. For example, the smallest spool of fiber optic cable is 500ft long, so the test setup using only this spool in the altitude simulator has a *nominal height* of 500ft. However, the measured height in a particular setup will typically differ from the nominal height by a small amount. This small offset varies between the different altimeters under test. The difference between measured height and the nominal height of the setup can be attributed in part to the extra cabling going to and from the altitude simulator, but primarily is a result of different calibration settings for each altimeter.

The calibration procedure is an important part of installing an altimeter onto an aircraft. When an aircraft is on the ground, the TX and RX antennas used by the altimeter are naturally several feet off the ground, in line with the airframe. To compensate for the varying heights of airframes, avionics manufacturers developed a calibration procedure so that each altimeter could be programmed upon installation to output an altitude of 0ft when the plane is on the ground. Because these tests are only concerned with *height error*, rather than the most precise height measurement possible in the setup, this calibration is not corrected for in test procedures. Instead, a variable called *correct_height* is calculated in post processing as the median altitude with no interference. Any height error attributable to interference is measured as a distortion from this correct height.

#### 2.3.1.2 Sequence Control

The primary purpose of the test main loop is to subject an altimeter to various modulation formats, gradually stepping up the power of each until the altitude readings from an altimeter are distorted or broken. The main loop determines the type of modulation, power level, and timing, and as each signal is turned on or off by the VSG, stores the parameters for the signal in the *Interference Signals* table for use in post processing, an example of which is shown in Table 2.2. Each unique modulation format and power combination will have two entries in the *Interference Signals* table, corresponding to the RF ON and RF OFF states of the VSG.

A variety of parameters controls the progression of different interference signals. The *interfer-*

| ID | Altimeter | Start Time | End Time | Modulation | Power dBm | RF State |
|---|---|---|---|---|---|---|
| 1 | Altimeter A | 2017-06-11 19:23:06 | 2017-06-11 19:23:07 | MSK | -10 | OFF |
| 2 | Altimeter A | 2017-06-11 19:23:07 | 2017-06-11 19:23:08 | MSK | -10 | ON |

Table 2.2: Example Interference Signals Table

*ence_duration* and *signal_off_duration*, define the length of time the altimeter will be subjected to a particular interference signal, as well as the length of time the altimeter will have to recover from any error caused by the previous signal. Throughout the main loop, each signal's Start Time and End time is calculated using interference duration variables.

The next variable which is important to the progression of a test is a list called *modulation_formats*, which contains strings corresponding to the different modulations the VSG will generate. MSK and OFDM signals of varying bandwidths will be listed here. Each string in the modulation formats list will be passed to a helper function called *choose_carrier_frequency*, which gives the option for different modulation formats to be put on different carriers, as well as for carrier *power_min*, *power_max*, and *power_step*

#### *2.3.1.3 Precision of Timing Commands*

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